Adversarial Attack on Attackers: Post-Process to Mitigate Black-Box Score-Based Query Attacks

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Abstract

The score-based query attacks (SQAs) pose practical threats to deep neural networks by crafting adversarial perturbations within dozens of queries, only using the model's output scores. Nonetheless, we note that if the loss trend of the outputs is slightly perturbed, SQAs could be easily misled and thereby become much less effective. Following this idea, we propose a novel defense, namely Adversarial Attack on Attackers (AAA), to confound SQAs towards incorrect attack directions by slightly modifying the output logits. In this way, (1) SQAs are prevented regardless of the model's worst-case robustness; (2) the original model predictions are hardly changed, *i.e.*, no degradation on clean accuracy; (3) the calibration of confidence scores can be improved simultaneously. Extensive experiments are provided to verify the above advantages. For example, by setting $\ell_\infty = 8/255$ on CIFAR-10, our proposed AAA helps WideResNet-28 secure 80.59% accuracy under Square attack (2500 queries), while the best prior defense (*i.e.*, adversarial training) only attains 67.44%. Since AAA attacks SQA's general greedy strategy, such advantages of AAA over 8 defenses can be consistently observed on 8 CIFAR-10/ImageNet models under 6 SQAs, using different attack targets and bounds. Moreover, AAA calibrates better without hurting the accuracy. Our code would be released.

1 Introduction

Deep Neural Networks (DNNs) are vulnerable to adversarial examples (AEs), where human-imperceptible perturbations added to clean samples can fool DNNs to give wrong predictions [1, 2]. Recently, such a threat is made practically feasible by the black-box score-based query attacks (SQAs) [3, 4, 5], as they only require the same information as users to craft efficient AEs. Users, for better judgments, need the model's prediction confidence indicated by DNNs' output scores, which is the only knowledge needed by SQAs to perform attacks. In contrast, white-box attacks [6, 7, 8] or transfer-based attacks [9, 10] require the gradients or training data of DNNs. Moreover, it has been shown that SQAs can achieve a non-trivial attack success rate by a reasonable number of queries, *e.g.*, dozens, compared to thousands of queries for decision-based query attacks [11, 12, 13]. Thus, such feasibility and effectiveness of SQAs are attracting increasing attention from defenders [14].

Defending against SQAs is a different goal compared to improving the *worst-case* robustness as commonly studied [15, 16, 17]. Because in *real-world scenarios* which SQAs are designed for, DNNs are treated as black boxes, in which the only interaction between models and users/attackers is the model's output scores. Thus, altering the scores is all defenders could do here, either in direct or indirect ways. Most existing defenses indirectly change outputs by optimizing the model [8, 18, 19] or pre-processing the inputs [14, 20], which, however, severely affect models' normal performance for different reasons. Training a robust model, *e.g.*, by adversarial training [8, 21], diverts the model's attention to learning AEs, yielding the so-called accuracy-robustness trade-off [22]. Randomizing

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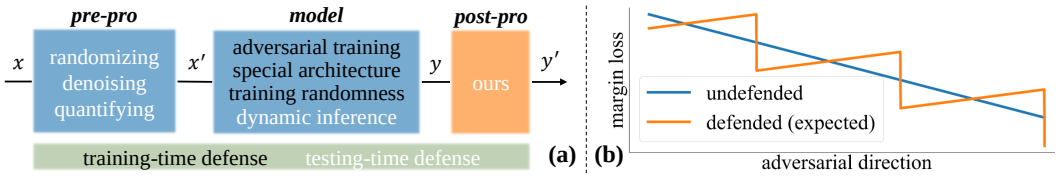

Figure 1: Compared to existing defenses on inputs or models, AAA post-processes to avoid SQAs as in (a). Our main idea is to show attackers the incorrect attack direction as illustrated in (b). Specifically, if we perturb the original blue loss curve to the orange one, then attackers that trying to decrease the loss would be mostly cheated away from their true destiny, *i.e.*, the adversarial direction.

[14, 23, 24, 25, 26] and blurring [20, 27, 28, 29] inputs reduce the signal-noise ratio, inevitably hurdling accurate decision. Dynamic inference [19, 30] is time-consuming due to the test-time optimization on model. Thus, it is imperative to develop a user-friendly defense against SQAs. In this paper, we hereby consider a post-processing defense as demonstrated in Fig. 1 (a), which naturally enjoys the benefits as follows: (1) model's decision is hardly affected since good predictions have already been obtained; (2) model calibration can be simultaneously improved via post-processing [31, 32] to output accurate prediction confidence; (3) it can be flexibly used as a plug-in module for pre-trained models with negligible test-time computation overhead. Despite these merits, it remains unexplored that by post-processing,

How to serve users while avoiding SQA attackers when they access the same output information?

Since SQAs are black-box attacks that find the adversarial direction to update AEs by observing the loss change indicated by DNN's output scores, we can perturb such scores directly to fool attackers into incorrect attack tracks. Following this idea, we propose the adversarial attack on attackers (AAA), which reverses the loss trend so that attackers, trying to greedily update AEs following the original trend, are led to the non-adversarial path farther away from the decision boundary as shown in Fig. 1 (b). Specifically, AAA directly optimizes DNN's logits to control the output loss to approximate the reversed curve, which is orange in Fig. 1 (b), where one could see that attackers that are threatening to the undefended model (going adversarial by reducing loss) would be attacked to help the defended DNN predict (going non-adversarial by reducing loss). Now that a post-processing module is adopted here, we could simultaneously use it to calibrate the model as commonly proposed [31, 33]. Thus, a simple plug-in post-module is all you need to both fool attackers and offer users accurate confidence.

By post-processing, AAA not only lowers the calibration error without hurting accuracy in all cases, but also efficiently prevents SQAs, *e.g.*, helping a WideResNet-28 [34] on CIFAR-10 [35] secure 80.59% accuracy under Square attack [5] (2500 queries), while the best prior defense (*i.e.*, adversarial training [36]) only attains 67.44%. Because AAA attacks the general greedy update of SQAs, such advantages of AAA over 8 baseline defenses can be consistently observed on 8 CIFAR-10/ImageNet models under 6 SQAs, using different attack targets, norms, bounds, and losses, verifying AAA a user-friendly, effective, and generalizable defense.

Contributions

- We analyze current defenses from the view of SQA defenders and point out that a post-processing module forms not only effective but also user-friendly and plug-in defenses.
- We design a novel adversarial attack on attackers (AAA) defense that fools SQA attackers to incorrect attack directions by slightly perturbing the DNN output scores.
- We conduct comprehensive experiments showing that AAA outperforms the other 8 defenses in the accuracy, calibration, and protection from all tested 6 SQAs under various settings.

2 Related work

Query attacks are black-box attacks that only require the model's output information. Query attacks can be divided into score-based query attacks (SQAs) [3, 4, 5, 37, 38, 39, 40] and decision-based query attacks (DQAs) [11, 12, 13, 41]. SQAs greedily update AEs from original samples by

observing the loss change indicated by DNN's output scores, *i.e.*, logits or probabilities. Early SQAs try to estimate DNN's gradients by additional queries around the sample [38, 42]. Recently, it is validated query-efficient to perform fast pure random-search SQAs [4, 5]. It has also been proposed to use pre-trained surrogate models in SQAs [39, 43], which, however, demands unfeasible access to DNN's training sample as in transfer-based attacks [9, 10]. Thus, we do not focus on defending such SQAs as also in [14]. Besides SQAs, DQAs rely only on DNN's decisions, *e.g.*, the top-1 predictions, to generate AEs. Since DQAs could not perform the greedy update, they start crafting the AE from a different sample and keep DNN's prediction wrong during the attack. Currently, DQAs need thousands of queries to reach a non-trivial attack success rate [44] compared to dozens of times for SQAs [5] as compared in Appendix A, limiting their threats. Additionally, SQAs are mostly applicable and attackers do not have to resort to DQAs because, in the real world, DNNs must not only be accurate but also indicate when they tend to be incorrect [31] by outputting confidence scores.

Adversarial defense mainly has two different goals. The first goal is to improve DNN's worst-case robustness [17], which demands DNNs to have no AE around clean samples bounded by a norm ball. Such robustness is originally evaluated by gradient-based white-box attacks [6, 7], but later, gradient obfuscation phenomenon is discovered [15], motivating evaluations to incorporate random noise and black-box attacks [16] in adaptive methods [16, 45, 46]. In this assessment, adversarial training (AT) [8, 21] is validated as the most effective defense, and other methods, *e.g.*, using more or augmented data [47, 48], designing special architecture [18, 49, 50], and inducing randomness in training [51, 52], all need collaborations with AT to achieve good performance. Another defense goal is to mitigate real-case adversarial threats, and the defense performance is evaluated by the feasible and query-efficient SQAs. A more robust model in the worst cases certainly protects itself in real cases. Besides, it is also possible to defend by dynamic inference [19, 30], and randomizing [14, 23, 24, 25], denoising [20, 27] or quantifying [28, 29] inputs. However, all aforementioned defenses on inputs or models exert a non-negligible impact on accuracy, calibration, or inference speed due to the focus on learning AEs in AT, the reduction of signal-noise ratio in pre-processing, or the costly test-time optimization in dynamic inference as compared meticulously in Section 3.

Model calibration performance is a higher demand for a good model besides high accuracy. Besides correct predictions, model calibration additionally requires DNNs to produce accurate confidence in their predictions [53]. For instance, exactly 80% of the samples predicted with 80% confidence should be correctly predicted. In this point of view, the expected calibration error (ECE) [32] is widely used to quantify the error between accuracy and confidence. Various methods have been proposed to improve DNN's calibration in training [33, 54, 55, 56] or by a post-processing module after training [31, 32, 57]. Among them, temperature scaling [32] is a simple but effective method [31], which divides all output logits by a single scalar tuned by a validation set so that the ECE in testing samples would be significantly reduced. Since division is a simple post-processing operation, calibration could be simultaneously achieved by AAA, the first post-processing defense. There have been methods to avoid attacks by calibration [56] or calibrate by attack [33], but the simultaneous improvement of defense and calibration has not been reported to the best of our knowledge.

3 Preliminaries and motivation

Before presenting the proposed method, we first introduce the key ideas of SQAs and analyze existing defenses. For a [R3.3] sample $\boldsymbol{x}$ labelled by y, an SQA on a DNN f generates an AE $\boldsymbol{x}'$ by minimizing the margin between logits [4, 5, 40, 58] as

$$\mathcal{L}(f(\boldsymbol{x}), y) = f_y(\boldsymbol{x}) - \max_{k \neq y} f_k(\boldsymbol{x}), \tag{1}$$

namely the margin loss [7]. For defenders without the label y, it is possible to calculate the unsupervised margin loss based only on the logits vector $\boldsymbol{z} = f(\boldsymbol{x})$ as [R3.3]

$$\mathcal{L}_{\mathrm{u}}(\boldsymbol{z}) \triangleq \mathcal{L}\left(f(\boldsymbol{x}), \hat{y}\right)) \tag{2}$$

by assuming the model prediction $\hat{y}$ to be correct, since handling originally misclassified samples falls beyond the scope of defense [17]. For attackers with label y, it can be known that the attack succeeds if $\mathcal{L}(f(\boldsymbol{x}), y) < 0$. To quickly realize this, SQAs only update AEs if a query $\boldsymbol{x}_{\mathrm{q}}$ has a lower margin loss compared to the current best query $\boldsymbol{x}_k$, *i.e.*,

$$\boldsymbol{x}_{k+1} = \begin{cases} \boldsymbol{x}_{\mathrm{q}}, & \mathcal{L}(f(\boldsymbol{x}_{\mathrm{q}}), y) < \mathcal{L}(f(\boldsymbol{x}_k), y), \\ \boldsymbol{x}_k, & \mathcal{L}(f(\boldsymbol{x}_{\mathrm{q}}), y) \geq \mathcal{L}(f(\boldsymbol{x}_k), y). \end{cases} \tag{3}$$

Existing SQAs [4, 5, 40] are quite effective, capable of halving the accuracy within 100 queries on CIFAR-10 when $\ell_\infty = 8/255$, posing significant and practical threats. Aware of this, the first defense specifically against SQAs has been recently proposed [14] to pre-process inputs by random noise. Besides, other existing defenses are also useful to avoid SQAs, among which the most representative ones are adversarial training (AT) [8, 21], dynamic inference [19, 30], and pre-processing [14, 28]. These defenses work in different mechanisms as illustrated in Fig. 1 (a) and Section 2. Here in Table 1, we present a comparison of their key characteristics related to the defense performance.

Table 1: Expectation and effects of current defenses (unpreferable effects are marked in red)

	expectation	AT [8, 21]	pre-pro [14, 28]	dyn-inf [19, 30]	AAA (ours)
accuracy	$=$	$\downarrow\downarrow$	$\downarrow$	$=$	$=$
calibration	$\uparrow$	/	$\downarrow$	$\downarrow$	$\uparrow$
testing cost	$=$	$=$	$=$	$\uparrow\uparrow\uparrow$	$=$
training cost	$=$	$\uparrow\uparrow\uparrow$	$=$	$=$	$=$
acc under SQA	$\uparrow$	$\uparrow\uparrow$	$\uparrow$	$\uparrow$	$\uparrow\uparrow\uparrow$

Real-case defenders are expected to serve users and meanwhile avoid SQA attackers. The former demands good accuracy, calibration, and inference speed. While the latter requires good protection, and preferably, no additional training (denoted as "$=$"). As a training-time defense on model, AT exerts a significant impact on accuracy [22], *e.g.*, >10% accuracy drop on ImageNet [49], with several-fold training computation and an indefinite impact (denoted as "/") on calibration. Pre-processing is a test-time defense on input, which avoids SQAs by reducing the input's signal-noise ratio but inevitably hurts normal performance. Recently, the dynamic inference is proposed as a test-time defense by optimizing the model, which shows no accuracy drop but dramatically increases the computation, *e.g.*, DENT [19] consumes >700% test-time calculation. Given the above discussion, it is imperative to develop a user-friendly and efficient method to effectively defend against SQAs.

4 Adversarial attack on attackers

Defending by post-processing naturally carries the advantages of good accuracy and calibration [31], no additional training and negligible test-time computation. Although it does not improve the commonly-studied worst-case robustness [16], its potential to defeat SQAs in real cases has not been explored yet to the best of our knowledge. By investigating current defenses from the perspective of SQA defenders in Sec. 3, it is interesting to find that in the real world, no matter whether defenders alter inputs, models, or outputs, what users/attackers get are just the changes in outputs, *i.e.*, the black-box setting. Thus, it is reasonable and preferable for SQA defenders to directly manipulate DNN's output scores, which has already become a standard practice in model calibration [31].

But how? Now that attackers conduct the adversarial attack on the model, why cannot we defenders actively perform an adversarial attack on attackers? If attackers search for the adversarial direction by scores, we can manipulate such scores to cheat them into an incorrect attack path. Following this idea, we develop the adversarial attack on attackers (AAA) to control what the SQA attackers base their actions on, *i.e.*, the loss (1) indicated by the DNN's output scores. Under such direct misleading, SQA attackers, following their original policy, would be guided to wherever we want them to go due to their greediness, seeing (3). Therefore, we can adopt the extreme fooling that leads attackers to walk opposite towards their destiny, *i.e.*, the non-adversarial direction. In this way, attackers are attacked to actually help DNNs become more confident in predictions.

Reversing the attacker's path by directly altering outputs is simple. Since SQA attackers observe the margin loss (1), what we should do is force the modified loss to increase when the original unmodified loss actually decreases. This can be achieved by a one-to-one mapping between unmodified and modified loss values, *e.g.*, outputting large margin loss (high confidence) when the original margin is small (model is not confident). However, this naive method prevents users from getting accurate prediction confidence since it greatly changes scores to reverse the overall loss trend along the adversarial direction. Thus, we alternatively reverse the loss in a small interval while keeping the overall trend unchanged as in Fig. 1 (b). This design cheats attackers in most cases, but only requires slight modifications on scores so that the precision of confidence is largely preserved.

Specifically, we periodically set *loss attractors* and encourage the DNN's unsupervised margin loss (2) to move towards its closest attractor [R1.2, R3.1, R3.3]

$$l_{\mathrm{a}} = (\text{floor}\ (l_0/t) + 1/2) \times t, \tag{4}$$

where $l_0 = \mathcal{L}_{\mathrm{u}}(\boldsymbol{z_0})$ is the unmodified loss, and $\boldsymbol{z_0}$ means the unmodified logits. t is the period of attractor intervals, a constant hyper-parameter set by defenders, and "floor" denotes rounding down decimals to integers. For example, if $t = 4$, then according to (4), the closest loss attractor of logits with $l_0 = 0 \rightarrow 4$ is $l_{\mathrm{a}} = 2$. As we can see, the $1/2$ bias is necessary to avoid setting an attractor on $l_{\mathrm{a}} = 0$, *i.e.*, the decision boundary, because approximating the logits to it may flip model's decision.

Periodically-set loss attractors divide logits with different l_0 into intervals, so that we could reverse the loss trend in each of the interval to cheat attackers into the opposite attack direction as in Fig. 1 (b). However, reversing the trend demands more than mapping in-interval losses to a fixed value l_{a}. It requires mapping a small loss with a large one. Thus, we set the target loss value l_{t} for logits as

$$l_{\mathrm{t}} = l_{\mathrm{a}} - \alpha \times (l_0 - l_{\mathrm{a}}). \tag{5}$$

That is, if the unmodified loss l_0 is larger than l_{a} by l_{diff}, we hope the modified loss l_{t} to be smaller than l_{a} by $\alpha \times l_{\mathrm{diff}}$. In this way, as a sample is actually close to the decision boundary (l_0 decreases), AAA outputs an increasing l_{t} to mislead attackers away from this adversarial direction.

Although the periodic design has already altered output confidence very slightly, we could also step further to improve the precision of confidence because post-processing logits is a standard practice in model calibration [32, 57]. Thus, simultaneous defense and calibration is obtainable in a single AAA module by controlling the loss while encouraging the output confidence $\sigma(\boldsymbol{z}) = \max(\text{softmax}(\boldsymbol{z}))$ to approach the calibrated one p_{t} as

$$\min_{\boldsymbol{z}} \quad \| \mathcal{L}_{\mathrm{u}}(\boldsymbol{z}) - l_{\mathrm{t}} \|_1 + \beta \cdot \| \sigma(\boldsymbol{z}) - p_{\mathrm{t}} \|_1, \tag{6}$$

where the first item requires the output loss to form the reversed curve so that attackers would be cheated to non-adversarial directions, while the second item motivates the output confidence to be accurate, and β controls the balance between them. Through this design, DNN's output could be both accurate and misleading, achieving two seemingly contradictory goals at the same time.

The calibrated confidence p_{t} is obtainable by various model calibration methods [32, 57]. Among them, temperature scaling [32] is simple but effective [31], which divides all logits by a scalar T as $p_{\mathrm{t}} = \sigma(\boldsymbol{z}_0/T)$. The temperature T is tuned by a validation set to minimize the calibration error, and here, such tuning is conducted when the optimization (6) is also performed so that we can find the temperature that suits AAA best. After that, T is fixed for inference in AAA post-processing module.

We summarize our algorithm in Alg. 1. AAA first calculates the original loss l_0, according to which sets the target loss l_{t} that forms the reversed loss curve. Then AAA optimizes the logits to reach the target loss, and also the target confidence p_{t}, which is obtained by dividing the original logits using a pre-tuned temperature T. The overall procedure is conducted in test-time with only optimization on the logits, making AAA a computation-efficient, plug-in, and model-agnostic method with good accuracy, calibration, and defense against SQAs.

Algorithm 1 Adversarial Attack on Attackers

Input: the logits $\boldsymbol{z}_0$, model's temperature T, AAA hyper-parameters.
Output: post-processed logits $\boldsymbol{z}$

1: calculate original loss $l_0 = \mathcal{L}_{\mathrm{u}}(\boldsymbol{z}_0)$ by (2)
2: set target loss l_{t} by (5)
3: set target confidence $p_{\mathrm{t}} = \sigma(\boldsymbol{z}_0/T)$
4: initialize $\boldsymbol{z} = \boldsymbol{z}_0$ and optimize it for (6)
5: **return** $\boldsymbol{z}$

5 Experiments

5.1 Setup

We evaluate AAA along with 8 defense baselines, including random noise defense (RND [33]), adversarial training (AT [36, 59, 49]), dynamic inference (DENT [19]), training randomness (PNI [51]), and ensemble (TRS [60]). Results of AT with extra data [22]) are in Appendix A. AAA uses hyper-parameters $\alpha = 1, t = 6, \beta = 5$, and an Adam optimizer [61] with learning rate $0.1, \beta_1 = 0.9, \beta_2 = 0.999$, and the iteration of optimization 100. To calibrate simultaneously by AAA, we perform temperature scaling using 1K/5K samples for CIFAR-10 testing set / ImageNet

validation set respectively to and make them disjoint with the testing samples in attack as much as possible. Detailed hyper-parameters of other defenses and attacks are in Appendix E.

The defenses are assessed by 6 state-of-the-art SQAs, which are random search methods including Square [5], SignHunter [40], and SimBA [4], and gradient estimation methods including NES [58], and Bandits [3]. [R3.3] Square attack [5] selects a decreasing size of random square perturbations. SignHunter [40] estimates the sign of gradient and flips corresponding perturbations. SimBA [4] randomly samples perturbations given an orthonormal basis. NES [58] adopts the Natural Evolutionary Strategies to for gradient estimation. Bandits [3] jointly uses the time and data-dependent gradient prior. Some SQAs use pre-trained models [39, 43], which, however, demands unfeasible access to DNN's training sample. To evaluate real-case defenses against training-based attacks, we alternatively consider a practical SQA QueryNet [62] based on model stealing. Results of DQAs and SQAs using other than margin loss are put in Appendix A. Since AAA aims to defend in real cases without resorting to randomness, it would be unsuitable to evaluate AAA by the common adaptive or white-box attacks [16], e.g., EOT [15]. We mostly perform untargeted ℓ_∞ attacks, but we also test the targeted and ℓ_2 attacks under different bounds to observe the generalization of defenses.

We use 8 DNNs, which are mostly WideResNets [34] as in [17]. The pre-trained models of PNI [51] / TRS [60] are ResNet-20 [63], and we also test ResNeXt-101 [64] in ImageNet. Other studied DNNs come from RobustBench [17] and torchvision [65] as specified in Appendix E. AT models are tested using the same bound as in AT, if not otherwise stated. We use all 10K CIFAR-10 testing samples. For ImageNet, we randomly-select 1K validation samples from all 1K classes respectively (1 image in 1 class) to eliminate the class bias as in [62]. All images are rescaled to $[0, 1]$, and the ImageNet ones are resized to 224×224. Before feeding them to DNNs, we quantify images to 8-bit, imitating the real-case 8-bit image setting as in [62]. Experiments are performed on an NVIDIA Tesla A100 GPU but could be run on any GPU with over 4GB memory.

As defenders, we are concerned about DNN's remaining accuracy after it being attacked by SQAs for a certain query times. Thus, we report such *SQA adversarial accuracy* after 100 and 2500 queries, reflecting DNN's performance under mild and extreme SQAs. We include the average query times, another metric commonly used by attackers, in Appendix C. To measure the calibration, the expected calibration error (ECE) [32] is commonly used. ECE divides all N testing samples into M bins, and each bin contains samples with confidence ranging from the mth quantile to the $(m+1)^{\text{th}}$ quantile of $[0, 1]$. Then ECE is calculated by the difference between accuracy and confidence as $\frac{1}{N}\sum_{m=1}^{M}\left|\sum_{i\in B_m}\mathbf{1}(\hat{y}_i = y_i) - \sum_{i\in B_m}\hat{p}_i^{\hat{y}_i}\right|$, where $\hat{y}_i$ is the predicted label of the ith sample in the mth bin B_m, and $\hat{p}_i^{\hat{y}_i}$ represents the probability confidence of this prediction.

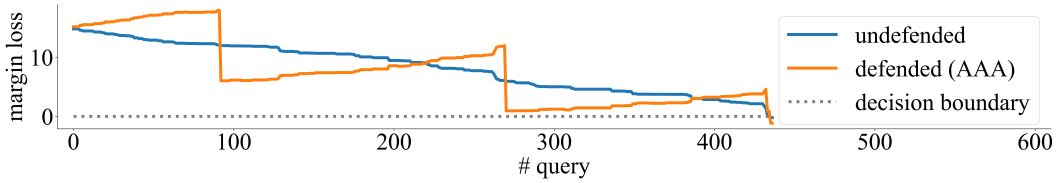

Figure 2: The AAA-defended (with the above hyper-parameters) and undefended margin loss value when attacking the undefended WideResNet-28 [34] in RobustBench [17] by Square attack [5] ($\ell_\infty = 8/255$) using the 9953th CIFAR-10 test sample (other samples have similar trends as in Appendix B). AAA fools attackers precisely as shown by the tiny symmetric oscillations of two lines.

5.2 Visual illustration of AAA

We first visually illustrate the mechanism and effects of AAA. AAA, besides fooling attackers, also calibrates the model, forming the loss curve as in Fig. 2. Slightly different from the ideal defense in Fig. 1 (b) is that the orange curve is lowered for calibration. However, calibration does not hurdle fooling attackers, *i.e.*, the orange line is mostly going opposite to the blue line in a precisely symmetric manner. Also, two lines cross the decision boundary at the same time, meaning that AAA does not change the decision.

Besides the loss, it is also necessary to observe the output probabilities of AAA, which is displayed in Fig. 3 (left). AAA, indicated by the orange lines, changes the scores slightly without hurting

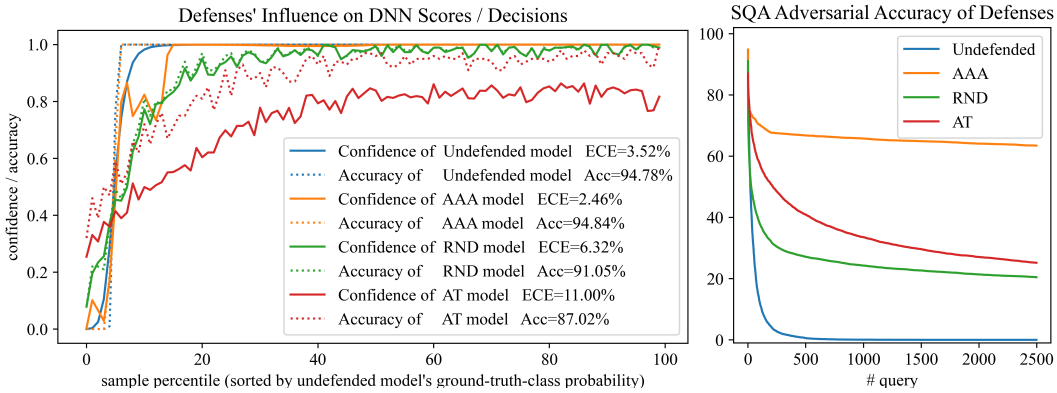

Figure 3: The left figure illustrates the change of output scores for different defenses. We first sort 10K testing samples in ascending order according to their ground-truth-class probability predicted by the undefended model (blue line), and then divide them into 100 bins, so that the left bins in the figure stand for low-confidence or misclassified samples, and vice versa. Then for samples in each bin, we plot the confidence (solid lines) and accuracy (dotted line) for AT [36], RND [33], and AAA. Compared to AT and RND, AAA alters scores most slightly without influencing the accuracy curve. The right figure shows DNN's accuracy under Square attack [5] when $\ell_2 = 2.5$, indicating that AAA outperforms alternatives in defending SQAs by a large margin with also the highest clean accuracy.

accuracy (dotted lines) compared to RND [33] and AT [36]. By such small modifications, AAA not only improves the calibration but also prevents SQAs by misleading them into incorrect directions. As displayed by the right part of Fig. 3, AAA is super effective in avoiding SQAs, even if it is a query-efficient attack working at a large bound. Specifically, AAA preserves a standard trained DNN to have >60% accuracy after 2500 queries, doubling the performance of AT and tripling that for RND.

Table 2: The defense performance under attacks (#query $= 100/2500$)

Model	Metric / Attack	None	AT [36, 59, 49]	RND [14]	AAA (ours)
CIFAR-10	ECE (%)	3.52	11.00	6.32	**2.46**
$\ell_\infty = \frac{8}{255}$	Acc (%)	94.78	87.02	91.05	**94.84**
	Square [5]	39.38 / 00.09	78.30 / 67.44	60.83 / 49.15	**81.36 / 80.59**
Wide-	SignHunter [40]	41.14 / 00.04	78.87 / 66.79	61.02 / 47.82	**79.41 / 76.71**
ResNet-	SimBA [4]	53.04 / 03.95	84.21 / 75.85	76.39 / 64.34	**88.86 / 83.36**
28 [34]	NES [58]	83.42 / 12.24	85.92 / 81.01	86.23 / 68.19	**90.62 / 85.95**
	Bandit [3]	69.86 / 41.03	**83.62** / 76.25	70.44 / 41.65	80.86 / **78.36**
ImageNet	ECE (%)	5.42	5.03	5.79	**4.30**
$\ell_\infty = \frac{4}{255}$	Acc (%)	77.11	66.30	75.32	**77.17**
	Square [5]	52.27 / 09.25	59.20 / 51.11	58.67 / 50.54	**63.13 / 62.51**
Wide-	SignHunter [40]	53.05 / 13.88	59.47 / 56.22	59.36 / 52.98	**62.35 / 56.80**
ResNet-	SimBA [4]	71.79 / 20.90	65.64 / 47.60	66.36 / 63.27	**74.16 / 67.14**
50 [34]	NES [58]	77.11 / 64.93	66.30 / 64.38	71.33 / 66.05	**77.12 / 67.06**
	Bandit [3]	71.33 / 65.77	65.30 / 63.98	65.15 / 61.38	**72.15 / 70.53**
ImageNet	ECE (%)	8.37	**5.74**	8.93	7.38
$\ell_\infty = \frac{4}{255}$	Acc (%)	**78.21**	63.94	76.75	**78.21**
	Square [5]	54.51 / 11.73	57.99 / 51.47	58.56 / 48.20	**66.32 / 65.77**
Res-	SignHunter [40]	54.12 / 13.30	59.14 / 56.49	58.02 / 52.50	**62.72 / 59.60**
NeXt-	SimBA [4]	70.86 / 24.64	59.40 / 57.53	68.31 / 66.16	**74.06 / 67.26**
101 [64]	NES [58]	**78.21** / 66.24	63.94 / 62.51	73.37 / **69.30**	**78.21** / 68.51
	Bandit [3]	72.19 / 67.73	63.18 / 62.26	67.69 / 64.62	**72.91 / 71.48**

5.3 Numerical results of AAA

We report the main numerical results in Table 2, where RND and AAA are directly implemented in the undefended model denoted as "None". The AT method for the three models are PSSiLU [36], vanilla AT [59], and feature denoising [49], respectively. According to Table 2, AAA not only consistently reduces ECE by >12%, but also does not hurt clean accuracy. In contrast, the AT models lose >7% accuracy and RND also endures a drop in accuracy and calibration. Under SQAs, AAA preserves a significantly higher accuracy than the undefended model, which is totally destroyed. The most threatening SQAs in two datasets more than halve the CIFAR-10 model's accuracy within 100 queries and degrade ImageNet ones to <15% by 2500 times. However, the AAA model remains >75% and >55% accuracy in extreme cases. AT and RND are useful in mitigating SQAs, but it is AAA that tops the defense performance in almost all cases.

Besides AT and RND, diverse defenses have also been proposed, and it would be interesting to see their results, which we report in Appendix F. The conclusion is that they are not comparable to AAA in real cases regarding the accuracy, calibration, and defense performance.

5.4 Generalization of AAA

Aside from the untargeted ℓ_∞ attacks, we also conduct targeted attacks, ℓ_2 attacks under different bounds to study the generalization of AAA. A targeted attack is successful only if an AE is mispredicted as a pre-set class, which, is randomly chosen from incorrect classes for each sample here. And ℓ_2 attacks bound the perturbations by ℓ_2 norm, which is reported to fool DNNs better [10]. Here we additionally validate AAA's plug-in advantage by combining it with AT. Note that what differs from AAA and most existing defenses [49, 50, 51] combined with AT is that AAA has already achieved excellent defense performance, so such a combination is feasible but not necessary. We choose Square attack [5] to perform the above evaluations because it is the most effective SQA as tested in Table 2. The results are presented in Table 3, where all models are exactly the same as in Table 2 (CIFAR-10) without tuning hyper-parameters of defense to fairly evaluate the generalization of different methods. The results of ℓ_2 AT model and other ℓ_∞ AT models are put in Appendix A.

In the difficult targeted attack setting, the undefended model remains only 2.84% accuracy after 2500 queries, which is approximately just the accuracy drop of the AAA model. For ℓ_2 attacks, AAA is still capable of mitigating threats without hurting users, and its superiority is more outstanding as the attack bound becomes larger. AT models, although robust, suffer from attacks under a large or different norm ball [56]. Thus, its defense effects decrease as SQA alters the setting, seeing the bottom line. Defended by AAA, however, this drawback would be greatly avoided. An ℓ_∞ AT model, even under $\ell_2 = 2.5$ attack after 2500 queries, is hardly influenced, *i.e.*, increasing query times after 100 queries hardly better the attack performance, discouraging SQA attackers.

Table 3: Generalization of AAA tested by Square attack [5] (#query $= 100/2500$, CIFAR-10)

Metric / Attack	None	AAA (ours)	AT [36]	AT-AAA
ECE (%)	3.52	**2.46**	11.00	**10.56**
Acc (%)	94.78	**94.84**	**87.02**	**87.02**
untargeted $\ell_\infty = 8/255$	39.38 / 00.09	**81.36 / 80.59**	78.30 / 67.44	**80.80 / 80.13**
targeted $\ell_\infty = 8/255$	75.59 / 02.84	**92.05 / 91.62**	85.75 / 82.72	**86.22 / 86.13**
untargeted $\ell_2 = 0.5$	81.53 / 18.75	**92.66 / 92.63**	84.26 / 78.97	**85.12 / 84.31**
untargeted $\ell_2 = 2.5$	12.77 / 00.01	**70.35 / 63.46**	57.88 / 25.19	**74.03 / 73.72**

5.5 Time consumption of AAA

[R1.3, R2.2] We study the influence of optimization times in AAA to see the balance between the amount of computation and defense performance. AAA's runtime is estimated by inferring 10K CIFAR-10 samples in a WideResNet28 model. The results are shown in Table 4. As we see, optimizing low-dimensional logits is not costly, and good defense and calibration results are also obtainable by 60-80 iterations, which costs less time. Since optimizing logits is independent of model size, model owners could determine AAA runtime precisely.

Table 4: Influence of the optimization times in AAA (100-query Square attack on CIFAR-10)

# iter	0	20	40	60	80	100
ECE	3.52	2.87	2.81	2.66	2.53	2.53
Adv-Acc	39.38	79.29	80.92	81.37	81.28	81.36
inference time per sample (ms)	1.016	1.034	1.088	1.099	1.143	1.163

A study of other hyper-parameters has been put in Appendix G. An intuitive conclusion is that AAA is insensitive to even exponentially tuned hyper-parameters. And a larger α, a larger t, or a smaller β that highlights defense more v.s. calibration thereby increases the adversarial accuracy and ECE.

5.6 Adaptive attacks of AAA

[R2.1, R3.2] Designing adaptive attacks, though possible, is costly and easy to bypass in real-world scenarios. Because here, attackers and defenders are in a double-blind relationship, i.e., attackers do not know the model, including the defense strategy. Thus, the discovery process of defense strategies for developing adaptive attacks would require additional queries and creative deductions. After that, attackers also have to devote considerable manual efforts to figure out what defenders actually do. In this regard, AAA imposes a great hurdle to adaptive attackers.

But still, it is interesting to see that after unveiling defender's strategy by great effort, how adaptive attackers could break the AAA model. There are two straightforward adaptive attacks against AAA: going bidirectional or opposite to the original attack direction, which are both based on the exceptional loss change that attackers observe to decide the update direction. However, adaptive attackers are also foolable because the dramatic drop of loss across intervals could be smoothed, e.g. by using a sine function to design the target loss as $l_t = l_a - \alpha \times \sin(\pi(1 - 2(l_0 - l_a)/t))$. In this way, neither direction of search is likely to figure out the defense strategy, seeing results below.

Table 5: AAA under adaptive attacks (100 queries)

Defense	None	AAA	AAA-sin
Square	39.38	81.36	79.78
bidirectional Square	57.09	62.91	75.36
opposite Square	94.78	57.31	75.23

The bidirectional / opposite search weakens AAA from 81.36% to 62.91% / 57.31%, but the sine-like function that ascends and descends the loss along the original attack direction fools both non-adaptive and adaptive attacks. By designing sine l_t, the defense performance for the regular attack is kept at 79.78% while the performance under bidirectional / opposite search is improved to 75.36% / 75.23%. Thus, AAA is effective in mitigating adaptive SQAs.

6 Conclusion, impacts and limitations

We develop a novel defense against score-based query attacks (SQAs). Our main idea is to actively attack the attackers (AAA), misleading them into incorrect attack directions. AAA achieves that by post-processing DNN's logits while enforcing the new output confidence to be calibrated, making AAA a deterministic plug-in test-time defense with improvements in calibration and accuracy by costing negligible computation overhead. Compared to alternative defenses, AAA is effective in mitigating SQAs according to our study on 8 defenses, 6 SQAs, and 8 DNNs under various settings.

As a defense in real-world applications, AAA greatly mitigates the adversarial threat without requiring huge computational burden. For example, in autonomous driving or supervision systems, the post-processing defense module could be directly implemented in pre-trained models. Despite the low cost, the benefits of adopting AAA are profound. In most cases, users would be provided with a more accurate confidence score so that they know better when the model tends to fail. In adversarial cases, SQAs, the most threatening attack in real cases, would be effectively prevented.

AAA is developed to especially prevent SQAs. Thus, defending our types of attacks is beyond our scope. For example, AAA does not improve the worst-case robustness evaluated in white-box settings [16, 46] where attackers have complete knowledge of the model (the AutoAttack [16] robust accuracy would be increased in an undesirable manner by AAA). Also, AAA is not applicable to avoiding transfer-based attacks and decision-based query attacks, which are either unfeasible or inefficient in the real world, because AAA induces only a negligible impact on the decision boundary.

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Checklist

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes] See the third paragraph in Sec. 6.
   (c) Did you discuss any potential negative societal impacts of your work? [Yes] See the second paragraph in Sec. 6 for potential impacts. Negative ones have not been identified since we aim at defense.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [N/A] Our contributions are mostly empirical.
   (b) Did you include complete proofs of all theoretical results? [N/A] Our contributions are mostly empirical.
3. If you ran experiments...
   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [Yes] All the code would be released with detailed instructions and annotations. Core code of AAA is shown in Appendix D. The data are described in experimental setup in Sec. 5.1.
   (b) Did you specify all the training details (*e.g.*, data splits, hyperparameters, how they were chosen)? [Yes] Details are presented in Sec. 5.1 and Appendix E
   (c) Did you report error bars (*e.g.*, with respect to the random seed after running experiments multiple times)? [Yes] Error bars and computation amount are reported in Appendix C.
   (d) Did you include the total amount of compute and the type of resources used (*e.g.*, type of GPUs, internal cluster, or cloud provider)? [Yes] Our devices are described in Sec. 5.1, and the amount of computation is quantified in Appendix C.
4. If you are using existing assets (*e.g.*, code, data, models) or curating/releasing new assets...
   (a) If your work uses existing assets, did you cite the creators? [Yes] We state the source of DNNs in experimental setup in Sec. 5.1.
   (b) Did you mention the license of the assets? [Yes] Most used code assets are under MIT License. Square attack is under BSD 3-Clause License. ImageNet is under a custom research and non-commercial license.
   (c) Did you include any new assets either in the supplemental material or as a URL? [Yes] We would release our code as an asset.
   (d) Did you discuss whether and how consent was obtained from people whose data you're using/curating? [N/A] Our empirical studies are based on public datasets.
   (e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? [N/A] Our used public datasets generally do not contain personally identifiable information or offensive content.
5. If you used crowdsourcing or conducted research with human subjects...
   (a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A] Our experiments involve no human subjects and crowdsourcing.
   (b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A] Our experiments involve no human subjects or crowdsourcing.
   (c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A] Our experiments involve no human subjects or crowdsourcing.