Label-Only Membership Inference Attacks

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Abstract
Membership inference is one of the simplest privacy threats faced by machine learning models that are trained on private sensitive data. In this attack, an adversary infers whether a particular point was used to train the model, or not, by observing the model’s predictions. Whereas current attack methods all require access to the model’s predicted confidence score, we introduce a label-only attack that instead evaluates the robustness of the model’s predicted (hard) labels under perturbations of the input, to infer membership. Our label-only attack is not only as-effective as attacks requiring access to confidence scores, it also demonstrates that a class of defenses against membership inference, which we call “confidence masking” because they obfuscate the confidence scores to thwart attacks, are insufficient to prevent the leakage of private information. Our experiments show that training with differential privacy or strong $\ell_2$ regularization are the only current defenses that meaningfully decrease leakage of private information, even for points that are outliers of the training distribution.

1. Introduction
Machine learning algorithms are often trained on sensitive or private user information, e.g., medical records (Stanfill et al., 2010), conversations (Devlin et al., 2018), or financial information (Ngai et al., 2011). Trained models can inadvertently leak information about their training data (Shokri et al., 2016; Carlini et al., 2019)—violating users’ privacy.

In perhaps the simplest form of information leakage, membership inference (MI) (Shokri et al., 2016) attacks enable an adversary to determine whether or not a data point was used in the training data. Revealing just this information can cause harm—it leaks information about specific individuals instead of the entire population. Consider a model trained to learn the link between a cancer patient’s morphological data and their reaction to some drug. An adversary with a victim’s morphological data and query access to the trained model cannot directly infer if the victim has cancer. However, inferring that the victim’s data was part of the model’s training set reveals that the victim indeed has cancer.

Existing MI attacks exploit the higher confidence that models exhibit on their training data (Pyrgelis et al., 2017; Truex et al., 2018; Hayes et al., 2019; Salem et al., 2018). An adversary queries the model on a candidate data point to obtain the model’s confidence and infers the candidate’s membership in the training set based on a decision rule. The difference in prediction confidence is largely attributed to overfitting (Shokri et al., 2016; Yeom et al., 2018).

A large body of work has been devoted to understanding and mitigating MI leakage in ML models. Existing defense strategies fall into two broad categories and either

1. reduce overfitting (Truex et al., 2018; Shokri et al., 2016; Salem et al., 2018); or,
2. perturb a model’s predictions so as to minimize the success of known membership attacks (Nasr et al., 2018a; Jia et al., 2019; Yang et al., 2020).

Defenses in (1) use regularization techniques or increase the amount of training data to reduce overfitting. In contrast, the adversary-aware defenses of (2) explicitly aim to minimize the MI advantage of a particular attack. They do so either by modifying the training procedure (e.g., an additional loss penalty) or the inference procedure after training. These defenses implicitly or explicitly rely on a strategy that we call confidence-masking¹, where the MI signal in the model’s confidence scores is masked to thwart existing attacks.

We introduce label-only MI attacks. Our attacks are more general: an adversary need only obtain (hard) labels—without prediction confidences—of the trained model. This threat model is more realistic, as ML models deployed in user-facing products need not expose raw confidence scores. Thus, our attacks can be mounted on any ML classifier.

¹Similar to gradient masking from the adversarial examples literature (Papernot et al., 2017).
In the label-only setting, a naive baseline predicts misclassified points as non-members. Our focus is surpassing this baseline. To this end, we will have to make multiple queries to the target model. We show how to extract fine-grained MI signal by analyzing a model’s robustness to perturbations of the target data, which reveals signatures of its decision boundary geometry. Our adversary queries the model for predicted labels on augmentations of data points (e.g., translations in vision domains) as well as adversarial examples.

We make the following contributions. In § 5.1, we introduce the first label-only attacks, which match confidence-vector attacks. By combining them, we outperform all others. In § 5.2, 5.3 and 5.4, we show that confidence masking is not a viable defense to privacy leakage, by breaking two canonical defenses that use it—MemGuard and Adversarial Regularization. In § 6, we evaluate two additional techniques to reducing overfitting: data augmentation and transfer learning. We find that data augmentation can worsen MI leakage while transfer learning can mitigate it. In § 7, we introduce “outlier MI”: a stronger property that defenses should satisfy to protect MI of worst-case inputs; at present, differentially private training and (strong) L2 regularization appear to be the only effective defenses. Our code is available at https://github.com/cchoquette/membership-inference.

2. Background and Related Works

Membership inference attacks (Shokri et al., 2016) are a form of privacy leakage that identify if a given data sample was in a machine learning model’s training dataset. Given a sample x and access to a trained model h, the adversary uses a classifier or decision rule f_h, to compute a membership prediction f(x; h) \in \{0, 1\}, with the goal that f(x; h) = 1 whenever x is a training point. The main challenge in mounting a MI attack is creating the attack classifier f, under various assumptions about the adversary’s knowledge of h and its training data distribution. Most prior work assumes that an adversary has only black-box access to the trained model h, via a query interface that on input x returns part or all of the confidence vector h(x) \in [0, 1]^C (for a classification task with C classes).

The attack classifier f is often trained on a local shadow (or, source) model h_s, which is trained on the same (or a similar) distribution as h’s training data. Because the adversary trained h_s, they can assign membership labels to any input x, and use this dataset to train f. Salem et al. (2018) later showed that this strategy succeeds even when the adversary only has data from a different, but similar, task and that shadow models are unnecessary: a threshold predicting f(x; h) = 1 when the max prediction confidence, \max h(x), is above a tuned threshold, suffices.

Yeom et al. (2018) investigate how querying related inputs x’ to x can improve MI. Song et al. (2019) explore how models explicitly trained to be robust to adversarial examples can become more vulnerable to MI (similar to our analysis of data augmentation in § 6). Both works are crucially different because they use a different attack methodology and assume access to the confidence scores. Sablayrolles et al. (2019) demonstrate that black-box attacks (like ours) can approximate white-box attacks by effectively estimating the model loss for a data point. Refer to Appendix § A for a detailed background, including on defenses.

3. Attack Model Design

Our proposed MI attacks improve on existing attacks by (1) combining multiple strategically perturbed samples (queries) as a fine-grained signal of the model’s decision boundary, and (2) operating in a label-only regime. Thus, our attacks pose a threat to any query-able ML service.

3.1. A Naive Baseline: The Gap Attack

Label-only MI attacks face a challenge of granularity. For any query x, our attack model’s information is limited to only the predicted class-label, \text{argmax}_i h(x)_i. A simple baseline attack (Yeom et al., 2018) — that predicts any misclassified data point as a non-member of the training set—is a useful benchmark to assess the extra (non-trivial) information that MI attacks, label-only or otherwise, can extract. We call this baseline the gap attack because its accuracy is directly related to the gap between the model’s accuracy on training data (\text{acc}_{\text{train}}) and held out data (\text{acc}_{\text{test}}):

\begin{equation}
\frac{1}{2} + \frac{\text{acc}_{\text{train}} - \text{acc}_{\text{test}}}{2},
\end{equation}

where \text{acc}_{\text{train}}, \text{acc}_{\text{test}} \in [0, 1]. To exploit additional leakage on top of this baseline attack (achieve non-trivial MI), any label-only adversary must necessarily make additional queries to the model. To the best of our knowledge, this trivial baseline is the only attack proposed in prior work that uses only the predicted label, y = \text{argmax}_i h(x)_i.

3.2. Attack Intuition

Our strategy is to compute label-only “proxies” for the model’s confidence by evaluating its robustness to strategic input perturbations of x, either synthetic (i.e., data augmentation) or adversarial (examples) (Szegedy et al., 2013). Following a max-margin perspective, we predict that data points that exhibit high robustness are training data points. Works in the adversarial example literature share a similar perspective that non-training points are closer to the decision boundary and thus more susceptible to perturbations (Tanay & Griffin, 2016; Tian et al., 2018; Hu et al., 2019).

Our intuition for leveraging robustness is two-fold. First,
models trained with data augmentation have the capacity to overfit to them (Zhang et al., 2016). Thus, we evaluate any “effective” train-test gap on the augmented dataset by evaluating $x$ and its augmentations, giving us a more fine-grained MI signal. For models not trained using augmentation, their robustness to perturbations can be a proxy for model confidence. Given the special case of (binary) logistic regression models, with a learned weight vector $w$ and bias $b$, the model will output a confidence score for the positive class of the form: $h(x) := \sigma(w^\top x + b)$, where $\sigma(t) = \frac{1}{1+e^{-t}} \in (0, 1)$ is the logistic function.

Here, there is a monotone relationship between the confidence at $x$ and the Euclidean distance to the model’s decision boundary. This distance is $(w^\top x + b)/\|w\|_2 = \sigma^{-1}(h(x))/\|w\|_2$. Thus, obtaining a point’s distance to the boundary yields the same information as the confidence score. Computing this distance is exactly the problem of finding the smallest adversarial perturbation, which can be done using label-only access to a classifier (Brendel et al., 2017; Chen et al., 2019). Our thesis is that this relationship will persist for deep, non-linear models. This thesis is supported by prior work that suggests that deep neural networks can be closely approximated by linear functions in the vicinity of the data (Goodfellow et al., 2014).

3.3. Data Augmentation

Our data augmentation attacks create a MI classifier $f(x; h)$ for a model $h$. Given a target point $(x_0, y_{\text{true}})$, the adversary trains $f$ to output $f(x_0, h) = 1$, if $x_0$ was a training member. To do this, they tune $f$ to maximize MI accuracy on a source (or “shadow”) model assuming knowledge of the target model’s architecture and training data distribution. They then “transfer” $f$ to perform MI by querying the black-box model $h$. Using $x_0$, we create additional data points $\{\hat{x}_1, \ldots, \hat{x}_N\}$ via different data augmentation strategies, described below. We query the target model $h(\hat{h}$ in tuning) to obtain labels $(y_0, y_1, \ldots, y_N) \leftarrow (h(x), h(\hat{x}_1), \ldots, h(\hat{x}_N))$. Let $b_i \leftarrow \mathbb{I}(y_{\text{true}} = (y_i))$ be the indicator function for whether the i-th queried point was misclassified. Finally, we apply $f(b_0, \ldots, b_N) \to \{0, 1\}$ to classify $x_0$.

We experiment with two common data augmentations in the computer vision domain: image rotations and translations. For rotations, we generate $\hat{N} = 3$ images as rotations by a magnitude $\pm r^o$ for $r \in [1, 15]$. For translations, we generate $\hat{N} = 4d + 1$ translated images satisfying $|i| + |j| = d$ for a pixel bound $d$, where we horizontal shift by $\pm i$ and vertical shift by $\pm j$. In both we include the source image.

3.4. Decision Boundary Distance

These attacks predict membership using a point’s distance to the model’s decision boundary. Here, we extend the intuition that this distance can be a proxy for confidence of linear models (see § 3.2) to deep neural networks.

Recall that confidence-thresholding attacks predict highly confident samples as members (Salem et al., 2018). Given some estimate $\text{dist}_h(x, y)$ of a point’s $\ell_2$-distance to the model’s boundary, we predict $x$ a member if $\text{dist}_h(x, y) > \tau$ for some threshold $\tau$. We define $\text{dist}_h(x, y) = 0$ for misclassified points, where $\text{argmax}_y h(x_i) \neq y$, because no perturbation was needed. We tune $\tau$ on a shadow $h_\tau$, and find that even crude estimates, e.g., Gaussian noise, can lead to nearly comparable attacks (see § 5.5). We now discuss methods for estimating $\text{dist}(x, y)$.

A White-Box Baseline for estimating $\text{dist}(x, y)$ is an idealized white-box attack and is therefore not label-only. We use adversarial-examples generated by the Carlini and Wagner attack (Carlini & Wagner, 2017): given $(x, y)$ the attack tries to find the closest point $x'$ to $x$ in the Euclidean norm, such that $\text{argmax}_y h(x') \neq y$.

Label-only attacks use only black-box access. We rely on label-only adversarial example attacks (Brendel et al., 2017; Chen et al., 2019). These attacks start from a random point $x'$ that is misclassified, i.e., $h(x') \neq y$. They then “walk” along the boundary while minimizing the distance to $x$. We use “HopSkipJump” (Chen et al., 2019), which closely approximates stronger white-box attacks.

Robustness to random noise is a simpler approach based on random perturbations. Again, our intuition stems from linear models: a point’s distance to the boundary is directly related to the model’s accuracy when it is perturbed by isotropic Gaussian noise (Ford et al., 2019). We compute a proxy for $d_h(x, y)$ by evaluating the accuracy of $h$ on $N$ points $\tilde{x}_i = x + N(0, \sigma^2 I)$, where $\sigma$ is tuned on $h$. For binary features we instead use Bernoulli noise: each $x_j \in x$ is flipped with probability $p$, which is tuned on $\hat{h}$.

Many signals for robustness can be combined to improve the attack performance. We evaluate $d_h(x, y)$ for augmentations of $x$ from § 3.3. We only evaluate this attack where indicated due to its high query cost (see § 5.5).

4. Evaluation Setup

Our evaluation is aimed at understanding how label-only MI attacks compare with prior attacks that rely on access to a richer query interface. To this end, we use an identical evaluation setup as prior works (Nasr et al., 2018b; Shokri et al., 2016; Long et al., 2017; Truex et al., 2018; Salem et al., 2018) (see Appendix § B). We answer the following questions in our evaluation, § 5, § 6 and § 7:

1. Can label-only MI attacks match prior attacks that use
We provide a detailed account of model architectures and work has almost exclusively studied (confidence-based) MI. These include datasets where MI attacks have been shown to succeed, a label-only query interface is sufficient. In general, we should not expect our label-only attacks to exceed the performance of prior MI attacks since the former uses strictly less information from queries than the latter. There are three notable exceptions: our combined attack\(^2\) (§ 5.1), “confidence masking” defenses (§ 5.2), and models trained with significant data augmentation (§ 6.1). In the latter two cases, we find that existing attacks severely underestimate MI.

### 4.1. Attack Setup

We provide a detailed account of model architectures and training procedures in Supplement § B.1 and of our threat model in Supplement § C. We evaluate our attacks on 8 datasets used by the canonical work of Shokri et al. (2016). These include 3 computer vision tasks\(^3\), which are our main focus because of the importance of data augmentation to them, and 4 non-computer-vision tasks\(^4\) to showcase our attacks’ transferability. We train target neural networks on subsets of the original training data, exactly as performed by Shokri et al. (2016) and several later works (in both data amount and train-test gap). Controlling the training set size lets us control the amount of overfitting, which strongly influences the strength of MI attacks (Yeom et al., 2018). Prior work has almost exclusively studied (confidence-based) MI attacks on these small datasets where models exhibit a high degree of overfitting. Recall that our goal is to show that label-only attacks match confidence-based approaches: scaling MI attacks (whether confidence-based or label-only) to larger training datasets is an important area of future work.

### 5. Evaluation of Label-Only Attacks

#### 5.1. Label-Only Attacks Match Confidence-Vector Attacks

We first focus on question 1). Recall from § 3.1 that any label-only attack (with knowledge of \(y\)) is always trivially lower-bounded by the baseline gap attack of Yeom et al. (2018), predicting any misclassified point as a non-member. Our main result is that our label-only attacks consistently outperform the gap attack and perform on-par with prior confidence-vector attacks; by combining attacks, we can even surpass the canonical confidence-vector attacks.

Observing Figure 1 and Table 1 (a) and (c), we see that the confidence-vector attack outperforms the baseline gap attack, demonstrating that it exploits non-trivial MI. Remarkably, we find that our label-only boundary distance attack performs at least on-par with the confidence-vector attack. Moreover, our simpler but more query efficient (see § 5.5) data augmentation attacks also consistently outperform the baseline but fall short of the confidence-vector attacks. Finally, combining these two label-only attacks, we can consistently outperform every other attack. These models were not trained with data augmentation; in § 6.1, we find that when they are, our data augmentation attacks outperform all others. Finally, we verify that as the training set size increases, all attacks monotonically decrease because the train-test gap is reduced. Note that on CIFAR-100, we experiment with the largest training subset possible: 30,000 data points, since we use the other half as the source model training set (and target model non-members).

**Beyond Images** We show that our label-only attacks can be applied outside of the image domain in Table 2. Our label-only attack evaluates a model’s accuracy under random perturbations, by adding Gaussian noise for continuous-featured inputs, and flipping binary values according to Bernoulli noise (see § 3.4). Using 10,000 queries, our attacks closely match (at most 4 percentage-point degradation) confidence-based attacks. Note that our attacks could also be instantiated in audio or natural language domains, using existing adversarial examples attacks (Carlini & Wagner, 2018) and data augmentations (Zhang et al., 2015).

#### 5.2. Breaking Confidence Masking Defenses

Answering question 2), we showcase an example where our label-only attacks outperform prior attacks by a significant margin, despite the strictly more restricted query interface that they assume. We evaluate defenses against MI attacks and show that while these defenses do protect against existing confidence-vector attacks, they have little...
to no effect on our label-only attacks. Because any ML
classifier providing confidences also provides the predicted
labels, our attacks fall within their threat model, refuting
these defenses’ security claims.

We identify a common pattern to these defenses that we call
confidence masking, wherein defenses aim to prevent MI by
directly minimizing the privacy leakage in a model’s confi-
cidence scores. To this end, confidence-masking defenses
explicitly or implicitly mask (or, obfuscate) the informa-
tion contained in the model’s confidences, (e.g., by adding noise)
to thwart existing attacks. These defenses, however, have a
minimal effect on the model’s predicted labels. Mem-
Guard (Jia et al., 2019) and prediction purification (Yang et al., 2020)
explicitly maintain the invariant that the model’s predicted
labels are not affected by the defense, i.e.,

\[
\forall x, \quad \text{argmax } h(x) = \text{argmax } h_{\text{defense}}(x),
\]

where \( h_{\text{defense}} \) is the defended version of the model \( h \).

An immediate issue with the design of confidence-masking
defenses is that, by construction, they will not prevent any
label-only attack. Yet, these defenses were reported to drive
the success rates of existing MI attacks to within chance.
This result suggests that prior attacks fail to properly extract
membership information contained in the model’s predicted
labels, and implicitly contained within its scores. Our label-
only attack performances clearly indicate that confidence
masking is not a viable defense strategy against MI.

We show that two peer-reviewed defenses, MemGuard (Jia
et al., 2019) and adversarial regularization (Nasr et al.,
2018a), fail to prevent label-only attacks, and thus, do not
significantly reduce MI compared to an undefended model.

Other proposed defenses, e.g., reducing the precision or car-
dinality of the confidence-vector (Shokri et al., 2016; Truex
et al., 2018; Salem et al., 2018), and recent defenses like
prediction purification (Yang et al., 2020), also rely on confi-
dence masking: they are unlikely to resist label-only attacks.
See Supplement § D for more details on these defenses.

5.3. Breaking MemGuard

We implement the strongest version of MemGuard that can
make arbitrary changes to the confidence-vector while leaving
the model’s predicted label unchanged. Observing Figure 1 and Table 1 (b) and (d), we see that MemGuard success-
fully defends against prior confidence-vector attacks, but as expected, offers no protection against our label-only
attacks. All our attacks significantly outperform the (non-
adaptive) confidence-vector and the baseline gap attack.

The main reason that Jia et al. (2019) found MemGuard to
protect against confidence-vector attacks is because these at-
tacks were not properly adapted to this defense. Specifically,
MemGuard is evaluated against confidence-vector attacks
that are tuned on source models without MemGuard enabled.
This observation also holds for other defenses such as Yang
et al. (2020). Thus, these attacks’ membership predictors are
tuned to distinguish members from non-members based on
high confidence scores, which these defenses obfuscate. In
a sense, a label-only attack like ours is the “right” adaptive
attack against these defenses: since the model’s confidence
scores are no longer reliable, the adversary’s best strategy
is to use hard labels, which these defenses explicitly do not

![Figure 1. Accuracy of MI attacks on CIFAR-10. We evaluate
100 to 10,000 training points and compare the baseline gap attack,
the confidence-vector attack that relies on a fine-grained query in-
terface, and our label-only attacks based on data augmentation and
distance to the decision boundary. We also show the confidence-
vector attack performance against MemGuard, noting that our
label-only performances remain nearly unaltered. For the data
augmentation attack, we report the best accuracy across multiple
values of \( r \) (rotation angle) and \( d \) (number of translated pixels).](image)

### Table 1. Accuracy of MI attacks on CIFAR-100 and MNIST.
The target models are trained using 30,000 data points for CIFAR-
100 and 1,000 for MNIST. Tables (a) and (c) report results without
any defense; (b) and (d) with MemGuard (Jia et al., 2019), which
prevents the confidence-vector attacks via “confidence masking”.
‘Combined’ refers to the boundary and translation attack. Results
that are affected by confidence masking are marked in red.

| Attack Model        | Attack Accuracy | Attack Model        | Attack Accuracy |
|---------------------|-----------------|---------------------|-----------------|
| (a) CIFAR-100 Undefended |                 | (b) CIFAR-100 MemGuard |                 |
| Gap attack          | 83.5            | Gap attack          | 83.5            |
| Confidence-vector   | 88.1            | Confidence-vector   | 50.0            |
| Data augmentation   | 84.6            | Data augmentation   | 84.6            |
| Boundary distance   | 88.0            | Boundary distance   | 88.0            |
| Combined            | 89.2            | Combined            | 89.2            |
| (c) MNIST Undefended |                 | (d) MNIST MemGuard  |                 |
| Gap attack          | 53.2            | Gap attack          | 53.2            |
| Confidence-vector   | 55.7            | Confidence-vector   | 50.0            |
| Data augmentation   | 53.9            | Data augmentation   | 53.9            |
| Boundary distance   | 57.8            | Boundary distance   | 57.8            |
| Combined            | 58.7            | Combined            | 58.7            |
Table 2. Accuracy of membership inference attacks on Texas, Purchase, Location, and Adult. Where augmentations may not exist, noise robustness can still perform on or near par with confidence-vector attacks. The target models are trained exactly as in (Shokri et al., 2016): 1, 600 points for Location and 10,000 for the rest. Our noise robustness attack uses 10,000 queries. Tables (a), (c), (e), and (g) report results without any defense. Tables (b), (d), (f), and (h) report results with MemGuard (Jia et al., 2019), which prevents the confidence-vector attacks via “confidence-masking”. Results that are affected by confidence masking are marked in red.

(a) Texas Undefended (b) Texas MemGuard
| Attack               | Accuracy | Attack   | Accuracy |
|----------------------|----------|----------|----------|
| Gap attack           | 73.9     | Gap attack | 73.9     |
| Confidence-vector    | 84.0     | Confidence-vector | 50.0     |
| Noise Robustness     | 80.3     | Noise Robustness | 80.3     |

(c) Purchase Undefended (d) Purchase MemGuard
| Attack               | Accuracy | Attack   | Accuracy |
|----------------------|----------|----------|----------|
| Gap attack           | 67.1     | Gap attack | 67.1     |
| Confidence-vector    | 86.1     | Confidence-vector | 50.0     |
| Noise Robustness     | 87.4     | Noise Robustness | 87.4     |

(e) Location Undefended (f) Location MemGuard
| Attack               | Accuracy | Attack   | Accuracy |
|----------------------|----------|----------|----------|
| Gap attack           | 72.1     | Gap attack | 72.1     |
| Confidence-vector    | 92.6     | Confidence-vector | 50.0     |
| Noise robustness     | 89.2     | Noise Robustness | 89.2     |

(g) Adult Undefended (h) Adult MemGuard
| Attack               | Accuracy | Attack   | Accuracy |
|----------------------|----------|----------|----------|
| Gap attack           | 58.7     | Gap attack | 58.7     |
| Confidence-vector    | 59.9     | Confidence-vector | 50.0     |
| Noise Robustness     | 58.7     | Noise Robustness | 58.7     |

modify. Moving forward, we recommend that the trivial gap baseline serve as an indicator of confidence masking: a confidence-vector attack should not perform significantly worse than the gap attack for a defense to protect against MI. Thus, to protect against (all) MI attacks, a defense cannot solely post-process the confidence-vector—the model will still be vulnerable to label-only attacks.

5.4. Breaking Adversarial Regularization

The work of Nasr et al. (2018a) differs from MemGuard and prediction purification in that it does not simply obfuscate confidence vectors at test time. Rather, it jointly trains a target model and a defensive confidence-vector MI classifier in a min-max fashion: the attack model to maximize MI and the target model to produce accurate outputs that yet fool the attacker. See Supplement § D for more details.

We train a target model defended using adversarial regularization, exactly as in (Nasr et al., 2018a). By varying its hyper-parameters, we achieve a defended state where the confidence-vector attack is within 3 percentage points of chance, as shown in Supplement Figure 9. Again, our label-only attacks significantly outperform this attack (compare Figures 6 (a) and (b)) because the train-test gap is only marginally reduced; this defense is not entirely ineffective—it prevents label-only attacks from exploiting beyond 3 percentage points of the gap attack. However, when label-only attacks are sufficiently defended, it achieves significantly worse test accuracy trade-offs than other defenses (see Figure 5). And yet, evaluating the defense solely on confidence-vector attacks overestimates the achieved privacy.

5.5. The Query Complexity of Label-Only Attacks

We now answer question 3) and investigate how the query budget affects the success rate of different label-only attacks.

Recall that our rotation attack evaluates \( N = 3 \) queries of images rotated by \( r \circ \) and our translation attack \( N = 4d + 1 \) for shifts satisfying a total displacement of \( d \). Figure 2 (a)-(b) shows that there is a range of perturbation magnitudes for which the attack exceeds the baseline (i.e., 1 ≤ \( r \leq 8 \) for rotations, and 1 ≤ \( d \leq 2 \) for translations). When the augmentations are too small or too large, the attack performs poorly because the augmentations have a similar effect on both train and test samples (i.e., small augmentations rarely change model predictions and large augmentations often cause misclassifications). An optimal parameter choice (\( r \) and \( d \)) outperforms the baseline by 3-4 percentage-points, which an adversary can tune using its local source model. As we will see in § 6, these attacks outperform all others on models that used data augmentation at training time.

In Figure 2 (c), we compare different boundary distance attacks, discussed in § 3.4. With ≈2,500 queries, the label-only attack matches the white-box upper-bound using ≈2,000 queries and also matches the best confidence-vector attack (see Figure 1). With ≈12,500 queries, our combined attack can outperform all others. Query limiting would likely not be a suitable defense, as Sybil attacks (Douceur, 2002) can circumvent it; even in low query regimes (<100) our attacks outperform the trivial gap by 4 percentage points. Finally, with <300 queries, our simple noise robustness attack outperforms our other label-only attacks. At large query budgets, our boundary distance attack produces more precise distance estimates and outperforms it. Note that the monetary costs are modest at ≈$0.25 per sample\(^5\).

\(^5\)https://www.clarifai.com/pricing
6. Defending with Better Generalization

Since confidence-masking defenses cannot robustly defend against MI attacks, we now investigate to what extent standard regularization techniques—that aim to limit a models’ ability to overfit to its training set—can. We study how data augmentation, transfer learning, dropout (Srivastava et al., 2014), $\ell_1/\ell_2$ regularization, and differentially private (DP) training (Abadi et al., 2016) impact MI.

We explore three questions in this section:

A. How does training with data augmentation impact MI attacks, especially those that evaluate augmented data?
B. How well do other standard machine learning regularization techniques help in reducing MI?
C. How do these defenses compare to differential privacy, which can provide formal guarantees against any form of membership leakage?

6.1. Training with Data Augmentation Exacerbates MI

Data augmentation is commonly used in machine learning to reduce overfitting and encourage generalization, especially in low data regimes (Shorten & Khoshgoftaar, 2019; Mikolajczyk & Grochowski, 2018). Data augmentation is an interesting case study for our attacks. As it reduces a model’s overfitting, one would expect it to reduce MI. But, a model trained with augmentation will have been trained to strongly recognize $x$ and its augmentations, which is precisely the signal that our data augmentation attacks exploit.

We train target models with data augmentation similar to § 3.3 and focus on translations as they are most common in computer vision. We use a simple pipeline where all translations of each image is evaluated in a training epoch. Though this differs slightly from the standard random sampling, we choose it to illustrate the maximum MI when the adversary’s queries exactly match the samples seen in training.

Observe from Figure 3 that augmentation reduces overfitting and improves generalization: test accuracy increases from 49.7% without translations to 58.7% at $d = 5$ and the train-test gap decreases. Due to improved generalization, the confidence-vector and boundary distance attacks’ accuracies decrease. Yet, the success rate of the data augmentation attack increases. This increase confirms our initial intuition that the model now leaks additional membership information via its invariance to training-time augmentation. Though the model trained with $d = 5$ pixel shifts has higher test accuracy, our data augmentation attack exceeds the confidence-vector performance on the non-augmented model. This. Thus, model generalization is not the only variable affecting its membership leakage: models that overfit less on the original data may actually be more vulnerable to MI because they implicitly overfit more on a related dataset.

Attacking a high-accuracy ResNet We use, without modification, the pipeline from FixMatch (Sohn et al., 2020), which trains a ResNet-28 to 96% accuracy on the CIFAR-10 dataset, comparable to the state of the art. As with our other experiments, this model is trained using a subset of CIFAR-10, which sometimes leads to observably overfit models indicated by a higher gap attack accuracy. We train models using four regularizations, all random: vertical flips, shifts by up to $d = 4$ pixels, image cutout (DeVries & Taylor, 2017), and (non-random) weight decay of magnitude 0.0005. All are either enabled or disabled.

Our results here, shown in Figure 4 corroborate those ob-

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Though we find in Supplement Figure 8 that the attack is strongest when the adversary correctly guesses $d$, we note that these values are often fixed for a domain and image resolution. Thus, adversarial knowledge of the augmentation pipeline is not a strong assumption.
tained with the simpler pipeline above: though test accuracy improves, our data augmentation attacks match or outperform the confidence-vector attack.

### 6.2. Other Techniques to Prevent Overfitting

We explore questions B)-C) using other standard regularization techniques, with details in Supplement E. In transfer learning, we either only train a new last layer (last layer fine-tuning), or fine tune the entire model (full fine-tuning).

We pre-train a model on CIFAR-100 to 51.6% test accuracy and then use transfer learning. We find that boundary distance attack performed on par with the confidence-vector in all cases. We observe that last layer fine-tuning degrades all our attacks to the generalization gap, preventing non-trivial MI (see Figure 10 in Supplement § F). This result corroborates intuition: linear layers have less capacity to overfit compared to neural networks. We observe that full fine-tuning leaks more membership inference but achieves better test accuracies, as shown in Figure 5.

Finally, DP training (Abadi et al., 2016) formally enforces that the trained model does not strongly depend on any individual training point—that it does not overfit. We use differentially private gradient descent (DP-SGD) (Abadi et al., 2016) (see Supplement § E). To achieve comparable test accuracies as undefended models, the formal privacy guarantees become mostly meaningless (i.e., $\epsilon > 100$).

In Figure 6, we find that most forms of regularization fail to prevent even the baseline gap attack from reaching 60% accuracy or more. Only strong $\ell_2$ regularization ($\lambda \geq 1$) and DP training consistently reduced MI. Figure 5 gives us a best understanding of the privacy-utility trade-off. We see that both prevent MI at a high cost in test-accuracy—they cause the model to underfit. However, we also clearly see the utility benefits of transfer learning: these models achieve consistently better test-accuracy due to features learned from non-private data. Combining DP training with transfer learning mitigates privacy leakage at only minimal cost in test accuracy, achieving the best tradeoff. When transfer learning is not an option, dropout performs better.

### 7. Worst-Case (Outlier) MI

Here, we perform MI only for a small subset of “outliers”. Even if a model generalizes well on average, it might still
have overfit to unusual data in the tails of the distribution (Carlini et al., 2019). We use a similar but modified process as Long et al. (2018) to identify potential outliers. First, the adversary uses a source model $\hat{h}$ to map each targeted data point, $x$, to its feature space, or the activations of its penultimate layer, denoted as $z(x)$. We define two points $x_1, x_2$ as neighbors if their features are close, i.e., $d(z(x_1), z(x_2)) \leq \delta$, where $d(\cdot, \cdot)$ is the cosine distance and $\delta$ is a tunable parameter. An outlier is a point with less than $\gamma$ neighbors in $z(x)$ where $\gamma$ is another tunable parameter. Given a dataset $X$ of potential targets and an intended fraction of outliers $\beta$ (e.g., 1% of $X$), we tune $\delta$ and $\gamma$ so that a $\beta$-fraction of points $x \in X$ are outliers. We use precision as the MI success metric.

We run our attacks on the outliers of the same models as in Figure 6. We find in See Figure 11 in Supplement Section F, that we can always improve the attack by targeting outliers, but that strong $L^2$ regularization and DP training prevent MI. As before, we find that the label-only boundary distance attack matches the confidence-vector attack performance. 

8. Conclusion

We developed three new label-only membership inference attacks that can match, and even exceed, the success of prior confidence-vector attacks, despite operating in a more restrictive adversarial model. Their label-only nature requires fundamentally different attack strategies, that—in turn—cannot be trivially prevented by obfuscating a model’s confidence scores. We have used these attacks to break two state-of-the-art defenses to membership inference attacks.

We have found that the problem with these “confidence-masking” defenses runs deeper: they cannot prevent any label-only attack. As a result, any defenses against MI necessarily have to help reduce a model’s train-test gap.

Finally, via a rigorous evaluation across many proposed defenses to MI, we have shown that differential privacy (with transfer learning) provides the strongest defense, both in an average-case and worst-case sense, but that it may come at a cost in the model’s test accuracy.

To center our analysis on comparing the confidence-vector and label-only settings, we use the same threat model as prior work (Shokri et al., 2016) and leave a fine-grained analysis of label-only attacks under reduced adversarial knowledge (e.g., reduced data and model architecture knowledge (Yeom et al., 2018; Salem et al., 2018)) to future work.

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Label-Only Membership Inference Attacks

References

Abadi, M., Chu, A., Goodfellow, I., McMahan, H. B., Mironov, I., Talwar, K., and Zhang, L. Deep learning with differential privacy. In Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security, CCS ’16, pp. 308–318, New York, NY, USA, 2016. Association for Computing Machinery. ISBN 9781450343934. doi: 10.1145/2976749.2978318. URL https://doi.org/10.1145/2976749.2978318.

Bengio, Y., Goodfellow, I., and Courville, A. Deep learning, volume I. MIT press, 2017.

Brendel, W., Rauber, J., and Bethge, M. Decision-based adversarial attacks: Reliable attacks against black-box machine learning models. arXiv preprint arXiv:1712.04248, 2017.

Carlini, N. and Wagner, D. Towards evaluating the robustness of neural networks. In 2017 ieee symposium on security and privacy (sp). pp. 39–57. IEEE, 2017.

Carlini, N. and Wagner, D. Audio adversarial examples: Targeted attacks on speech-to-text. In 2018 IEEE Security and Privacy Workshops (SPW), pp. 1–7. IEEE, 2018.

Carlini, N., Liu, C., Erlingsson, Ú., Kos, J., and Song, D. The secret sharer: Evaluating and testing unintended memorization in neural networks. In 28th {USENIX} Security Symposium ({USENIX} Security 19), pp. 267–284, 2019.

Chen, J., Jordan, M. I., and Wainwright, M. J. Hopskipjumpattack: A query-efficient decision-based attack. 2019.

Cubuk, E. D., Zoph, B., Mane, D., Vasudevan, V., and Le, Q. V. Autoaugment: Learning augmentation policies from data, 2018.

Cui, X., Goel, V., and Kingsbury, B. Data augmentation for deep neural network acoustic modeling. IEEE/ACM Transactions on Audio, Speech, and Language Processing, 23(9):1469–1477, 2015.

Devlin, J., Chang, M.-W., Lee, K., and Toutanova, K. Bert: Pre-training of deep bidirectional transformers for language understanding, 2018.

DeVries, T. and Taylor, G. W. Improved regularization of convolutional neural networks with cutout. arXiv preprint arXiv:1708.04552, 2017.

Doucet, J. R. The sybil attack. In International workshop on peer-to-peer systems, pp. 251–260. Springer, 2002.

Fadaee, M., Bisazza, A., and Monz, C. Data augmentation for low-resource neural machine translation. Proceedings of the 55th Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers), 2017. doi: 10.18653/v1/p17-2090. URL http://dx.doi.org/10.18653/v1/p17-2090.

Ford, N., Gilmer, J., Carlini, N., and Cubuk, D. Adversarial examples are a natural consequence of test error in noise. arXiv preprint arXiv:1901.10513, 2019.

Fredrikson, M., Jha, S., and Ristenpart, T. Model inversion attacks that exploit confidence information and basic countermeasures. In Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security, pp. 1322–1333, 2015.

Gal, Y. Uncertainty in deep learning. University of Cambridge, 1: 2016.

Goodfellow, I. J., Shlens, J., and Szegedy, C. Explaining and harnessing adversarial examples, 2014.

Hayes, J., Melis, L., Danezis, G., and Cristofaro, E. D. Logan: Membership inference attacks against generative models. Proceedings on Privacy Enhancing Technologies, 2019(1):133 – 152, 2019. URL https://content.sciendo.com/view/journals/popets/2019/1/article-p133.xml.

He, K., Zhang, X., Ren, S., and Sun, J. Deep residual learning for image recognition, 2015.

Hu, S., Yu, T., Guo, C., Chao, W.-L., and Weinberger, K. Q. A new defense against adversarial images: Turning a weakness into a strength. In Advances in Neural Information Processing Systems, pp. 1635–1646, 2019.

Jayaraman, B., Wang, L., Evans, D., and Gu, Q. Revisiting membership inference under realistic assumptions. arXiv preprint arXiv:2005.10881, 2020.

Jia, J., Salem, A., Backes, M., Zhang, Y., and Gong, N. Z. Memguard: Defending against black-box membership inference attacks via adversarial examples. In Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security, pp. 259–274, 2019.

Leino, K. and Fredrikson, M. Stolen memories: Leveraging model memorization for calibrated white-box membership inference. arXiv preprint arXiv:1906.11798, 2019.

Long, Y., Bindschaedler, V., and Gunter, C. A. Towards measuring membership privacy. arXiv preprint arXiv:1712.09136, 2017.

Long, Y., Bindschaedler, V., Wang, L., Bu, D., Wang, X., Tang, H., Gunter, C. A., and Chen, K. Understanding membership inferences on well-generalized learning models. arXiv preprint arXiv:1802.04989, 2018.

Maas, A. L., Hannun, A. Y., and Ng, A. Y. Rectifier nonlinearities improve neural network acoustic models. In Proc. icml, volume 30, pp. 3, 2013.

Mikolajczyk, A. and Grochowski, M. Data augmentation for improving deep learning in image classification problem. In 2018 International Interdisciplinary PhD Workshop (IIPHDW), pp. 117–122, May 2018. doi: 10.1109/IIPHDW.2018.8388338.

Murphy, K. P. Machine Learning: A Probabilistic Perspective. The MIT Press, 2012. ISBN 0262018020, 9780262018029.

Nasr, M., Shokri, R., and Houmansadr, A. Machine learning with membership privacy using adversarial regularization. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, pp. 634–646, 2018a.

Nasr, M., Shokri, R., and Houmansadr, A. Machine learning with membership privacy using adversarial regularization. In Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, pp. 634–646, 2018b.

Ngai, E. W., Hu, Y., Wong, Y. H., Chen, Y., and Sun, X. The application of data mining techniques in financial fraud detection: A classification framework and an academic review of literature. Decision support systems, 50(3):559–569, 2011.
Label-Only Membership Inference Attacks

Papernot, N., McDaniel, P., Goodfellow, I., Jha, S., Celik, Z. B., and Swami, A. Practical black-box attacks against machine learning. In Proceedings of the 2017 ACM on Asia Conference on Computer and Communications Security, ASIA CCS ’17, pp. 506–519, New York, NY, USA, 2017. ACM. ISBN 978-1-4503-4944-4. doi: 10.1145/3052973.3053009. URL http://doi.acm.org/10.1145/3052973.3053009.

Perez, L. and Wang, J. The effectiveness of data augmentation in image classification using deep learning, 2017.

Pyrgelis, A., Troncoso, C., and De Cristofaro, E. Knock knock, who's there? membership inference on aggregate location data. arXiv preprint arXiv:1708.06145, 2017.

Sablayrolles, A., Douze, M., Schmid, C., Ollivier, Y., and Jégou, H. White-box vs black-box: Bayes optimal strategies for membership inference. In International Conference on Machine Learning, pp. 5558–5567. PMLR, 2019.

Sajjad, M., Khan, S., Muhammad, K., Wu, W., Ullah, A., and Baik, S. W. Multi-grade brain tumor classification using deep cnn with extensive data augmentation. Journal of computational science, 30:174–182, 2019.

Salem, A., Zhang, Y., Humbert, M., Berrang, P., Fritz, M., and Backes, M. Mi-leaks: Model and data independent membership inference attacks and defenses on machine learning models, 2018.

Shalev-Shwartz, S. and Ben-David, S. Understanding machine learning: From theory to algorithms. Cambridge university press, 2014.

Shokri, R., Stronati, M., Song, C., and Shmatikov, V. Membership inference attacks against machine learning models, 2016.

Shorten, C. and Khoshgoftaar, T. M. A survey on image data augmentation for deep learning. Journal of Big Data, 6(1):60, 2019.

Sohn, K., Berthelot, D., Li, C.-L., Zhang, Z., Carlini, N., Cubuk, E. D., Kurakin, A., Zhang, H., and Raffel, C. Fixmatch: Simplifying semi-supervised learning with consistency and confidence, 2020.

Song, L., Shokri, R., and Mittal, P. Privacy risks of securing machine learning models against adversarial examples. In Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security, pp. 241–257, 2019.

Srivastava, N., Hinton, G., Krizhevsky, A., Sutskever, I., and Salakhutdinov, R. Dropout: a simple way to prevent neural networks from overfitting. The journal of machine learning research, 15(1):1929–1958, 2014.

Stanfill, M. H., Williams, M., Fenton, S. H., Jenders, R. A., and Hersh, W. R. A systematic literature review of automated clinical coding and classification systems. Journal of the American Medical Informatics Association, 17(6):646–651, 2010.

Szegedy, C., Zaremba, W., Sutskever, I., Bruna, J., Erhan, D., Goodfellow, I., and Fergus, R. Intriguing properties of neural networks. arXiv preprint arXiv:1312.6199, 2013.

Tan, C., Sun, F., Kong, T., Zhang, W., Yang, C., and Liu, C. A survey on deep transfer learning. In International conference on artificial neural networks, pp. 270–279. Springer, 2018.

Tanay, T. and Griffin, L. A boundary tilting perspective on the phenomenon of adversarial examples. arXiv preprint arXiv:1608.07690, 2016.

Taylor, L. and Nitschke, G. Improving deep learning with generic data augmentation. In 2018 IEEE Symposium Series on Computer Intelligent (SSCI), pp. 1542–1547, Nov 2018. doi: 10.1109/SSCI.2018.8628742.

Tian, S., Yang, G., and Cai, Y. Detecting adversarial examples through image transformation, 2018.

Tramèr, F., Zhang, F., Juels, A., Reiter, M. K., and Ristenpart, T. Stealing machine learning models via prediction apis. In 25th {USENIX} Security Symposium ({USENIX} Security 16), pp. 601–618, 2016.

Truex, S., Liu, L., Gursoy, M. E., Yu, L., and Wei, W. Towards demystifying membership inference attacks. arXiv preprint arXiv:1807.09173, 2018.

Wang, B. and Gong, N. Z. Stealing hyperparameters in machine learning. 2018 IEEE Symposium on Security and Privacy (SP), pp. 36–52, 2018.

Yang, Z., Shao, B., Xuan, B., Chang, E.-C., and Zhang, F. Defending model inversion and membership inference attacks via prediction purification, 2020.

Yeom, S., Giacomelli, I., Fredrikson, M., and Jha, S. Privacy risk in machine learning: Analyzing the connection to overfitting. In 2018 IEEE 31st Computer Security Foundations Symposium (CSF), pp. 268–282. IEEE, 2018.

Zhang, C., Bengio, S., Hardt, M., Recht, B., and Vinyals, O. Understanding deep learning requires rethinking generalization. arXiv preprint arXiv:1611.03530, 2016.

Zhang, X., Zhao, J., and LeCun, Y. Character-level convolutional networks for text classification. In Proceedings of the 28th International Conference on Neural Information Processing Systems - Volume 1, NIPS’15, pp. 649–657, Cambridge, MA, USA, 2015. MIT Press.
A. Background

A.1. Machine Learning

We consider supervised classification tasks (Murphy, 2012; Shalev-Shwartz & Ben-David, 2014), wherein a model is trained to predict some class label $y$, given input data $x$. Commonly, $x$ may be an image or sentence and $y$ is then the corresponding label, e.g., a digit 0-9 or a text sentiment.

We focus our study on neural networks (Bengio et al., 2017): functions composed as a series of linear-transformation layers, each followed by a non-linear activation. The overall layer structure is called the model’s *architecture* and the learnable parameters of the linear transformations are the *weights*. For a classification problem with $K$-classes, the last layer of a neural network outputs a vector $v$ of $K$ values (often called logits). The *softmax* function is typically used to convert the logits into normalized confidence scores:

$$\text{softmax}(v)_i := \frac{e^{v_i}}{\sum_{i=1}^{K} e^{v_i}}, \quad v_i \in [0, 1].$$

For a model $h$, we define the model’s output $h(x)$ as the vector of softmax values. The model’s predicted label is the class with highest confidence, i.e., $\arg\max h(x)_i$.

A.1.1. Data Augmentation

Augmentations are natural transformations of existing data points that preserve class semantics (e.g., small translations of an image), which are used to improve the generalization of a classifier (Cubuk et al., 2018; Sohn et al., 2020; Taylor & Nitschke, 2018). They are commonly used on state-of-the-art models (He et al., 2015; Cubuk et al., 2018; Perez & Wang, 2017) to increase the diversity of the finite training set, without the need to acquire more labeled data (in a costly process). Augmentations are especially important in low-data regimes (Sajjad et al., 2019; Fadaee et al., 2017; Cui et al., 2015) and are domain-specific: they apply to a certain type of input, e.g., images or text.

We focus on image classifiers, where the main types of augmentations are affine transformations (rotations, reflections, scaling, and shifts), contrast adjustments, cutout (DeVries & Taylor, 2017), and blurring (adding noise). By synthesizing a new data sample as an augmentation of an existing data sample, $x' = \text{augment}(x)$, the model can learn a more semantically-meaningful set of features. Data augmentation can potentially teach the machine learning model to become invariant to the augmentation (e.g., rotationally or translationally invariant).

A.1.2. Transfer Learning

Transfer learning is a common technique used to improve generalization in low-data regimes (Tan et al., 2018). By leveraging data from a source task, it is possible to transfer knowledge to a target task. Commonly, a model is trained on the data of the source task and then fine-tuned on data from the output task. In the case of neural networks, it is common to fine-tune either the entire model or just the last layer.

A.2. Membership Inference

Membership inference attacks (Shokri et al., 2016) are a form of privacy leakage that identify if a given data sample was in a machine learning model’s training dataset. Given a sample $x$ and access to a trained model $h$, the adversary uses a classifier or decision rule $f_h$ to compute a membership prediction $f(x; h) \in \{0, 1\}$, with the goal that $f(x; h) = 1$ whenever $x$ is a training point. The main challenge in mounting a membership inference attack is creating the classifier $f$, under various assumptions about the adversary’s knowledge of $h$ and its training data distribution.

Prior work assumes that an adversary has only black-box access to the trained model $h$, via a query interface that on input $x$ returns part or all of the confidence vector $h(x)$.

Shadow Models The original membership inference attack of Shokri et al. (Shokri et al., 2016) creates a membership classifier $f(x; h)$, tuned on a number of local “shadow” (or, source) models. Assuming the adversary has access to data from the same (or similar) distribution as $h$’s training data, the shadow model approach trains the auxiliary source models $h_i$ on this data. Since $h_i$ is trained by the adversary, they know whether or not any data point was in the training set, and can thus construct a dataset of confidence vectors $h_i(x)$ with an associated membership label $m \in \{0, 1\}$. The adversary trains a classifier $f$ to predict $m$ given $h_i(x)$. Finally, the adversary queries the targeted model $h$ to obtain $h(x)$ and uses $f$ to predict the membership of $x$ in $h$’s training data.

Salem et al. (Salem et al., 2018) later showed that this attack strategy can succeed even without data from the same distribution as $h$, and only with data from a similar task (e.g., a different vision task). They also showed that training shadow models is unnecessary: applying a simple threshold predicting $f(x; h) = 1$ ($x$ is a member) when the max prediction confidence, $\max_i h(x)$, is above a tuned threshold, suffices.

Towards Label-only Approaches Yeom et al. (Yeom et al., 2018) propose a simple baseline attack: the adversary predicts a data point $x$ as being a member of the training set when $h$ classifies $x$ correctly. The accuracy of this baseline...
Label-Only Membership Inference Attacks

attack directly reflects the gap in the model’s train and test accuracy: if \( h \) overfits (i.e., obtains higher accuracy) on its training data, this baseline attack will achieve non-trivial membership inference. We call this the gap attack. If the adversary’s target points are equally likely to be members or non-members of the training set (see Appendix B.2), this attack achieves an accuracy of

\[
\frac{1}{2} + \frac{(\text{acc}_{\text{train}} - \text{acc}_{\text{test}})}{2},
\]

where \( \text{acc}_{\text{train}}, \text{acc}_{\text{test}} \in [0, 1] \) are the target model’s accuracy on training data and held out data respectively.

To the best of our knowledge, this is the only attack proposed in prior work that makes use of only the model’s predicted label, \( y = \arg\max_i h(x_i) \). Our goal is to investigate how this simple baseline can be surpassed to achieve label-only membership inference attacks that perform on par with attacks that use access to the model’s confidence scores.

**Indirect Membership Inference** The work of Long et al. (Long et al., 2018) investigates membership inference through *indirect access*, wherein the adversary only queries \( h \) on inputs \( x' \) that are related to \( x \), but not \( x \) directly. Our label-only attacks similarly make use of information gleaned from querying \( h \) on data points related to \( x \) (specifically, perturbed versions of \( x \)).

The main difference is that we focus on label-only attacks, whereas the work of Long et al. (Long et al., 2018) assumes adversarial access to the model’s confidence scores. Our attacks will also be allowed to query and obtain the label at the chosen point \( x \).

**Adversarial Examples and Membership Inference** Song et al. (Song et al., 2019) also make use of adversarial examples to infer membership. Their approach crucially differs from ours in two aspects: (1) they assume access to and predict membership using the confidence scores, and (2) they target models that were explicitly trained to be robust to adversarial examples. In this sense, (2) bares some similarities with our attacks on models trained with data augmentation (see Section 6, where we also find that a model’s invariance to some perturbations can leak additional membership signal).

**Defenses** Defenses against membership inference broadly fall into two categories.

First, standard regularization techniques, such as L2 weight normalization (Shokri et al., 2016; Jia et al., 2019; Truex et al., 2018; Nasr et al., 2018a), dropout (Jia et al., 2019), or differential privacy have been proposed to address the role that overfitting plays in a membership inference attack’s success rate (Shokri et al., 2016). Heavy regularization has been shown to limit overfitting and to effectively defend against membership inference, but may result in a significant degradation in the model’s accuracy. Moreover, Yeom et al. (Yeom et al., 2018) show that overfitting is sufficient, but not necessary, for membership inference to be possible.

Second, defenses may reduce the information contained in a model’s confidences, e.g., by truncating them to a lower precision (Shokri et al., 2016), reducing the dimensionality of the confidence-vector to only some top \( k \) scores (Shokri et al., 2016; Truex et al., 2018), or perturbing confidences via an adversary-aware “minimax” approach (Nasr et al., 2018a; Yang et al., 2020; Jia et al., 2019). These defenses modify either the model’s training or inference procedure to produce minimally perturbed confidence vectors that thwart existing membership inference attacks. We refer to these defenses as “confidence-masking” defenses.

**Outliers in Membership Inference** Most membership inference research is focused on protecting the average-case user’s privacy: the success of a membership inference attack is evaluated over a large dataset. Long et al. (Long et al., 2018) focus on understanding the vulnerability of outliers to membership inference. They show that some (<100) outlier data points can be targeted and have their membership inferred to high (up to 90%) precision (Long et al., 2017; 2018). Recent work explores how overfitting impacts membership leakage from a defender’s (white-box) perspective, with complete access to the model (Leino & Fredrikson, 2019).

**B. Evaluation Setup**

Because our main goal is to show that label-only attacks can match the success of prior attacks, we consider a similar threat model that matches prior work—except that we restrict the adversary to label-only queries.

As in prior work (Shokri et al., 2016), we assume that the adversary has: (1) full knowledge of the task; (2) knowledge of the target model’s architecture and training setup; (3) partial data knowledge, i.e., access to a disjoint partition of data samples from the same distribution as the target model’s training data (see below for more details); and (4) knowledge of the targeted points’ labels, \( y \).

**B.1. Our Threat Model**

**Generating Membership Data** Some works have explored generating data samples \( x \) for which to perform membership inference on, which assumes the least data knowledge (Shokri et al., 2016; Fredrikson et al., 2015). These cases work best with minimal numbers of features or binary features because they can take many queries (Shokri et al., 2016). Other works assumes access to the confidence vectors (Fredrikson et al., 2015). Our work assumes that
candidate samples have already been found by the adversary. We leave to future work the efficient discovery of these samples on high-dimensionality data using a label-only query interface.

In our threat model, we always use a disjoint, non-overlapping (i.e., no data points are shared) set of samples for training and test data for the target model. The source model uses another two separate subsets of the task’s total data pool. Due to the balanced priors we assume, all subsets (i.e., the target model training and test sets, and the source model training and test sets) are always of the same size. In the case of CIFAR100, we use the target models training dataset (members) as the source models test dataset (non-members), and vice versa.

Model Architectures For computer vision tasks, we use two representative model architectures, a standard convolutional neural network (CNN) and a ResNet (He et al., 2015). Our CNN has four convolution layers with ReLU activations. The first two $3 \times 3$ convolutions have 32 filters and the second two have 64 filters, with a max-pool in between the two. To compute logits we feed the output through a fully-connected layer with 512 neurons. This model has 1.2 million parameters. Our ResNet-28 is a standard Wide ResNet-28 taken directly from (Sohn et al., 2020) with 1.4 million parameters. On Purchase-100, we use a fully connected neural network with one hidden layer of size 128 and the Tanh activation function, exactly as in (Shokri et al., 2016). For Texas-100, Adult, and Locations we mimic this model but add a second hidden layer matching the first.

For the attacks from prior work based on confidence vectors, and our new label-only attacks based on data augmentations, we use shallow neural networks as membership predictor models $f$. Specifically, for augmentations, we use two layers of 10 neurons and LeakyReLU activations (Maas et al., 2013). The confidence-vector attack models use a single hidden layer of 64 neurons, as originally proposed by Shokri et al. (Shokri et al., 2016). We train a separate prediction model for each class We observe minimal changes in attack performance by changing the architecture, or by replacing the predictor model $f$ by a simple thresholding rule. Our combined boundary distance and augmentation attack uses neural networks as well. For simplicity, our decision boundary distance attacks use a single global thresholding rule, 2,500 queries, and the L2 distance metric. See Section 3.4 for more details.

B.2. On Measuring Success

Some recent works have questioned the use of (balanced) accuracy as a measure of attack success and proposed other measures more suited for imbalanced priors: where any data point targeted by the adversary is a-priori unlikely to be a training point (Jayaraman et al., 2020). As our main goal is to study the effect of the model’s query interface on the ability to perform membership inference, we focus here on the same balanced setting considered in most prior work. We also note that the assumption that the adversary has a (near-) balanced prior need not be unrealistic in practice: For example, the adversary might have query access to models from two different medical studies (trained on patients with two different conditions) and might know a-priori that some targeted user participated in one of these studies, without knowing which.

C. Threat Model

The goal of a membership inference attack is to determine whether or not a candidate data point was used to train a given model. In Table 3, we summarize different sets of assumptions made in prior work about the adversary’s knowledge and query access to the model.

C.1. Adversarial Knowledge

The membership inference threat model originally introduced by Shokri et al. (Shokri et al., 2016), and used in many subsequent works (Long et al., 2017; Truex et al., 2018; Salem et al., 2018; Song et al., 2019; Nasr et al., 2018b), assumes that the adversary has black-box access to the model $h$ (i.e., they can only query the model for its prediction and confidence but not inspect its learned parameters). Our work also assumes black-box model access, with the extra restriction (see Section C.2 for more details) that the model only returns (hard) labels to queries. Though studying membership inference attacks with white-box model access (Leino & Fredrikson, 2018) has merits (e.g., for upper-bounding the membership leakage), our label-only restriction inherently presumes a black-box setting (as otherwise, the adversary could just run $h$ locally to obtain confidence scores). Although we are focused on the label-only domain, our attack methodologies can be applied for analysis in the white-box domain.

Assuming a black-box query interface, there are a number of other dimensions to the adversary’s assumed knowledge of the trained model:

Task Knowledge refers to global information about the model’s prediction task and, therefore, of its prediction API. Examples of task knowledge include the total number of classes, the class-labels (dog, cat, etc.), and the input format ($32 \times 32$ RGB or grayscale images, etc.). Task knowledge is always assumed to be known to the adversary, as it is necessary for the classifier service to be useful to a user.

Training Knowledge refers to knowledge about the model architecture (e.g., the type of neural network, its number of layers, etc.) and how it was trained (the training
Table 3. Survey of membership inference threat models. $\mathcal{L}$ is the model’s loss function, $\tau$ is a calibration term reflecting the difficulty of the sample, $\theta$ are the model parameters centered around $\theta^*$, $\theta_0$ are the parameters on all other datapoints (other than $x$), $\text{aug}(x)$ is a data augmentation of $x$ (e.g., image translation), $x'$ is an adversarial-example of $x$, and $\text{dist}(x,y)$ is the distance from $x$ to the decision boundary. Train, data, label, and model knowledge mean, respectively, that the adversary (1) knows the model’s architecture and training algorithm, (2) has access to other samples from the training distribution, (3) knows the true label, $y$ for a given $x$, and (4) knows the model parameter values.

| Query Interface | Attack Feature | Knowledge | Source |
|-----------------|----------------|-----------|--------|
| confidence vector | $h(x), y$ | train, data label | (Shokri et al., 2016) |
| confidence vector | $h(x)$ | train, data | (Long et al., 2017) |
| confidence vector | $h(x)$ | -- | (Salem et al., 2018) |
| confidence vector | $\mathcal{L}(h(x), y)$ | label | (Yeom et al., 2018) |
| confidence vector | $-(\theta - \theta_0)^T \nabla_{\theta} \mathcal{L}(h(x), y)$ | label | (Sablayrolles et al., 2019) |
| confidence vector | $h(x'), y$ | train, data label, model | (Song et al., 2019) |
| label-only | $\text{argmax} h(x), y$ | label | (Yeom et al., 2018) |
| label-only | $\text{argmax} \ h(\text{aug}(x)), y$ | train, data label | ours |
| label-only | $\text{dist}(h(x), y)$ | train, data label | ours |
| label-only | $\text{dist}(\text{aug}(x), y)$ | train, data label | ours |

algorithm, training dataset size, etc.). This information could be publicly available or inferable from a model extraction attack (Tramèr et al., 2016; Wang & Gong, 2018).

Data Knowledge constitutes knowledge about the data that was used to train the target model. Full knowledge of the training data renders membership inference trivial because the training members are already known. Partial knowledge may consist in having access to (or the ability to generate) samples from the same or a related data distribution.

Label Knowledge refers to knowledge of the true label $y$ for each point $x$ for which the adversary is predicting membership. Whether knowledge of a data point implies knowledge of its true label depends on the application scenario. Salem et al. (Salem et al., 2018) show that attacks that rely on knowledge of query labels can often be matched by attacks that do not.

C.2. Query Interface

Our paper studies a different query interface than most prior membership inference work. The choice of query interface ultimately depends on the application needs where the target model is deployed. We define two types of query interfaces, with different levels of response granularity:

Full confidence vectors On a query $x$, the adversary receives the full vector of confidence scores $h(x)$ from the classifier. In a multi-class scenario, each value in this vector corresponds to an estimated confidence that this class is the correct label. Restricting access to only part of the confidence vector has little effect on the adversary’s success (Shokri et al., 2016; Truex et al., 2018; Salem et al., 2018).

Label-only Here, the adversary only obtains the predicted label $y = \text{argmax}_i h(x)_i$, with no confidence scores. This is the minimal piece of information that any query-able machine learning model must provide and is thus the most restrictive query interface for the adversary. Such a query interface is also realistic, as the adversary may only get indirect access to a deployed model in many settings. For example, the model may be part of a larger system taking actions based on the model’s predictions—the adversary can only observe the system’s actions but not the internal model’s confidence scores.

In this work, we focus exclusively on the above label-only regime. Thus, in contrast to prior research (Shokri et al., 2016; Hayes et al., 2019; Truex et al., 2018; Salem et al., 2018), our attacks can be mounted against any machine learning service, regardless of the granularity provided by the query interface.

D. Confidence-Masking Defense Descriptions

MemGuard This defense solves a constrained optimization problem to compute a defended confidence-vector $h_{\text{defense}}(x) = h(x) + n$, where $n$ is an adversarial noise vector that satisfies the following constraints: (1) the model still outputs a vector of “probabilities”, i.e., $h_{\text{defense}}(x) \in [0, 1]^K$ and $\|h_{\text{defense}}(x)\|_1 = 1$; (2) the model’s predictions are unchanged, i.e., $\text{argmax}_{i} h_{\text{defense}}(x) = \text{argmax}_{i} h(x)$; and (3) the noisy confidence vector “fools” existing membership inference attacks. To enforce the third constraint, the defender
locally creates a membership attack predictor \( f \), and then optimizes the noise \( n \) to cause \( f \) to mis-predict membership.

**Prediction Purification** Prediction purification (Yang et al., 2020) is a similar defense. It trains a purifier model, \( G \), that is applied to the output vector of the target model. That is, on a query \( x \), the adversary receives \( G(h(x)) \). The purifier model \( G \) is trained so as to minimize the information content in the confidence vector, whilst preserving model accuracy. While the defense does not guarantee that the model’s labels are preserved at all points, the defense is by design incapable of preventing the baseline gap attack, and it is likely that our stronger label-only attacks would similarly be unaffected (intuitively, \( G(h(x)) \) is just another deterministic classifier, so the membership leakage from a point’s distance to the decision boundary should not be expected to change).

**Adversarial Regularization** This defense trains the target model in tandem with a defensive membership classifier. This defensive membership classifier is a neural network that accepts both the confidence-vector, \( h(x) \), of the target model, and the true label, \( y \), that is one-hot encoded. Following the input \( h(x) \) there are four fully connected layers of sizes 100, 1024, 512, 64. Following the input \( y \), there are three fully connected layers of sizes 100, 512, 64. The two 64 neuron layers are concatenated (to make a layer of size 128), and passed through three more fully connected layers of sizes 256, 64, and the output layer of size 1. ReLU activations are used after every layer except the output, which uses a sigmoid activation. The defensive membership classifier and the target model are trained in tandem. First the target model is trained a few (here, 3) epochs. Then for \( k \) steps, the defensive membership classifier is trained using an equal batch on members and non-members (which should be different from the held-out set for the target model). After, the target model is trained on one batch of training data. The target model’s loss function is modified to include a regularization term using the output of the defensive classifier on the training data. This regularization term is weighted by \( \lambda \).

**E. Description of Common Regularizers**

Dropout (Srivastava et al., 2014) is a simple regularization technique, wherein a fraction \( \rho \in (0, 1) \) of weights are randomly “dropped” (i.e., set to zero) in each training step. Intuitively, dropout samples a new random neural network at each step, thereby preventing groups of weights from overfitting. At test time, the model is deterministic and uses all the learned weights. We experiment with different dropout probabilities \( \rho \).

L1 and L2 regularization simply add an additional term of the form \( \lambda \cdot ||w|| \) to the model’s training loss, where \( w \) is a vector containing all of the model’s weights, the norm is either L1 or L2, and \( \lambda > 0 \) is a hyper-parameter governing the scale of the regularization relative to the learning objective. Strong regularization (i.e., large \( \lambda \)) reduces the complexity of the learned model (i.e., it forces the model to learn smaller weights). We experiment with different regularization constants \( \lambda \).

Differential privacy guarantees that any output from a (randomized) algorithm on some dataset \( D \), would have also been output with roughly the same probability (up to a multiplicative \( e^\epsilon \) factor) if one point in \( D \) were arbitrarily modified. For differential privacy, we use DP-SGD (Abadi et al., 2016), a private version of stochastic gradient descent that clips per-example gradients to an L2 norm of \( \tau \), and adds Gaussian noise \( \mathcal{N}(0, c^2\tau^2) \) to each batch’s gradient. We train target models with fixed parameters \( c = 0.5 \) and \( \tau = 2 \). We train for a varied number of steps, to achieve provable differential privacy guarantees for \( 10 \leq \epsilon \leq 250 \).

**F. Additional Figures**

![Figure 7. Attack accuracy of our label-only attacks for various numbers of shadow models.](image_url)

Target and source models are trained on 1000 data points from CIFAR-10. The number of shadow models does not have a significant impact on the attack accuracy.
**Figure 8.** Attack accuracy of our translation attack for various choices of $d$. Target models are trained on 2500 data points from CIFAR-10 with varied sizes of translation augmentations. The attack’s accuracy is maximized when it evaluates the same size $d$ of translations as used for training.

**Figure 9.** Accuracy of membership inference attacks on CIFAR-10 models protected with Adversarial Regularization (Nasr et al., 2018a). Target models are trained on a subset of 2500 images. We test several values of $k$, the ratio of maximization to minimization steps and find that setting $k = 1$ enabled the target model to converge to a defended state. We report results as we vary the second hyper-parameter, $\lambda$, which balances the two training objectives (low training error and low membership leakage). This defense strategy does not explicitly aim to reduce the train-test gap and thus does not protect against label-only attacks. However, we find that this defense prevents attacks from exploiting beyond 3 percentage points of the gap attack. Test accuracy ranges from 45% to 20%, where $\lambda \geq 3$ had a test accuracy below 35%.

**Figure 10.** Accuracy of membership inference attacks on CIFAR-10 models trained with transfer learning. The source model for transfer learning is trained on all of CIFAR-100. Models are tuned on subsets of CIFAR-10.

**Figure 11.** Outlier membership inference attacks on defended models. Target and source models are trained on a subset of 2500 points from CIFAR-10. $\beta = 2\%$ outliers are identified with less than $\gamma = 10$ neighbors. We show precision-improvement from the undefended model, using our label-only boundary distance attack.