

50.039 Theory and Practice of Deep Learning

W8-S2 Introduction to Attacks and Defense on Neural Networks

Matthieu De Mari



About this week (Week 8)

1. What are **attacks** on Neural Networks (NNs)?
2. Why are attacks an **important concept** when studying NNs?
3. What are the different **types of attacks** and what is the intuition behind basic attacks?
4. How to **defend** against such attacks?
5. **State-of-the-art** of attacks and defense, **open questions** in research.

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4. How to **defend** against such attacks?
5. **State-of-the-art** of attacks and defense, **open questions** in research.

In the last episode

- Noising samples is sometimes good enough to produce adversarial samples and make a trained Neural Network malfunction.
- This exploits the intrinsic properties/limits of Neural Networks.
- The problem, however, is that noising is too random, and is often not guaranteed to work.
- Can we implement **more advanced attacks**, with higher **success rates**?
- Can we “**target**” these attacks to produce adversarial samples with expected effects on Neural Networks?
- And later, can we **defend** against these attacks?

Some more taxonomy on attacks

Definition (**untargeted** attack):

The objective of an **untargeted attack** is to produce an attack sample, which will simply be misclassified.

Noising was an **untargeted attack**, as we attempted to modify a sample in such a way that it would be classified as anything but its ground truth label.

Definition (**targeted** attack):

The objective of a **targeted attack** is to produce an attack sample, which will be misclassified as a specific class.

As such, **targeted attacks** are often **more complex** than **untargeted ones**.

E.g., modify a picture of a **dog (original label)** so it is misclassified as a **cat (target label)**.

Some more taxonomy on attacks

Definition (**black-box** attack):

A **black-box** attack does not exploit any properties of the model.

Black-box attacks assume that they can **only try inputs and access the outputs of the model under attack**.

Noising was therefore a **black-box** and **untargeted** attack.

Definition (**white-box** attack):

A **white-box** attack attempts to exploit properties of the model, e.g. its gradients, logits, weights, etc.

White-box attacks therefore assume that the model as a whole can be accessed, including its **weights** and **gradients**.

White-box attacks attempt to **learn** how the model works, to make it malfunction in a certain way.

Some more taxonomy on attacks

Definition (**one-shot** attack):

A **one-shot attack** attempts to produce a single attack sample, and if this attack fails, it simply retries on a different sample.

Noising was therefore a **one-shot attack**. It attempted to noise a sample to have it misclassified.

However, if this attempt failed, it simply tried on another sample.

Definition (**iterated** attack):

An **iterated attack** attempts to produce an attack sample, like the one-shot attacks.

However, it will try to **adjust the said sample** until it either

- **makes the model malfunction (in an expected way),**
- **or reaches a maximal number of allowed iterations.**

The iterated attacks are often more robust and efficient.

About attacks

Attacks on neural networks can be very creative, and is currently a very active research field. In this lecture, and in the interest of time, we will only cover some of the basic ones.

- What matters is to understand the intuition behind these basic attacks, more specifically how we might use information about the model to tailor our attacks and enhance their efficacy.
- In the next lecture, we will then discuss some more advanced attack techniques, for general knowledge.
- To summarize, keep in mind that the potential for attacks is quite unlimited and researchers have been very creative...!

About attacks

Basic attacks (to be discussed today):

1. **Untargeted**, **one-shot**, **white-box** gradient attack
2. **Untargeted**, **one-shot**, **white-box** fast gradient sign attack
3. **Untargeted**, **iterated**, **white-box** fast gradient sign attack
4. **Targeted**, **one-shot**, **white-box** fast gradient sign attack
5. **Targeted**, **iterated**, **white-box** fast gradient sign attack

About attacks

Basic attacks (to be discussed today):

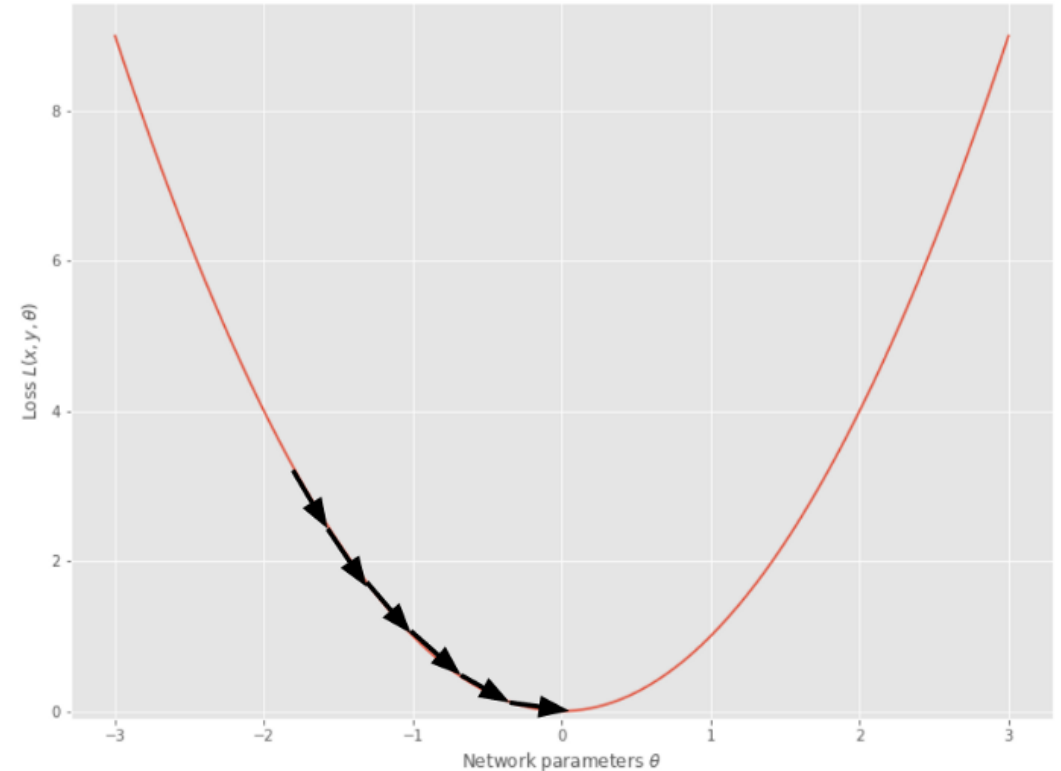
1. **Untargeted, one-shot, white-box gradient** attack
2. **Untargeted, one-shot, white-box fast gradient** sign attack
3. **Untargeted, iterated, white-box fast gradient** sign attack
4. **Targeted, one-shot, white-box fast gradient** sign attack
5. **Targeted, iterated, white-box fast gradient** sign attack

Note: “Gradient” seems to be the important keyword here, but why are gradients used for attacks?

A reminder on gradient descent

- When **training** a neural network, we attempt to adjust the weights of a model θ , to minimize a loss function $L(x, \theta, y)$.
- We typically use an optimizer, which implements some version of the **gradient descent** algorithm.

$$\theta \leftarrow \theta - \alpha \nabla_{\theta} L(x, \theta, y)$$



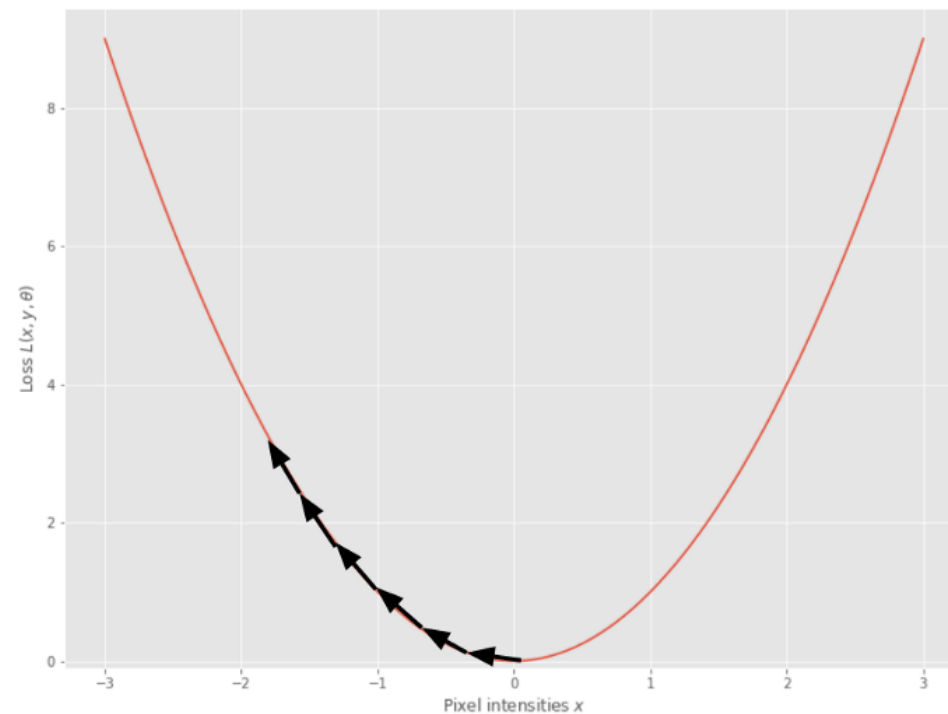
In a sense, gradients tell us how to improve the model performance by adjusting its parameters meaningfully.

Using Gradient Ascent to Attack

A possible approach to “smarter” attacks would then turn this process on its head.

- If we held the parameters of the model constant and differentiated the loss with respect to some input sample x ,
- We could then create a sample \tilde{x} , in a such a way that the expected loss of the model would increase on that sample.

- To do so, we would simply have to use some **gradient ascent** on this sample x .



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$$\theta \leftarrow \theta - \alpha \nabla_{\theta} L(x, \theta, y)$$

(Gradient **descent** on **parameters**,
a.k.a. “**training**” a model)

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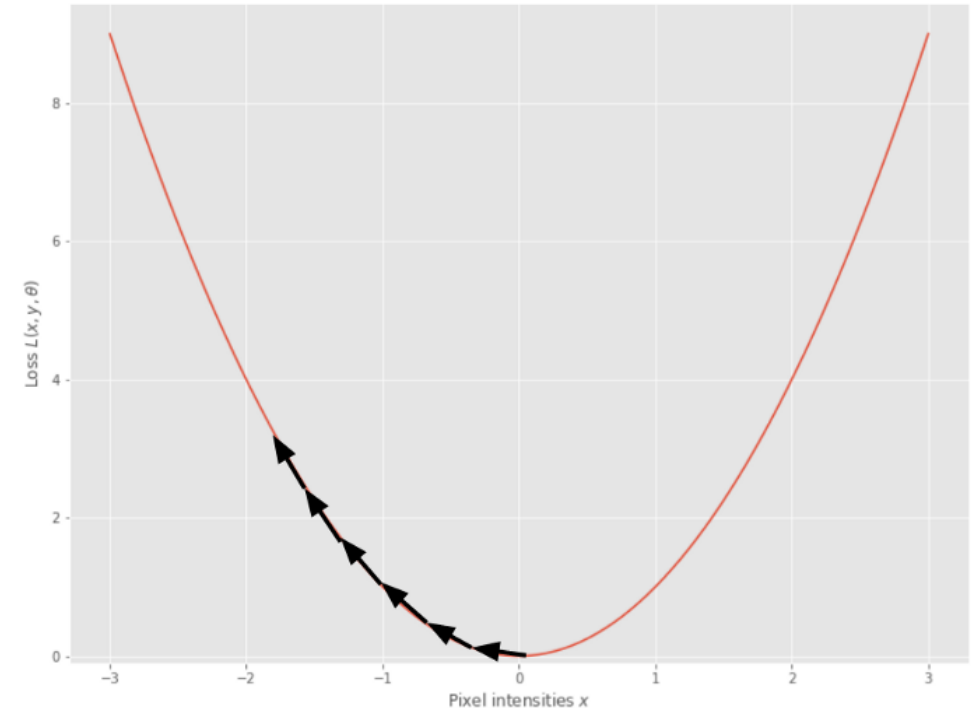
$$\tilde{x} \leftarrow x + \alpha \nabla_x L(x, \theta, y)$$

(Gradient **ascent** on a **sample**,
a.k.a. “**attacking**” a model)

A note on losses, softmax and gradients

- Most gradient-based attacks can operate on the gradients computed from the loss function $L(x, \theta, c)$, for instance, to move away from the original class c .
- To do so, by **increasing the loss** for said sample x and class c , using **gradient ascent** on the loss.

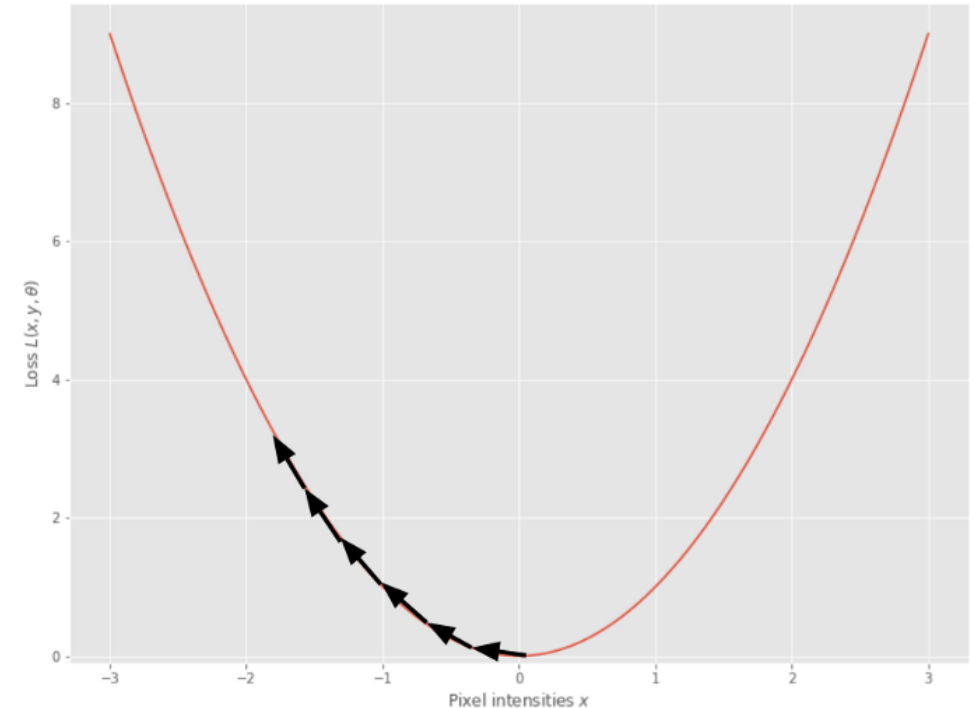
$$\tilde{x} \leftarrow x + \alpha \nabla_x L(x, \theta, c)$$



A note on losses, softmax and gradients

- Some papers however mention that it would be preferable to use the logits $f_c(x)$ to **minimize the value of these logits (\approx final vector before softmax and argmax decision)**.
- In that case, we would use **gradient descent** to minimize the probability of class c to be chosen!

$$\tilde{x} \leftarrow x - \alpha \nabla_x f_c(x)$$



Note: this second approach (logits) often works better, because of the softmax might end up messing up the gradients sometimes.

Untargeted Gradient Attack

Definition (untargeted gradient attack):

The **untargeted gradient attack** takes a single sample x , of original class $c \in \mathcal{C}$ and attempts to produce a sample \tilde{x} of class $\tilde{c} \in \mathcal{C}$, with $\tilde{c} \neq c$.

$$c = \operatorname{argmax}_{i \in \mathcal{C}} (f_i(x))$$

And then two options...

Untargeted Gradient Attack (option #1)

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$$c = \operatorname{argmax}_{i \in \mathcal{C}} (f_i(x))$$

And then two options...

- **Option #1:** look for the most probable class $c \in \mathcal{C}$ and use gradient **ascent** to move the sample **away from its original class**, with step ϵ .

$$\tilde{x} \leftarrow x + \epsilon \nabla_x L(x, \theta, c)$$

The attack is successful if

$$\tilde{c} = \operatorname{argmax}_{i \in \mathcal{C}} (f_i(\tilde{x})) \neq c$$

Untargeted Gradient Attack (option #2, not implemented in notebooks)

Definition (untargeted gradient attack):

The **untargeted gradient attack** takes a single sample x , of original class $c \in \mathcal{C}$ and attempts to produce a sample \tilde{x} of class $\tilde{c} \in \mathcal{C}$, with $\tilde{c} \neq c$.

$$c = \operatorname{argmax}_{i \in \mathcal{C}} (f_i(x))$$

And then two options...

- **Option #2:** look for the least probable class $c^* \in \mathcal{C}$ and use gradient **descent** to move the sample **in the direction of the least probable class**, with step ϵ .

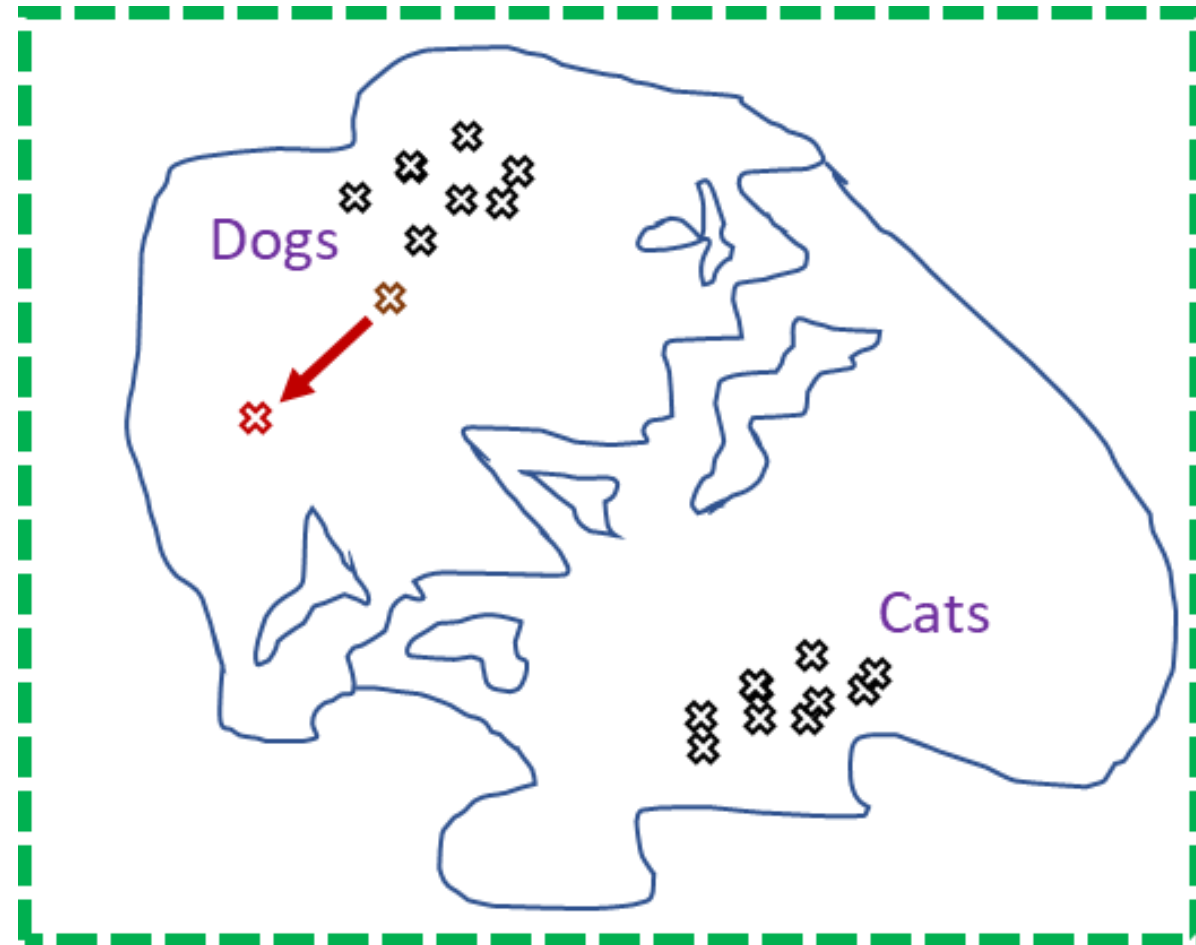
$$\begin{aligned} c^* &= \operatorname{argmin}_{i \in \mathcal{C}} (f_i(x)) \\ \tilde{x} &\leftarrow x - \epsilon \nabla_x L(x, \theta, c^*) \end{aligned}$$

The attack is successful if

$$\tilde{c} = \operatorname{argmax}_{i \in \mathcal{C}} (f_i(\tilde{x})) \neq c$$

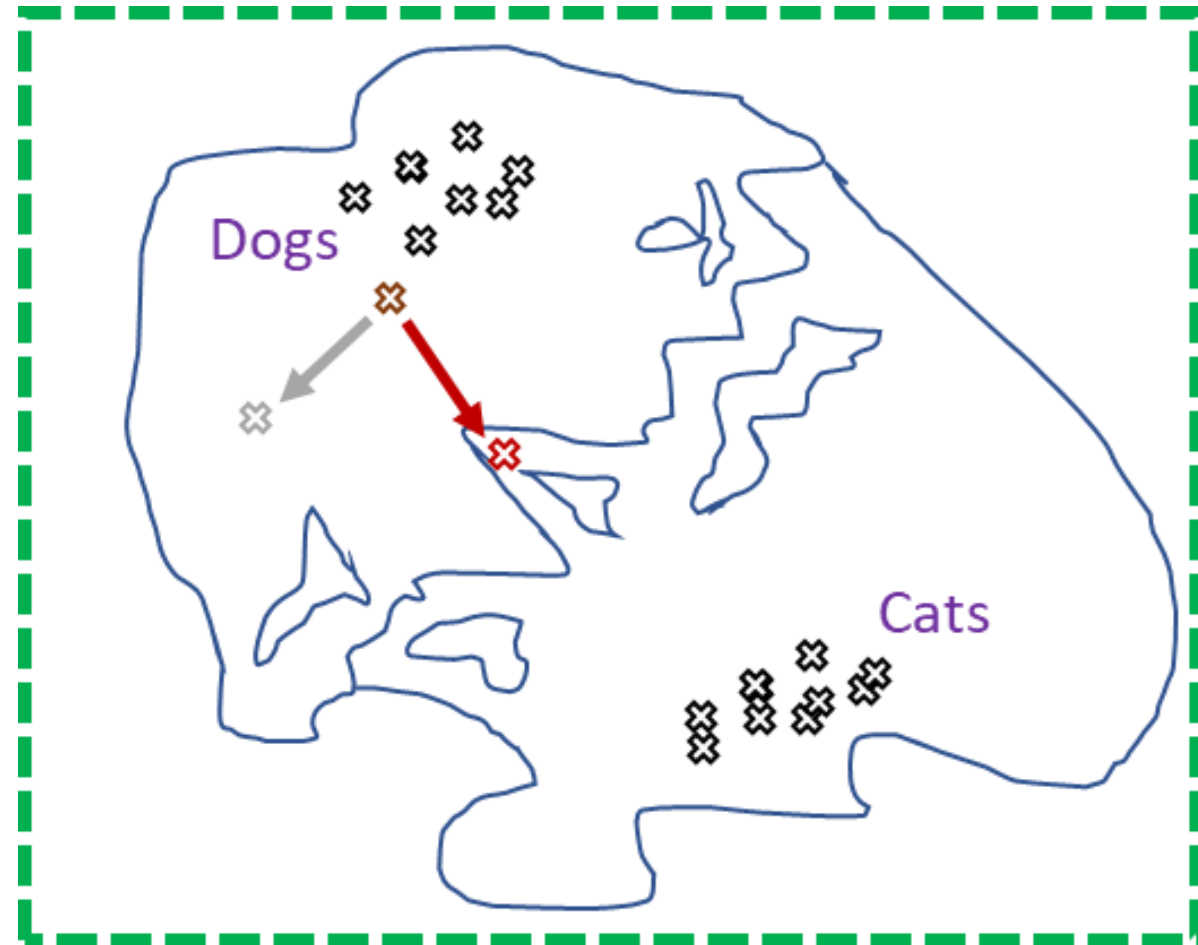
Why gradient attack works better than randomly noising

- When randomly noising a **sample** to make an **attack sample**, we move randomly in the feature map.



Why gradient attack works better than randomly noising

- When randomly noising a **sample** to make an **attack sample**, we move randomly in the feature map.
- When using gradient attack, we move in a more meaningful direction, which might help our **original sample** become **misclassified**.



Untargeted gradient attack code

- The **untargeted gradient attack (option #1)** takes a single sample x , of original class $c \in C$ and attempts to produce a sample \tilde{x} of class $\tilde{c} \in C$, with $\tilde{c} \neq c$.
- It uses gradient ascent to move the original sample **away from the most probable class** (i.e. its original one) to generate an attack sample.

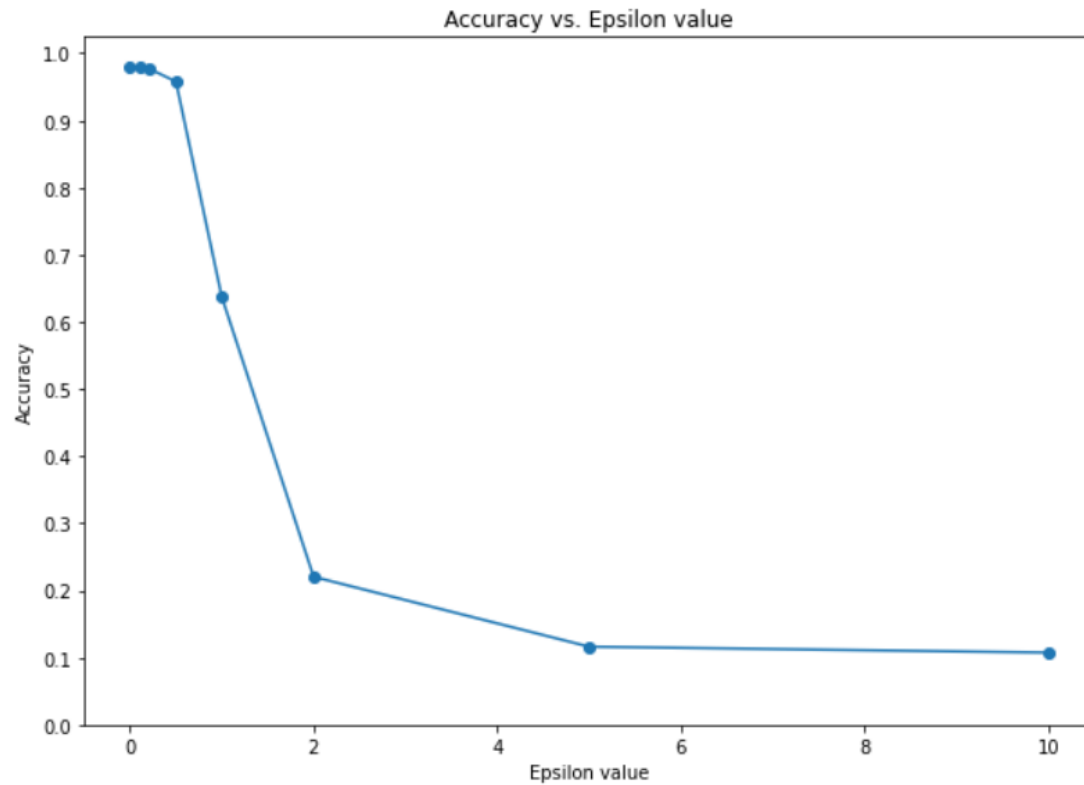
```
1 def ugm_attack(image, epsilon, data_grad):
2
3     # Create the attack image by adjusting
4     # each pixel of the input image
5     eps_image = image + epsilon*data_grad
6
7     # Clipping eps_image to maintain pixel
8     # values into the [0, 1] range
9     eps_image = torch.clamp(eps_image, 0, 1)
10
11     # Return
12     return eps_image
```

Line 5 easily implements
$$\tilde{x} \leftarrow x + \epsilon \nabla_x L(x, \theta, c)$$

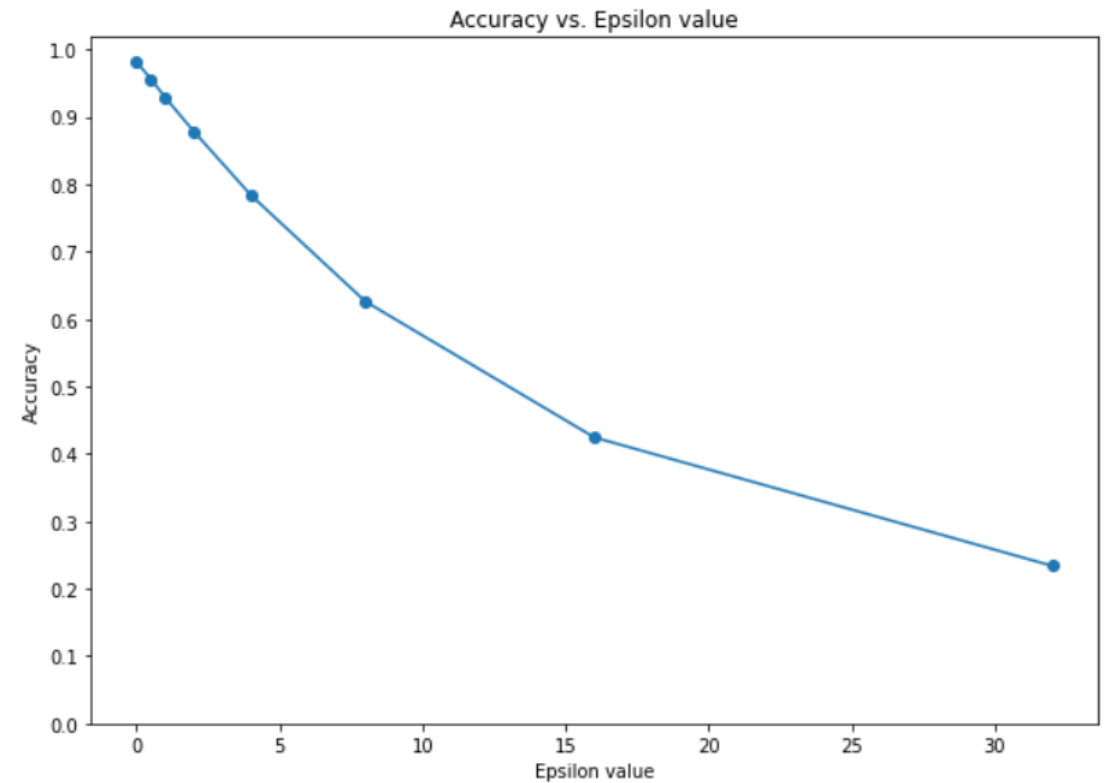
(Taken from notebook 2.)

Untargeted gradient vs. epsilon noising

- Epsilon Noising Method

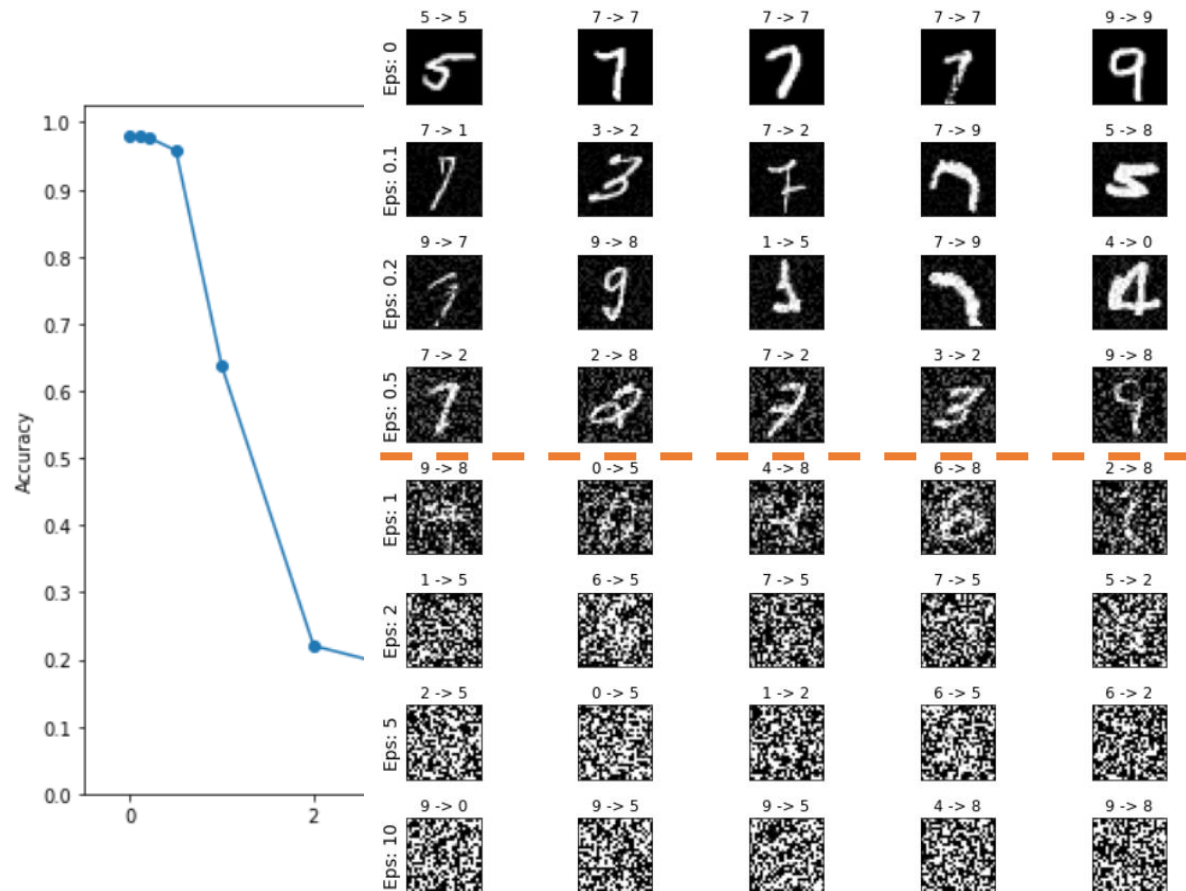


- Untargeted Gradient Method

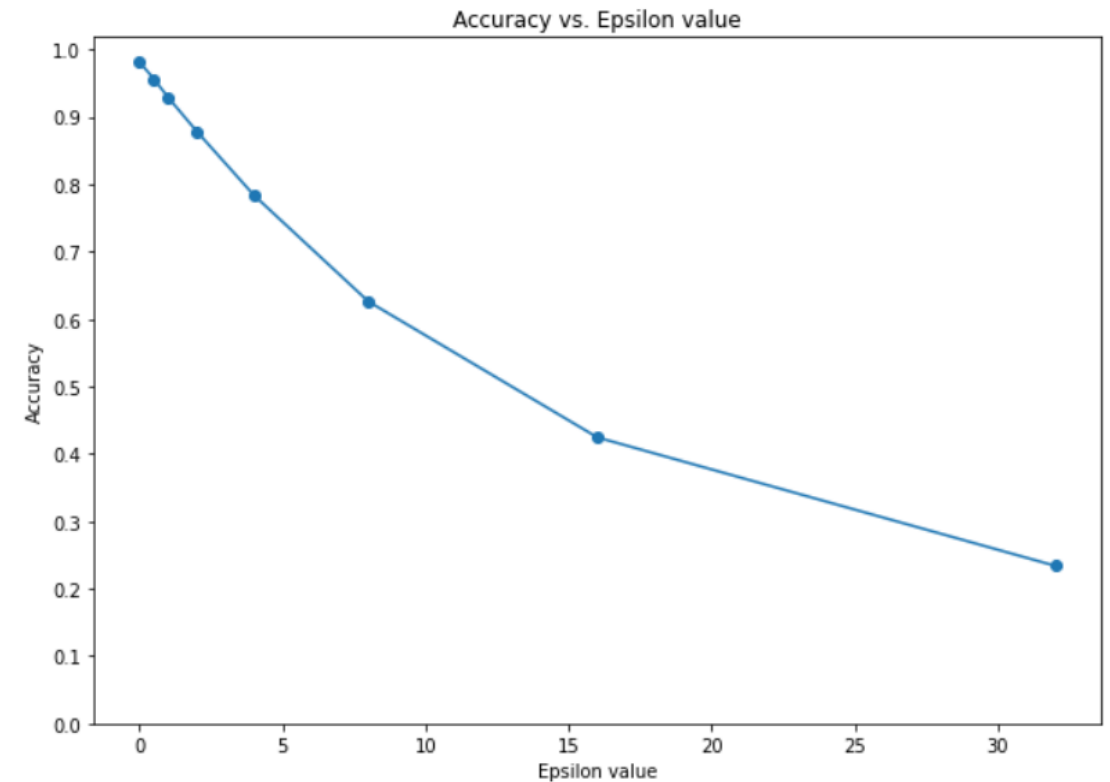


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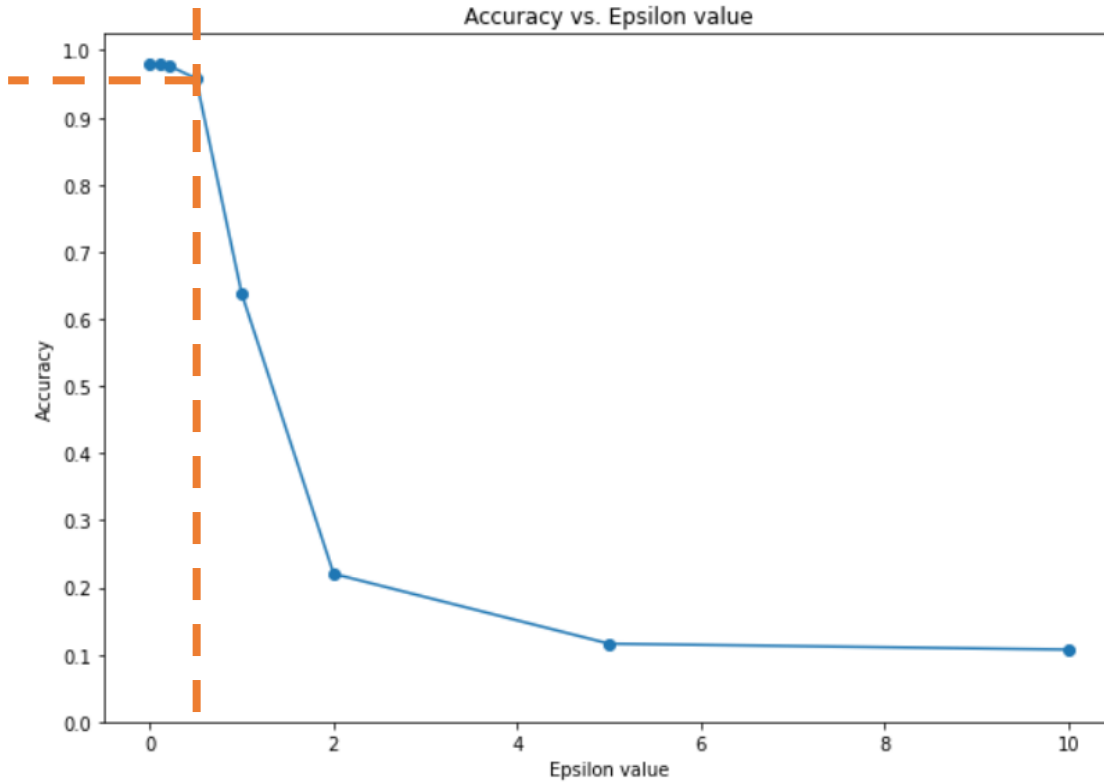


- Untargeted Gradient Method

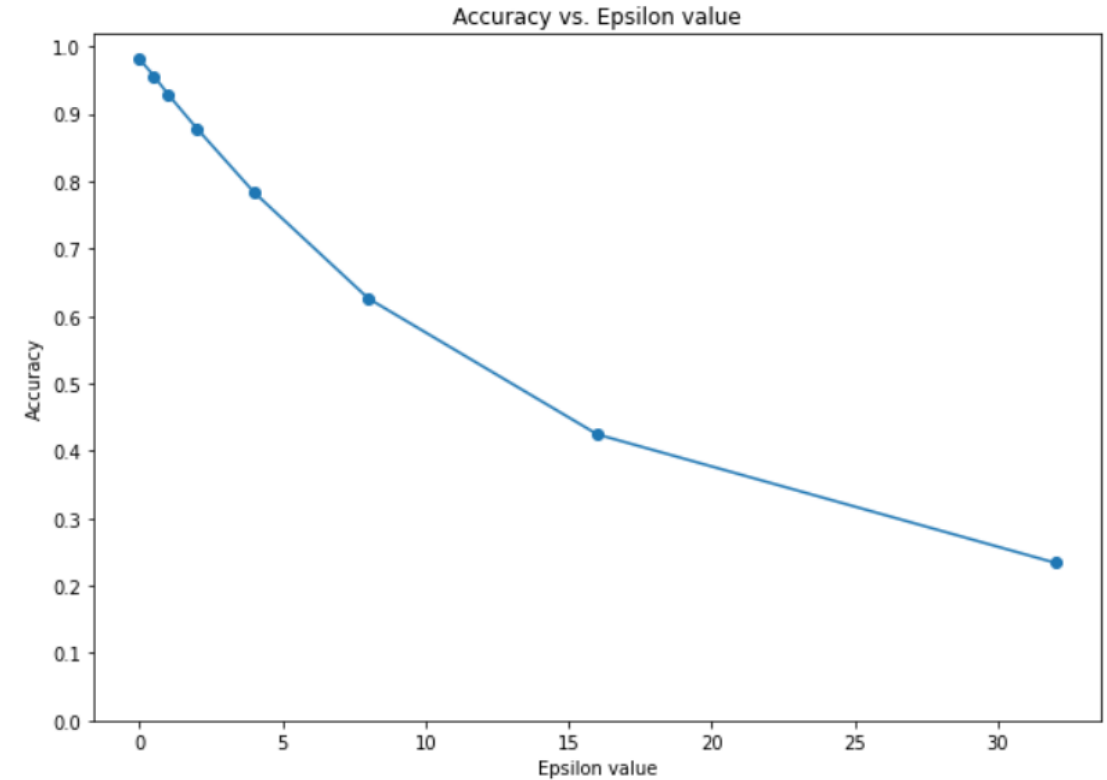


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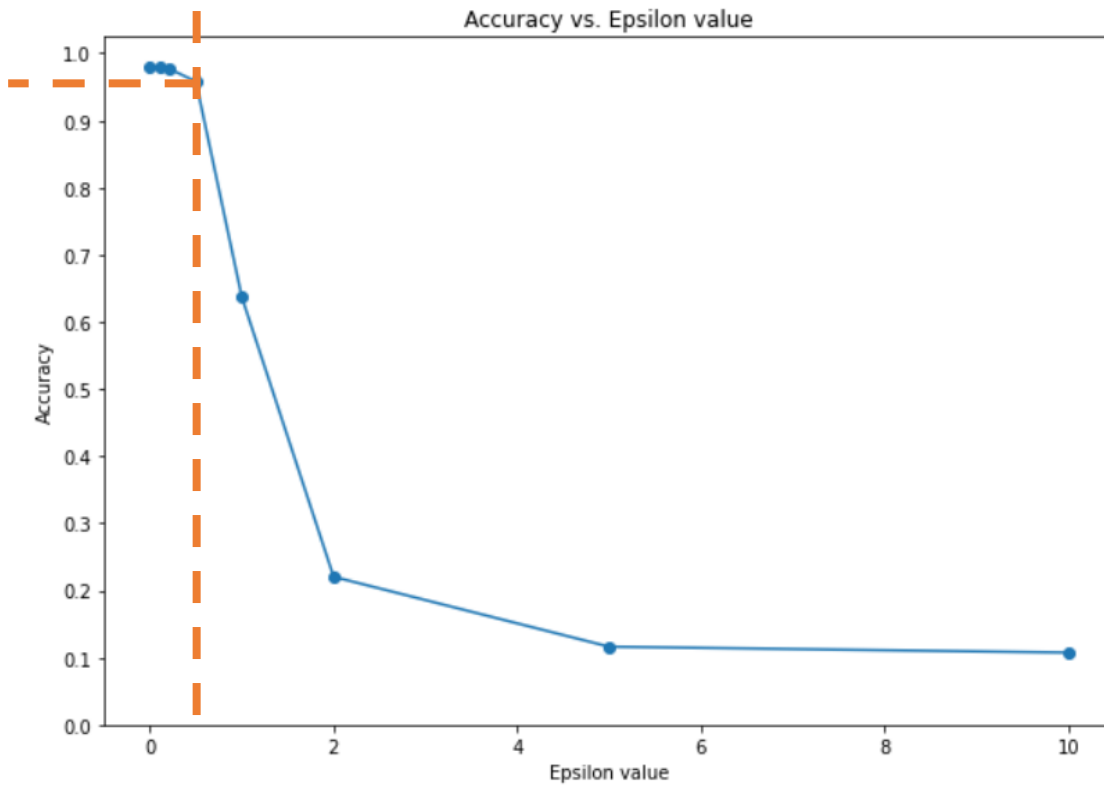


- Untargeted Gradient Method

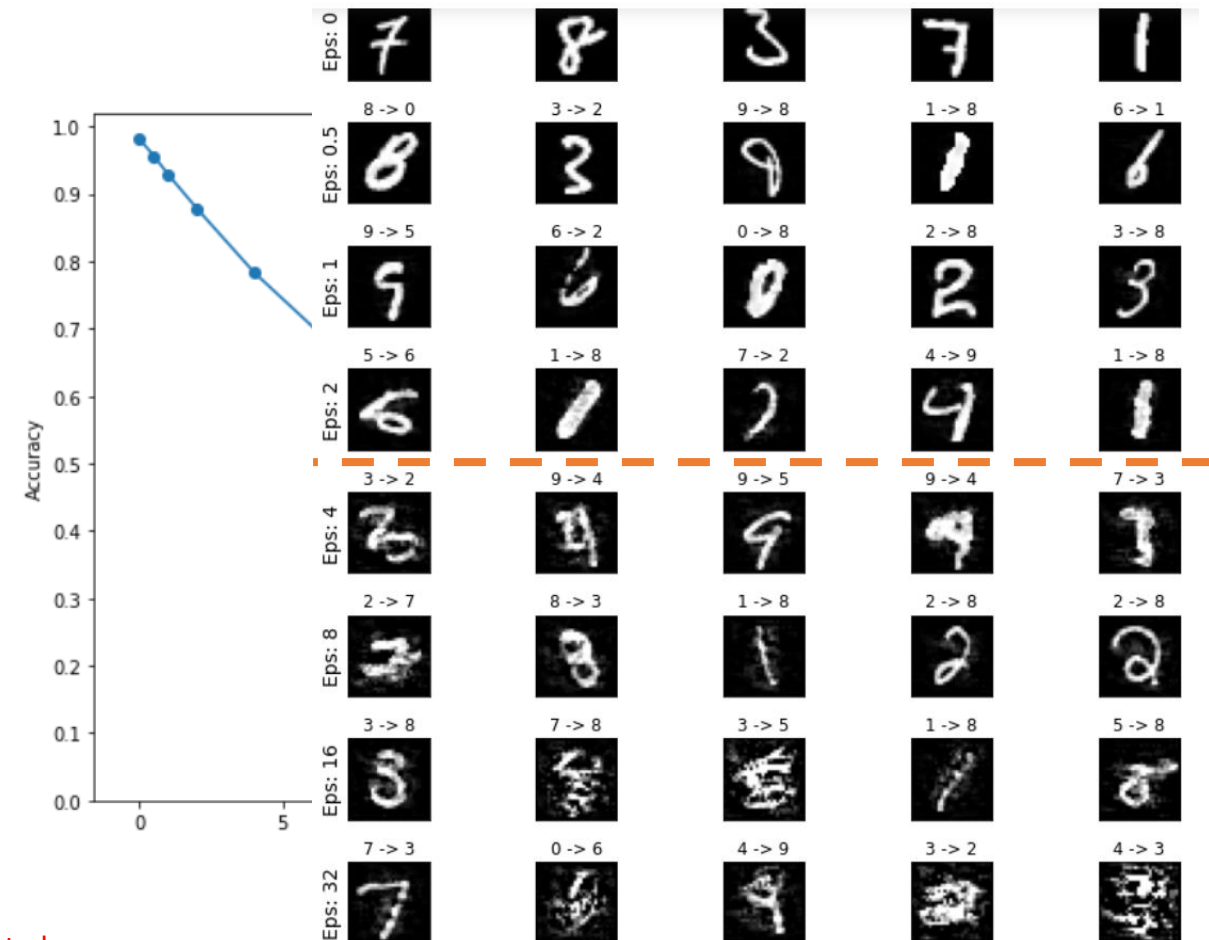


Untargeted gradient vs. epsilon noising

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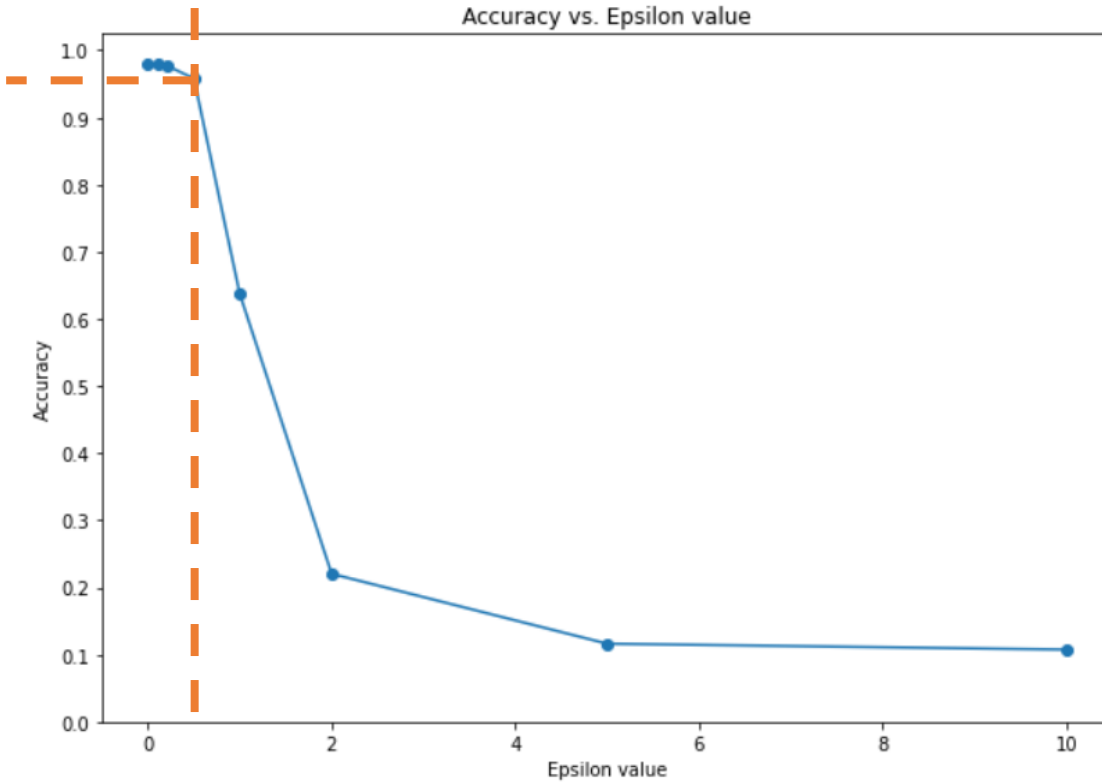


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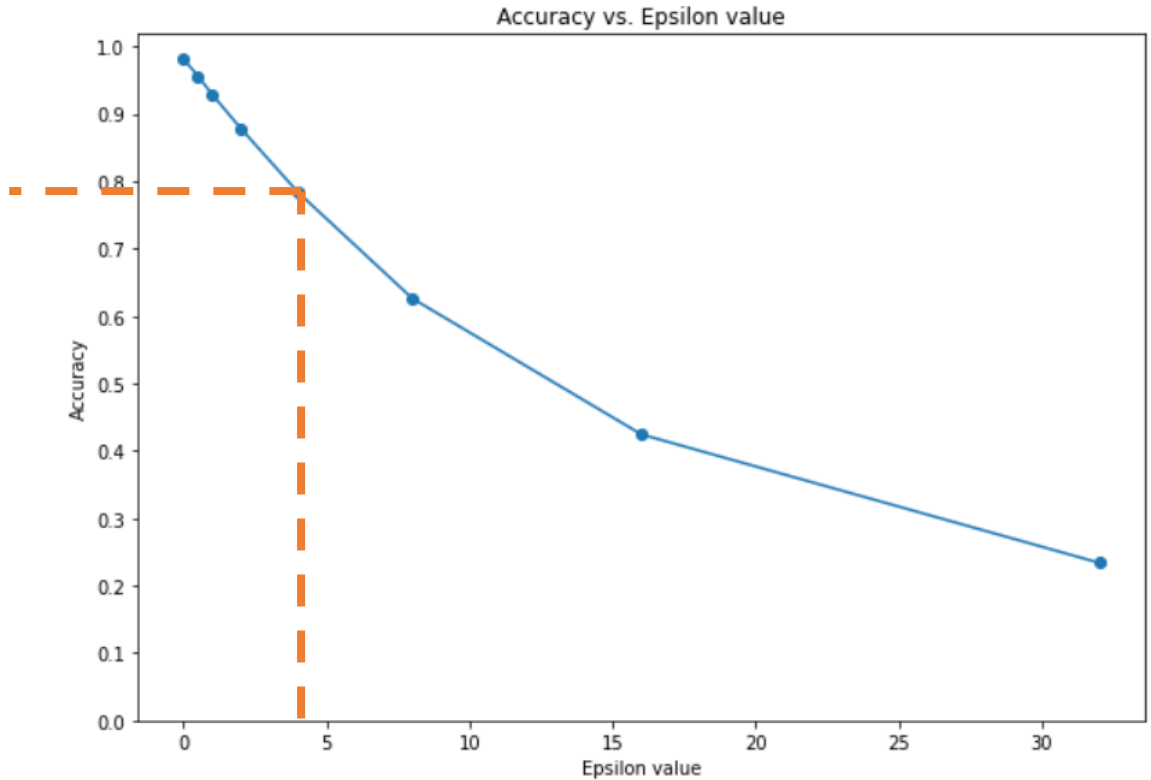


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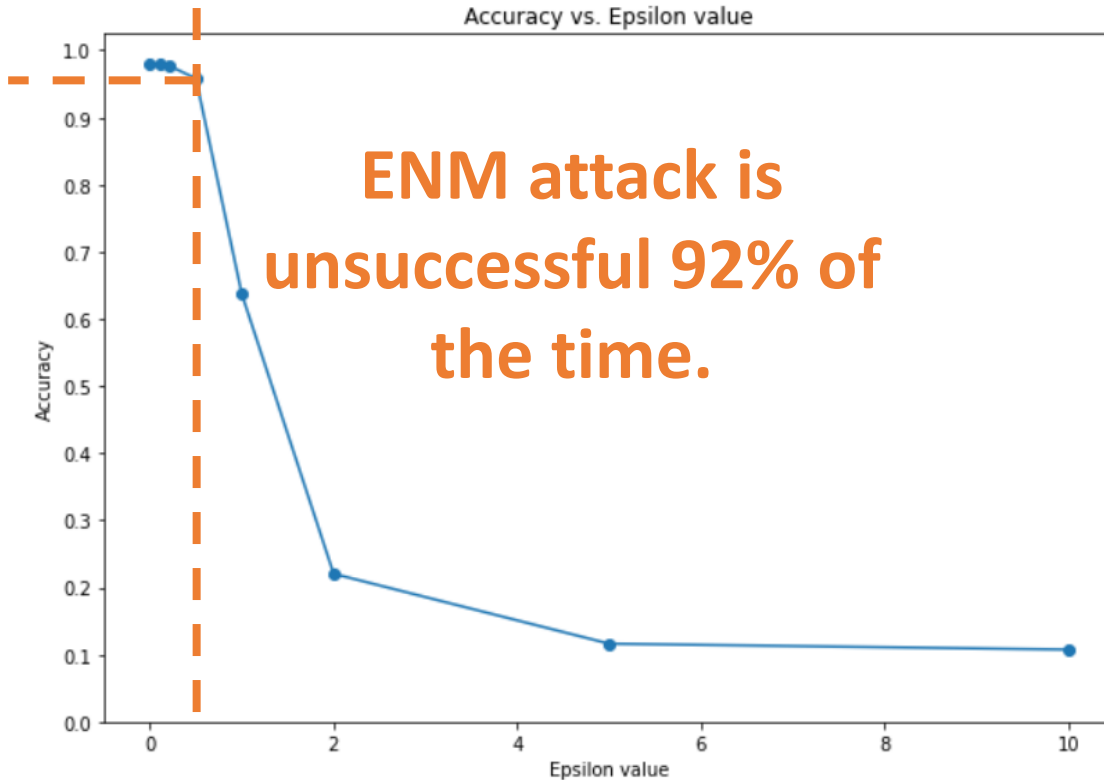


- Untargeted Gradient Method

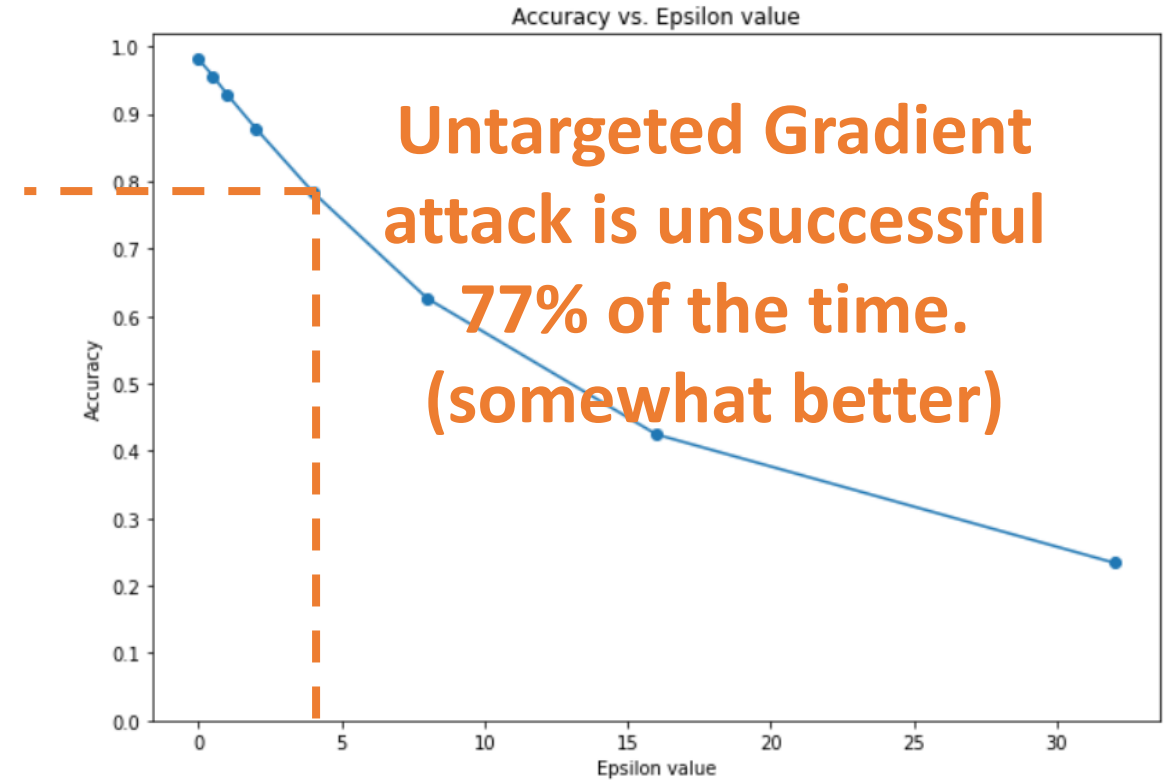


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- Epsilon Noising Method

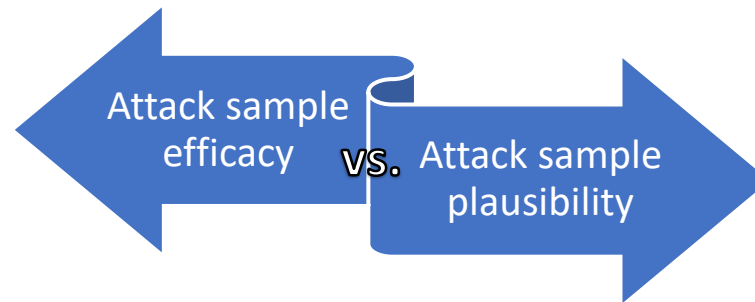


- Untargeted Gradient Method



Untargeted gradient attack recap

- Like the Epsilon Noising Method from lecture 1, the Untargeted Gradient Method is an attack which is subject to the same tradeoff we identified earlier.



- However, it performs better than the Epsilon Noising Method, as it is able to produce plausible attack samples that seem to fool the models better ($\sim 92\%$ vs. $\sim 77\%$).

Untargeted gradient attack recap

This being said, it suffers from several problems:

- Its **efficacy is still rather low** (fails $\sim 77\%$ of the time).

Untargeted gradient attack recap

This being said, it suffers from several problems:

- Its efficacy is still rather low (fails $\sim 77\%$ of the time).
- It is a **one-shot** attack, which does not necessarily make sense.
 - The gradient descent algorithm takes multiple steps (batches + epochs) during training to converge...
 - Why would a single step of gradient attack be enough?
 - We should repeat the gradient attack multiple times (i.e. make it **iterated**).

Untargeted gradient attack recap

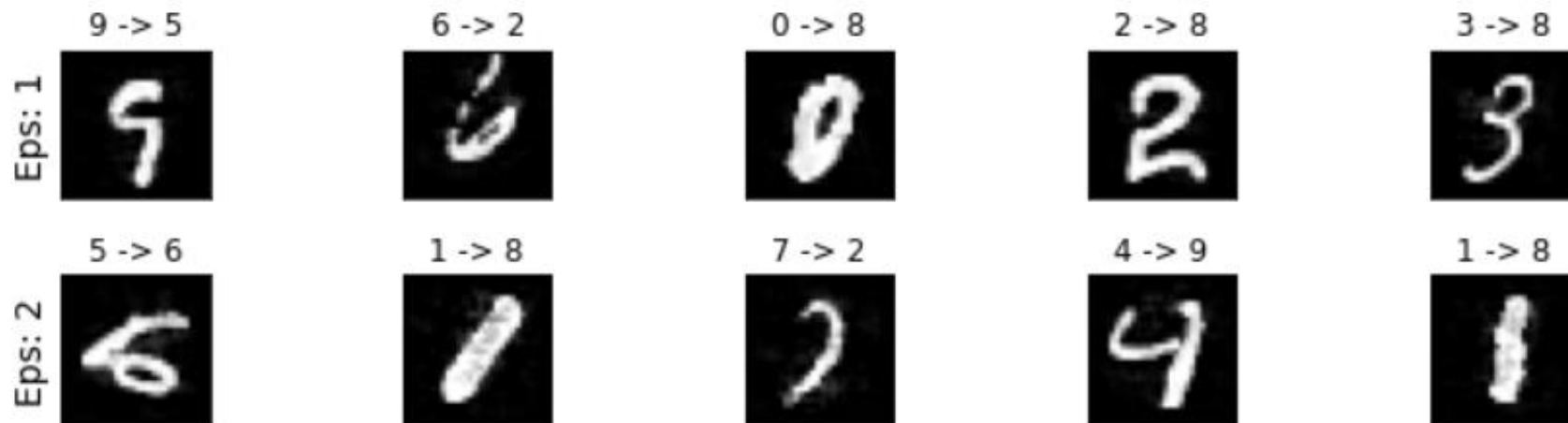
This being said, it suffers from several problems:

- Its efficacy is still rather low (fails $\sim 77\%$ of the time).
- It is a **one-shot** attack.
- It is **untargeted**.
 - It attempts to invalidate the sample by moving away from its original label,
 - or in the direction of the least probable class.
 - This seems to indicate we can orient the direction in which we move and therefore **target** classes...

Untargeted gradient attack recap

This being said, it suffers from several problems:

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- Its **plausibility** is not too great.



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- (It has a **heavy computational cost**, as it requires the gradients from the model to be applied on a sample.)

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- It is a **one-shot** attack.
- It is **untargeted**.
- Its **plausibility is not too great**.
- (It has a **heavy computational cost**, as it requires the gradients from the model to be applied on a sample.)
- Our next attack, the **Fast Gradient Sign Method** attempts to solve this heavy computational issue and help make more plausible samples.

Fast Gradient Sign Method (FGSM)

Definition (Fast Gradient Sign Method attack):

The **Fast Gradient Sign Method attack** only uses the **sign** of the gradient to create an attack sample.

$$\tilde{x} \leftarrow x + \epsilon \nabla_x L(x, \theta, c)$$

(Gradient attack)

$$\tilde{x} \leftarrow x + \epsilon \text{sign}(\nabla_x L(x, \theta, c))$$

(FGSM attack)

```
1 def fgsm_attack(image, epsilon, data_grad):
2     # Get element-wise signs of each element of the data gradient
3     data_grad_sign = data_grad.sign()
4
5     # Create the attack image by adjusting each pixel of the input image
6     eps_image = image + epsilon*data_grad_sign
7
8     # Clipping eps_image to maintain pixel values into the [0, 1] range
9     eps_image = torch.clamp(eps_image, 0, 1)
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(FGSM attack)

- **Important property:** this also helps to make more plausible samples, as it will, by design, verify $\|\tilde{x} - x\|_\infty \leq \epsilon$.
- (Plausibility constraint, we did not have it in the previous attacks!)

```

1 def fgsm_attack(image, epsilon, data_grad):
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```

A reminder about norms

- **L^0 norm:** bounds the total number of pixels in \tilde{x} that can be modified with respect to x (though they can be modified by any amount).
- **L^1 norm:** bounds the average absolute distance between the values of pixels in \tilde{x} and the corresponding pixels in x .
- **L^2 norm:** bounds the total squared distance between the values of pixels in \tilde{x} and the corresponding pixels in x . Often referred to as the Euclidean distance.
- **L^∞ norm:** bounds the maximum difference between any pixel in \tilde{x} and the corresponding pixel in x . Often referred to as max norm.

$$\|\tilde{x} - x\|_\infty = \max_{i,j} |\tilde{x}_{i,j} - x_{i,j}|$$

Testing the FGSM attack

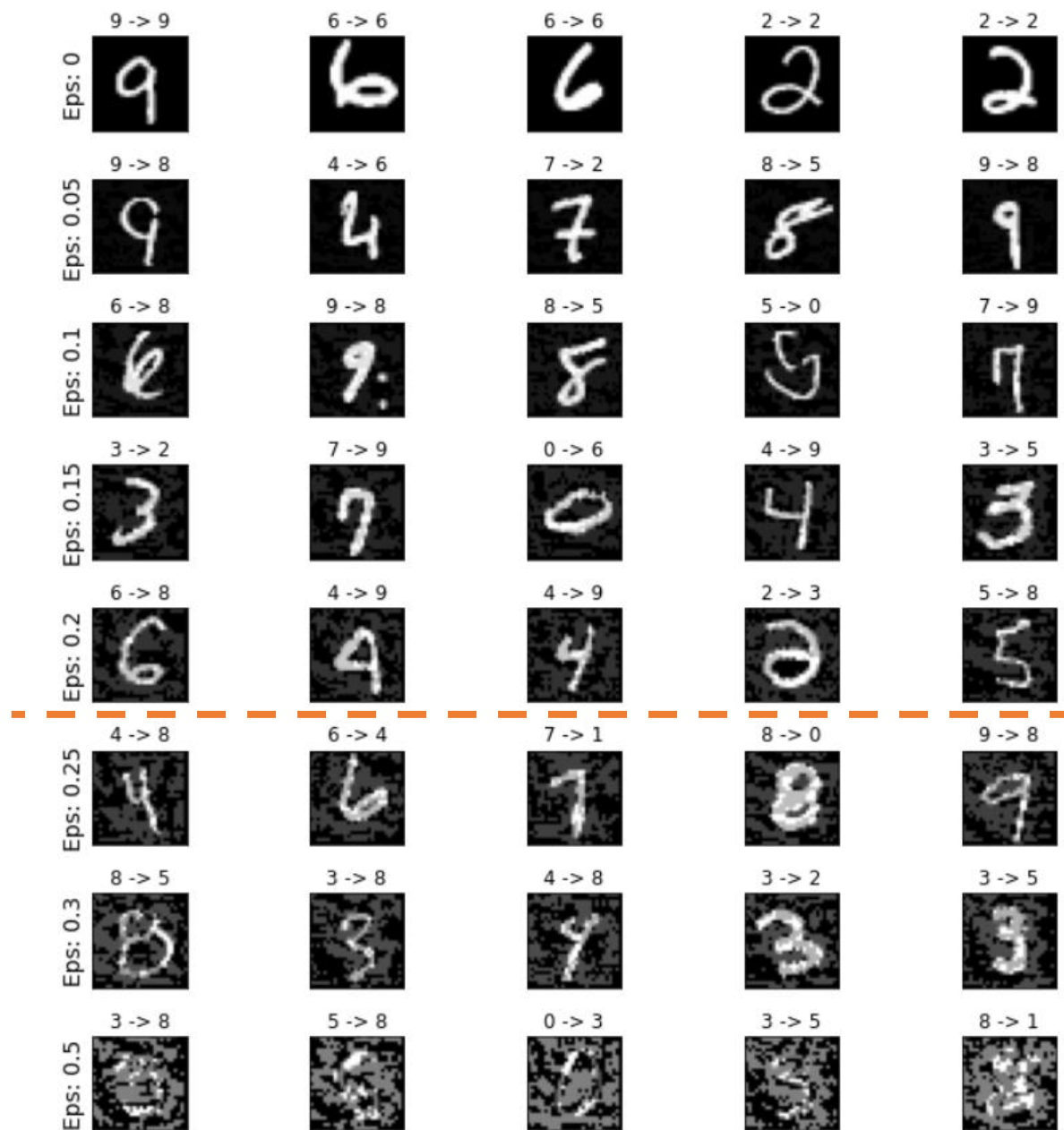
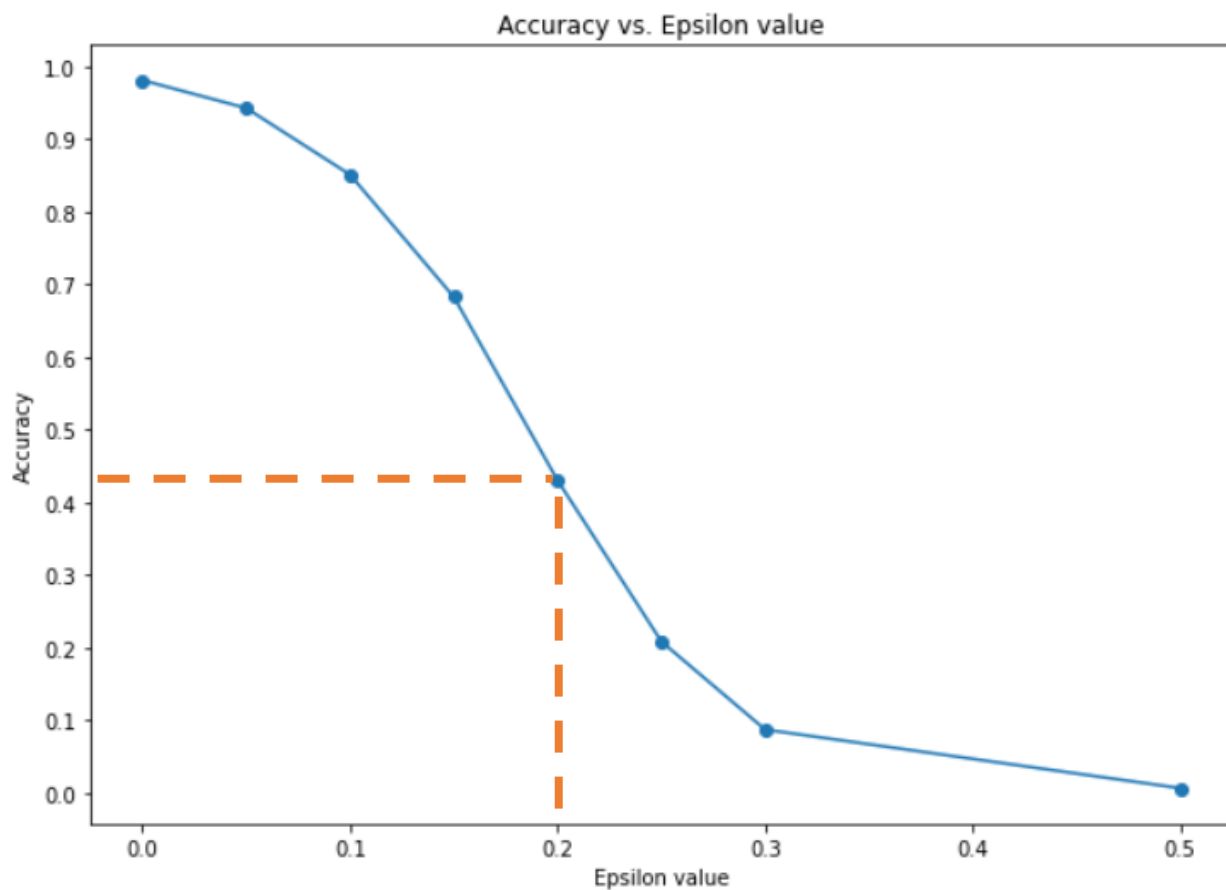
- The FGSM attack works just fine, and it might even make the **model completely malfunction!**
- In the noising approach, the model had to guess randomly and ended up getting a 10% accuracy for large values of epsilon.
- Here, the FGSM will strongly push the model to malfunction, eventually leading to a **0%** accuracy.

```
1 epsilons = [0, .05, .1, .15, .2, .25, .3, .5]
2 accuracies = []
3 examples = []
4
5 # Run test() function for each epsilon
6 for eps in epsilons:
7     acc, ex = test(model, device, test_loader, eps)
8     accuracies.append(acc)
9     examples.append(ex)
```

```
Epsilon: 0 - Test Accuracy = 9810/10000 = 0.981
Epsilon: 0.05 - Test Accuracy = 9426/10000 = 0.9426
Epsilon: 0.1 - Test Accuracy = 8510/10000 = 0.851
Epsilon: 0.15 - Test Accuracy = 6826/10000 = 0.6826
Epsilon: 0.2 - Test Accuracy = 4301/10000 = 0.4301
Epsilon: 0.25 - Test Accuracy = 2082/10000 = 0.2082
Epsilon: 0.3 - Test Accuracy = 869/10000 = 0.0869
Epsilon: 0.5 - Test Accuracy = 63/10000 = 0.0063
```

From Notebook 3.

Testing the FGSM attack



lion

Original: 291



golden retriever

Modified: 207



Difference



Restricted

lion

Original: 291



golden
retriever

Modified: 207



Difference



Background pixels were changed and this lead to an entire different classification result?! This indicates that our model probably has a wrong classification logic somewhere...

From [Goodfellow2015].

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However, it will try to **adjust the said sample** until it either

- **makes the model malfunction in an expected way,**
- **or reaches a maximal number of allowed iterations.**

The iterated attacks are often more robust and efficient.

Iterative FGSM attack (from [Kurakin2016])

Definition (iterative Fast Gradient Sign Method attack):

The **iterative Fast Gradient Sign Method attack** will repeat the FGSM attack until it reaches a maximal number of iterations or makes the model malfunction.

$$\begin{aligned}x_0 &= x \\x_{n+1} &\leftarrow x_n + \epsilon \operatorname{sign}(\nabla_{x_n} L(x_n, \theta, c))\end{aligned}$$

Core idea behind iterating: gradient descent was used for several iterations to train our model, so why should our attacks be using only one iteration of gradient ascent?

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The objective of a **targeted attack** is to produce an attack sample, which will be misclassified as a specific class.

As such, **targeted attacks** are often **more complex** than **untargeted ones**.

E.g., modify a picture of a **dog (original label)**, so it is misclassified as a **cat (target label)**.

Targeted FGSM attack

Definition (targeted Fast Gradient Sign Method attack):

The **targeted Fast Gradient Sign Method attack** will use the FGSM attack but will use the gradients of a targeted class \tilde{c} .

This follows the same logic as moving towards the least probable class as in Gradient attack option #2, but you can use it with any class of your choice \tilde{c} instead of the least probable one. This attack uses gradient descent to move the sample towards the targeted class \tilde{c} .

This is repeated until it reaches a maximal number of iterations or makes the model malfunction with targeted class \tilde{c} .

$$\tilde{x} \leftarrow x - \epsilon \text{sign}(\nabla_x L(x, \theta, \tilde{c}))$$

Untargeted gradient attack recap

This being said, it suffers from several problems:

- Its efficacy is still rather low (fails $\sim 77\%$ of the time).
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- It is **untargeted**.
- Its **plausibility is not too great**.
- (It has a **heavy computational cost**, as it requires the gradients from the model to be applied on a sample.)

Iterative and Targeted FGSM attack

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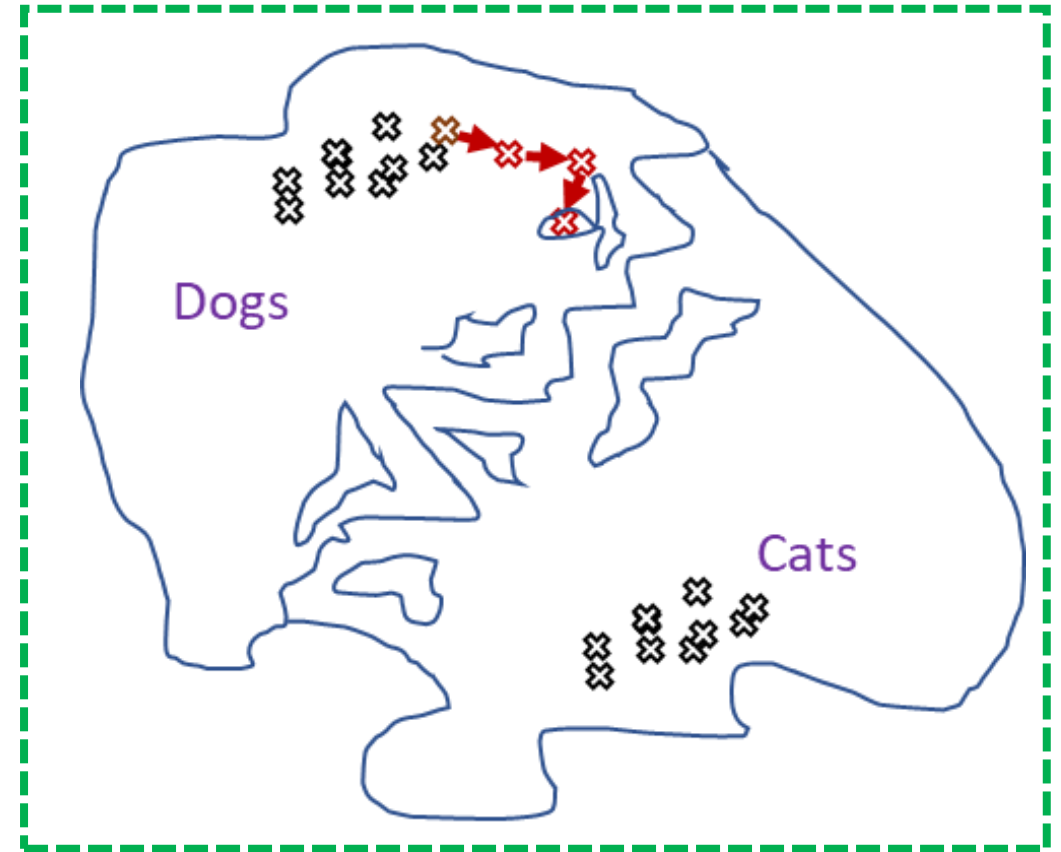
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This is repeated until it reaches a maximal number of iterations or makes the model malfunction with targeted class \tilde{c} .

$$\begin{aligned} x_0 &= x \\ x_{n+1} &\leftarrow x_n - \epsilon \text{sign}(\nabla_x L(x_n, \theta, \tilde{c})) \end{aligned}$$

Why gradient attack works better than randomly noising

- When randomly noising a **sample** to make an **attack sample**, we move randomly in the feature map.
- When using a gradient-type attack, we move in a more meaningful direction, which might help our **original sample** become **misclassified**.
- **Iterating** allows for smaller steps and **better plausibility** in general (smaller changes in original image).



```

1 def itfgsm_attack(image, epsilon, model, orig_class, target_class, iter_num = 10):
2
3     # Convert target class to a LongTensor with one element
4     # (Expected format for the F.nll_loss later on)
5     target_class_var = Variable(torch.from_numpy(np.asarray([target_class])))
6     target_class_torch = target_class_var.type(torch.LongTensor)
7     worked = False
8
9     for i in range(iter_num):
10         # Zero out previous gradients
11         image.grad = None
12         # Forward pass
13         out = model(image)
14         # Calculate loss
15         pred_loss = F.nll_loss(out, target_class_torch)
16
17         # Do backward pass and retain graph
18         #pred_loss.backward()
19         pred_loss.backward(retain_graph = True)
20
21         # Add noise to processed image
22         eps_image = image - epsilon*torch.sign(image.grad.data)
23         eps_image.retain_grad()
24
25         # Clipping eps_image to maintain pixel values into the [0, 1] range
26         eps_image = torch.clamp(eps_image, 0, 1)
27
28         # Forward pass
29         new_output = model(eps_image)
30         # Get prediction
31         _, new_label = new_output.data.max(1)
32
33         # Check if the new_label matches target, if so stop
34         if new_label == target_class_torch:
35             worked = True
36             break
37         else:
38             image = eps_image
39             image.retain_grad()
40
41     return eps_image, worked, i

```

From Notebook 4.

Testing the ITFGSM attack

```

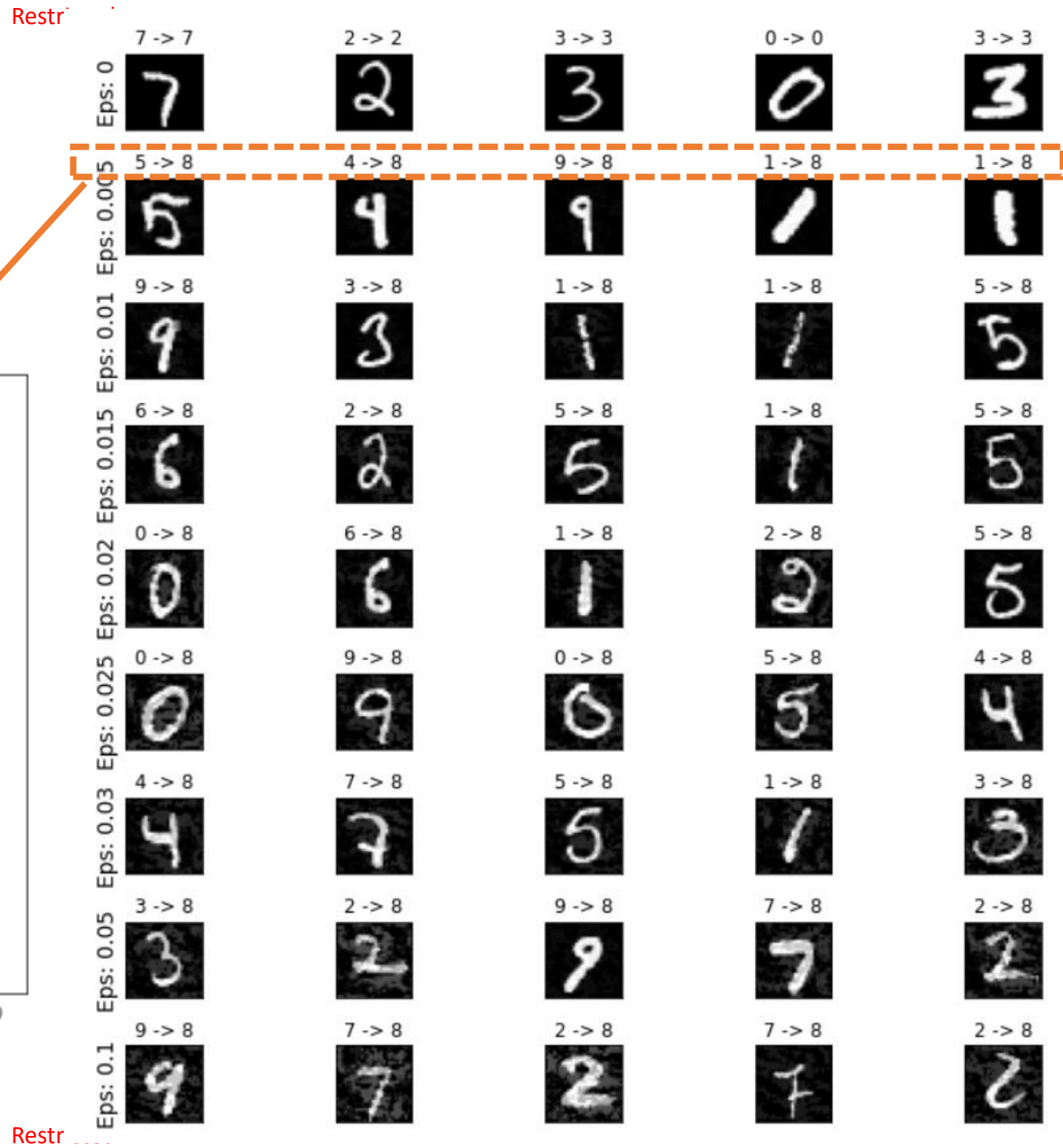
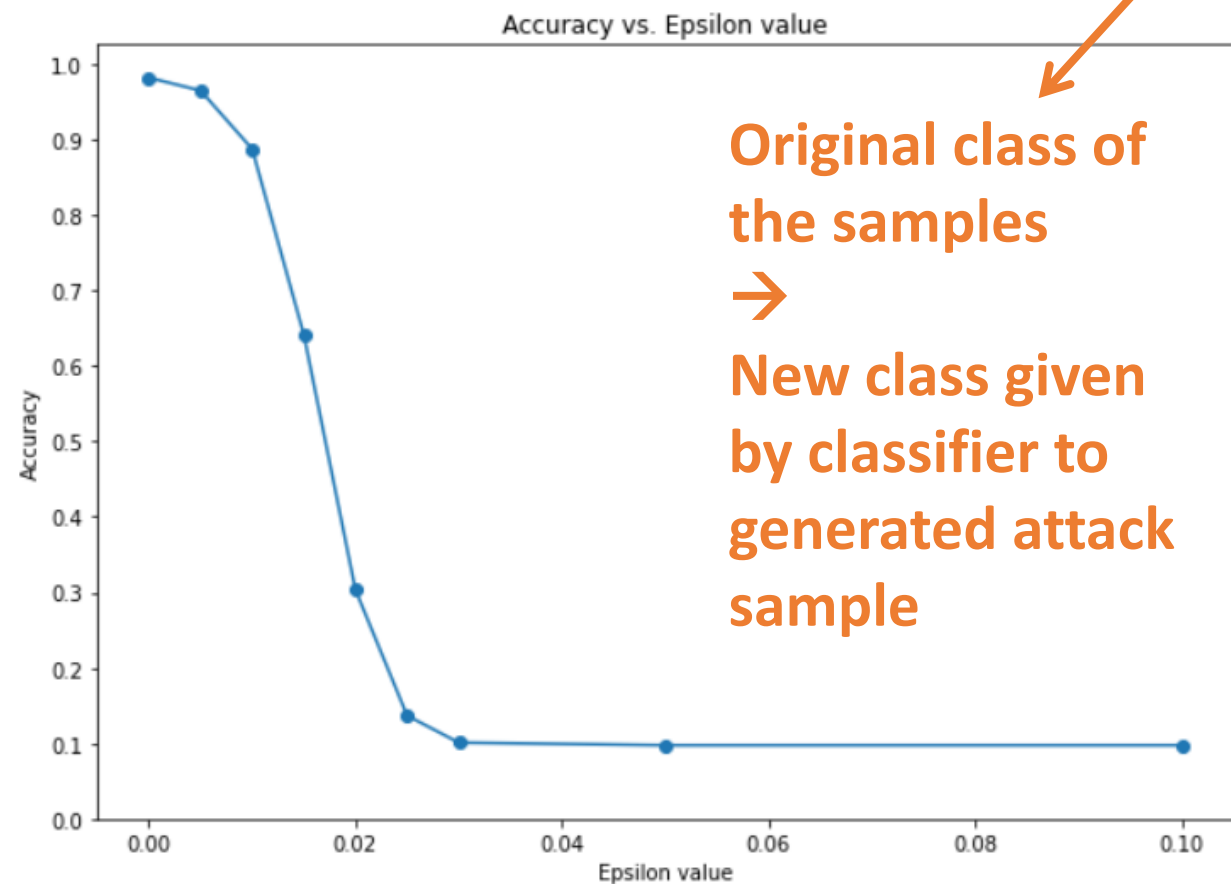
1 def test(model, device, test_loader, epsilon):
2
3     # Target class
4     target_class = 8
5
6     # Counter for correct values (used for accuracy)
7     correct_counter = 0
8
9     # List of successful adversarial samples
10    adv_examples_list = []
11
12    # Loop over all examples in test set
13    for image, label in test_loader:
14
15        # If the initial label is already matching the target class,
16        # do not bother attacking, skip current image
17        if target_class == label.item():
18            correct_counter += 1
19            continue
20
21        # Send the data and label to the device
22        image, label = image.to(device), label.to(device)
23
24        # Set requires_grad attribute of tensor to force torch to
25        # keep track of the gradients of the image
26        # (Needed for the ugm_attack() function!)
27        image.requires_grad = True
28
29        # Pass the image through the model
30        output = model(image)
31        # Get the index of the max log-probability
32        init_pred = output.max(1, keepdim = True)[1]
33
34        # If the initial prediction is wrong, do not bother attacking, skip current image
35        if init_pred.item() != label.item():
36            continue
37
38        # Call TFGSM Attack
39        eps_image, worked, iterations = itfgsm_attack(image, epsilon, model, label, target_class)

```

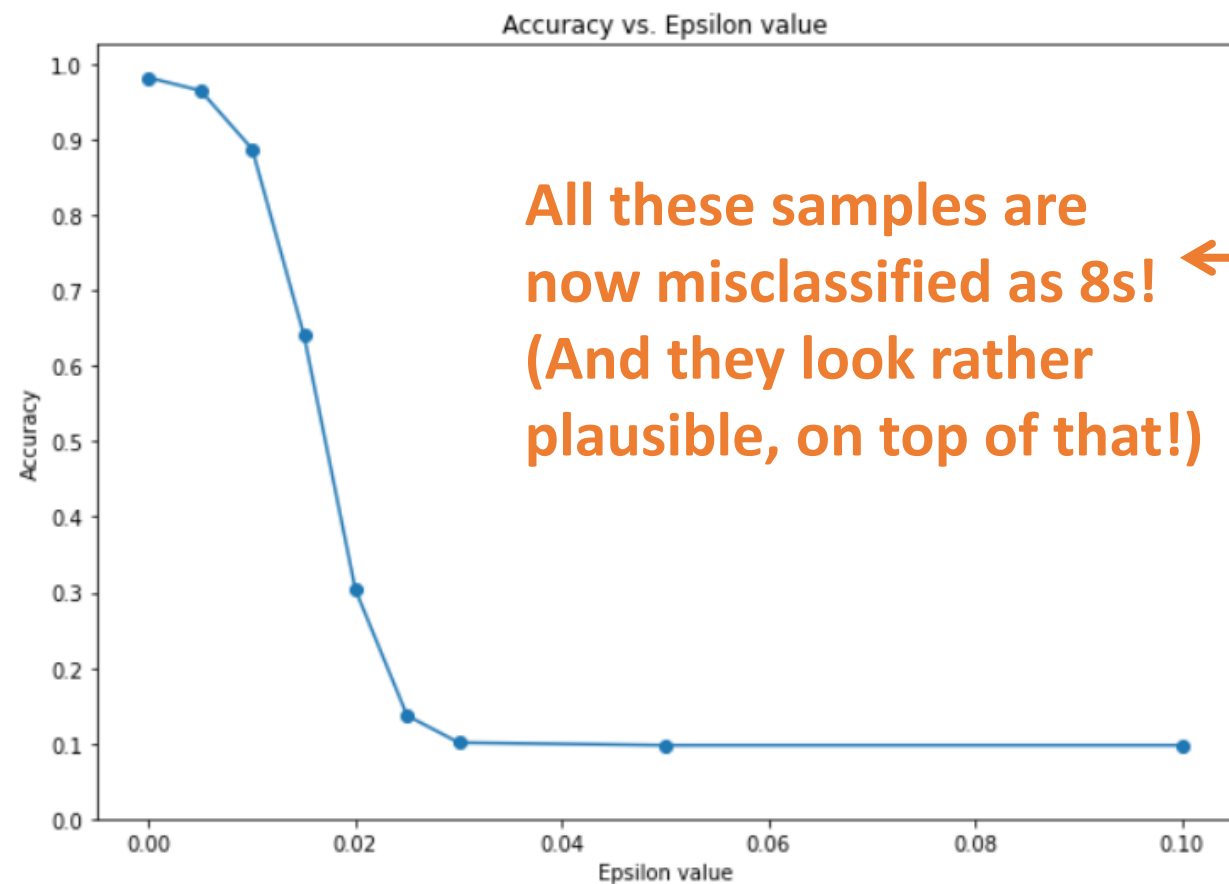
If sample is already of the target class, attack cannot happen...

We cannot modify a picture of an 8 so that it becomes misclassified as an 8! Skip these.

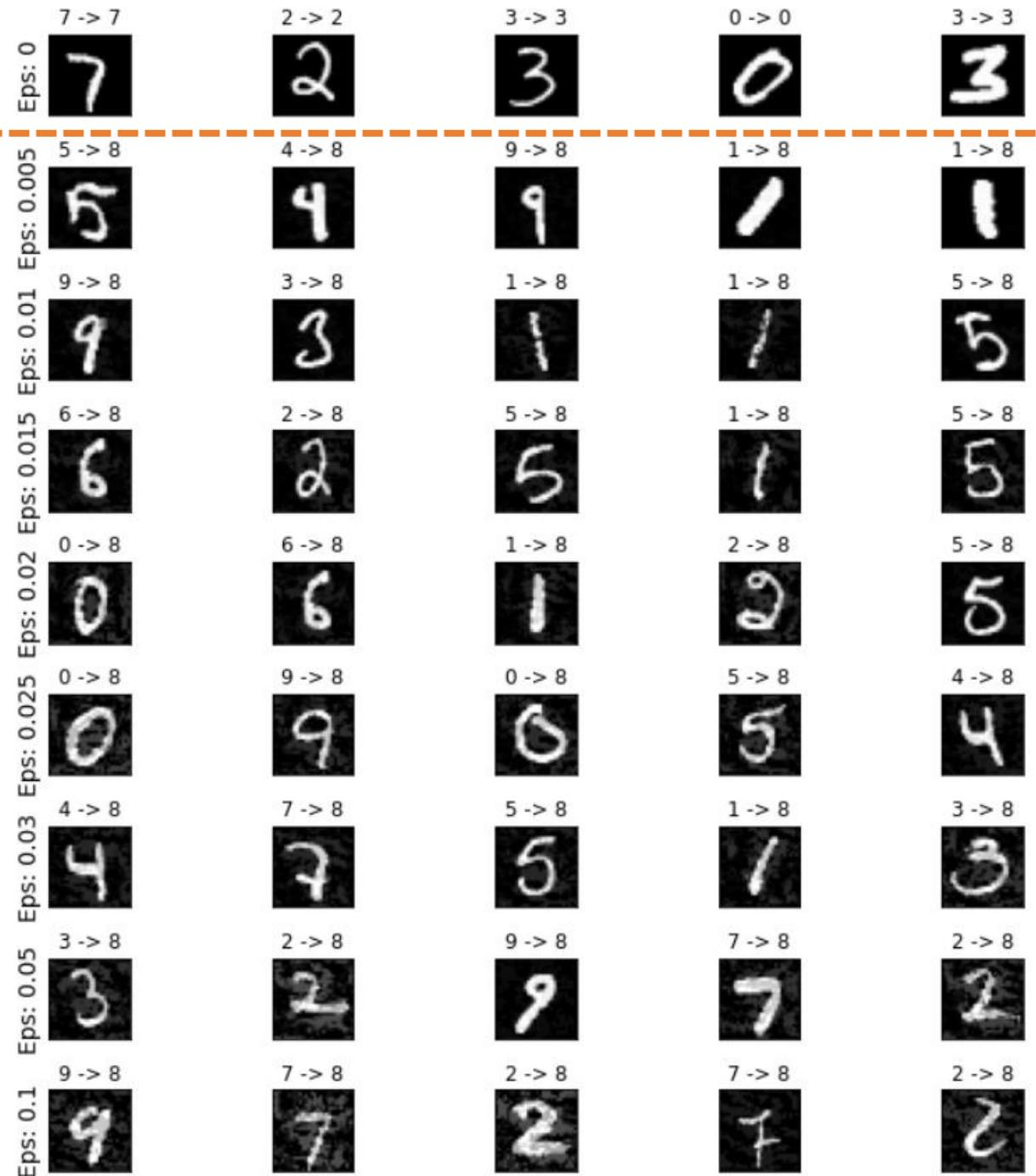
Testing the ITFGSM attack



Testing the ITFGSM attack

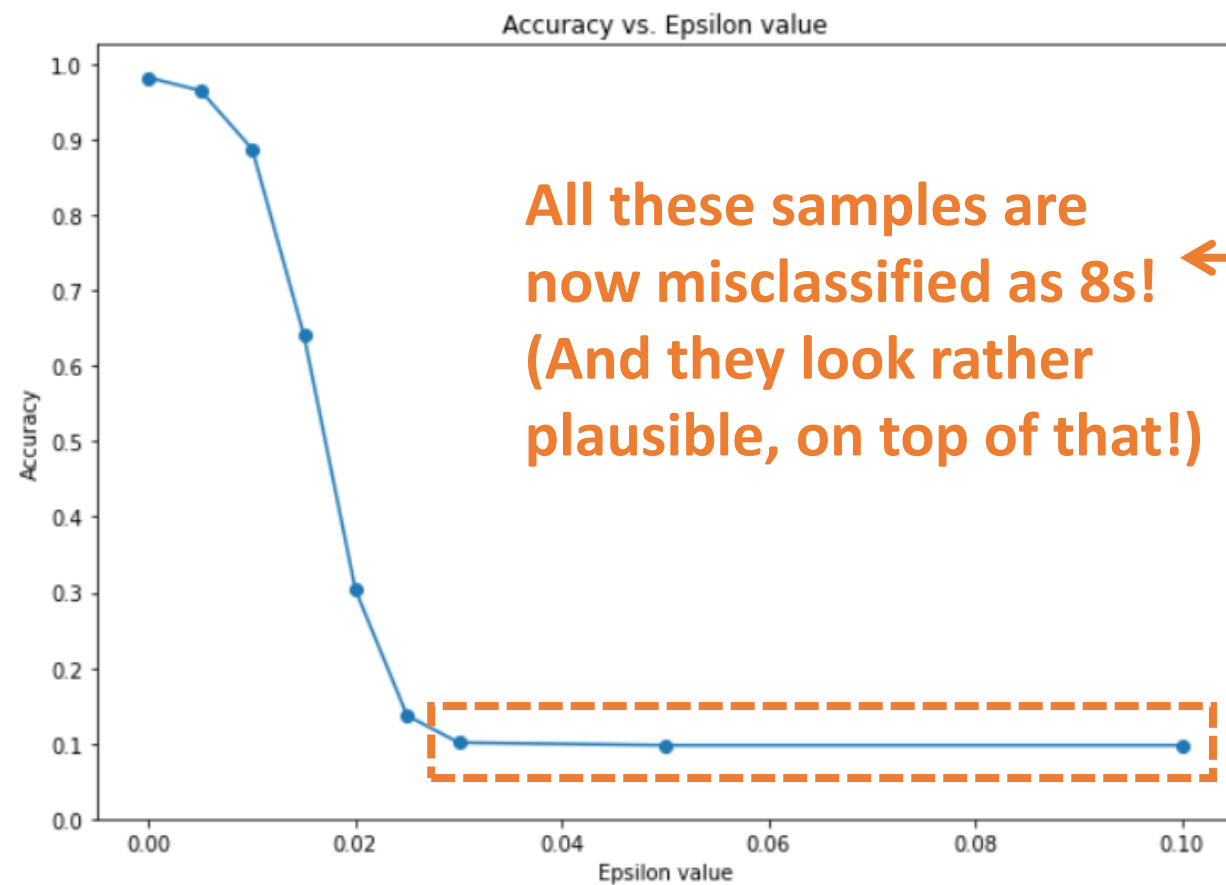


Restr



Restr

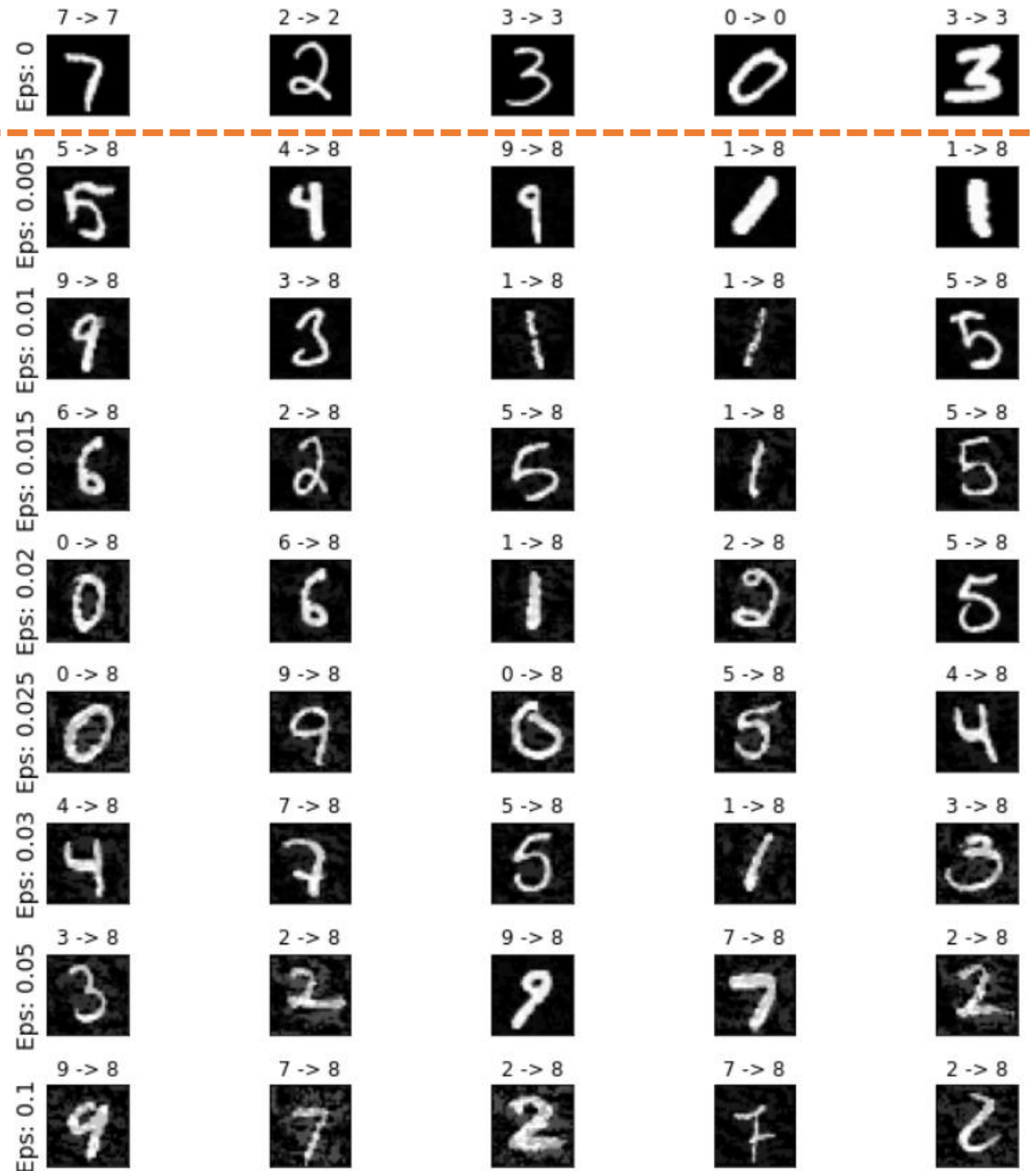
Testing the ITFGSM attack



~10% of samples in MNIST are 8s

Restr

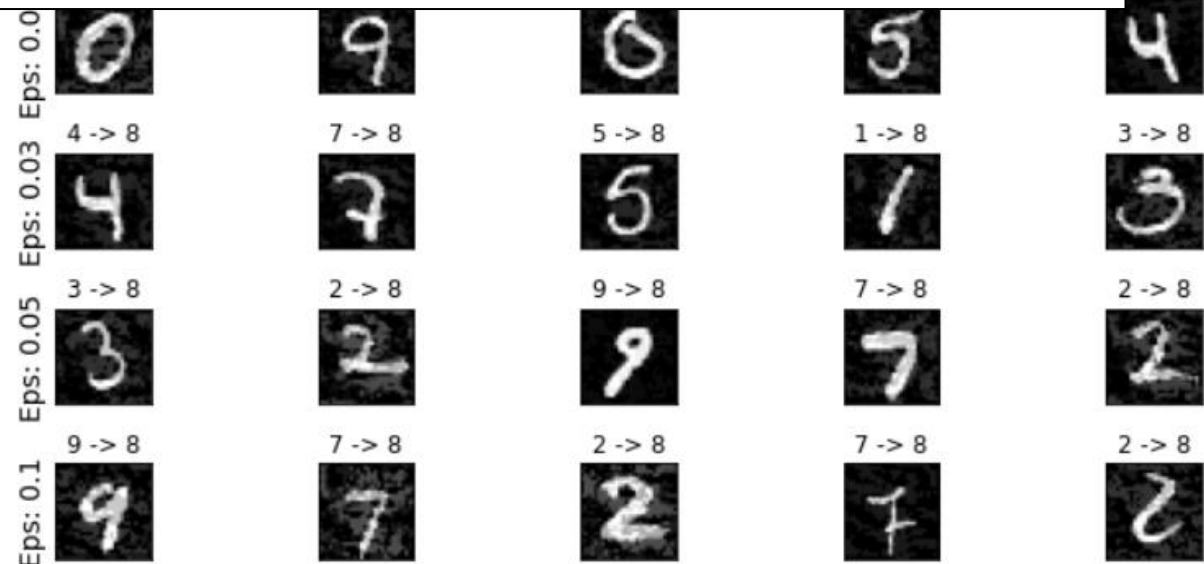
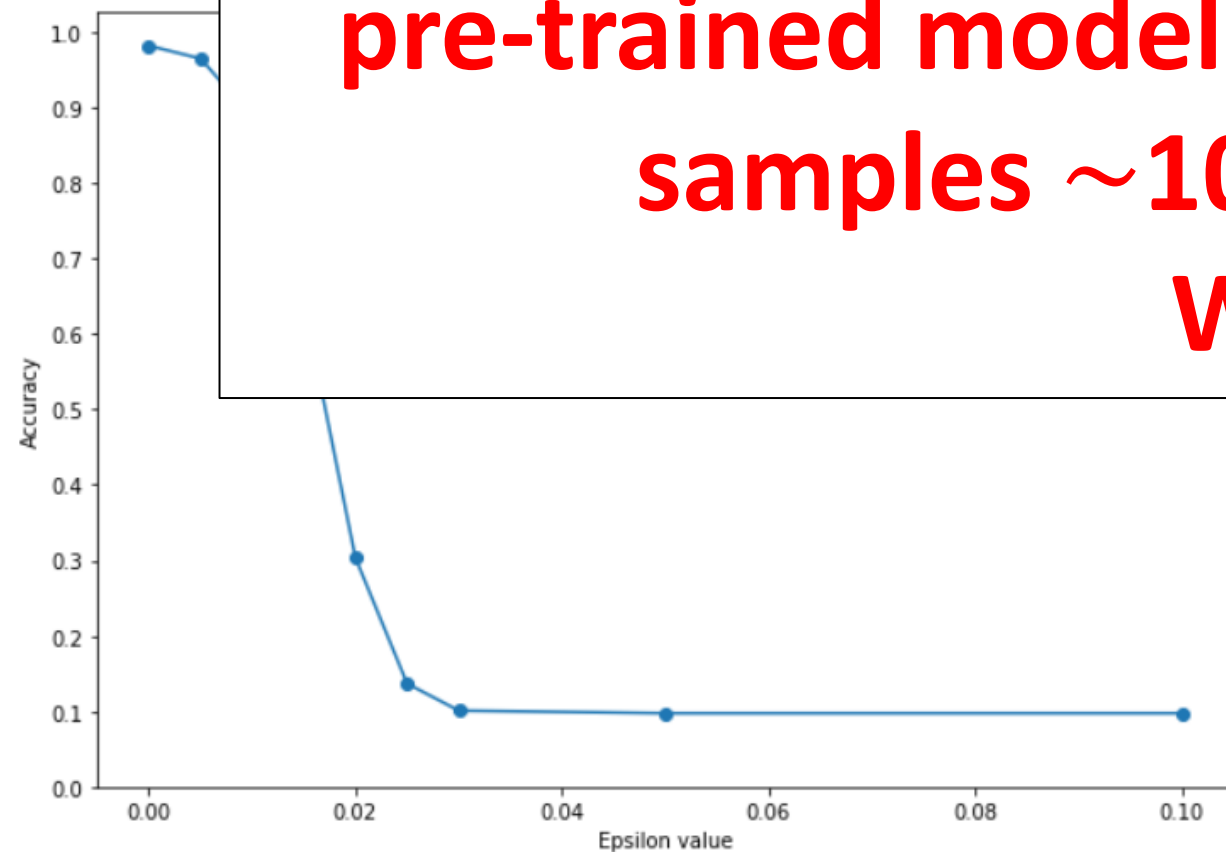
Restr



Restr



We did it!
We managed to completely destroy our
pre-trained model so that it misclassifies
samples ~100% of the time!
Woot!



Restr

(Wait, actually, that is scary, I never EVER want to trust a Neural Network again...!)



Restr

7 -> 7

2 -> 2

3 -> 3

0 -> 0

3 -> 3

Restr

Remember, there is more... Reason #2: Defense

Definition (**Defense** on Neural Networks):

In adversarial machine learning, **defense** refers to machine learning techniques that attempt to **protect models from being attacked** by malicious attempts.

Important: defense mechanisms often rely on an understanding of how attacks work.

SOMETHING
FOR LATER...

Conclusion (W8S2)

- Using gradient-based attacks can help produce attacks with higher success rates.
- Using Fast Gradient Sign Method gives an extra plausibility constraint, in the form of a max norm constraint between the original image and attack image.
- This can lead to a devastating attack!
- Iterations were used during training, so might as well use them in attacks as well.
- Iterating greatly helps with plausibility.
- Iterated FGSM can technically lead to a full failure of our pre-trained model...!
- Defense is very much needed!

Learn more about these topics

Out of class, for those of you who are curious

- [Goodfellow2015] **Goodfellow** et al., “**Explaining and Harnessing Adversarial Examples**”, 2015.
<https://arxiv.org/abs/1412.6572>
- [Kurakin2016] **Kurakin** et al. “**Adversarial examples in the physical world**”, 2016.
<https://arxiv.org/abs/1607.02533>
- Implementing more advanced gradient ascent, e.g. FGSM with gradient ascent and momentum as in [Dong2017] Y. Dong et al. “**Boosting Adversarial Attacks with Momentum**”, 2017.
<https://arxiv.org/abs/1710.06081>

Learn more about these topics

Tracking important names (Track their works and follow them on Scholar, Twitter, or whatever works for you!)

- **Alexei Kurakin**: Researcher at **Google Brain**.
<http://kurakin.me/>
<https://scholar.google.com/citations?user=nCh4qyMAAAAJ&hl=en>
- **Ian Goodfellow**: (Former?) director at **Apple** and **PhD** from **Stanford**, wrote a book that is considered the Bible of Deep Learning, and inventor of GANs (later).
<https://www.iangoodfellow.com/>
<https://www.deeplearningbook.org/>
<https://scholar.google.ca/citations?user=iYN86KEAAAJ&hl=en>

Learn more about these topics

Tracking important names (Track their works and follow them on Scholar, Twitter, or whatever works for you!)

- **Yoshua Bengio**: Professor at **University of Montreal**, one of the three Godfathers of Deep Learning and **2018 Turing Award** winner (highest distinction in Computer Science).

<https://yoshuabengio.org>

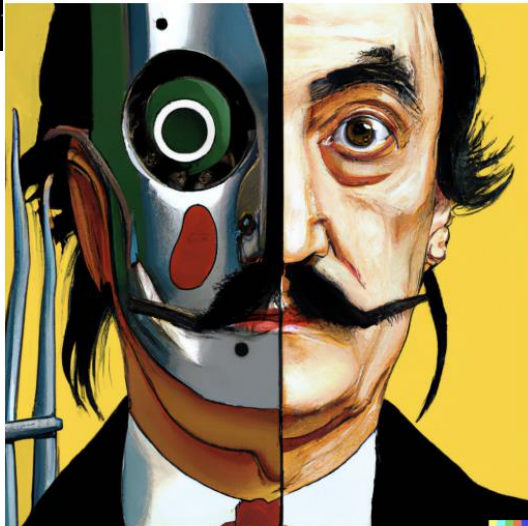
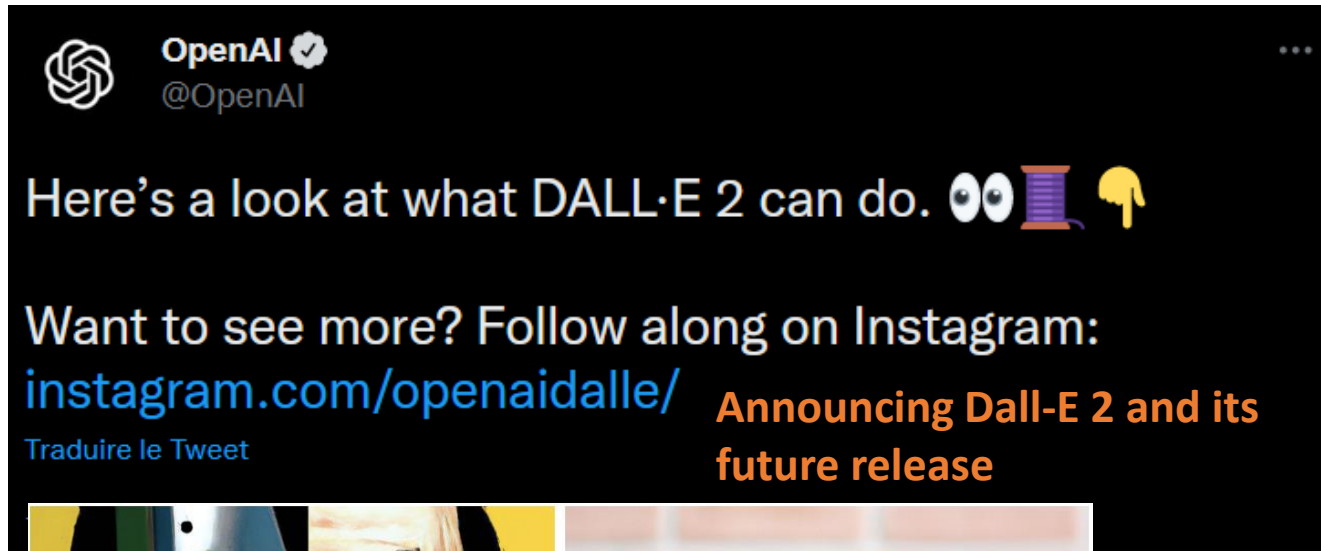
<https://scholar.google.com/citations?user=kukA0LcAAAAJ&hl=fr>

- **Samy Bengio**: Senior Director at **Apple**, inventor of **PyTorch (!)**, (and brother of Yoshua Bengio).

<https://bengio.abracadoudou.com>

<https://scholar.google.com/citations?user=Vs-MdPcAAAAJ&hl=fr>

Twitter, the theater for AI/DL drama and announcements



vibrant portrait painting of Salvador Dalí with a robotic half face



a shiba inu wearing a beret and black turtleneck

