



## Adversarial Examples

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October 15, 2024

# Today's Agenda

## 1 Intriguing properties of neural networks

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Christian Szegedy

Google Inc.

Wojciech Zaremba

New York University

Illya Sutskever

Google Inc.

Joan Bruna

New York University

Dumitru Erhan

Google Inc.

Ian Goodfellow

University of Montreal

Rob Fergus

New York University

Facebook Inc.

## Abstract

- Deep neural networks are powerful learning models that achieve excellent performance on visual and speech recognition problems.
  - It can be difficult to interpret and can have **counter-intuitive properties**.

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- The paper discusses two counter-intuitive properties of deep neural networks.
  - 1 There is no distinction between individual high level units and random linear combinations of high level units.
    - It suggests that **it is the space**, rather than the individual units, that **contains the semantic information** in the high layers of neural networks.

# Abstract

- Deep neural networks are powerful learning models that achieve excellent performance on visual and speech recognition problems.
- It can be difficult to interpret and can have **counter-intuitive properties**.
  
- The paper discusses two counter-intuitive properties of deep neural networks.
  - 1 There is no distinction between individual high level units and random linear combinations of high level units.
    - It suggests that **it is the space**, rather than the individual units, that **contains the semantic information** in the high layers of neural networks.
  - 2 The authors found that applying an **imperceptible non-random perturbation** to a test image, it is possible to arbitrarily **change the networks prediction**.
    - They term the so perturbed examples **Adversarial Examples**.
    - They found that adversarial examples are relatively robust, and are **shared by neural networks** with varied number of layers, activations or trained on different subsets of the training data (**Transferability**).

## Notation

- Denote by  $x \in \mathbb{R}^m$  an input image, and  $\phi(x)$  activation values of some layer, where  $m$  is the input dimension.
  - We denote by  $f : \mathbb{R}^m \rightarrow \{1\dots k\}$  a classifier mapping image pixel value vectors to a discrete label set.
  - We assume that  $f$  has an associated continuous loss function denoted by  $loss_f : \mathbb{R}^m \times \{1\dots k\} \rightarrow \mathbb{R}^+$ .

## Units of $\phi(x)$

- Traditional computer vision systems rely on feature extraction: often a single feature is easily interpretable, e.g. a histogram of colors.
  - Some works interpret an activation of a hidden unit as a meaningful feature. They look for input images which maximize the activation value of this single feature.
  - The aforementioned technique can be formally stated as visual inspection of images  $x'$ , which satisfy (or are close to maximum attainable value):

$$x' = \underset{x \in \mathcal{I}}{\operatorname{argmax}} \langle \phi(x), e_i \rangle \quad (1)$$

where  $\mathcal{I}$  is a hold-out set of images from the data distribution that the network was not trained on and  $e_i$  is the natural basis vector associated with the  $i$ -th hidden unit.

# Units of $\phi(x)$



0 5 D 5 5 0 6 5 0 5

(a) Unit sensitive to lower round stroke.



5 9 5 6 9 6 5 9 6 5

(c) Unit sensitive to left, upper round stroke.



2 2 2 2 2 2 2 3 2 2

(b) Unit sensitive to upper round stroke, or lower straight stroke.



2 2 2 2 2 6 2 2 2 6

(d) Unit sensitive to diagonal straight stroke.

## Units of $\phi(x)$

- The experiments show that any random direction  $v \in R^n$  gives rise to similarly interpretable semantic properties.
- More formally, They find that images  $x'$  are semantically related to each other, for many  $x'$  such that

$$x' = \underset{x \in \mathcal{I}}{\operatorname{argmax}} \langle \phi(x), v \rangle \quad (2)$$

- This suggests that the natural basis is not better than a random basis for inspecting the properties of  $\phi(x)$ .
- This puts into question the notion that neural networks disentangle variation factors across coordinates.

# Units of $\phi(x)$



(a) Direction sensitive to upper straight stroke, or lower round stroke.



(c) Direction sensitive to round top stroke.



(b) Direction sensitive to lower left loop.



(d) Direction sensitive to right, upper round stroke.

## Network Level Inspection

- So far, unit-level inspection methods had relatively little utility beyond confirming certain intuitions regarding the complexity of the representations learned by a deep neural network
- **Network level inspection** methods can be useful in the context of explaining classification decisions made by a model
  - For instance, identify the parts of the input which led to a correct classification of a given visual input instance
- Such global analyses are useful in that they can make us understand better the input-to-output mapping represented by the trained network.

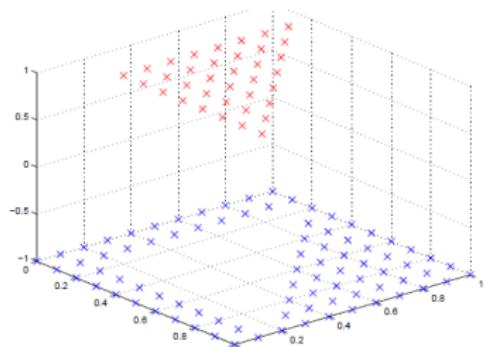
## How to Explain Individual Classification Decisions

A probability function  $P : \mathbb{R}^d \rightarrow [0, 1]$  of a classification model learned from examples  $\{(x_1, y_1), \dots, (x_n, y_n)\} \in \mathbb{R}^d \times \{-1, +1\}$  (binary classification) the explanation vector for a classified test point  $x_0$  is the local gradient of  $p$  at  $x_0$ :

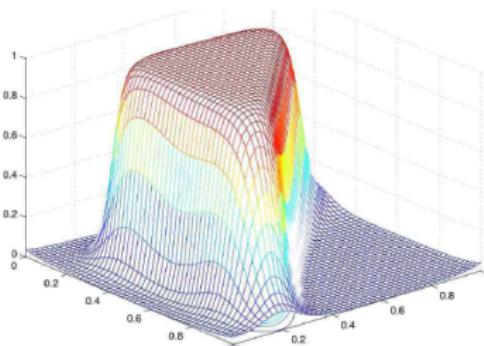
$$\eta_p(x_0) = \nabla_{x_0} P(x_0)$$

- By this definition the explanation  $\eta$  is again a  $d$ -dimensional vector just like the test point  $x_0$  is.
- The sign of each of its individual entries indicates whether the prediction would increase or decrease when the corresponding feature of  $x_0$  is increased locally and each entry's absolute value give the amount of influence in the change in prediction.
- As a vector  $\eta$  gives the direction of the steepest ascent from the test point to higher probabilities for the positive class.

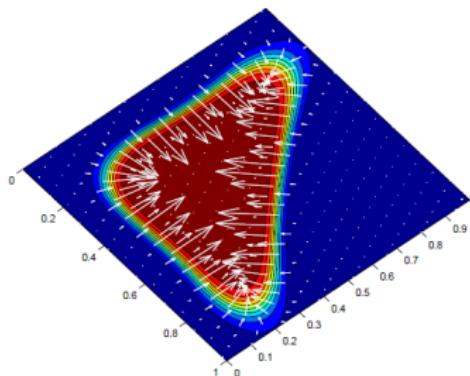
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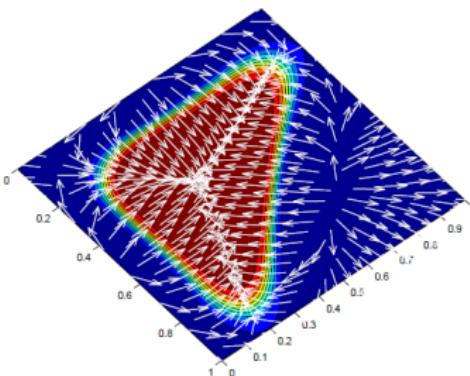
(a) Object



(b) Model



(c) Local explanation vectors



(d) Direction of explanation vectors

# How to Explain Individual Classification Decisions



Figure 5: USPS digits (test set bottom part): 'twos' (left) and 'eights' (right) with correct classification. For each digit from left to right: (i) explanation vector (with black being negative, white being positive), (ii) the original digit, (iii-end) artificial digits along the explanation vector towards the other class.

# Blind Spots in Neural Networks

- Generally speaking, the output layer unit of a neural network is a **highly nonlinear function** of its input.
- It has been argued that the deep stack of non-linear layers in between the input and the output unit of a neural network are a way for the model to encode a **non-local generalization prior** over the input space.
  - In other words, it is assumed that it is possible for the output unit to assign nonsignificant (and, presumably, non- $\epsilon$ ) probabilities to regions of the input space that contain no training examples in their vicinity.
    - Such regions can represent, for instance, the same objects from different viewpoints, which are relatively far (in pixel space), but which share nonetheless both the label and the statistical structure of the original inputs.

# Smoothness Prior (Local Generalization)

## Smoothness Prior

For a small enough radius  $\epsilon \geq 0$  in the vicinity of a given training input  $x$ , an  $x + r$  satisfying  $\|r\| \leq \epsilon$  will get assigned a high probability of the correct class by the model.

- This kind of smoothness prior is typically valid for computer vision problems.
- In general, imperceptibly tiny perturbations of a given image do not normally change the underlying class.

The main result of the paper is that **for deep neural networks, the smoothness assumption does not hold**.

## Blind Spots

- In some sense, what we describe is a way to **traverse the manifold** represented by the network in an efficient way (by optimization) and finding **adversarial examples** in the input space.
- The adversarial examples represent **low-probability (high-dimensional) pockets in the manifold**, which are hard to efficiently find by simply randomly sampling the input around a given example.

## Formal description

For a given  $x \in \mathbb{R}^m$  image and target label  $l \in \{1\dots k\}$ , we aim to solve the following box-constrained optimization problem:

Minimize  $\|r\|_2$  subject to:

$$f(x + r) = l$$

$$x + r \in [0, 1]^m$$

- Informally,  $x' = x + r$  is the closest image to  $x$  classified as  $l$  by  $f$ .

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- The minimizer  $r$  might not be unique.
- This task is non-trivial only if  $f(x) \neq l$ .
- In general, the exact computation of  $x'$  is a hard problem, so we approximate it by using a box-constrained L-BFGS.

## Formal description

Recall: Generalized Lagrange Function (KarushKuhnTucker (KKT) )

Suppose we wish to maximize  $f(x)$  subject to  $g_j(x) = 0$  for  $j = 1, \dots, J$ , and  $h_k(x) \geq 0$  for  $k = 1, \dots, K$ .

$$\begin{aligned} & \text{Minimize} && f(x) \\ & \text{subject to} && g_j(x) = 0 \quad \text{for } j = 1, \dots, J \\ & && h_k(x) \geq 0 \quad \text{for } k = 1, \dots, K \end{aligned}$$

We introduce Lagrange multipliers  $\{\lambda_j\}$  and  $\{\mu_k\}$ , and then optimize the Lagrangian function given by

$$L(x, \{\lambda_j\}, \{\mu_k\}) = f(x) + \sum_{j=1}^J \lambda_j g_j(x) + \sum_{k=1}^K \mu_k h_k(x)$$

subject to  $\mu_k \geq 0$  and  $\mu_k h_k(x) = 0$  for  $k = 1, \dots, K$ .

The optimal point  $x^*$  of the above constrained optimization on  $f(x)$  is the same as the optimal point of the unconstrained optimization  $L$ .

(See this playlist for more information about Lagrange multipliers)

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- In general, the exact computation of  $x'$  is a hard problem, so we approximate it by using a box-constrained L-BFGS.

Concretely, we find an approximation of  $x'$  by performing line-search to find the minimum  $c > 0$  for which the minimizer  $r$  of the following problem satisfies  $f(x + r) = l$ .

Minimize  $c\|r\|_2 + loss_f(x + r, l)$  subject to  $x + r \in [0, 1]^m$

- Since neural networks are non-convex in general, so we end up with an approximation to find solution.

# Adversarial Examples



Figure 5: Adversarial examples generated for AlexNet [9].(Left) is a correctly predicted sample, (center) difference between correct image, and image predicted incorrectly magnified by 10x (values shifted by 128 and clamped), (right) adversarial example. All images in the right column are predicted to be an “ostrich, *Struthio camelus*”. Average distortion based on 64 examples is 0.006508. Please refer to <http://goo.gl/huaGPb> for full resolution images. The examples are strictly randomly chosen. There is not any postselection involved.

# Experimental results

## Intriguing properties

- **100% success rate**
  - For all the networks we studied (MNIST, AlexNet (ImageNet)), for each sample, we have always managed to generate very close, visually hard to distinguish, adversarial examples that are misclassified by the original network.

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- **Cross training-set generalization**
  - A relatively large fraction of examples will be misclassified by networks trained from scratch on a **disjoint training set**.

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- **Cross training-set generalization**
  - A relatively large fraction of examples will be misclassified by networks trained from scratch on a **disjoint training set**.

The above observations suggest that adversarial examples are somewhat **universal** and not just the results of overfitting to a particular model or to the specific selection of the training set.

# Experimental results

Model Name	Description	Training error	Test error	Av. min. distortion
FC10( $10^{-4}$ )	Softmax with $\lambda = 10^{-4}$	6.7%	7.4%	0.062
FC10( $10^{-2}$ )	Softmax with $\lambda = 10^{-2}$	10%	9.4%	0.1
FC10(1)	Softmax with $\lambda = 1$	21.2%	20%	0.14
FC100-100-10	Sigmoid network $\lambda = 10^{-5}, 10^{-5}, 10^{-6}$	0%	1.64%	0.058
FC200-200-10	Sigmoid network $\lambda = 10^{-5}, 10^{-5}, 10^{-6}$	0%	1.54%	0.065
AE400-10	Autoencoder with Softmax $\lambda = 10^{-6}$	0.57%	1.9%	0.086

Table 1: Tests of the generalization of adversarial instances on MNIST.

- The last column measures the minimum average pixel level distortion necessary to reach 0% accuracy on the training set.
- The distortion is measured by  $\sqrt{\frac{\sum_i (x'_i - x_i)^2}{n}}$  between the original  $x$  and distorted  $x'$  images, where  $n = 28 \times 28 = 784$  is the number of image pixels. The pixel intensities are scaled to be in the range [0, 1].

# Cross-model Generalization

	$\text{FC10}(10^{-4})$	$\text{FC10}(10^{-2})$	$\text{FC10}(1)$	$\text{FC100-100-10}$	$\text{FC200-200-10}$	$\text{AE400-10}$	Av. distortion
$\text{FC10}(10^{-4})$	100%	11.7%	22.7%	2%	3.9%	2.7%	0.062
$\text{FC10}(10^{-2})$	87.1%	100%	35.2%	35.9%	27.3%	9.8%	0.1
$\text{FC10}(1)$	71.9%	76.2%	100%	48.1%	47%	34.4%	0.14
$\text{FC100-100-10}$	28.9%	13.7%	21.1%	100%	6.6%	2%	0.058
$\text{FC200-200-10}$	38.2%	14%	23.8%	20.3%	100%	2.7%	0.065
$\text{AE400-10}$	23.4%	16%	24.8%	9.4%	6.6%	100%	0.086
Gaussian noise, $\text{stddev}=0.1$	5.0%	10.1%	18.3%	0%	0%	0.8%	0.1
Gaussian noise, $\text{stddev}=0.3$	15.6%	11.3%	22.7%	5%	4.3%	3.1%	0.3

Table 2: Cross-model generalization of adversarial examples. The columns of the Tables show the error induced by distorted examples fed to the given model. The last column shows average distortion wrt. original training set.

## Cross-training-set Generalization

- To study cross-training-set generalization, we have partitioned the 60000 MNIST training images into two parts  $P_1$  and  $P_2$  of size 30000 each and trained three non-convolutional networks with sigmoid activations on them.
- Table 3 summarizes the basic facts about these models. After we generate adversarial examples with 100% error rates with minimum distortion for the test set, we feed these examples to the each of the models.

Model	Error on $P_1$	Error on $P_2$	Error on Test	Min Av. Distortion
FC100-100-10: 100-100-10 trained on $P_1$	0%	2.4%	2%	0.062
FC123-456-10: 123-456-10 trained on $P_1$	0%	2.5%	2.1%	0.059
FC100-100-10' trained on $P_2$	2.3%	0%	2.1%	0.058

Table 3: Models trained to study cross-training-set generalization of the generated adversarial examples. Errors presented in Table correpond to original not-distorted data, to provide a baseline.

## Cross-model-and-training-set Generalization

- In the last experiment, we magnify the effect of our distortion by using the examples  $x + 0.1 \frac{r}{\|r\|_2}$  rather than  $x'$ .
- This magnifies the distortion on average by 40%, from stddev 0.06 to 0.1.
- The intriguing conclusion is that the adversarial examples remain hard for models trained even on a disjoint training set, although their effectiveness decreases considerably.

	FC100-100-10	FC123-456-10	FC100-100-10'
Distorted for FC100-100-10 (av. stddev=0.062)	100%	26.2%	5.9%
Distorted for FC123-456-10 (av. stddev=0.059)	6.25%	100%	5.1%
Distorted for FC100-100-10' (av. stddev=0.058)	8.2%	8.2%	100%
Gaussian noise with stddev=0.06	2.2%	2.6%	2.4%
Distorted for FC100-100-10 amplified to stddev=0.1	100%	98%	43%
Distorted for FC123-456-10 amplified to stddev=0.1	96%	100%	22%
Distorted for FC100-100-10' amplified to stddev=0.1	27%	50%	100%
Gaussian noise with stddev=0.1	2.6%	2.8%	2.7%

Table 4: Cross-training-set generalization error rate for the set of adversarial examples generated for different models. The error induced by a random distortion to the same examples is displayed in the last row.

## Spectral Analysis of Unstability

- The adversarial examples show that there exist **small additive perturbations** of the input (in Euclidean sense) that produce **large perturbations at the output** of the last layer.
- Mathematically, if  $\phi(x)$  denotes the output of a network of  $K$  layers corresponding to input  $x$  and trained parameters  $W$ , we write

$$\phi(x) = \phi_K(\phi_{K-1}(\dots\phi_1(x; W_1)\dots; W_{K-1}) W_K)$$

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- The instability of  $\phi(x)$  can be explained by inspecting the upper **Lipschitz constant** of each layer.

## Lipschitz continuity

A function  $f : I \rightarrow R$  over some set  $I \subseteq \mathbb{R}^d$  is called Lipschitz continuous if there exists a positive real constant  $L$  such that, for all  $x, y \in I$ ,

$$|f(y) - f(x)| \leq L\|y - x\|_2$$

or

$$f(x) - L\|y - x\|_2 \leq f(y) \leq f(x) + L\|y - x\|_2$$

We call  $L$  the Lipschitz constant of  $f$  over  $I$ .

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Let functions  $f_1$  and  $f_2$  be both Lipschitz continuous with constants  $L_1$  and  $L_2$ , the upper Lipschitz constant of their composition  $f_1 \circ f_2$  is  $L_1 L_2$ .

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$$|f_1(f_2(y)) - f_1(f_2(x))| \leq L_1 |f_2(y) - f_2(x)| \leq L_1 L_2 \|y - x\|_2$$

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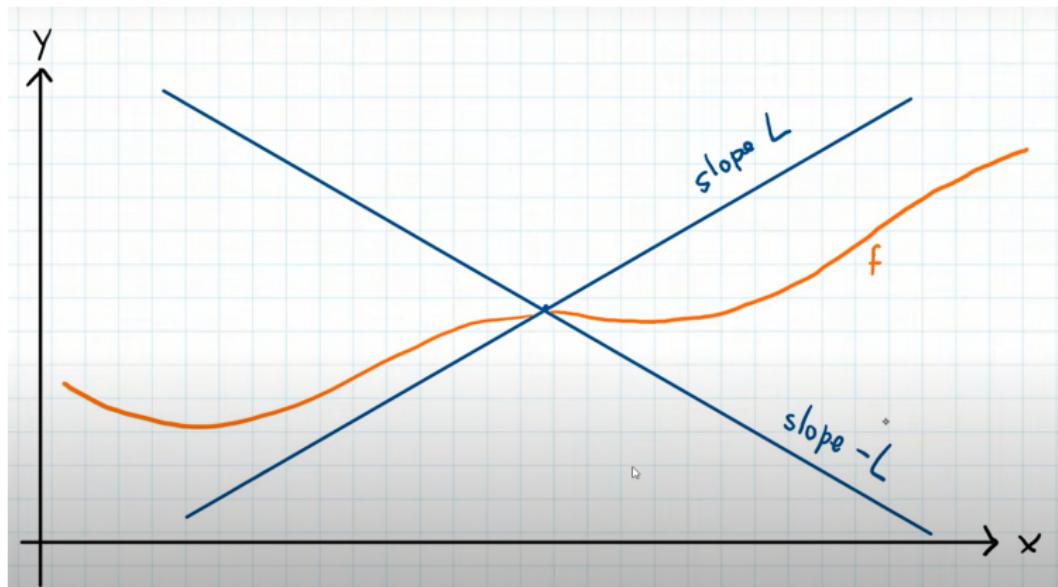
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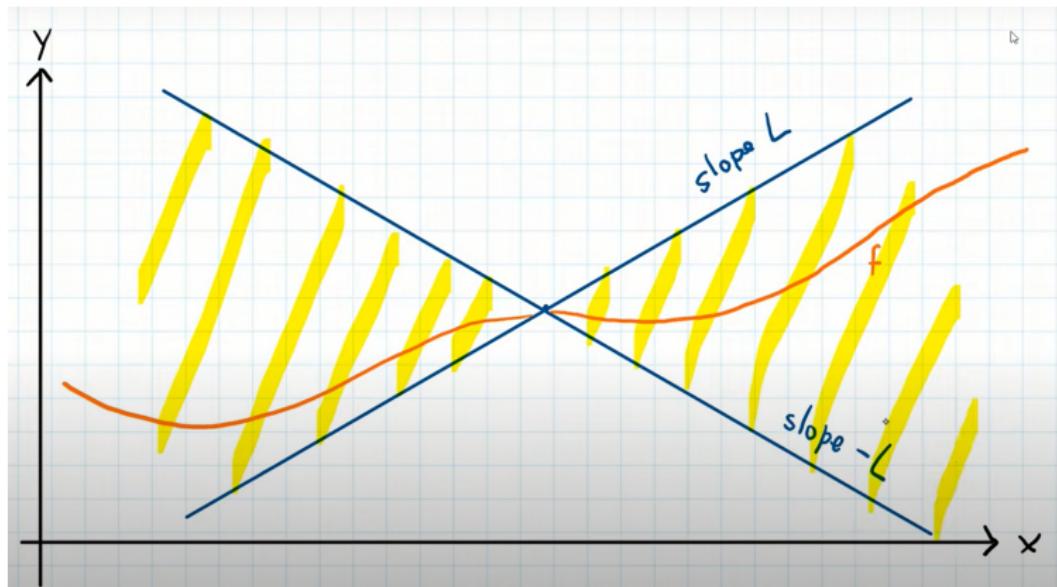
$$|f_1(f_2(y)) - f_1(f_2(x))| \leq L_1 |f_2(y) - f_2(x)| \leq L_1 L_2 \|y - x\|_2$$

Generally, Let  $f = f_1 \circ f_2 \circ \dots \circ f_K$  and the Lipschitz constant of  $f_i$  be  $L_i$  for all  $i \in \{1, 2, \dots, K\}$ , then the Lipschitz constant of  $f$  is  $L \leq \prod_{k=1}^K L_k$ .

# Lipschitz continuity



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- Mathematically, if  $\phi(x)$  denotes the output of a network of  $K$  layers corresponding to input  $x$  and trained parameters  $W$ , we write

$$\phi(x) = \phi_K(\phi_{K-1}(\dots\phi_1(x; W_1)\dots; W_{K-1})W_K)$$

where  $\phi_k$  denotes the operator mapping layer  $k - 1$  to layer  $k$ .

- The instability of  $\phi(x)$  can be explained by inspecting the *upper Lipschitz constant* of each layer, defined as the constant  $L_k > 0$  such that

$$\forall x, r, \|\phi_k(x; W_k) - \phi_k(x + r; W_k)\| \leq L_k \|r\|$$

- The resulting network thus satisfies  $\|\phi(x + r) - \phi(x)\| \leq L \|r\|$ , with  $L \leq \prod_{k=1}^K L_k$ .

## Lipschitz continuity

Let  $f : I \rightarrow R$  be a continuous and differentiable function over some set  $I \subseteq \mathbb{R}^d$ , if we have  $\|f'(x)\|_2 \leq m$  for all  $x \in I$ , then  $m$  is the upper Lipschitz constant of  $f$  ( $L \leq m$ ).

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## Proof sketch:

Mean value theorem: Let  $f : I \rightarrow R$  be a continuous and differentiable function over some set  $I \subseteq \mathbb{R}^d$ , For all  $a, b \in I$  ( $b > a$ ), there exists some  $c \in (a, b)$  such that:

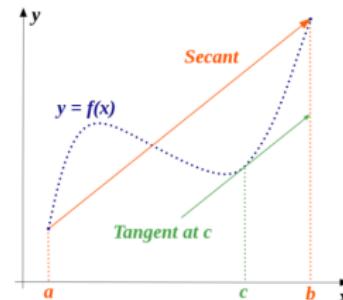
$$f'(c) = \frac{f(b) - f(a)}{b - a}$$

For all  $a, b \in I$ , there exist  $c \in (a, b)$ , such that:

$$|f(b) - f(a)| = \|f'(c).b - a\|_2 \leq \|f'(c)\|_2 \|b - a\|_2.$$

Since we know that  $\|f'(c)\|_2 \leq m$ , we have

$$|f(b) - f(a)| \leq m \|b - a\|_2.$$



## Spectral Analysis of Unstability

- ReLU and max pooling layers have a Lipschitz constant of 1.
  - The upper bound of derivative is 1.

# Spectral Analysis of Unstability

- ReLU and max pooling layers have a Lipschitz constant of 1.
  - The upper bound of derivative is 1.
- Batch normalization layer has a Lipschitz constant of  $\frac{\gamma}{\sqrt{\sigma^2 + \epsilon}}$ 
  - $\nabla_x BN(x) = \nabla_x \gamma \frac{x - \mu}{\sqrt{\sigma^2 + \epsilon}} + \beta = \frac{\gamma}{\sqrt{\sigma^2 + \epsilon}}$

# Spectral Analysis of Unstability

- ReLU and max pooling layers have a Lipschitz constant of 1.
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- Linear layers ( $Wx$ ) have the Lipschitz constant of  $\sigma(W)$ , where  $\sigma$  is the spectral norm (largest singular value).
  - Lipschits constant of linear layers

$$\|Wy - Wx\|_2 \leq L\|y - x\|_2 \Rightarrow \|W(y - x)\|_2 \leq L\|y - x\|_2$$

$$\underset{z=y-x}{\Rightarrow} \|Wz\|_2 \leq L\|z\|_2 \Rightarrow L \geq \frac{\|Wz\|_2}{\|z\|_2} \Rightarrow L = \sigma(W)$$

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- The spectral norm of a matrix  $A \in \mathbb{R}^{m \times n}$  is defined as

$$\sigma(A) = \max_{x \in \mathbb{R}^n, x \neq 0} \frac{\|Ax\|_2}{\|x\|_2}$$

which corresponds to the largest singular value of  $A$

Spectral norm definition source.

# Spectral Analysis of Unstability

Layer	Size	Stride	Upper bound
Conv. 1	$3 \times 11 \times 11 \times 96$	4	2.75
Conv. 2	$96 \times 5 \times 5 \times 256$	1	10
Conv. 3	$256 \times 3 \times 3 \times 384$	1	7
Conv. 4	$384 \times 3 \times 3 \times 384$	1	7.5
Conv. 5	$384 \times 3 \times 3 \times 256$	1	11
FC. 1	$9216 \times 4096$	N/A	3.12
FC. 2	$4096 \times 4096$	N/A	4
FC. 3	$4096 \times 1000$	N/A	4

Table 5: Frame Bounds of each rectified layer of the network from [9].

$$2.75 \times 10 \times 7 \times 7.5 \times 11 \times 3.12 \times 4 \times 4 \approx 793000$$

- Notice that we compute upper bounds: large bounds do not automatically translate into existence of adversarial examples; however, small bounds guarantee that no such examples can appear.

## References

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