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UNIVERSITY OF WISCONSIN–MADISON

Towards Semantic Adversarial Examples

Somesh Jha

Oct 10, 2019

SAS 2019

Thanks to Nicolas Papernot, Ian Goodfellow and Jerry Zhu

for some slides.

Joint work with Tommaso Dreossi and Sanjit Seshia (Berkeley)

Plan

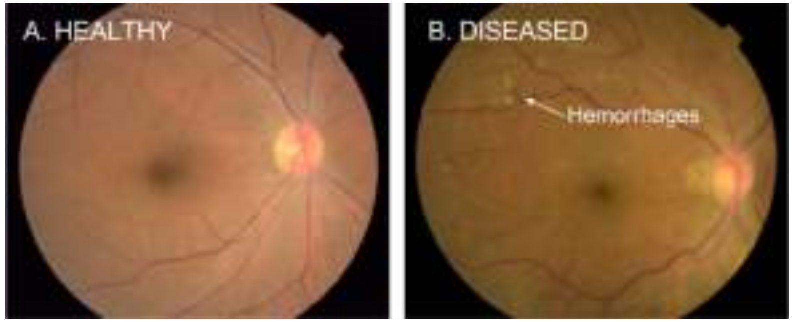
- Part I [Adversarial ML] ~25mins
  - Different types of attacks
  - Test-time attacks
  - Defenses
  - Theoretical explorations
- Part II [Opportunities in FM] ~Rest of the talk
  - Opportunities for FM researchers
  - Focus on lot of work by Tommaso and Sanjit

Announcements/Caveats

- Please ask questions during the talk
  - If we don't finish, fine☺

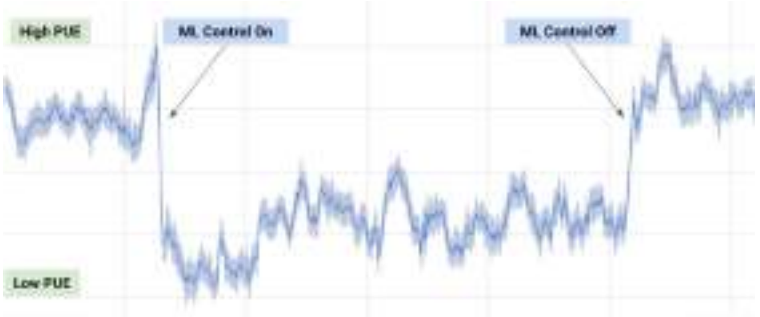
- More slides than I can cover
  - Lot of skipping will be going on
- Fast moving area
  - Apologies if I don't mention your paper
- Legend

Machine learning brings social disruption at scale



Healthcare

Source: Peng and Gulshan (2017)



Energy

Source: Deepmind

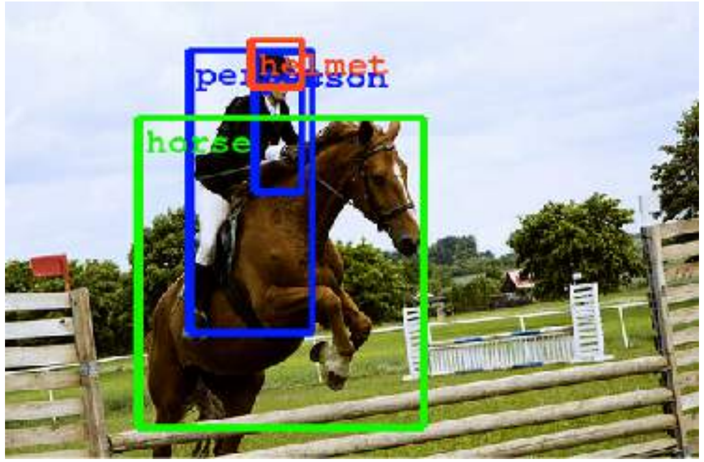
Transportation

Source: Google

Education

Source: Gradescope

ML reached "human-level performance" on many IID tasks circa 2013



(Szegedy et al, 2014)

...recognizing objects and faces....

(Taigmen et al, 2013)

(Goodfellow et al, 2013)

...solving CAPTCHAS and reading addresses...

(Goodfellow et al, 2013)

ML beating doctors☺

- NOVEMBER 15, 2017
  - Stanford algorithm can diagnose pneumonia better than radiologists
- April 14, 2017
  - Self-taught artificial intelligence beats doctors at predicting heart attacks
- ….

Machine learning is deployed in adversarial settings

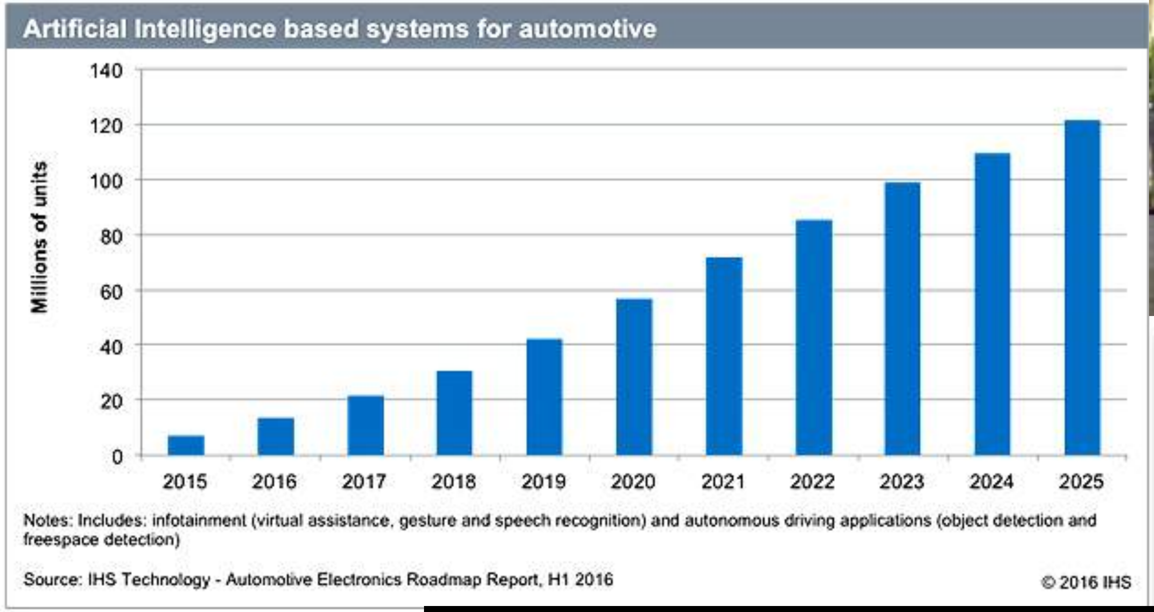
Microsoft's Tay chatbot

Training data poisoning

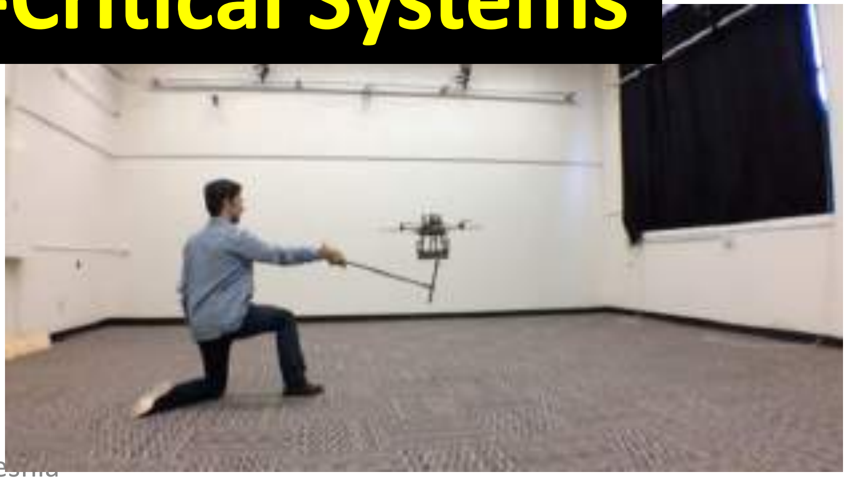
YouTube filtering

Content evades detection at *inference*

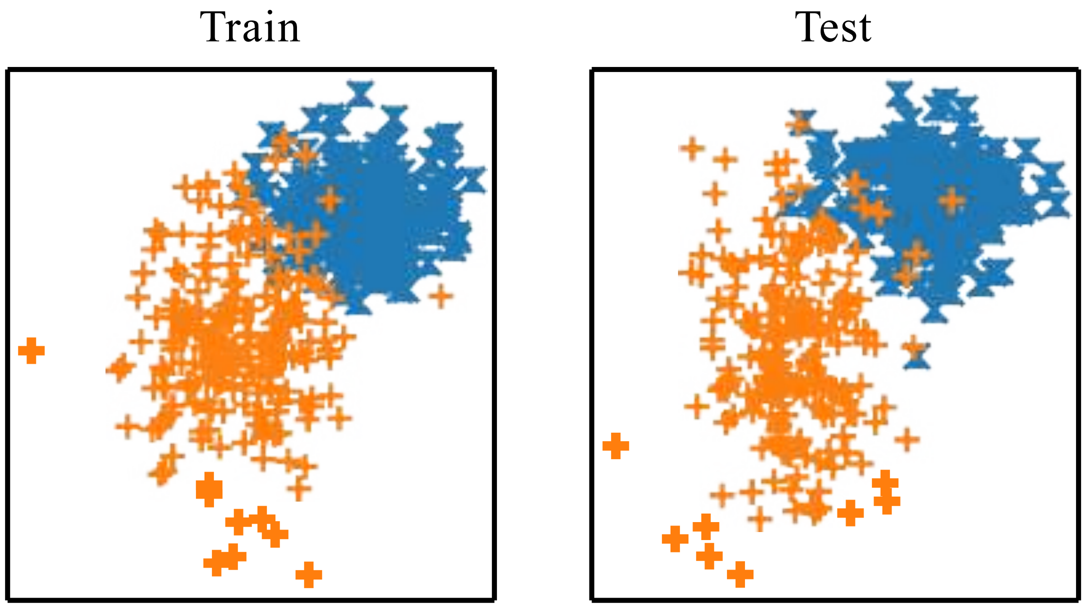
ML in CPS



Many Safety-Critical Systems



I.I.D. Machine Learning



I: Independent

I: Identically

D: Distributed

All train and test examples drawn independently from same distribution

Security Requires Moving Beyond I.I.D.

- Not identical: attackers can use unusual inputs

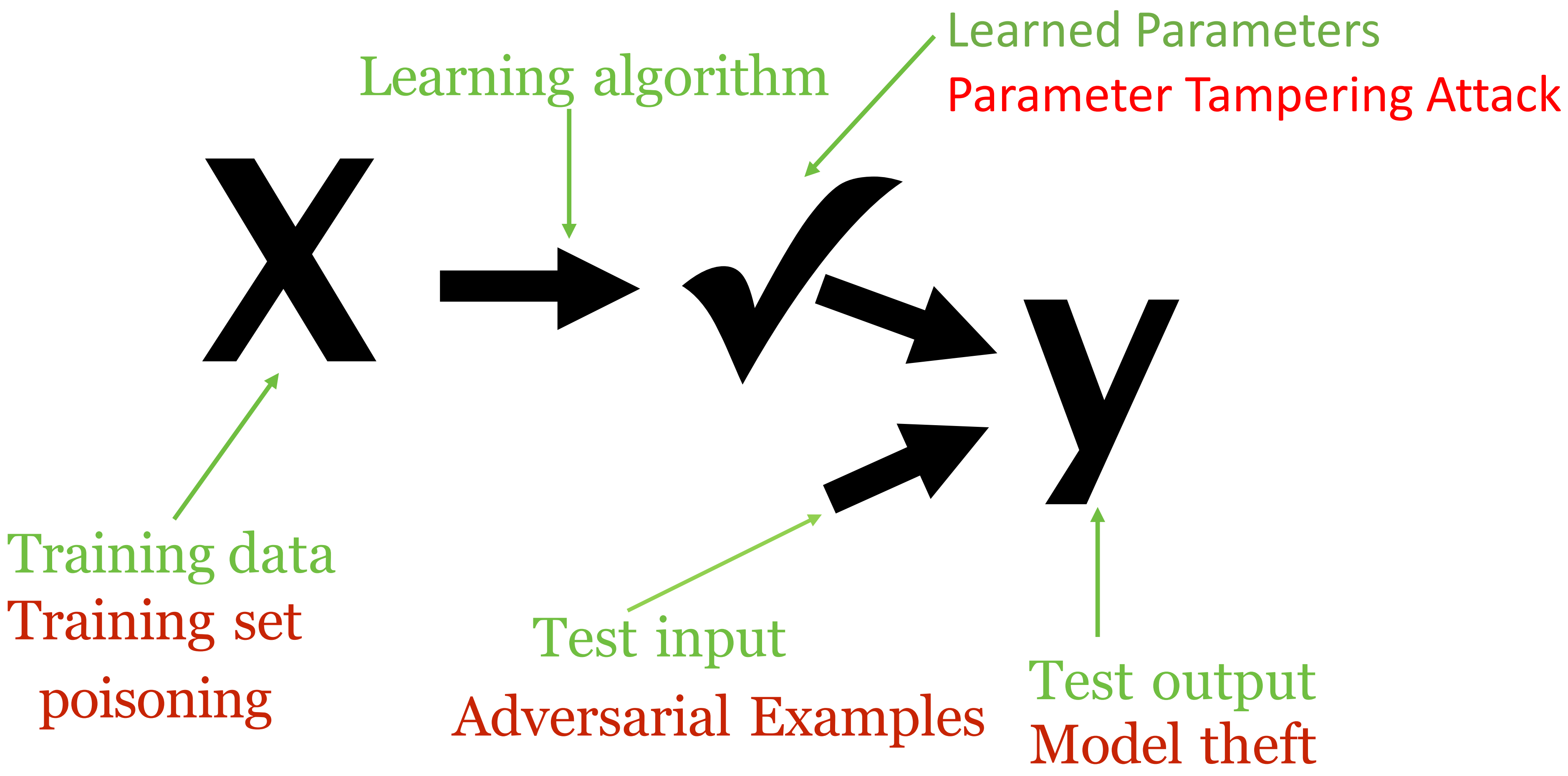
(Eykholt et al, CVPR 2017)

- Not independent: attacker can repeatedly send a single mistake ("test set attack")

Adversarial Learning is not new!!

- *Lowd:* I spent the summer of 2004 at Microsoft Research working with Chris Meek on the problem of spam.
  - We looked at a common technique spammers use to defeat filters: adding "good words" to their emails.
  - We developed techniques for evaluating the robustness of spam filters, as well as a theoretical framework for the general problem of learning to defeat a classifier *(Lowd and Meek, 2005)*
- But…
  - New resurgence in ML and hence new problems
  - Lot of new theoretical techniques being developed
    - High dimensional robust statistics, robust optimization, …

Attacks on the machine learning pipeline



ML (Basics)

- Supervised learning
- Entities
  - *(Sample Space)* $Z = X \times Y$
    - (data, label) (x, y)
  - *(Distribution over* Z *)* D
  - *(Hypothesis Space)* H
  - *(loss function)* l: $(H \times Z) \rightarrow R$

ML (Basics)

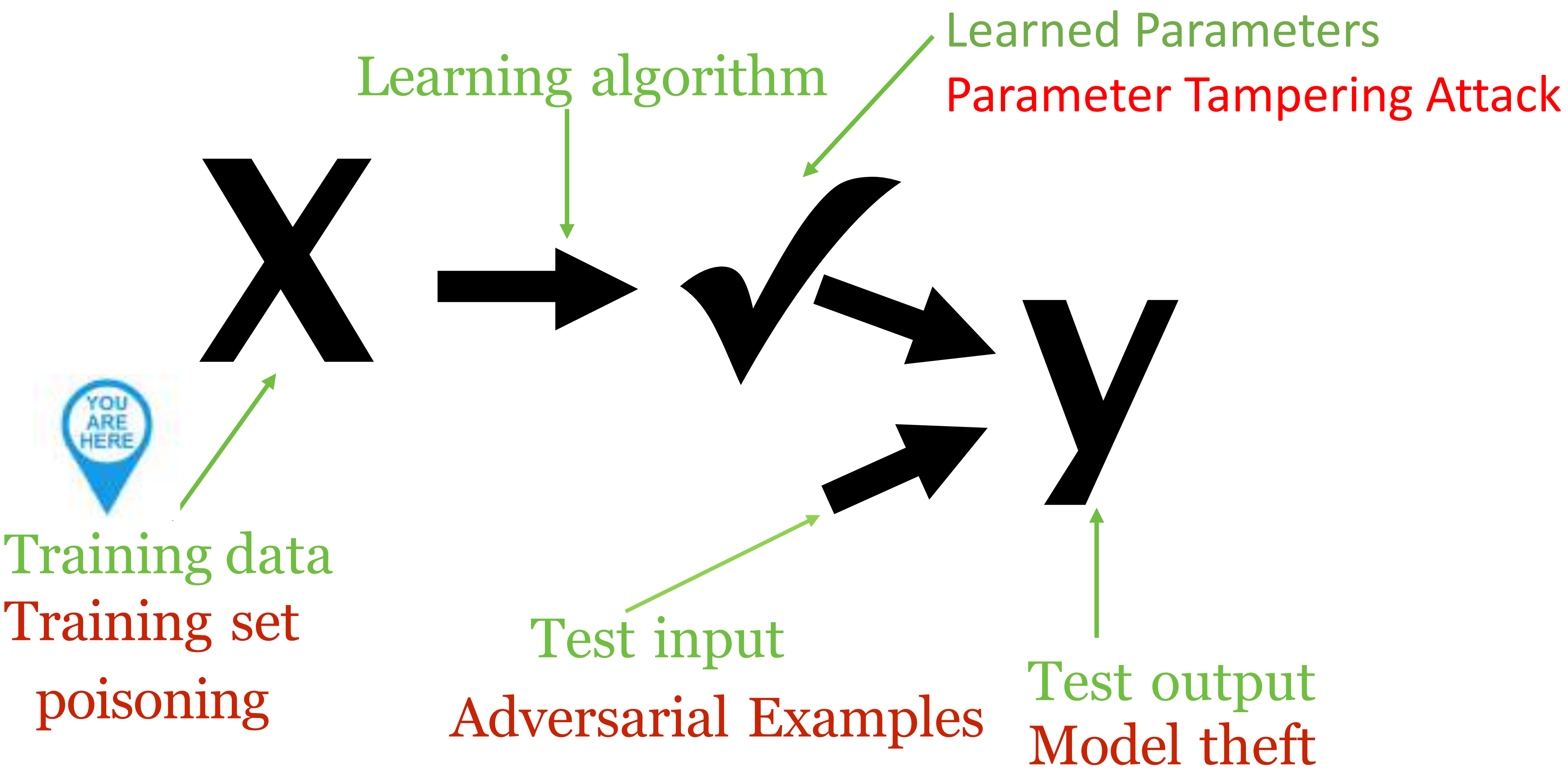
- *Learner's problem*
  - Find $w \in H$ that minimizes
    - $E_{\{z \sim D\}}\, l(w, z) \ + \lambda\, R(w)$
    - $\frac{1}{m} \sum_{\{i=1\}}^{m} l\big(w, (x_i, y_i)\big) \ + \lambda\, R(w)$
- *Sample* set $S = \{(x_1, y_1), \dots, (x_m, y_m)\}$
- *Stochastic Gradient Descent (SGD)*
  - (iteration) $w[t+1] = w[t] \ - \eta_t l'(w[t], (x_{\{i_t\}}, y_{\{i_t\}})$
  - (learning rate) η_t
  - …

ML (Basics)

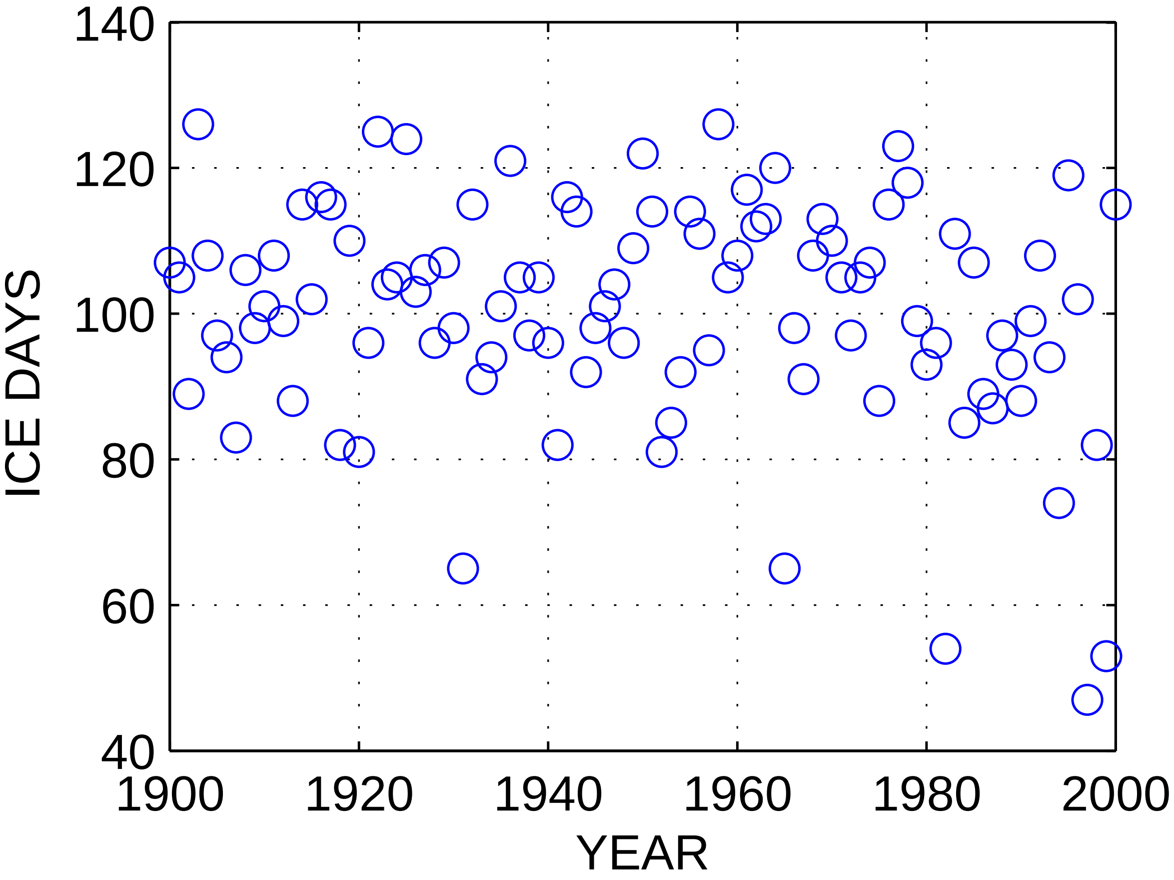
- After Training
  - $F_w : X \to Y$
  - $F_w(x) \ = \ \underset{\{y \in Y\}}{\operatorname{argmax}} \ s(F_w)(x)$
  - (softmax layer) $s(F_w)$
  - Sometimes we will write F_w simply as F
    - w will be implicit

Training Time Attack

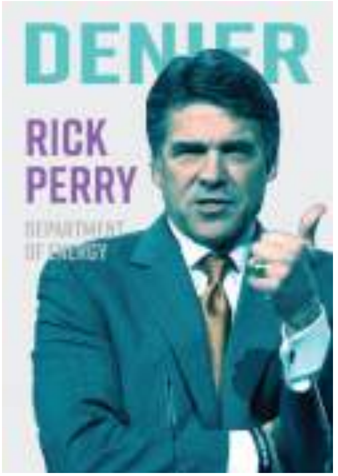
Attacks on the machine learning pipeline

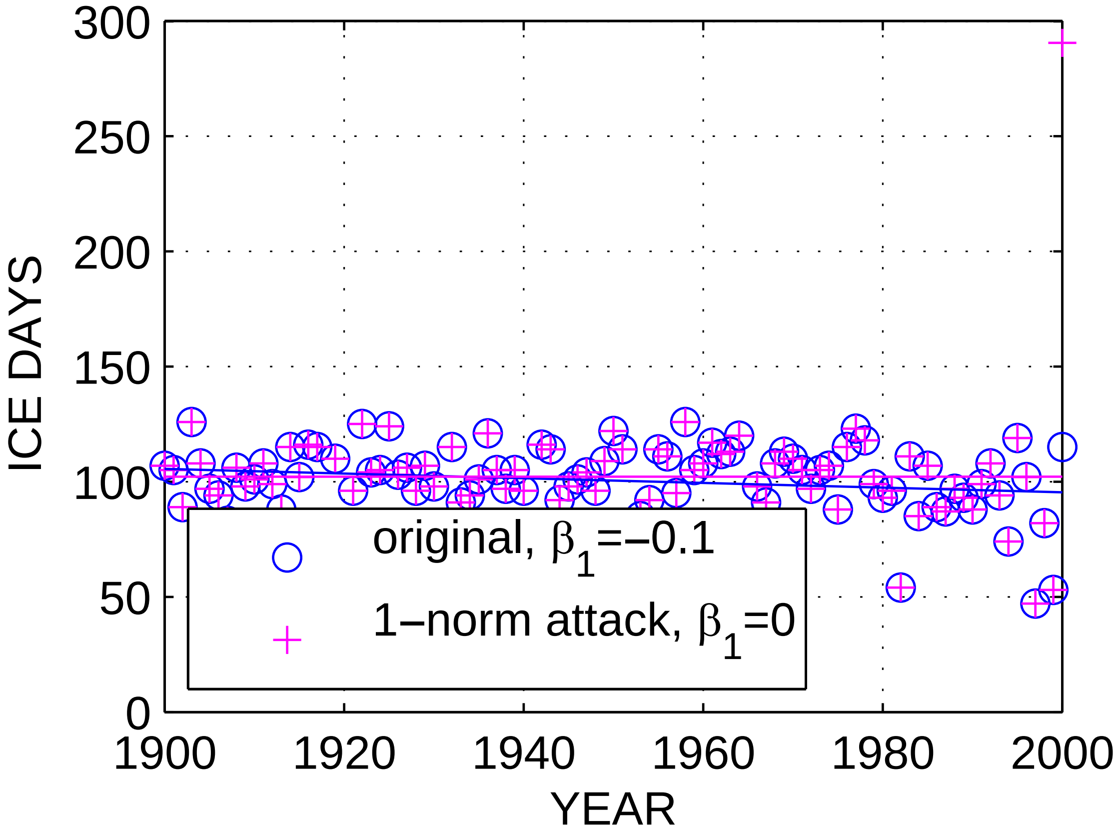


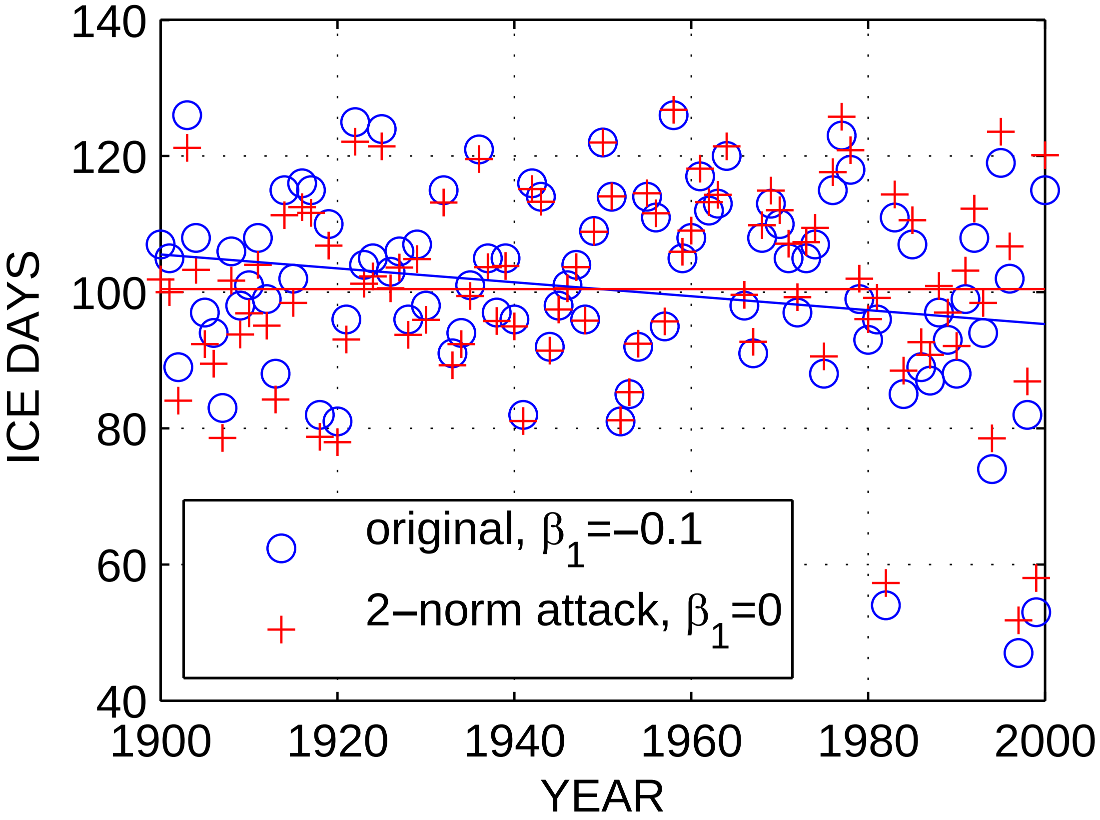
Lake Mendota Ice Days



Poisoning Attacks

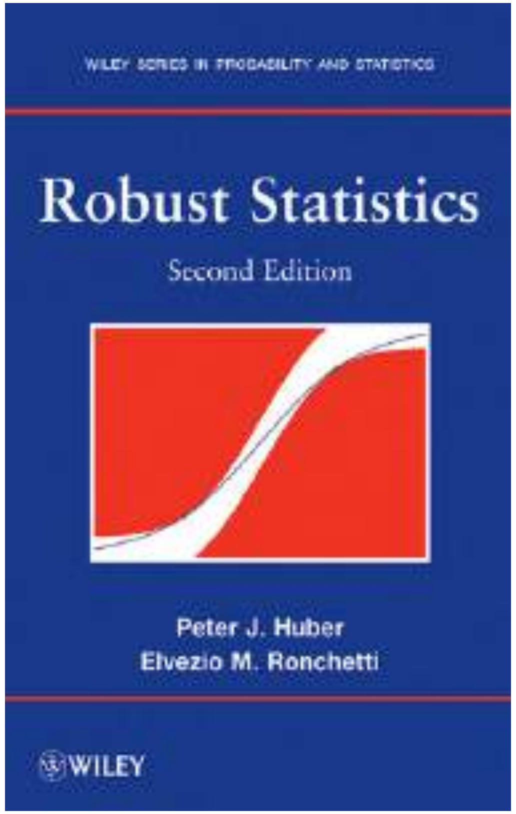






Formalization

- *Alice* picks a data set S of size m
- *Alice* gives the data set to *Bob*
- *Bob* picks
  - $\epsilon\, m$ points S^B
  - Gives the data set $S \cup S^B$ back to Alice
  - Or could replace some points in S
- Goal of Bob
  - Maximize the error for Alice
- Goal of Alice
  - Get close to learning from clean data

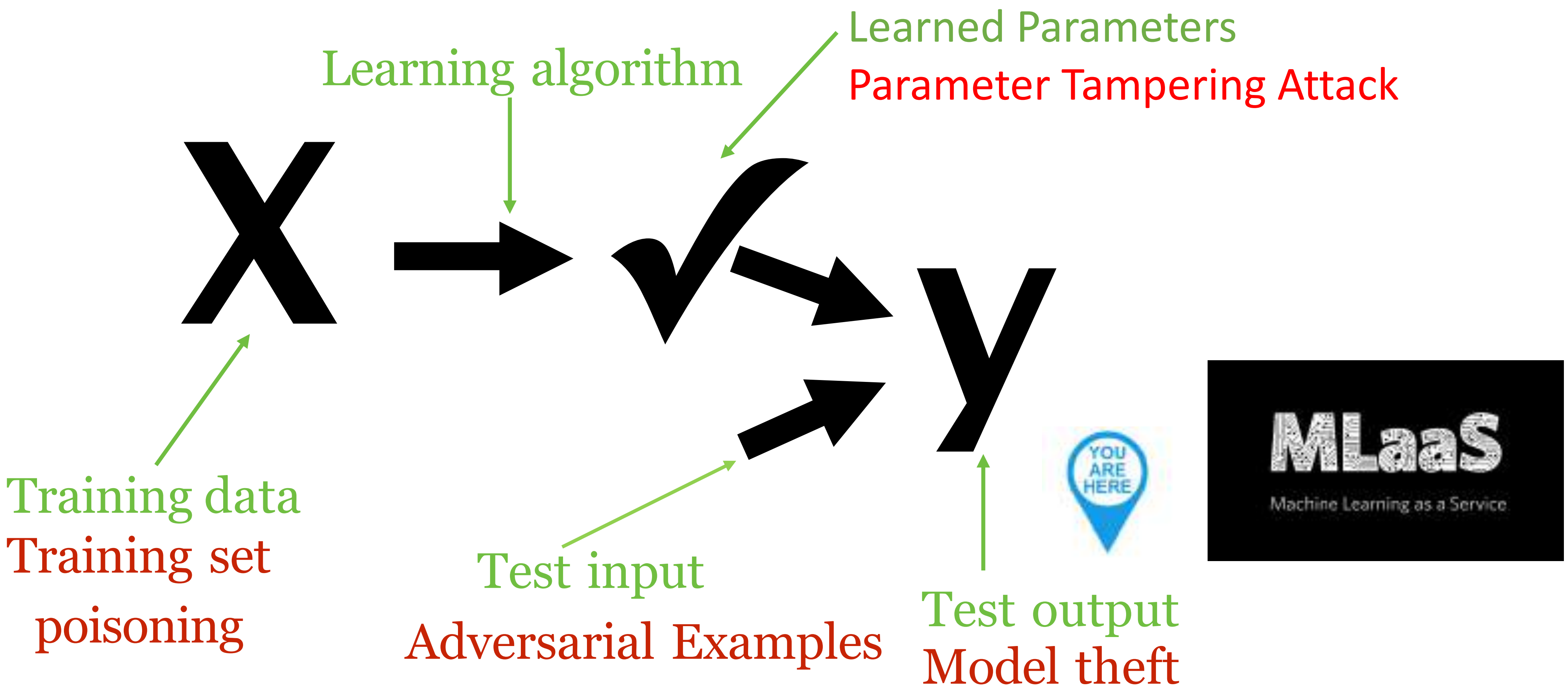


Representative Papers

- Being Robust (in High Dimensions) Can be Practical
  I. Diakonikolas, G. Kamath, D. Kane, J. Li, A. Moitra, A. Stewart
  ICML 2017
- Certified Defenses for Data Poisoning Attacks. Jacob Steinhardt, Pang Wei Koh, Percy Liang. NIPS 2017
- Scott Alfeld, Xiaojin Zhu, and Paul Barford. Explicit defense actions against test-set attacks. AAAI 2017
- Poison Frogs! Targeted Clean-Label Poisoning Attacks on Neural Networks, NIPS 18
- …

Model Extraction/Theft Attack

Attacks on the machine learning pipeline



Model Theft

- Model theft: extract model parameters by queries (intellectual property theft)
  - Given a classifier F
  - Query F on $q_1, \ldots, q_n$ and learn a classifier G
  - $F \approx G$
- Goals: leverage active learning literature to develop new attacks and preventive techniques
- *Papers:*
  - *Stealing Machine Learning Models using Prediction APIs*, Tramer et al., Usenix Security 2016
  - *Exploring Connections Between Active Learning and Model Extraction,* Chandrasekaran et al, Usenix Security 2020

Fake-News Attacks

Fake News Attacks

Abusive use of machine learning:

Using GANs to generate **fake content** (a.k.a deep fakes)

Strong societal implications:

elections, automated trolling, court evidence …

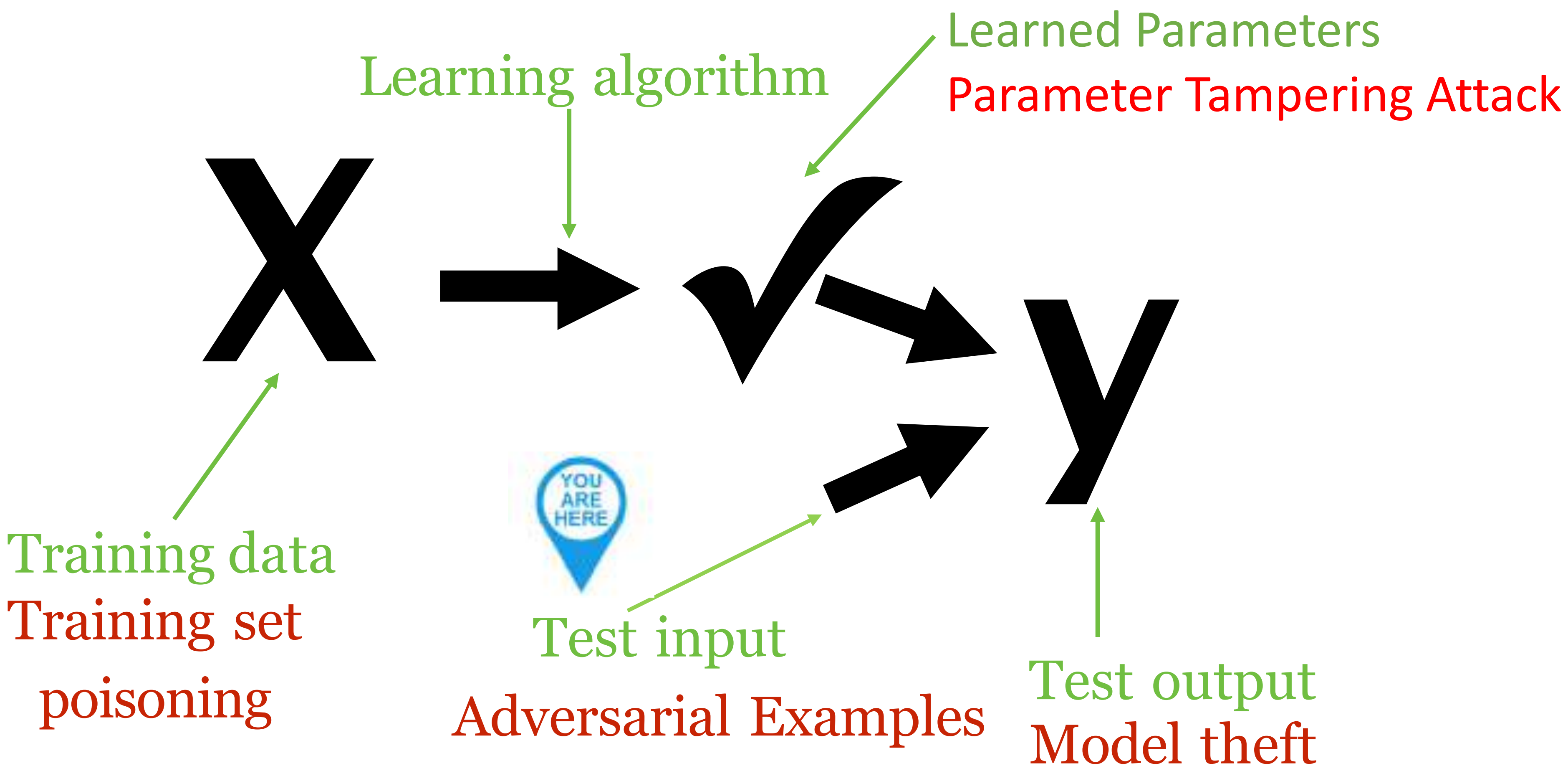
Generative media:

- Video of Obama saying things he never said, …
- Automated reviews, tweets, comments, indistinguishable from human-generated content

Obama Fake Video

Test-time Attacks

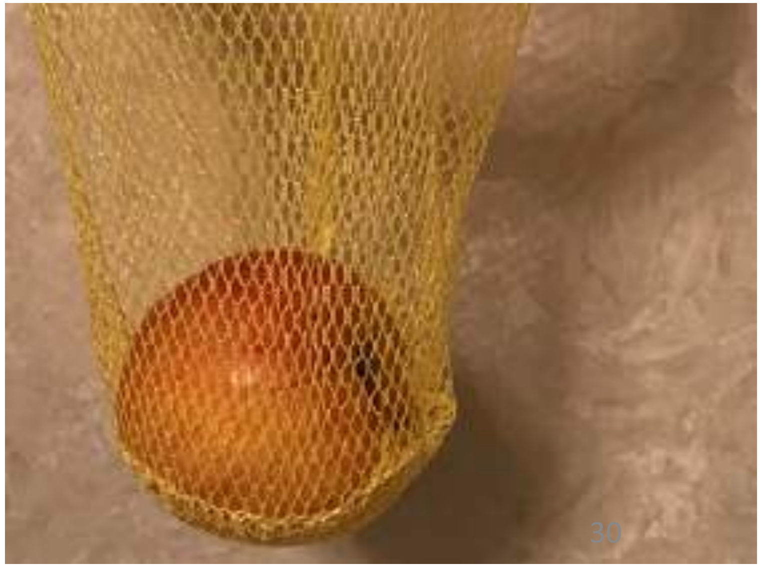
Attacks on the machine learning pipeline



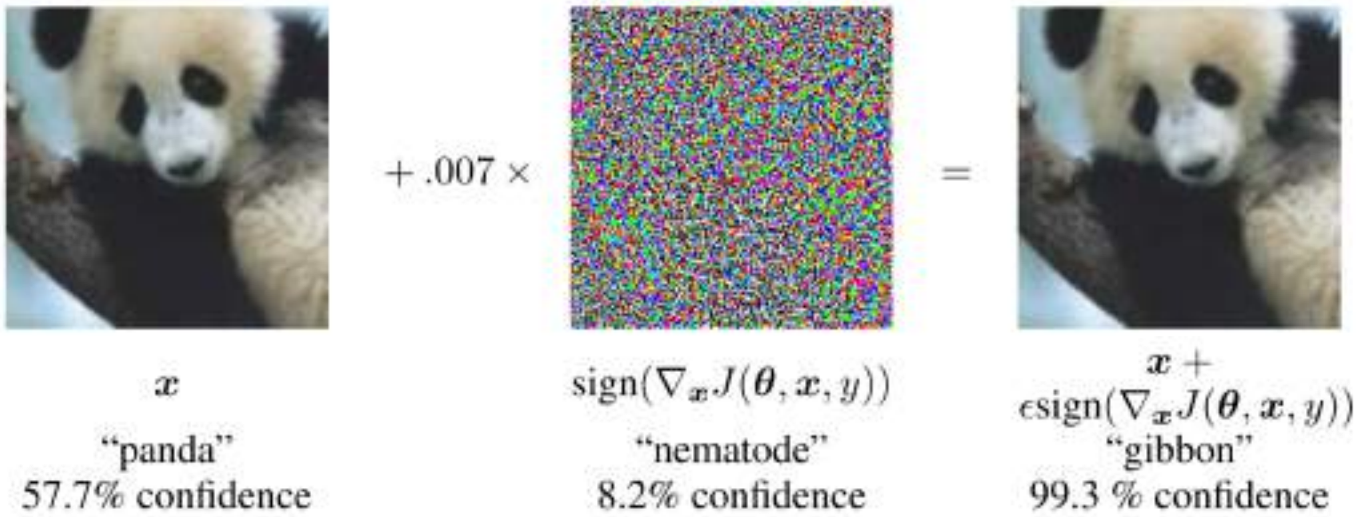
Definition

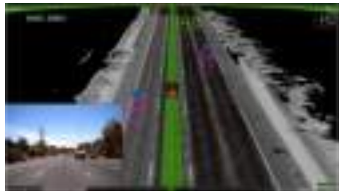
"Adversarial examples are inputs to machine learning models that an attacker has intentionally designed to cause the model to make a mistake"

(Goodfellow et al 2017)



What if the adversary systematically found these inputs?





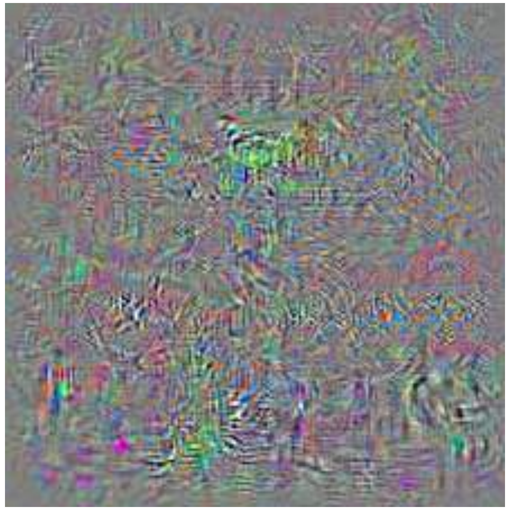
Biggio et al., Szegedy et al., Goodfellow et al., Papernot et al.

Good models make surprising mistakes in non-IID setting

“Adversarial examples”

Schoolbus

+



Perturbation

(rescaled for visualization)

=

Ostrich

(Szegedy et al, 2013)

Adversarial Examples

88% tabby cat

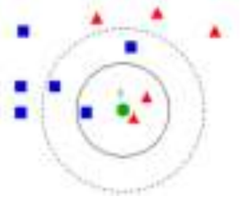
99% guacamole

Don’t Bring Your Turtle to a Gun Fight

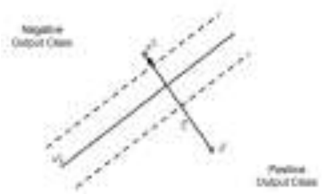
Adversarial examples…

… *beyond deep learning*

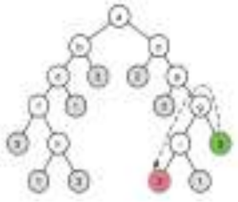
Logistic Regression



Nearest Neighbors

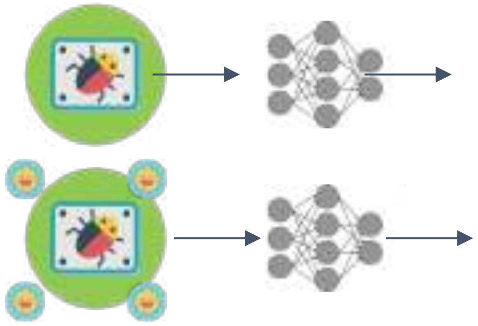


Support Vector Machines



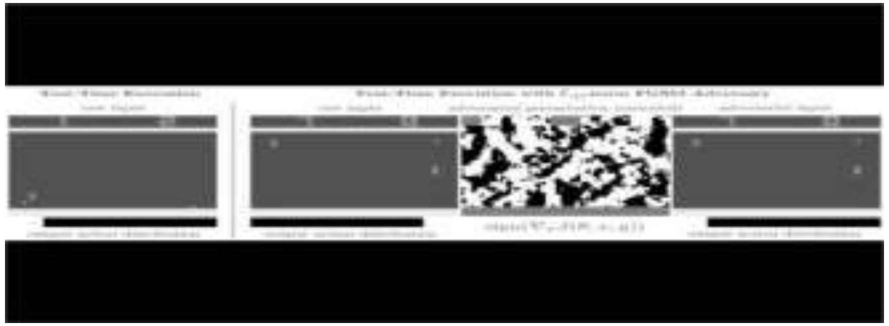
Decision Trees

… *beyond computer vision*



P[X=**Malware**] = **0.90**
P[X=Benign] = 0.10

P[X*=Malware] = 0.10
P[X*=**Benign**] = **0.90**



Formal Definition (Local Robustness)

- Let $O \subseteq X \times X$ be a binary oracle
  - $O(x, x') = 1$ (examples x and x' "perceived" same)
  - Otherwise 0 (Examples are "perceived" different)
- Targeted local robustness $TR^O(x, F, t)$
  - $\forall x' : \;\; O(x, x') \Rightarrow \neg(F(x') = t)$
- Global targeted robustness predicate/metric $GTR^O(F, t)$
  - $E_{\{x \sim D\}}\,(TR^o\,(x, F, t))$
- Observation
  - Targeted adversarial examples are counterexamples to $GTR^O(F, t)$

Global Robustness

- *Local robustness predicate* $R^O(x, F)$
  - $\forall x' : \quad O(x, x') \Rightarrow (F(x) = F(x'))$
- *Global robustness predicate/metric* $GR^O(F)$
  - $E_{\{x \sim D\}}\,(R^O(x, F))$
- Observation
  - adversarial examples are counterexamples to $GR^O(F)$

Instantiating the Oracle

- Ideal
  - $O(x, x') = 1$ iff a human perceives x and x'as same images
  - Difficulty:
    - We don’t completely how human perception works☹
- What researchers actually use
  - $O(x, x') = 1$ iff x and x' are close under some norm
    - L_∞
    - L_1
    - L_p $(p \geq 2)$

Threat Model

- White Box
  - Complete access to the classifier F
- Black Box
  - Oracle access to the classifier F
  - for a data x receive $F(x)$
- Grey Box
  - Black-Box + "some other information"
  - Example: structure of the defense

FGSM (white box, misclassification)

- Take a step in the
  - direction of the gradient of the loss function
  - $\delta = \epsilon \, sign(\Delta_x \, l(w, x, F(x)))$
  - Essentially opposite of what SGD step is doing
- Paper
  - Goodfellow, Shlens, Szegedy. Explaining and harnessing adversarial examples. ICLR 2015

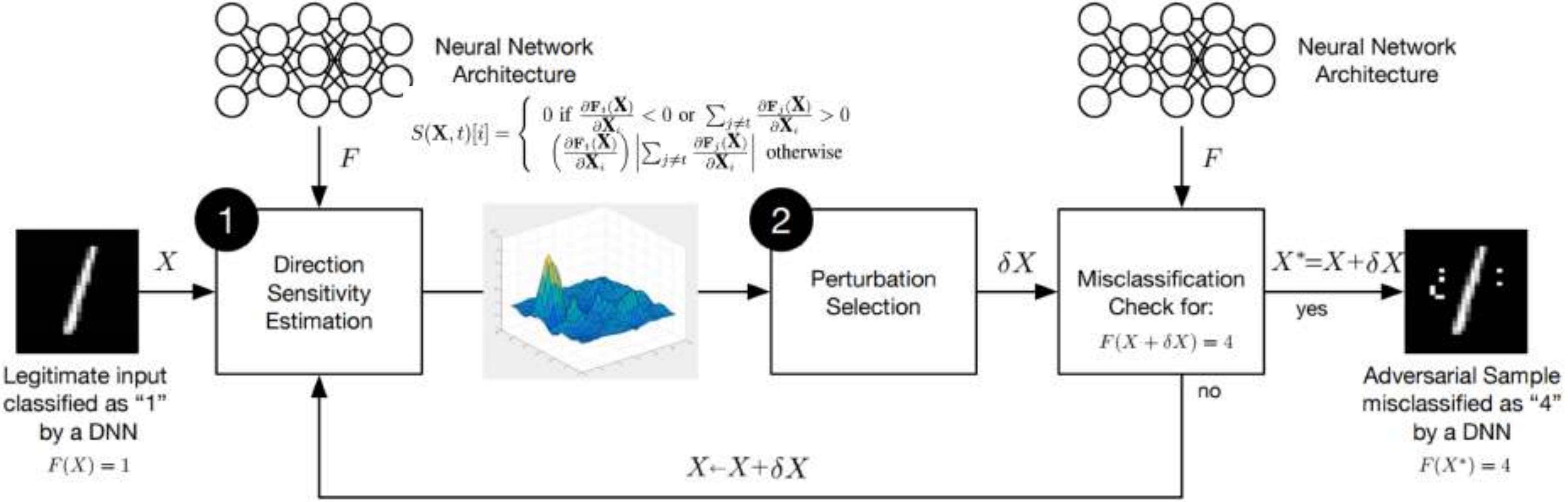
PGD (white box, misclassification)

- $\text{Proj}_{\{B(x,\epsilon)\}}\ (y)$
  - Project y to the ball $B(x,\epsilon)$

- Iterate the following step
  - $x_{\{k+1\}} = \text{Proj}_{\{B(x,\epsilon)\}}\,(\,x_k + \epsilon\ sign\ \Delta_x\ \ l\big(w, x, F(x)\big))$

- Intuition:
  - Take a FGSM step, and
  - Project it down to the ball

JSMA (white-box, targeted)



$$S(\mathbf{X},t)[i] = \begin{cases} 0 \text{ if } \frac{\partial \mathbf{F}_t(\mathbf{X})}{\partial \mathbf{X}_i} < 0 \text{ or } \sum_{j \neq t} \frac{\partial \mathbf{F}_j(\mathbf{X})}{\partial \mathbf{X}_i} > 0 \\ \left(\frac{\partial \mathbf{F}_t(\mathbf{X})}{\partial \mathbf{X}_i}\right) \left| \sum_{j \neq t} \frac{\partial \mathbf{F}_j(\mathbf{X})}{\partial \mathbf{X}_i} \right| \text{ otherwise} \end{cases}$$

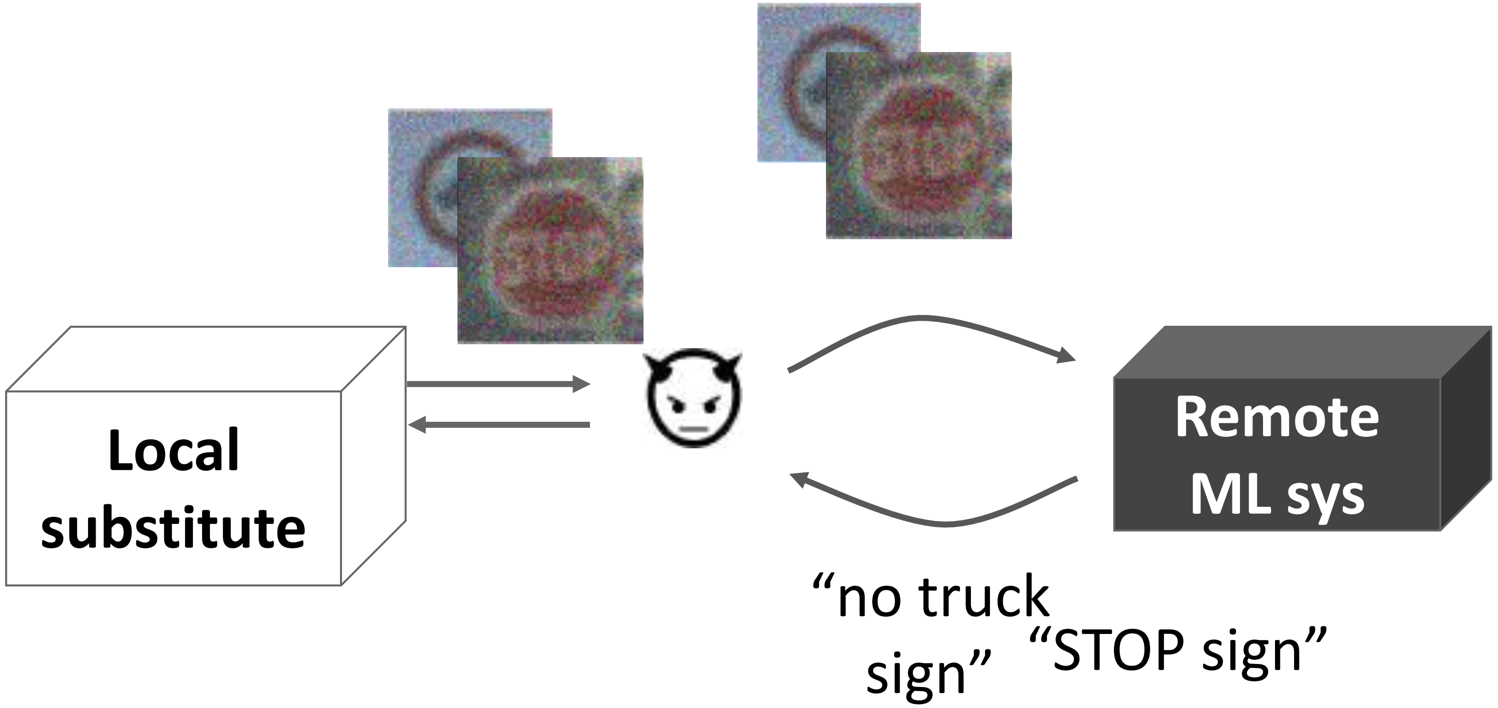
The Limitations of Deep Learning in Adversarial Settings [IEEE EuroS&P 2016]
Nicolas Papernot, Patrick McDaniel, Somesh Jha, Matt Fredrikson, Z. Berkay Celik, and Ananthram Swami

Other Attacks (White-box, targeted)

- Carlini-Wagner (CW)
    - Use optimization engines (i.e. Adam) in a black-box manner

- Athalye-Carlini-Wagner
    - More on this later….
    - Builds on CW

Attacking remotely hosted black-box models



Practical Black-Box Attacks against Machine Learning [AsiaCCS 2017]
Nicolas Papernot, Patrick McDaniel, Ian Goodfellow, Somesh Jha, Z.Berkay Celik, and Ananthram Swami

Abstract Algorithm

- Choose S (substitute network)
- Interact with the classifier F in a black-box manner
- Train the substitute network S
- Run white-box attack on S

FM Perspective

- <u>Gradient Free Optimization</u>
  - *Black-box Adversarial Attacks with Limited Queries and Information*, Andrew Ilyas, Logan Engstrom, **Anish Athalye**, and Jessy Lin, *ICML 2018*
  - *Query-Efficient Hard-Label Black-box Attacks: An Optimization-based Approach, Cheng etl al., ICML 2019*

- These are very powerful black-box learner
- *Problem: Use these in verification*

Defense

Robust Defense Has Proved Elusive

- Quote
  - *In a case study, examining noncertified white-box-secure defenses at ICLR 2018, we find obfuscated gradients are a common occurrence, with 7 of 8 defenses relying on obfuscated gradients. Our new attacks successfully circumvent 6 completely and 1 partially.*
- Paper
  - Obfuscated Gradients Give a False Sense of Security: Circumventing Defenses to Adversarial Examples.
  - Anish Athalye, Nicholas Carlini, and David Wagner, *ICML 2018*

Certified Defenses

- Robustness predicate $Ro(x, F, \epsilon)$
  - For all $x' \in B(x, \epsilon)$ we have that $F(x) = F(x')$

- Robustness certificate $RC(x, F, \epsilon) \Rightarrow Ro(x, F, \epsilon)$

- *We should be developing defenses with certified defenses*

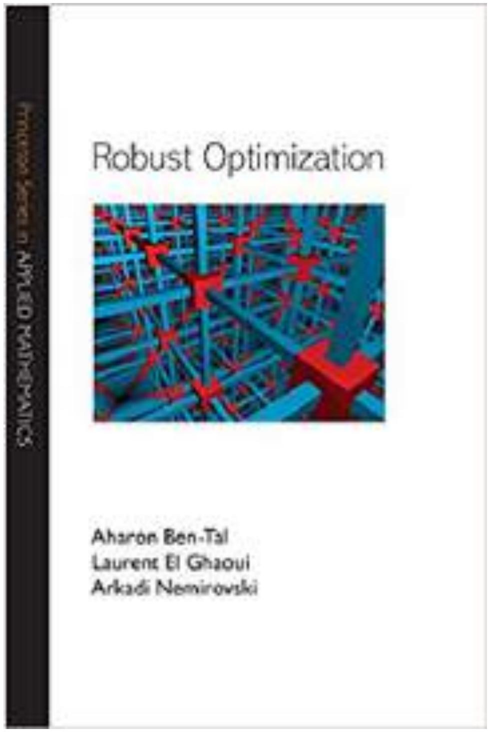
Semidefinite relaxations for certifying robustness to adversarial examples , Aditi Raghunathan, Jacob Steinhardt and Percy Liang

Verification of DNNs

- **Towards Fast Computation of Certified Robustness for ReLU Networks**
  - Tsui-Wei Weng, Huan Zhang, Hongge Chen, Zhao Song, Cho-Jui Hsieh, Duane Boning, Inderjit S. Dhillon, Luca Daniel, *ICML 2018*
  - Activation function limited to: $f(x) = x^+ = \max(0, x)$

- Follow up of CAV 17 paper by Katz et al.
  - Quote: *" … our algorithms are more than 10,000 times faster"*
  - Based on spectral techniques
- $F, x \vDash Ro(x, F, \epsilon)$

Robust Objectives



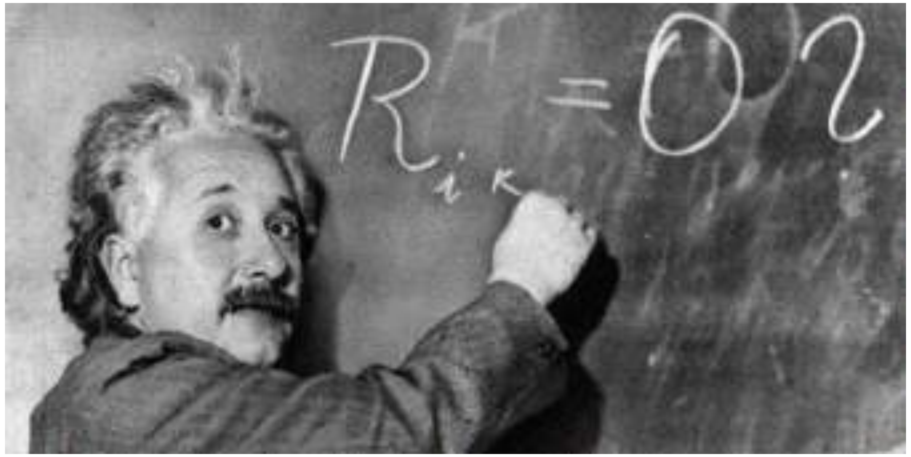
- Use the following objective
  - $\min_{w} \quad E_z\left[\max_{\{z' \in B(z,\epsilon)\}} \quad l(w, z')\right]$
  - Outer minimization use SGD
  - Inner maximization use PGD
- A. Madry, A. Makelov, L. Schmidt, D. Tsipras, A. Vladu. Towards Deep Learning Models Resistant to Adversarial Attacks. ICLR 2018
- A. Sinha, H. Namkoong, and J. Duchi. Certifying Some Distributional Robustness with Principled Adversarial Training. ICLR 2018

Adversarial Training

1. Train the model naturally (the procedure I described first)
2. Adversarial training for each element x_i
    1. Run PGD attack from x_i and get z_i (adversarial example)
    2. Use natural training on z_i

Note: Using attack technique to make the model more robust

Analogy: Counterexample guided re-training (refinement?)



Theoretical Explanations

Three Directions (Representative Papers)

- Lower Bounds
  - A. Fawzi, H. Fawzi, and O. Fawzi. Adversarial Vulnerability for any Classifier.

- Sample Complexity
  - Analyzing the Robustness of Nearest Neighbors to Adversarial Examples, Yizhen Wang, Somesh Jha, Kamalika Chaudhuri, ICML 2018
  - Adversarially Robust Generalization Requires More Data. Ludwig Schmidt, Shibani Santurkar, Dimitris Tsipras, Kunal Talwar, Aleksander Mądry, ICLR 2018
    - *We show that already in a simple natural data model, the sample complexity of robust learning can be significantly larger than that of "standard" learning.*

Three Directions (Contd)

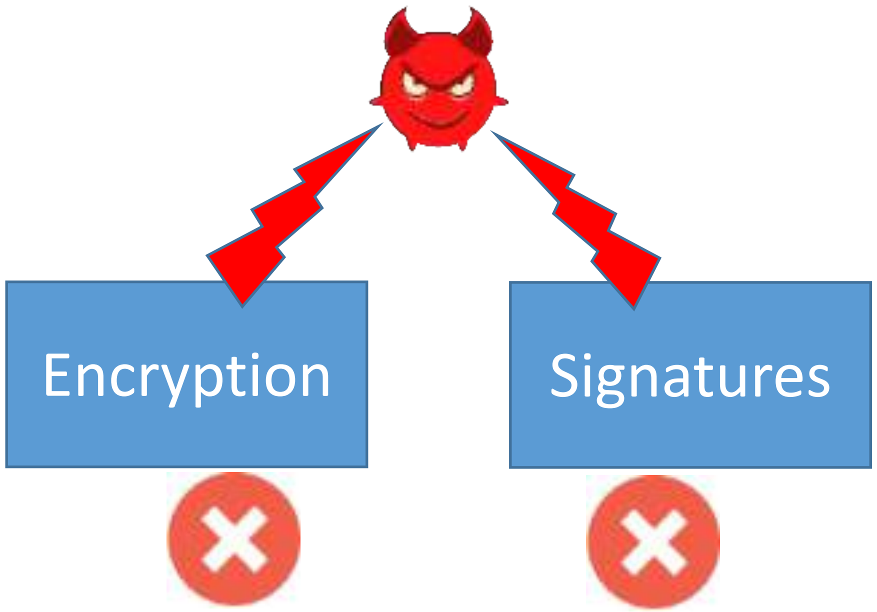
- Computational Complexity
  - *Adversarial examples from computational constraints*. Sébastien Bubeck, Eric Price, Ilya Razenshteyn, ICML 2019
  - *Computational Limitations in Robust Classification and Win-Win Results.* Akshay Degwekar and Vinod Vaikuntanathan, COLT 2019
- Jury is Still Out!!

Adversarially Robust Learning Could Leverage Computational Hardness

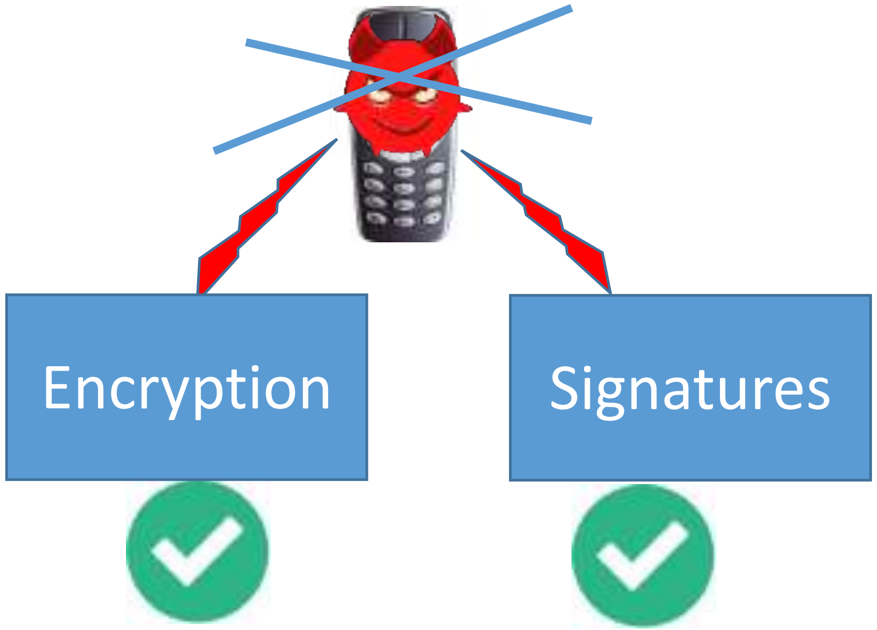
Sanjam Garg Somesh Jha Saeed Mahloujifar Mohammad Mahmoody

Cryptography is based on **computational** hardness

Information Theoretic Adversary



Computationally bounded adversary



We study whether there is any learning task for which it is possible to design classifiers that are only robust against **polynomial-time adversaries**.

We show that computational limitation of attackers can indeed be useful in robust learning by demonstrating a classifier that is **only robust** against **poly-time adversaries**

Several Interesting Directions/Questions

- Can the underlying task be made more natural?

- Can this direction lead to practical/deployable defenses?

Verification, Analysis, Testing

Formal Definition

- Let $O \subseteq X \times X$ be a binary oracle
  - $O(x, x') = 1$ (examples x and x' "perceived" same)
  - Otherwise 0 (Examples are "perceived" different)
- *Local robustness predicate* $R^O(x, F)$
  - $\forall x' : \ O(x, x') \Rightarrow (F(x) = F(x'))$
- *Global robustness predicate* $GR^O(F)$
  - $\forall x \ GR^O(F)$
- Observation
  - adversarial examples are counterexamples to $GR^O(F)$

Decision Procedures

- Decision procedures for verifying local robustness at a point
  - Safety Verification of DNNs, CAV 2017
  - ReLUplex: An Efficient SMT Solver for Verifying DNNs, CAV 2017
  - …
- Great work, but
  - Scalability (see earlier slide)
  - Not coupled with some of the ML techniques being developed
- Problem
  - *Can these decision procedures help in adversarial training?*

Analysis/Testing

- DeepXplore, SOSP 17
- Formal Symbolic Analysis of Neural Networks using Symbolic Intervals, Usenix Security 2018
- AI2: Abstract Interpretation of Neural Networks, Oakland 2018
  - See also follow up work by Isil Dillig’s group (PLDI 2019)
- Problem
  - *Can these techniques help in adversarial training?*

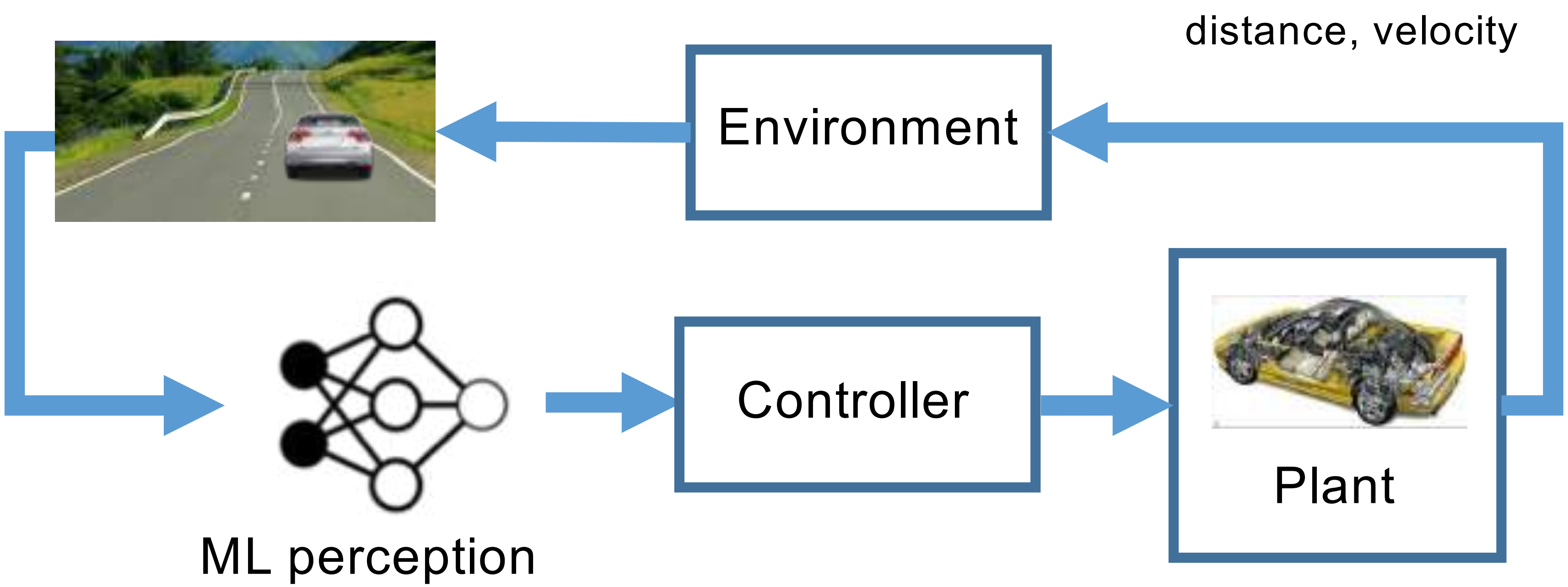
Glaring Omission from AML

- Specification of the system that is using ML
  - Control loop for flying a drone

- Problem
  - *Can we do better if we are more "application aware"?*
- Good read…
  - **Towards Verified Artificial Intelligence,** Sanjit A. Seshia, Dorsa Sadigh, S. Shankar Sastry

Automatic Emergency Braking System

- Goal: Brake whenever an obstacle is detected



Dreossi, Donze, Seshia, “Compositional Falsification of Cyber-Physical Systems with Machine Learning Components’, NFM 2017.

Theme 1

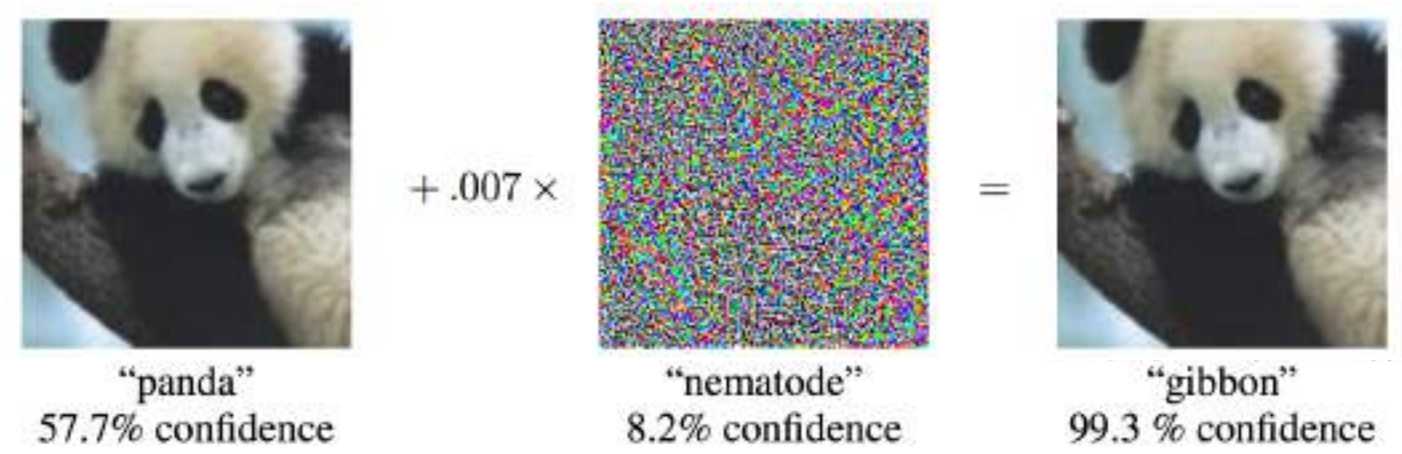
- We allowed only one kind of transformation
  - Add a vector δ

- Allow richer transformations
  - Relevant to the application
  - Translation, cloudy background, …..
  - Paper
    - A Rotation and Translation Suffice: Fooling CNNs with Simple Transformations
- Problem:
  - *Construct adversarial examples given a specification of transformations?*

Semantic Adversarial Analysis and Training

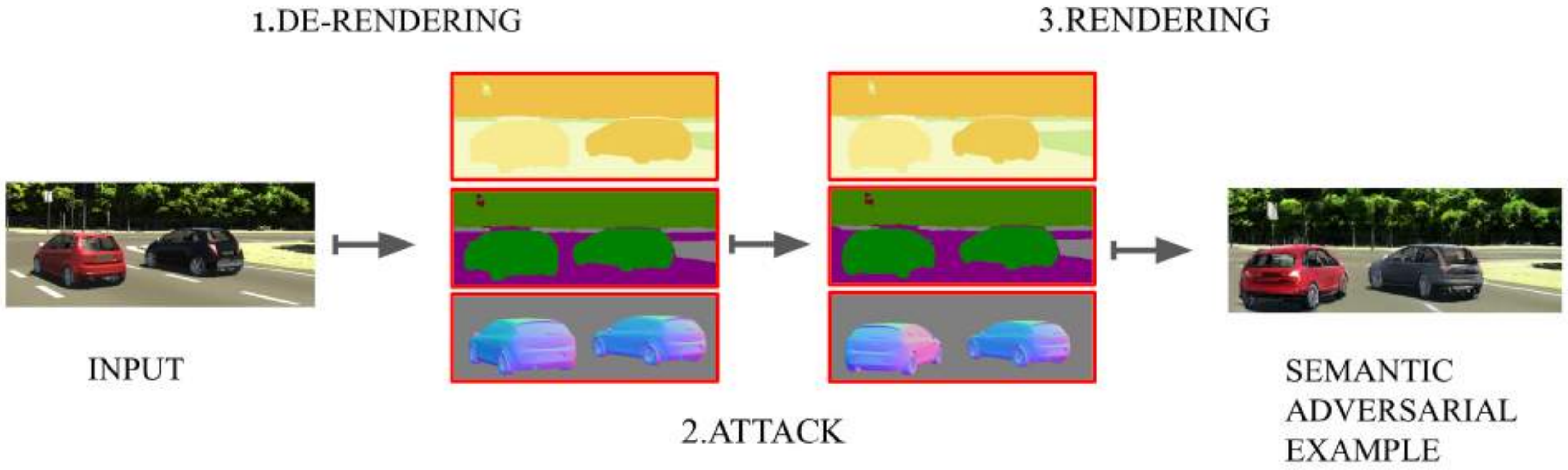
DNN analysis must be more *semantic*

- Semantic modification
- System-level specification
- Sematic (re-)training
- Confidence-based analysis



Non-semantic perturbation (i.e., noise)

Semantic perturbation (i.e., translation)



Generating Semantic Adversarial Examples with Differentiable Rendering
Jain et al. (In submission, but on arxiv)

3d-aware scene manipulation via inverse graphics.
Yao et al. In Advances in neural information processing systems, 2018.

Theme 2

- Problem:
  - *Construct adversarial examples that actually lead to system-level failures?*

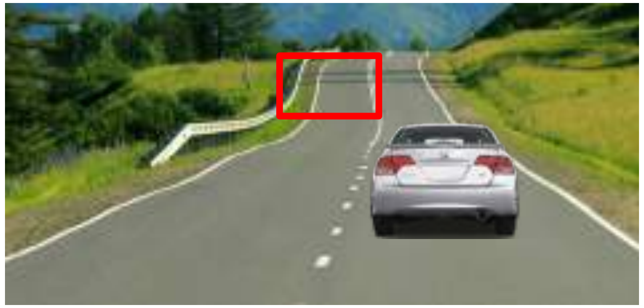
- We can then use these examples for adversarial training
- More on this later…

Semantic Adversarial Analysis and Training

DNN analysis must be more *semantic*

- Semantic modification
- System-level specification
- Sematic (re-)training
- Confidence-based analysis

Example: AEBS Counterexamples?

		
Perception-level spec: *“detect cars”*	✗	✗
System-level spec: *“do not crash”*	✓	✗

Does not affect the system

Semantic Adversarial Analysis and Training

DNN analysis must be more *semantic*

Example: AEBS
Spec: *"do not crash"*

- Semantic modification
- System-level specification
- Semantic (re-)training
- Confidence-based analysis

Semantic augmentation

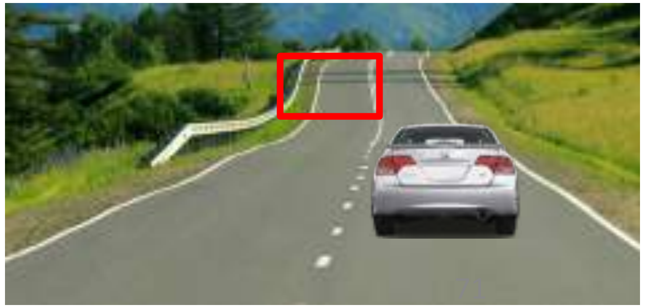
Original Training set

\+

vs

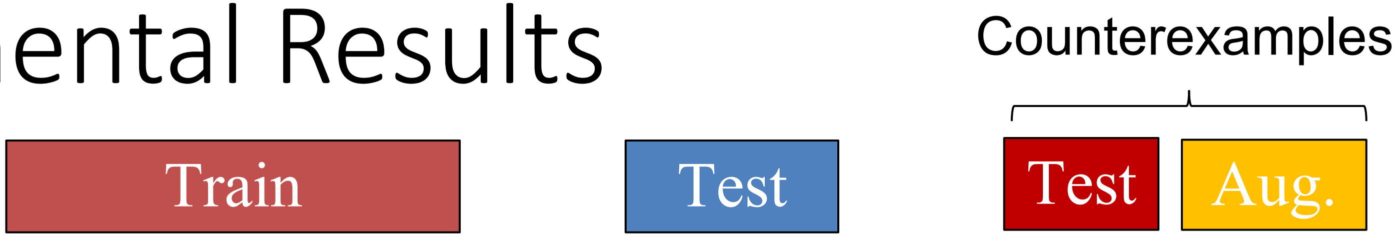
Original Training set

\+



Dreossi, Ghosh, Yue, Keutzer, Sangiovanni-Vincentelli, Seshia, "Counterexample-Guided Data Augmentation", IJCAI 2018.

Experimental Results



- Augmentation methods comparison

Counterexample-guided augmentation

Model	Precision	Recall
Original	0.61	0.74
Standard augmentation	0.69	0.80
Random	0.76	0.87
Halton	0.79	0.87
Distance constraint	0.75	0.86

"Counterexample-Guided Data Augmentation", T. Dreossi, S. Ghosh, X. Yue, K. Keutzer, A. Sangiovanni-Vincentelli, S. A. Seshia, IJCAI 2018.

Theme 3

- Problem:
  - *Can we use ML in a white-box manner to synthesize more resilient controllers?*

- Some evidence that using confidence measure (i.e. output of softmax layer) can help
  - *Reinforcing Adversarial Robustness using Model Confidence Induced by Adversarial Training*, Xi Wu, Uyeong Jang, Jiefeng Chen, Lingjiao Chen, Somesh Jha, ICML 2018

Semantic Adversarial Analysis and Training

DNN analysis must be more *semantic*

- Semantic modification
- System-level specification
- Semantic (re-)training
- Confidence-based analysis

Example: AEBS
Spec: *"do not crash"*

Prediction: car 49 %

AEBS (threshold 50%) → No car *Keep going*

vs

AEBS (confidence analysis) → Maybe car… *Better slow down*

Theme 3

- Problem:
  - *Can we generate adversarial examples that matter (i.e. cause system-level failure)?*

T. Dreossi, A. Donze, and S. A. Seshia. *Compositional Falsification of Cyber-Physical Systems with Machine Learning Components*, In NASA Formal Methods Symposium, May 2017.

Compositional Falsification

Statement

given a formal specification φ (say in a formalism such as signal temporal logic) and a CPS+ML model M,

find an input for which M does not satisfy φ.

Problem:

How do handle the ML component?

Obvious Strategies

- Treat ML component as any other component and
  - Let “abstraction refinement” handle it
  - Will it work?

    X

    - DNN models are constantly getting bigger (>= 20 million parameters)
    - Some folks are talking about a billion parameters

- Use adversarial example generator as a “black box”

  X

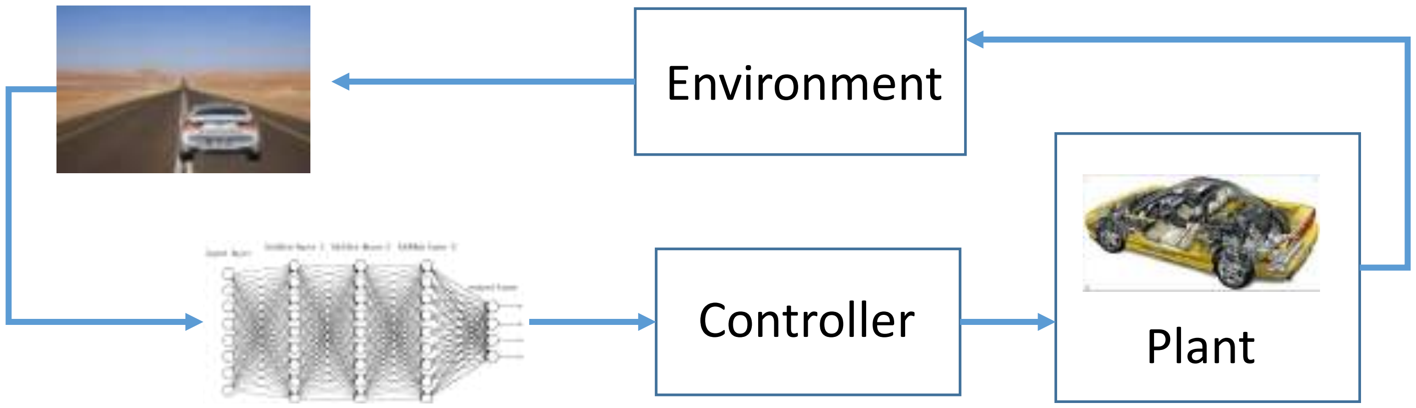
  - Will it work?
    - Will generate lot of examples that won’t falsify the system
    - Density of “spurious” adversarial examples is too large
      - This is a conjecture!!!

Our Approach: Use a System-Level Specification

- ✗ "Verify the Deep Neural Network Object Detector"
- ✓ "Verify the System containing the Deep Neural Network"

Formally Specify the *End-to-End Behavior* of the System

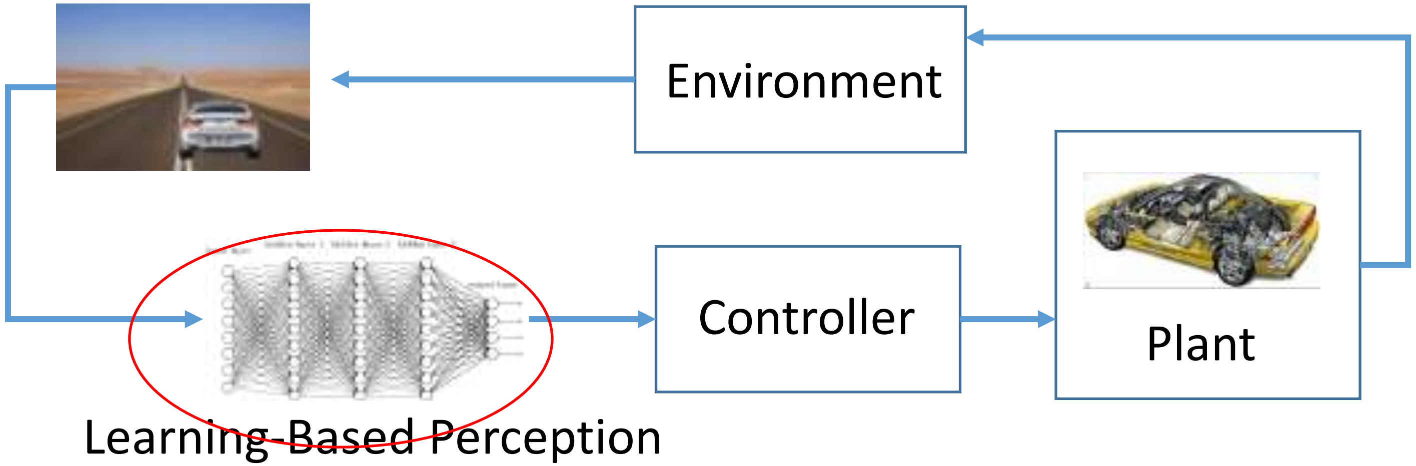
Temporal Logic: **G** (*dist*(ego vehicle, env object) > Δ)



Learning-Based Perception

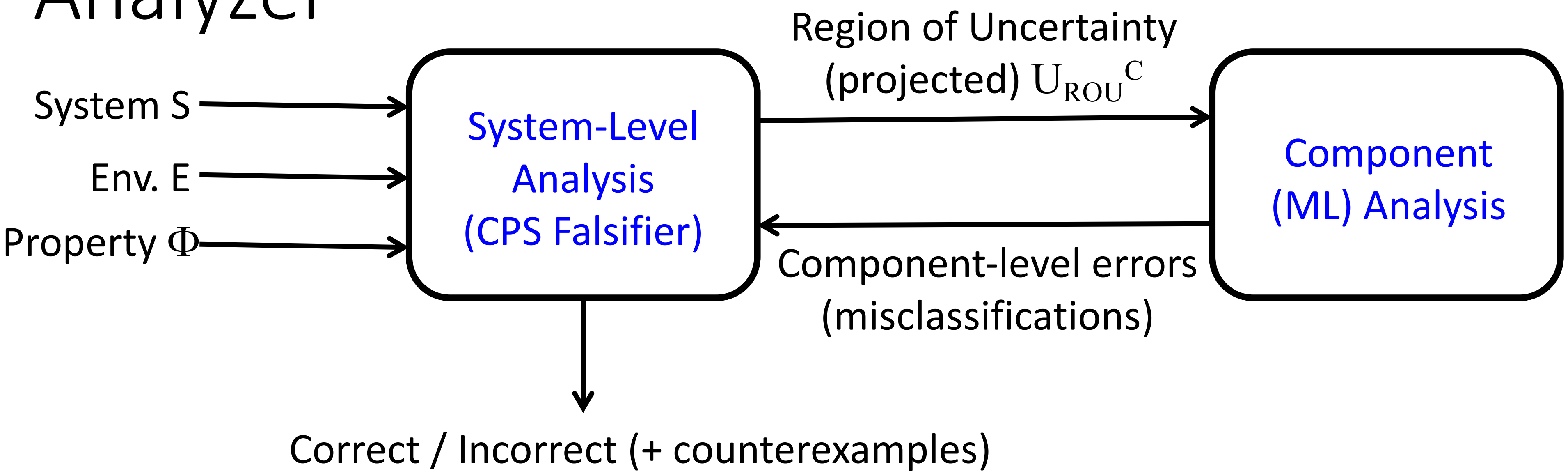
Compositional Falsification

- *Challenge:* Very High Dimensionality of Input Space!
- Standard solution: Use *Compositional (Modular)* Verification



- However: *no formal spec*. for neural network component!
- Compositional Verification *without* Compositional Specification?!!

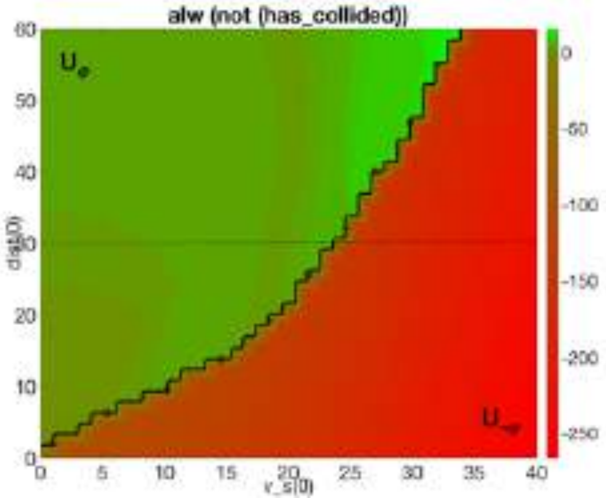
Compositional Approach: Combine Temporal Logic CPS Falsifier with ML Analyzer



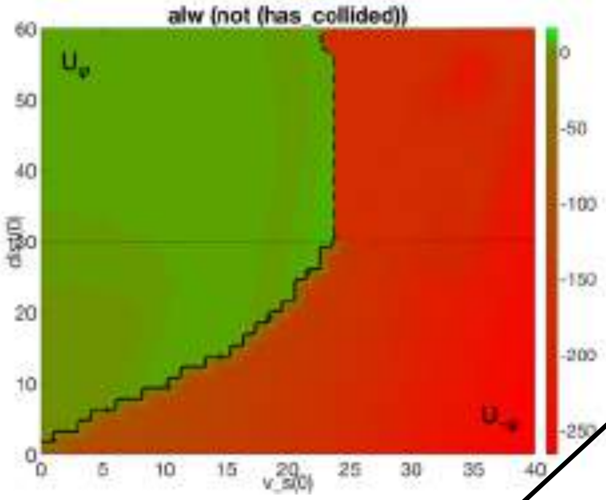
- CPS Falsifier uses abstraction of ML component
  - Optimistic analysis: assume ML classifier is always correct
  - Pessimistic analysis: assume classifier is always wrong
- Difference is the region of uncertainty where output of the ML component "matters"

Identifying Region of Uncertainty (*ROU*) for Automatic Emergency Braking System

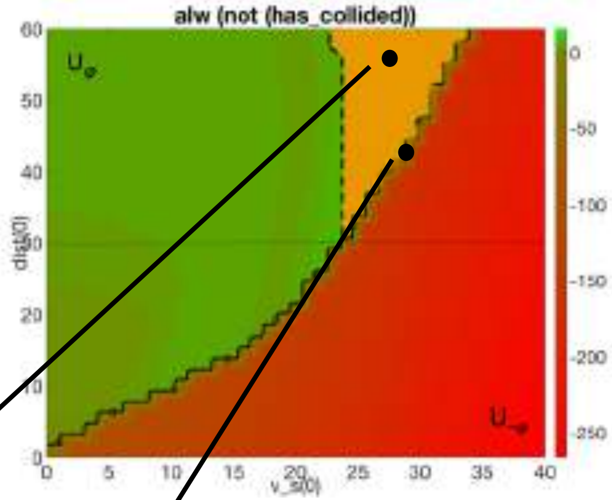
Green → environments where the property is satisfied



ML always correct



ML always wrong



Potentially unsafe region depending on ML component (yellow)

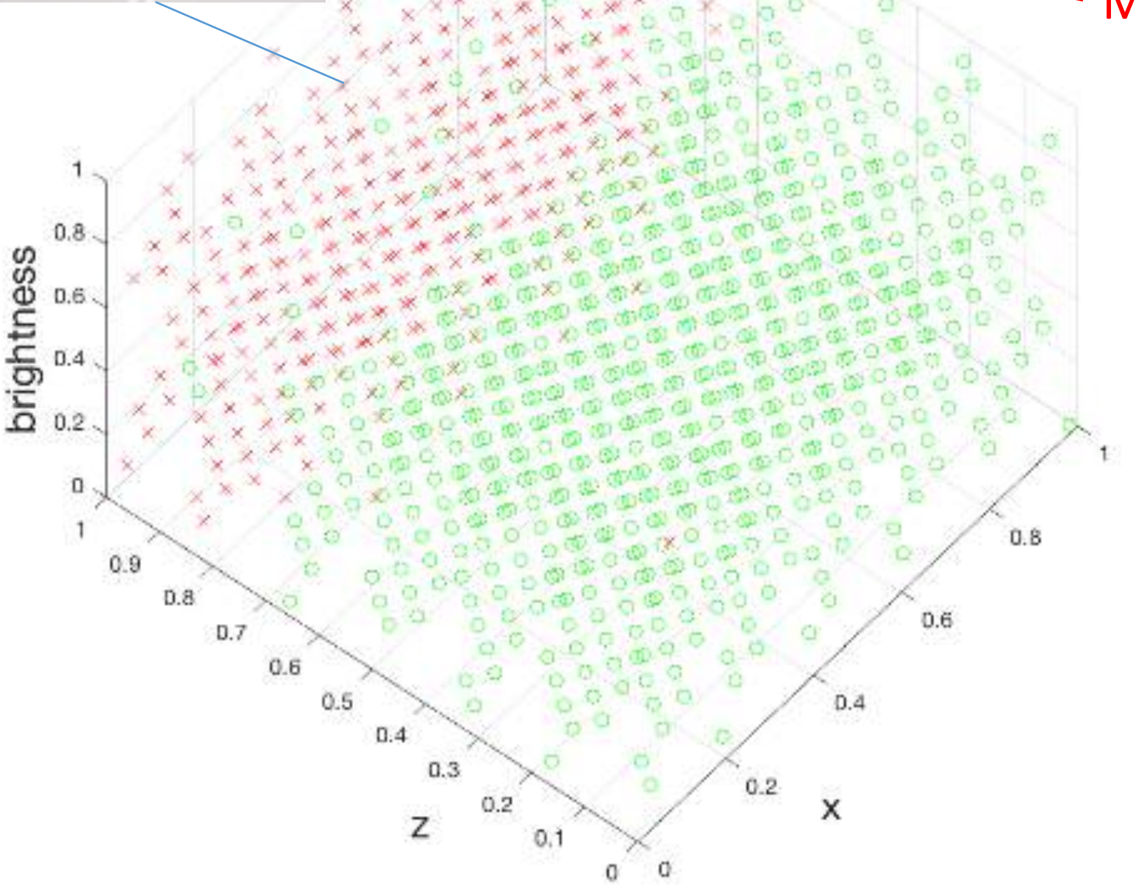
Sample Result

This misclassification may not be of concern

Inception-v3

Neural Network

(pre-trained on ImageNet using TensorFlow)



Misclassifications

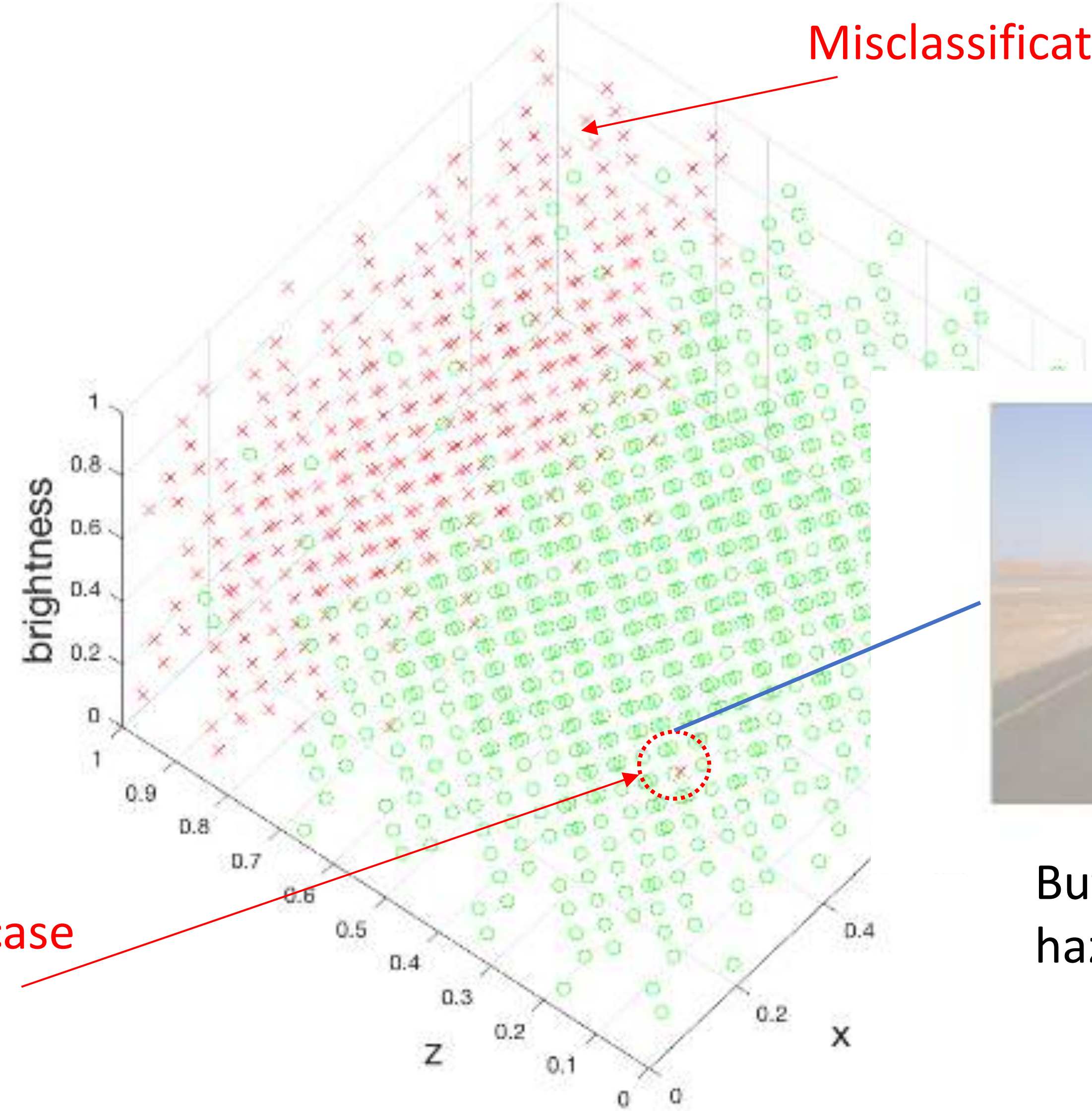
Sample Result

Misclassifications

Inception-v3

Neural Network

(pre-trained on ImageNet using TensorFlow)



Corner case Image

But this one is a real hazard!

Theme 4 (*)

- Problem:
  - *Can we use the specification to modify the loss function?*

- Intuition
  - *Steer the ML model towards correcting mis-classifications that cause system-level failure?*
  - Initial results, but inconclusive!
    - Trained with hinge loss
    - Does reduce the impact of the collision

Future

Exciting Area

- Several problems mentioned during the talk

- Get involved
  - Several workshops coming up
  - Don’t ignore the email invitations ☺

- Release benchmarks!
  - https://www.robust-ml.org/
  - https://github.com/tensorflow/cleverhans

Get involved!

https://github.com/tensorflow/cleverhans

cleverhans