Principles for Verified Learning-Based CPS

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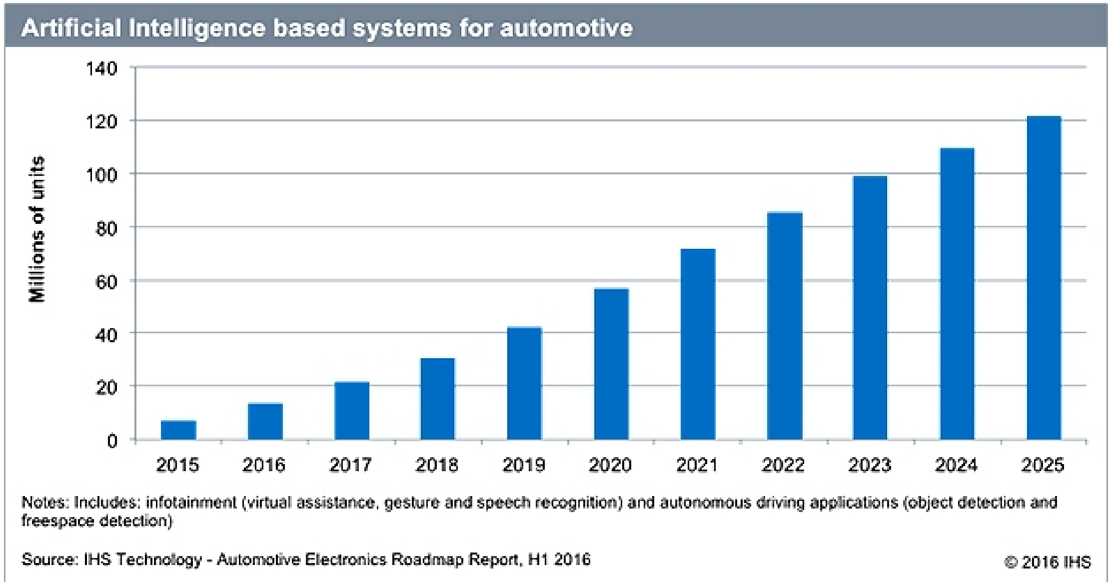
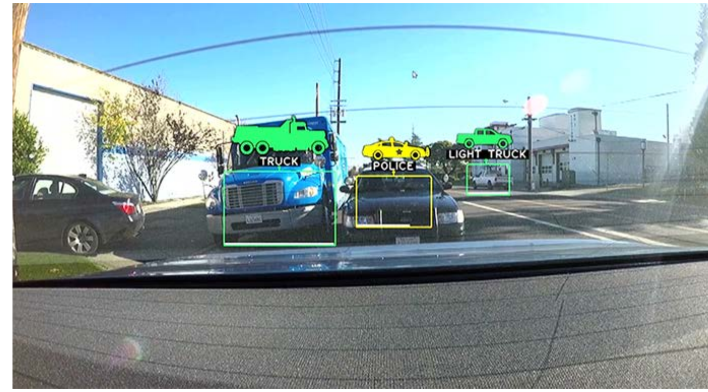
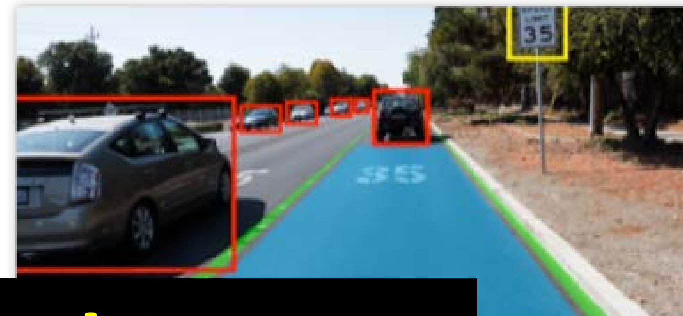
Growing Use of Machine Learning/AI in Cyber-Physical Systems







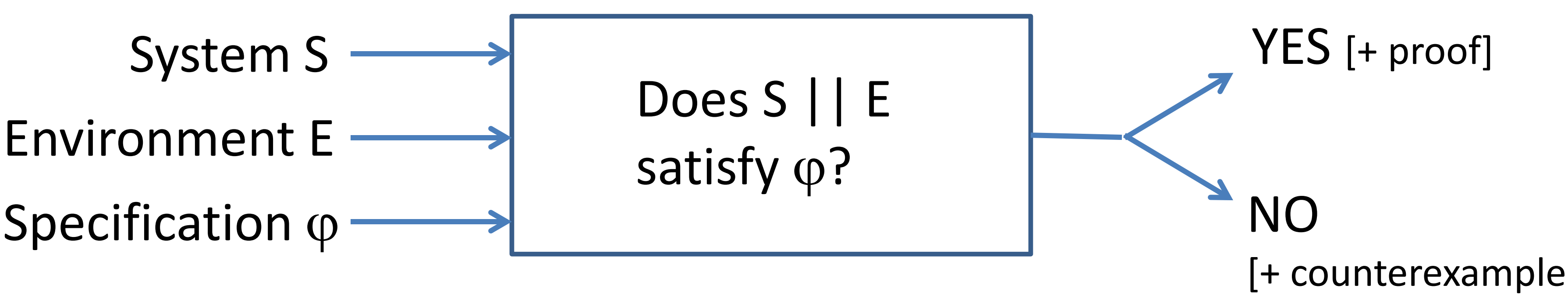
Many Safety-Critical Systems

AI / Cognitive Systems / Learning Systems

Computational Systems that attempt to mimic aspects of human intelligence, including especially the ability to learn from experience.

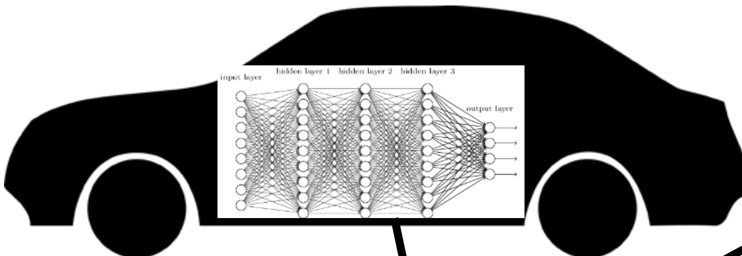
Formal Methods / Verification

Computational Proof Techniques: SAT Solving, SMT Solving, Directed simulation, Model checking, Theorem proving, …



Challenges for Verified AI

S. A. Seshia, D. Sadigh, S. S. Sastry. *Towards Verified Artificial Intelligence*. July 2016. https://arxiv.org/abs/1606.08514.



System **S**

Environment **E**

Specification **φ**

Does S || E satisfy φ?

YES [+ proof]

NO [+ counterexample]

Design Correct-by-Construction instead?

Counterexamples, etc. from Rich Signal Spaces?

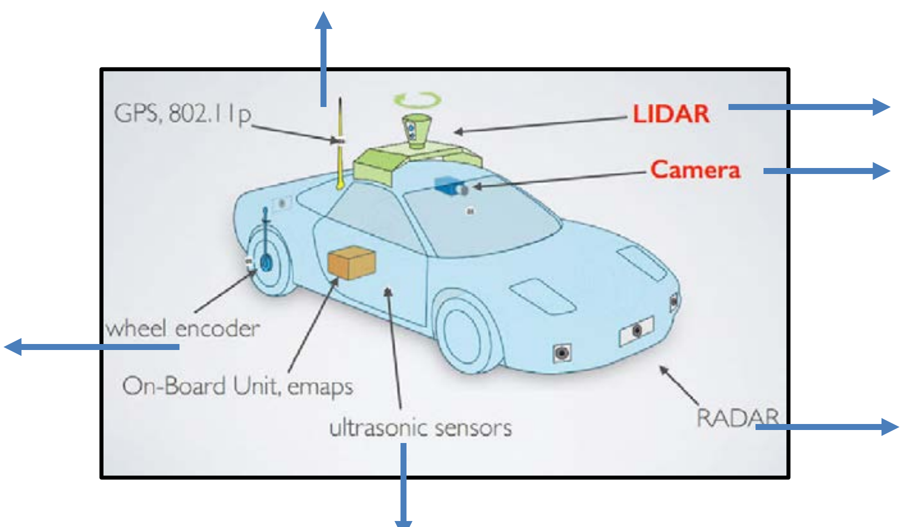
Principle 1: Environment Modeling -- Introspection and Action

#1: Introspective Environment Modeling

Impossible to model all possible scenarios

Approach: ***Introspect on System to Model the Environment***

<u>Identify:</u> (i) **Interface** between System & Environment,
(ii) (Weakest) **Assumptions** needed to Guarantee Safety/Correctness

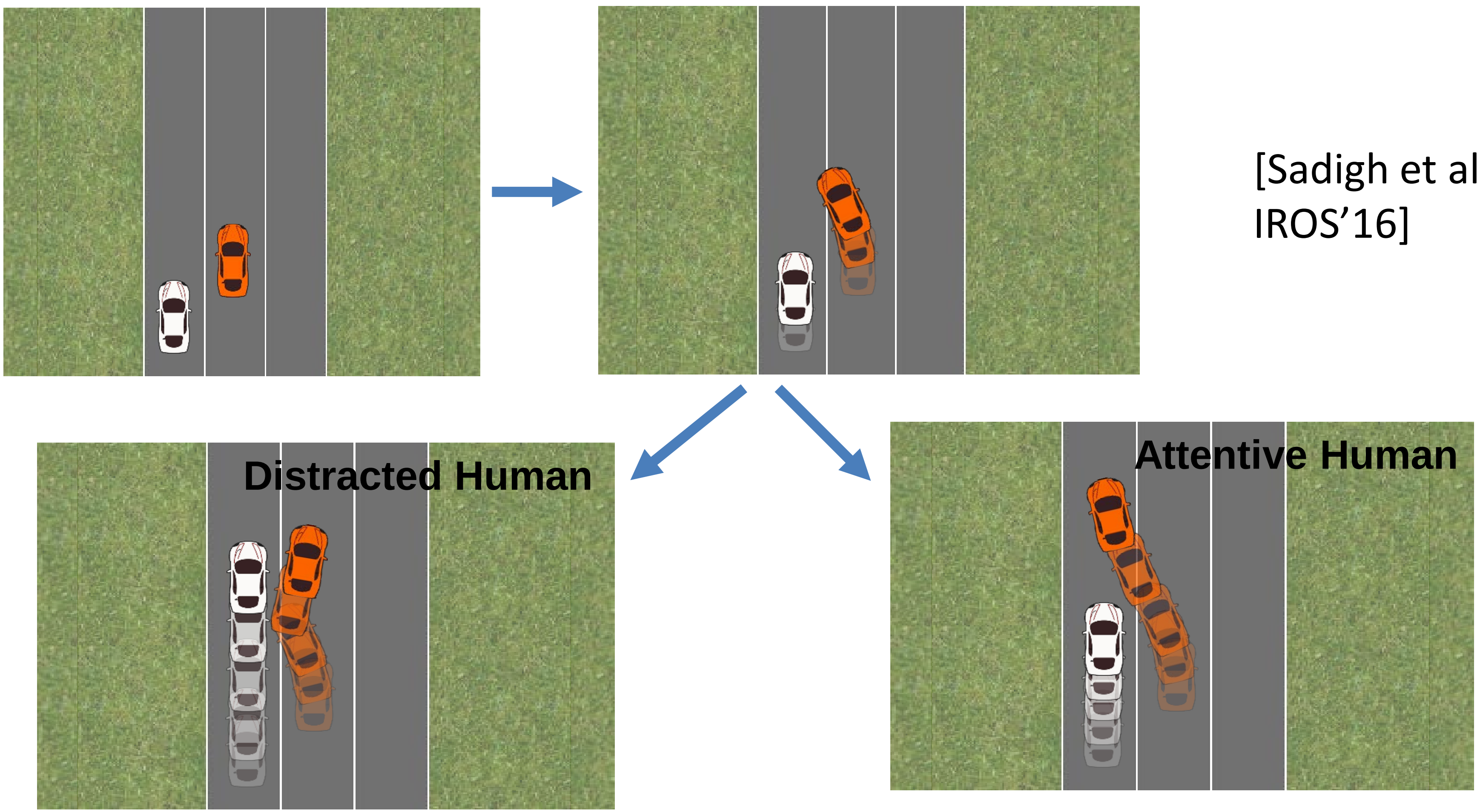


Algorithmic techniques to *generate weakest interface assumptions* and *monitor them at run-time* for potential violation/mitigation

[Li, Sadigh, Sastry, Seshia; TACAS'14]

#2: Active Data Gathering and Learning

Monitor and Interact with the Environment, Offline and Online, to Model It.



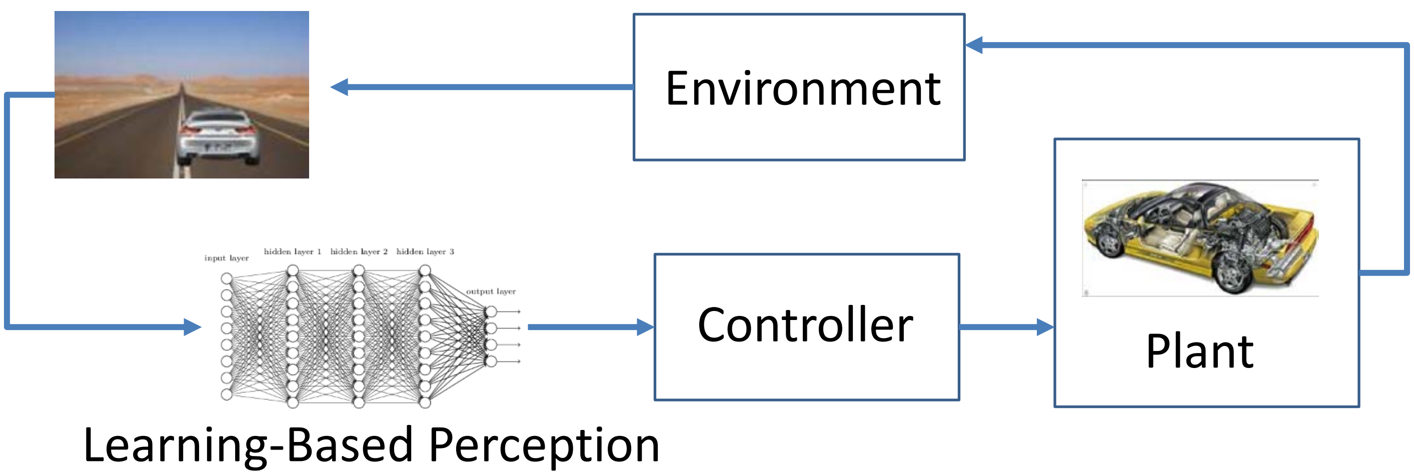
[Sadigh et al., IROS'16]

Principle 2: Formal Specification -- Go System Level

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

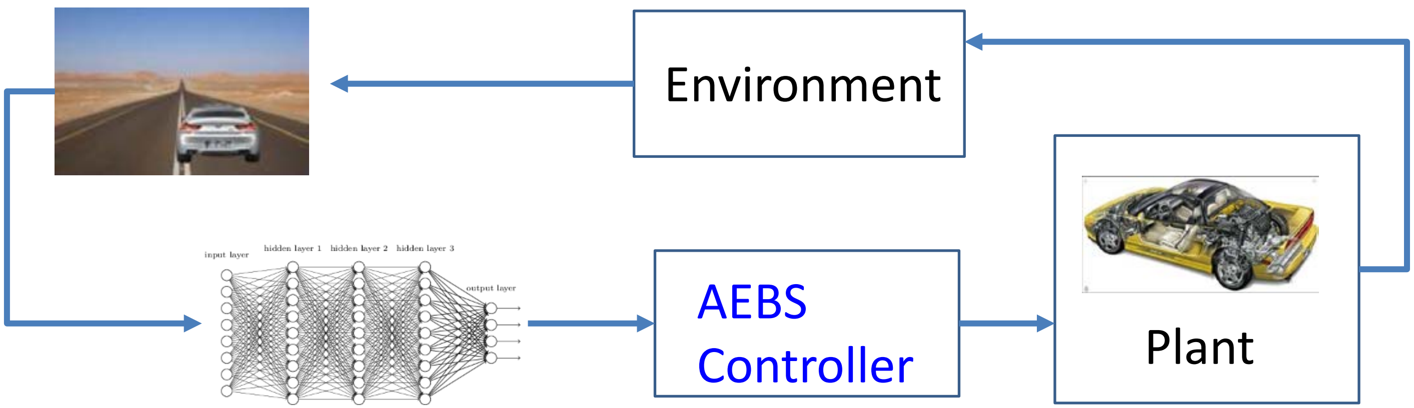


Spec: **G** (*dist*(ego vehicle, env object) > Δ)

Principle 3: Learning Systems Complexity -- Abstract and Explain

Principle 4: Efficient Training, Testing, and Verification -- Verification-Guided Analysis and Improvisation

The Problem: Verify Automatic Emergency Braking System (AEBS)

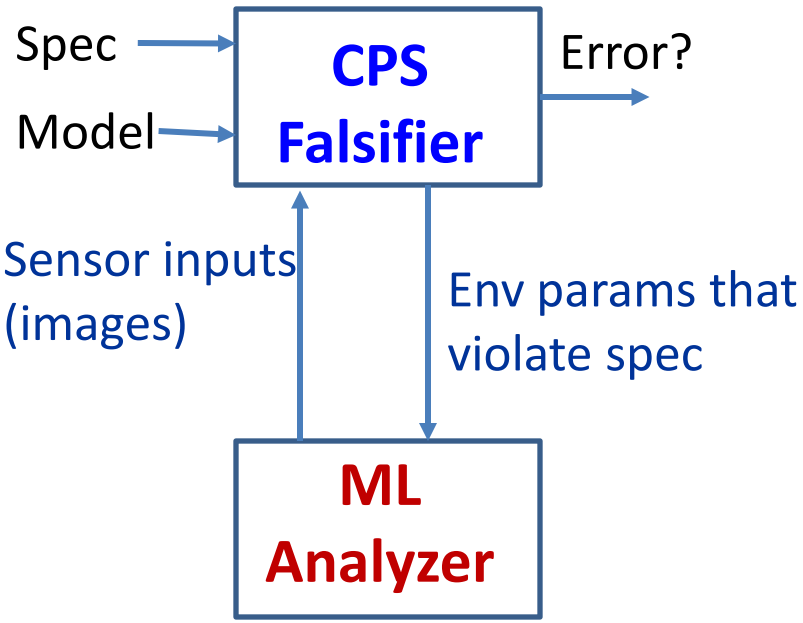


Deep Learning-Based Object Detection

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

- Controller, Plant, Env models in Matlab/Simulink
- Multiple Deep Neural Networks: Inception-v3, AlexNet, …

Our Approach: Combine Temporal Logic CPS Falsifier with ML Analyzer



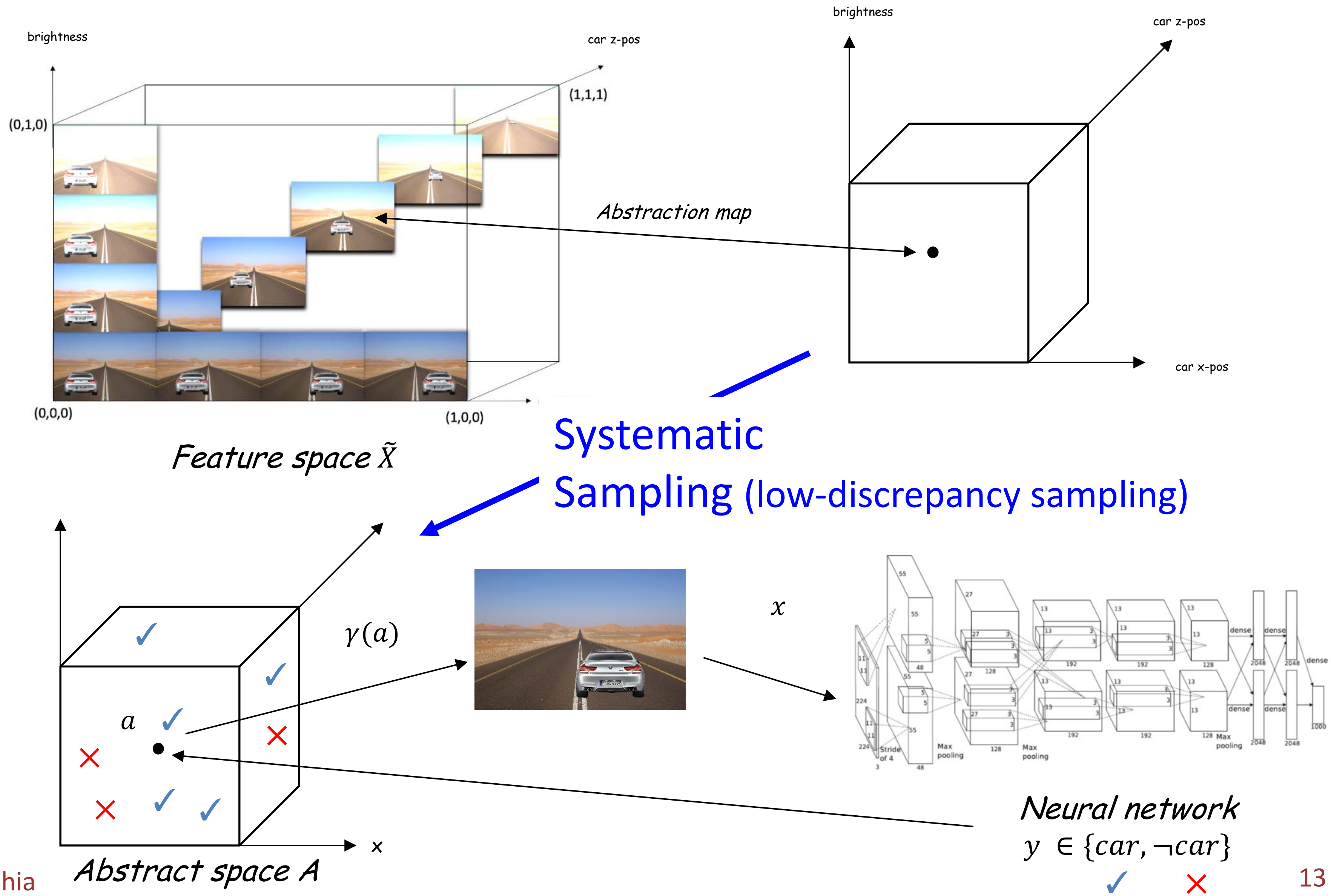
- CPS Falsifier uses abstraction of ML component
  - Optimistic analysis: assume ML classifier is always correct
  - Pessimistic analysis: assume classifier is always wrong
- Difference is the region of interest where output of the ML component “matters”

Compositional:

CPS Falsifier and ML Analyzer can be designed and run independently (& communicate)!

Machine Learning Analyzer

Systematically Explore Region of Interest in the Image (Sensor) Space



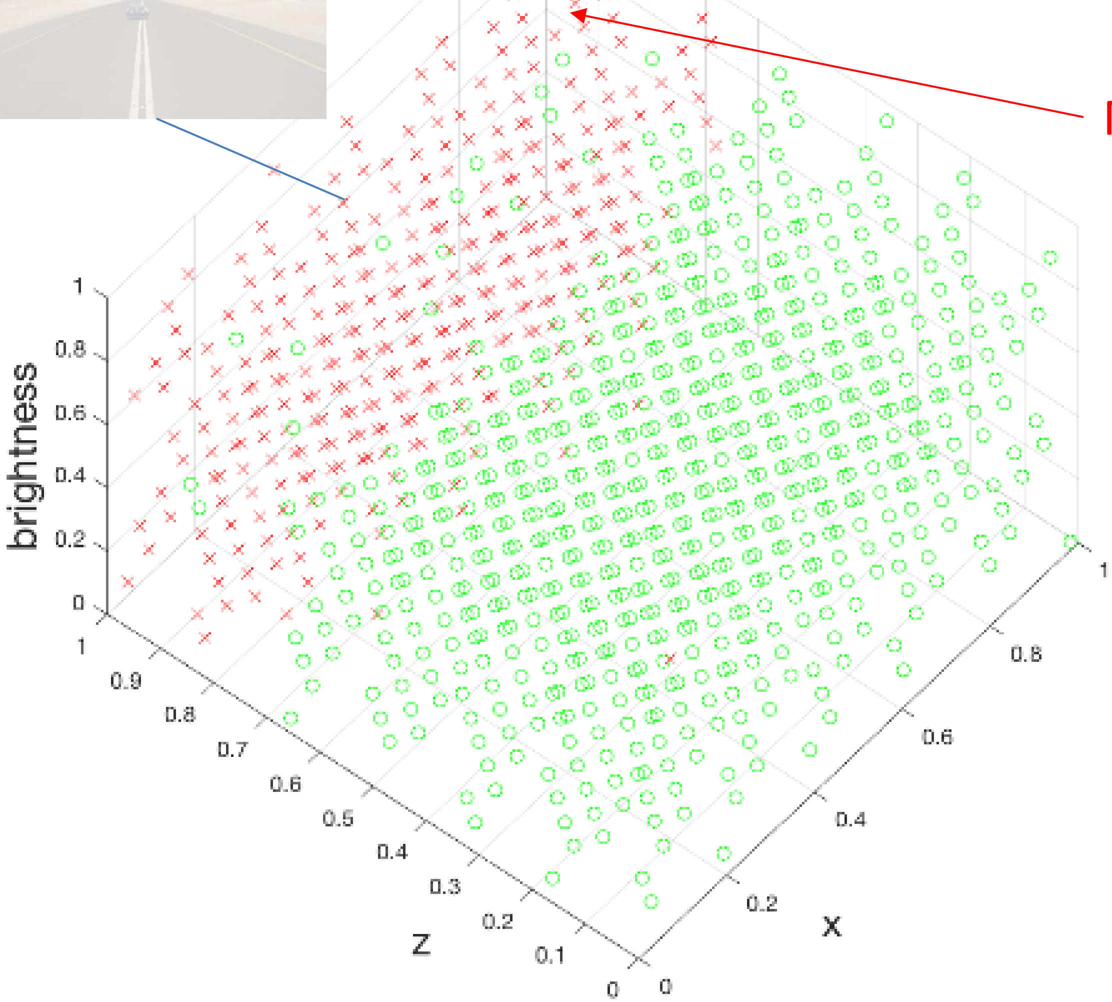
Sample Result

This misclassification may not be of concern

Inception-v3

Neural Network

(pre-trained on ImageNet using TensorFlow)

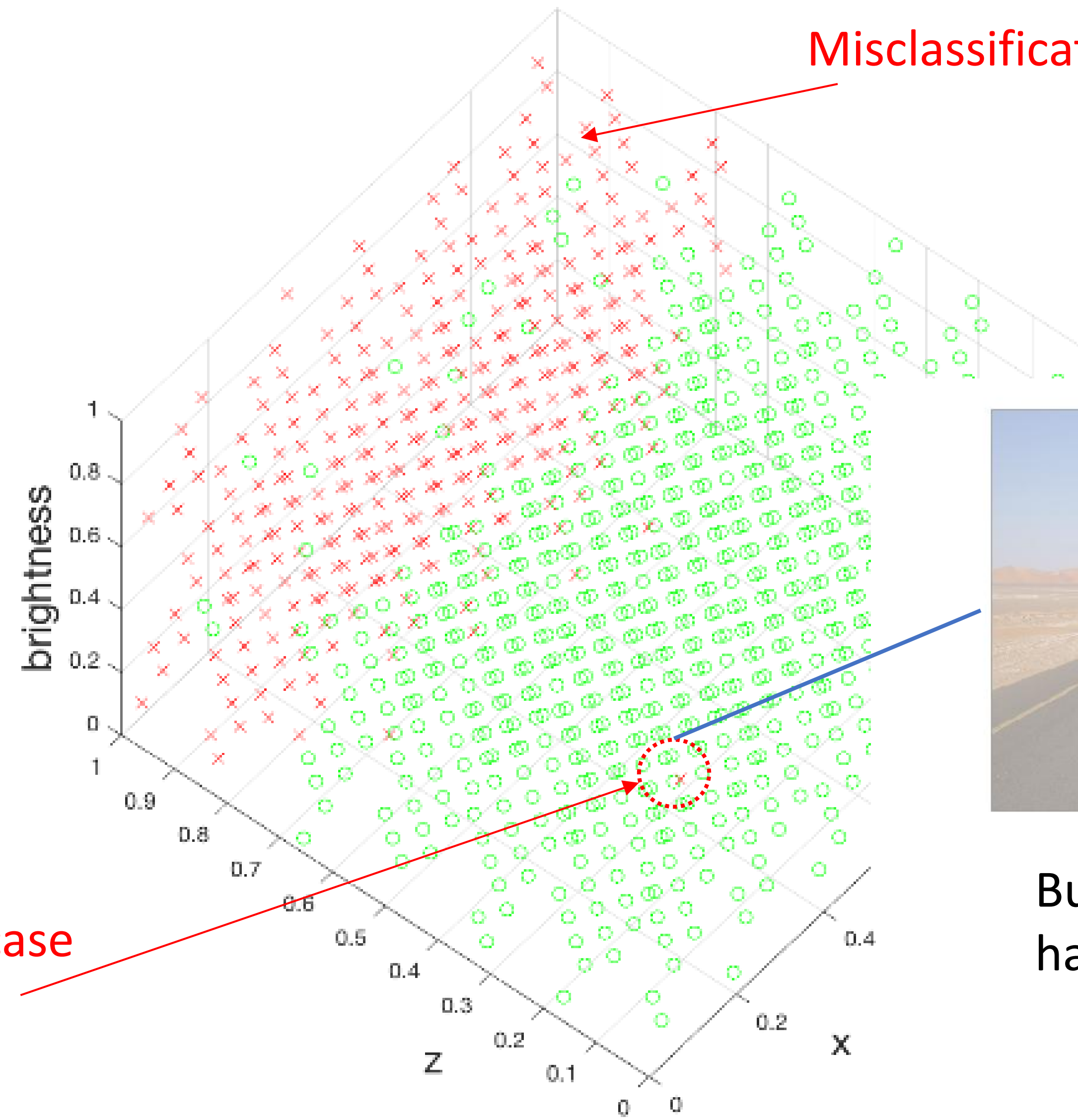


Misclassifications

Sample Result

Misclassifications

Inception-v3
Neural Network
(pre-trained on ImageNet using TensorFlow)



Corner case Image

But this one is a real hazard!

Principle 5: Correct-by-Construction -- Formal Inductive Synthesis

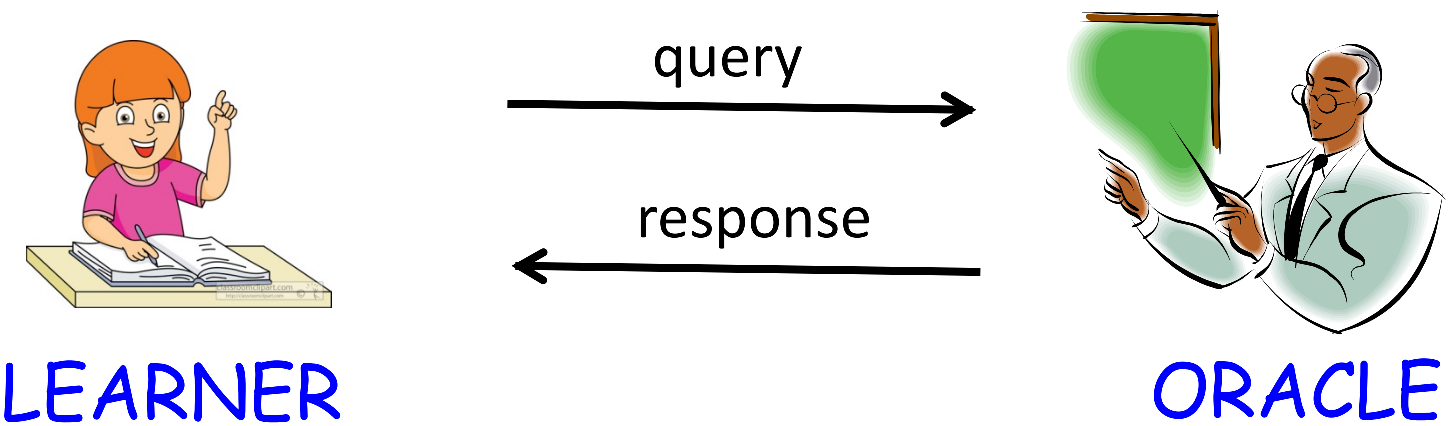
Correct-by-Construction Design with Formal Inductive Synthesis

Inductive Synthesis: Learning from Examples (ML)

Formal Inductive Synthesis: Learn from Examples *while satisfying a Formal Specification*

Key Idea: **Oracle-Guided Learning**

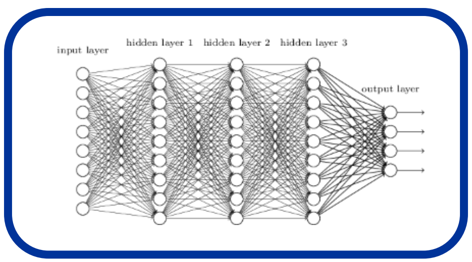
Combine Learner with Oracle (e.g., Verifier) that answers Learner's Queries



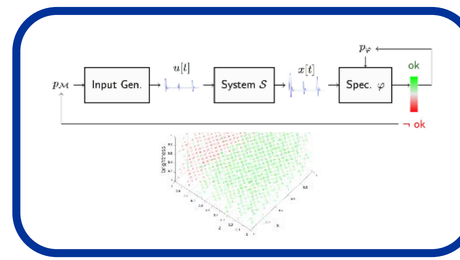
[Jha & Seshia, "A Theory of Formal Synthesis via Inductive Learning", 2015, Acta Informatica 2017.]

Verifier-Guided Training of Deep Neural Networks

- Instance of Oracle-Guided Inductive Synthesis
- Oracle is Verifier (CPSML Falsifier) used to perform counterexample-guided training of DNNs
- Substantially increase accuracy with only few additional examples



Learned Classifier



DEEP NEURAL NETWORK

FALSIFIER (CPS + ML)

Towards Verified Learning-based CPS

Challenges		Principles
1. Environment (incl. Human) Modeling	→	Data-Driven, Introspective Environment Modeling
2. Specification	→	System-Level Specification; Robustness/Quantitative Spec.
3. Learning Systems Complexity	→	Abstract & Explain
4. Efficient Training, Testing, Verification	→	Verification-Guided, Adversarial Analysis and Improvisation
5. Design for Correctness	→	Formal Inductive Synthesis

Exciting Times Ahead!!! Thank you!

S. A. Seshia, D. Sadigh, S. S. Sastry. *Towards Verified Artificial Intelligence*. July 2016. https://arxiv.org/abs/1606.08514.