Automated Testing of Cyber-Physical Systems

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Huawei Workshop

December 15, 2017

Acknowledgements

- Lionel Briand
- Raja Ben Abdessalem
- Reza Matinnejad
- Industry partners: IEE, SES and Delphi

Lionel

Raja

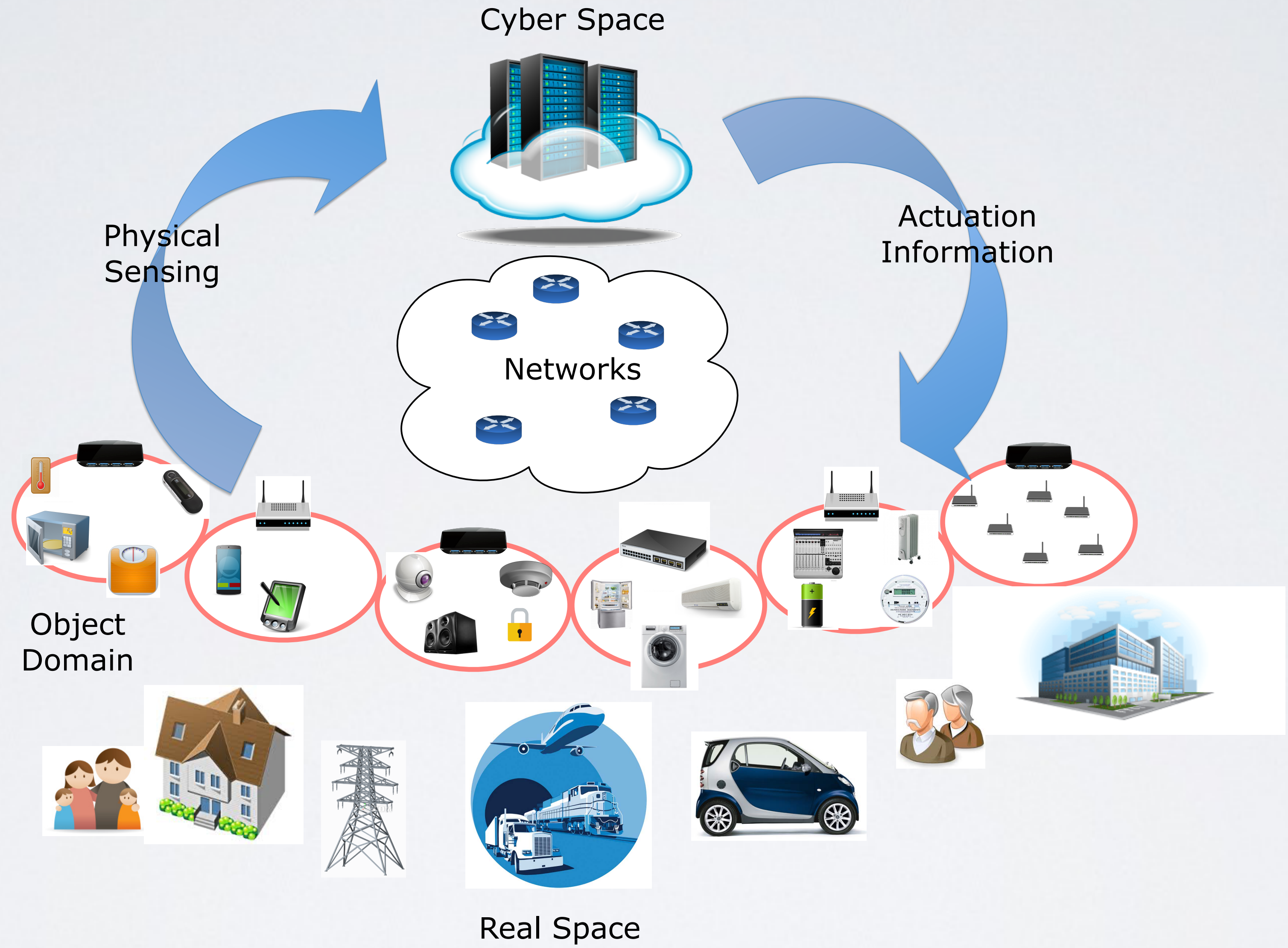
Reza

a sense for innovation IEE

SES beyond frontiers

DELPHI

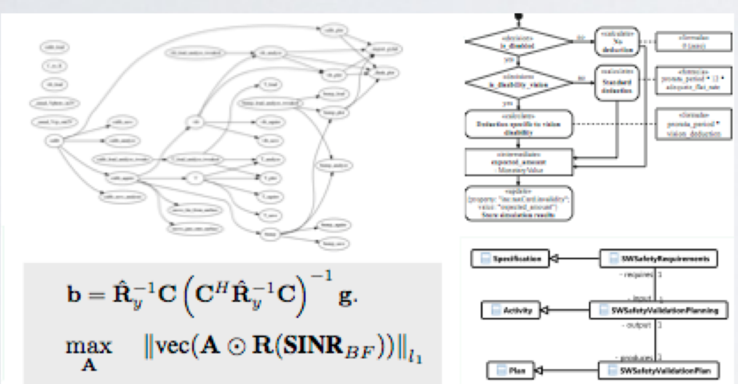
Cyber Physical Systems



Model-Based Development

CPS Model-Based Development

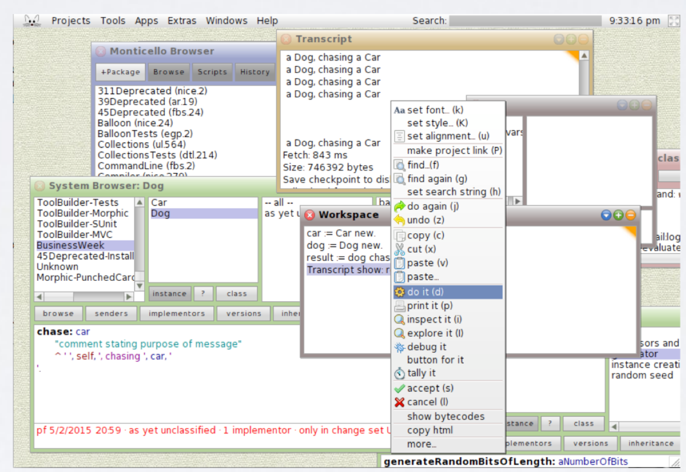
Model in the Loop
MiL



Function modeling (Matlab/Simulink)

- Controller
- Plant/Environment

Software in the Loop
SiL



Architecture modeling (C-Code/SysML)

- Real-time analysis
- Integration

Hardware in the Loop
HiL

Deployment (embedded-C)

- Testing (Expensive)

Model Testing

Design

Requirements

Models

Oracles

Do we find an error by **testing** models?

Fundamental Questions

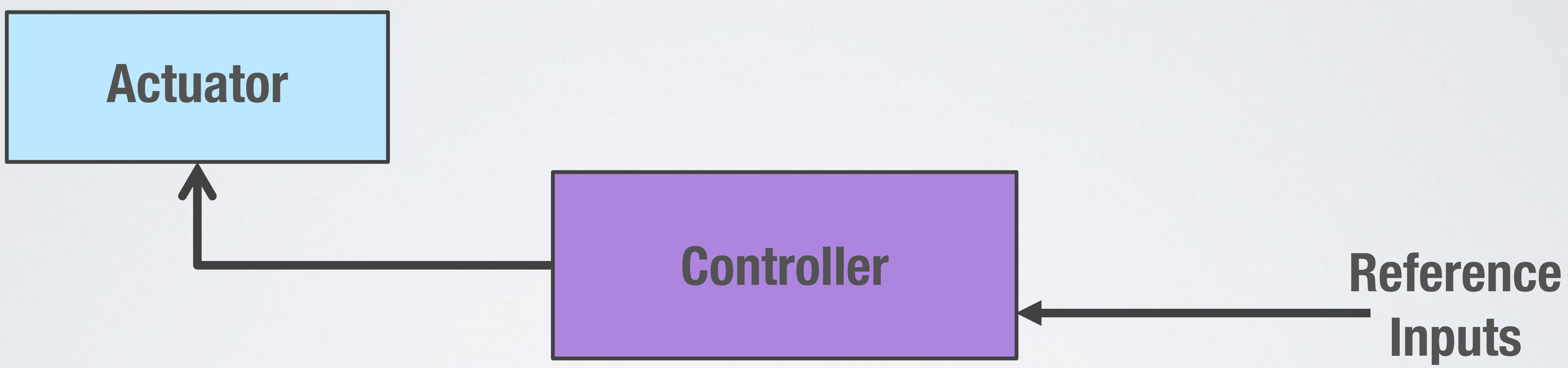
- What are the **useful and realistic models** of CPSs?
- How to **specify test oracles** to enable **effective testing of system requirements and design**?
- How to **design scalable testing** techniques?
  - Test case generation
  - Test case selection
  - Fault localization

ARTIFICIAL INTELLIGENCE

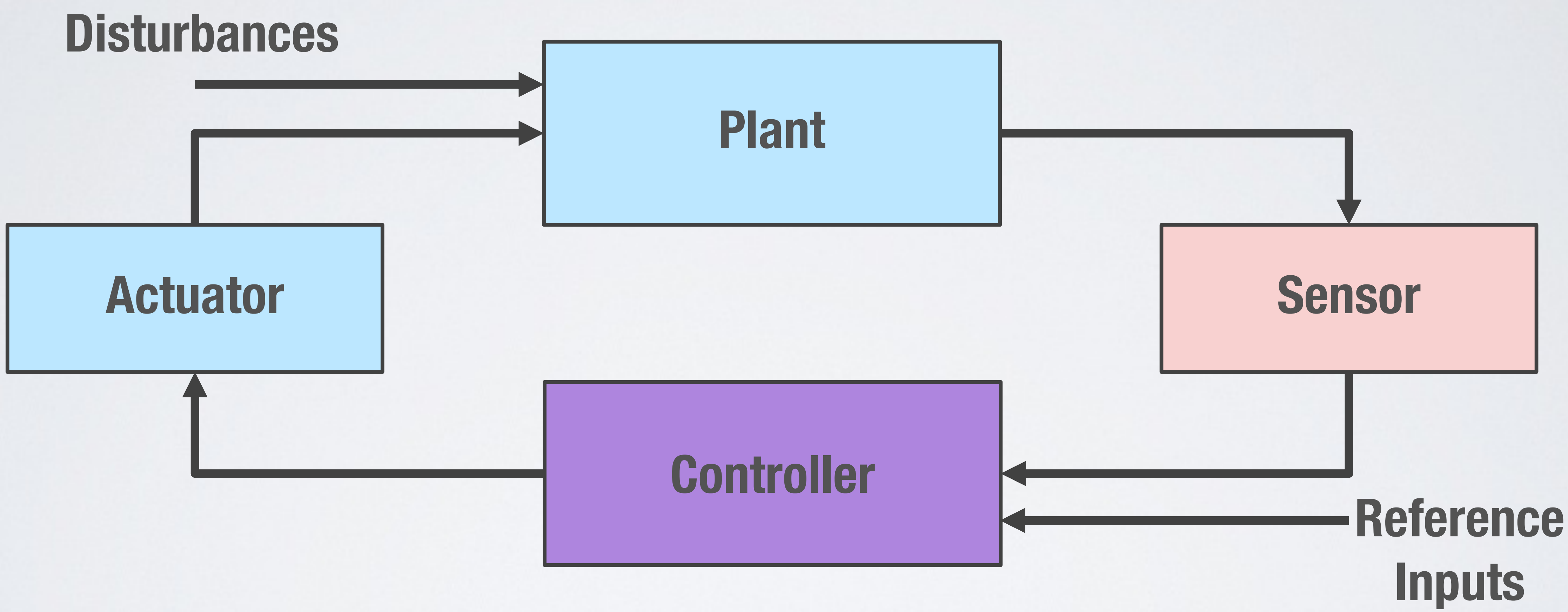
CPS Models

- have **dynamic** behaviors
- are **executable**
- are **hybrid** – capture both discrete (algorithms) and continuous (physical dynamics) computations
- exhibit **uncertainty** e.g., about the environment

Open Loop Controllers

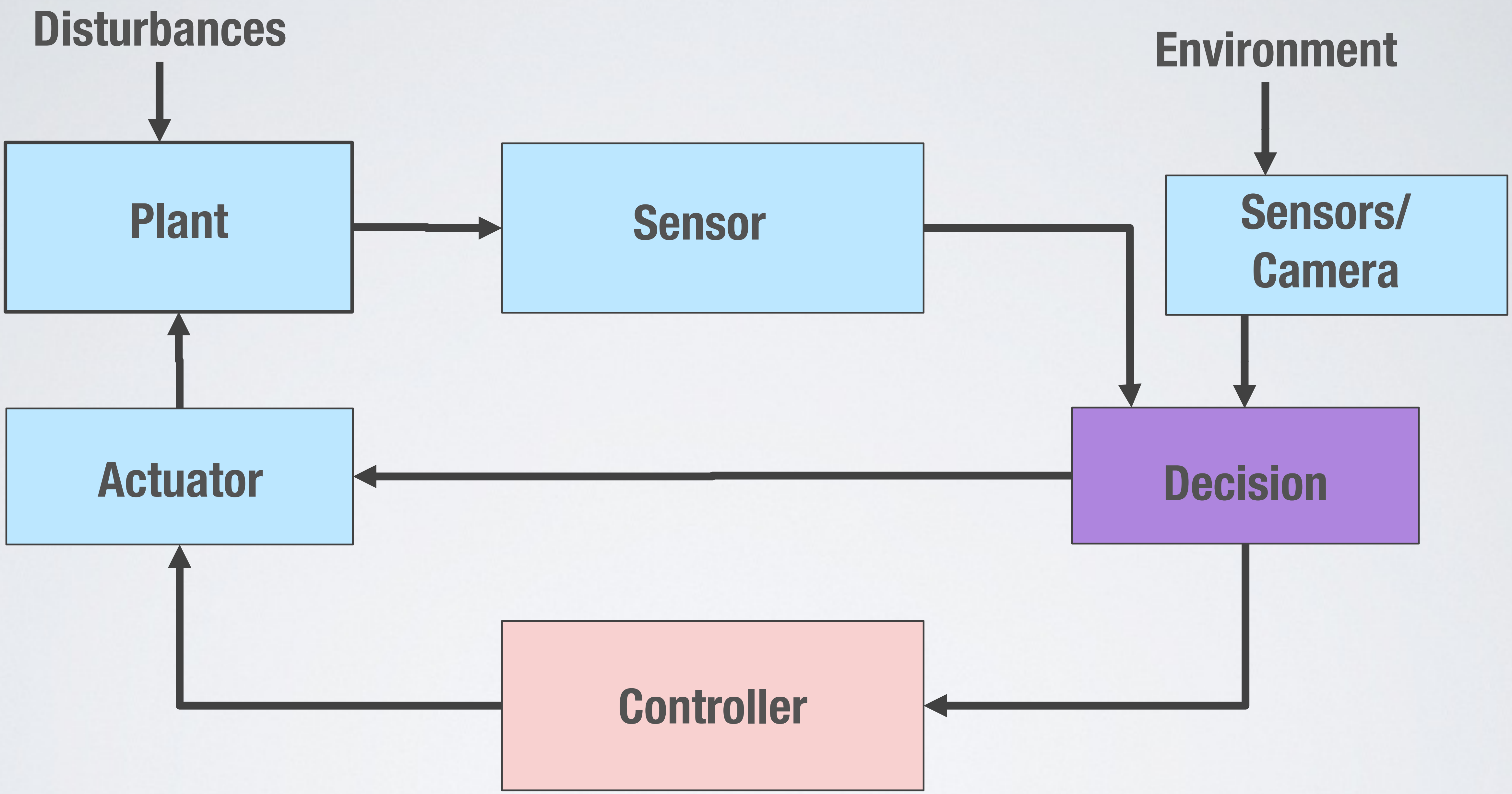


Closed Loop Controllers



Controllers + Plants

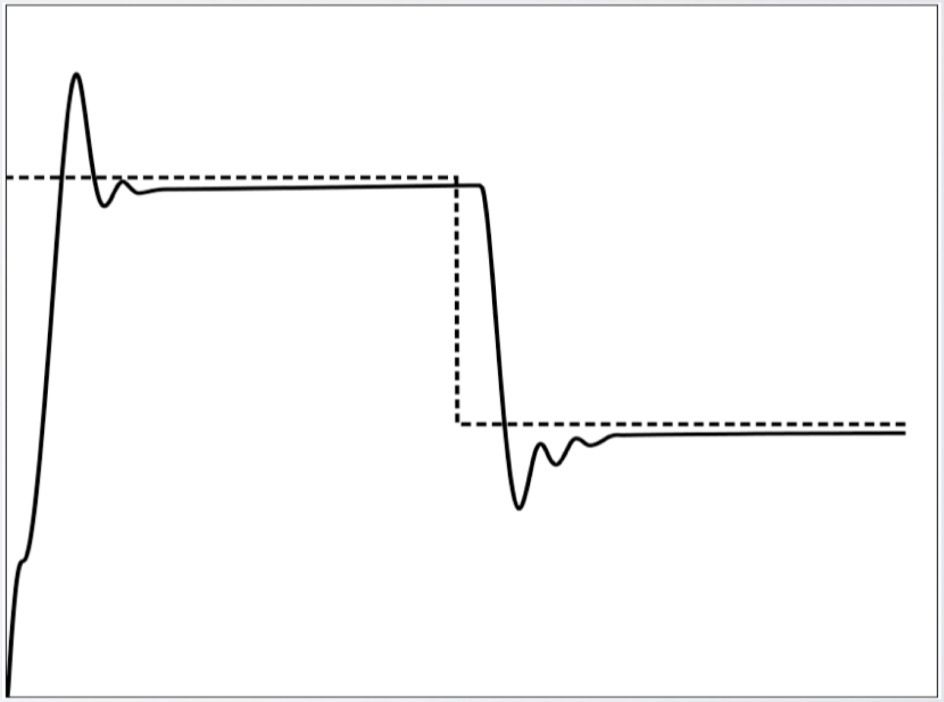
Autonomous Controllers



Controllers + Plants + Decision

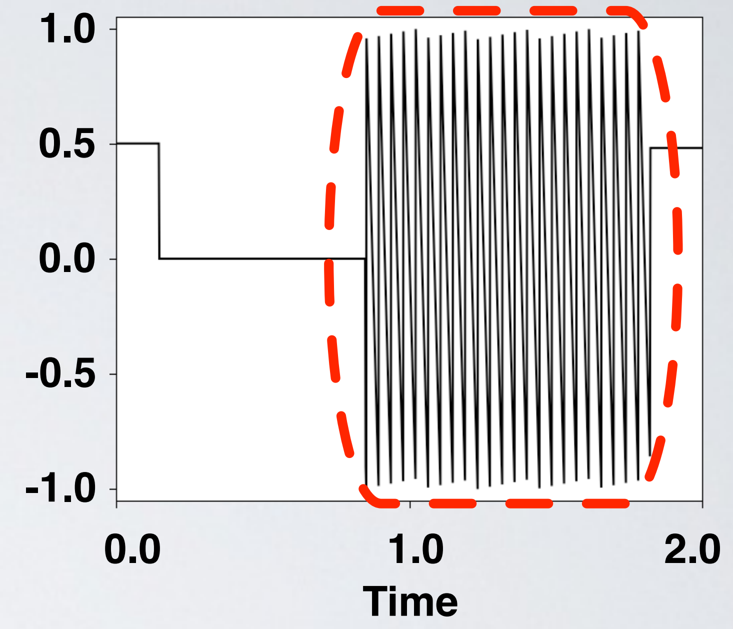
CPS Test Oracles

- System outputs are **signals**
  - Engineers inspect changes in outputs over continuous time periods
- Test oracles
  - may be **heuristic** or **partial**
  - are often **quantitative** and not binary
  - might be **effort-intensive** or difficult to **automate**

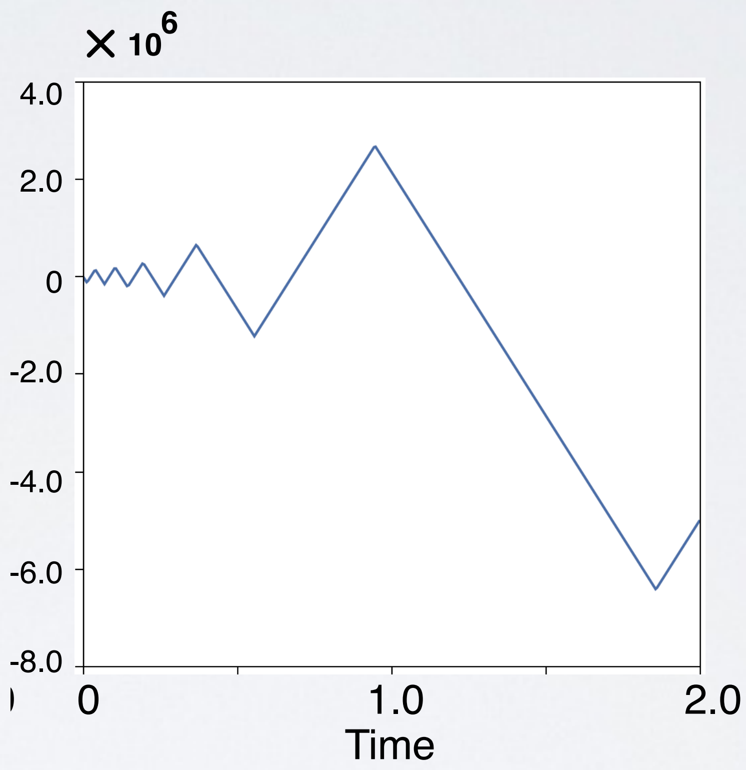


Anti Patterns– Partial Oracles

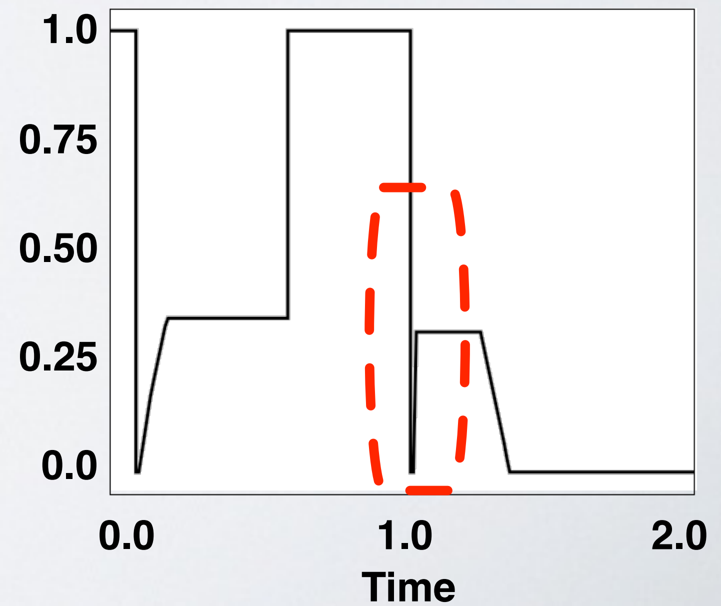
- Instability



- Growth to infinity

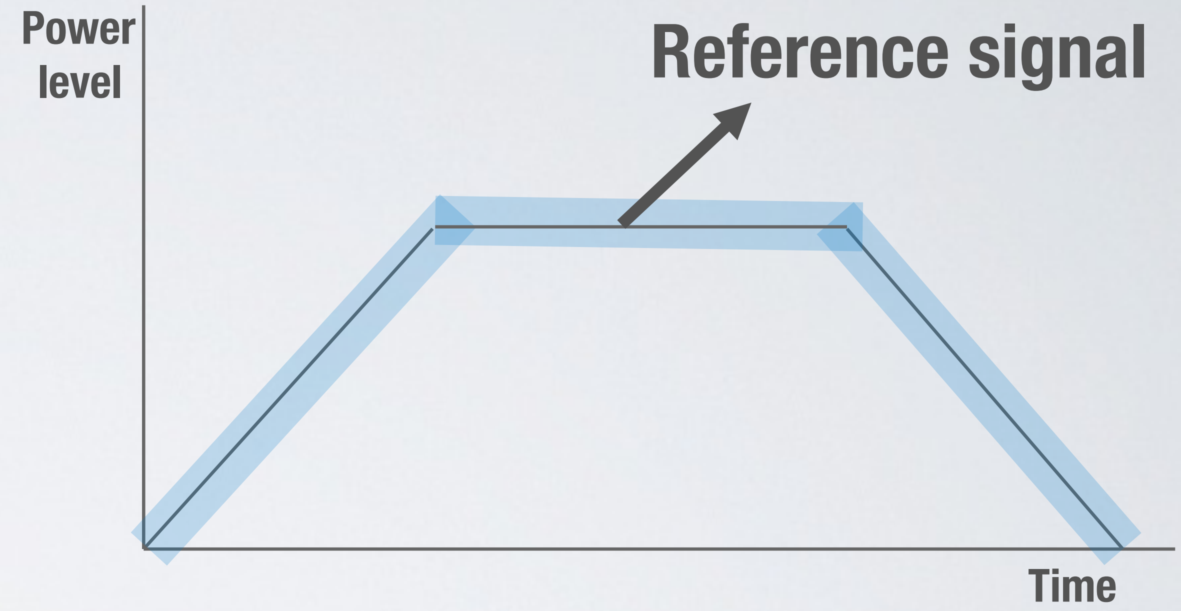


- Discontinuity

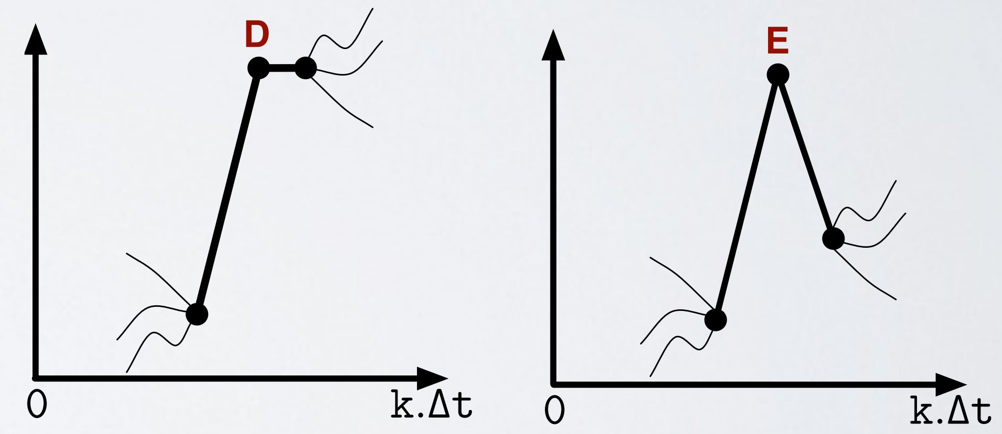


Application Specific Oracles

- A reference signal + error margin



- (Sequences of) Signal features



- Temporal properties: ``The system response should occur within 32ms''

CPS Testing Challenges

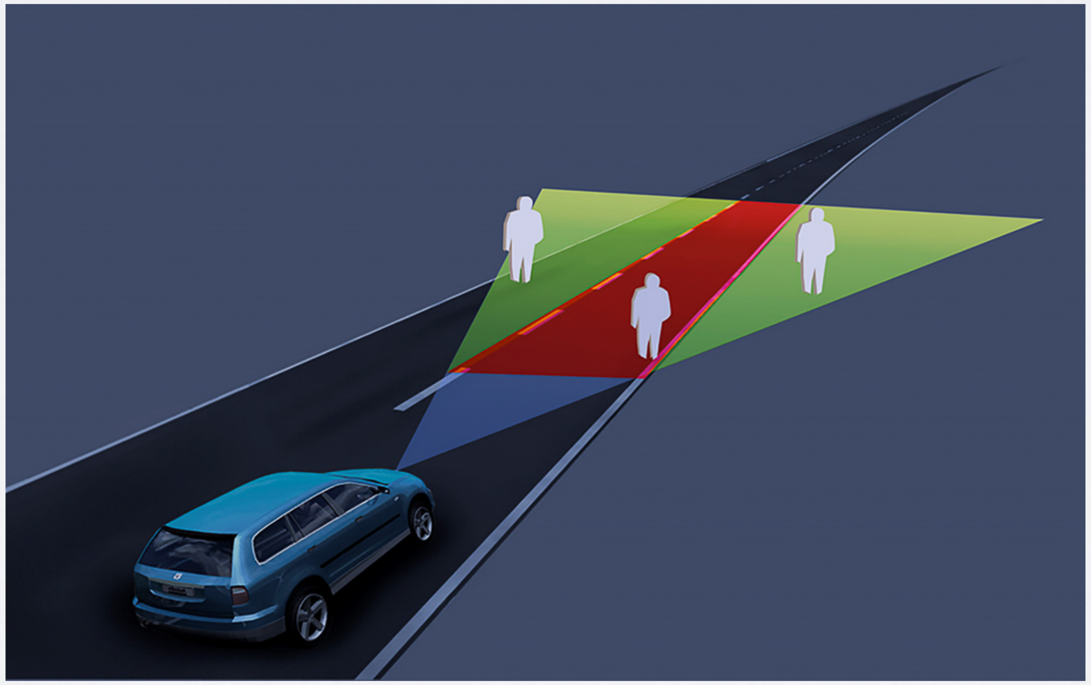
- Test input space is **large** and **multi-dimensional**
- Model executions are **time consuming**
- **Fault localization** is difficult
- **Limited time budget** for testing
  - Test oracles are expensive
  - Running the test cases on HiL is expensive

Our Solutions

Challenges	Our solution
Test input space is large	**Metaheuristic search** to identify **worst case/critical behaviors**
Simulation takes time	**Surrogate models** to predict the simulation outcome **without running** simulations
Fault localization is difficult	**Classification techniques** to **explain** system failures
Expensive HiL Testing	**Test case prioritization** using **multi-objective** search

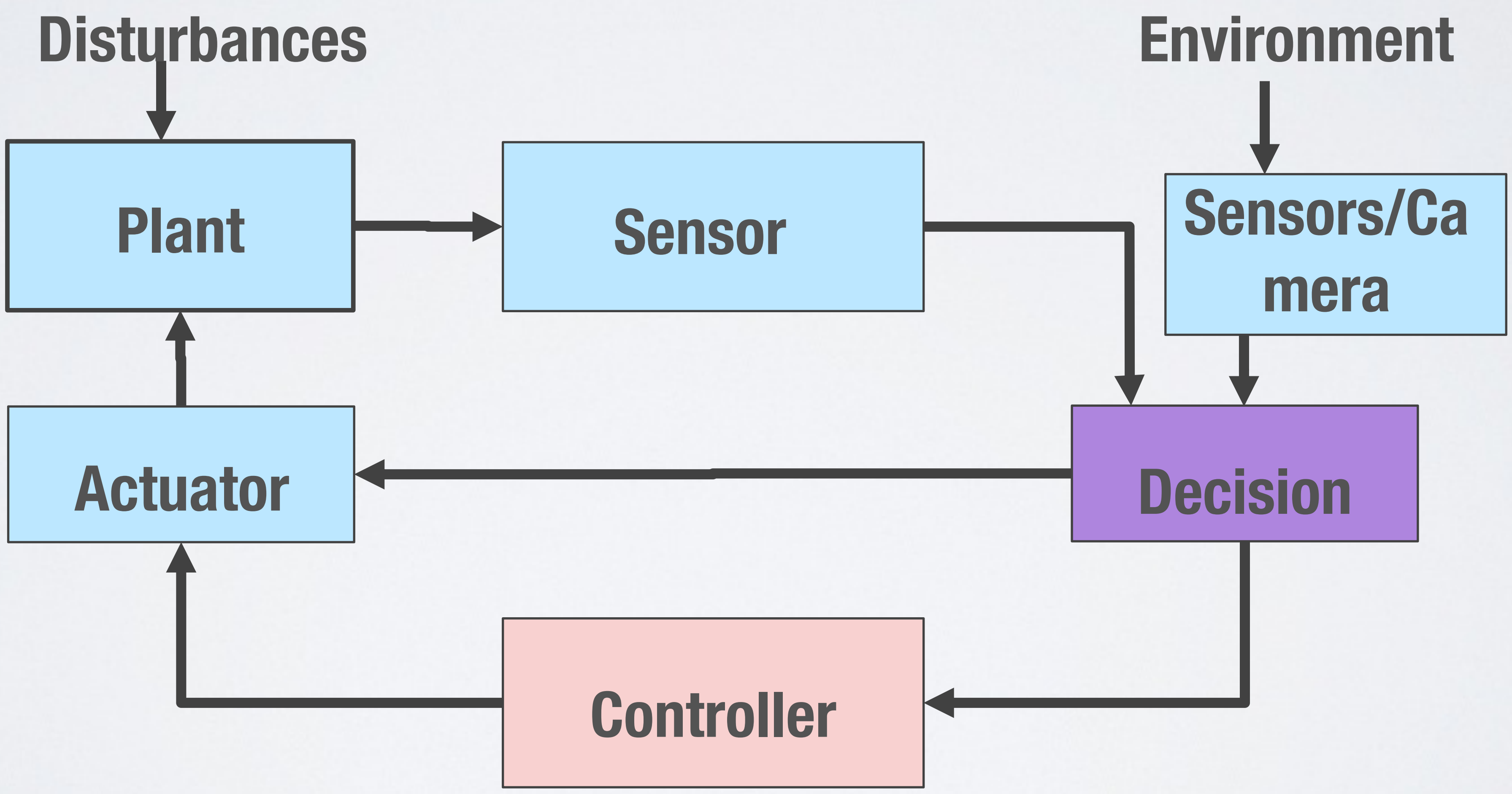
Example Projects

Testing Advanced Driver Assistance Systems



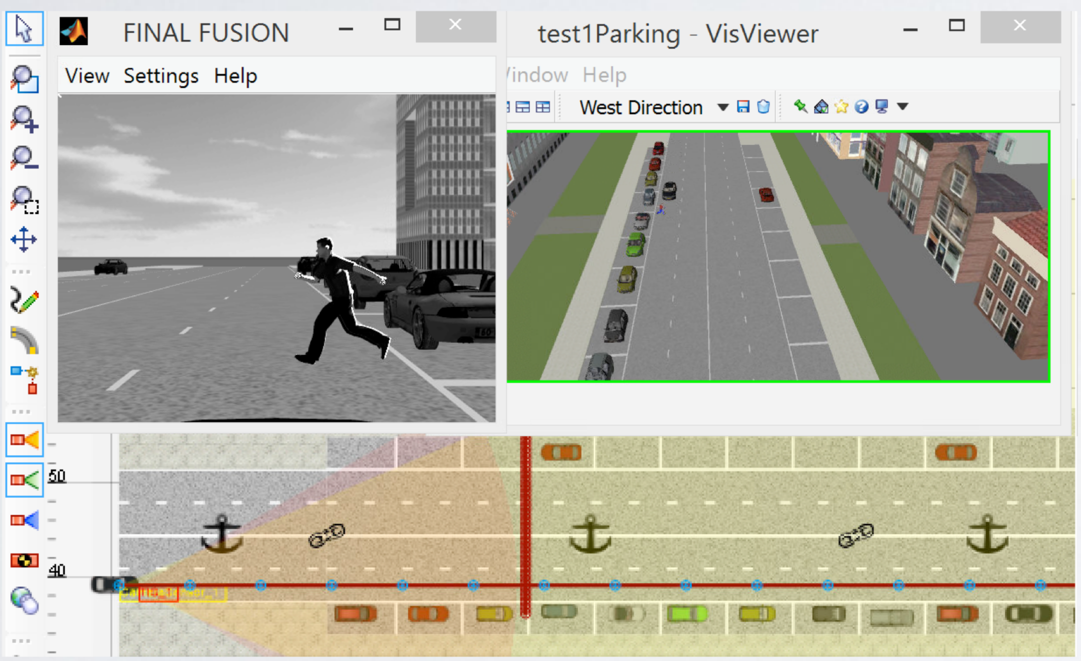
Advanced Driver Assistance Systems (ADAS)

Decisions are made over time based on sensor data



Testing Advanced Driver Assistance Systems (self-driving cars)

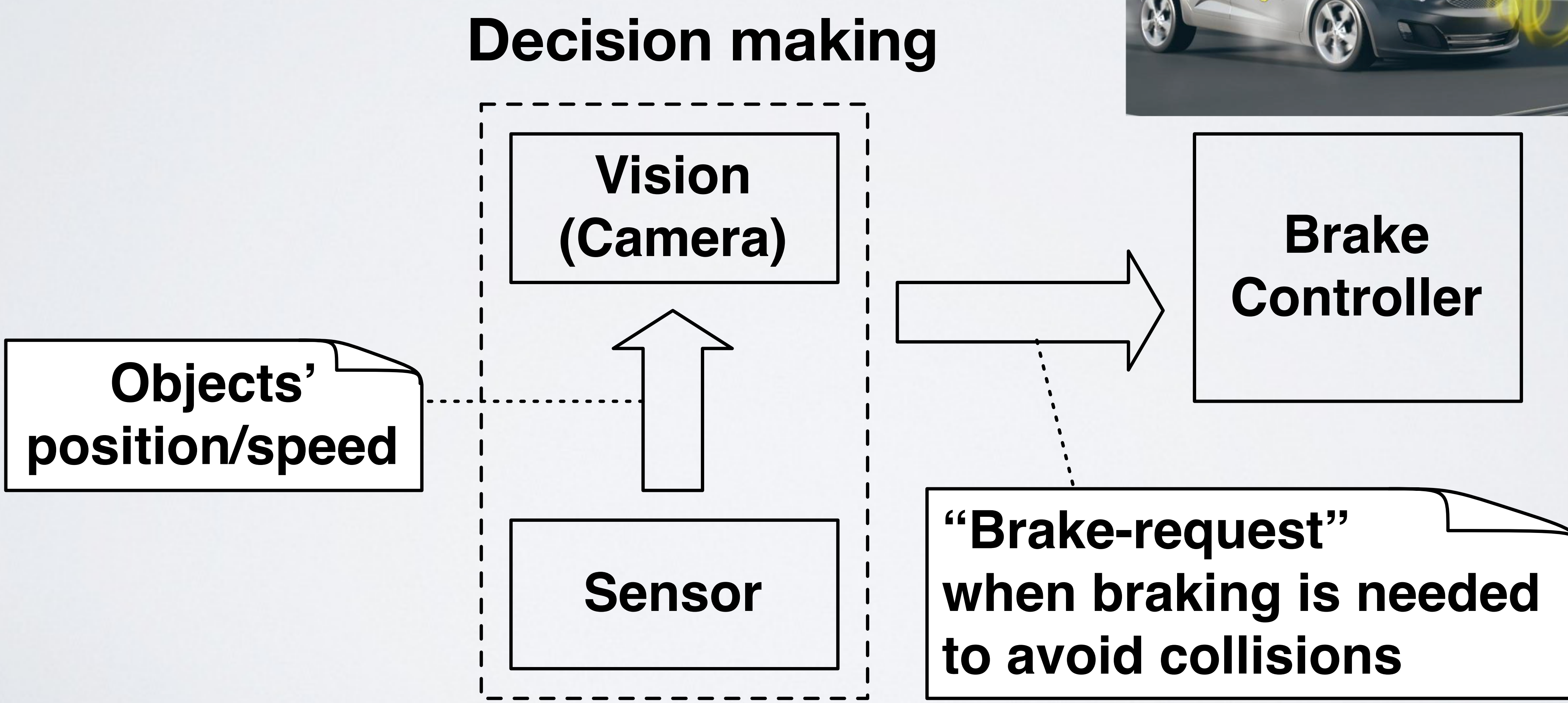
Models -- A simulator based on Physical/Mathematical models



Oracles -- description of crashes

- Test generation based on **meta-heuristic** search
- **Surrogate** modeling to speed up search
- **Classification** to help with fault localization

Automated Emergency Braking System (AEB)



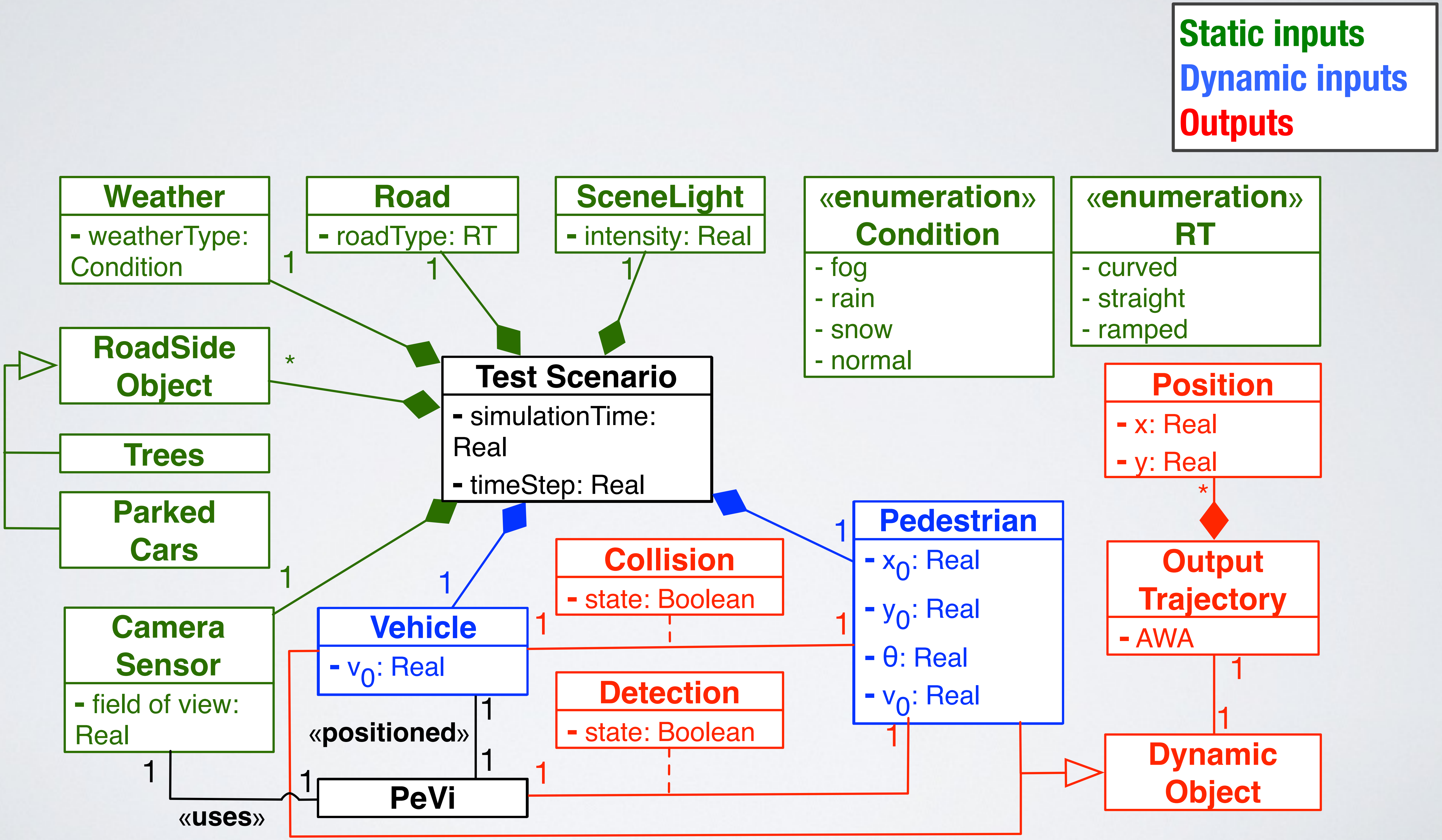
Physics-Based Simulations

AEB Critical Behavior -- Oracle

Example:

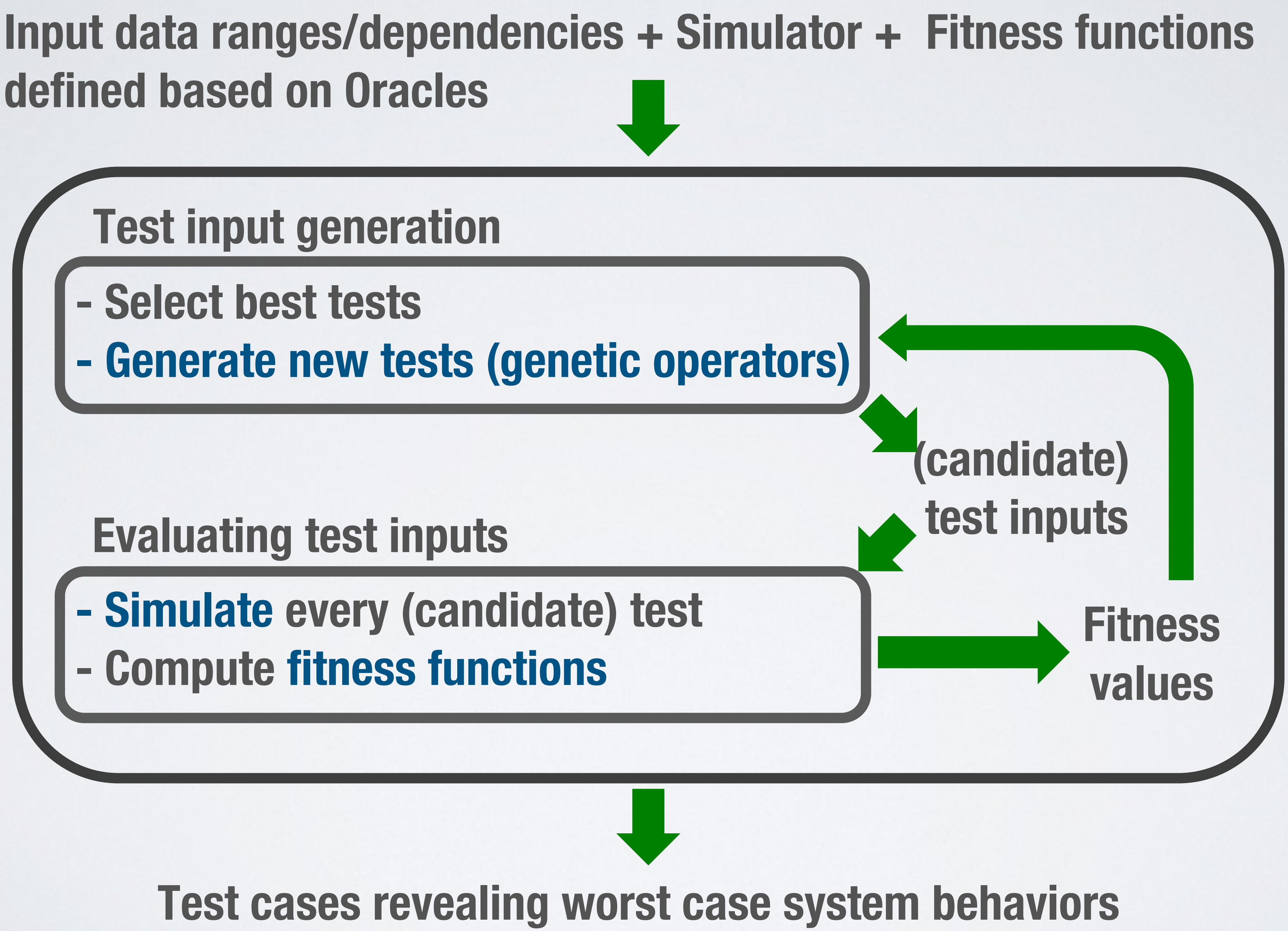
CB: "AEB detects a pedestrian in front of the car with a high degree of certainty, but an accident happens where the car hits the pedestrian with a relatively high speed"

Input/Output Specification



Generating Critical Test Scenarios via Metaheuristic Search

Black-Box Search-based Testing



An example critical scenario

Improving Search Time Performance via Surrogate (Prediction) Models

Improving Time Performance

- Individual simulations take on average around 1min
- It takes 8 hours to run our search-based test generation (≈ 500 simulations)

➔We use **surrogate modeling** to improve the search

- **Goal:** Predict fitness based on dynamic variables
- Neural networks

Surrogate Modeling

Input data ranges/dependencies + Simulator + Fitness functions defined based on Oracles

Test inpu

- Select b
- Generat

Evaluati

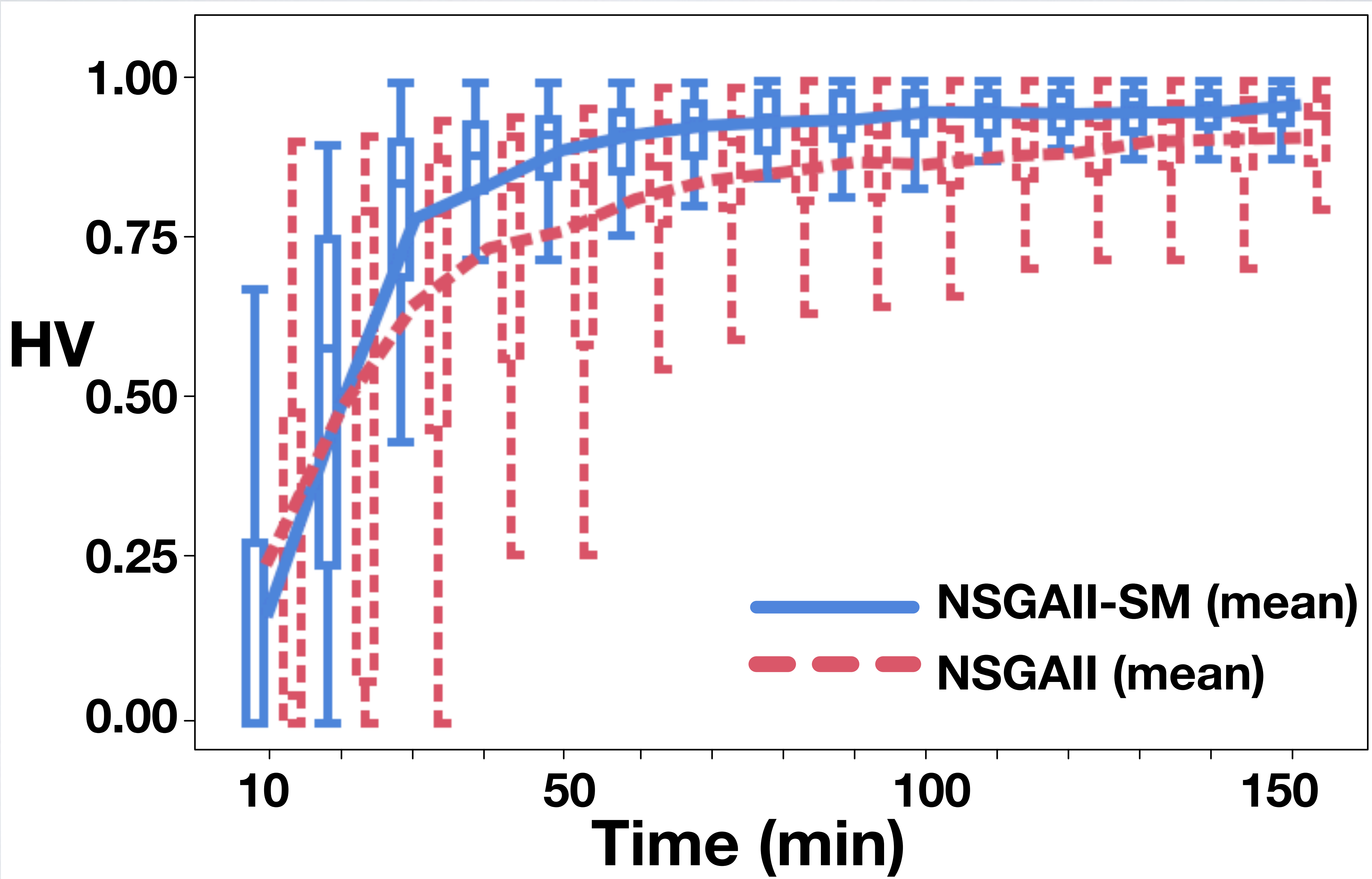
- **Simulate** every (candidate) test
- Compute fitness functions

Fitness values

Uses prediction values & prediction errors to run simulations only for the solutions likely to be selected

Test cases revealing worst case system behaviors

Results – Surrogate Modeling



Guiding Search via Classification Models

Search Guided by Classification

Input data ranges/dependencies + Simulator + Fitness functions defined based on Oracles

Test input generation

Build a classification tree
Select/generate tests in the fittest regions
Apply genetic operators (Optional)

(candidate) test inputs

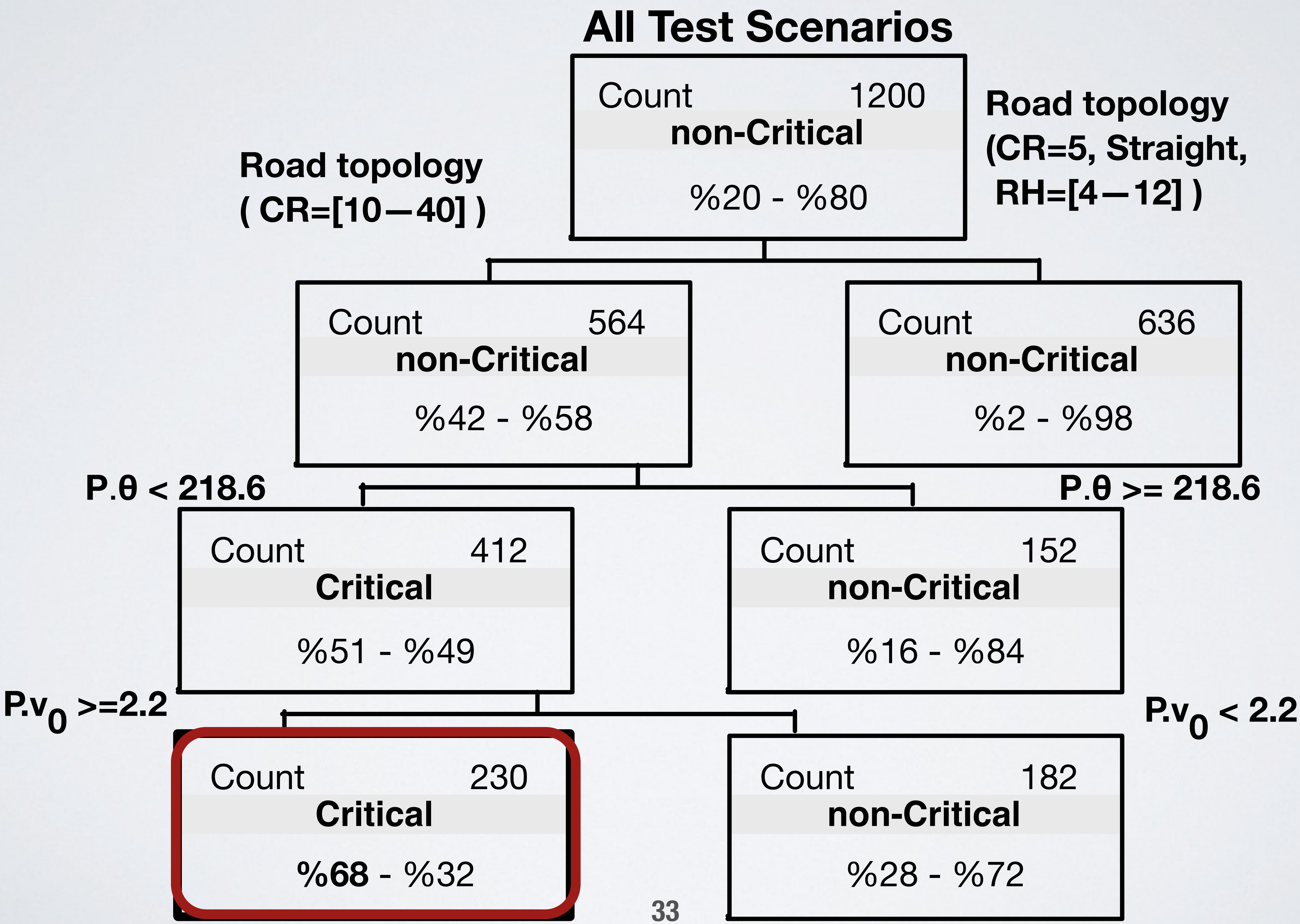
Evaluating test inputs

- Simulate every (candidate) test
- Compute fitness functions

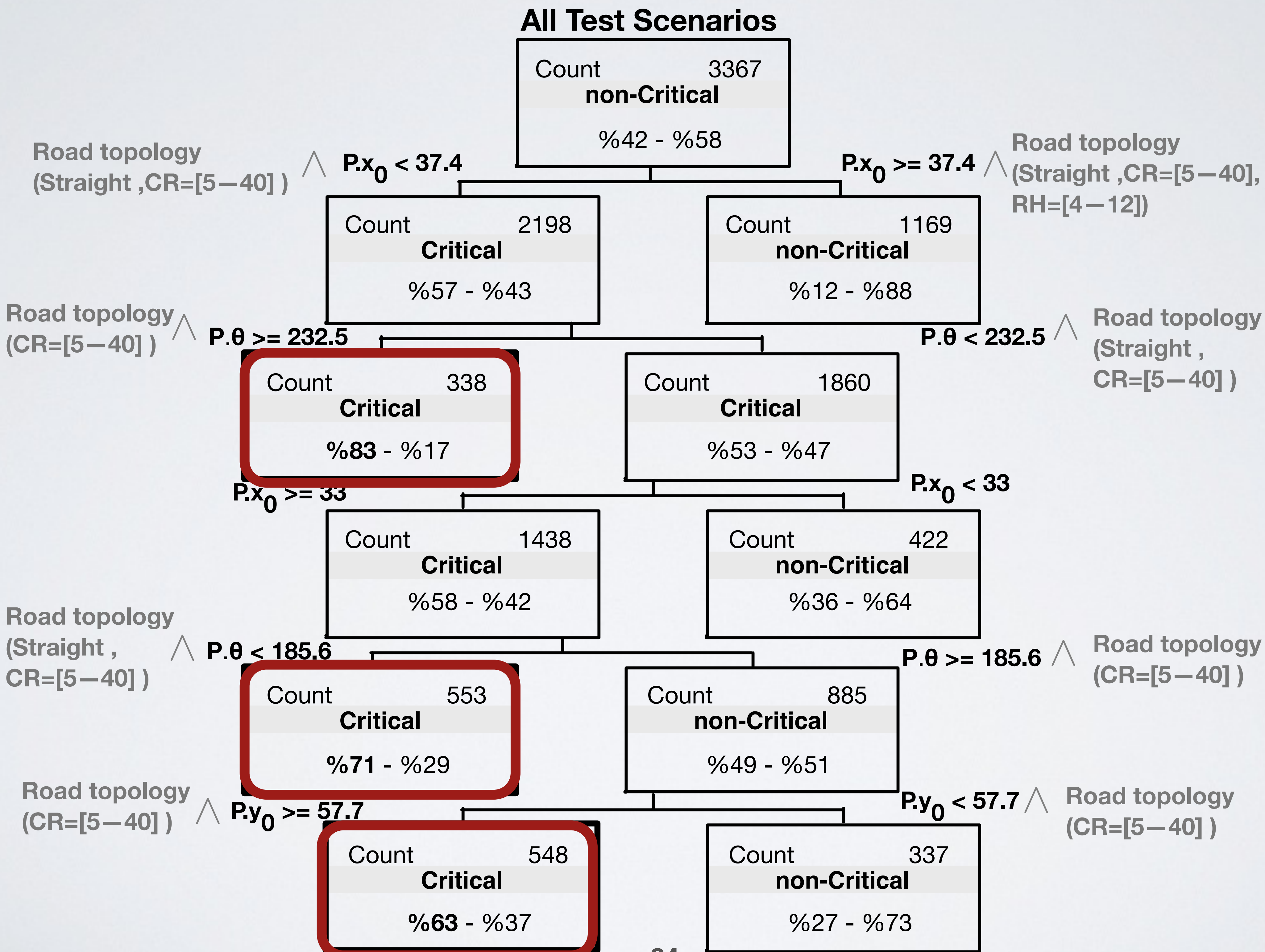
Fitness values

Test cases revealing worst case system behaviors +
A characterization of critical input regions

Initial Classification Model



Refined Classification Model

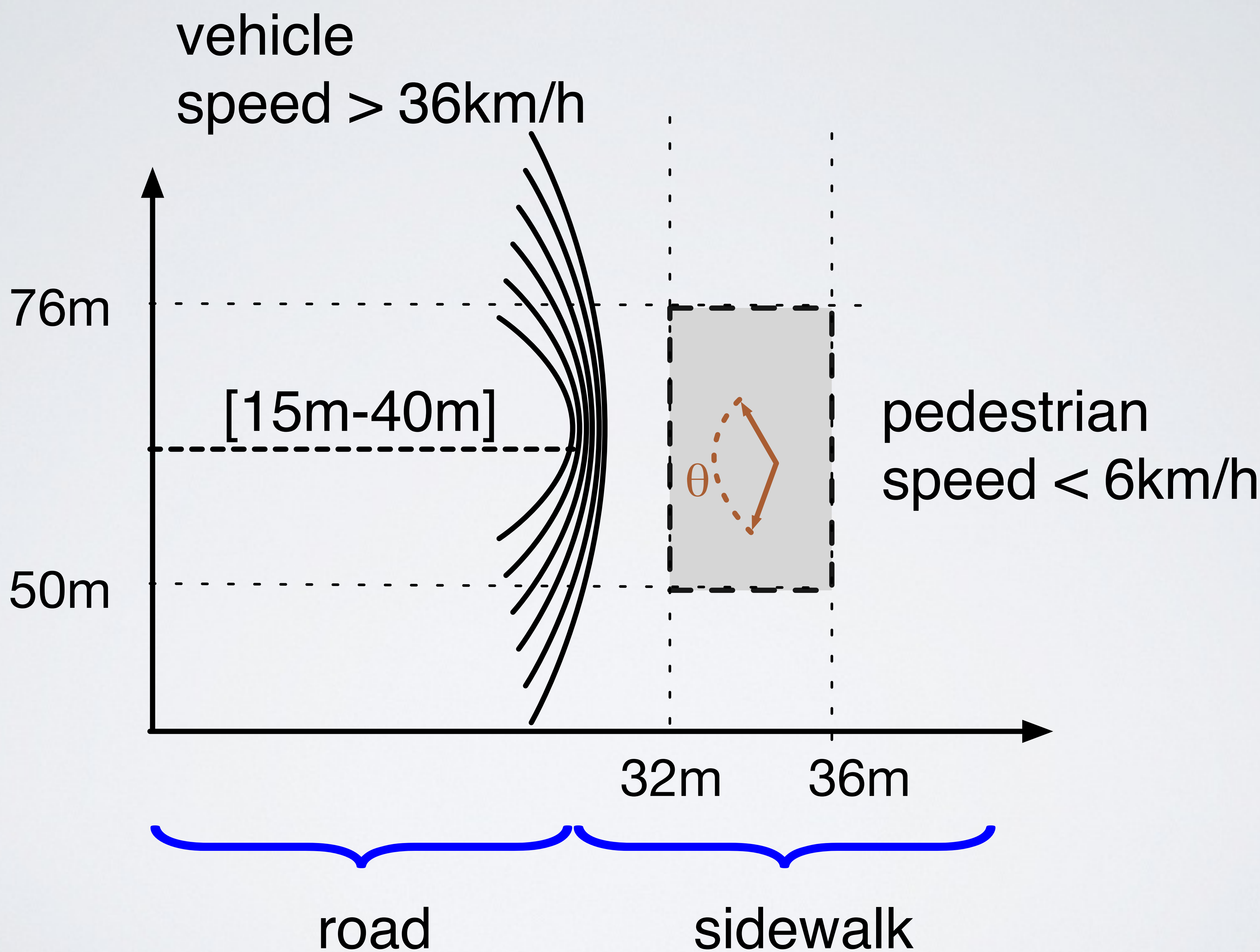


Outputs of Our Approach

- **Failure Detection**
  - (Search + Classification) generates 78% more **distinct, critical test scenarios** compared to a baseline search algorithm

- **Failure Explanation**
  - A characterization of the input space showing under what input conditions the system is likely to fail
  - Visualized by diagrams or regression trees

Failure Explanation



Usefulness

The characterizations of the different critical regions can help with:

(1) **Debugging** the system or the simulator

(2) **Identifying hardware changes** to increase ADAS safety

(3) **Identifying proper warnings** to drivers

Other Project Examples

Automotive Systems

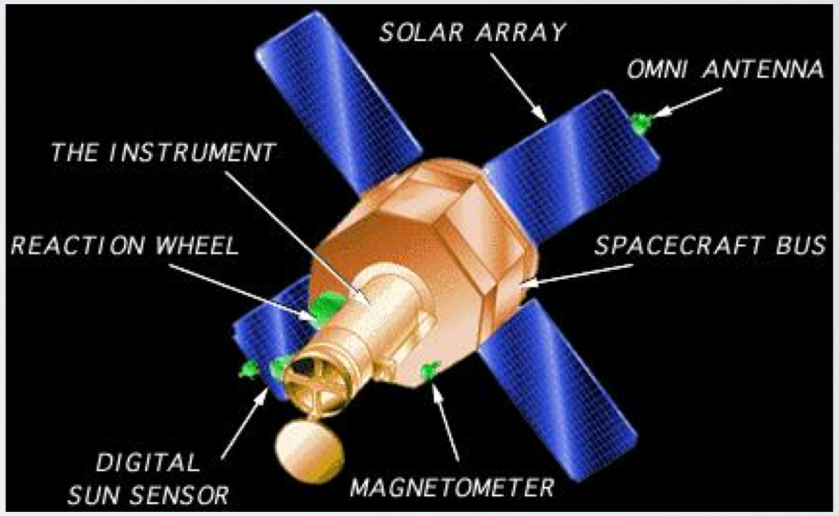
- Testing controller implemented in Simulink

- Analysis of CPU time usage in ECU software

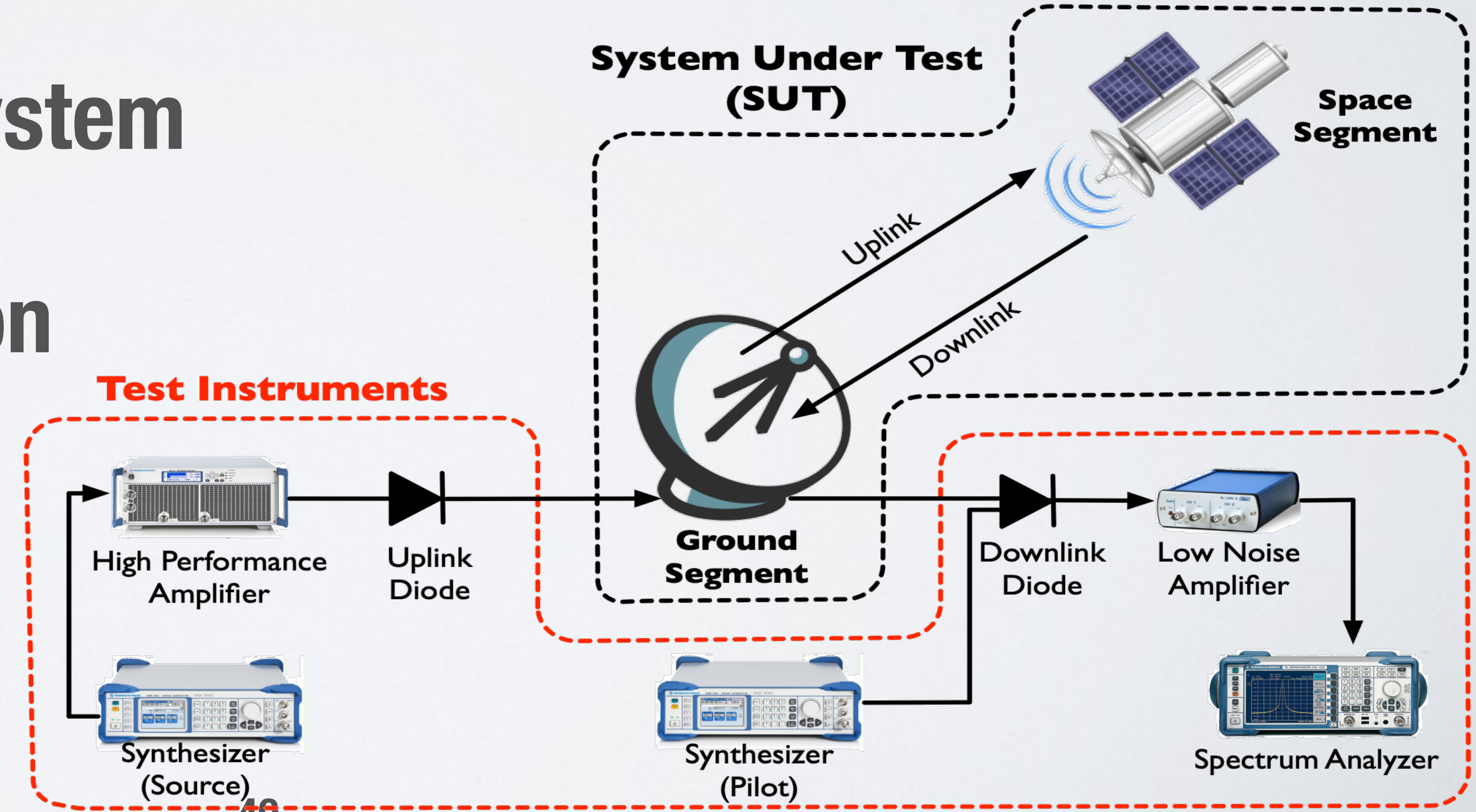
- Fault localisation in Simulink models

Model Testing Satellite Systems

- Control system
  - MiL/SiL testing



- Data communication system
  - Test case prioritization for HiL



Conclusions

Model Testing

Design

Requirements

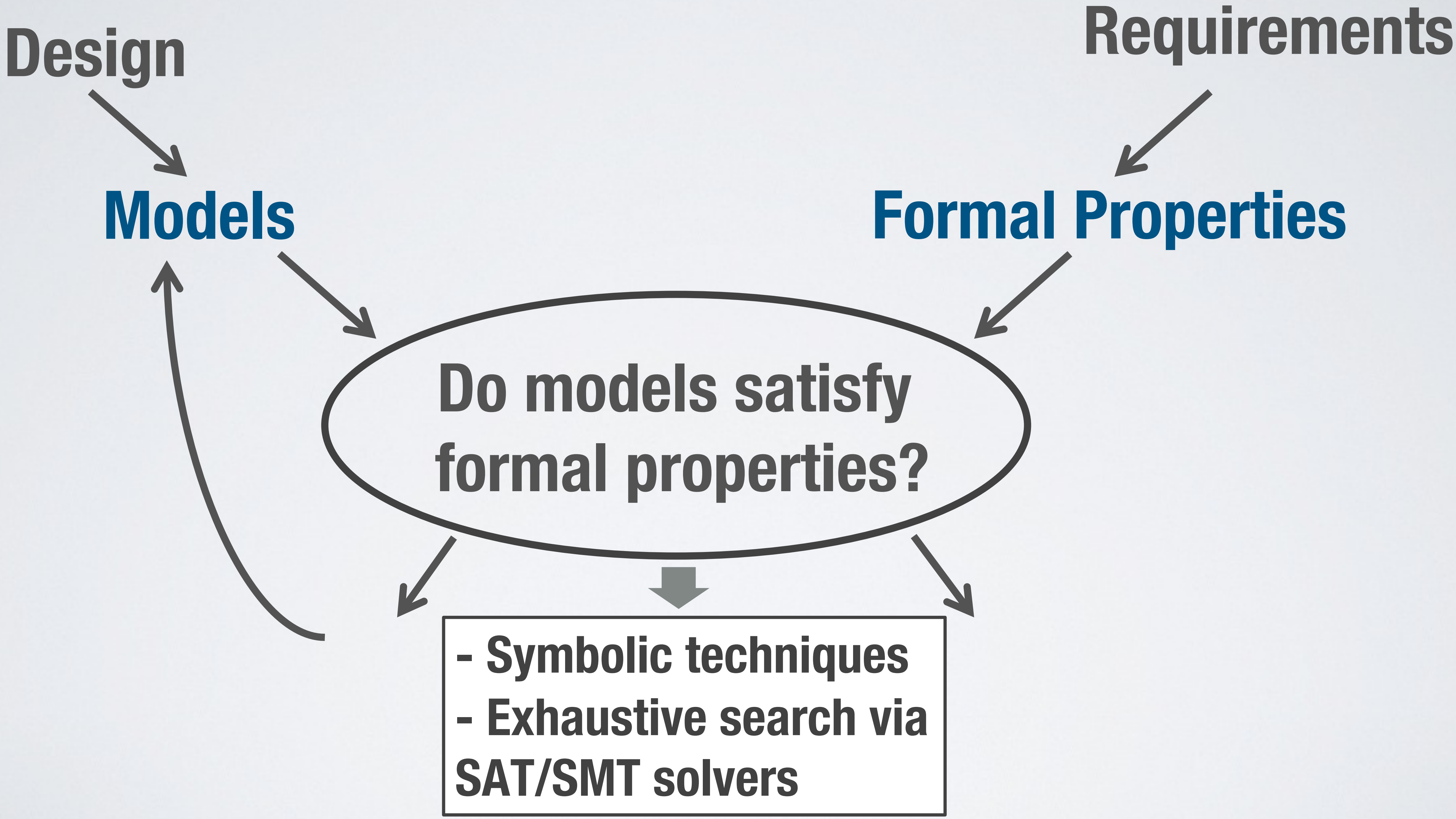
Models

Oracle

Do we find an error by **testing** models?

- Search
- Prediction models
- Classification models

Model **Checking**



Related Work: Model Checking

- **Incompatibility** issues with CPS models
  - **Continuous mathematical models**, e.g., differential equations
  - Library functions in **binary code**
  - **Non-linear** behavior
    - **Complex mathematical operators**
    - **Saturation** of actuators and sensors
    - Reliance on **measured data**

Related Work: Model Checking

- **Unrealistic assumptions** about CPS test oracles
  - Discrete/exact/complete/binary/automatable
  - Focus on structural coverage
- **Scalability**

Search-Based Solutions

- Are Versatile
  - Decrease modeling requirements
  - Relax assumptions on test oracles
- Are scalable, e.g., easy to parallelize
- Can be combined with: Machine learning; Statistics; Solvers, e.g., SMT, CP
- But,
  - are context-dependent
  - require massive empirical studies

Future Work

- Model testing solutions in other CPS contexts
  - Heterogeneous modeling and co-simulation
  - Modeling dynamic properties and risk
  - Uncertainty modeling enabling probabilistic test oracles
  - Executable model at a proper level of precision for testing purposes
  - Systematic ways to build fitness functions for oracles

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Automated Testing of Cyber-Physical Systems

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Huawei Workshop on Applications of AI to Software Engineering

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Results

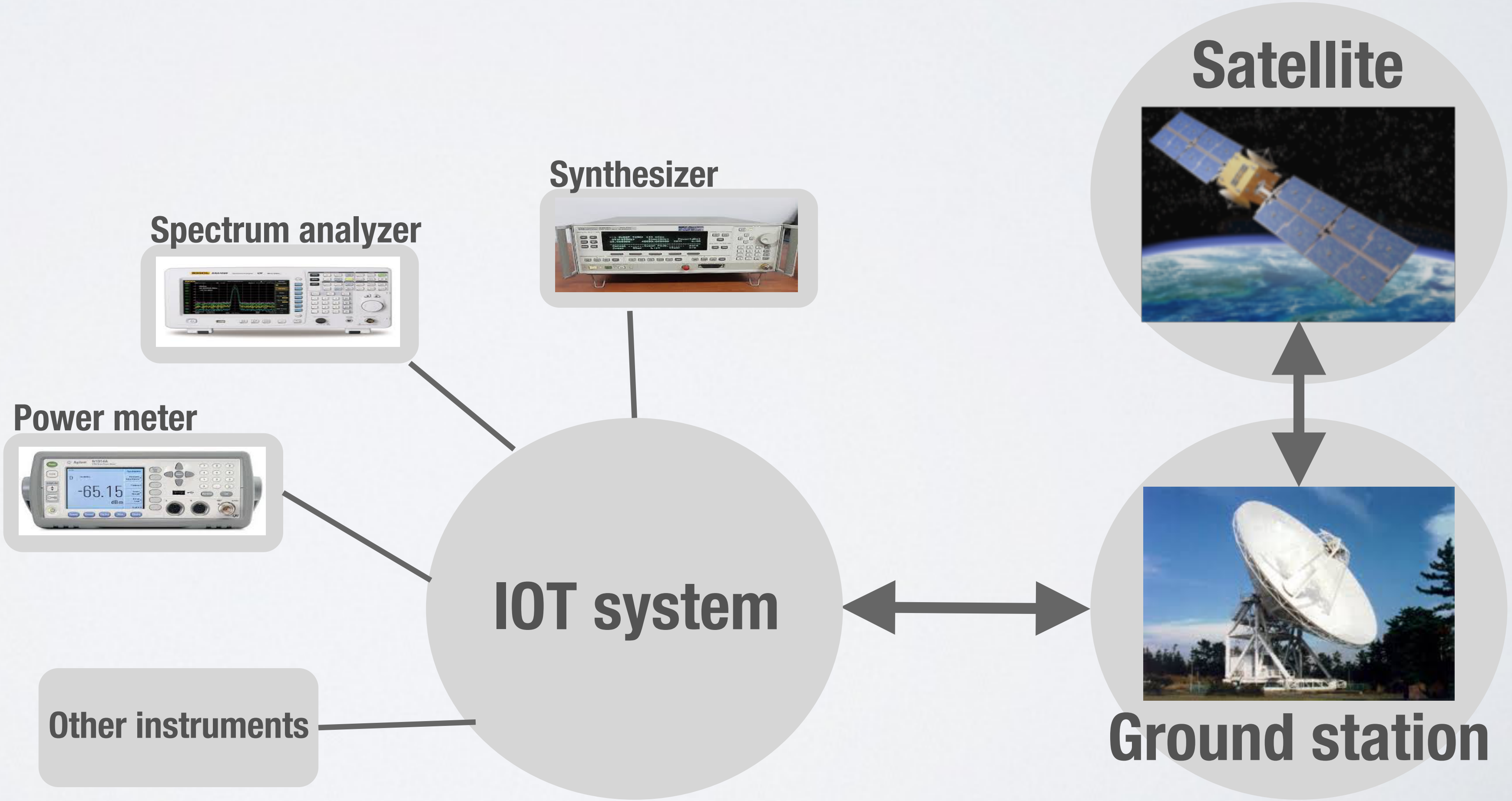
- The test scenarios by our search-based approach helped engineers **identify** several **critical behaviors**
  - The critical test scenarios are available at:

    https://sites.google.com/site/testingpevi

- Under tight time budget, our search algorithm with surrogate models is more **accurate** and **safer** compared to the baseline search algorithm

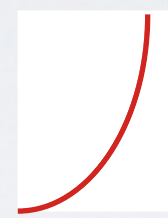
- Our classification guided search generates 78% more **distinct, critical test scenarios** compared to the baseline search algorithm

Part II. Model Testing Satellite Systems



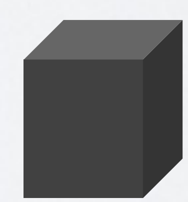
Test Case Prioritization (HiL)

- Problem
  - Test case prioritization



Search space: exponential growth
E.g., two test cases: a, b
Possible test suites: (a), (b), (a,b), (b,a)

- Context
  - System validation and acceptance testing of CPS



Black box testing

Results – Worst Runs