Role of Formal Verification in Certifying Autonomous Vehicles

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By **BILL VLASIC** and **NEAL E. BOUDETTE** JUNE 30, 2016

JACK STEWART TRANSPORTATION 03.11.17 7:00 AM

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Uber has grounded its self-driving cars in Arizona after one was involved in an accident

Johana Bhuiyan
Saturday, 25 Mar 2017 | 3:29 PM ET

TECHNOLOGY NEWS | Mon Mar 27, 2017 | 5:55pm EDT

Uber resumes self-driving program three days after Arizona crash

Doomsday in 10 Years!

Doomsday

Tuesday, April 1, 2025

Google Car Claims 100 Live

In a shocking incident in Menlo Park, CA. a Google car claimed the lives of 100 individuals. Sources from Google seems to suggest that the cause for this accident is a software bug because of some un-reviewed code written by a teenage intern. Tech companies like Microsoft, Facebook, and Amazon issued public statements condemning Google because 90 of the 100 people dead in the accident worked in one of these companies.

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Massive Amazon cloud service outage disrupts sites

Elizabeth Weise , USATODAY Published 1:51 p.m. ET Feb. 28, 2017 | Updated 6:56 a.m. ET March 1, 2017

Here's Why Amazon's Cloud Suffered a Meltdown This Week

> Unfortunately, one of the inputs to the command was entered incorrectly and a larger set of servers was removed than intended. The servers that were inadvertently removed supported two other S3 subsystems.


With great software, comes great risks!

Avoiding The Doomsday

Certified Autonomous Vehicle

This Talk: How Formal Verification Can Help in Certifying Autonomous Vehicles.

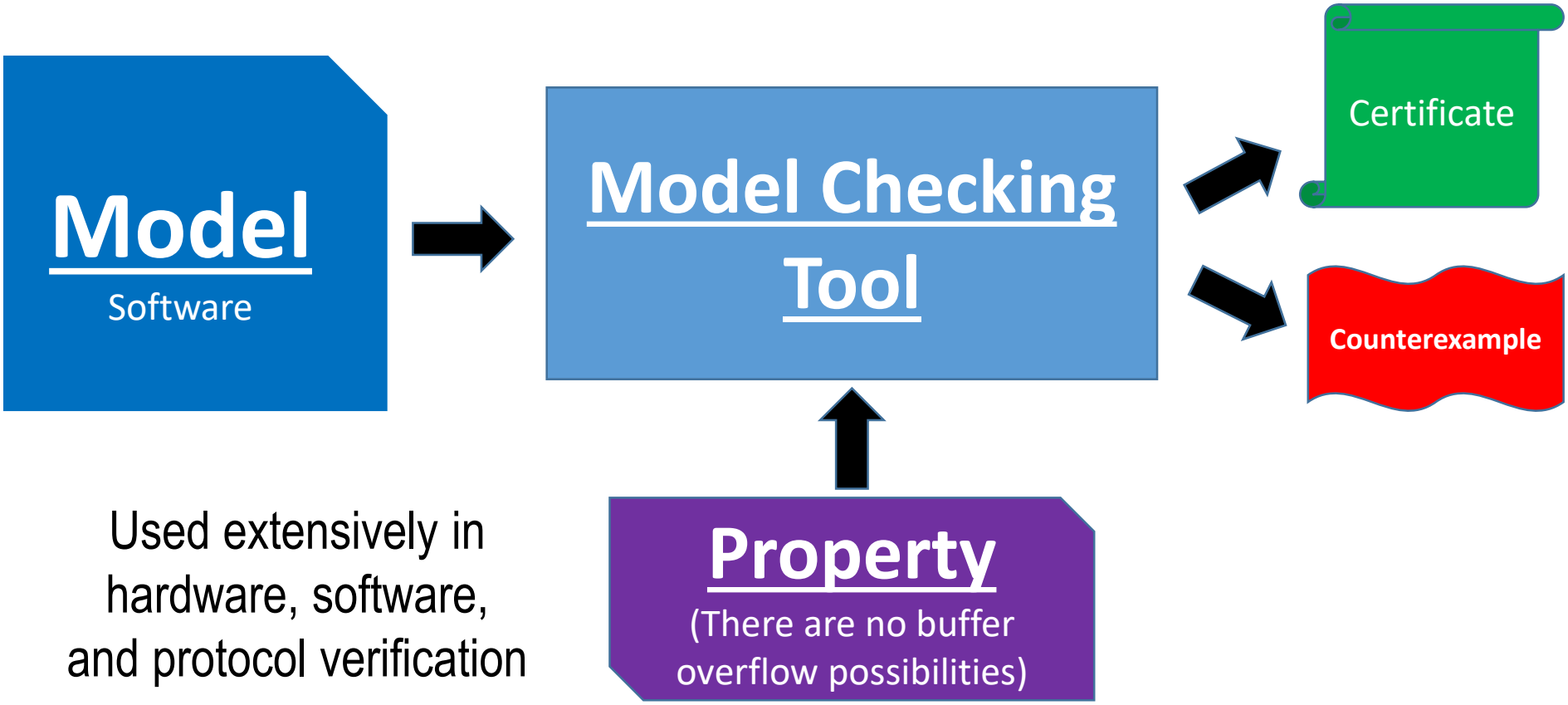
Certified Autonomous Vehicle

Outline

- ✓Avoiding Doomsday For Autonomous Vehicles
- Formal Verification 101
- Success Stories of Formal Verification
- Roadmap for Certification of Autonomous Vehicles
- Conclusions

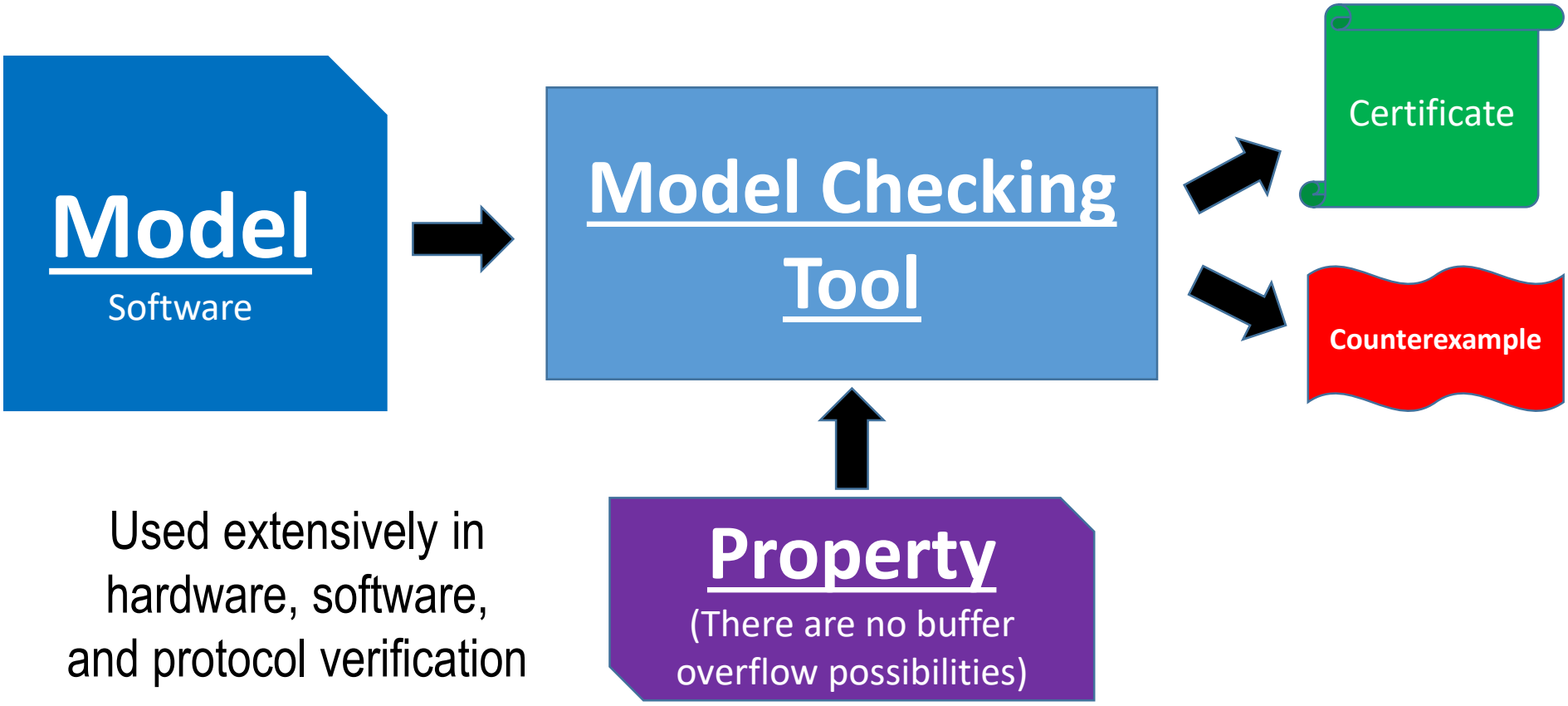
Formal Verification 101

- Model Checking: Algorithmically verifying if your given model satisfies a given property.



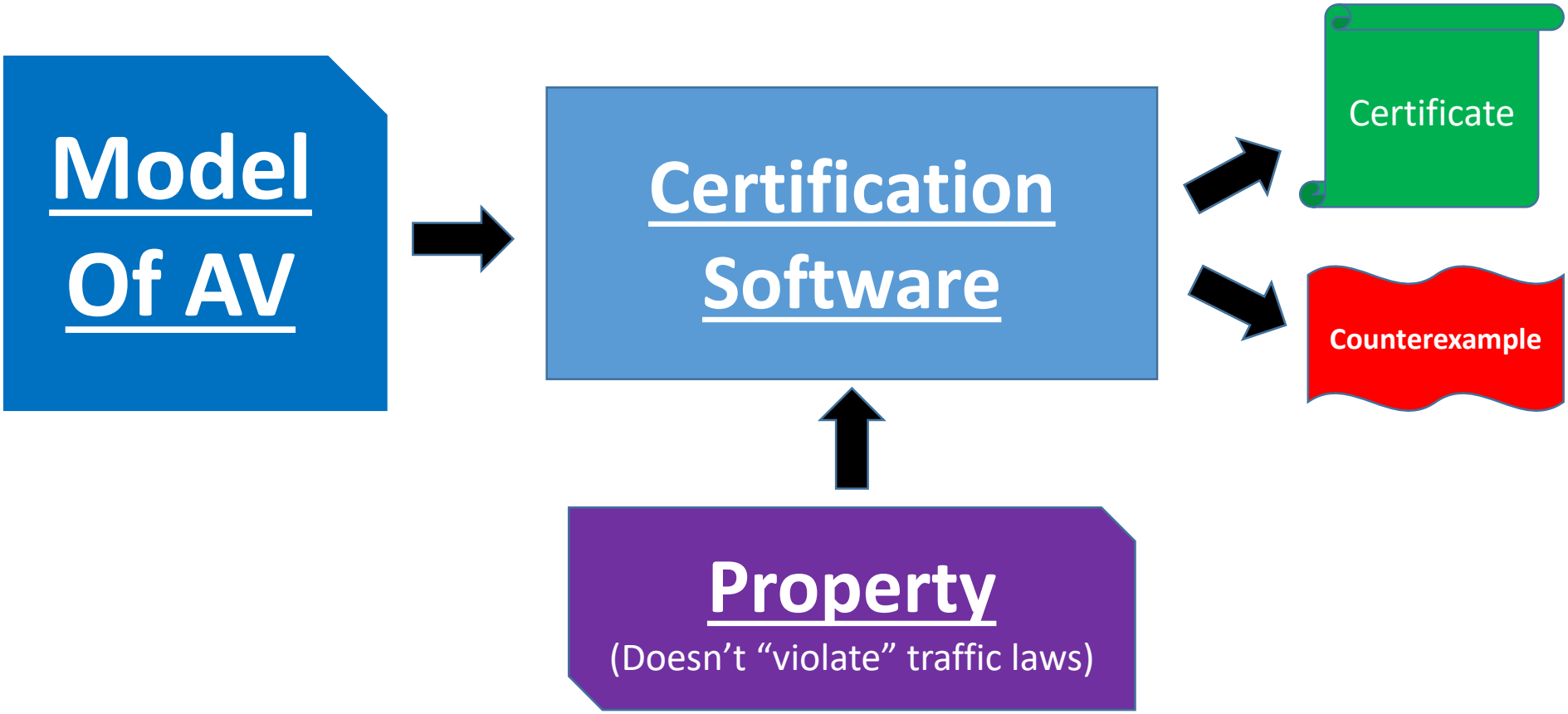
Model Checking ≠ Extensive Testing

- Model Checking considers all possible executions and will either return a proof or counterexample.



Used extensively in hardware, software, and protocol verification

Verification of Autonomous Vehicle



Why Software For Certification?

Ex. Aerospace domain: Certification for avionic systems is done manually.

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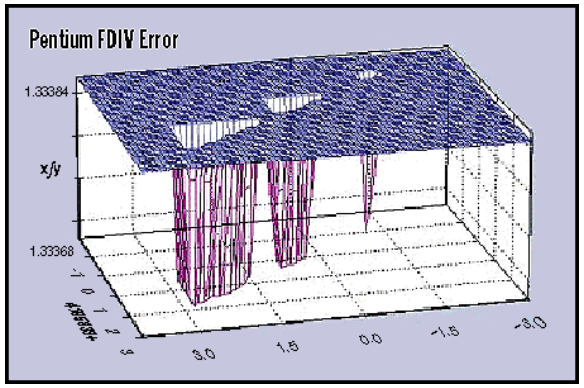
As the complexity of the system increases, manual certification cost increases exponentially. Automating the certification process using Formal Verification is our only hope.

Success Stories of Formal Verification

Disaster Scenarios

Bad software caused some serious damage!



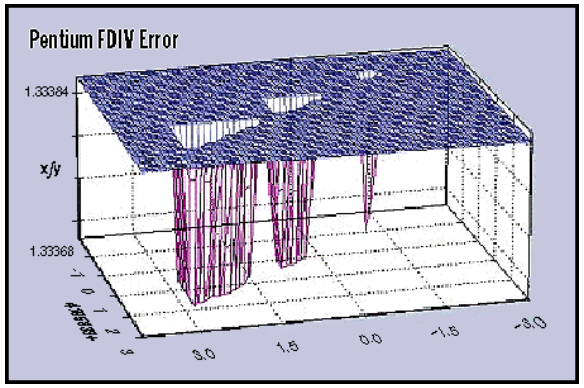
Intel Pentium bug caused loss of reputation and money.

Ariane 5 crashed within a few minutes after launch

Software bug caused Toyota to recall 1.2M Prius cars

Software race condition caused northeast blackout of 2003

Avoiding Doomsday



Intel now uses Synopsys/Cadence tools for formal verification.

Static analysis could catch the bug during the analysis

NASA review of Toyota's code mentions using Formal verification tools.

AbsInt: A Tool For Software Verification Of Flight Control Software.

The flight control software in some AIRBUS systems have been fully verified to not have any buffer overflow or division by zero errors.

Aviation | Automotive | Space | Energy | Communication →

AIRBUS — For over a decade, Airbus France has been using our tools in the development of safety-critical avionics software for several airplane types, including the flight control software of the A380, the world's largest passenger aircraft.

HONDA — Honda has been using our tools in developing the FADEC software of a turbofan engine.

TUM — The Technical University of Munich is using our tools in the development, testing and optimization of flight control and navigation algorithms.

SLAM: Static Verifier for Windows Drivers

Used for verifying device drivers for Windows.

"Things like even software verification, this has been the Holy Grail of computer science for many decades but now in some very key areas, for example, driver verification we're building tools that can do actual proof about the software and how it works in order to guarantee the reliability."
Bill Gates, April 18, 2002. Keynote address at WinHec 2002

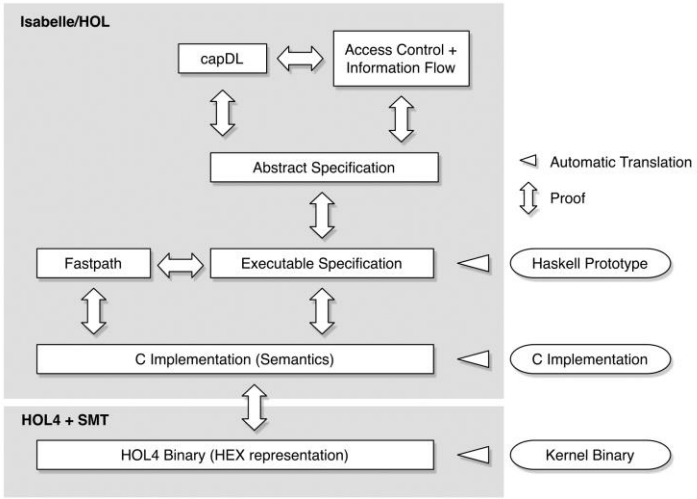
Low rate of false positives – around 4%.

IEEE Property Specification Language

- Combined industry + academia effort for standardizing the specification language for hardware.
- Part of Verilog, VHDL, SystemC, and SystemVerilog.
- Intel, IBM, Freescale, Synopsis, Cadence, etc.

SeL4: A Formally Verified Microkernel

Uses mechanical proof checker Isabelle/HOL



Proving >> Development

Code = 10K lines

Proof > 120K lines

Properties of microkernel are encoded as theorems and proved in Isabelle/HOL

SeL4 has been deployed on Unmanned Little-Bird helicopter.

RED Team hackers couldn't hack it even after 6 months while having access to source code!

How To Certify Autonomous Vehicles: A Formal Verification Approach And Research Directions

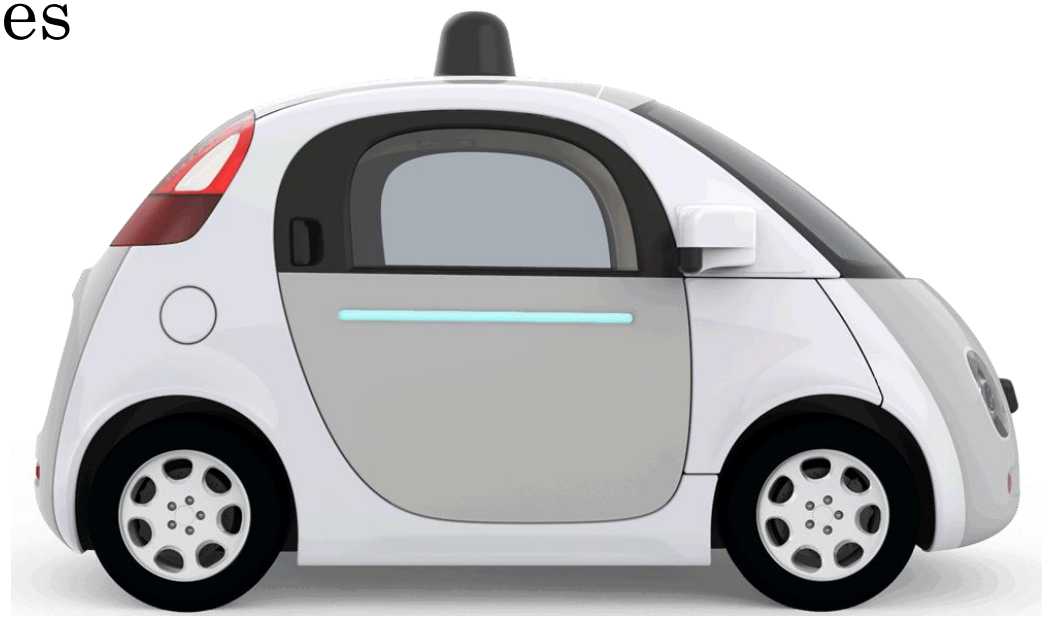
Levels of Abstraction

1. High level traffic rules

   "Always stop at a red light"

2. Motion primitives

   Controllers for turning car and avoiding collisions.

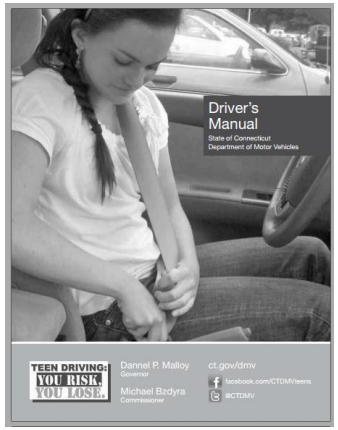


3. Real time correctness

   A command issued will run with a maximum latency of 20ms

High Level Traffic Rules

- For the humans, by the humans.



Official driver's manual provided by
State of Connecticut Department of Motor Vehicles.

60 page document describing the rules of the road.

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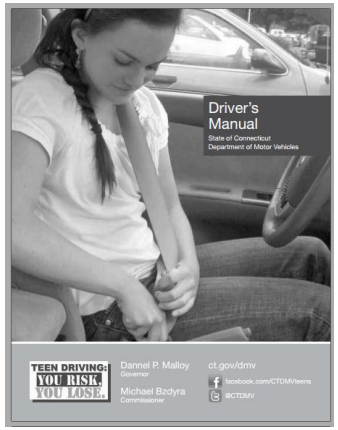

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How does a computer understand these rules?

Traffic Rules For A Computer?

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- Solution: encode traffic rules as logic formulae.
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- Example PSL specification for hardware circuits:

  "an acknowledgement is issued within 4 cycles of receiving a request"

  ```
  always(req -> {[*4]; ack;})
  ```

- Example from Connecticut DMV manual:

  "merging with any traffic should take at most 2 seconds"

  ```
  always(mergeBegin -> {[*2]; mergeEnd;})
  ```

Linear Temporal Logic – A Logic For Describing Temporal Properties

- Linear Temporal Logic (LTL): A logical framework for expressing temporal specification of behaviors.

```
always(req -> {[*4]; ack;})
```

- Variants of temporal logic (timed logics) for specifying real-time behaviors.

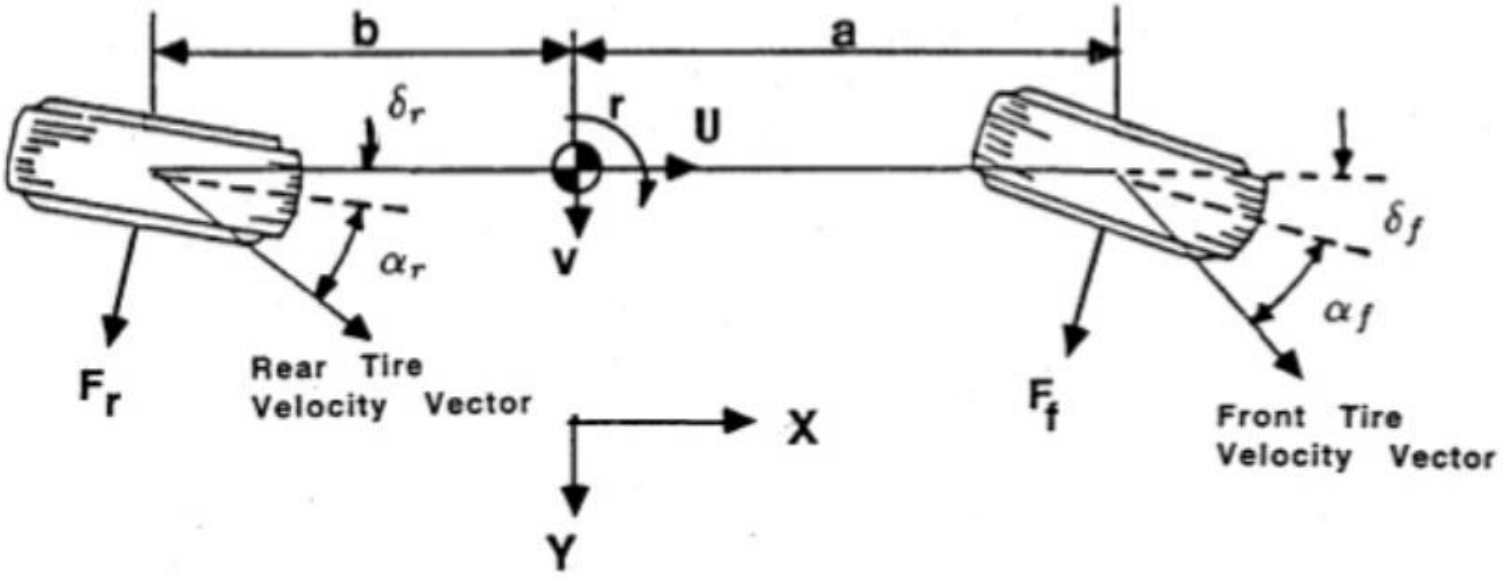
Research Direction

NextGen Traffic Manual: List of formulae in suitable temporal logic.

Motion Primitives

Motion Primitives

- Behavior of car can be modeled in a *"bicycle model"*



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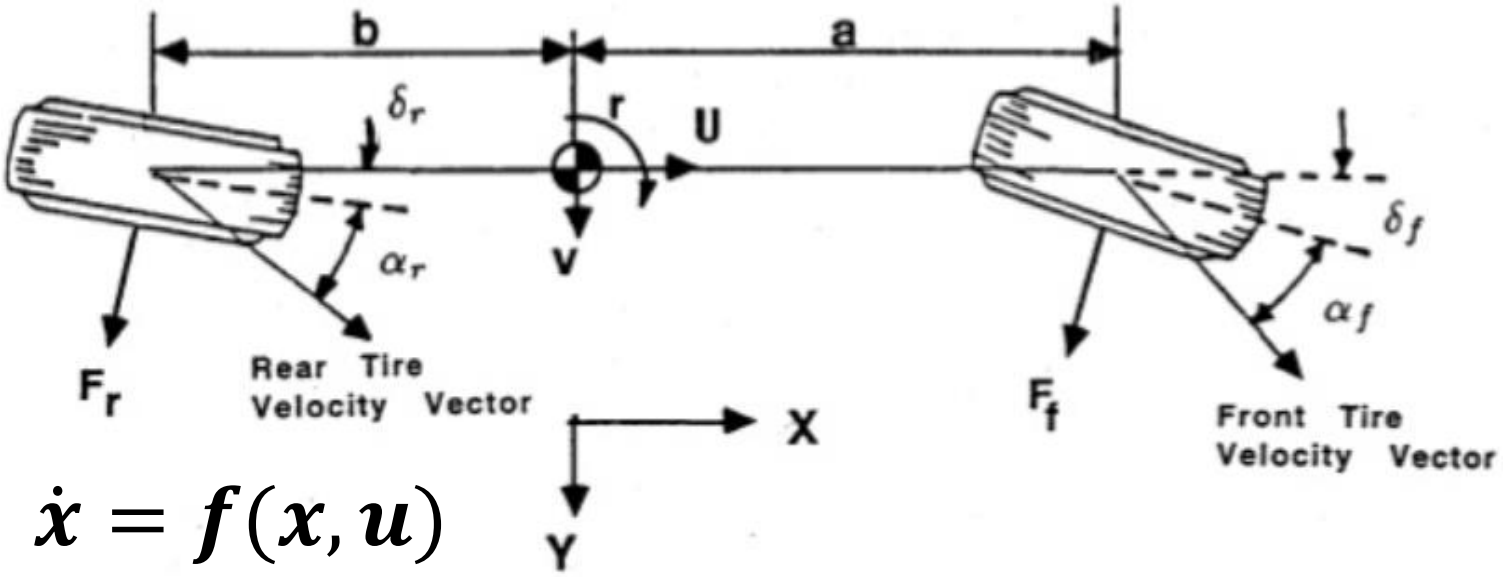
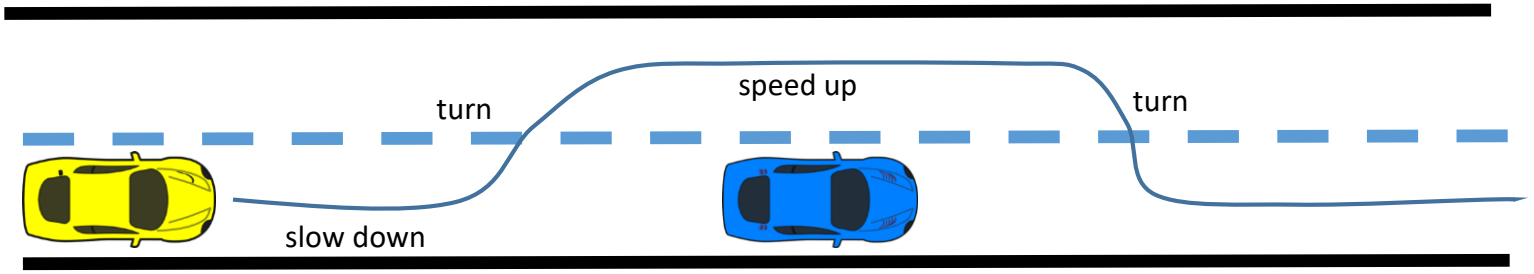


$$\dot{x} = f(x, u)$$

- Given the model $\dot{x} = f(x, u)$, are the controllers for turning, passing, and breaking, **safe**?

Verification of Motion Primitives.

- Hybrid Systems Verification (Computer Science + Control)

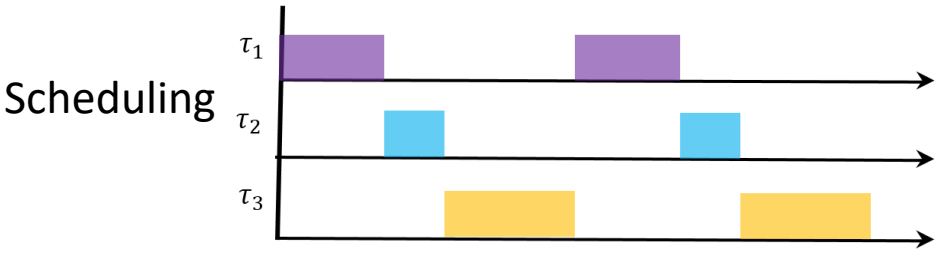


CSE5905 HW Prob.: Generate parameters for autonomous car [**simpler model**] Controller and verify using C2E2 (my tool) if the safety specifications are satisfied

Research Direction
Scalable Verification Tools For Handling Complex ODE Model

Real-Time Behavior

- In theory, the hardware just runs one process, in practice, the hardware juggles various processes.
- Example: the mars rover had 50 processes while landing!
- Each of these processes are handled by scheduler.



How To Guarantee Real-Time Behavior?

- Real-Time Systems in Computer Science.

- Worst Case Execution Time (WCET) Problem:
  Given a program P and a hardware platform H what is the worst case running time of P on H?

- Very mature software tools for analyzing WCET.

Formal Verification For Certified Autonomous Vehicles

1. High level traffic rules

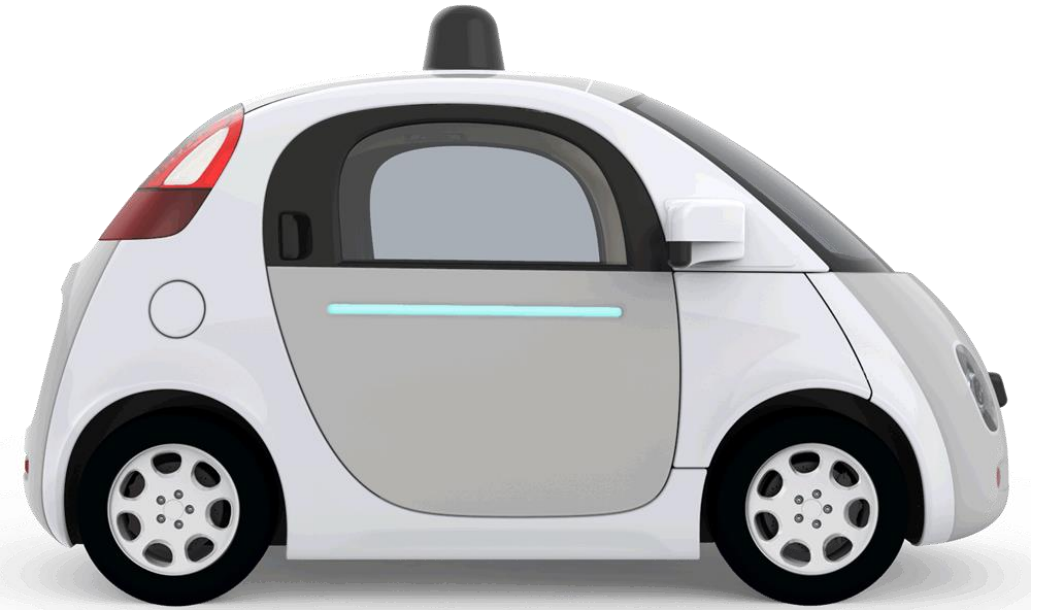
   "Always stop at a red light"

   Use Temporal Logic

2. Motion primitives

   Controllers for turning car and avoiding collisions.

   Use Hybrid Systems Verification Tools



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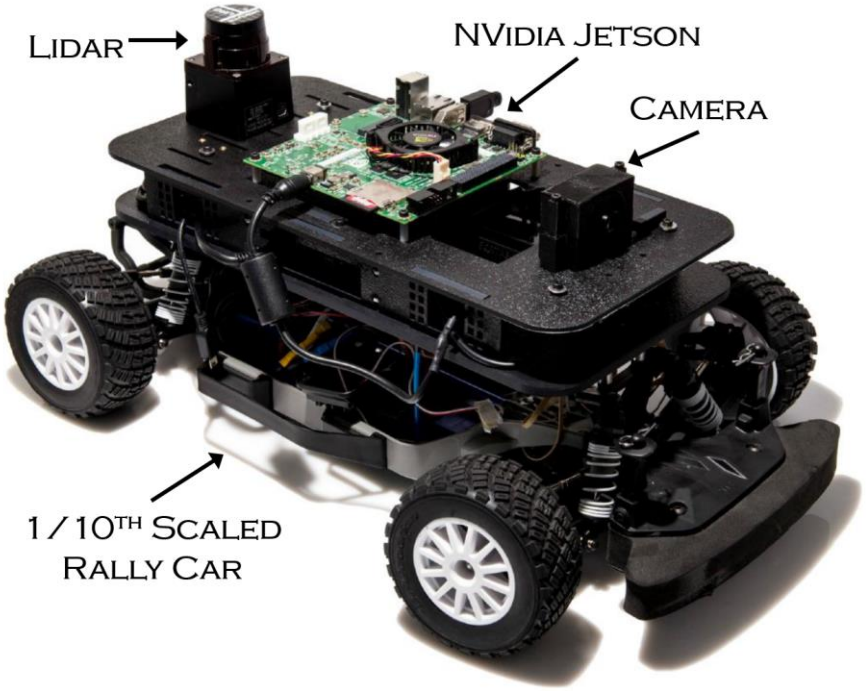
   Use WCET Tools From Real-Time Systems

Prototype – Lab Version

Miniature version of autonomous vehicle



Thank You. Questions?