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Autonomous Vehicles and Software Safety Engineering

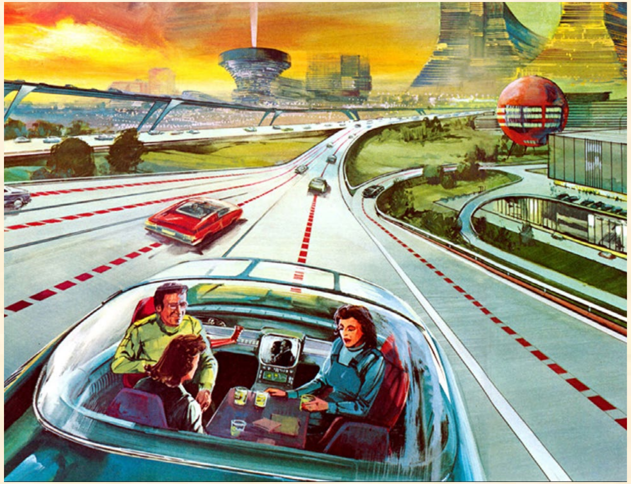
Carnegie Mellon University

@PhilKoopman

Overview

- Autonomous Vehicles almost "solved"
  - But … "almost" is misleading

- Huge challenge: safety
  - AVs present additional challenges
  - Perception edge cases are a limiting factor
  - Testing alone won't get us to safety



[General Motors]

- Safety requires a standards + safety case approach
  - Life cycle argument supporting deployment safety
  - ANSI/UL 4600 standard for #DidYouThinkofThat ?

AV Problem 98% Solved For 25+ Years

NO HANDS ACROSS AMERICA
Carnegie Mellon University • Delco Electronics • AssistWare Technology

July 1995

TRIP COMPLETE !!!
2797/2849 miles (98.2%)

- D.C. to San Diego
  - CMU Navlab 5
  - Dean Pomerleau & Todd Jochem
    https://www.cs.cmu.edu/~tjochem/nhaa/nhaa_home_page.html
  - AHS San Diego demo Aug 1997
- Remaining challenges:
  - That last 2% … and the safety driver

CMU NREC: 35+ Years Of Cool Robots

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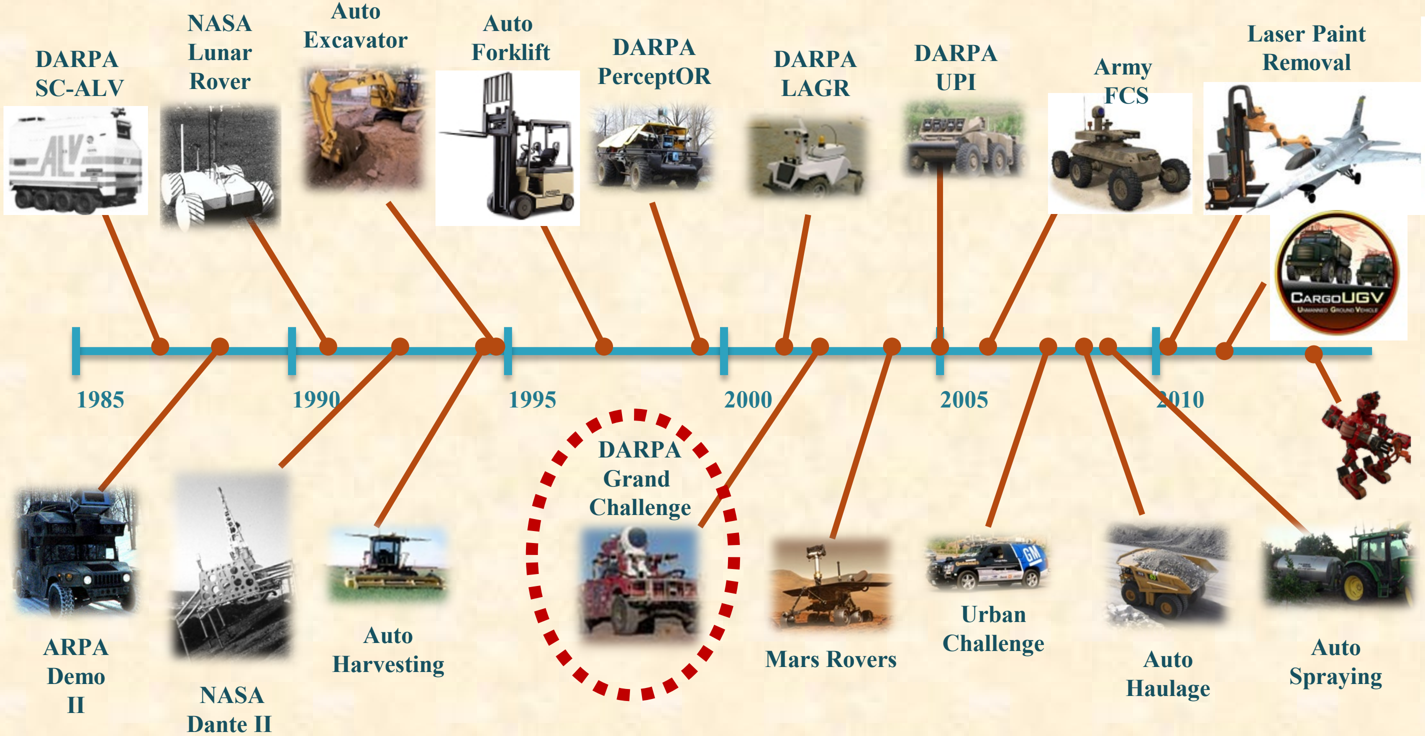
Machinery Safety

Software Safety



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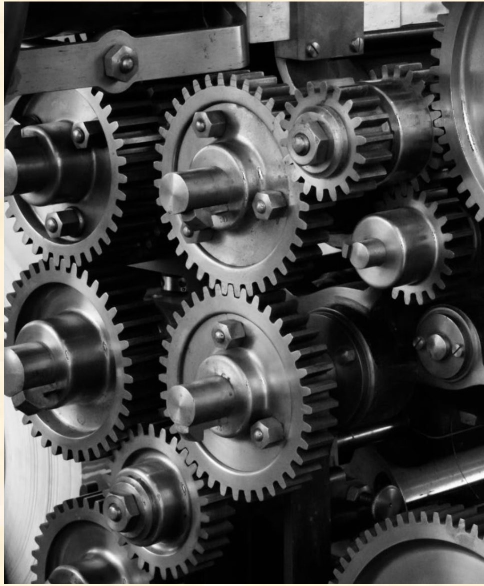
Software Safety Engineering

- Safety is a system property
  - Correctness is not enough for safety
- Safety engineering emphasis on hazard mitigation
  - Identify hazards: if X goes wrong, could result in loss event
    - Includes hardware failures, tool defects, environmental surprises
  - Predict risk = probability * consequence
    - The tricky part is: “Probably Never * Catastrophic”
  - Mitigate risk via:
    - Engineering rigor: process quality, analysis, test, redundancy patterns
    - Functional safety: detect and shut down malfunctioning equipment
    - Safety of Intended Function (SOTIF): resilience to requirements gaps, inconsistent sensor data, unexpected environments

Why Is AV Safety Complicated?



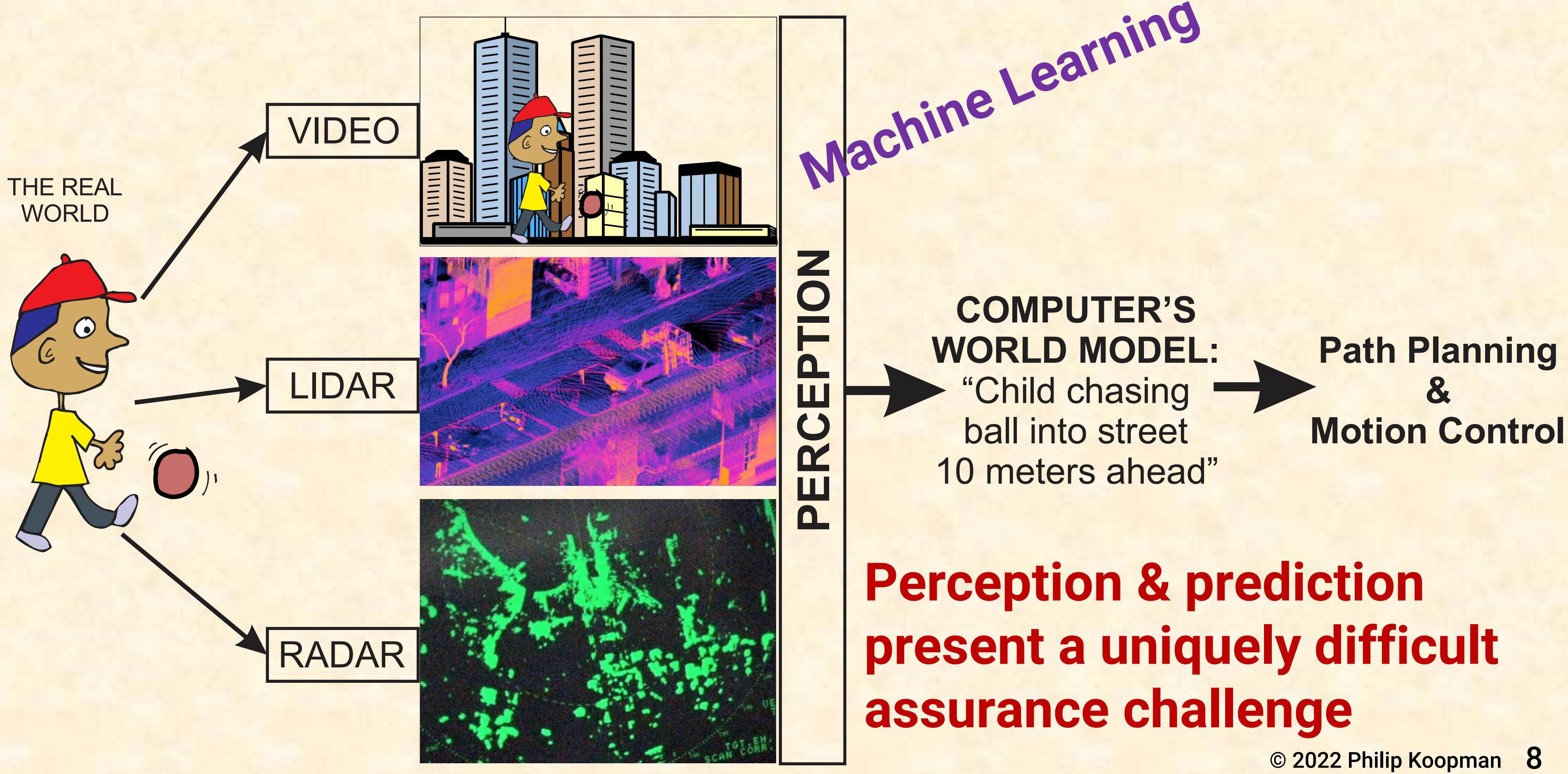
- Public expectations
  - Expect super-human machine performance
  - Trust too easily given, backlash when broken
- Technical challenges
  - Machine Learning safety is work in progress
  - Statistical approach vs. high severity rare events
- Historical industry culture clash
  - Autonomy researchers: it’s all about the cool small-scale demo
  - Silicon Valley: move fast + break things
  - Automotive: blame driver for not mitigating equipment failures
  - Regulators: test-centric; weak digital safety expertise

Should You Trust an AV?

- Heaviest technical lift is perception/prediction safety

Ford VSSA 2021 https://bit.ly/3njionT

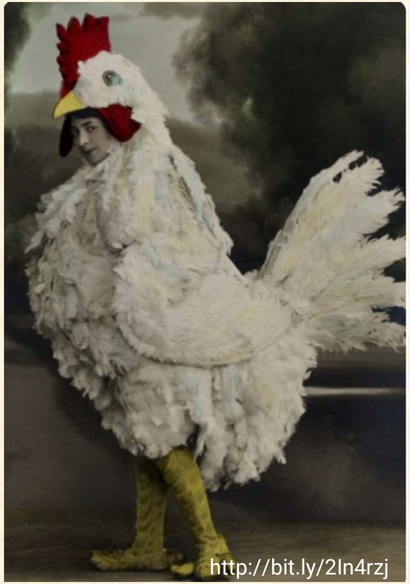
Perception Builds the World Model



Perception & prediction present a uniquely difficult assurance challenge

Edge Cases As A Limiting Factor

- Machine learning is best at what it has already seen
  - But the world is full of novelty
  - Perception/prediction poor at recognizing it is just guessing
- Is this a Person or Chicken?
- Edge Case are surprises
  - You won’t see these in testing



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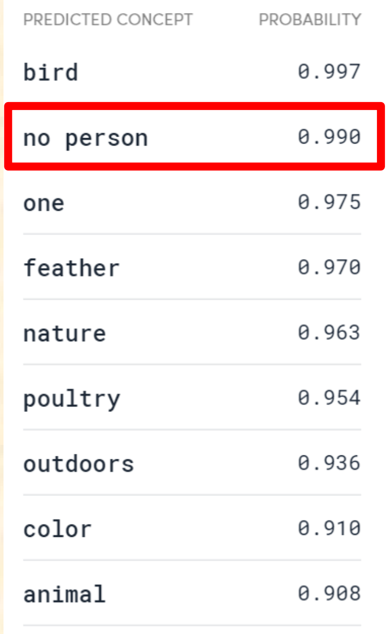

PREDICTED CONCEPT	PROBABILITY
bird	0.997
no person	0.990
one	0.975
feather	0.970
nature	0.963
poultry	0.954
outdoors	0.936
color	0.910
animal	0.908

https://www.clarifai.com/demo

➔ Edge cases are the stuff you didn’t think of!

The Challenge Is Covering Everything

- Have you covered the possible unknowns?

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https://goo.gl/J3SSyu

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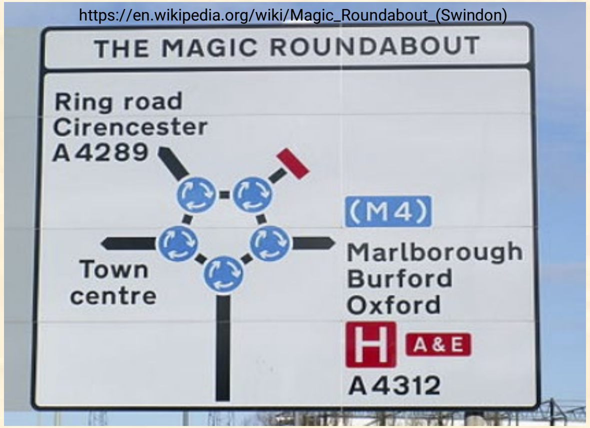


https://en.wikipedia.org/wiki/Magic_Roundabout_(Swindon)

Brute Force AV Validation: Public Road Testing

- Good for identifying "easy" cases
  - Expensive and potentially dangerous

http://bit.ly/2toadfa

Autonomy Testing Risks

- Uber ATG fatality, Tempe AZ/US: March 2018
  - Uber ATG closed: January 2021
- Local Motors injury, Whitby CA: Dec. 2021
  - Company closed: Jan. 2022
- Pony.AI crash: CA/US: Oct. 2021
  - Uncrewed test permit revoked
- WeRide sleeping test driver: Oct. 2021
  - Company deflects issue / no apparent regulator action
- Easymile shuttle phantom braking injuries: (2019, 2020)
- SAE J3018 standard for testing safety (2015; 2020 update)
  - Only Argo.AI publicly pledges conformance

https://bit.ly/3AupcWb

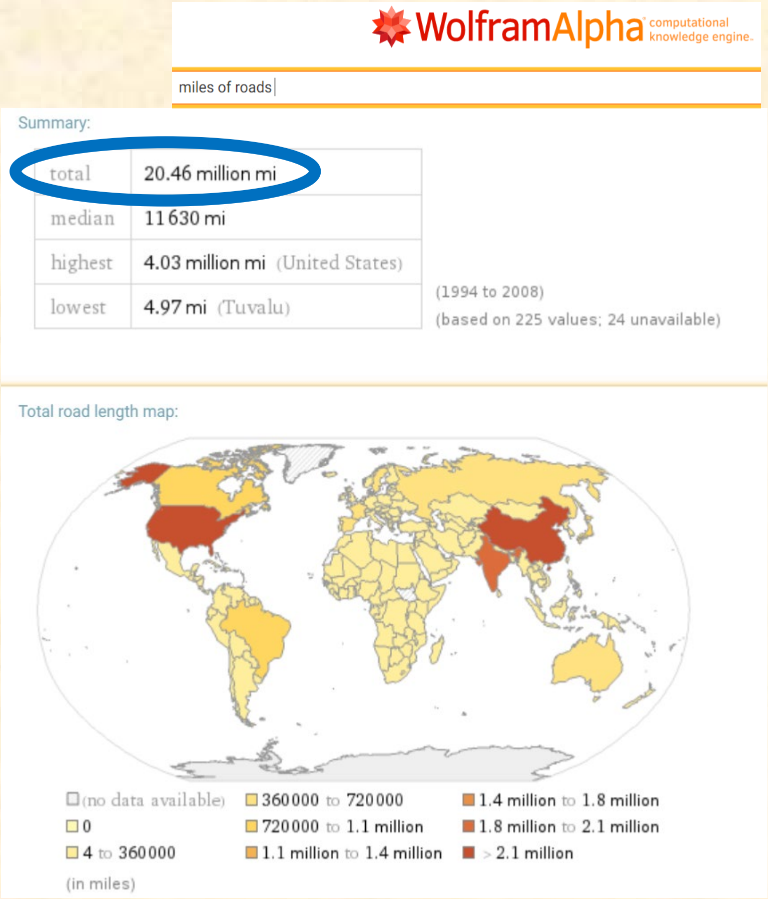
Brute Force Road Testing

- If 100M miles/critical mishap…
  - Test 3x–10x longer than mishap rate
    ➔ Need 1 Billion miles of testing
- That's ~25 round trips
  on every road in the world
  - With fewer than 10 critical mishaps

…

- Start over for each software update

➔ Brute force testing impracticable



WolframAlpha computational knowledge engine.

miles of roads

Summary:

total	20.46 million mi
median	11 630 mi
highest	4.03 million mi (United States)
lowest	4.97 mi (Tuvalu)

(1994 to 2008)
(based on 225 values; 24 unavailable)

Total road length map:

□ (no data available)	□ 360000 to 720000	□ 1.4 million to 1.8 million
□ 0	□ 720000 to 1.1 million	□ 1.8 million to 2.1 million
□ 4 to 360000	□ 1.1 million to 1.4 million	□ > 2.1 million

(in miles)

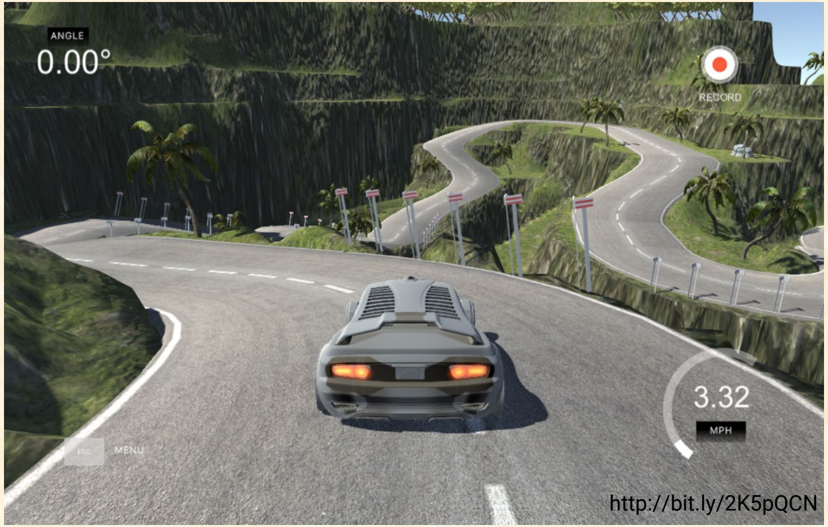
Closed Course Testing

- Safer, but expensive
  - Not scalable
  - Only tests things you have thought of!

Volvo / Motor Trend

Simulation

- Highly scalable; less expensive than road testing
  - Simulation validation ("tool qualification")
  - Only tests things you have thought of!



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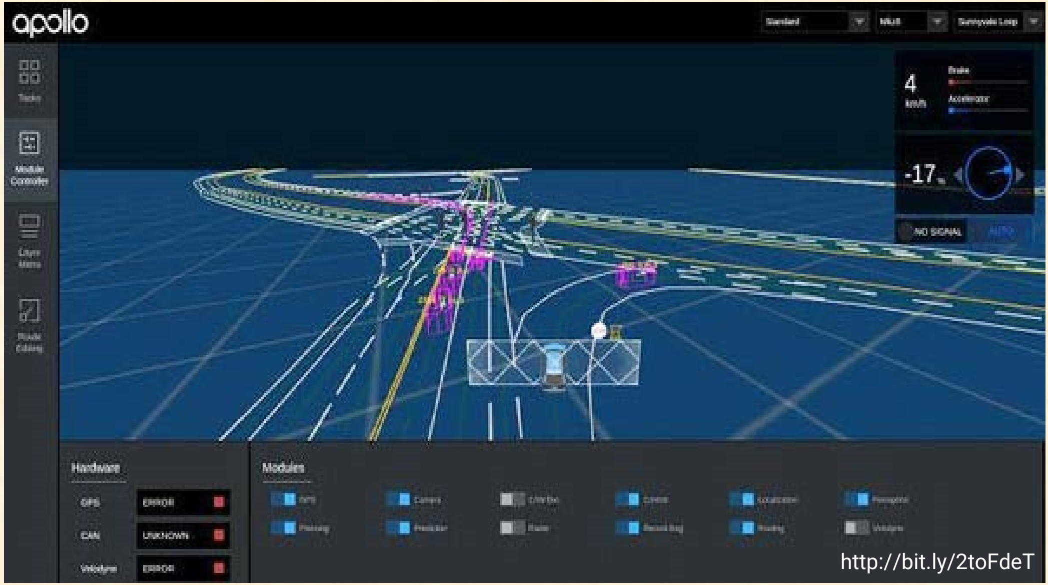
Udacity



Hardware

GPS ERROR

CAN UNKNOWN

Velodyne ERROR

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Apollo

How Much Do You Trust Simulation?

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- Would you put your child in front of this self driving car:
  - 10,000M simulation miles
    … perhaps with a simulator error?
  - 100M miles data collected
    … perhaps missing some relevant scenarios?
  - 10M of road testing
    … that missed high risk situations?
  - Designed with research-quality tooling
    … with no safety qualification?
  - With 5% labeling errors in training data?

- Need simulation and other tool qualification

Industry Safety Standards Can Help

- ISO 26262 – Functional Safety
  - Covers run-time faults & design defects
  - Assumes complete requirements known
- ISO 21448 – SOTIF
  - SOTIF: “Safety Of The Intended Function”
  - Iteratively mitigate discovered “unknowns”
- Also need: #DidYouThinkofThat? lists
  - A technically substantive safety argument
  - Evidence of coverage initially + feedback from surprises
  - Continuously improve based on lessons learned
  - A way to organize everything to ensure safety

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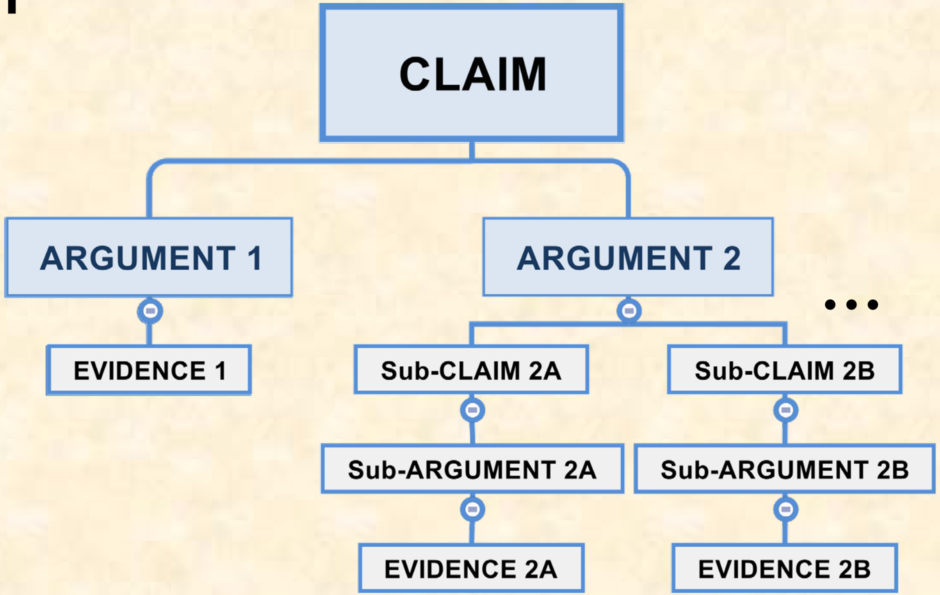
Safety Cases To Organize Safety Argument

- Claim – a property of the system
  - “System avoids pedestrians”
- Argument – why this is true
  - “Detect & maneuver to avoid”
- Evidence – supports argument
  - Tests, analysis, simulations, …
- Sub-claims/arguments address complexity
  - “Detects pedestrians” // evidence
  - “Maneuvers around detected pedestrians” // evidence
  - “Stops if can’t maneuver” // evidence



Lifecycle, Maintenance & Supply Chain

- Safety related maintenance
  - What maintenance is required for safety?
  - How do you know it is done effectively?

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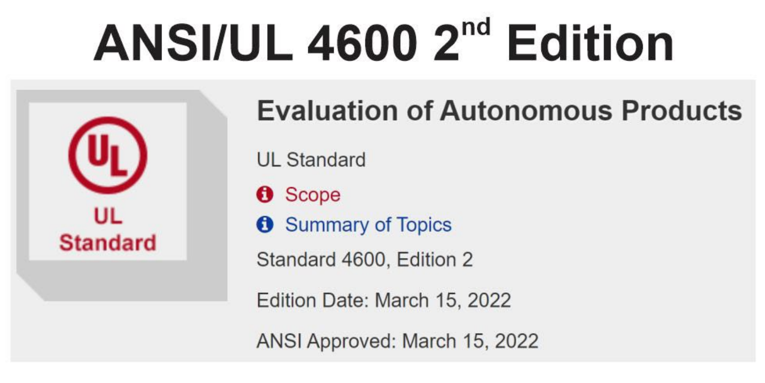
- Safety related aspects of lifecycle
  - Requirements/design/ML training
  - Handoff to manufacturing; deployment
  - Supply chain
  - Field modifications & updates
  - Operation, retirement & disposal

- Safety case kept updated during system lifecycle

UL 4600 – An Autonomy Safety Standard

- Evaluation of a Safety Case
  - Independently assess safety case
  - Mix & match supporting standards
  - Discourages questionable practices
  - Extensive #DidYouThinkofThat? lists
- “Unknowns” are first class citizens
  - Balance between analysis & field experience
  - Field monitoring used for continual safety case improvement
  - Assessment findings & field data used to update practices
- ANSI/UL 4600 2nd Edition issued March 2022
  - 3rd edition to address heavy trucks in progress



ANSI/UL 4600 2nd Edition

Evaluation of Autonomous Products

UL Standard

Scope

Summary of Topics

Standard 4600, Edition 2

Edition Date: March 15, 2022

ANSI Approved: March 15, 2022

The Path To Achieving AV Safety

- Cultural reconciliation within industry
  - Safety for on-road testing (driver & vehicle)
  - Mature beyond a rushed demo mentality
- Stakeholder trust for acceptable safety
  - System-level safety for machine learning
  - Independent safety assessments
- Use industry safety standards
  - Reform “standards optional” regulations
  - Traditional software safety … PLUS …
    - Account for unknown unknowns at deployment
  - UL 4600 Autonomous Vehicle Safety Standard

http://bit.ly/2MTbT8F (sign modified)