# Self-Driving Vehicles, SLAM, and Databases


**John Leonard**

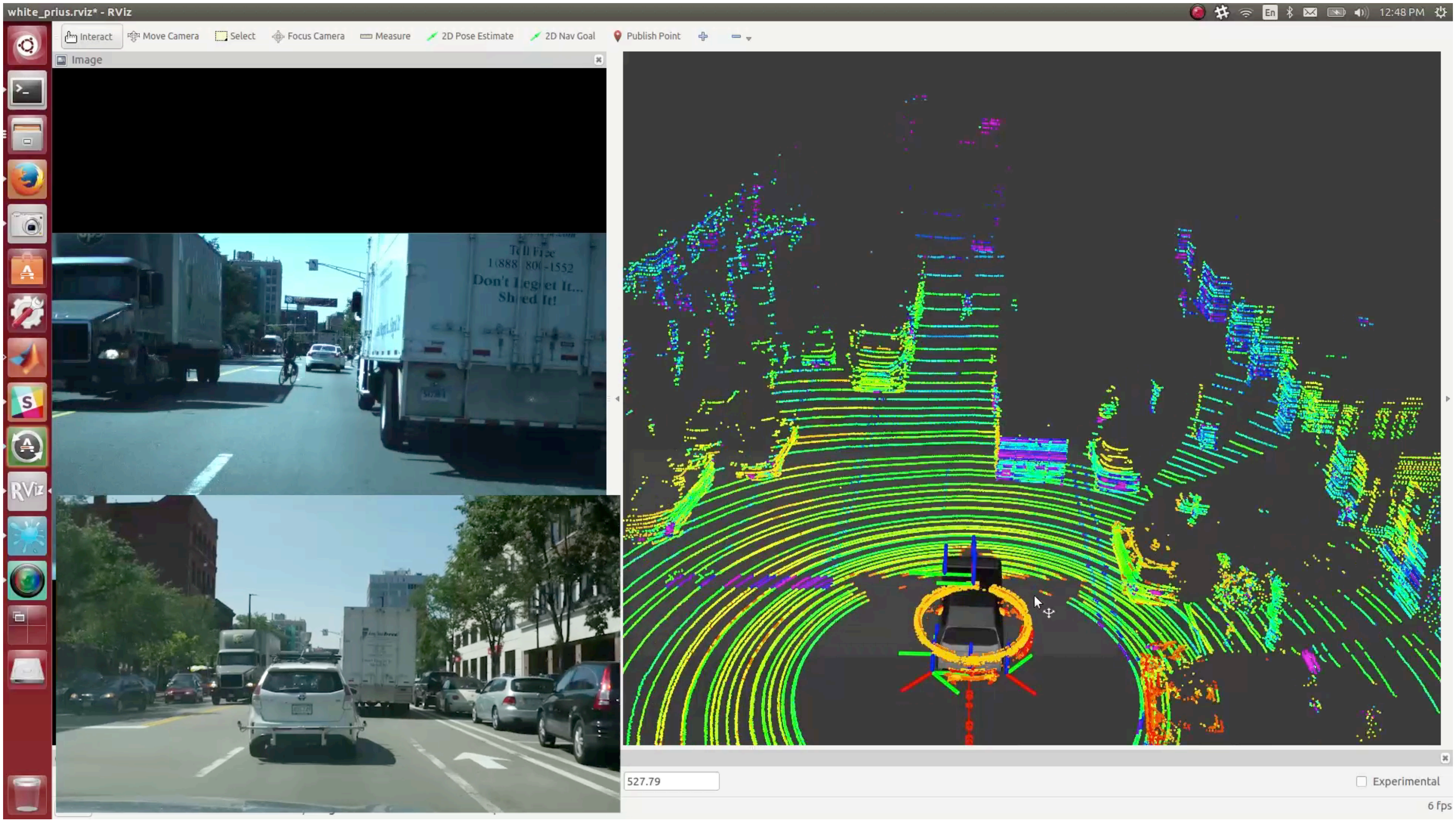
**MIT MechE CSAIL**



Autonomous Driving, 2007

Manual Data Collection (10x), 2016

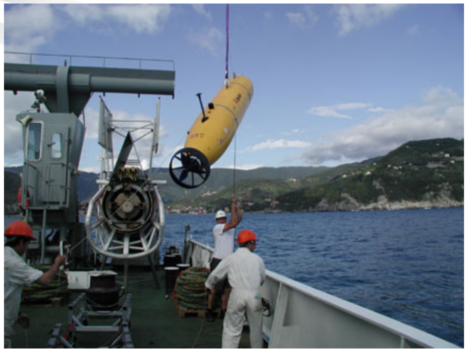
# Data Collection, Summer 2016



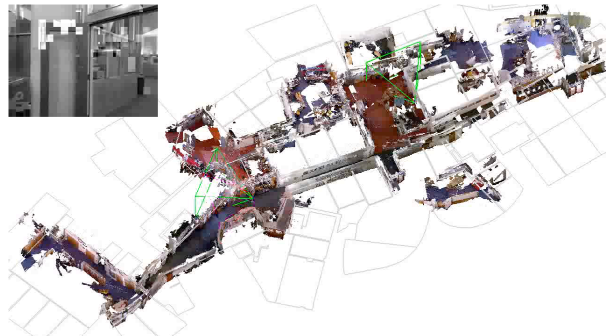

MIT CSAIL-Toyota Project Data Collection (Central Square, Cambridge MA)

Dr. Liam Paull, Prof. Daniela Rus, et al.

# My Background



Autonomous Underwater Vehicles



Mapping and Localization


Self-Driving Vehicles

Education:
- University of Pennsylvania, BSEE (1987)
- University of Oxford, DPhil (1991)

History of MIT Positions:

Mapping and Localization

- MIT Sea Grant  AUV Lab (1991-1996)
- Dept. of Ocean Engineering (1996-2004)
- Dept of Mechanical Engineering 2005-present
- Artificial Intelligence Laboratory (2002-2004) and CSAIL (2005-present)

Current Positions:
- Samuel C. Collins Professor, MIT MechE & MIT CSAIL
- **Director of Autonomous Driving Research, Toyota Research Institute**

Research Interests:
- Self-Driving Vehicles; Mapping and Localization;  Marine Robotics

# Outline

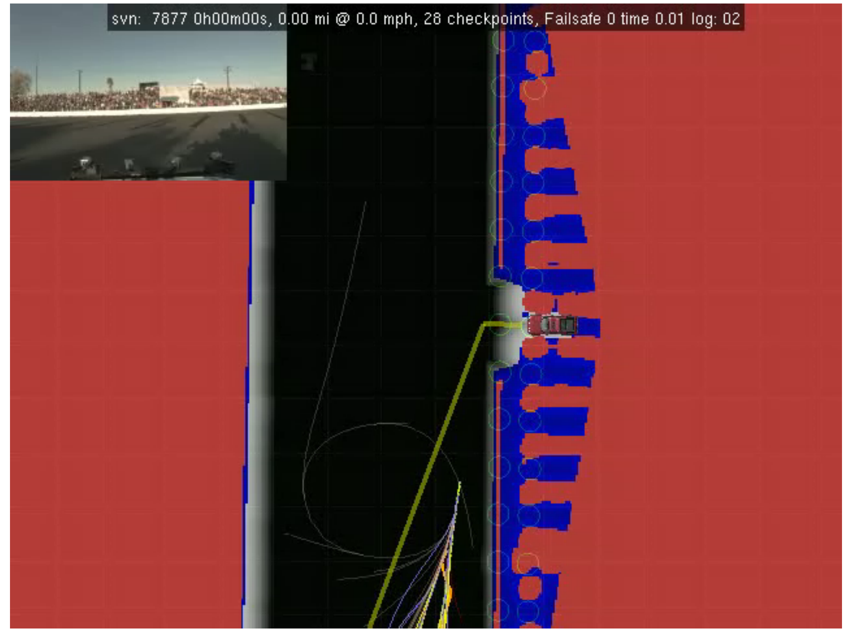
- **An Introduction to Self-Driving Vehicles**
- Technical Challenges and Opportunities
- Mapping and Localization
- Database Technology and Self-Driving Vehicles

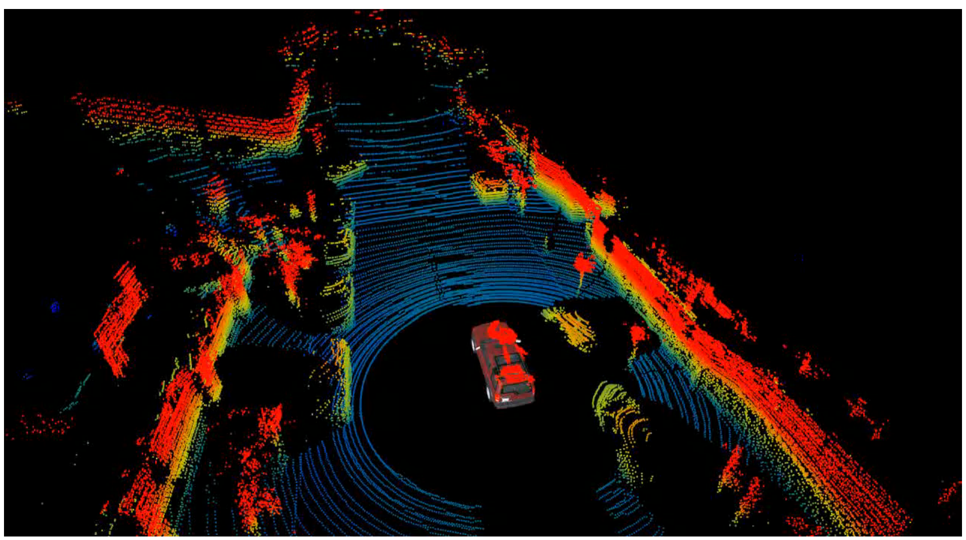
# MIT DARPA Urban Challenge Team (2006-2007)

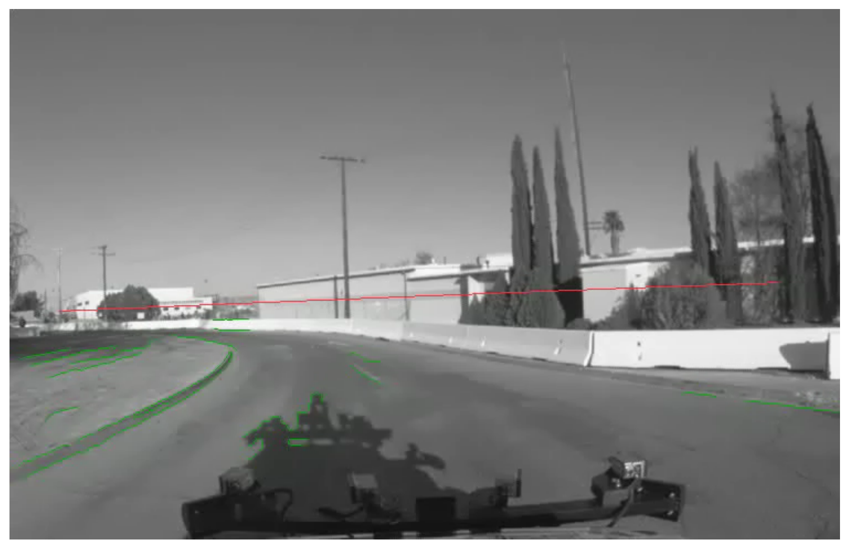
# Robocars (The Science Channel, Summer 2008)

2007 DARPA Urban Challenge

# MIT DARPA Urban Challenge Team (2006-2007)

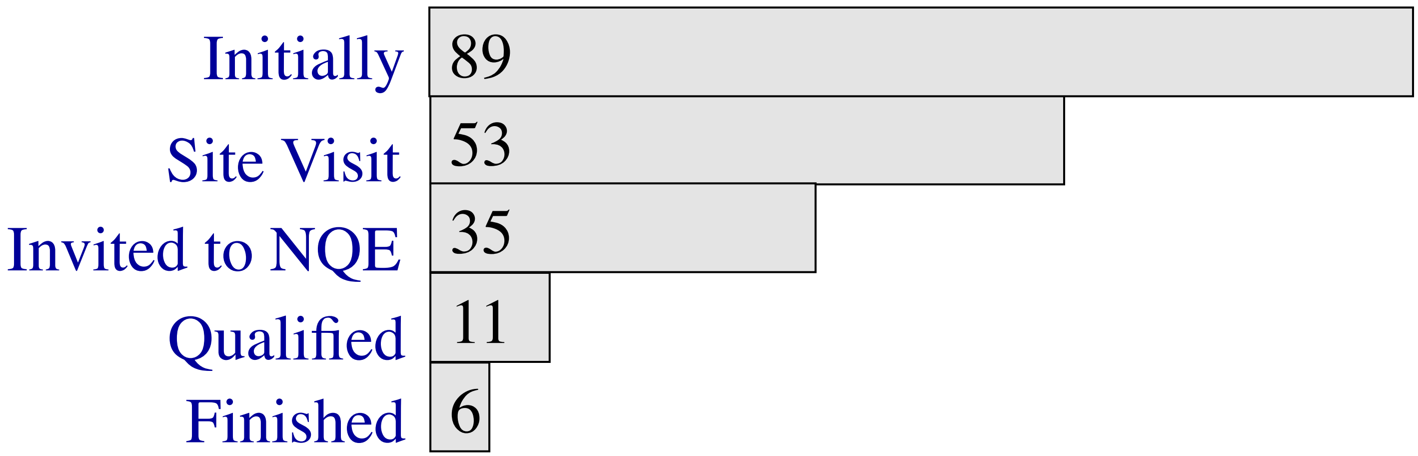


Leonard et al., JFR 2008 ; Karaman and Frazzoli, IJRR 2011; Huang et al., AR 2009

# MIT Land Rover LR3 (Talos)

- Blade cluster
  - 10 blades each with two 2.33GHz dual-core processors → 40 cores
- A **lot** of sensors
  - Applanix IMU/GPS
  - 12 SICK Lidars
  - Velodyne (~64 Lidars)
  - 15 radars
  - 5 cameras
- 6 kW generator

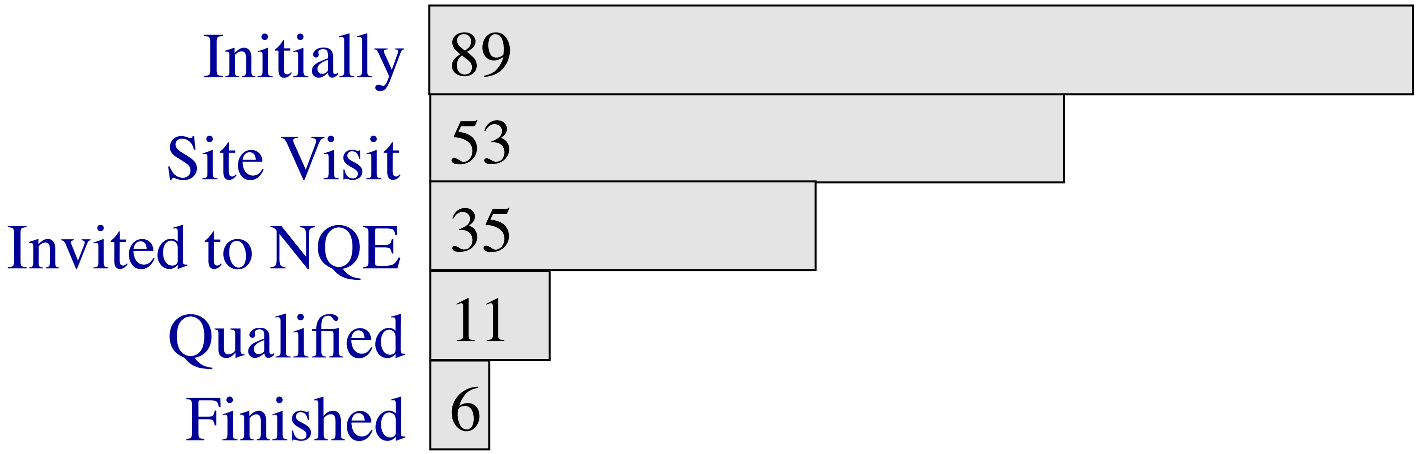

# 2007 Urban Challenge Results



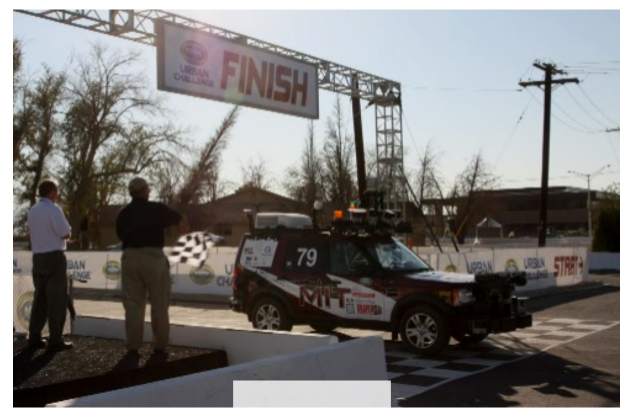


CMU 1st place | Stanford 2nd place | Virginia Tech 3rd place

# 2007 Urban Challenge Results








CMU
1st place

Stanford
2nd place

Virginia Tech
3rd place

MIT
4th place

# 2007 DARPA Urban Challenge – Collision between MIT and Cornell

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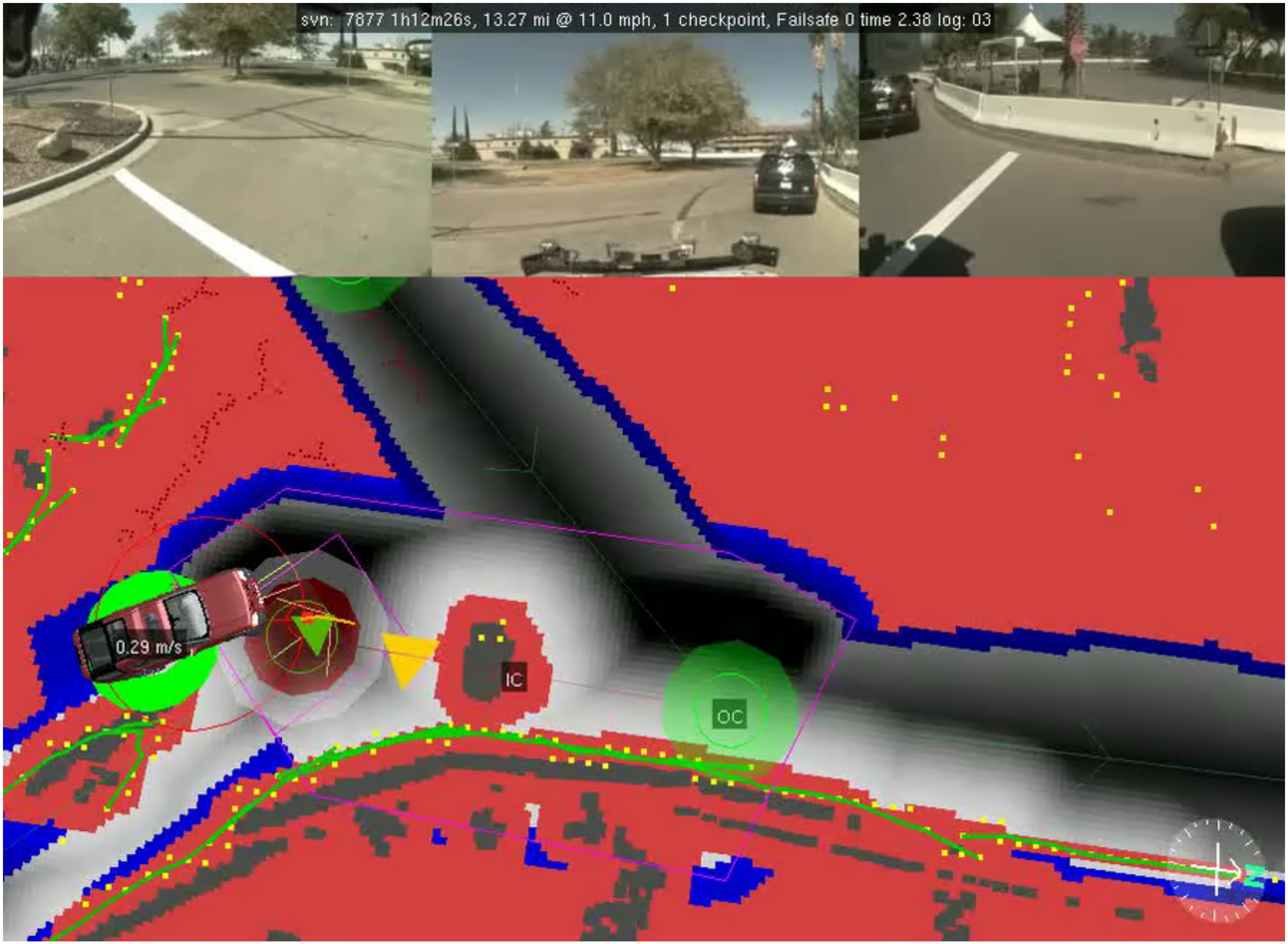
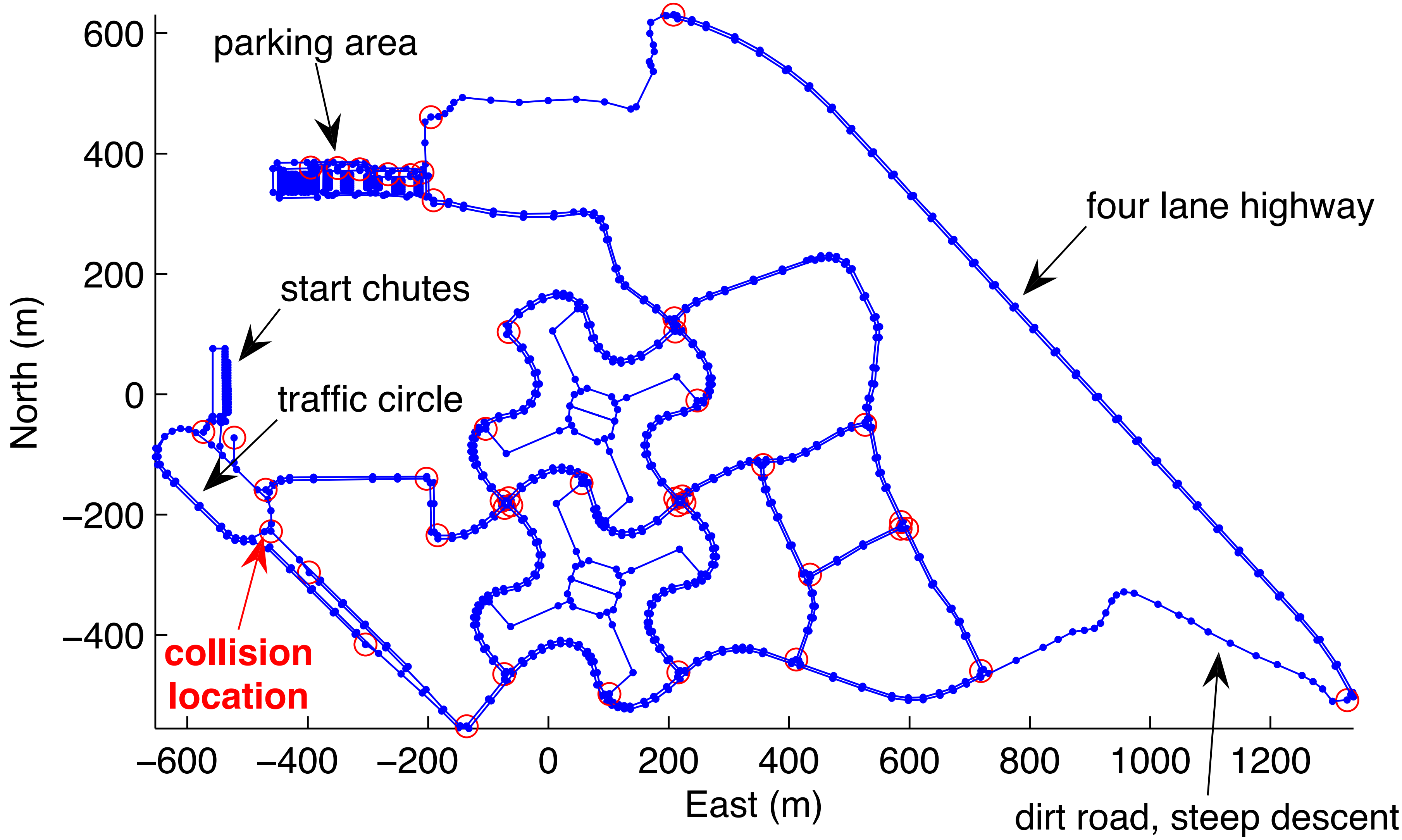


# 2007 DARPA Urban Challenge – Collision between MIT and Cornell


L. Fletcher, S. Teller, E. Olson, D. Moore, Y. Kuwata, J. How, J. Leonard, I. Miller, M. Campbell, D. Huttenlocher, and others, "The MIT–Cornell collision and why it happened." In Journal of Field Robotics, 25(10), pages 775-807. 2008.

# Second robot-to-robot car accident in history (MIT and Cornell)

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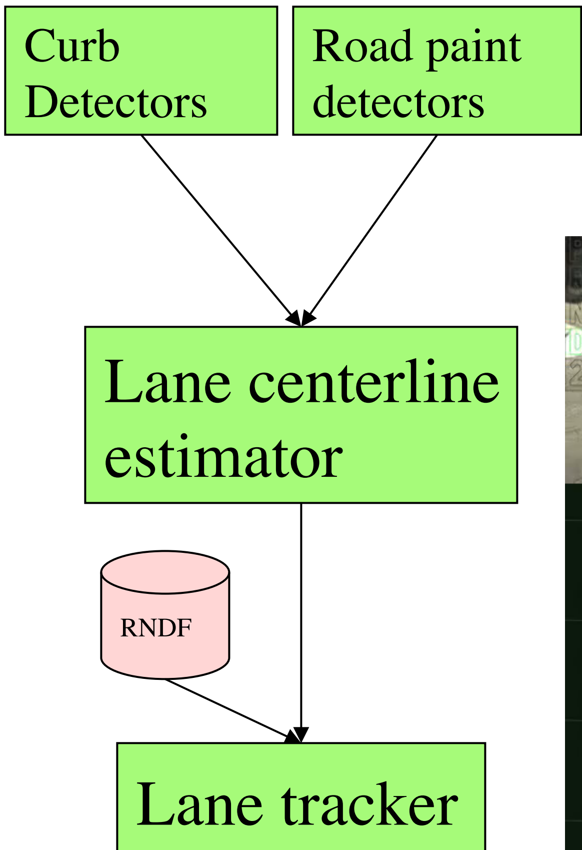
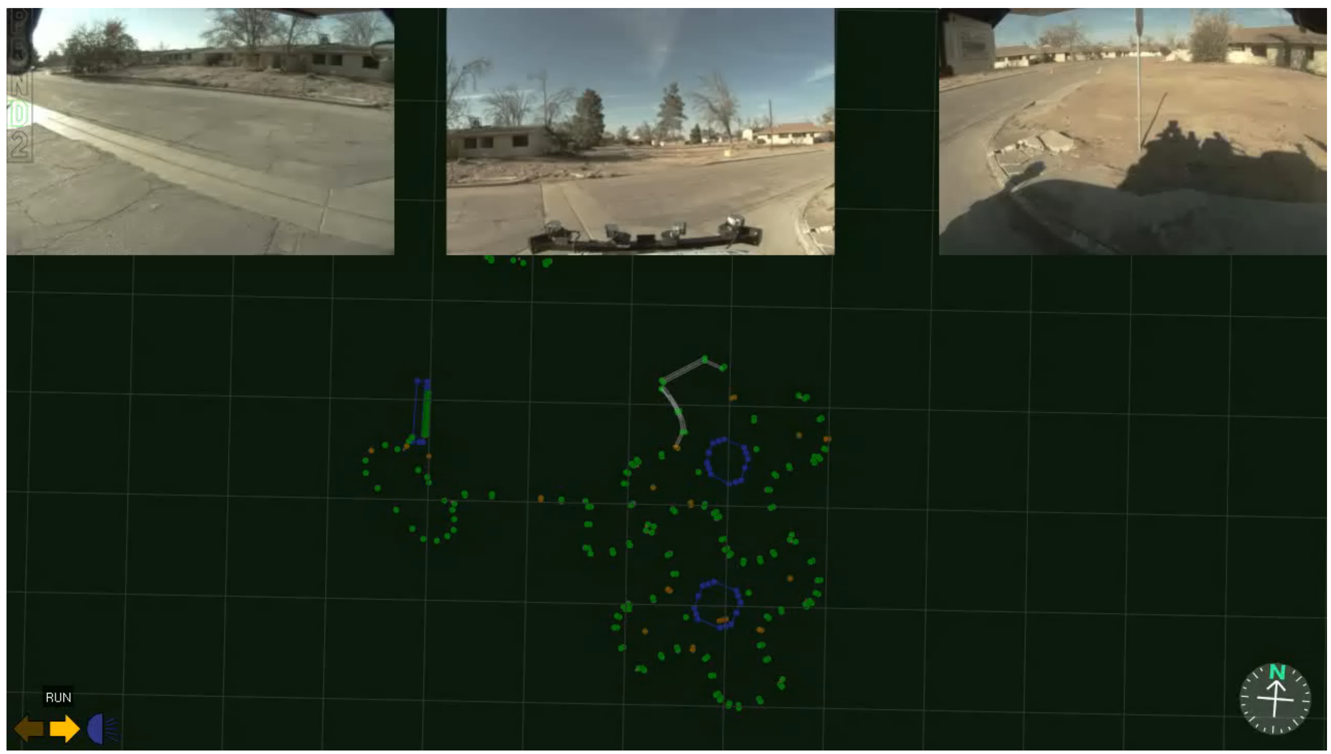
# Perception-based Navigation (Albert Huang & Seth Teller)



# Alternative: Localization using an *a priori* High Definition map


Courtesy: https://plus.google.com/+GoogleSelfDrivingCars/videos

New York Times Oct 9th, 2010

SMARTER THAN YOU THINK

# Google Cars Drive Themselves, in Traffic

Ramin Rahimian for The New York Times

Dmitri Dolgov, a Google engineer, in a self-driving car parked in Silicon Valley after a road test.

By JOHN MARKOFF
Published: October 9, 2010

MOUNTAIN VIEW, Calif. — Anyone driving the twists of Highway 1 between San Francisco and Los Angeles recently may have glimpsed a Toyota Prius with a curious funnel-like cylinder on the roof. Harder to notice was that the person at the wheel was not actually driving.

New York Times Oct 9th, 2010

## Autonomous Driving

Google's modified Toyota Prius uses an array of sensors to navigate public roads without a human driver. Other components, not shown, include a GPS receiver and an inertial motion sensor.

**LIDAR**
A rotating sensor on the roof scans more than 200 feet in all directions to generate a precise three-dimensional map of the car's surroundings.

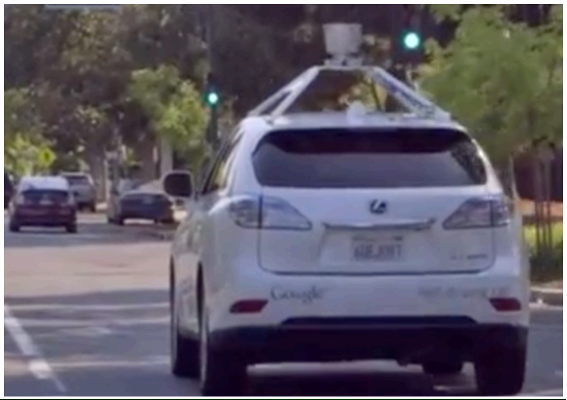
**POSITION ESTIMATOR**
A sensor mounted on the left rear wheel measures small movements made by the car and helps to accurately locate its position on the map.


**VIDEO CAMERA**
A camera mounted near the rear-view mirror detects traffic lights and helps the car's onboard computers recognize moving obstacles like pedestrians and bicyclists.

**RADAR**
Four standard automotive radar sensors, three in front and one in the rear, help determine the positions of distant objects.

Source: Google

THE NEW YORK TIMES; PHOTOGRAPHS BY RAMIN RAHIMIAN FOR THE NEW YORK TIMES

# Google Self-Driving Car Project Timeline

- Jan, 2009 to Oct, 2010 – “Clandestine” Phase
  - Autonomous execution of ten 100-mile routes
  - 140,000 miles driven; “outed” by J. Markoff
- Oct, 2010 to Mar, 2012 – Prius phase
  - Thrun TED Talk; Thrun NY Times Op Ed article
  - Steve Mahan / Taco Bell video
- Apr, 2012 to Sep (approx), 2013 – “Chauffer
  - Highway driving trial with 140 Googlers
  - “Attention problem” identified
- Oct, 2013 (approx) to April, 2014 – City driving
- May, 2014 to present – “Level 4” vehicles (25 mph)
- December, 2016 – spinout of Waymo, partnerships

Images from Google Self-Driving Car Youtube/Google+ Pages

# Tesla CEO Elon Musk and Nvidia CEO Jen-Hsun Huang declare self-driving cars “solved”

by Bradley Berman   MARCH 18, 2015, 2:41 PM EDT

Fortune article by Bradley Burman, published on March 18, 2015

*“Tesla’s Musk minimized the challenges necessary to achieve a future where self-driving cars will become commonplace. `I view it as a solved problem’, said Musk,* ***who compared autonomous cars with elevators*** *that used to require operators, but are now self-service.”*

2016 Tesla Autopilot – 2nd generation system (8 cameras)


http://youtube.com/watch?v=hLaEV72elj0

Fall, 2016

# Potential Benefits of Self-Driving Vehicles

- Safety
  - Over 5 Million vehicle crashes per year in the US
  - 93% of accidents have human error as a primary factor
  - Over 30,000 fatalities in the US due to traffic accidents per year
- Increased Road Network Efficiency
- Recovery of Time Lost due to Commuting
- Reduced Need for Parking in Cities
- Radically New Models for Personal Mobility and the Distribution of Goods and Services

"Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations" Daniel J. Fagnant and Kara M. Kockelman, Eno Center for Transportation, October 2013

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- An Introduction to Self-Driving Vehicles
- **Technical Challenges and Opportunities**
- Mapping and Localization
- Database Technology and Self-Driving Vehicles

# Questions for Self-Driving Vehicles

- Technological
- Economic
- Employment
- Ethical
- Legal
- Security
- Energy and the environment

MIT Technology Review

NEWS & ANALYSIS FEATURES VIEWS

46 COMMENTS

FEATURED STORY

**October, 2013**

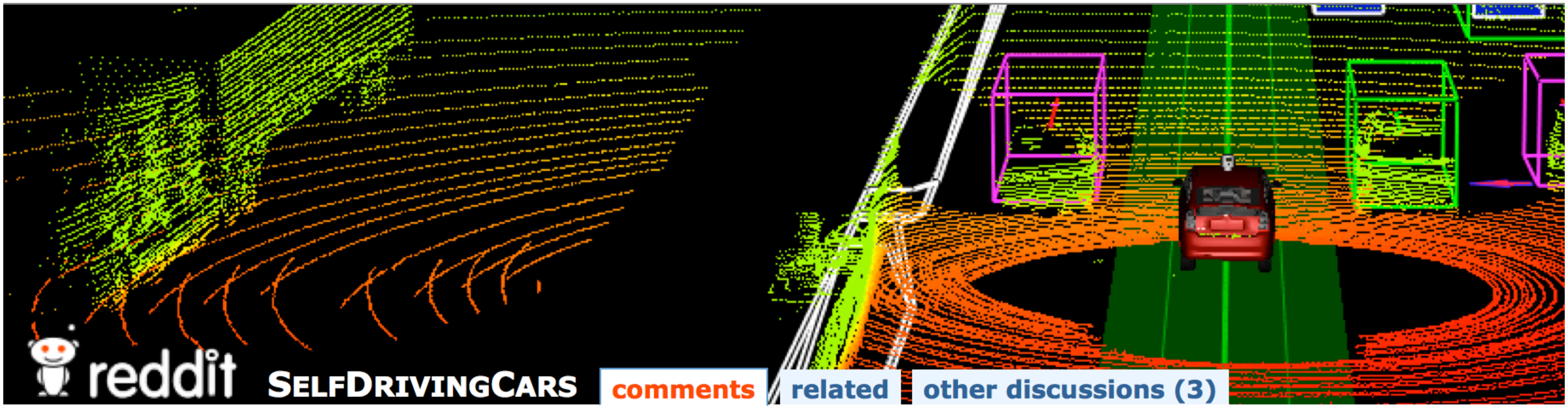
# Driverless Cars Are Further Away Than You Think

By Will Knight on October 22, 2013

Before traveling to Germany, I visited John Leonard, an MIT professor who works on robot navigation, to find out more about the limits of vehicle automation. Leonard led one of the teams involved in the DARPA Urban Challenge, an event in 2007 that saw autonomous vehicles race across mocked-up city streets, complete with stop-sign intersections and moving traffic. The challenge inspired new research and new interest in autonomous driving, but Leonard is restrained in his enthusiasm for the commercial trajectory that autonomous driving has taken since then. “Some of these fundamental questions, about representing the world and being able to predict what might happen – we might still be decades behind humans with our machine technology,” he told me. “There are major, unsolved, difficult issues here. We have to be careful that we don’t overhype how well it works.”

http://www.technologyreview.com/featuredstory/520431/driverless-cars-are-further-away-than-you-think/

MY SUBREDDITS FRONT - ALL - RANDOM | PICS - FUNNY - GAMING - ASKREDDIT - WORLDNEWS - NEWS - VIDEOS - IAMA - TODAYILEARNED - WTF - AWW - TECHNOLO

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A Test Drive of the Most Advanced Driverless Cars (technologyreview.com)

submitted 14 days ago by walky22talky

**21 comments** **share**

## all 21 comments

sorted by: **best**

[–] **walky22talky** [S] 7 points 14 days ago

> MIT's John Leonard, for one, does not believe total autonomy is imminent. "I do not expect there to be taxis in Manhattan with no drivers in my lifetime,"

Talk about a Debby downer. He is not even 50 years old.

**permalink**

[–] **ShadowRam** 6 points 14 days ago

> MIT's Leonard, for one, does not believe total autonomy is imminent. "I do not expect there to be taxis in Manhattan with no drivers in my lifetime," he said, before quickly adding, "And I don't want to see taxi drivers out of business. They know where they're going, and—at least in Europe—they're courteous and safe, and they get you where you need to be. That's a very valuable societal role."

Sounds more like someone that is afraid of the technology and has trust issues with machines.

**permalink** **parent**

http://www.reddit.com/r/SelfDrivingCars/

# Difficult Situations for Self-Driving Vehicles

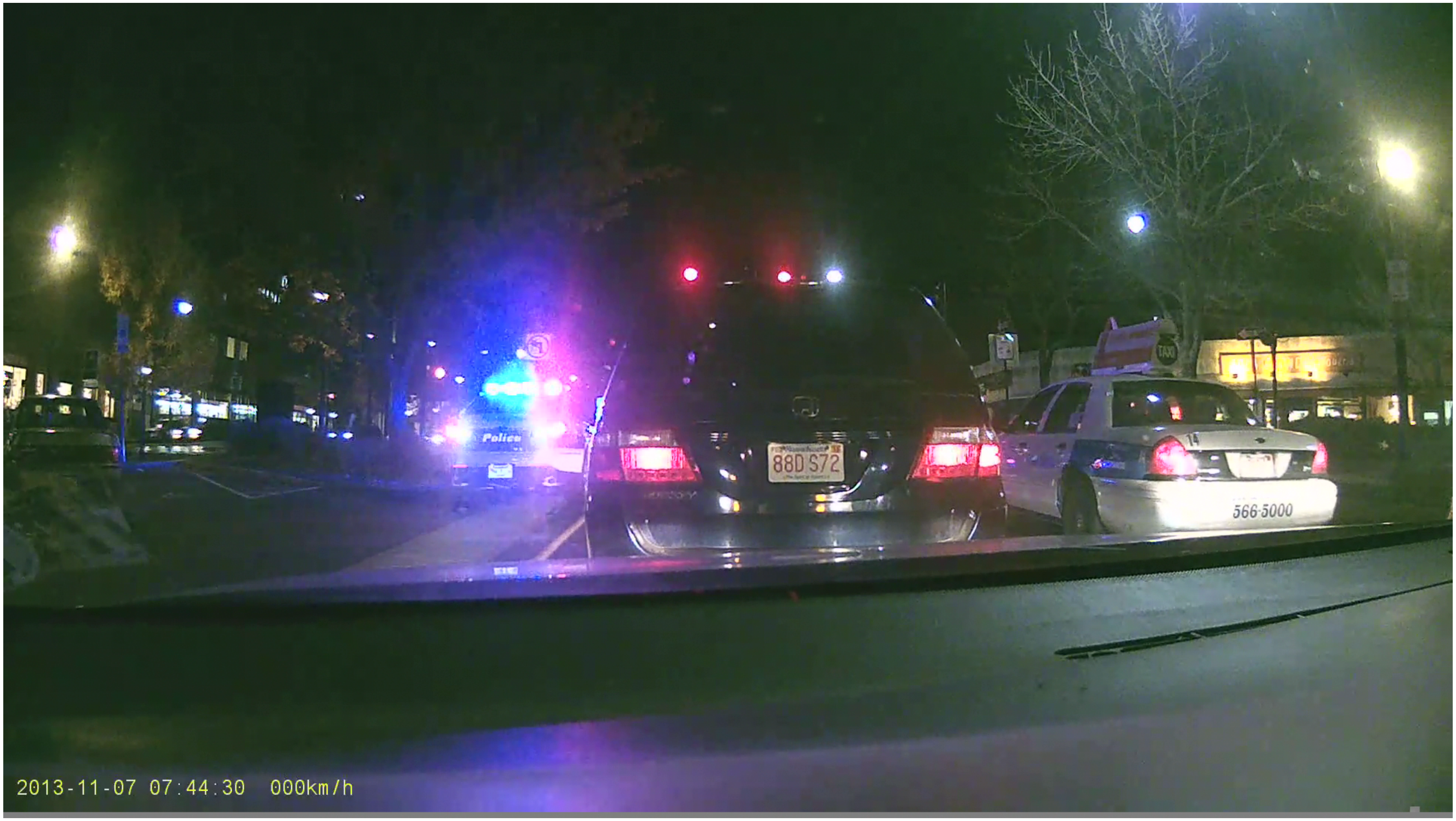
Left turn across traffic



Traffic cops, crossing guards, police/fire


Changes to road surface markings

# Police Officers Directing Traffic



# What do you see in this Picture?

# Difficult Weather Conditions

# Alternative: Localization using an *a priori* High Definition map


Courtesy: https://plus.google.com/+GoogleSelfDrivingCars/videos

# Summary: The Big Questions Going Forward

Technical Challenges:

- Maintaining Maps
- Adverse Weather
- Interacting with People
- Robust Computer Vision (towards $P_D=1.0$, $P_{FA} = 0.0$)?

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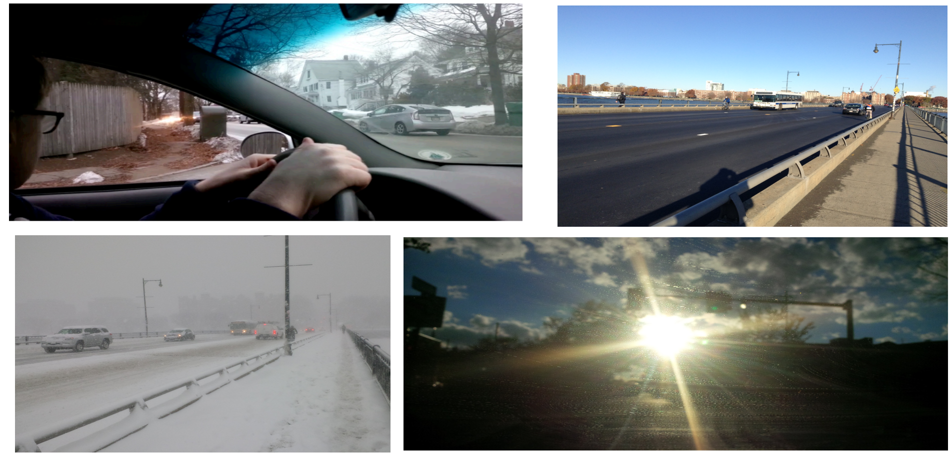

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The big question for Level 2 and Level 3 approaches?

- Can humans be trusted to take control when necessary?

# Forget the Google Car, get an S-Class and a Coke

This Active Lane Assist hack is incredible.

By Alex Kierstein July 30, 2014 / Photos by YouTube



https://www.youtube.com/watch?v=Kv9JYqhFV-M

# Humans will do stupid things


https://www.youtube.com/watch?v=zY_zqEmKV1k

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The big question for Level 2 and Level 3 approaches?

- Can humans be trusted to take control when necessary?

The big question for Level 4 approaches?

- Can near-perfect ROC curves be obtained in a wide variety of demanding settings?

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- Maintaining Maps
- Adverse Weather
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The big question for Level 2 and Level 3 approaches?

- Can humans be trusted to take control when necessary?

The big question for Level 4 approaches?

- Can near-perfect ROC curves be obtained in a wide variety of demanding settings?

Can we deploy Autonomous Vehicle technology sooner?

(Human must pay attention, but autonomy will jump in to prevent accidents)

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- An Introduction to Self-Driving Vehicles
- Technical Challenges and Opportunities
- **Mapping and Localization**
- Database Technology and Self-Driving Vehicles

SMARTER THAN YOU THINK

# Guided by Computers and Sensors, a Smooth Ride at 60 Miles Per Hour

By JOHN MARKOFF

Published: October 9, 2010





MOUNTAIN VIEW, Calif. — As we merged with freeway traffic on Highway 101, one of Silicon Valley's busiest freeways, Christopher Urmson, the man in the driver's seat, gestured, not touching the steering wheel.

Enlarge This Image

Ramin Rahimian for The New York Times

A car driven by computer hardware recently attracted the attention of a bicyclist in Mountain View, Calif.

Mr. Urmson is a Google engineer, and last Wednesday, I sat belted in the back seat as he talked and as the car, a Toyota Prius equipped by Google with radar, video, motion sensors and a GPS device, drove itself at 60 miles an hour.

My eyes were glued to the 22-inch three-dimensional color display in front of Dmitri Dolgov, an artificial intelligence researcher at Google who was riding shotgun. It showed the world around us in great detail, down to painted lane markers, stop signs, traffic lights and a sliding green column that indicated our path. A blocky yellow object representing a car was coming up behind us in the lane we were entering as the robotic, female voice of the Prius announced, "Preparing to change lane."

"Don't worry, we have plenty of room," Dr. Urmson said.

We followed a 12-mile planned route in a vehicle that looks different from the striking Google Street View cars, which are distinguished by a six-and-a-half-foot-tall camera mast.

**Smarter Than You Think**

Articles in this series are examining the recent advances in artificial intelligence and robotics and their potential impact on society.

Previous Articles in the Series »

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Smarter Than You Think: Google Cars Drive Themselves, in Traffic (October 10, 2010)

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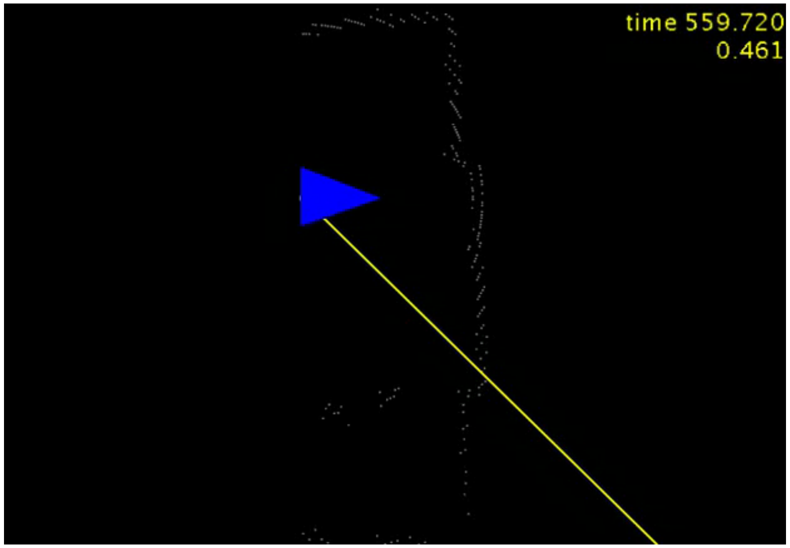
New York Times Oct 9th, 2010

## Guided by Computers and Sensors, a Smooth Ride at 60 Miles Per Hour

"One main technique used by the Google team is known as SLAM, or **simultaneous localization and mapping**, which builds and updates a map of a vehicle's surroundings while keeping the vehicle located within the map. To make a SLAM map, the car is first driven manually along a route while its sensors capture location, feature and obstacle data. Then a group of software engineers annotates the maps, making certain that road signs, crosswalks, street lights and unusual features are all embedded. The cars then drive autonomously over the mapped routes, recording changes as they occur and updating the map. The researchers said they were surprised to find how frequently the roads their robots drove on had changed."

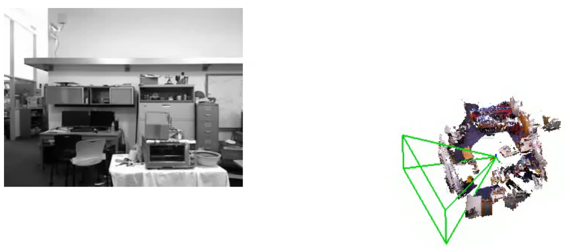
New York Times Oct 9th, 2010

# Simultaneous Localization and Mapping

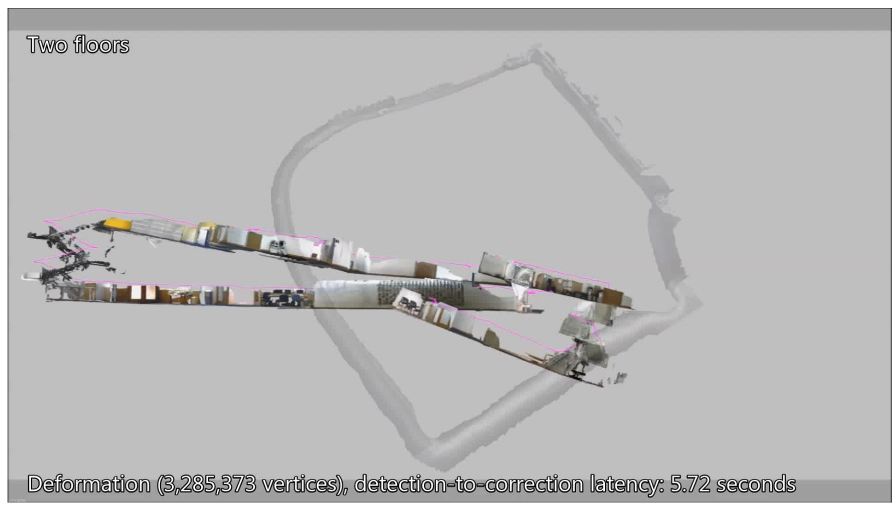



Olson, ICRA 2006

Bosse, PhD Thesis, 2003

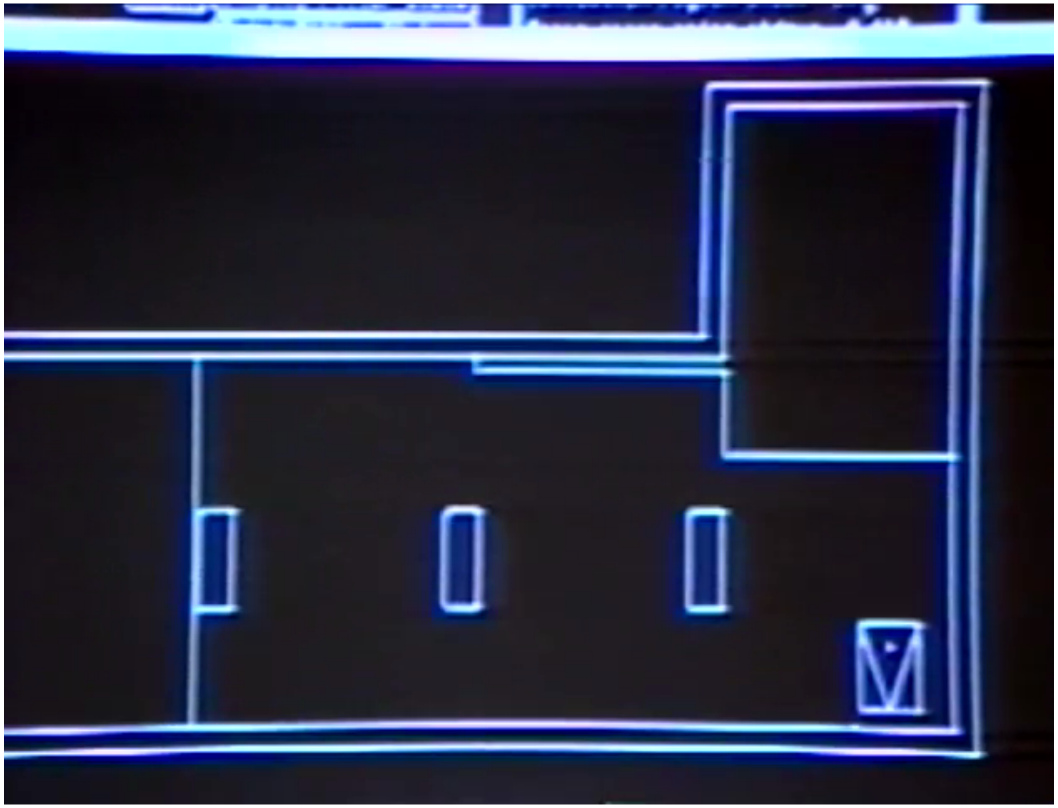


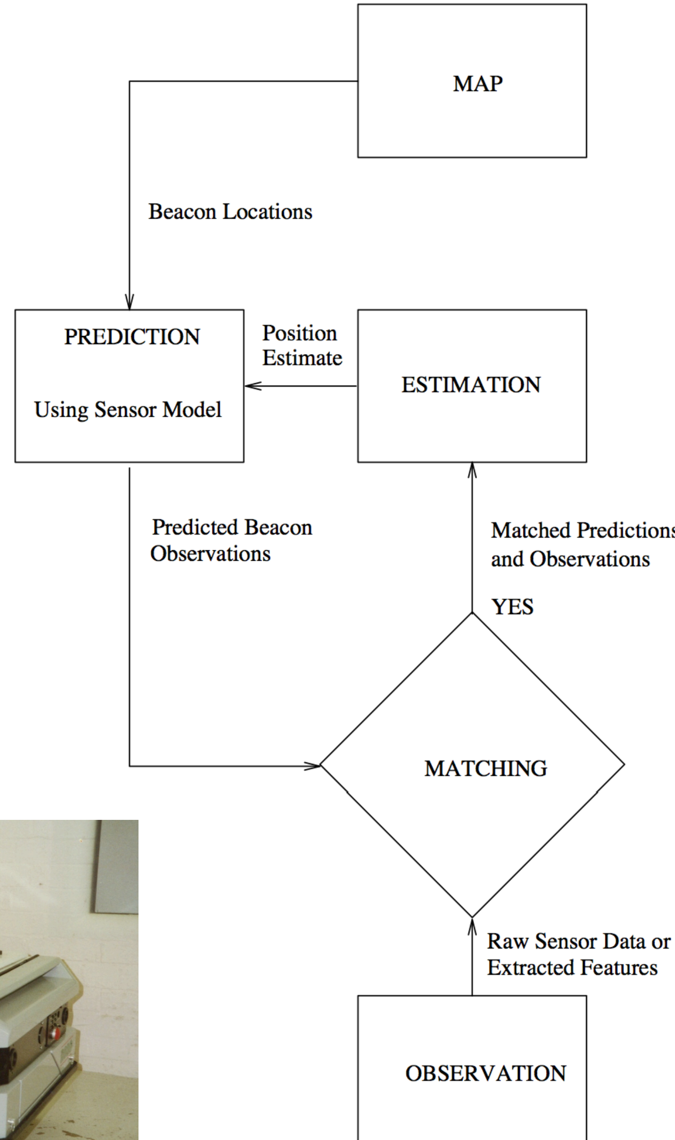
Johannsson, ICRA 2013




Whelan, IJRR 2014

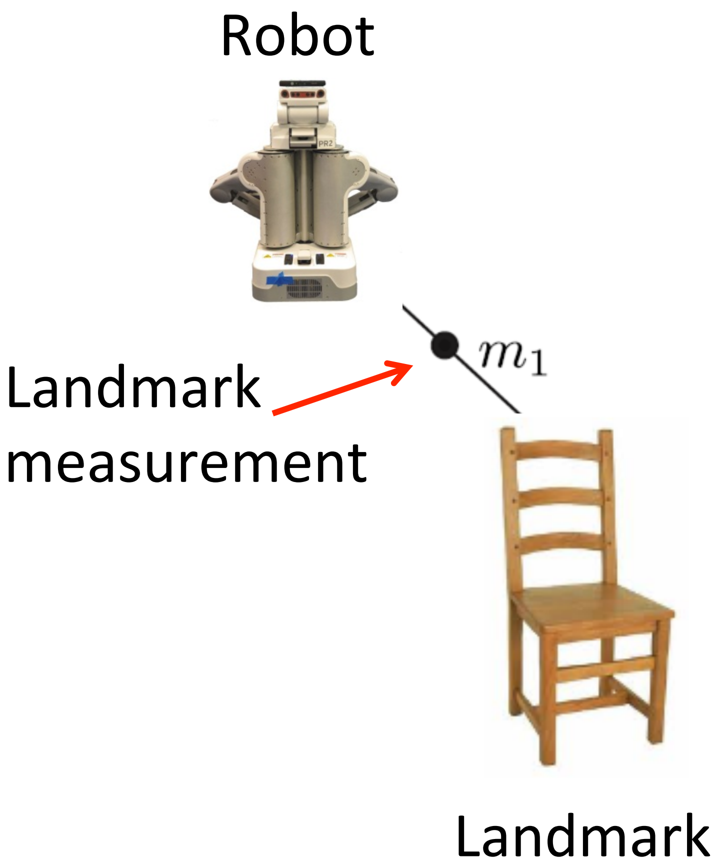
# 1987-1990: Oxford D. Phil. Thesis: Localization given an a prior map






Jenkin Building Basement, Oxford, 1990

# The Mapping Problem (t=0)

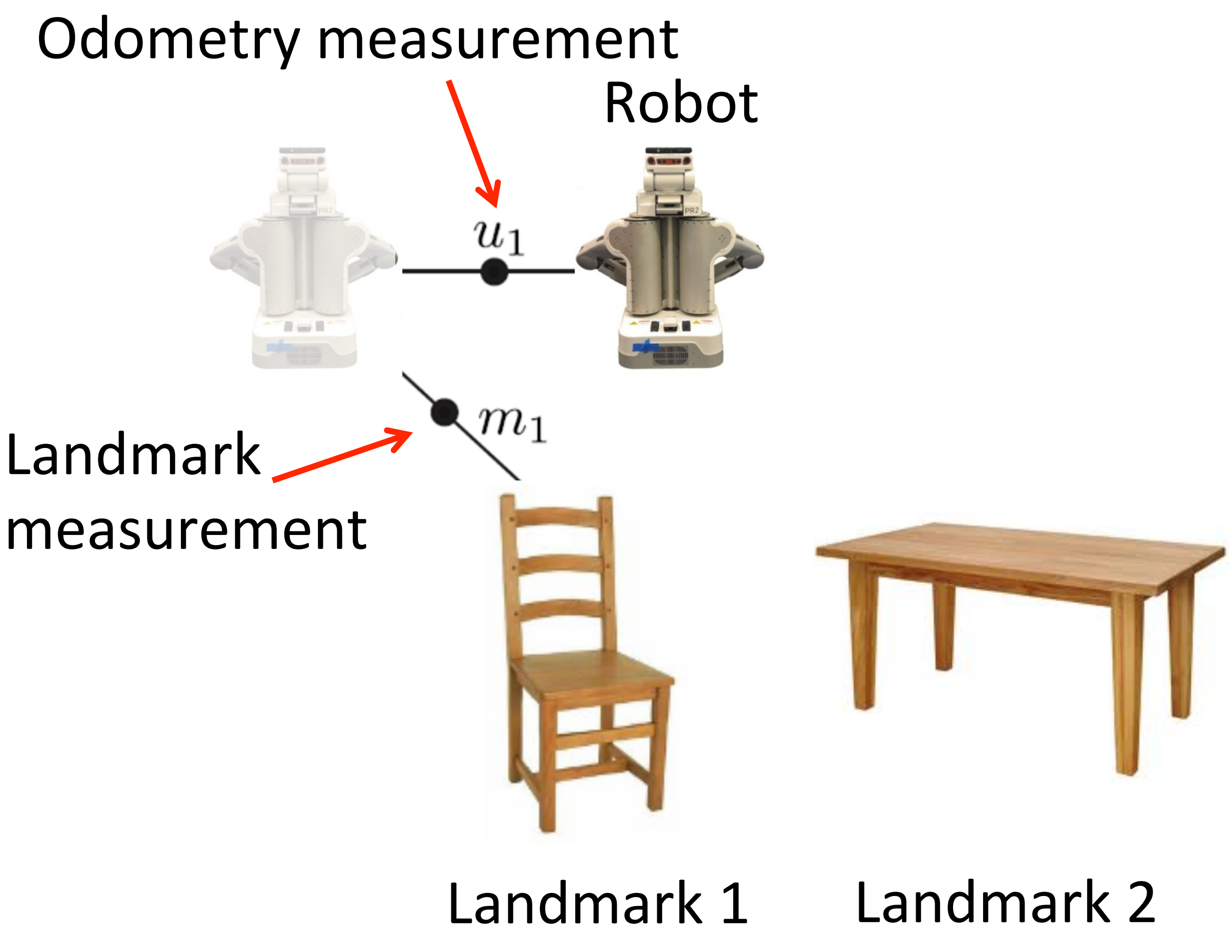



Onboard sensors:

- Wheel odometry
- Inertial measurement unit (gyro, accelerometer)
- Sonar
- Laser range finder
- Camera
- RGB-D sensors

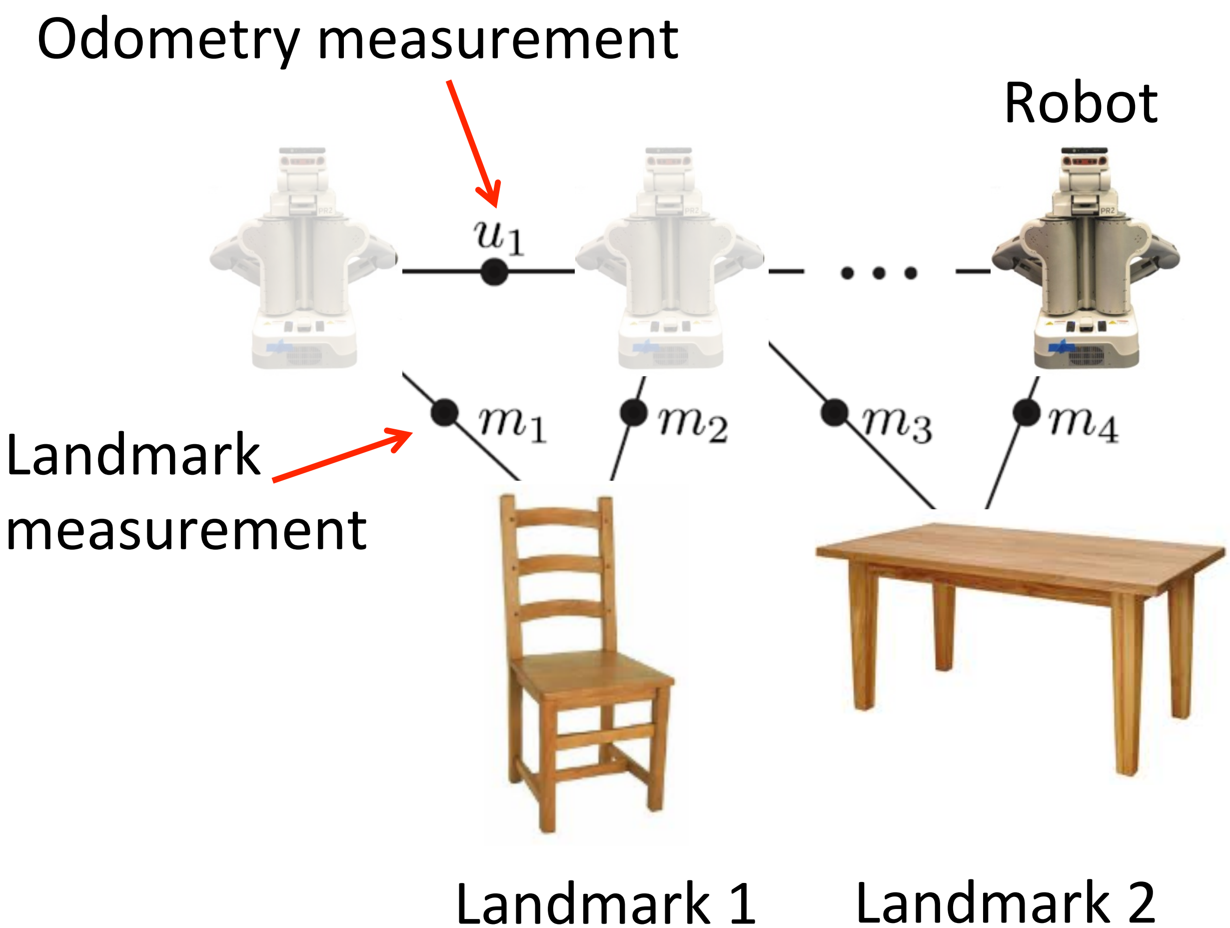
Courtesy Michael Kaess

# The Mapping Problem (t=1)



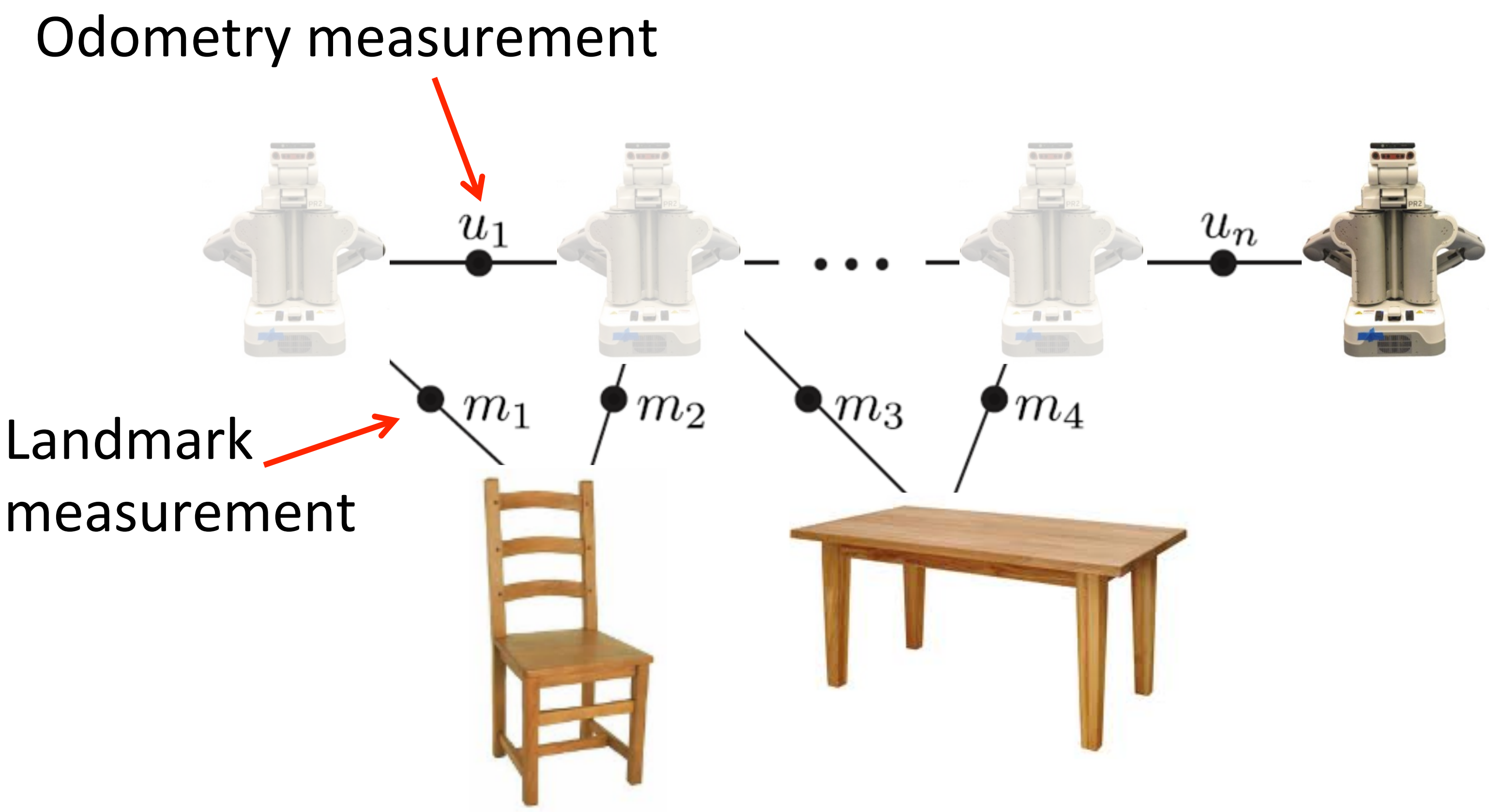

Courtesy Michael Kaess

# The Mapping Problem (t=n-1)



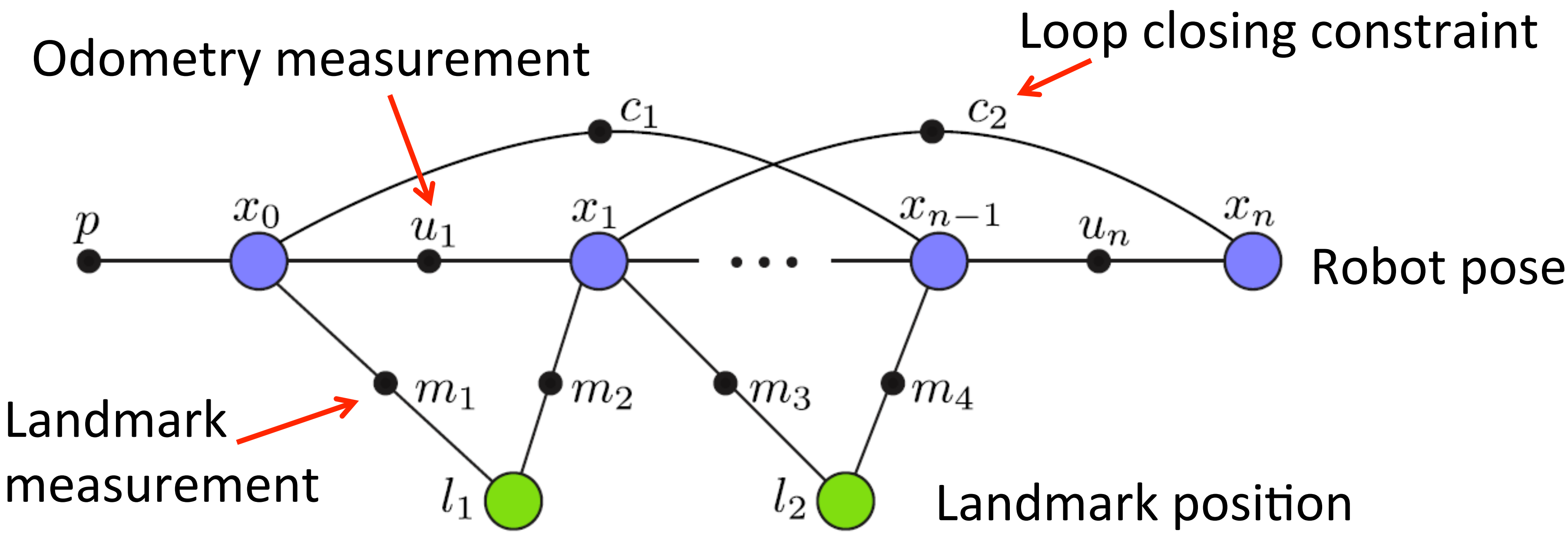

Courtesy Michael Kaess

# The Mapping Problem (t=n)

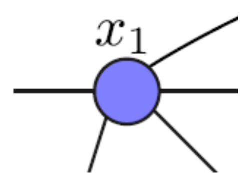


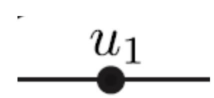

Courtesy Michael Kaess

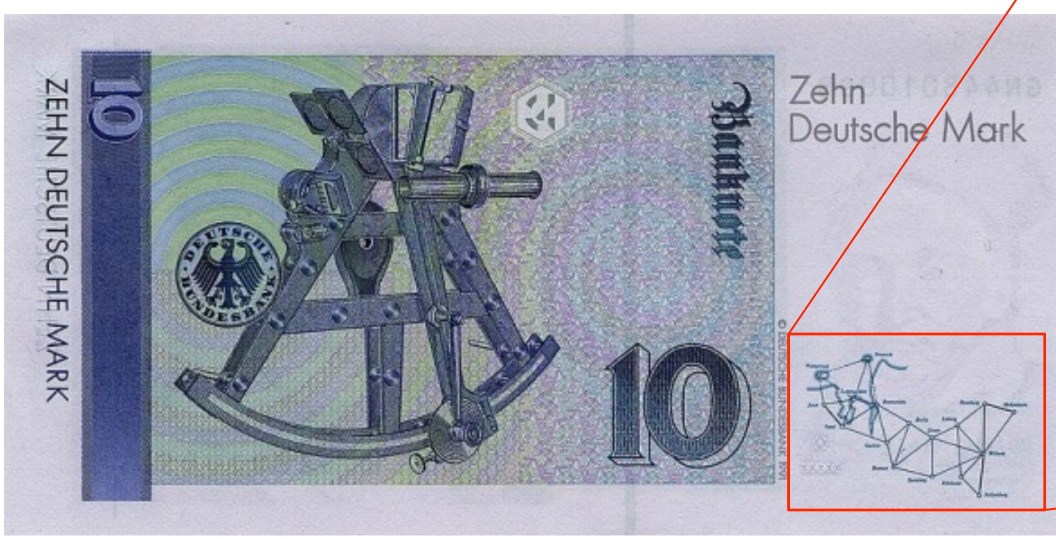
# Factor Graph Representation




Bipartite graph with ***variable nodes*** and ***factor nodes***

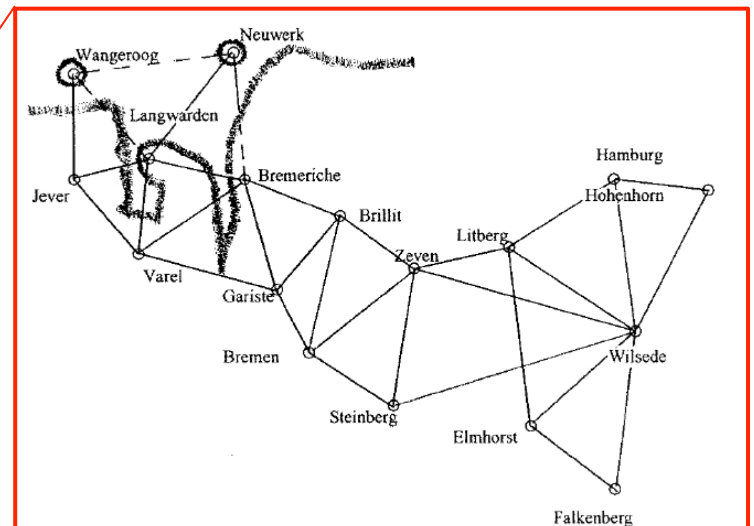


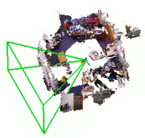



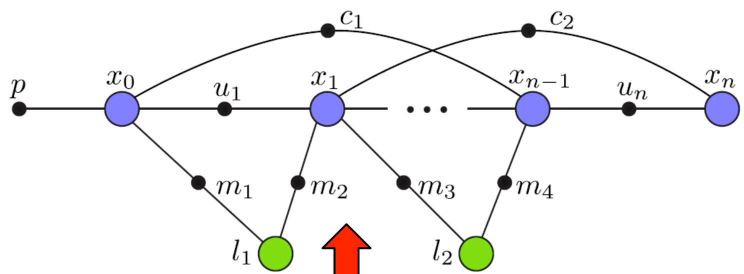

# Carl Friedrich Gauss

## 1828: Triangulation of Kingdom of Hanover



# State of the Art circa 2012: Pose Graph Optimization

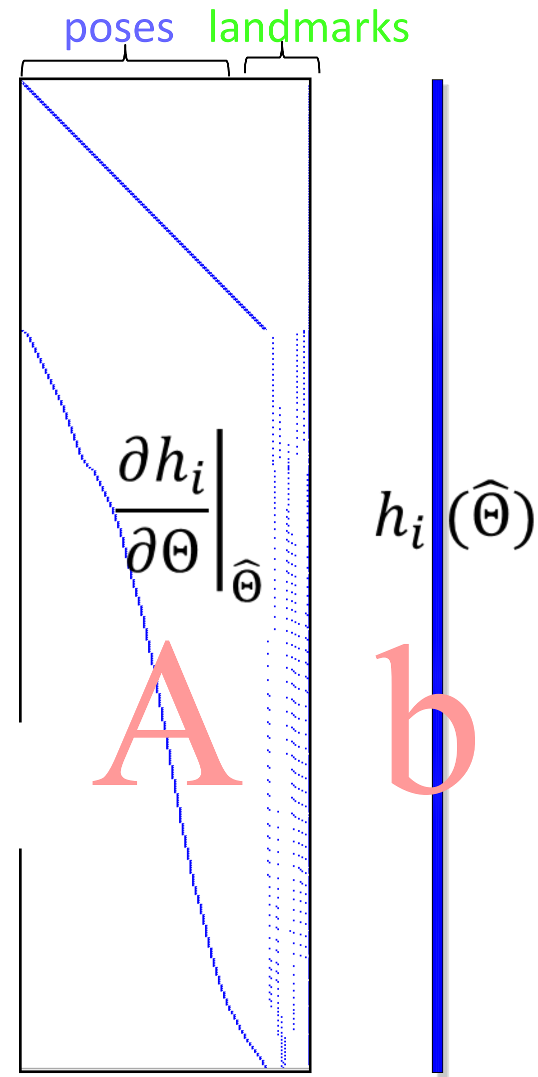





$$\text{argmax}_\Theta \prod_i p_i(\Theta)$$

$$\text{argmin}_\Theta \sum_i \|h_i(\Theta)\|_\Xi{}^2$$

$$\text{argmin}_\theta \|A\theta - b\|^2$$

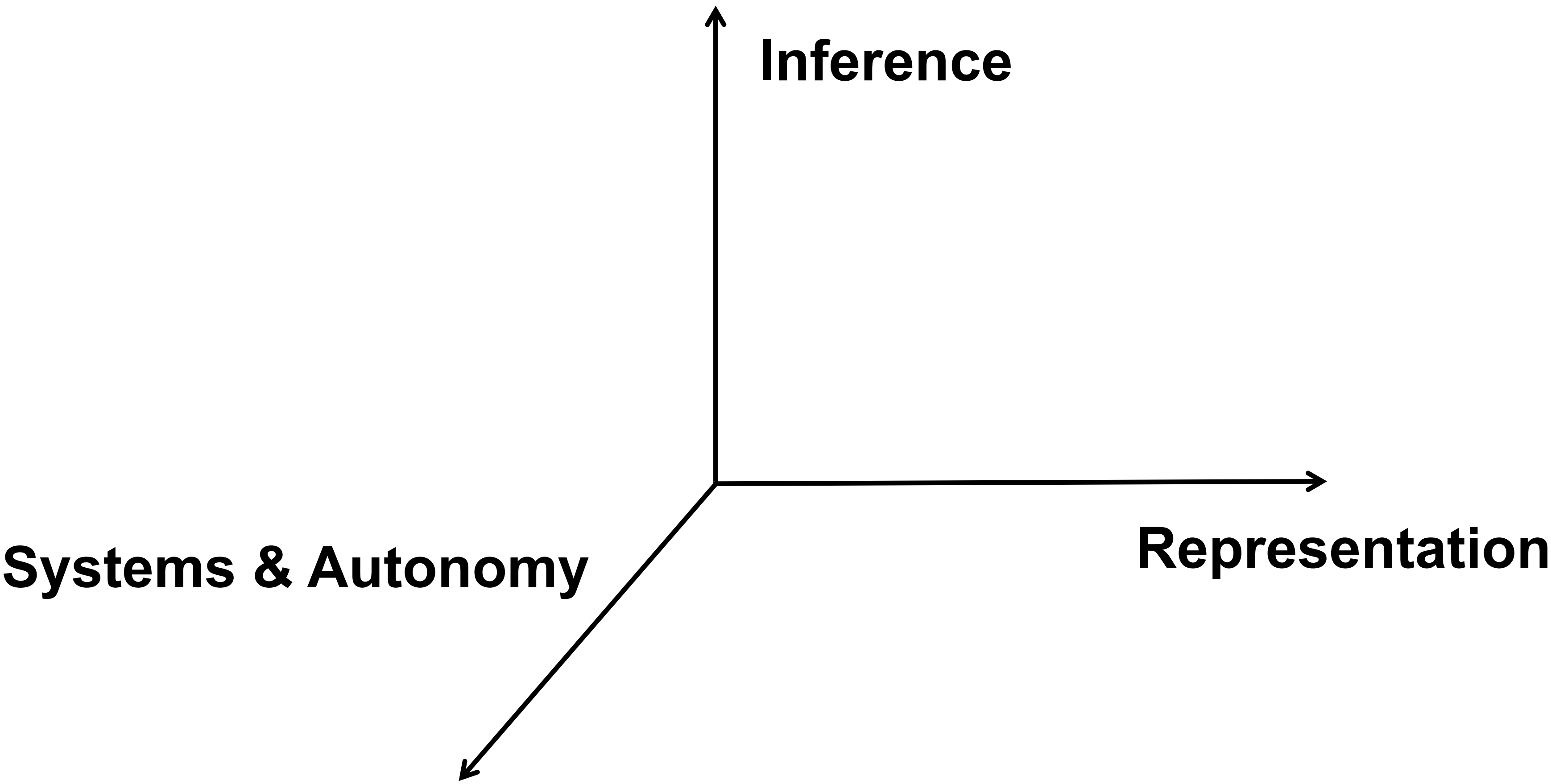



Pose Graph Optimization Algorithms:

[Lu&Milios 97, Konolige 04, Folkesson 04, Eustice 05, Frese 06, Olson 06, Dellaert 06, Grisetti et al. 10]

See Kaess et al. “iSAM2: Incremental Smoothing an Mapping Using the Bayes Tree”, IJRR 2012, for a recent state-of-the-art method incorporating fluid relinearization

# Why is SLAM Difficult?



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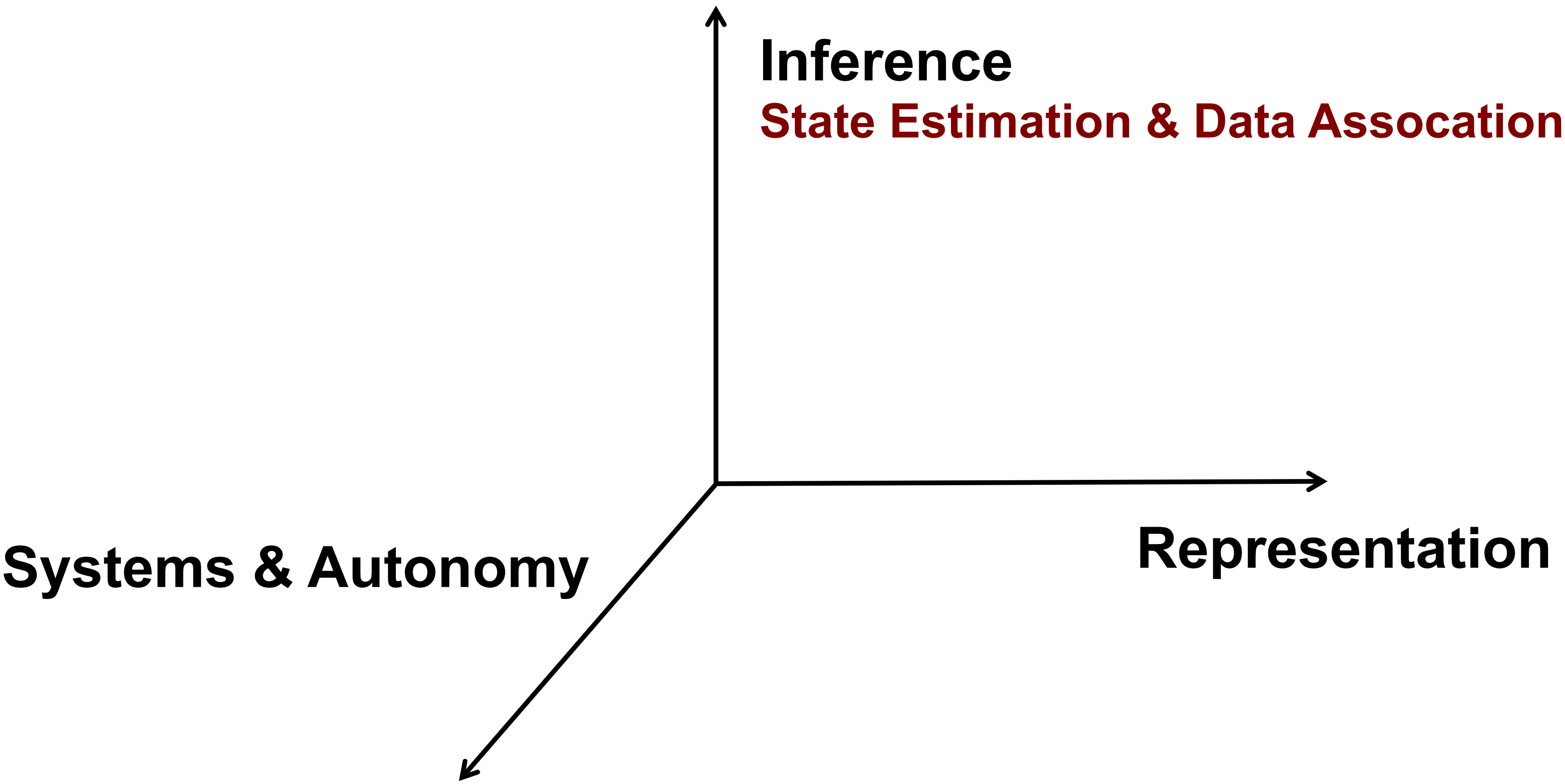

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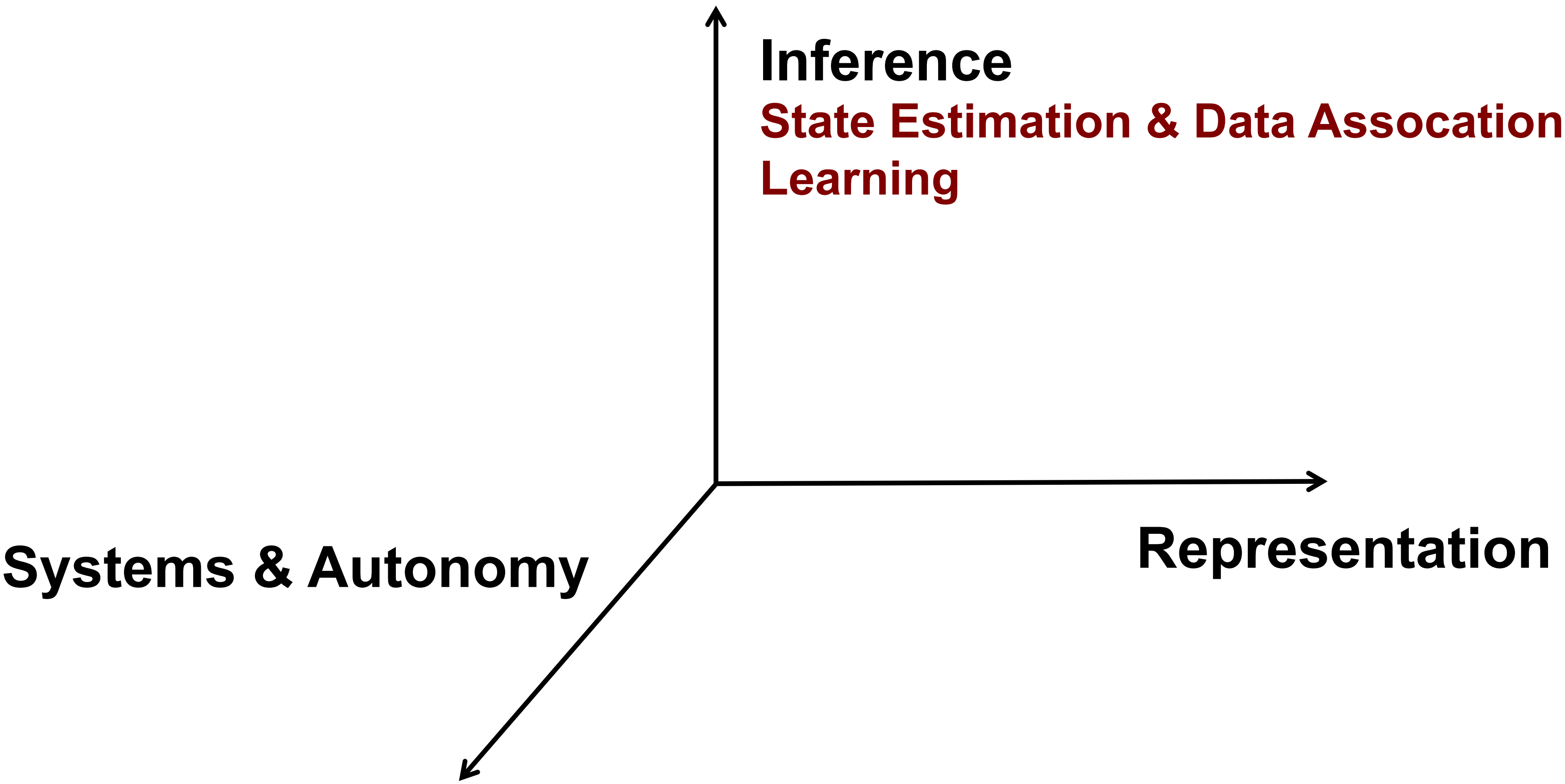
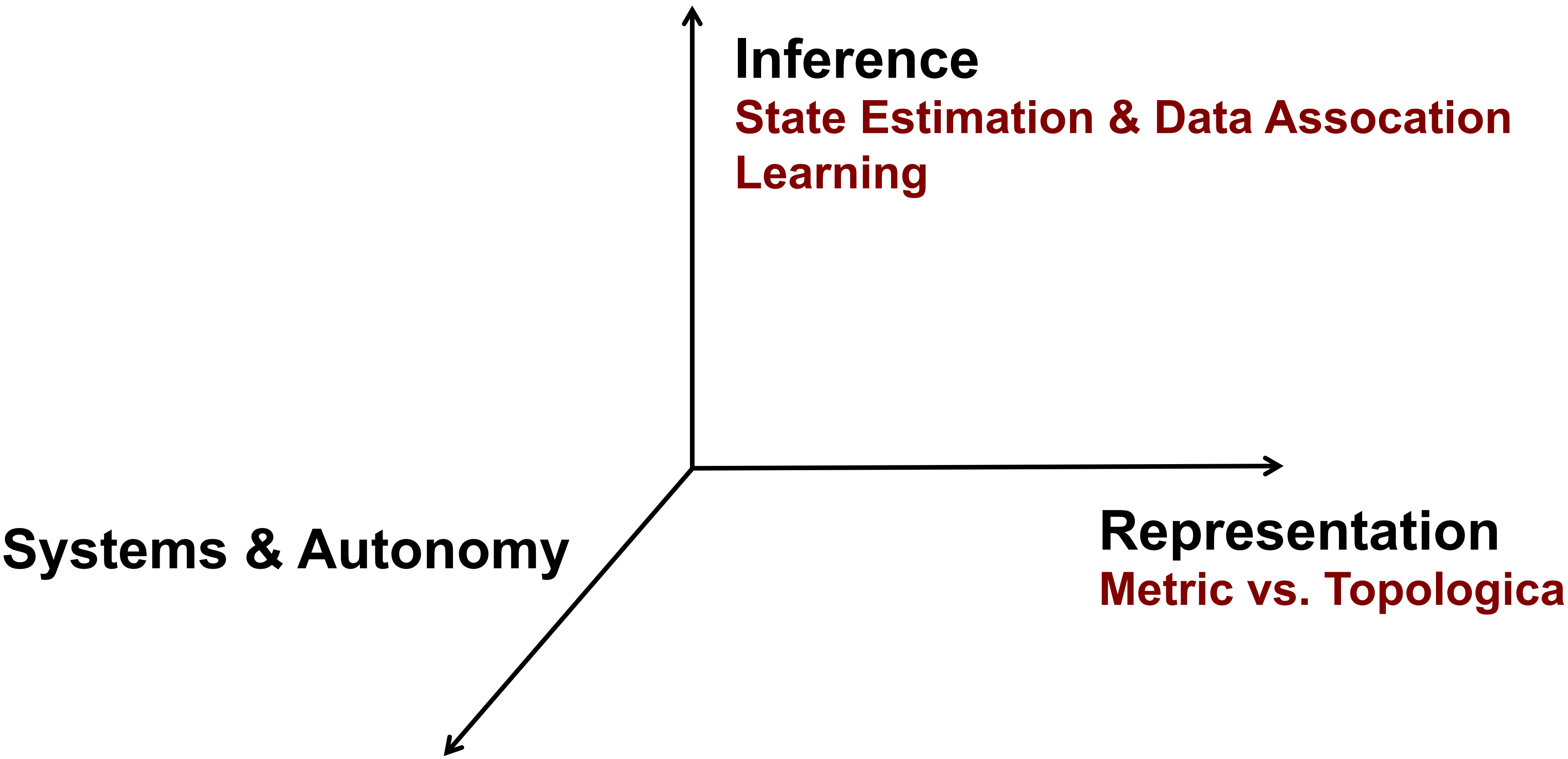


# Why is SLAM Difficult?



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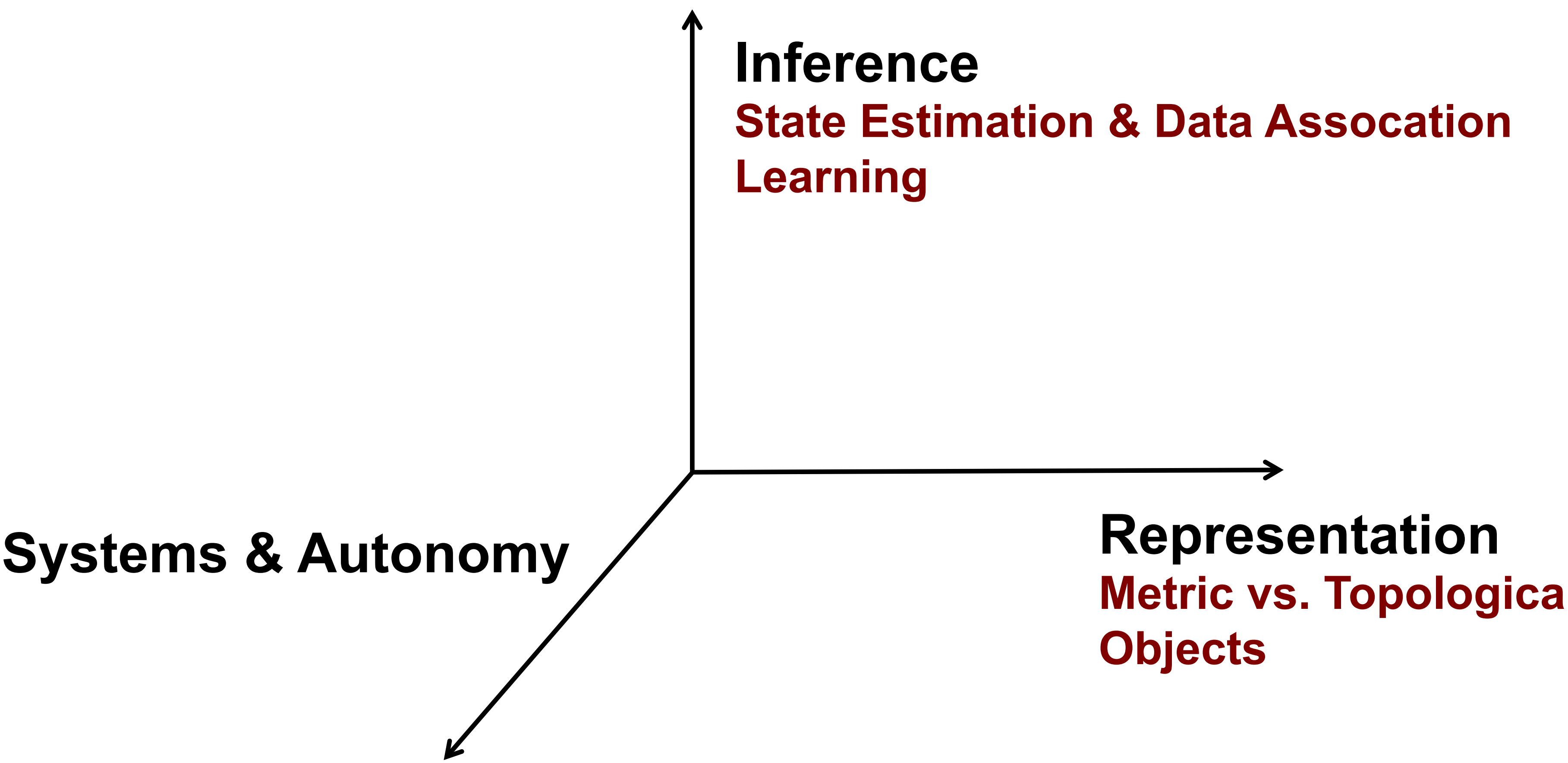

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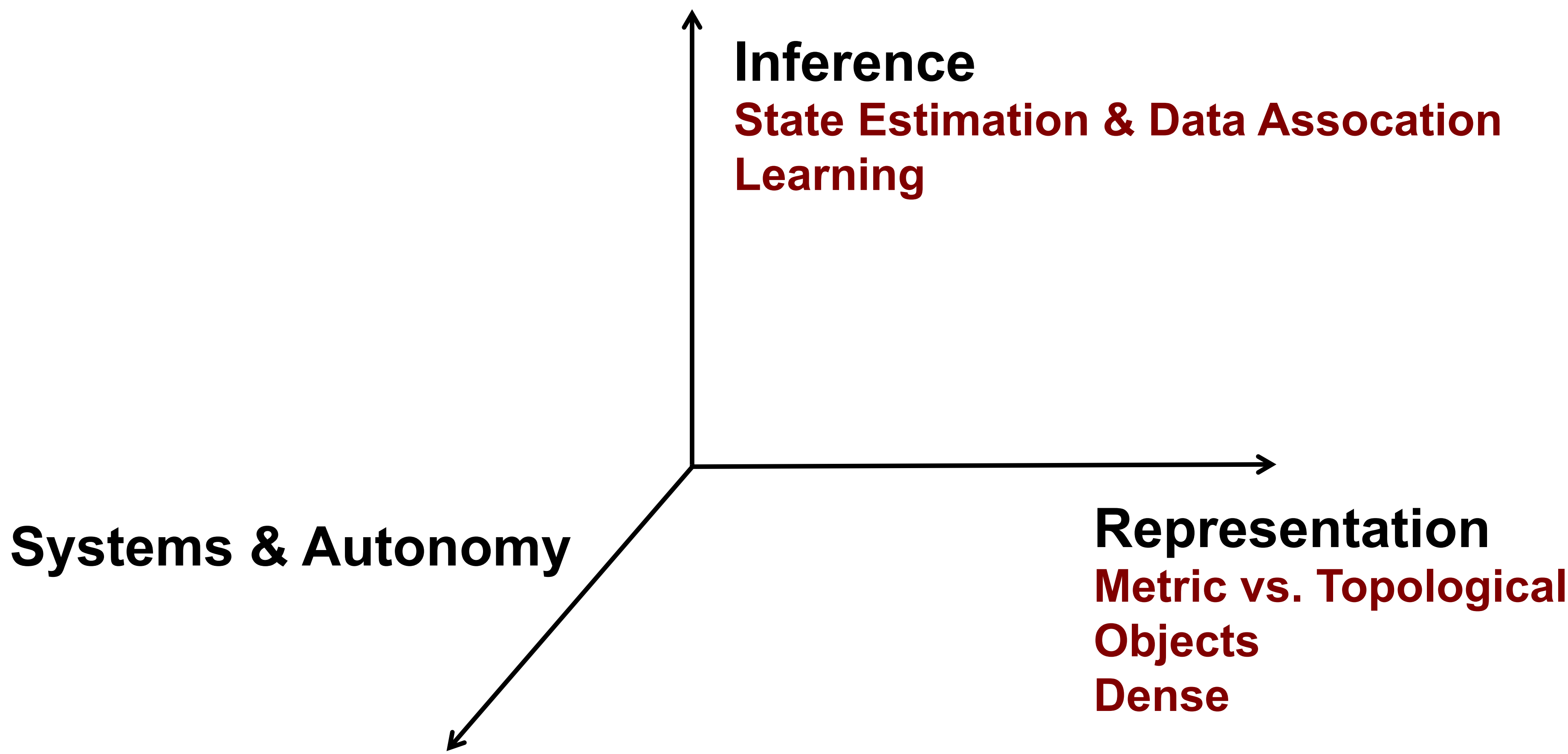

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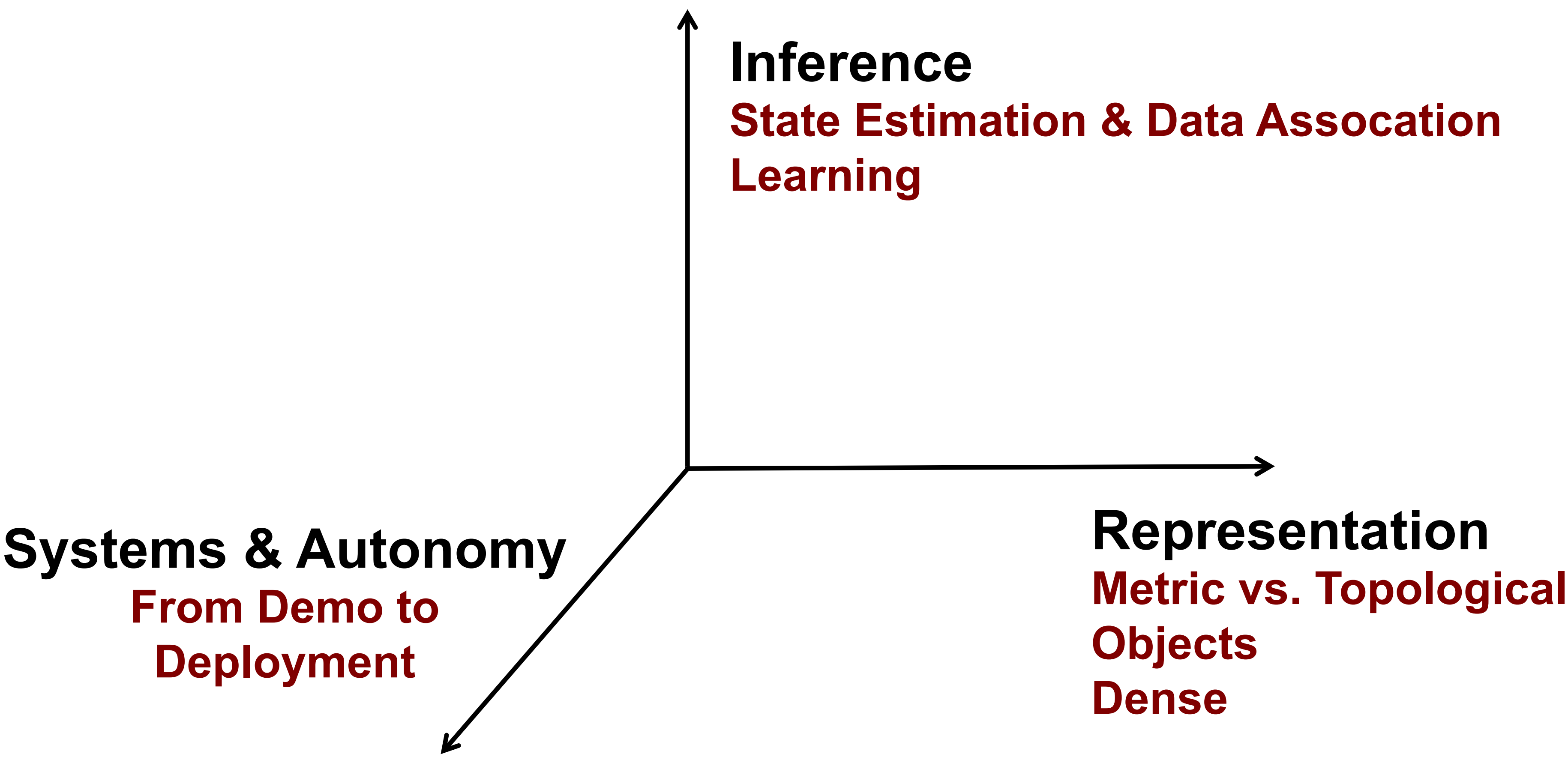


# Example: Autonomous vehicles

A car's-eye view...


Source: Google self-driving car project

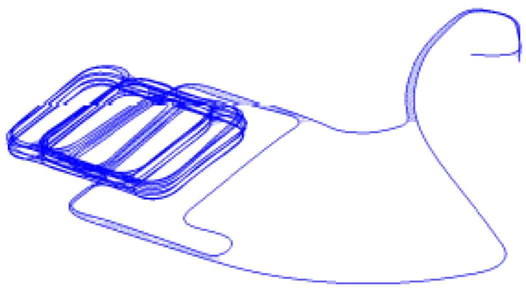
# Example: Autonomous vehicles

But what if the map is *wrong*?

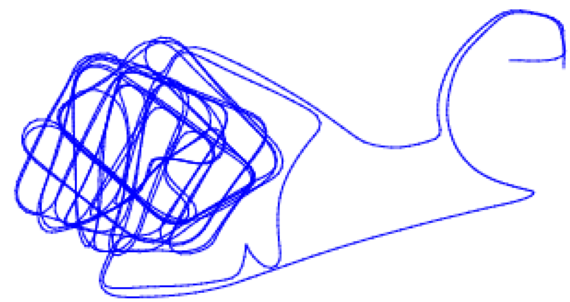

Source: Google self-driving car project

# Example: Autonomous vehicles

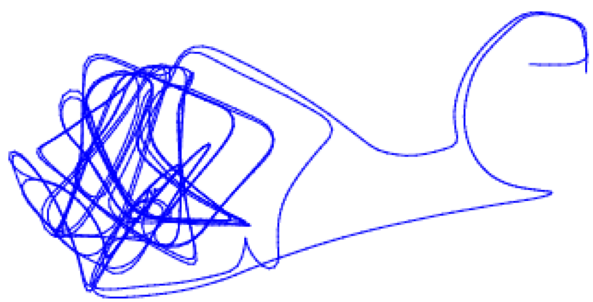
But what if the map is *wrong*?



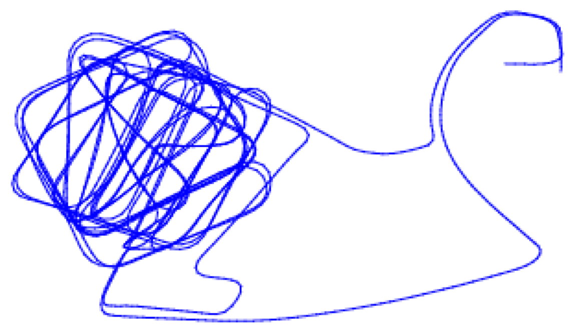
Correct solution



Wrong estimate



Wrong estimate

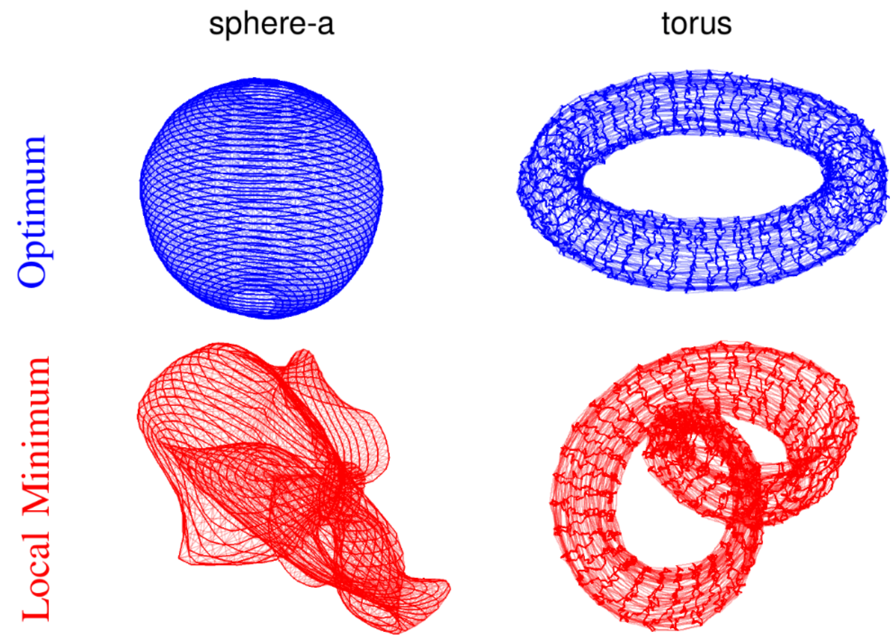


Wrong estimate

# MIT PhD Thesis of David Rosen (August, 2016) Certifiably Correct SLAM

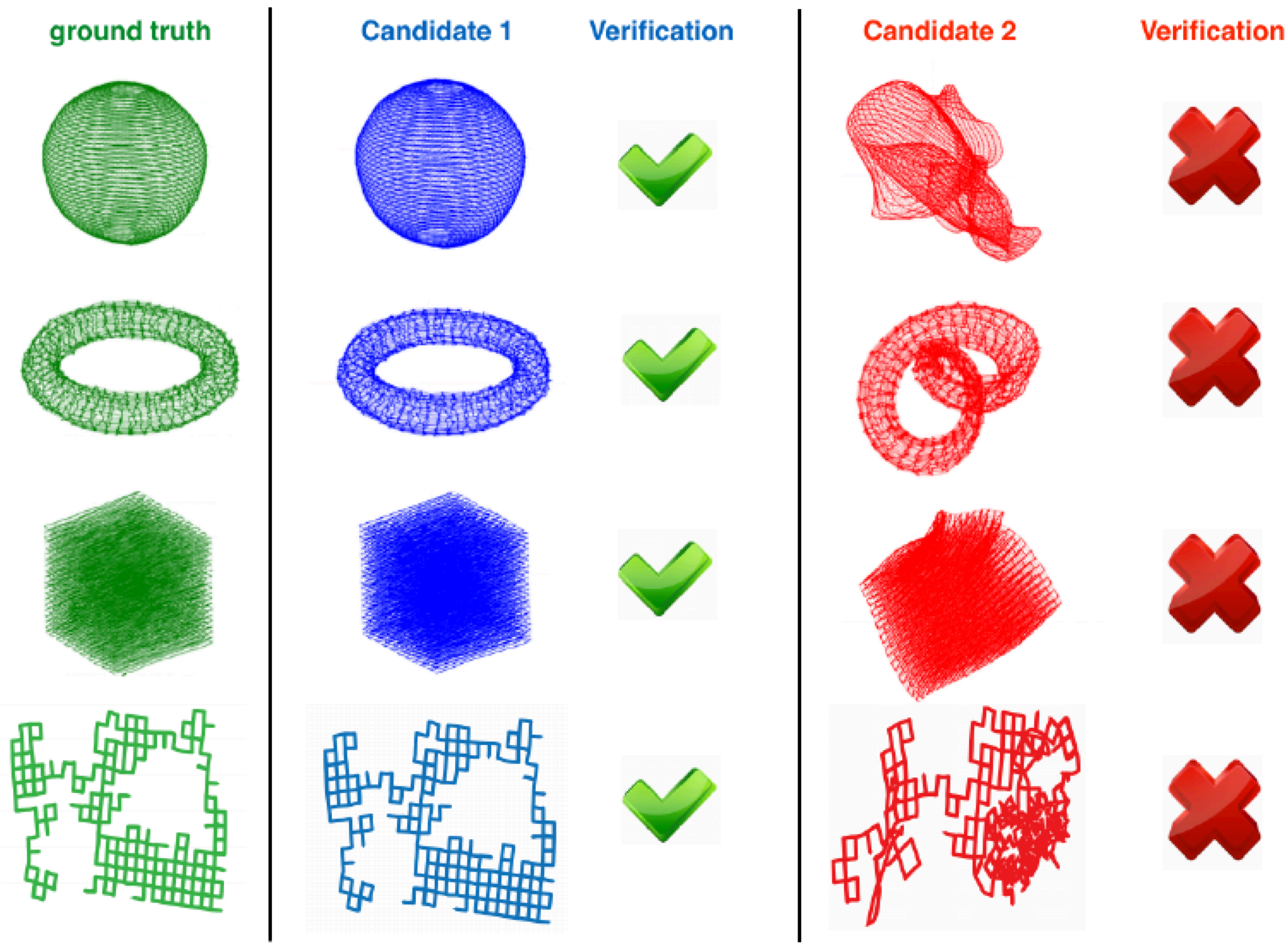
**Problem:** How can we evaluate the global quality of a proposed solution (i.e. local optimum) $\hat{x}$ for the SLAM problem?

- Quantification of suboptimality gap?
- Certification of global optimality?

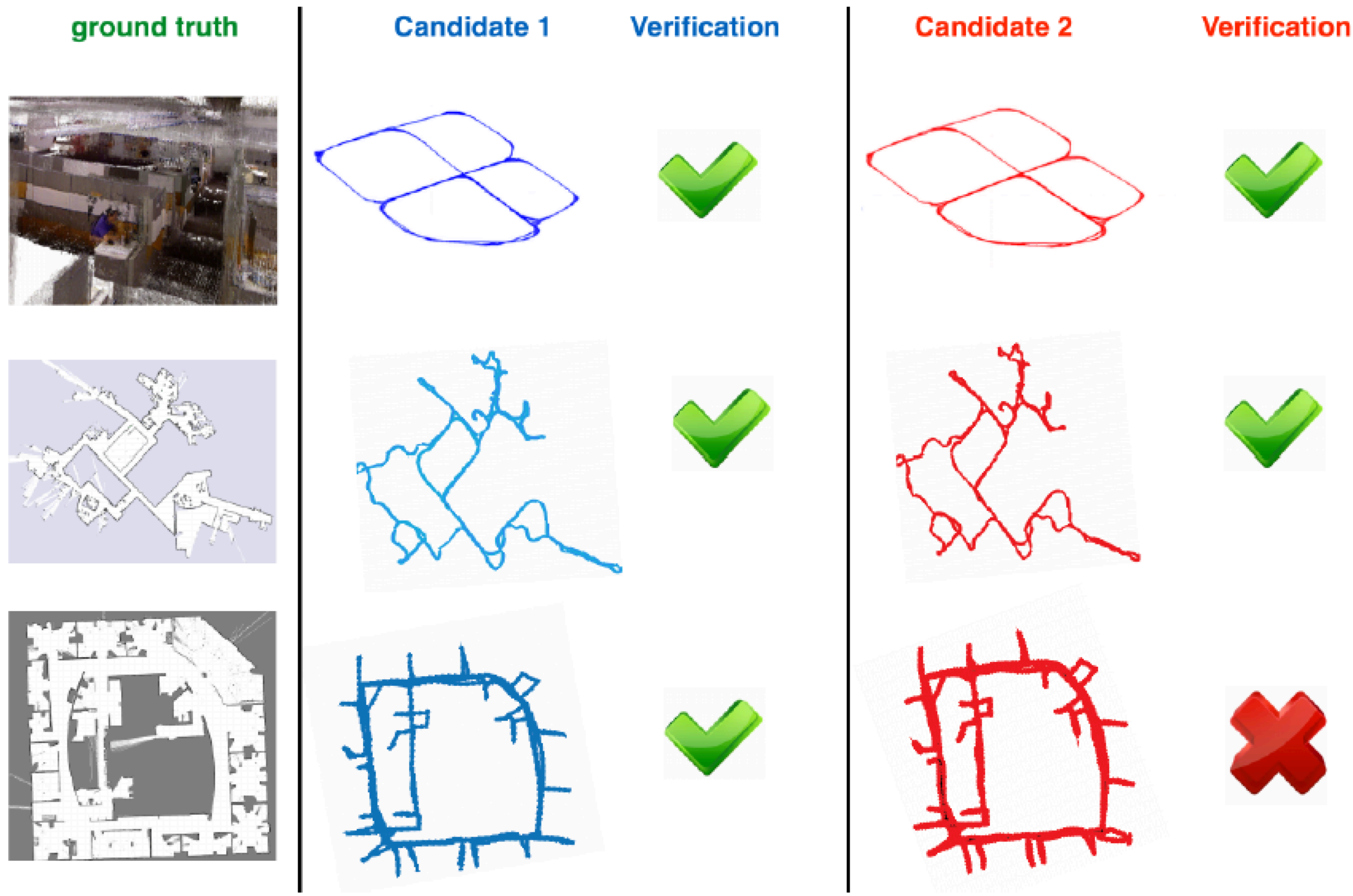



- First development and implementation of a Certifiably Correct SLAM algorithm
- Recently received the Best Paper Award at WAFR 2016 (Workshop on Algorithmic Foundations of Robotics)

# Experiments: Simulated data



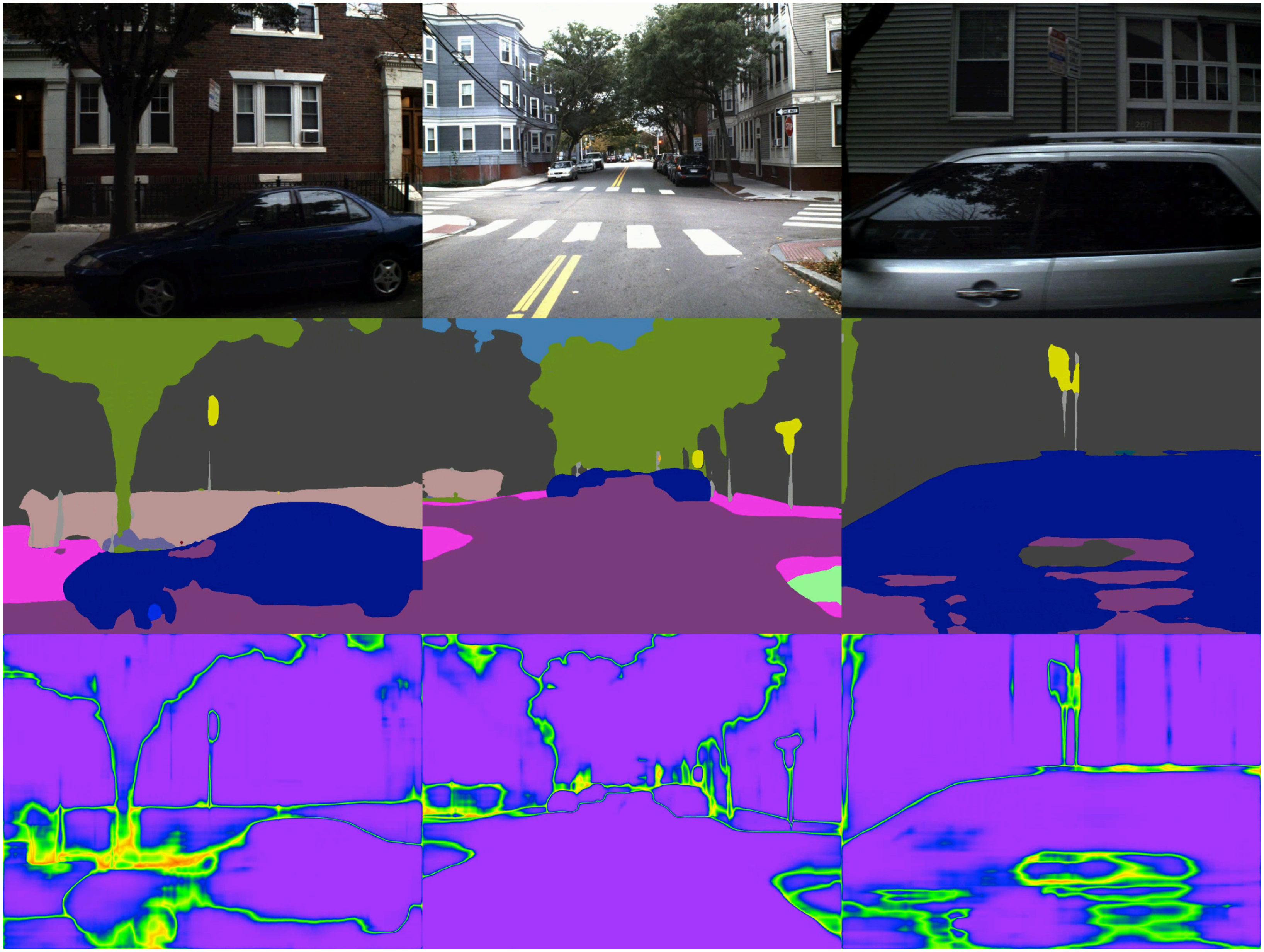
# Experiments: Real data



# Outline

- An Introduction to Self-Driving Vehicles
- Technical Challenges and Opportunities
- Mapping and Localization
- **Database Technology and Self-Driving Vehicles**

# 2017: Computer Vision Has Made Amazing Progress



Simon Stent, TRI

# Conclusion and Future Research Challenges

Research Goals:

- My dream is to achieve *persistent autonomy* and *lifelong map learning* for self-driving in challenging environments
- Can we robustly integrate perception, mapping and localization with real-time planning and control?

Open Questions:

- Robustness – we would love to have guarantees of performance, but we do not have them for most approaches
- We need dynamic scene understanding and robust vision (recent work in computer vision is very exciting, but current precision-recall curves indicate we have a long way to go)
- Interaction with humans may be *the key issue* in the short-term
- We will be "drowning in a sea of data" – huge challenges and opportunities for the database community

## Its an Exciting Time to Work in Mobile Sensing!

Postdocs and PhD students that can build real-time 3D perception, navigation and motion planning systems are in high demand:

- Virtual Reality
- Mobile Devices
- Self-Driving Vehicles
- Drones

Big tech companies such as Google, Apple, Facebook and Uber

Small startups such as skydio

Traditional companies in transition, such as Toyota, GM, Ford, Delphi, Continental, Bosch…