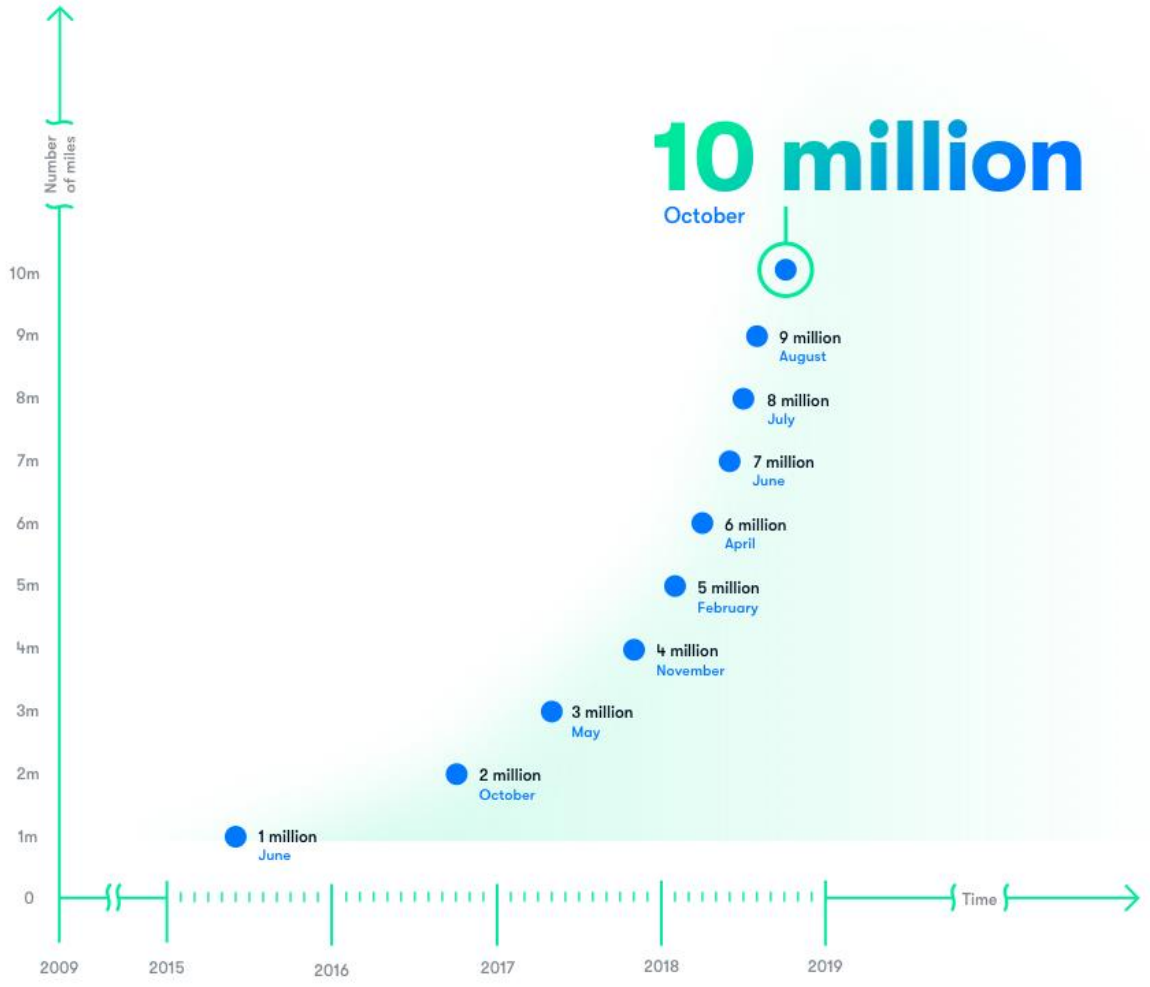
Self-Driving Cars: State-of-the-Art (2019)

Mission: Improve Access, Increase Efficiency, and Save Lives

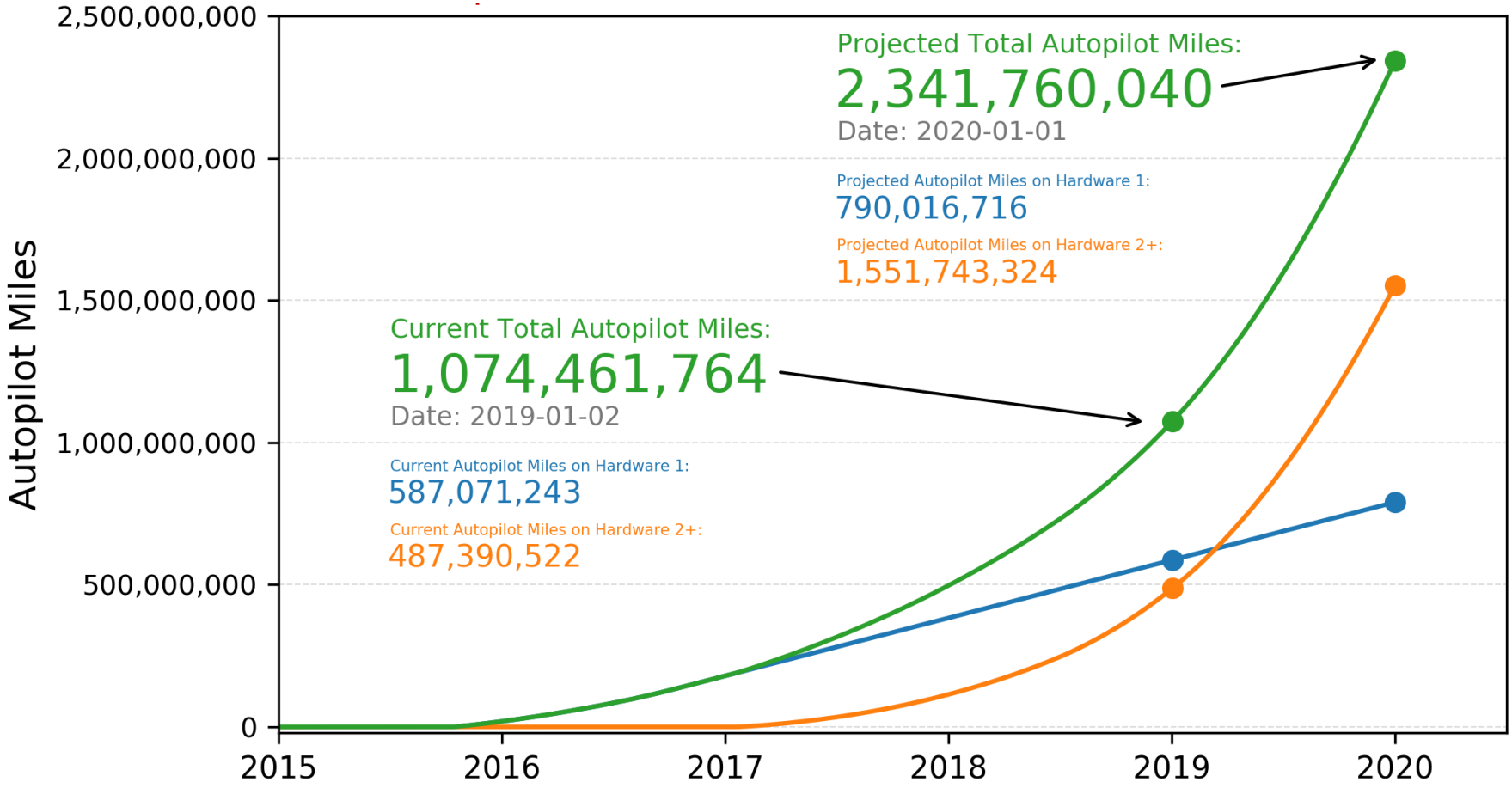
2018 in Review:
Waymo Reaches 10 Million Miles



10 million miles and counting

WAYMO

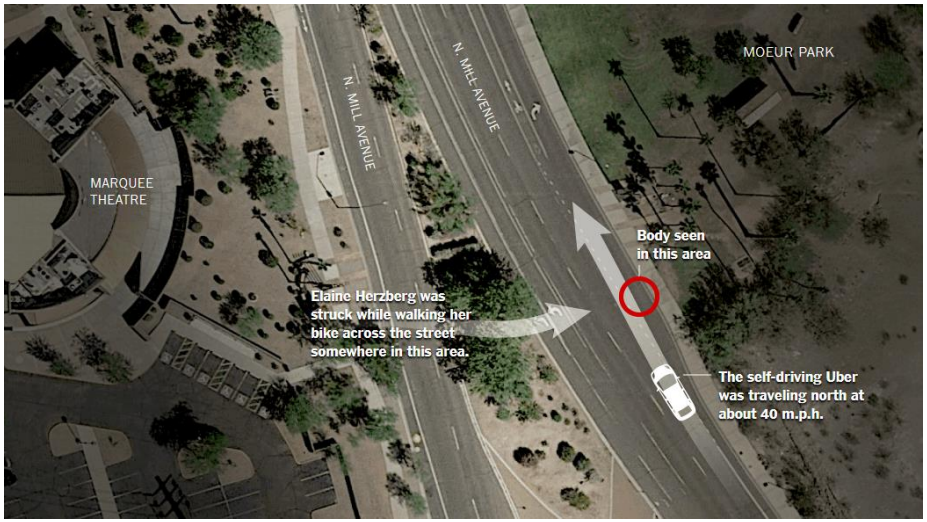
2018 in Review:
Tesla Autopilot Reaches 1 Billion Miles



2018 in Review:

Fatalities: Autonomous and Semi-Autonomous

- Uber (L3/L4)
  - Pedestrian fatality
  - Tempe, Arizona
  - Mar 18, 2018



- Tesla Autopilot (L2)
  - Driver fatality
  - Mountain View, California
  - Mar 23, 2018

2018 in Review:

Public Testing with Autonomous Taxi Services

(Small-scale, often low-speed, almost always with safety driver)

- Voyage (in Villages, Florida)
- Optimus Ride (in Union Point, MA)
- Drive.ai (Arlington, Texas)
- May Mobility (Detroit, Michigan)
- Waymo One (Phoenix, Arizona)
- Nuro (Scottsdale, Arizona)
- Uber (Pittsburgh, PA)
- Aptiv (Last Vegas, Boston, Pittsburgh, Singapore)
- Aurora (San Francisco, Pittsburgh)
- Cruise (San Francisco, Arizona, Michigan)

Predictions

- Predictions lack definition for:
  - Number of cars for “meaningful” deployment, or
  - Number of cars for “commercially viable” deployment

Let’s be specific for purpose of discussion.

We have to define the level beyond “demo”, “prototype”, “testing.”

Meaningful deployment = **10,000 vehicles**

(For reference: 46,000 active Uber drivers in NYC)

2018 in Review:

Announcements for Consumer-Facing Fully-Autonomous Vehicle (Testing and Beyond)

- **Tesla**: 2019
- **Nissan**: 2020
- **Honda**: 2020
- **Toyota**: 2020 (highway)
- **Renault-Nissan**: 2020 (urban)
- **Hyundai**: 2020 (highway)
- **Volvo**: 2021 (highway)
- **BMW**: 2021
- **Ford**: 2021
- **Fiat-Chrysler:** 2021
- **Daimler**: 2020-25

Predictions

Maarten Sierhuis Director, Nissan R&D

January 2017

“We will always need the human in the loop."

Karl Iagnemma President, Aptiv Autonomous Mobility

January 2017

"(Teleoperation) is going to be massively important. Even cars that can handle just about anything will have the occasional failure, even if that's being hit by another vehicle. And in that case, you want a human around to decide what to do."

Gill Pratt, Toyota Research Institute

January 2017

- “None of us in the automobile or IT industries are close to achieving true Level 5 autonomy, we are not even close.”

Predictions: The Full Spectrum

Elon Musk, Tesla

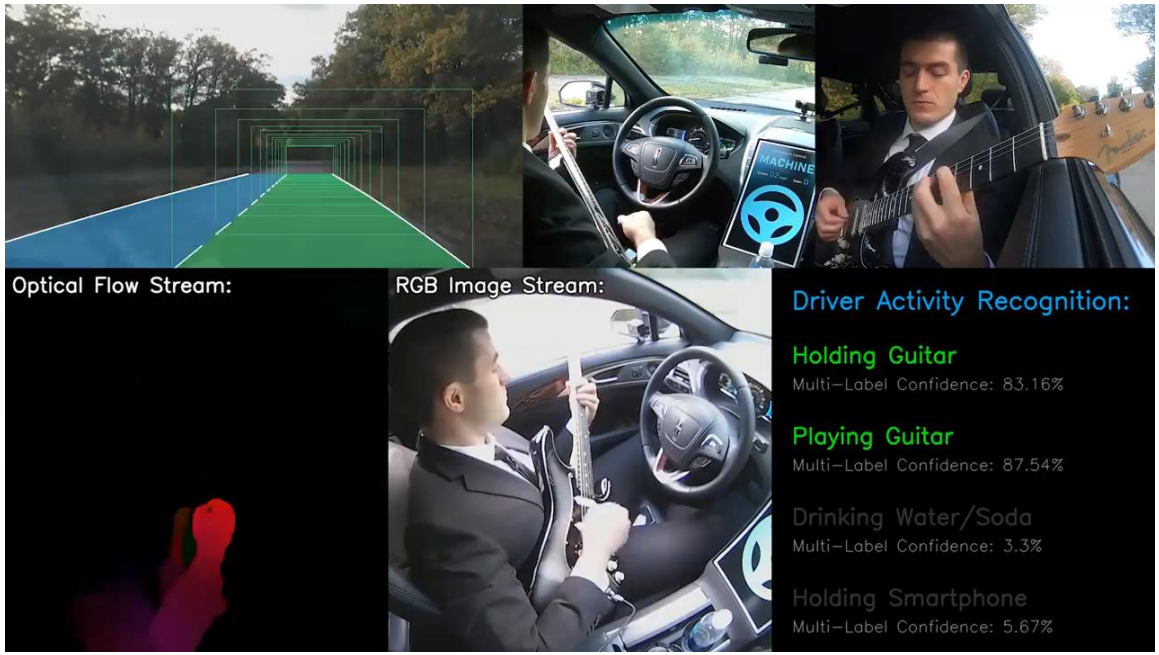
- February 2017: "My guess is that in probably 10 years it will be very unusual for cars to be built that are not fully autonomous."
- February 2018: "The upcoming autonomous coast-to-coast drive will showcase a major leap forward for our self-driving technology."

- Rodney Brooks

  =2031: A major city bans manually driven cars from a non-trivial portion of a city.
- **>2045:** Majority of US cities ban manually driven cars with drivers from a non-trivial portion of a city.

Beyond Predictions:
Human-Centered Autonomous Vehicles

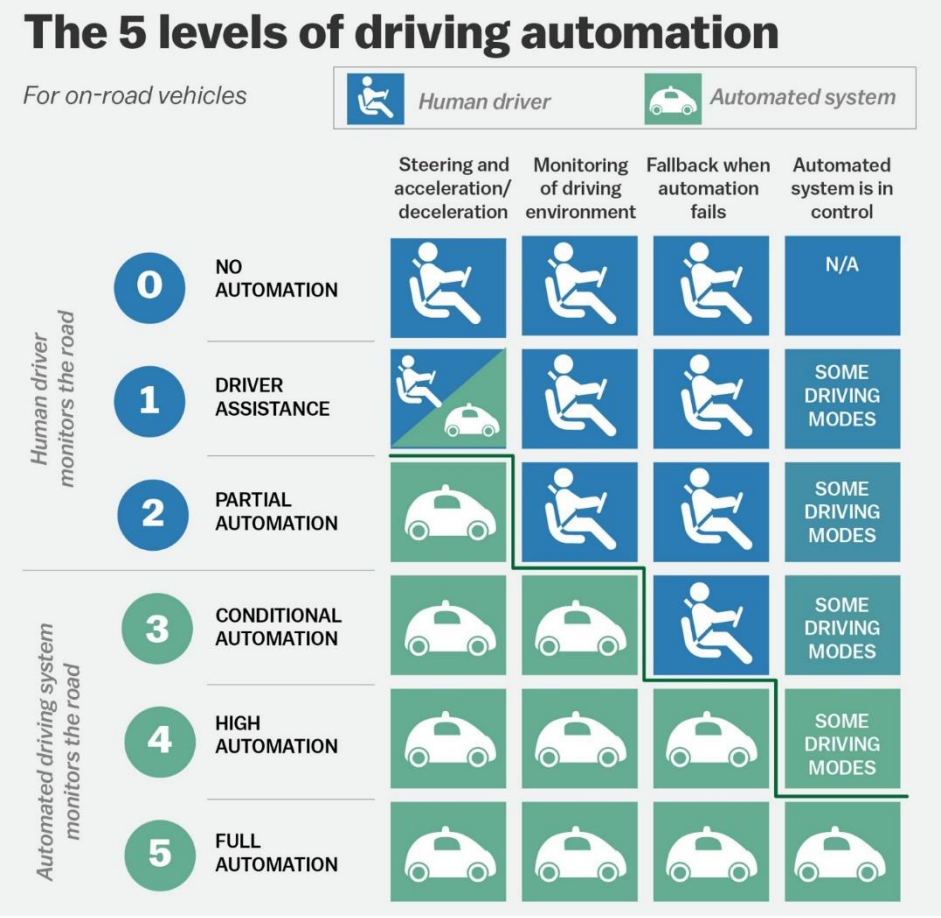
- Autonomy will not be adopted because it is safer.
- Autonomy will not be adopted because it is faster.
- Autonomy will not be adopted because it is cheaper.
- Autonomy will be adopted if creates a better human experience.



Full video: https://www.youtube.com/watch?v=fCLI6kxFFTE

Levels of Automation (SAE J3016)

- Useful for initial discussion (especially for policy making), but not useful for design and engineering of the underlying intelligence and the holistic system performance:



Beyond Traditional Levels: **Two** AI Systems

- **Starting point:**
  - All cars are manually controlled until the AI system shows itself to be available and is elected to be turned on by the human.
- **A1:** Human-Centered Autonomy
  - **Definition:** AI is not fully responsible
  - Feature axis:
    - Where/how often is it "available"? (traffic, highway, sensor-based, etc.)
    - How many seconds for take-over? (0, 1, 10, etc)
    - Teleoperation support
- **A2:** Full Autonomy
  - **Definition:** AI is fully responsible
  - Notes:
    - No teleoperation
    - No 10-second rule: It's allowed to ask for human help, but not guaranteed to ever receive it.
    - Arrive to a **safe** destination or safe harbor.
    - Allow the human to take over **when they choose to**.

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Beyond Traditional Levels: **Two** AI Systems

L0 →

- **Starting point:**
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L1, L2, L3 →

- **A1:** Human-Centered Autonomy
  - **Definition:** AI is not fully responsible

L4, L5 →

- **A2:** Full Autonomy
  - **Definition:** AI is fully responsible

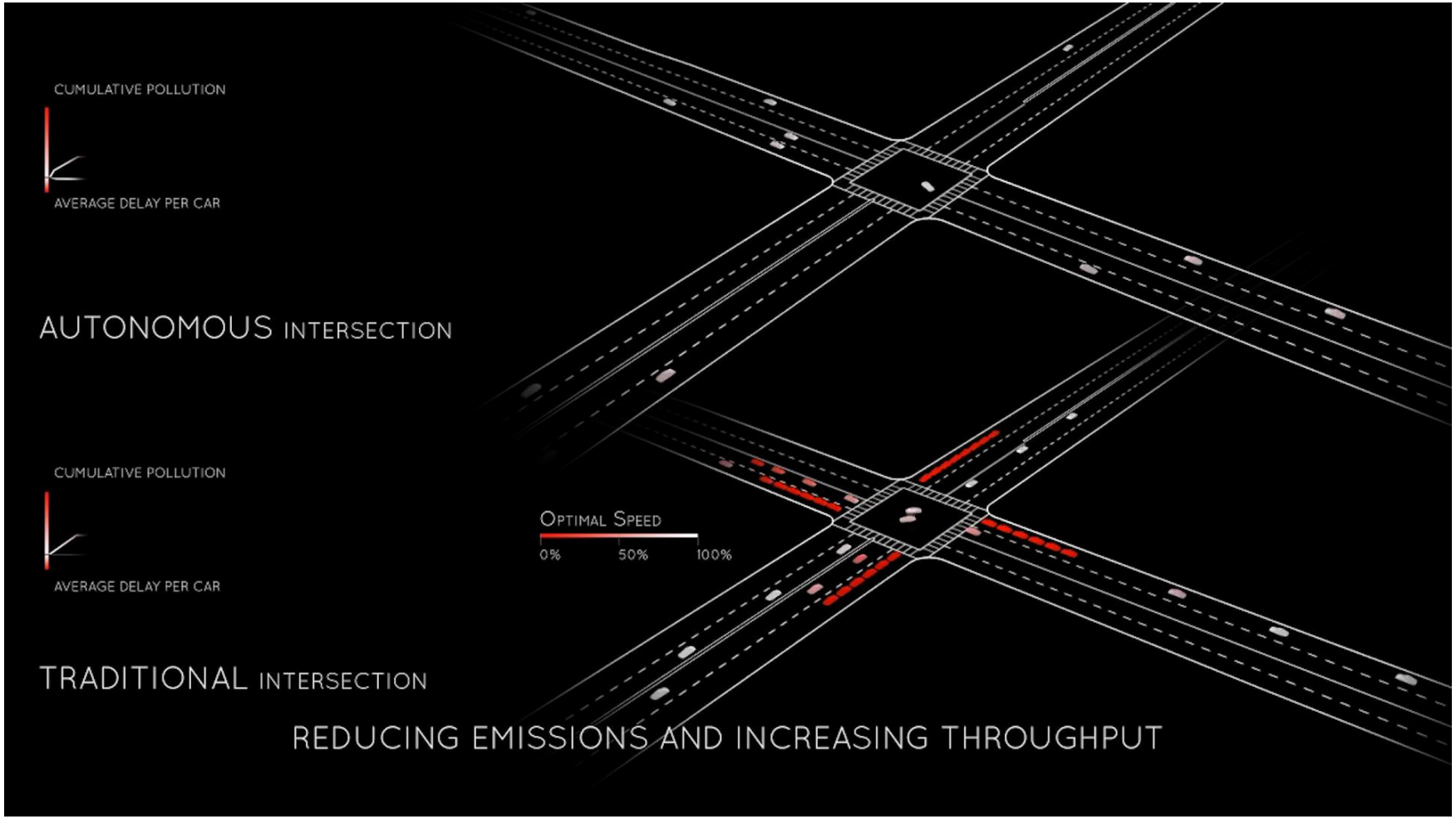
Vehicle Autonomy Proliferation Strategies

- Fully-autonomous (L4 – with constraints)
  - Last mile delivery
  - Highway trucking (possibly with platooning)
  - Specified urban routes (personalized public transit)
  - Closed communities – slow-moving transport
  - Zero occupancy ride sharing delivery

- Semi-autonomous (L2 – driver still responsible)
  - Fully-autonomous options above + teleoperation
  - High-autonomy highway travel (on-ramp to off-ramp)
  - Low-autonomy unrestricted travel (ADAS)

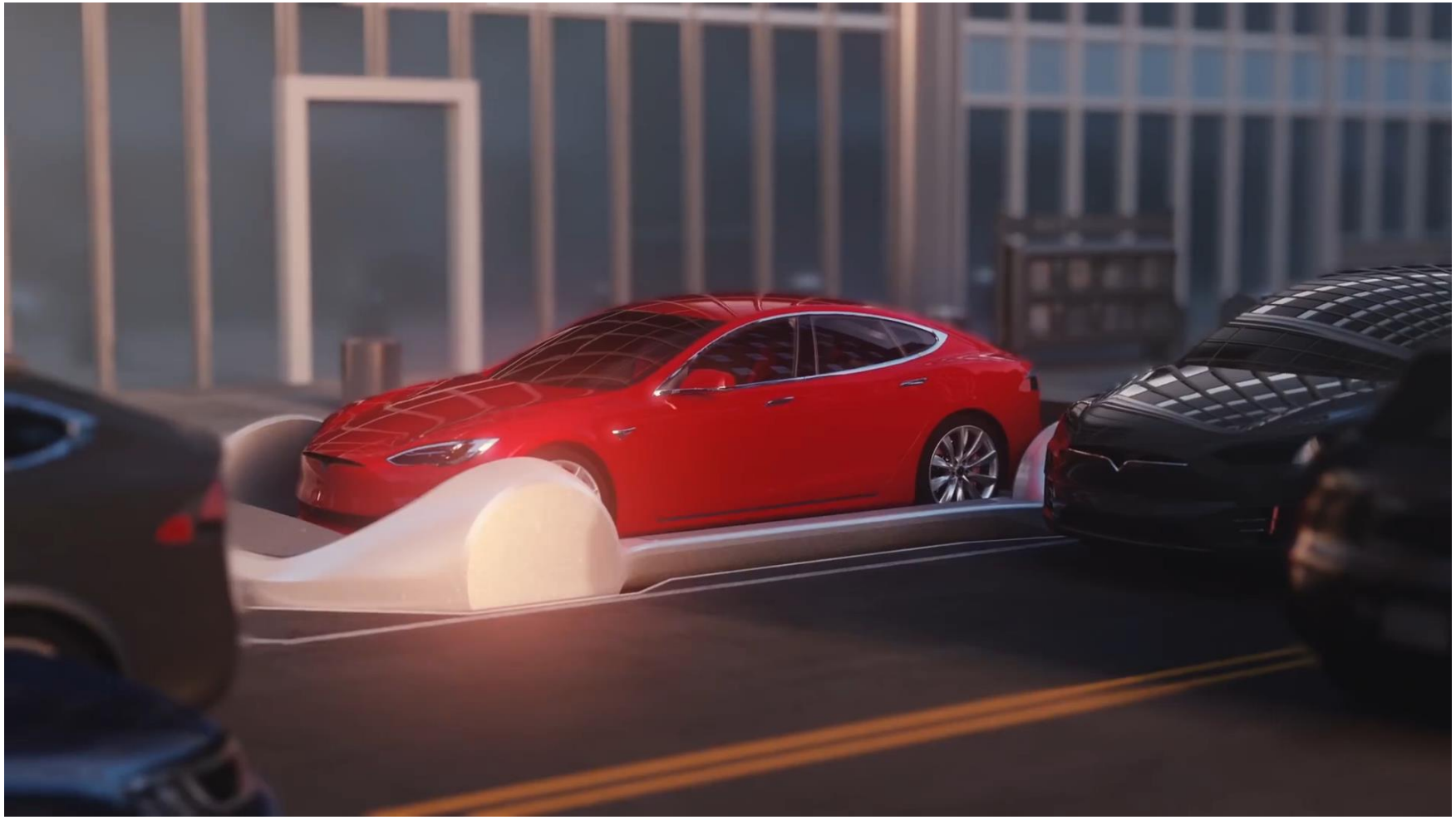
Vehicle Autonomy Proliferation Strategies

Other Interesting (Out-of-the-Box) Ideas



Vehicle Autonomy Proliferation Strategies

Other Interesting (Out-of-the-Box) Ideas



Vehicle Autonomy Proliferation Strategies

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Vehicle Autonomy Proliferation Strategies

Other Interesting (Out-of-the-Box) Ideas

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Let’s be specific for purpose of discussion.

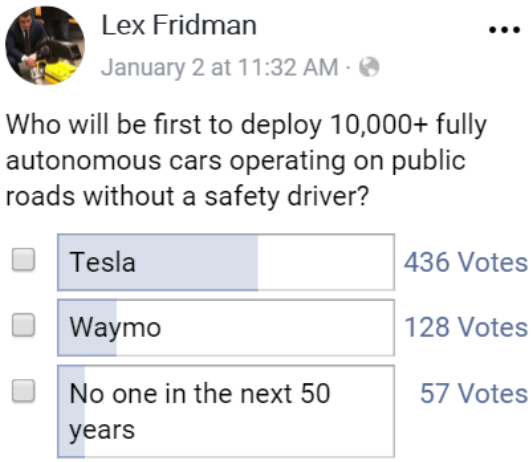
We have to define the level beyond “demo”, “prototype”, “testing.”

Meaningful deployment = **10,000 vehicles**

(For reference: 46,000 active Uber drivers in NYC)

Who will be first...

...to deploy 10,000+ fully autonomous cars operating on public roads without a safety driver?



Twitter: http://bit.ly/2M3iIVj
Facebook: http://bit.ly/2sdMRI8

Results: 57% - Tesla

21% - Waymo

14% - Someone else

8% - No one in the next 50 years

1998:

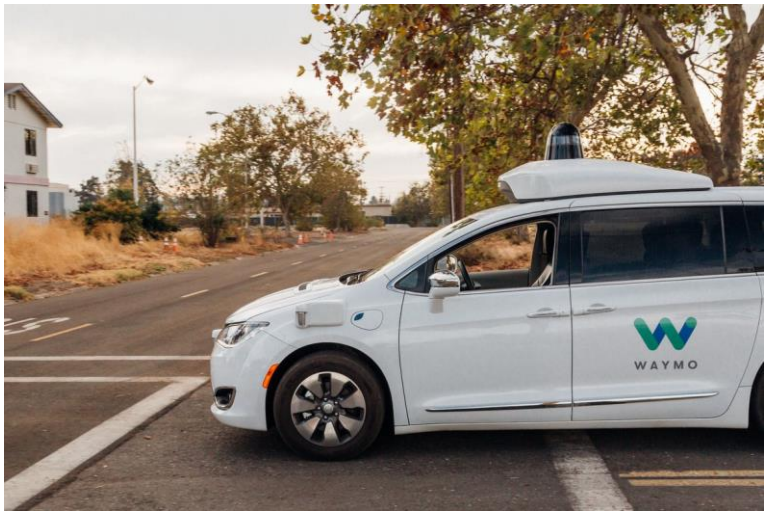
2005 DARPA Grand Challenge

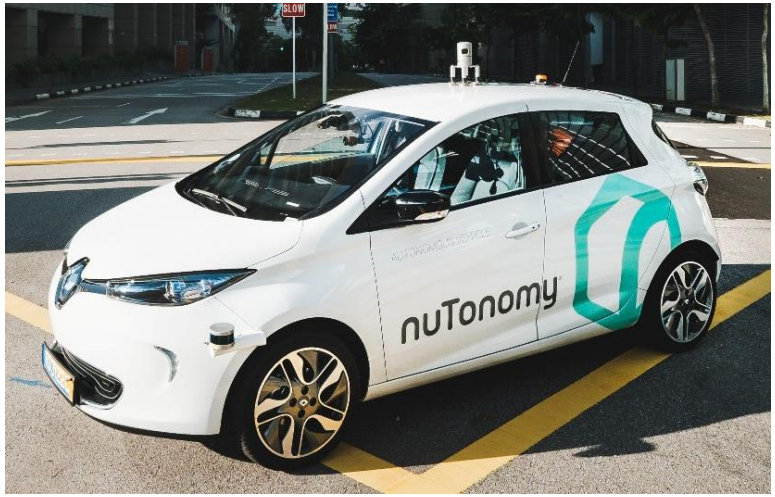
2007 DARPA (Urban) Grand Challenge

Boss

“The rest is just stamp collecting”

- Ernest Rutherford





Popular View on Autonomous Vehicles:

1. The driving task is easy
2. Humans are bad at driving
3. Humans and automation don't mix well

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Maybe the above is true.

But what if it is not…

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But what if it is not…

Driving Tasks is Hard

Driving Tasks is Hard

Driving Tasks is Hard

Why **Not** Deep Learning? Unintended Consequences

Human

AI (Deep RL Agent)

Player gets reward based on:

1. Finishing time
2. Finishing position
3. Picking up “turbos”

Popular View on Autonomous Vehicles:

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Maybe the above is true.

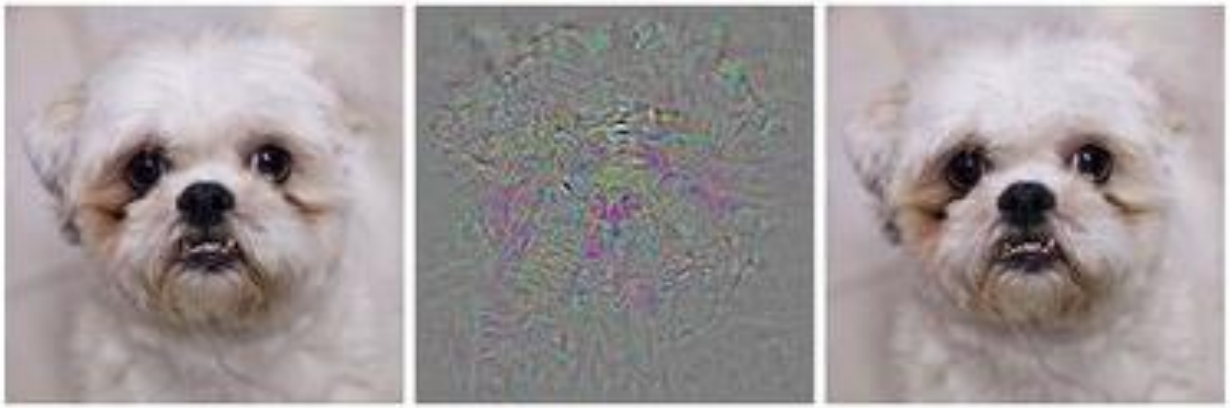
But what if it is not…

Our intuition about our flaws is flawed

Visual perception: 540,000,000 years of data

Bipedal movement: 230,000,000 years of data

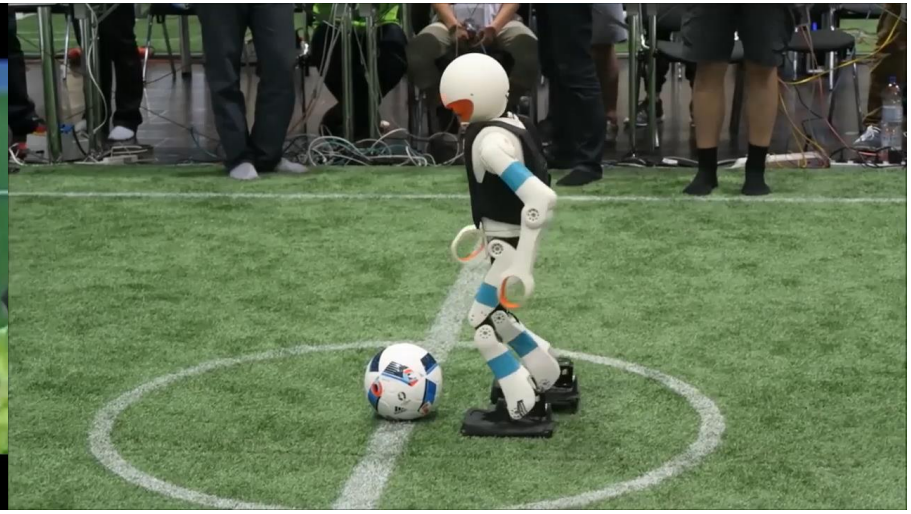
Abstract thought: 100,000 years of data



Prediction: **Dog** + Distortion Prediction: **Ostrich**

"Encoded in the large, highly evolve sensory and motor portions of the human brain is a **billion years of experience** about the nature of the world and how to survive in it.... Abstract thought, though, is a new trick, perhaps less than **100 thousand years** old. We have not yet mastered it. It is not all that intrinsically difficult; it just seems so when we do it."
- *Hans Moravec, Mind Children (1988)*

Humans Are Amazing



Humans Are Amazing

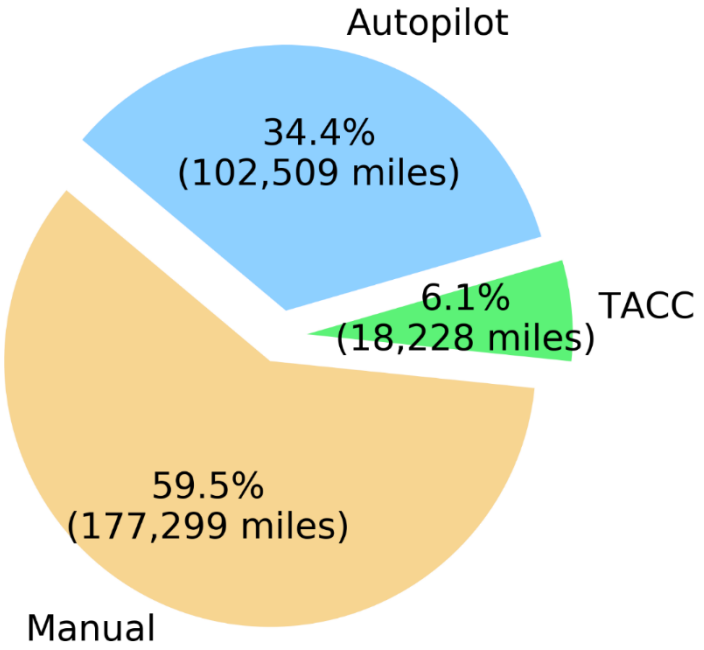
Popular View on Autonomous Vehicles:

1. The driving task is easy
2. Humans are bad at driving
3. **Humans and automation don't mix well**

Maybe the above is true.

But what if it is not…

Humans and automation **can** mix well

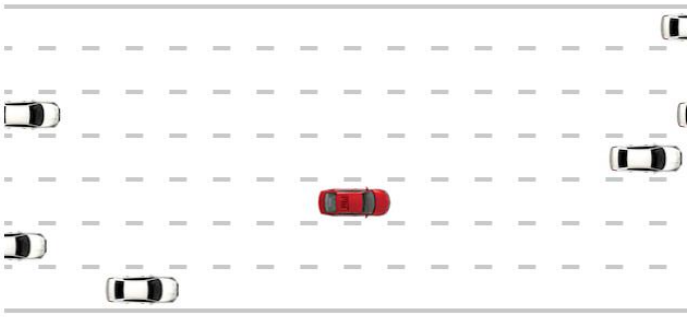


34.4% of the **miles** driven are with Autopilot engaged

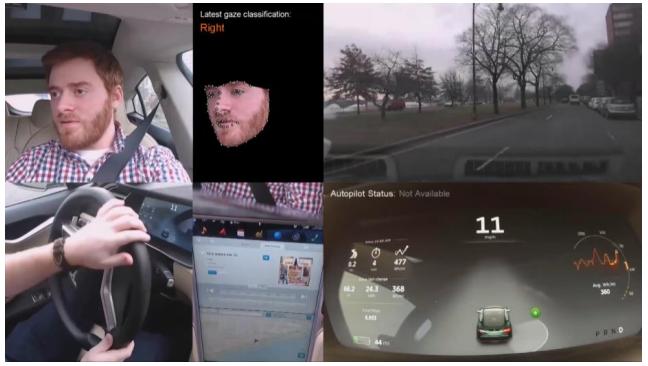
Human-Centered Approach

90% ← No — Human Needed — Yes → 10%

Solve the perception-control problem where **possible**:



And where **not possible**: involve the human



Shared Autonomy vs Full Autonomy

	Performance Level Required	
	Shared Autonomy	Full Autonomy
Sensor Robustness [2]	Good	Exceptional
Mapping [23]	Good	Exceptional
Localization [17]	Good	Exceptional
Scene Perception [7]	Good	Exceptional
Motion Control [4]	Good	Exceptional
Behavioral Planning [21]	Good	Exceptional
Safe Harbor	Good	Exceptional
External HMI [14]	Good	Exceptional
Teleoperation* [9]	Good	Exceptional
Vehicle-to-Vehicle* [16]	Good	Exceptional
Vehicle-to-Infrastructure* [19]	Good	Exceptional
Driver Sensing [13]	Exceptional	Good
Driver Communication	Exceptional	Good
Driver Collaboration	Exceptional	Good
Personalization	Exceptional	Good

MIT Human-Centered Autonomous Vehicle

Full video: https://www.youtube.com/watch?v=OoC8oH0CLGc

Two Approaches: Vision vs Lidar

- Vision Sensors + Deep Learning
  - **Pros:**
    - Highest resolution information
    - Feasible to collect data at scale and **learn**
    - Roads are designed for human eyes
    - Cheap
  - **Cons:**
    - Not accurate (without **a lot** of data)
    - Not explainable, not consistent
- Lidar + Maps
  - **Pros:**
    - Explainable, consistent
    - Accurate
  - **Cons:**
    - Does not improve over time
    - Expensive

Camera

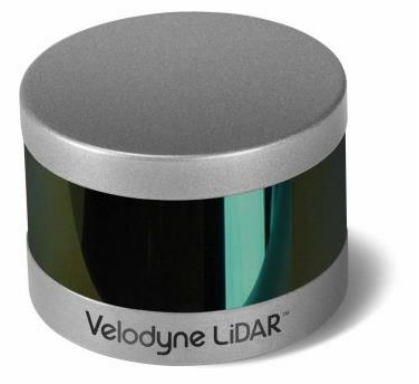
LIDAR

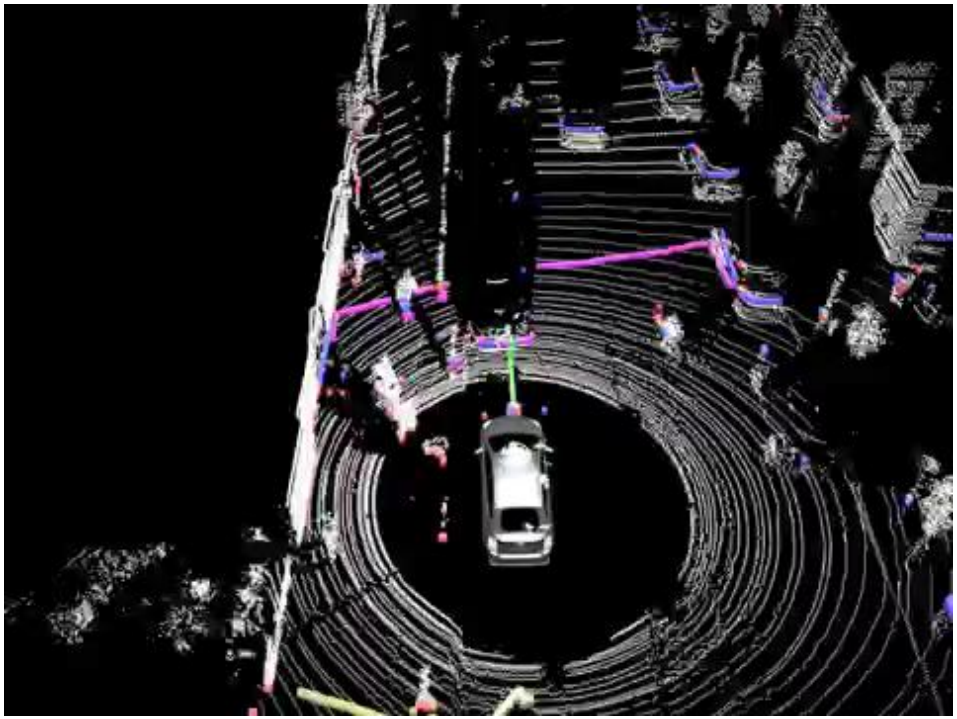
Radar

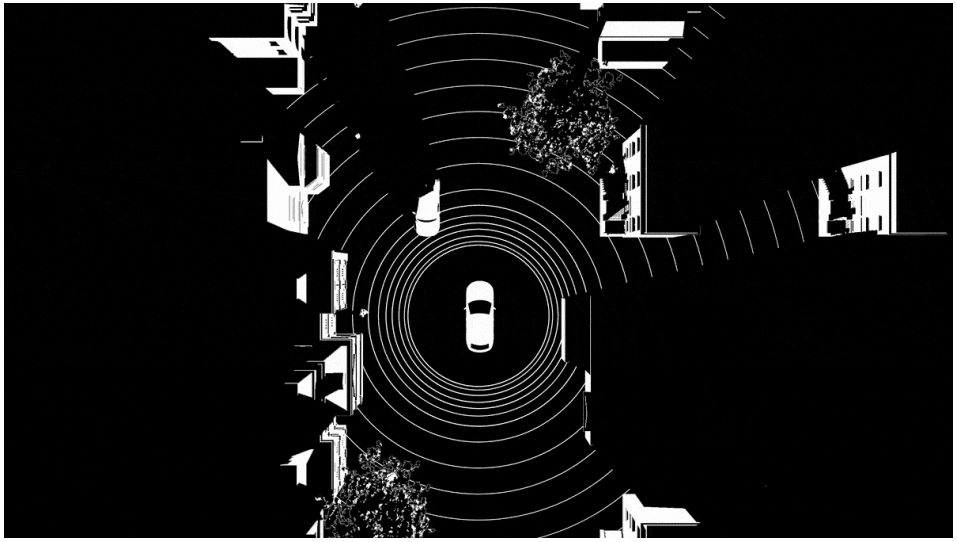
Radar

- Cheap
- Does well in extreme weather
- Low resolution
- Most used automotive sensor for object detection and tracking

LIDAR

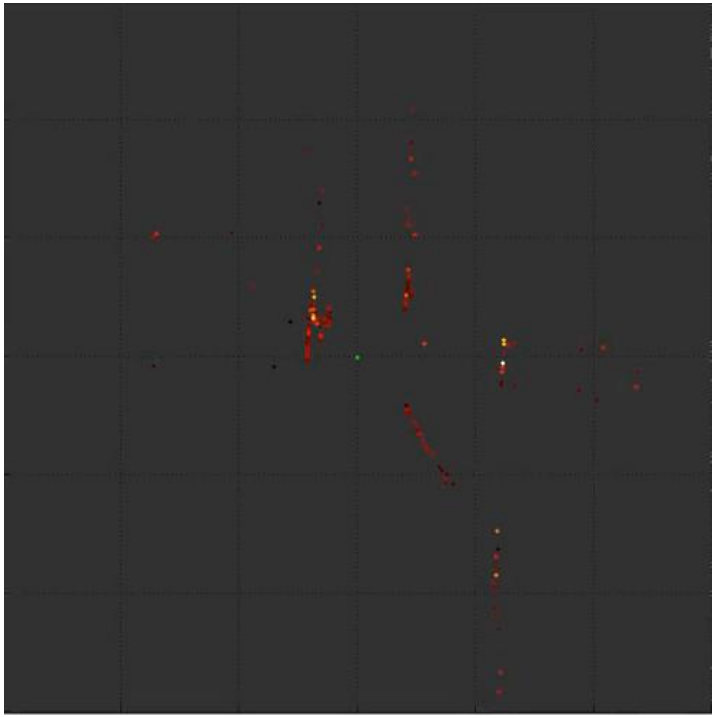


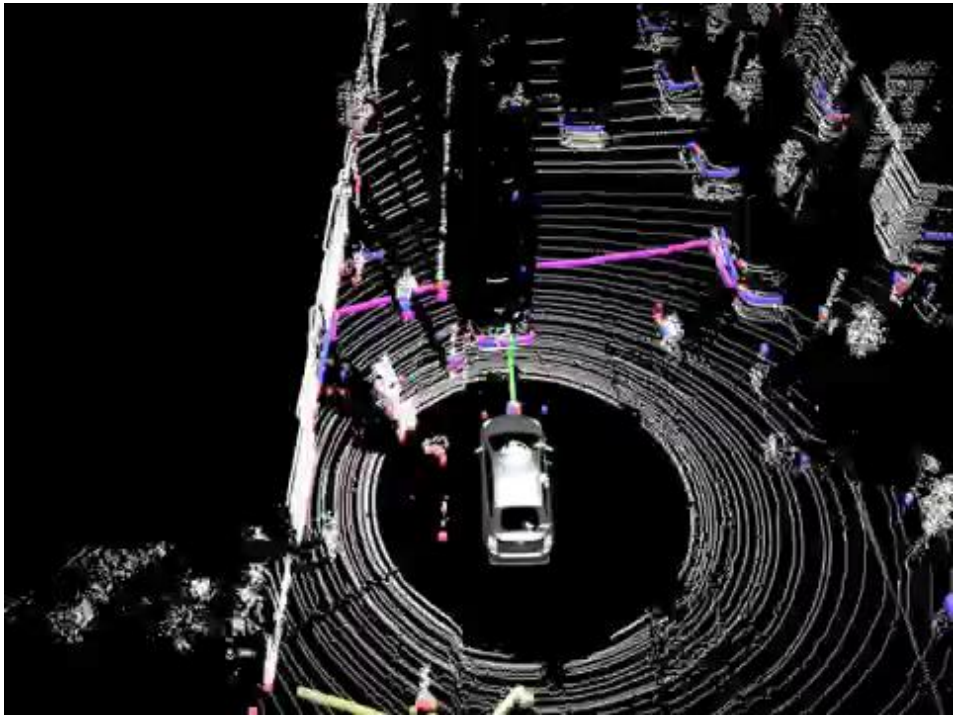




- Expensive
- Extremely accurate depth information
- Resolution much higher than radar
- 360 degrees of visibility

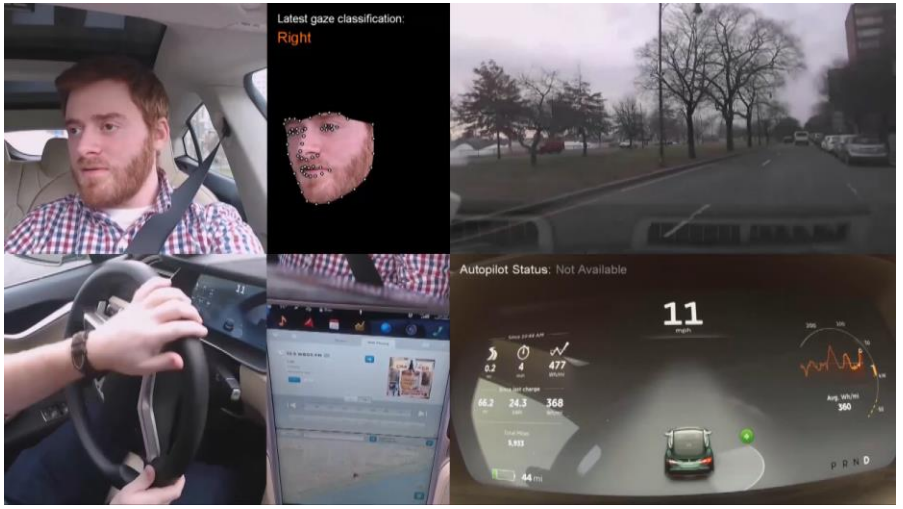
Resolution: LIDAR vs Radar



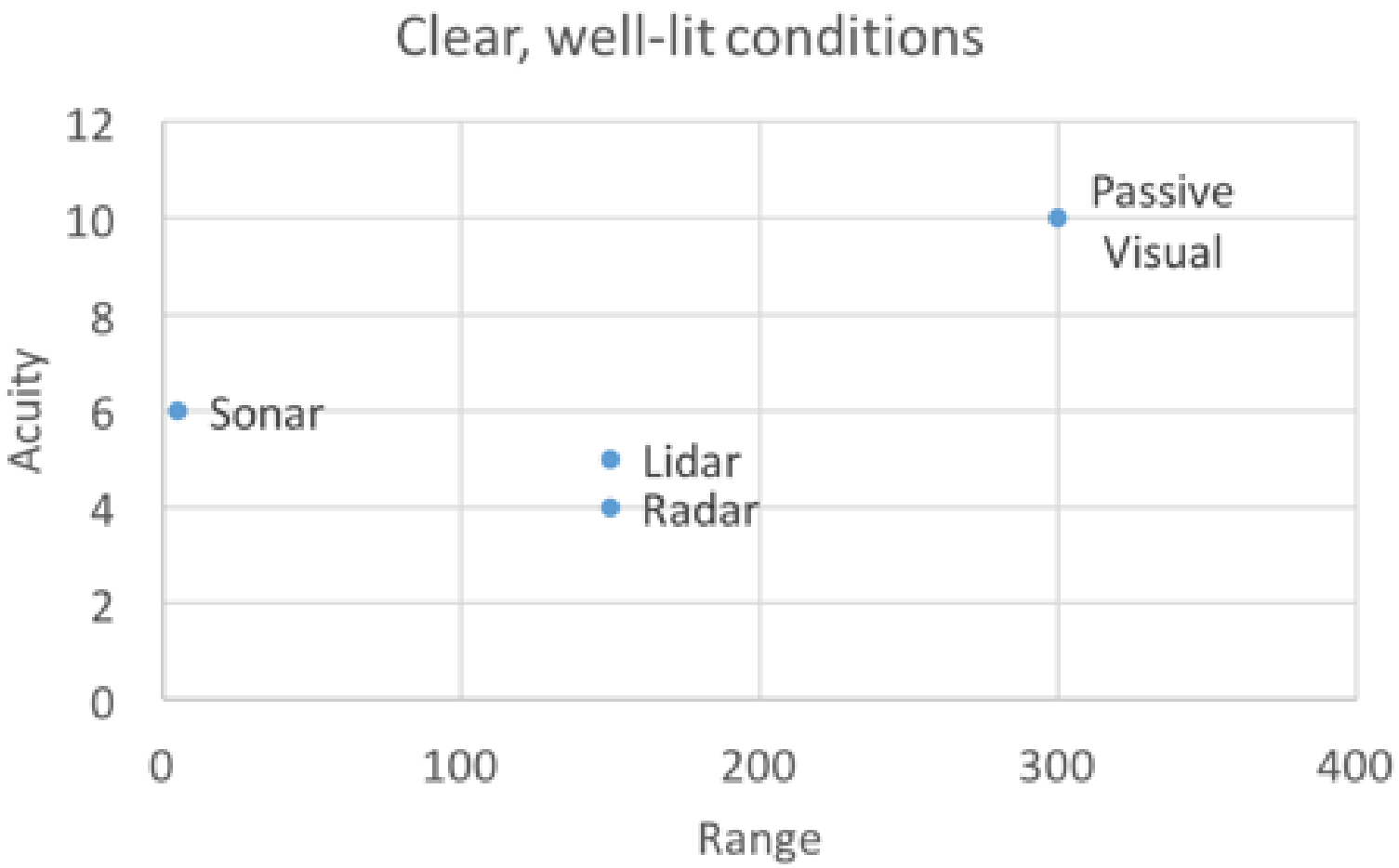


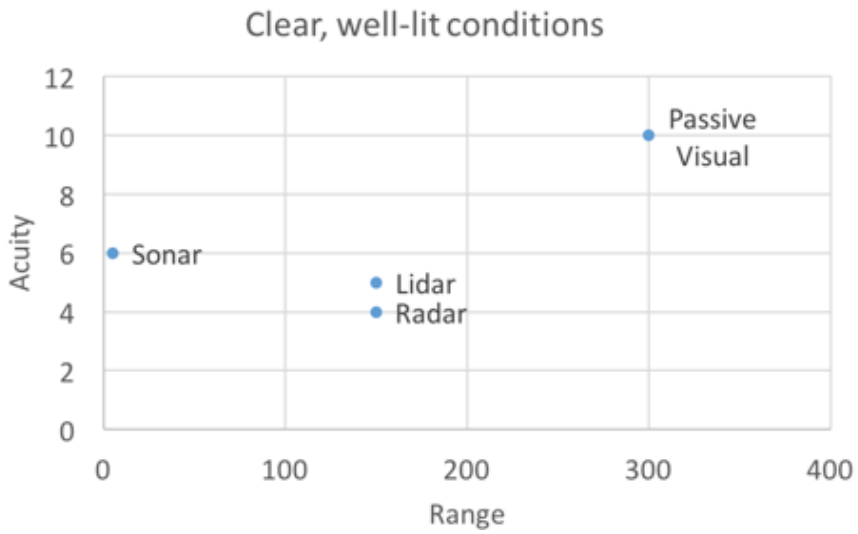
Camera

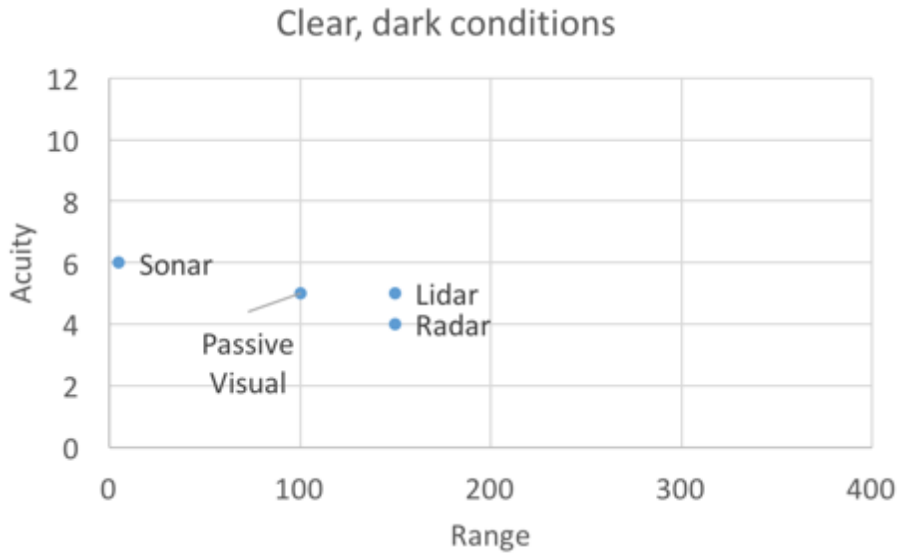
- Cheap
- Highest resolution
- Huge data = deep learning
- Human brains use similar sensor technology for driving
- Bad at depth estimation
- Not good in extreme weather

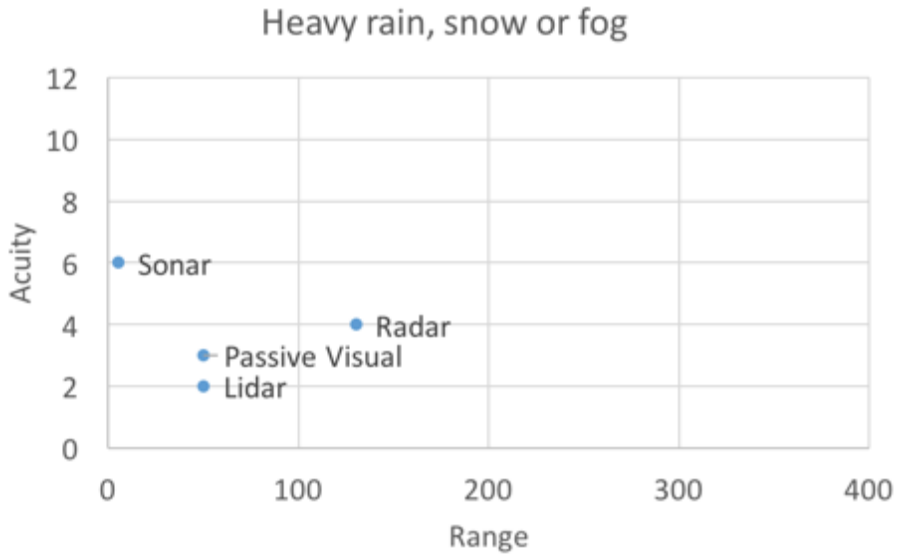


Range Comparison

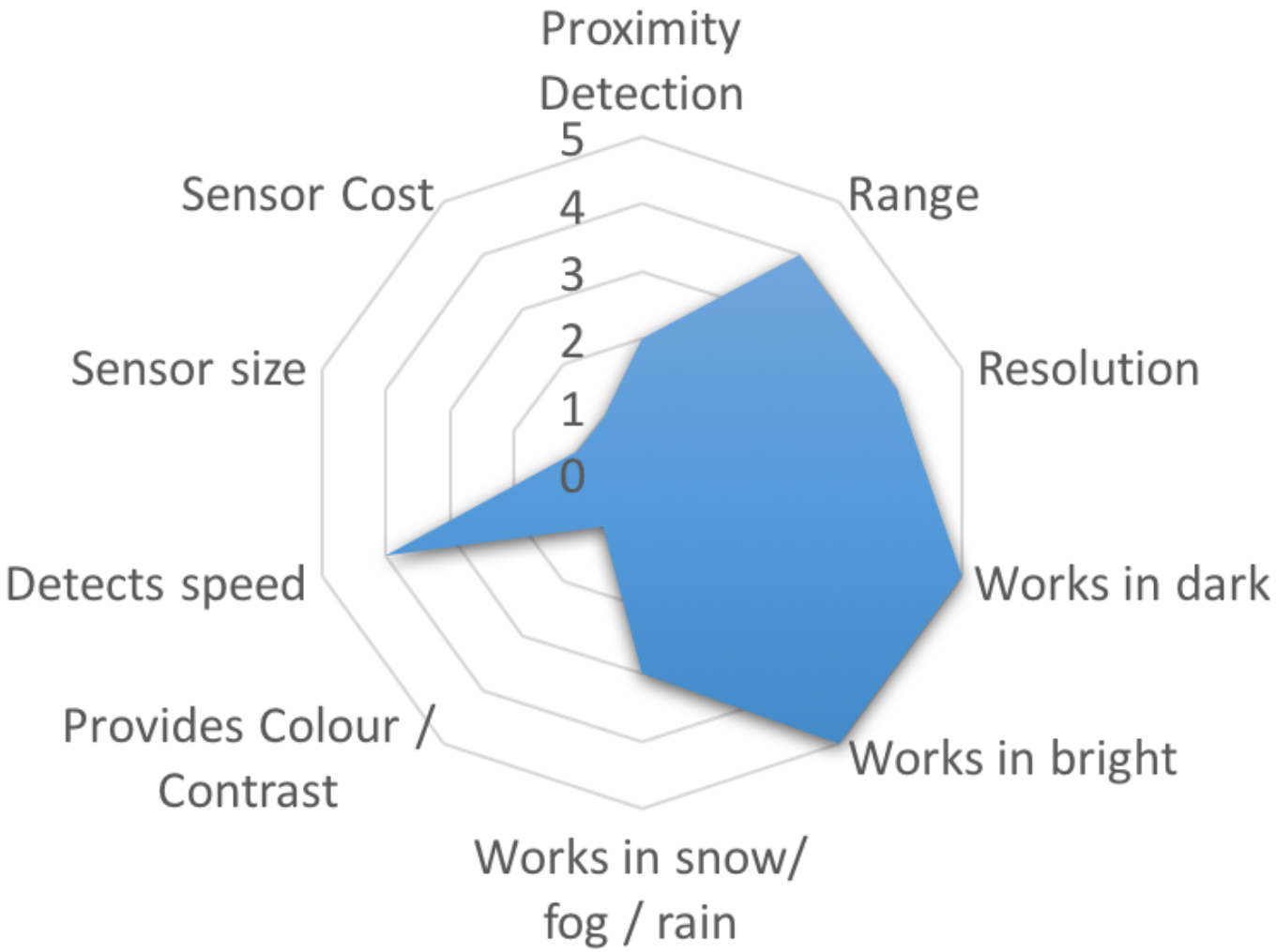



Clear, well-lit conditions
Acuity
Range
Sonar
Passive Visual
Lidar
Radar

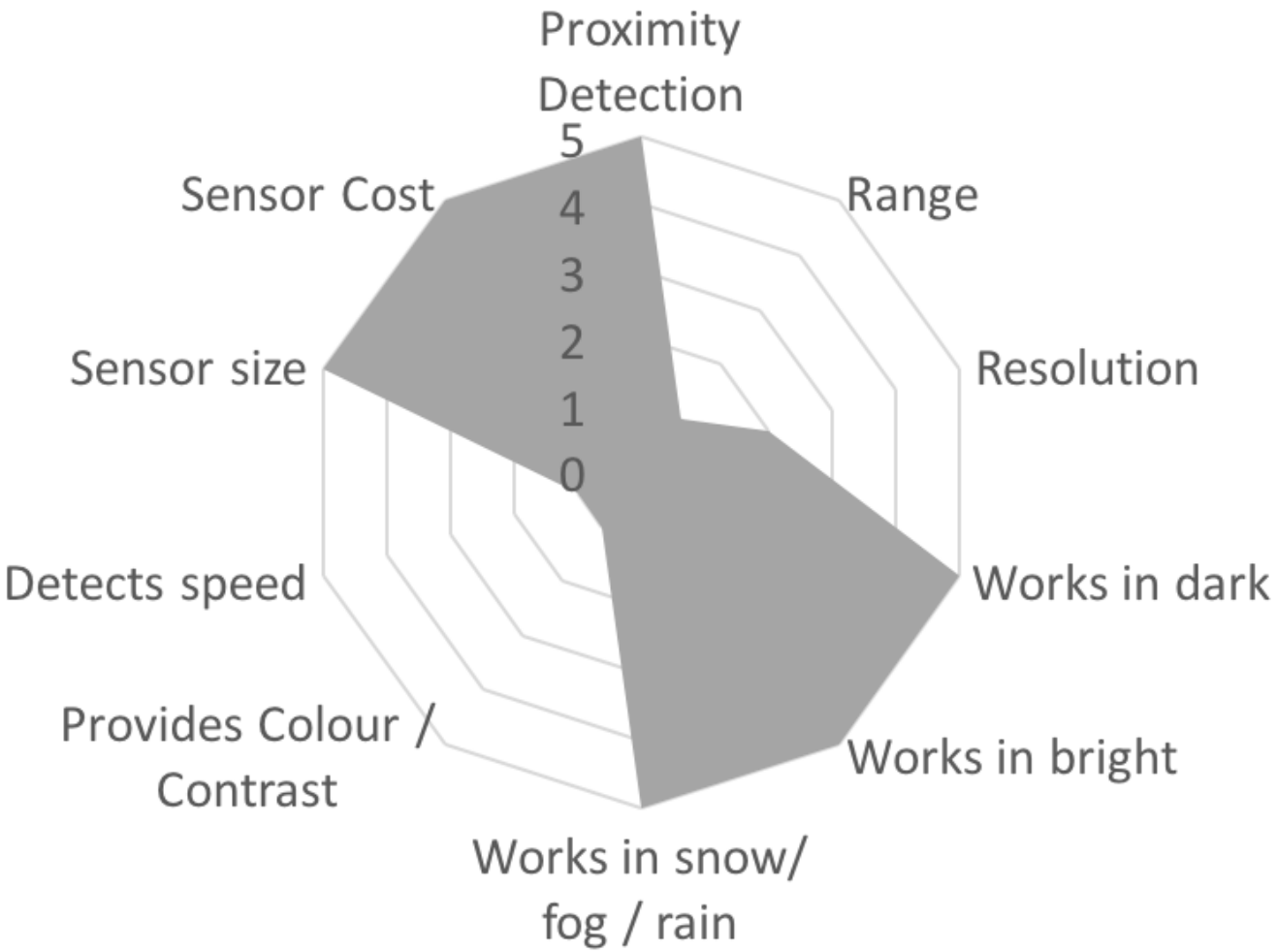

Clear, dark conditions
Acuity
Range
Sonar
Passive Visual
Lidar
Radar


Heavy rain, snow or fog
Acuity
Range
Sonar
Radar
Passive Visual
Lidar

Lidar


Proximity Detection
5
4
3
2
1
0
Range
Resolution
Works in dark
Works in bright
Works in snow/ fog / rain
Provides Colour / Contrast
Detects speed
Sensor size
Sensor Cost

Ultrasonic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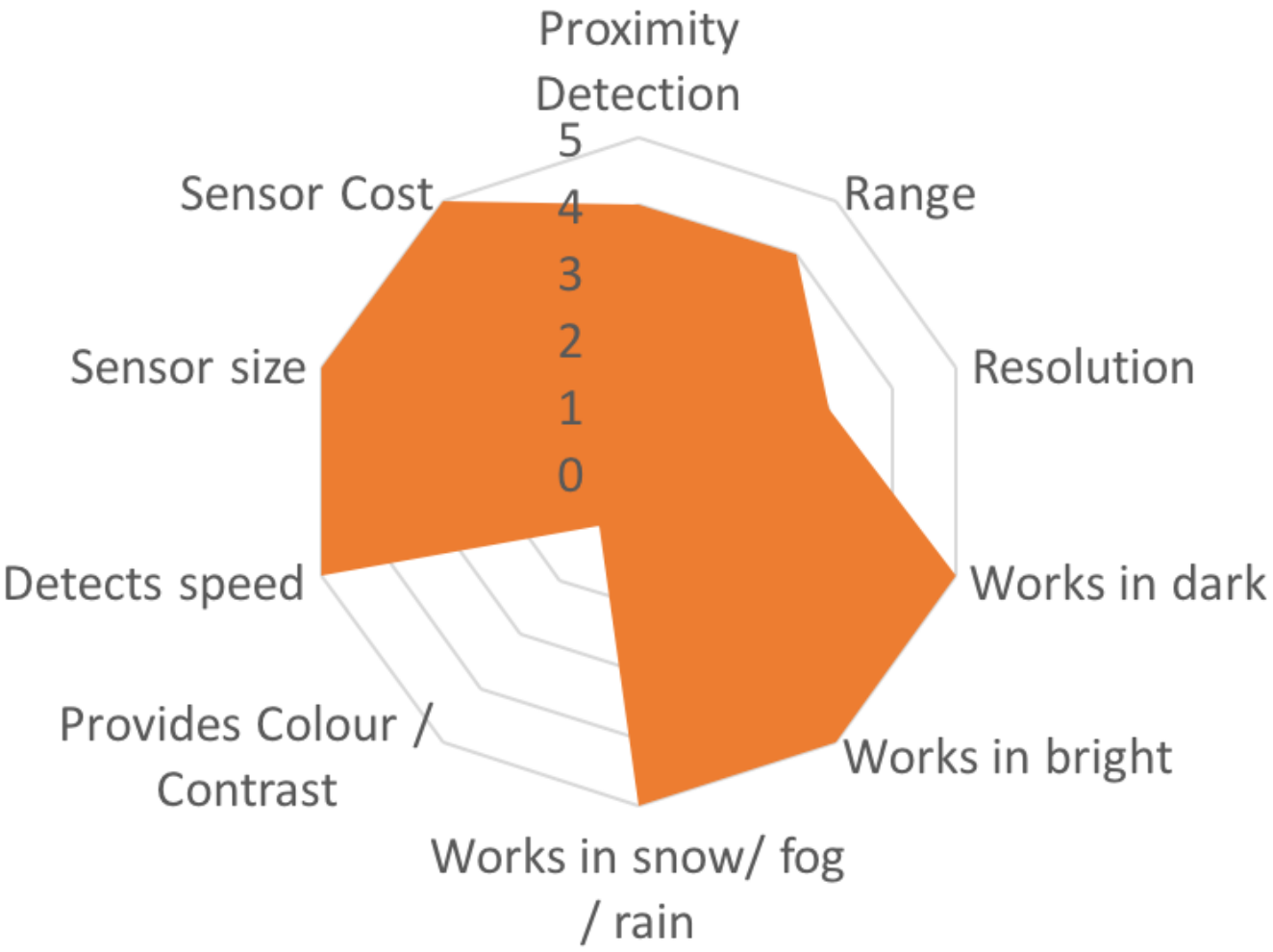
4
3
2
1
0

Radar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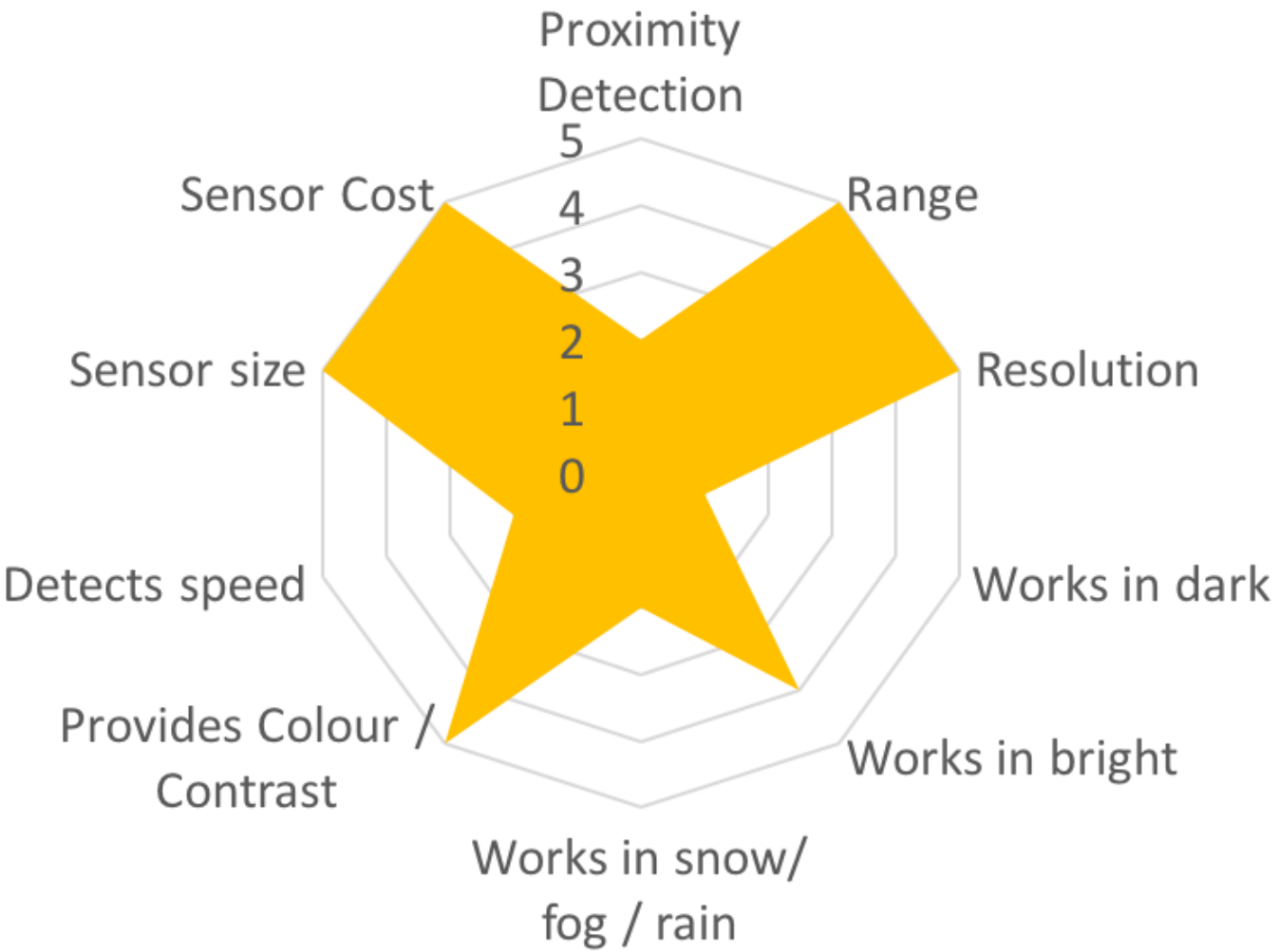
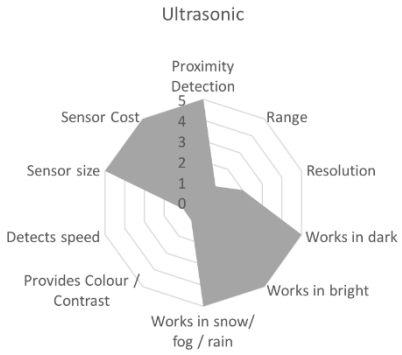
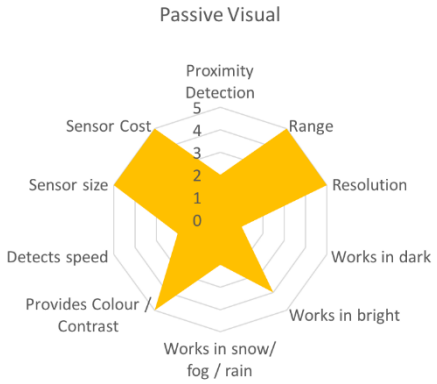
Sensor Cost

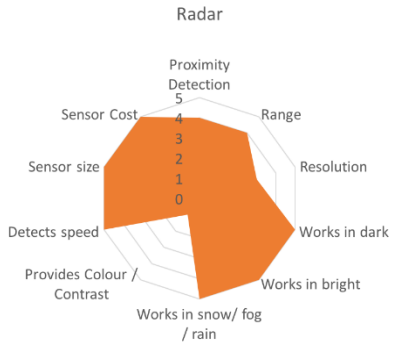
Passive Visual

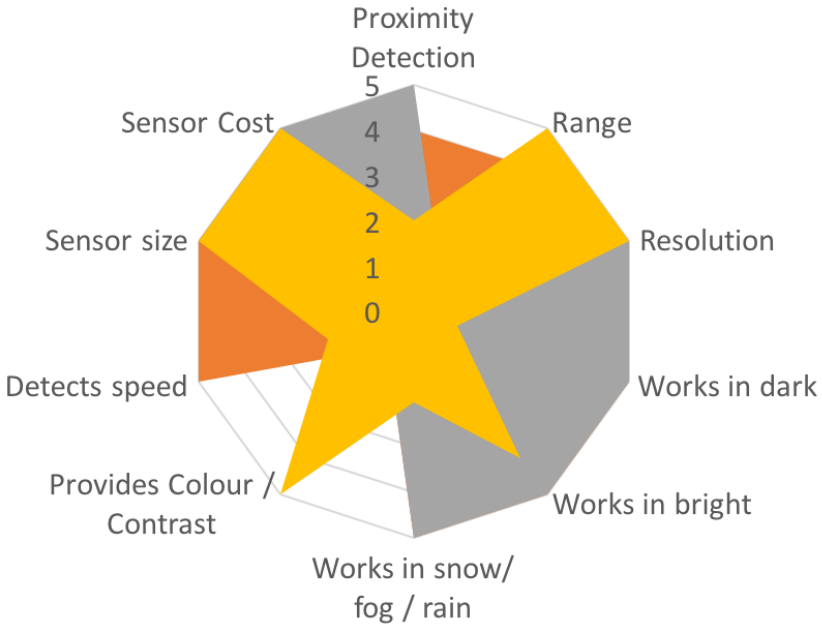


Sensor Fusion



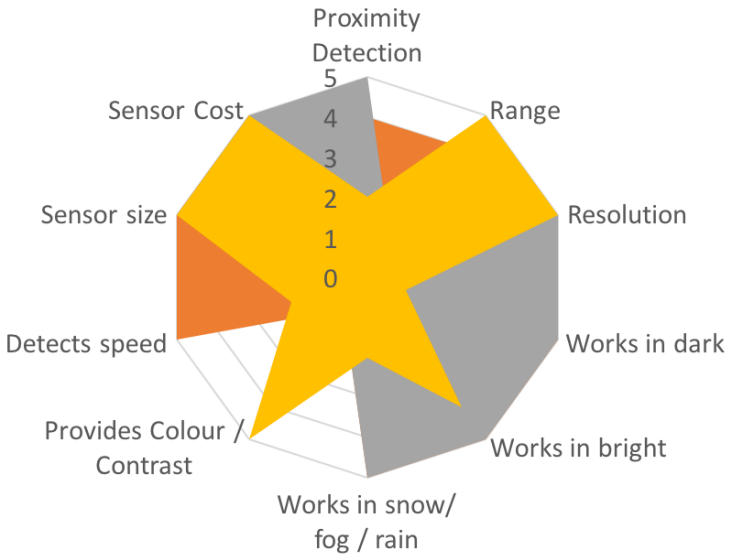


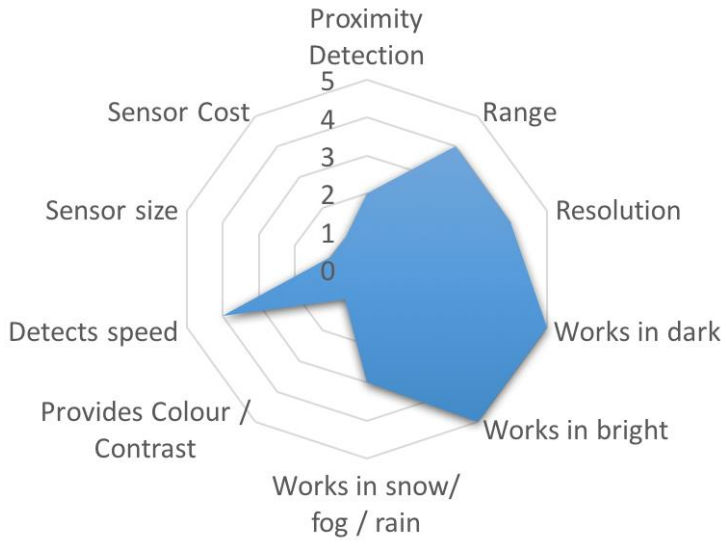




Future of Sensor Technology: Camera vs LIDAR

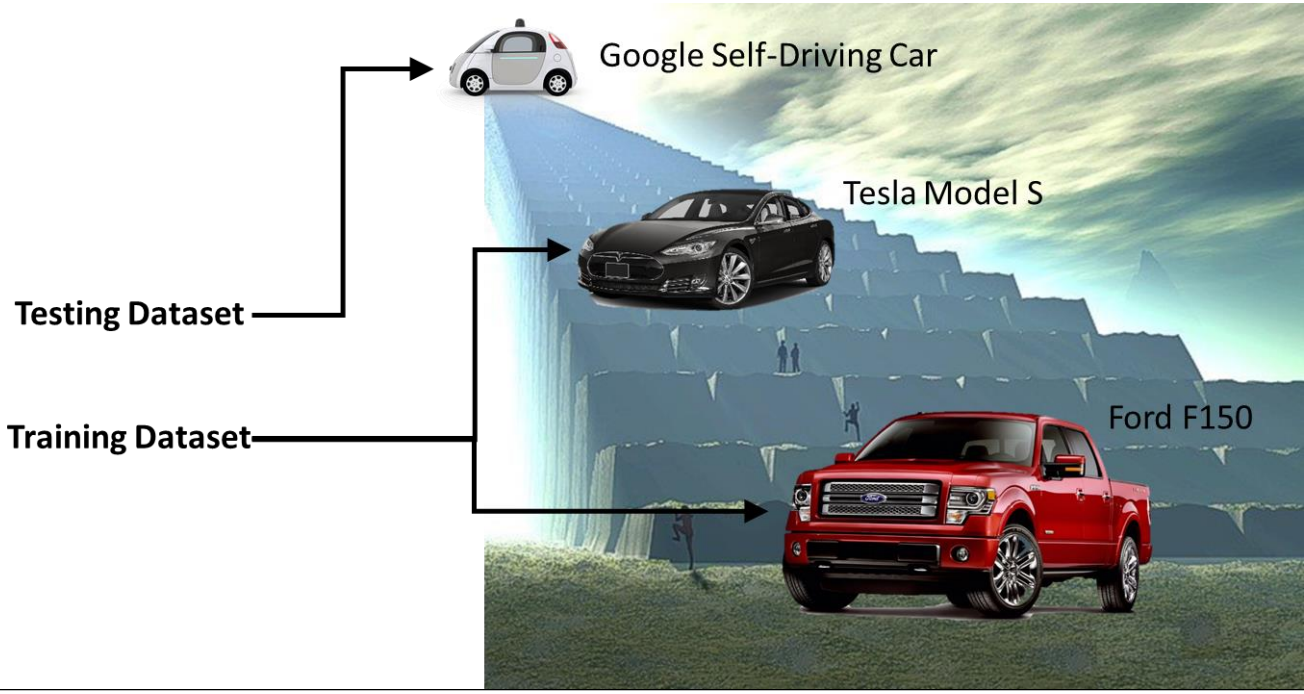
- **Radar and Ultrasonic:**
  - Always there to help
- **Camera:**
  - Annotated driving data grows
  - Deep learning algorithms improve
- **LIDAR:**
  - Range increases
  - Cost drops (solid-state LIDAR)





- **Huge Data**
  Billions of miles reduced to billions of edge cases
- **Machine Learning**
  Algorithms that learn from data that need minimal human-supervision
- **Human-Centered**
  Car helps human pay attention and ask human to help when needed.

In the mean time…



Vision vs Lidar
L2 vs L4

- Vision Sensors + Deep Learning
  - **Pros:**
    - Highest resolution information
    - Feasible to collect data at scale and **learn**
    - Roads are designed for human eyes
    - Cheap
  - **Cons:**
    - Not accurate (without **a lot** of data)
    - Not explainable, not consistent
- Lidar + Maps
  - **Pros:**
    - Explainable, consistent
    - Accurate
  - **Cons:**
    - Does not improve over time
    - Expensive

Example L2 System:

Tesla Autopilot

1+ billion miles

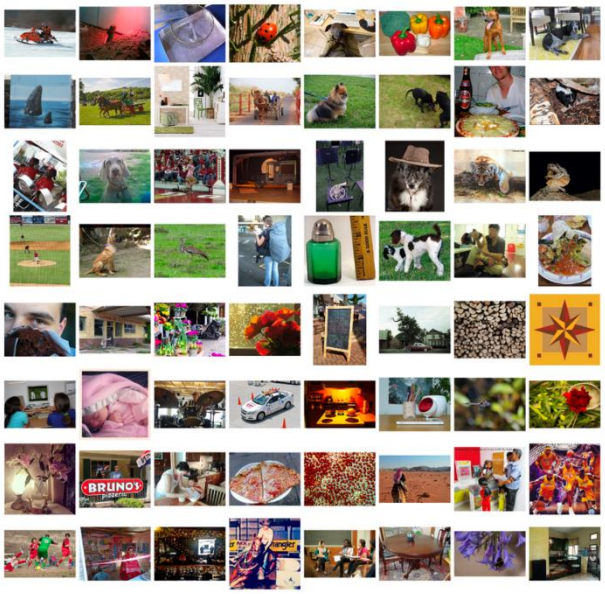
Example L4 System:

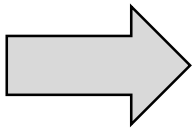
Waymo

10+ million miles

The Road Ahead

IMAGENET





The New York Times

Wielding Rocks and Knives, Arizonans Attack Self-Driving Cars

A Waymo autonomous vehicle in Chandler, Ariz., where the driverless cars have been attacked by residents on several occasions. Caitlin O'Hara for The New York Times

- Our opportunity as artificial intelligence researchers and engineers to improve and save peoples' lives at a mass scale.

Thank You

Website:

deeplearning.mit.edu

- Videos and slides posted on the website
- Code posted on GitHub: https://github.com/lexfridman/mit-deep-learning