

Self-Driving Cars

Lecture 1 – Introduction

Prof. Dr.-Ing. Andreas Geiger

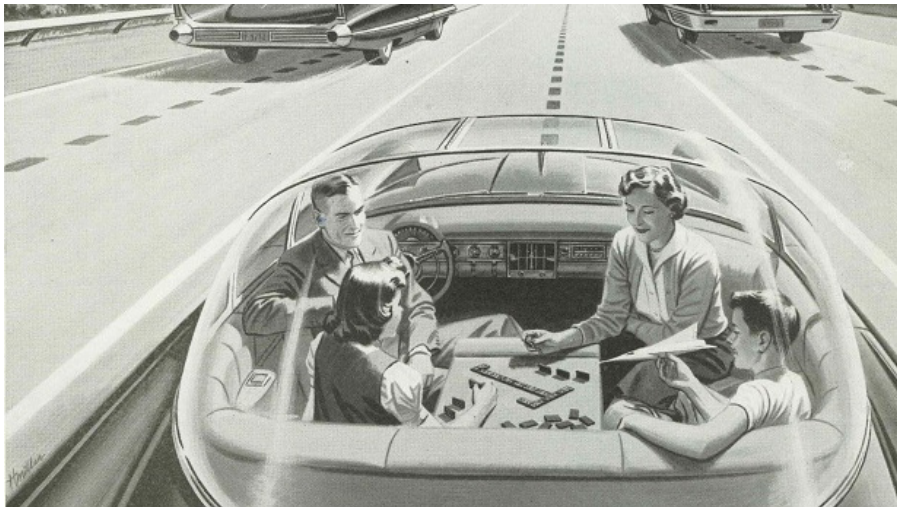
Autonomous Vision Group
University of Tübingen

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European Laboratory for Learning and Intelligent Systems

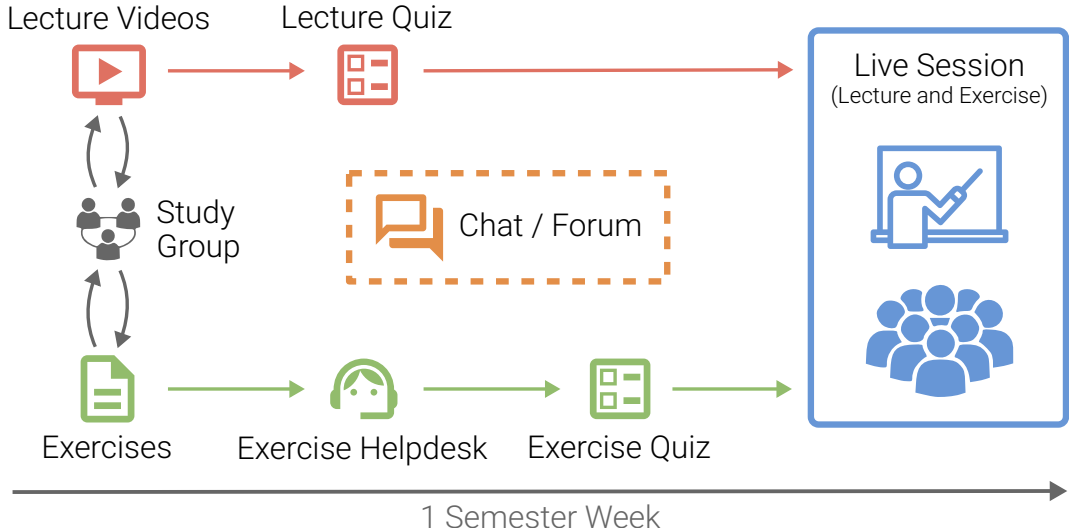
Self-Driving - A Human Dream



Self-Driving - A Human Dream



Flipped Classroom



Agenda

1.1 Organization

1.2 Introduction

1.3 History of Self-Driving

1.1

Organization

Team



Prof. Dr.-Ing.
Andreas Geiger



Daniel
Dauner



Bernhard
Jaeger



Naama
Pearl

Lectures offered by our research group:

- ▶ Deep Learning (recommended for 1st semester MSc)
- ▶ Computer Vision (recommended for 2nd semester MSc)
- ▶ Self-Driving Cars (recommended for **3rd semester MSc**)

Contents

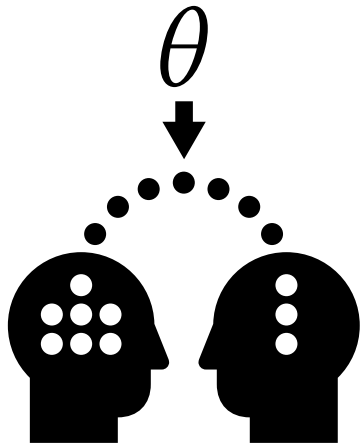
Goal: Develop an understanding of the capabilities and limitations of autonomous driving solutions and gain a basic understanding of the entire system comprising perception, planning and vehicle control. Training agents in simple environments.

- ▶ History of self-driving cars
- ▶ End-to-end learning for self-driving (imitation/reinforcement learning)
- ▶ Modular approaches to self-driving
- ▶ Perception (camera, lidar, radar)
- ▶ Localization (with visual and road maps)
- ▶ Navigation and path planning
- ▶ Vehicle models and control algorithms

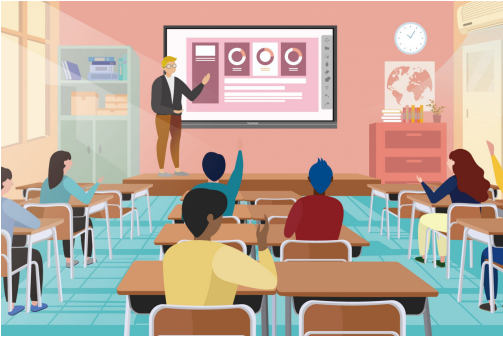
Teaching Philosophy

What is Teaching?

- ▶ Knowledge transfer (bidirectional)
- ▶ Understanding
- ▶ Learning to learn
- ▶ Critical thinking
- ▶ Engaging students
- ▶ Fostering discussion
- ▶ Apply knowledge in practice
- ▶ Having some fun along the way ..



Flipped Classroom



Regular Classroom

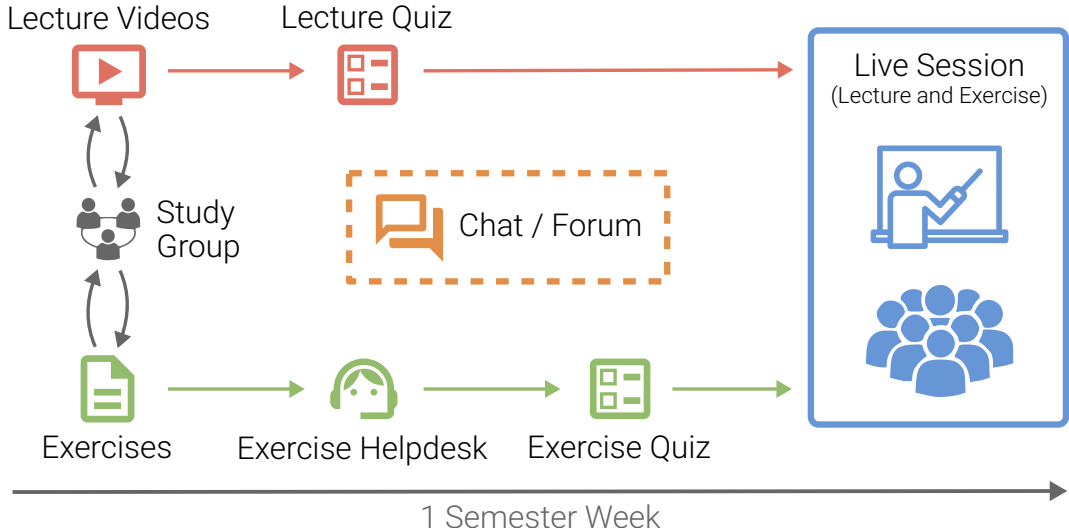
- ▶ Lecturer “reads” lecture in class
- ▶ Students digest content at home
- ▶ Little “quality time”, no fun



Flipped Classroom

- ▶ Students watch lectures at home
- ▶ Content discussed during lecture
- ▶ Maximize interaction time

Flipped Classroom



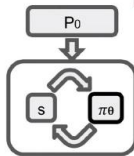
Flipped Classroom

Formal Definition of Imitation Learning

General Imitation Learning:

$$\operatorname{argmin}_{\theta} \mathbb{E}_{s \sim P(s|\pi_{\theta})} [\mathcal{L}(\pi^*(s), \pi_{\theta}(s))]$$

- State distribution $P(s|\pi_{\theta})$ depends on rollout determined by current policy π_{θ}



Self-Driving Cars — Andreas Geiger, 2021/22
Tübingen Machine Learning - 6 / 48

Self-Driving Cars - Lecture 1.3 (Introduction: History of Self-Driving Cars) 54:29

Self-Driving Cars - Lecture 2.1 (Imitation Learning: Introduction) 13:30

Self-Driving Cars - Lecture 2.2 (Imitation Learning: Deep Learning) 38:05

Self-Driving Cars - Lecture 2.3 (Imitation Learning: Imitation Learning) 27:45

Self-Driving Cars - Lecture 2.4 (Imitation Learning: Imitation Learning) 17:31

Self-Driving Cars - Lecture 3.1 (Direct Perception: Direct Perception) 22:31

Self-Driving Cars - Lecture 3.2 (Direct Perception: Conditional Perception) 25:26

- High quality lecture videos
- Available anytime, anywhere
- Slides available while watching

- Can be watched multiple times
- Adjustable speed, closed captions
- Questions $\Rightarrow$ chat & live sessions

Organization

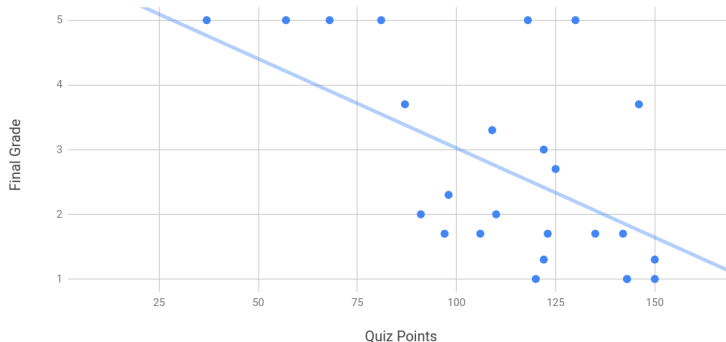
Organization

- ▶ Lectures provided in advance via YouTube
 - ▶ Students must watch lecture before joining live session – **mark your calendar!**
 - ▶ Students are encouraged to ask questions via the chat – fast feedback
- ▶ Live sessions (Wednesdays: 9:00-12:00)
 - ▶ Lecture Q&A, exercise introduction and Q&A, live exercises
 - ▶ Will not be hybrid and not recorded
 - ▶ No tutorials by student assistants (this is a Master course), instead we provide:
 - ▶ Plenary discussion via Q&A sessions – **make use of it!**
 - ▶ Individual help via weekly helpdesk – **make use of it!**
 - ▶ Fast feedback via chat – **make use of it!**
- ▶ Exam
 - ▶ Written, bonus upon participation in quizzes and coding challenges
- ▶ Course Website with YouTube, Slide, Exercise, Quiz, Chat and Zoom links:
<https://uni-tuebingen.de/de/123611>
- ▶ **Register** to Lecture Quiz Server **today** to participate in this course!

Exercises

- ▶ Exercises are offered every 2 weeks, 6 assignments in total
- ▶ Exercises deepen the understanding with pen & paper and coding tasks
- ▶ Solving the exercises is not a prerequisite to participate in the exam
- ▶ But exercise tasks are **highly relevant** for the exam $\Rightarrow$ continuous participation

[Slides / Exercises](#)



Exercises

- ▶ Problems handed out, introduced and discussed in the live sessions
- ▶ Can be conducted in groups of up to 2 students
- ▶ We offer a helpdesk every week via zoom to answer your questions
- ▶ We do not grade exercises, but hand out and discuss the solutions instead
- ▶ But how do I stay motivated to watch the lectures and solve the exercises?

AVG Lecture Quiz Server

- ▶ We provide quiz questions to students during lectures 2-12
- ▶ Students gain a bonus for the exam
- ▶ Students collect AI generated Pokemon!
- ▶ Answers may not be shared
- ▶ Participation is voluntary
- ▶ Past quizzes only visible to participants
- ▶ Deadline: Mondays, 9pm
- ▶ Ask if questions are ambiguous
- ▶ **Register today** with your student email

<https://uni-tuebingen.de/de/123611>

Edit Assignment

Each correct answer yields +1 point. Each incorrect answer yields -1 point. Meaningful student questions yield +1 point. If you wish, you may answer only a subset of the questions. The minimum overall score that can be attained in this assignment is 0 points.

Computer Vision | Summer 22 | Lecture 2

Opening: 21 Apr. 2022 (21:00) - Closing: 28 Apr. 2022 (21:00)

1. What is an ideal point?

- ☐ An inhomogeneous point
- ☐ A point at infinity

[Clear](#)

2. What is the dimensionality of a 4D point represented in homogeneous coordinates?

3. How many degrees of freedom has a 3D line?

4. Affine transformations preserve

- ☐ parallel lines
- ☐ lengths
- ☐ angles

[Clear](#)

5. The diameter of a telecentric lens should be

- ☐ about as large as the object/scene
- ☐ significantly larger than the object
- ☐ significantly smaller than the object

[Clear](#)

6. Increasing the depth of a 3D point in perspective projection

- ☐ increases the (x,y) pixel coordinates
- ☐ decreases the (x,y) pixel coordinates
- ☐ does not affect the (x,y) pixel coordinates

[Clear](#)

7. Perspective projection

- ☐ is linear when using homogeneous coordinates
- ☐ is linear when using inhomogeneous coordinates

[Clear](#)

8. Assume a point light source. Diffuse materials

- ☐ scatter light uniformly in all directions at any given surface point
- ☐ scatter more light into the mirror direction than into other directions at any given surface point
- ☐ scatter the same amount of light independent of the surface normal

[Clear](#)





OpenAI ChatGPT 4.0

- ▶ **Spending time** on the exercises is the **most effective** way to prepare for the exam
- ▶ Using **ChatGPT** or solutions from previous years will **harm you** (we have evidence)
- ▶ It is simple: Don't use ChatGPT, don't lookup solutions (individual responsibility)
- ▶ ChatGPT will not help you in the exam: you need to deeply understand the topic
- ▶ The goal of our quizzes is to motivate you to engage with the materials

AVG Lecture Quiz Server: Student Questions

We appreciate your feedback:

- ▶ Questions stipulate thinking and provide valuable feedback to us
- ▶ Questions make a live session more fun and enjoyable
- ▶ Ask **questions** at any time via the lecture **Quiz Server Chat**
- ▶ We will answer them and select some for discussion during the live session
- ▶ Ask **questions** during the **live session**
- ▶ Dare to ask “trivial” questions – many others are wondering as well
- ▶ Our goal is to build a relationship of trust and openness in this class

Chat



Andreas Geiger | 14 Apr. 2023 (17:16)

This is the chatroom for our lecture.



Andreas Geiger | 14 Apr. 2023 (17:18)

It supports multiple threads which can be associated with specific lectures or quiz questions.

It also supports **markdown** and latex:



$$x = \int_0^1 \frac{5}{20} x \, dx$$

Send Message (Ctrl+Enter)

Helpdesk

- ▶ We offer a weekly zoom helpdesk where our TAs will provide individual support
- ▶ Ask anything about the exercise within a small group of people to the TA
- ▶ Share your screen to show a problem
- ▶ Start working on your exercise early
- ▶ Helpdesk hours (join anytime):
 1. Mondays 10:00-12:00
 2. Fridays 13:00-15:00

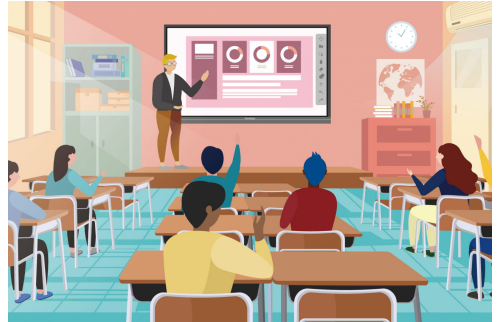
Live Sessions

1. Lecture Q&A

- ▶ Live lecture
- ▶ Discussion of quiz questions
- ▶ Discussion of student questions
- ▶ Discussion of live questions

2. Exercise Q&A

- ▶ Exercise introduction
- ▶ Exercise discussion
- ▶ Live exercises



What will the exam look like?

- ▶ Written main and make-up exam
- ▶ You may choose freely (but no 3rd exam)
- ▶ Registration via Quiz Server
- ▶ Only pen and ruler allowed (no notes)
- ▶ Duration: 90 minutes
- ▶ 5 Tasks, 10 points each, 25 points will pass
- ▶ Bonus added only to passed exams
- ▶ Tasks cover both lectures and exercises
- ▶ Mix of knowledge, calculation, multiple choice
- ▶ Old exams available on Quiz Server (now)

More information: <https://uni-tuebingen.de/de/123611>



Self-Driving Cars

Exam, Winter 2021/22

Tübingen, Feb 22, 2022

Student Number:	
Seat Number:	
First Name:	
Last Name:	
Date of Birth:	
Program of Study (e.g., 'Informatik'):	
Master ☐ Bachelor ☐	

Task	1	2	3	4	5	Σ
Maximal Score	10	10	10	10	10	50
Attained Score						
Correction						

Remarks:

- Leave your bag and jacket at the front desk. Only take your **pen, ruler, student ID** with you.
- Notes, books, printouts, smartphones or calculators are not permitted.
- Have your student ID ready for inspection.
- Write your full name at the top of **every** page.
- Use the space provided for your answers. You can use the back side if you need more space.
- Additional paper can be obtained at the front desk.
- Use black or blue pen. Pencil or red pens are not allowed and will lead to a score of 0.
- A total score of **25** is sufficient for passing the exam. The duration of the exam is **90 minutes**.

Good Luck!

Bonus Points

- ▶ 11 lecture quizzes (10 points per quiz)
- ▶ 110 quiz points in total
- ▶ Formula: bonus points = $\left\lfloor \frac{\text{quiz points}}{36} \right\rfloor$
 - ▶ ≥ 18 quiz points $\Rightarrow$ 1 bonus point
 - ▶ ≥ 54 quiz points $\Rightarrow$ 2 bonus points
 - ▶ ≥ 90 quiz points $\Rightarrow$ 3 bonus points
- ▶ Bonus added only to passed exams

Bonus Points

- ▶ You obtain additional bonus points through participation in our 3 coding challenges
- ▶ Formula:
 - ▶ Total score $\geq 800 \Rightarrow$ 1 bonus point
 - ▶ Total score $\geq 1400 \Rightarrow$ 2 bonus points
 - ▶ Total score $\geq 2000 \Rightarrow$ 3 bonus points
- ▶ Bonus added only to passed exams
- ▶ Up to $3+3=6$ bonus points in total

Coding Challenges

- ▶ Challenges
 - ▶ Will be using PyTorch and OpenAI Gym
 - ▶ Challenge 1: Imitation Learning
 - ▶ Challenge 2: Reinforcement Learning
 - ▶ Challenge 3: Modular Pipeline
- ▶ Challenges can be conducted in groups of up to 2 students
- ▶ 3-4 weeks per challenge with live Q&A sessions in between
- ▶ Winners may present their approaches during last live session
 - ▶ Create your groups via the Quiz Server assignment
 - ▶ Find team partners here, via the chat or the TAs
 - ▶ Solutions of a group must indicate all group members
- ▶ Solutions may not be shared across groups

OpenAI Gym

 Gymnasium Documentation

Q Search

INTRODUCTION

Basic Usage

Compatibility with Gym

v21 to v26 Migration Guide

API

Env

Register and Make

Spaces

Wrappers

Vector

Utils

Experimental

ENVIRONMENTS

Classic Control

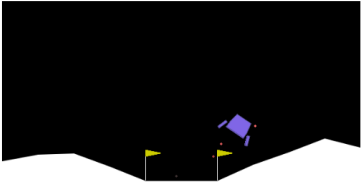
Box2D

Bipedal Walker

Car Racing

 Gymnasium

An API standard for reinforcement learning with a diverse collection of reference environments



Gymnasium is a maintained fork of OpenAI's Gym library. The Gymnasium interface is simple,

OpenAI Gym: Car Racing Environment

 Gymnasium Documentation

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API
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Register and Make
Spaces
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Vector
Utils
Experimental

ENVIRONMENTS
Classic Control
Box2D
 Bipedal Walker
 Car Racing

Car Racing



This environment is part of the Box2D environments which contains general information about the environment.

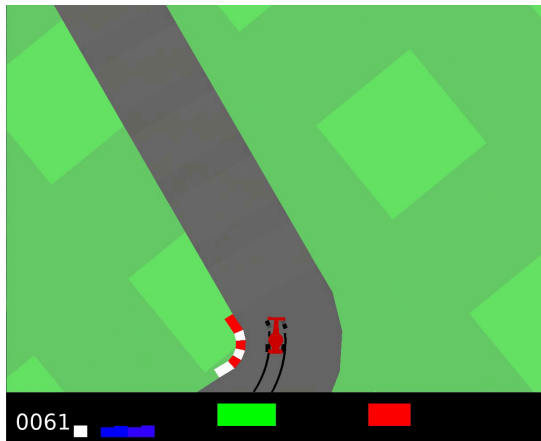
Action Space	<code>Box([-1.0, 0.0], 1.0, (3,), float32)</code>
Observation Space	<code>Box(0, 255, (96, 96, 3), uint8)</code>
import	<code>gymnasium.make("CarRacing-v2")</code>

Description

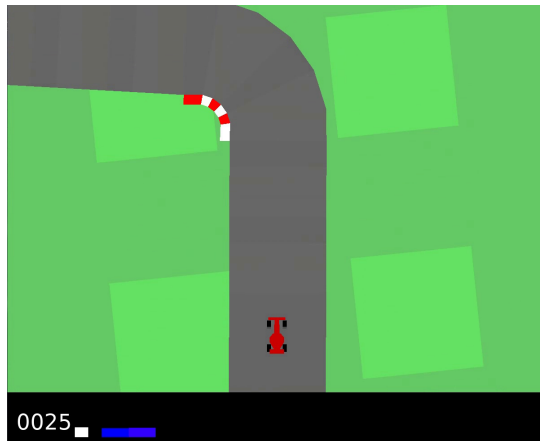
The easiest control task to learn from pixels - a top-down racing environment. The generated track is random every episode.

Some indicators are shown at the bottom of the window along with the state RGB buffer. From left to right: true speed, four ABS sensors, steering wheel position, and gyroscope. To play yourself (it's rather fast for humans), type:

Challenge 1: Imitation Learning

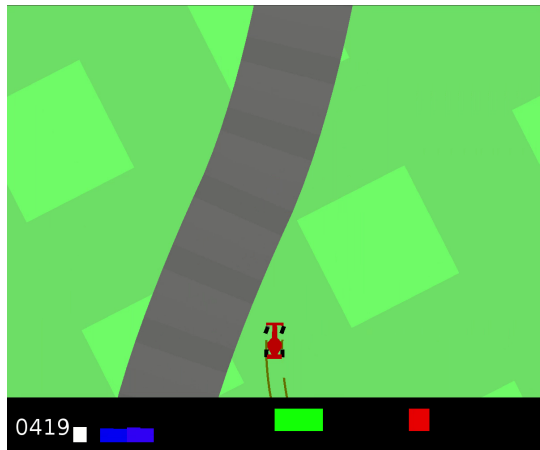
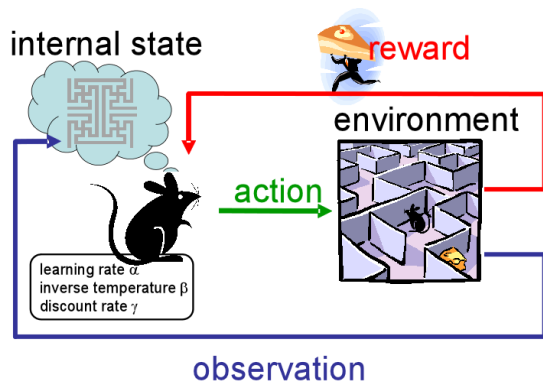


Trainer
(Human Driver)

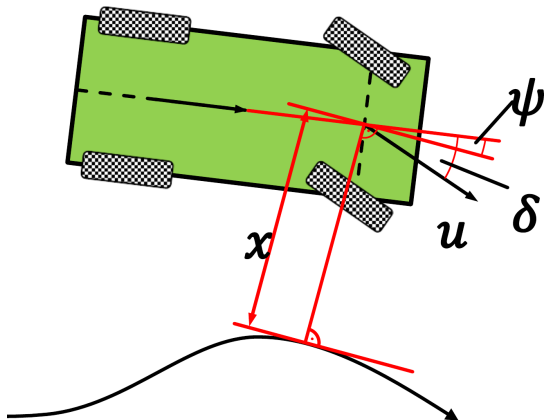


Trainee
(Neural Network)

Challenge 2: Reinforcement Learning



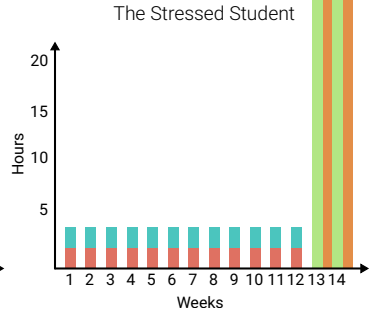
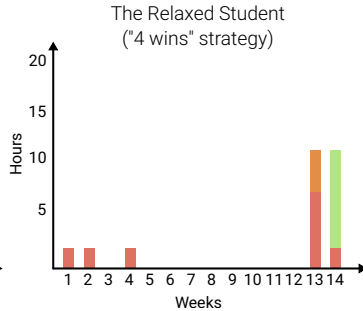
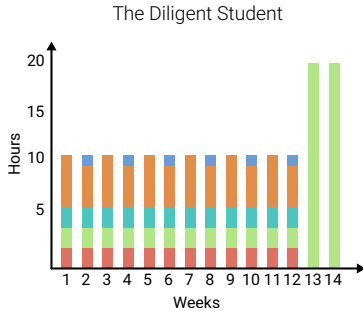
Challenge 3: Modular Pipeline



Work Ethics

This lecture has 9 ECTS, corresponding to a total workload of ~ 270 hours (MHB)

Lecture Videos Self-Study Live Sessions Exercises Quizzes



Course Materials and Prerequisites

Course Materials

Books:

- ▶ Janai et al.: Computer Vision for Autonomous Vehicles
<https://arxiv.org/abs/1704.05519>
- ▶ Chen et al.: End-to-end Autonomous Driving: Challenges and Frontiers
<https://arxiv.org/abs/2306.16927>
- ▶ Szeliski: Computer Vision: Algorithms and Applications
<https://szeliski.org/Book/>
- ▶ Goodfellow, Bengio, Courville: Deep Learning
<http://www.deeplearningbook.org>

Talks, Courses and Tutorials:

- ▶ Stachniss (Bonn): Self-Driving Cars
<https://www.ipb.uni-bonn.de/sdc-2020/>
- ▶ Tesla AI Day 2021 and 2022
<https://www.youtube.com/watch?v=j0z4FweCy4M>
https://www.youtube.com/watch?v=0DSJsvid_SU
- ▶ Fridman (MIT): Self-Driving Cars
<https://deeplearning.mit.edu/>
- ▶ Urtasun (UoT): All about SD
<http://www.allaboutselfdriving.com/>

Course Materials

Related Courses:

- ▶ McAllester (TTI-C): Fundamentals of Deep Learning
<http://mcallester.github.io/ttic-31230/Fall12020/>
- ▶ Leal-Taixe, Niessner (TUM): Introduction to Deep Learning
<http://niessner.github.io/I2DL/>
- ▶ Grosse (UoT): Intro to Neural Networks and Machine Learning
http://www.cs.toronto.edu/~rgrosse/courses/csc321_2018/
- ▶ Li (Stanford): Convolutional Neural Networks for Visual Recognition
<http://cs231n.stanford.edu/>
- ▶ Abbeel, Chen, Ho, Srinivas (Berkeley): Deep Unsupervised Learning
<https://sites.google.com/view/berkeley-cs294-158-sp20/home>

Course Materials

Tutorials:

- ▶ The Python Tutorial

<https://docs.python.org/3/tutorial/>

- ▶ NumPy Quickstart

<https://numpy.org/devdocs/user/quickstart.html>

- ▶ PyTorch Tutorial

<https://pytorch.org/tutorials/>

Frameworks / IDEs:

- ▶ Visual Studio Code

<https://code.visualstudio.com/>

- ▶ Google Colab

<https://colab.research.google.com>

Prerequisites

Math:

- ▶ Linear algebra, probability and information theory. If unsure, have a look at:
Goodfellow et al.: [Deep Learning \(Book\)](#), Chapters 1-4
Luxburg: [Mathematics for Machine Learning \(Lecture\)](#)
Deisenroth et al.: [Mathematics for Machine Learning \(Book\)](#)

Computer Science:

- ▶ Variables, functions, loops, classes, algorithms

Deep Learning:

- ▶ Geiger: [Deep Learning \(Lecture\)](#)

Python and PyTorch:

- ▶ <https://docs.python.org/3/tutorial/>
- ▶ <https://pytorch.org/tutorials/>

Prerequisites

Linear Algebra:

- ▶ Vectors: $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$
- ▶ Matrices: $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$
- ▶ Operations: $\mathbf{A}^T, \mathbf{A}^{-1}, \text{Tr}(\mathbf{A}), \det(\mathbf{A}), \mathbf{A} + \mathbf{B}, \mathbf{AB}, \mathbf{Ax}, \mathbf{x}^T \mathbf{y}$
- ▶ Norms: $\|\mathbf{x}\|_1, \|\mathbf{x}\|_2, \|\mathbf{x}\|_\infty, \|\mathbf{A}\|_F$
- ▶ SVD: $\mathbf{A} = \mathbf{UDV}^T$

Prerequisites

Probability and Information Theory:

- ▶ Probability distributions: $P(X = x)$
- ▶ Marginal/conditional: $p(x) = \int p(x, y)dy$, $p(x, y) = p(x|y)p(y)$
- ▶ Bayes rule: $p(x|y) = p(y|x)p(x)/p(y)$
- ▶ Conditional independence: $x \perp\!\!\!\perp y \mid z \Leftrightarrow p(x, y|z) = p(x|z)p(y|z)$
- ▶ Expectation: $\mathbb{E}_{x \sim p} [f(x)] = \int_x p(x)f(x)dx$
- ▶ Variance: $\text{Var}(f(x)) = \mathbb{E} [(f(x) - \mathbb{E}[f(x)])^2]$
- ▶ Distributions: Bernoulli, Categorical, Gaussian, Laplace
- ▶ Entropy: $H(x)$, KL Divergence: $D_{KL}(p||q)$

Prerequisites

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$$\mathbf{A} = \begin{pmatrix} 3 & 1 \\ 2 & 1 \end{pmatrix} \quad \mathbf{B} = \begin{pmatrix} 1 & 2 \\ 3 & 1 \end{pmatrix} \Rightarrow \mathbf{AB} = \begin{pmatrix} 6 & 7 \\ 5 & 5 \end{pmatrix}$$

$$\mathbf{Ax} = \mathbf{b}$$

$$\mathbf{A}^{-1}\mathbf{Ax} = \mathbf{A}^{-1}\mathbf{b}$$

$$\mathbf{I}_N \mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$$

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{b}$$

$$\hat{\mathbf{w}}_{ML} = \underset{\mathbf{w}}{\operatorname{argmax}} \underbrace{\sum_{i=1}^N \log p_{\text{model}}(y_i | \mathbf{x}_i, \mathbf{w})}_{\text{Log-Likelihood}}$$

$$\sum_{i=1}^M \frac{\partial f}{\partial g_i} \frac{dg_i}{dx}$$

$$\mathbf{x}^T \mathbf{y} = (\mathbf{x}^T \mathbf{y})^T = \mathbf{y}^T \mathbf{x} = \mathbf{x}^T \mathbf{y}$$

Math for Deep Learning

Prof. Dr. Andreas Geiger

New Practical (SS26): Autonomous Robotics with Duckietown



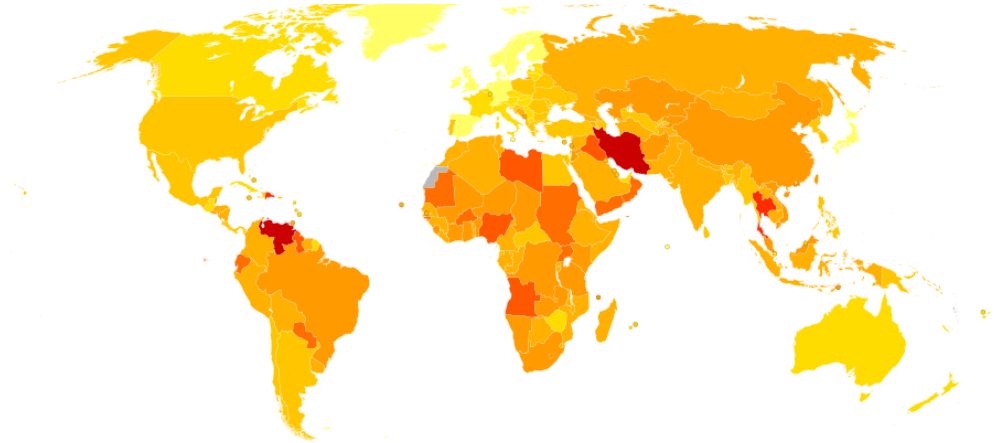


Thank You!

Looking forward to our discussions

Why Self-Driving Cars?

Road Fatalities in 2017



- ▶ USA: 32,700 Germany: 3,300 World: 1,300,000
- ▶ Main factors: speeding, intoxication, distraction, etc.

Benefits of Autonomous Driving

- ▶ Lower risk of accidents
- ▶ Provide mobility for elderly and people with disabilities
 - ▶ In the US 45% of people with disabilities still work
- ▶ Decrease pollution for a more healthy environment
- ▶ New ways of public transportation
 - ▶ Car pooling
 - ▶ Car sharing
- ▶ Reduce number of cars (95% of the time a car is parked)

Uber Commercial (2018)



Uber Fatal Accident (2018)



Self-driving is Hard

Human performance: 1 fatality per 100 mio miles

Error rate to improve on: 0.000001 %

Challenges:

- ▶ Snow, heavy rain, night
- ▶ Unstructured roads, parking lots
- ▶ Pedestrians, erratic behavior
- ▶ Reflections, dynamics
- ▶ Rare and unseen events
- ▶ Merging, negotiating, reasoning
- ▶ Ethics: what is good behavior?
- ▶ Legal questions

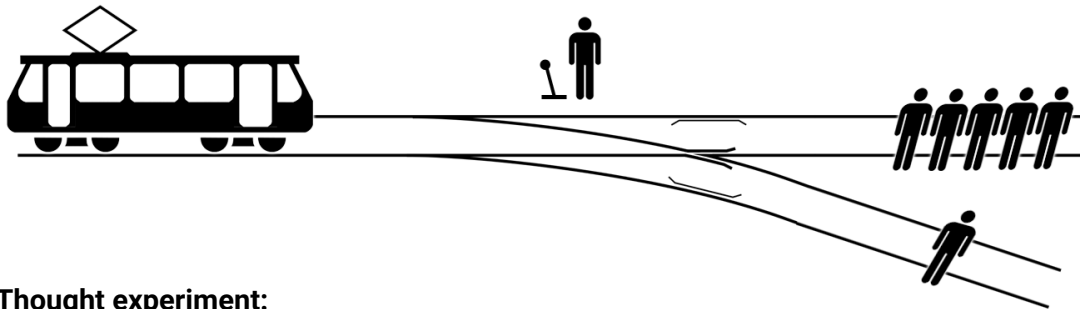


http://theoatmeal.com/blog/google_self_driving_car

Unstructured Traffic



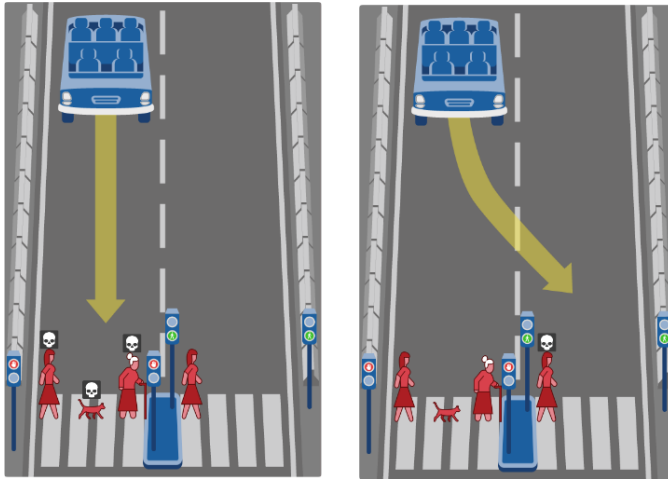
The Trolley Problem (1905)



Thought experiment:

- ▶ You observe a train that will kill 5 people on the rail tracks if it continues
- ▶ You have the option to pull a lever to redirect the train to another track
- ▶ However, the train will kill one (other) person on that alternate track
- ▶ What is your decision? What is the correct/ethical decision?

The MIT Moral Machine



1.3

History of Self-Driving

The Automobile

1886: Benz Patent-Motorwagen Nummer 1



1886: Benz Patent-Motorwagen Nummer 1

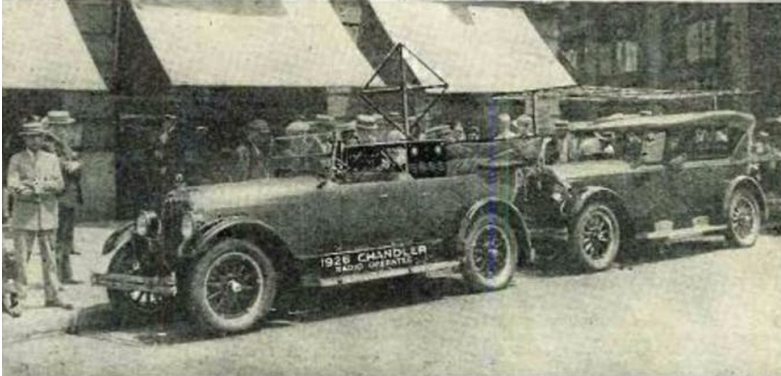
- ▶ Benz 954 cc single-cylinder four-stroke engine (500 watts)
- ▶ Weight: 100 kg (engine), 265 kg (total)
- ▶ Maximal speed: 16 km/h
- ▶ Consumption: 10 liter / 100 km (!)
- ▶ Construction based on the tricycle, many bicycle components
- ▶ 29.1.1886: patent filed
- ▶ 3.7.1886: first public test drive in Mannheim
- ▶ 2.11.1886: patent granted, but investors stayed skeptical
- ▶ First long distance trip (106 km) by Bertha Benz in 1888 with Motorwagen Nummer 3 (without knowledge of her husband) fostered commercial interest
 - ▶ First gas station: pharmacy in Wiesloch near Heidelberg

1886: Benz Patent-Motorwagen Nummer 1



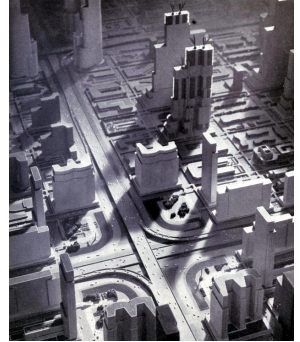
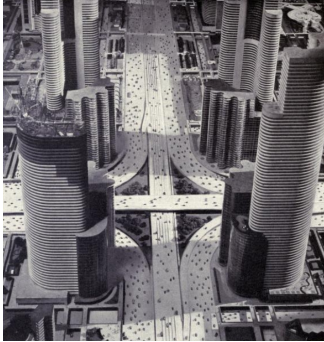
Self-Driving Cars

1925: Phantom Auto – “American Wonder” (Houdina Radio Control)



In the summer of 1925, Houdina’s driverless car, called the American Wonder, traveled along Broadway in New York City—trailed by an operator in another vehicle—and down Fifth Avenue through heavy traffic. It turned corners, sped up, slowed down and honked its horn. Unfortunately, the demonstration ended when the American Wonder crashed into another vehicle filled with photographers documenting the event. (Discovery Magazine)

1939: Futurama – New York World's Fair



- ▶ Exhibit at the New York World's Fair in 1939 sponsored by General Motors
- ▶ Designed by Norman Bel Geddes' - his vision of the world 20 years later (1960)
- ▶ Radio-controlled electric cars, electromagnetic field via circuits in roadway
- ▶ #1 exhibition, very well received (great depression), prototypes by RCA & GM

1956: General Motors Firebird II



1956: General Motors Firebird II

"PROGRESS POSSIBILITY"

The Electronically Controlled Car on the Safety Autoway of Tomorrow

For several years General Motors has played an important role in the continuing campaign to bring our highways up to date.

At the same time, our designers and engineers have continuously planned and worked to make the motorcar an ever safer form of transportation.

Now the Styling Section of General Motors—under the leadership of Harley J. Earl, GM Vice President in charge of Styling—has created for the Motorama of 1956 a dramatic and daring concept of a Highway of Tomorrow.

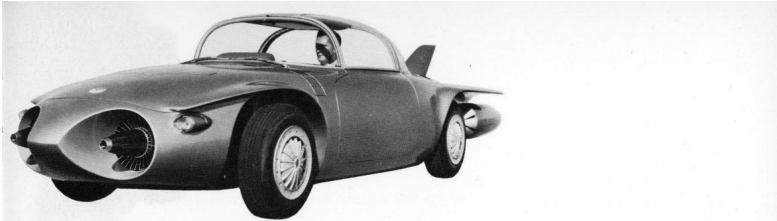
Shown on VistaVision film in Technicolor, and on the Motorama stage, this amazing concept places control

of the motorcar in the hands of an "electronic brain"—actually releasing the driver from the wheel.

Though the realization of such a "dream highway" belongs in the far, far future—it utilizes present-day knowledge and experience gained through electronic control and computation, radar and television—all now in operation.

To present this spectacular vision on film—General Motors built a replica of such a highway on the Arizona desert—as well as a more complete miniature highway on a Hollywood stage for filming purposes. What's more, they incorporated, in the Firebird II, elements helpful in demonstrating such an electronically controlled operation.

1956: General Motors Firebird II



These include a Dashboard View screen which has two panels. The left panel is for "internal communication" between car and driver (information he would normally receive from visible instruments as to fuel supply, engine operation and temperature). It also reveals a radar pattern when he guides the car onto the electronic control-strip for automatic steering.

"External communication" from the control tower in his Autoway Zone also appears on this panel.

The right-hand panel supplies normal television reception, and two-way television communication with motels, other cars, etc.

Rearview mirror is replaced by a small circular view

screen on the left side of the dashboard which projects images picked up by a TV camera at the rear of the car.

The steering control handles are designed to slide forward out of the way when car is on automatic control.

Extending from the two engine air scoops on each side of the nose of the car are probes or antennas which pick up wave impulses from the conductor strip in the center of the control lane.

None of these features is operative in the Firebird II. They serve merely to complete the demonstration of how an electronically controlled car should be equipped to function on the electronic Safety Autoway.

1960: RCA Labs' Wire Controlled Car & Aeromobile

PAGE FOUR

THE PRESS-COURIER—PHONE HU 3-1101

Reporter Rides Driverless Car

"Smart Road"
Used to Test
"Smart Auto"

By Doc Quigg

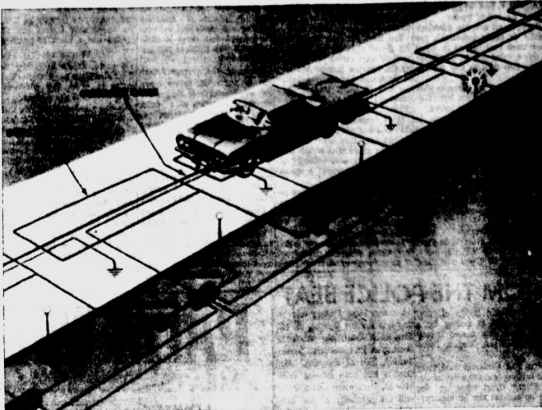
PRINCETON, N. J. (UPI)—Washington Irving put the headless horseman on paper. A corporation named RCA now has put the driverless car on the road. The automation tends to be as scary as the ghost, until you get used to it. But someday we may have to live with it.

The road is a private one, souped up mightily with loops and lengths of electronic gear buried within the asphalt pavement, at the research center of the Radio Corp. of America. It's about as automatic as a road can get, and in effect it does the driving.

The "electronic highway" can sense the presence of any metallic vehicle on its surface and tell you where the vehicle is, how fast it is going, and in what direction. RCA engineers admitted that a herd of cattle would not be detected, unless they were dressed in armor—but then, the limited access highway of the future will be closed to cows.

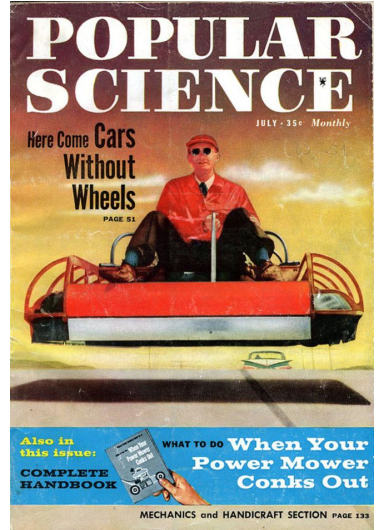
Smart Road

Given such a smart road, it remained to smarten up the auto-



DRIVERLESS CAR—Engineers at the RCA research center at Princeton, N. J., are experimenting with a driverless automobile that scoots around an electronic test track shown in diagram above. The elements of the test track include a series of

rectangular wire loops, a continuous guidance cable buried beneath the pavement, and a chain of transistorized detector circuits along the roadside, each linked to one of the buried loops.



1970: Citroen DS19



- Steered by sensing magnetic cables in the road, up to 130 km/h

1986: Navlab 1



► Vision-based navigation

Jochem, Pomerleau, Kumar and Armstrong: PANS: A Portable Navigation Platform. IV, 1995.

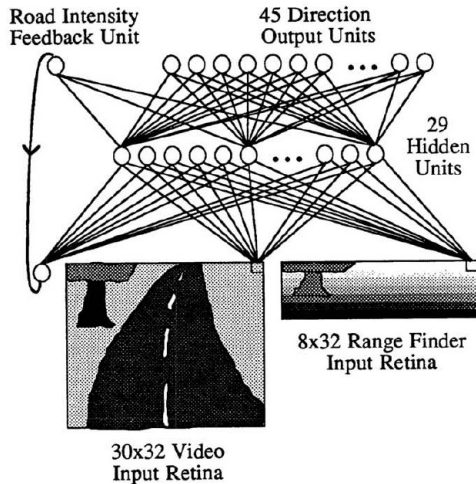
Navlab Overview

- ▶ Project at Carnegie Mellon University, USA
- ▶ 1986: Navlab 1: 5 computer racks (Warp supercomputer)
- ▶ 1988: First semi-autonomous drive at 20 mph
- ▶ 1990: Navlab 2: 6 mph offroad, 70 mph highway driving
- ▶ 1995: Navlab 5: “No Hands Across America” (2850 miles, 98 % autonomy)
- ▶ PANS: Portable Advanced Navigation Support
- ▶ Compute: 50 Mhz Sparc workstation (only 90 watts)
- ▶ Main focus: lane keeping (lateral but no longitudinal control, i.e., no steering)
- ▶ Position estimation: Differential GPS + Fibre Optic Gyroscope (IMU)
- ▶ Low-level control: HC11 microcontroller

1988: ALVINN

ALVINN: An Autonomous Land Vehicle in a Neural Network

- ▶ Forward-looking, vision based driving
- ▶ Fully connected neural network maps road images to vehicle turn radius
- ▶ Directions discretized (45 bins)
- ▶ Trained on simulated road images
- ▶ Tested on unlined paths, lined city streets and interstate highways
- ▶ 90 consecutive miles at up to 70 mph



1988: ALVINN



1995: AURORA

AURORA: Automotive Run-Off-Road Avoidance System

- ▶ Downward-looking (mounted at side)
- ▶ Adjustable template correlation
- ▶ Tracks solid or dashed lane marking
- ▶ shown to perform robustly even when the markings are worn or their appearance in the image is degraded
- ▶ Mainly tested as a lane departure warning system (“time to crossing”)

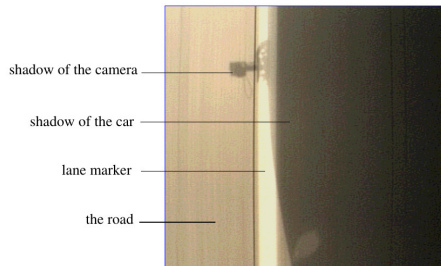
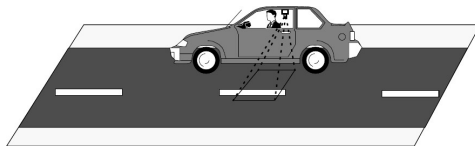


Figure 2: A typical image of a lane marker on the road

1986: VaMoRs – Bundeswehr Universität Munich



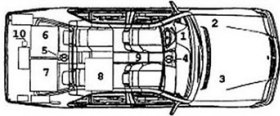
- ▶ Developed by Ernst Dickmanns in context of EUREKA-Prometheus (€800 mio.) (PROgramMme for a European Traffic of Highest Efficiency and Unprecedented Safety, 1987- 1995)
- ▶ Demonstration to Daimler-Benz Research 1986 in Stuttgart
- ▶ Longitudinal & lateral guidance with lateral acceleration feedback
- ▶ Speed: 0 to 36 km/h

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1994: VAMP – Bundeswehr Universität Munich



- | | |
|--------------------------------------|--|
| 1 Torque motor for steering | 6, 8 Transputer system, image processing |
| 2 brake system | 7 processors for gaze & locomotion control |
| 3 electric throttle control | 8 user interface |
| 4 front platform } for 2 CCD cameras | 9 linear accelerometers |
| 5 rear platform } | 10 angular rate sensors |



- ▶ 2nd Generation Transputer (60 processors), bifocal saccade vision, no GPS
- ▶ 1678 km autonomous ride Munich to Odense, 95% autonomy (up to 158 km)
- ▶ Autonomous driving speed record: 180 km/h (lane keeping)
- ▶ Convoi driving, automatic lane change (triggered by human)

1992: Summary Paper by Dickmanns

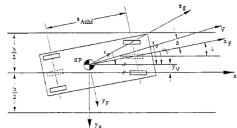
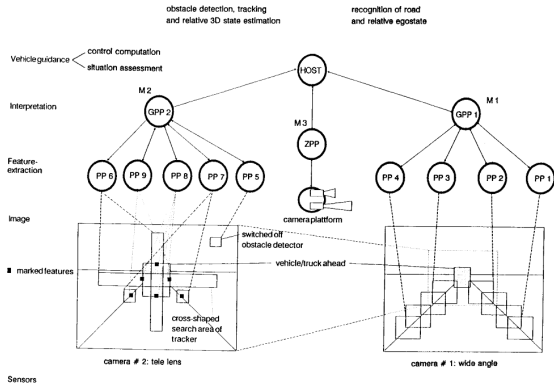


Fig. 7. Substitute model for lateral vehicle motion.

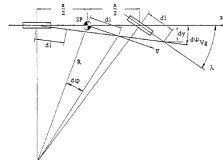


Fig. 8. Steering kinematics.

The steer angle is set by a stepping motor, the dynamic behavior of which is roughly modeled as an integrator

$$\dot{\lambda} = k_{\lambda} \cdot U. \quad (30)$$

Collecting these relations results in a linear velocity-dependent fourth-order state model

$$\begin{aligned} \dot{\lambda} &= k_{\lambda} \cdot U \\ \dot{\beta} &= -2K \cdot \beta + (V/a - K) \cdot \lambda \\ \dot{y}_c &= V \cdot (\psi_v + \beta) \\ \dot{\psi} &= V/a \cdot \lambda - V \cdot C_{0h} \end{aligned}$$

or in matrix-vector notation

$$\dot{\mathbf{x}}_v = \mathbf{A}_v \cdot \mathbf{x}_v + \mathbf{b}_v \cdot U + \mathbf{B}_c \cdot C_{0h} \quad (31)$$

where

$$\mathbf{A}_v = \begin{bmatrix} 0 & 0 & 0 & 0 \\ b_F & a_F & 0 & 0 \\ 0 & V & 0 & V \\ c_F & 0 & 0 & 0 \end{bmatrix}; \quad \mathbf{x}_v = \begin{bmatrix} \lambda \\ \beta \\ y_c \\ \psi_v \end{bmatrix}; \quad \mathbf{b}_v = \begin{bmatrix} k_{\lambda} \\ 0 \\ 0 \\ 0 \end{bmatrix}; \quad \mathbf{B}_c = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -V \end{bmatrix}$$

with the elements

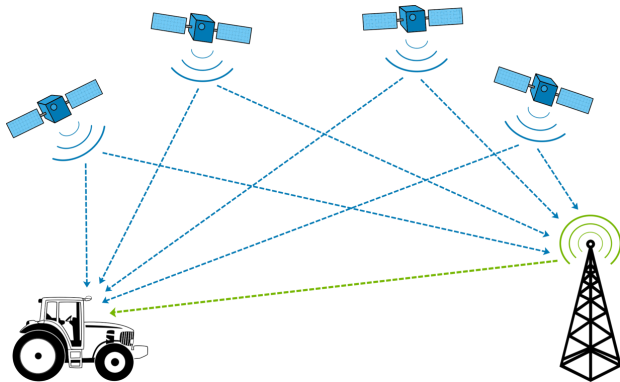
$$c_F = V/a, \quad b_F = c_F - K$$

1995: Invention of Adaptive Cruise Control (ACC)



- ▶ 1992: Lidar-based distance control by Mitsubishi (throttle control & downshift)
- ▶ 1997: Laser adaptive cruise control by Toyota (throttle control & downshift)
- ▶ 1999: DISTRONIC radar-assisted ACC by Mercedes-Benz (S-Class), level 1 autonomy

2000: First Technological Revolution: GPS, IMUs & Maps



- ▶ NAVSTAR GPS available with 1 meter accuracy, IMUs improve up to 5 cm
- ▶ Navigation systems and road maps available
- ▶ Accurate self-localization and ego-motion estimation algorithms

2004: Darpa Grand Challenge 1 (Limited to US Participants)



- ▶ 1st competition in the Mojave Desert along a 240 km route, \$1 mio prize money
- ▶ No traffic, dirt roads, driven by GPS (2935 points, up to 4 per curve).
- ▶ None of the robot vehicles finished the route. CMU traveled the farthest distance, completing 11.78 km of the course before hitting a rock.

2005: Darpa Grand Challenge 2 (Limited to US Participants)



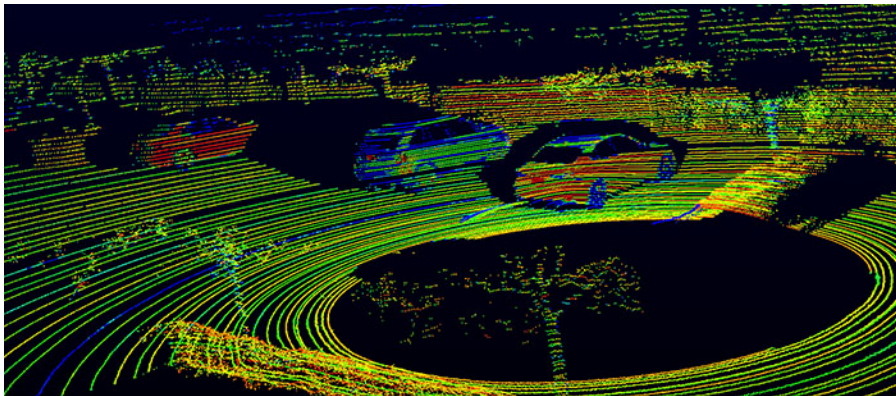
- ▶ 2nd competition in the Mojave Desert along a 212 km route, \$2 mio prize money
- ▶ Five teams finished (Stanford team 1st in 6:54 h, CMU team 2nd in 7:05 h)

2006: Park Shuttle Rotterdam



- ▶ 1800 meters route from metro station Kralingse Zoom to business park Rivium
- ▶ One of the first truly driverless car, but dedicated lane, localization via magnets

2006: Second Technological Revolution: Lidars & High-res Sensors



- ▶ High-resolution Lidar
- ▶ Camera systems with increasing resolution
- ▶ Accurate 3D reconstruction, 3D detection & 3D localization

2007: Darpa Urban Challenge (International Participants)



- ▶ 3rd competition at George Air Force Base, 96 km route, urban driving, \$2 mio
- ▶ Rules: obey traffic law, negotiate, avoid obstacles, merge into traffic
- ▶ 11 US teams received \$1 mio funding for their research
- ▶ Winners: CMU 1st (4:10), Stanford's Stanley 2nd (4:29). No non-US participant.

2009: Google starts working on Self-Driving Car



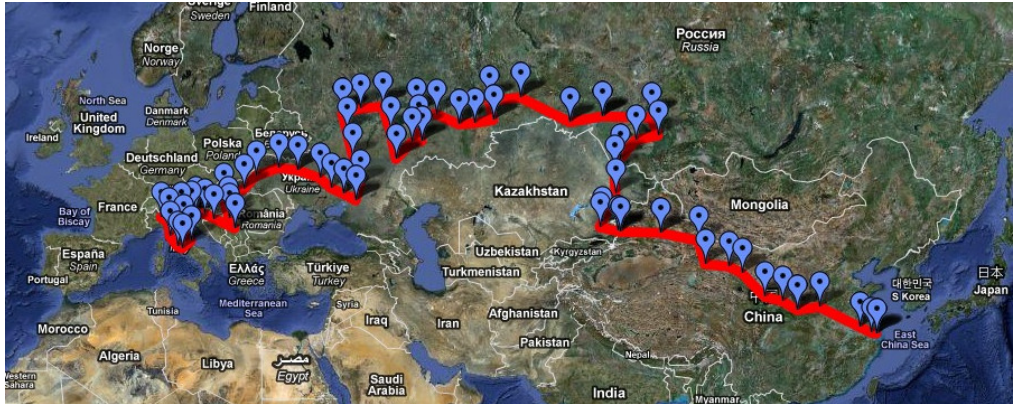
- ▶ Led by Sebastian Thrun, former director of Stanford AI lab and Stanley team
- ▶ Others: Chris Urmson, Dmitri Dolgov, Mike Montemerlo, Anthony Levandowski
- ▶ Renamed "Waymo" in 2016 (Google spend \$1 billion until 2015)

2010: VisLab Intercontinental Autonomous Challenge (VIAC)



- ▶ July 20 to October 28: 16,000 kilometres trip from Parma, Italy to Shanghai, China
- ▶ The second vehicle automatically followed the route defined by the leader vehicle by following it either visually or thanks to GPS waypoints sent by the lead vehicle

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2010: Pikes Peak Self-Driving Audi TTS



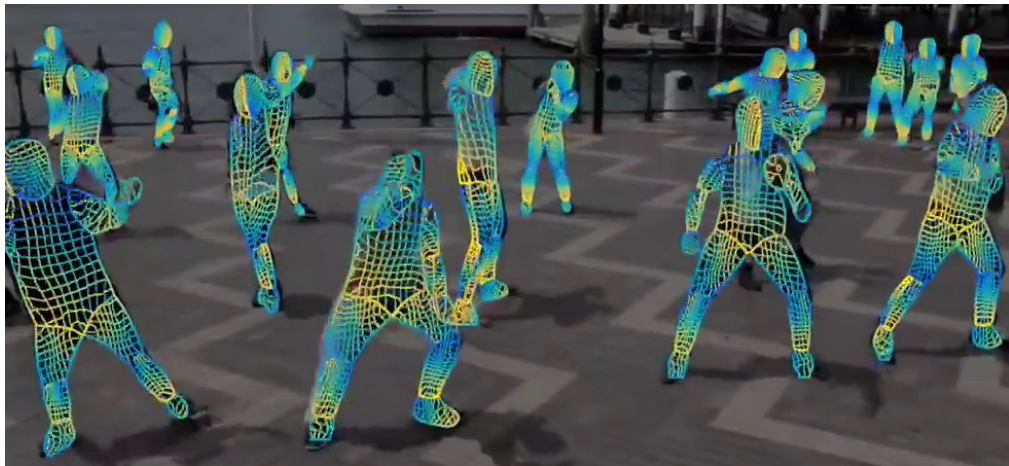
- ▶ Pikes Peak International Hill Climb (since 1916): 20 km, 1440 Hm, Summit: 4300 m
- ▶ Audi TTS completes track in 27 min (record in 2010: 10 min, now: 8 min)

2010: Stadtpilot (Technical University Braunschweig)



- Goal: geofenced innercity driving based on laser scanners, cameras and HD maps
- Challenges: traffic lights, roundabouts, etc. Similar efforts by FU Berlin and others

2012: Third Technological Revolution: Deep Learning



- Representation learning boosts in accuracy across tasks and benchmarks

2012: Third Technological Revolution: New Benchmarks

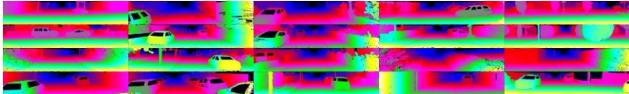
The KITTI Vision Benchmark Suite
A project of Karlsruhe Institute of Technology
and Toyota Technological Institute at Chicago



home setup **stereo** flow sceneflow depth odometry object tracking road semantics raw data submit results

Andreas Geiger (MPI Tübingen) | Philip Lenz (KIT) | Christoph Stiller (KIT) | Raquel Urtasun (University of Toronto)

Stereo Evaluation 2012



The stereo / flow benchmark consists of 194 training image pairs and 195 test image pairs, saved in loss less png format. Our evaluation server computes the average number of bad pixels for all non-occluded or occluded (=all groundtruth) pixels. We require that all methods use the same parameter set for all test pairs. Our development kit provides details about the data format as well as MATLAB / C++ utility functions for reading and writing disparity maps and flow fields.

- [Download stereo/optical flow data set \(2 GB\)](#)
- [Download stereo/optical flow calibration files \(1 MB\)](#)
- [Download multi-view extension \(20 frames per scene, all cameras\) \(17 GB\)](#)
- [Semantic and instance labels for 60 images and car labels for all training images \(1 MB\)](#)
- [Download stereo/optical flow development kit \(3 MB\)](#)

Our evaluation table ranks all methods according to the number of non-occluded erroneous pixels at the specified disparity / end-point error threshold.

2013: Mercedes Benz S500 Intelligent Drive



- ▶ Autonomous ride on historic Bertha Benz route by Daimler R&D and KIT/FZI
- ▶ Novelty: close to production stereo cameras / radar (but requires HD maps)

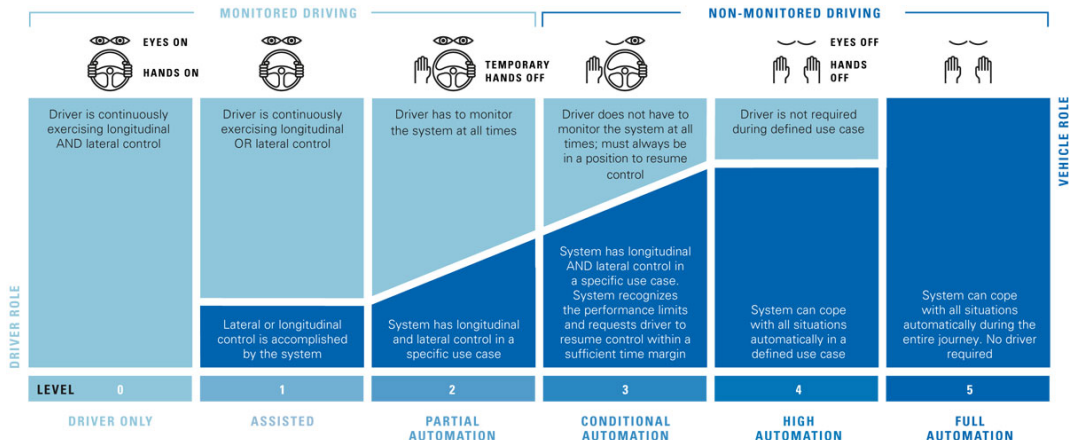
2014: Mercedes S Class



Advanced ADAS (Level 2 Autonomy):

- ▶ Autonomous steering, lane keeping, acceleration/braking, collision avoidance, driver fatigue monitoring in city traffic and highway speeds up to 200 km/h

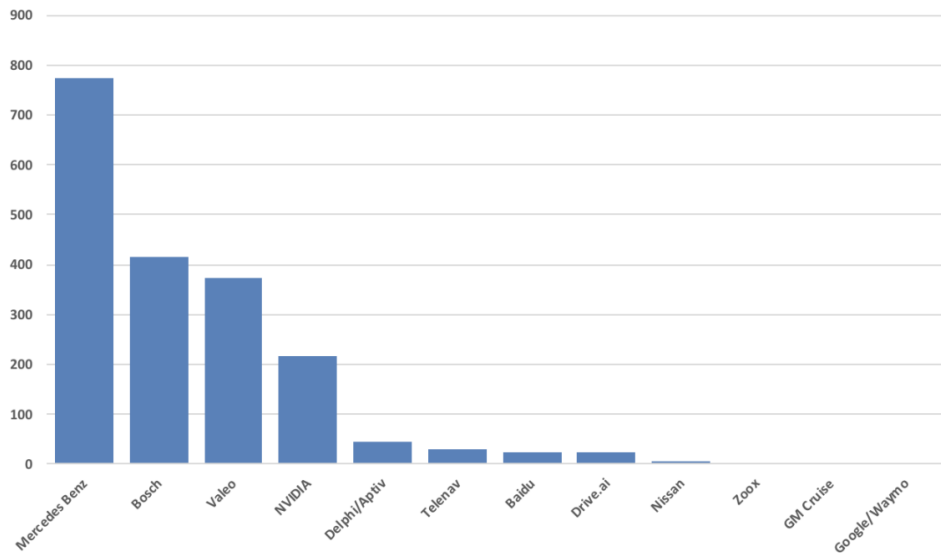
2014: Society of Automotive Engineers: SAE Levels of Autonomy



Mike Lemanski

► Lateral control = steering, Longitudinal control = gas/brake

Disengagement per 1000 miles (California Dept. of Motor Veh., 2017)



2015: Uber starts Self-Driving Research



- Uber hires 50 robotic researchers and academics from CMU, shut down in 2020

2016: OTTO



- ▶ Self-driving truck company, bought by Uber for \$625 mio., later shut down

2015: Tesla Model S Autopilot



Tesla Autopilot 2015 (Level 2 Autonomy):

- ▶ Lane keeping for limited-access highways (hands off time: 30-120 seconds)
- ▶ Doesn't read traffic signals, traffic signs or detect pedestrians/cyclists

2016: Tesla Model S Autopilot: Fatal Accident 1



2018: Tesla Model X Autopilot: Fatal Accident 2



2018: Tesla Model X Autopilot: Fatal Accident 2

The National Transportation Safety Board (NTSB) said that four seconds before the 23 March crash on a highway in Silicon Valley, which killed Walter Huang, 38, the car stopped following the path of a vehicle in front of it. Three seconds before the impact, it **sped up** from 62mph to 70.8mph, and the car **did not brake** or steer away, the NTSB said. After the fatal crash in the city of Mountain View, Tesla noted that the driver had received multiple warnings to put his hands on the wheel and said he did not intervene during the five seconds before the car hit the divider. But the NTSB report revealed that these alerts were made more than 15 minutes before the crash. In the 60 seconds prior to the collision, the driver also had his hands on the wheel on three separate occasions, though not in the final six seconds, according to the agency. As the car headed toward the barrier, there was **no precrash braking** or evasive steering movement, the report added.

The Guardian (June, 2018)

2018: Waymo (former Google) announced Public Service



- ▶ In 2018 driving without safety driver in a geofenced district of Phoenix
- ▶ By 2021 also in suburbs of Arizona, San Francisco and Mountain View

2018: Nuro Last-mile Delivery



- Founded by two of the Google self-driving car engineers

Self-Driving Industry

- ▶ NVIDIA: Supplier of self-driving hardware and software
- ▶ Waabi: Startup by Raquel Urtasun (formly Uber)
- ▶ Aurora: Startup by Chris Urmson (formerly CMU, Google, Waymo)
- ▶ Argo AI: Startup by Bryan Salesky (now Ford/Volkswagen)
- ▶ Zoox: Startup by Jesse Levinson (now Amazon)
- ▶ Cruise: Startup by Kyle Vogt (now General Motors)
- ▶ NuTonomy: Startup by Doug Parker (now Delphi/Aptiv)
- ▶ Efforts in China: Baidu Apollo, AutoX, Pony.AI
- ▶ Comma.ai: Custom open-source dashcam to retrofit any vehicle
- ▶ Wayve: Startup focusing on end-to-end self-driving

Self-Driving Industry

The Building Blocks of Autonomy

Prepared by  VISION SYSTEMS INTELLIGENCE



Copyright 2016 – Vision Systems Intelligence, LLC.

Business Models

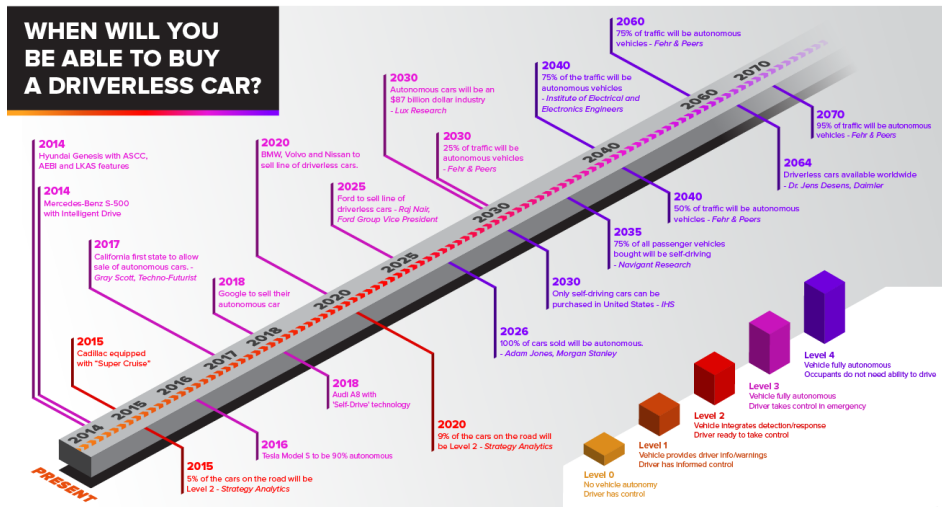
Autonomous or nothing (Google, Apple, Uber)

- ▶ Very risky, only few companies can do this
- ▶ Long term goals

Introduce technology little by little (all car companies)

- ▶ Car industry is very conservative
- ▶ ADAS as intermediate goal
- ▶ Sharp transition: how to maintain the driver engaged?

Wild Predictions about the Future of Self-Driving



Sources: Mercedes-Benz, GM News, Strategy Analytics, Automotive News, Nissan News, Navigant Research, Volvo News, Fehr & Peers, Lux Research, IHS

Summary

- ▶ Self-driving has a long history
- ▶ Highway lane-keeping of today was developed over 30 years ago
- ▶ Increased robustness $\Rightarrow$ introduction of level 3 for highways in 2019
- ▶ Increased interest after DARPA challenge and new benchmarks (e.g., KITTI)
- ▶ Many claims about full self-driving (e.g., Elon Musk), but level 4/5 stays hard
- ▶ Waymo introduced first public service end of 2018 (with safety driver)
- ▶ Waymo/Tesla seem ahead of competition in full self-driving, but no winner yet
- ▶ But several setbacks (Uber, Tesla accidents)
- ▶ Most existing systems require laser scanners and HD maps (exception: Tesla)
- ▶ Driving as an engineering problem, quite different from human cognition