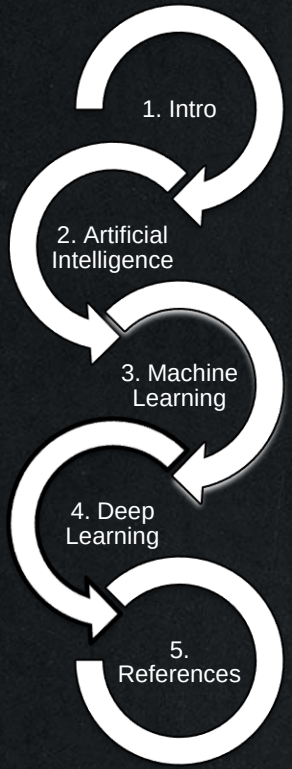
Scientific Machine and Deep Learning for Design and Construction in Civil Engineering

@ ETH Zürich 2021

Agenda



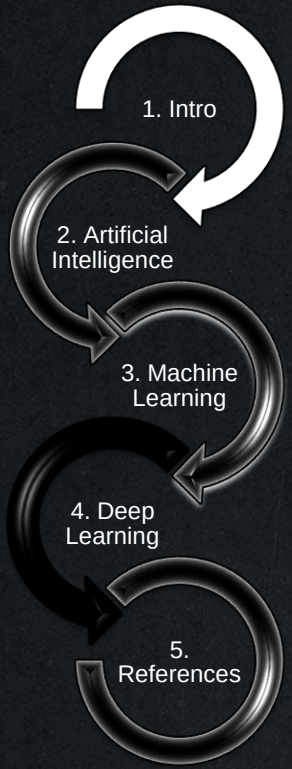
1 **Introduction**

2 **Artificial Intelligence**

3 **Machine Learning**

4 **Deep Learning**

5 **References**



01. Introduction

Lectures

1

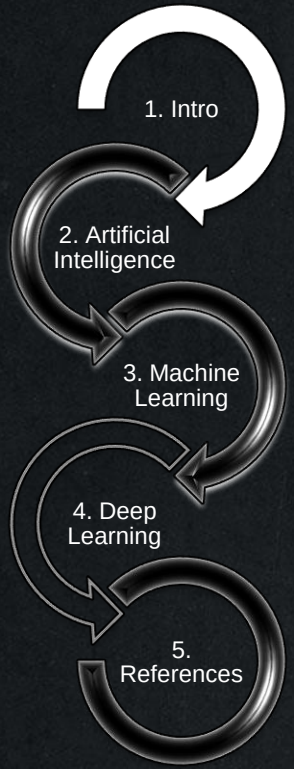
Dr. Michael A. Kraus
- PhD with honors 2019 @ Bundeswehr University Munich
- Post-Doc @ Stanford University
- Post-Doc @ ETH Zürich

2

Dr. Danielle Griego
- PhD 2020 @ ETH Zürich
- Post-Doc @ ETH Zürich
- Executive Director of Design++

3

Sophia Kuhn, M.Sc.
- M.Sc. Civil Engineering 2021 @ ETH Zürich
- PhD candidate @ ETH Zürich



01. Introduction

Organisation of Lectures

1

Lectures
- …

2

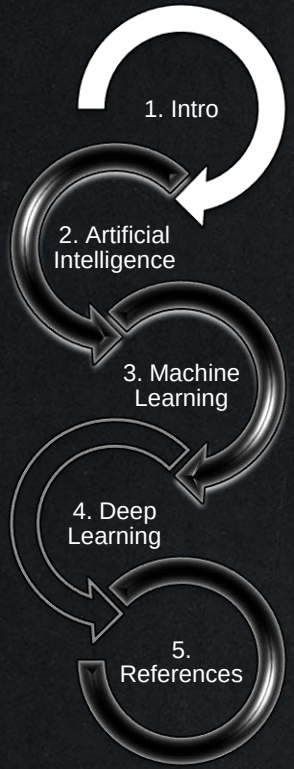
Exercises
- …

3

Homework
- …

Resources:

https://mkrausai.github.io/lectures/2021_SciML/



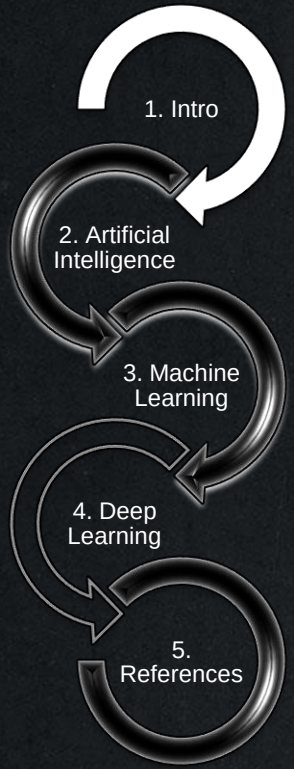
01. Introduction

Organisation of Lectures

DATE	CLASS TOPIC	MATERIAL
27.09	Introductory Class	slides
27.09	Fundamentals of Machine Learning - Part 1: Data and essential Maths/Statistics	slides
04.10	Fundamentals of Machine Learning - Part 2: Supervised Learning	
04.10	*Exercise 1: Introduction to Python and Pandas*	
11.10	Fundamentals of Machine Learning - Part 3: Unsupervised Learning	
18.10	Fundamentals of Machine Learning - Part 3: Data Processing and Visualisation	
18.10	*Student Projects Pitches*	
18.10	*Exercise 2.1: Data Processing and Visualisation*	
18.10	*Exercise 2.2: ML Workflow and Regression and Classification*	
25.10	Introduction to Scientific Machine Learning	
01.11	Introduction to Scientific Deep Learning	
01.11	*Exercise 3: Scientific Machine Learning*	
08.11	1st Project Consultation (in person, at ETH Hönngerberg)	
15.11	Feature Engineering	
15.11	*Exercise 4: Feature Engineering*	
22.11	Guest Talk, Graph-NeuralNetwork based SciML, by Professor Julija Zavadlav, Dept. of Mechanical Engineering, TU Munich	
29.11	2nd Project Consultation (in person, at ETH Hönngerberg)	
06.12	Guest Talk, Physics-informed Neural Networks at scale, by Mohammad Nabian, NVIDIA	
13.12	Final Project Presentation (in person and online, at ETH Hönngerberg)	
20.12	Final Project Presentation (in person and online, at ETH Hönngerberg)	

legend

we work
you work
others work

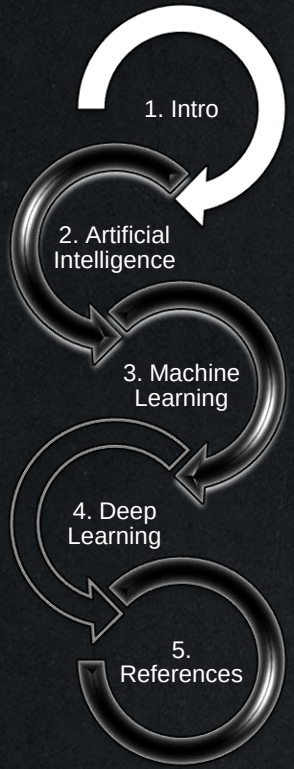


01. Introduction

Organisation of Lectures

Grading

- final presentation (15 min + 5 min public Q&A)
- report / paper
- 5 min examination

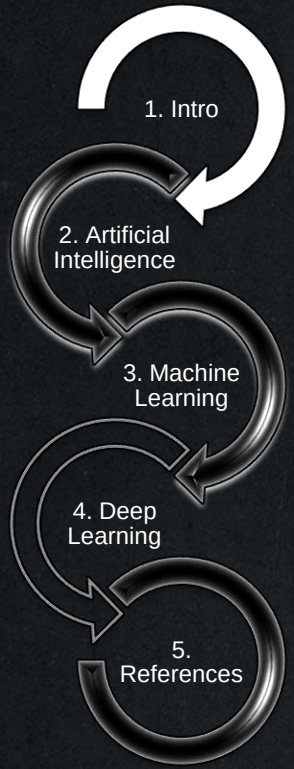


01. Introduction

Organisation of Lectures

Final Project

1. Formulate 1-2 specific question(s) of interest to you
2. State your hypothesis/expected outcome based on supporting lit erature (minimum 3 sources), your expertise, and intuition
3. Answer that question through your analysis, by:
   - Selecting the best available data sources
   - Applying the relevant algorithms
4. Summarize your results. Show a clear conclusion, does your an alysis answer your question(s), if not how could your process be improved if given more time. What additional data would improv e your analysis?
5. Conclusions & lessons learned
6. Include motivation and references



01. Introduction

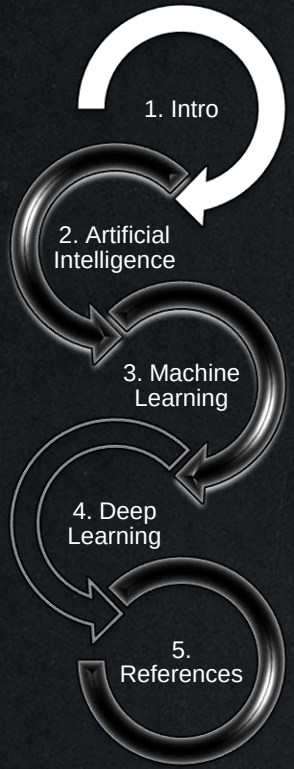
Organisation of Lectures

Important Dates

- 04.10.2021 (end of lecture) - we provide some topics

Project owner	contact	Topic
Selen Ercan	ercan@arch.ethz.ch	Robotic Plaster Spraying: an adaptive, thin-layer (spray-based) printing process
Christoph Weibel	waibel@arch.ethz.ch	Solar potentials surrogate modeling with a database of ~20k fish-eye images of urban environments with corresponding solar potentials time series
Romana Rust	rust@arch.ethz.ch	Digital fabrication and robotics production parameters
Michael Kraus	kraus@ibk.baug.ethz.ch	Explainable AI methods for modelling Pinch Tests for Reinforced Concrete
Michael Kraus	kraus@ibk.baug.ethz.ch	Bridge Aesthetics Survey Data
Michael Kraus	kraus@ibk.baug.ethz.ch	GraphNN as Digital Twins for structural analysis
Michael Kraus	kraus@ibk.baug.ethz.ch	Glass Fracture Modelling using Deep Learning

….but ideally you have an idea and data!



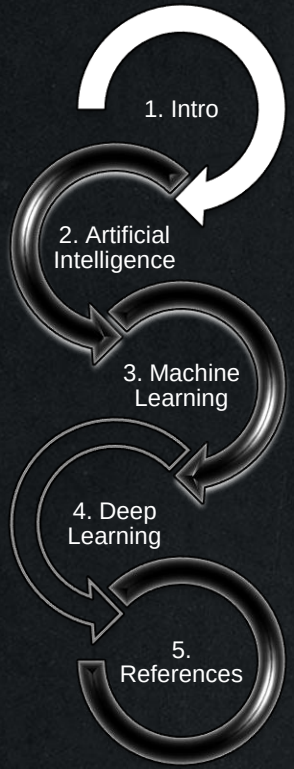
01. Introduction

Organisation of Lectures

Important Dates

- 15.10.2021 - Hand in 1-2 page project concept ‚pitch‘
  - Motivation
  - Research question(s)
  - Data (source, type, description)
  - Work Packages / Time Line

- 18.10.2021 – 3 min project pitch
- 08.11.2021 – 1st project consultation (10 minutes)
- 29.11.2021 – 2nd project consultation (10 minutes)
- 13.12.2021 – Final project presentations
- 20.12.2021 – Final project presentations



01. Introduction

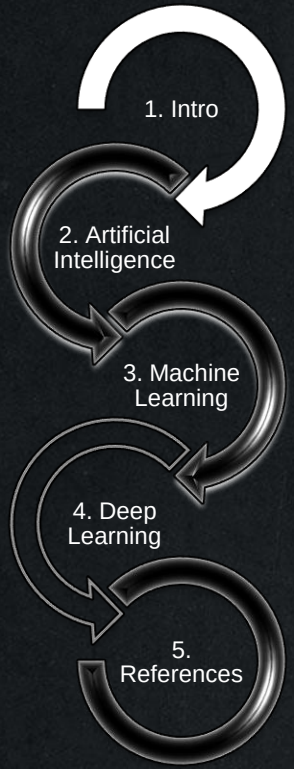
Organisation of Lectures

Keep in mind

- Using both / either, „traditional“ ML or SciML are ok for the project

Logistics

- preferred format: git / overleaf



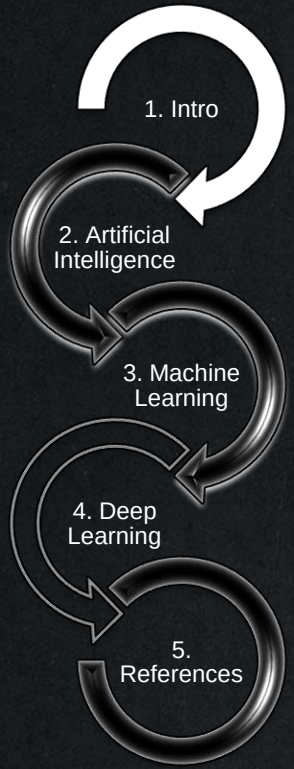
01. Introduction

Intention and Goal of this Lecture

Class Objectives

1. Understand the potential of AI/ML/SciML for civil engineering applications
2. Create models for different problem's structures: regression, classification, time-series, decision problems, etc.
3. How to incorporate domain knowledge to reach *SciML*
4. Train and evaluate models using empirical data

understand theory behind existing algorithms while being able to apply ML algorithms to research your own questions



01. Introduction

Intention and Goal of this Lecture

Code of Conduct

you have no obligation to show up yet for final presentation

The "easy" way

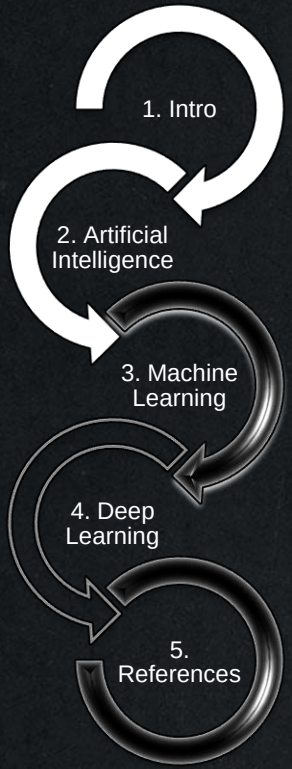
from *Goulet (2020)*

Goulet, J.-A.. (2020).
Probabilistic Machine Learning for Civil Engineers. MIT Press

Murphy, K. (2012).
Machine learning: A probabilistic perspective. MIT Press.

Russell, S. and Norvig, P. (1995).
Artificial Intelligence, A modern approach. Prentice-Hall.

Q & A

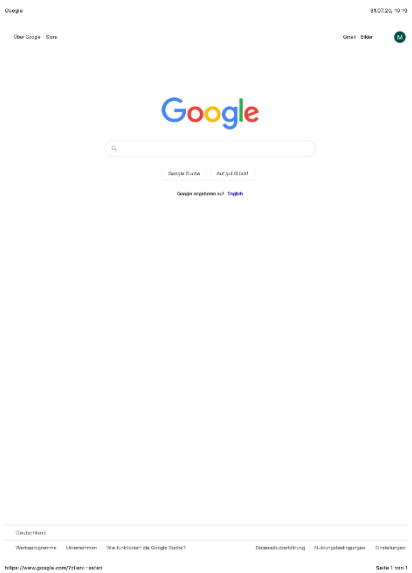


02. Artificial Intelligence

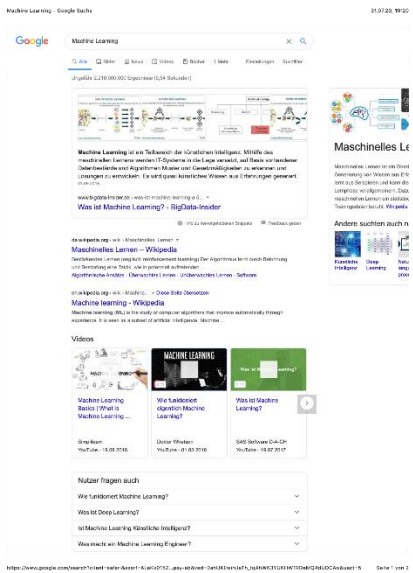
AI, Machine Learning and Deep Learning

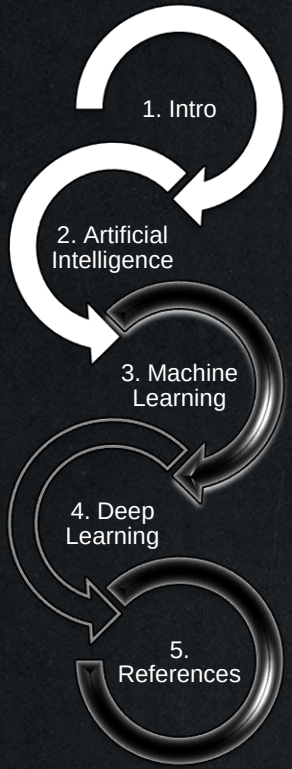
What Artificial Intelligence, Machine Learning and Deep Learning?

- Try to google it!
- You are using it every day! Every web search on google works so well, since AI and machine learning algorithms are applied to rank the pages



Magic happens!



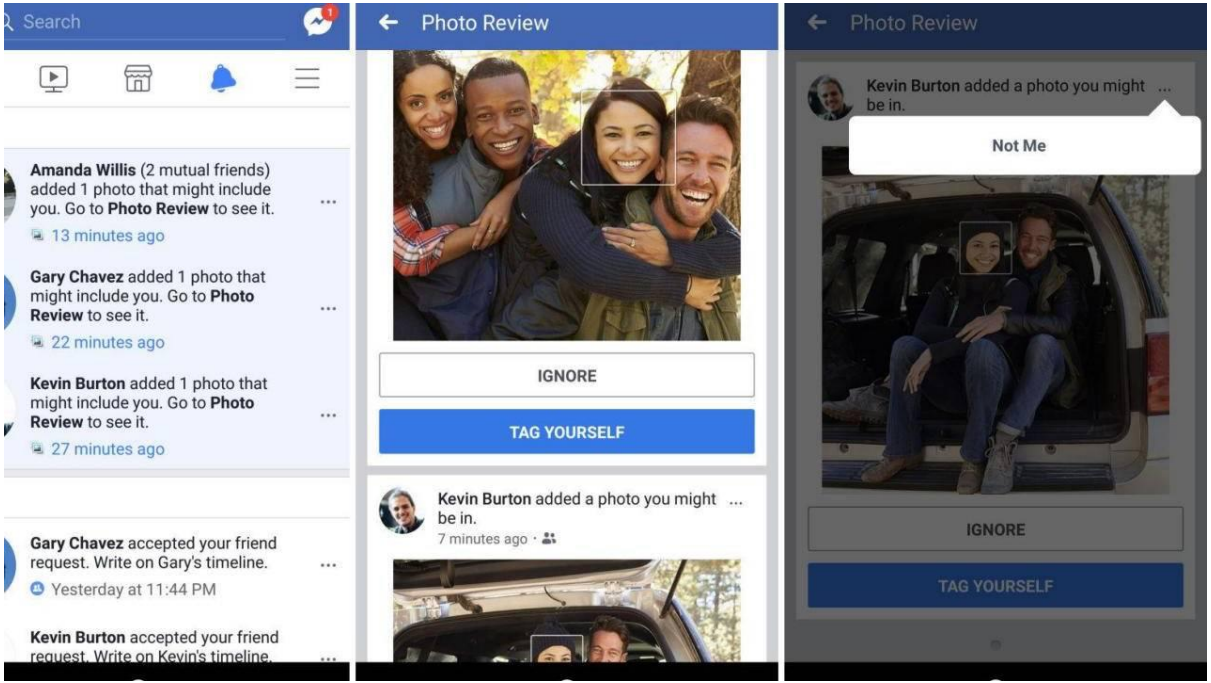


02. Artificial Intelligence

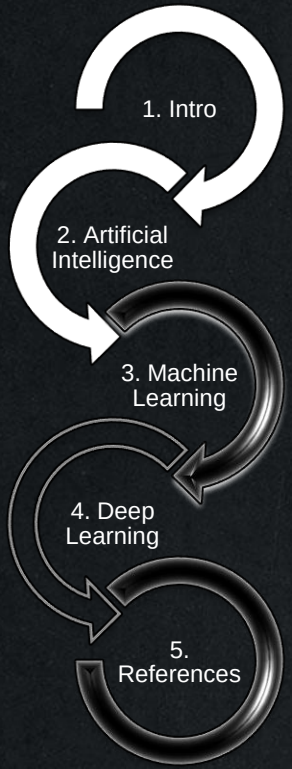
AI, Machine Learning and Deep Learning

What Artificial Intelligence, Machine Learning and Deep Learning?

- Facebook and Apple recognizes friends of you in pictures
- …



https://www.slashgear.com/wp-content/uploads/2019/11/facebook-face-recognition-1280x720.jpg

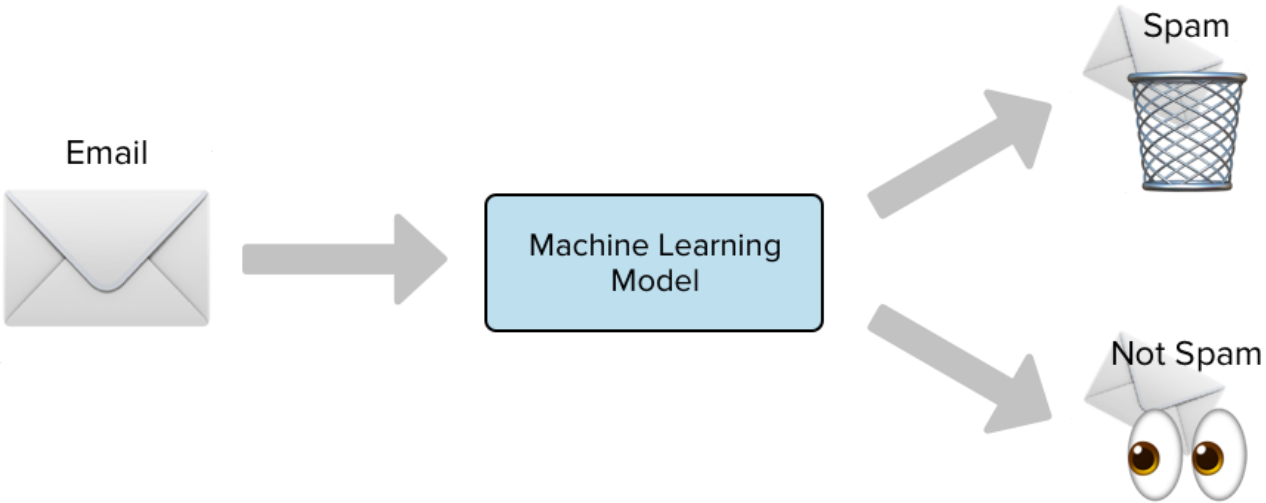


02. Artificial Intelligence

AI, Machine Learning and Deep Learning

What Artificial Intelligence, Machine Learning and Deep Learning?

- Spam Filter to distinguish spam from non-spam emails
- …



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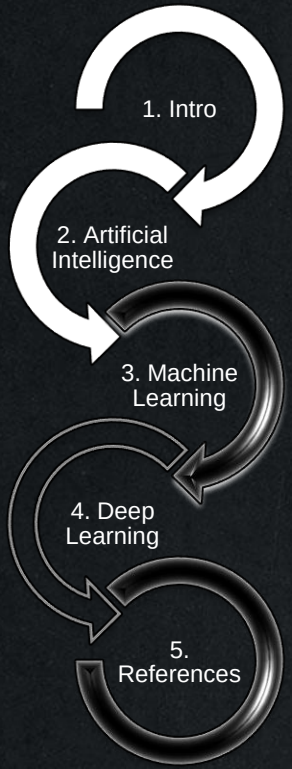
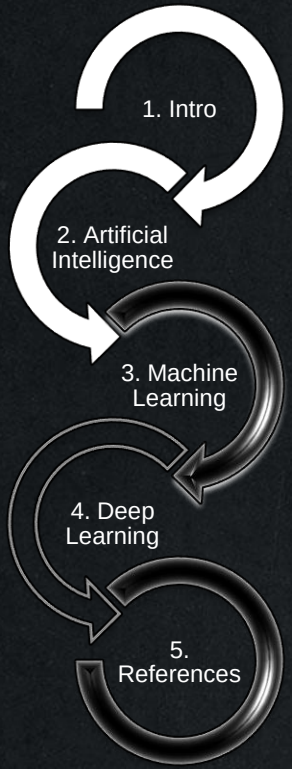


02. Artificial Intelligence

AI, Machine Learning and Deep Learning

What Artificial Intelligence, Machine Learning and Deep Learning?

„AI, ML and DL is the science of getting com puters to learn and make predictions, without being explicitly programmed!“

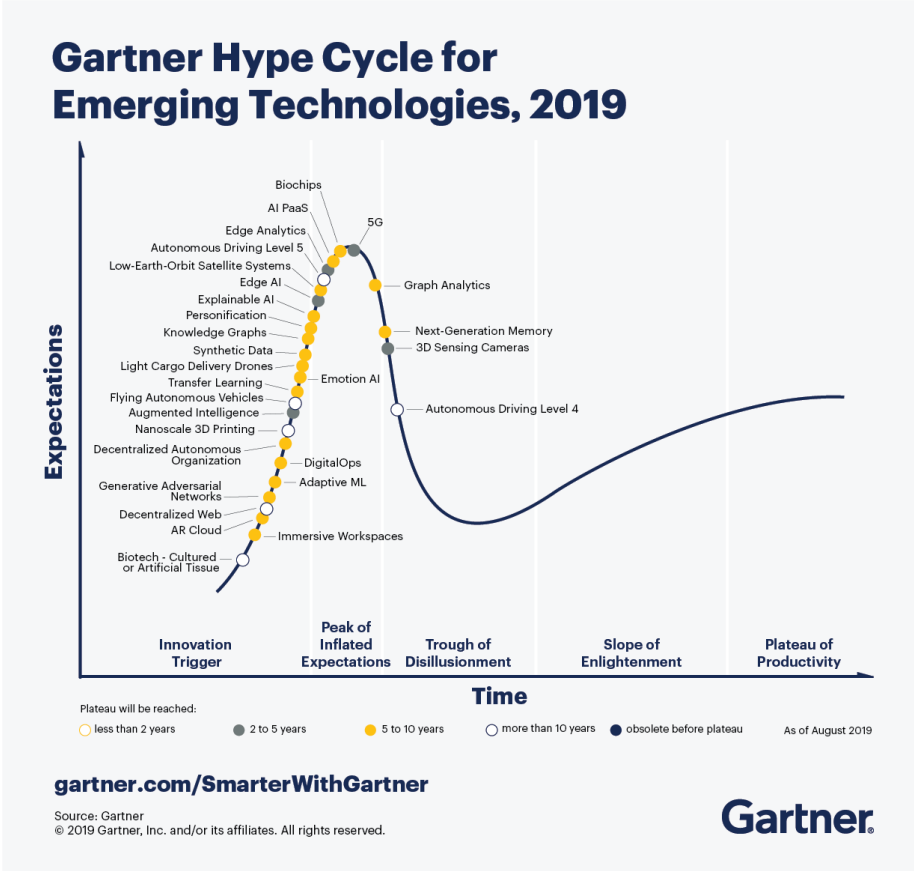


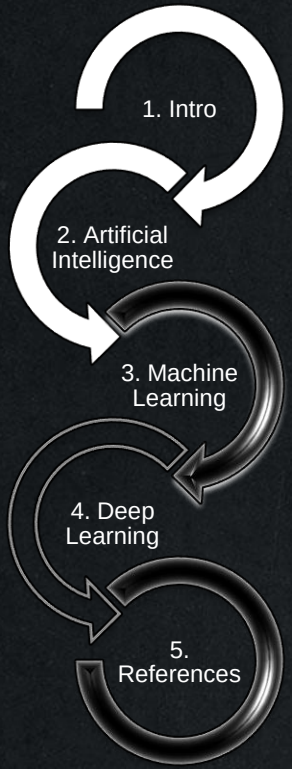
02. Artificial Intelligence

AI, Machine Learning and Deep Learning – Hype Cycle

Advanced AI and Analytics

- Adaptive machine learning
- Edge AI
- Edge analytics
- Explainable AI
- AI PaaS
- Transfer Learning
- Generative adversial networks



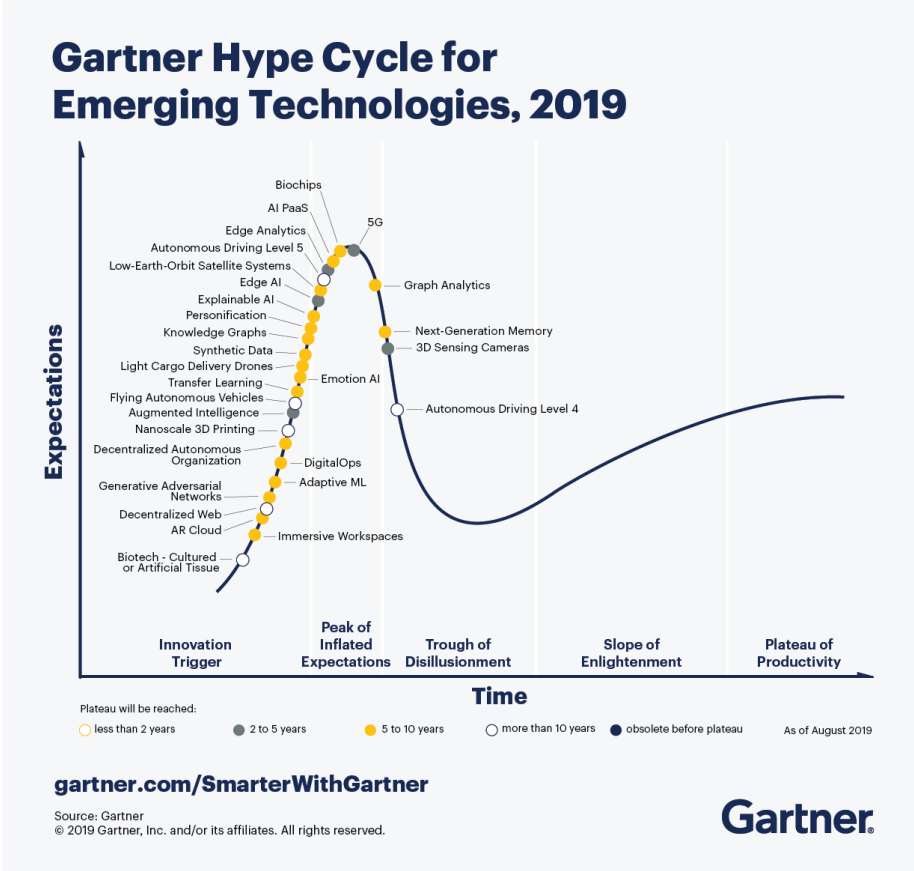


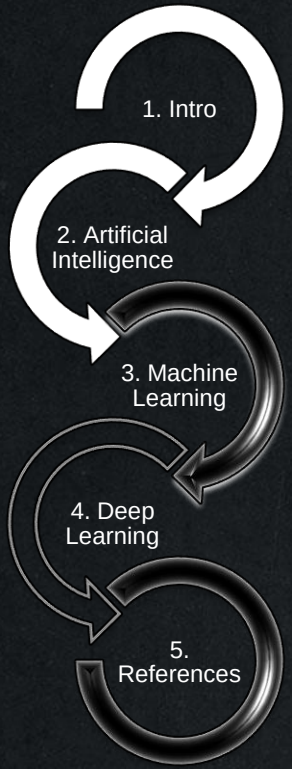
02. Artificial Intelligence

AI, Machine Learning and Deep Learning – Hype Cycle

Augmented Human

- Biochips
- Personification
- Augmented Intelligence
- Emotion AI
- Biotech (cultured or artificial tissue)



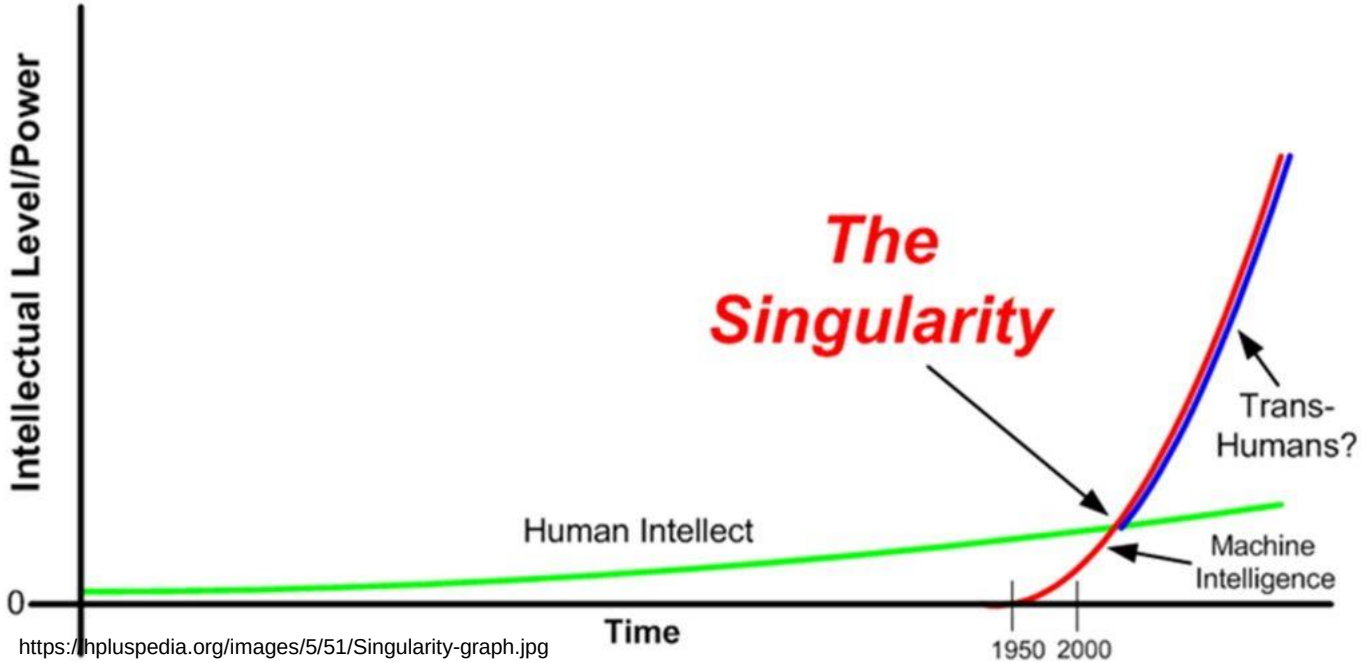


02. Artificial Intelligence

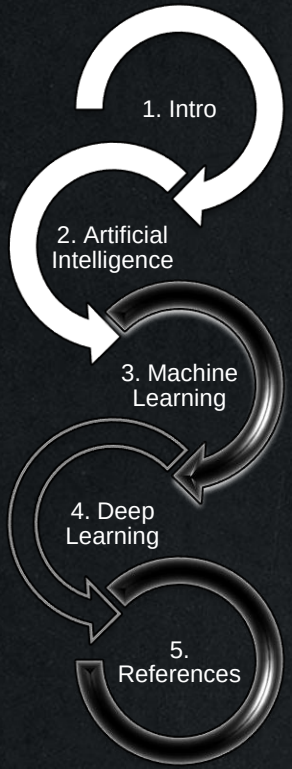
AI, Machine Learning and Deep Learning

Where are we now?

- The Singularity (more fully, the “Technological Singularity”) is an envisaged future time period when artificial intelligence becomes more generally capable than humans



https://hpluspedia.org/images/5/51/Singularity-graph.jpg

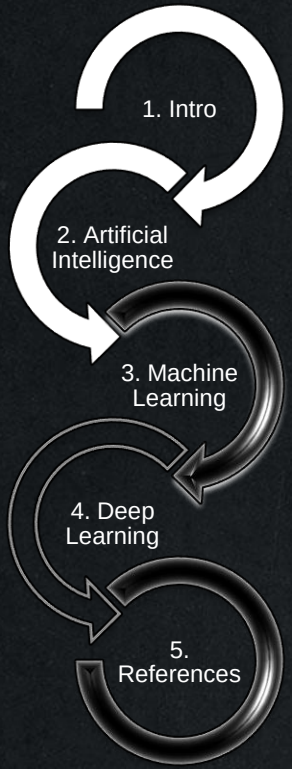


02. Artificial Intelligence

AI, Machine Learning and Deep Learning

What does this course teach?

- Differences between the terms of Artificial Intelligence, Machine Learning and Deep Learning
- Mathematical Background
  - Linear Algebra, Statistics and Optimization
- Machine Learning Models
  - Supervised / Unsupervised Learning, Regression Classification, Clustering
- Deep Learning
- Application to various fields of civil engineering like
  - Architectural design, statics / mechanics, geotechics, hydraulic engineering, glass engineering, …

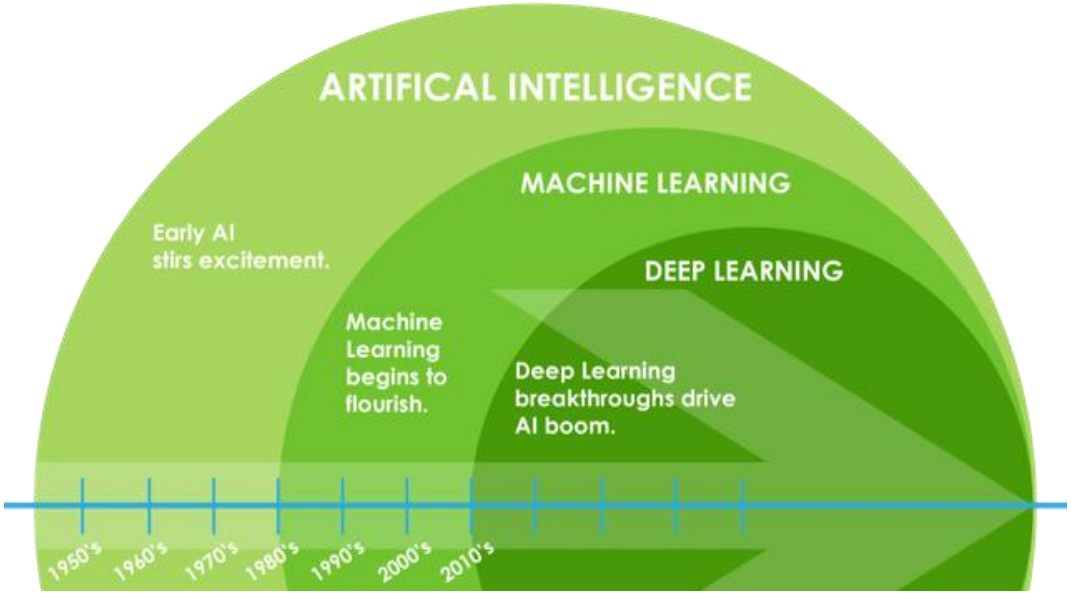


02. Artificial Intelligence

AI, Machine Learning and Deep Learning

What are the differences?

- Artificial Intelligence is the umbrella term of that sciences
- Machine and deep learning are subforms of AI
- Historical development of AI, machine learning (ML) and deep learning (DL)



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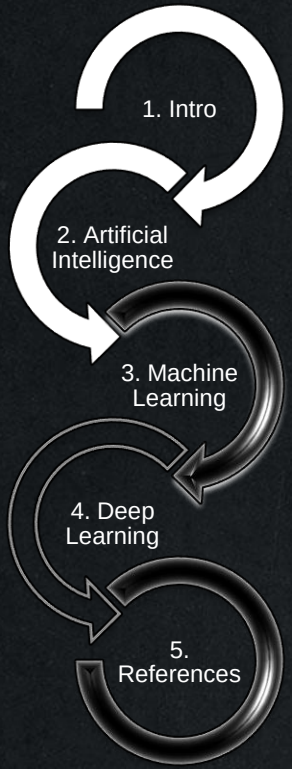
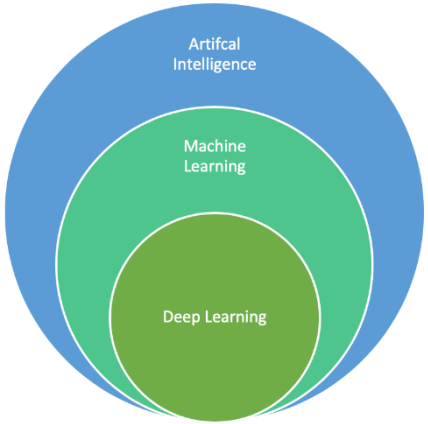


02. Artificial Intelligence

AI, Machine Learning and Deep Learning

What does the terms AI, ML and DL mean?

- No definition of all three terms can be found in German Duden
- Simple definitions are for example…
  - *AI means getting a computer to mimic human behaviour in some way.*
  - *Machine learning is a subset of AI, and it consists of the techniques that enable computers to figure things out from the data and deliver AI applications.*
  - *Deep learning, meanwhile, is a subset of machine learning that enables computers to solve more complex problems.*



Let's dive deeper now.

02. Artificial Intelligence

Definition of AI

Artificial Intelligence

Apple’s Siri

Amazon’s Alexa

Tesla’s Autopilot

- Artificial intelligence (AI) is the simulation of human intelligence processes by machines

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Definition of AI

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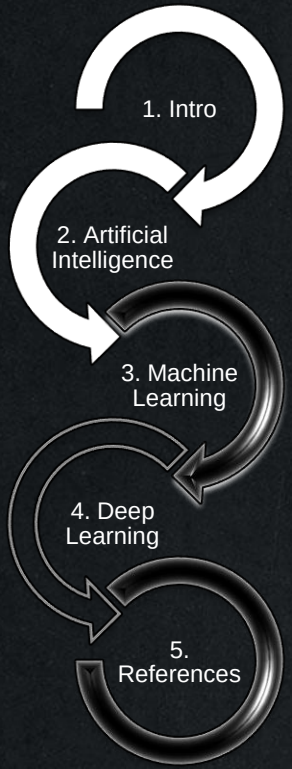
- Artificial intelligence (AI) is the simulation of human intelligence processes by machines
- "The theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages."



02. Artificial Intelligence

Definition of AI

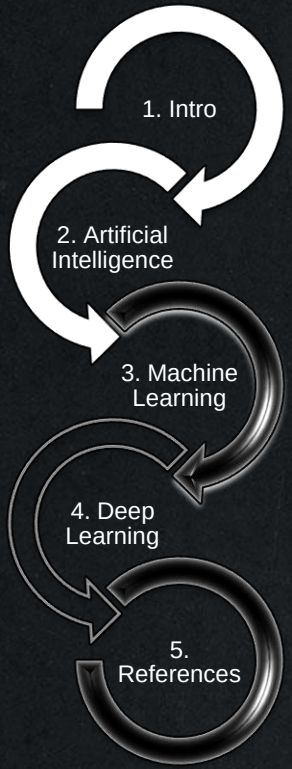
Artificial Intelligence

Apple's Siri

Amazon's Alexa

Tesla's Autopilot

- Artificial intelligence (AI) is the simulation of human intelligence processes by machines
- "The theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages."
- Almost all business today employ some type of AI like Health Care, Education, Finance, Law, Engineering, Risk Management and many more



02. Artificial Intelligence

Definition of AI

Artificial Intelligence

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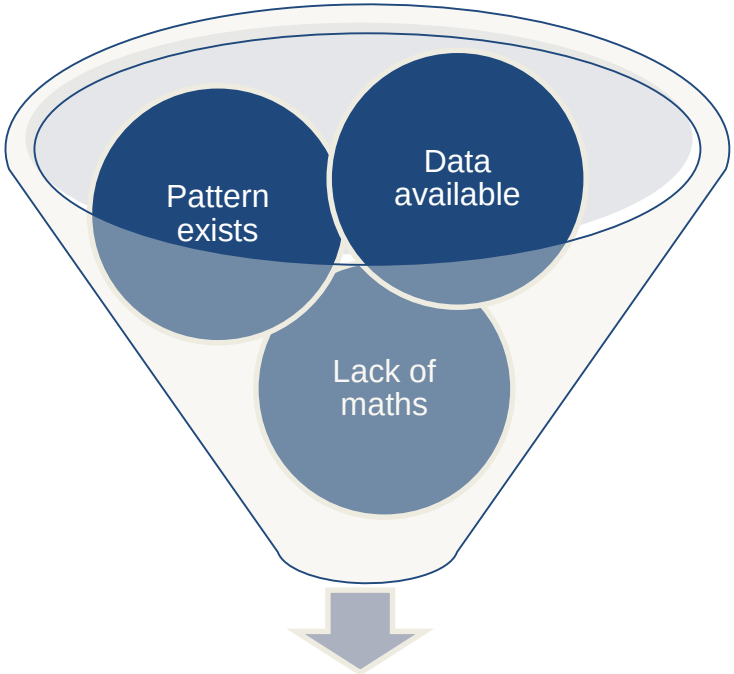
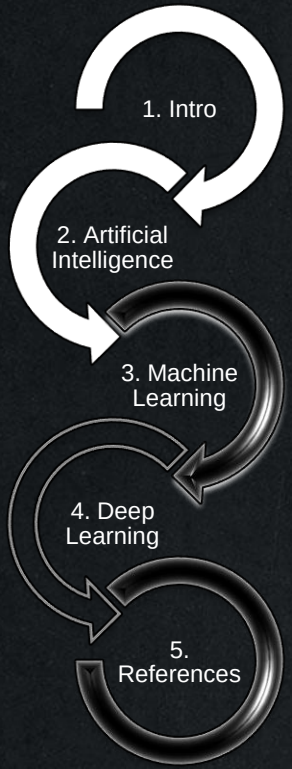
- "The theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages."
- Almost all business today employ some type of AI like Health Care, Education, Finance, Law, Engineering, Risk Management and many more
- Many technologies incorporate AI including **Automation, Machine Learning, Machine Vision, Natural Language Processing** and **Robotics**

02. Artificial Intelligence

AI - Ingredients



Necessary components for an AI implementation

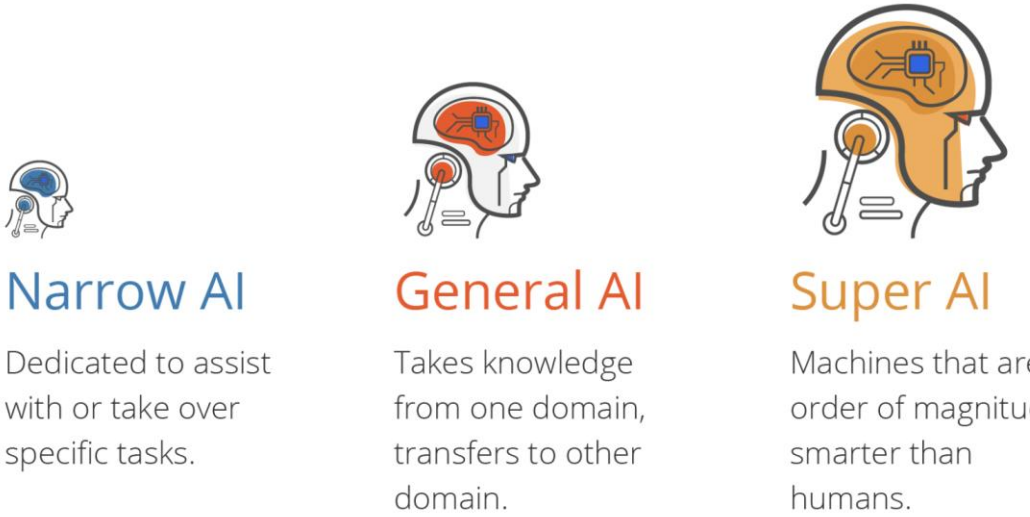


02. Artificial Intelligence

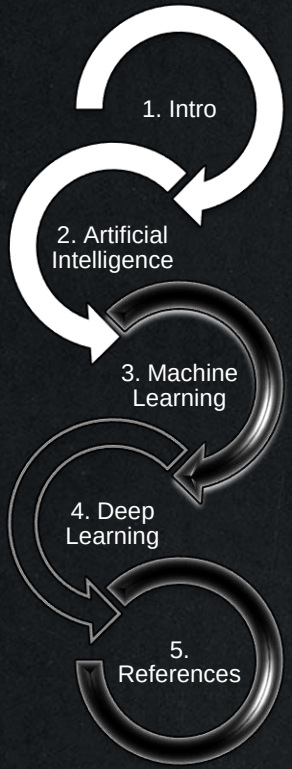
Types of AI

Narrow AI

- Type of intelligence which is only good for a certain task
- Often referred to as “weak AI”, but not due to actually being weak — they’re just not. intelligent at a human, or near-human level.
- Narrow, or weak AI can still perform tasks that would take a regular human (or a team of humans) years to achieve, even if they’re not good for anything else



https://apro-software.com/machine-learning-and-deep-learning/

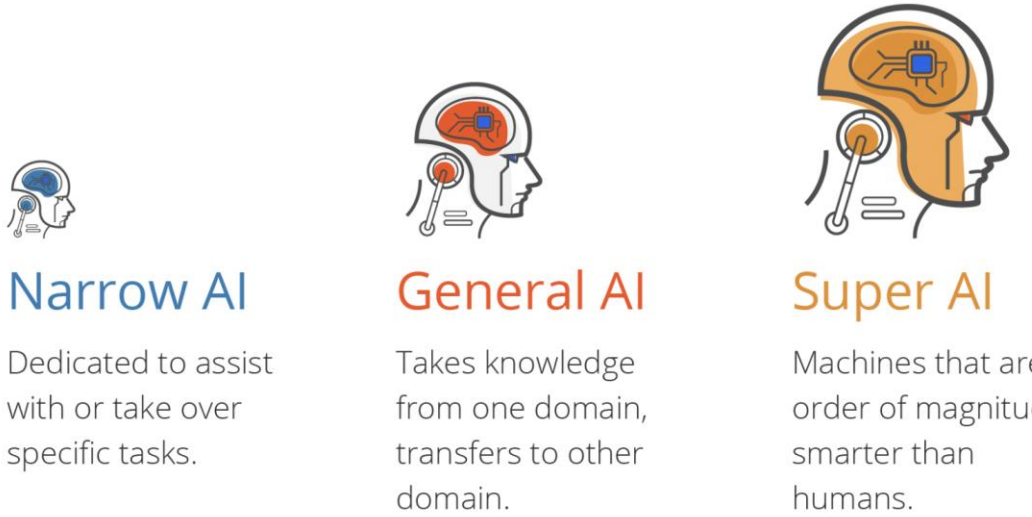


02. Artificial Intelligence

Types of AI

General AI

- General AI, sometimes referred to as “strong AI” is the AI type that’s closest to human intelligence
- So far it has been unachievable
- Even though computers are millions of times better than us at analysing and processing raw data, they’ve never been able of thinking abstractly or coming up with original ideas



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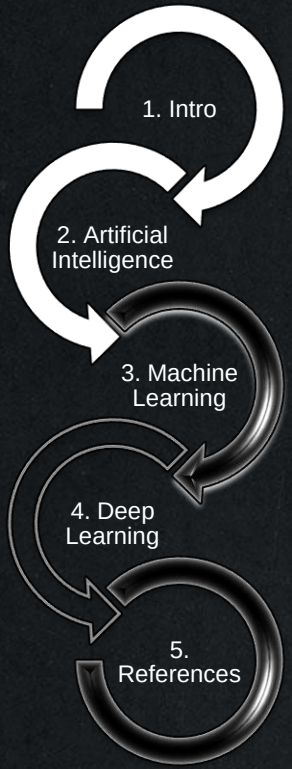
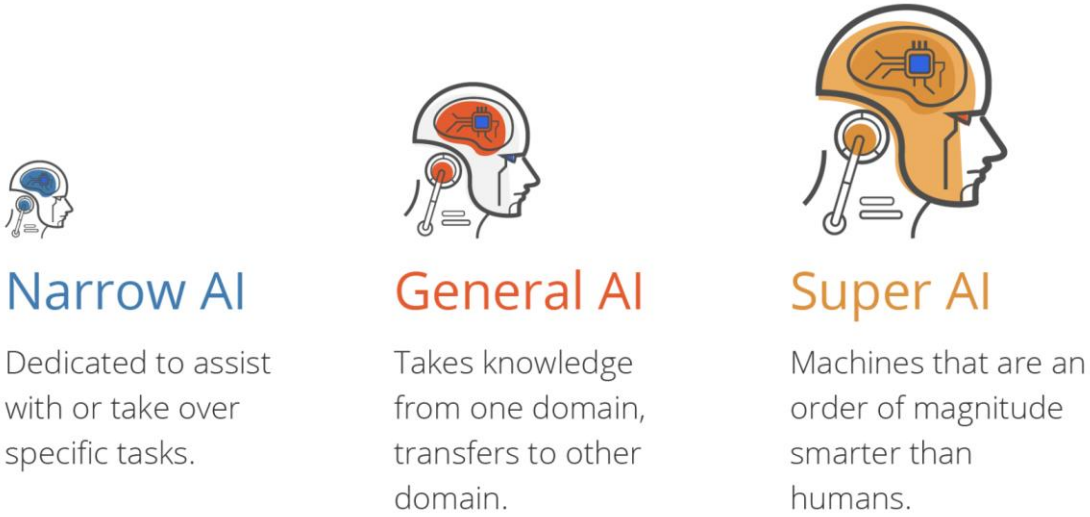


02. Artificial Intelligence

Types of AI

Super AI

- Super AI would theoretically surpass human intelligence in ways we can't imagine
- A super AI would be better than us at everything, from more academic and scientific efforts, all the way to creative and social endeavours



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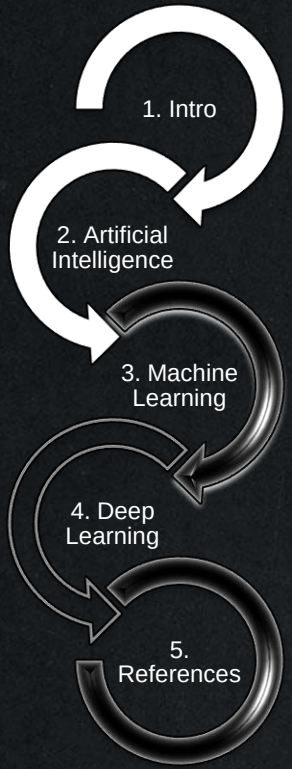
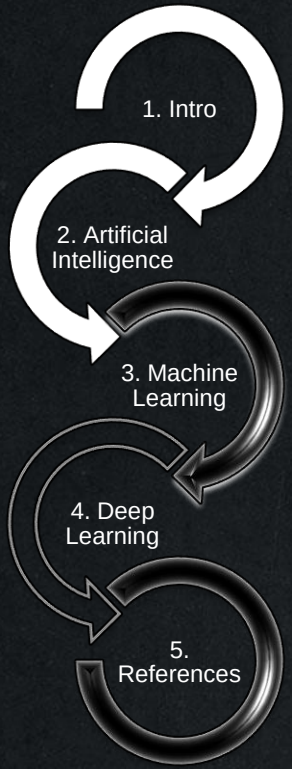


02. Artificial Intelligence

Giving computers ability to learn

How does this work?

- In 1959, Arthur Samuel, a pioneer in the field of machine learning (ML) defined it as the “field of study that gives computers the ability to learn without being explicitly programmed”
- In this age of modern technology, there is one resource that we have in abundance: a large amount of structured and unstructured data.
- Building intelligent machines to transform data into knowledge
- Second half of the twentieth century, machine learning evolved as a subfield of **Artificial Intelligence** (**AI**) that involved self-learning algorithms that derived knowledge from data in order to make predictions



02. Artificial Intelligence

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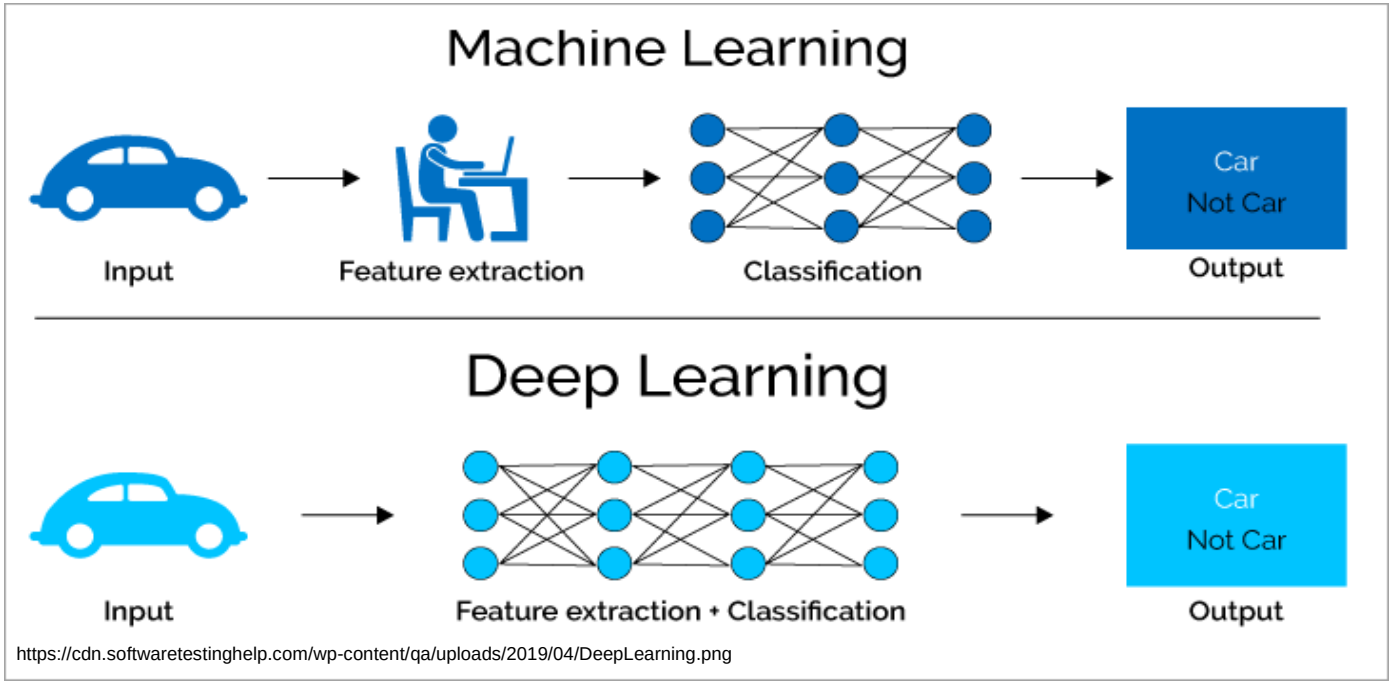

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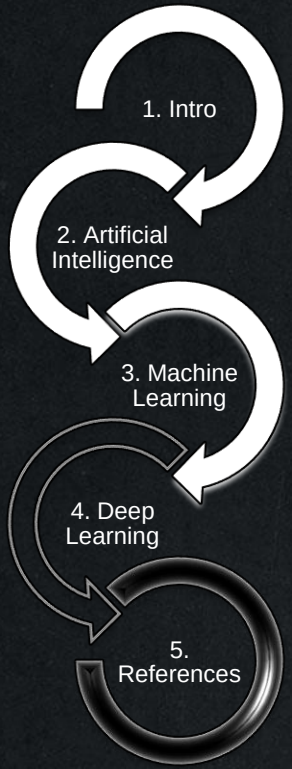
⇢Data-driven decisions

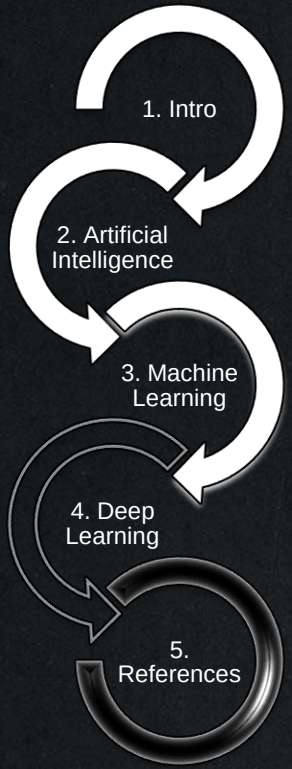


03. Machine Learning

Definitions and Examples

How to understand what Machine Learning is?

- Machine Learning
  - Grew out of work in AI
  - New capability for computers
- Examples
  - Database mining:
    - Large datasets from growth of automation / web.
    - E.g. web click data, medical records, biology, engineering
  - Applications can’t program by hand
  - Self-customizing programs
  - Understanding human learning



03. Machine Learning

Definitions and Examples

How to understand what Machine Learning is?

Arthur Samuel (1959)

„Machine Learning is the science of getting computers to learn and make predictions, without being explicitly programmed!“

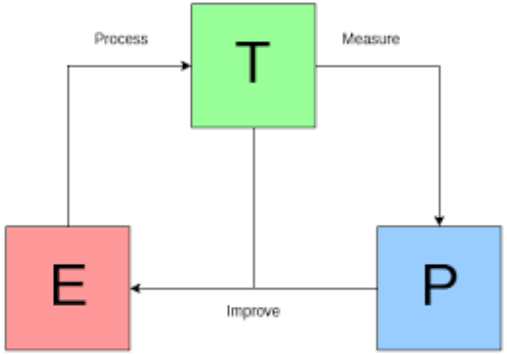
03. Machine Learning

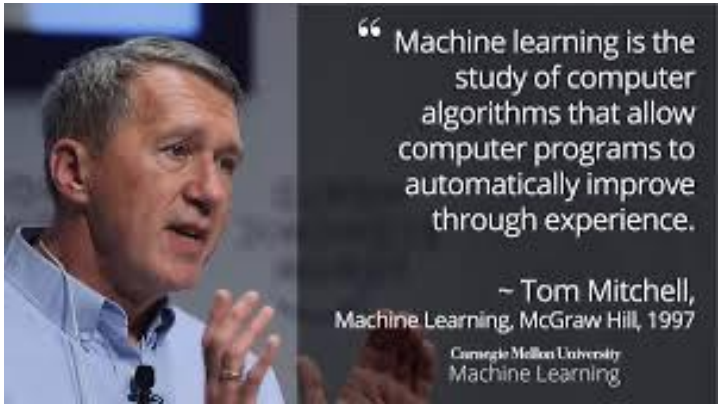
Definitions and Examples

How to understand what Machine Learning is?

Tom Mitchel (1998)

„A computer program is said to learn from experience E with respect to some task T and some performance measure P, if its performance on T, as measured by P, improves with experience E. “





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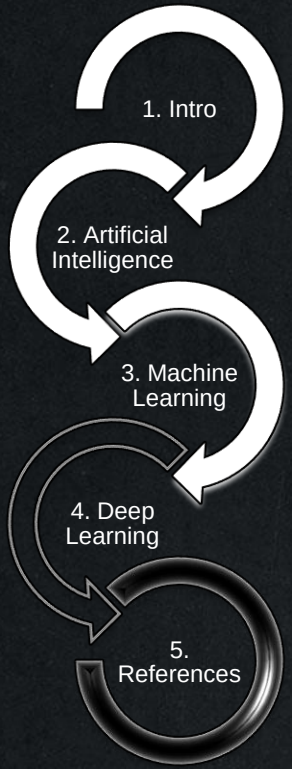


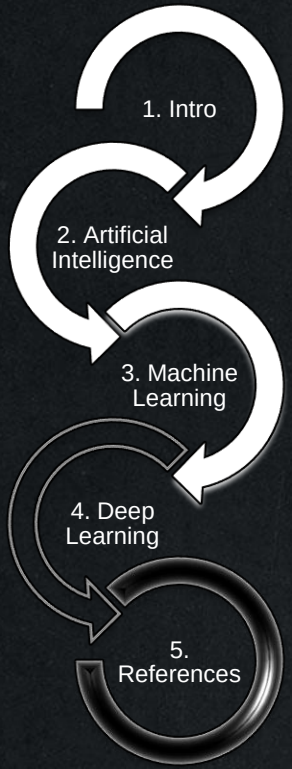
03. Machine Learning

Definitions and Examples

Quiz:
Suppose your email program watches which emails do or do not mark as spam, and based on that learns how to better filter spam. What is the task T in this setting?

- Classifying emails as spam or not spam — T
- Watching you label emails as spam or not spam — E
- The number (or fraction of emails correctly classified as spam / not spam — P
- None on the above – this is not a machine learning problem

Tom Mitchel (1998)
„A computer program is said to learn from experience E with respect to some task T and some performance measure P, if its performance on T, as measured by P, improves with experience E. “

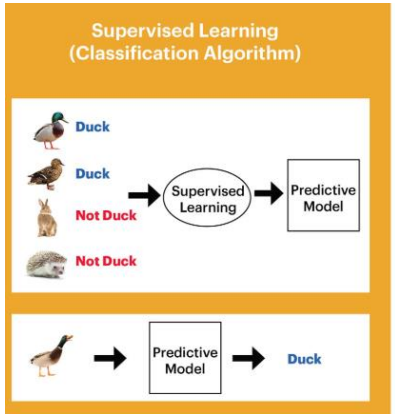


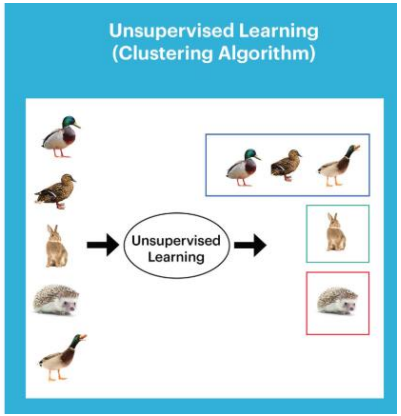
03. Machine Learning

Definitions and Examples

What is Machine Learning?

- Machine Learning algorithms can be structured in
  - Supervised Learning
  - Unsupervised Learning





- Others: Reinforcement Learning and Recommender Systems
- Also talk about:
  - Projects done via AI, ML and DL in civil engineering
  - Practical advice for applying learning algorithms

03. Machine Learning

Definitions and Examples

Limitations of Machine Learning?

- Machine-learning programs often fail to deliver expected results
  - Lack of suitable data
  - Lack of access to data
  - Data bias
  - Privacy problems
  - Badly chosen tasks
  - Badly chosen algorithms
  - Lack of ressources

Explaining the world, daily
The Economist explains

The Economist explains

Why Uber's self-driving car killed a pedestrian

It was the first fatal accident of its kind

https://www.economist.com/img/b/1280/720/90/sites/default/files/20180602_BLP501.jpg

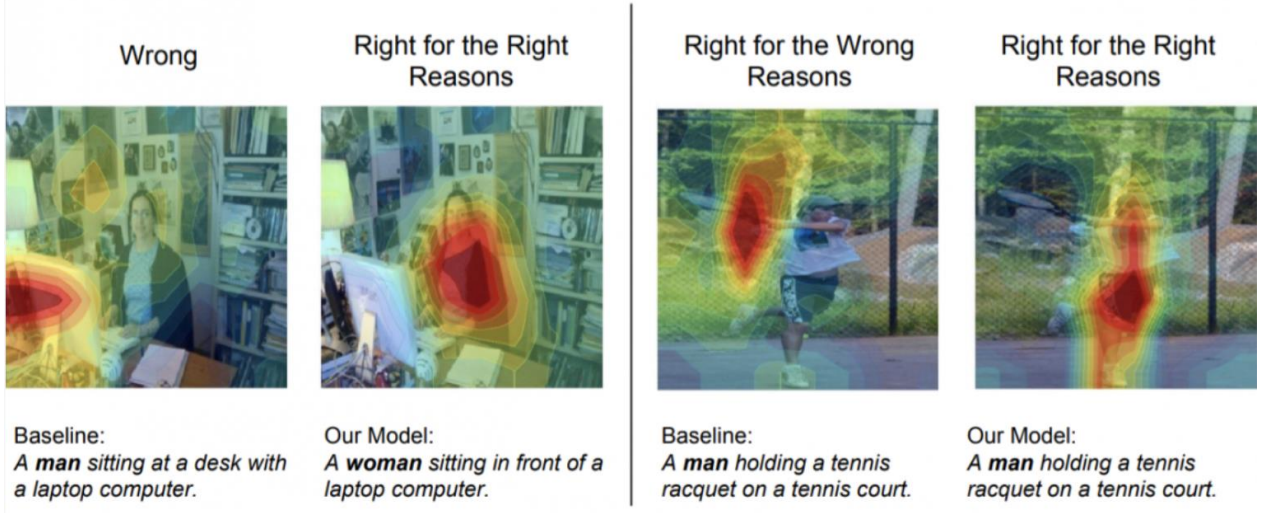
https://www.honda-ri.de/wp-content/uploads/2017/02/machine_ethics-1.jpg

03. Machine Learning

Definitions and Examples

Ethics on Machine Learning - AI

- Machine learning poses a host of ethical questions
- Ethics of artificial intelligence concerned with adding moral behaviours to machines
- Machine ethics differs from other ethical fields related to engineering and technology
- Machine ethics should not be confused with computer ethics, which focuses on human use of computers



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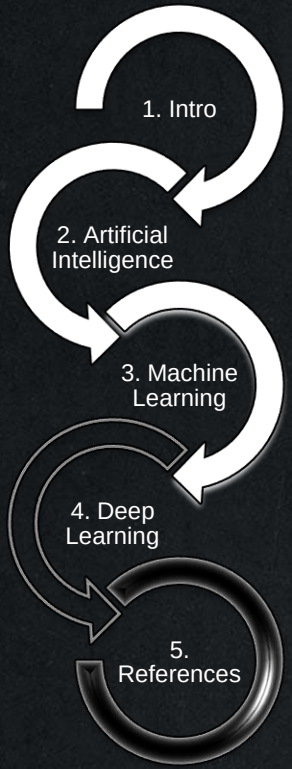
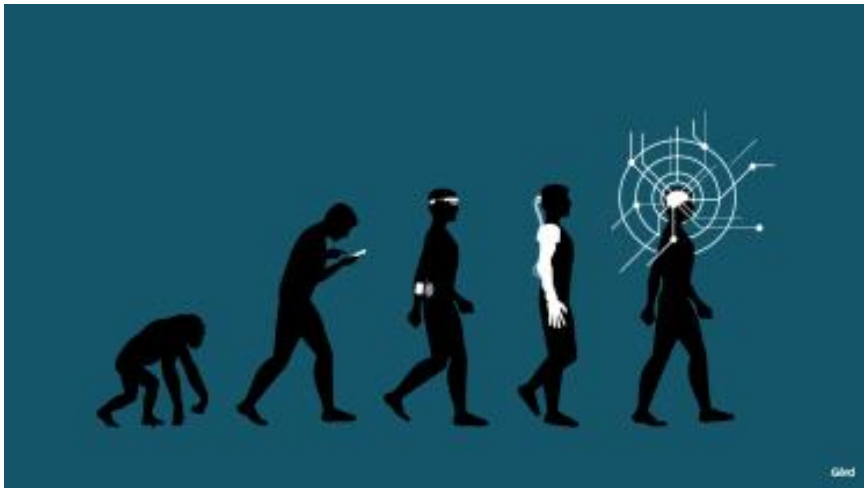


03. Machine Learning

Definitions and Examples

Ethics on Machine Learning – AI control problem

- Fear of general artificial intelligence or superintelligence of machines
- How to build an intelligent agent that will aid its creators, while avoiding inadvertently building a superintelligence that will harm its creators?
  - "capability control" - limiting an AI's ability to influence the world
  - "motivational control" - building an AI whose goals are aligned with human value



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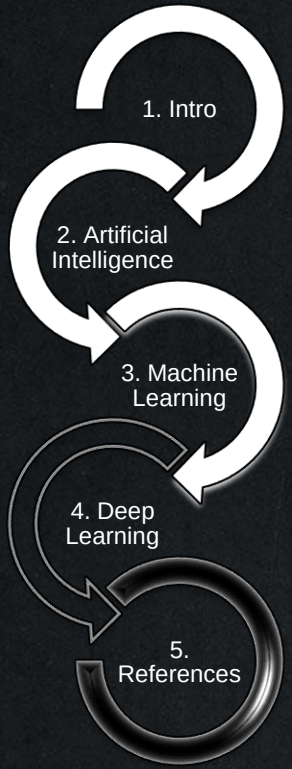
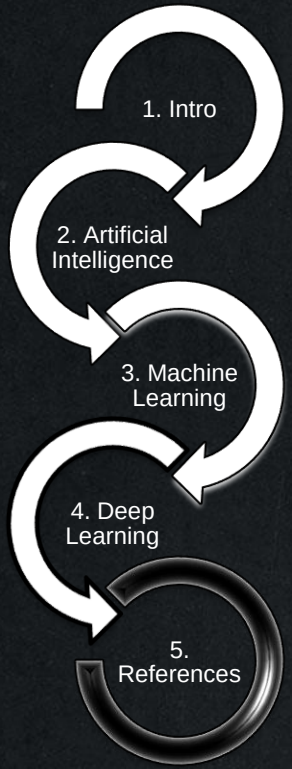


03. Machine Learning

Definitions and Examples

Ethics on Machine Learning?

- Training of biased datasets, may exhibit these biases upon uses (algorithmic bias)
- Job hiring data from a firm with racist hiring policies may lead to a machine learning system duplicating the bias by scoring job applicants against similarity to previous successful applicants
- A 2015 study found that women were less likely to be shown high-income job ads by Google's AdSense.
- Another study found that Amazon's same-day delivery service was intentionally made unavailable in black neighborhoods.

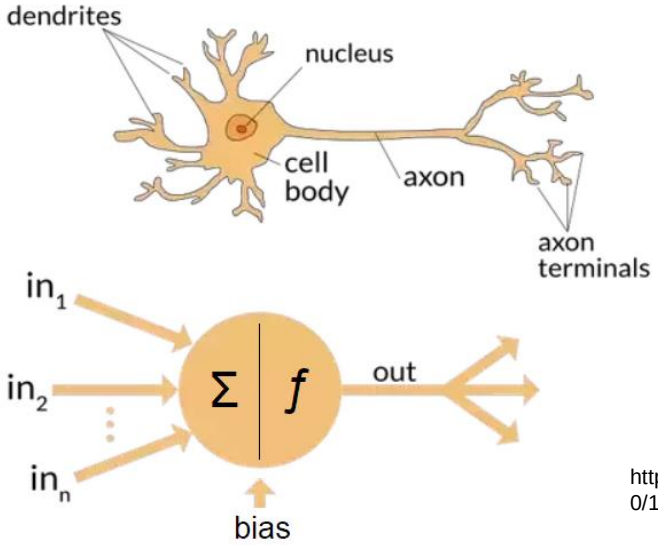


04. Deep Learning

Definitions and Examples

What is Deep Learning?

- DL is part of the broader family of machine learning
- Based on so-called artificial neural networks, which are inspired by the human brain
- Thus, trying to mimic the human brain



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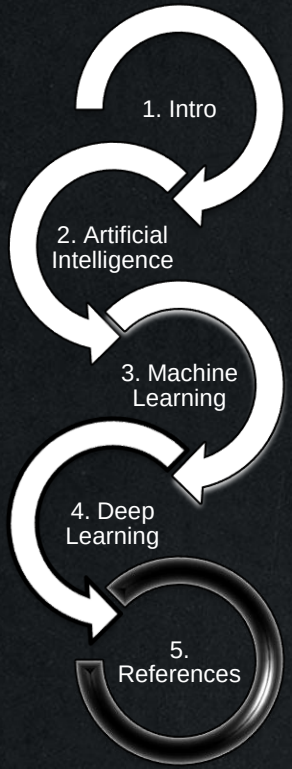
- Learning can be supervised, semi-supervised and unsupervised

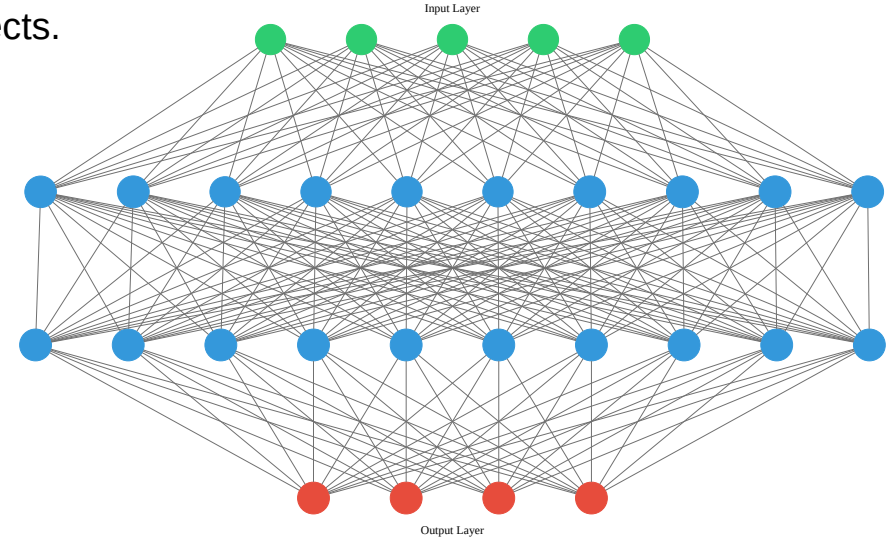


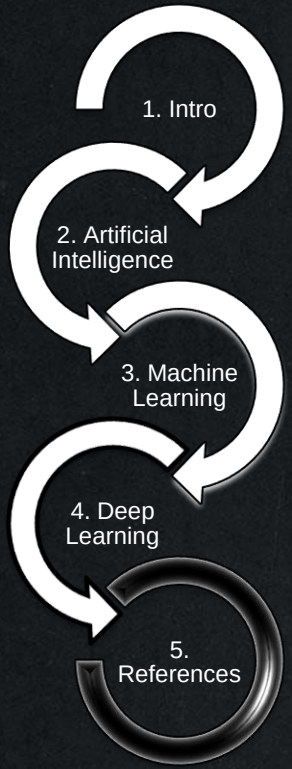
04. Deep Learning

Definitions and Examples

What is Deep Learning?

- Deep learning uses a multi-layered structure of algorithms called neural networks
- The individual layers of neural networks can also be thought of as a sort of filter that works from gross to subtle, increasing the likelihood of detecting and outputting a correct result
- The human brain works similarly. Whenever we receive new information, the brain tries to compare it with known objects.



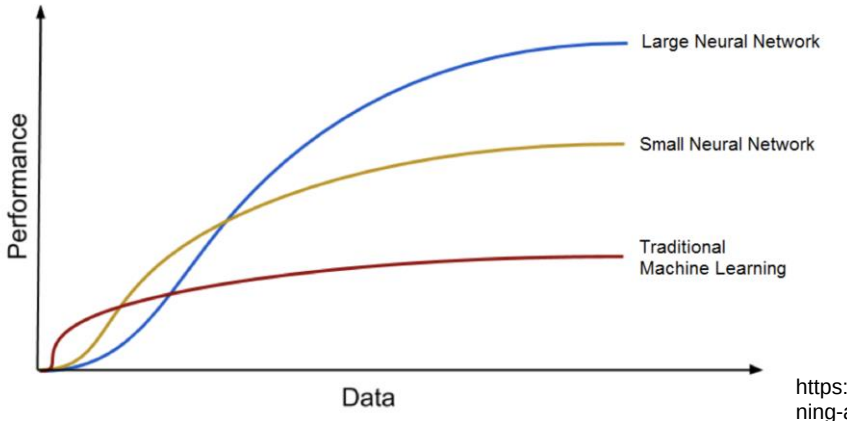


04. Deep Learning

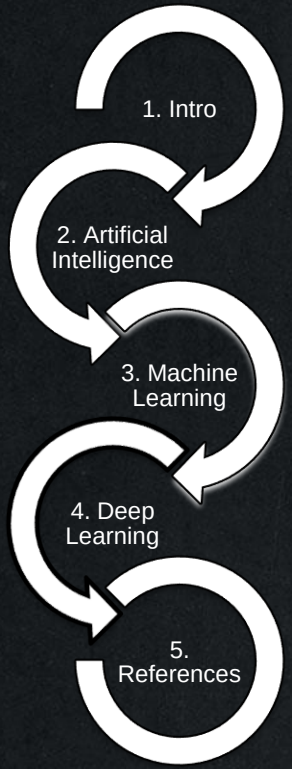
Definitions and Examples

Why is Deep Learning so popular?

- The first advantage of deep learning over machine learning is the needlessness of the so-called feature extraction
- Incredible good results using huge amount of data in comparison to classical machine learning algorithms
- “The analogy to deep learning is that the rocket engine is the deep learning models and the fuel is the huge amounts of data we can feed to these algorithms.”



https://towardsdatascience.com/what-is-deep-learning-and-how-does-it-work-2ce44bb692ac

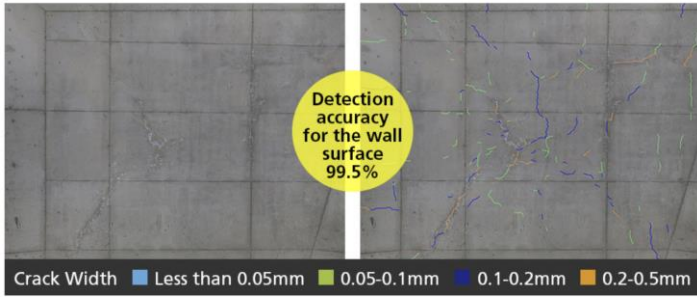


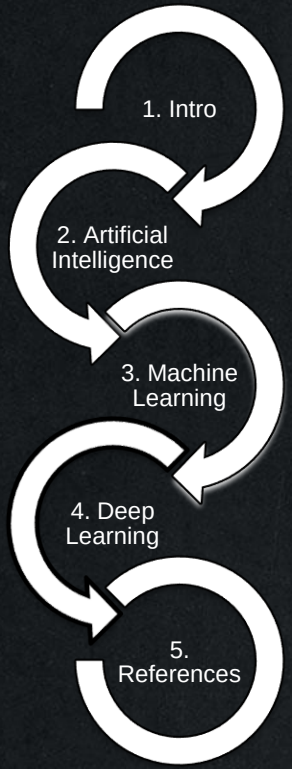
05. References

AI in Building Industry

Quality Management

- Deep learning techniques to improve the quality of their construction processes
- Image recognition of photos taken with manual drones is used to identify risk areas and is also compared with existing construction plans to detect possible construction errors
- Through reinforcing learning, AI algorithms can use trial and error techniques to identify the best processes



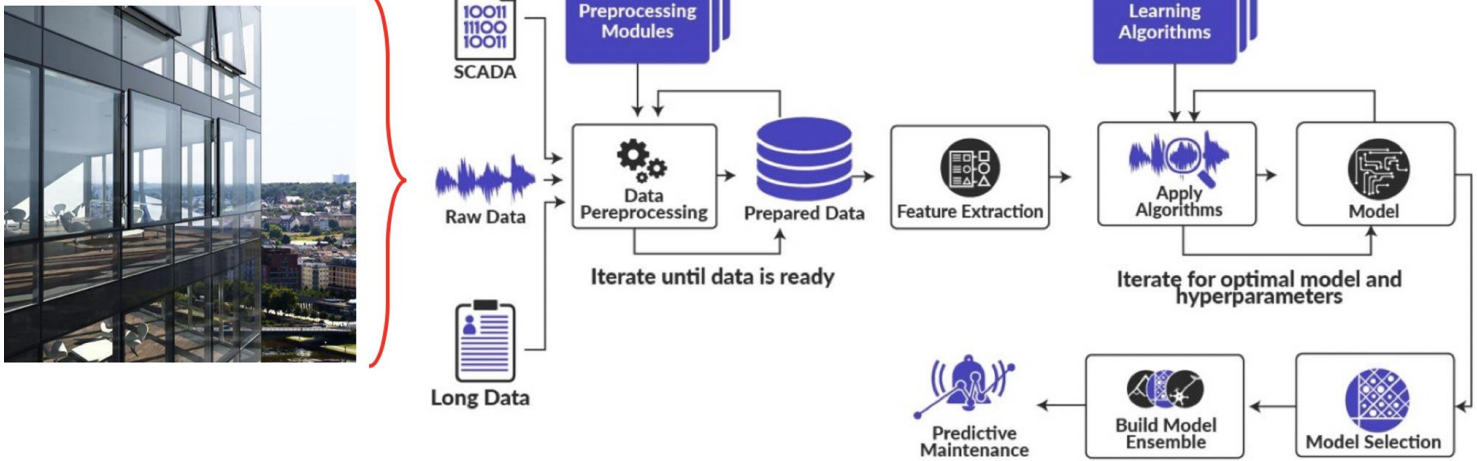


05. References

AI in Building Industry

Maintenance

- Predictive maintenance concept based on sensor data and AI algorithms
- AI detects anomalous behaviour of the sensor data and then suggests a maintenance d ate specifically and individually for a construction project



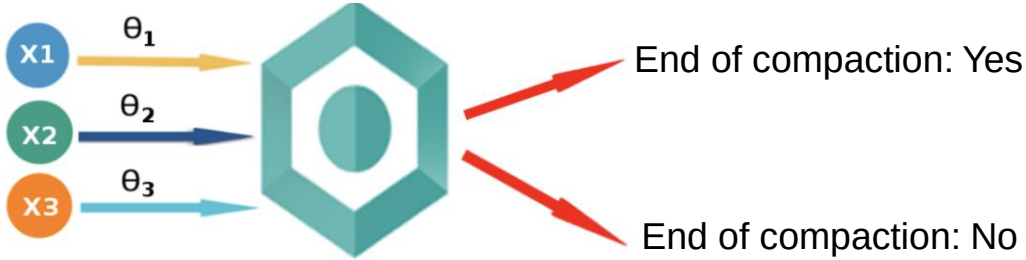
05. References

AI Technologies and M&M Projects

AI - Automation

- Ability of machines to learn from past experiences using historical data
- **M&M:** Prediction of end of compaction

Multivariate Time Series Classification

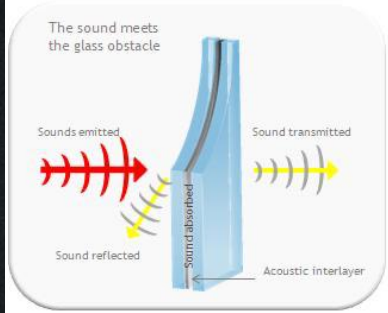


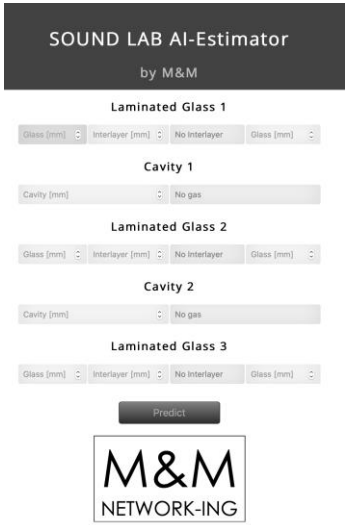
05. References

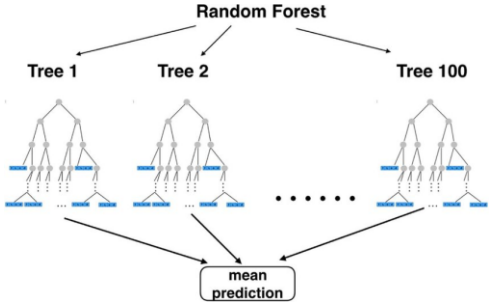
AI Technologies and M&M Projects

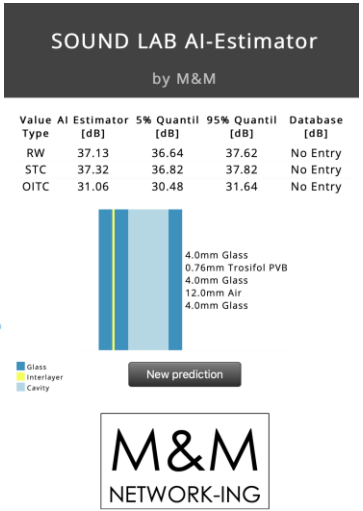
AI - Machine Learning

- An artificial system learns from exam ples and can generalize them after the learning phase is over.
- **M&M:** Prediction of sound insulation value









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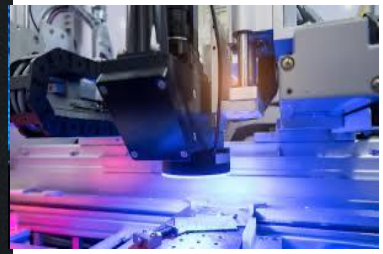
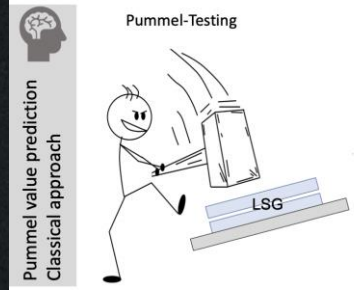
AI Technologies and M&M Projects

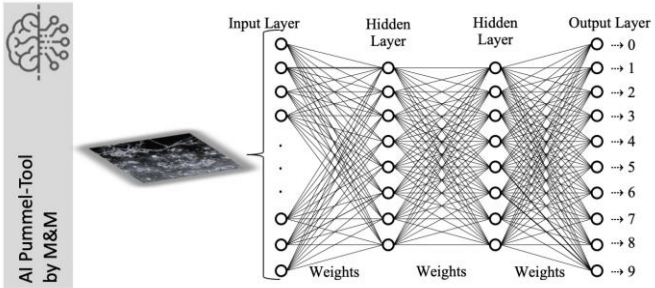


AI - Machine Vision

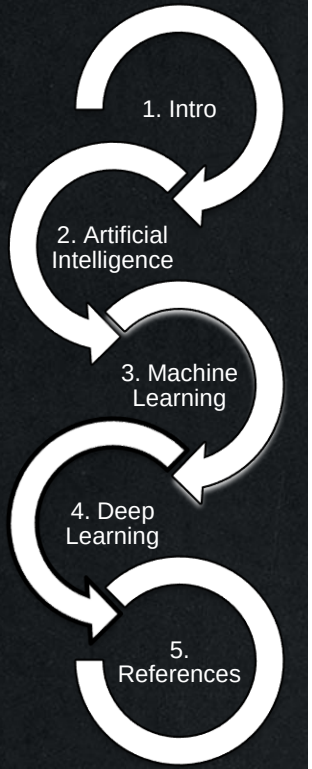
- Machine vision covers all industrial a pplications in which automated proce sses are controlled based on visual s ystems.
- **M&M:** Prediction pummel value



Classical Approach



AI Approach by M&M



05. References

Pummel Test

1

What is the pummel test

- Test for quality assurance of laminated (safety) glass (LSG)
- Indication of the degree of adhesion between glass and polymer interlayer
- Important for quality control

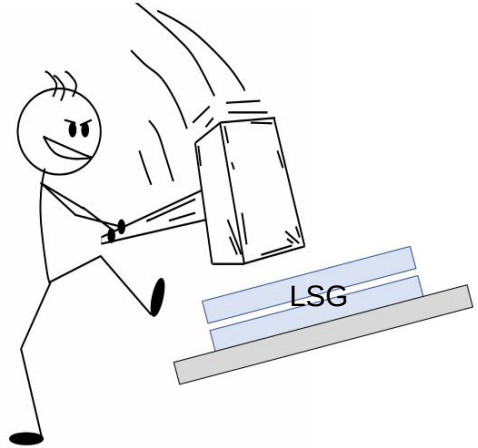
2

How is the pummel test carried out?

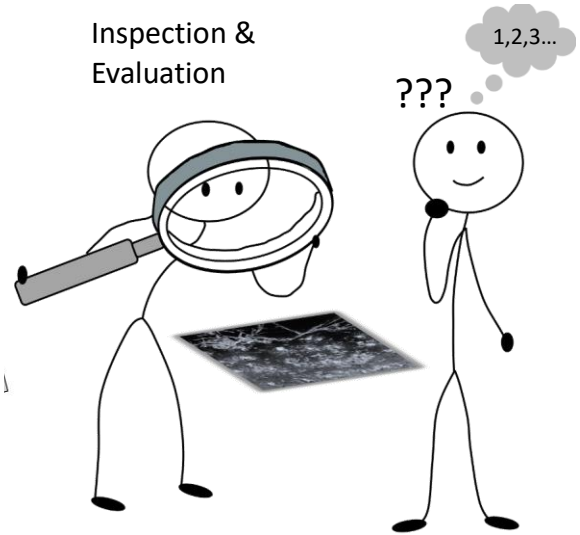
- Processing of laminated glass with a hammer
- Visual inspection of the destroyed glass by humans
- Classification of the broken glass based on Pummel-Scale

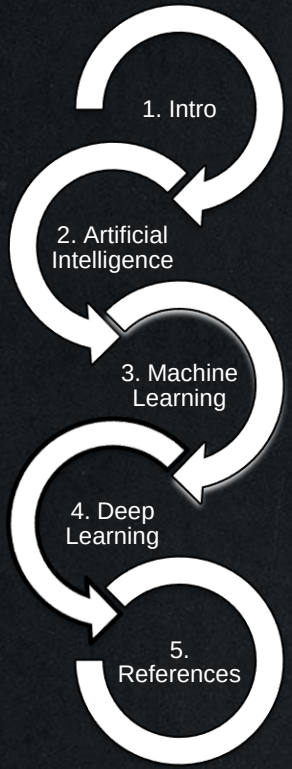
Pummel value prediction
Classical approach

Pummel-Testing



Inspection & Evaluation





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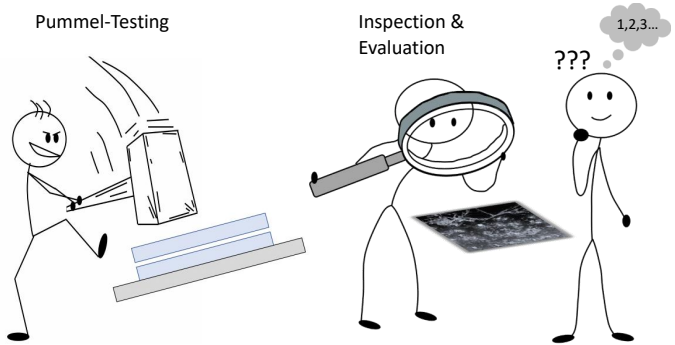
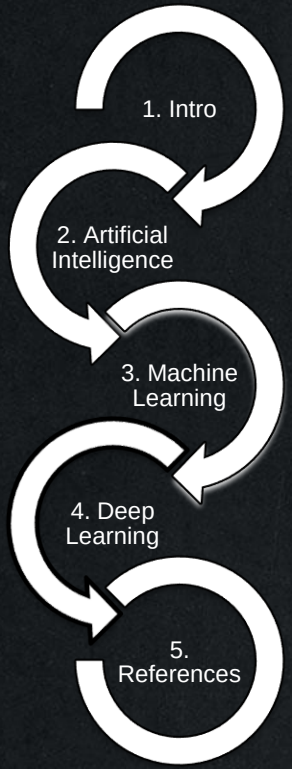
Pummel value prediction
Classical approach



Problem

- No automated process
- Manpower is required to perform the test and evaluation
- No unbiased evaluation of the Pummel value by humans



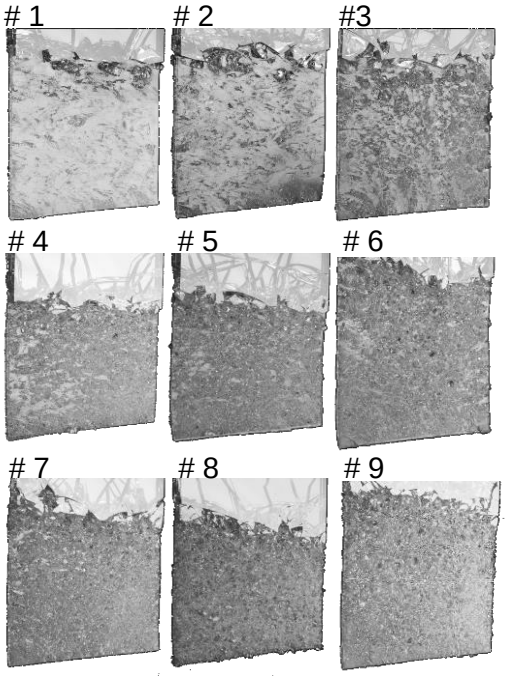
05. References

Pummel Test Data

1

Available Data

- Data provided by manufacturers
- Pummel scale (pictures -> pummel value)



05. References

Data & Model

1

Available Data

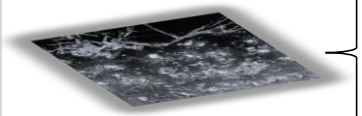
- Data provided by manufacturers
- Pummel scale (pictures -> pummel value)

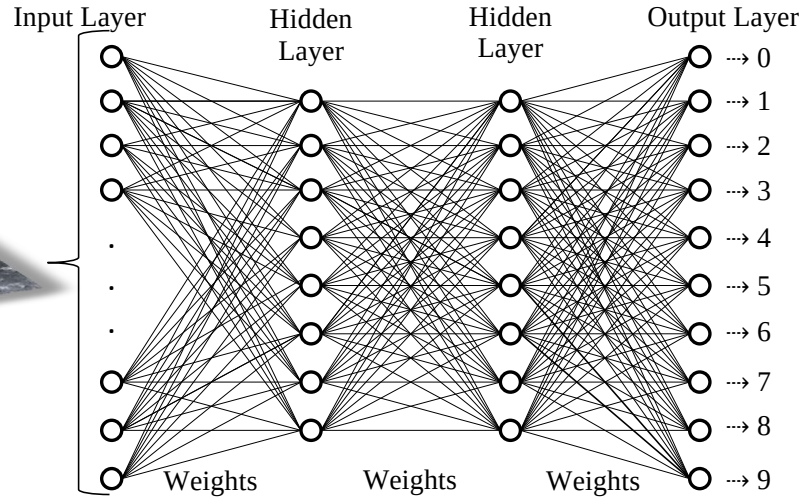
2

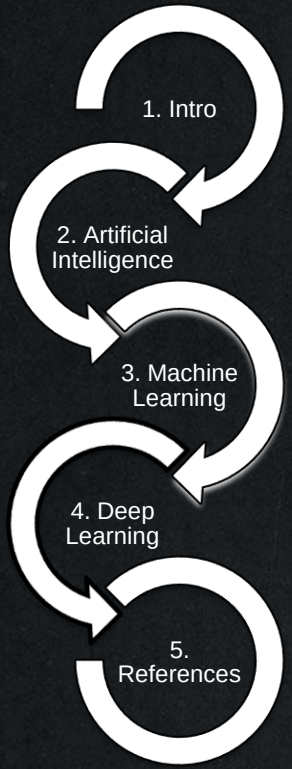
AI Pummel-Tool

- Classification by Neural Network

AI Pummel-Tool by M&M







05. References

Literature

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