The role of artificial intelligence in geophysics: current and future

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Outline

Part I: What is AI ?

- Knowledge bases system
- Learning from experience and data
- Supervised, unsupervised learning
- Basics of deep learning

Part II : Current applications of AI in geophysics

- Why is AI relevant to geophysics?
- Seismic processing and interpretation
- Supervised ML
- Clustering
- Generative models

Part III: Perspectives of AI in geophysics

- Data collection with autonomous vehicles
- Physics-informed neural networks
- The inverse problem
- Fast machine learning
- Getting rid of the non-uniqueness curse?

Conclusions

What is artificial intelligence (AI) ?

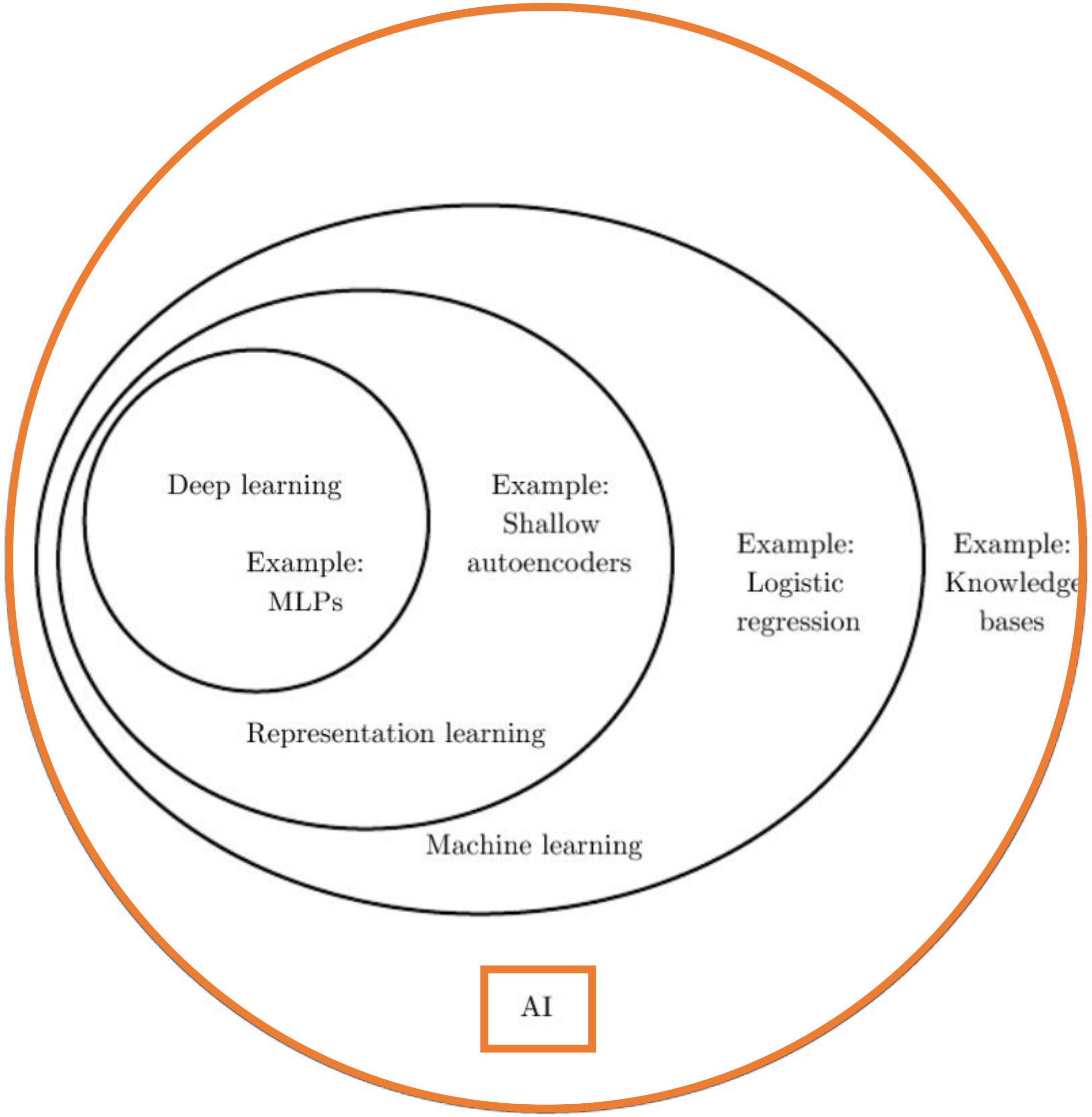
What is artificial intelligence?

- ***"AI, or Artificial Intelligence, refers to the development of computer systems that can perform tasks that typically require human intelligence."***
  ChatGPT-3.5

- ***"AI leverages computers and machines to mimic the problem-solving and decision-making capabilities of the human mind"***
  IBM

- **"relevant to any intellectual task; it is truly a universal field"**
  Russel and Norvig (Artificial Intelligence, A modern approach)

- **"in the long run, AI is the only science"**
  Woody Bledsoe

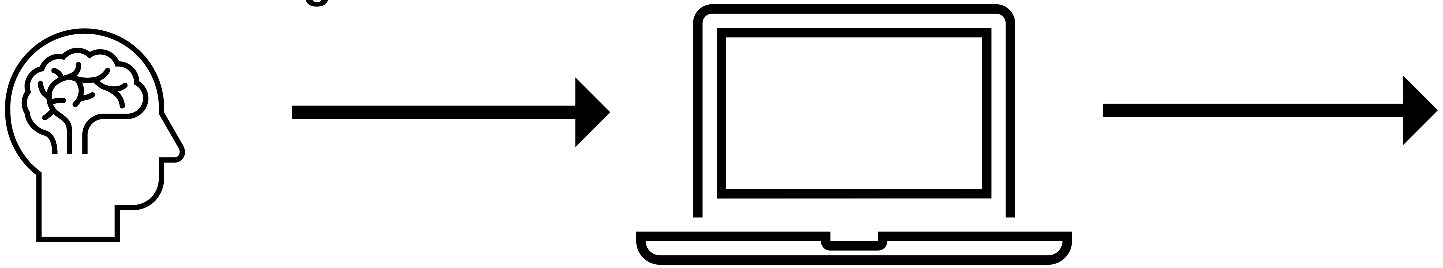


Goodfellow et al. (2016)

Knowledge bases system

Inference, logical deduction, induction

Hard-coded knowledge



Output
(Ex: Diagnosis)

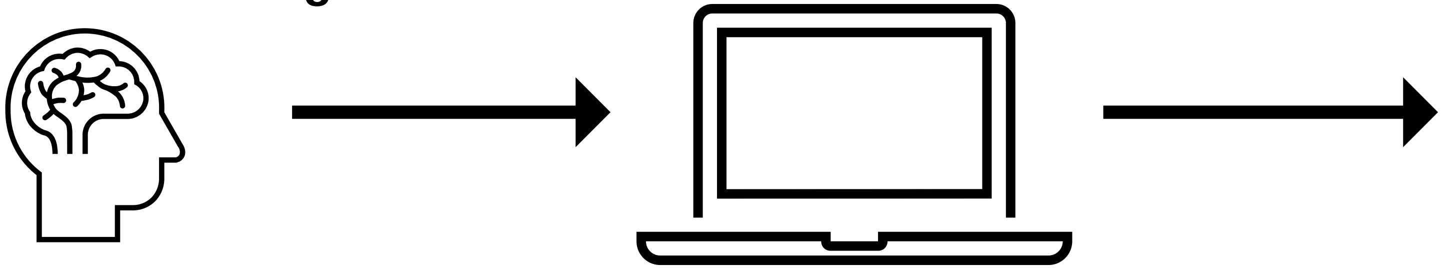
Algorithm are based on hard-coded knowledge, set of mathematical rules, axioms:

- Ex: IF the patient has a fever AND the patient reports chills AND the patient has a positive blood culture for bacteria XTHEN the diagnosis is likely bacterial infection caused by bacteria XCF (Certainty Factor) = 0.8
- Rules of a chess game
- Intellectually difficult for humans but relatively easy for computers

Knowledge bases system

Hard-coded knowledge

Inference, logical deduction, induction



Output / Decision / Diagnosis
(Ex: MYCIN)

Limitations

- How to set up hard-coded rules for object or speech recognition?
- The most intuitive tasks for human beings are difficult to represent by a set of rules
- The challenge is to represent the expertise of human specialist accurately

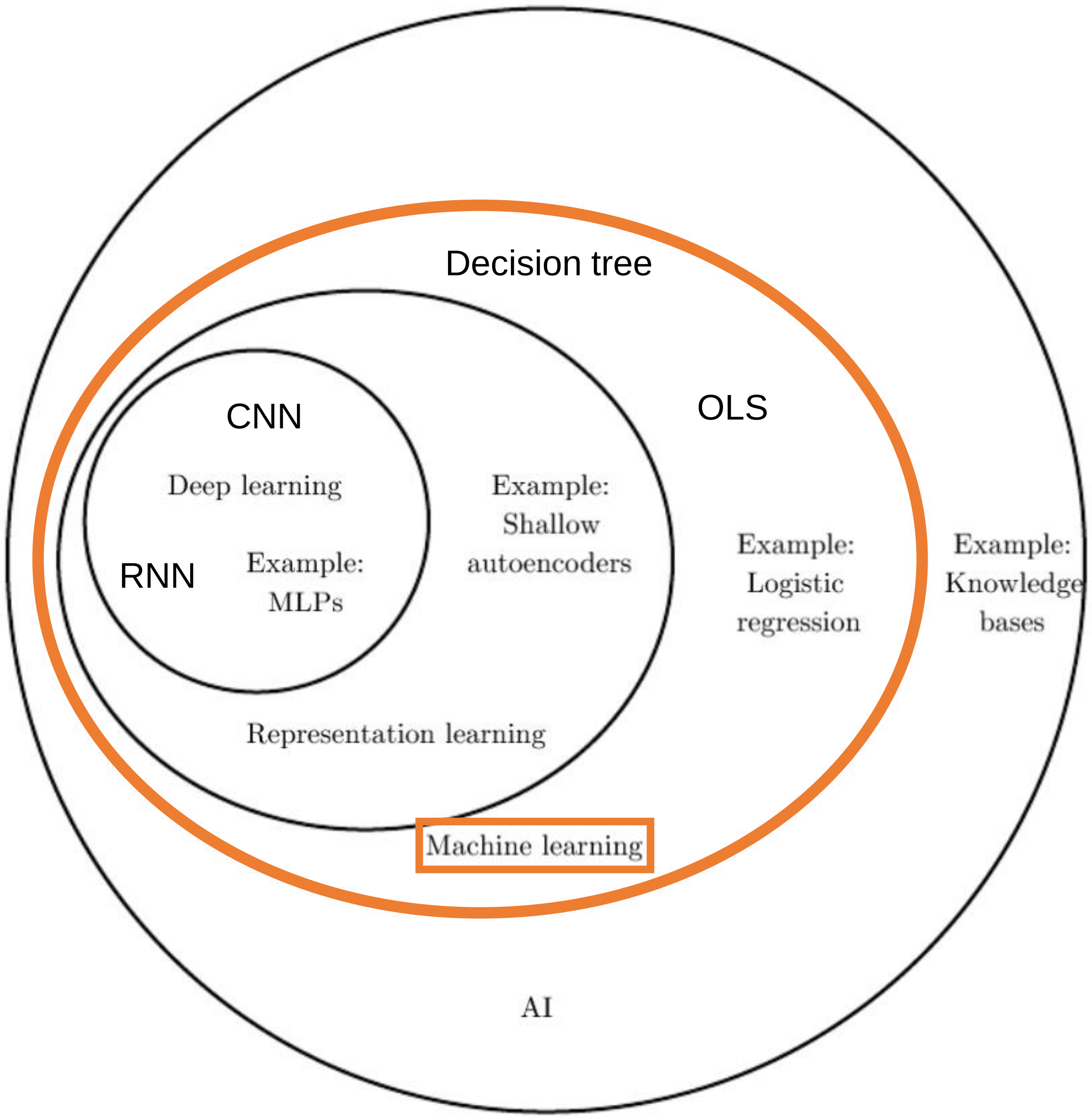
What is machine learning?

- Definition: Machine learning is a set of techniques that enables **computer systems** and algorithms to **improve** with **experience** and **data**

- Nowadays, AI is pretty much about **Machine Learning**

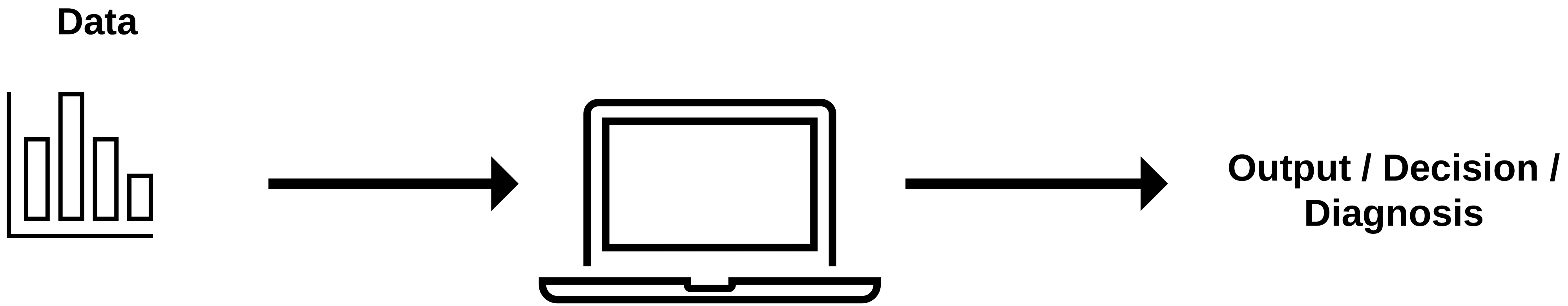
"Learning is fueled by knowledge, and human-scale learning demands a human-scale amount of knowledge"

Douglas Lenat (1989)



Goodfellow et al. (2016)

What is machine learning?

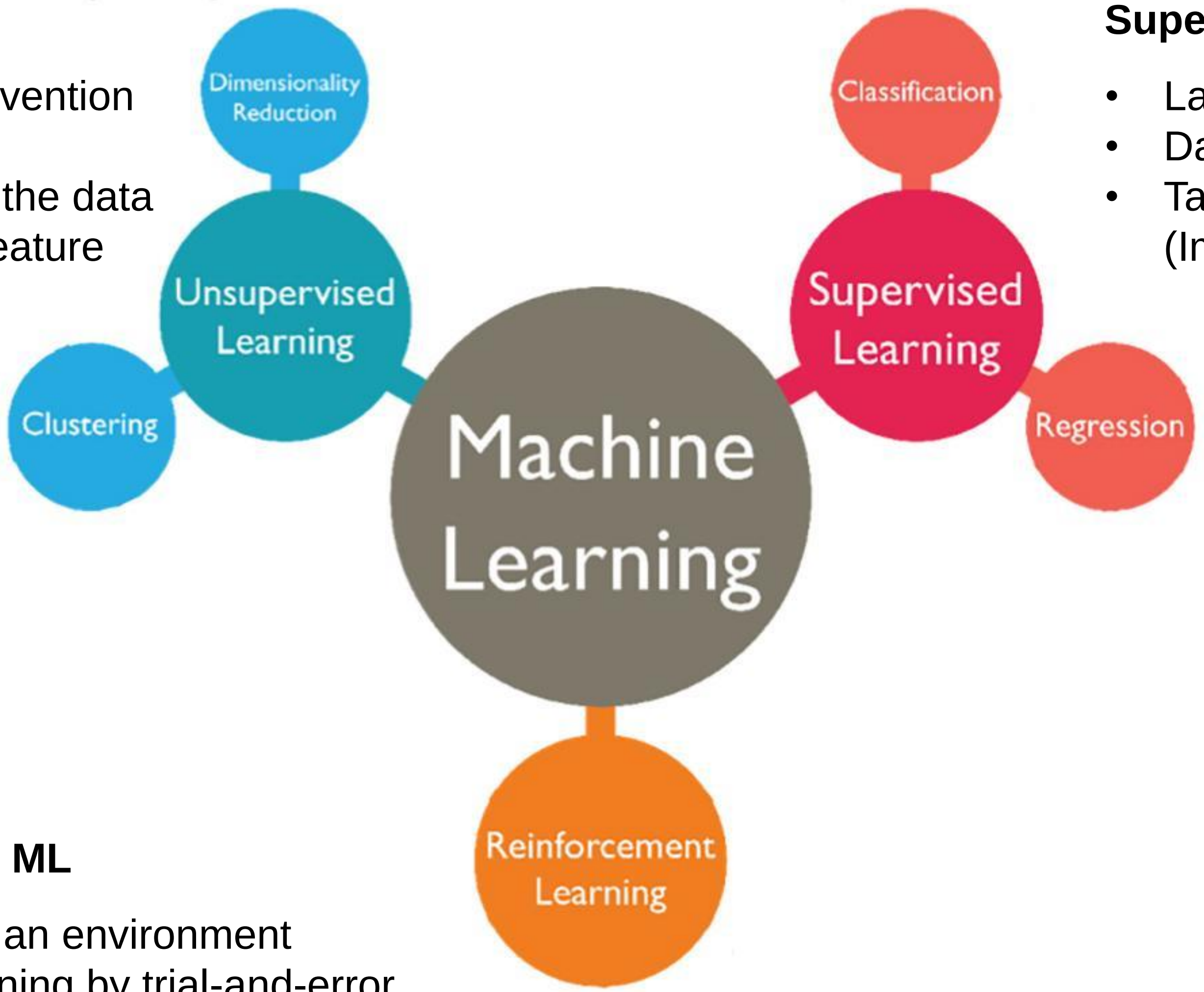


- A plethora of techniques and tools
- Ordinary least square, logistic regression, decision tree, clustering, feed-forward neural networks
- For both regression and classification tasks

What is machine learning (ML) ?

Unsupervised ML

- Does not require human intervention or labels
- Find patterns and features in the data
- Learn the representation or feature itself



Supervised ML

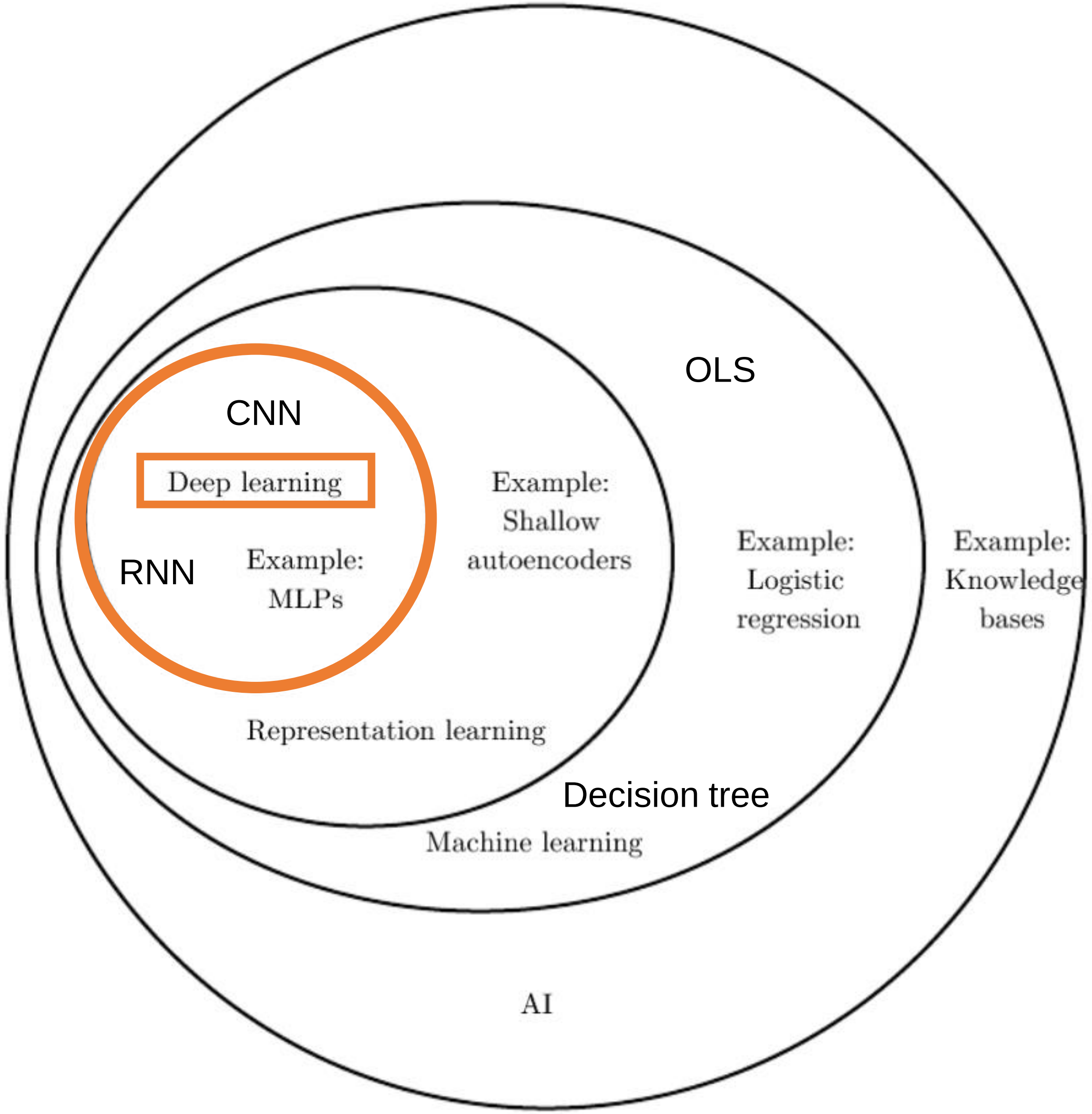
- Labelled data by humans
- Data greedy
- Take decades to build labelled dataset (ImageNet)

Reinforcement ML

- Interact with an environment
- Achieve learning by trial-and-error
- Policy is adapted according to reward and punishement

Hjorth-Jensen M., FYS-STK4155 (2022)

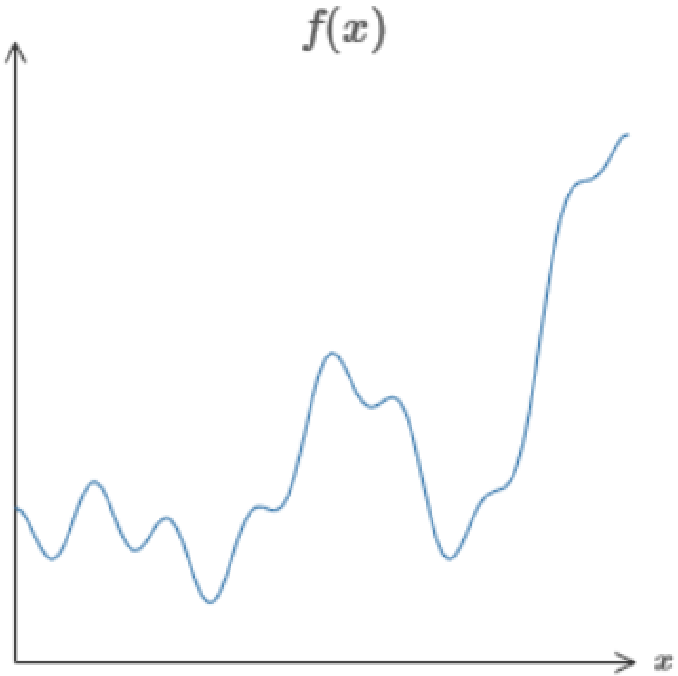
What is deep learning (DL)?



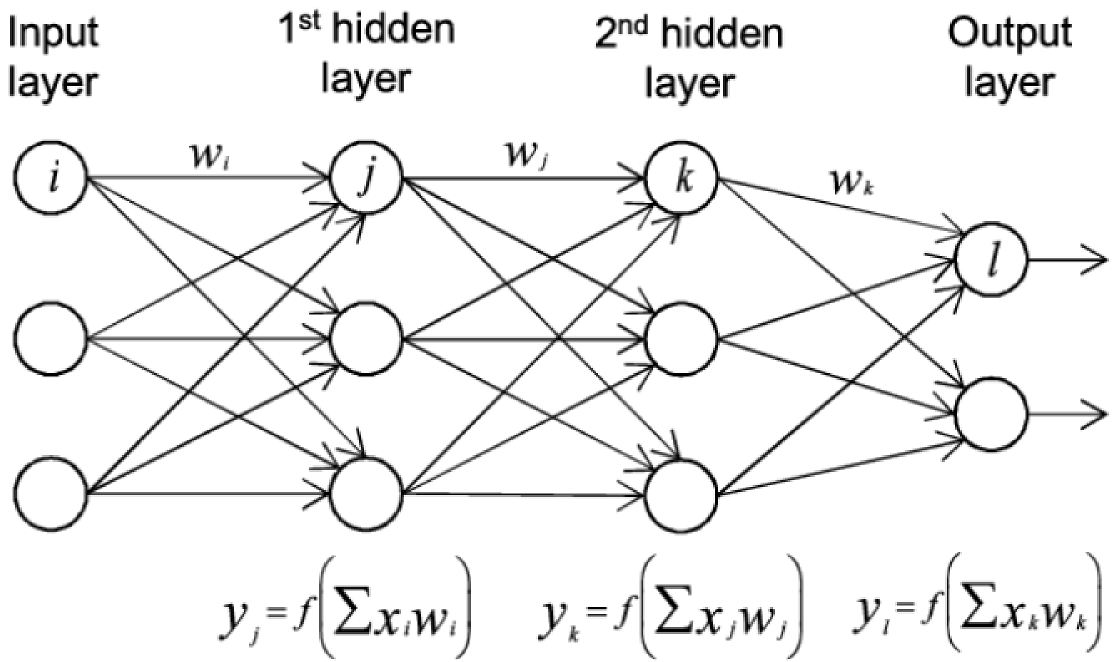
Goodfellow et al. (2016)

Basics of deep learning

Universal approximation theorem: a **feed-forward neural network** with just a single hidden layer containing a finite number of neurons can approximate **any continuous multidimensional function** to arbitrary accuracy.



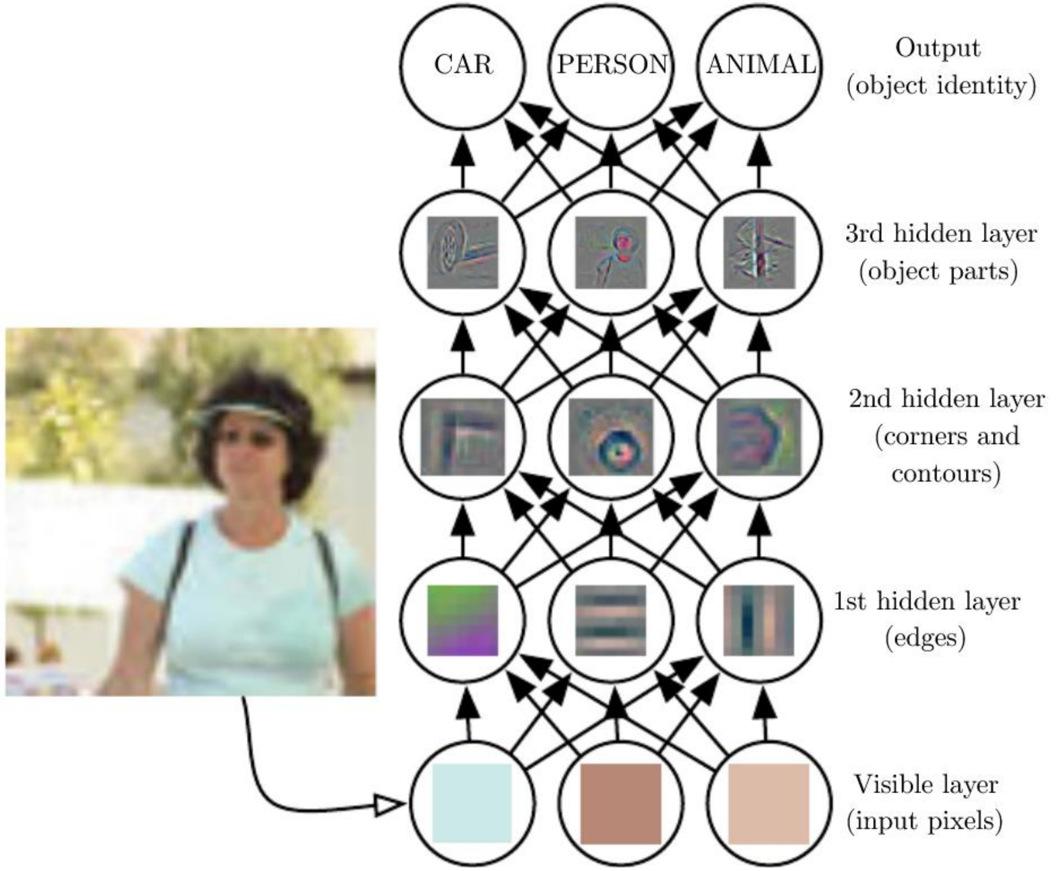
Artificial neural network with 2 hidden layers



Basics of deep learning

- During training, neural network **weights** and **biases** are updated with the **backpropagation algorithm**
- The **depth** of the neural network is the number of hidden layers, hence **deep learning**
- Neural networks is the predominant **programming paradigm** in AI, capable of learning complicated tasks like **pattern recognition**
- There are a **plethora** of deep learning algorithms: CNN, RNN, GNN, ANN, PINN, autoencoders, etc.
- Active research in DL are narrowly linked to advances in the field of **mathematical optimization**

Neural networks with 3 hidden layers



Goodfellow et al. (2016)

Current use of AI in geophysics

Why is ML relevant for geophysics?

- Like any other natural sciences, **geophysics** relies heavily on **observations**
- Modern geophysics is **computationally-intensive** and advances ML are often important in optimization of calculations and data storages
- Any advances in **optimization** techniques with ML can be applied to **objective functions** in **geophysical inversion**
- In this trial lecture, we will focus on **solid earth geophysics**

"Since the fundamental task of optimizing an objective function is also central to modern machine learning efforts, recent geophysical studies have also sought to exploit advances from that sphere."

Valentine and Sambridge (2023)

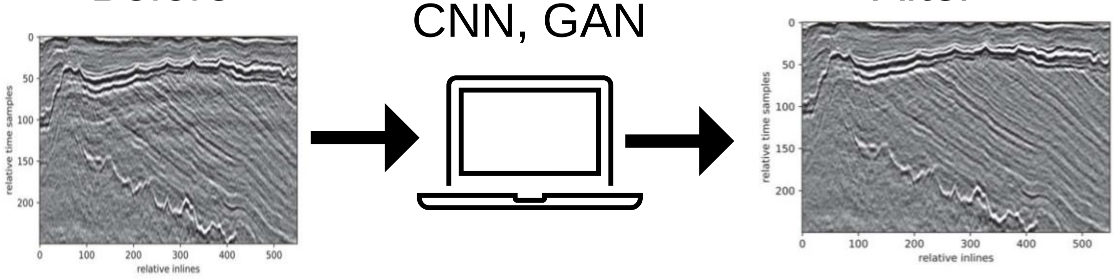
Seismic processing

Denoising

Before

CNN, GAN

After

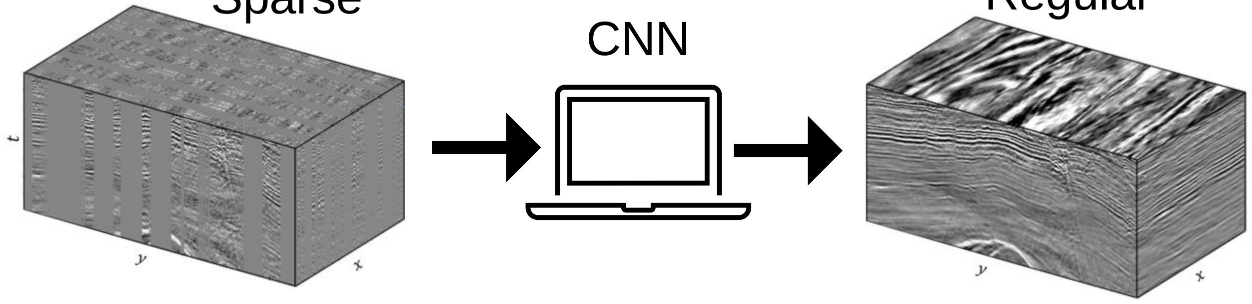


Interpolation

Sparse

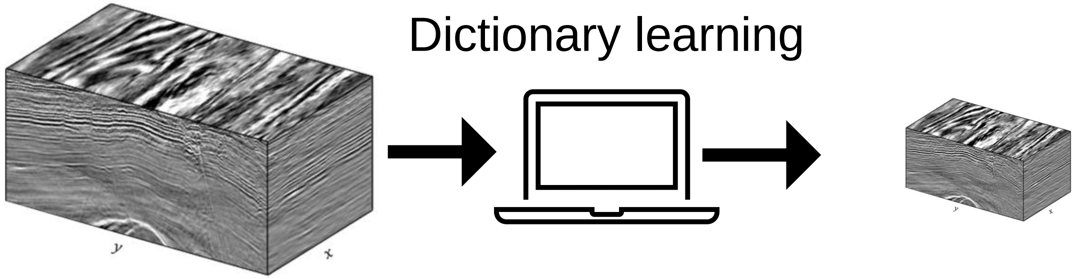
CNN

Regular



Data compression

Dictionary learning

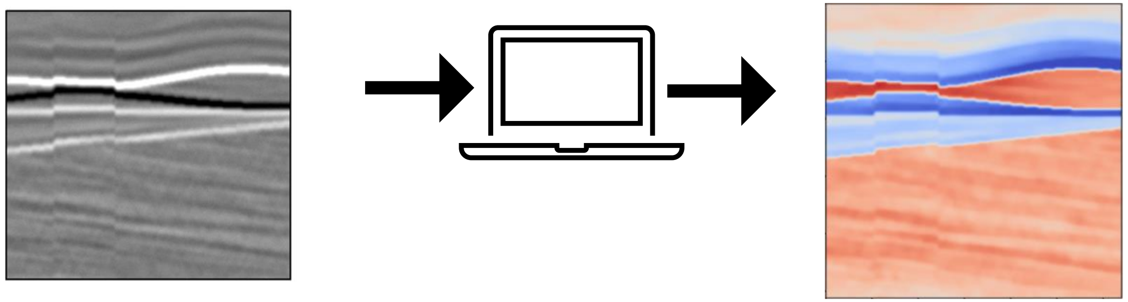


Inversion / tomography

Data

CNN

Velocity

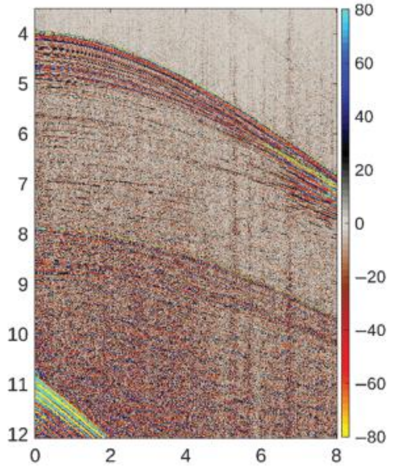


Bugge, PhD thesis (2020)

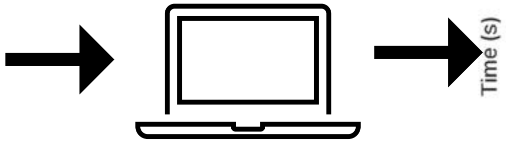
Greiner, PhD thesis (2022)

Seismic data compression

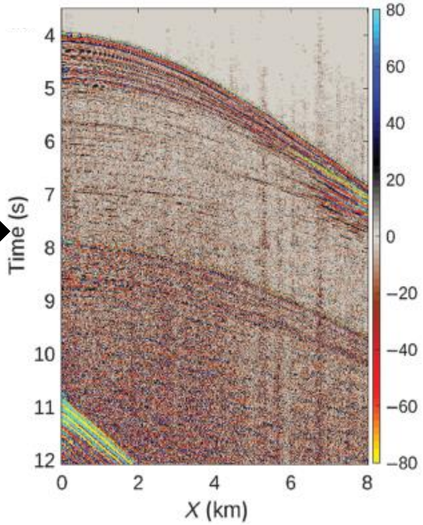
Raw data



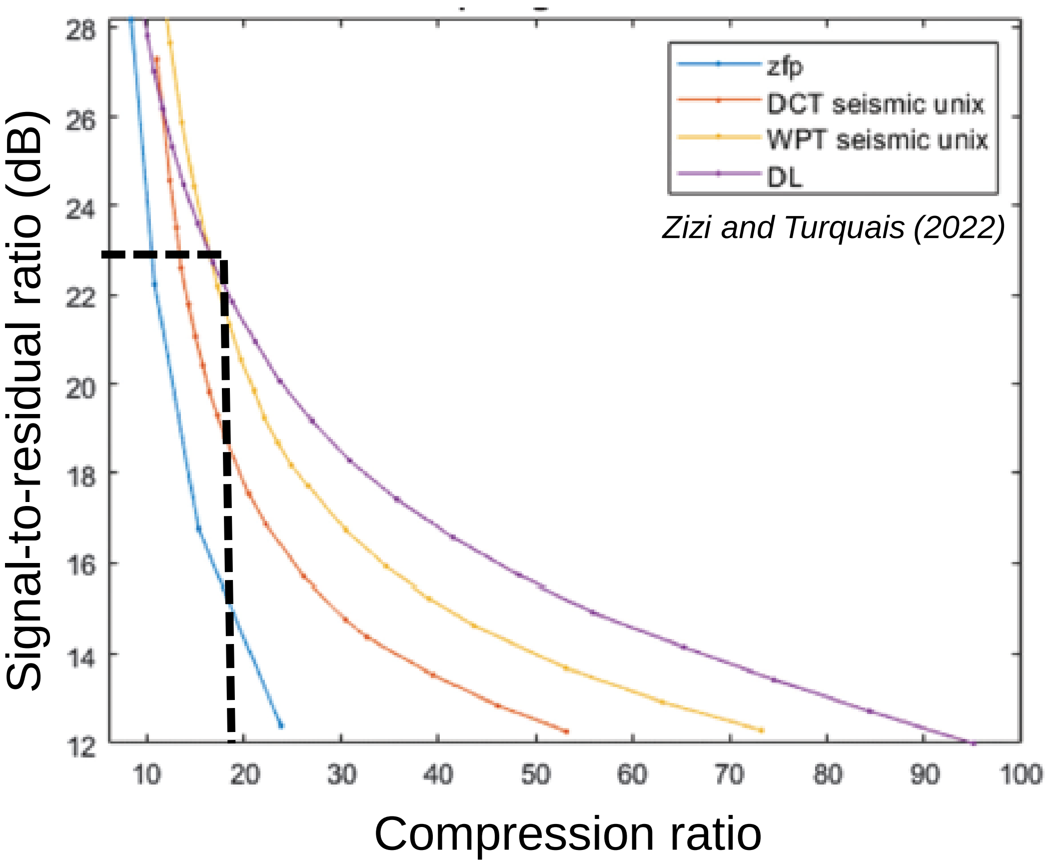
Dictionary learning



Data after compression/decompression



Performance of compression method

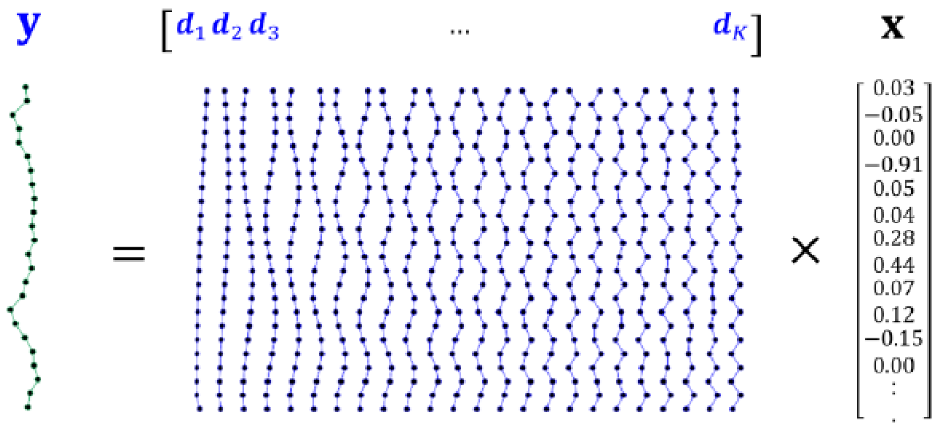


- **Deep learning-based** compression **outperforms** conventional technics for **compression ratio** exceeding **20**

- Deep learning-based compression fully exploits the **redundancy** in the data and can significantly reduce **disk size requirements**

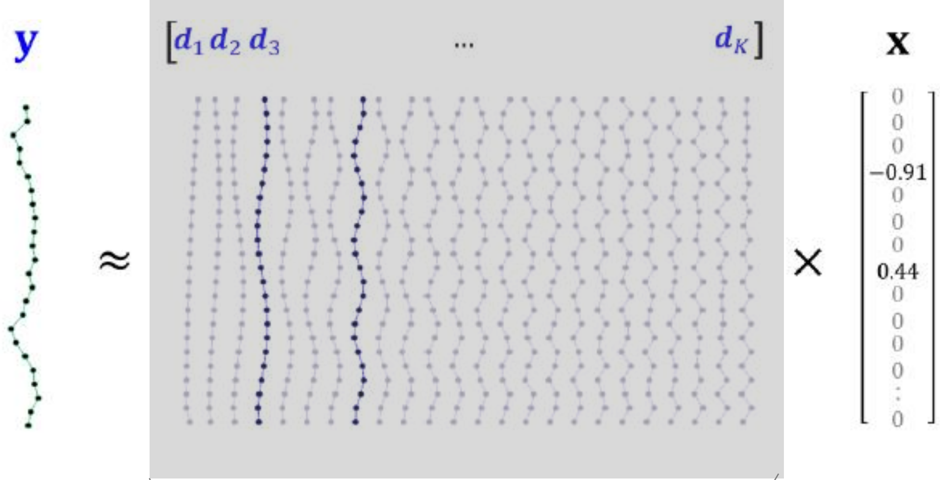
Seismic data compression

Exact representation



Zizi, PhD thesis (2023)

Sparse representation

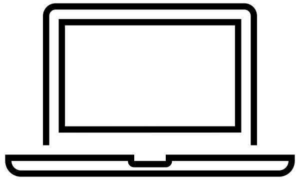


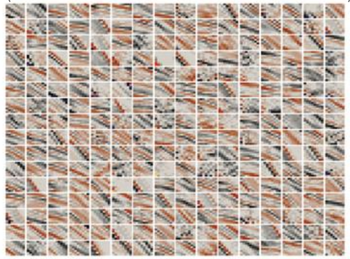
Dictionary

Dictionary learning

Shot gathers

Singular Value Decomposition

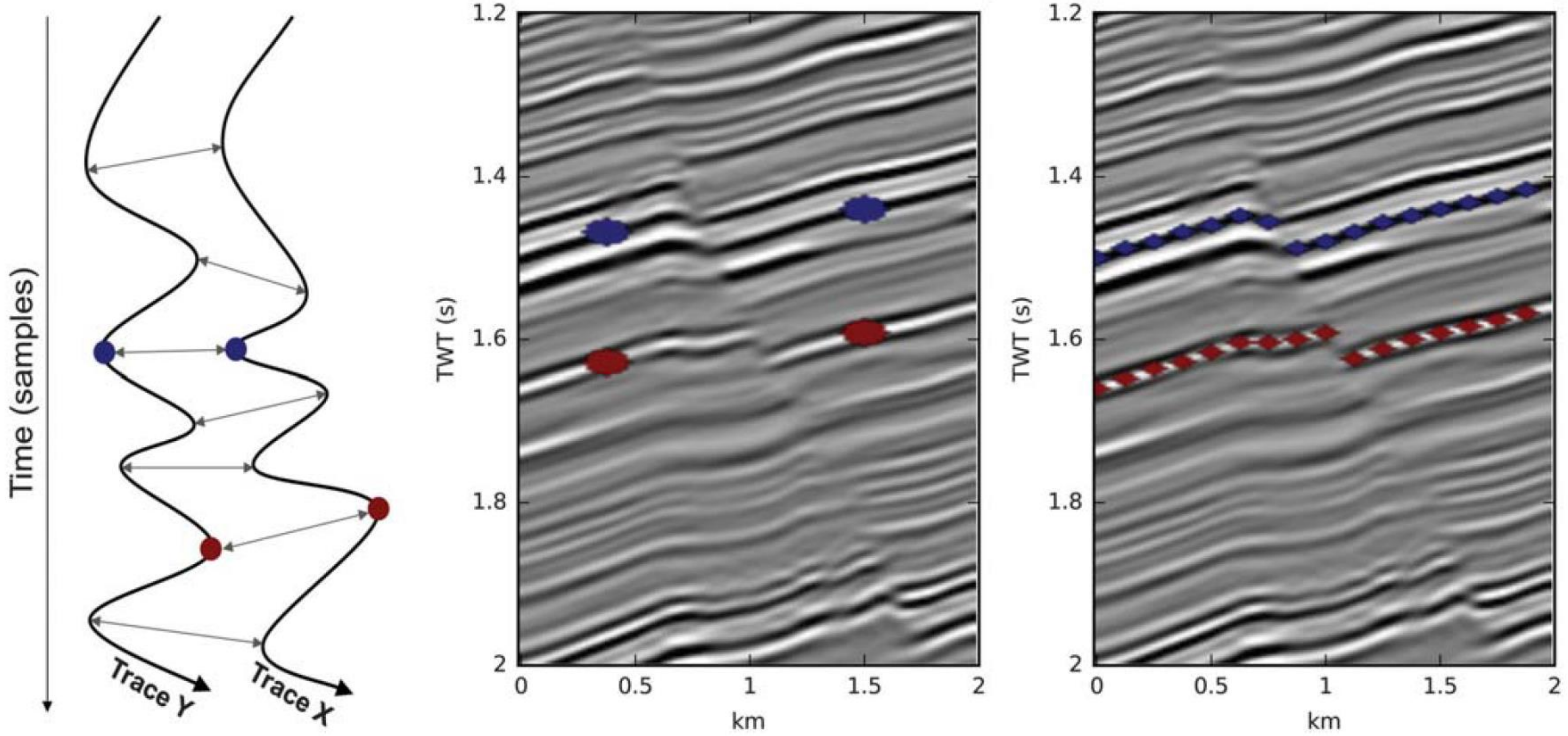




Dictionary learned from data

Zizi and Turquais (2022)

Seismic interpretation



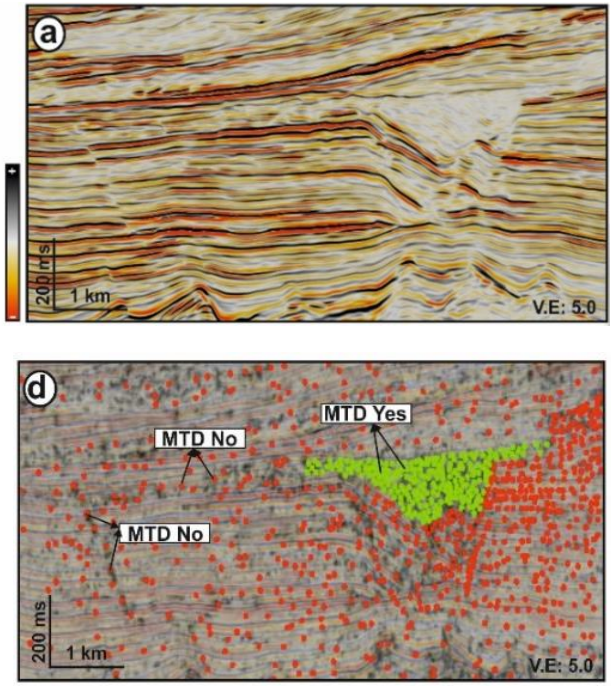
- **Dynamic time warping** measures the similarity between temporal sequences to find the optimal match. It is commonly used for speech recognition tasks.

- The algorithm can be used to track seismic horizons within a given sequences

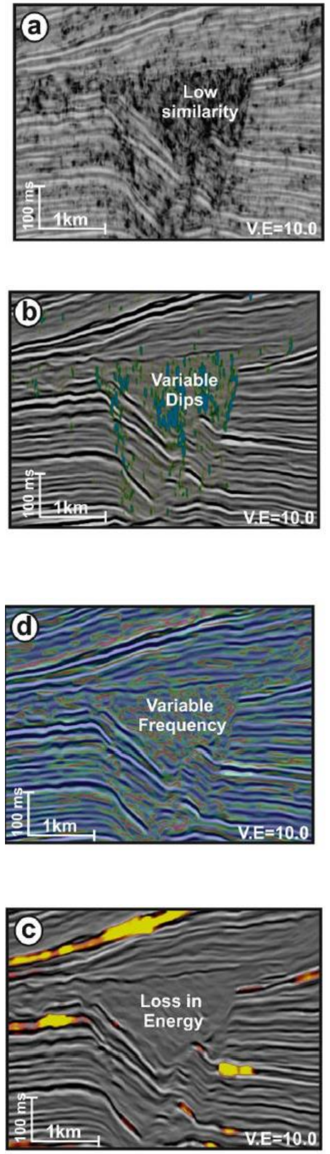
Bugge, PhD thesis (2020)

Automated interpretation of mass transport deposits

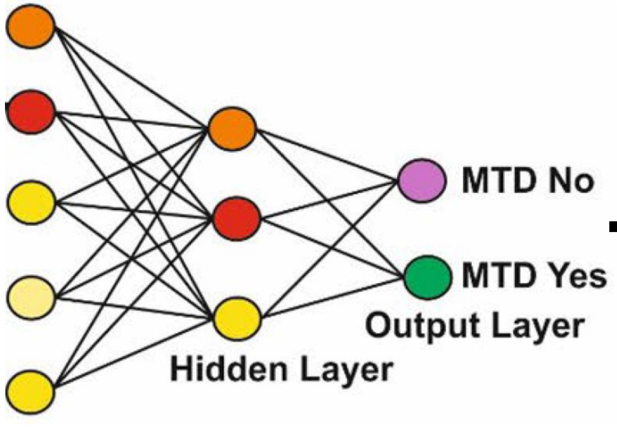
3D Seismic data
~700 labels (MTD: yes/no)



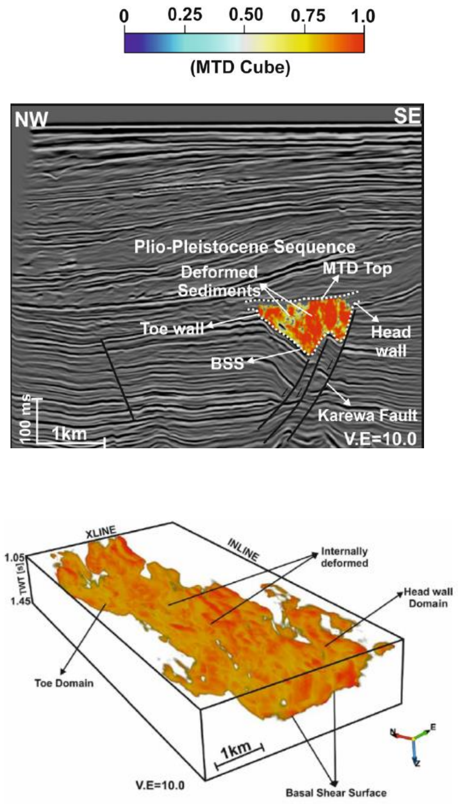
Seismic attributes



Feed-forward neural network
(95% accuracy score)



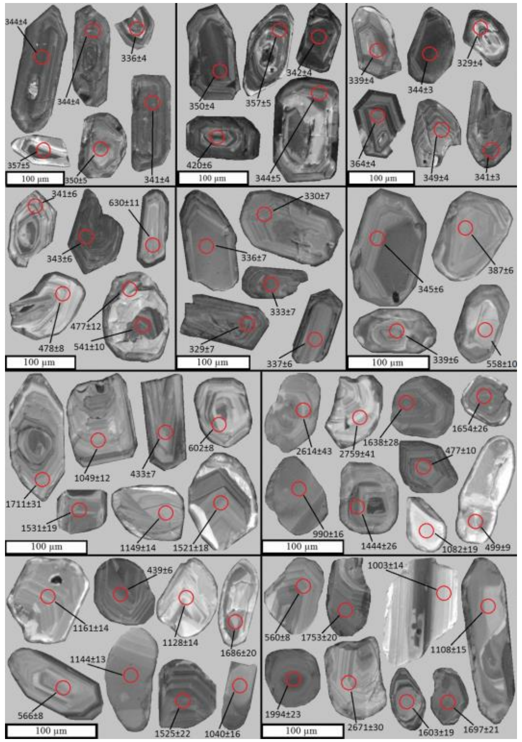
3D MTD geobody



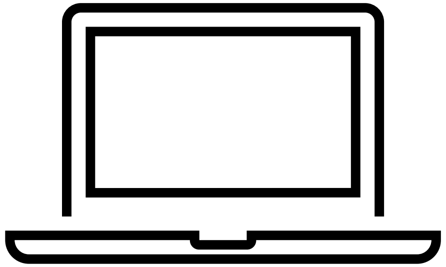
Kumar and Sain (2020)

Support Vector Machine

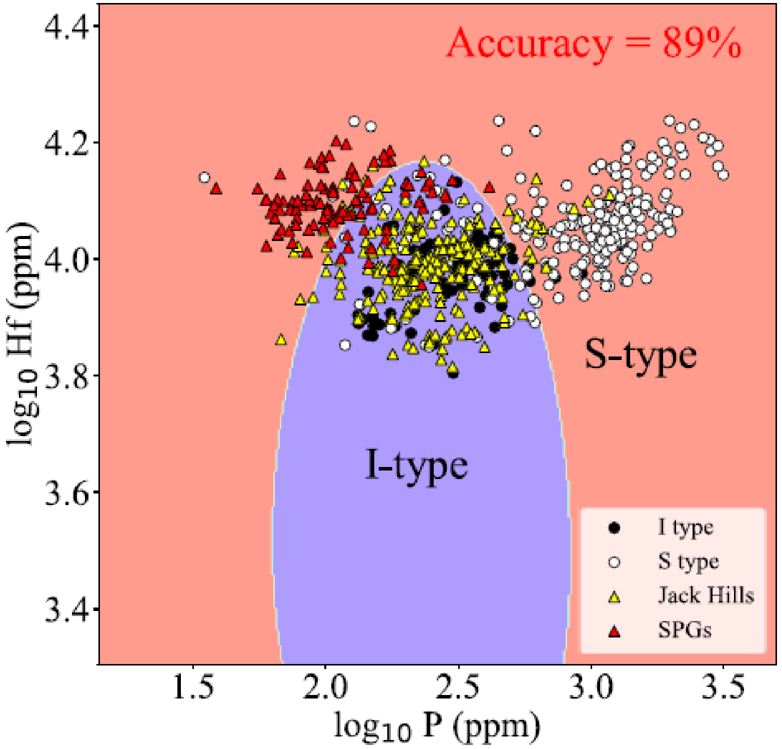
Zircon chemistry data



Support Vector Machine



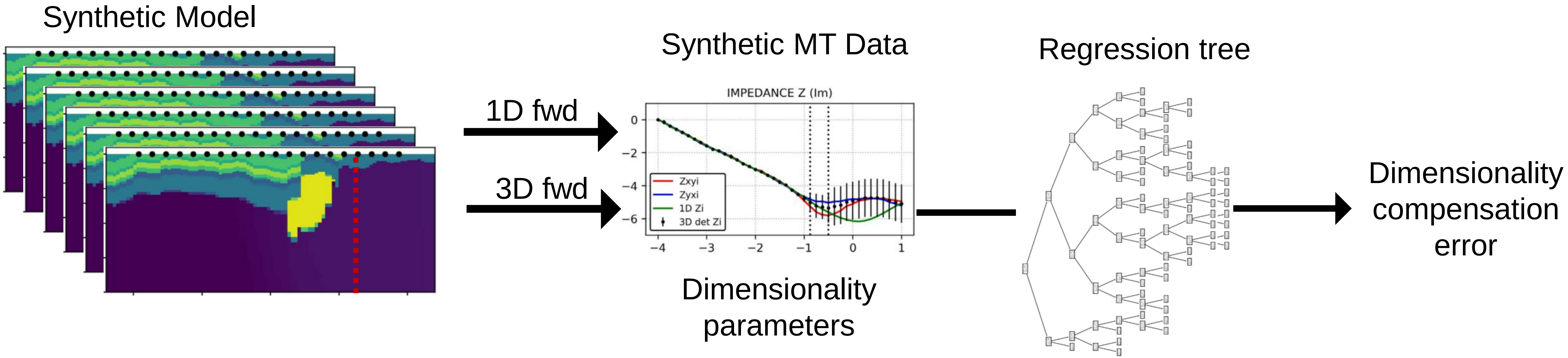
Classification task:
Igneous (I-type) or Sedimentary (S-type) magma?



Zagórska et al. (2020)

Chen et al. (2023)

Regression tree



- The objective of the workflow is to train a decision tree to **recognize 3D effects** in MT data and **compensate** for them in the data **uncertainty**

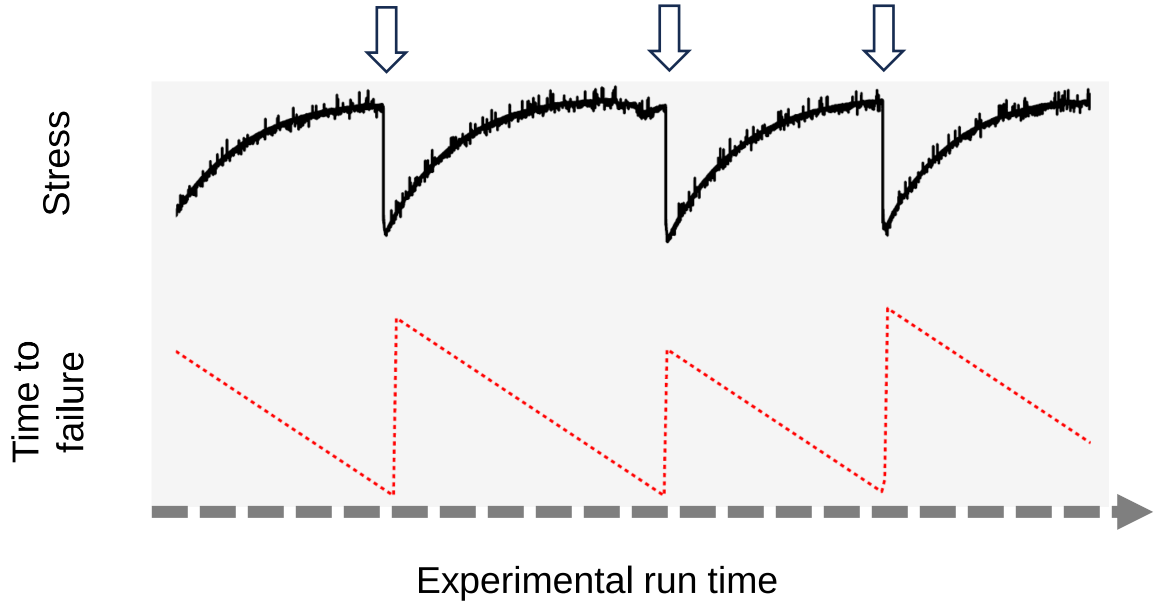
- This is a supervised ML algorithm that requires numerical modelling of the synthetic training set

- The resulting model performance and **generalization** depends the **accuracy** of the **numerical modelling** and the **volume** of data

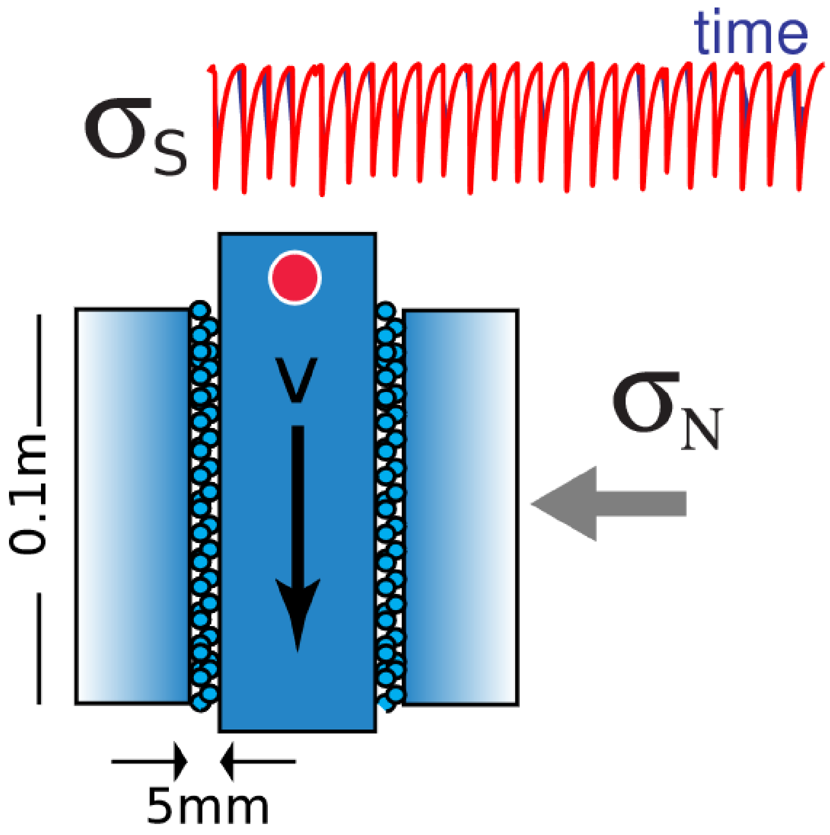
Seillé and Vissler (2019)

Predicting laboratory earthquake with ML

- The objective of this study is train a ML model to predict the **time to fault failure** in a laboratory («Labquake»).
- The experiments is based on **continuous accoustic recording** with the goal to infer failure time
- Traditional approaches rely exclusively on **Earthquakes catalogs** that contain human biases



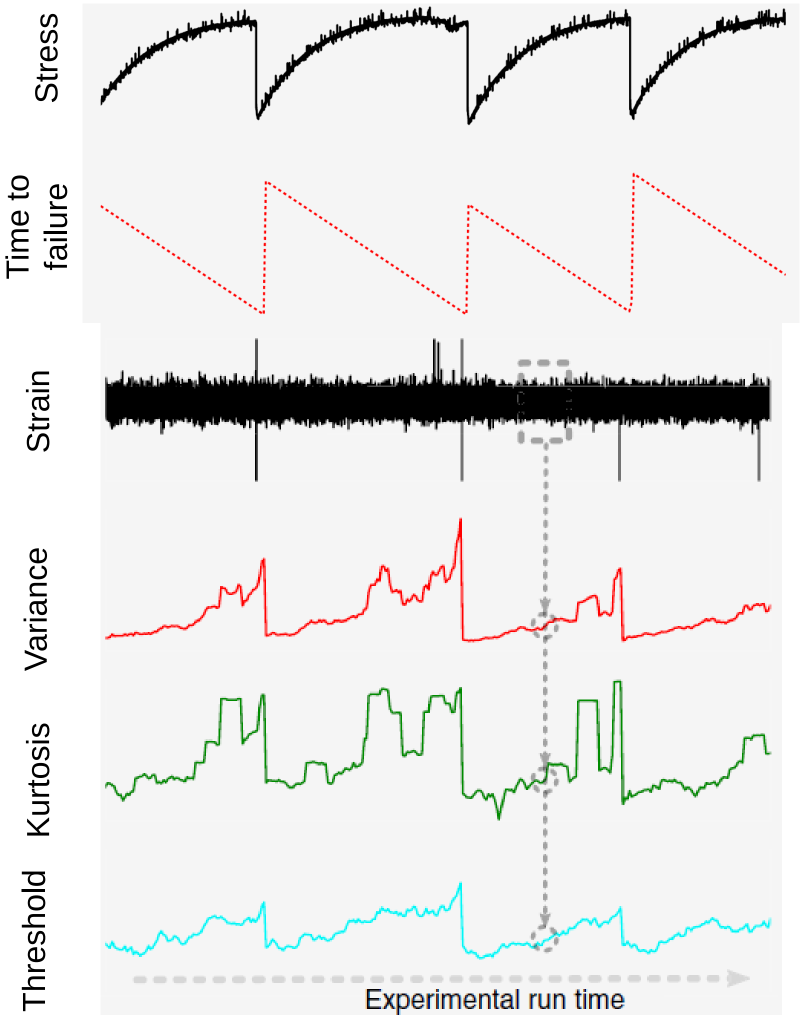
Experimental setup



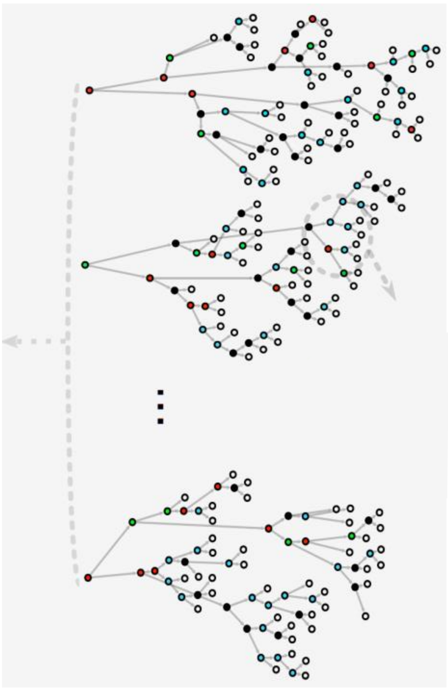
Rouet-Leduc et al. (2017)

Predicting laboratory earthquake with ML

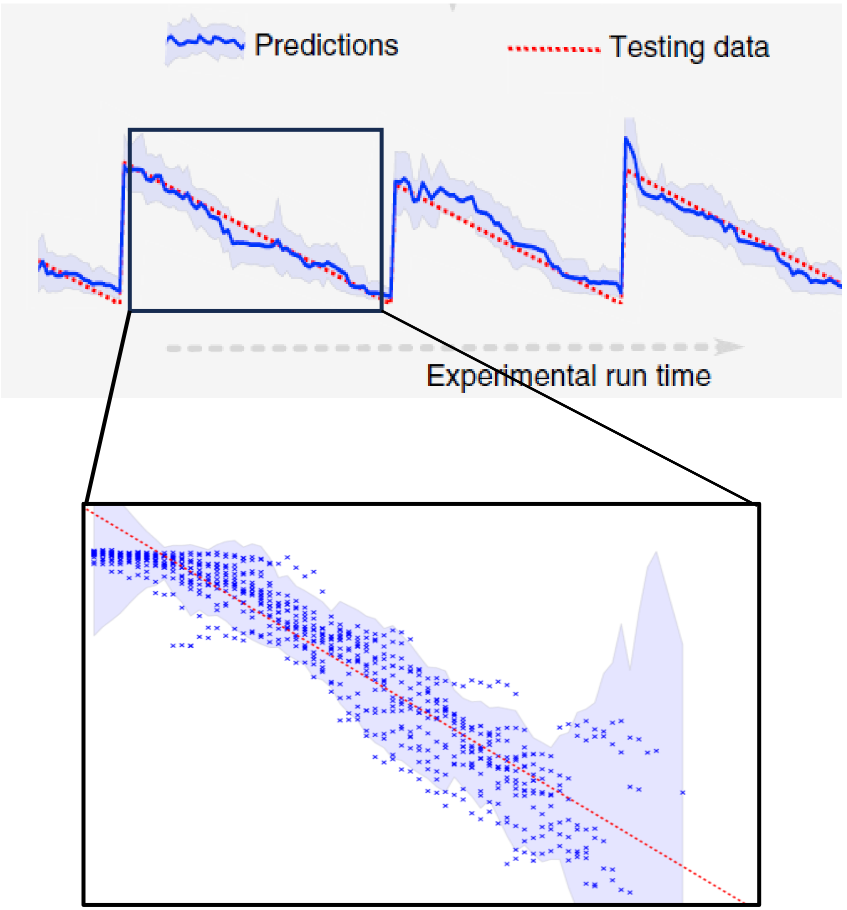
Data: Real-time accoustic recording



Random forest



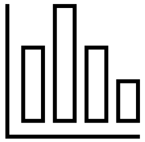
Prediction: Time to failure



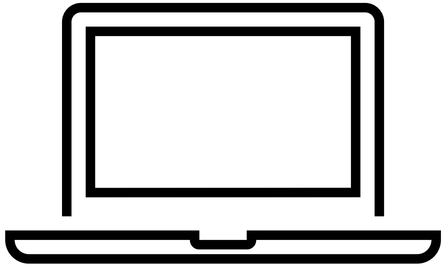
Rouet-Leduc et al. (2017)

Unsupervised learning - Clustering

Unlabeled Data

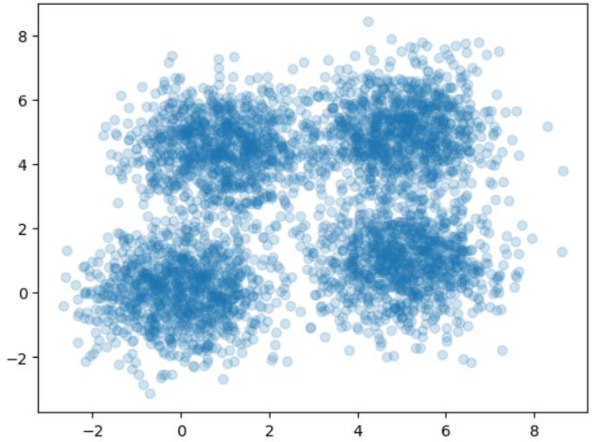


K-mean algorithm

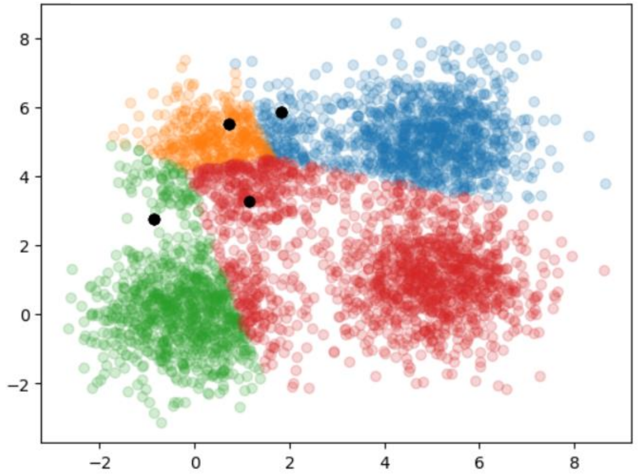


Clusters

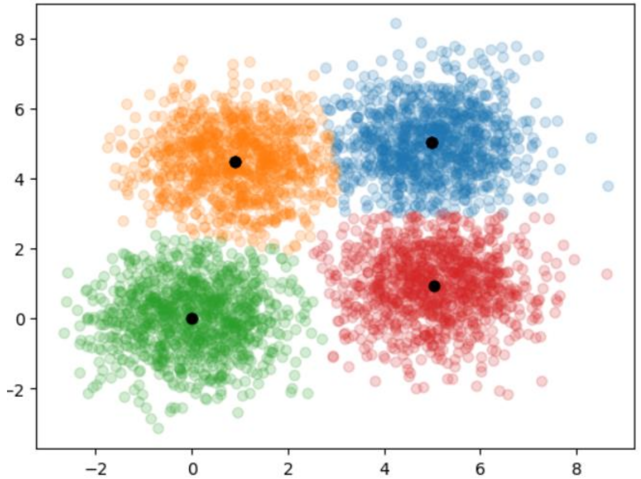
Unlabeled dataset



Random initialization

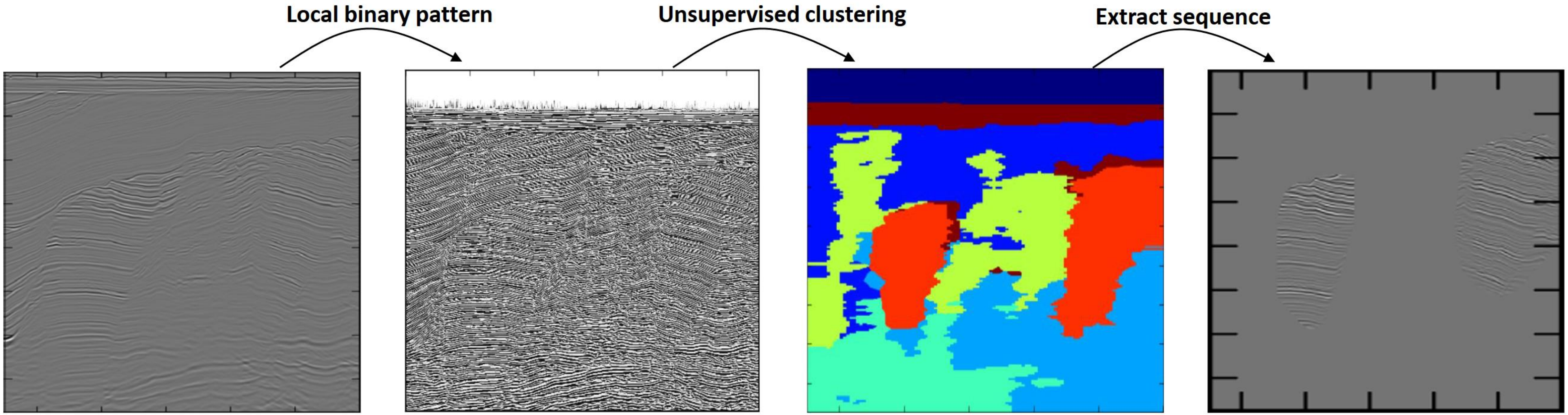


Final clusters



Hjorth-Jensen M., FYS-STK4155 (2022)

Clustering

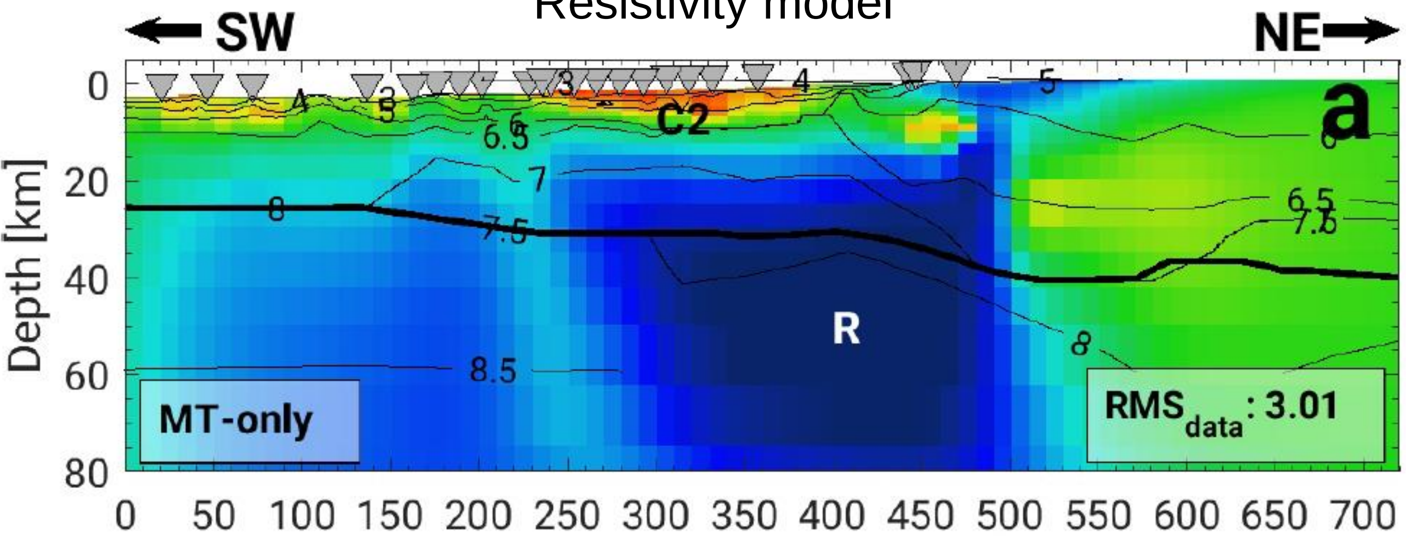


- **Clustering** is an **unsupervised** ML method. The task is to group data-set into **distinct categories** based on some measure of equality of the data. This measure is often referred to as a **metric** or **(dis)-similarity measure.** The **K-mean clustering** algorithm uses the euclidian distance as metrics.

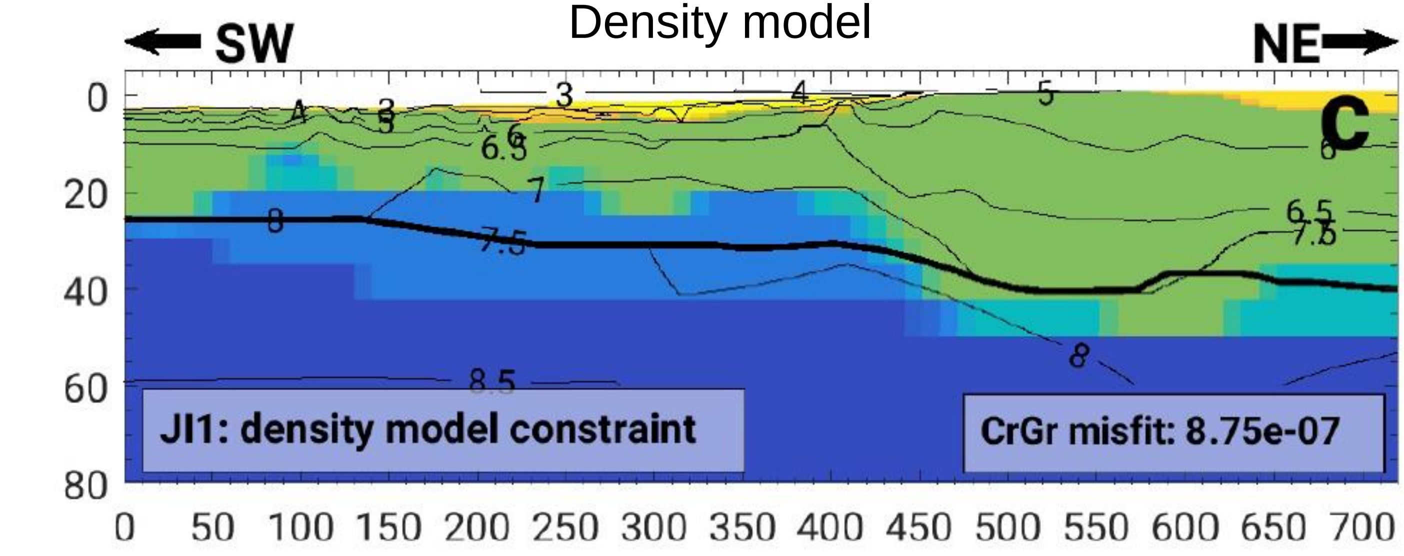
Bugge, PhD thesis (2020)

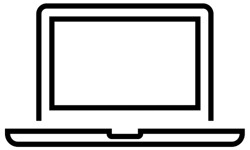
Clustering

Resistivity model

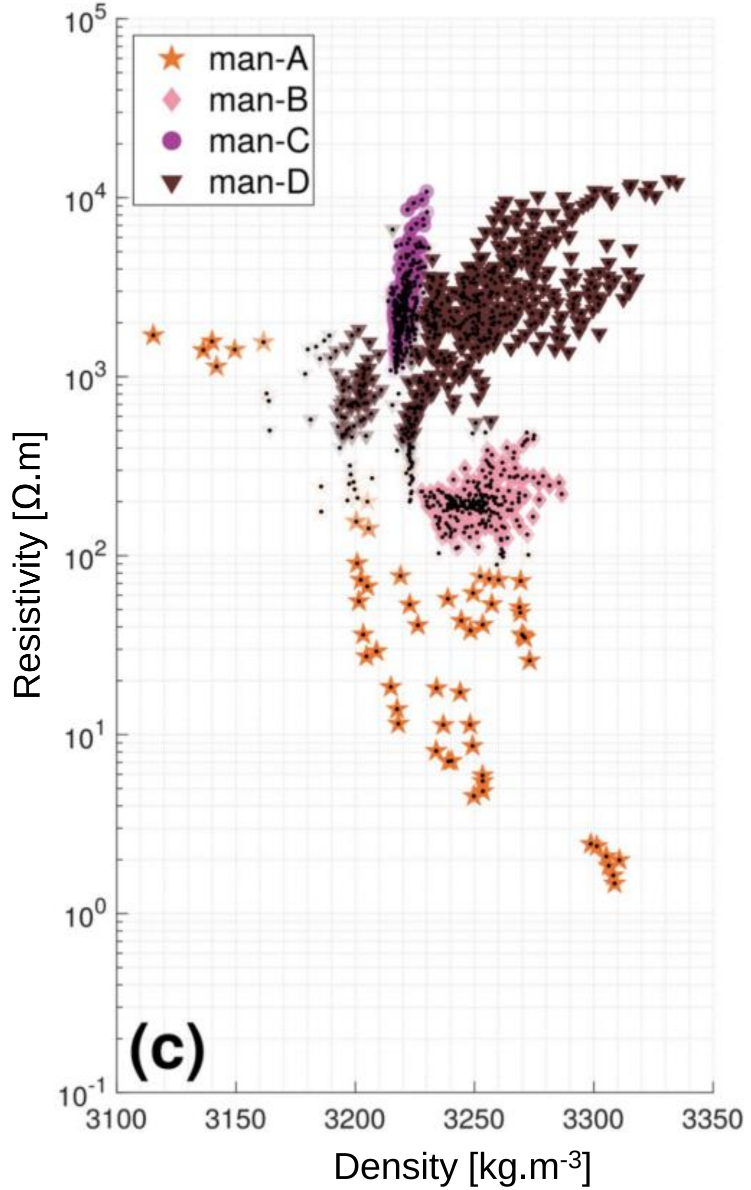


Density model



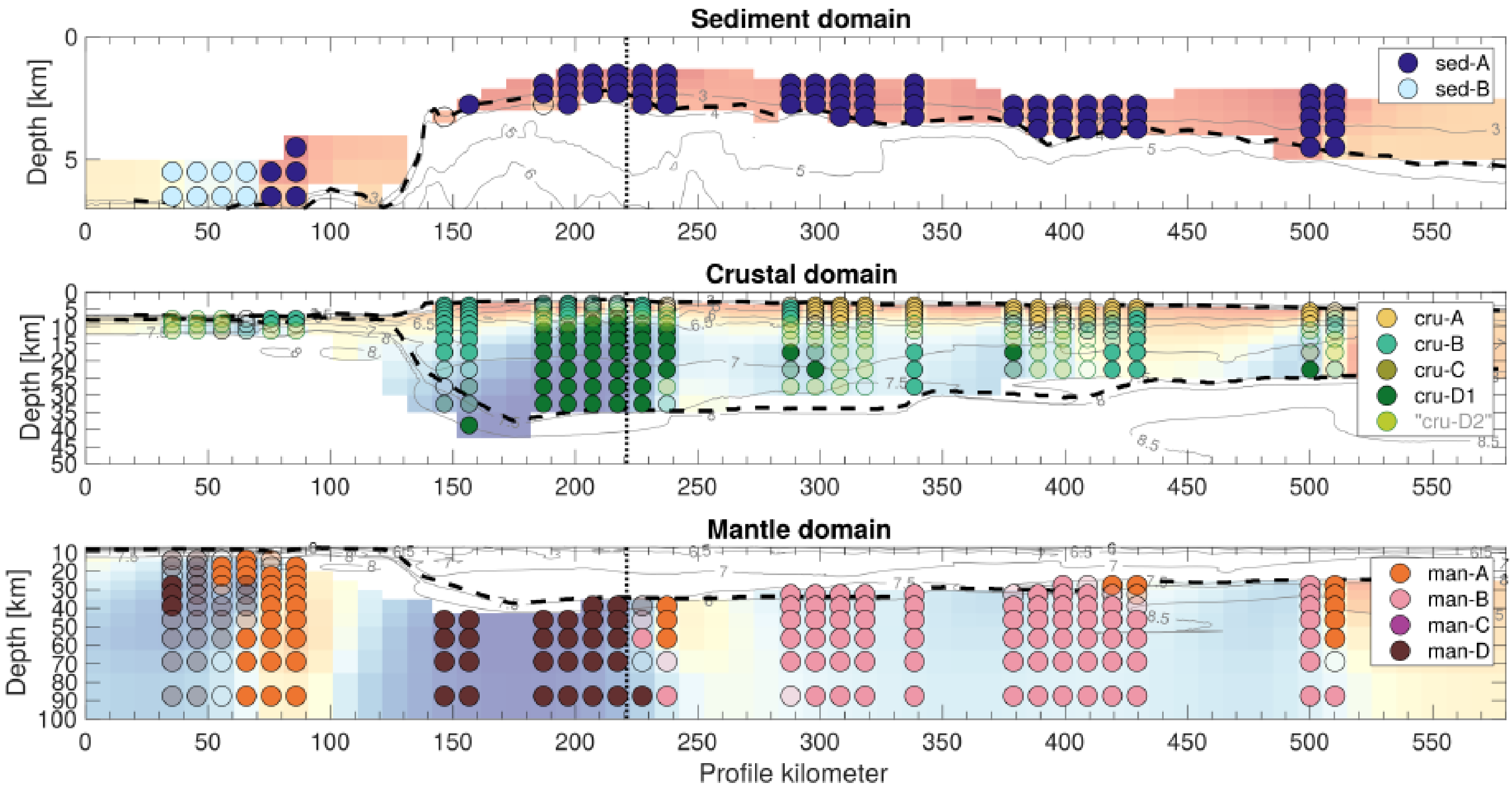


Clusters in mantle domain



Franz et al. (2023)

Clustering



Franz et al. (2023)

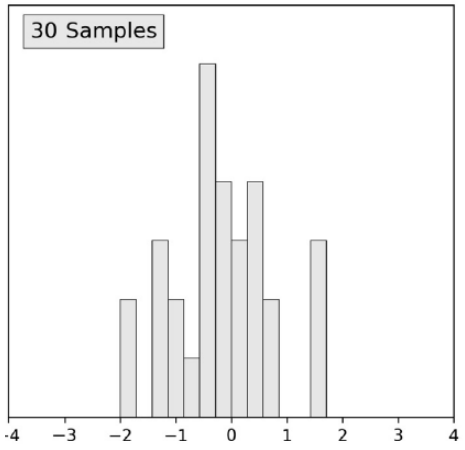
Generative models

- **Generative modeling** is a branch of machine learning that involves training a model to produce **new data** that is **similar** to a given dataset.

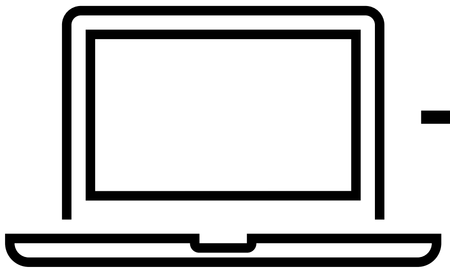
- The generative modeling learns a **probability distribution** from training samples

- The objective is to build a model that can generate **new sets of features** that look as if they have been created using the same rules as the **original data**

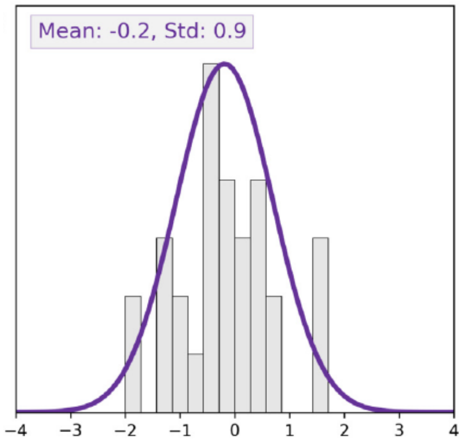
Unlabeled, Data samples



Generative Adversarial Network (GAN)

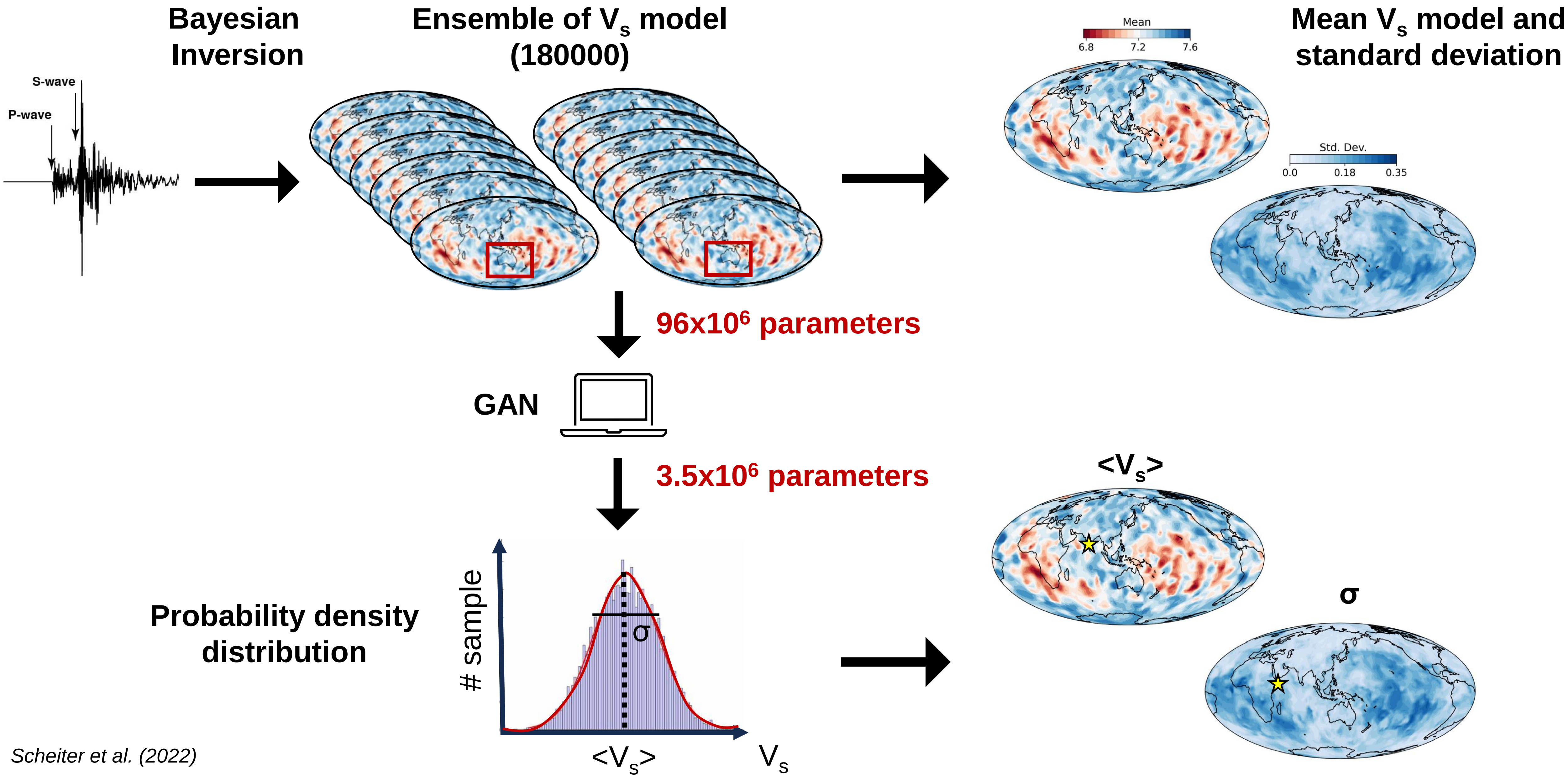


Gaussian distribution



Scheiter et al. (2022)

Shear velocity at mantle-core boundary

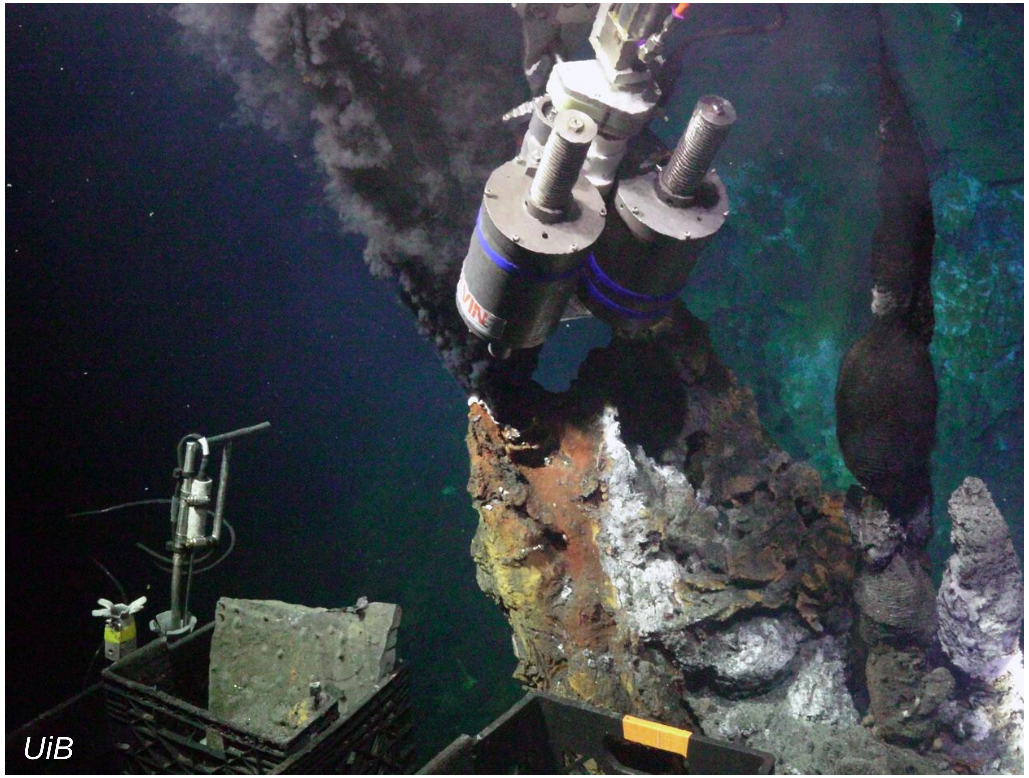


Scheiter et al. (2022)

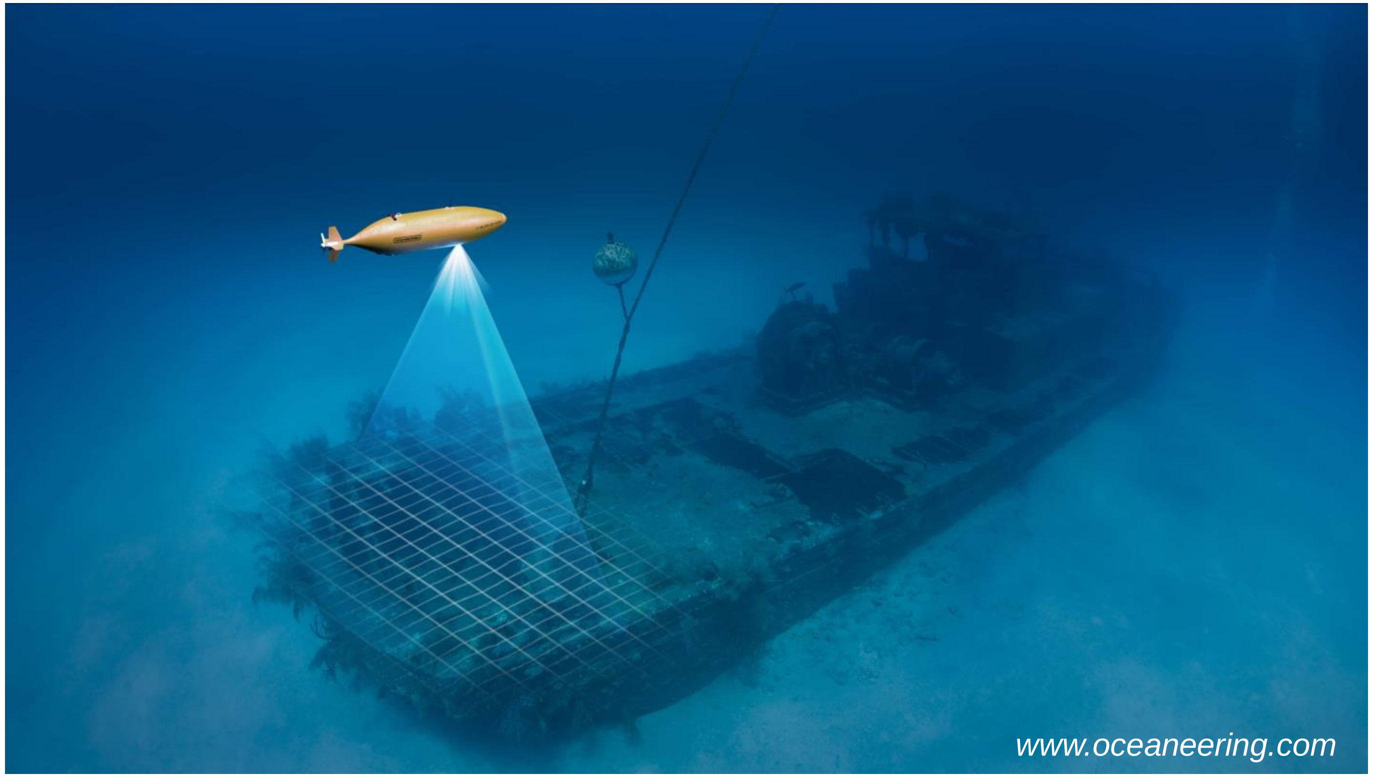
Perspectives for AI in geophysics

Data acquisition – autonomous vehicles

Deep sea exploration



Autonomous underwater vehicles (AUVs)

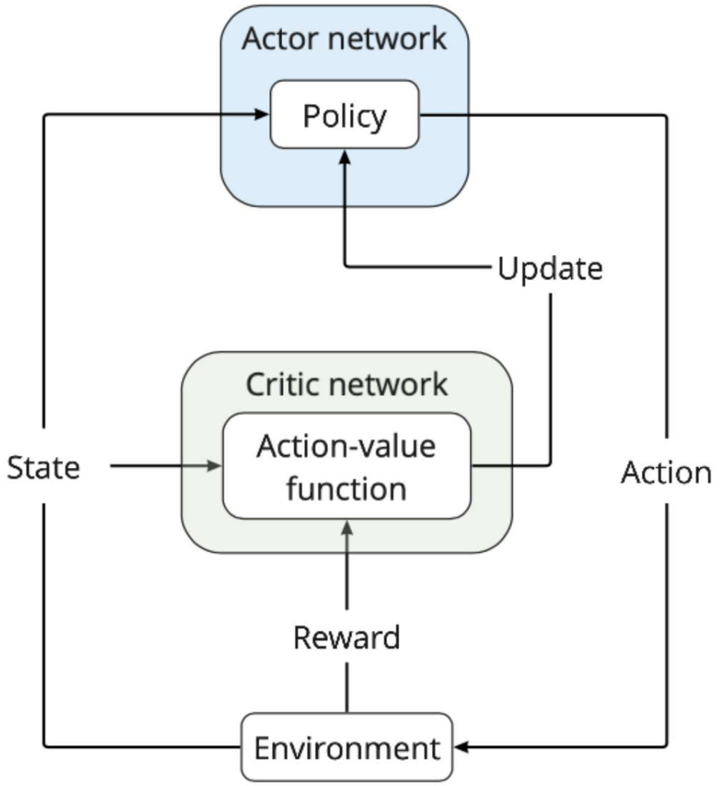


- Access to challenging and remote environments requires advanced autonomous technologies
- How can an AUV on a mid-ocean ridge at 3000 meters under the surface automatically correct for its sail lane?

Deep Reinforcement learning

- **Reinforcement Learning** is inspired by behavioural psychology, where learning is achieved by **trial-and-error**, solely from **rewards** and punishments, interacting with a dynamic **environment**

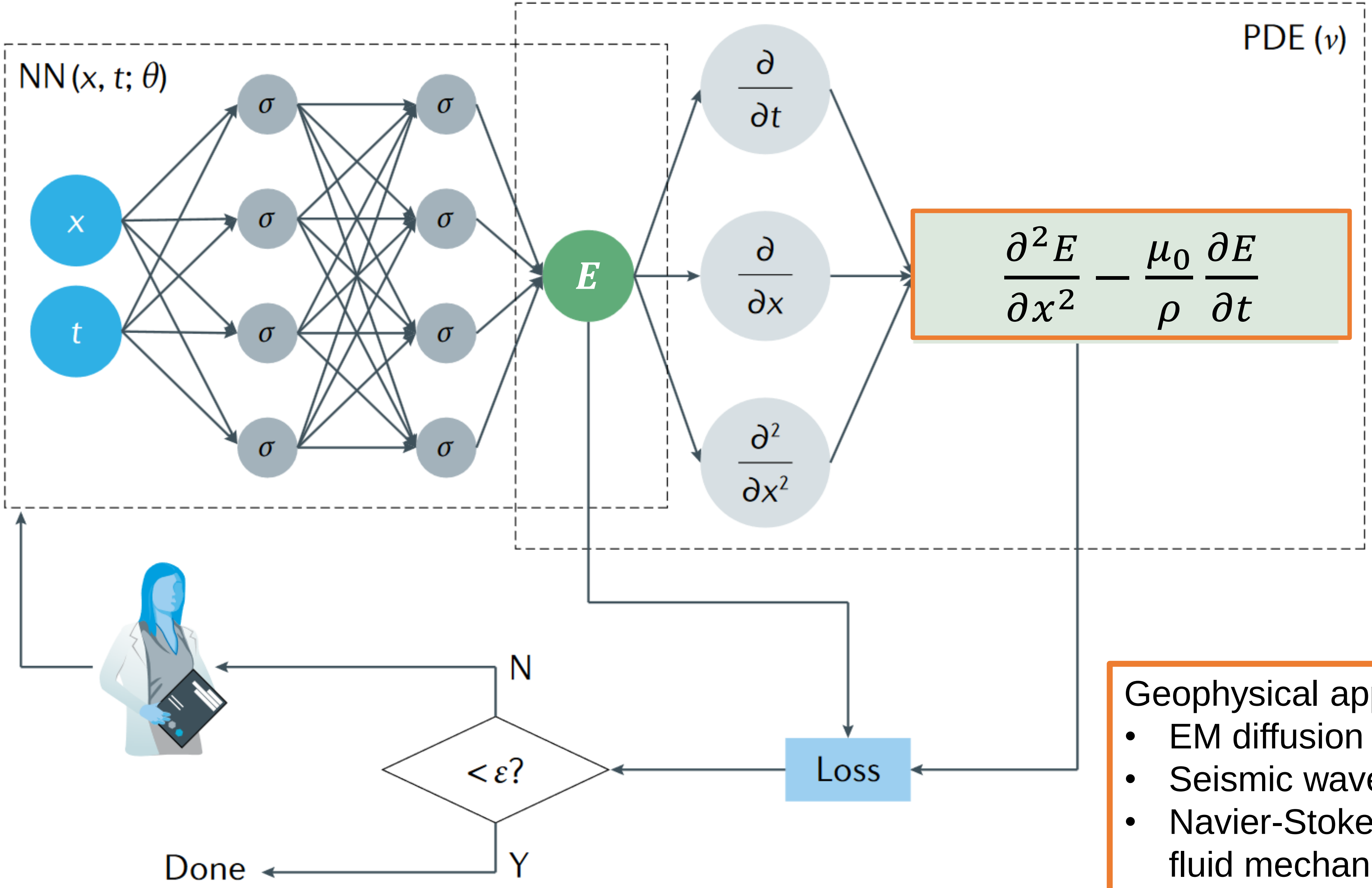
- Deep reinforcement learning use neural network ability to learn from **pixels** or creating control policies in robotics based on sensors like **camera inputs**



Example

- Actor/Agent: Robot, AUV
- Environment: Deep sea, mid-ocean ridge
- State: Position, sail line etc.
- Policy: Correct sail line to avoid collision
- Action: Correct sail line by 15 degrees

Physics-informed neural network (PINN)



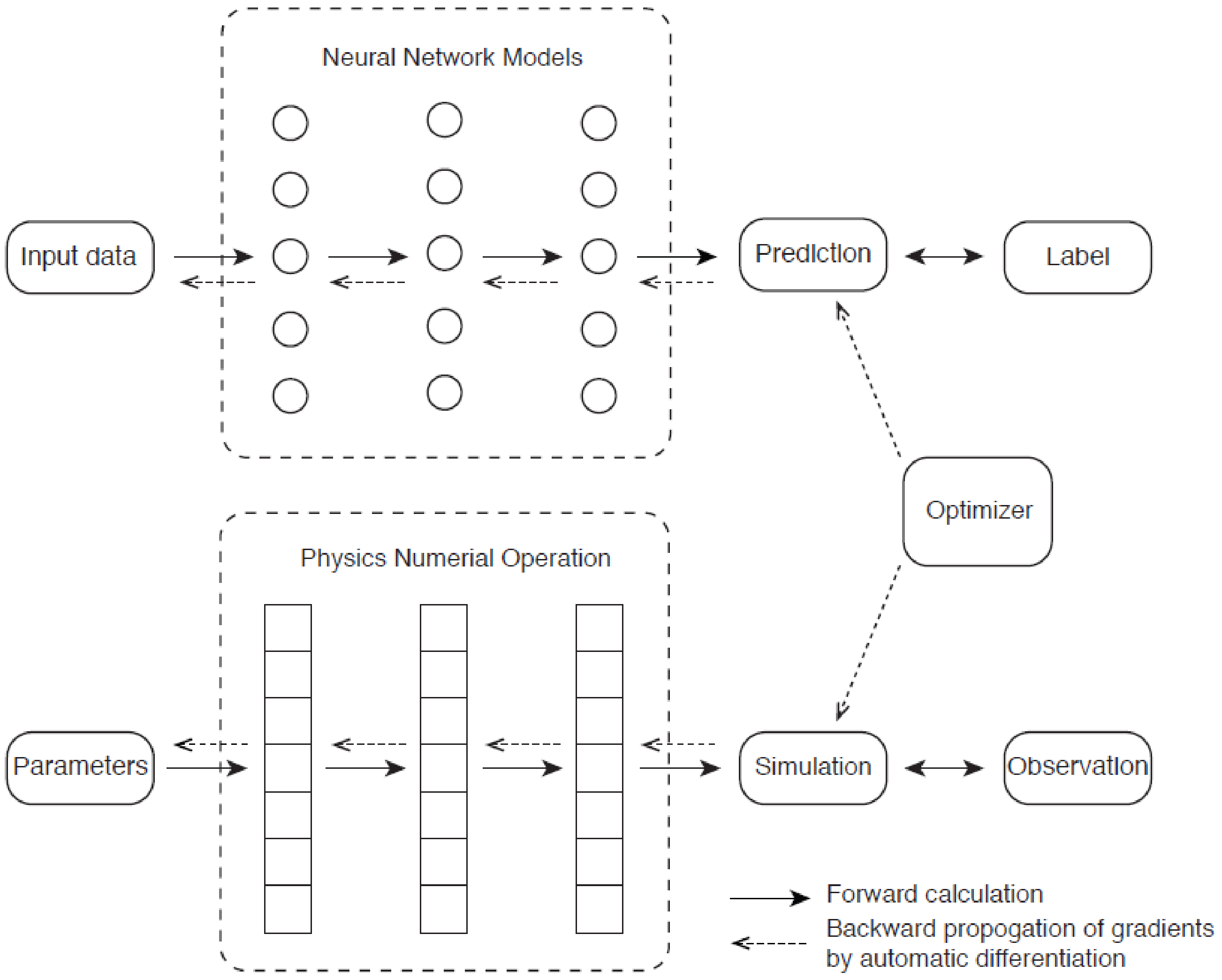
Geophysical applications:

- EM diffusion equation
- Seismic wave propagation
- Navier-Stokes equations for fluid mechanics

Karniadakis et al. (2021)

PINN for inverse problem

- PINN can **outperform grid-based**, traditional, ill-posed inverse problem
- PINN, also known as hybrid modelling, will obey physical laws while being fully **adaptative** when **theory is weak**
- PINN will not replace physical modelling but **complement** it and **enrich** it
- PINN for inverse problem is build on deep learning **framework** (TensorFlow, PyTorch) and do not require **expensive softwares**!



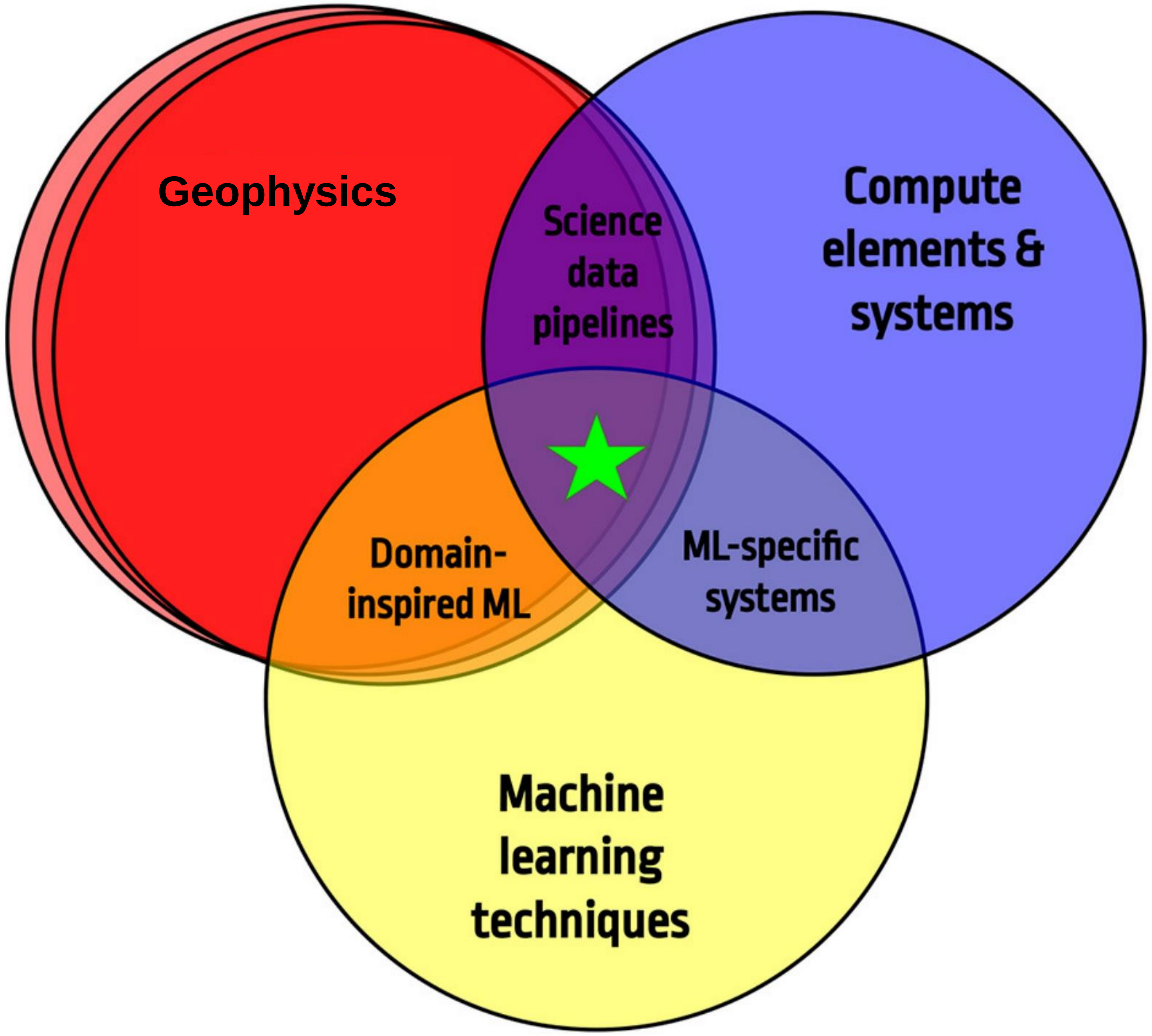
Zhu et al. (2020)

Fast Machine Learning

“The more efficiently we can test hypothesis, the faster we can achieve discovery”

Deiana et al. (2022)

- The concept of fast ML is to find the confluence of domain-specific challenges, ML and High-Performance computing to accelerate Science.



Deiana et al. (2022)

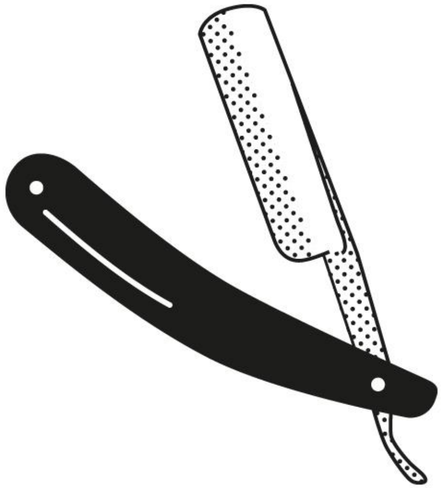
Breaking the curse of non-uniqueness?

- For the inverse problem, PINN can substitute grid-based modelling at a lower computational cost

- PINN can be adapted to Bayesian inversion schemes to produce large ensemble of models

- Train generative models from samples to optimize storage size

- We can expect dramatic improvement in the characterization of the solution space and uncertainty quantification.



The end of Occam’s razor?

Conclusions

Conclusions

- Machine Learning for **Geophysics:** benefits from advances in **high-performance computing**

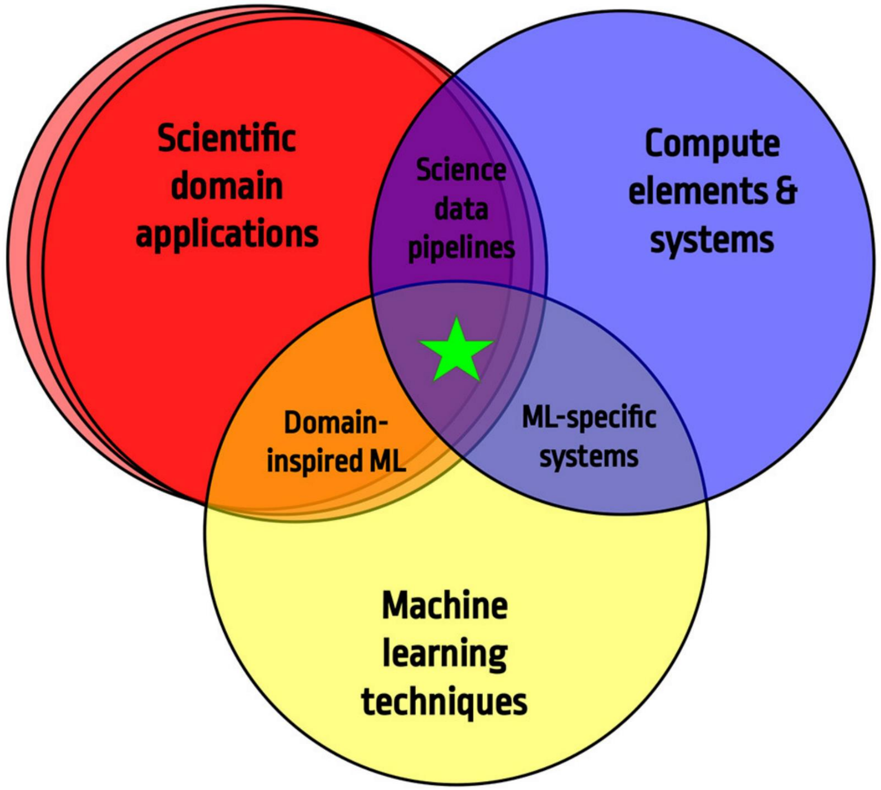
- Let’s remind us that machine learning has an **environmental impact**.

- Nowadays, AI is pretty much about Machine Learning, which is in turn linked to advances in the field of **deep learning**

- Will **machine learning** break the **curse of non-uniqueness** in geophysical inversion?

- In an **educational** perspective, there is a need for a **demystification** of AI

- Train and provide **guidelines** to students, understand the **limitations** and **ethical** implications of AI (data privacy, accountability etc.)



Deiana et al. (2022)

Thank you for your attention!