An introduction to machine learning

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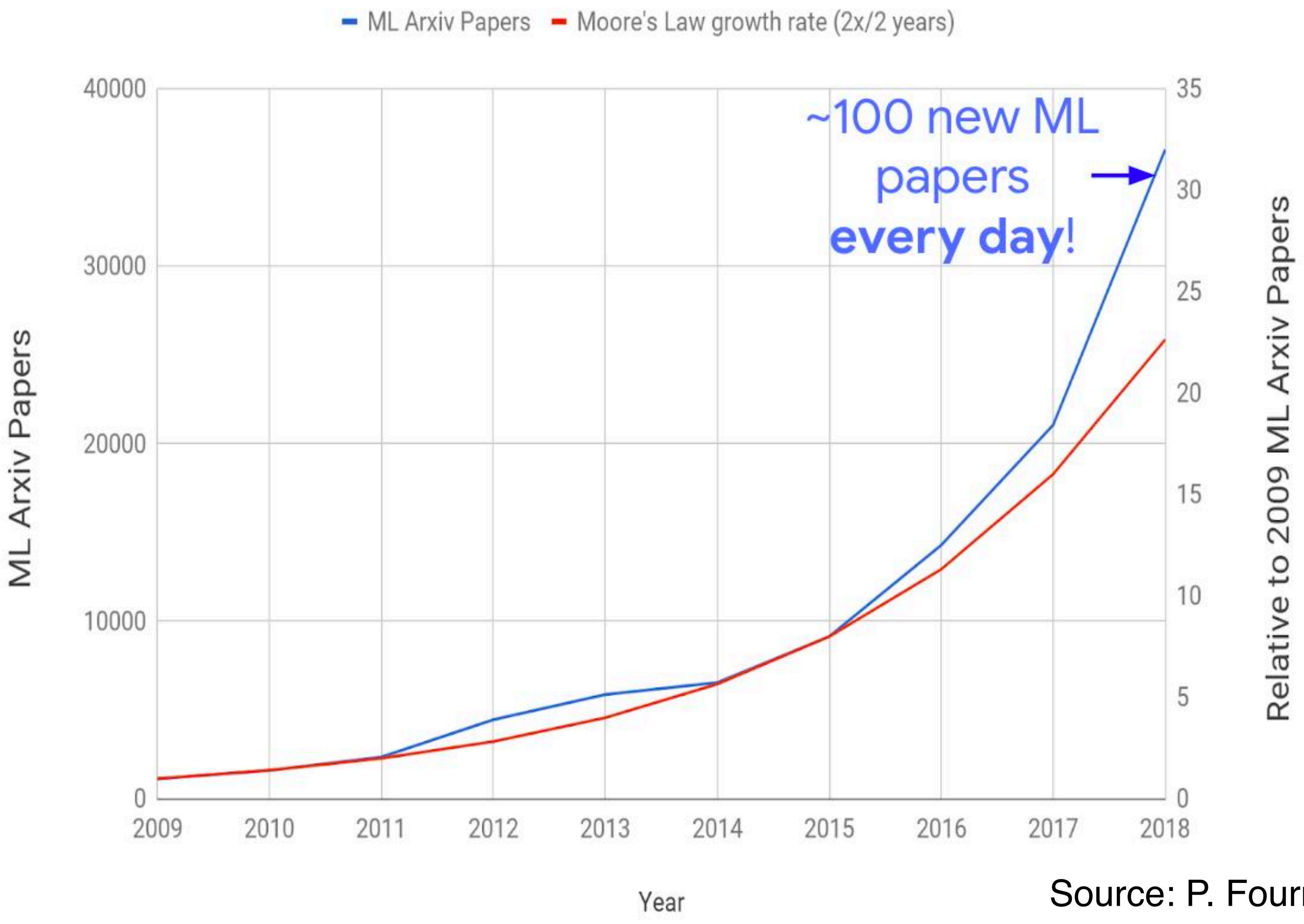
What is machine learning?

- Branch of artificial intelligence focused on learning structure **from data**
- Has been around for a while; overlaps with statistics, data mining, others
- 2012: the year of the deep learning revolution
- Today, deep learning is state of the art in many domains of AI

Machine Learning Arxiv Papers per Year



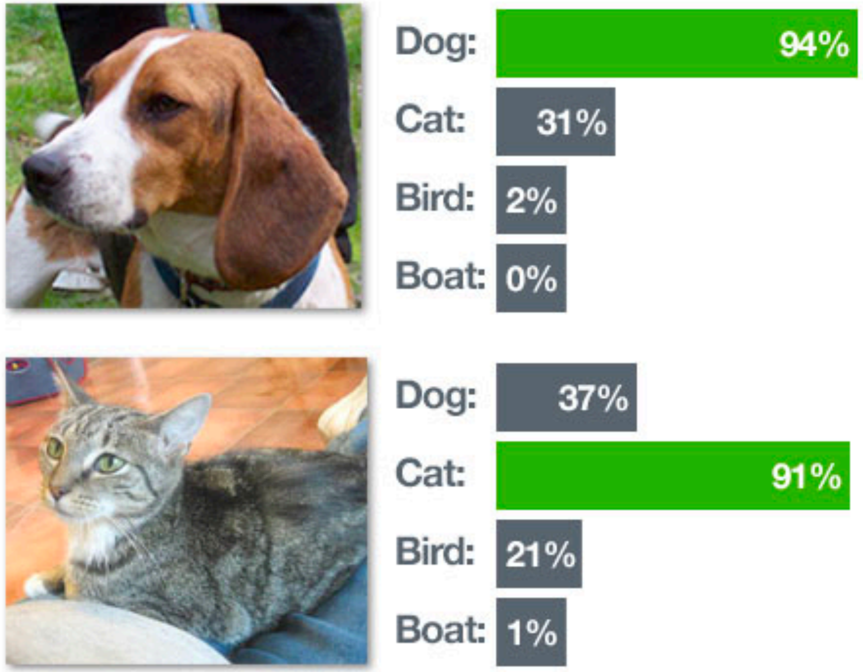
Source: P. Fournier-Viger

Supervised learning

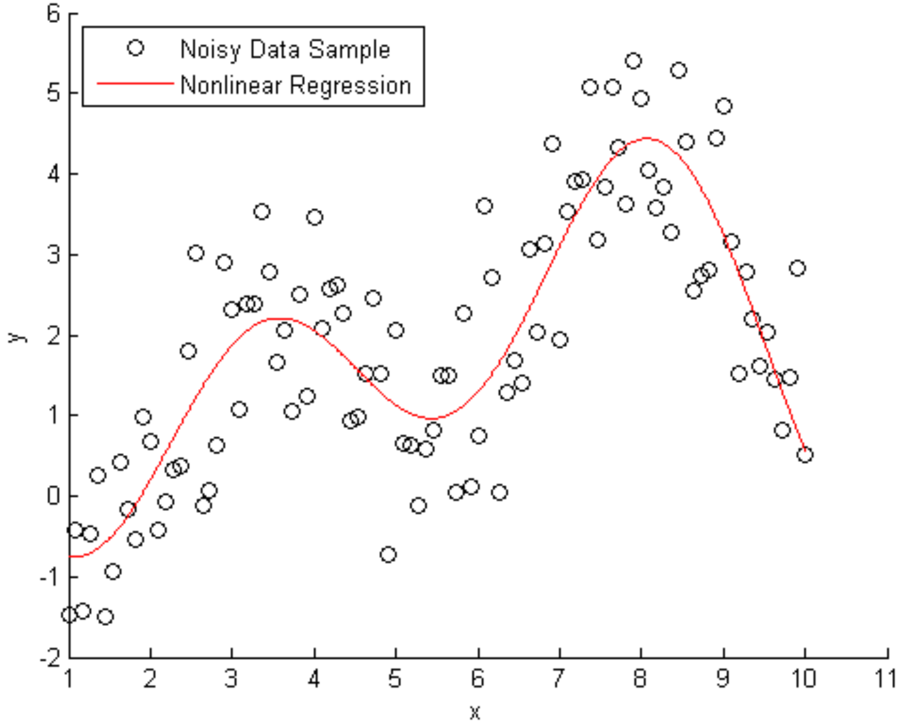
- Supervised learning focuses on learning mapping function, f

- $y = f(x)$
  - x: features (D dimensional)
  - y: targets; labels (C dimensional)
  - y discrete (classification), or continuous (regression)

Classification

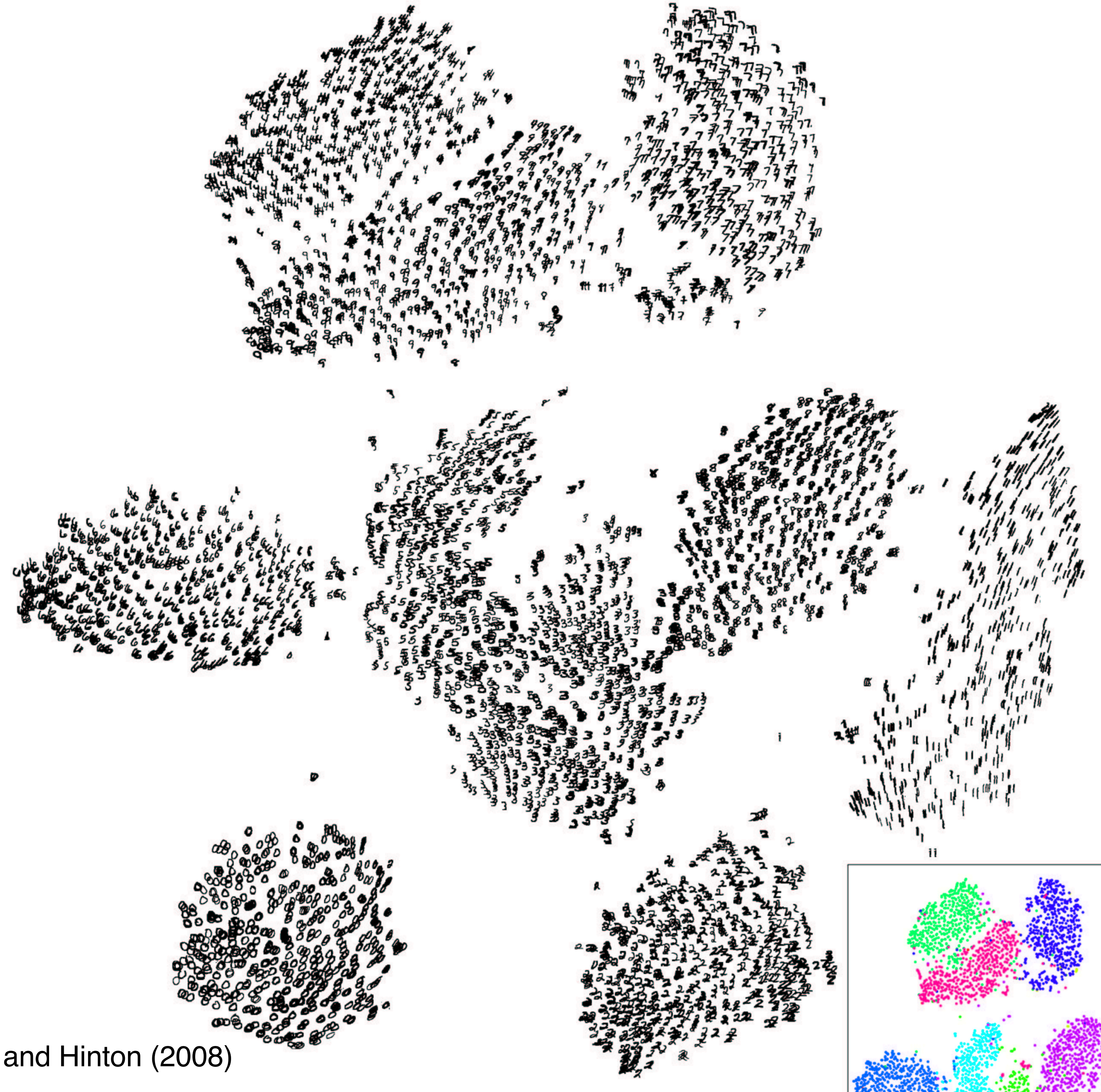


Regression



Unsupervised learning

- Unsupervised learning: learn a useful representation of a dataset



Van Der Maaten and Hinton (2008)

Supervised learning

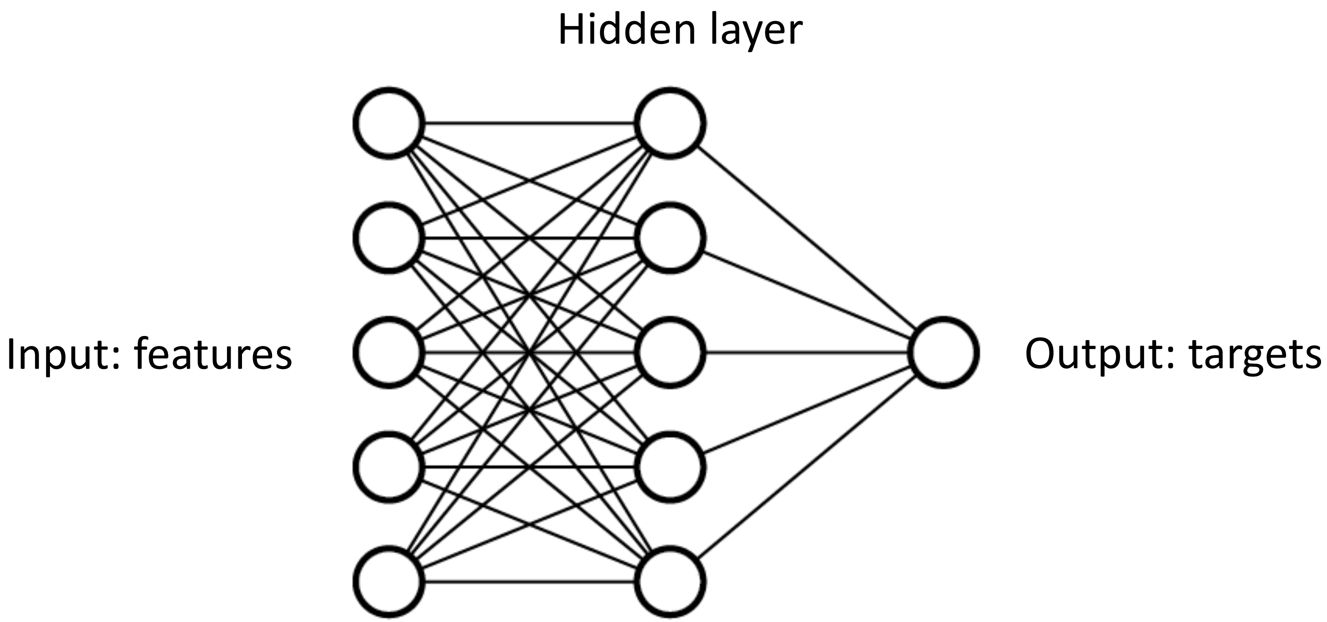
- f: a (potentially) non-linear parametric model
- f is learned from data (x, y) to minimize prediction error on **independent** test data
  - The hallmark of supervised learning!
- Requires ground-truth labeled samples
- Which f is learned? Depends on:
  - Model architecture (parameterization of f)
  - Loss function (a definition of error)
  - Optimization algorithm for training (many ML models are highly non-convex)
  - Many other factors

Many types of supervised models:

- Linear models
- Neural networks (really broad category)
- Support vector machines
- Ensemble models (e.g. random forest)
- k-nearest neighbors
- …

Neural networks form the basis for modern ML

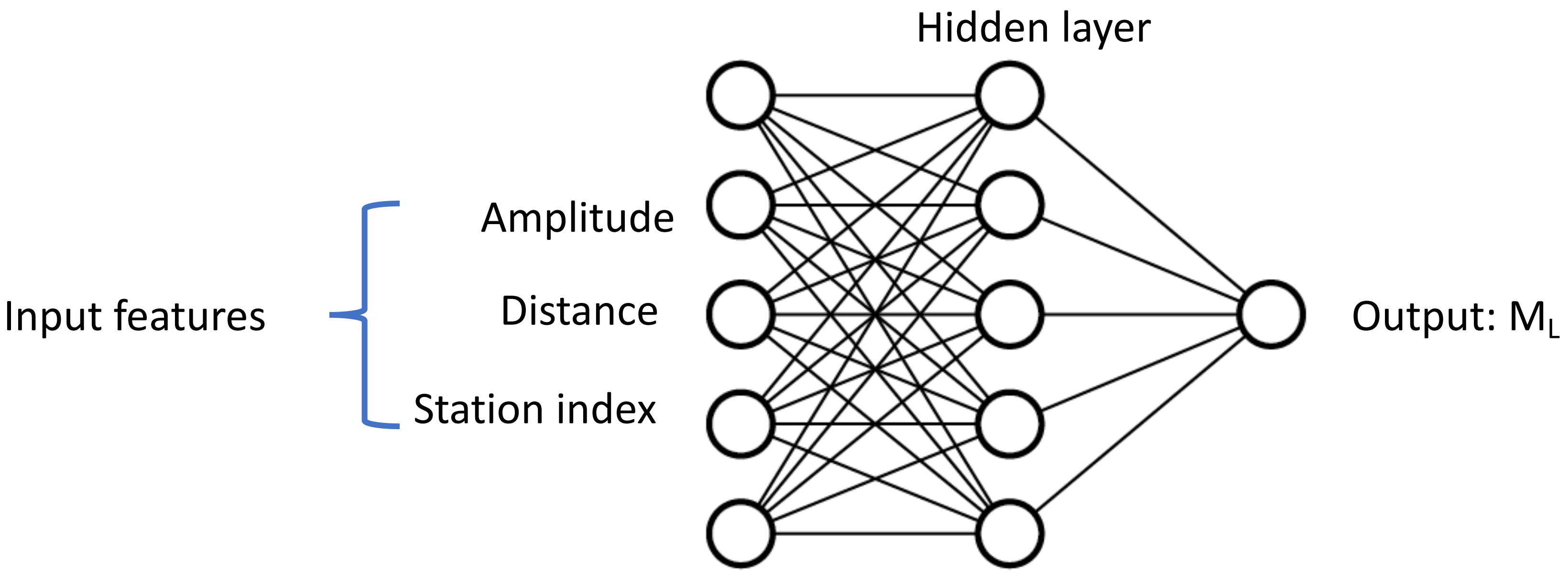
- Neural networks are layered systems designed to perform non-linear mappings
- Mapping function to be learned from lots of (*x*, *y*) data
- Can approximate **any*** non-linear function
- f : Not required to be known
- Excellent at classification and regression but generally require well-engineered features



$$y = \varphi(w_1\varphi(w_2x + b_2) + b_1)$$

$\varphi(x)$: A non-linear activation function

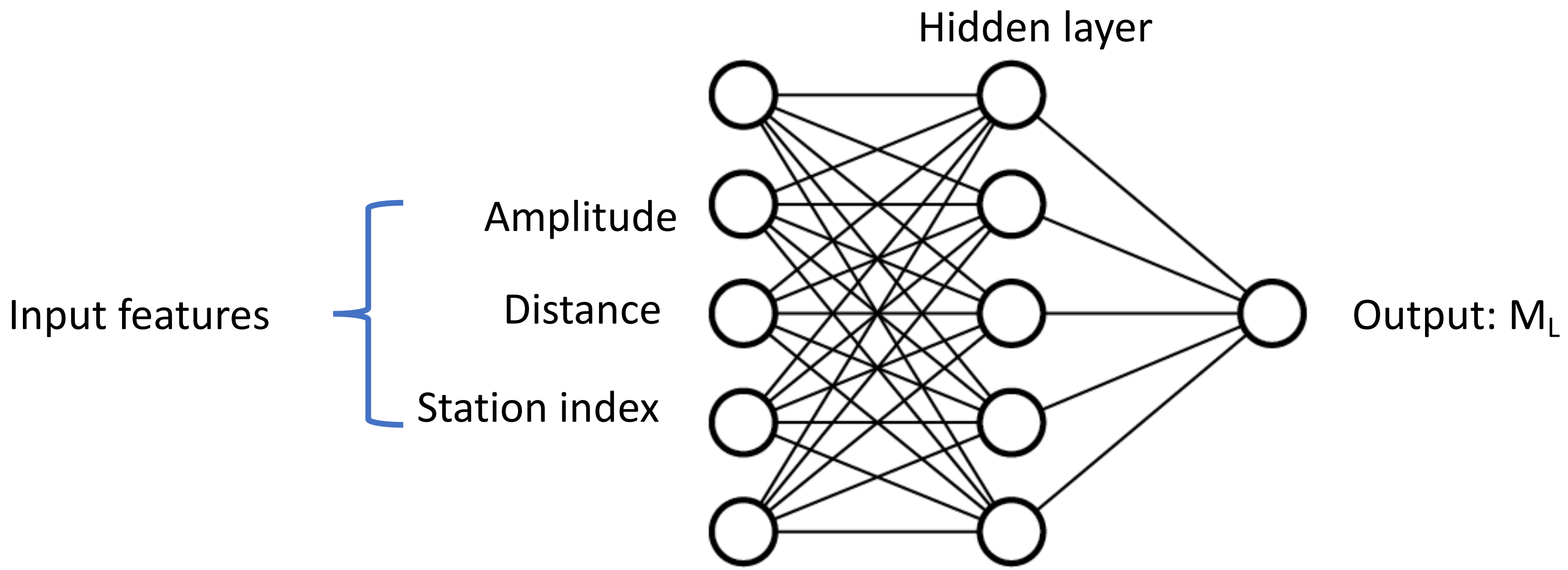
Example: local magnitude



We could train this model to learn ML without knowing the functional form.

The network would learn from a large catalog of earthquakes

Example: local magnitude

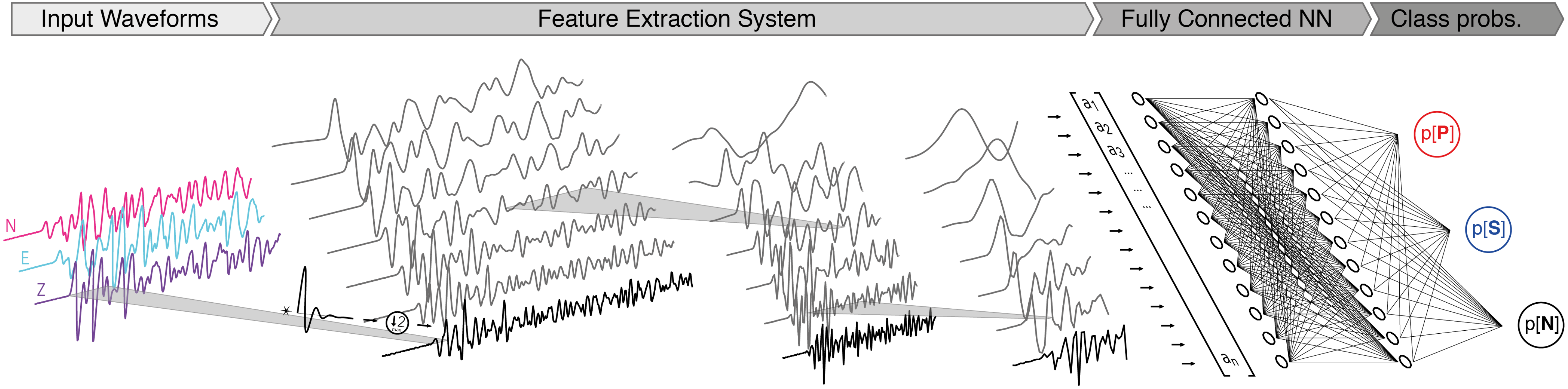


The features have been “engineered” from the waveforms and location

Could we have used a raw waveform as input instead?

Convolutional neural networks

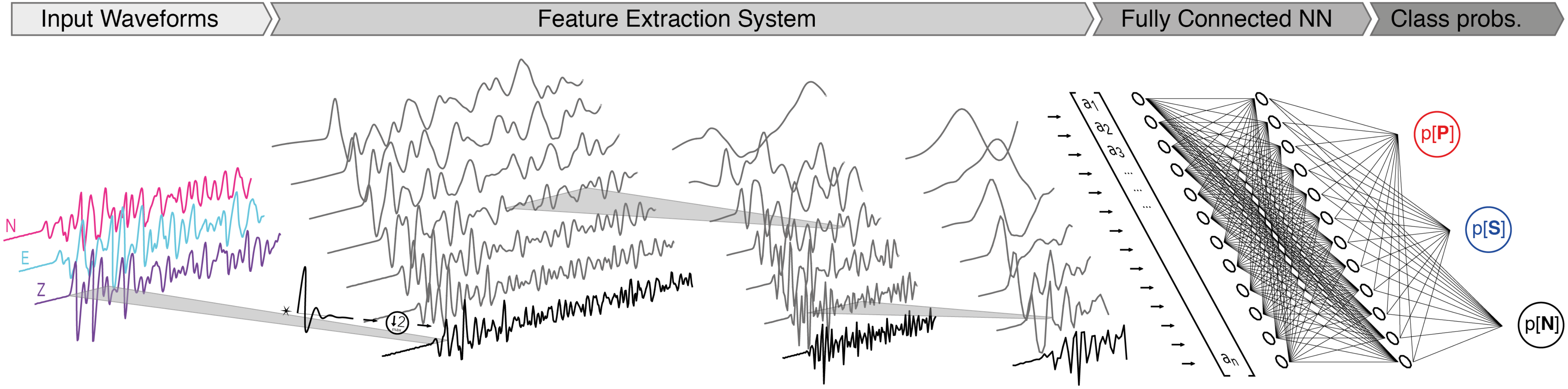
- Input images directly (or seismograms), without need for feature extraction
- Learnable feature extraction systems
- Hierarchical network of learned filters to be convolved with input (convolution layer)
- Periodic decimation of information between layers to span all length scales (pooling layer)



Ross et al. (2018), BSSA

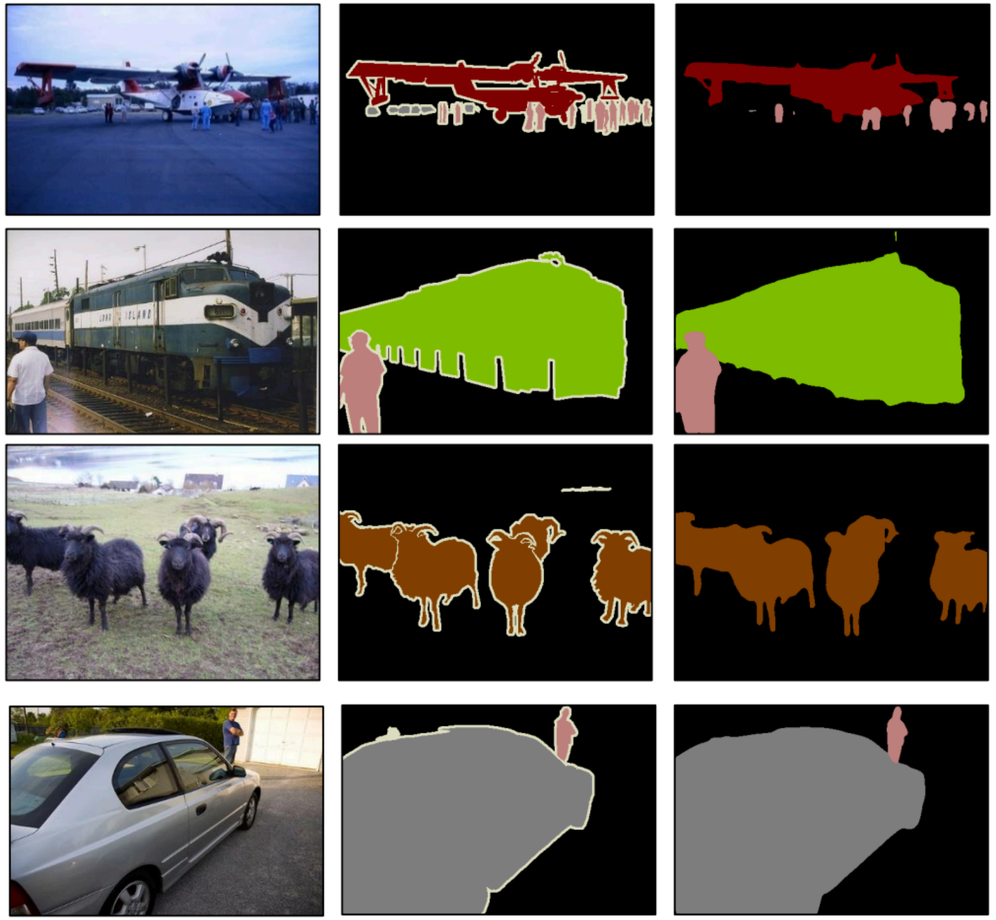
Convolutional neural networks

- Excellent at invariant pattern recognition (e.g. translation, reflection, distortion)
- Capable of generalizing the knowledge contained in extremely large datasets
  - Not necessary for input to exactly match something previously observed
- Major limitation is large amounts of labeled data samples



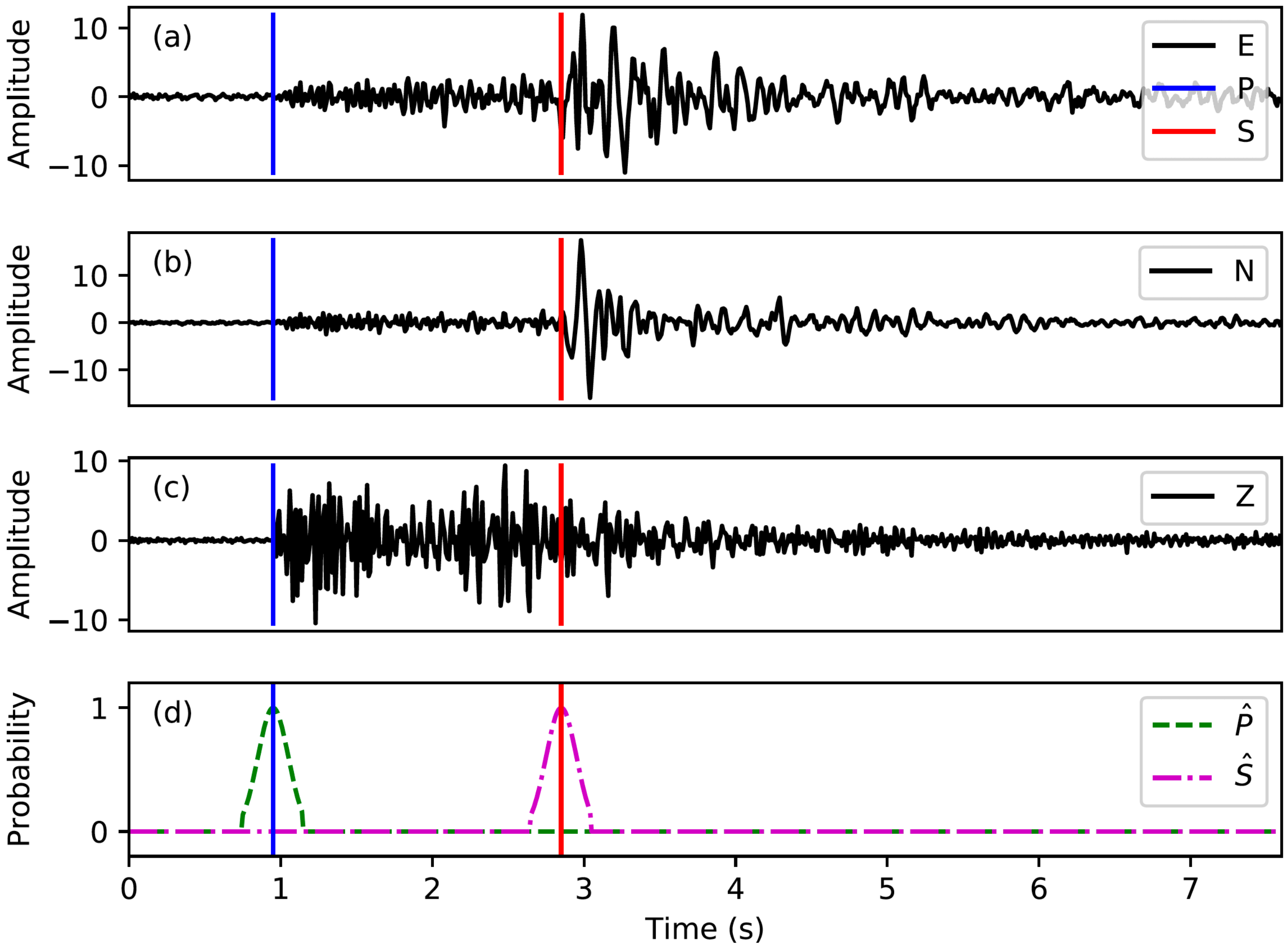
Ross et al. (2018), BSSA

One step further: semantic segmentation



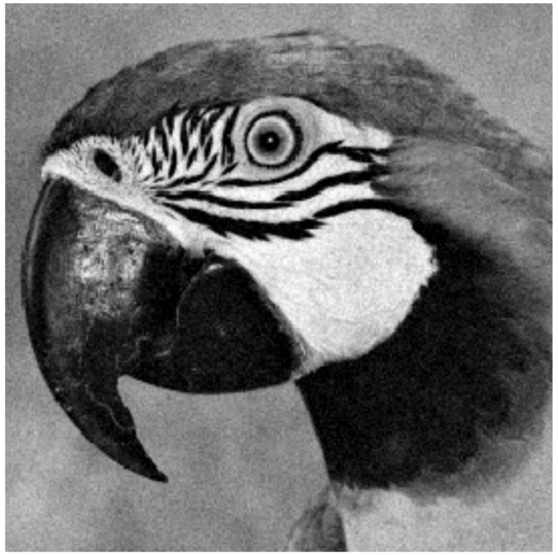
But: need tons of images with pixel-wise labels

Fu et al. 2019



Zhu and Beroza (2018)

Image denoising w/ deep convolutional networks



Noisy training image,
$\sigma = 10$ (max level)

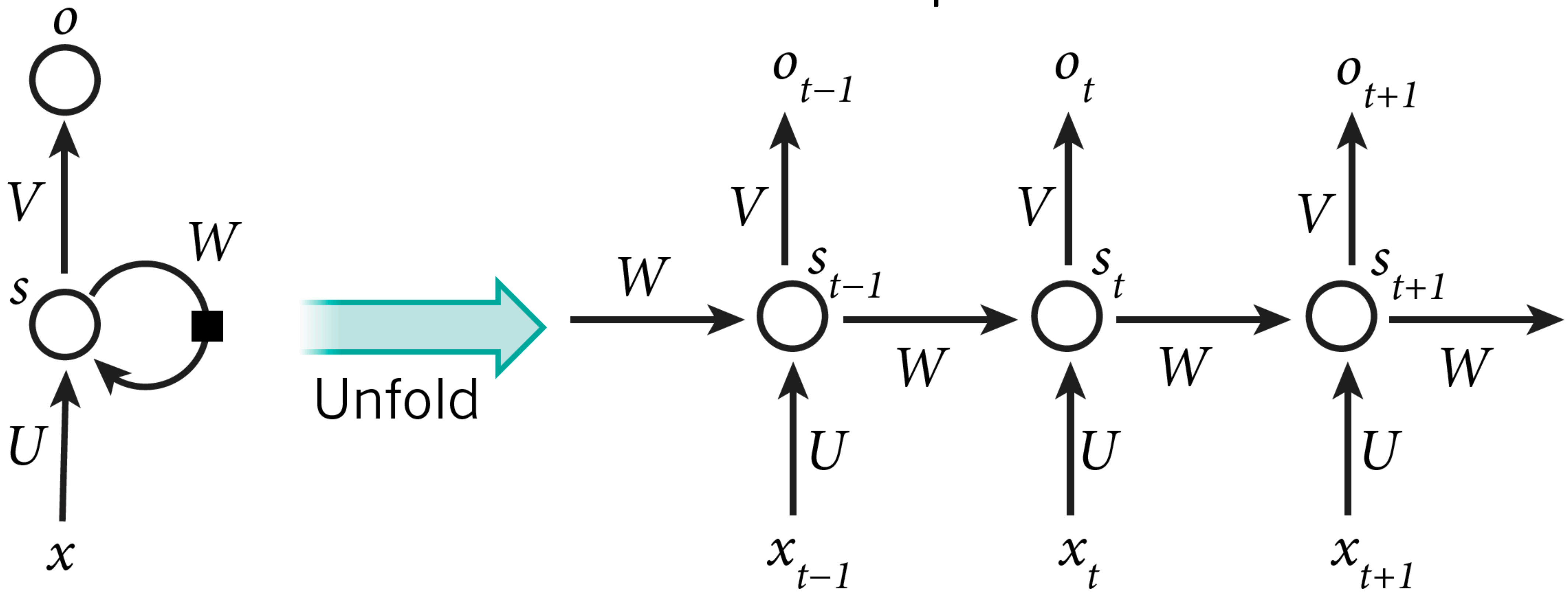
Noisy test image,
$\sigma = 90$

Test image, denoised
by CNN

Test image, denoised
by BF-CNN

Mohan et al. 2020, ICLR

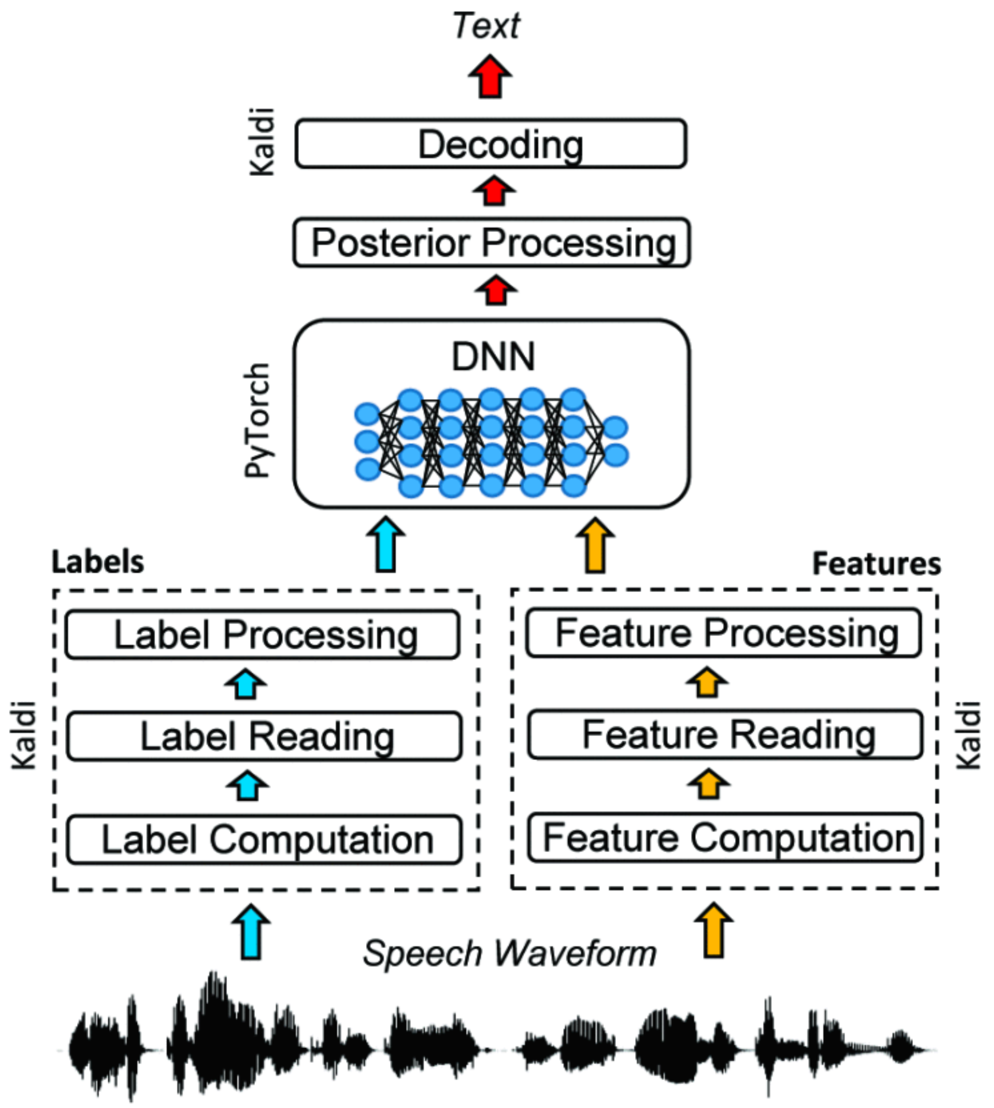
Recurrent networks act on sequential datasets



LeCun et al. 2015, Nature

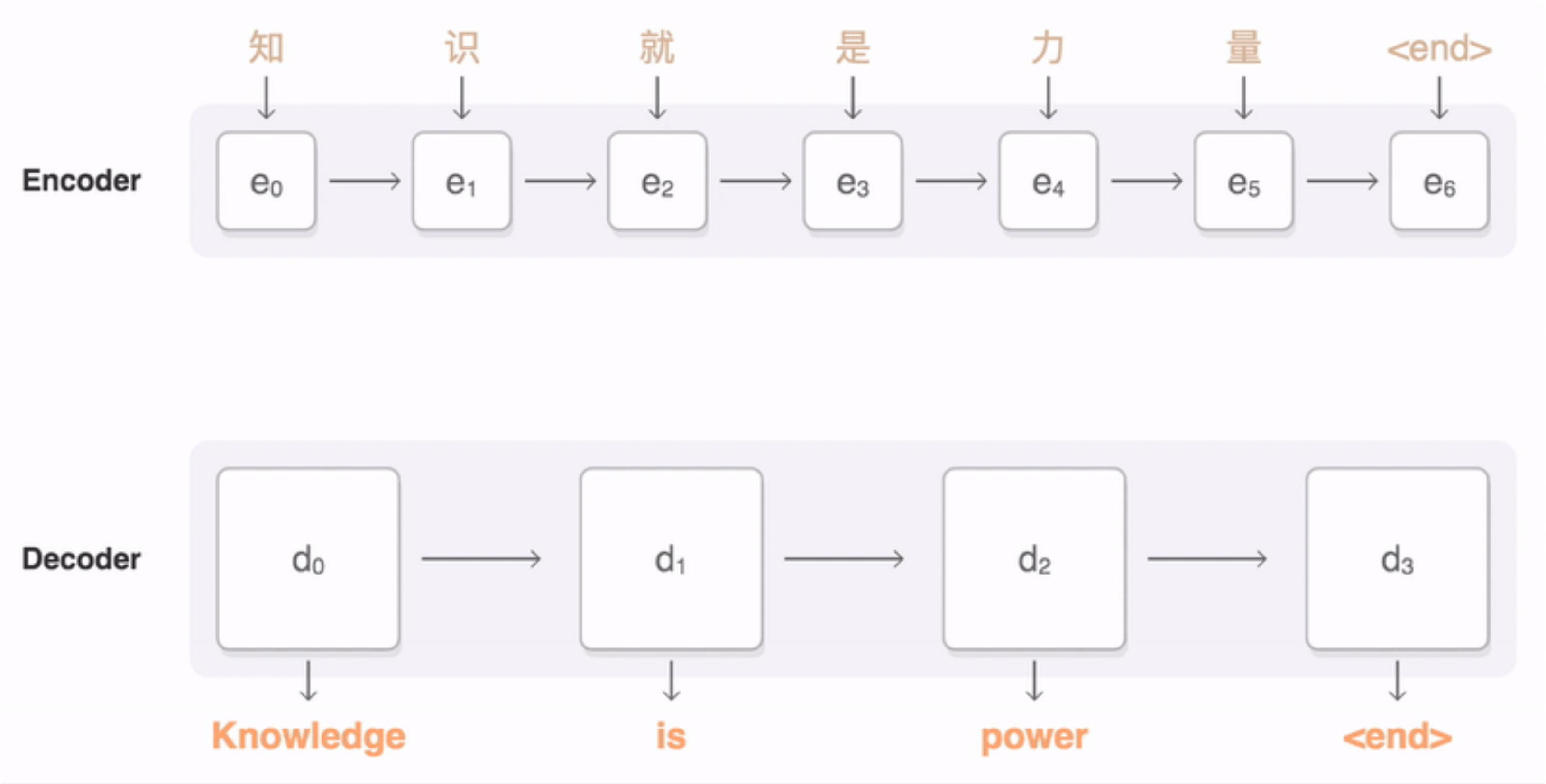
- Many types of physical datasets are multivariate time series
- Doesn't need to have time; could just be positioning/context (e.g. words in a sentence)
- RNN variants (Long Short-term memory, LSTM; Gated recurrent unit, GRU) have shared parameters across all sequence elements

RNNs achieve outstanding performance on speech recognition



Ravanelli et al. 2019

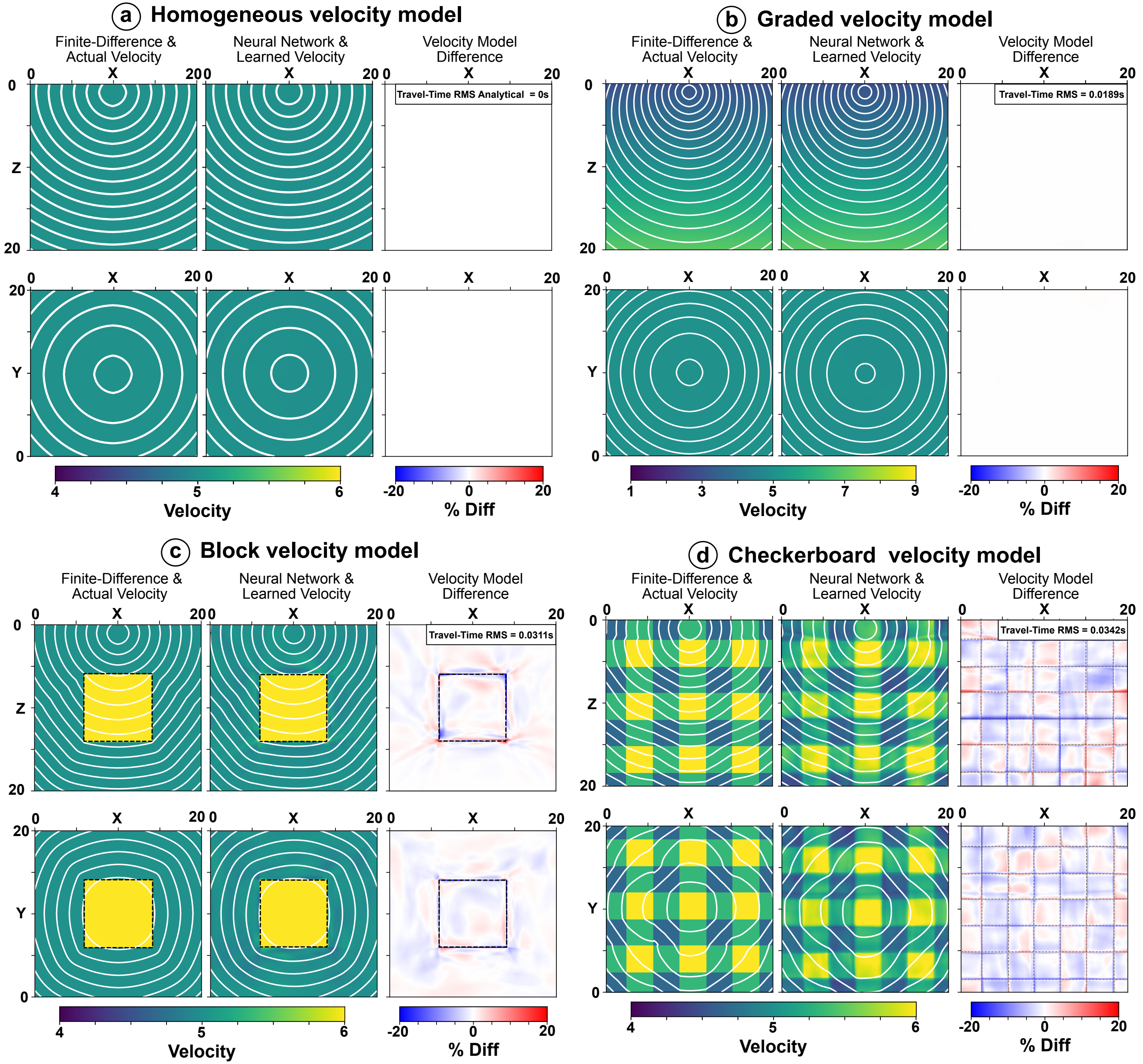
Encoder/decoder models are excellent at language translation



Source: Google

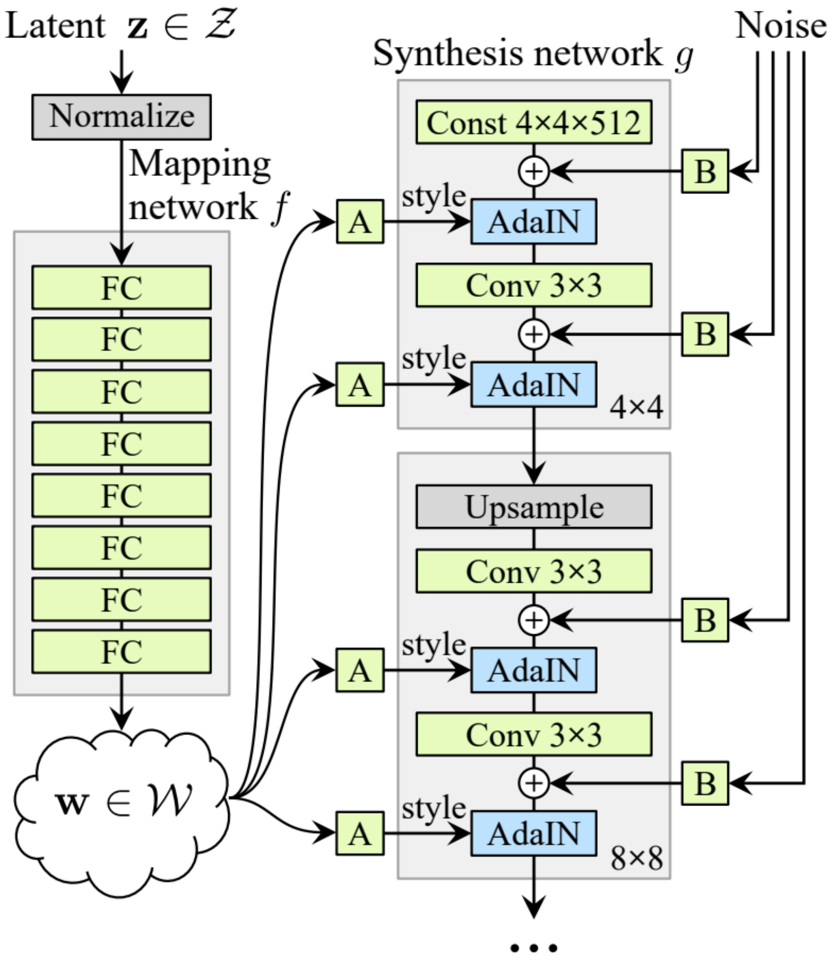
One RNN encodes a sentence into a latent representation.
2nd RNN decodes it into target language.

EikoNet: a deep learning approach to ray tracing



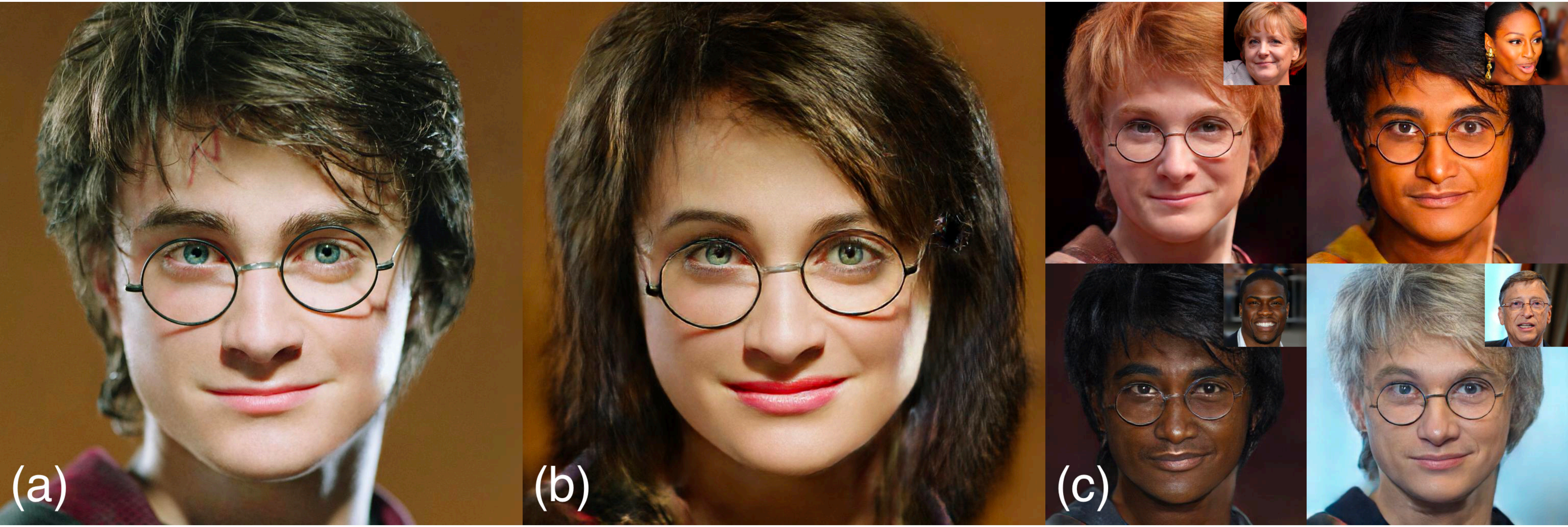
Smith et al. (2020), arXiv: 2004.00361

Generative adversarial networks are a major advance in AI



(b) Style-based generator

Karras et al. (2016)



Viazovetskyi et al. (2020)

Many types of supervised models:

- How to choose what algorithm to use?
  - Mathematical structure of the data
  - Amount of data available
  - How good is your ground truth?
  - Computational demands
  - Interpretability of learned features

- State of the art models are often not the most practical

- Requires knowledge of different algorithms (often experience-based)

Training a supervised learning model

- ML distinguishes between parameters and hyperparameters
  - Parameters characterize the model itself. Learned from the data
  - Hyperparameters affect model performance; not necessarily learned.
    - e.g. optimization, model architecture, regularization weights,

- Training a ML model is the process by which the parameters are learned

- Deep neural networks are generally trained with stochastic gradient descent

- Involves iteratively updating parameters to minimize prediction error on ground truth. Always measure performance on out-of-sample test data!

Training a supervised learning model

- How much data do I need? Very problem/model/algorithm specific.
- Often want 10x as much data as number of model parameters to fight overfitting
- Modern deep neural networks have 10^6-10^7 parameters
- Lots of regularization strategies for dealing with

What if I don’t have (much) ground truth?

- Sim2real approaches often are effective
  - Synthesize training data from a model that you trust
  - Train the model with synthetic data
  - Apply trained model to real data

- Transfer learning:
  - Train a model on a surrogate (plentiful) dataset to learn coarse structure
  - Fine tune model on limited actual dataset

Why did ML research explode over the last decade?

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Deng et al. (2009)

Source: www.image-net.org

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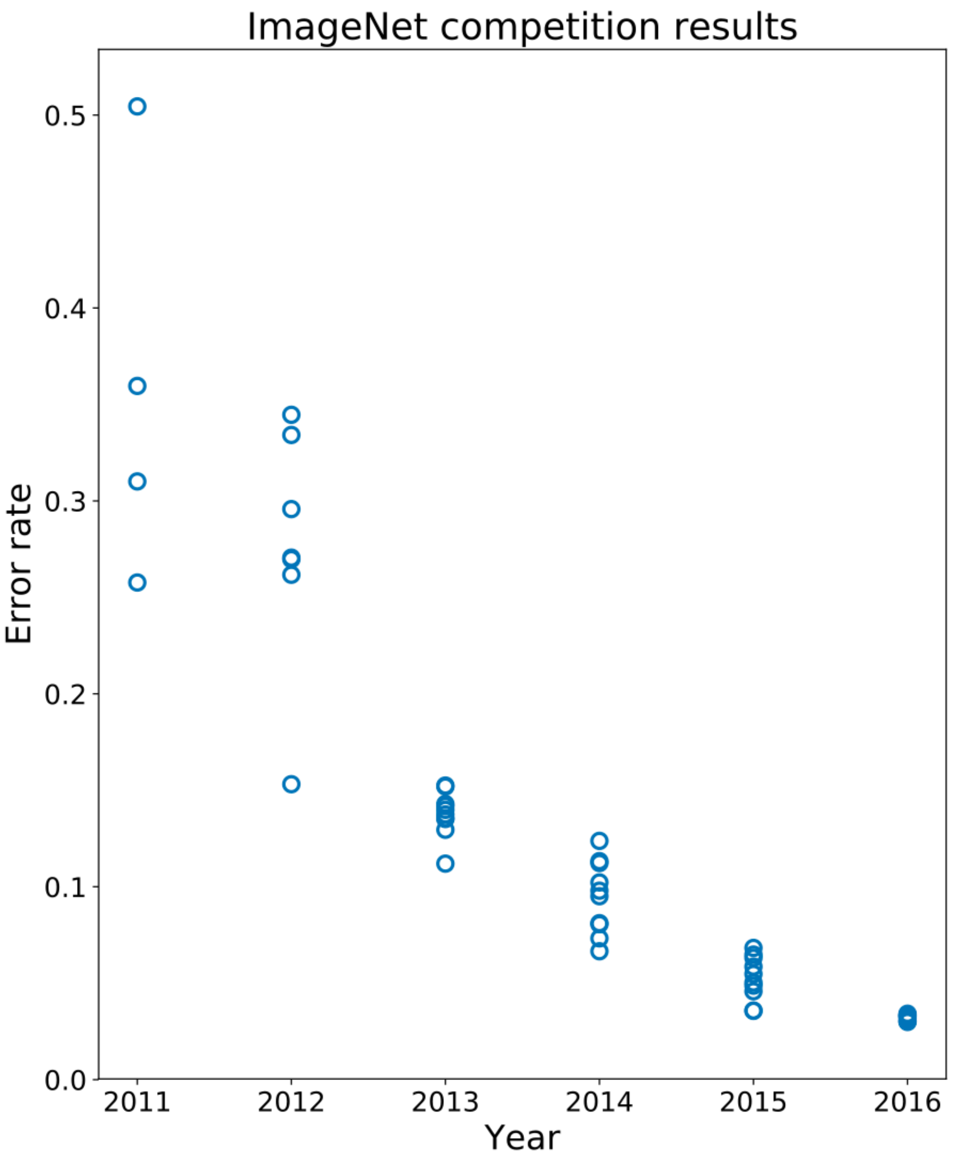

Deng et al. (2009)

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Summary

- ML is a rapidly growing field. Can’t possibly cover w/ 1 lecture
  - Strongly recommend taking a formal ML course
- Has led to major advances in all areas of science and technology
- Provides tools for (e.g. Bergen et al. 2019):
  - Automation
  - Accelerating compute
  - Data discovery
- Will be a key component of geophysics research going forward