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Statistical Machine Learning

Yuan YAO
HKUST

Course Information

- ▶ Course web:
 - ▶ <https://yao-lab.github.io/course/statml/2022/>
- ▶ Time and Venue:
 - ▶ Lecture: **MonWed, 10:30-11:50am**
 - ▶ Zoom Meetings from CANVAS
 - ▶ Or Rm 2503, Lift 25-26 (87)
- ▶ Instructor:
 - ▶ Yuan Yao <yuany@ust.hk> (<https://yao-lab.github.io/>)
- ▶ Teaching Assistant:
 - ▶ LIU, Xuantong <xliude@connect.ust.hk>

Course Content

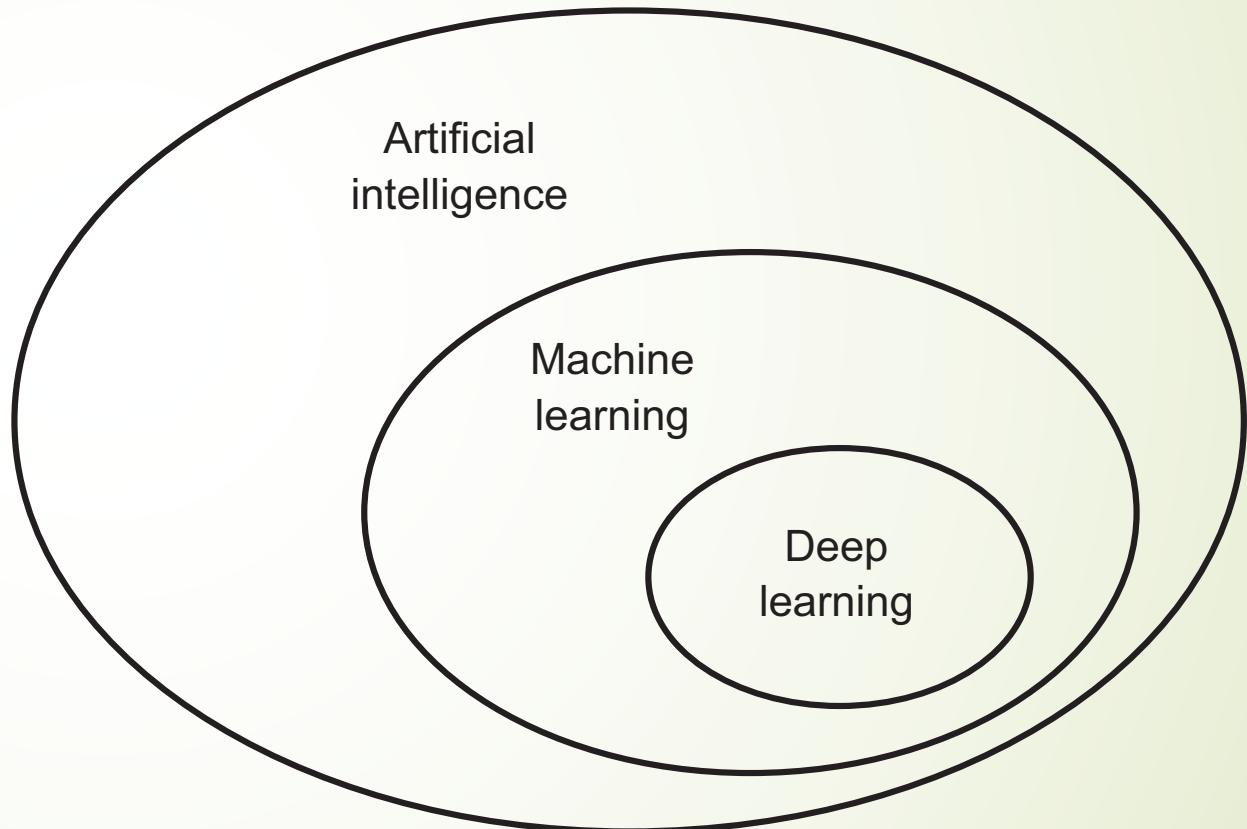
- ▶ Supervised Learning:
 - ▶ working knowledge about linear regression, classification, logistic regression, decision trees (CART), boosting, random forests, support vector machines, neural networks, etc.
- ▶ Unsupervised and Self-supervised Learning:
 - ▶ PCA, Generative Models, Generative Adversarial Networks
 - ▶ Self-supervision, e.g. masked language models etc.
- ▶ Reinforcement Learning:
 - ▶ Markov Decision Process and online learning, etc.
- ▶ **No exams. Project-based evaluation.**



A Brief History of AI, Machine Learning, and Deep Learning

Artificial Intelligence, Machine Learning, and Deep Learning

- ▶ AI is born in 1950s, when a handful of pioneers from the nascent field of computer science started asking **whether computers could be made to “think”**—a question whose ramifications we’re still exploring today.



A brief history of AI



Nathaniel Rochester

Marvin L. Minsky

John McCarthy

Oliver G. Selfridge

Ray Solomonoff

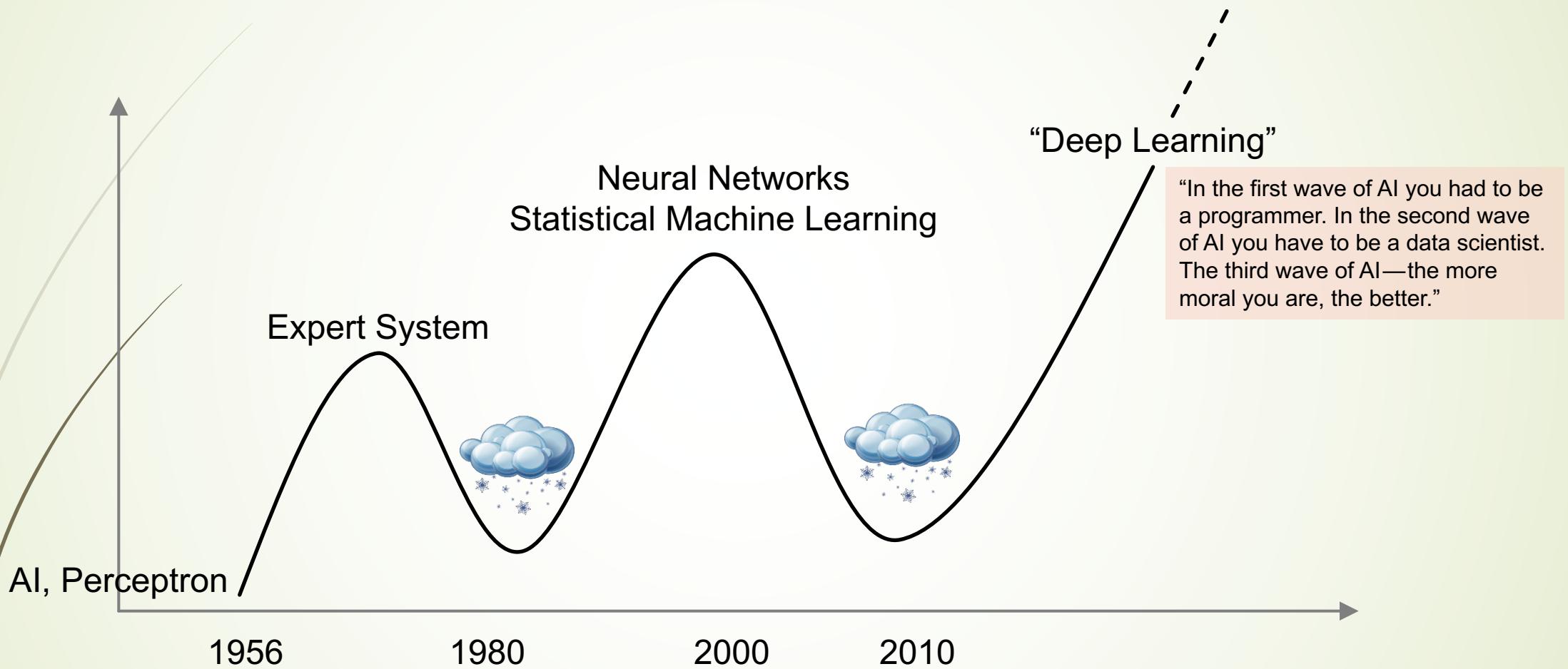
Trenchard More

Claude E. Shannon

August 1956

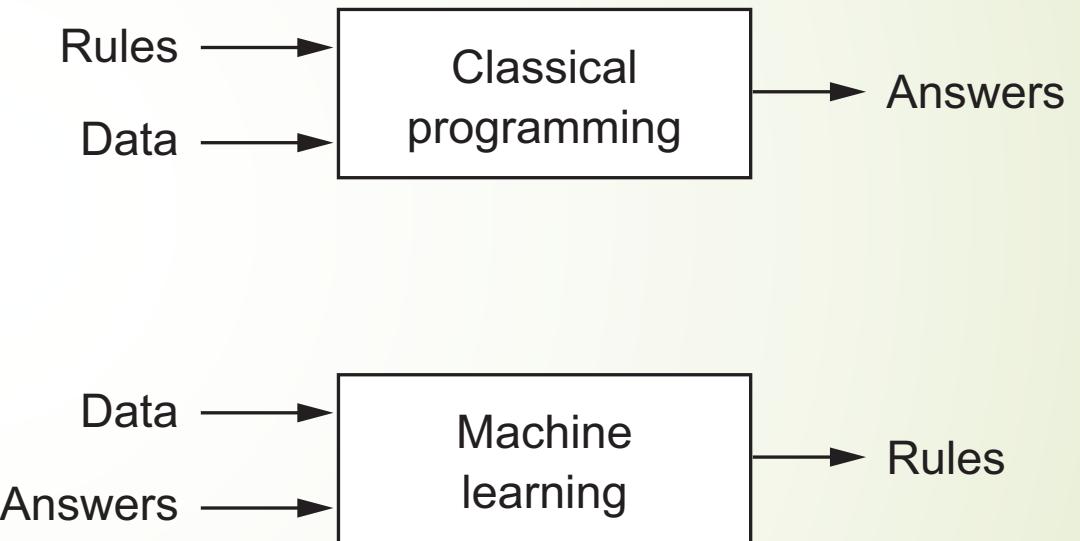
- ▶ **1943:** McCulloch & Pitts proposed a boolean circuit model of neurons
- ▶ **1949:** Donald Hebb proposed **Hebbian learning rule**.
- ▶ **1950:** Alan Turing published "**Computing Machinery and Intelligence**" with **Turing test**.
- ▶ **1956:** John McCarthy at the Dartmouth Conference coined terminology "**Artificial Intelligence**"
- ▶ **1957:** Rosenblatt invented **Perceptron**
- ▶ **1960s:** golden years till **1969 Minsky-Papert's** critical book **Perceptron**
- ▶ **1970s:** the first AI winter
- ▶ **1980s:** boom of AI with **Expert System**
- ▶ **1990s:** the second AI winter, rise of **statistical machine learning**
- ▶ **1997: IBM Deep Blue** beats world chess champion Kasparov
- ▶ **2012:** return of neural networks as **deep learning** (speech, ImageNet in computer vision, NLP, ...)
- ▶ **2016-2017: Google AlphaGo “Lee” and Zero**
- ▶ **2020: Google AlphaFold**
- ▶ ...

History of A.I.



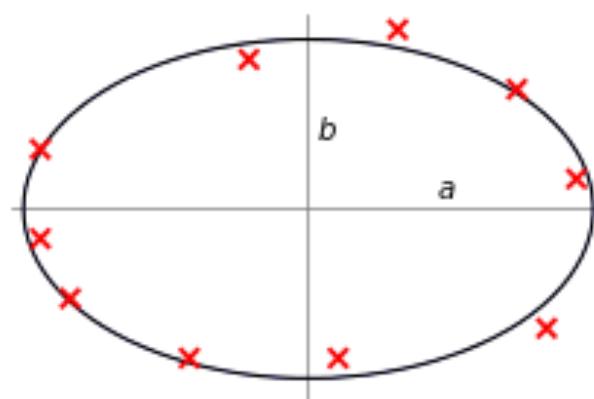
Statistical Machine Learning is a new paradigm of computer programming

- ▶ During 1950s-1980s, two competitive ideas of realizing AI exist
 - ▶ Rule based inference, or called **Expert System**
 - ▶ Statistics based inference, or called **Machine Learning**
- ▶ 1990s- Machine Learning becomes dominant



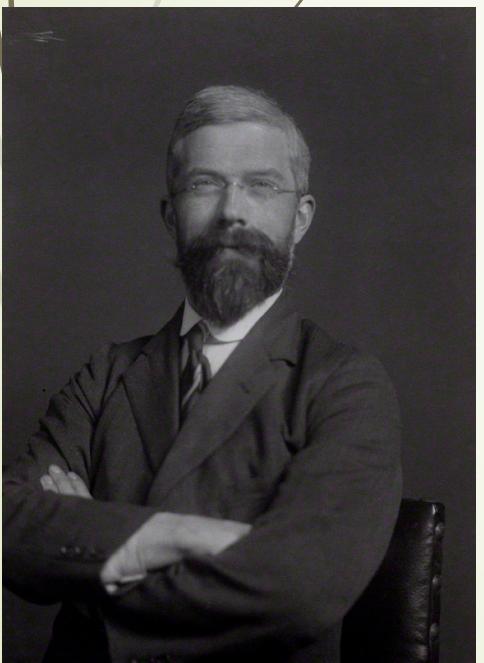
The 1st machine learning method: Least Squares

- Invention:
 - ▶ **Carl Friederich Gauss** (~1795/1809/1810),
 - ▶ Adrien-Marie Legendre (1805)
 - ▶ Robert Adrain (1808)
- Application:
 - ▶ Prediction of the location of asteroid Ceres after it emerged from behind the sun (Franz Xaver von Zach 1801)
 - ▶ Orbits of planets, Newton Laws
 - ▶ Statistics,
 - ▶ ...



Fisher's Maximum Likelihood Principle (1912-1922)

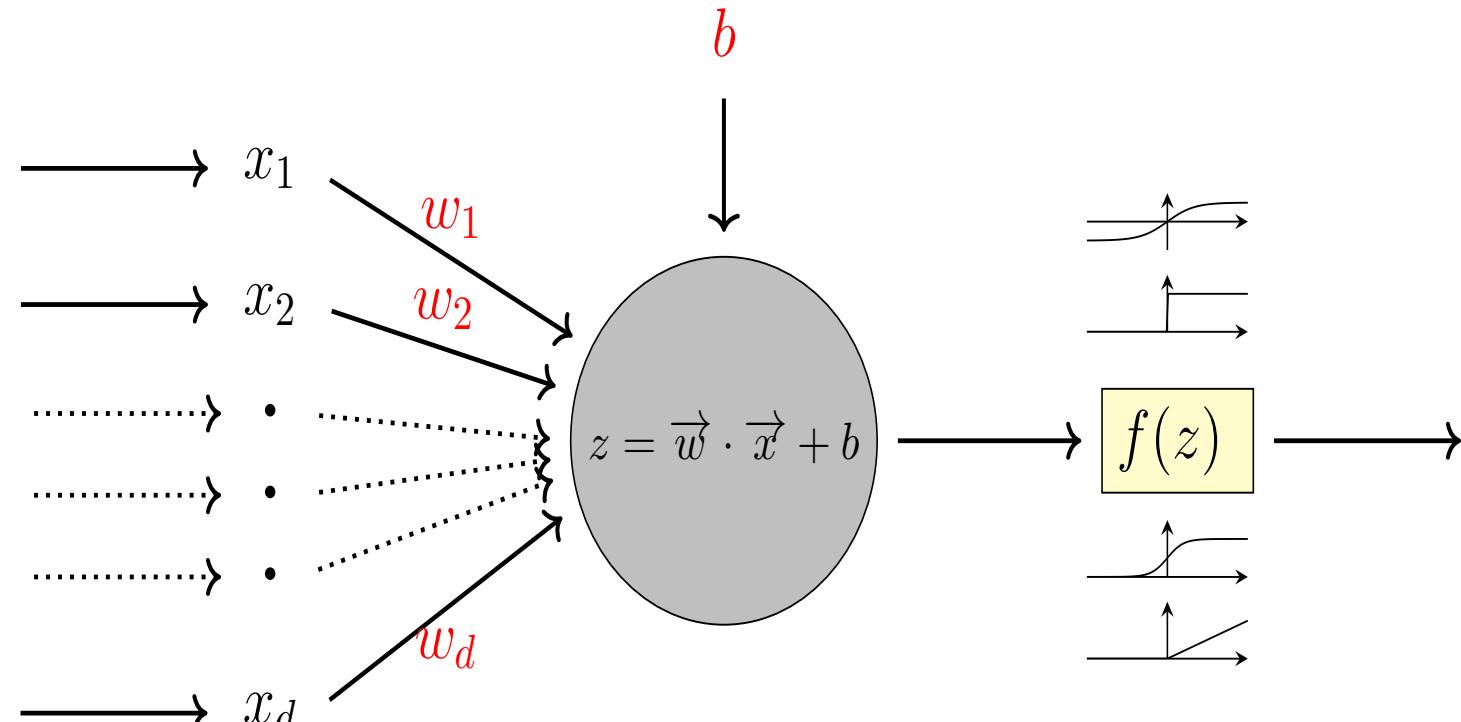
- ▶ **The least square method is the maximum likelihood estimate** (most probable values of the unknown parameters) when the noise is Gaussian.
- ▶ Fisher, R. A. (1912) **On an absolute criterion for fitting frequency curves.** *Messenger of Mathematics* 41:155-160.
- ▶ Fisher, R. A. (1922). **On the mathematical foundations of theoretical statistics.** *Philos. Trans. Roy. Soc. London Ser. A* 222:309-368.
- ▶ Aldrich, John (1997). **R. A. Fisher and the Making of Maximum Likelihood 1912 -- 1922.** *Statistical Science*, 12(3):162-176.



The 1st neural network: Perceptron



- Invented by Frank Rosenblatt (1957)





The Perceptron Algorithm for classification

$$\ell(w) = - \sum_{i \in \mathcal{M}_w} y_i \langle w, \mathbf{x}_i \rangle, \quad \mathcal{M}_w = \{i : y_i \langle \mathbf{x}_i, w \rangle < 0, y_i \in \{-1, 1\}\}.$$

The Perceptron Algorithm is a *Stochastic Gradient Descent* method
(Robbins-Monro 1951, Ann. Math. Statist. 22(3): 400-407):

$$\begin{aligned} w_{t+1} &= w_t - \eta_t \nabla_i \ell(w) \\ &= \begin{cases} w_t - \eta_t y_i \mathbf{x}_i, & \text{if } y_i w_t^T \mathbf{x}_i < 0, \\ w_t, & \text{otherwise.} \end{cases} \end{aligned}$$

Finiteness of Stopping Time and Margin

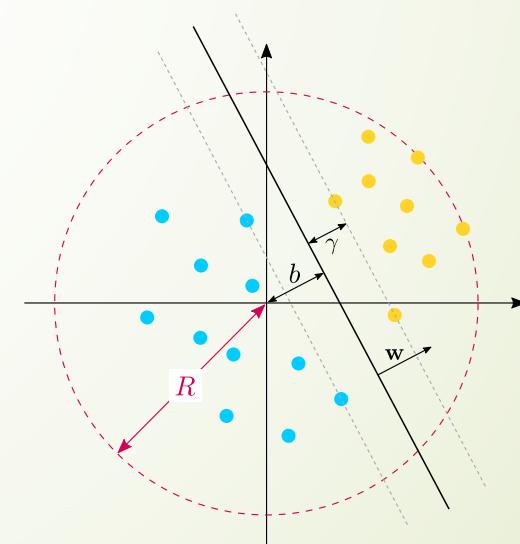
The perceptron convergence theorem was proved by [Block \(1962\)](#) and [Novikoff \(1962\)](#). The following version is based on that in [Cristianini and Shawe-Taylor \(2000\)](#).

Theorem 1 (Block, Novikoff). *Let the training set $S = \{(\mathbf{x}_1, t_1), \dots, (\mathbf{x}_n, t_n)\}$ be contained in a sphere of radius R about the origin. Assume the dataset to be linearly separable, and let \mathbf{w}_{opt} , $\|\mathbf{w}_{\text{opt}}\| = 1$, define the hyperplane separating the samples, having functional margin $\gamma > 0$. We initialise the normal vector as $\mathbf{w}_0 = \mathbf{0}$. The number of updates, k , of the perceptron algorithms is then bounded by*

$$k \leq \left(\frac{2R}{\gamma} \right)^2. \quad (10)$$

Input ball: $R = \max_i \|\mathbf{x}_i\|$.

Margin: $\gamma := \min_i y_i f(\mathbf{x}_i)$



Hilbert's 13th Problem

Algebraic equations (under a suitable transformation) of degree up to 6 can be solved by functions of two variables. What about

$$x^7 + ax^3 + bx^2 + cx + 1 = 0?$$

Hilbert's conjecture: $x(a, b, c)$ cannot be expressed by a superposition (sums and compositions) of bivariate functions.

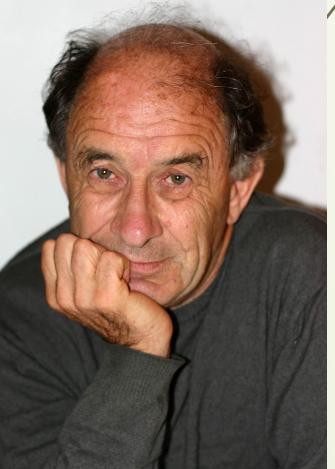
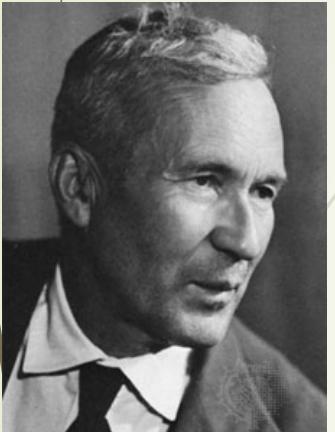


Question: can every continuous (analytic, C^∞ , etc) function of n variables be represented as a superposition of continuous (analytic, C^∞ , etc) functions of $n - 1$ variables?

Theorem (D. Hilbert)

There is an analytic function of three variables that cannot be expressed as a superposition of bivariate ones.

Kolmogorov's Superposition Theorem



Theorem (A. Kolmogorov, 1956; V. Arnold, 1957)

Given $n \in \mathbb{Z}^+$, every $f_0 \in C([0, 1]^n)$ can be represented as

$$f_0(x_1, x_2, \dots, x_n) = \sum_{q=1}^{2n+1} g_q \left(\sum_{p=1}^n \phi_{pq}(x_p) \right),$$

where $\phi_{pq} \in C[0, 1]$ are increasing functions independent of f_0 and $g_q \in C[0, 1]$ depend on f_0 .

- Can choose g_q to be all the same $g_q \equiv g$ (Lorentz, 1966).
- Can choose ϕ_{pq} to be Hölder or Lipschitz continuous, but not C^1 (Fridman, 1967).
- Can choose $\phi_{pq} = \lambda_p \phi_q$ where $\lambda_1, \dots, \lambda_n > 0$ and $\sum_p \lambda_p = 1$ (Sprecher, 1972).

If f is a multivariate continuous function, then f can be written as a superposition of composite functions of mixtures of continuous functions of single variables:
finite **composition** of continuous functions of a **single variable** and the **addition**.

Kolmogorov's Exact Representation is not stable or smooth

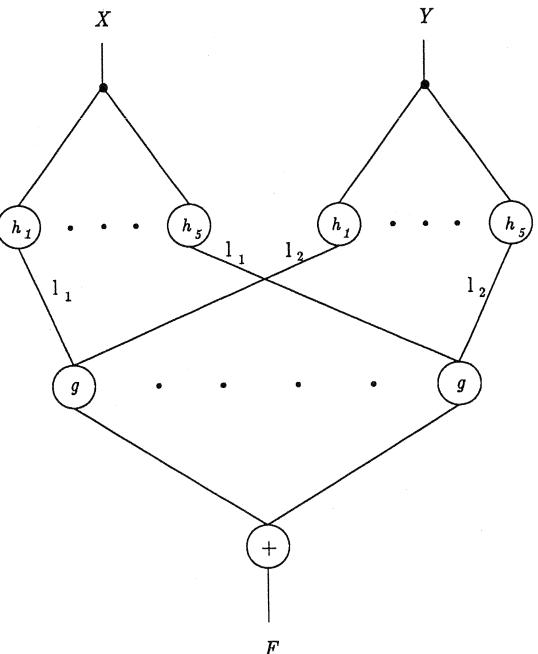


Figure 1: The network representation of an improved version of Kolmogorov's theorem, due to Kahane (1975). The figure shows the case of a bivariate function. The Kahane's representation formula is $f(x_1, \dots, x_n) = \sum_{q=1}^{2n+1} g[\sum_{p=1}^n l_p h_q(x_p)]$ where h_q are strictly monotonic functions and l_p are strictly positive constants smaller than 1.

- ▶ [Girosi-Poggio'1989] Representation Properties of Networks:
Kolmogorov's Theorem Is Irrelevant,
<https://www.mitpressjournals.org/doi/pdf/10.1162/neco.1989.1.4.465>
- ▶ Lacking smoothness in h and g
[Vitushkin'1964] fails to guarantee the **generalization ability (stability)** against noise and perturbations
- ▶ The representation is **not universal** in the sense that g and h both depend on the function F to be represented.



Universal Approximate Representation

[Cybenko'1989, Hornik et al. 1989, Poggio-Girosi'1989, ...]

For continuous $f : [0, 1]^N \rightarrow \mathbb{R}$ and $\varepsilon > 0$ there exists

$$F(x) = \alpha^\top \sigma(Wx + \beta)$$

$$= \sum_i \alpha_i \sigma \left(\sum_j W_{i,j} x_j + \beta_i \right)$$

such that for all x in $[0, 1]^N$ we have $|F(x) - f(x)| < \varepsilon$.

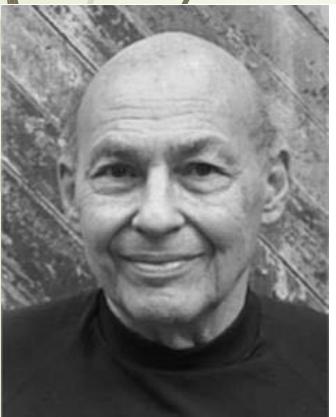
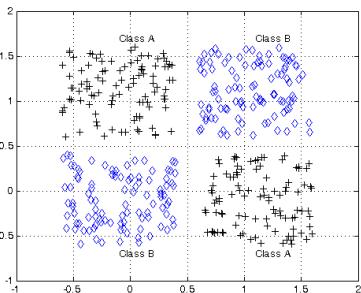
Complexity (regularity, smoothness) thereafter becomes the central pursuit in Approximation Theory.

Locality or Sparsity of Computation

Minsky and Papert, 1969

Perceptron can't do **XOR** classification

Perceptron needs infinite global
information to compute **connectivity**

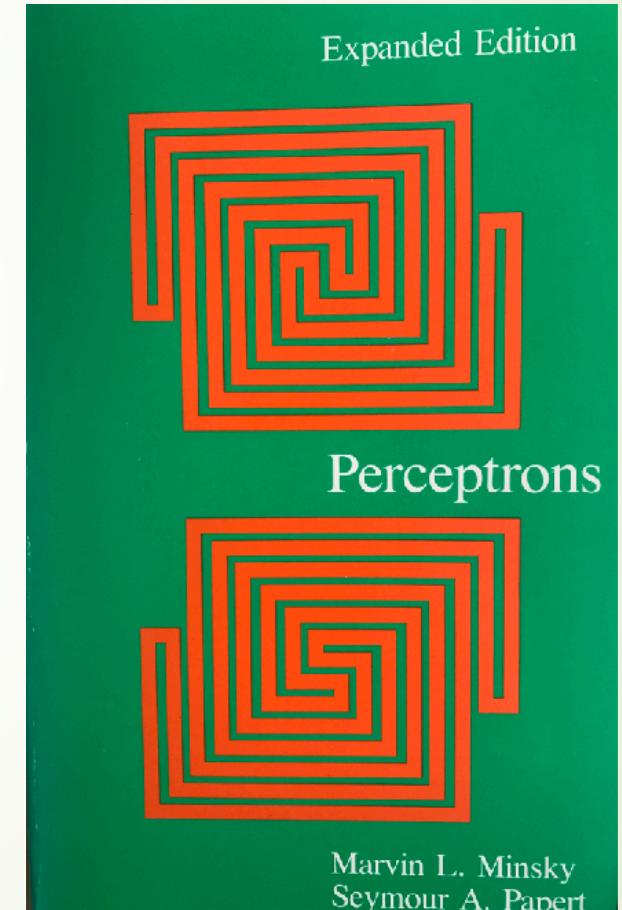


Marvin Minsky



Seymour Papert

Locality or Sparsity is important:
Locality in time?
Locality in space?

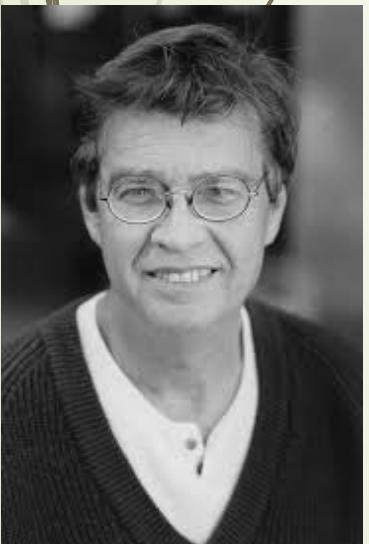


Multilayer Perceptrons (MLP) and Back-Propagation (BP) Algorithms

D.E. Rumelhart, G. Hinton, R.J. Williams (1986)
Learning representations by back-propagating errors, Nature, 323(9): 533-536

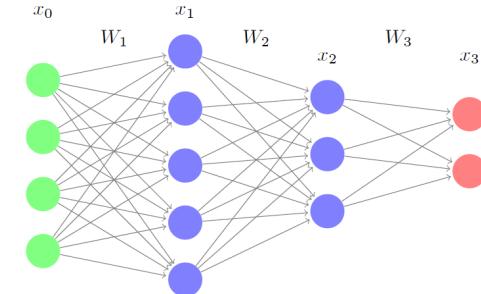
BP algorithms as **stochastic gradient descent** algorithms (**Robbins–Monro 1950; Kiefer–Wolfowitz 1951**) with Chain rules of Gradient maps

Deep network may classify **XOR**. Yet **topology?**



We address complexity and geometric invariant properties first.

NATURE VOL. 323 9 OCTOBER 1986 LETTERS TO NATURE 533



Learning representations by back-propagating errors

David E. Rumelhart*, Geoffrey E. Hinton† & Ronald J. Williams*

* Institute for Cognitive Science, C-015, University of California, San Diego, La Jolla, California 92093, USA
† Department of Computer Science, Carnegie-Mellon University, Pittsburgh, Philadelphia 15213, USA

more difficult when we introduce hidden units whose actual or desired states are not specified by the task. (In perceptrons, there are 'feature analysers' between the input and output that are not true hidden units because their input connections are fixed by hand, so their states are completely determined by the input vector: they do not learn representations.) The learning units should be active in order to help achieve the desired input-output behaviour. This amounts to deciding what these units should represent. We demonstrate that a general purpose and relatively simple procedure is powerful enough to construct appropriate learned representations.

The simplest form of the learning procedure is for layered networks which have a layer of input units at the bottom, any number of intermediate layers, and a layer of output units at the top. Connections within a layer or from higher to lower layers are forbidden, but connections can skip intermediate layers. An input vector is presented to the network by setting the states of the input units. Then the states of the units in each layer are determined by applying equations (1) and (2) to the connections coming from lower layers. All units within a layer have their states set in parallel, but different layers have their states set sequentially, starting at the bottom and working upwards until the states of the output units are determined.

There have been many attempts to design self-organizing neural networks. The aim is to find a powerful synaptic modification rule that will allow an arbitrarily connected neural network to develop an internal structure that is appropriate for a particular task domain. The task is specified by giving the desired state vector of the output units for each state vector of the input units. If the input units are directly connected to the output units it is relatively easy to find learning rules that iteratively adjust the relative strengths of the connections so as to progressively reduce the difference between the actual and desired output vectors¹. Learning becomes more interesting but

We describe a new learning procedure, back-propagation, for networks of neurone-like units. The procedure repeatedly adjusts the weights of the connections in the network so as to minimize a measure of the difference between the actual output vector of the net and the desired output vector. As a result of the weight adjustments, internal 'hidden' units which are not part of the input or output code to represent important features of the task domain, and the regularities in the task are captured by the interactions of these units. The ability to create useful new features distinguishes back-propagation from earlier, simpler methods such as the perceptron, counter-propagation and the

The total input, x_j , to unit j is a linear function of the outputs, y_i , of the units that are connected to j and of the weights, w_{ij} , on these connections

$$x_j = \sum_i y_i w_{ij} \quad (1)$$

Units can be given biases by introducing an extra input to each unit which always has a value of 1. The weight on this extra input is called the bias and is equivalent to a threshold of the opposite sign. It can be treated just like the other weights.

A unit has a real-valued output, y_j , which is a non-linear function of its total input

$$y_j = \frac{1}{1 + e^{-x_j}} \quad (2)$$

¹ To whom correspondence should be addressed

Parallel Distributed Processing

by Rumelhart and McClelland, 1986



Minsky and Papert set out to show which functions can and cannot be computed by this class of machines. They demonstrated, in particular, that such perceptrons are unable to calculate such mathematical functions as parity (whether an odd or even number of points are on in the retina) or the topological function of connectedness (whether all points that are on are connected to all other points that are on either directly or via other points that are also on) without making use of absurdly large numbers of predicates. The analysis is extremely elegant and demonstrates the importance of a mathematical approach to analyzing



of multilayer networks that compute parity). Similarly, it is not difficult to develop networks capable of solving the connectedness or inside/outside problem. Hinton and Sejnowski have analyzed a version of such a network (see Chapter 7).

Essentially, then, although Minsky and Papert were exactly correct in their analysis of the *one-layer perceptron*, the theorems don't apply to systems which are even a little more complex. In particular, it doesn't apply to multilayer systems nor to systems that allow feedback loops.

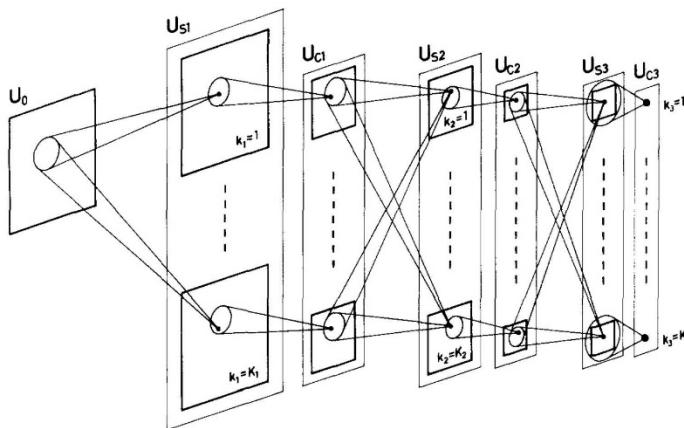
Convolutional Neural Networks: shift invariances and locality

Biol. Cybernetics 36, 193–202 (1980)

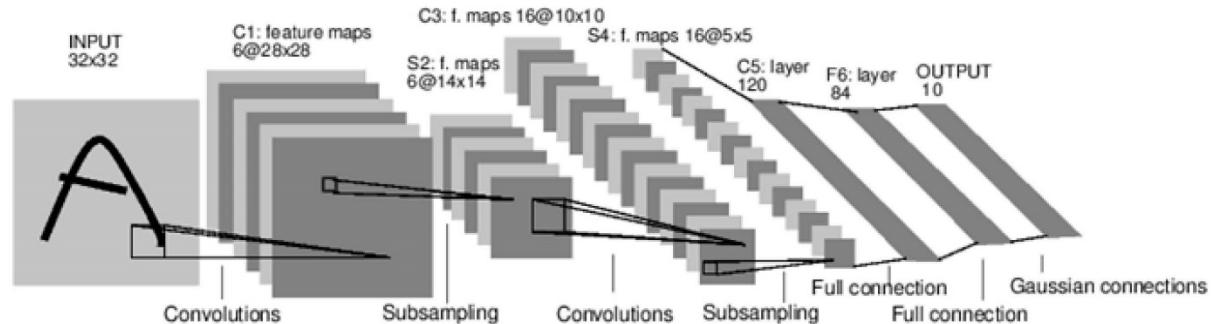
**Neocognitron: A Self-organizing Neural Network Model for a Mechanism of Pattern Recognition
Unaffected by Shift in Position**

Kunihiko Fukushima

NHK Broadcasting Science Research Laboratories, Kinuta, Setagaya, Tokyo, Japan



- Can be traced to *Neocognitron* of Kunihiko Fukushima (1979)
- Yann LeCun combined convolutional neural networks with back propagation (1989)
- Imposes **shift invariance** and **locality** on the weights
- Forward pass remains similar
- Backpropagation slightly changes – need to sum over the gradients from all spatial positions

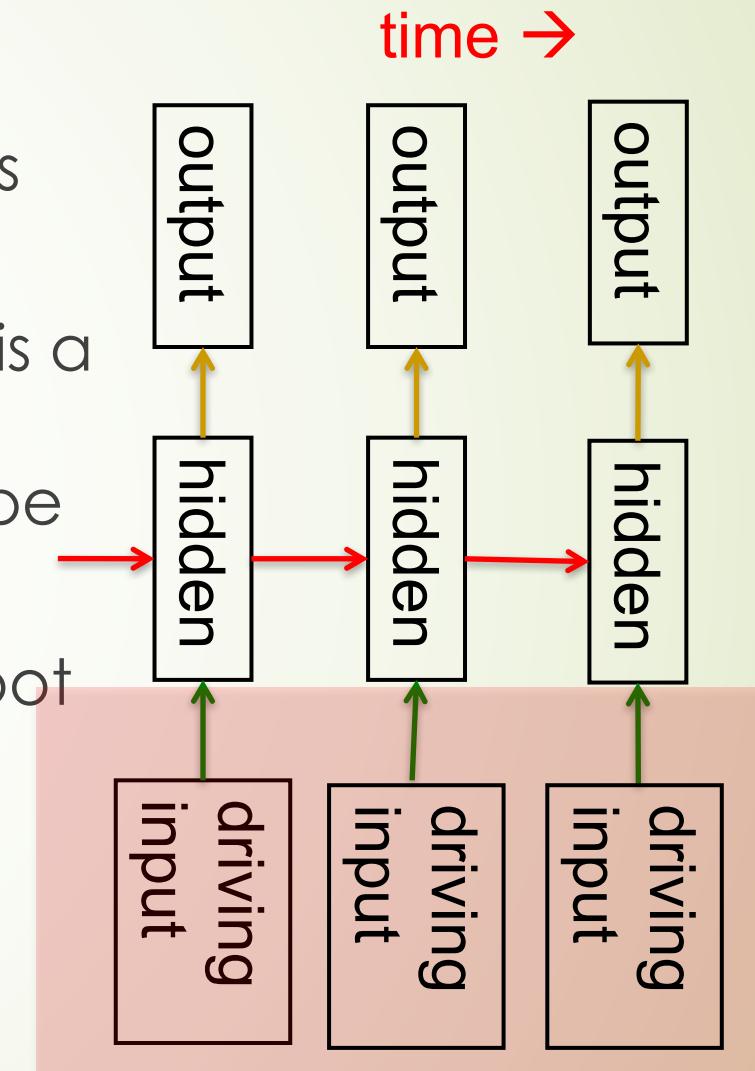


Time series: Linear Dynamical Systems (1940s-)

- ▶ The hidden state has linear dynamics with Gaussian noise and produces the observations using a linear model with Gaussian noise.
- ▶ Kalman Filter: A linearly transformed Gaussian is a Gaussian. So the distribution over the hidden state given the data so far is Gaussian. It can be computed using “Kalman filtering”.
- ▶ To predict the next output (so that we can shoot down the missile) we need to infer the hidden state.

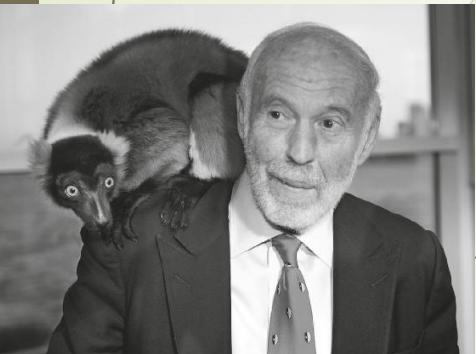
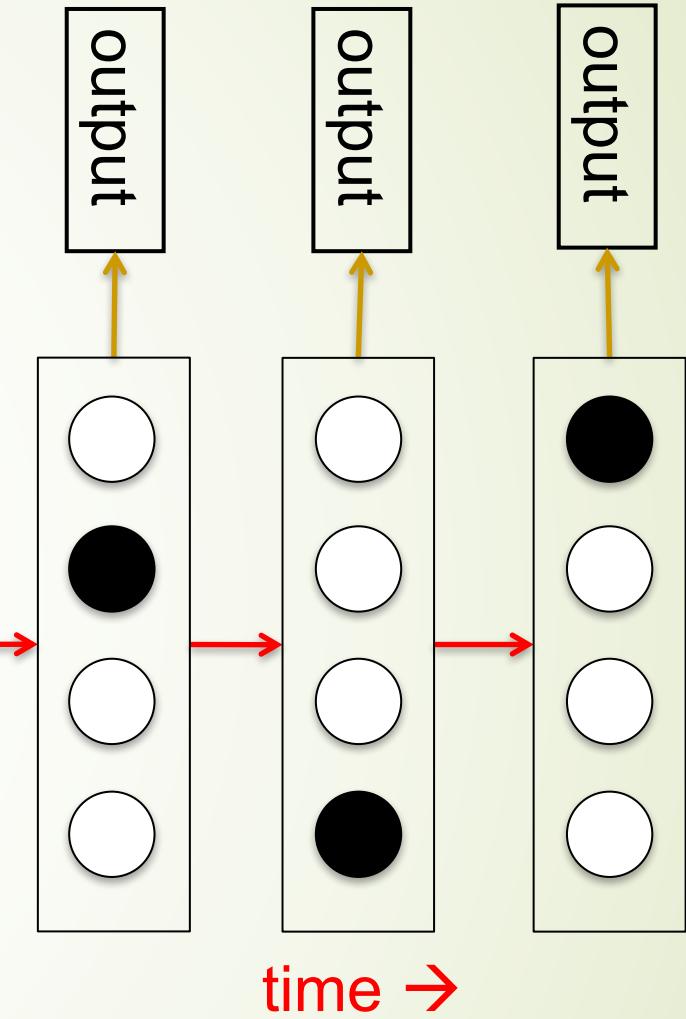
$$h_t = W_{hh}h_{t-1} + W_{hx}x_t + \epsilon_t^h$$

$$y_t = W_{yh}h_t + W_{yx}x_t + \epsilon_t^y$$



Hidden Markov Models (1970s-)

- ▶ Hidden Markov Models have a discrete one-of-N hidden state. Transitions between states are stochastic and controlled by a transition matrix. The outputs produced by a state are stochastic.
 - ▶ We cannot be sure which state produced a given output. So the state is “hidden”.
 - ▶ It is easy to represent a probability distribution across N states with N numbers.
- ▶ To predict the next output we need to infer the probability distribution over hidden states.
- ▶ HMMs have efficient algorithms (**Baum-Welch** or **EM Algorithm**) for inference and learning.
- ▶ **Jim Simons** hires Lenny Baum as the founding member of Renaissance Technologies in 1979



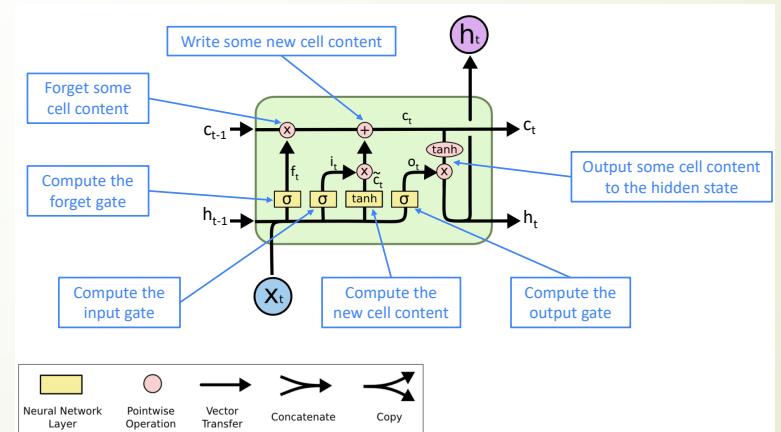
Lenny Baum became a devoted Go player despite his deteriorating eyesight.

Recurrent Neural Networks (1986-)

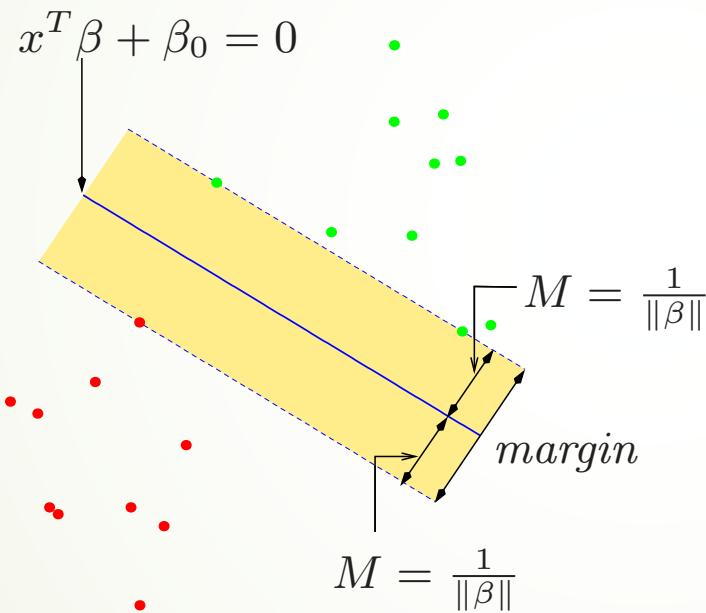
- ▶ **The issue of a hidden Markov model (HMM):**
 - ▶ At each time step it must select one of its hidden states. So with N hidden states it can only remember $\log(N)$ bits about what it generated so far.
- ▶ RNNs are very powerful, because they combine two properties:
 - ▶ Distributed hidden state that allows them to store a lot of information about the past efficiently.
 - ▶ Non-linear dynamics that allows them to update their hidden state in complicated ways.
- ▶ Rumelhart et al. enables training by **BP** algorithm
 - ▶ With enough neurons and time, RNNs can compute anything that can be computed by your computer.

Long-Short-Term-Memory (LSTM)

- ▶ Sepp Hochreiter; Jürgen Schmidhuber (1997). "Long short-term memory". *Neural Computation*. 9 (8): 1735–1780. (<https://www.bioinf.jku.at/publications/older/2604.pdf>)
- ▶ Introduction of short path to learn deep networks without vanishing gradient problem.



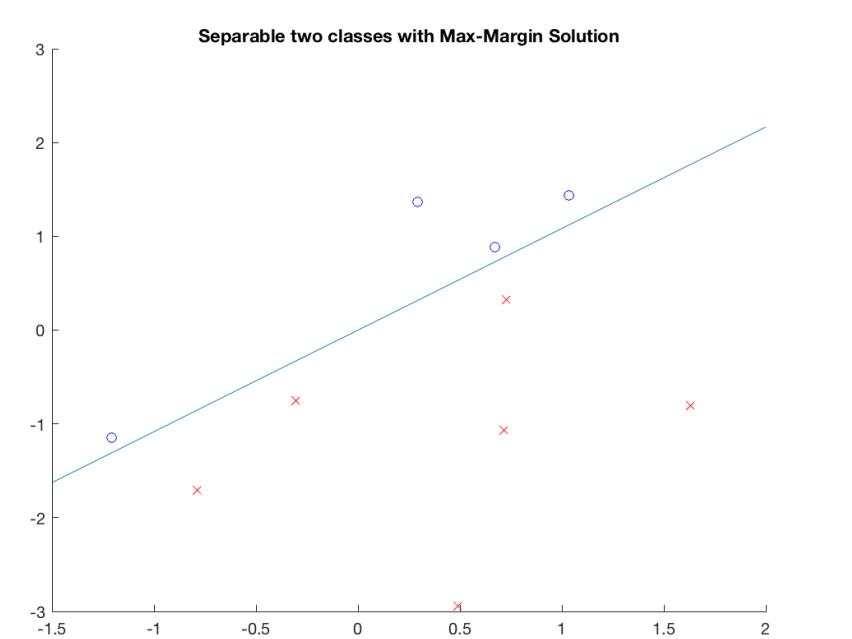
Max-Margin Classifier (SVM)



Vladimir Vapnik, 1994

$$\text{minimize}_{\beta_0, \beta_1, \dots, \beta_p} \|\beta\|^2 := \sum_j \beta_j^2$$

subject to $y_i(\beta_0 + \beta_1 x_{i1} + \dots + \beta_p x_{ip}) \geq 1$ for all i



MNIST Dataset Test Error

LeCun et al. 1998



Simple SVM performs as well as Multilayer Convolutional Neural Networks which need careful tuning (LeNets)

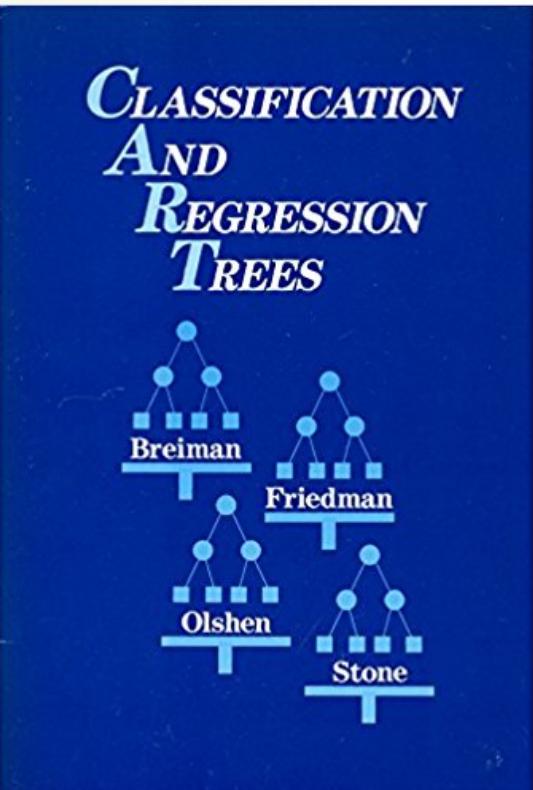
Dark era for NN: 1998-2012



2000-2010: The Era of SVM, Boosting, ... as nights of Neural Networks



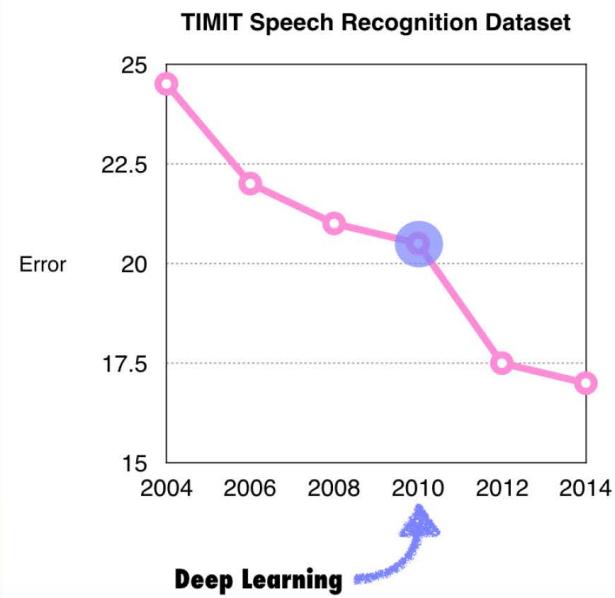
Decision Trees and Boosting



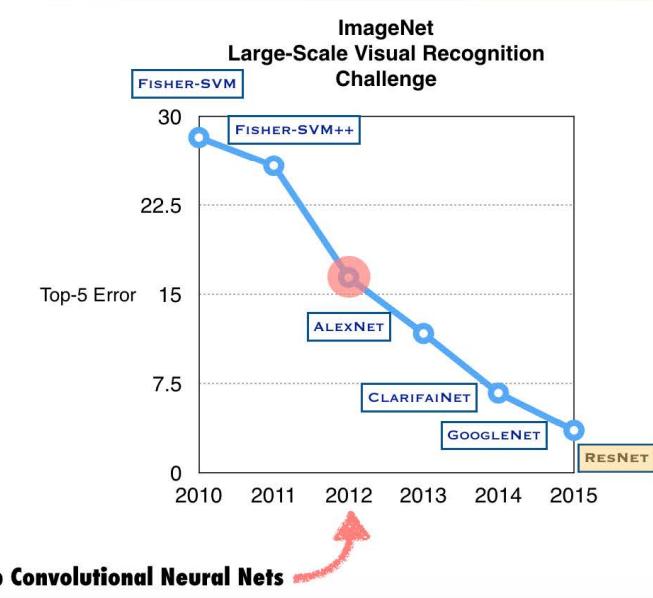
- ▶ Breiman, Friedman, Olshen, Stone, (1983): CART
- ▶ ``The Boosting problem'' (M. Kearns & L. Valiant):
Can a set of weak learners create a single strong learner? (三个臭皮匠顶个诸葛亮?)
- ▶ Breiman (1996): Bagging
- ▶ Freund, Schapire (1997): **AdaBoost** ("the best off-the-shelf algorithm" by Breiman)
- ▶ Breiman (2001): **Random Forests**

Around the year of 2012: return of NN as `deep learning'

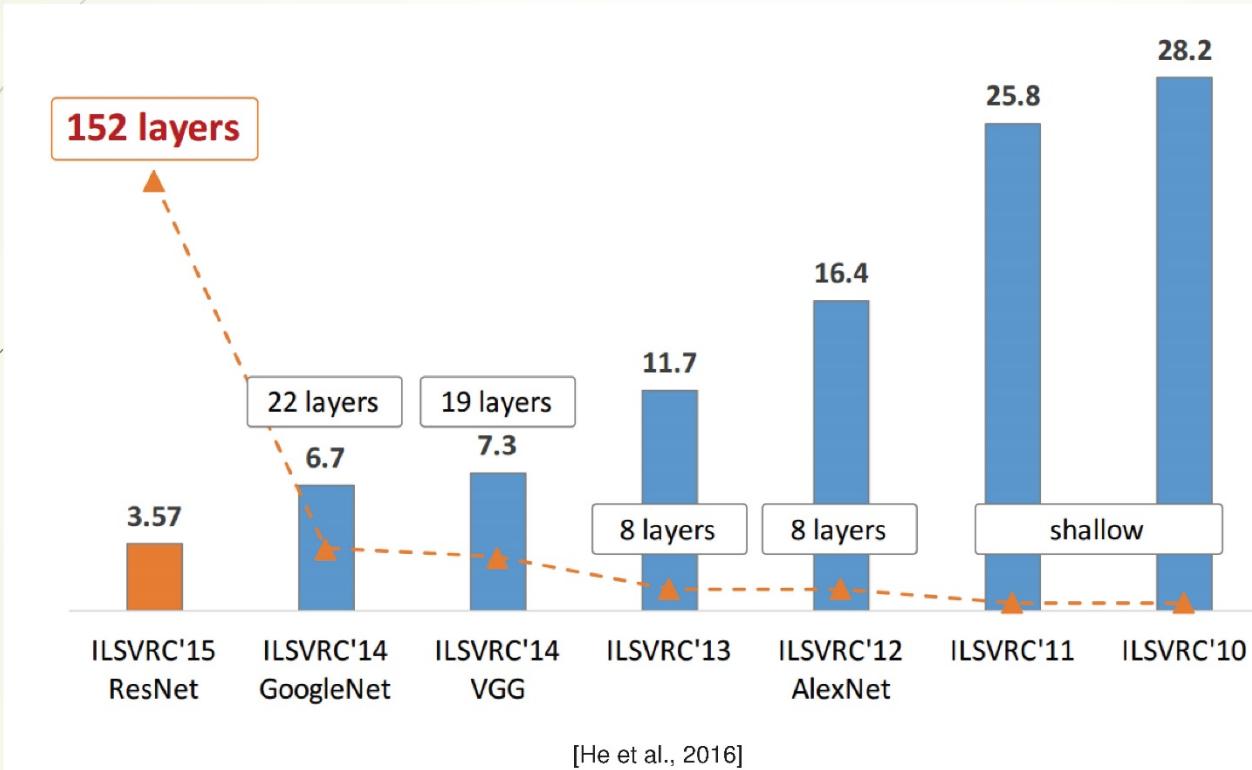
Speech Recognition: TIMIT



Computer Vision: ImageNet

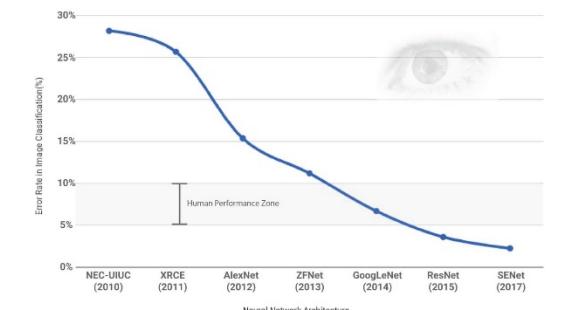


Depth as function of year



ILSVRC ImageNet Top 5 errors

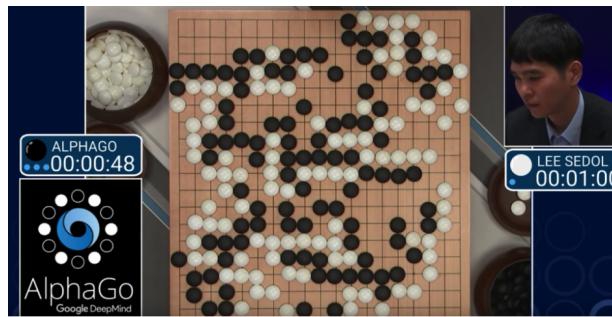
- ImageNet (subset):
 - 1.2 million training images
 - 100,000 test images
 - 1000 classes
- ImageNet large-scale visual recognition Challenge



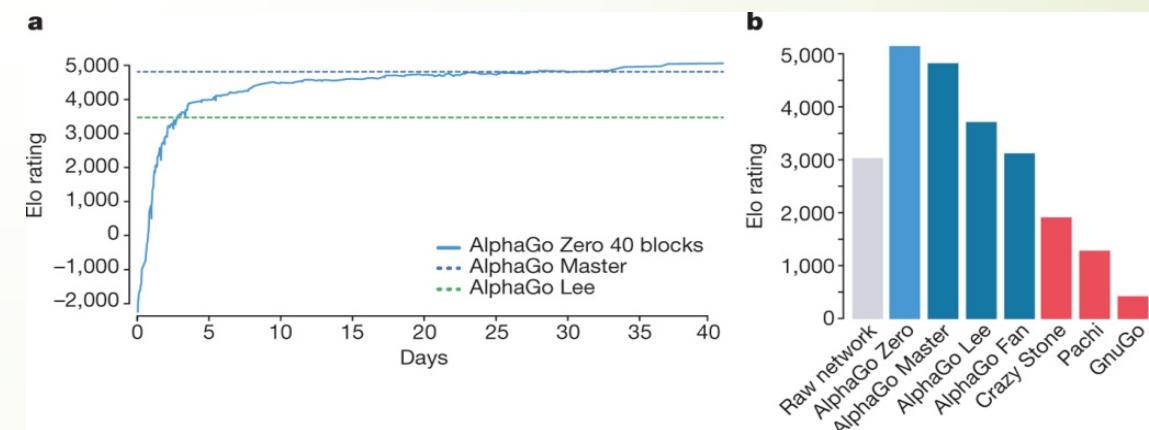
Reaching Human Performance Level in Games



Deep Blue in 1997



AlphaGo "LEE" 2016

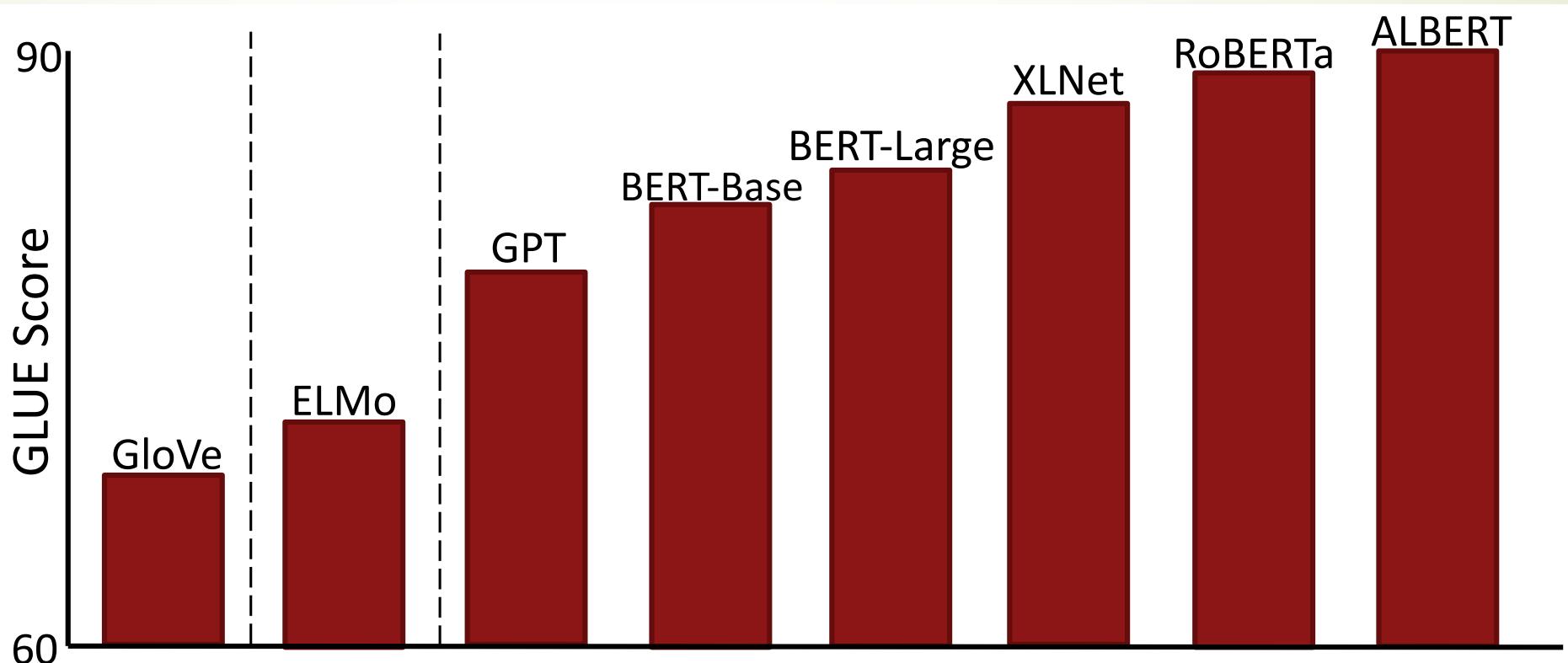




Natural Language Processing (NLP) and Machine Translation

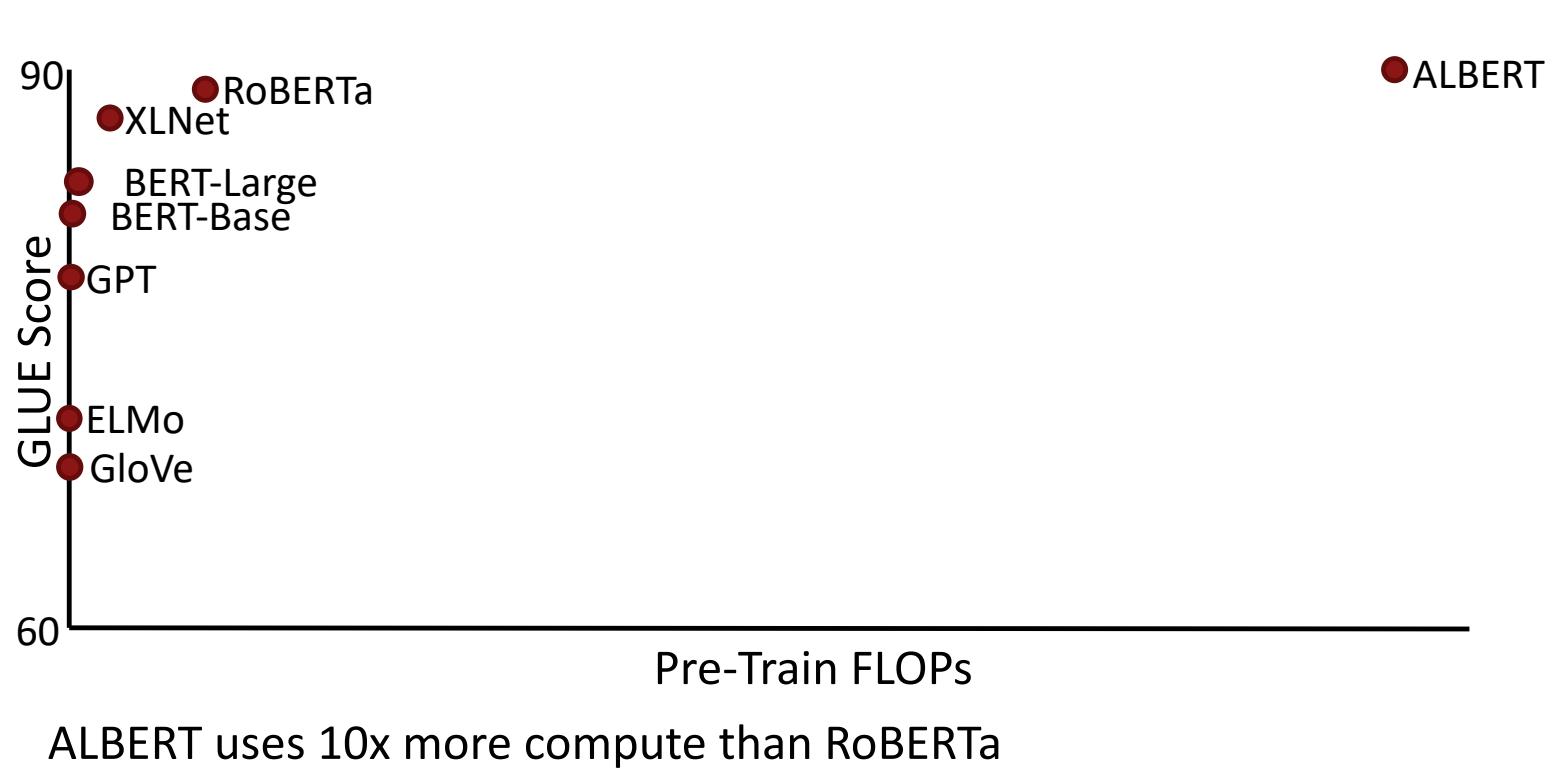
- ▶ In **2013-2015**, **LSTMs** started achieving state-of-the-art results
 - ▶ Successful tasks include: handwriting recognition, speech recognition, machine translation, parsing, image captioning
 - ▶ LSTM became the dominant approach
- ▶ In **2019**, other approaches (e.g. **Transformers**) have become more dominant for certain tasks.
 - ▶ For example in **WMT** (a MT conference + competition):
 - ▶ In WMT 2016, the summary report contains "RNN" 44 times
 - ▶ In WMT 2018, the report contains "RNN" 9 times and "Transformer" 63 times
- ▶ **Source:** "Findings of the 2016 Conference on Machine Translation (WMT16)", Bojar et al. 2016, <http://www.statmt.org/wmt16/pdf/W16-2301.pdf>
- ▶ **Source:** "Findings of the 2018 Conference on Machine Translation (WMT18)", Bojar et al. 2018, <http://www.statmt.org/wmt18/pdf/WMT028.pdf>

Rapid Progress for NLP Pretraining (GLUE Benchmark)



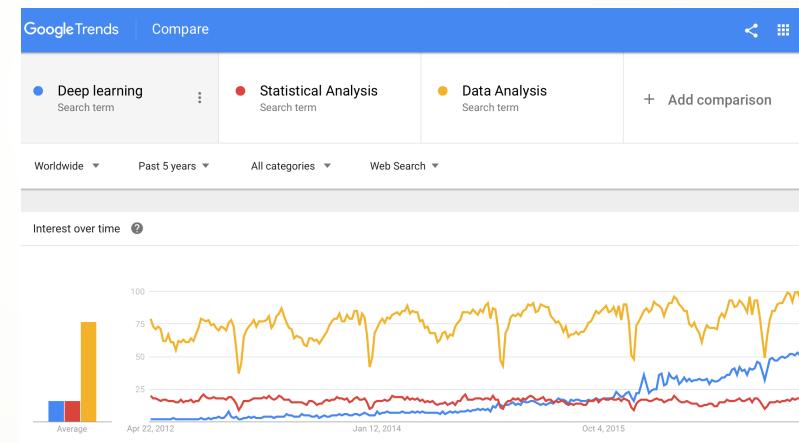
Over 3x reduction in error in 2 years, “superhuman” performance

More compute, more better?

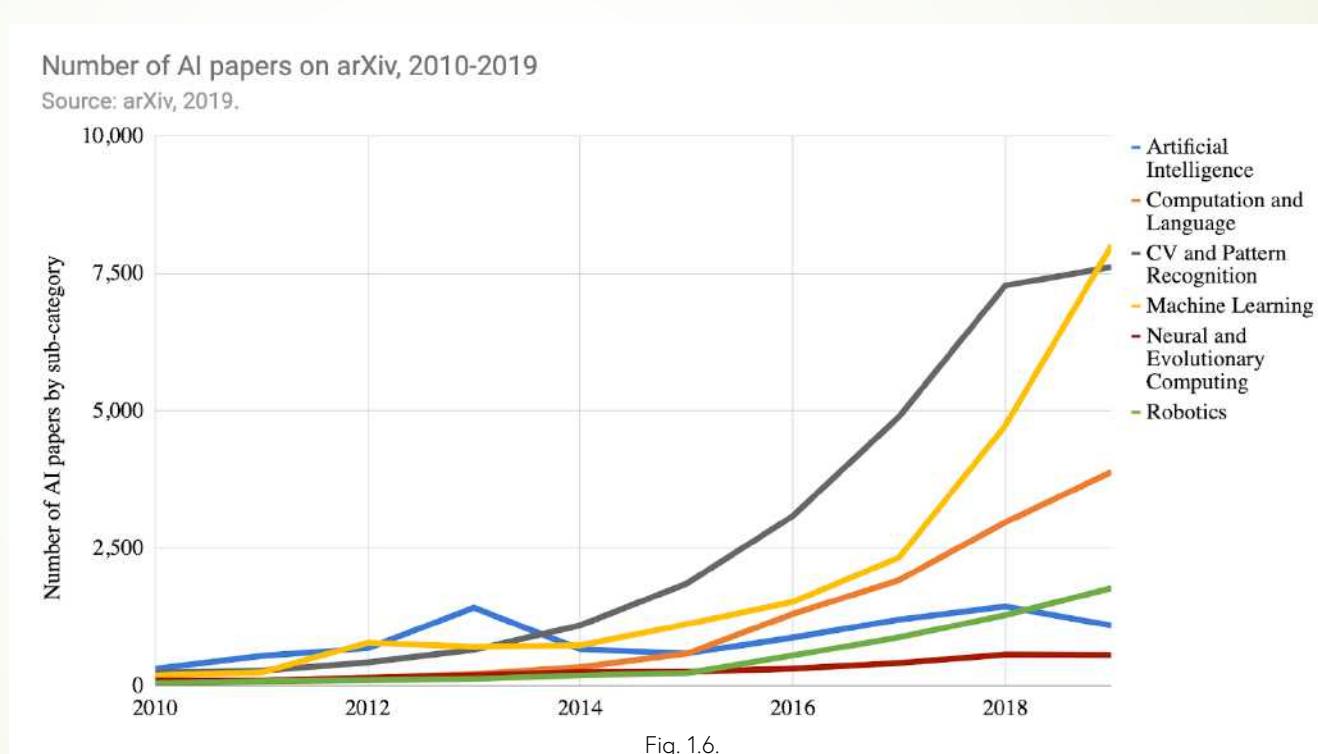


Growth of Deep Learning

'Deep Learning' is coined by Hinton et al. in their Restricted Boltzman Machine paper, *Science* 2006, not yet popular until championing ImageNet competitions.



Number of AI papers on arXiv, 2010-2019

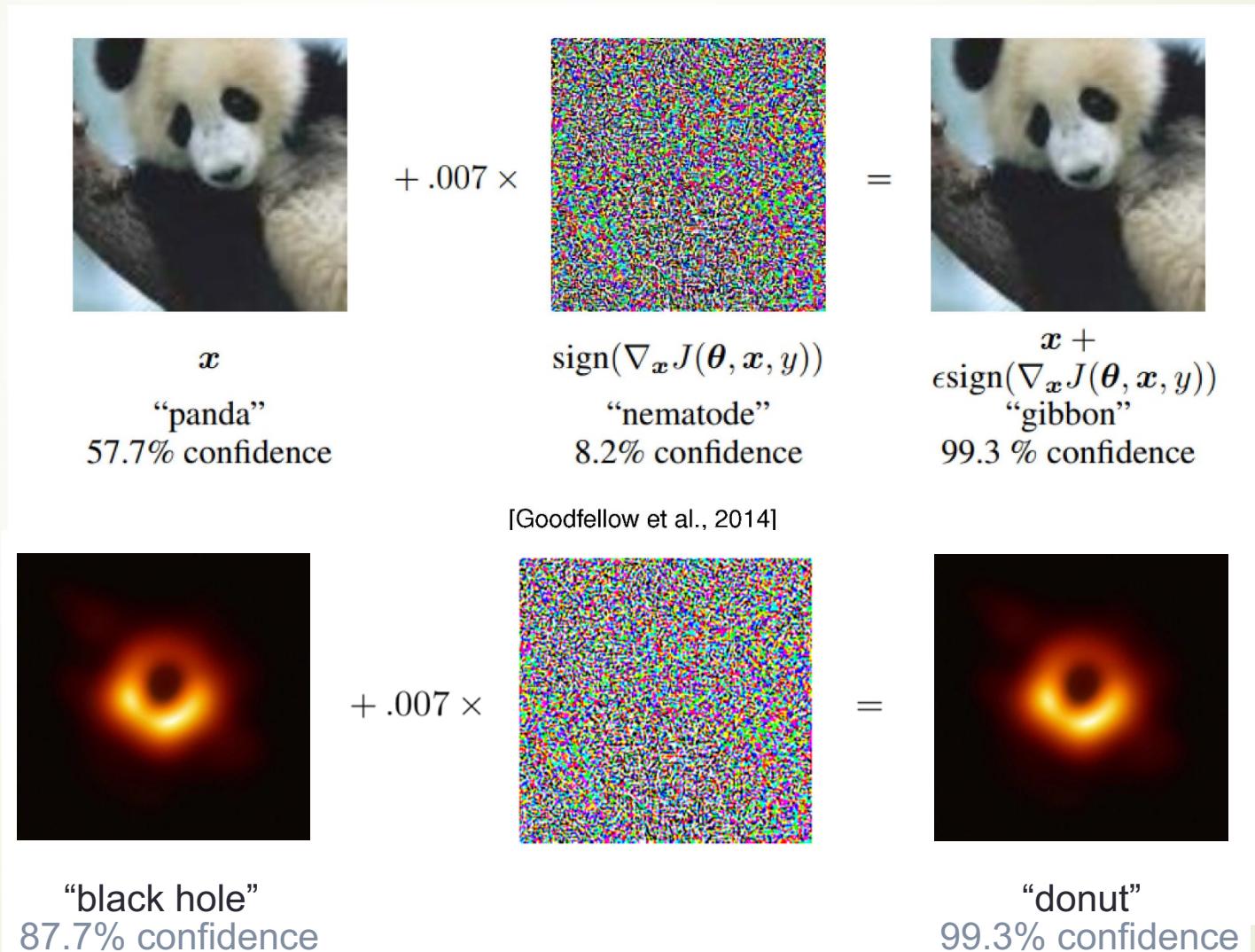


Some Cold Water: Tesla Autopilot Misclassifies Truck as Billboard



Problem: Why? How can you trust a blackbox?

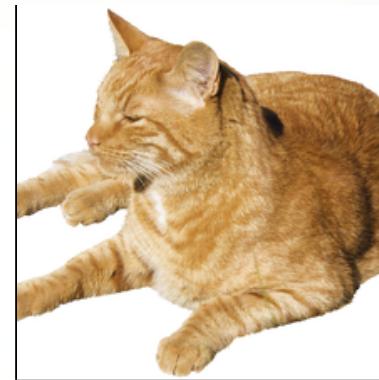
Deep Learning may be fragile in generalization against noise!



CNN learns **texture** features, not shapes



(a) Texture image
81.4% **Indian elephant**
10.3% indri
8.2% black swan



(b) Content image
71.1% **tabby cat**
17.3% grey fox
3.3% Siamese cat



(c) Texture-shape cue conflict
63.9% **Indian elephant**
26.4% indri
9.6% black swan

Geirhos et al. ICLR 2019

<https://videoken.com/embed/W2HvLBMhCJQ?tocitem=46>

Overfitting causes privacy leakage

- Model inversion attack leaks privacy



Figure: Recovered (Left), Original (Right)

What's wrong with deep learning?

Ali Rahimi NIPS'17: Machine (deep) Learning has become **alchemy**.

<https://www.youtube.com/watch?v=ORHFOnaEzPc>

Yann LeCun CVPR'15, invited talk: **What's wrong with deep learning?**
One important piece: **missing some theory (clarity in understanding)**!

<http://techtalks.tv/talks/whats-wrong-with-deep-learning/61639/>



Being alchemy is certainly not a shame, not wanting to work on advancing to chemistry is a shame! -- **by Eric Xing**



“ Shall we see soon an
emergence
from Alchemy to Science
in deep leaning? ”

How can we teach our students in the next generation science rather than alchemy?

All models are wrong, but some are useful ...

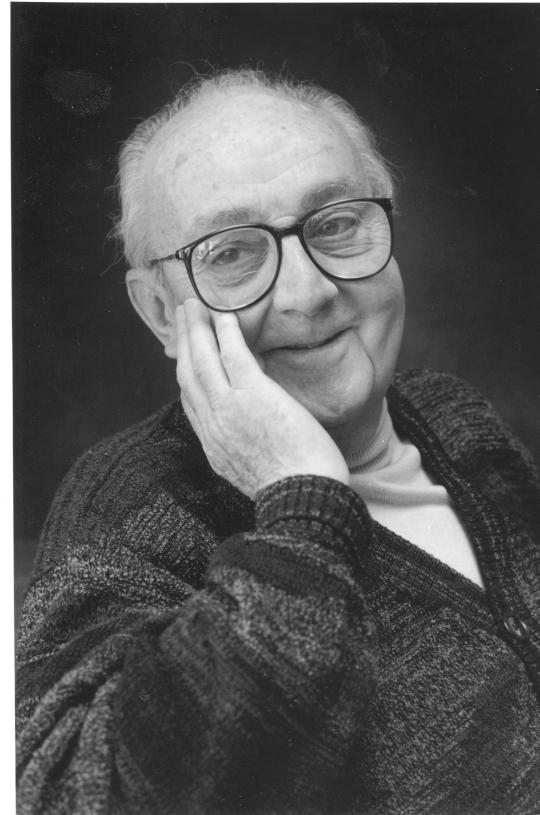


Figure 7: George Box: “Essentially, all models are wrong, but some are useful.”



In this class

- ▶ Understand its principles: statistics, optimization
- ▶ Analyze the real world data with the methods
- ▶ Team-work in projects (no more than 3 persons per team)!

Thank you!

