

PV021: Neural networks

Tomáš Brázdil

Course organization

Course materials:

- ▶ **Main:** The lecture
- ▶ Neural Networks and Deep Learning by Michael Nielsen
<http://neuralnetworksanddeeplearning.com/>
(Extremely well-written online textbook (a little outdated))
- ▶ Deep Learning by Ian Goodfellow, Yoshua Bengio, and Aaron Courville
<http://www.deeplearningbook.org/>
("Classical" overview of the theory of neural networks (a little outdated))
- ▶ Probabilistic Machine Learning: An Introduction by Kevin Murphy
<https://probml.github.io/pml-book/book1.html>
(Greatly advanced ML textbook with (almost) up-to-date basic neural networks.)
- ▶ Infinitely many online tutorials on everything (to build intuition)

Suggested: deeplearning.ai courses by Andrew Ng

Evaluation:

- ▶ Project (Dr. Tomáš Foltýnek)
 - ▶ implementation of a selected model + analysis of given data
 - ▶ implementation C/C++/Java/Rust **without the use of any specialized libraries for data analysis and machine learning**
 - ▶ need to get over a given accuracy threshold (a gentle one, just to eliminate non-functional implementations)

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 - ▶ need to get over a given accuracy threshold (a gentle one, just to eliminate non-functional implementations)
- ▶ Oral exam
 - ▶ I may ask about anything from the lecture! You will get a detailed manual specifying the mandatory knowledge.

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Q: Why should you attend this course when there are infinitely many great resources elsewhere?

A: There are at least two reasons:

- ▶ You may discuss issues with me, my colleagues and other students.
- ▶ I will make you truly learn fundamentals by heart.

Notable features of the course

- ▶ Use of mathematical notation and reasoning (mandatory for the exam)
- ▶ Sometimes goes deeper into statistical underpinnings of neural networks learning
- ▶ The project demands a complete working solution which must satisfy a prescribed performance specification

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An example of an instruction email (from another course with the same system):

It is typically not sufficient to devote a single afternoon to the preparation for the exam.

You have to know `_everything_` (which means every single thing) starting with the slide 42 and ending with the slide 245 with notable exceptions of slides: 121 - 123, 137 - 140, 165, 167.

Proofs presented on the whiteboard are also mandatory.

Machine learning in general

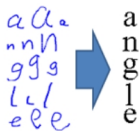
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 - ▶ learns to recognize spam from a database of "labeled" emails
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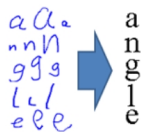
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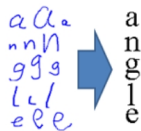
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 - ▶ and lots of much, much more sophisticated applications ...
- ▶ Basic attributes of learning algorithms:
 - ▶ **representation**: ability to capture the inner structure of training data
 - ▶ **generalization**: ability to work properly on new data



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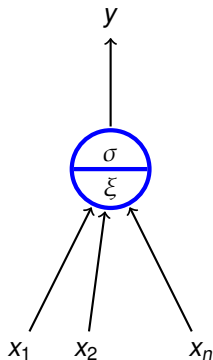
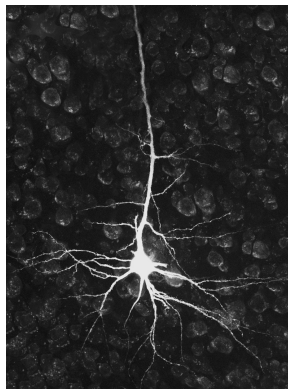
There are many types of models:

- ▶ decision trees
- ▶ support vector machines
- ▶ hidden Markov models
- ▶ Bayes networks and other graphical models
- ▶ **neural networks**
- ▶ ...

Neural networks, based on models of a (human) brain, form a natural basis for learning algorithms!

Artificial neural networks

- ▶ **Artificial neuron** is a *rough mathematical approximation* of a biological neuron.
- ▶ **(Artificial) neural network (NN)** consists of a number of interconnected artificial neurons. "Behavior" of the network is encoded in connections between neurons.



Why artificial neural networks?

Modelling of biological neural networks (computational neuroscience).

- ▶ simplified mathematical models help to identify important mechanisms
 - ▶ How the brain receives information?
 - ▶ How the information is stored?
 - ▶ How the brain develops?
 - ▶ ...

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 - ▶ ...
- ▶ neuroscience is strongly multidisciplinary; precise mathematical descriptions help in communication among experts and in design of new experiments.

I will not spend much time on this area!

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Neural networks in machine learning.

- ▶ Typically primitive models, far from their biological counterparts (but often inspired by biology).
- ▶ Strongly oriented towards concrete application domains:
 - ▶ decision making and control - autonomous vehicles, manufacturing processes, control of natural resources
 - ▶ games - backgammon, poker, GO, Starcraft, ...
 - ▶ finance - stock prices, risk analysis
 - ▶ medicine - diagnosis, signal processing (EKG, EEG, ...), image processing (MRI, CT, WSI ...)
 - ▶ text and speech processing - machine translation, *text generation*, speech recognition
 - ▶ other signal processing - filtering, radar tracking, noise reduction
 - ▶ art - music and painting generation, deepfakes
 - ▶ ...

I will concentrate on this area!

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 - ▶ a blurred photo of a rabbit may still be classified as an image of a rabbit
- ▶ Graceful degradation
 - ▶ Experiments have shown that damaged neural network is still able to work quite well
 - ▶ Damaged network may re-adapt, remaining neurons may take on functionality of the damaged ones

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- ▶ We will concentrate on
 - ▶ basic techniques and principles of neural networks,
 - ▶ fundamental models of neural networks and their applications.
- ▶ You should learn
 - ▶ basic models
(multilayer perceptron, convolutional networks, recurrent networks, transformers, autoencoders and generative adversarial networks)

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 - ▶ Basic information about current implementations
(TensorFlow-Keras, Pytorch)

Biological neural network

- ▶ Human neural network consists of approximately 10^{11} (100 billion on the short scale) neurons; a single cubic centimeter of a human brain contains almost 50 million neurons.
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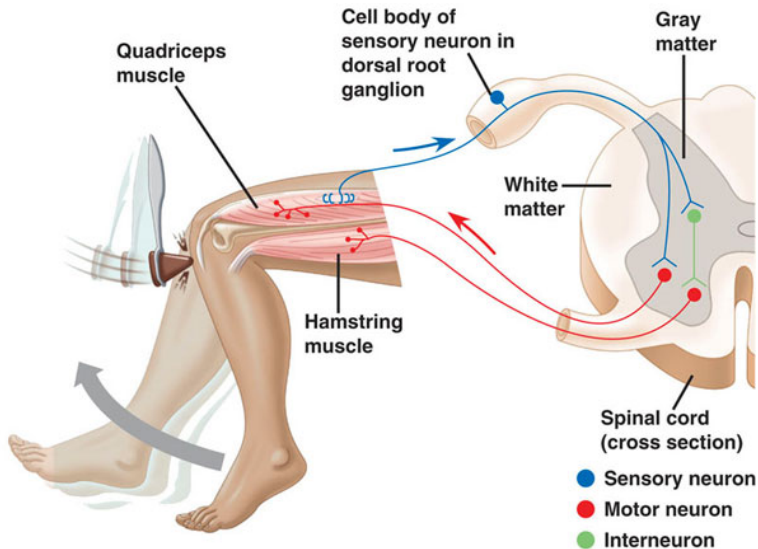
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- ▶ Afterwards, the output signal is transferred via PNS to *effectors* (e.g. muscle cells).

Biological neural network



Summation

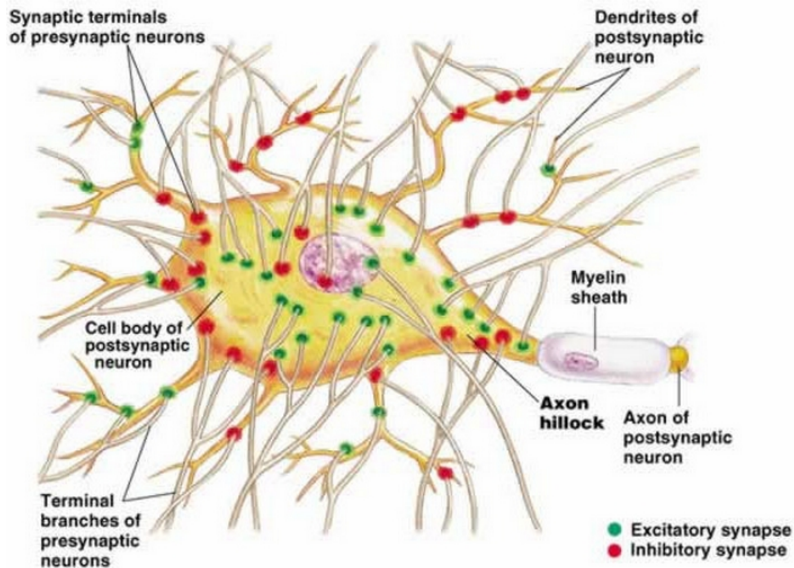
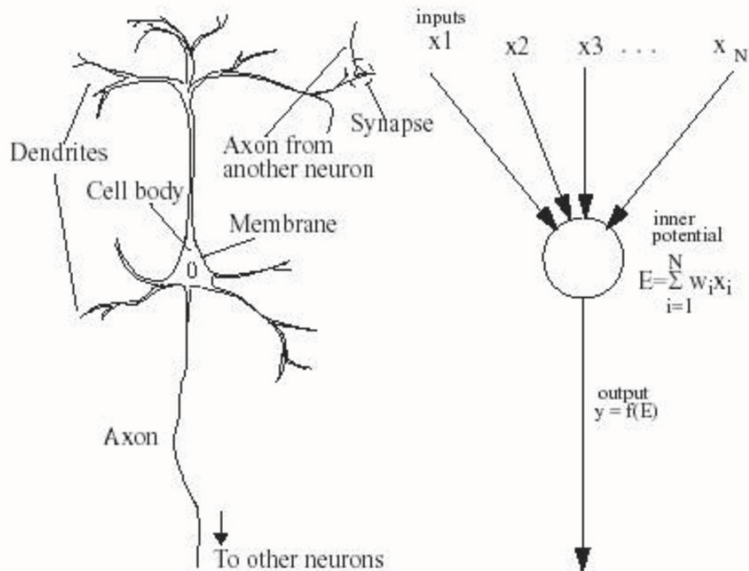


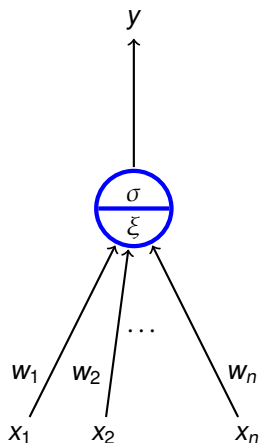
Figure 48.11(a), page 972, Campbell's *Biology*, 5th Edition

Biological and Mathematical neurons

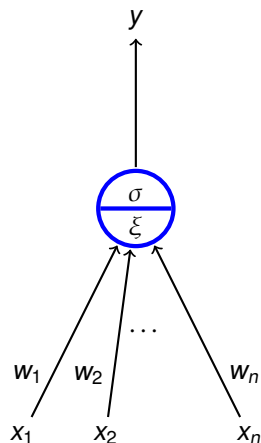


Formal neuron (without bias)

- ▶ $x_1, \dots, x_n \in \mathbb{R}$ are **inputs**

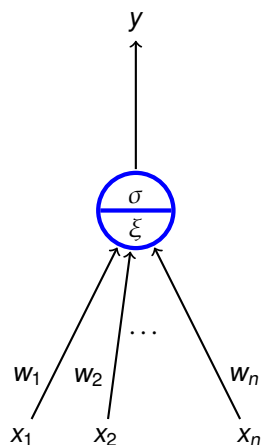


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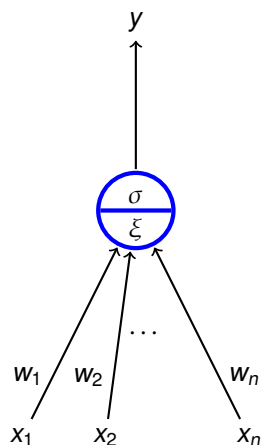
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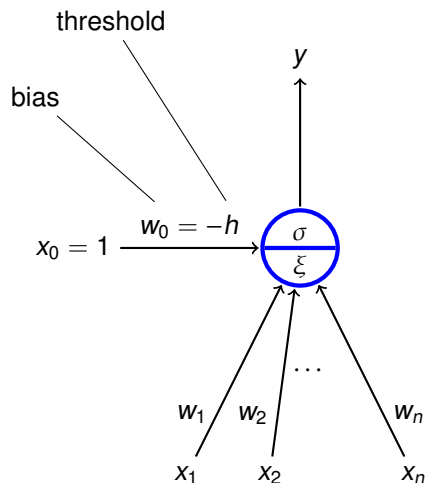
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- ▶ y is an **output** given by $y = \sigma(\xi)$
where σ is an **activation function**;
e.g. a *unit step function*

$$\sigma(\xi) = \begin{cases} 1 & \xi \geq h; \\ 0 & \xi < h. \end{cases}$$

where $h \in \mathbb{R}$ is a *threshold*.

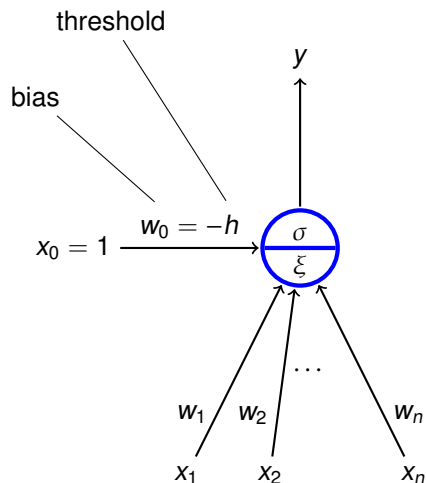
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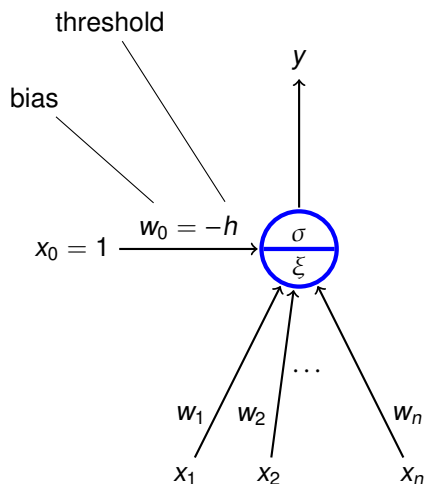


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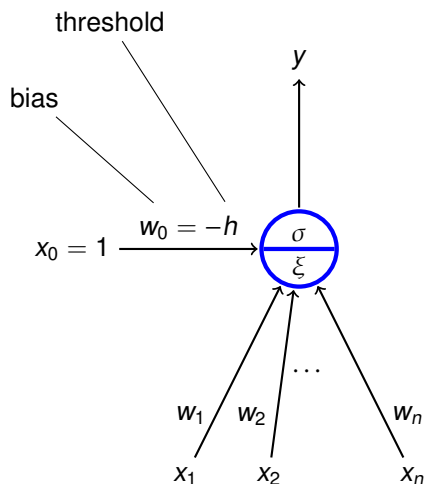


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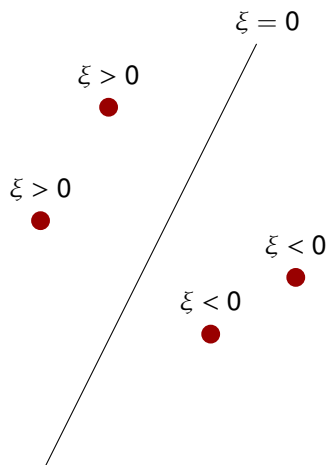


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$$\sigma(\xi) = \begin{cases} 1 & \xi \geq 0; \\ 0 & \xi < 0. \end{cases}$$

(The threshold h has been substituted with the new input $x_0 = 1$ and the weight $w_0 = -h$.)

Neuron and linear separation



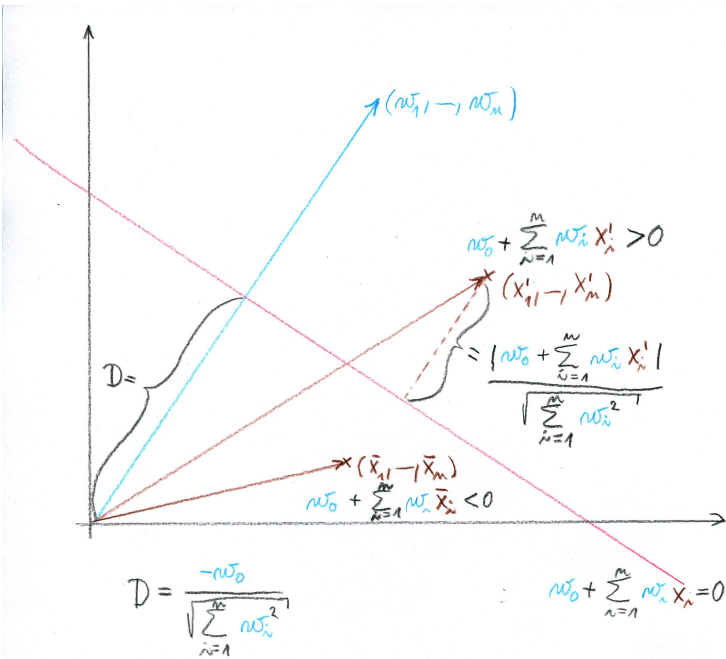
- ▶ inner potential

$$\xi = w_0 + \sum_{i=1}^n w_i x_i$$

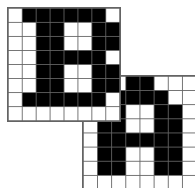
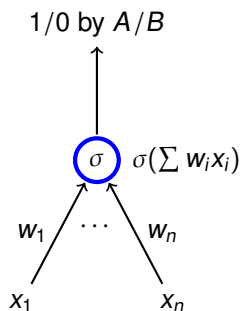
determines a separation hyperplane in the n -dimensional **input space**

- ▶ in 2d line
- ▶ in 3d plane
- ▶ ...

Neuron geometry

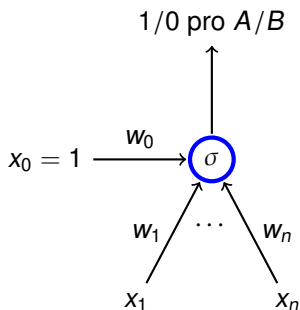
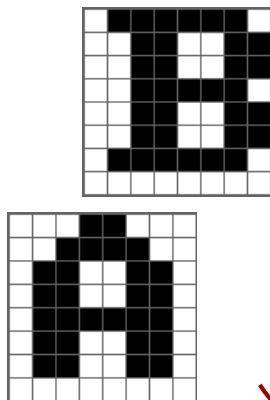


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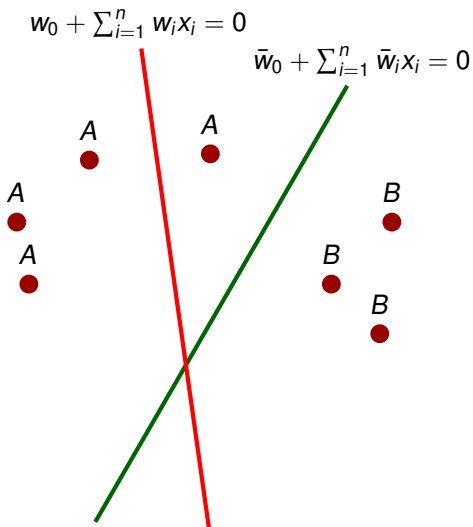
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Neuron and linear separation



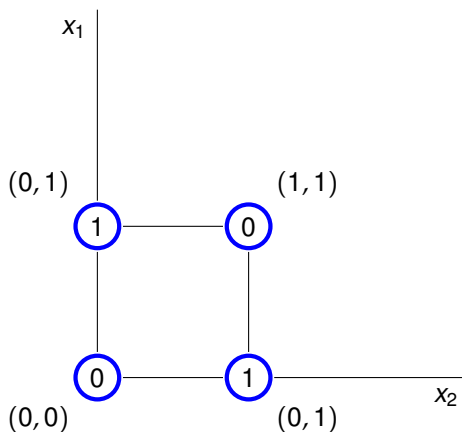
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Neuron and linear separation



- ▶ Red line classifies incorrectly
- ▶ Green line classifies correctly (may be a result of a correction by a learning algorithm)

Neuron and linear separation (XOR)



- ▶ No line separates ones from zeros.

Neural network consists of formal neurons interconnected in such a way that the output of one neuron is an input of several other neurons.

In order to describe a particular type of neural networks we need to specify:

- ▶ **Architecture**
How the neurons are connected.
- ▶ **Activity**
How the network transforms inputs to outputs.
- ▶ **Learning**
How the weights are changed during training.

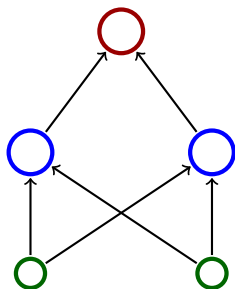
Architecture

Network architecture is given as a digraph whose nodes are neurons and edges are connections.

We distinguish several categories of neurons:

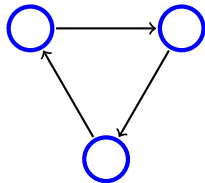
- ▶ **Output neurons**
- ▶ **Hidden neurons**
- ▶ **Input neurons**

(In general, a neuron may be both input and output; a neuron is hidden if it is neither input, nor output.)



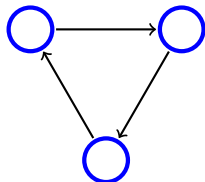
Architecture – Cycles

- ▶ A network is **cyclic** (recurrent) if its architecture contains a directed cycle.

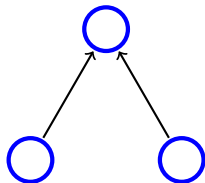


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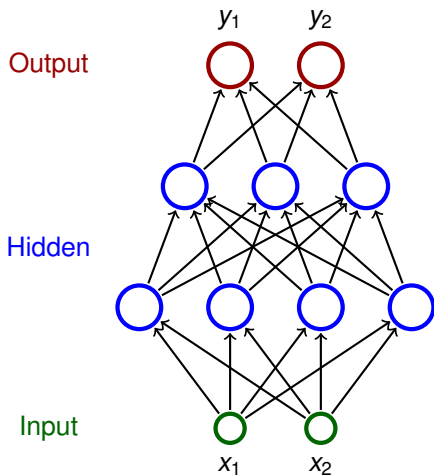
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- ▶ Otherwise it is **acyclic** (feed-forward)

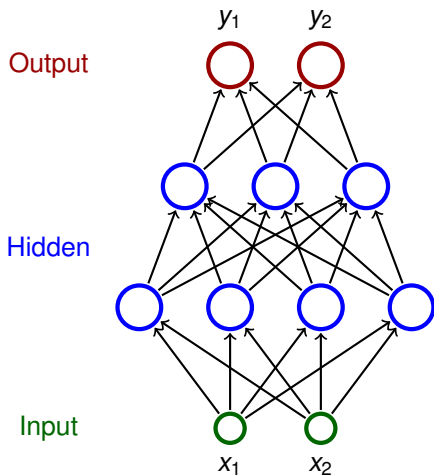


Architecture – Multilayer Perceptron (MLP)



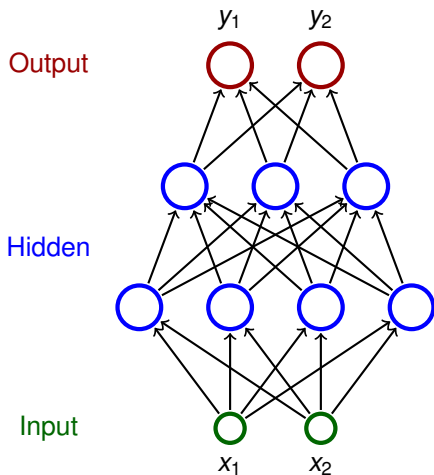
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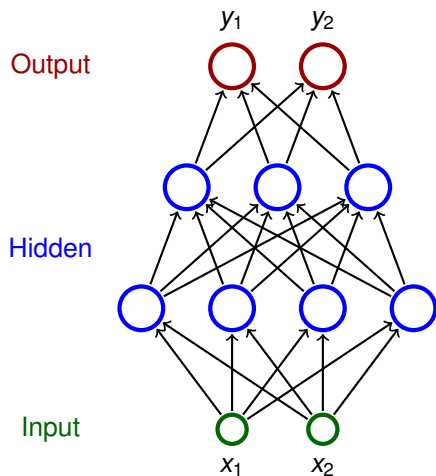
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- ▶ Neurons in the i -th layer are connected with all neurons in the $i + 1$ -st layer

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- ▶ Neurons in the i -th layer are connected with all neurons in the $i + 1$ -st layer
- ▶ Architecture of a MLP is typically described by numbers of neurons in individual layers (e.g. 2-4-3-2)

Activity

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- ▶ **Initial state**

Input neurons set to values from the network input
(each component of the network input corresponds to an input neuron)

Values of the remaining neurons set to 0.

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MLP uses the following selection rule:

In the i -th step evaluate all neurons in the i -th layer.

Activity – semantics of a network

Definition

Consider a network with n neurons, k input, ℓ output.

Let $A \subseteq \mathbb{R}^k$ and $B \subseteq \mathbb{R}^\ell$. Suppose that the network stops on every input of A .

Then we say that the network computes a function $F : A \rightarrow B$ if for every network input \vec{x} the vector $F(\vec{x}) \in B$ is the output of the network after the computation on \vec{x} stops.

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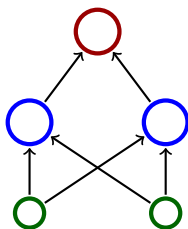
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Example 1

This network computes a function from \mathbb{R}^2 to \mathbb{R} .



Activity – inner potential and activation functions

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There are special types of neural networks where the inner potential is computed differently, e.g., as a "distance" of an input from the weight vector:

$$\xi = \|\vec{x} - \vec{w}\|$$

here $\|\cdot\|$ is a vector norm, typically Euclidean.

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There are many activation functions, typical examples:

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- ▶ (Logistic) sigmoid

$$\sigma(\xi) = \frac{1}{1 + e^{-\lambda \cdot \xi}} \quad \text{here } \lambda \in \mathbb{R} \text{ is a } \textit{steepness} \text{ parameter.}$$

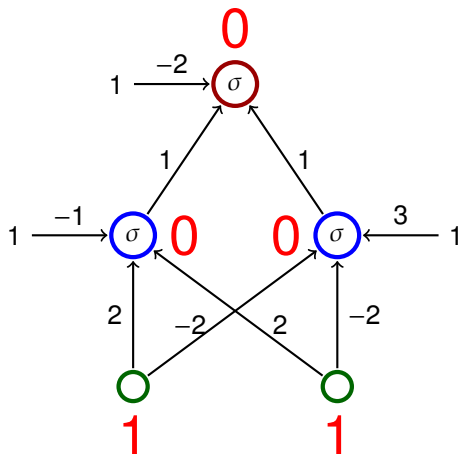
- ▶ Hyperbolic tangens

$$\sigma(\xi) = \frac{1 - e^{-\xi}}{1 + e^{-\xi}}$$

- ▶ ReLU

$$\sigma(\xi) = \max(\xi, 0)$$

Activity – XOR



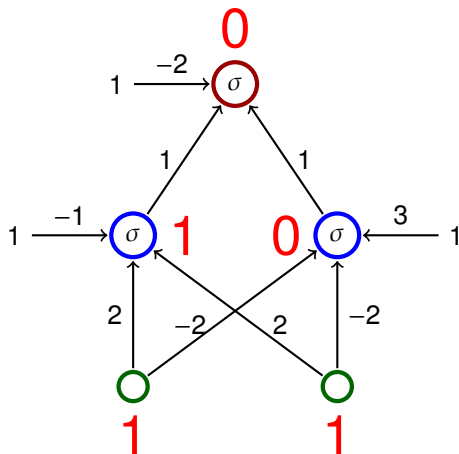
- ▶ Activation function is a unit step function

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- ▶ The network computes $XOR(x_1, x_2)$

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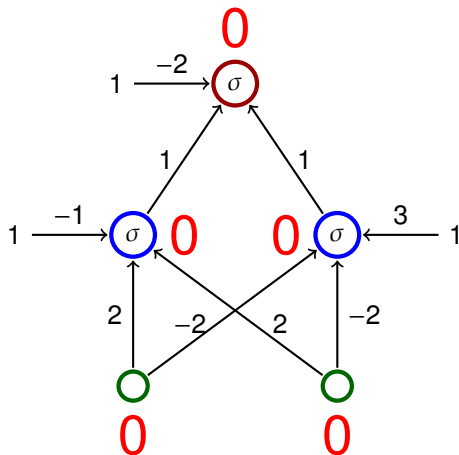
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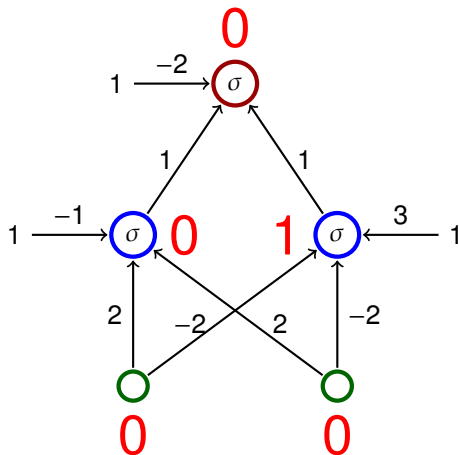
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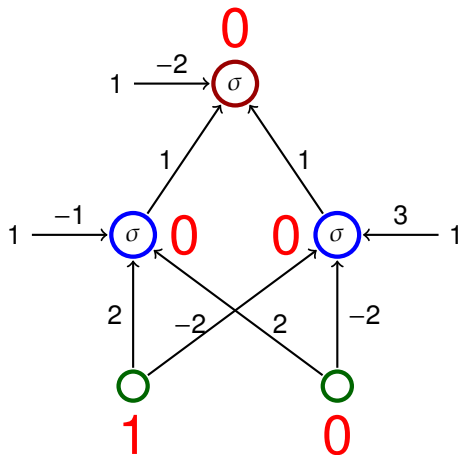
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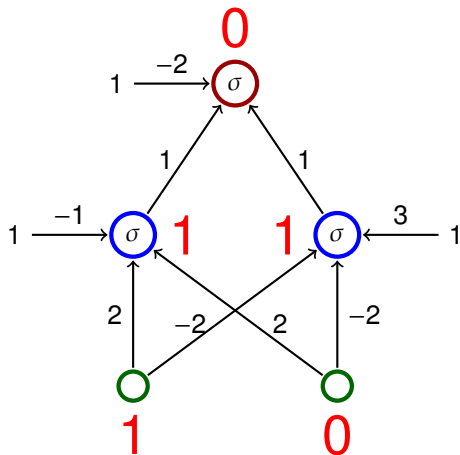
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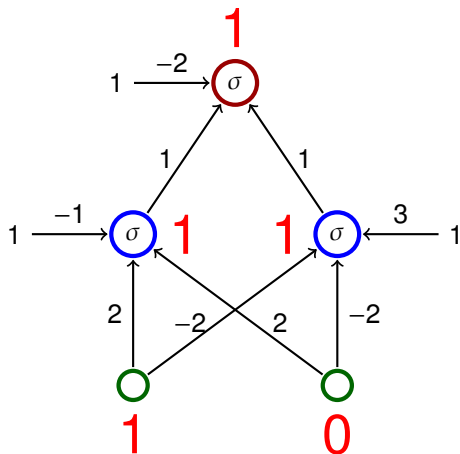
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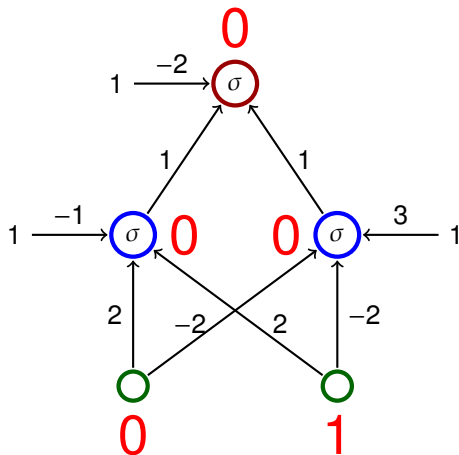
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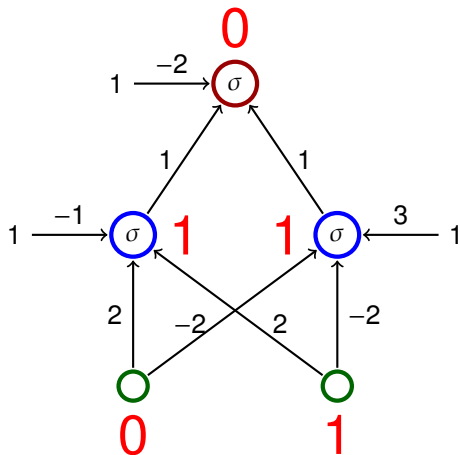
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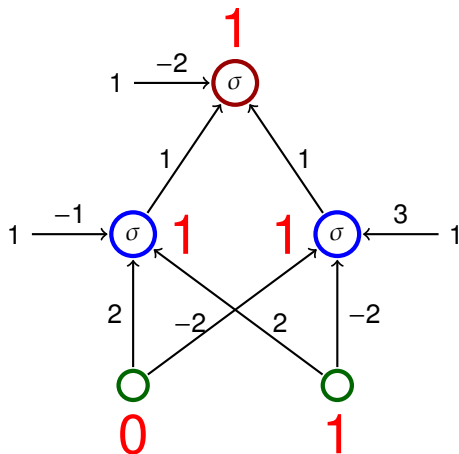
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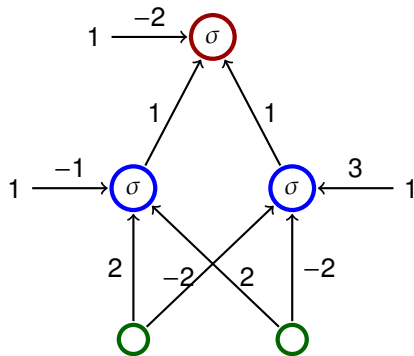
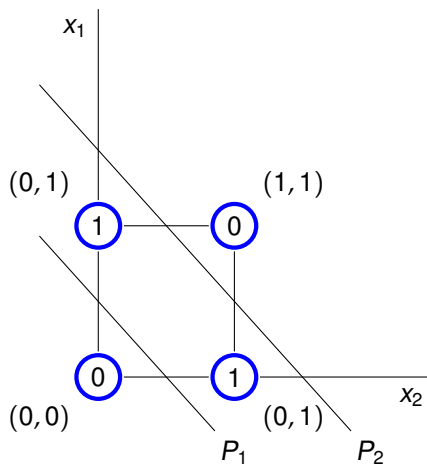
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Activity – MLP and linear separation



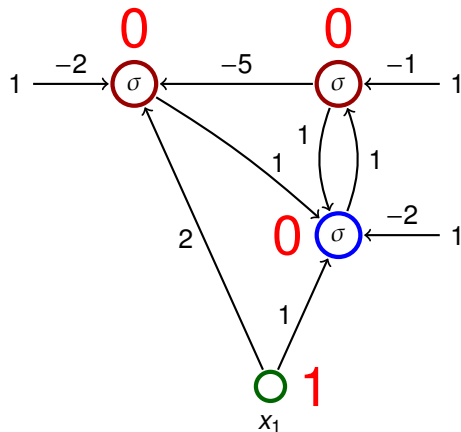
- ▶ The line P_1 is given by $-1 + 2x_1 + 2x_2 = 0$
- ▶ The line P_2 is given by $3 - 2x_1 - 2x_2 = 0$

Activity – example

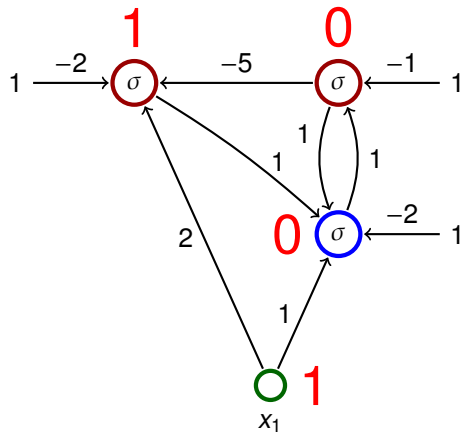
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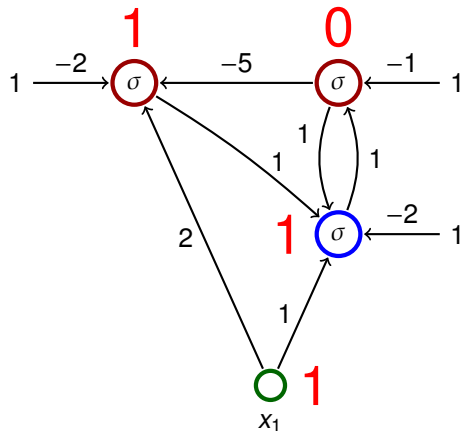
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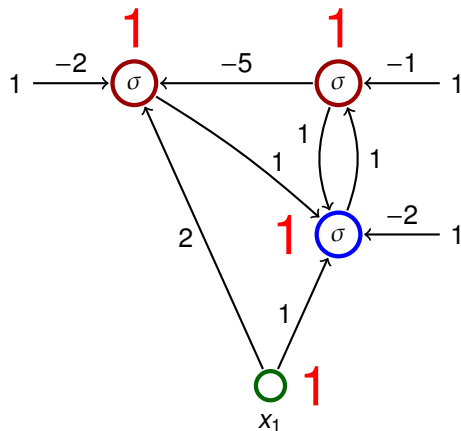


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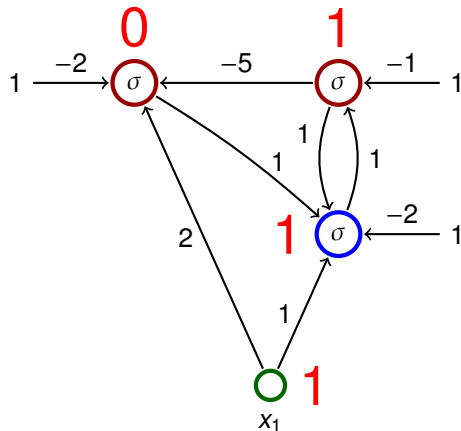


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- ▶ **initial configuration**

weights can be initialized randomly or using some sophisticated algorithm

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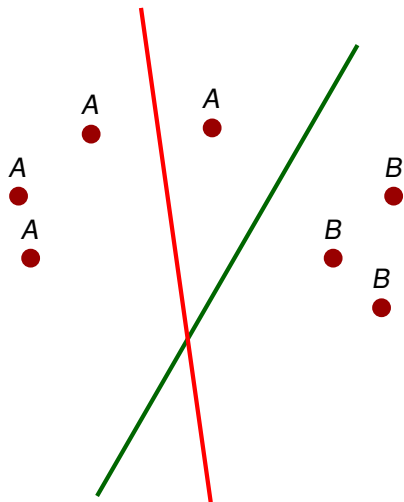
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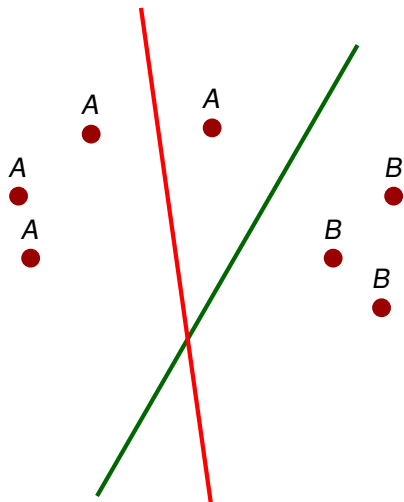
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- ▶ Unsupervised learning
 - ▶ The training set contains only inputs.
 - ▶ The goal is to determine distribution of the inputs (clustering, deep belief networks, etc.)

Supervised learning – illustration

- ▶ classification in the plane using a single neuron

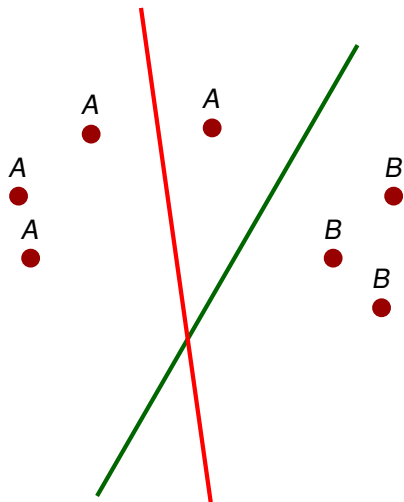


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- ▶ training examples are of the form (point, value) where the value is either 1, or 0 depending on whether the point is either *A*, or *B*
- ▶ the algorithm considers examples one after another
- ▶ whenever an incorrectly classified point is considered, the learning algorithm turns the line in the direction of the point

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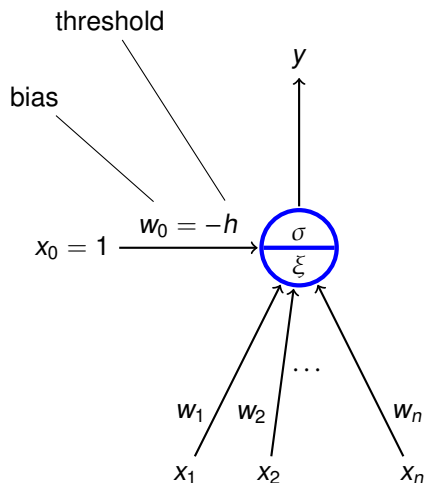
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 - ▶ "close" inputs typically get similar values
- ▶ Graceful degradation
 - ▶ damage typically causes only a decrease in precision of results

Expressive power of neural networks

Formal neuron (with bias)



- ▶ $x_0 = 1, x_1, \dots, x_n \in \mathbb{R}$ are **inputs**
- ▶ $w_0, w_1, \dots, w_n \in \mathbb{R}$ are **weights**
- ▶ ξ is an **inner potential**;
almost always $\xi = w_0 + \sum_{i=1}^n w_i x_i$
- ▶ y is an **output** given by $y = \sigma(\xi)$
where σ is an **activation function**;
e.g. a *unit step function*

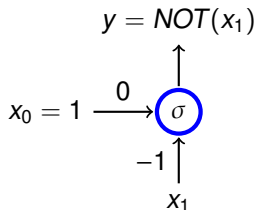
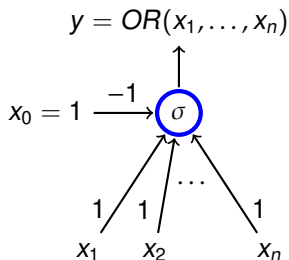
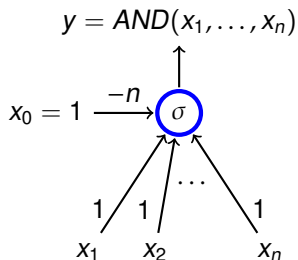
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Boolean functions

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Theorem

Let σ be the unit step function. Two layer MLPs, where each neuron has σ as the activation function, are able to compute all functions of the form $F : \{0, 1\}^n \rightarrow \{0, 1\}$.

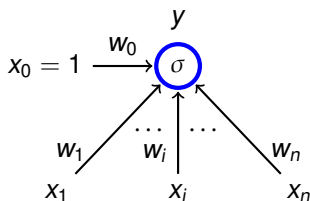
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Proof.

- ▶ Given a vector $\vec{v} = (v_1, \dots, v_n) \in \{0, 1\}^n$, consider a neuron $N_{\vec{v}}$ whose output is 1 iff the input is \vec{v} :

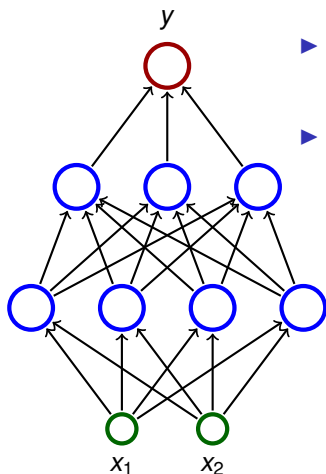


$$w_0 = -\sum_{i=1}^n v_i$$

$$w_i = \begin{cases} 1 & v_i = 1 \\ -1 & v_i = 0 \end{cases}$$

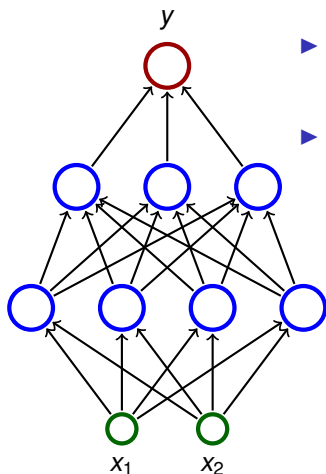
- ▶ Now let us connect all outputs of all neurons $N_{\vec{v}}$ satisfying $F(\vec{v}) = 1$ using a neuron implementing *OR*. □

Non-linear separation



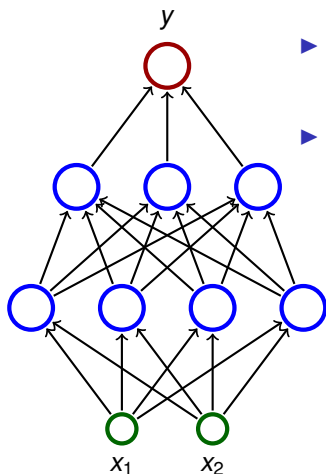
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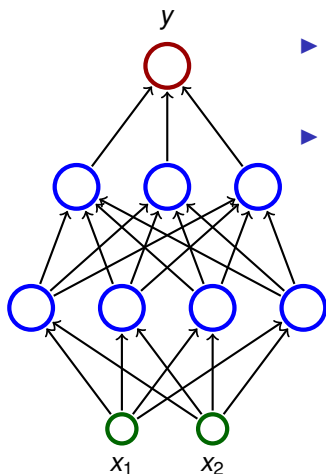
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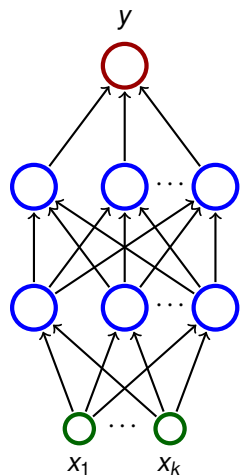
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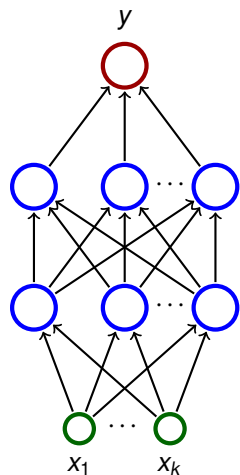
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 - ▶ The third layer may e.g. make unions of some convex sets.

Non-linear separation – illustration



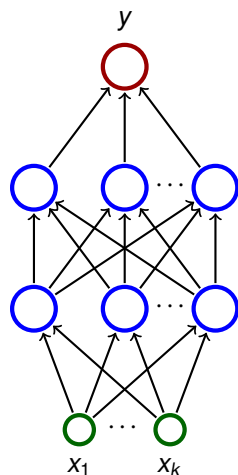
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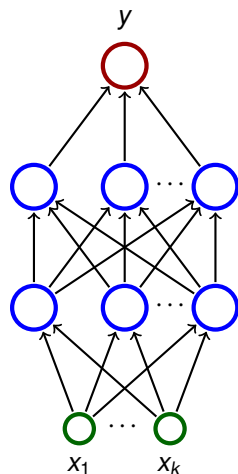
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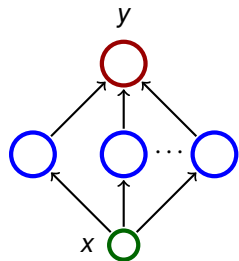
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 - ▶ Finally, connect outputs of the nets N_K satisfying $K \cap A \neq \emptyset$ using a neuron implementing *OR*.

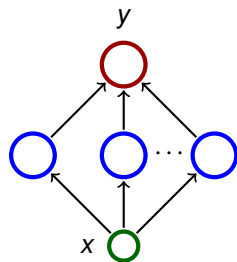
Power of ReLU



Consider a two layer network

- ▶ with a single input and single output;
- ▶ hidden neurons with the ReLU activation:
 $\sigma(\xi) = \max(\xi, 0)$;
- ▶ the output neuron with identity activation:
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Power of ReLU

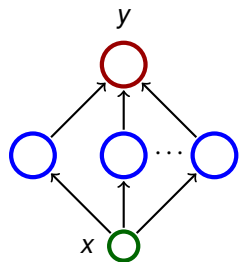


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Power of ReLU



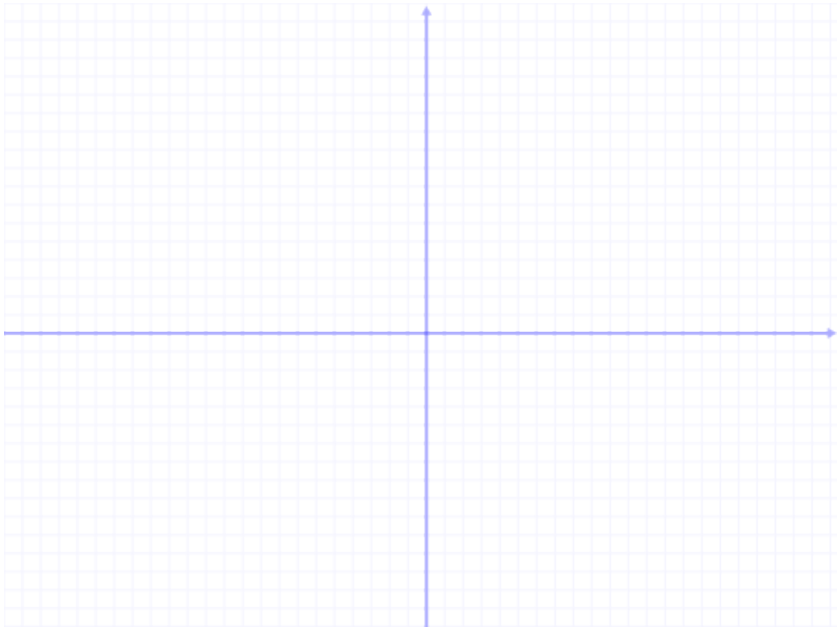
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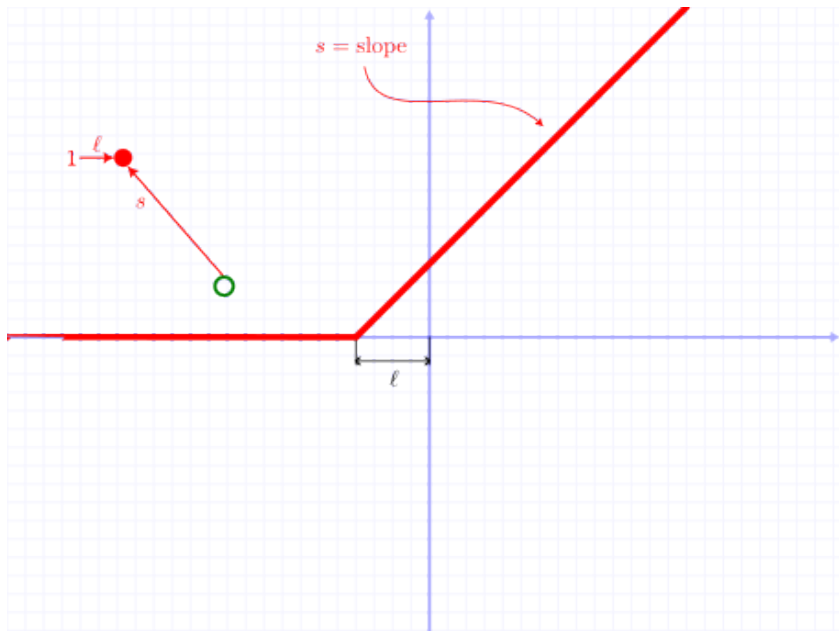
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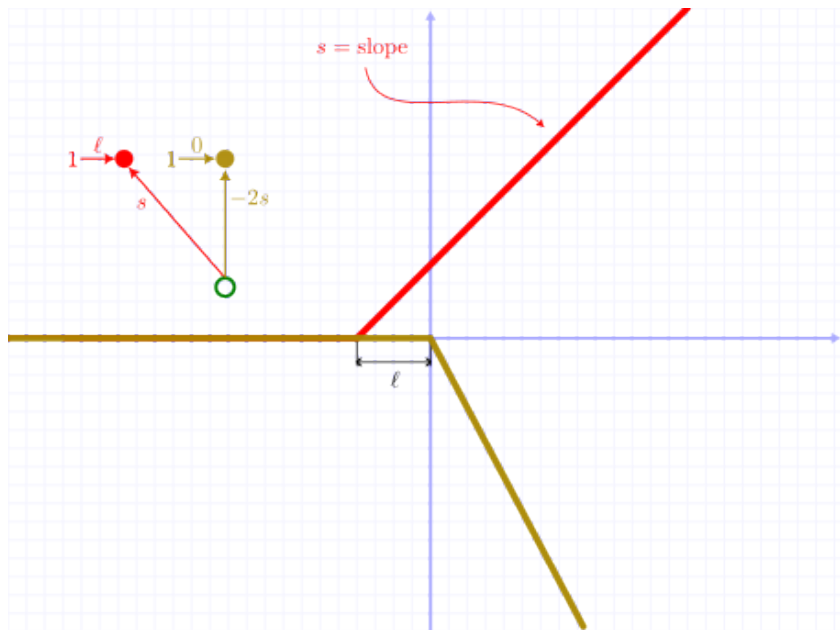
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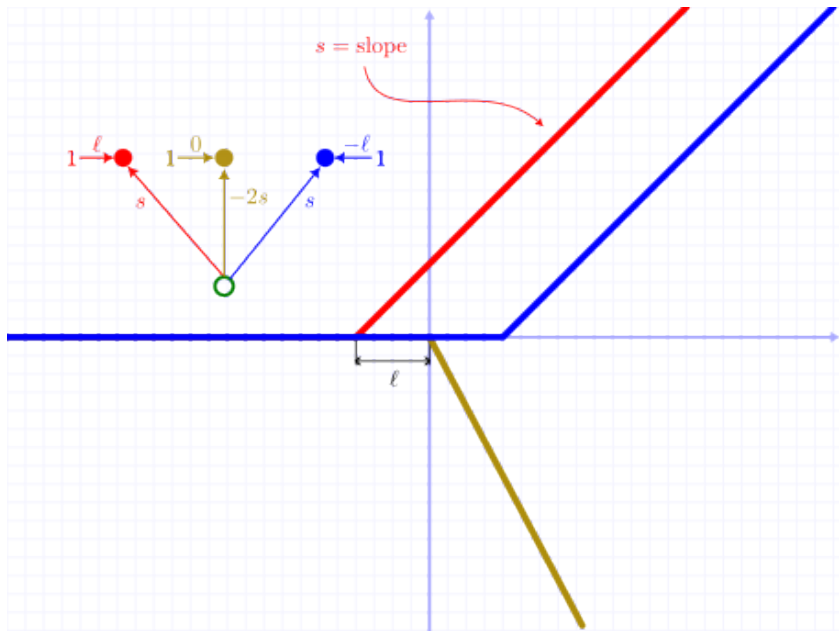
For every open subset $A \subseteq [0, 1]$ there is a network of the above type such that for "most" $x \in [0, 1]$ we have that $x \in A$ iff the network's output is > 0 for the input x .

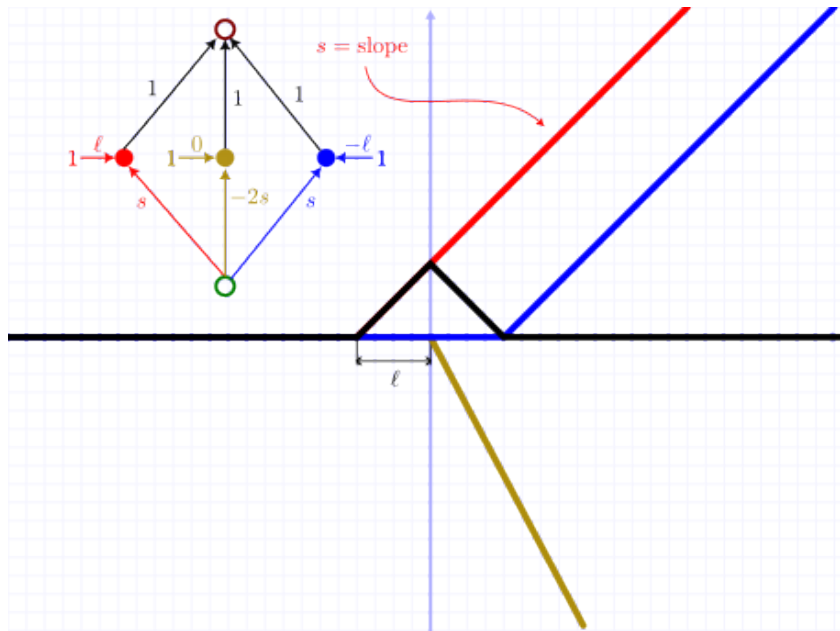
Just consider a continuous function f where $f(x)$ is the minimum difference between x and a point on the boundary of A . Then uniformly approximate f using the networks.

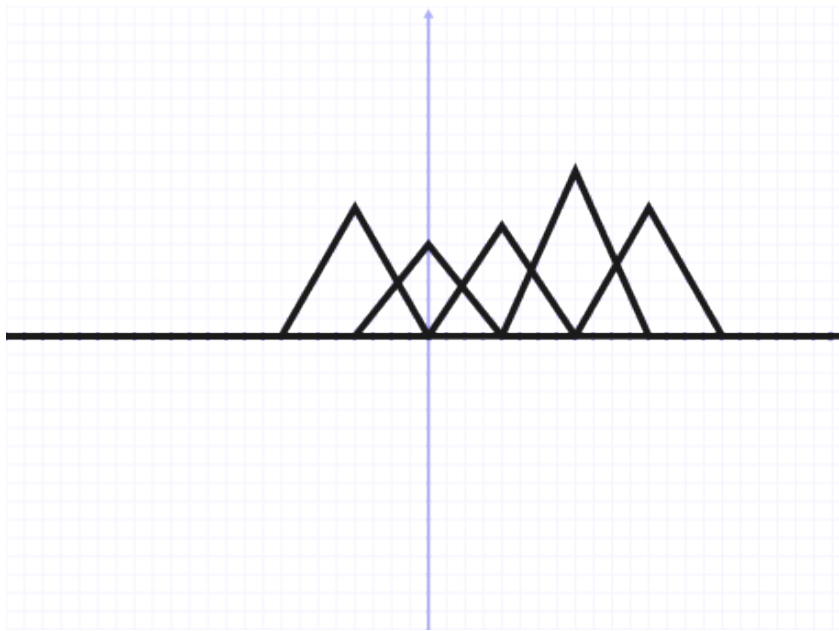


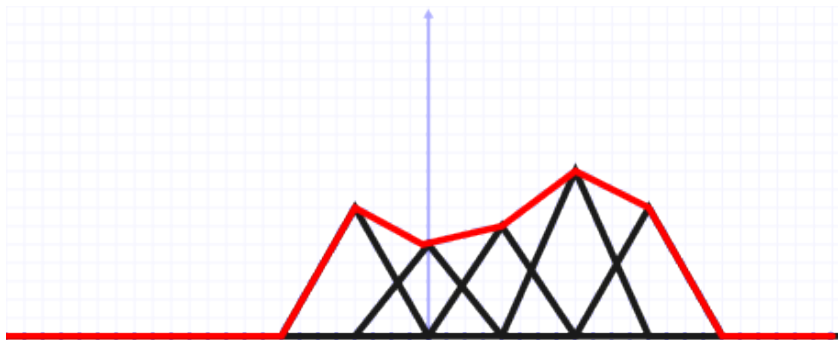












Red = sum of black

Non-linear separation - sigmoid

Theorem (Cybenko 1989 - informal version)

Let σ be a continuous function which is sigmoidal, i.e. satisfies

$$\sigma(x) = \begin{cases} 1 & \text{for } x \rightarrow +\infty \\ 0 & \text{for } x \rightarrow -\infty \end{cases}$$

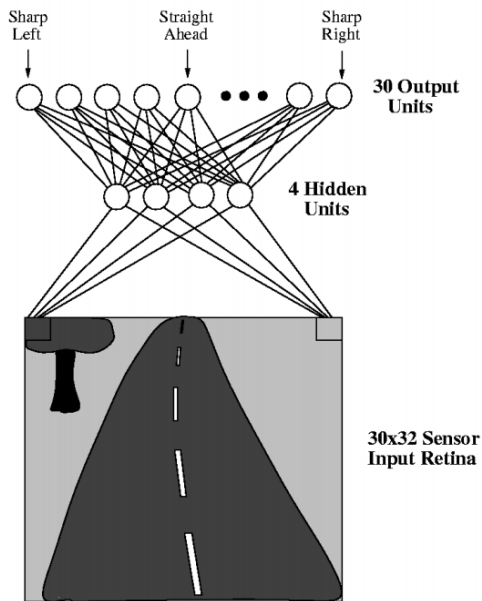
For every "reasonable" set $A \subseteq [0, 1]^n$, there is a **two layer network** where each hidden neuron has the activation function σ (output neurons are linear), that satisfies the following:

For "most" vectors $\vec{v} \in [0, 1]^n$ we have that $\vec{v} \in A$ iff the network output is > 0 for the input \vec{v} .

For mathematically oriented:

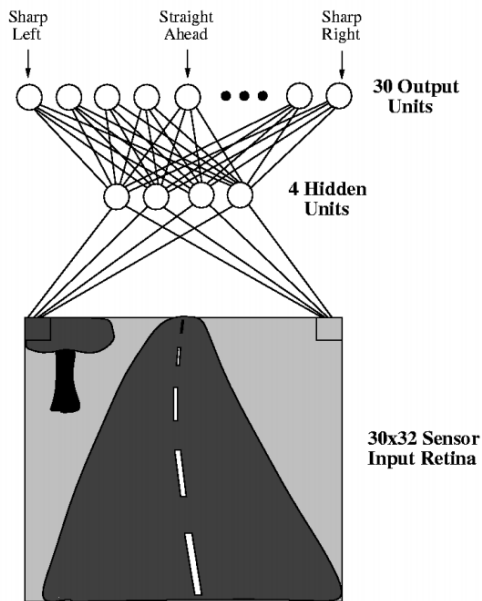
- ▶ "reasonable" means Lebesgue measurable
- ▶ "most" means that the set of incorrectly classified vectors has the Lebesgue measure smaller than a given $\varepsilon > 0$

Non-linear separation - practical illustration



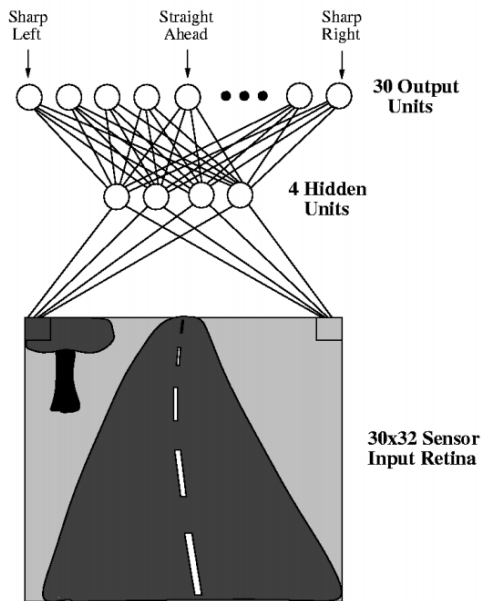
► ALVINN drives a car

Non-linear separation - practical illustration



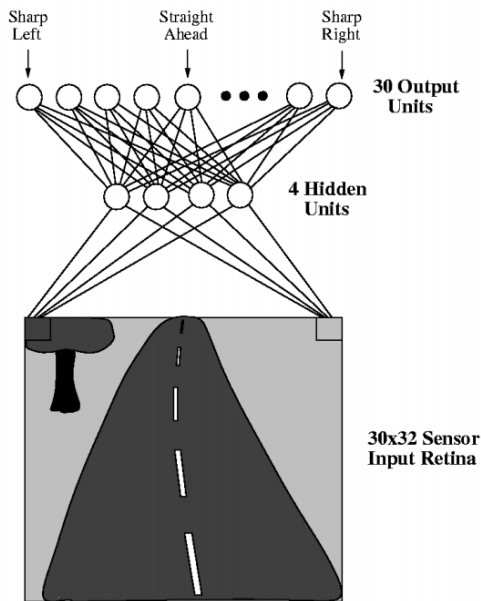
- ▶ ALVINN drives a car
- ▶ The net has $30 \times 32 = 960$ inputs (the input space is thus \mathbb{R}^{960})

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- ▶ ALVINN drives a car
- ▶ The net has $30 \times 32 = 960$ inputs (the input space is thus \mathbb{R}^{960})
- ▶ Input values correspond to shades of gray of pixels.
- ▶ Output neurons "classify" images of the road based on their "curvature".

Function approximation - two-layer networks

Theorem (Cybenko 1989)

Let σ be a continuous function which is sigmoidal, i.e., is increasing and satisfies

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For every continuous function $f : [0, 1]^n \rightarrow [0, 1]$ and every $\varepsilon > 0$ there is a function $F : [0, 1]^n \rightarrow [0, 1]$ computed by a **two layer network** where each hidden neuron has the activation function σ (output neurons are linear), that satisfies the following

$$|f(\vec{v}) - F(\vec{v})| < \varepsilon \quad \text{for every } \vec{v} \in [0, 1]^n.$$

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- ▶ We encode words $\omega \in \{0, 1\}^+$ into numbers as follows:

$$\delta(\omega) = \sum_{i=1}^{|\omega|} \frac{\omega(i)}{2^i} + \frac{1}{2^{|\omega|+1}}$$

E.g. $\omega = 11001$ gives $\delta(\omega) = \frac{1}{2} + \frac{1}{2^2} + \frac{1}{2^5} + \frac{1}{2^6}$
(= 0.110011 in binary form).

Neural networks and computability

A network **recognizes** a language $L \subseteq \{0, 1\}^+$ if it computes a function $F : A \rightarrow \mathbb{R}$ ($A \subseteq \mathbb{R}$) such that

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 - ▶ For every recursively enumerable language $L \subseteq \{0, 1\}^+$ there is a recurrent network with rational weights and less than 1000 neurons, which recognizes L .
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Summary of theoretical results

- ▶ Neural networks are very strong from the point of view of theory:
 - ▶ All Boolean functions can be expressed using two-layer networks.
 - ▶ Two-layer networks may approximate any continuous function.
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Summary of theoretical results

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 - ▶ All Boolean functions can be expressed using two-layer networks.
 - ▶ Two-layer networks may approximate any continuous function.
 - ▶ Recurrent networks are at least as strong as Turing machines.
- ▶ These results are purely theoretical!
 - ▶ "Theoretical" networks are extremely huge.
 - ▶ It is very difficult to handcraft them even for simplest problems.
- ▶ From practical point of view, the most important advantages of neural networks are: learning, generalization, robustness.

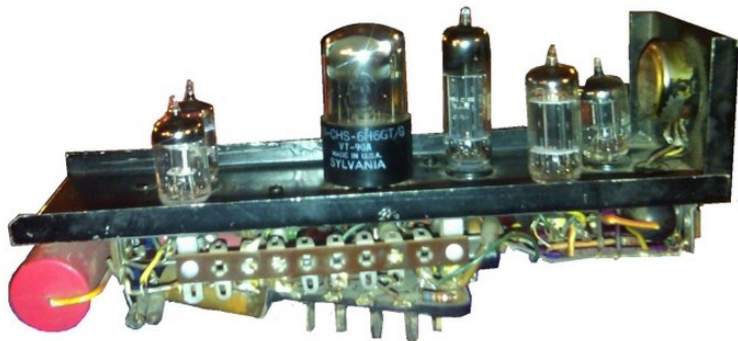
Neural networks vs classical computers

	Neural networks	"Classical" computers
Data	implicitly in weights	explicitly
Computation	naturally parallel	sequential, localized
Robustness	robust w.r.t. input corruption & damage	changing one bit may completely crash the computation
Precision	imprecise, network recalls a training example "similar" to the input	(typically) precise
Programming	learning	manual

History & implementations

History of neurocomputers

- ▶ 1951: SNARC (Minski et al)
 - ▶ the first implementation of neural network
 - ▶ a rat strives to exit a maze
 - ▶ 40 artificial neurons (300 vacuum tubes, engines, etc.)



History of neurocomputers

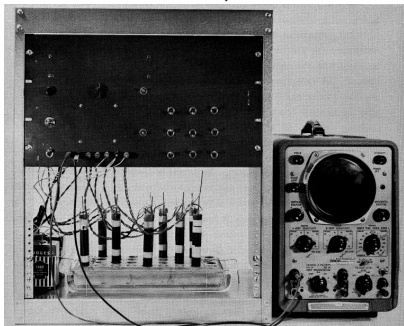
- ▶ 1957: Mark I Perceptron (Rosenblatt et al) - the first successful network for image recognition



- ▶ single layer network
- ▶ image represented by 20×20 photocells
- ▶ intensity of pixels was treated as the input to a perceptron (basically the formal neuron), which recognized figures
- ▶ weights were implemented using potentiometers, each set by its own engine
- ▶ it was possible to arbitrarily reconnect inputs to neurons to demonstrate adaptability

History of neurocomputers

- ▶ 1960: ADALINE (Widrow & Hof)



- ▶ single layer neural network
- ▶ weights stored in a newly invented electronic component **memistor**, which remembers history of electric current in the form of resistance.
- ▶ Widrow founded a company Memistor Corporation, which sold implementations of neural networks.
- ▶ 1960-66: several companies concerned with neural networks were founded.

History of neurocomputers

- ▶ 1967-82: dead still after publication of a book by Minski & Papert (published 1969, title *Perceptrons*)
- ▶ 1983-end of 90s: revival of neural networks
 - ▶ many attempts at hardware implementations
 - ▶ application specific chips (ASIC)
 - ▶ programmable hardware (FPGA)
 - ▶ hw implementations typically not better than "software" implementations on universal computers (problems with weight storage, size, speed, cost of production etc.)

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- ▶ end of 90s-cca 2005: NN suppressed by other machine learning methods (support vector machines (SVM))
- ▶ 2006-now: The boom of neural networks!
 - ▶ deep networks – often better than any other method
 - ▶ GPU implementations
 - ▶ ... specialized hw implementations (Google's TPU)

Some highlights

- ▶ Breakthrough in image recognition.
Accuracy of image recognition improved by an order of magnitude in 5 years.
- ▶ Breakthrough in game playing.
Superhuman results in Go and Chess almost without any human intervention. Master level in Starcraft, poker, etc.
- ▶ Breakthrough in machine translation.
Switching to deep learning produced a 60% increase in translation accuracy compared to the phrase-based approach previously used in Google Translate (in human evaluation)
- ▶ Breakthrough in speech processing.
- ▶ Breakthrough in text generation.
GPT-4 generates pretty realistic articles, short plays (for a theatre) have been successfully generated, etc.

Example

This slide was automatically generated by asking GPT-4 "Give me a beamer slide with complexity of Steepest descent, Neton's method and BFGS".

Computational Complexity

Algorithm	Computational Complexity
Steepest Descent	$O(n)$ per iteration
Newton's Method	$O(n^3)$ to compute Hessian and solve system
BFGS	$O(n^2)$ to update Hessian approximation

Table: Summary of the computational complexity for each optimization algorithm.

- ▶ Steepest Descent: Simple but often slow, requiring many iterations.
- ▶ Newton's Method: Fast convergence but expensive per iteration.
- ▶ BFGS: Quasi-Newton, no Hessian needed, good speed and iteration count balance.

Example Source

```
\begin{frame}{Computational Complexity}
\begin{table}
\begin{tabular}{l c}
\hline
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```


History in waves ...

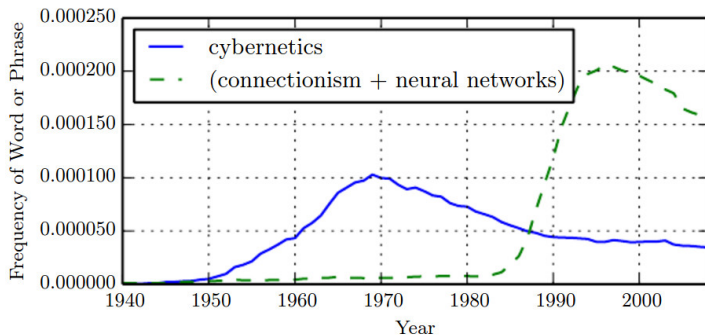
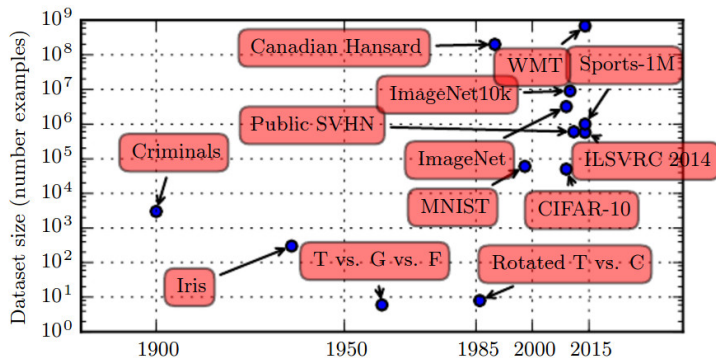


Figure: The figure shows two of the three historical waves of artificial neural nets research, as measured by the frequency of the phrases "cybernetics" and "connectionism" or "neural networks" according to Google Books (the third wave is too recent to appear).

Current hardware – What do we face?

Increasing dataset size ...



... weakly-supervised pre-training using hashtags from the Instagram uses $3.6 * 10^9$ images.

Revisiting Weakly Supervised Pre-Training of Visual Perception Models. Singh et al.

<https://arxiv.org/pdf/2201.08371.pdf>, 2022

GPT-3 Training Dataset

45 TB text data from multiple sources

<i>Dataset</i>	Quantity (tokens)	Weight in training mix	Epochs elapsed when training for 300B tokens
<i>Common Crawl (filtered)</i>	410 billion	60%	0.44
<i>WebText2</i>	19 billion	22%	2.9
<i>Books1</i>	12 billion	8%	1.9
<i>Books2</i>	55 billion	8%	0.43
<i>Wikipedia</i>	3 billion	3%	3.4

Common Crawl corpus contains petabytes of data collected over 8 years of web crawling. The corpus contains raw web page data, metadata extracts and text extracts with light filtering.

WebText2 is the text of web pages from all outbound Reddit links from posts with 3+ upvotes.

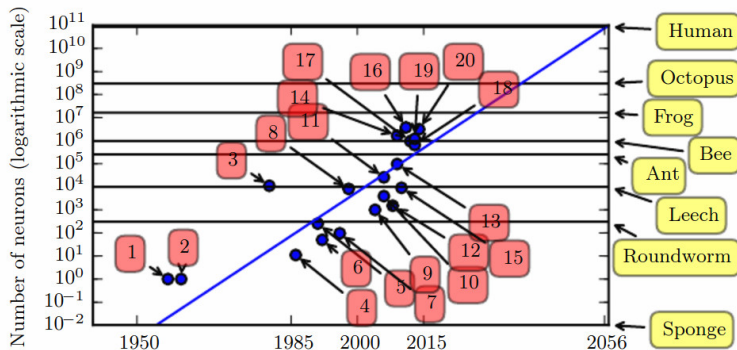
Books1 & Books2 are two internet-based books corpora.

Wikipedia pages in the English language are also part of the training corpus.

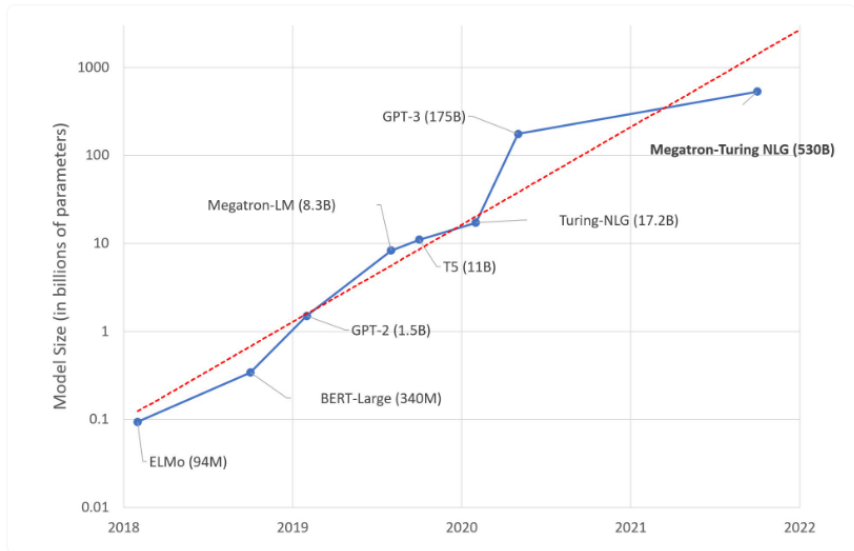
Source: Kindra Cooper. OpenAI GPT-3: Everything You Need to Know. Springboard. 2023

Current hardware – What do we face?

... and thus increasing size of neural networks ...



2. ADALINE
4. Early back-propagation network (Rumelhart et al., 1986b)
8. Image recognition: LeNet-5 (LeCun et al., 1998b)
10. Dimensionality reduction: Deep belief network (Hinton et al., 2006)
... here the third "wave" of neural networks started
15. Digit recognition: GPU-accelerated multilayer perceptron (Ciresan et al., 2010)
18. Image recognition (AlexNet): Multi-GPU convolutional network (Krizhevsky et al., 2012)
20. Image recognition: GoogLeNet (Szegedy et al., 2014a)



GPT-4's Scale: GPT-4 has 1.8 trillion parameters across 120 layers, which is over 10 times larger than GPT-3.

Current hardware – What do we face?

... as a reward we get this ...

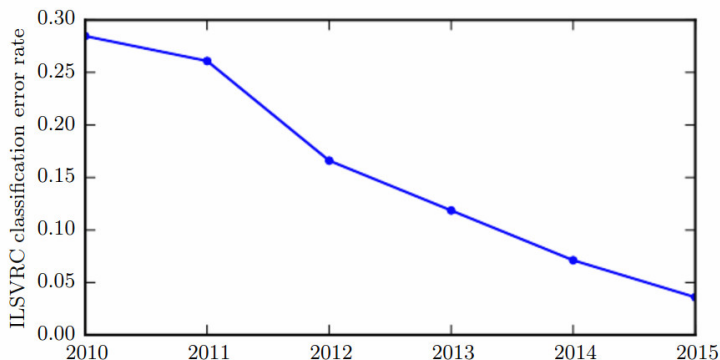


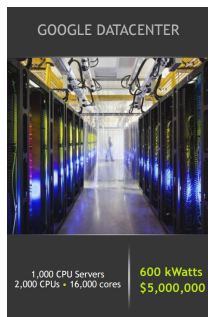
Figure: Since deep networks reached the scale necessary to compete in the ImageNet Large Scale Visual Recognition Challenge, they have consistently won the competition every year, and yielded lower and lower error rates each time. Data from Russakovsky et al. (2014b) and He et al. (2015).

Current hardware

In 2012, Google trained a large network of 1.7 billion weights and 9 layers

The task was image recognition (10 million youtube video frames)

The hw comprised a 1000 computer network (16 000 cores), computation took three days.



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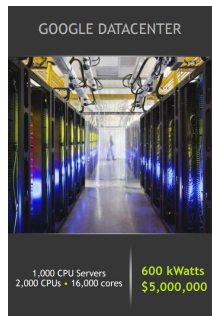
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In 2014, similar task performed on Commodity Off-The-Shelf High Performance Computing (COTS HPC) technology: a cluster of GPU servers with Infiniband interconnects and MPI.

Able to train 1 billion parameter networks on just 3 machines in a couple of days.

Able to scale to 11 billion weights (approx. 6.5 times larger than the Google model) on 16 GPUs.

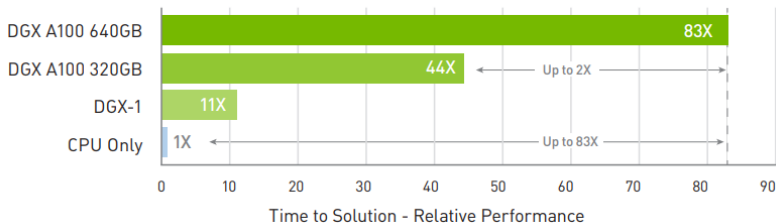


Current hardware – NVIDIA DGX Station

- ▶ 8x GPU (Nvidia A100 80GB Tensor Core)
- ▶ 5 petaFLOPS
- ▶ System memory: 2 TB
- ▶ Network: 200 Gb/s InfiniBand



Up to 83X Higher Throughput than CPU, 2X Higher Throughput than DGX A100 320GB on Big Data Analytics Benchmark



Deep learning in clouds

Big companies offer cloud services for deep learning:

- ▶ Amazon Web Services
- ▶ Google Cloud
- ▶ Deep Cognition
- ▶ ...

Advantages:

- ▶ Do not have to care (too much) about technical problems.
- ▶ Do not have to buy and optimize highend hw/sw, networks etc.
- ▶ Scaling & virtually limitless storage.

Disadvantages:

- ▶ Do not have full control.
- ▶ Performance can vary, connectivity problems.
- ▶ Have to pay for services.
- ▶ Privacy issues.

Current software

- ▶ **TensorFlow** (Google)
 - ▶ open source software library for numerical computation using data flow graphs
 - ▶ allows implementation of most current neural networks
 - ▶ allows computation on multiple devices (CPUs, GPUs, ...)
 - ▶ Python API
 - ▶ **Keras**: a part of TensorFlow that allows easy description of most modern neural networks
- ▶ **PyTorch** (Facebook)
 - ▶ similar to TensorFlow
 - ▶ object oriented
 - ▶ ... majority of new models in research papers implemented in PyTorch

<https://www.cioinsight.com/big-data/pytorch-vs-tensorflow/>

- ▶ **Theano (dead)**:
 - ▶ The "academic" grand-daddy of deep-learning frameworks, written in Python. Strongly inspired TensorFlow (some people developing Theano moved on to develop TensorFlow).
- ▶ There are others: Caffe, Deeplearning4j, ...

Current software – Keras

```
from keras.models import Sequential
from keras.layers import Dense, Dropout, Activation
from keras.optimizers import SGD

model = Sequential()
# Dense(64) is a fully-connected layer with 64 hidden units.
# in the first layer, you must specify the expected input data shape
# here, 20-dimensional vectors.
model.add(Dense(64, input_dim=20, init='uniform'))
model.add(Activation('tanh'))
model.add(Dropout(0.5))
model.add(Dense(64, init='uniform'))
model.add(Activation('tanh'))
model.add(Dropout(0.5))
model.add(Dense(10, init='uniform'))
model.add(Activation('softmax'))

sgd = SGD(lr=0.1, decay=1e-6, momentum=0.9, nesterov=True)
model.compile(loss='categorical_crossentropy',
              optimizer=sgd,
              metrics=['accuracy'])

model.fit(X_train, y_train,
          nb_epoch=20,
          batch_size=16)
score = model.evaluate(X_test, y_test, batch_size=16)
```

Current software – Keras functional API

```
from keras.layers import Input, Dense
from keras.models import Model

# This returns a tensor
inputs = Input(shape=(784,))

# a layer instance is callable on a tensor, and returns a tensor
output_1 = Dense(64, activation='relu')(inputs)
output_2 = Dense(64, activation='relu')(output_1)
predictions = Dense(10, activation='softmax')(output_2)

# This creates a model that includes
# the Input layer and three Dense layers
model = Model(inputs=inputs, outputs=predictions)
model.compile(optimizer='rmsprop',
              loss='categorical_crossentropy',
              metrics=['accuracy'])
model.fit(data, labels) # starts training
```

Current software – TensorFlow

```
41 # tf Graph input
42 X = tf.placeholder("float", [None, n_input])
43 Y = tf.placeholder("float", [None, n_classes])
44
45 # Store layers weight & bias
46 weights = {
47     'h1': tf.Variable(tf.random_normal([n_input, n_hidden_1])),
48     'h2': tf.Variable(tf.random_normal([n_hidden_1, n_hidden_2])),
49     'out': tf.Variable(tf.random_normal([n_hidden_2, n_classes]))
50 }
51 biases = {
52     'b1': tf.Variable(tf.random_normal([n_hidden_1])),
53     'b2': tf.Variable(tf.random_normal([n_hidden_2])),
54     'out': tf.Variable(tf.random_normal([n_classes]))
55 }
```

Current software – TensorFlow

```
58 # Create model
59 def multilayer_perceptron(x):
60     # Hidden fully connected layer with 256 neurons
61     layer_1 = tf.add(tf.matmul(x, weights['h1']), biases['b1'])
62     # Hidden fully connected layer with 256 neurons
63     layer_2 = tf.add(tf.matmul(layer_1, weights['h2']), biases['b2'])
64     # Output fully connected layer with a neuron for each class
65     out_layer = tf.matmul(layer_2, weights['out']) + biases['out']
66     return out_layer
67
68 # Construct model
69 logits = multilayer_perceptron(X)
```

Current software – PyTorch

```
36 class Net(nn.Module):
37     def __init__(self, input_size, hidden_size, num_classes):
38         super(Net, self).__init__()
39         self.fc1 = nn.Linear(input_size, hidden_size)
40         self.relu = nn.ReLU()
41         self.fc2 = nn.Linear(hidden_size, num_classes)
42
43     def forward(self, x):
44         out = self.fc1(x)
45         out = self.relu(out)
46         out = self.fc2(out)
47         return out
48
49 net = Net(input_size, hidden_size, num_classes)
```


Other software implementations

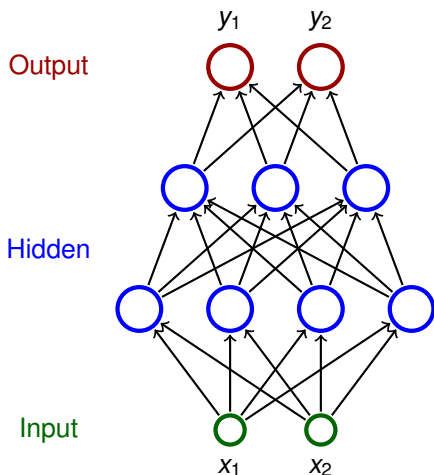
Most "mathematical" software packages contain some support of neural networks:

- ▶ MATLAB
- ▶ R
- ▶ STATISTICA
- ▶ Weka
- ▶ ...

The implementations are typically not on par with the previously mentioned dedicated deep-learning libraries.

MLP training – theory

Architecture – Multilayer Perceptron (MLP)



- ▶ Neurons partitioned into **layers**; one input layer, one output layer, possibly several hidden layers
- ▶ layers numbered from 0; the input layer has number 0
 - ▶ E.g., a three-layer network has two hidden layers and one output layer
- ▶ Neurons in the i -th layer are connected with all neurons in the $i + 1$ -st layer
- ▶ Architecture of a MLP is typically described by the numbers of neurons in individual layers (e.g., 2-4-3-2)

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(in particular, w_{j0} is the weight of the connection from the formal unit input, i.e., $w_{j0} = -b_j$ where b_j is the bias of the neuron j)

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MLP – activity

- ▶ inner potential of neuron j :

$$\xi_j = \sum_{i \in j_{\leftarrow}} w_{ji} y_i$$

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(y_j depends on the configuration \vec{w} and the input \vec{x} , so we sometimes write $y_j(\vec{w}, \vec{x})$)

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- ▶ The network computes a function $\mathbb{R}^{|X|} \rightarrow \mathbb{R}^{|Y|}$. Layer-wise computation: First, all input neurons are assigned values of the input. In the ℓ -th step, all neurons of the ℓ -th layer are evaluated.

MLP – learning

- ▶ Given a **training dataset** \mathcal{T} of the form

$$\left\{ \left(\vec{x}_k, \vec{d}_k \right) \mid k = 1, \dots, p \right\}$$

Here, every $\vec{x}_k \in \mathbb{R}^{|X|}$ is an *input vector* and every $\vec{d}_k \in \mathbb{R}^{|Y|}$ is the desired network output. For every $j \in Y$, denote by d_{kj} the desired output of the neuron j for a given network input \vec{x}_k (the vector \vec{d}_k can be written as $(d_{kj})_{j \in Y}$).

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- ▶ **Error function:**

$$E(\vec{w}) = \sum_{k=1}^p E_k(\vec{w})$$

where

$$E_k(\vec{w}) = \frac{1}{2} \sum_{j \in Y} \left(y_j(\vec{w}, \vec{x}_k) - d_{kj} \right)^2$$

This is just an example of an error function; we shall see other error functions later.

MLP – learning algorithm

Batch algorithm (gradient descent):

The algorithm computes a sequence of weight vectors

$\vec{w}^{(0)}, \vec{w}^{(1)}, \vec{w}^{(2)}, \dots$

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), weights $\vec{w}^{(t+1)}$ are computed as follows:

$$w_{ji}^{(t+1)} = w_{ji}^{(t)} + \Delta w_{ji}^{(t)}$$

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$$\Delta w_{ji}^{(t)} = -\varepsilon(t) \cdot \frac{\partial E}{\partial w_{ji}}(\vec{w}^{(t)})$$

is a *weight update* of w_{ji} in step $t + 1$ and $0 < \varepsilon(t) \leq 1$ is a *learning rate* in step $t + 1$.

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Note that $\frac{\partial E}{\partial w_{ji}}(\vec{w}^{(t)})$ is a component of the gradient ∇E , i.e. the weight update can be written as $\vec{w}^{(t+1)} = \vec{w}^{(t)} - \varepsilon(t) \cdot \nabla E(\vec{w}^{(t)})$.

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For every w_{ji} we have

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and for every $j \in Z \setminus X$ we get

$$\frac{\partial E_k}{\partial y_j} = y_j - d_{kj} \quad \text{for } j \in Y$$

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(Here all y_j are in fact $y_j(\vec{w}, \vec{x}_k)$).

Derivation of backprop.

Consider $k = 1, \dots, p$ and a weight w_{ji} . By the chain rule:

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since

$$\frac{\partial y_j}{\partial \xi_j} = \frac{\partial(\sigma_j(\xi_j))}{\partial \xi_j} = \sigma'_j(\xi_j)$$

$$\frac{\partial \xi_j}{\partial w_{ji}} = \frac{\partial(\sum_{r \in j_{\leftarrow}} w_{jr} y_r)}{\partial w_{ji}} = y_i$$

Derivation of backdrop. (cont.)

$$\text{For } j \in Y: \frac{\partial E_k}{\partial y_j} = \frac{\partial \left(\frac{1}{2} \sum_{r \in Y} (y_r - d_{kr})^2 \right)}{\partial y_j} = y_j - d_{kj}$$

Derivation of backdrop. (cont.)

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... and another application of the chain rule:

$$\text{For } j \notin Y: \frac{\partial E_k}{\partial y_j} =$$

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since

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MLP – error function gradient (history)

- ▶ If $y_j = \sigma_j(\xi_j) = \frac{1}{1+e^{-\xi_j}}$ for all $j \in Z$, then

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and thus for all $j \in Z \setminus X$:

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- 3. compute $\frac{\partial E_k}{\partial w_{ji}}$** for all w_{ji} using

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- 4.** $\mathcal{E}_{ji} := \mathcal{E}_{ji} + \frac{\partial E_k}{\partial w_{ji}}$

The resulting \mathcal{E}_{ji} equals $\frac{\partial E}{\partial w_{ji}}$.

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Compute $\frac{\partial E_k}{\partial y_j}$ for all $j \in Z$ as follows:

- ▶ if $j \in Y$, then $\frac{\partial E_k}{\partial y_j} = y_j - d_{kj}$
- ▶ if $j \in Z \setminus Y \cup X$, then assuming that j is in the ℓ -th layer and assuming that $\frac{\partial E_k}{\partial y_r}$ has already been computed for all neurons in the $\ell + 1$ -st layer, compute

$$\frac{\partial E_k}{\partial y_j} = \sum_{r \in j^{\rightarrow}} \frac{\partial E_k}{\partial y_r} \cdot \sigma'_r(\xi_r) \cdot w_{rj}$$

(This works because all neurons of $r \in j^{\rightarrow}$ belong to the $\ell + 1$ -st layer.)

Complexity of the batch algorithm

Computation of $\frac{\partial E}{\partial w_{ji}}(\vec{w}^{(t-1)})$ stops in time linear in the size of the network plus the size of the training set.

(assuming unit cost of operations including computation of $\sigma'_r(\xi_r)$ for given ξ_r)

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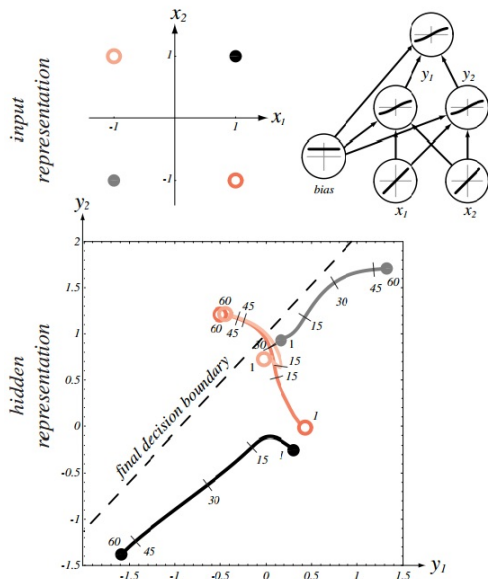
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Note that the speed of convergence of the gradient descent cannot be estimated ...

Illustration of the gradient descent – XOR



Source: Pattern Classification (2nd Edition); Richard O. Duda, Peter E. Hart, David G. Stork

MLP – learning algorithm

Online algorithm:

The algorithm computes a sequence of weight vectors $\vec{w}^{(0)}, \vec{w}^{(1)}, \vec{w}^{(2)}, \dots$

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), weights $\vec{w}^{(t+1)}$ are computed as follows:

$$w_{ji}^{(t+1)} = w_{ji}^{(t)} + \Delta w_{ji}^{(t)}$$

where

$$\Delta w_{ji}^{(t)} = -\varepsilon(t) \cdot \frac{\partial E_k}{\partial w_{ji}}(w_{ji}^{(t)})$$

is the *weight update* of w_{ji} in the step $t + 1$ and $0 < \varepsilon(t) \leq 1$ is the *learning rate* in the step $t + 1$.

There are other variants determined by the selection of the training examples used for the error computation (more on this later).

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), weights $\vec{w}^{(t+1)}$ are computed as follows:
 - ▶ Choose (randomly) a set of training examples $T \subseteq \{1, \dots, p\}$
 - ▶ Compute

$$\vec{w}^{(t+1)} = \vec{w}^{(t)} + \Delta \vec{w}^{(t)}$$

where

$$\Delta \vec{w}^{(t)} = -\varepsilon(t) \cdot \sum_{k \in T} \nabla E_k(\vec{w}^{(t)})$$

- ▶ $0 < \varepsilon(t) \leq 1$ is a *learning rate* in step $t + 1$
- ▶ $\nabla E_k(\vec{w}^{(t)})$ is the gradient of the error of the example k

Note that the random choice of the minibatch is typically implemented by randomly shuffling all data and then choosing minibatches sequentially.

Regression: Output and Error

- ▶ For **regression**, the output activation is typically the identity, i.e., $y_i = \sigma(\xi_i) = \xi_i$ for $i \in Y$.

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$$\{(\vec{x}_k, \vec{d}_k) \mid k = 1, \dots, p\}$$

Here, every $\vec{x}_k \in \mathbb{R}^{|X|}$ is an *input vector* and every $\vec{d}_k \in \mathbb{R}^{|Y|}$ is the desired network output. For every $i \in Y$, denote by d_{ki} the desired output of the neuron i for a given network input \vec{x}_k (the vector \vec{d}_k can be written as $(d_{ki})_{i \in Y}$).

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- ▶ The error function *mean squared error (mse)*:

$$E(\vec{w}) = \frac{1}{p} \sum_{k=1}^p E_k(\vec{w})$$

where

$$E_k(\vec{w}) = \frac{1}{2} \sum_{i \in Y} (y_i(\vec{w}, \vec{x}_k) - d_{ki})^2$$

Maximum Likelihood vs Least Squares

Fix a training set $D = \{(x_1, d_1), (x_2, d_2), \dots, (x_p, d_p)\}$, $d_k \in \mathbb{R}$.

Consider a single output neuron o .

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$$d_k = y_o(\vec{w}, \vec{x}_k) + \epsilon_k$$

- ▶ \vec{w} are **unknown constants**
- ▶ ϵ_k are normally distributed with mean 0 and an unknown variance σ^2

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Denote by $p(d_1, \dots, d_p \mid \vec{w}, \sigma^2)$ the probability density of the values d_1, \dots, d_p assuming fixed $x_1, \dots, x_p, \vec{w}, \sigma^2$.

(For the interested: The independence and definition of d_k 's imply

$$p(d_1, \dots, d_p \mid \vec{w}, \sigma^2) = \prod_{k=1}^p N[y_o(\vec{w}, \vec{x}_k), \sigma^2](d_k)$$

$N[y_o(\vec{w}, \vec{x}_k), \sigma^2](d_k)$ is a normal dist. with the mean $y_o(\vec{w}, \vec{x}_k)$ and var. σ^2 .)

Maximum Likelihood vs Least Squares

Our goal is to find the weights \vec{w} that maximize the likelihood

$$L(\vec{w}, \sigma^2) := p(d_1, \dots, d_p \mid \vec{w}, \sigma^2)$$

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Theorem

The unique \vec{w} that minimize the least squares error $E[\vec{w}]$ maximize $L(\vec{w}, \sigma^2)$ for an arbitrary variance σ^2 .

Classification: Output and Error

- ▶ The output activation function *softmax*:

$$y_i = \sigma_i(\xi_{j_1}, \dots, \xi_{j_k}) = \frac{e^{\xi_i}}{\sum_{j \in Y} e^{\xi_j}} \quad \text{Here } Y = \{j_1, \dots, j_k\}$$

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- ▶ The error function (*categorical*) *cross entropy*:

$$E(\vec{w}) = -\frac{1}{p} \sum_{k=1}^p \sum_{i \in Y} d_{ki} \log(y_i(\vec{w}, \vec{x}_k))$$

Gradient with Softmax & Cross-Entropy

Assume that V is the layer just below the output layer Y .

$$\begin{aligned} E(\vec{w}) &= -\frac{1}{p} \sum_{k=1}^p \sum_{i \in Y} d_{ki} \log(y_i(\vec{w}, \vec{x}_k)) \\ &= -\frac{1}{p} \sum_{k=1}^p \sum_{i \in Y} d_{ki} \log\left(\frac{e^{\xi_i}}{\sum_{j \in Y} e^{\xi_j}}\right) \\ &= -\frac{1}{p} \sum_{k=1}^p \sum_{i \in Y} d_{ki} \left(\xi_i - \log\left(\sum_{j \in Y} e^{\xi_j}\right) \right) \\ &= -\frac{1}{p} \sum_{k=1}^p \sum_{i \in Y} d_{ki} \left(\sum_{\ell \in V} w_{i\ell} y_\ell - \log\left(\sum_{j \in Y} e^{\sum_{\ell \in V} w_{j\ell} y_\ell}\right) \right) \end{aligned}$$

Now compute the derivatives $\frac{\delta E}{\delta y_\ell}$ for $\ell \in V$.

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Assume a single output neuron $o \in Y = \{0\}$.

- ▶ The output activation function *logistic sigmoid*:

$$\sigma_o(\xi_o) = \frac{e^{\xi_o}}{e^{\xi_o} + 1} = \frac{1}{1 + e^{-\xi_o}}$$

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Here $\vec{x}_k = (x_{k0}, x_{k1}, \dots, x_{kn}) \in \mathbb{R}^{n+1}$, $x_{k0} = 1$, is the k -th input, and $d_k \in \{0, 1\}$ is the desired output.

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- ▶ The error function (*Binary*) *cross-entropy*:

$$E(\vec{w}) = - \sum_{k=1}^p d_k \log(y_o(\vec{w}, \vec{x}_k)) + (1 - d_k) \log(1 - y_o(\vec{w}, \vec{x}_k))$$

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The *likelihood*:

$$L(\vec{w}) = \prod_{k=1}^p (y_o(\vec{w}, \vec{x}_k))^{d_k} \cdot (1 - y_o(\vec{w}, \vec{x}_k))^{(1-d_k)}$$

$\log(L) =$

$$\sum_{k=1}^p (d_k \cdot \log(y_o(\vec{w}, \vec{x}_k)) + (1 - d_k) \cdot \log(1 - y_o(\vec{w}, \vec{x}_k)))$$

and thus $-\log(L)$ = the cross-entropy.

Minimizing the cross-entropy maximizes the log-likelihood (and vice versa).

Squared Error vs Logistic Output Activation

Consider a single neuron model $y = \sigma(w \cdot x) = 1/(1 + e^{-w \cdot x})$ where $w \in \mathbb{R}$ is the weight (ignore the bias).

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Squared error $E(w) = \frac{1}{2}(y - d)^2$.

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Thus

- ▶ If $d = 1$ and $y \approx 0$, then $\frac{\delta E}{\delta w} \approx 0$
- ▶ If $d = 0$ and $y \approx 1$, then $\frac{\delta E}{\delta w} \approx 0$

The gradient of E is small even though *the model is wrong!*

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For $d = 1$

$$\frac{\delta E}{\delta w} = -\frac{1}{y} \cdot y \cdot (1 - y) \cdot x = -(1 - y) \cdot x$$

which is close to $-x$ for $y \approx 0$.

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which is close to x for $y \approx 1$.

MLP training – practical issues

Practical issues of gradient descent

- ▶ Training efficiency:
 - ▶ What size of a minibatch?
 - ▶ How to choose the learning rate $\varepsilon(t)$ and control SGD ?
 - ▶ How to pre-process the inputs?
 - ▶ How to initialize weights?
 - ▶ How to choose desired output values of the network?

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 - ▶ How to choose desired output values of the network?
- ▶ Quality of the resulting model:
 - ▶ When to stop training?
 - ▶ Regularization techniques.
 - ▶ How large network?

For simplicity, I will illustrate the reasoning on MLP + mse. Later we will see other topologies and error functions with different but always somewhat related issues.

Issues in gradient descent

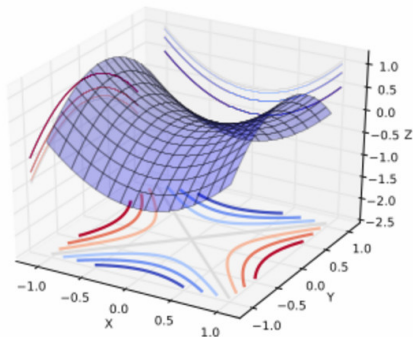
- ▶ Small networks: Lots of local minima where the descent gets stuck.
- ▶ The model identifiability problem: Swapping incoming weights of neurons i and j leaves the same network topology – **weight space symmetry**.
- ▶ Recent studies show that for sufficiently large networks, all local minima have low values of the error function.

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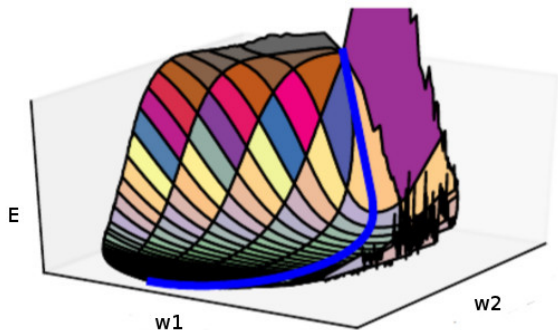
Saddle points

One can show (by a combinatorial argument) that larger networks have exponentially more saddle points than local minima.



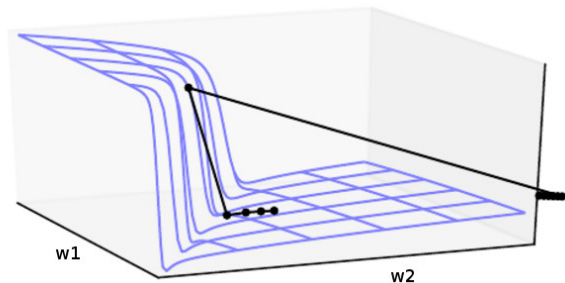
Issues in gradient descent – too slow descent

- ▶ flat regions

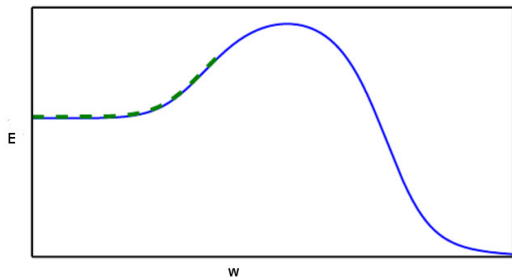


Issues in gradient descent – too fast descent

- ▶ steep cliffs: the gradient is extremely large, descent skips important weight vectors



Issues in gradient descent – local vs global structure



What if we initialize on the left?

Gradient Descent in Large Networks

Theorem

Assume (roughly),

- ▶ activation functions: "smooth" ReLU (softplus)

$$\sigma(z) = \log(1 + \exp(z))$$

In general: Smooth, non-polynomial, analytic, Lipschitz continuous.

- ▶ inputs \vec{x}_k of Euclidean norm equal to 1, desired values d_k such that all $|d_k|$ are bounded by a constant,
- ▶ the number of hidden neurons per layer sufficiently large (polynomial in certain numerical characteristics of inputs roughly measuring their similarity, and exponential in the depth of the network),
- ▶ the learning rate constant and sufficiently small.

The gradient descent converges (with high probability w.r.t. random initialization) to a global minimum with zero error at a linear rate.

Later, we get to a special type of network called ResNet where the above result demands only polynomially many neurons per layer (w.r.t. depth).

Issues in computing the gradient

- ▶ vanishing and exploding gradients

$$\frac{\partial E_k}{\partial y_j} = y_j - d_{kj} \quad \text{for } j \in Y$$

$$\frac{\partial E_k}{\partial y_j} = \sum_{r \in j^{\rightarrow}} \frac{\partial E_k}{\partial y_r} \cdot \sigma'_r(\xi_r) \cdot w_{rj} \quad \text{for } j \in Z \setminus (Y \cup X)$$

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- ▶ inexact gradient computation:
 - ▶ Minibatch gradient is only an estimate of the true gradient.
 - ▶ Note that the standard deviation of the estimate is (roughly) σ / \sqrt{m} where m is the size of the minibatch and σ is the variance of the gradient estimate for a single training example.
(E.g. minibatch size 10 000 means 100 times more computation than the size 100 but gives only 10 times less deviation.)

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- ▶ If all examples in the batch are to be processed in parallel (as is the typical case), then the amount of memory scales with the batch size. For many hardware setups, this is the limiting factor in batch size.
- ▶ It is common (especially when using GPUs) for power of 2 batch sizes to offer better runtime. The typical power of 2 batch sizes ranges from 32 to 256, with 16 sometimes being attempted for large models.

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- ▶ Larger batches provide a more accurate estimate of the gradient but with less than linear returns.
- ▶ Multicore architectures are usually underutilized by extremely small batches.
- ▶ If all examples in the batch are to be processed in parallel (as is the typical case), then the amount of memory scales with the batch size. For many hardware setups, this is the limiting factor in batch size.
- ▶ It is common (especially when using GPUs) for power of 2 batch sizes to offer better runtime. The typical power of 2 batch sizes ranges from 32 to 256, with 16 sometimes being attempted for large models.
- ▶ Small batches can offer a regularizing effect, perhaps due to the noise they add to the learning process.

It has been observed in practice that when using a larger batch, there is a degradation in the quality of the model, as measured by its ability to generalize.

Momentum

The issue in the gradient descent:

- ▶ $\nabla E(\vec{w}^{(t)})$ constantly changes direction (but the error steadily decreases).



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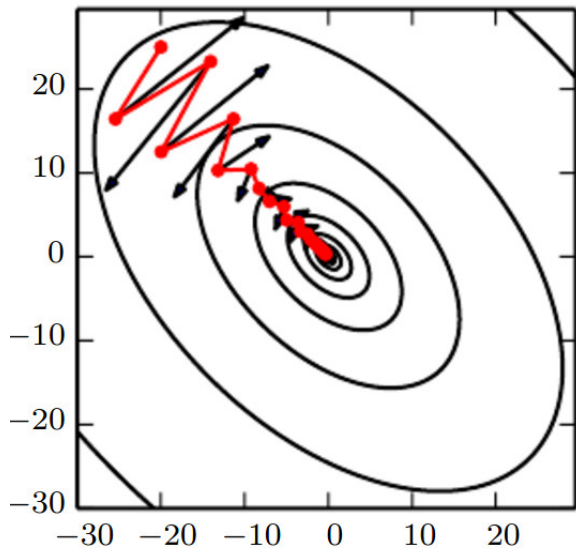


Solution: In every step, add the change made in the previous step (weighted by a factor α):

$$\Delta \vec{w}^{(t)} = -\varepsilon(t) \cdot \sum_{k \in T} \nabla E_k(\vec{w}^{(t)}) + \alpha \cdot \Delta \vec{w}^{(t-1)}$$

where $0 < \alpha < 1$.

Momentum – illustration



SGD with momentum

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), weights $\vec{w}^{(t+1)}$ are computed as follows:
 - ▶ Choose (randomly) a set of training examples $T \subseteq \{1, \dots, p\}$
 - ▶ Compute

$$\vec{w}^{(t+1)} = \vec{w}^{(t)} + \Delta \vec{w}^{(t)}$$

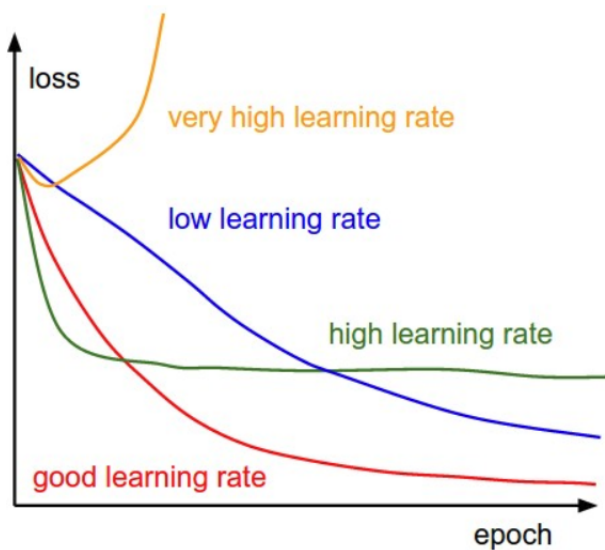
where

$$\Delta \vec{w}^{(t)} = -\varepsilon(t) \cdot \sum_{k \in T} \nabla E_k(\vec{w}^{(t)}) + \alpha \Delta \vec{w}^{(t-1)}$$

- ▶ $0 < \varepsilon(t) \leq 1$ is a *learning rate* in step $t + 1$
- ▶ $0 < \alpha < 1$ measures the "influence" of the momentum
- ▶ $\nabla E_k(\vec{w}^{(t)})$ is the gradient of the error of the example k

Note that the random choice of the minibatch is typically implemented by randomly shuffling all data and then choosing minibatches sequentially.

Learning rate



Search for the learning rate

- ▶ Use settings from a successful solution of a similar problem as a baseline.
- ▶ Search for the learning rate using the learning monitoring:
 - ▶ Search through values from small (e.g. 0.001) to (0.1), possibly multiplying by 2.
 - ▶ Train for several epochs, observe the learning curves (see cross-validation later).

Adaptive learning rate

- ▶ Power scheduling: Set $\epsilon(t) = \epsilon_0 / (1 + t/s)$ where ϵ_0 is an initial learning rate and s is a constant number
(after s steps the learning rate is $\epsilon_0/2$, after $2s$ it is $\epsilon_0/3$ etc.)

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(the learning rate decays faster than in the power scheduling)
- ▶ Piecewise constant scheduling: A constant learning rate for a number of steps/epochs, then a smaller learning rate, and so on.
- ▶ 1cycle scheduling: Start by increasing the initial learning rate from ϵ_0 linearly to ϵ_1 (approx. $\epsilon_1 = 10\epsilon_0$) halfway through training. Then decrease from ϵ_1 linearly to ϵ_0 . Finish by dropping the learning rate by several orders of magnitude (still linearly).
According to a 2018 paper by Leslie Smith, this may converge much faster (100 epochs vs 800 epochs on the CIFAR10 dataset).

For a comparison of some methods, see: AN EMPIRICAL STUDY OF LEARNING RATES IN DEEP NEURAL NETWORKS FOR SPEECH RECOGNITION, Senior et al

So far, we have considered fixed schedules for learning rates.

It is better to have

- ▶ larger rates for weights with smaller updates,
- ▶ smaller rates for weights with larger updates.

AdaGrad uses individually adapting learning rates for each weight.

SGD with AdaGrad

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), compute $\vec{w}^{(t+1)}$:
 - ▶ Choose (randomly) a minibatch $T \subseteq \{1, \dots, p\}$
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$$w_{ji}^{(t+1)} = w_{ji}^{(t)} + \Delta w_{ji}^{(t)}$$

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where

$$\Delta w_{ji}^{(t)} = -\frac{\eta}{\sqrt{r_{ji}^{(t)} + \delta}} \cdot \sum_{k \in T} \frac{\partial E_k}{\partial w_{ji}}(\vec{w}^{(t)})$$

and

$$r_{ji}^{(t)} = r_{ji}^{(t-1)} + \left(\sum_{k \in T} \frac{\partial E_k}{\partial w_{ji}}(\vec{w}^{(t)}) \right)^2$$

- ▶ η is a constant expressing the influence of the learning rate, typically 0.01.
- ▶ $\delta > 0$ is a smoothing term (typically 1e-8) avoiding division by 0.

The main disadvantage of AdaGrad is the accumulation of gradients throughout the learning process.

In case the learning needs to get over several "hills" before settling in a deep "valley," the weight updates get far too small before getting to it.

RMSProp uses an exponentially decaying average to discard history from the extreme past so that it can converge rapidly after finding a convex bowl as if it were an instance of the AdaGrad algorithm initialized within that bowl.

SGD with RMSProp

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
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$$r_{ji}^{(t)} = \rho r_{ji}^{(t-1)} + (1 - \rho) \left(\sum_{k \in T} \frac{\partial E_k}{\partial w_{ji}}(\vec{w}^{(t)}) \right)^2$$

- ▶ η is a constant expressing the influence of the learning rate (Hinton suggests $\rho = 0.9$ and $\eta = 0.001$).
- ▶ $\delta > 0$ is a smoothing term (typically $1e-8$) avoiding division by 0.

Other optimization methods

There are more methods, such as AdaDelta and Adam (RMSProp combined with momentum).

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Unfortunately, there is currently no consensus on this point.

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Currently, the most popular optimization algorithms actively in use include SGD, SGD with momentum, RMSProp, RMSProp with momentum, AdaDelta, and Adam.

The choice of which algorithm to use, at this point, seems to depend largely on the user's familiarity with the algorithm.

Choice of (hidden) activations

Generic requirements imposed on activation functions:

1. differentiability
(to do gradient descent)
2. non-linearity
(linear multi-layer networks are equivalent to single-layer)
3. monotonicity
(local extrema of activation functions induce local extrema of the error function)
4. "linearity"
(i.e. preserve as much linearity as possible; linear models are easiest to fit; find the "minimum" non-linearity needed to solve a given task)

The choice of activation functions is closely related to input preprocessing and the initial choice of weights.

Input preprocessing

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For example, the height vs. weight of a person, the max. speed of a car (in km/h) vs. its price (in CZK), etc.

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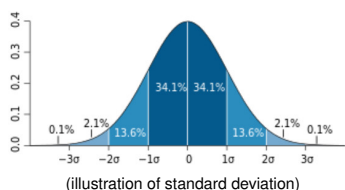
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- ▶ Large inputs have a greater influence on the training than the small ones. Also, too large inputs may slow down learning (saturation of some activation functions).
- ▶ Typical standardization:
 - ▶ average = 0 (subtract the mean)
 - ▶ variance = 1 (divide by the standard deviation)

Here, the mean and standard deviation may be estimated from the data (the training set).



Initial weights - intuition

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Consider the behavior of a deep network:

- ▶ Small weights make the values of inner potentials vanish.
- ▶ Large weights make the values of inner potentials explode.

Hence, we want to choose weights so that the inner potentials of neurons are stable (similar in all layers of the network).

Normal LeCun initialization

- ▶ Assume the input data have the mean = 0 and the variance = 1. Consider a neuron j from the first layer with n inputs. Assume its weights are chosen randomly by the normal distribution $\mathcal{N}(0, w^2)$.
Assume that all random choices are independent of each other.
- ▶ **The rule:** Choose the standard deviation of weights w so that the *standard deviation* of ξ_j (denote by σ_j) satisfies $\sigma_j \approx 1$.

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- ▶ The same works for higher layers; n corresponds to the number of neurons in the layer one level lower.

This gives *normal LeCun initialization*:

$$w_i \sim \mathcal{N}\left(0, \frac{1}{n}\right)$$

Derivation of the LeCun initialization

Consider a single neuron without bias with the inner potential

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- ▶ $w_i \in \mathcal{N}(0, w^2)$ for $i = 1, \dots, n$ where w is a constant,
- ▶ $\mathbb{E}x_i = 0$ and $\text{Var}[x_i] = \mathbb{E}[(x_i - \mathbb{E}x_i)^2] = 1$ for $i = 1, \dots, n$

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and $\text{Var}[w_i x_i] = \mathbb{E}[w_i^2 x_i^2] - \mathbb{E}[w_i x_i]^2 \stackrel{\text{ind.}}{=} \mathbb{E}[w_i^2] \mathbb{E}[x_i^2] - 0 = w^2$
implies

$$\text{Var}[\xi] = \text{Var}\left[\sum_{i=1}^n w_i x_i\right] \stackrel{\text{ind.}}{=} \sum_{i=1}^n \text{Var}[w_i x_i] = \sum_{i=1}^n w^2 = n \cdot w^2$$

Normal Glorot initialization

The previous heuristic for weight initialization ignores the variance of the gradient (i.e., it is concerned only with the "size" of activations in the forward pass).

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Glorot & Bengio (2010) presented a **normalized initialization** by choosing weights randomly from the following normal distribution:

$$N\left(0, \frac{2}{m+n}\right) = N\left(0, \frac{1}{(m+n)/2}\right)$$

Here n is the number of inputs to the layer, m is the number of neurons in the layer above.

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This is designed to compromise between the goal of initializing all layers to have the same activation variance and the goal of initializing all layers to have the same gradient variance.

This gives *normal Glorot initialization* (also called *normal Xavier initialization*):

$$w_i \sim \mathcal{N}\left(0, \frac{2}{m+n}\right)$$

Uniform LeCun initialization

- ▶ Assume that the input data have mean = 0 and variance = 1.

Consider a neuron j from the first layer with n inputs. Assume its weights are chosen randomly by the uniform distribution

$U(-w, w)$.

Assume that all random choices are independent of each other.

- ▶ As before, we want the standard deviation σ_j of the inner potential ξ_j to be approximately 1.
- ▶ Basic properties of the variance of independent variables give

$$\sigma_j = \sqrt{\frac{n}{3}} \cdot w.$$

Thus by putting $w = \sqrt{\frac{3}{n}}$ we obtain $\sigma_j = 1$.

We obtain *uniform LeCun initialization*:

$$w_i \sim U\left(-\sqrt{\frac{3}{n}}, \sqrt{\frac{3}{n}}\right)$$

Uniform Glorot initialization

Similarly to the normal case, we want to normalize the initialization w.r.t. both forward and backward passes.

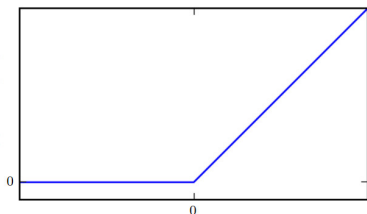
We obtain *uniform Glorot initialization* (aka *uniform Xavier init.*):

$$w_i \sim U\left(-\sqrt{\frac{6}{m+n}}, \sqrt{\frac{6}{m+n}}\right) = U\left(-\sqrt{\frac{3}{(m+n)/2}}, \sqrt{\frac{3}{(m+n)/2}}\right)$$

Here n is the number of inputs to the layer, m is the number of neurons in the layer above.

Modern activation functions

For hidden neurons, sigmoidal functions are often substituted with piece-wise linear activation functions. Most prominent is ReLU:



$$\sigma(\xi) = \max\{0, \xi\}$$

- ▶ THE default activation function recommended for most feedforward neural networks.
- ▶ As close to linear function as possible; very simple; does not saturate for large potentials.
- ▶ Dead for negative potentials.

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The ReLU is not a symmetric function. So even if the inner potential ξ_j has variance = 1, it is not true of the output (the variance is halved).

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Modifying the normal LeCun initialization to take the halving variance into account, we obtain *normal He initialization*:

$$w_i \in \mathcal{N}\left(0, \frac{2}{n}\right) \quad \left(\text{LeCun is } w_i \in \mathcal{N}\left(0, \frac{1}{n}\right)\right)$$

More modern activation functions

- ▶ Leaky ReLU (green board):
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- ▶ ELU: "Smoothed" ReLU:

$$\sigma(\xi) = \begin{cases} \alpha(\exp(\xi) - 1) & \text{for } \xi < 0 \\ \xi & \text{for } \xi \geq 0 \end{cases}$$

Here α is a parameter, ELU converges to $-\alpha$ as $\xi \rightarrow -\infty$. As opposed to ReLU: Smooth, always non-zero gradient (but saturates), slower to compute.

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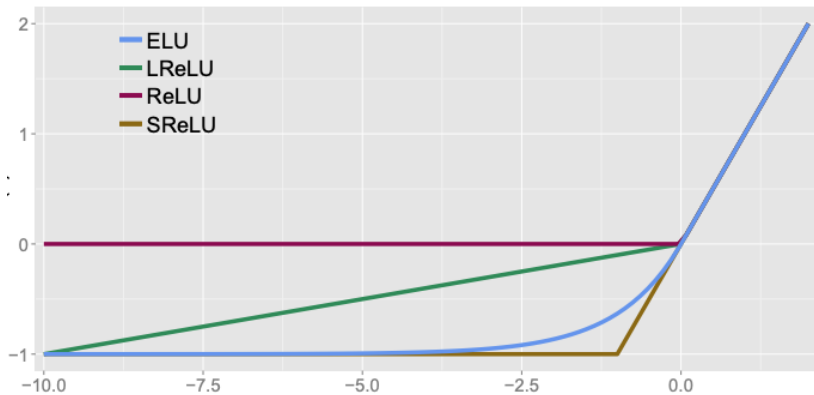
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- ▶ SELU: Scaled variant of ELU: :

$$\sigma(\xi) = \lambda \begin{cases} \alpha(\exp(\xi) - 1) & \text{for } \xi < 0 \\ \xi & \text{for } \xi \geq 0 \end{cases}$$

Self-normalizing, i.e. output of each layer will tend to preserve a mean (close to) 0 and a standard deviation (close to) 1 for $\lambda \approx 1.050$ and $\alpha \approx 1.673$, properly initialized weights (see below) and normalized inputs (zero mean, standard deviation 1).



Initializing with Normal Distribution

Denote by n the number of inputs to the initialized layer, and m the number of neurons in the layer.

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- ▶ normal LeCun:

$$w_i \sim \mathcal{N}\left(0, \frac{1}{n}\right)$$

Suitable for SELU (by the authors)

How to choose activation of hidden neurons

- ▶ The default is ReLU.
- ▶ According to Aurélien Géron:

SELU > ELU > leakyReLU > ReLU > tanh > logistic

For discussion see: Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow: Concepts, Tools, and Techniques to Build Intelligent Systems, Aurélien Géron

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Consider the ℓ -th layer of the network.

Note that the output values of neurons in the ℓ -th layer can be seen as inputs to the sub-network consisting of all layers above the ℓ -th one.

Batch normalization (roughly)

Intuition: Instead of keeping mean = 0 and variance = 1 implicitly due to a clever weight initialization, we may **renormalize values of neurons** throughout the layers.

Consider the ℓ -th layer of the network.

Note that the output values of neurons in the ℓ -th layer can be seen as inputs to the sub-network consisting of all layers above the ℓ -th one.

What if we standardize the values of the ℓ -th layer as we did with the input data?

For this we need to form a "dataset" of values of the ℓ -th layer.

Batch normalization (roughly)

Let us consider the ℓ -th layer with n neurons.

Consider a batch of training examples:

$$\{(\vec{x}_k, \vec{d}_k) \mid k = 1, \dots, p\}$$

(This is typically a minibatch.)

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$$\vec{z}_k = (z_{k1}, \dots, z_{kn})$$

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- ▶ Set all components of all vectors \vec{z}_k to the mean = 0 and the variance = 1 and obtain *normalized vectors*: $\hat{z}_1, \dots, \hat{z}_p$.
- ▶ For every $k = 1, \dots, p$ give

$$\vec{\gamma} \cdot \hat{z}_k + \delta$$

as the output of the ℓ -th layer instead of \vec{z}_k . Here $\vec{\gamma}$ and δ are new trainable weights.

Normalization

During the **training**, the normalized vectors $\hat{z}_1, \dots, \hat{z}_p$ are computed as follows:

$$\hat{z}_{ki} = \frac{z_{ki} - \mu_i}{s_i}$$

Here

$$\mu_i = \frac{1}{p} \sum_{k=1}^p z_{ki}$$

$$s_i = \sqrt{\frac{1}{p} \sum_{k=1}^p (z_{ki} - \mu_i)^2}$$

During **inference**, where we have just a single value \vec{z} of the layer ℓ for an input \vec{x} , we use μ_i and s_i estimated on a population (e.g., a larger sample of the training set).

Generalization

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Intuition: Generalization = ability to cope with new unseen instances.

Data are mostly noisy, so it is not good idea to fit exactly.

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In case of function approximation, the network should not return exact results as in the training set.

More formally: It is typically assumed that the training set has been generated as follows:

$$d_{kj} = g_j(\vec{x}_k) + \Theta_{kj}$$

where g_j is the "underlying" function corresponding to the output neuron $j \in Y$ and Θ_{kj} is random noise.

The network should fit g_j not the noise.

Methods improving generalization are called **regularization methods**.

Regularization

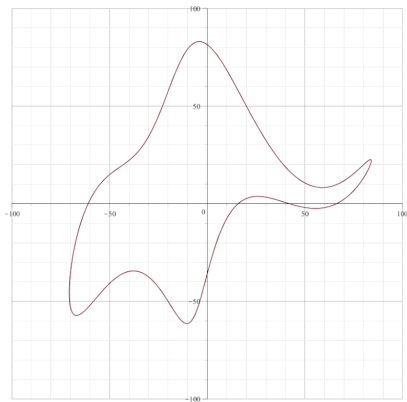
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Regularization is a big issue in neural networks, as they typically use a huge amount of parameters and thus are very susceptible to overfitting.

von Neumann: **"With four parameters, I can fit an elephant, and with five, I can make him wiggle his trunk."**

Elephant



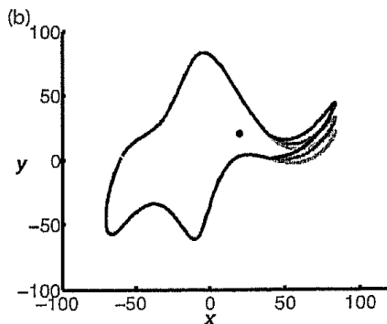
$$x(t) = -60 \cos(t) + 30 \sin(t) - 8 \sin(2t) + 10 \sin(3t)$$

$$y(t) = 50 \sin(t) + 18 \sin(2t) - 12 \cos(3t) + 14 \cos(5t)$$

The four parameters are complex numbers (e.g., $-60 + 50i$).

Mayer, Jurgen; Khairy, Khaled; Howard, Jonathon (May 12, 2010). "Drawing an elephant with four complex parameters". American Journal of Physics. 78 (6)

Fifth Elephant



Parameter	Real part	Imaginary part
$p_1 = 50 - 30i$	$B_1^x = 50$	$B_1^y = -30$
$p_2 = 18 + 8i$	$B_2^x = 18$	$B_2^y = 8$
$p_3 = 12 - 10i$	$A_3^x = 12$	$B_3^y = -10$
$p_4 = -14 - 60i$	$A_3^x = -14$	$A_1^y = -60$
$p_5 = 40 + 20i$	Wiggle coeff. = 40	$x_{cyc} = y_{cyc} = 20$

Regularization

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... and I ask you, prof. Neumann:

What can you fit with 40GB of parameters??

Early stopping

Early stopping means that we stop learning before it reaches a minimum of the error E .

When to stop?

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When to stop?

In many applications the error function is not the main thing we want to optimize.

E.g. in the case of a trading system, we typically want to maximize our profit not to minimize (strange) error functions designed to be easily differentiable.

Also, as noted before, minimizing E completely is not good for generalization.

For start: We may employ standard approach of training on one set and stopping on another one.

Early stopping

Divide your dataset into several subsets:

- ▶ **training set** (e.g. 60%) – train the network here
- ▶ **validation set** (e.g. 20%) – use to stop the training
- ▶ **test set** (e.g. 20%) – use to evaluate the final model

What to use as a stopping rule?

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What to use as a stopping rule?

You may observe E (or any other function of interest) on the validation set, if it does not improve for last k steps, stop.

Alternatively, you may observe the gradient, if it is small for some time, stop.

(some studies shown that this traditional rule is not too good: it may happen that the gradient is larger close to minimum values; on the other hand, E does not have to be evaluated which saves time.)

To compare models you may use ML techniques such as various types of cross-validation etc.

Size of the network

Similar problem as in the case of the training duration:

- ▶ Too small network is not able to capture intrinsic properties of the training set.
- ▶ Large networks overfit faster.

Solution: Optimal number of neurons :-)

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Solution: Optimal number of neurons :-)

- ▶ there are some (useless) theoretical bounds
- ▶ there are algorithms dynamically adding/removing neurons (not much use nowadays)
- ▶ In practice: Start with an existing network solving similar problem.

If you are trully desperate trying to solve a brand new problem, you may try an ancient rule of thumb: the number of neurons \approx ten times less than the number of training instances.

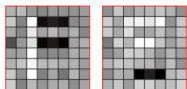
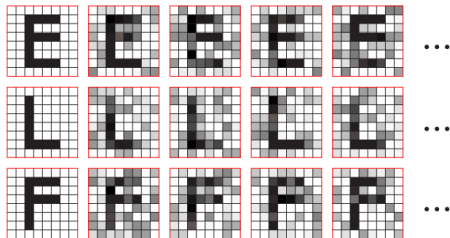
Experiment, experiment, experiment.

Feature extraction

Consider a two-layer network. Hidden neurons are supposed to represent "patterns" in the inputs.

Example: Network 64-2-3 for letter classification:

sample training patterns



learned input-to-hidden weights

Ensemble methods

Techniques for reducing generalization error by combining several models.

The reason that ensemble methods work is that different models will usually not make all the same errors on the test set.

Idea: Train several different models separately, then have all of the models vote on the output for test examples.

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Bagging:

- ▶ Generate k training sets T_1, \dots, T_k by *sampling from \mathcal{T} uniformly with replacement*.

If the number of samples is $|\mathcal{T}|$, then on average $|T_i| = (1 - 1/e)|\mathcal{T}|$.

- ▶ For each i , train a model M_i on T_i .
- ▶ Combine outputs of the models: for regression by averaging, for classification by (majority) voting.

Dropout

The algorithm: In every step of the gradient descent

- ▶ choose randomly a set N of neurons, each neuron is included independently with probability $1/2$,
(in practice, different probabilities are used as well).
- ▶ do forward and backward propagations only using the selected neurons
(i.e. leave weights of the other neurons unchanged)

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Dropout resembles bagging: Large ensemble of neural networks is trained "at once" on parts of the data.

Dropout is not exactly the same as bagging: The models share parameters, with each model inheriting a different subset of parameters from the parent neural network. This parameter sharing makes it possible to represent an exponential number of models with a tractable amount of memory.

In the case of bagging, each model is trained to convergence on its respective training set. This would be infeasible for large networks/training sets.

Dropout – details

- ▶ The inner potential of a neuron j **without dropout**:

$$\xi_j = \sum_{i \in j_{\leftarrow}} w_{ji} y_i$$

- ▶ The inner potential of a neuron j **with dropout**:

$$r_i \sim \text{Bernoulli}(1/2) \quad \text{for all } i \in j_{\leftarrow} \setminus \{0\}$$

$$\xi_j = \sum_{i \in j_{\leftarrow}} w_{ji} (r_i y_i)$$

(Intuitively, randomly chosen neurons are masked out.)

- ▶ During inference do not drop out neurons and multiply values of neurons with 1/2.

This compensates for the fact that without the drop out there are twice as many neurons.

Weight decay and L2 regularization

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Penalising large weights gives stronger indication about their importance.

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Weight decay is equivalent to the gradient descent with a constant learning rate ε and the following error function:

$$E'(\vec{w}) = E(\vec{w}) + \frac{\zeta}{2\varepsilon}(\vec{w} \cdot \vec{w})$$

Here $\frac{\zeta}{2\varepsilon}(\vec{w} \cdot \vec{w})$ is the L2 regularization that penalizes large weights.

We use the gradient descent with a constant learning rate to illustrate the equivalence between L2 regularization and the weight decay. Both methods can be combined with other learning algorithms (AdaGrad, etc.).

There are many more practical tips, optimization methods, regularization methods, etc.

For a very nice survey see

<http://www.deeplearningbook.org/>

... and also all other infinitely many urls concerned with deep learning.

Some application(s)

MLP applications

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- ▶ Various applications:
 - ▶ ALVINN - autonomous driving car
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 - ▶ ...
- ▶ Two-layer MLPs are usually not much better than non-neural models.

MNIST – handwritten digits recognition

- ▶ Database of labeled images of handwritten digits: 60 000 training examples, 10 000 testing.
- ▶ Dimensions: 28 x 28, digits are centered to the "center of gravity" of pixel values and normalized to a fixed size.
- ▶ More at <http://yann.lecun.com/exdb/mnist/>

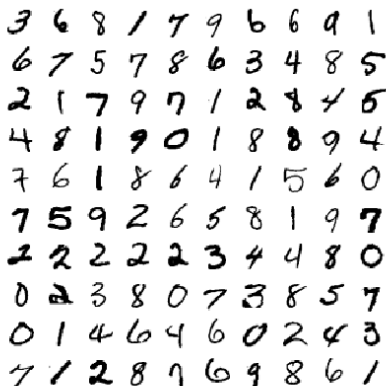


Fig. 4. Size-normalized examples from the MNIST database.

The database is used as a standard benchmark in lots of publications.

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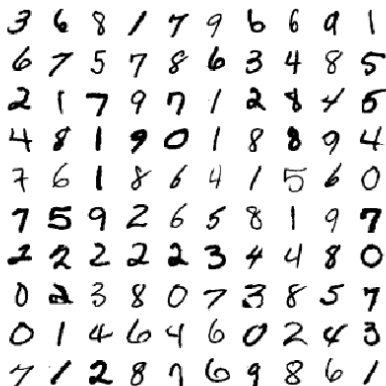


Fig. 4. Size-normalized examples from the MNIST database.

The database is used as a standard benchmark in lots of publications.

Allows comparison of various methods.

One of the best "old" results is the following:

6-layer NN 784-2500-2000-1500-1000-500-10 (on GPU)
(Ciresan et al. 2010)

Abstract: Good old on-line back-propagation for plain multi-layer perceptrons yields a very low 0.35 error rate on the famous MNIST handwritten digits benchmark. All we need to achieve this best result so far are many hidden layers, many neurons per layer, numerous deformed training images, and graphics cards to greatly speed up learning.

A famous application of a learning **convolutional** network LeNet-1 in 1998.

Y. LeCun, L. Bottou, Y. Bengio, and P. Haffner. Gradient-based learning applied to document recognition. Proceedings of the IEEE, 1998

MNIST – LeNet1

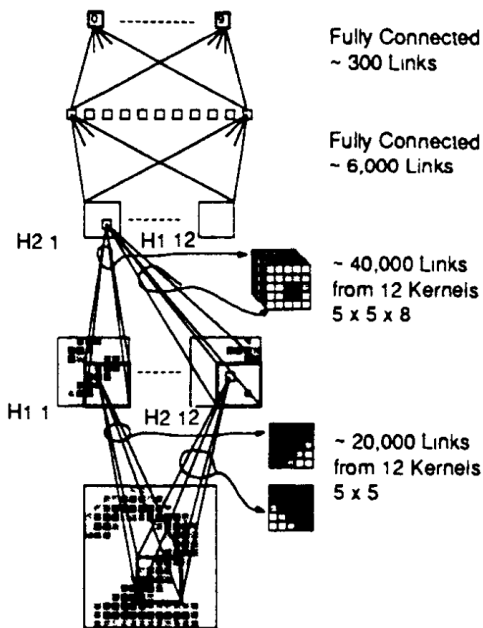
10 Output Units

Layer H3
30 Hidden Units

Layer H2
 $12 \times 16 = 192$
Hidden Units

Layer H1
 $12 \times 64 = 768$
Hidden Units

256 Input Units



Interpretation of output:

- ▶ the output neuron with the highest value identifies the digit.
- ▶ the same, but if the two largest neuron values are too close together, the input is rejected (i.e. no answer).

Learning:

Inputs:

- ▶ training on 7291 samples, tested on 2007 samples

Results:

- ▶ error on test set without rejection: 5%
- ▶ error on test set with rejection: 1% (12% rejected)

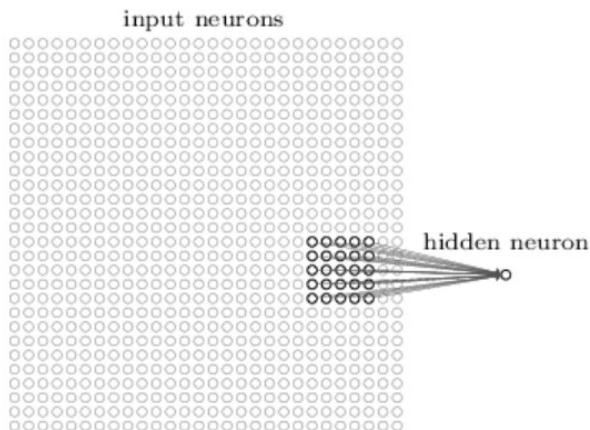
- ▶ compare with dense MLP with 40 hidden neurons: error 1% (19.4% rejected)

Convolutional Networks

Some parts of the lecture are based on the online book Neural Networks and Deep Learning by Michael Nielsen.

<http://neuralnetworksanddeeplearning.com/index.html>

Convolutional networks - local receptive fields

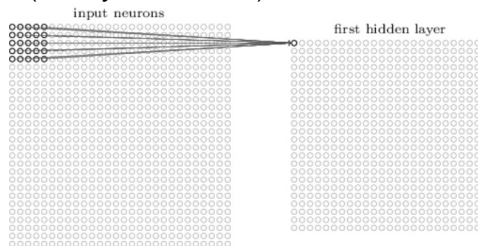


Every neuron is connected with a field of $k \times k$ (in this case 5×5) neurons in the lower layer (this field is *receptive field*).

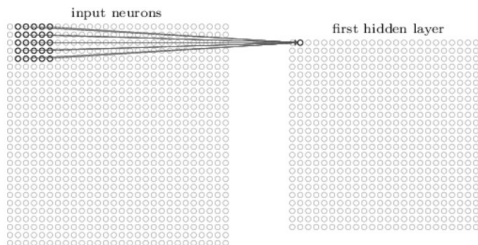
The neuron is "standard": Computes a weighted sum of its inputs and applies an activation function.

Convolutional networks - stride length

Then we slide the local receptive field over by one pixel to the right (i.e., by one neuron) to connect to a second hidden neuron:

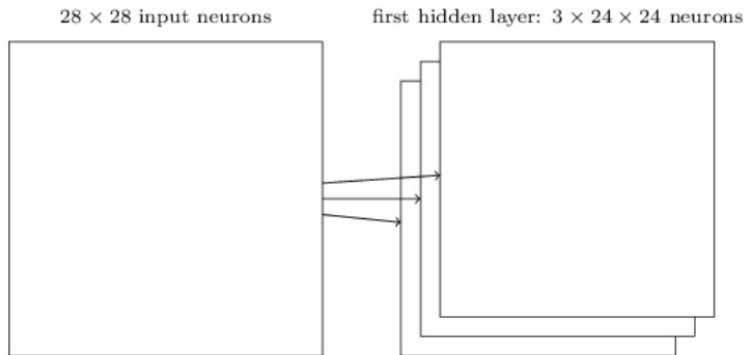


The "size" of the slide is called *stride length*.



The group of all such neurons is *feature map*. all these neurons *share weights and biases*!

Feature maps

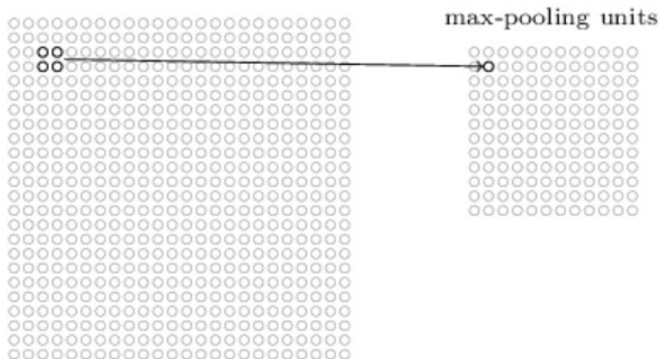


Each feature map represents a property of the input that is supposed to be spatially invariant.

Typically, we consider several feature maps in a single layer.

Pooling

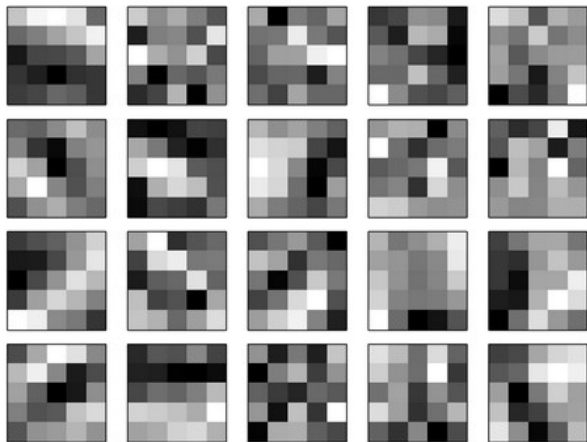
hidden neurons (output from feature map)



Neurons in the pooling layer compute functions of their receptive fields:

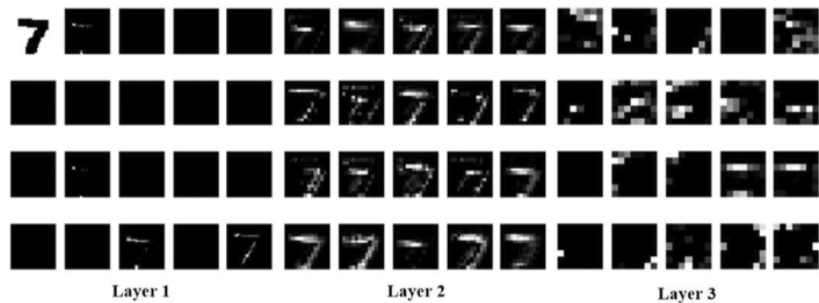
- ▶ **Max-pooling** : maximum of inputs
- ▶ **L2-pooling** : square root of the sum of squares
- ▶ **Average-pooling** : mean
- ▶ ...

Trained receptive fields

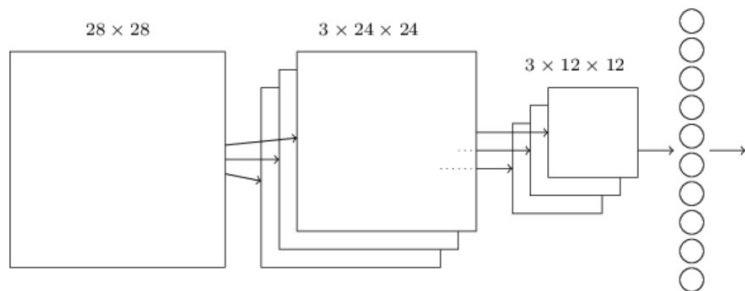


(20 feature maps, receptive fields 5×5)

Trained feature maps



Simple convolutional network

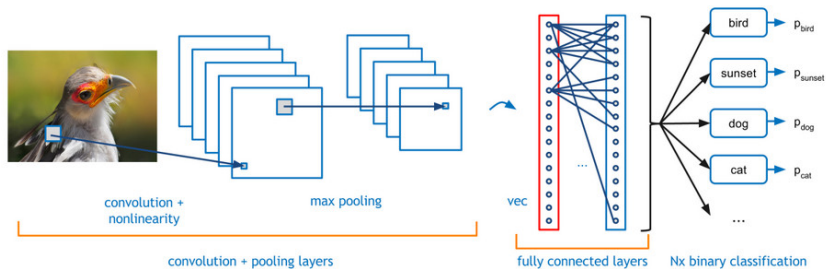


28×28 input image, 3 feature maps, each feature map has its own max-pooling (field 5×5 , stride = 1), 10 output neurons.

Each neuron in the output layer gets input from each neuron in the pooling layer.

Trained using backprop, which can be easily adapted to convolutional networks.

Convolutional network

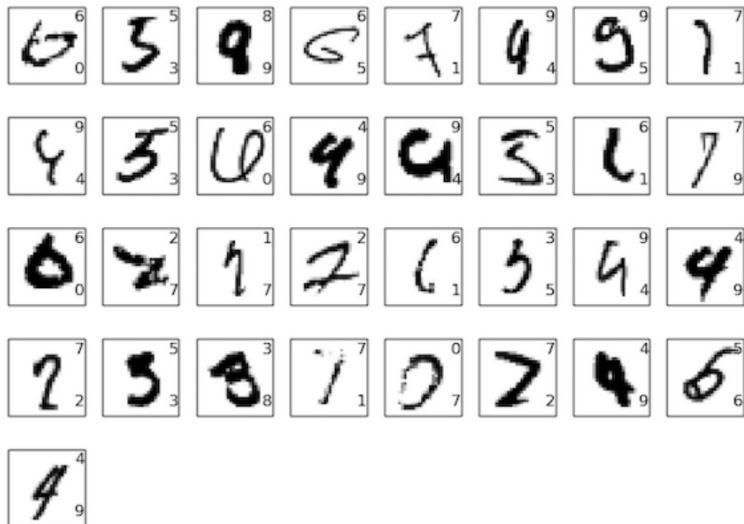


Simple convolutional network vs MNIST

two convolutional-pooling layers, one 20, second 40 feature maps, two dense (MLP) layers (1000-1000), outputs (10)

- ▶ Activation functions of the feature maps and dense layers: ReLU
- ▶ max-pooling
- ▶ output layer: soft-max
- ▶ Error function: negative log-likelihood (= cross-entropy)
- ▶ Training: SGD, mini-batch size 10
- ▶ learning rate 0.03
- ▶ L2 regularization with "weight" $\lambda = 0.1$ + dropout with prob. 1/2
- ▶ training for 40 epochs (i.e., every training example is considered 40 times)
- ▶ Expanded dataset: displacement by one pixel to an arbitrary direction.
- ▶ Committee voting of 5 networks.

Out of 10,000 images in the test set, only these 33 have been incorrectly classified:



ImageNet Large-Scale Visual Recognition Challenge (ILSVRC)

Competition in classification over a subset of images from ImageNet.

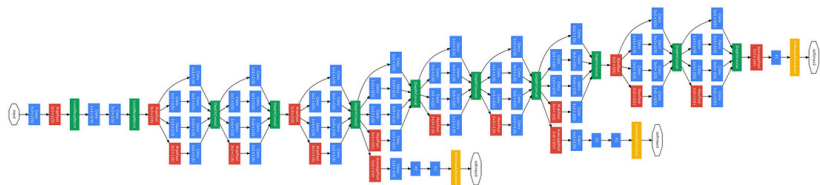
Started in 2010, assisted in a breakthrough in image recognition.

The training set 1.2 million images, 1000 classes. Validation set: 50 000, test set: 150 000.

Many images contain more than one object \Rightarrow model is allowed to choose five classes, the correct label must be among the five. (top-5 criterion).

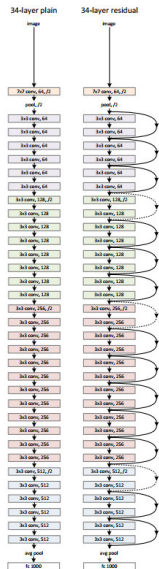
The same set as in 2012, top-5 criterion.

GoogLeNet: deep convolutional network, 22 layers

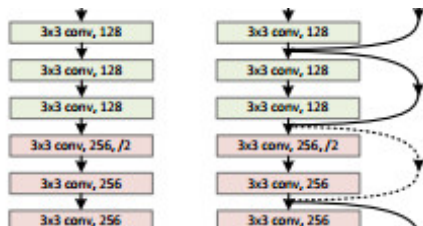


Results:

- ▶ Accuracy 93.33% top-5



- ▶ Deep convolutional network - ResNet
- ▶ Various numbers of layers, the winner has 152 layers
- ▶ Skip connections implementing residual learning
- ▶ Error **3.57%** in top-5.



Further development of CNN architectures

Convolutional networks made a breakthrough in image recognition.

See IB031 for discussion of ILSVRC challenge.

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- ▶ Image classification
Binary, or many classes, 2D, 3D, ... nD "images" and movies. Various architectures.
- ▶ Image segmentation
I.e., partitioning pixels of images, a HUGE amount of CNN variants (U-Net, fully convolutional, etc.)
- ▶ Object detection
Bounding box prediction, R-CNN architectures
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For more details, see

PA228 Machine Learning in Image Processing.

Convolutional networks – learning theory

Convolutional networks – architecture

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- ▶ **dense** layer L_m : Each neuron of L_m connected with each neuron of L_{m-1} .
- ▶ **convolutional** layer L_m : Neurons organized into disjoint **feature maps**, all neurons of a given feature map *share weights* (but have different inputs)
- ▶ **pooling** layer: "Neurons" organized into **pooling maps**, all neurons
 - ▶ compute a simple aggregate function (such as max),
 - ▶ have *disjoint inputs*.

Pooling after convolution is usually applied to each feature map separately. I.e., a single pooling map after each feature map.

Convolutional networks – architecture

- ▶ Denote
 - ▶ X a set of *input* neurons
 - ▶ Y a set of *output* neurons
 - ▶ Z a set of *all* neurons ($X, Y \subseteq Z$)
- ▶ individual neurons denoted by indices i, j etc.
 - ▶ ξ_j is the inner potential of the neuron j *after the computation stops*
 - ▶ y_j is the output of the neuron j *after the computation stops*

(define $y_0 = 1$ is the value of the formal unit input)

- ▶ w_{ji} is the weight of the connection **from i to j**
(in particular, w_{j0} is the weight of the connection from the formal unit input, i.e. $w_{j0} = -b_j$ where b_j is the bias of the neuron j)
- ▶ j_{\leftarrow} is a set of all i such that j is adjacent from i
(i.e. there is an arc **to** j from i)
- ▶ j_{\rightarrow} is a set of all i such that j is adjacent to i
(i.e. there is an arc **from** j to i)
- ▶ $[ji]$ is a set of all connections (i.e. pairs of neurons) sharing the weight w_{ji} .

Convolutional networks – activity

- ▶ neurons of dense and convolutional layers:

- ▶ inner potential of neuron j :

$$\xi_j = \sum_{i \in j_{\leftarrow}} w_{ji} y_i$$

- ▶ activation function σ_j for neuron j (arbitrary differentiable):

$$y_j = \sigma_j(\xi_j)$$

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- ▶ Neurons of pooling layers: Apply the "pooling" function:

- ▶ max-pooling:

$$y_j = \max_{i \in j_{\leftarrow}} y_i$$

- ▶ avg-pooling:

$$y_j = \frac{\sum_{i \in j_{\leftarrow}} y_i}{|j_{\leftarrow}|}$$

A convolutional network is evaluated layer-wise (as MLP), for each $j \in Y$ we have that $y_j(\vec{w}, \vec{x})$ is the value of the output neuron j after evaluating the network with weights \vec{w} and input \vec{x} .

Convolutional networks – learning

Learning:

- ▶ Given a **training set** \mathcal{T} of the form

$$\left\{ \left(\vec{x}_k, \vec{d}_k \right) \mid k = 1, \dots, p \right\}$$

Here, every $\vec{x}_k \in \mathbb{R}^{|X|}$ is an *input vector* and every $\vec{d}_k \in \mathbb{R}^{|Y|}$ is the desired network output. For every $j \in Y$, denote by d_{kj} the desired output of the neuron j for a given network input \vec{x}_k (the vector \vec{d}_k can be written as $(d_{kj})_{j \in Y}$).

- ▶ **Error function – squared error (for example):**

$$E(\vec{w}) = \sum_{k=1}^p E_k(\vec{w})$$

where

$$E_k(\vec{w}) = \frac{1}{2} \sum_{j \in Y} \left(y_j(\vec{w}, \vec{x}_k) - d_{kj} \right)^2$$

Convolutional networks – SGD

The algorithm computes a sequence of weight vectors

$\vec{w}^{(0)}, \vec{w}^{(1)}, \vec{w}^{(2)}, \dots$

- ▶ weights in $\vec{w}^{(0)}$ are randomly initialized to values close to 0
- ▶ in the step $t + 1$ (here $t = 0, 1, 2 \dots$), weights $\vec{w}^{(t+1)}$ are computed as follows:
 - ▶ Choose (randomly) a set of training examples $T \subseteq \{1, \dots, p\}$
 - ▶ Compute

$$\vec{w}^{(t+1)} = \vec{w}^{(t)} + \Delta \vec{w}^{(t)}$$

where

$$\Delta \vec{w}^{(t)} = -\varepsilon(t) \cdot \frac{1}{|T|} \sum_{k \in T} \nabla E_k(\vec{w}^{(t)})$$

Here T is a *minibatch* (of a fixed size),

- ▶ $0 < \varepsilon(t) \leq 1$ is a *learning rate* in step $t + 1$
- ▶ $\nabla E_k(\vec{w}^{(t)})$ is the gradient of the error of the example k

Note that the random choice of the minibatch is typically implemented by randomly shuffling all data and then choosing minibatches sequentially.

Epoch consists of one round through all data.

Backprop

Recall that $\nabla E_k(\vec{w}^{(t)})$ is a vector of all partial derivatives of the form $\frac{\partial E_k}{\partial w_{ji}}$.

How to compute $\frac{\partial E_k}{\partial w_{ji}}$?

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First, switch from derivatives w.r.t. w_{ji} to derivatives w.r.t. y_j :

- ▶ Recall that for every w_{ji} where j is in a dense layer, i.e. does not share weights:

$$\frac{\partial E_k}{\partial w_{ji}} = \frac{\partial E_k}{\partial y_j} \cdot \sigma'_j(\xi_j) \cdot y_i$$

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- ▶ Now for every w_{ji} where j is in a convolutional layer:

$$\frac{\partial E_k}{\partial w_{ji}} = \sum_{r \in [ji]} \frac{\partial E_k}{\partial y_r} \cdot \sigma'_r(\xi_r) \cdot y_\ell$$

- ▶ Neurons of pooling layers do not have weights.

Backprop

Now compute derivatives w.r.t. y_j :

- ▶ for every $j \in Y$:

$$\frac{\partial E_k}{\partial y_j} = y_j - d_{kj}$$

This holds for the squared error, for other error functions the derivative w.r.t. outputs will be different.

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- ▶ for every $j \in Z \setminus Y$ such that j^\rightarrow is either a dense layer, or a convolutional layer:

$$\frac{\partial E_k}{\partial y_j} = \sum_{r \in j^\rightarrow} \frac{\partial E_k}{\partial y_r} \cdot \sigma'_r(\xi_r) \cdot w_{rj}$$

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- ▶ for every $j \in Z \setminus Y$ such that $j \rightarrow$ is max-pooling: Then $j \rightarrow = \{i\}$ for a single "max" neuron and we have

$$\frac{\partial E_k}{\partial y_j} = \begin{cases} \frac{\partial E_k}{\partial y_i} & \text{if } j = \arg \max_{r \in i \leftarrow} y_r \\ 0 & \text{otherwise} \end{cases}$$

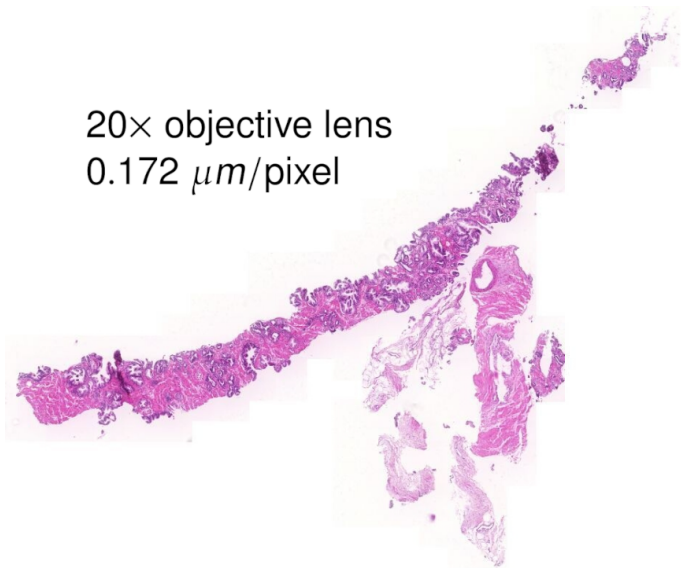
The gradient can be propagated from the output layer downwards as in MLP.

Convolutional networks – summary

- ▶ Conv. nets. are nowadays the most used networks in image processing (and also in other areas where input has some local, "spatially" invariant properties)
2024 update: Vision transformers are gradually taking over.
- ▶ Typically trained using the gradient descent and its modifications (such as Adam).
- ▶ Due to the weight sharing allow (very) deep architectures.
- ▶ Typically extended with more adjustments and tricks in their topologies.

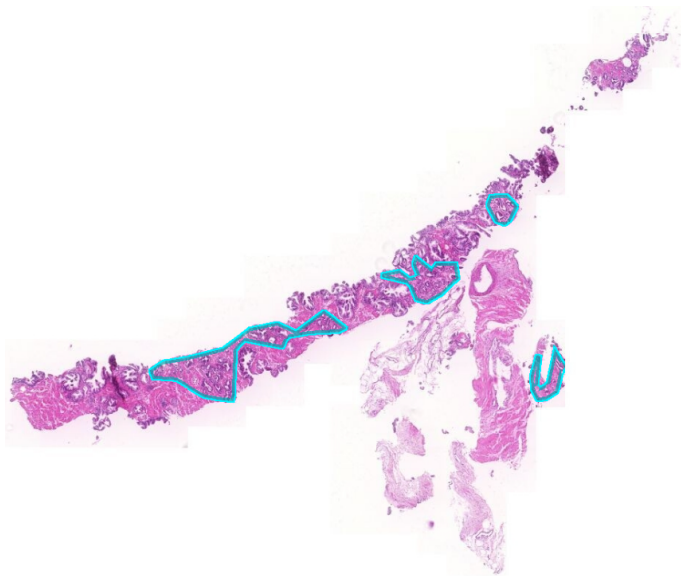
The problem of cancer detection in WSI

20× objective lens
0.172 $\mu\text{m}/\text{pixel}$



The problem: Detect cancer in this image.

The problem of cancer detection in WSI

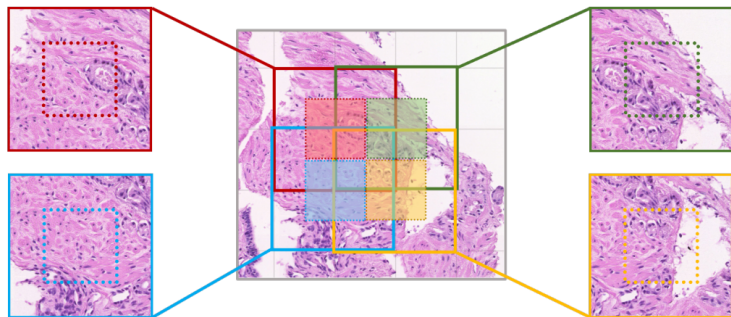


- ▶ WSI annotated by pathologists, **not** pixel level precise!

Input data

WSI too large, 105,185 px \times 221,772 px

Cut into patches of size 512 px \times 512 px



Patch positive **iff** the inner square intersects the annotation

Training on WSI

Our dataset from Masaryk Memorial Cancer Institute:

- ▶ 785 WSI from 166 patients
(698 WSI for training, 87 WSI for testing)
- ▶ Cut into 7,878,675 patches for training, 193,235 patches for testing.

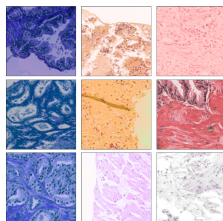
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- ▶ random vertical and horizontal flips
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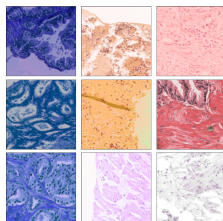
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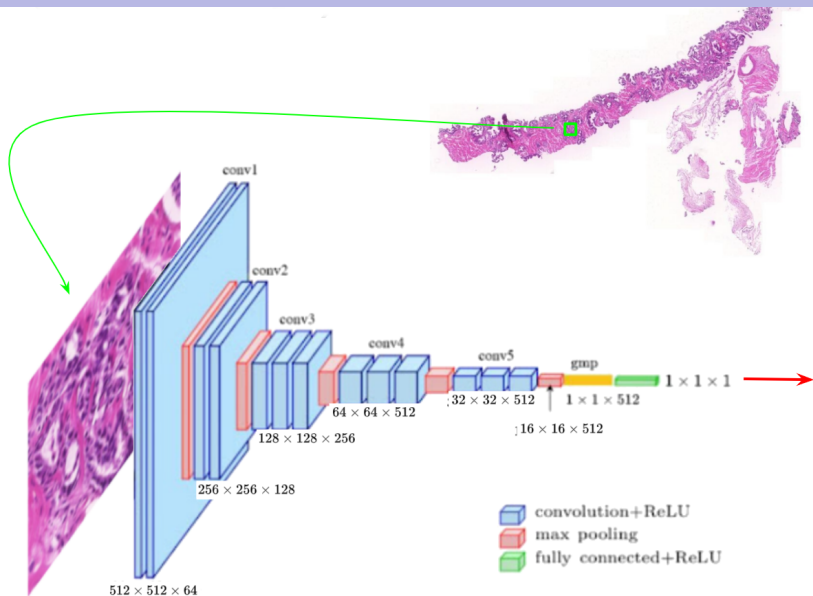
Dataset augmentation:

- ▶ random vertical and horizontal flips
- ▶ random color perturbations



- ▶ Training data three step sampling:
 1. randomly select a label
 2. randomly select a slide containing at least a single patch with the label
 3. randomly select a patch with the label from the slide

VGG16



3×3 convolutions, stride 1, padding 1. Max pooling 2×2 , stride 2.

- ▶ VGG16 pretrained on the ImageNet (of-the-shelf solution). Top fully connected parts removed, substituted with global max-pooling and a single dense layer.

Training VGG16 on WSI

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- ▶ The error $E = \text{cross-entropy}$

Training VGG16 on WSI

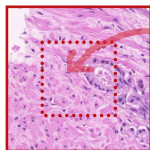
- ▶ VGG16 pretrained on the ImageNet (of-the-shelf solution). Top fully connected parts removed, substituted with global max-pooling and a single dense layer.
- ▶ The network has single logistic output - the probability of cancer in the patch
- ▶ The error E = cross-entropy
- ▶ Training:
 - ▶ RMSprop optimizer
 - ▶ The "forgetting" hyperparameter: $\rho = 0.9$
 - ▶ The initial learning rate 5×10^{-5}
 - ▶ If no improvement in E on validation data for 3 consecutive epochs \Rightarrow half the learning rate
 - ▶ If no improvement in ROCAUC on validation data for 5 consecutive epochs \Rightarrow terminate
 - ▶ Momentum with the weight $\alpha = 0.9$

Prediction



Model evaluation - attempt 2

Can we detect cancer in patches?



Any cancer here?

Predict I positive iff $F(I) \geq 0.75$

Single WSI:

		PREDICTED	
		Pos	Neg
TRUE	Pos	805	18
	Neg	48	614

All WSIs:

		PREDICTED	
		Pos	Neg
TRUE	Pos	24796	4340
	Neg	5345	158754

Ok, does it detect cancer?

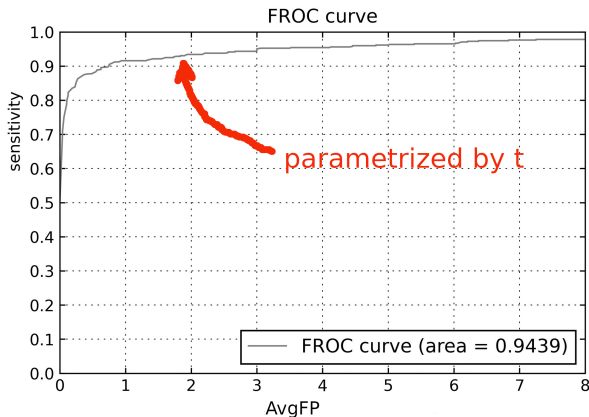
Model evaluation – attempt 3 – FROC

Detect *particular* tumors ?



How to evaluate the quality of tumor detection?

Model evaluation – attempt 3 – FROC



sensitivity \approx the proportion of tumors containing at least one patch I with $F(I) \geq t$ w.r.t. all tumors in all slides

AvgFP \approx average number of patches I with $F(I) \geq t$ in each non-cancerous slide

Is it good?

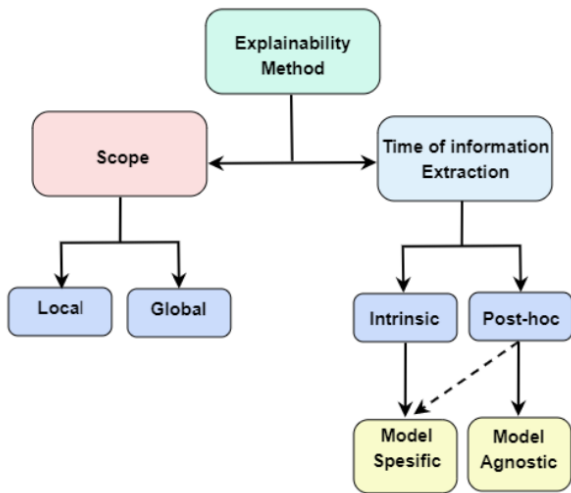
- ▶ Tile-based metric does not tell us whether cancer will be detected
- ▶ FROC curve captures tumor detection - however, WSI contains only cuts across tumors
- ▶ WSI level evaluation needs huge amounts of WSIs
Our later results shown that the system has approx. 0.98 AUC for WSI level tumor detection on thousands of WSI from MMCI
- ▶ The system broke down when we used WSIs from a completely different scanner and different hospital (they used slightly different colors).
We have corrected this by appropriate color normalization. But more data from more hospitals is needed!

Explainable methods (XAI)

XAI methods

The goal is to understand how and why the network does what it does.

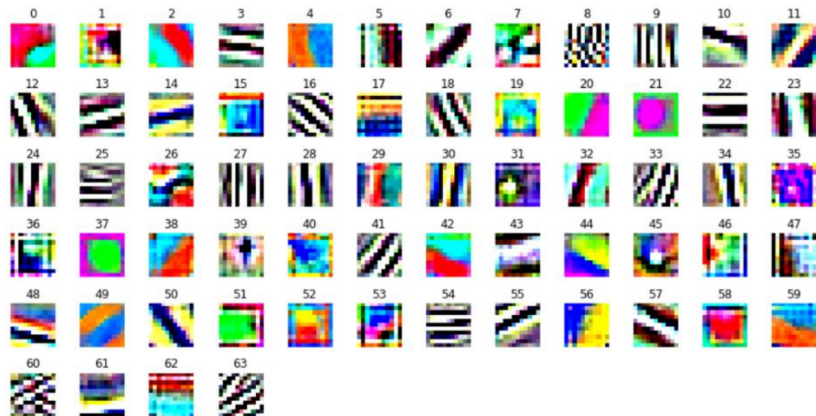
We will consider classification models only.



Methods based on various principles:

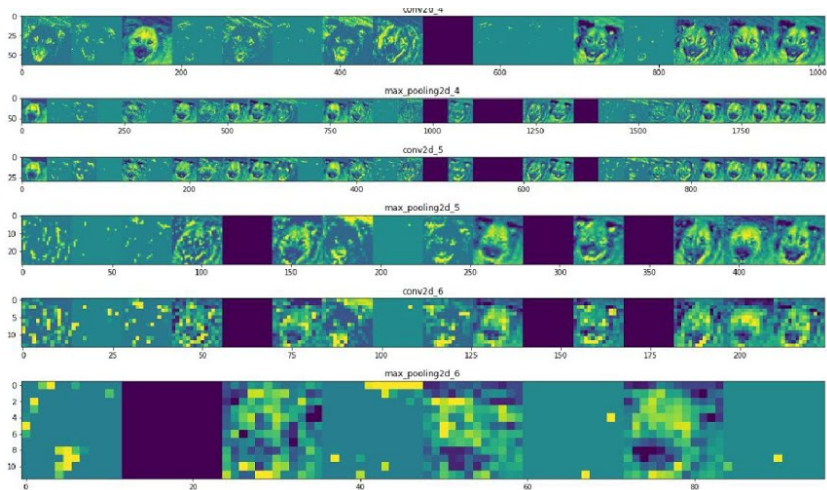
- ▶ Visualize weights and feature maps
- ▶ Visualize the most important inputs for a given class
- ▶ Visualize the effect of input perturbations on the output
- ▶ Construct an interpretable surrogate model

Alex-net - filters of the first convolutional layer

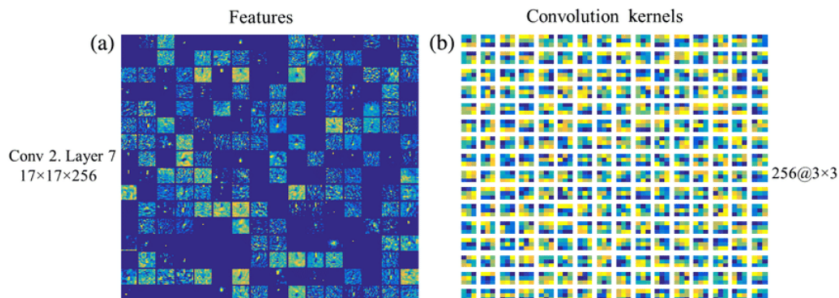


- ▶ 64 filters of depth 3 (RGB)
- ▶ Combined each filter RGB channels into one RGB image of size 11x11x3.

CNN - feature maps



CNN - feature maps - radar target classification



Synthetic-aperture radar (SAR) – used to create two-dimensional images or three-dimensional reconstructions of objects, such as landscapes.

Maximizing input

Now what if we try to find the most "representative" input vector for a given class?

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- ▶ Maximize

$$\xi_i(\vec{x}) - \lambda \|\vec{x}\|_2^2$$

over all input vectors \vec{x} .

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- ▶ A maximizing input vector computed using the gradient ascent.
- ▶ Gives the most "representative" input vector of the class represented by the neuron i .

Maximizing input - example



dumbbell



cup



dalmatian

Input specific saliency maps

The goal: Label features in a given input that are "most important" for the output of the network.

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Various approaches:

- ▶ gradient based
 - ▶ Gradient saliency maps
 - ▶ GradCAM
 - ▶ SmoothGrad
 - ▶ ...
- ▶ occlusion based
 - ▶ Simple occlusion maps
 - ▶ LIME
 - ▶ ...

Gradient based saliency

- ▶ Let us fix an output neuron i and an input vector \vec{x} .

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- ▶ **Idea:** Rank every input neuron $k \in X$ based on its influence on the value $\xi_i(\vec{x})$.

Note that the vector of input values is *fixed*.

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For every input neuron $k \in X$ we consider

$$\left| \frac{\partial \xi_i}{\partial y_k}(\vec{x}) \right|$$

to measure the importance of the input y_k for the output potential ξ_i with respect to the particular input vector \vec{x} .

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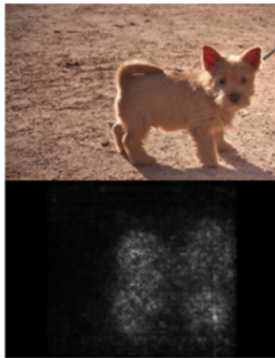
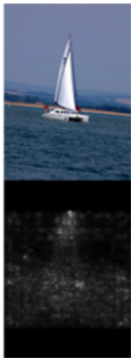
to measure the importance of the input y_k for the output potential ξ_i with respect to the particular input vector \vec{x} .

- ▶ Note that saliency comes from a surrogate local linear model given by the first-order Taylor approximation:

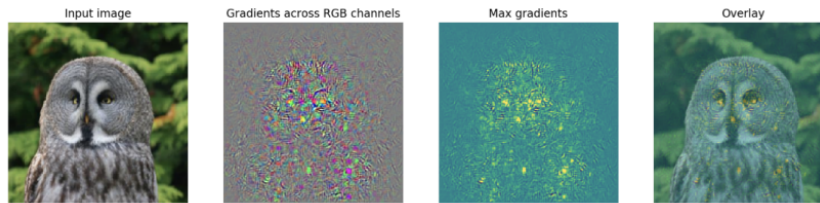
$$\xi_i(\vec{x}') \approx \xi_i(\vec{x}) + \left(\frac{\partial \xi_i}{\partial \mathbf{X}}(\vec{x}) \right) (\vec{x}' - \vec{x})$$

Here $\frac{\partial \xi_i}{\partial \mathbf{X}}$ is the vector of all partial derivatives $\frac{\partial \xi_i}{\partial y_k}$ where $k \in X$.

Saliency maps - example

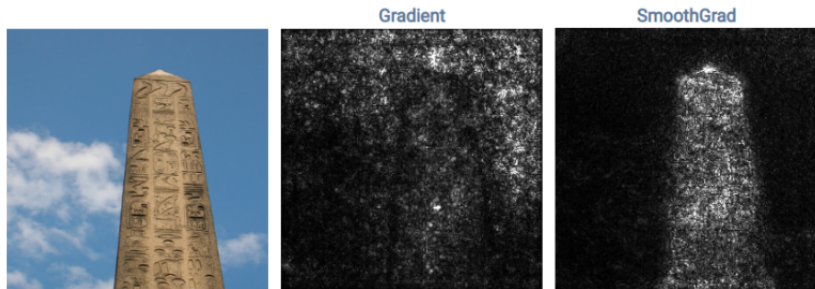


Saliency maps - example



Quite noisy, the signal is spread and does not say much about the perception of the owl.

Saliency maps - example



SmoothGrad:

- ▶ Do the following several times:
 - ▶ Add noise to the input image
 - ▶ Compute a saliency map
- ▶ Average the resulting saliency maps.

- ▶ Consider a convolutional network and fix an input image I of the network.

ALL values of all neurons y_j are computed on the input I .

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- ▶ Fix a convolutional layer L consisting of convolutional feature maps F^1, \dots, F^k .

Each F^ℓ is a set of neurons that belong to the feature map F^ℓ .

Slightly abusing notation, we write $F^\ell(I)$ to denote the tensor of all values of all neurons in $F^\ell(I)$.

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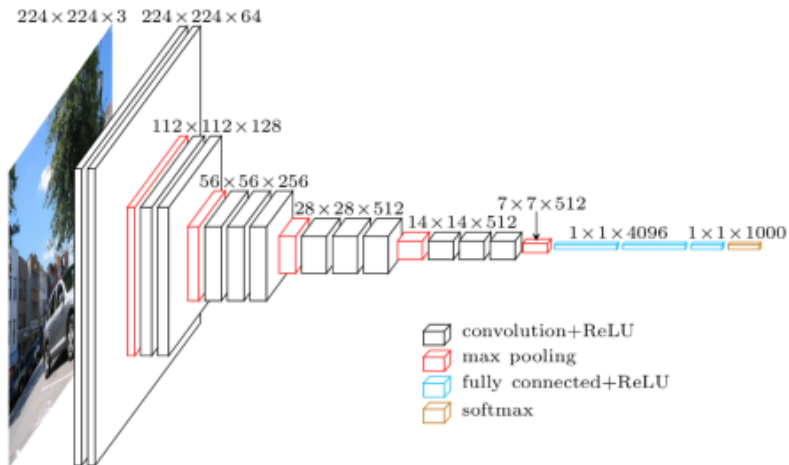
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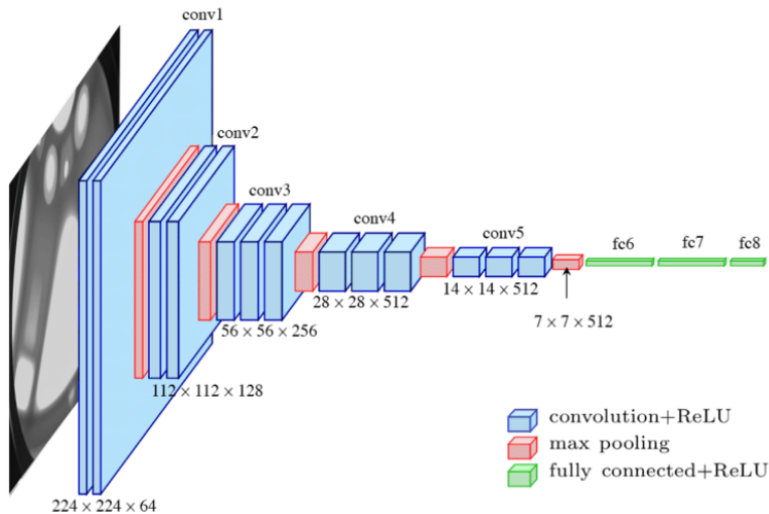
and the final *gradCAM heat map* for L is obtained using

$$M_i^L = \text{ReLU} \left(\sum_{\ell=1}^k \alpha_i^\ell F^\ell(I) \right)$$

GradCAM on VGG16

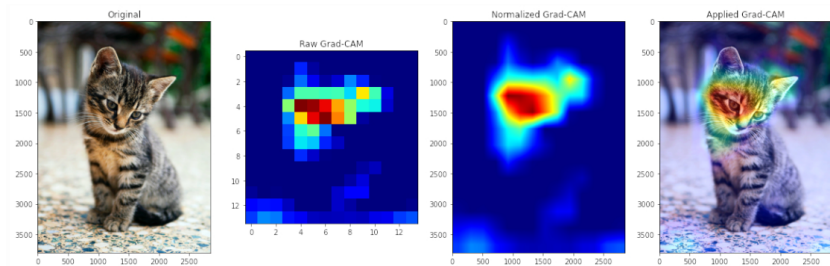


GradCAM on VGG16



Consider the last convolutional layer of the VGG16 (Block5,

GradCAM on VGG16

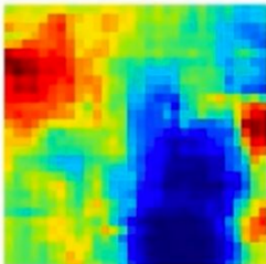
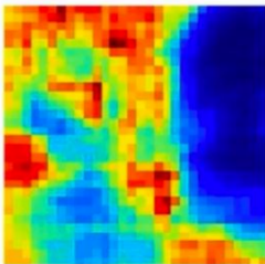
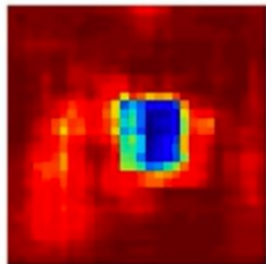


From left to right:

- ▶ An image of a cat (has to be resized to 224×224 to fit VGG16)
- ▶ The gradCAM heat map for the last convolutional layer and the class "cat"
- ▶ Rescaled and smoothed gradCAM heat map.
- ▶ The gradCAM overlay.

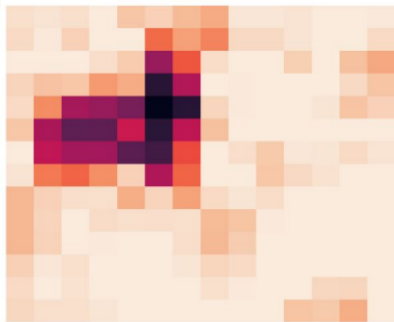
- ▶ Systematically cover parts of the input image.
- ▶ Observe the effect on the output value.
- ▶ Find regions with the largest effect.

Occlusion - example



Occlusion - example

['harmonica, mouth organ, harp, mouth harp']



LIME - for images

Let us fix an image I to be explained.

LIME - for images

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Outline:

- ▶ Consider superpixels of I as interpretable components.

LIME - for images

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Outline:

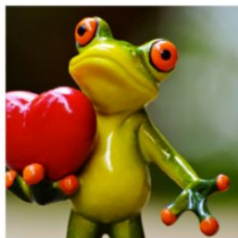
- ▶ Consider superpixels of I as interpretable components.
- ▶ Construct a linear model approximating the network around the image I with weights corresponding to the superpixels.

LIME - for images

Let us fix an image I to be explained.

Outline:

- ▶ Consider superpixels of I as interpretable components.
- ▶ Construct a linear model approximating the network around the image I with weights corresponding to the superpixels.
- ▶ Select the superpixels with weights of large magnitude as the important ones.

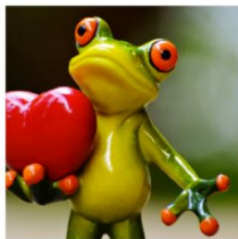


Original Image



Interpretable
Components

Superpixels as interpretable components



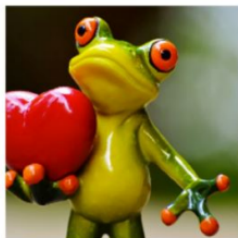
Original Image



Interpretable
Components

Denote by P_1, \dots, P_ℓ all superpixels of I .

Superpixels as interpretable components



Original Image

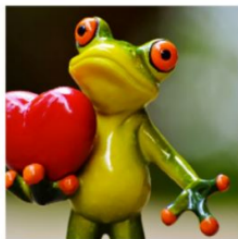


Interpretable
Components

Denote by P_1, \dots, P_ℓ all superpixels of I .

Consider binary vectors $\vec{x} = (x_1, \dots, x_\ell) \in \{0, 1\}^\ell$.

Superpixels as interpretable components



Original Image



Interpretable
Components

Denote by P_1, \dots, P_ℓ all superpixels of I .

Consider binary vectors $\vec{x} = (x_1, \dots, x_\ell) \in \{0, 1\}^\ell$.

Each such vector \vec{x} determines a "subimage" $I[\vec{x}]$ of I obtained by removing all P_k with $x_k = 0$.



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- ▶ Given the image I to be interpreted, consider the following training set:

$$\mathcal{T} = \{(\vec{x}_1, \xi_i(I[\vec{x}_1])), \dots, (\vec{x}_p, \xi_i(I[\vec{x}_p]))\}$$

Here $\vec{x}_h = (x_{h1}, \dots, x_{h\ell})$ are (some) binary vectors of $\{0, 1\}$.
E.g., randomly selected.

- ▶ Let us fix an output neuron i , we denote by $\xi_i(J)$ the inner potential of the output neuron i for the input image J .
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E.g., randomly selected.

- ▶ Train a linear model (ADALINE) with weights w_0, w_1, \dots, w_ℓ on \mathcal{T} .
Intuitively, the linear model approximates the network on "subimages" of I obtained by removing some superpixels.
- ▶ Inspect the weights (magnitude and sign).

More precisely, we train a linear model (ADALINE) F with weights $\vec{w} = w_0, w_1, \dots, w_\ell$ on \mathcal{T} minimizing the weighted mean-squared error

$$\mathcal{E}(\vec{w}) = \frac{1}{p} \sum_{k=1}^p \pi_k \cdot (F(\vec{x}_k) - \xi_i(I[\vec{x}_k]))^2 + \Omega(\vec{w})$$

where

- ▶ the weights are defined by

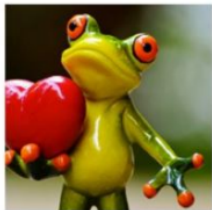
$$\pi_k = \exp\left(\frac{-(1 - \sqrt{1 - (s_k/\ell)})^2}{2\nu^2}\right)$$

Here s_k is the number of elements in \vec{x}_k equal to zero, ℓ is the number of superpixels, ν determines how much perturbed images are taken into account in the error.

Small ν means that π_k is close to zero for \vec{x}_k with many zeros.







- ▶ $\Omega(\vec{w})$ is a regularization term making the number of non-zero weights as small as possible.

LIME - example

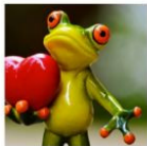


Original Image
 $P(\text{tree frog}) = 0.54$



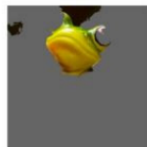
Perturbed Instances	$P(\text{tree frog})$
	 0.85
	 0.00001
	 0.52

LIME - example



Original Image
 $P(\text{tree frog}) = 0.54$

Perturbed Instances	$P(\text{tree frog})$
A perturbed version of the frog image where the background is dark and the frog is fragmented into red and yellow pieces.	 0.85
A perturbed version of the frog image where the background is dark and the frog's fragments are scattered.	 0.00001
The original frog image.	 0.52



Explanation

LIME - example



(a) Original Image



(b) Explaining *Electric guitar*

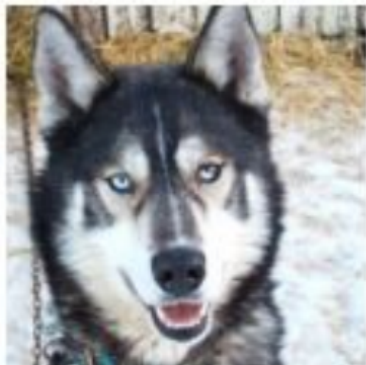


(c) Explaining *Acoustic guitar*



(d) Explaining *Labrador*

LIME - example



(a) Husky classified as wolf



(b) Explanation