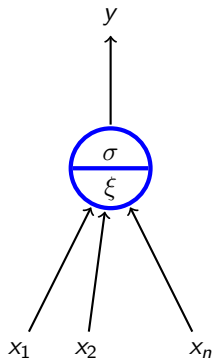
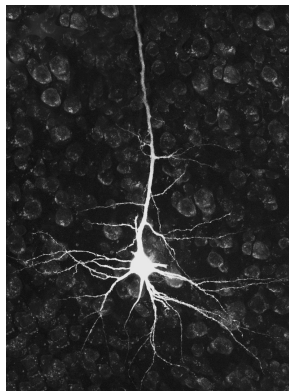


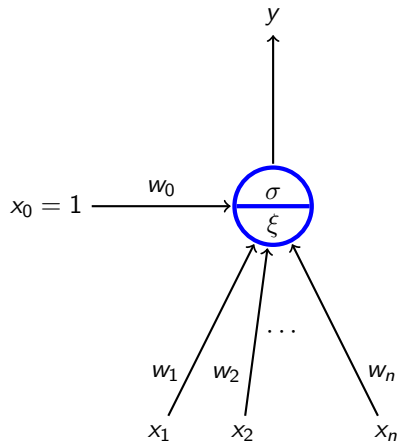
Neural Networks

(Primitive) Mathematical Model of Neuron



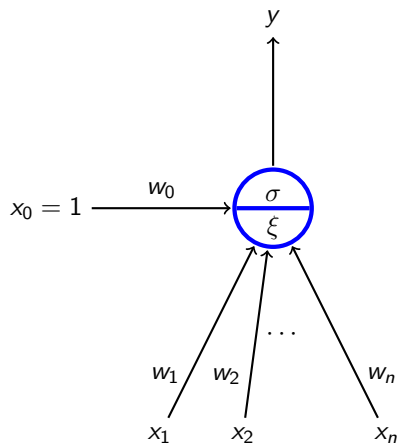
Formal neuron

- ▶ x_1, \dots, x_n real *inputs*

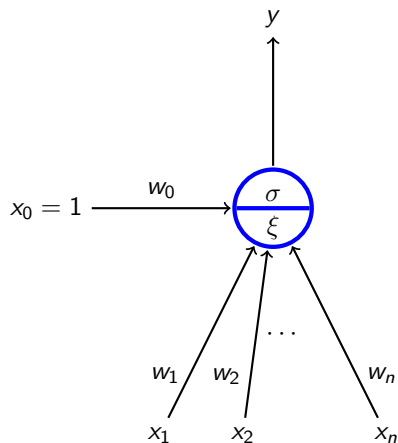


Formal neuron

- ▶ x_1, \dots, x_n real *inputs*
- ▶ x_0 special input, always 1

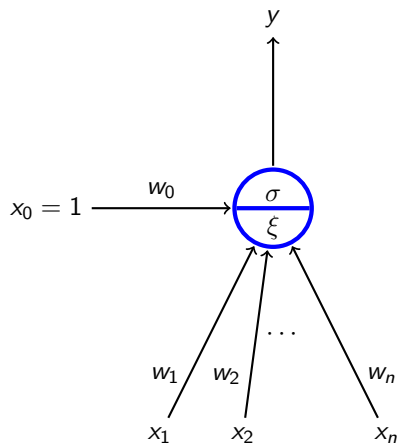


Formal neuron



- ▶ x_1, \dots, x_n real *inputs*
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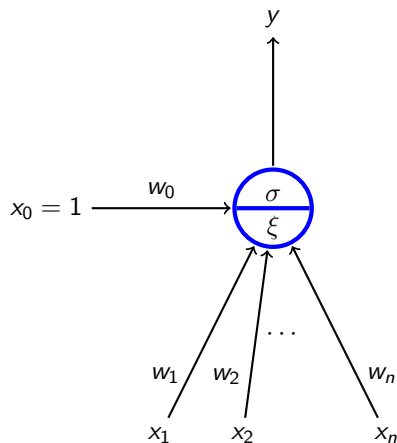
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In general, other potentials are considered (e.g. Gaussian), more on this in PV021.

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In general, other potentials are considered (e.g. Gaussian), more on this in PV021.
- ▶ y *output* defined by $y = \sigma(\xi)$ where σ is an *activation function*.
We consider several activation functions.
e.g., *linear threshold function*

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

Formal Neuron vs Linear Models

- ▶ If σ is a linear threshold function

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

We obtained a linear classifier.

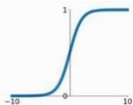
- ▶ If σ is identity, i.e., $\sigma(\xi) = \xi$, we obtain a linear (affine) function.
- ▶ If $\sigma(\xi) = 1/(1 + e^{-\xi})$ we obtain the logistic regression.

Also, other activation functions are used in neural networks!

Activation Functions

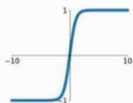
Sigmoid

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



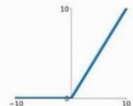
tanh

$$\tanh(x)$$



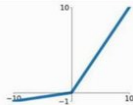
ReLU

$$\max(0, x)$$



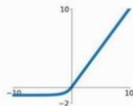
Leaky ReLU

$$\max(0.1x, x)$$



ELU

$$\begin{cases} x & x \geq 0 \\ \alpha(e^x - 1) & x < 0 \end{cases}$$

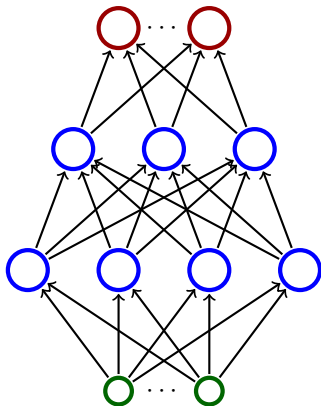


Multilayer Perceptron (MLP)

Output

Hidden

Input



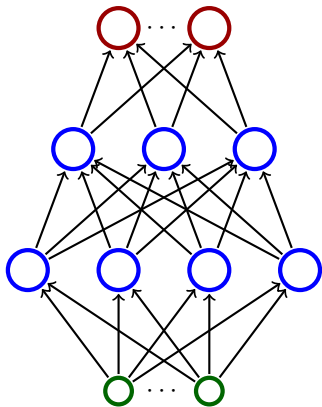
- ▶ Neurons are organized in *layers* (input layer, output layer, possibly several hidden layers)
- ▶ Layers are numbered from 0; The input is 0-th
- ▶ Neurons in the ℓ -th layer are connected with all neurons in the $\ell + 1$ -th layer

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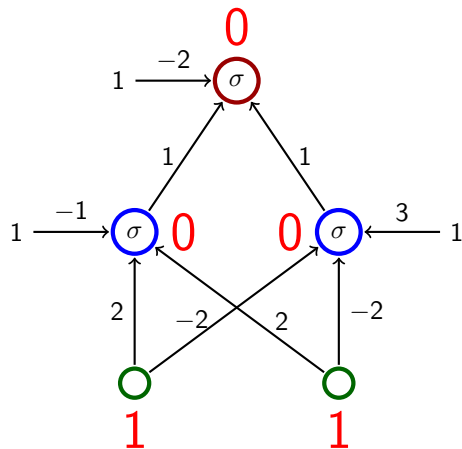
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Intuition: The network computes a function: Assign input values to the input neurons and 0 to the rest. Proceed upwards through the layers, one layer per step. In the ℓ -th step consider output values of neurons in $\ell - 1$ -th layer as inputs to neurons of the ℓ -th layer. Compute output values of neurons in the ℓ -th layer.

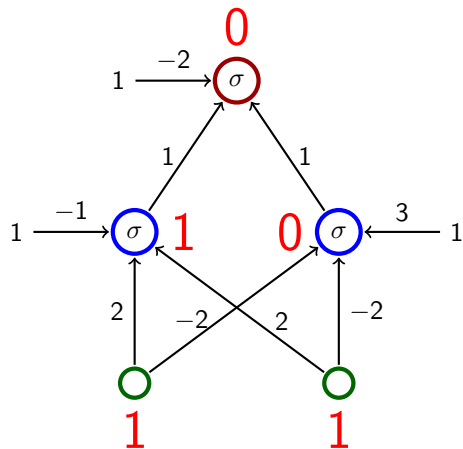
Example



- ▶ Activation function: linear threshold

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

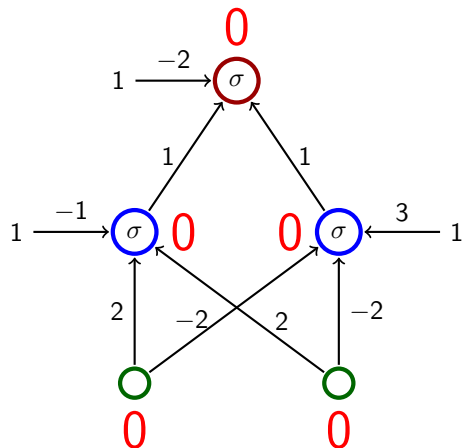
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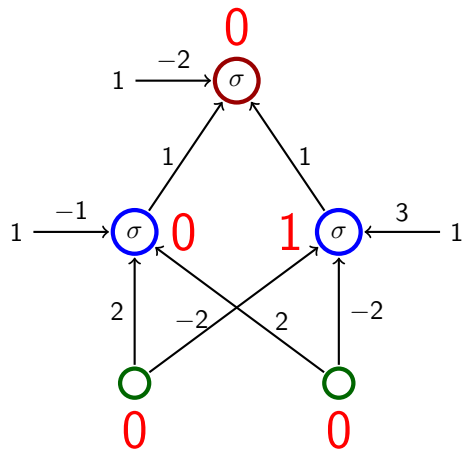
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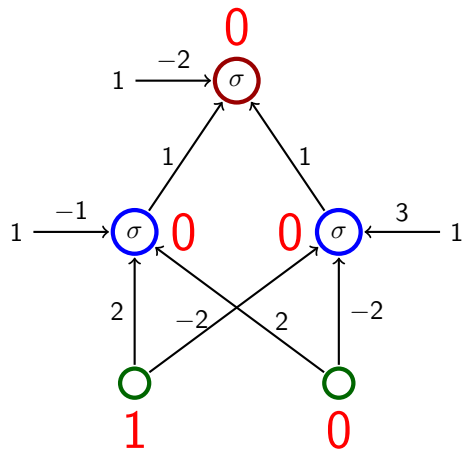
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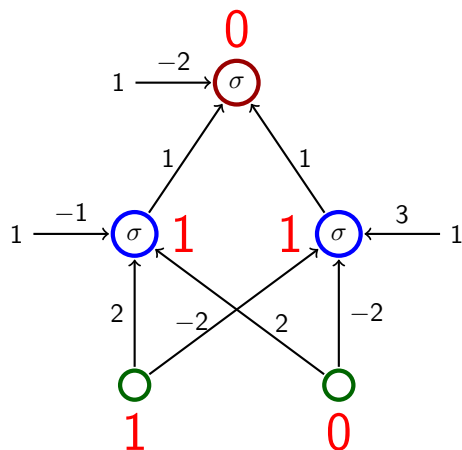
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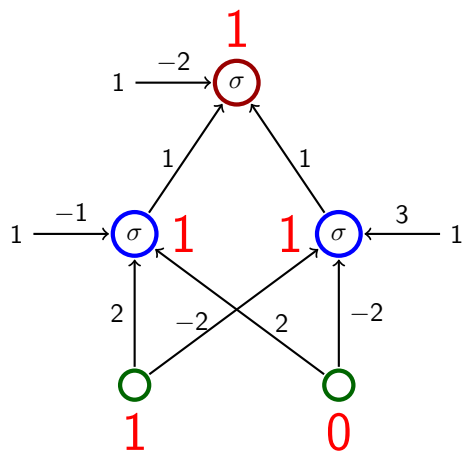
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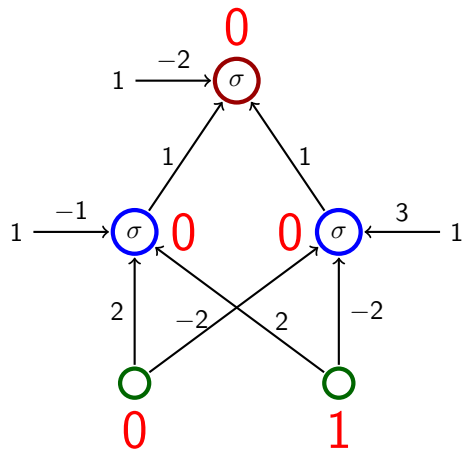
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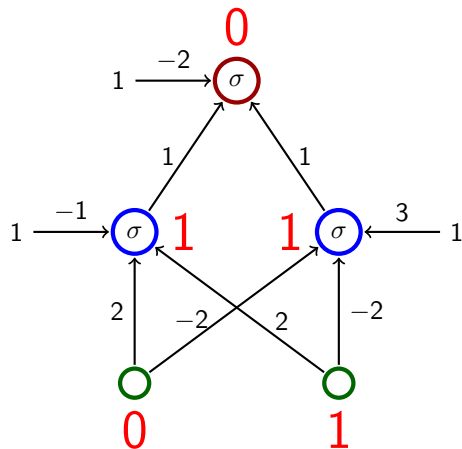
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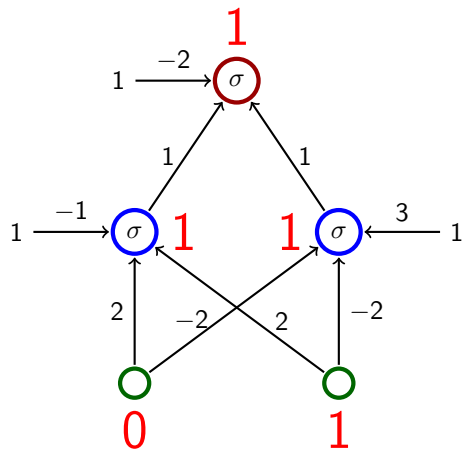
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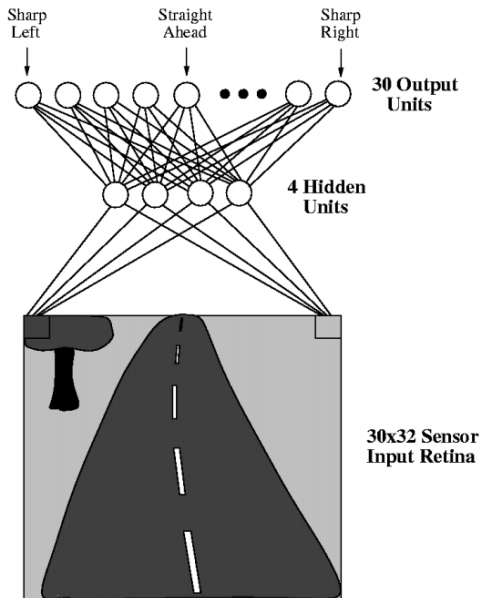
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Classical Example – ALVINN



- ▶ One of the first autonomous car driving systems (in the 90s)
- ▶ ALVINN drives a car
- ▶ The net has $30 \times 32 = 960$ input neurons (the input space is \mathbb{R}^{960}).
- ▶ The value of each input captures the shade of gray of the corresponding pixel.
- ▶ Output neurons indicate where to turn (to the center of gravity).

Source: <http://jmvidal.cse.sc.edu/talks/ann/alvin.html>

A Bit of History

- ▶ Perceptron (Rosenblatt et al., 1957)



- ▶ Single layer (i.e., no hidden layers), the activation function *linear threshold* (i.e., a bit more general linear classifier)
- ▶ Perceptron learning algorithm
- ▶ Used to recognize digits

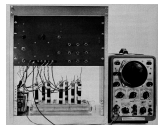
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- ▶ Adaline (Widrow & Hof, 1960)

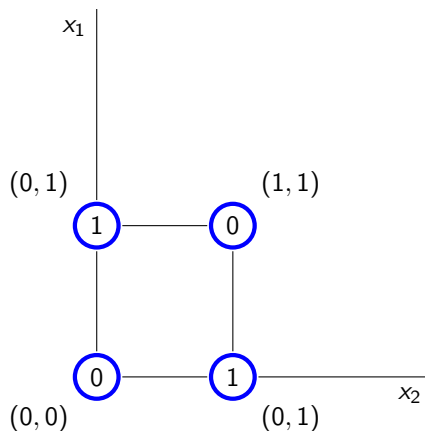


- ▶ Single layer, the activation function *identity* (i.e., a bit more linear function)
- ▶ Online version of the gradient descent
- ▶ Used a new circuitry element called *memristor* which was able to "remember" history of current in form of resistance

In both cases, the expressive power is somewhat limited- it can only express linear decision boundaries and linear (affine) functions.

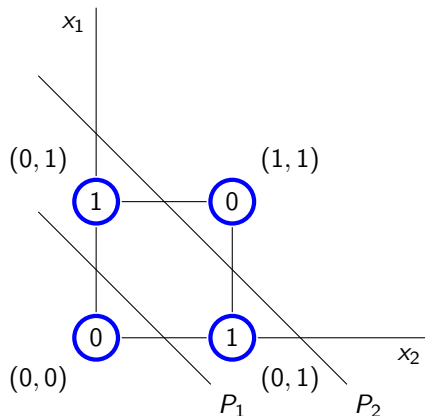
A Bit of History

One of the famous (counter)-examples: XOR



No perceptron can distinguish between ones and zeros.

XOR vs Multilayer Perceptron

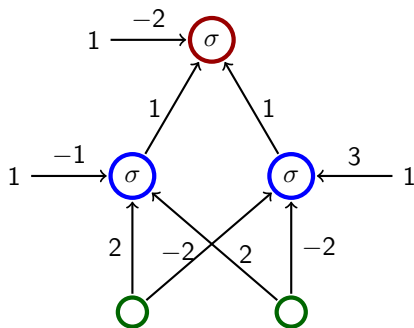


(Here, σ is a linear threshold function.)

$$P_1 : -1 + 2x_1 + 2x_2 = 0$$

$$P_2 : 3 - 2x_1 - 2x_2 = 0$$

The output neuron performs an intersection of half-spaces.

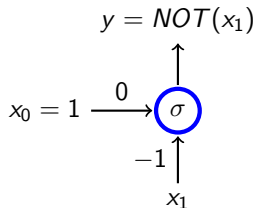
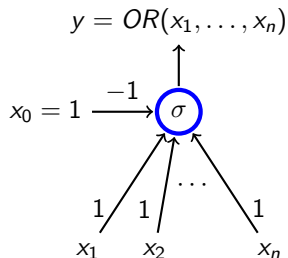
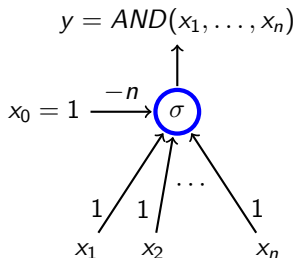


Boolean functions

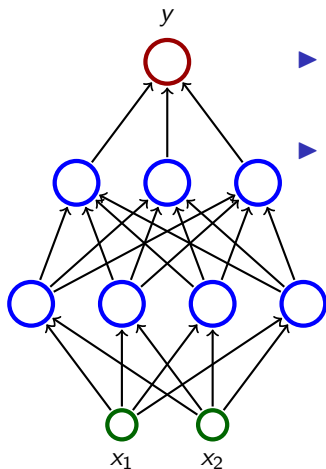
Activation function: *unit step function* $\sigma(\xi) = \begin{cases} 1 & \xi \geq 0; \\ 0 & \xi < 0. \end{cases}$

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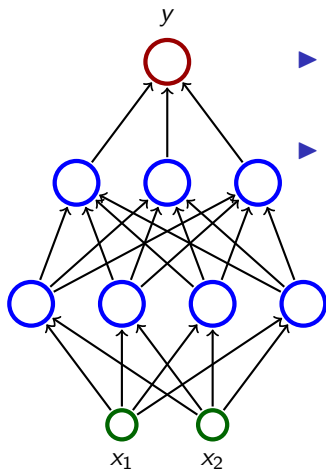


Non-linear separation



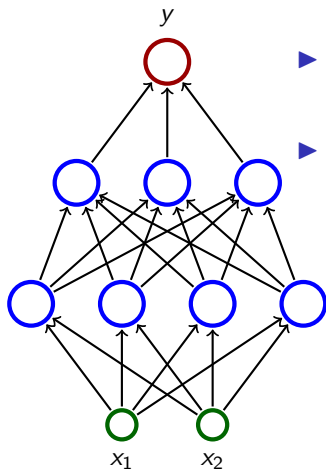
- ▶ Consider a three-layer network; each neuron has the unit step activation function.
- ▶ The network divides the input space in two subspaces according to the output (0 or 1).

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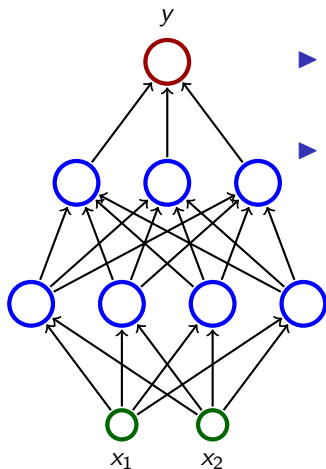
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 - ▶ The third layer may, e.g., make unions of some convex sets.

Example

Consider a triangle T in \mathbb{R}^2 determined by three vertices $(-1, -1), (1, -1), (-1, 2)$.

Give an example of a multilayer perceptron (MLP) with two input neurons and a single output neuron computing the function

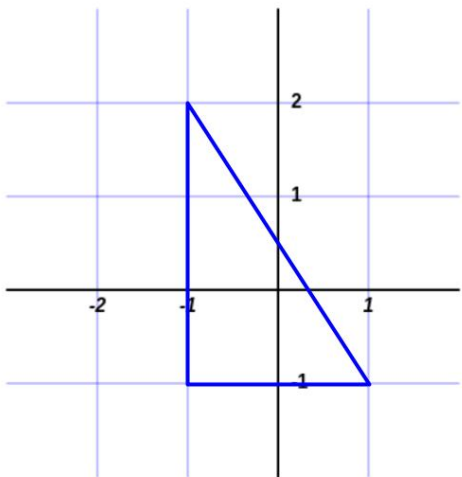
$F : \mathbb{R}^2 \rightarrow \{0, 1\}$ defined as follows:

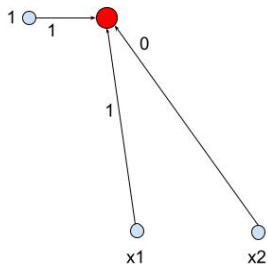
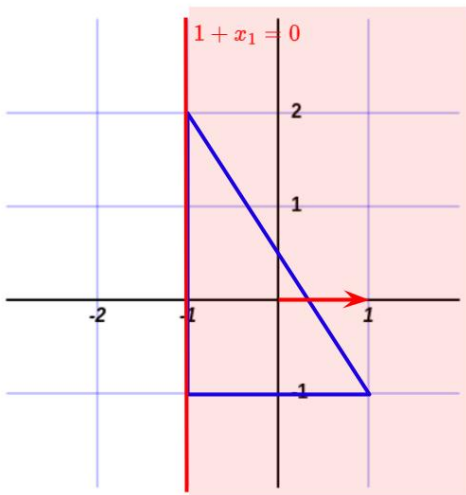
$F(x_1, x_2) = 1$ iff (x_1, x_2) lies either inside, or on the border of T

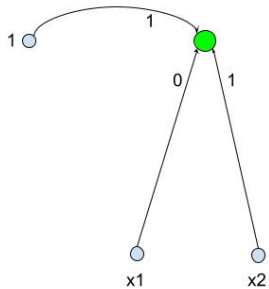
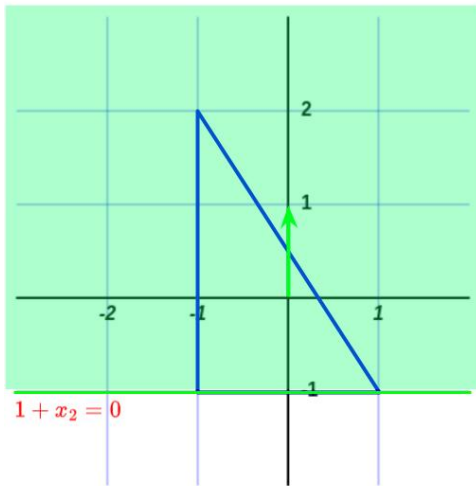
All activation functions in the network should be

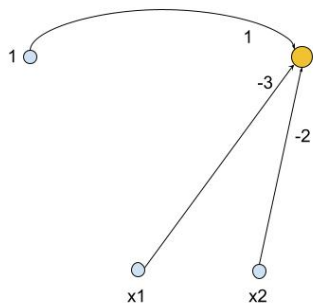
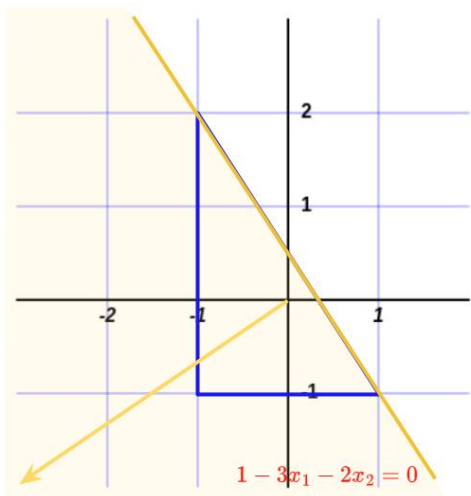
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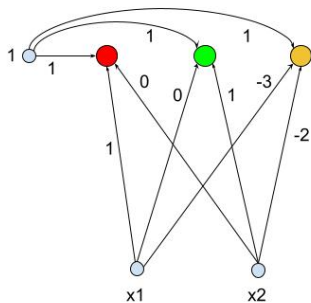
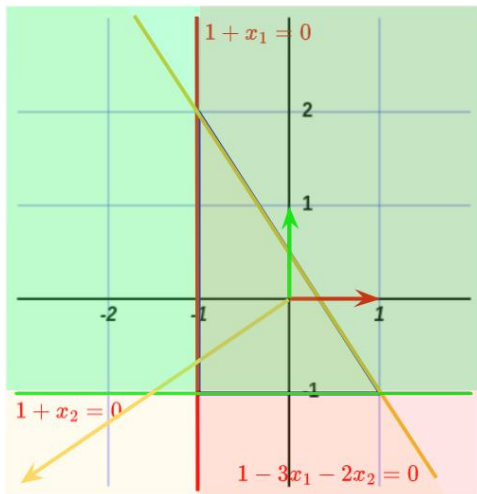
Homework: Consider $F(x_1, x_2) = 1$ iff (x_1, x_2) lies inside of T (but *not* on the border)



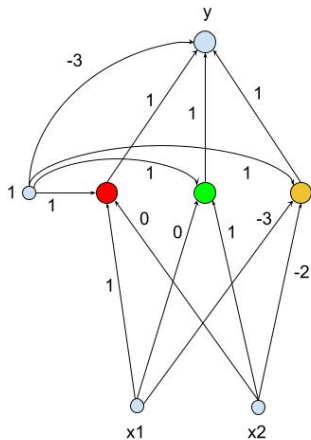
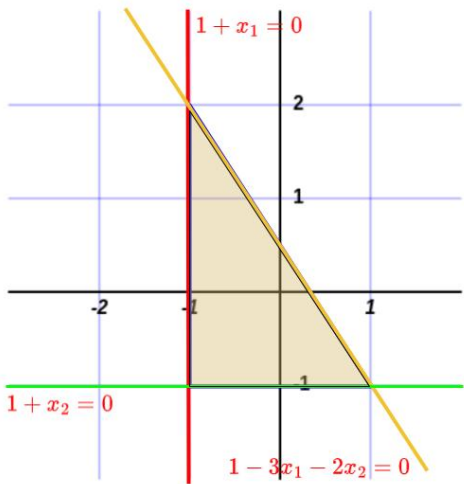








AND



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An efficient way of using the gradient descent was published in 1986!

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(i.e. j_{\leftarrow} is the layer directly below j)

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- ▶ j_{\leftarrow} is the set of all neurons from which there are edges to j
(i.e. j_{\leftarrow} is the layer directly below j)
- ▶ j_{\rightarrow} is the set of all neurons with edges from j .
(i.e. j_{\rightarrow} is the layer directly above j)

MLP – Notation

- ▶ Inner potential of a neuron j :

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

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- ▶ Fixing weights of all neurons, the network computes a function $F[\vec{w}] : \mathbb{R}^{|X|} \rightarrow \mathbb{R}^{|Y|}$ as follows: Assign values of a given vector $\vec{x} \in \mathbb{R}^{|X|}$ to the input neurons, evaluate the network, then $F[\vec{w}](\vec{x})$ is the vector of values of the output neurons.

Here, we implicitly assume a fixed ordering on input and output vectors.

MLP – Learning

- ▶ Given a set D of training examples:

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

Here $\vec{x}_k \in \mathbb{R}^{|\mathcal{X}|}$ and $\vec{d}_k \in \mathbb{R}^{|\mathcal{Y}|}$. We write d_{kj} to denote the value in \vec{d}_k corresponding to the output neuron j .

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- ▶ **Error Function:** $E(\vec{w})$ where \vec{w} is a vector of all weights in the network. The choice of E depends on the solved task (classification vs regression etc.).

Example (Squared error):

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

where

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

MLP – Batch Gradient Descent

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

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

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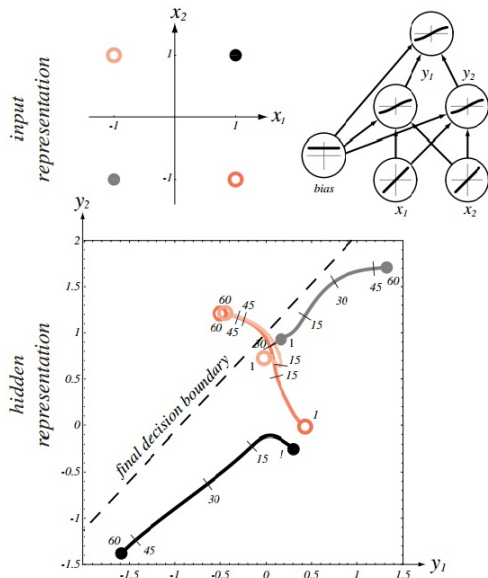
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Note that $\frac{\partial E}{\partial w_{ji}}(\vec{w}^{(t)})$ is a component of ∇E , i.e., the weight change in the step $t + 1$ can be written as follows: $\vec{w}^{(t+1)} = \vec{w}^{(t)} - \varepsilon(t) \cdot \nabla E(\vec{w}^{(t)})$.

Illustration of Gradient Descent – XOR



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

Stochastic Gradient Descent (SGD)

Assume that $E(\vec{w}) = \sum_{k=1}^p E_k(\vec{w})$ where $E_k(\vec{w})$ is an error w.r.t. the single training example (\vec{x}_k, \vec{d}_k) .

- ▶ 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.

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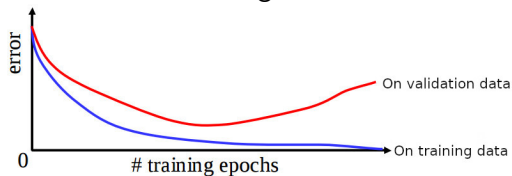
Comments on Training Algorithm

- ▶ Not guaranteed to converge to zero training error, may converge to a local minimum or oscillate indefinitely.
- ▶ In practice, does converge to low error for many large networks on (big) real data.
- ▶ Many epochs (thousands) may be required, hours or days of training for large networks.

There are many issues concerning learning efficiency (data normalization, selection of activation functions, weight initialization, learning rate, efficiency of the gradient descent itself, etc.) – see PV021.

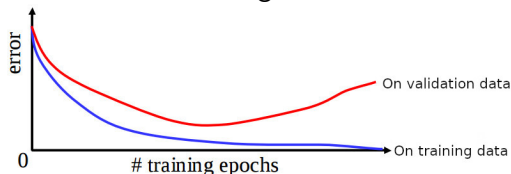
Overfitting

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- ▶ Keep a hold-out validation set and test the error of the network on this set after every epoch. Stop training when additional epochs increase the validation error.

The validation error can be measured by completely different means than the training error E .

Hidden Neurons Representations

Trained hidden neurons can be seen as newly constructed features.

E.g., in a two-layer network used for classification, the hidden layer transforms the input so that important features become explicit (and hence the result may become linearly separable).

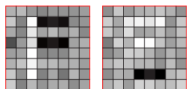
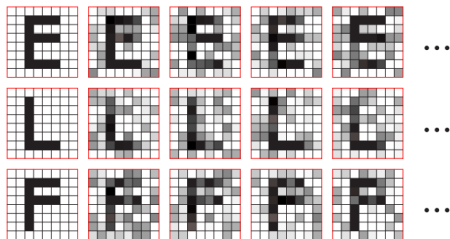
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Consider a two-layer MLP, 64-2-3, for classifying letters (three output neurons, each corresponding to one of the letters).

sample training patterns



learned input-to-hidden weights

Optimal Architecture?

- ▶ For MLP: Too few hidden neurons prevent the network from adequately fitting the data. Too many hidden units can result in overfitting.
(There are advanced methods that prevent overfitting even for rich models, such as regularization, where the error function penalizes overfitting – see PV021.)

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- ▶ There are (almost) infinitely many types of architectures of neural networks (convolutional, recurrent, transformers, adversarial, etc.) suitable for various tasks.
- ▶ **Transfer learning:** Start with a known solution to a related problem.

Simplified view: Preserve lower parts of the network trained to solve the related problem (feature extractors). Add your top part and then train only the new top part (or train the whole network but carefully).

How to Choose Activation Functions & Error

- ▶ **Hidden neurons:** "Almost" linear activations such as (leaky) ReLU ($y = \max(0, \xi)$)
Better than sigmoidal that saturate more often.
- ▶ **Output neurons:** Single output:
 - ▶ Regression: Typically "linear" output, i.e., no activation on the output neuron.
 - ▶ Binary classification: Logistic sigmoid $y = 1/(1 + e^{-\xi})$
- ▶ **Error:** Single output:
 - ▶ Regression: (Mean) squared error
 - ▶ Binary classification: Binary cross-entropy

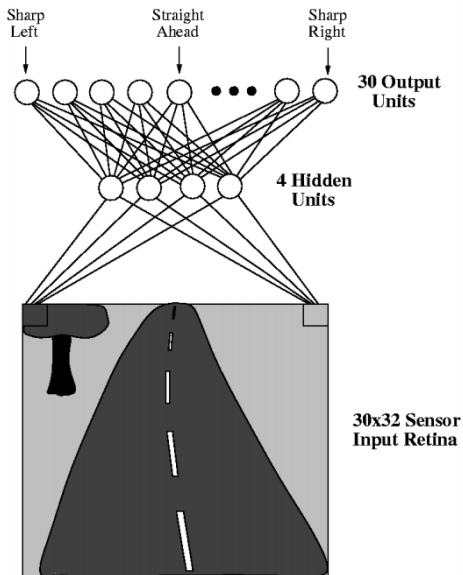
For multiple outputs and classification, use softmax output and cross-entropy.

Applications

- ▶ Image recognition, segmentation, etc.
- ▶ Machine translation and other text processing
- ▶ Text generation, image generation, movie generation, theatre plays generation
- ▶ Text to Speech and vice versa
- ▶ Finance, business predictions, fraud detection
- ▶ Game playing (backgammon is a classic example, AlphaGo is the famous one, computer games are the big ones, **bridge** is the hard one)
- ▶ (artificial brain and intelligence)
- ▶ ...

Text and image processing are possibly the most advanced deep learning applications.

ALVINN



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- ▶ Direction corresponds to the center of gravity.

, i.e., output neurons are considered as points of mass evenly distributed along a line. The weight of each neuron corresponds to its value.

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Trained while driving.

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 - ▶ \vec{x}_k = image of the road
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- ▶ the values \vec{d}_k computed using Gaussian distribution:

$$d_{ki} = e^{-D_i^2/10}$$

Where D_i is the distance between the i -th output from the one corresponding to the steering wheel's real direction.

(The authors claimed this approach is better than the binary output because similar road directions induce similar driver reactions.)

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Naive approach: just take images from the camera.

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 - ▶ let the driver go crazy! (a bit dangerous, expensive, unreliable)
- ▶ Images are very similar (the network sees the road from the right lane), overfitting.

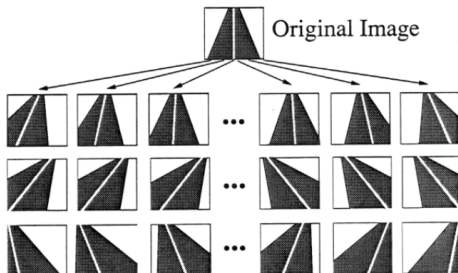
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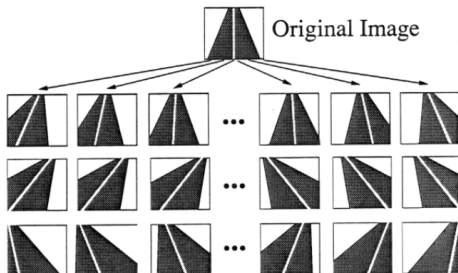
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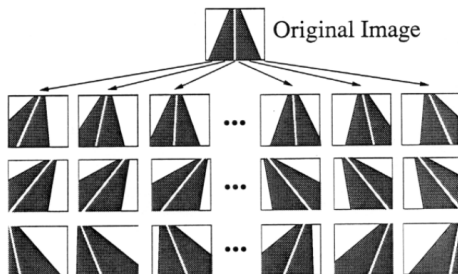
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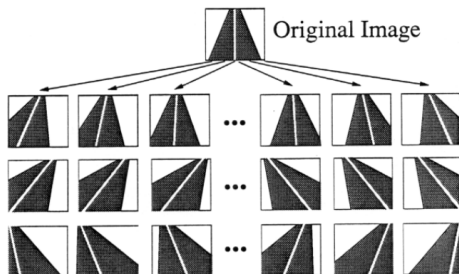


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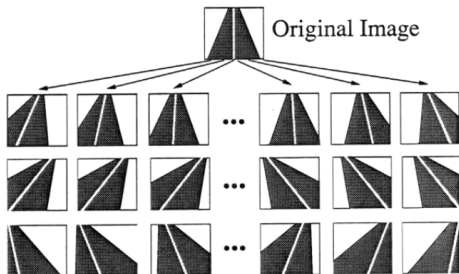
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The repetitiveness of images was solved as follows:

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- ▶ afterward, a new image is captured, 15 copies made, and these new 15 substitute 15 selected from the buffer (10 with the smallest training error, five randomly)

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(The speed was limited by the hydraulic controller of the steering wheel, not the learning algorithm.)

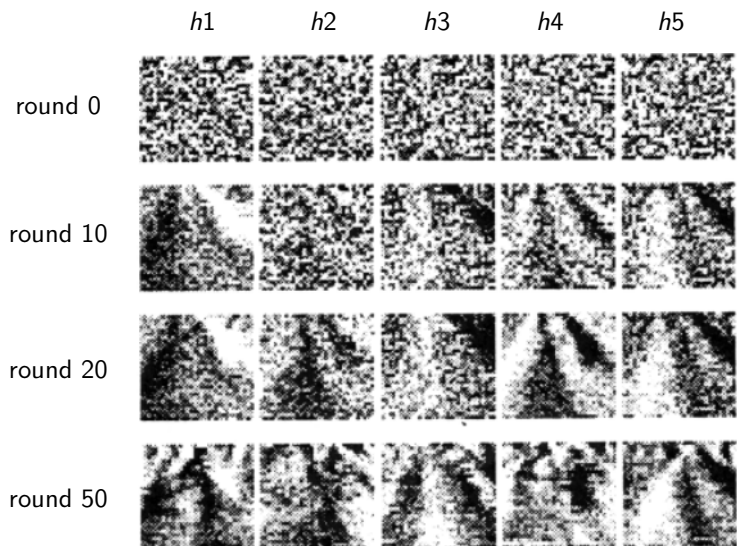
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- ▶ ALVINN was able to go through roads it had never "seen" and in different weather

ALVINN – Weight Learning



Here $h1, \dots, h5$ are values of hidden neurons.

Backpropagation

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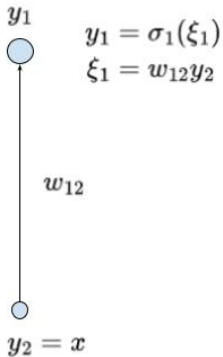
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- ▶ The error function is the squared error.
 - ▶ Assume that 1 is the output neuron,
 - ▶ which means that $y_1 = y_1[\vec{w}](x)$ is the output of the network with weights \vec{w} and the input x ,
 - ▶ and the error on D is then

$$E(\vec{w}) = \frac{1}{2}(y_1 - d)^2$$

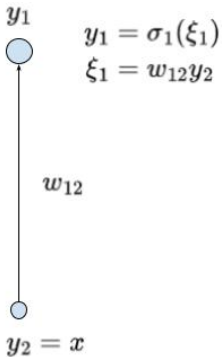
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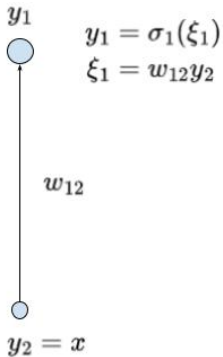
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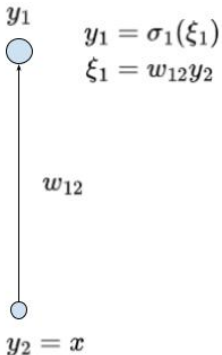
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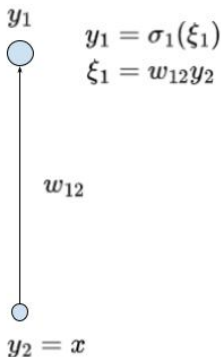
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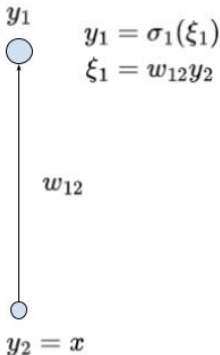
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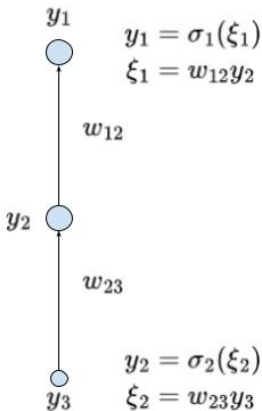
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$$\frac{\partial E}{\partial y_1} = y_1 - d$$

Note that if σ_1 is identity, we obtain exactly the gradient from the linear regression method. Considering σ_1 equal to the logistic sigmoid and E the cross-entropy, we get the logistic regression gradient.

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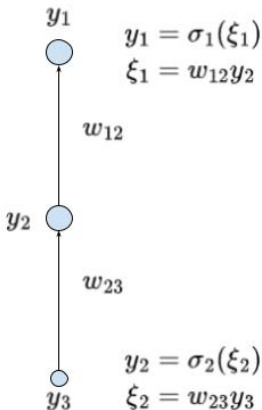
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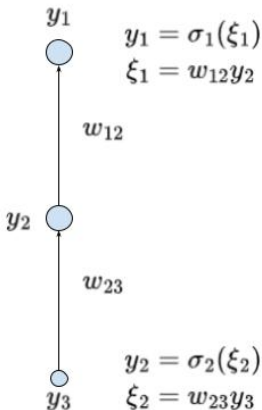


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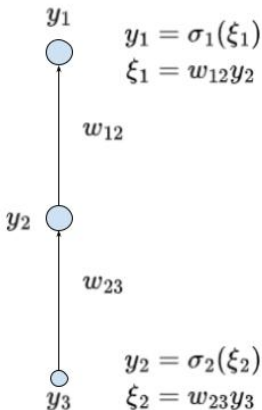
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$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



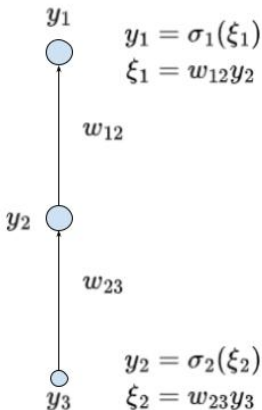
$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_3$$

$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

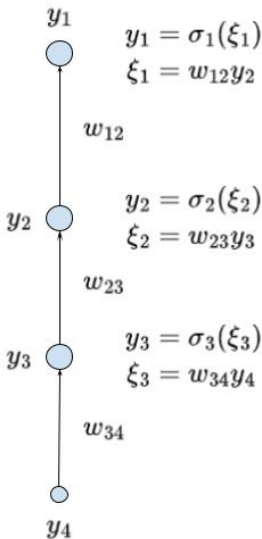
$$\frac{\partial E}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_3$$

$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_2} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{23}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_3$$

$$\frac{\partial E}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial \xi_3} \frac{\partial \xi_3}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \sigma'_3(\xi_3) y_4$$

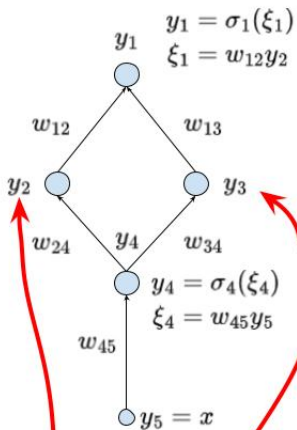
$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_2} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}$$

$$\frac{\partial E}{\partial y_3} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial y_3} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) w_{23}$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$y_2 = \sigma_2(\xi_2)$$

$$y_3 = \sigma_3(\xi_3)$$

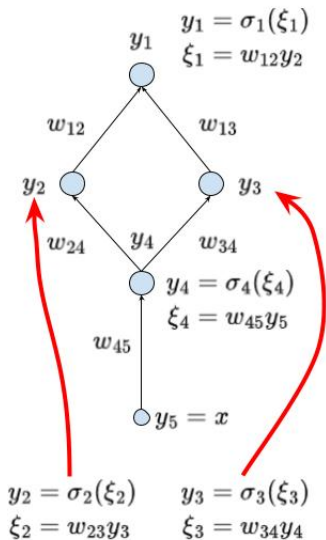
$$\xi_2 = w_{23}y_3$$

$$\xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$

$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

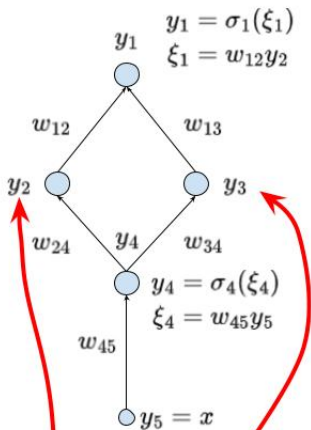


$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$

$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_3$$



$$y_2 = \sigma_2(\xi_2)$$

$$y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3$$

$$\xi_3 = w_{34}y_4$$

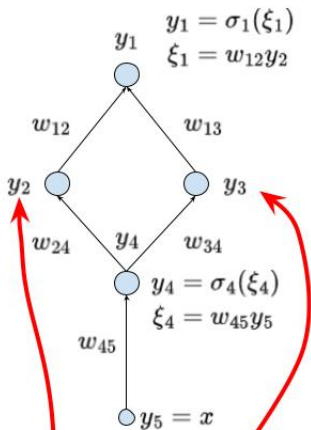
$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$

$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_3$$

$$\frac{\partial E}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_4$$



$$y_2 = \sigma_2(\xi_2)$$

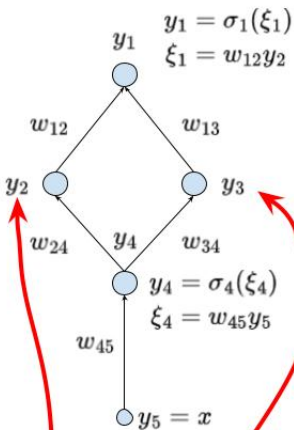
$$y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3$$

$$\xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_3$$

$$\frac{\partial E}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_4$$

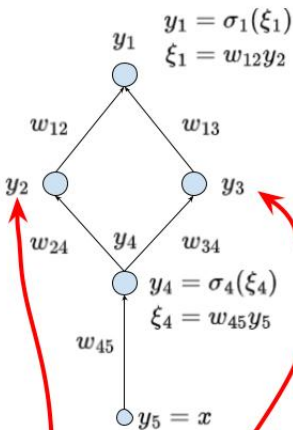
$$\frac{\partial E}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial \xi_3} \frac{\partial \xi_3}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \sigma'_3(\xi_3) y_4$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3 \quad \xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$y_2 = \sigma_2(\xi_2)$$

$$y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3$$

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$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{12}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_2$$

$$\frac{\partial E}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial w_{13}} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) y_3$$

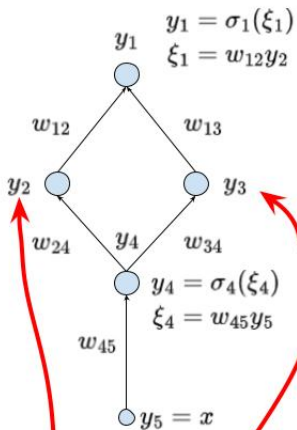
$$\frac{\partial E}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial w_{24}} = \frac{\partial E}{\partial y_2} \sigma'_2(\xi_2) y_4$$

$$\frac{\partial E}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial \xi_3} \frac{\partial \xi_3}{\partial w_{34}} = \frac{\partial E}{\partial y_3} \sigma'_3(\xi_3) y_4$$

$$\frac{\partial E}{\partial w_{45}} = \frac{\partial E}{\partial y_4} \frac{\partial y_4}{\partial \xi_4} \frac{\partial \xi_4}{\partial w_{45}} = \frac{\partial E}{\partial y_4} \sigma'_4(\xi_4) y_5$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



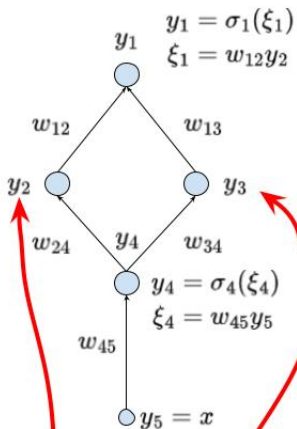
$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3 \quad \xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$\frac{\partial E}{\partial y_1} = y_1 - d$$

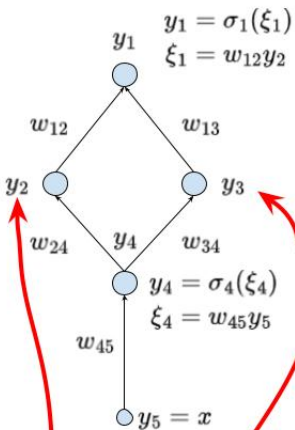
$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_2} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3 \quad \xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_2} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}$$

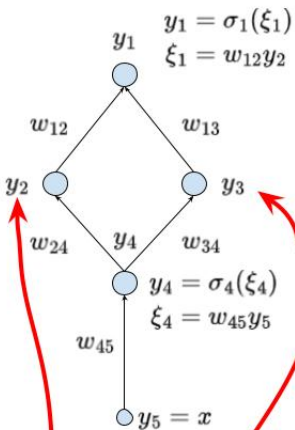
$$\frac{\partial E}{\partial y_3} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_3} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{13}$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3 \quad \xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



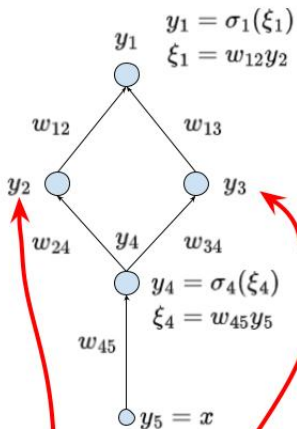
$$\frac{\partial E}{\partial y_1} = y_1 - d$$

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$$\frac{\partial E}{\partial y_1} = y_1 - d$$

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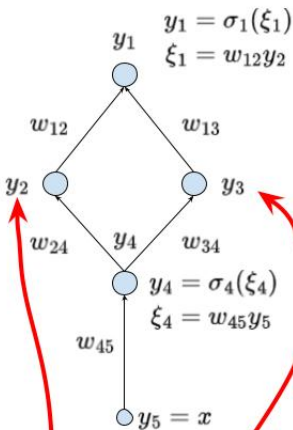
$$\frac{\partial E}{\partial y_4}$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

$$\xi_2 = w_{23}y_3 \quad \xi_3 = w_{34}y_4$$

$$D = \{(x, d)\}$$

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$$\frac{\partial E}{\partial y_1} = y_1 - d$$

$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_2} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}$$

$$\frac{\partial E}{\partial y_3} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_3} = \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{13}$$

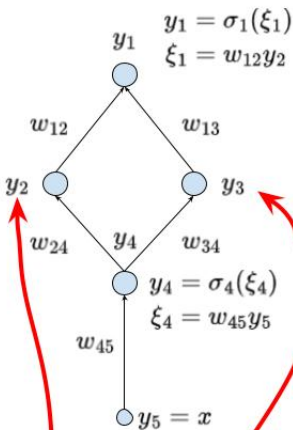
$$\frac{\partial E}{\partial y_4} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial y_4} + \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial y_4}$$

$$y_2 = \sigma_2(\xi_2) \quad y_3 = \sigma_3(\xi_3)$$

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$$D = \{(x, d)\}$$

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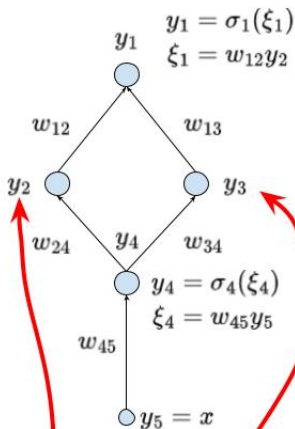
$$\frac{\partial E}{\partial y_3} = \frac{\partial E}{\partial y_1} \frac{\partial y_1}{\partial \xi_1} \frac{\partial \xi_1}{\partial y_3} = \frac{\partial E}{\partial y_1} \sigma_1'(\xi_1) w_{13}$$

$$\frac{\partial E}{\partial y_4} = \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial y_4} + \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial y_4}$$

$$= \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial y_4} + \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial \xi_3} \frac{\partial \xi_3}{\partial y_4}$$

$$D = \{(x, d)\}$$

$$E = \frac{1}{2}(y_1 - d)^2$$



$$y_2 = \sigma_2(\xi_2)$$

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$$\begin{aligned} \frac{\partial E}{\partial y_4} &= \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial y_4} + \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial y_4} \\ &= \frac{\partial E}{\partial y_2} \frac{\partial y_2}{\partial \xi_2} \frac{\partial \xi_2}{\partial y_4} + \frac{\partial E}{\partial y_3} \frac{\partial y_3}{\partial \xi_3} \frac{\partial \xi_3}{\partial y_4} \\ &= \frac{\partial E}{\partial y_2} \sigma_2'(\xi_2) w_{24} + \frac{\partial E}{\partial y_3} \sigma_3'(\xi_3) w_{34} \end{aligned}$$

MLP – Gradient Computation

Under our simplifying assumptions $D = \{(x, d)\}$ and $E = (y_1 - d)^2$ the gradient computation proceeds as follows:

Applying the chain rule, we obtain

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

where (after more applications of the chain rule)

$$\frac{\partial E_k}{\partial y_1} = y_1 - d$$

Keep in mind that 1 is the only output neuron which means that y_1 is the value of the network.

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

Here $y_r = y[\vec{w}](x)$ where \vec{w} are the current weights and x is the example input.

MLP – Gradient Computation – General!

Let us drop our simplifying assumptions!

- ▶ Given a set D of training examples:

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

Here $\vec{x}_k \in \mathbb{R}^{|X|}$ and $\vec{d}_k \in \mathbb{R}^{|Y|}$. We write d_{kj} to denote the value in \vec{d}_k corresponding to the output neuron j .

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- ▶ **Error Function:** $E(\vec{w})$ where \vec{w} is a vector of all weights in the network. The choice of E depends on the solved task (classification vs regression, etc.).

Example (Squared error):

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

where

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

MLP – Gradient Computation

For every weight w_{ji} we have (obviously)

$$\frac{\partial E}{\partial w_{ji}} = \sum_{k=1}^P \frac{\partial E_k}{\partial w_{ji}}$$

So now it suffices to compute $\frac{\partial E_k}{\partial w_{ji}}$, that is the error for a fixed training example (\vec{x}_k, \vec{d}_k) .

MLP – Gradient Computation

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Applying the chain rule, we obtain

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

where (more applications of the chain rule)

$\frac{\partial E_k}{\partial y_j}$ is computed directly for the output neurons $j \in Y$

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

(Here $y_r = y[\vec{w}](\vec{x}_k)$ where \vec{w} are the current weights and \vec{x}_k is the input of the k -th training example.)

MLP – Backpropagation

Input: A training set $D = \left\{ \left(\vec{x}_k, \vec{d}_k \right) \mid k = 1, \dots, p \right\}$ and the current vector of weights \vec{w} .

Note that the backprop. is repeated in every iteration of the gradient descent!

- ▶ Evaluate all values y_i of neurons using the standard bottom-up procedure with the input \vec{x}_k .

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Note that the backprop. is repeated in every iteration of the gradient descent!

- ▶ Evaluate all values y_i of neurons using the standard bottom-up procedure with the input \vec{x}_k .
- ▶ For every training example (\vec{x}_k, \vec{d}_k) compute $\frac{\partial E_k}{\partial y_j}$ using *backpropagation* through layers top-down :
 - ▶ For all $j \in Y$ compute $\frac{\partial E_k}{\partial y_j}$ by taking the derivative of the error.
e.g., in the case of the squared error, we have $\frac{\partial E_k}{\partial y_j} = y_j - d_{kj}$.

MLP – Backpropagation

Input: A training set $D = \left\{ \left(\vec{x}_k, \vec{d}_k \right) \mid k = 1, \dots, p \right\}$ and the current vector of weights \vec{w} .

Note that the backprop. is repeated in every iteration of the gradient descent!

- ▶ Evaluate all values y_i of neurons using the standard bottom-up procedure with the input \vec{x}_k .
- ▶ For every training example (\vec{x}_k, \vec{d}_k) compute $\frac{\partial E_k}{\partial y_j}$ using *backpropagation* through layers top-down :
 - ▶ For all $j \in Y$ compute $\frac{\partial E_k}{\partial y_j}$ by taking the derivative of the error. e.g., in the case of the squared error, we have $\frac{\partial E_k}{\partial y_j} = y_j - d_{kj}$.
 - ▶ In the layer ℓ , assuming that $\frac{\partial E_k}{\partial y_r}$ has been computed for all neurons r in the layer $\ell + 1$, compute

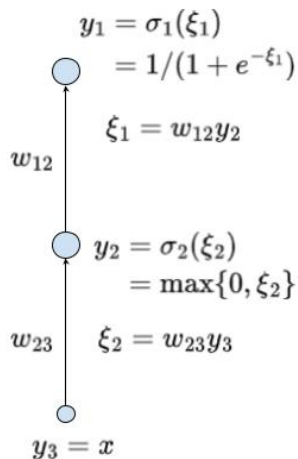
$$\frac{\partial E_k}{\partial y_j} = \sum_{r \in j \rightarrow} \frac{\partial E_k}{\partial y_r} \cdot \sigma'_r(\xi_r) \cdot w_{rj}$$

for all j from the ℓ -th layer. Here σ'_r is the derivative of σ_r .

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

Output: $\frac{\partial E}{\partial w_{ji}} = \sum_{k=1}^p \frac{\partial E_k}{\partial w_{ji}}$.

MLP Learning Example



Training set:

$$D = \{(x, d)\} = \{(1, 1)\}$$

That is

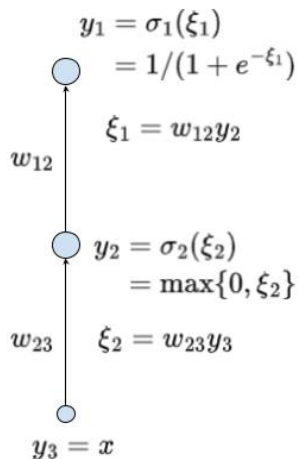
$$y_3 = x = 1$$

$$d = 1$$

Error cross-entropy:

$$\begin{aligned} E(\vec{w}) &= d \log(y_1) + (1 - d) \log(1 - y_1) \\ &= \log(y_1) \end{aligned}$$

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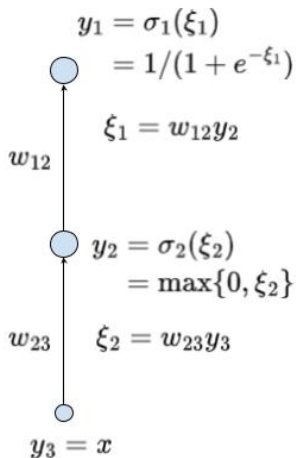
$$\begin{aligned} E(\vec{w}) &= d \log(y_1) + (1 - d) \log(1 - y_1) \\ &= \log(y_1) \end{aligned}$$

Assume the initial weight vector

$$\vec{w}^{(0)} = (w_{12}^{(0)}, w_{23}^{(0)}) = (\frac{1}{4}, 2).$$

Consider the learning rate $\varepsilon = 0.5$.

MLP Learning Example – Gradient Descent



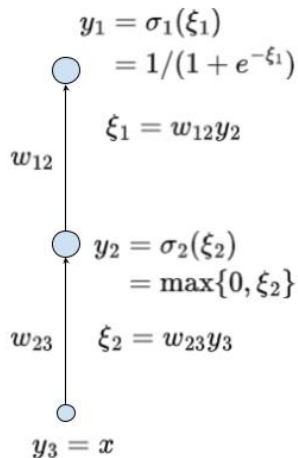
To make the gradient descent step:

$$w_{12}^{(1)} = w_{12}^{(0)} - \varepsilon \frac{\partial E}{\partial w_{12}}(\vec{w}^{(0)})$$

$$w_{23}^{(1)} = w_{23}^{(0)} - \varepsilon \frac{\partial E}{\partial w_{23}}(\vec{w}^{(0)})$$

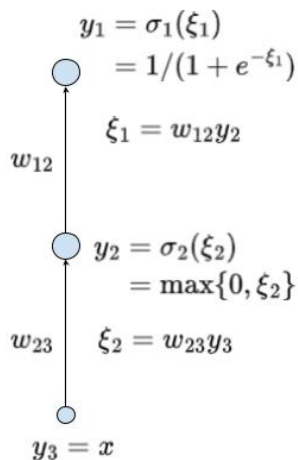
we need to compute the partial derivatives $\frac{\partial E}{\partial w_{12}}$ and $\frac{\partial E}{\partial w_{23}}$.

MLP Learning Example – Forward Pass



We have $x = 1$, $w_{12}^{(0)} = 1/4$, $w_{23}^{(0)} = 2$

MLP Learning Example – Forward Pass



We have $x = 1$, $w_{12}^{(0)} = 1/4$, $w_{23}^{(0)} = 2$

First, compute the **forward pass**

$$y_3 = x = 1$$

$$\xi_2 = w_{23}^{(0)} y_3 = 2y_3 = 2$$

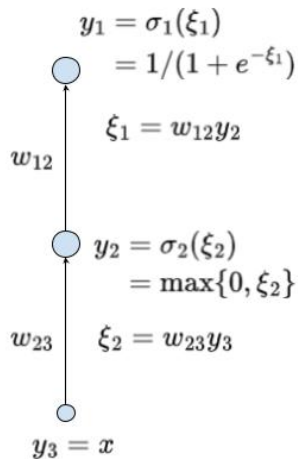
$$y_2 = \max\{0, \xi_2\} = 2$$

$$\xi_1 = w_{12}^{(0)} y_2 = \frac{1}{4} \cdot 2 = \frac{1}{2}$$

$$y_1 = 1/(1 + e^{-\xi_1}) = 1/(1 + e^{-(1/2)}) \\ = 0.6225$$

MLP Learning Example – Backward Pass

We have $w_{12}^{(0)} = 1/4$, $w_{23}^{(0)} = 2$, $y_1 = 0.6225$, $y_2 = 2$, $y_3 = 1$.

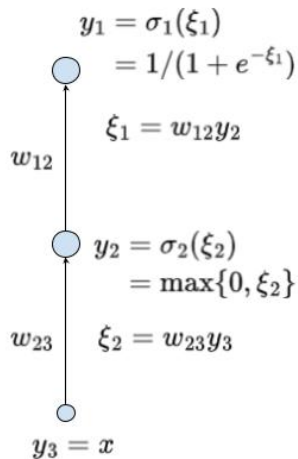


MLP Learning Example – Backward Pass

We have $w_{12}^{(0)} = 1/4$, $w_{23}^{(0)} = 2$, $y_1 = 0.6225$, $y_2 = 2$, $y_3 = 1$.

Proceed with the backward pass:

$$\frac{\partial E}{\partial y_1} = \frac{\partial \log(y_1)}{\partial y_1} = \frac{1}{y_1} = 1.6065$$



MLP Learning Example – Backward Pass

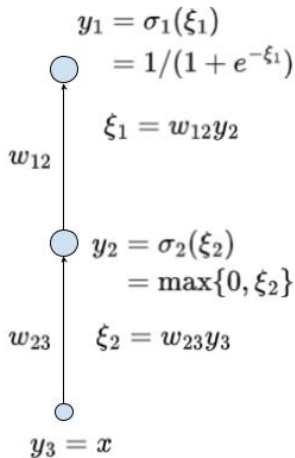
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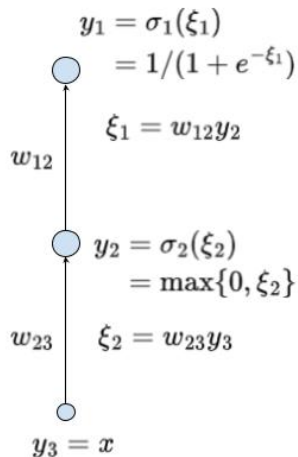
$$\frac{\partial E}{\partial y_1} = \frac{\partial \log(y_1)}{\partial y_1} = \frac{1}{y_1} = 1.6065$$

Since $\sigma'_1 = \sigma_1(1 - \sigma_1)$

$$\begin{aligned}\frac{\partial E}{\partial y_2} &= \frac{\partial E}{\partial y_1} \sigma'_1(\xi_1) w_{12}^{(0)} \\ &= \frac{\partial E}{\partial y_1} \sigma_1(\xi_1) (1 - \sigma_1(\xi_1)) w_{12}^{(0)} \\ &= \frac{\partial E}{\partial y_1} y_1 (1 - y_1) w_{12}^{(0)} \\ &= 1.6065 \cdot 0.6225 \cdot 0.3775 \cdot (1/4) \\ &= 0.09438\end{aligned}$$



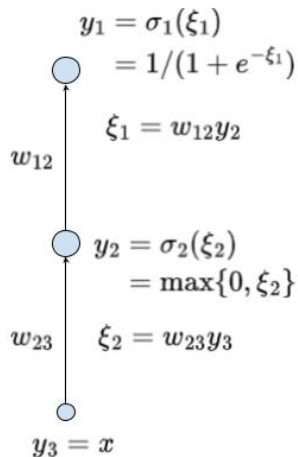
MLP Learning Example – The Gradient



We have

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MLP Learning Example – The Gradient



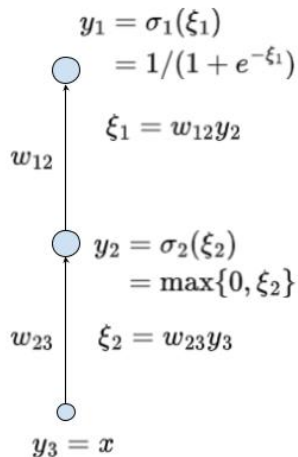
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Compute derivatives of E w.r.t. weights:

$$\begin{aligned} \frac{\partial E}{\partial w_{12}} &= \frac{\partial E}{\partial y_1} \sigma_1'(\xi_1) y_2 \\ &= \frac{\partial E}{\partial y_1} y_1 (1 - y_1) y_2 \\ &= 0.755 \end{aligned}$$

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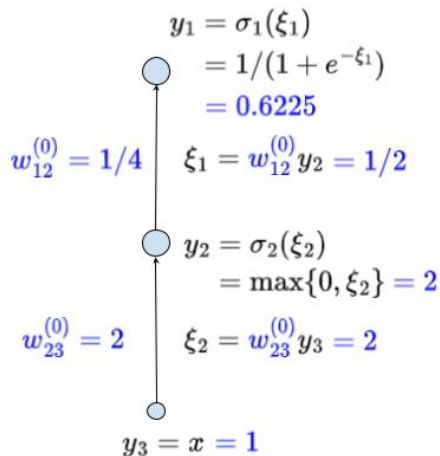
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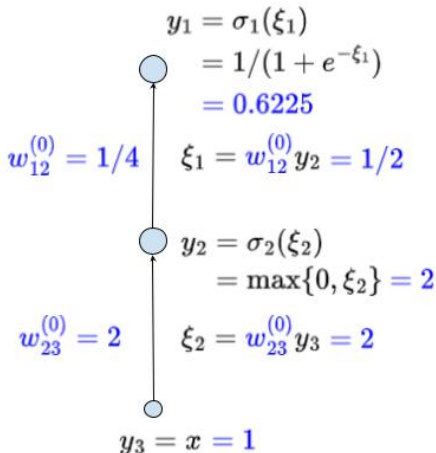
Backpropagation – Example – Summary

Forward pass (bottom up)



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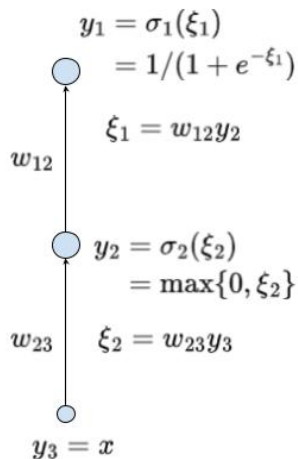


Backward pass (top down)

$$\frac{\partial E}{\partial y_1} = 1/y_1 = 1.6065$$
$$\frac{\partial E}{\partial w_{12}} = \frac{\partial E}{\partial y_1} y_1 (1 - y_1) y_2 = 0.755$$
$$\frac{\partial E}{\partial y_2} = \frac{\partial E}{\partial y_1} y_1 (1 - y_1) w_{12}^{(0)} = 0.09438$$
$$\frac{\partial E}{\partial w_{23}} = \frac{\partial E}{\partial y_2} 1 y_3 = 0.09438$$

Note that **WE HAVE NOT YET CHANGED ANY WEIGHTS!**

MLP Learning Example – Gradient Descent Step

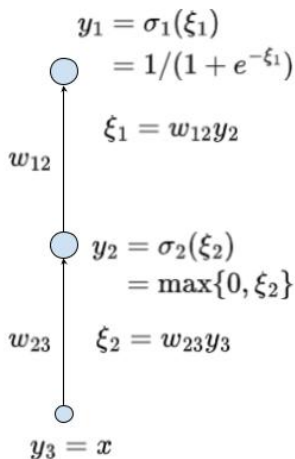


So **ONLY NOW** we can make the **learning step** and change the weights:

$$\begin{aligned}w_{12}^{(1)} &= w_{12}^{(0)} - \varepsilon \frac{\partial E}{\partial w_{12}}(\vec{w}^{(0)}) \\ &= \frac{1}{4} - 0.5 \cdot 0.755 \\ &= -0.127\end{aligned}$$

$$\begin{aligned}w_{23}^{(1)} &= w_{23}^{(0)} - \varepsilon \frac{\partial E}{\partial w_{23}}(\vec{w}^{(0)}) \\ &= 2 - 0.5 \cdot 0.09438 \\ &= 1.952\end{aligned}$$

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We have made just a **single** gradient descent step!

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An advice: Always concentrate the main effort on the solved problem formulation and, afterward, on the data you have at your disposal (and honestly separate the Test set right at the beginning).

Deep Learning

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Deep Learning

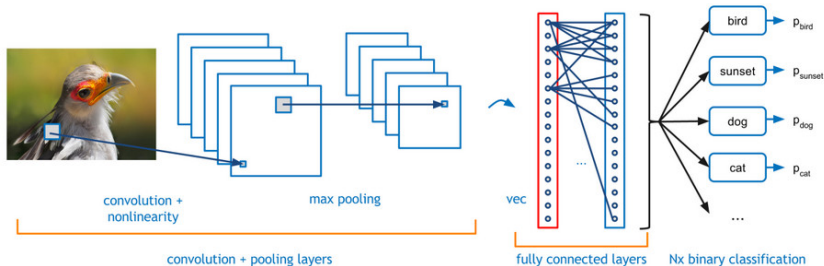
- ▶ Cybenko's theorem shows that two-layer networks are omnipotent – such results nearly killed NN when support vector machines were found to be easier to train in 00's.
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More precisely: The lowest hidden layer learns patterns in data, the second lowest learns patterns in data transformed through the first layer, and so on.

Deep Learning

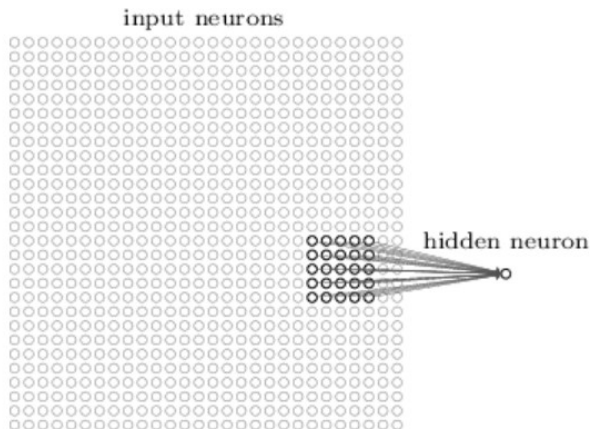
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More precisely: The lowest hidden layer learns patterns in data, the second lowest learns patterns in data transformed through the first layer, and so on.
 - ▶ Then use a supervised learning algorithm to only *fine tune* the weights to the desired input-output behavior.
- ▶ ... but the actual revolution started with convolutional networks trained on several GPUs.

Convolutional network

A specific architecture of neural networks from the 80s.



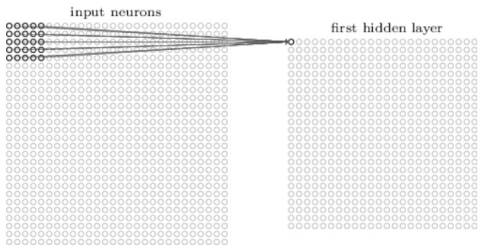
Convolutional layers



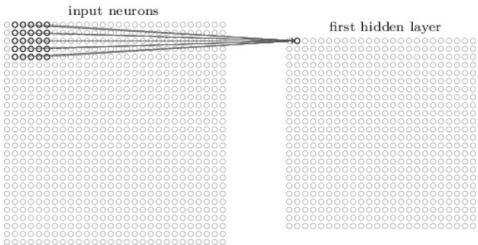
Every neuron is connected with a (typically small) *receptive field* of neurons in the lower layer.

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

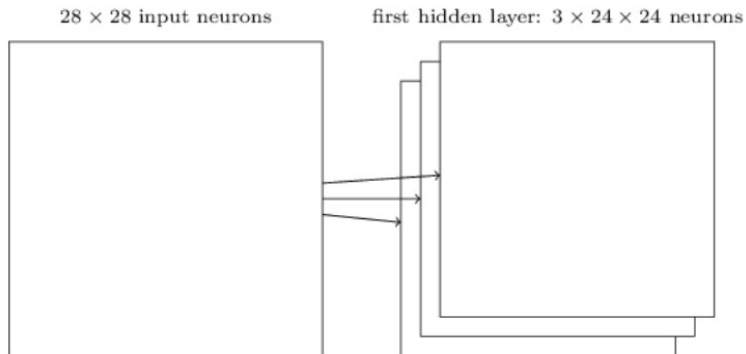
Convolutional layers



Neurons grouped into *feature maps* sharing weights.



Convolutional layers

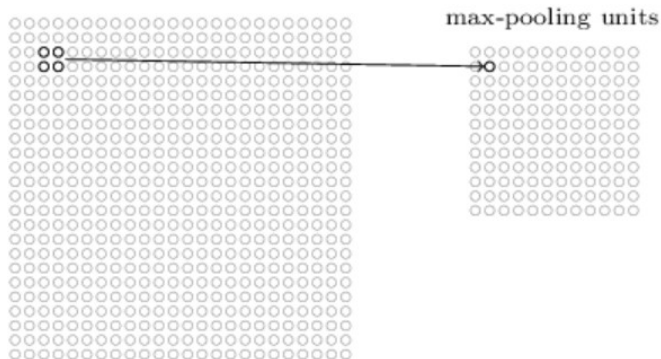


Each feature map represents a property of the input that is supposed to be spatially invariant.

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

Pooling layers

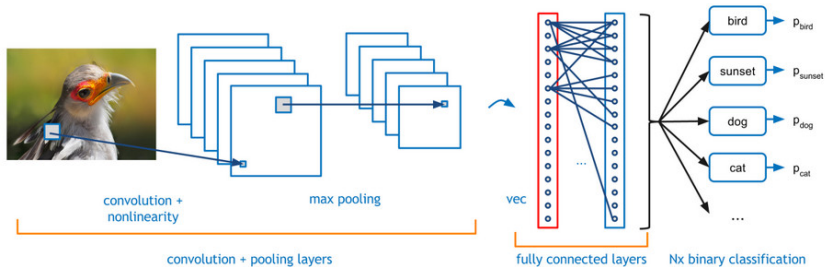
hidden neurons (output from feature map)



Neurons in the pooling layer compute simple functions of their receptive fields (the fields are typically disjoint):

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

Convolutional network



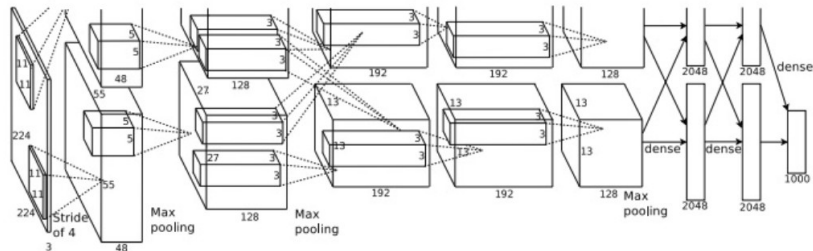
ImageNet Large-Scale Visual Recognition Challenge (ILSVRC)

Competition in classification over a subset of images from ImageNet.

In 2012, training saw 1,200,000 images and 1000 categories. Validation set 50,000, Test set 150,000.

Many images contain several objects → typical rule is top-5 highest probability assigned by the net.

ImageNet classification with deep convolutional neural networks, by Alex Krizhevsky, Ilya Sutskever, and Geoffrey E. Hinton (2012).



Trained on two GPUs (NVIDIA GeForce GTX 580)

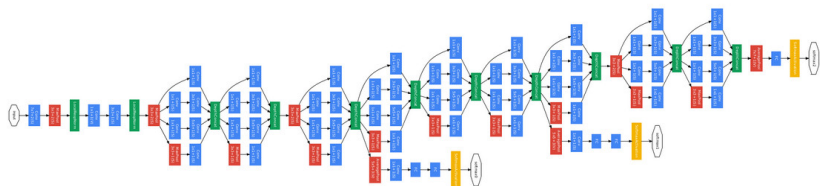
Results:

- ▶ Accuracy 84.7% in top-5 (second best alg. at the time: 73.8%)
- ▶ 63.3% in "perfect" classification (top-1)

ILSVRC 2014

The same set of images as in 2012, top-5 criterium.

GoogLeNet: deep convolutional net, 22 layers



Results:

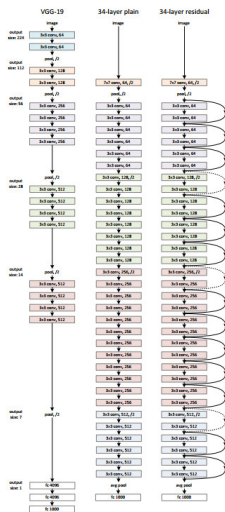
- ▶ 93.33% in top-5

Superhuman power?

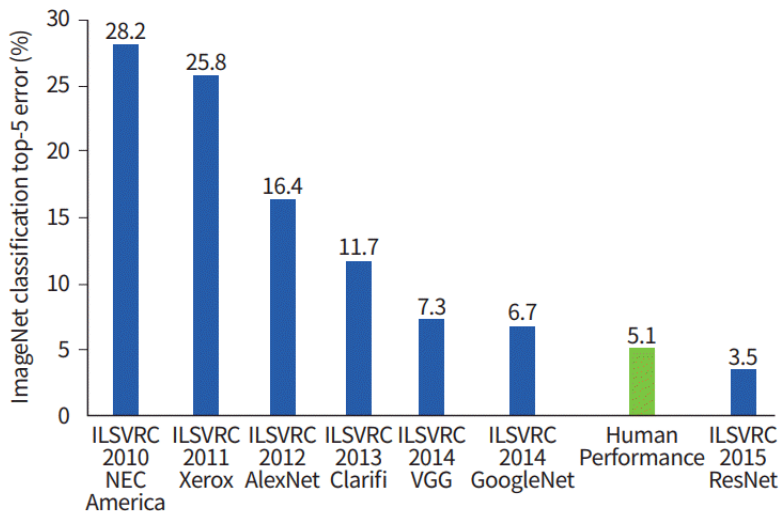
Superhuman GoogLeNet?!

Andrej Karpathy: ...the task of labeling images with 5 out of 1000 categories quickly turned out to be highly challenging, even for some friends in the lab who have been working on ILSVRC and its classes for a while. First, we thought we would put it up on [Amazon Mechanical Turk]. Then, we thought we could recruit paid undergrads. Then, I organized a labeling party of intense labeling effort only among the (expert labelers) in our lab. Then, I developed a modified interface that used GoogLeNet predictions to prune the number of categories from 1000 to only about 100. It was still too hard - people kept missing categories and getting up to ranges of 13-15% error rates. In the end, I realized that to get anywhere competitively close to GoogLeNet, it would be most efficient if I sat down and went through the painfully long training process and the subsequent careful annotation process myself. The labeling happened at a rate of about 1 per minute, but this decreased over time... Some images are easily recognized, while some pictures (such as those of fine-grained breeds of dogs, birds, or monkeys) can require multiple minutes of concentrated effort. I became very good at identifying breeds of dogs... Based on the sample of images I worked on, the GoogLeNet classification error turned out to be 6.8%... In the end, my error turned out to be 5.1%

- ▶ Microsoft network ResNet: 152 layers, complex architecture
- ▶ Trained on 8 GPUs
- ▶ **96.43% accuracy** in top-5



ILSVRC



Trumps-Soushen (The Third Research Institute of Ministry of Public Security)

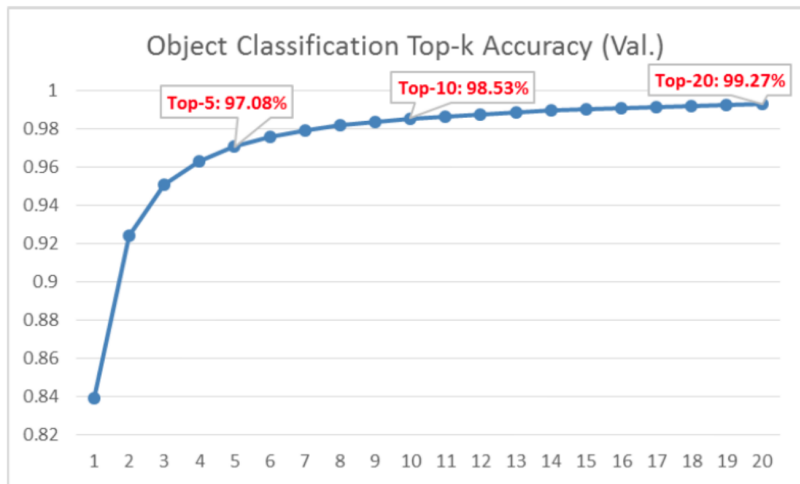
There is no new innovative technology or novelty by Trimps-Soushen.

Ensemble of the pre-trained models from previous years.

Each model is strong at classifying some categories but weak at categorizing others.

Test error: 2.99%

Top-k accuracy analyzed



<https://towardsdatascience.com/review-trimps-soushen-winner-in-ilsvrc-2016-image-classification-dfbc423111dd>

Top-20 typical errors

Out of 1458 misclassified images in Top-20:

Error Categories	Numbers	Percentages(%)
Label May Wrong	221	15.16
Multiple Objects (>5)	118	8.09
Non-Obvious Main Object	355	24.35
Confusing Label	206	14.13
Fine-grained Label	258	17.70
Obvious Wrong	234	16.05
Partial Object	66	4.53

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Top-k accuracy analyzed

Predict:

1 *pencil box*

2 *diaper*

3 *bib*

4 *purse*

5 *running shoe*

Ground Truth:

sleeping bag



<https://towardsdatascience.com/review-trimps-soushen-winner-in-ilsvrc-2016-image-classification-dfbc423111dd>

Top-k accuracy analyzed

Predict:

1 *dock*

2 *submarine*

3 *boathouse*

4 *breakwater*

5 *lifeboat*

Ground Truth:

paper towel



Top-k accuracy analyzed

Predict:

1 *bolete*

2 *earthstar*

3 *gyromitra*

4 *hen of the woods*

5 *mushroom*

Ground Truth:

stinkhorn



Top-k accuracy analyzed

Predict:

1 apron

2 plastic bag

3 sleeping bag

4 umbrella

5 bulletproof vest

Ground Truth:

poncho

