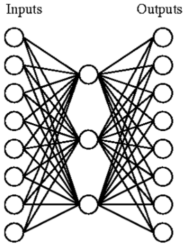
Artificial Neural Networks (ANNs)

Biologically inspired computational model:

(1) Simple computational units (neurons).
(2) Highly interconnected - connectionist view
(3) Vast parallel computation, consider:
  - Human brain has ~10^{11} neurons
  - Slow computational units, switching time ~10^{-3} sec (compared to the computer >10^{-10} sec)
  - Yet, you can recognize a face in ~10^{-1} sec
  - This implies only about 100 sequential, computational neuron steps - this seems too low for something as complicated as recognizing a face
  - Parallel processing

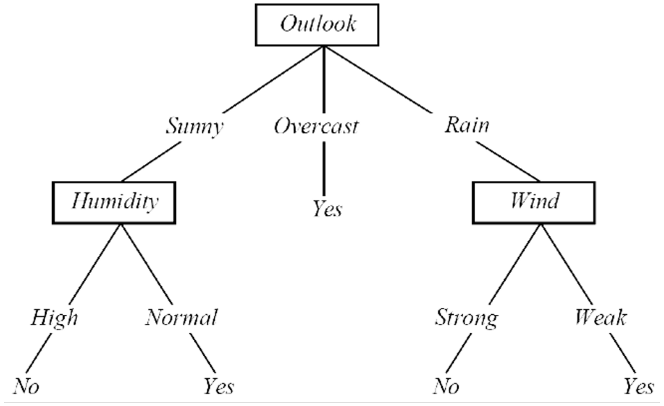


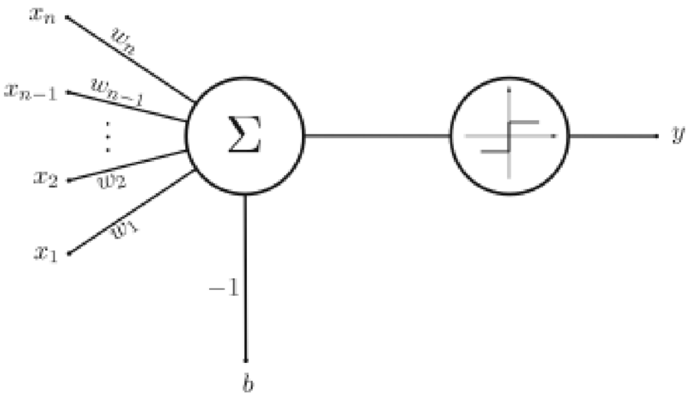
ANNs are naturally parallel - each neuron is a self-contained computational unit that depends only on its inputs.

Learning

We have seen machine learning with different representations:

1. (1) Decision trees -- symbolic representation of various decision rules -- “disjunction of conjunctions”
2. (2) Perceptron -- learning of weights that represent alinear decision surface classifying a set of objects into two groups



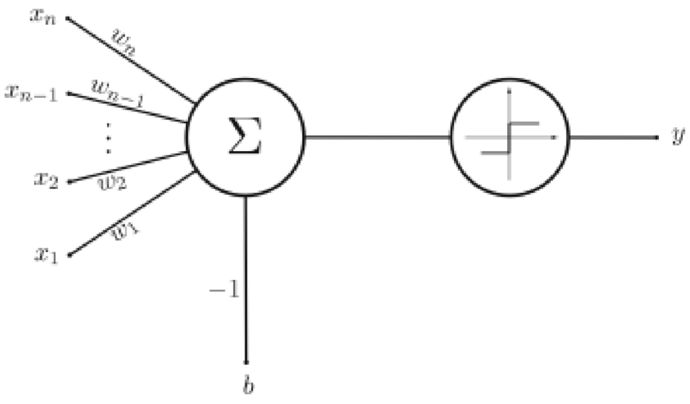


Different representations give rise to different hypothesis or model spaces.

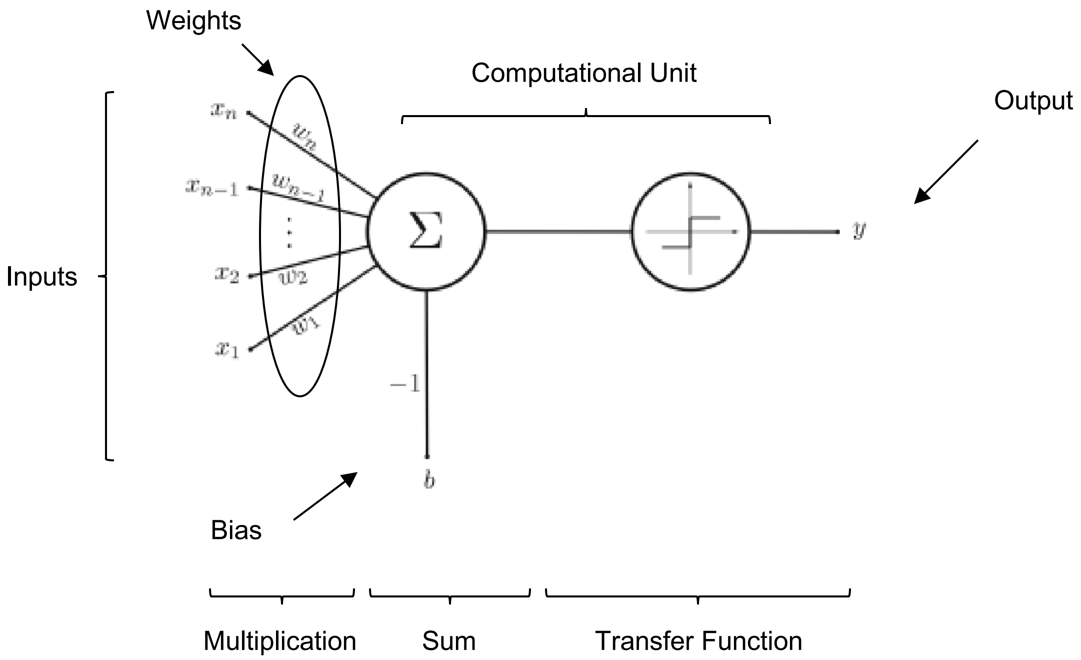
Machine learning algorithms search these model spaces for the best fitting model.

The Perceptron

- A simple, single layered neural "network" - only has a single neuron.
- However, even this simple neural network is already powerful enough to perform (linear) classification tasks.



The Architecture



Weights

Computational Unit

Output

Inputs

Bias

Multiplication

Sum

Transfer Function

Transfer Function:

$$\operatorname{sgn}(k) = \begin{cases} +1 \text{ if } k \geq 0 \\ -1 \text{ otherwise} \end{cases}$$

Perceptron Computation: $$y = \operatorname{sgn}\left(b + \sum_{i=1}^{m} w_i x_i \right)$$

Note: $y \in \{+1, -1\}$

Binary Classification

Computation

A perceptron computes the value,

$$y = \operatorname{sgn}\left(b + \sum_{i=1}^{m} w_i x_i\right)$$

Ignoring the activation function sgn and setting *m* = 1, we obtain,

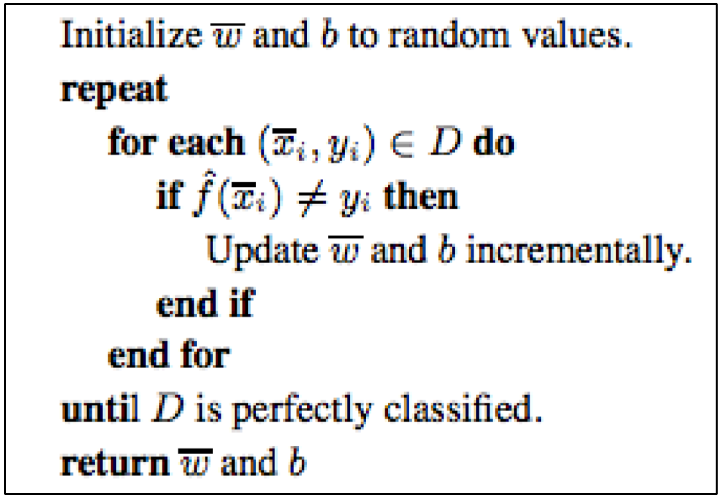
$$y' = b + w_1 x_1$$

But this is the equation of a <u>line</u> with slope *w* and offset *b*.

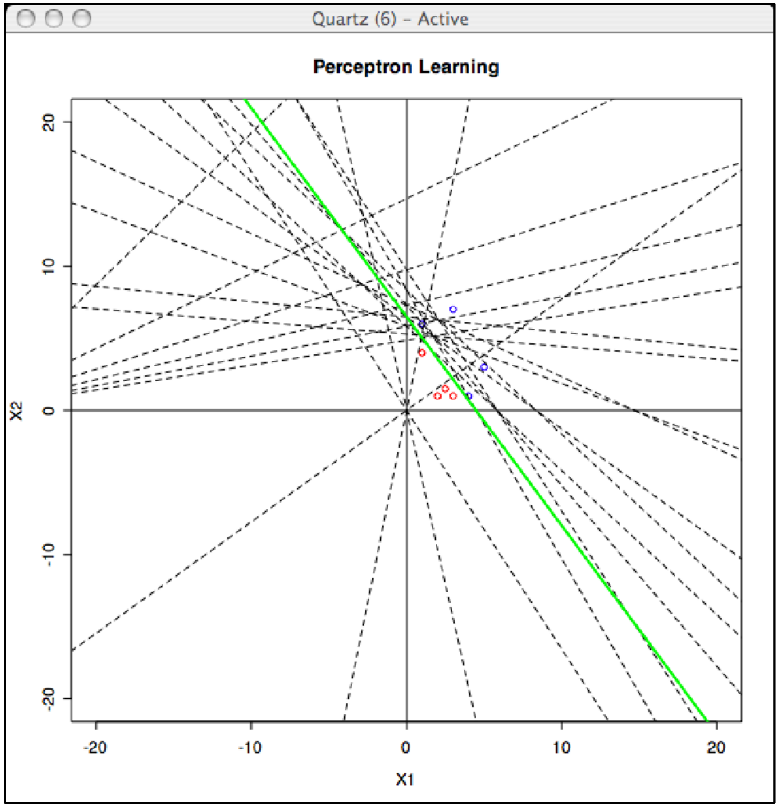
<u>Observation:</u> For the general case the perceptron computes a <u>hyperplane</u> in order to accomplish its classification task,

$$y' = b + \sum_{i=1}^{m} w_i x_i = b + \vec{w} \bullet \vec{x}$$

Perceptron Learning Revisited



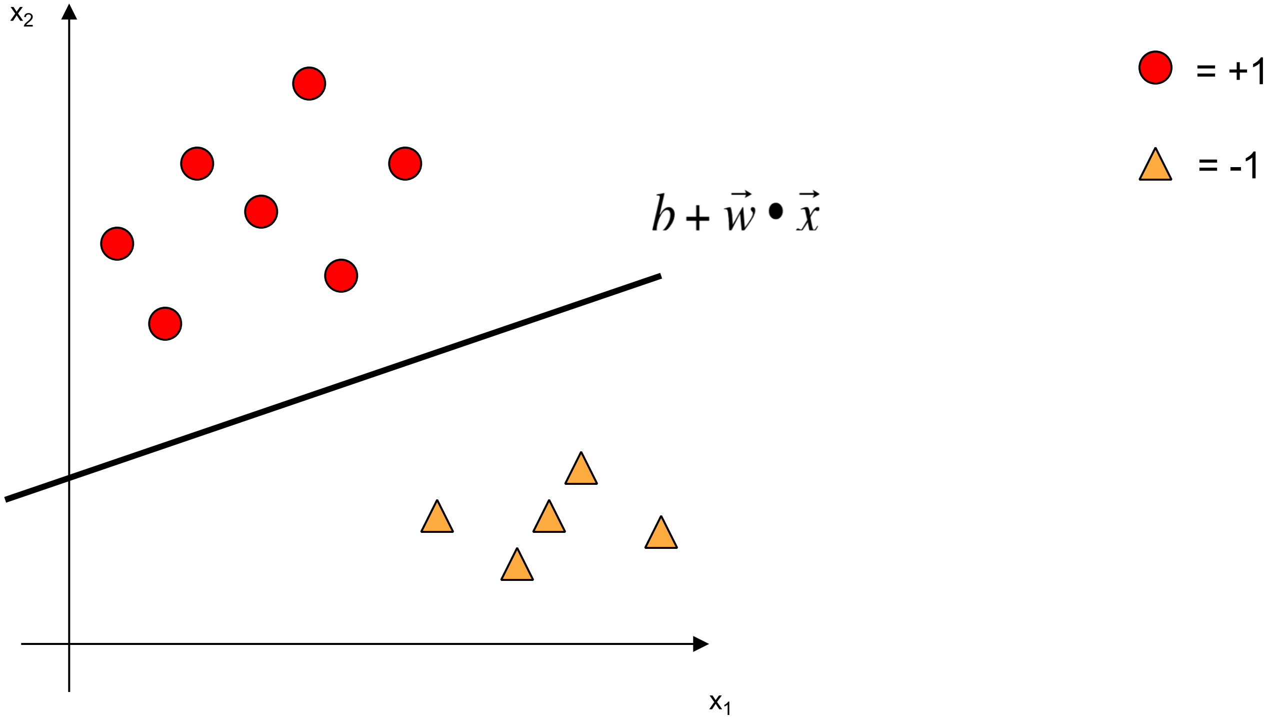
```
Initialize $\overline{w}$ and $b$ to random values.
repeat
    for each $(\overline{x}_i, y_i) \in D$ do
        if $\hat{f}(\overline{x}_i) \neq y_i$ then
            Update $\overline{w}$ and $b$ incrementally.
        end if
    end for
until $D$ is perfectly classified.
return $\overline{w}$ and $b$
```



Constructs a line (hyperplane) as a classifier

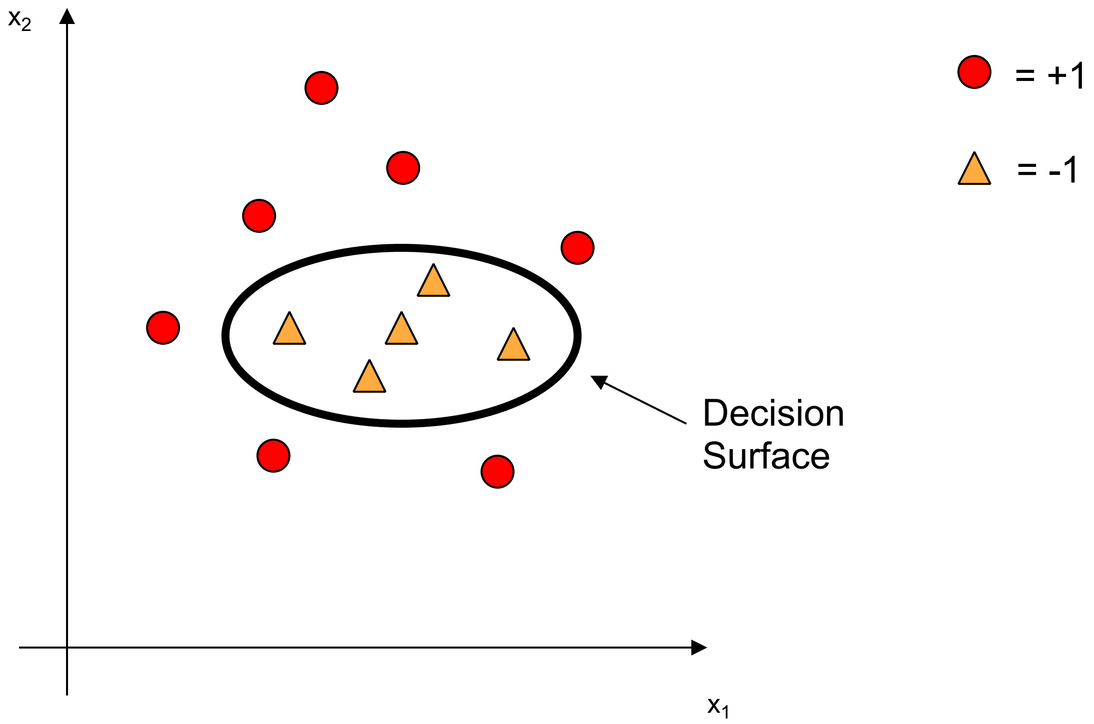
$$b + \vec{w} \bullet \vec{x}$$

Classification



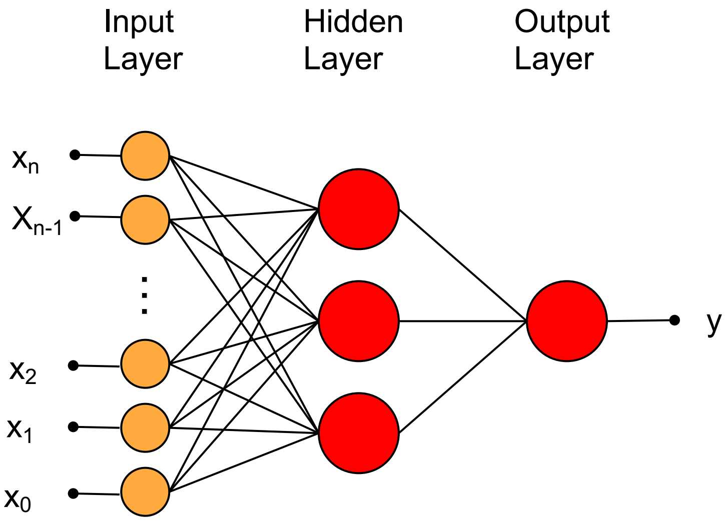
In order for the hyperplane to become a classifier we need to find *b* and *w* => learning!

What About Non-Linearity?



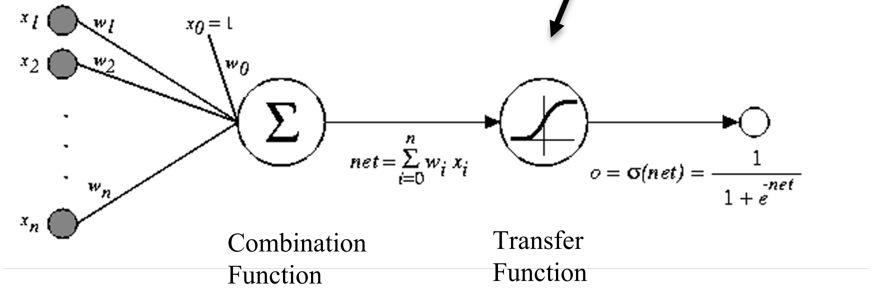
Can we learn this decision surface? …Yes! *Multi-Layer Perceptrons*

Multi-Layer Perceptrons (ANNs)



● ≡ Linear/Input Unit

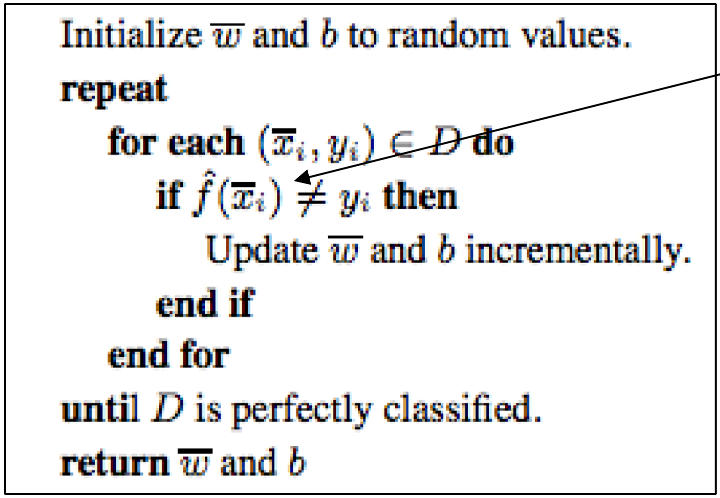
● ≡



Notice the smooth Transfer function!

How do we train?

Perceptron was easy:



```
Initialize $\overline{w}$ and $b$ to random values.
repeat
    for each $(\overline{x}_i, y_i) \in D$ do
        if $\hat{f}(\overline{x}_i) \neq y_i$ then
            Update $\overline{w}$ and $b$ incrementally.
        end if
    end for
until $D$ is perfectly classified.
return $\overline{w}$ and $b$
```

error

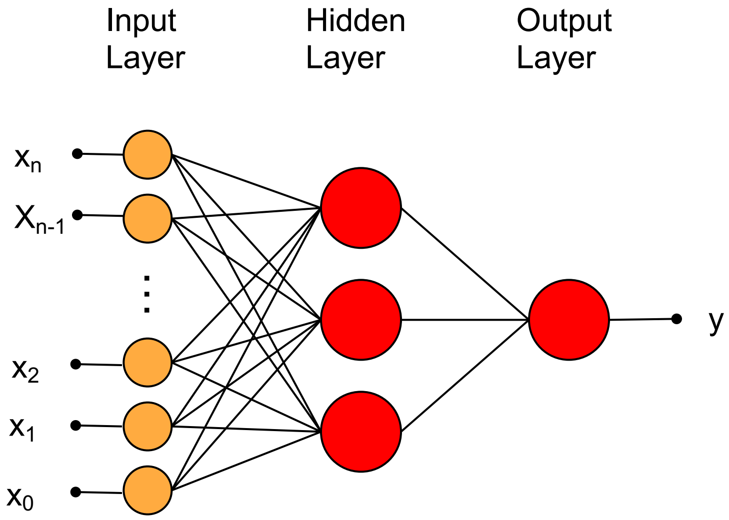
Every time we found an error of the predicted value $f(x_i)$ compared to the label in the training set y_i, we update w and b.

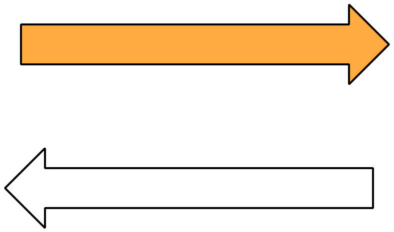
Not so easy in multi-layer neural networks – the error can occur deep in the network!

Artificial Neural Networks

Feed-forward with Backpropagation

We have to be a bit smarter in the case of ANNs: compute the signal (feed forward) and then use the error at the output to update all the weights by propagating the error back through the network.

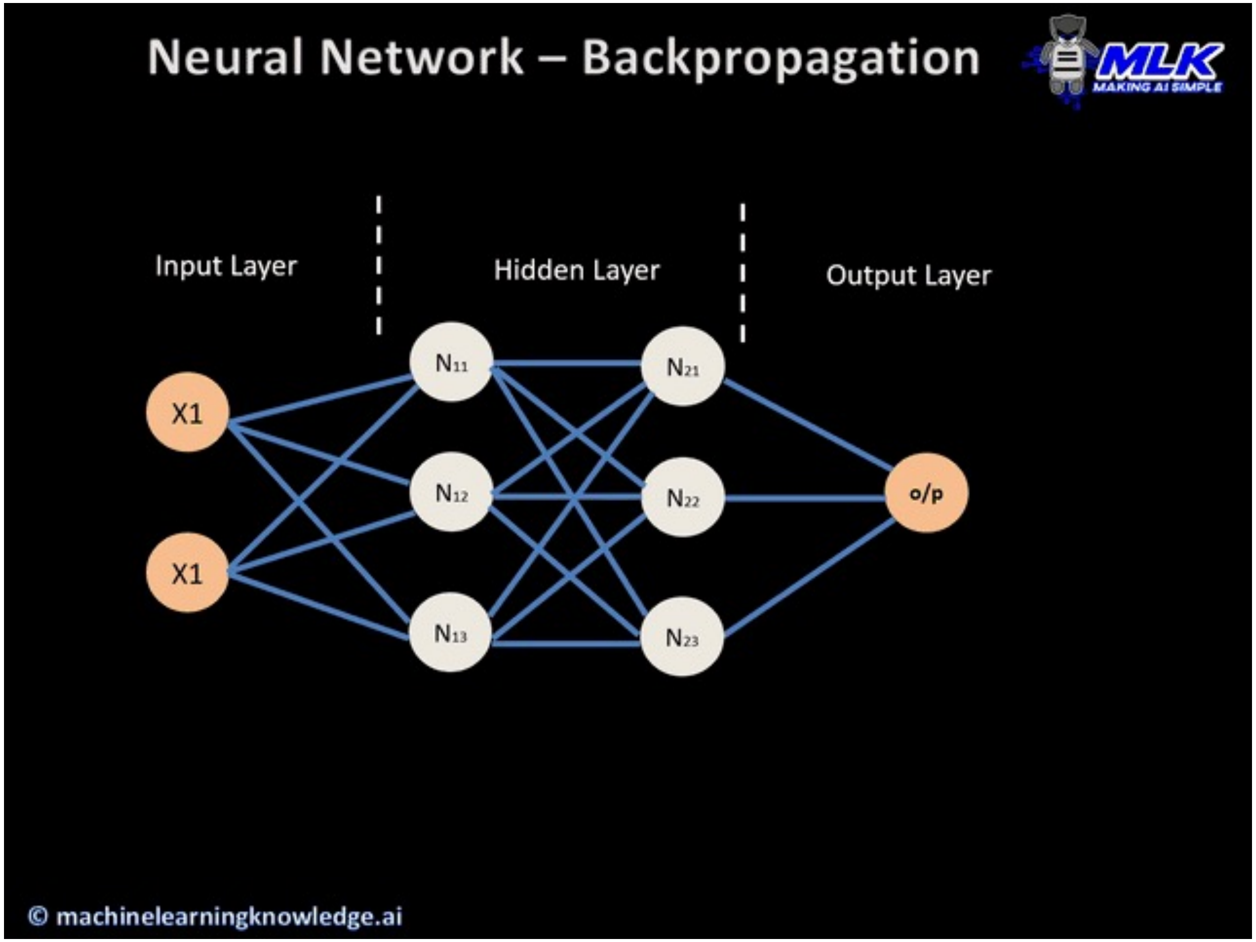




Signal Feed-forward

Error Backpropagation

Back Propagation Training



Backpropagation

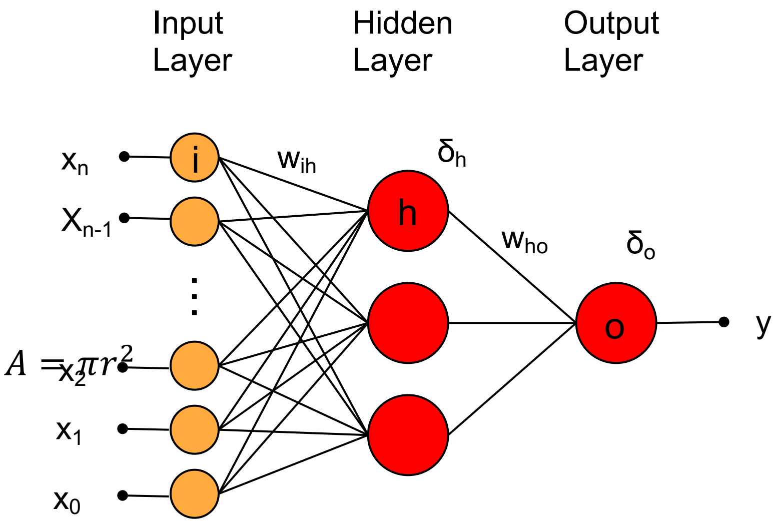
$E = (y' - y)^2$ (output error)

$\delta_0 = y(1-y)E$ (output node error)

$w_{ho} \leftarrow w_{ho} + \alpha\delta_o$ (weight update)

$\delta_h = y(1-y)w_{ho}\delta_o$ (hidden node error)

$w_{ih} \leftarrow w_{ih} + \alpha\delta_h$ (weight update)



$A = \pi r^2$

For this to work transfer Function has to be smooth!!

This only works because

$$\delta_o = y(1-y)E = \frac{\partial E}{\partial \boldsymbol{w}\cdot\boldsymbol{x}} = \frac{\partial (y'-y)^2}{\partial \boldsymbol{w}\cdot\boldsymbol{x}} = 2(\mathrm{y}' - \mathrm{y})\left(\frac{\partial y'}{\partial \boldsymbol{w}\cdot\boldsymbol{x}} - \frac{\partial y}{\partial \boldsymbol{w}\cdot\boldsymbol{x}}\right)$$

and the output y is differentiable because the transfer function is differentiable. Also note, everything is based on the *rate of change* of the error…we are searching in the direction where the rate of change will minimize the output error.

Backpropagation Algorithm

Note: this algorithm is for a NN with a single output node o and a single hidden layer. It can easily be generalized.

```
Initialize the weights in the network (often randomly)
 Do
     For each example e in the training set
         // forward pass
         y = compute neural net output
         y' = label for e from training data
         Calculate error $E = (y' - y)^2$ at the output units
         // backward pass
         Compute error $\delta_o$ for weights from a hidden node h to the output node o using E
         Compute error $\delta_h$ for weights from an input node i to hidden node h using $\delta_o$
         Update the weights in the network
 Until all examples classified correctly or stopping criterion satisfied
 Return the network
```

Source: http://en.wikipedia.org/wiki/Backpropagation

Neural Network Learning

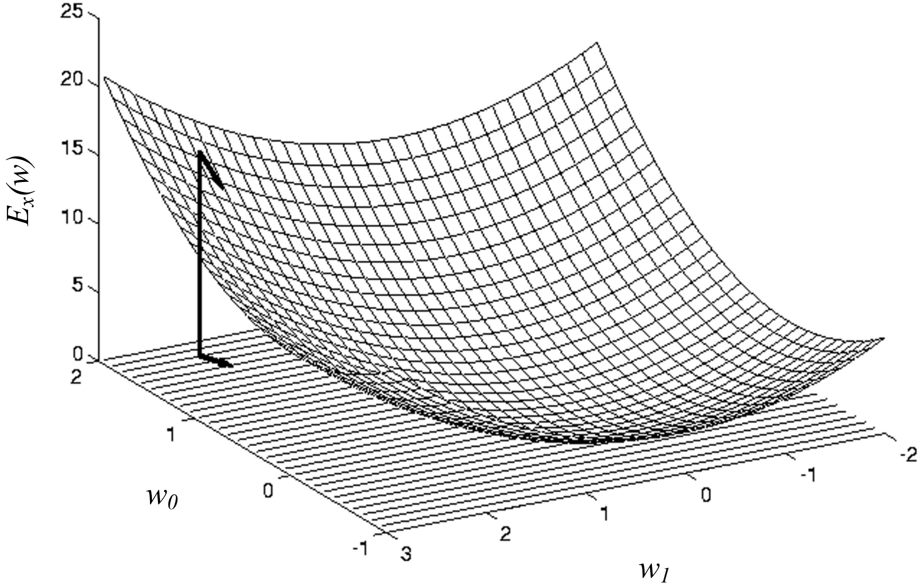
- Define the network error in terms of weights w as

$$E_x(w) = (y' - y)^2$$

for some training instance *x.*

- Use the gradient (slope) of the error surface to guide the search towards appropriate weights:

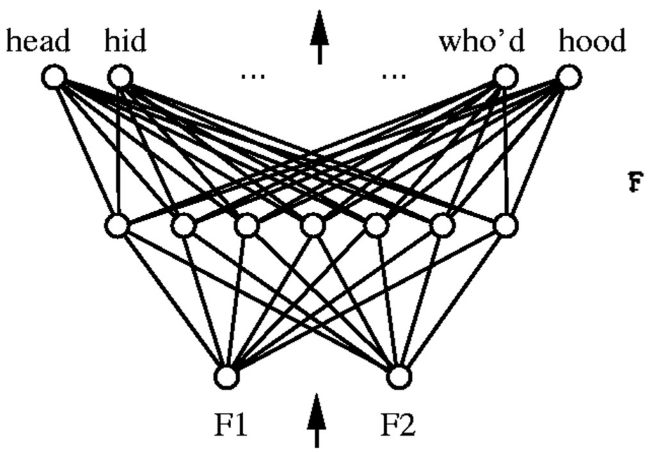
$$\Delta w_k = -\eta \frac{\partial E_x}{\partial w_k}$$

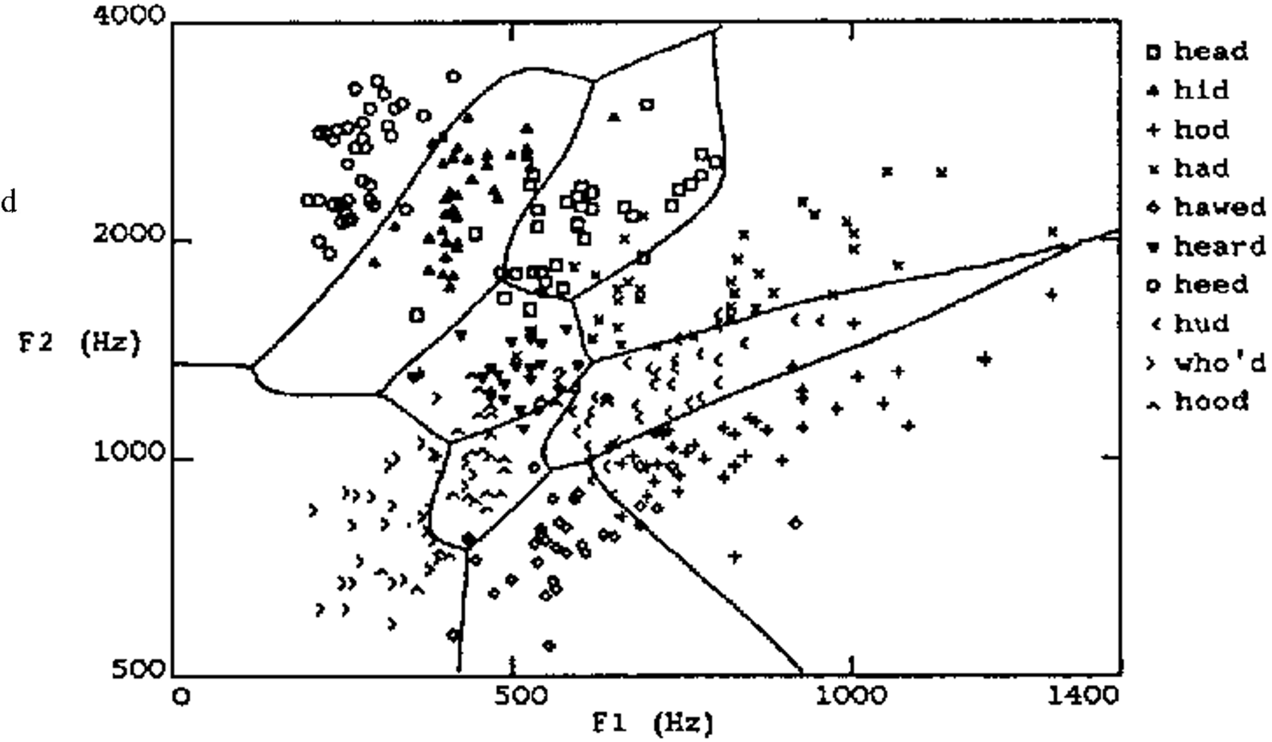


☞ Backpropagation can be understood as a stochastic gradient search on the error surface of the network.

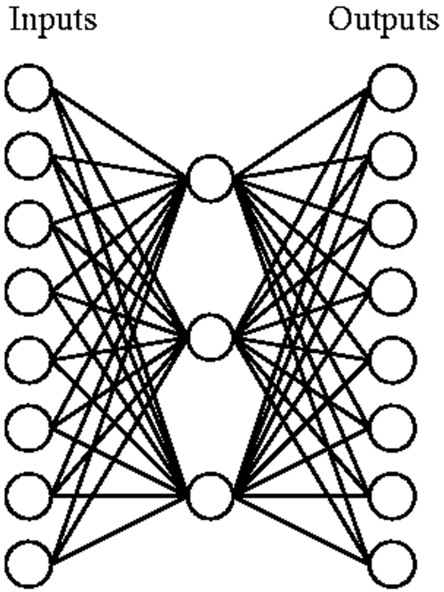
Representational Power

- Every bounded continuous function can be approximated with arbitrarily small error by a network with one hidden layer.
- Any function can be approximated to arbitrary accuracy by a network with two hidden layers.





Hidden Layer Representations

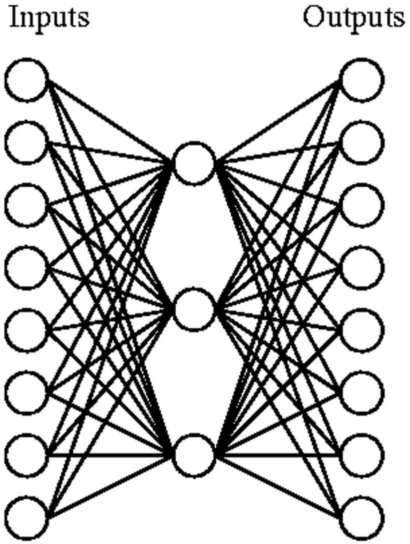


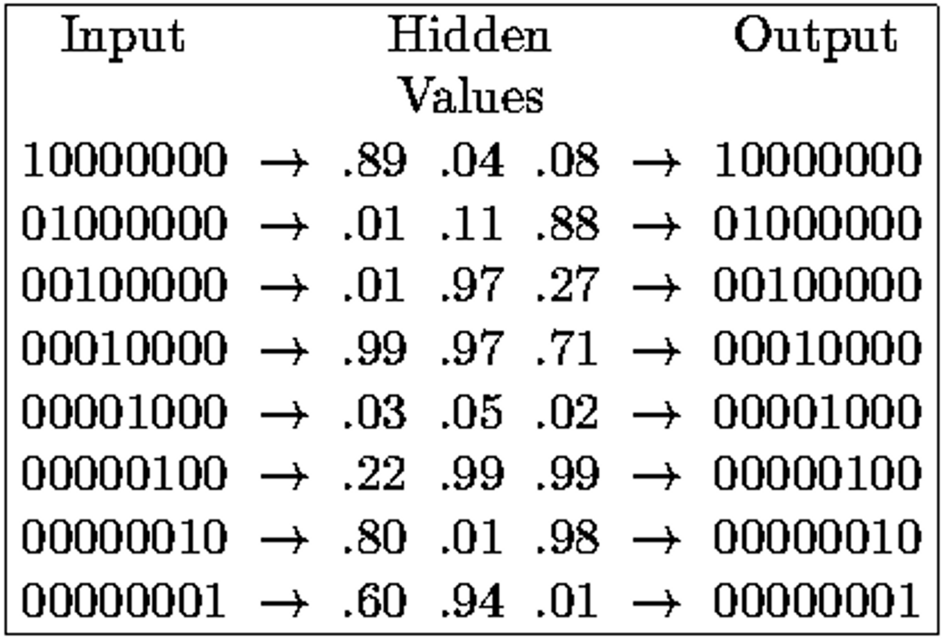
Target Function:

Input		Output
10000000	→	10000000
01000000	→	01000000
00100000	→	00100000
00010000	→	00010000
00001000	→	00001000
00000100	→	00000100
00000010	→	00000010
00000001	→	00000001

Can this be learned?

Hidden Layer Representations





Input		Hidden Values				Output
10000000	→	.89	.04	.08	→	10000000
01000000	→	.01	.11	.88	→	01000000
00100000	→	.01	.97	.27	→	00100000
00010000	→	.99	.97	.71	→	00010000
00001000	→	.03	.05	.02	→	00001000
00000100	→	.22	.99	.99	→	00000100
00000010	→	.80	.01	.98	→	00000010
00000001	→	.60	.94	.01	→	00000001

1 0 0
0 0 1
0 1 0
1 1 1
0 0 0
0 1 1
1 0 1
1 1 0

☞ This neural network architecture is sometimes also called autoencoder because of its ability to invent new representations of the input data and is a popular building block in deep-learning.