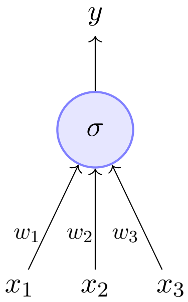
CS7015 (Deep Learning) : Lecture 2

McCulloch Pitts Neuron, Thresholding Logic, Perceptrons, Perceptron Learning Algorithm and Convergence, Multilayer Perceptrons (MLPs), Representation Power of MLPs

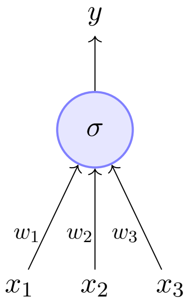
Mitesh M. Khapra

Department of Computer Science and Engineering
Indian Institute of Technology Madras



Artificial Neuron

- The most fundamental unit of a deep neural network is called an *artificial neuron*



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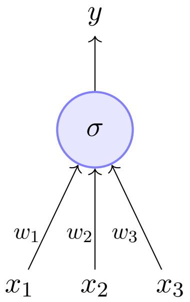

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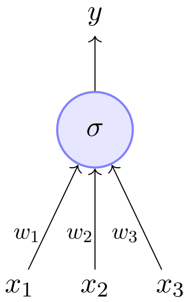

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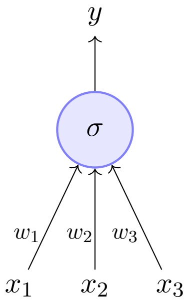

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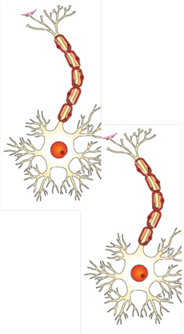
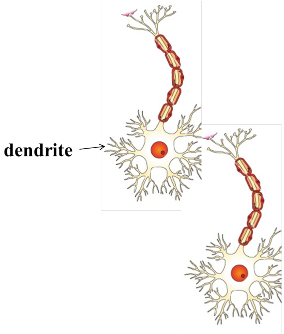
- We will first see what a biological neuron looks like ...



Biological Neurons*

*Image adapted from
https://cdn.vectorstock.com/i/composite/12,25/neuron-cell-vector-81225.jpg



Biological Neurons*

- **dendrite:** receives signals from other neurons

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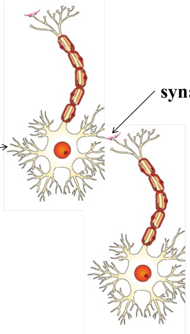

Biological Neurons*

- **dendrite:** receives signals from other neurons
- **synapse:** point of connection to other neurons

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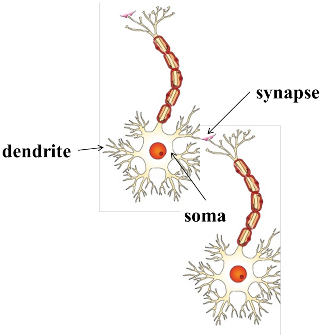

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- **dendrite:** receives signals from other neurons
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- **soma:** processes the information

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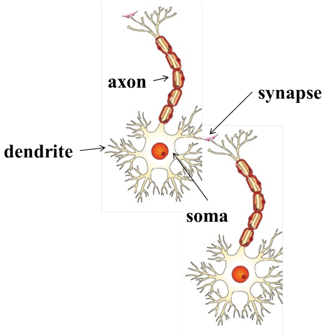

Biological Neurons*

- **dendrite:** receives signals from other neurons
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- **soma:** processes the information
- **axon:** transmits the output of this neuron

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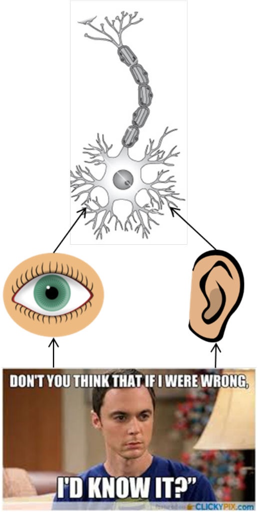

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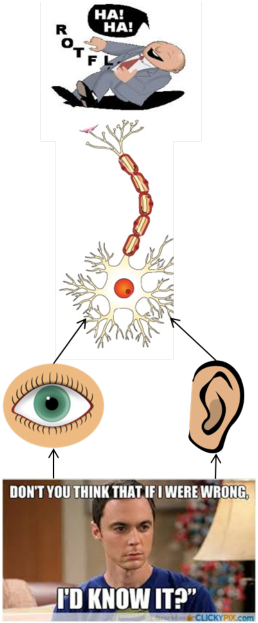
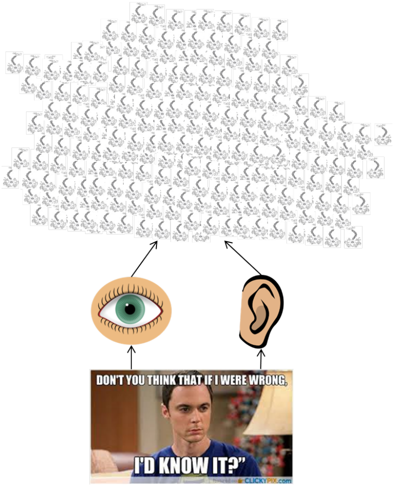


- Let us see a very cartoonish illustration of how a neuron works
- Our sense organs interact with the outside world
- They relay information to the neurons
- The neurons (may) get activated and produces a response (laughter in this case)

- Of course, in reality, it is not just a single neuron which does all this



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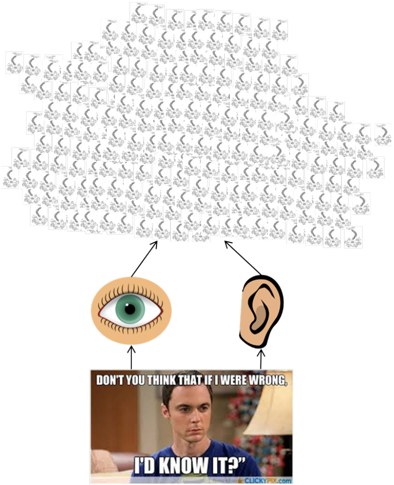
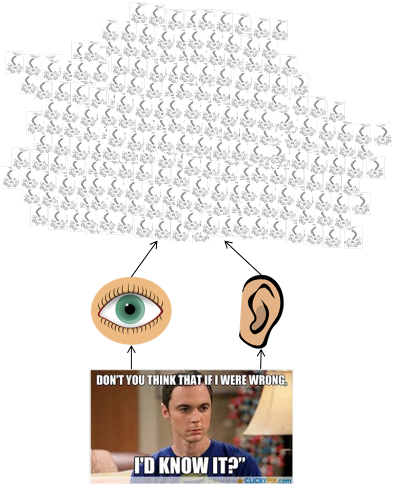
- There is a massively parallel interconnected network of neurons





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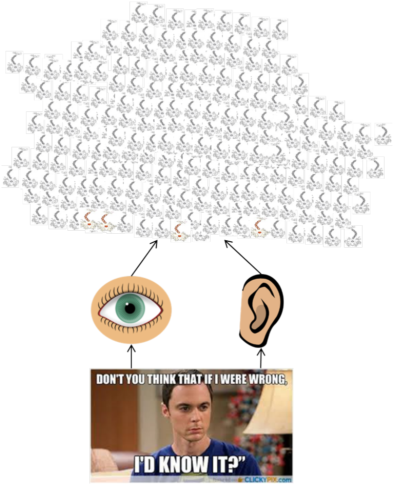

- Of course, in reality, it is not just a single neuron which does all this
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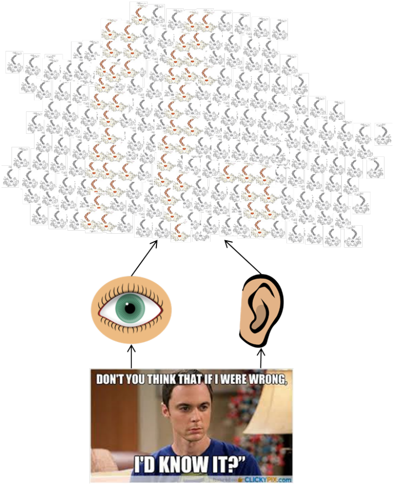
- The sense organs relay information to the lowest layer of neurons
- Some of these neurons may fire (in red) in response to this information and in turn relay information to other neurons they are connected to



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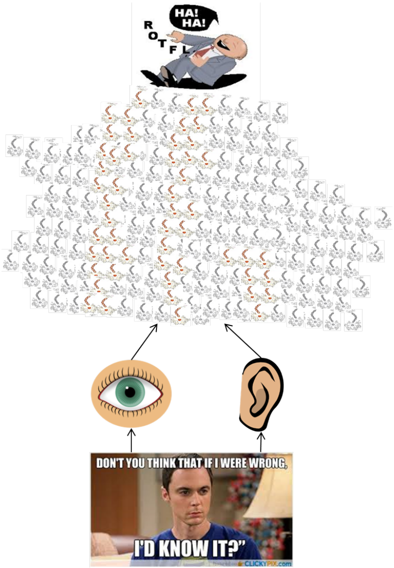
- These neurons may also fire (again, in red) and the process continues



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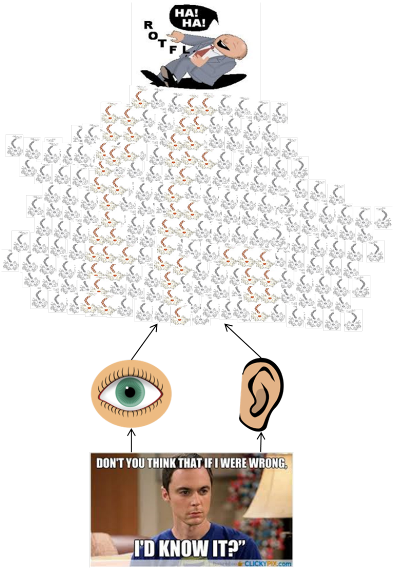

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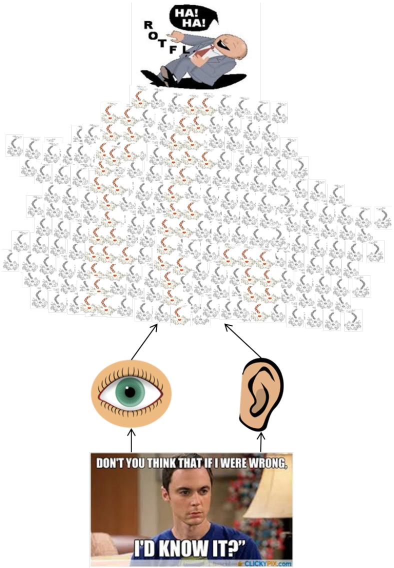
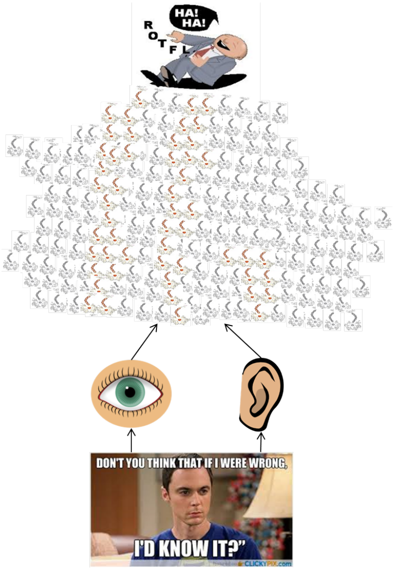
- An average human brain has around 10^{11} (100 billion) neurons !



- This massively parallel network also ensures that there is division of work



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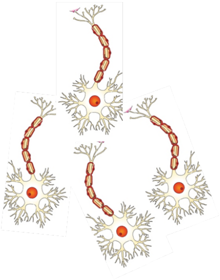
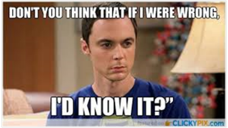
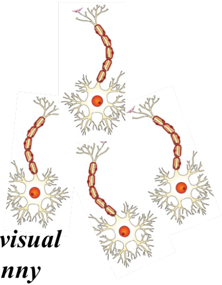
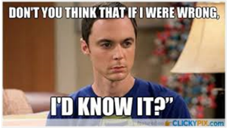




A simplified illustration

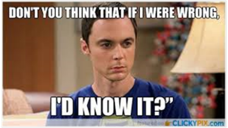


fires if visual is funny



A simplified illustration

- This massively parallel network also ensures that there is division of work
- Each neuron may perform a certain role or respond to a certain stimulus



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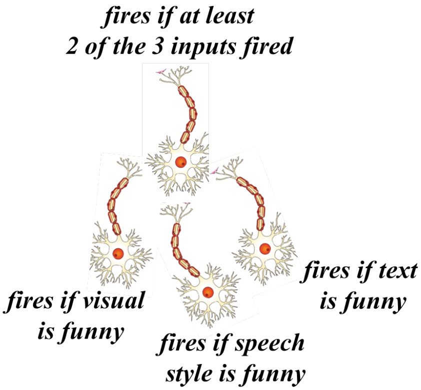

A simplified illustration

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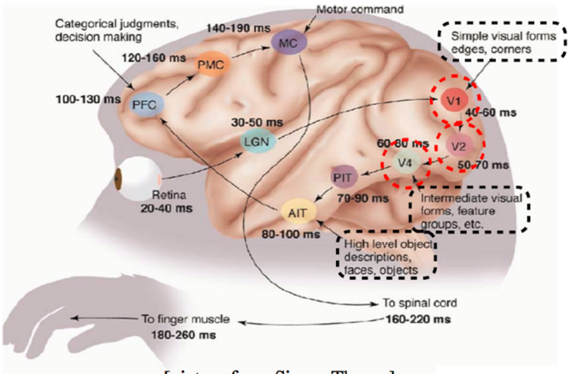
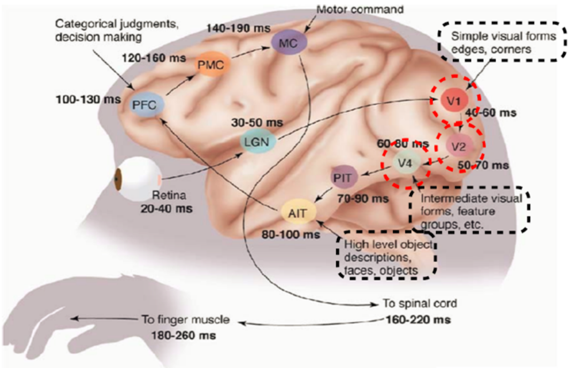
- The neurons in the brain are arranged in a hierarchy



[picture from Simon Thorpe]

- The neurons in the brain are arranged in a hierarchy
- We illustrate this with the help of visual cortex (part of the brain) which deals with processing visual information



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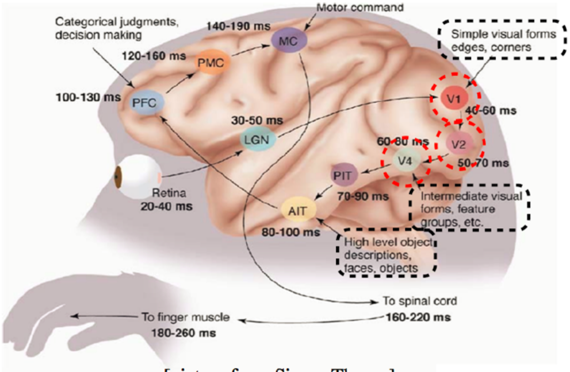
- Starting from the retina, the information is relayed to several layers (follow the arrows)



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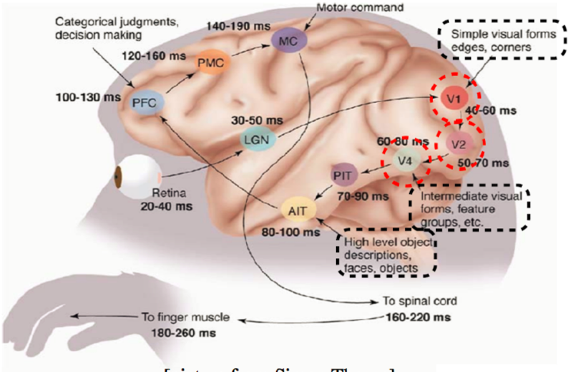
- Starting from the retina, the information is relayed to several layers (follow the arrows)
- We observe that the layers $V1$, $V2$ to AIT form a hierarchy (from identifying simple visual forms to high level objects)

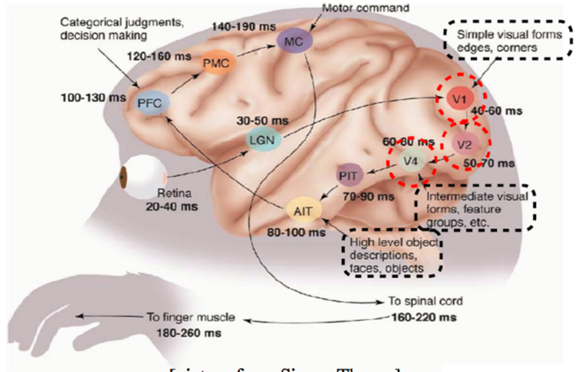


[picture from Simon Thorpe]

Layer 1: detect edges & corners

Sample illustration of hierarchical processing*

*Idea borrowed from Hugo Larochelle's lecture sli



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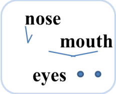

Layer 2: form feature groups

Sample illustration of hierarchical processing*

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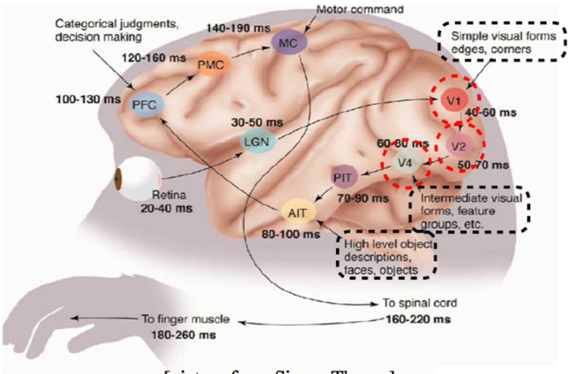

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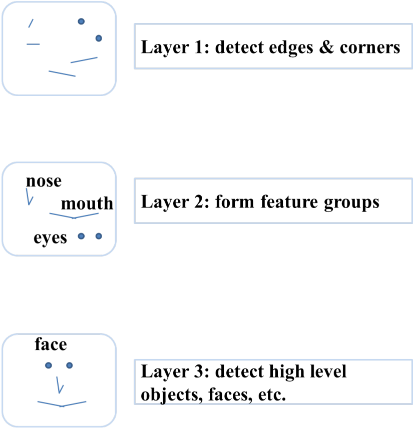

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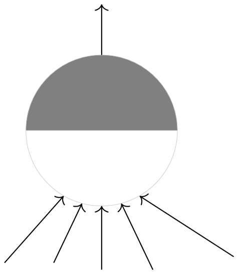
Disclaimer

- I understand very little about how the brain works !
- What you saw so far is an overly simplified explanation of how the brain works !
- But this explanation suffices for the purpose of this course !

From biological units to computational units ...



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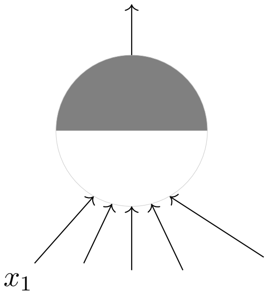

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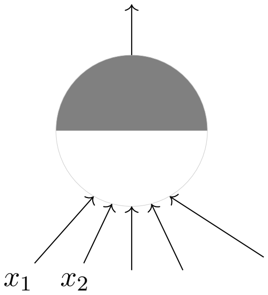

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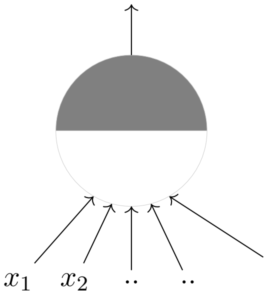

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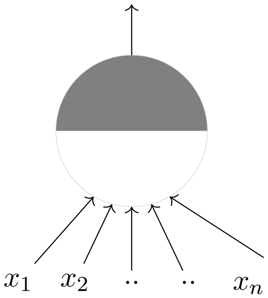

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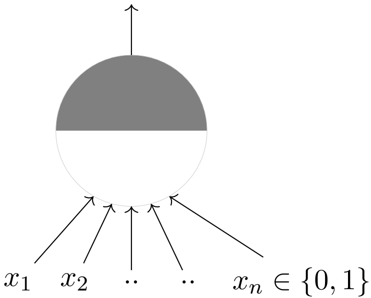

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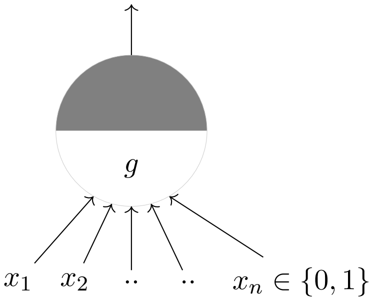

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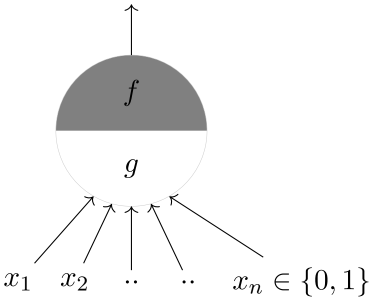

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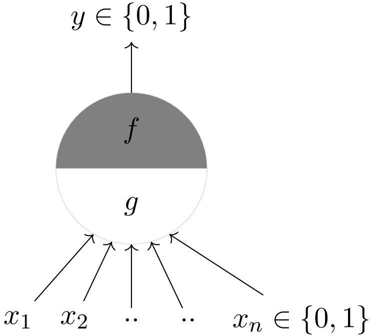

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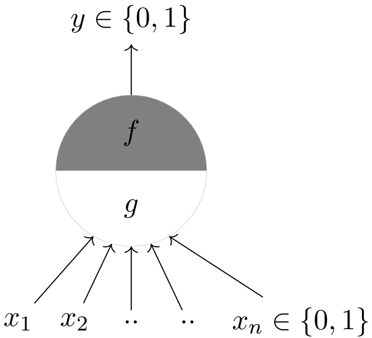

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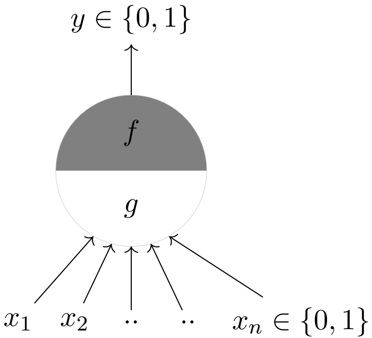

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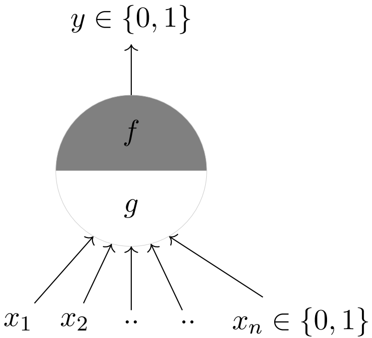

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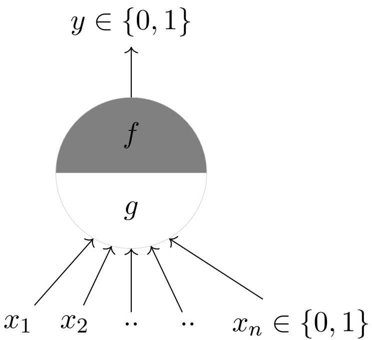

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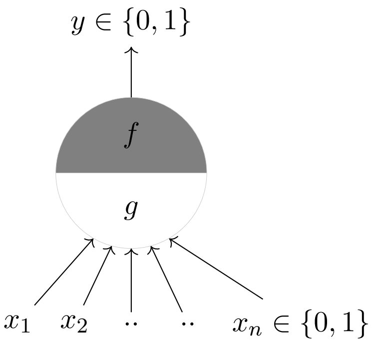

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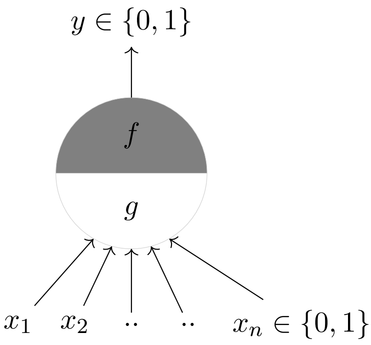
$$\begin{aligned} y = f(g(\mathbf{x})) &= 1 \quad if \quad g(\mathbf{x}) \geq \theta \\ &= 0 \quad if \quad g(\mathbf{x}) < \theta \end{aligned}$$



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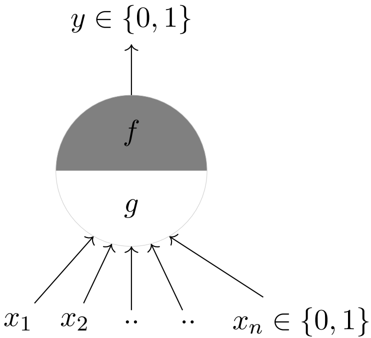
$$g(x_1, x_2, ..., x_n) = g(\mathbf{x}) = \sum_{i=1}^{n} x_i$$

$$\begin{aligned} y = f(g(\mathbf{x})) &= 1 \quad if \quad g(\mathbf{x}) \geq \theta \\ &= 0 \quad if \quad g(\mathbf{x}) < \theta \end{aligned}$$

- θ is called the thresholding parameter



- McCulloch (neuroscientist) and Pitts (logician) proposed a highly simplified model of the neuron (1943)
- **g** aggregates the inputs and the function **f** takes a decision based on this aggregation
- The inputs can be excitatory or inhibitory
- $y = 0$ if any x_i is inhibitory, else

$$g(x_1, x_2, ..., x_n) = g(\mathbf{x}) = \sum_{i=1}^{n} x_i$$

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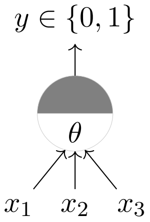
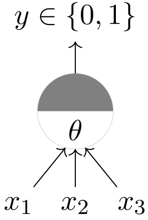
- θ is called the thresholding parameter
- This is called Thresholding Logic

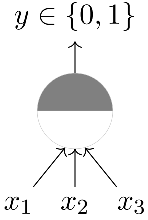
Let us implement some boolean functions using this McCulloch Pitts (MP) neuron ...



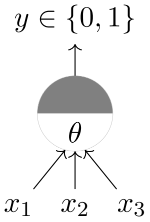
A McCulloch Pitts unit



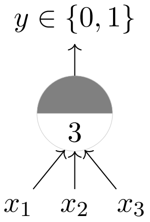
A McCulloch Pitts unit



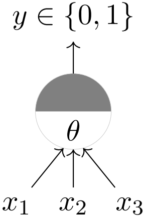
AND function



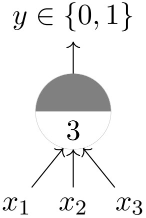
A McCulloch Pitts unit



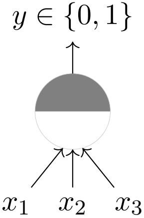
AND function



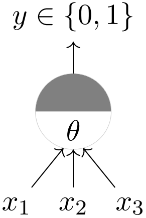
A McCulloch Pitts unit



AND function



OR function



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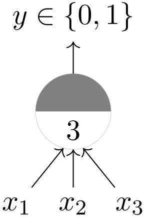
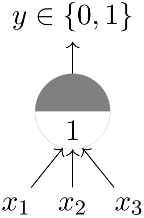
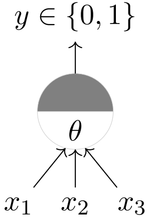


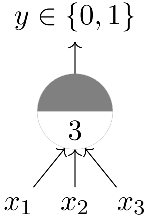
AND function



OR function



A McCulloch Pitts unit



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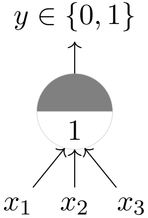
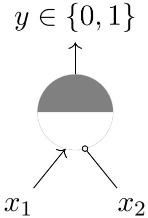


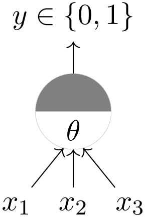
OR function



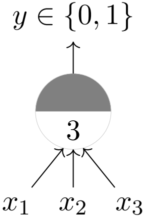
x_1 AND $!x_2$*

---

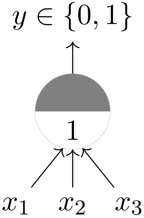
*circle at the end indicates inhibitory input: if any inhibitory input is 1 the output will be 0



A McCulloch Pitts unit



AND function



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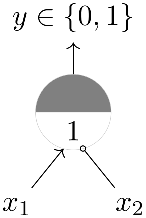

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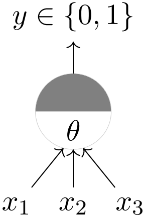
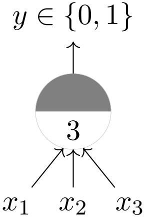


A McCulloch Pitts unit



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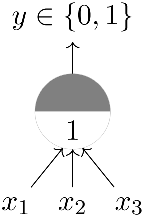

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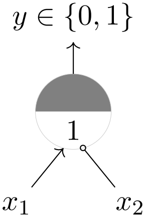
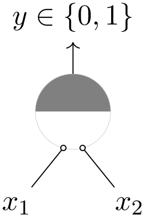


x_1 AND $!x_2$*



NOR function

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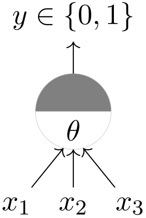
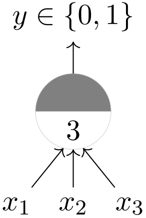
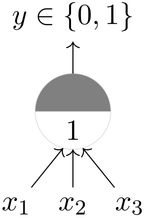


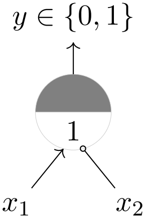
A McCulloch Pitts unit



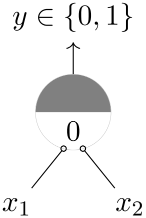
AND function



OR function



x_1 AND $!x_2$*



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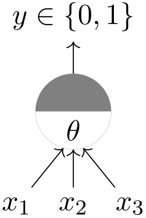
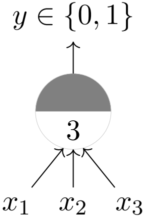
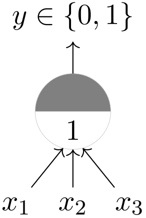


A McCulloch Pitts unit



AND function



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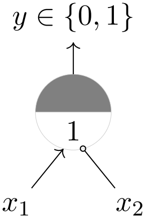

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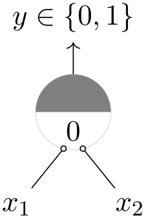
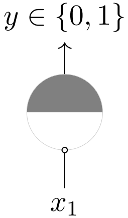
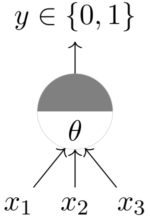


NOR function

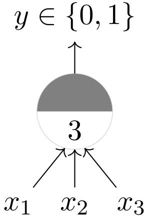


NOT function

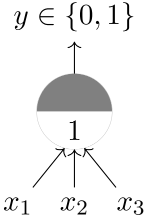
*circle at the end indicates inhibitory input: if any inhibitory input is 1 the output will be 0



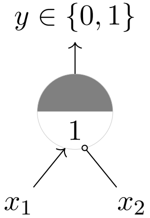
A McCulloch Pitts unit



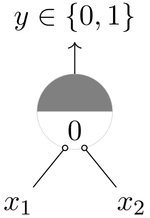
AND function



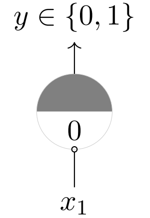
OR function



x_1 AND $!x_2$*



NOR function



NOT function

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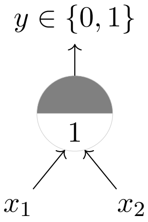
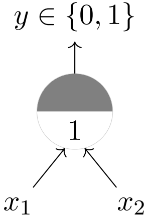
- Can any boolean function be represented using a McCulloch Pitts unit ?

- Can any boolean function be represented using a McCulloch Pitts unit ?
- Before answering this question let us first see the geometric interpretation of a MP unit ...



OR function

$x_1 + x_2 = \sum_{i=1}^{2} x_i \geq 1$



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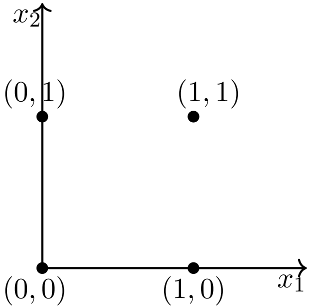

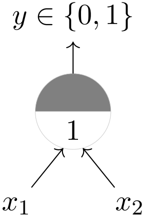

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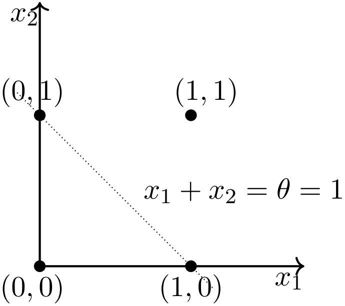

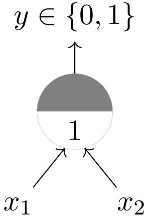

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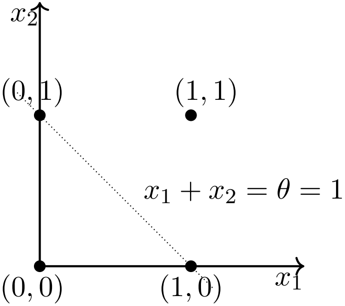
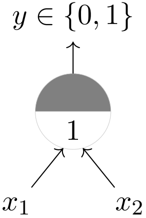


- A single MP neuron splits the input points (4 points for 2 binary inputs) into two halves



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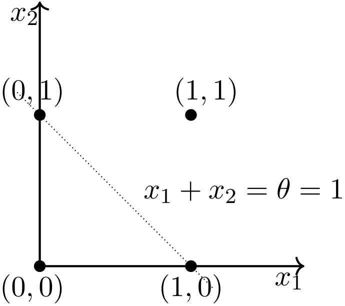
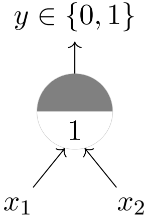


- A single MP neuron splits the input points (4 points for 2 binary inputs) into two halves
- Points lying on or above the line $\sum_{i=1}^{n} x_i$ and points lying below this line



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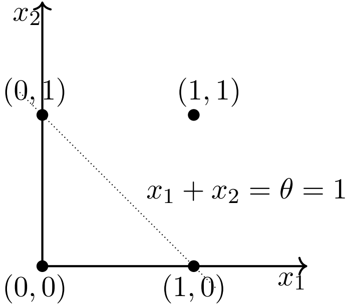
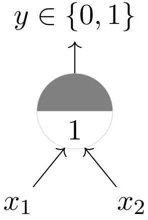


- A single MP neuron splits the input points (4 points for 2 binary inputs) into two halves
- Points lying on or above the line $\sum_{i=1}^{n} x_i$ and points lying below this line
- In other words, all inputs which produce an output 0 will be on one side ($\sum_{i=1}^{n} x_i < \theta$) of the line and all inputs which produce a 1 will lie on the other side ($\sum_{i=1}^{n} x_i \geq \theta$) of this line



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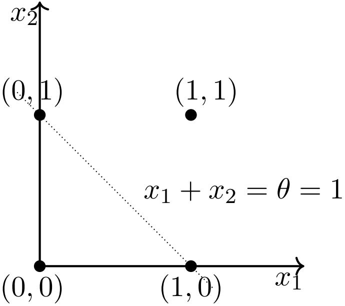

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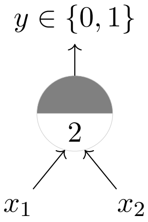
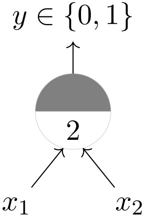
- Let us convince ourselves about this with a few more examples (if it is not already clear from the math)



AND function

$x_1 + x_2 = \sum_{i=1}^{2} x_i \geq 2$



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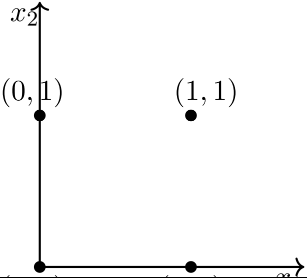

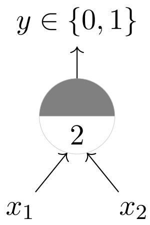

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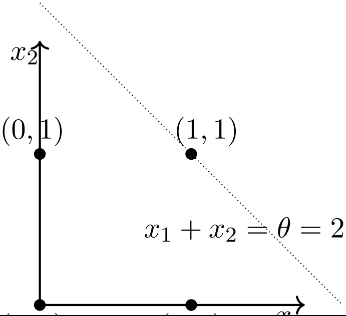

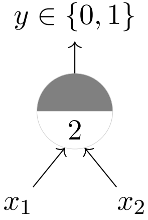

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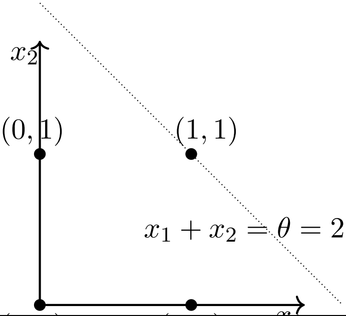
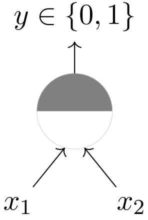
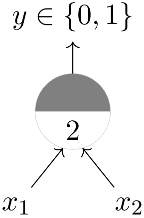




Tautology (always ON)



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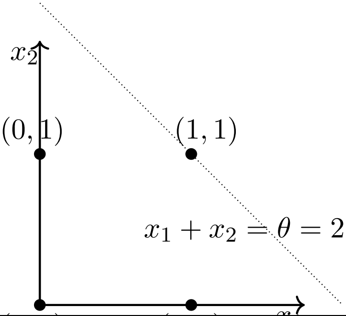
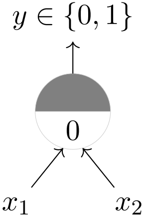
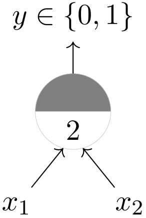




Tautology (always ON)



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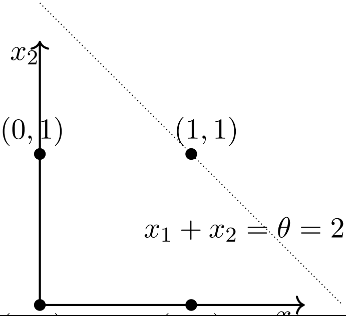

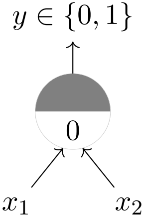

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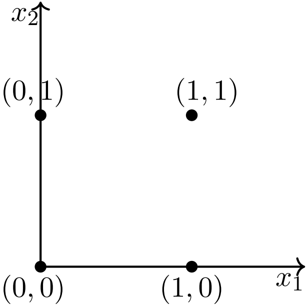

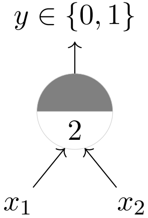

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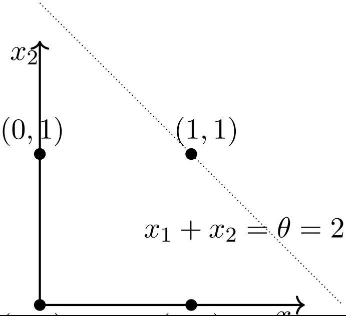

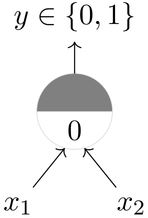

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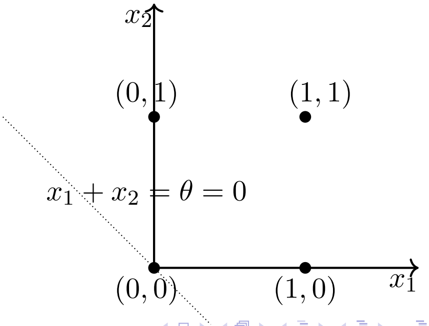

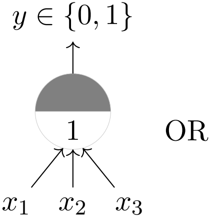

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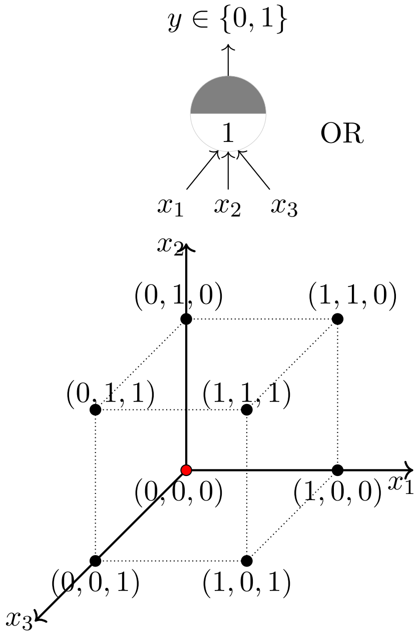

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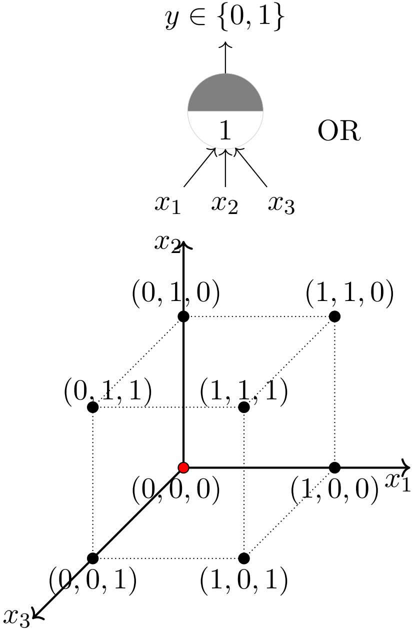

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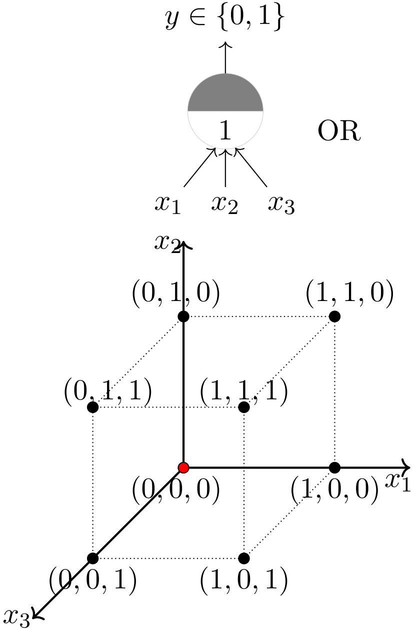

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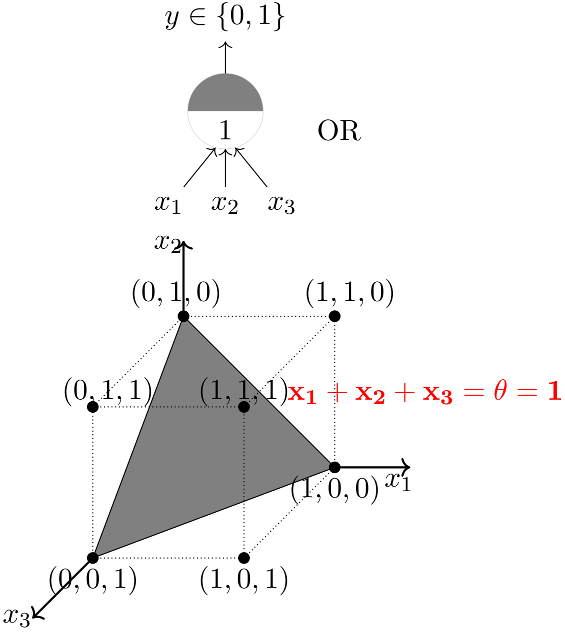
- For the OR function, we want a plane such that the point (0,0,0) lies on one side and the remaining 7 points lie on the other side of the plane



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- A single McCulloch Pitts Neuron can be used to represent boolean functions which are linearly separable
- Linear separability (for boolean functions) : There exists a line (plane) such that all inputs which produce a 1 lie on one side of the line (plane) and all inputs which produce a 0 lie on other side of the line (plane)

The story ahead ...

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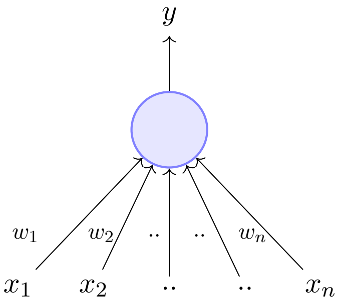

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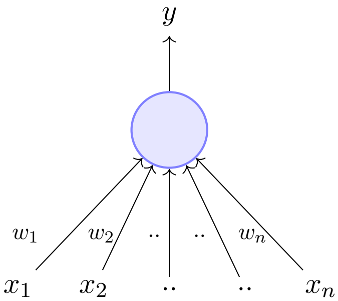

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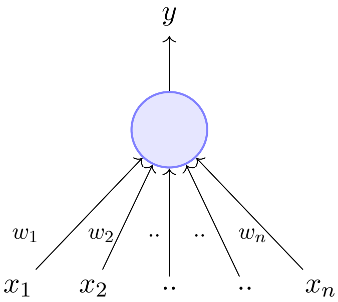

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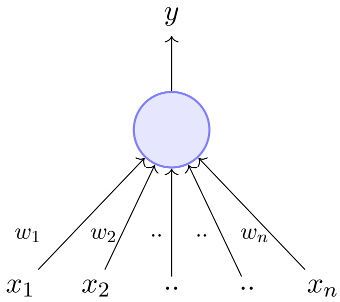

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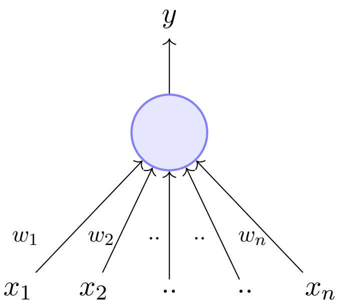

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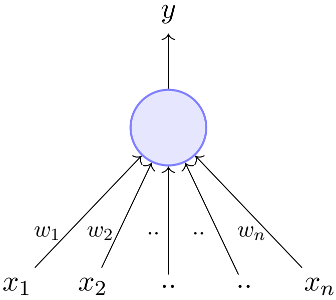
y
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x1
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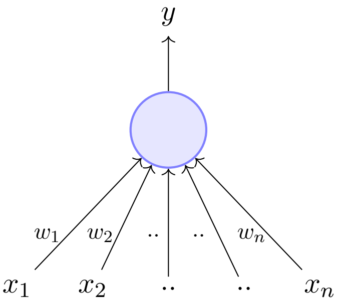

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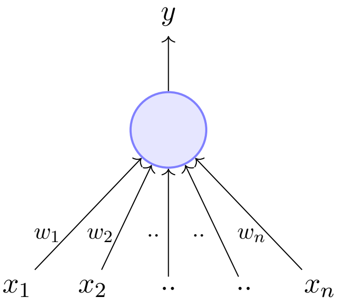

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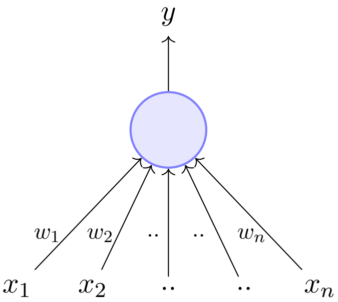

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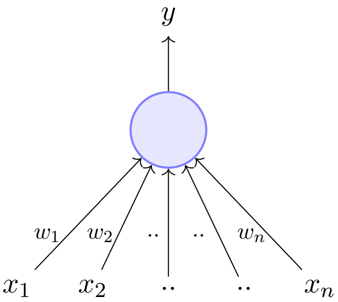

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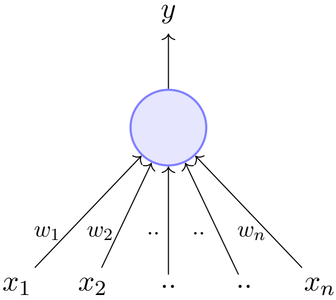

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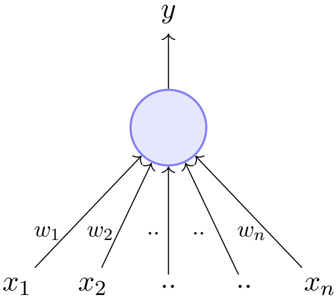

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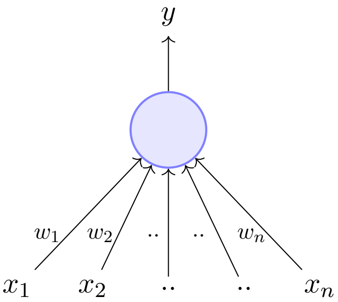

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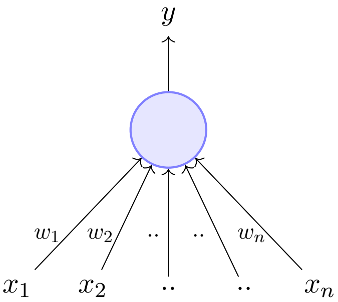

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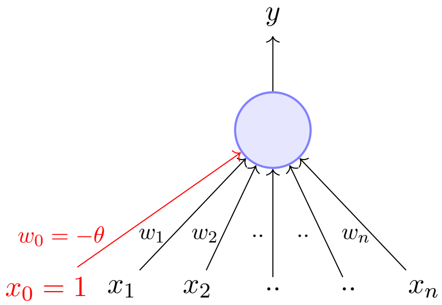

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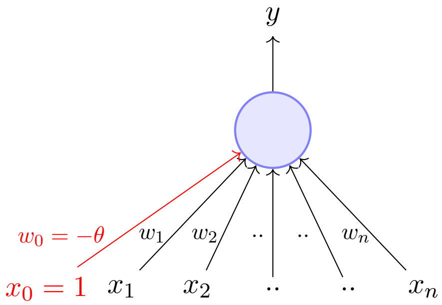

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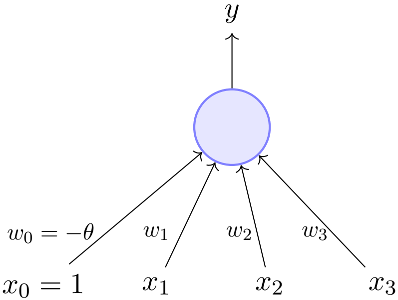
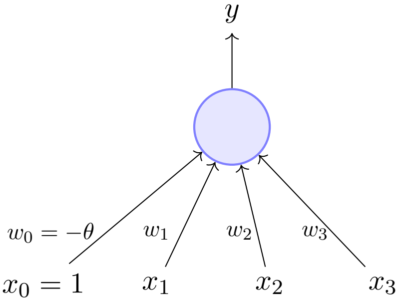
We will now try to answer the following questions:

- Why do we need weights ?
- Why is $w_0 = -\theta$ called the bias ?



- Why are we trying to implement boolean functions?



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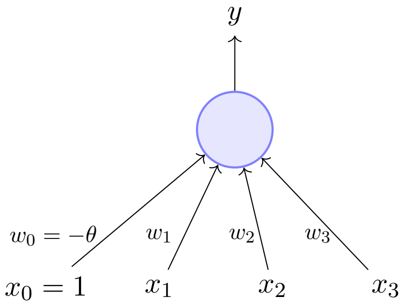

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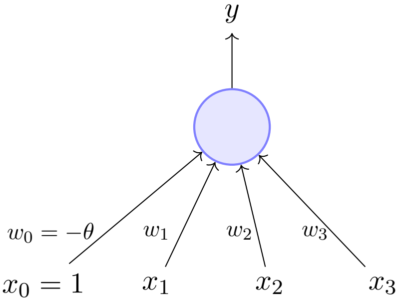

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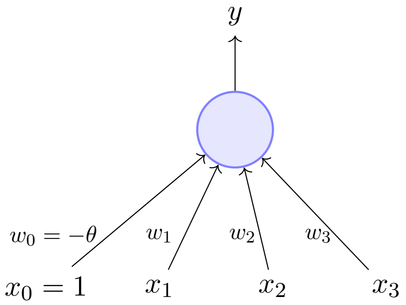

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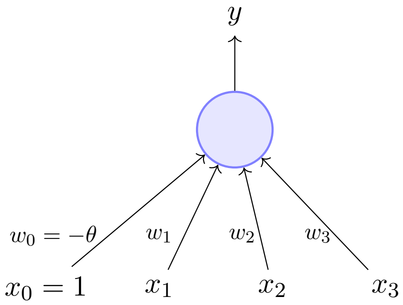

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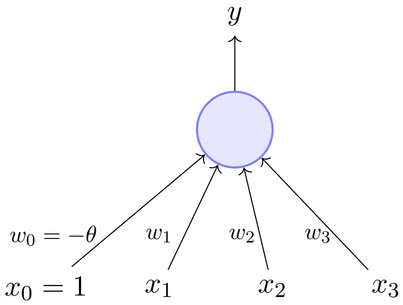
- Given the following weight assignments $w_0 = -2, w_1 = 1, w_2 = 1, w_3 = 2$, which input configurations will result in an output of 1 (watch



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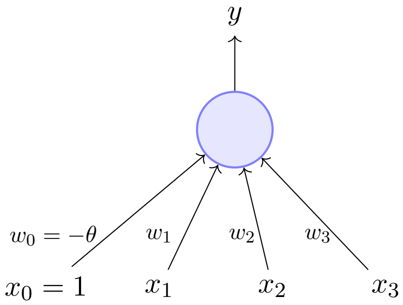

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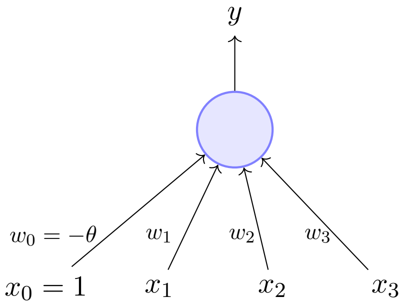

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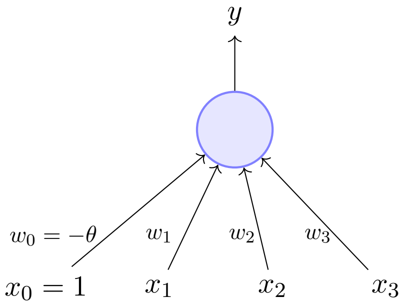

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- The weights $(w_1, w_2, ..., w_n)$ and the bias (w_0) will depend on the data (viewer history in this case)

What kind of functions can be implemented using the perceptron? Any difference from McCulloch Pitts neurons?

McCulloch Pitts Neuron

(assuming no inhibitory inputs)

$$y = 1 \quad if \sum_{i=0}^{n} x_i \geq \theta$$
$$= 0 \quad if \sum_{i=0}^{n} x_i < \theta$$

Perceptron

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$$= 0 \quad if \sum_{i=0}^{n} x_i < \theta$$

Perceptron

$$y = 1 \quad if \sum_{i=0}^{n} w_i * x_i \geq \theta$$
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- From the equations it should be clear that even a perceptron separates the input space into two halves
- All inputs which produce a 1 lie on one side and all inputs which produce a 0 lie on the other side
- In other words, a single perceptron can only be used to implement linearly separable functions

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- Then what is the difference ? The weights (including threshold) can be learned and the inputs can be real valued
- We will first revisit some boolean functions and then see the perceptron learning algorithm (for learning weights)

x_1	x_2	OR
0	0	

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0	0	0

x_1	x_2	OR	
0	0	0	$w_0 + \sum_{i=1}^{2} w_i x_i$

x_1	x_2	OR	
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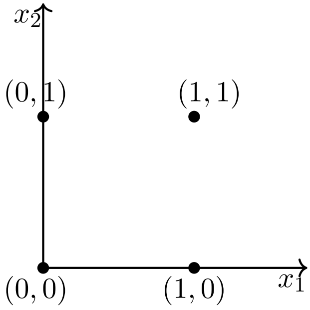

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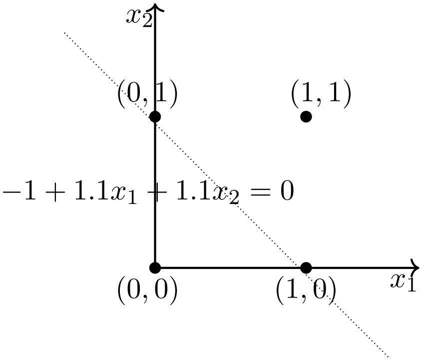

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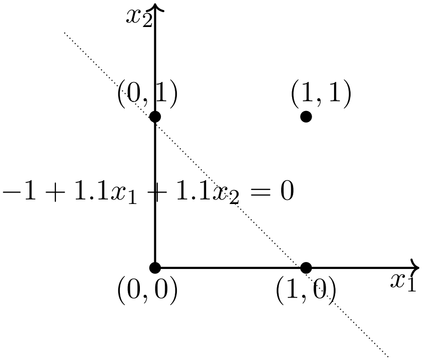

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- Note that we can come up with a similar set of inequalities and find the value of θ for a McCulloch Pitts neuron also

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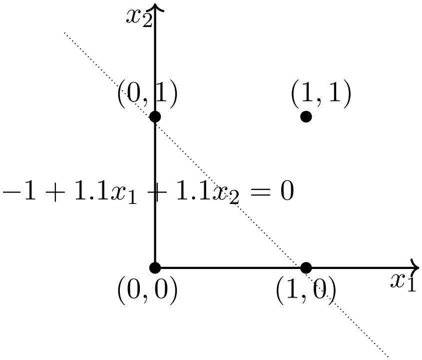

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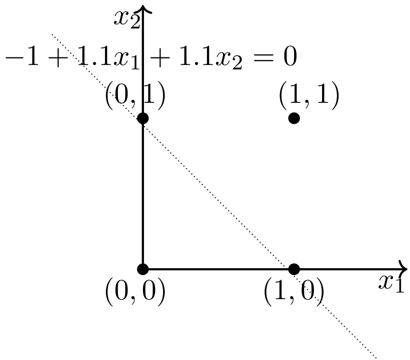
- Note that we can come up with a similar set of inequalities and find the value of θ for a McCulloch Pitts neuron also (Try it!)

Let us inspect this a bit more carefully ...

- Let us fix the threshold ($-w_0 = 1$) and try different values of w_1, w_2



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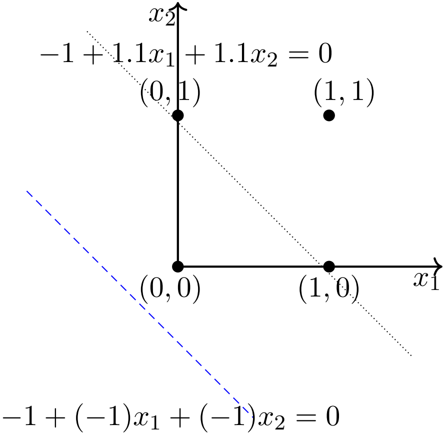
- Say, $w_1 = -1, w_2 = -1$



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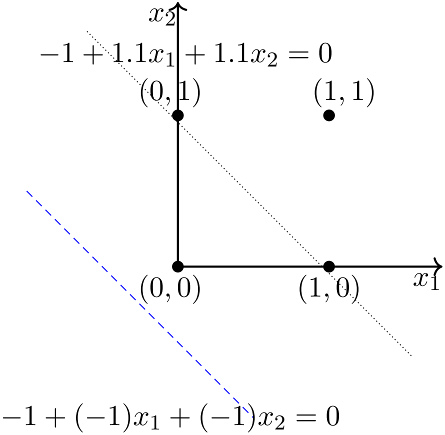
- What is wrong with this line?



- Let us fix the threshold ($-w_0 = 1$) and try different values of w_1, w_2
- Say, $w_1 = -1, w_2 = -1$
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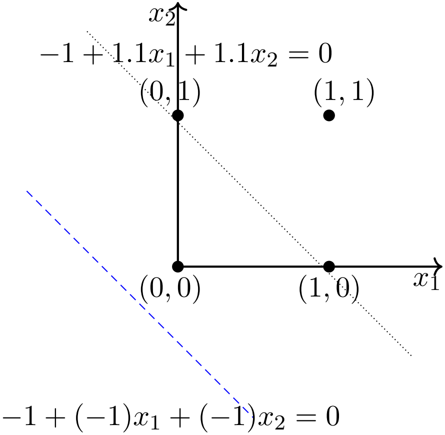

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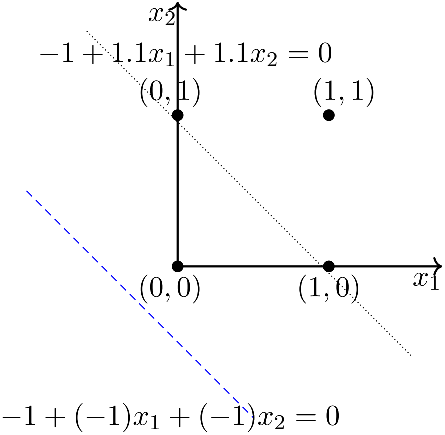
- Lets try some more values of w_1, w_2 and note how many errors we make



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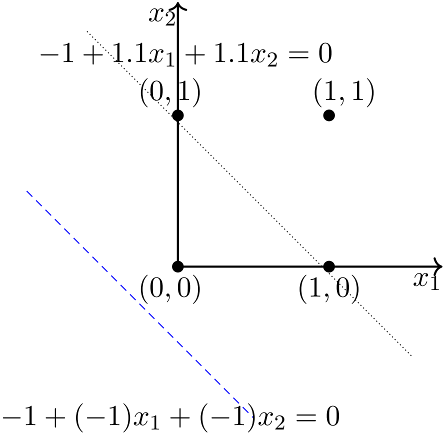
w_1	w_2	errors
-1	-1	1



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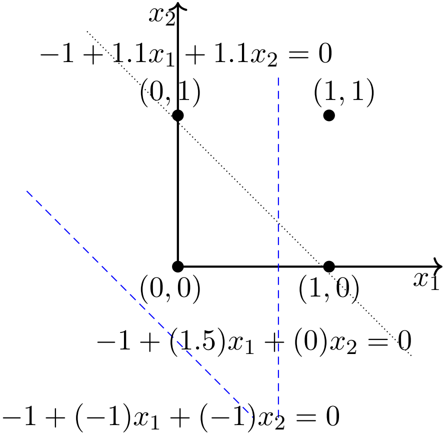

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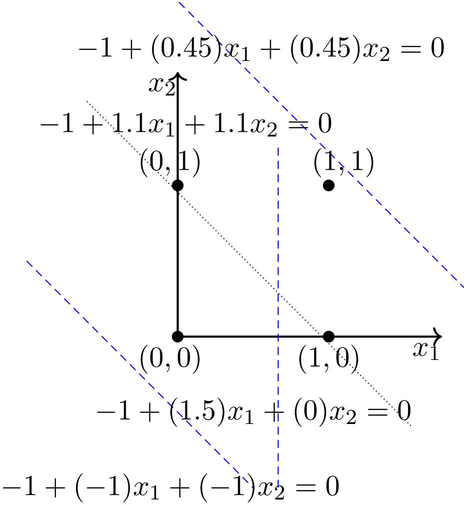
-1	-1	1
1.5	0	1
0.45	0.45	3



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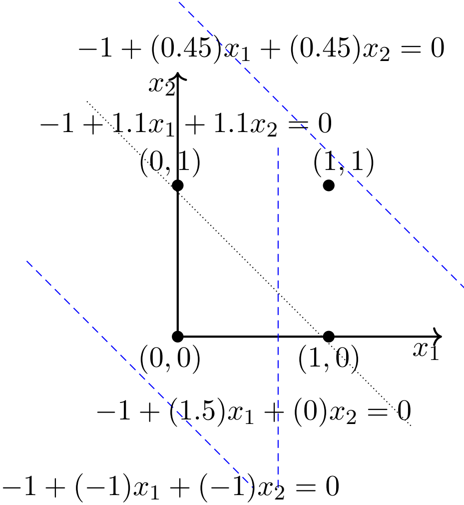

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w_1	w_2	errors
-1	-1	1
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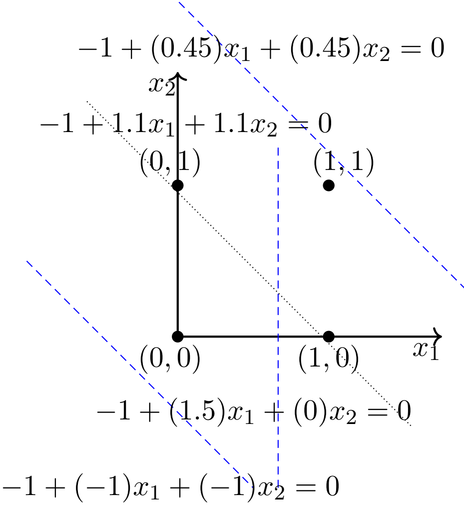
- We are interested in those values of w_0, w_1, w_2 which result in 0 error
- Let us plot the error surface corresponding to different values of w_0, w_1, w_2



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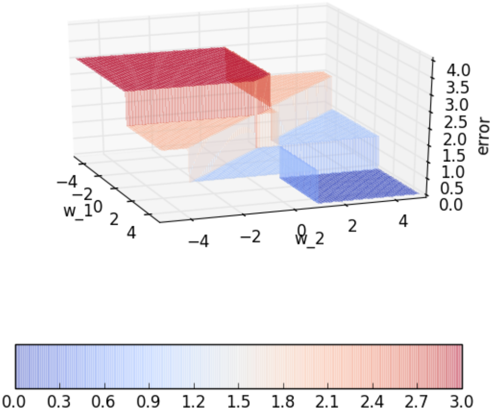
- For the OR function, an error occurs if $(x_1, x_2) = (0,0)$ but $-w_0+w_1*x_1+w_2*x_2 \geq 0$ or if $(x_1, x_2)! = (0,0)$ but $-w_0 + w_1 * x_1 + w_2 * x_2 < 0$



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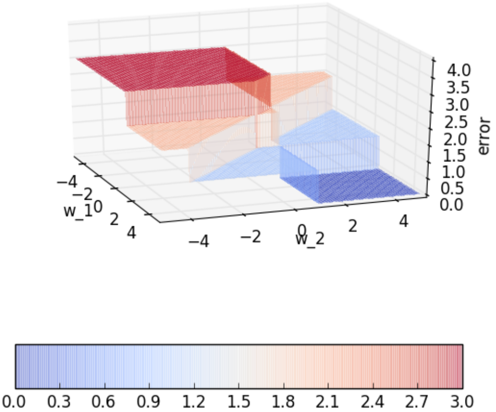

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- Apart from implementing boolean functions (which does not look very interesting) what can a perceptron be used for ?
- Our interest lies in the use of perceptron as a binary classifier. Let us see what this means...

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\begin{aligned}
x_1 &= isActorDamon \\
x_2 &= isGenreThriller \\
x_3 &= isDirectorNolan \\
x_4 &= imdbRating(scaled\ to\ 0\ to\ 1) \\
\dots & \quad \dots \\
x_n &= criticsRating(scaled\ to\ 0\ to\ 1)
\end{aligned}
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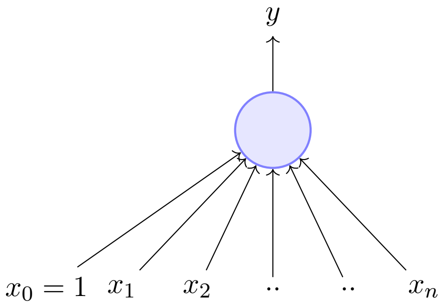

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- Suppose we are given a list of m movies and a label (class) associated with each movie indicating whether the user liked this movie or not : binary decision
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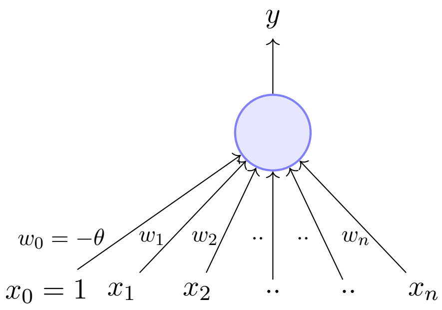
- We will assume that the data is linearly separable and we want a perceptron to learn how to make this decision



$x_1 = isActorDamon$

$x_2 = isGenreThriller$

$x_3 = isDirectorNolan$

$x_4 = imdbRating(scaled\ to\ 0\ to\ 1)$

... ...

$x_n = criticsRating(scaled\ to\ 0\ to\ 1)$

- Let us reconsider our problem of deciding whether to watch a movie or not
- Suppose we are given a list of m movies and a label (class) associated with each movie indicating whether the user liked this movie or not : binary decision
- Further, suppose we represent each movie with n features (some boolean, some real valued)
- We will assume that the data is linearly separable and we want a perceptron to learn how to make this decision
- In other words, we want the perceptron to find the equation of this separating plane (or find the values of $w_0, w_1, w_2, .., w_m$)

Algorithm: Perceptron Learning Algorithm

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$P \leftarrow inputs \quad with \quad label \quad 1;$

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- Why would this work ?

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- Why would this work ?
- To understand why this works we will have to get into a bit of Linear Algebra and a bit of geometry...

- Consider two vectors $\mathbf{w}$ and $\mathbf{x}$

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- The angle is 90° ($\because cos\alpha = \frac{w^T x}{||w||||x||} = 0$)

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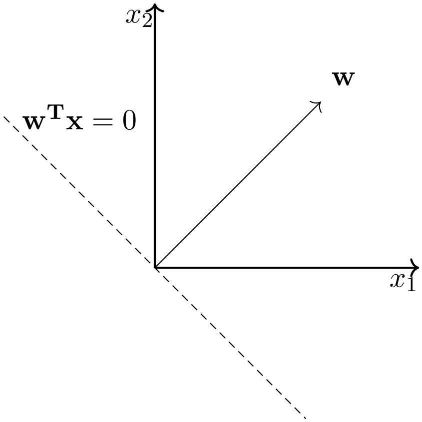
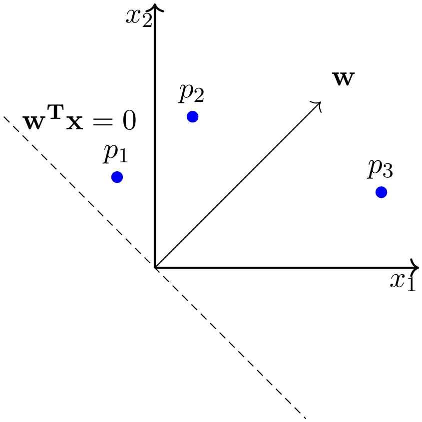
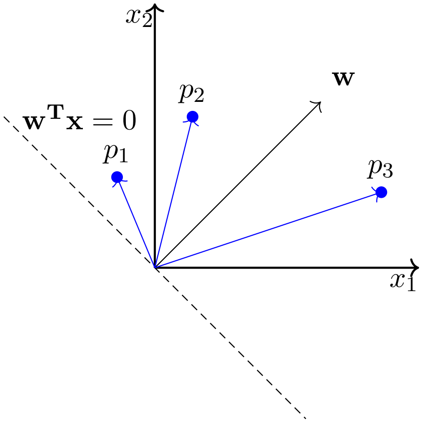
- The angle is 90° ($\because cos\alpha = \frac{w^T x}{||w||||x||} = 0$)
- Since the vector $\mathbf{w}$ is perpendicular to every point on the line it is actually perpendicular to the line itself


x_2
$\mathbf{w}$
$\mathbf{w^T x} = 0$
x_1

- Consider some points (vectors) which lie in the positive half space of this line (*i.e.*, $\mathbf{w}^{\mathbf{T}}\mathbf{x} \geq 0$)



- Consider some points (vectors) which lie in the positive half space of this line (*i.e.*, $\mathbf{w^T x} \geq 0$)
- What will be the angle between any such vector and $\mathbf{w}$?



- Consider some points (vectors) which lie in the positive half space of this line (*i.e.*, $\mathbf{w^T x} \geq 0$)
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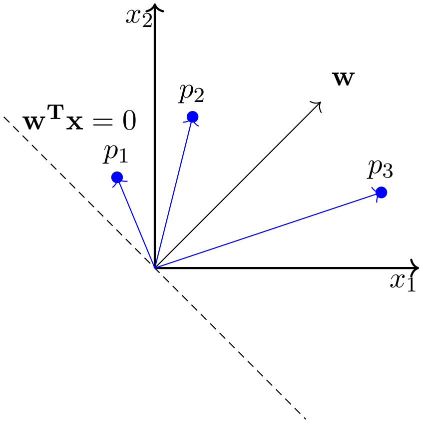

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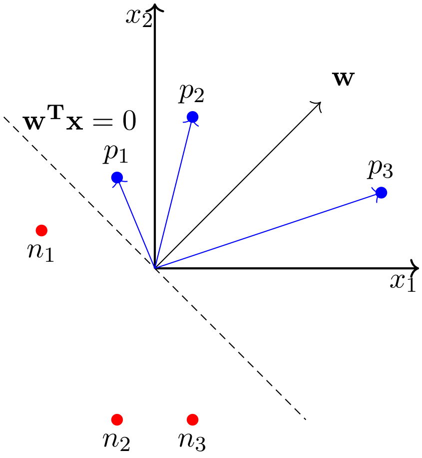
- What about points (vectors) which lie in the negative half space of this line (*i.e.*, $\mathbf{w^T x} < 0$)



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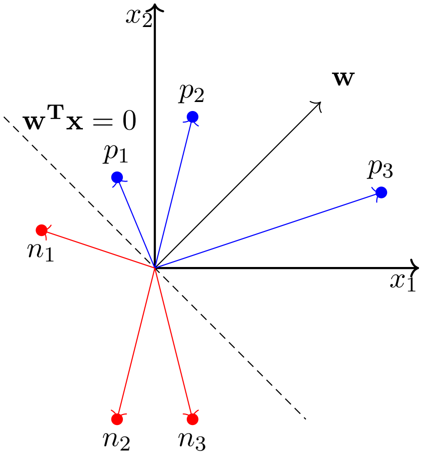

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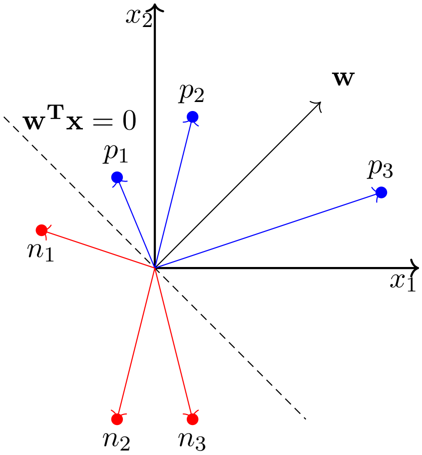
- Of course, this also follows from the formula ($cos\alpha = \frac{w^T x}{||w||||x||}$)



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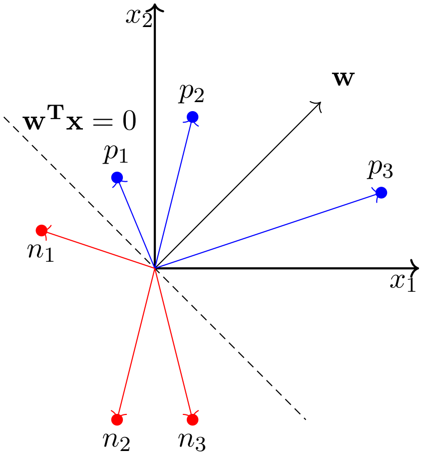
- Of course, this also follows from the formula ($cos\alpha = \frac{w^Tx}{||w||||x||}$)
- Keeping this picture in mind let us revisit the algorithm



Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

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Initialize $\mathbf{w}$ randomly;

while !*convergence* **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

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//the algorithm converges when all the inputs are classified correctly

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- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} + \mathbf{x}$

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$$cos(\alpha_{new}) \propto \mathbf{w_{new}}^T\mathbf{x}$$

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$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} + \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} + \mathbf{x}^T\mathbf{x} \end{aligned}$$

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$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w.x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w.x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in P$ if $\mathbf{w.x} < 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is greater than 90° (but we want α to be less than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} + \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} + \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} + \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha + \mathbf{x}^T\mathbf{x} \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w.x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w.x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in P$ if $\mathbf{w.x} < 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is greater than $90°$ (but we want α to be less than $90°$)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} + \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} + \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} + \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha + \mathbf{x}^T\mathbf{x} \\ cos(\alpha_{new}) &> cos\alpha \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in P$ if $\mathbf{w}.\mathbf{x} < 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is greater than 90° (but we want α to be less than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} + \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} + \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} + \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha + \mathbf{x}^T\mathbf{x} \\ cos(\alpha_{new}) &> cos\alpha \end{aligned}$$

- Thus α_{new} will be less than α and this is exactly what we want

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while !*convergence* **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than $90°$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$\cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than $90°$ (but we want α to be greater than $90°$)

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize **w** randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than $90°$ (but we want α to be greater than $90°$)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w.x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w.x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w.x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than 90° (but we want α to be greater than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$
$N \leftarrow inputs \quad with \quad label \quad 0;$
Initialize $\mathbf{w}$ randomly;
while $!convergence$ **do**
  Pick random $\mathbf{x} \in P \cup N$;
  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**
    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;
  end
  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**
    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;
  end
end
//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than $90°$ (but we want α to be greater than $90°$)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

$$cos(\alpha_{new}) \propto \mathbf{w_{new}}^T\mathbf{x}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than 90° (but we want α to be greater than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} - \mathbf{x})^T\mathbf{x} \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than $90°$ (but we want α to be greater than $90°$)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} - \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} - \mathbf{x}^T\mathbf{x} \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$
$N \leftarrow inputs \quad with \quad label \quad 0;$
Initialize $\mathbf{w}$ randomly;
while $!convergence$ **do**
    Pick random $\mathbf{x} \in P \cup N$;
    if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**
        $\mathbf{w} = \mathbf{w} + \mathbf{x}$;
    end
    if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**
        $\mathbf{w} = \mathbf{w} - \mathbf{x}$;
    end
end
//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than 90° (but we want α to be greater than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} - \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} - \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha - \mathbf{x}^T\mathbf{x} \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$

$N \leftarrow inputs \quad with \quad label \quad 0;$

Initialize $\mathbf{w}$ randomly;

while $!convergence$ **do**

  Pick random $\mathbf{x} \in P \cup N$;

  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**

    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;

  end

  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**

    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;

  end

end

//the algorithm converges when all the inputs are classified correctly

$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than 90° (but we want α to be greater than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} - \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} - \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha - \mathbf{x}^T\mathbf{x} \\ cos(\alpha_{new}) &< cos\alpha \end{aligned}$$

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$
$N \leftarrow inputs \quad with \quad label \quad 0;$
Initialize $\mathbf{w}$ randomly;
while $!convergence$ **do**
  Pick random $\mathbf{x} \in P \cup N$;
  if $\mathbf{x} \in P \quad and \quad \mathbf{w}.\mathbf{x} < 0$ **then**
    $\mathbf{w} = \mathbf{w} + \mathbf{x}$;
  end
  if $\mathbf{x} \in N \quad and \quad \mathbf{w}.\mathbf{x} \geq 0$ **then**
    $\mathbf{w} = \mathbf{w} - \mathbf{x}$;
  end
end
//the algorithm converges when all the inputs are classified correctly

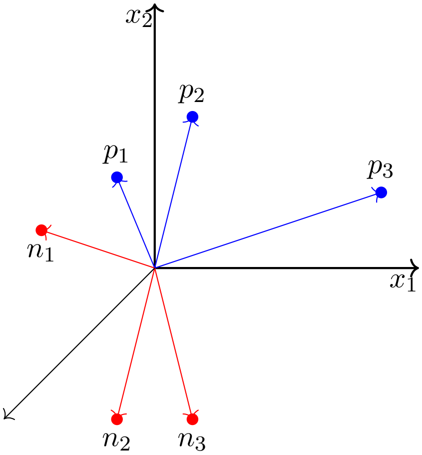
$$cos\alpha = \frac{\mathbf{w}^T\mathbf{x}}{||\mathbf{w}||||\mathbf{x}||}$$

- For $\mathbf{x} \in N$ if $\mathbf{w}.\mathbf{x} \geq 0$ then it means that the angle (α) between this $\mathbf{x}$ and the current $\mathbf{w}$ is less than 90° (but we want α to be greater than 90°)
- What happens to the new angle (α_{new}) when $\mathbf{w_{new}} = \mathbf{w} - \mathbf{x}$

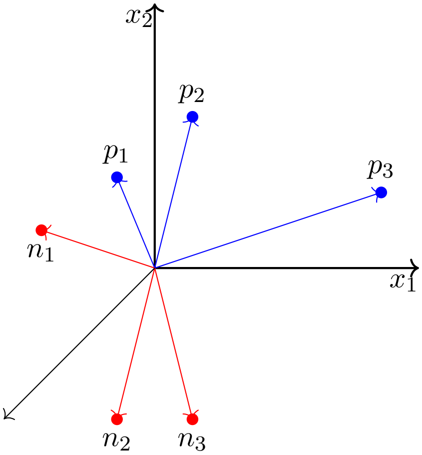
$$\begin{aligned} cos(\alpha_{new}) &\propto \mathbf{w_{new}}^T\mathbf{x} \\ &\propto (\mathbf{w} - \mathbf{x})^T\mathbf{x} \\ &\propto \mathbf{w}^T\mathbf{x} - \mathbf{x}^T\mathbf{x} \\ &\propto cos\alpha - \mathbf{x}^T\mathbf{x} \\ cos(\alpha_{new}) &< cos\alpha \end{aligned}$$

- Thus α_{new} will be greater than α and this is exactly what we want

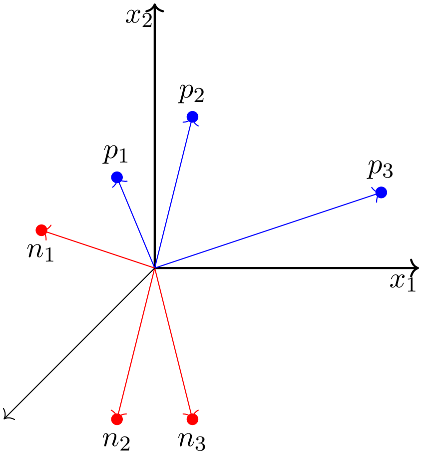
- We will now see this algorithm in action for a toy dataset



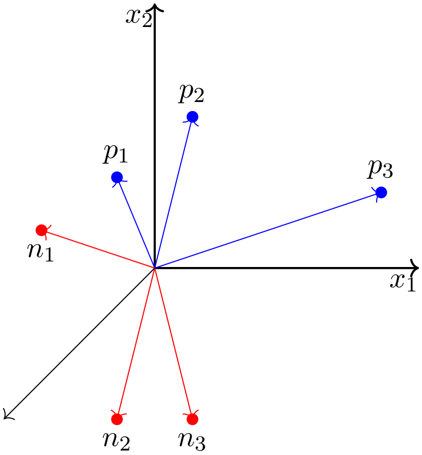
- We initialized $\mathbf{w}$ to a random value



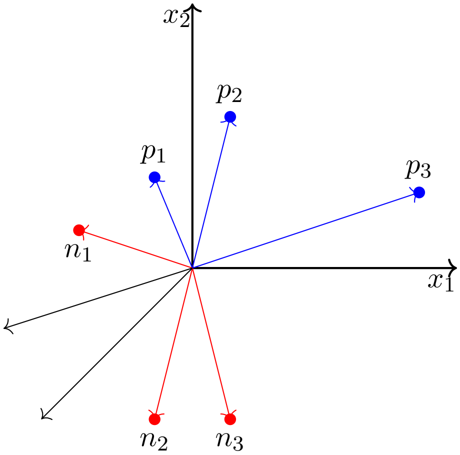
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)



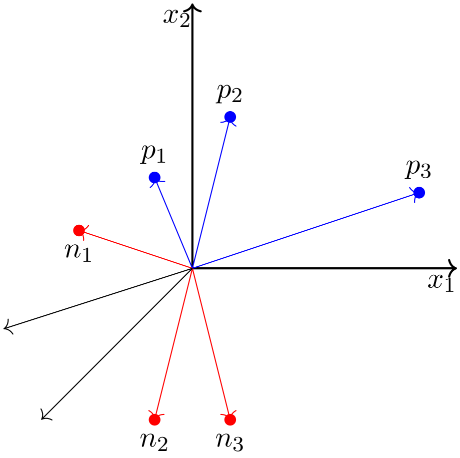
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points



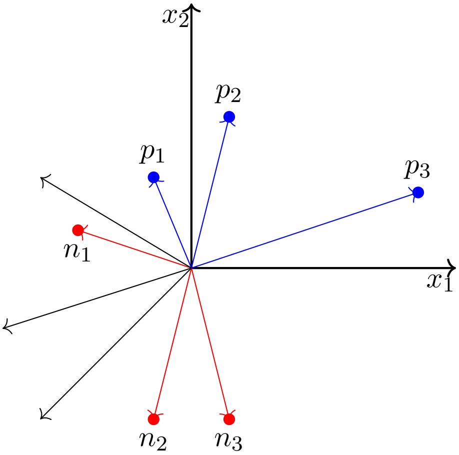
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, p_1), apply correction $\mathbf{w} = \mathbf{w} + \mathbf{x} \because \mathbf{w} \cdot \mathbf{x} < \mathbf{0}$ (you can check the angle visually)



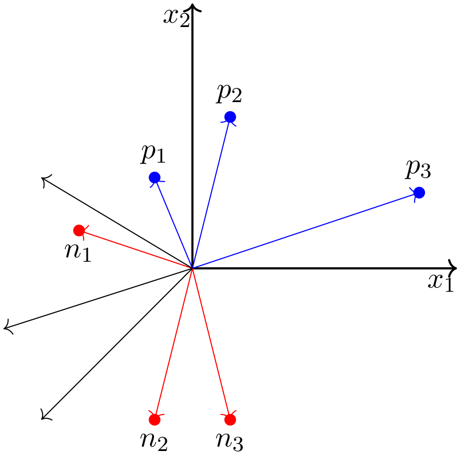
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, p_1), apply correction $\mathbf{w} = \mathbf{w} + \mathbf{x} \because \mathbf{w} \cdot \mathbf{x} < \mathbf{0}$ (you can check the angle visually)



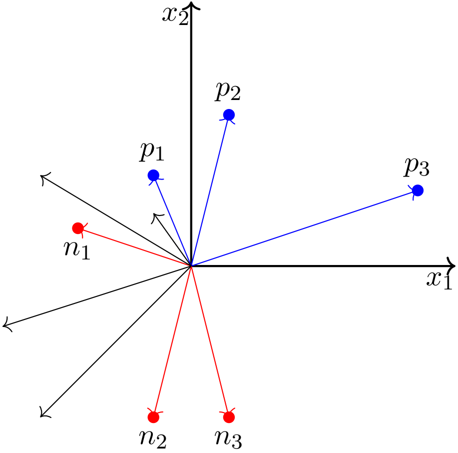
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, p_2), apply correction $\mathbf{w} = \mathbf{w} + \mathbf{x}$ $\because$ $\mathbf{w} \cdot \mathbf{x} < \mathbf{0}$ (you can check the angle visually)



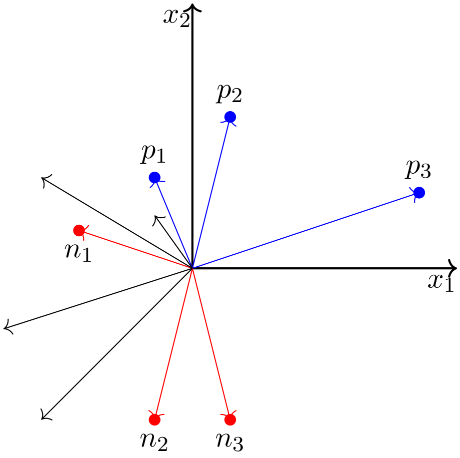
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, p_2), apply correction $\mathbf{w} = \mathbf{w} + \mathbf{x}$ $\because$ $\mathbf{w} \cdot \mathbf{x} < \mathbf{0}$ (you can check the angle visually)



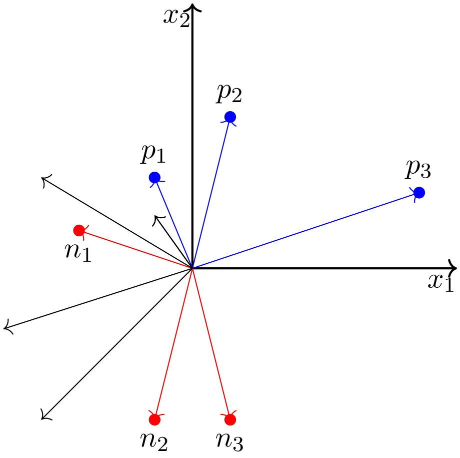
- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, n_1), apply correction $\mathbf{w} = \mathbf{w} - \mathbf{x}$ $\because$ $\mathbf{w} \cdot \mathbf{x} \geq \mathbf{0}$ (you can check the angle visually)



- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, n_1), apply correction $\mathbf{w} = \mathbf{w} - \mathbf{x} \because \mathbf{w} \cdot \mathbf{x} \geq \mathbf{0}$ (you can check the angle visually)



- We initialized $\mathbf{w}$ to a random value
- We observe that currently, $\mathbf{w} \cdot \mathbf{x} < 0$ ($\because$ angle $> 90°$) for all the positive points and $\mathbf{w} \cdot \mathbf{x} \geq 0$ ($\because$ angle $< 90°$) for all the negative points (the situation is exactly oppsite of what we actually want it to be)
- We now run the algorithm by randomly going over the points
- Randomly pick a point (say, n_3), no correction needed $\because \mathbf{w} \cdot \mathbf{x} < \mathbf{0}$ (you can check the angle visually)



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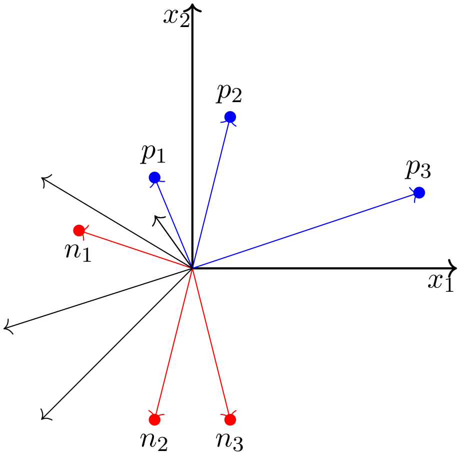

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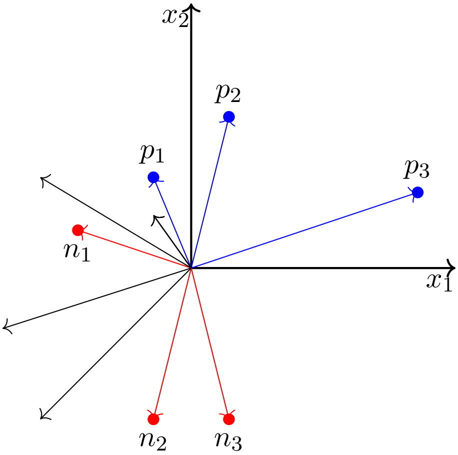

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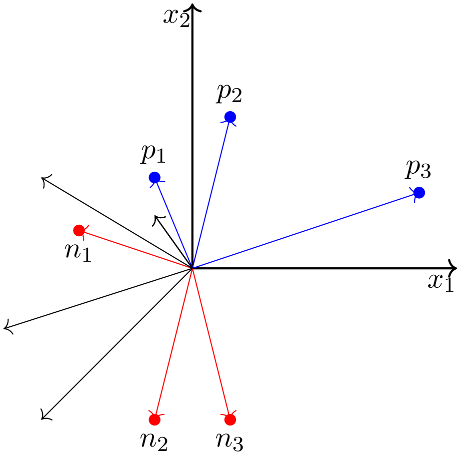

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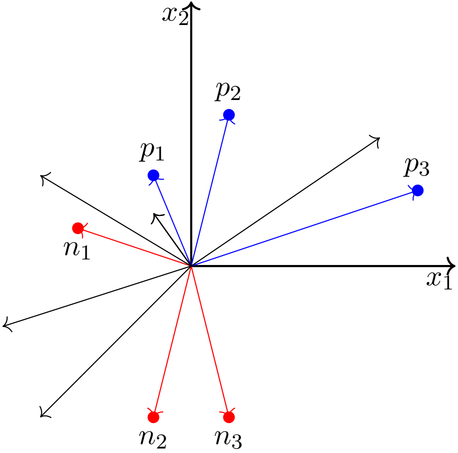

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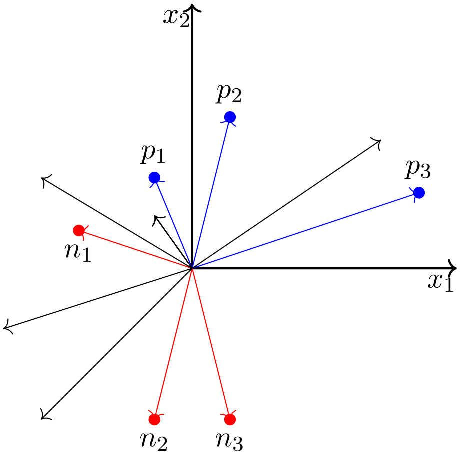

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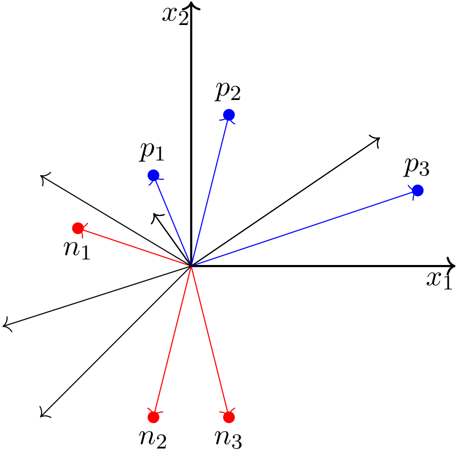

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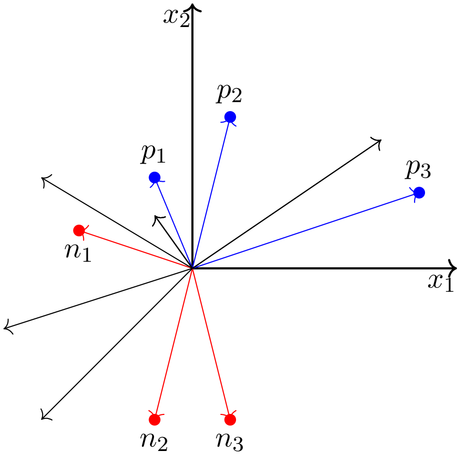

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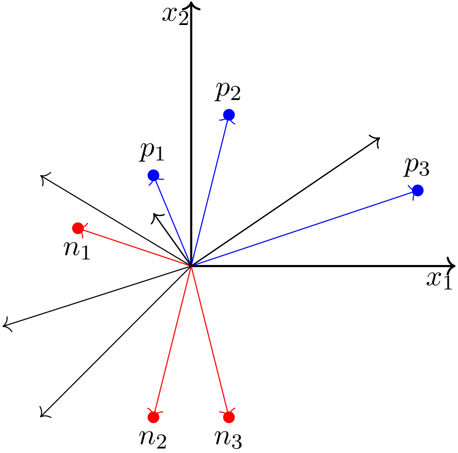

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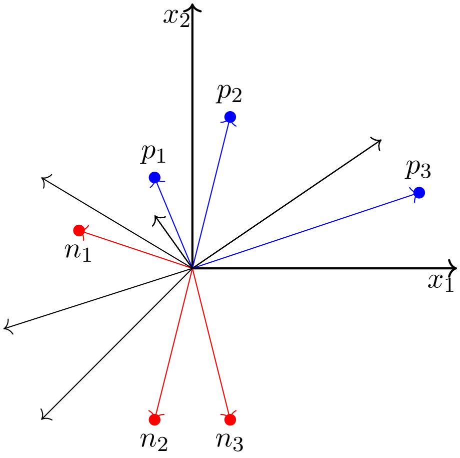

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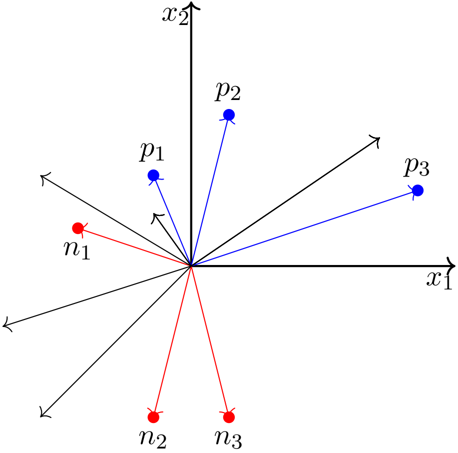

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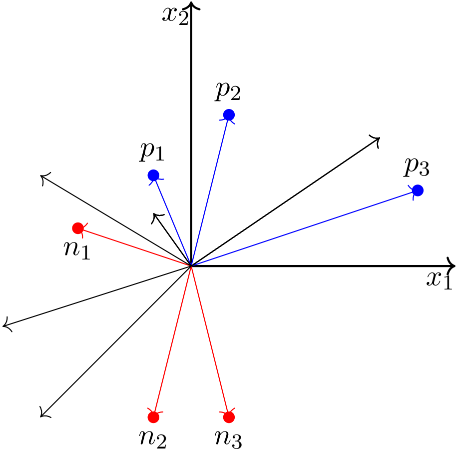

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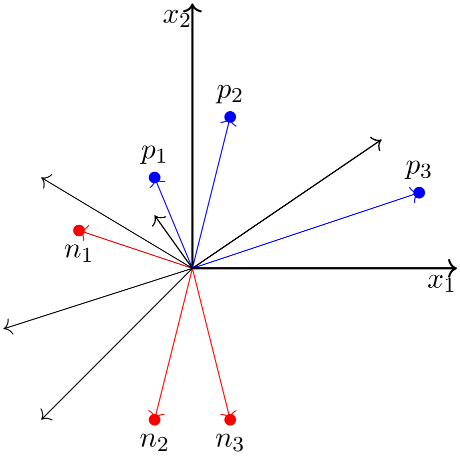

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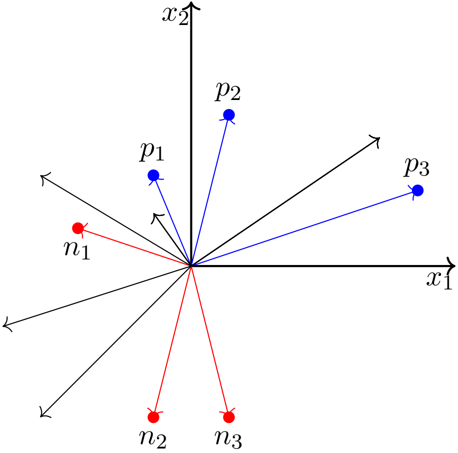

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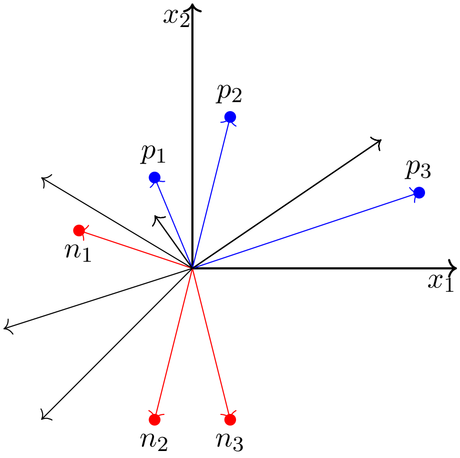

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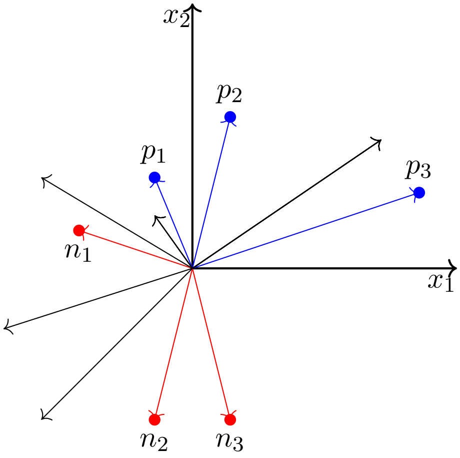

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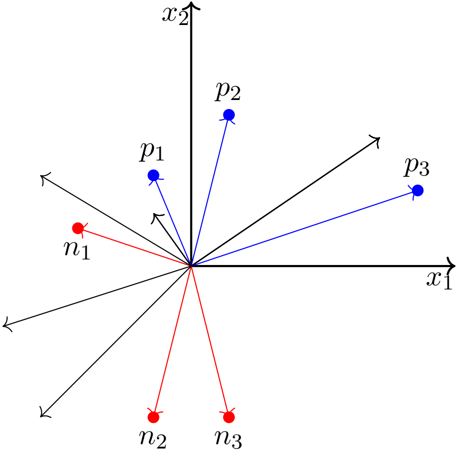

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- The algorithm has converged

- Now that we have some faith and intuition about why the algorithm works, we will see a more formal proof of convergence ...

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Proof: On the next slide

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//the algorithm converges when all the inputs are classified correctly

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    $\mathbf{w} = \mathbf{w} + \mathbf{p}$;
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end
//the algorithm converges when all the inputs are classified correctly
//notice that we do not need the other **if** condition because by construction we want all points in P' to lie in the positive half space $\mathbf{w}.\mathbf{p} \geq 0$

Setup:

- If $x \in N$ then $-x \in P$ ($\because w^T x < 0 \implies w^T(-x) \geq 0$)
- We can thus consider a single set $P' = P \cup N^-$ and for every element $p \in P'$ ensure that $w^T p \geq 0$
- Further we will normalize all the p's so that $||p|| = 1$ (notice that this does not affect the solution $\because if \quad w^T \frac{p}{||p||} \geq 0$ then $w^T p \geq 0$)
- Let w^* be the normalized solution vector (we know one exists as the data is linearly separable)

Algorithm: Perceptron Learning Algorithm

$P \leftarrow inputs \quad with \quad label \quad 1;$
$N \leftarrow inputs \quad with \quad label \quad 0;$
N^- *contains negations of all points in* N;
$P' \leftarrow P \cup N^-;$
Initialize $\mathbf{w}$ randomly;
while !*convergence* **do**
  Pick random $\mathbf{p} \in P'$;
  $\mathbf{p} \leftarrow \frac{p}{||p||}$ $\quad$ (*so now,*$||p|| = 1$) ;
  if $\mathbf{w.p} < 0$ **then**
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- But since $cos\beta \leq 1$, k must be bounded by a maximum number
- Thus, there can only be a finite number of corrections (k) to w and the algorithm will converge!

Coming back to our questions ...

- What about non-boolean (say, real) inputs ?
- Do we always need to hand code the threshold ?
- Are all inputs equal ? What if we want to assign more weight (importance) to some inputs ?
- What about functions which are not linearly separable ?

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- Do we always need to hand code the threshold ? No, we can learn the threshold
- Are all inputs equal ? What if we want to assign more weight (importance) to some inputs ? A perceptron allows weights to be assigned to inputs
- What about functions which are not linearly separable ?

Coming back to our questions ...

- What about non-boolean (say, real) inputs ? Real valued inputs are allowed in perceptron
- Do we always need to hand code the threshold ? No, we can learn the threshold
- Are all inputs equal ? What if we want to assign more weight (importance) to some inputs ? A perceptron allows weights to be assigned to inputs
- What about functions which are not linearly separable ? Not possible with a single perceptron but we will see how to handle this ..

- So what do we do about functions which are not linearly separable ?

- So what do we do about functions which are not linearly separable ?
- Let us see one such simple boolean function first ?

x_1	x_2	XOR	
0	0	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$
1	0	1	$w_0 + \sum_{i=1}^{2} w_i x_i \geq 0$
0	1	1	$w_0 + \sum_{i=1}^{2} w_i x_i \geq 0$
1	1	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$

x_1	x_2	XOR	
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0	1	1	$w_0 + \sum_{i=1}^{2} w_i x_i \geq 0$
1	1	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$

$$w_0 + w_1 \cdot 0 + w_2 \cdot 0 < 0 \implies w_0 < 0$$

x_1	x_2	XOR	
0	0	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$
1	0	1	$w_0 + \sum_{i=1}^{2} w_i x_i \geq 0$
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1	1	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$

$$w_0 + w_1 \cdot 0 + w_2 \cdot 0 < 0 \implies w_0 < 0$$

$$w_0 + w_1 \cdot 0 + w_2 \cdot 1 \geq 0 \implies w_2 > -w_0$$

x_1	x_2	XOR	
0	0	0	$w_0 + \sum_{i=1}^{2} w_i x_i < 0$
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x_1	x_2	XOR	
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- The fourth condition contradicts conditions 2 and 3

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0	1	1	$w_0 + \sum_{i=1}^{2} w_i x_i \geq 0$
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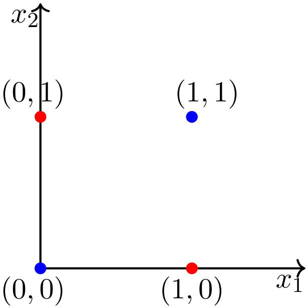

$$w_0 + w_1 \cdot 0 + w_2 \cdot 0 < 0 \implies w_0 < 0$$
$$w_0 + w_1 \cdot 0 + w_2 \cdot 1 \geq 0 \implies w_2 > -w_0$$
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- The fourth condition contradicts conditions 2 and 3
- Hence we cannot have a solution to this set of inequalities

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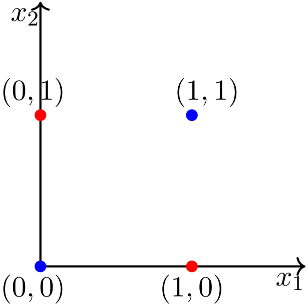
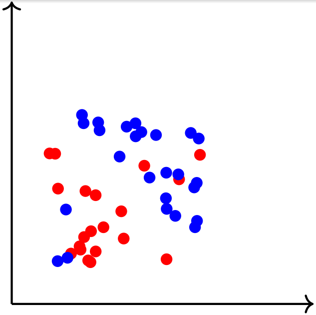
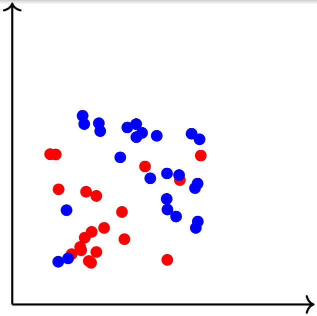


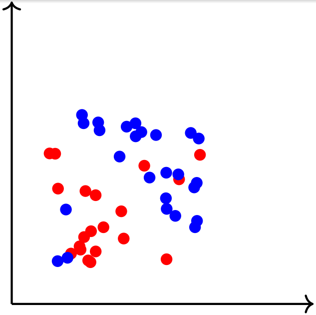
- And indeed you can see that it is impossible to draw a line which separates the red points from the blue points

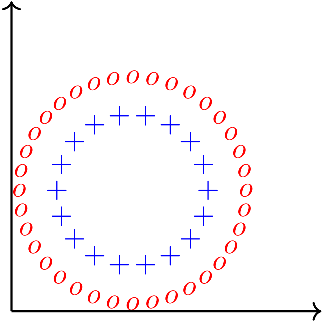


- Most real world data is not linearly separable and will always contain some outliers



- Most real world data is not linearly separable and will always contain some outliers
- In fact, sometimes there may not be any outliers but still the data may not be linearly separable





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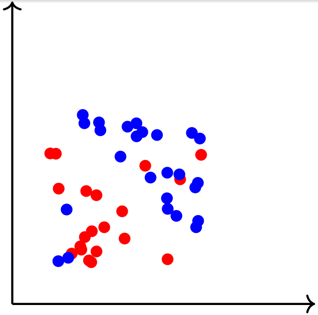
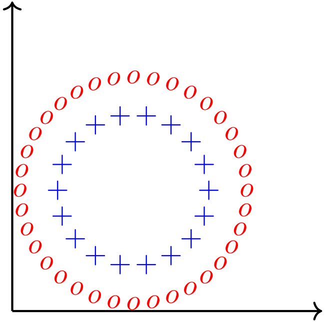
- In fact, sometimes there may not be any outliers but still the data may not be linearly separable
- We need computational units (models) which can deal with such data





- Most real world data is not linearly separable and will always contain some outliers
- In fact, sometimes there may not be any outliers but still the data may not be linearly separable
- We need computational units (models) which can deal with such data
- While a single perceptron cannot deal with such data, we will show that a network of perceptrons can indeed deal with such data

- Before seeing how a network of perceptrons can deal with linearly inseparable data, we will discuss boolean functions in some more detail ...

- How many boolean functions can you design from 2 inputs ?

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- Let us begin with some easy ones which you already know ..

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x_1	x_2
0	0
0	1
1	0
1	1

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x_1	x_2	f_1
0	0	0
0	1	0
1	0	0
1	1	0

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x_1	x_2	f_1
0	0	0
0	1	0
1	0	0
1	1	0

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x_1	x_2	f_1	f_2
0	0	0	0
0	1	0	0
1	0	0	0
1	1	0	1

- How many boolean functions can you design from 2 inputs ?
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x_1	x_2	f_1	f_2	f_8
0	0	0	0	0
0	1	0	0	1
1	0	0	0	1
1	1	0	1	1

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x_1	x_2	f_1	f_2	f_3	f_8
0	0	0	0	0	0
0	1	0	0	0	1
1	0	0	0	1	1
1	1	0	1	0	1

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x_1	x_2	f_1	f_2	f_3	f_4	f_8
0	0	0	0	0	0	0
0	1	0	0	0	0	1
1	0	0	0	1	1	1
1	1	0	1	0	1	1

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

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

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

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

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

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

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

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

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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

- Of these, how many are linearly separable ?

- How many boolean functions can you design from 2 inputs ?
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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

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- In general, how many boolean functions can you have for n inputs ?

- How many boolean functions can you design from 2 inputs ?
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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
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- Of these, how many are linearly separable ? (turns out all except XOR and !XOR - feel free to verify)
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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

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x_1	x_2	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

- Of these, how many are linearly separable ? (turns out all except XOR and !XOR - feel free to verify)
- In general, how many boolean functions can you have for n inputs ? 2^{2^n}
- How many of these 2^{2^n} functions are not linearly separable ? For the time being, it suffices to know that at least some of these may not be linearly inseparable (I encourage you to figure out the exact answer :-))

- We will now see how to implement **any** boolean function using a network of perceptrons ...

- For this discussion, we will assume True $= +1$ and False $=$ -1

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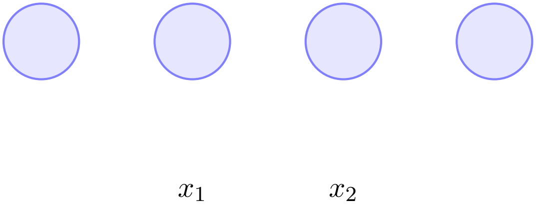
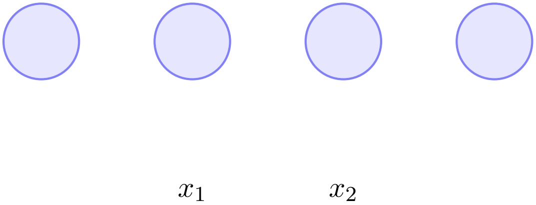
- We consider 2 inputs and 4 perceptrons



- For this discussion, we will assume True = +1 and False = -1
- We consider 2 inputs and 4 perceptrons
- Each input is connected to all the 4 perceptrons with specific weights



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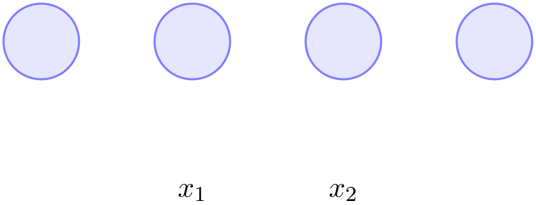

red edge indicates w = -1
blue edge indicates w = +1

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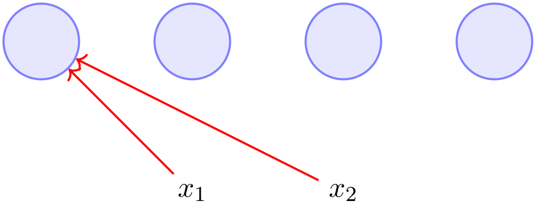
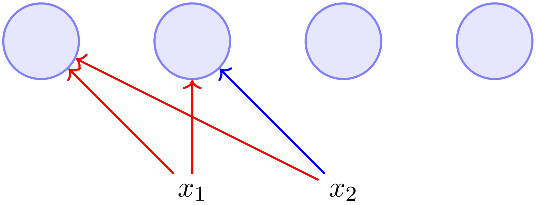


red edge indicates w = -1
blue edge indicates w = +1

- For this discussion, we will assume True = +1 and False = -1
- We consider 2 inputs and 4 perceptrons
- Each input is connected to all the 4 perceptrons with specific weights



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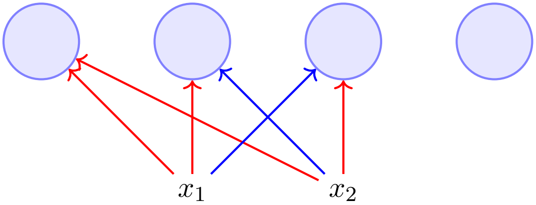

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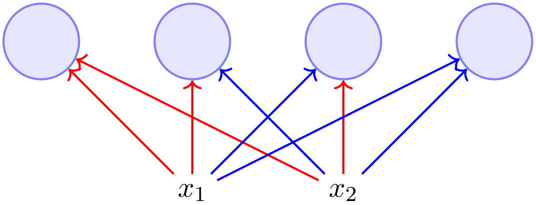

red edge indicates w = -1
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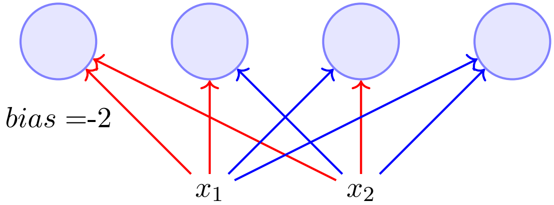
- For this discussion, we will assume True = +1 and False = -1
- We consider 2 inputs and 4 perceptrons
- Each input is connected to all the 4 perceptrons with specific weights
- The bias (w_0) of each perceptron is -2 (i.e., each perceptron will fire only if the weighted sum of its input is ≥ 2)



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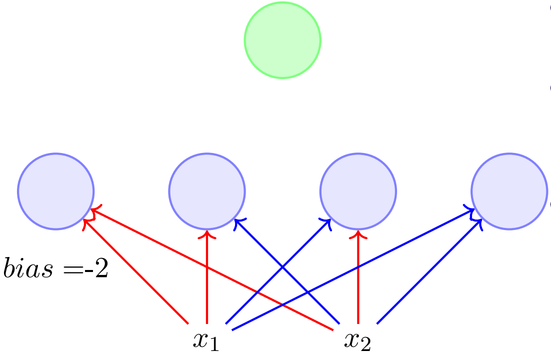

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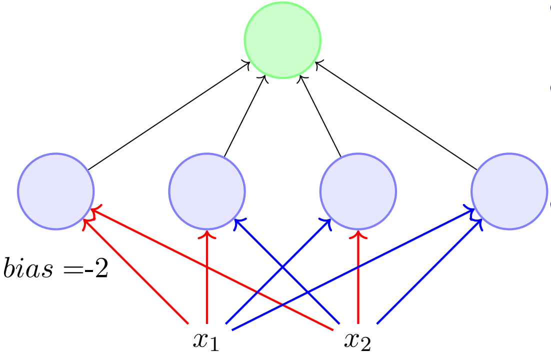
- Each of these perceptrons is connected to an output perceptron by weights (which need to be learned)



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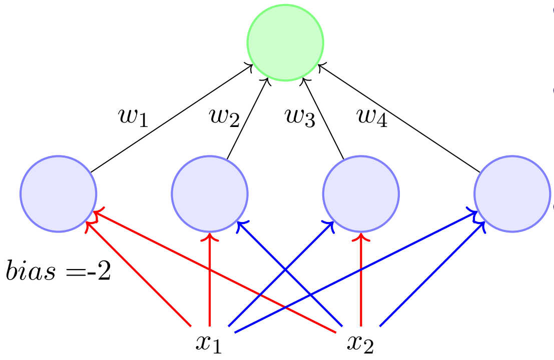

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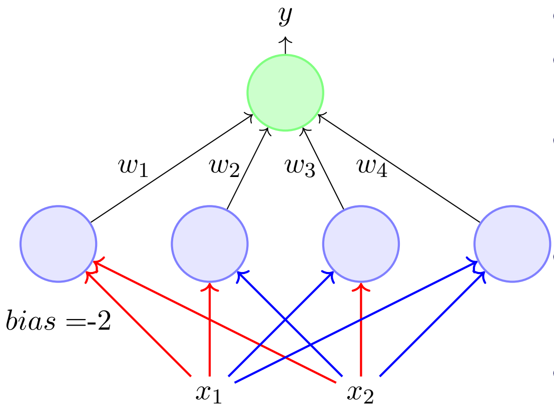

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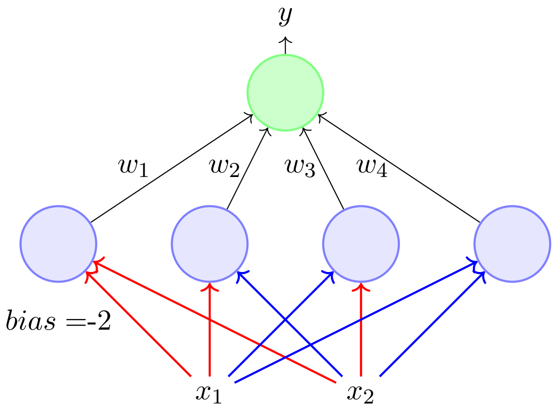
- Each of these perceptrons is connected to an output perceptron by weights (which need to be learned)
- The output of this perceptron (y) is the output of this network

Terminology:

- This network contains 3 layers



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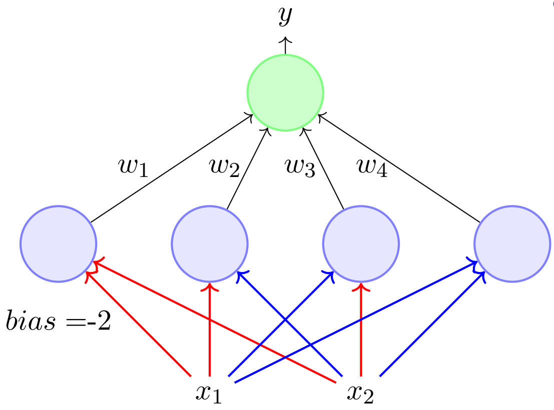

red edge indicates w = -1
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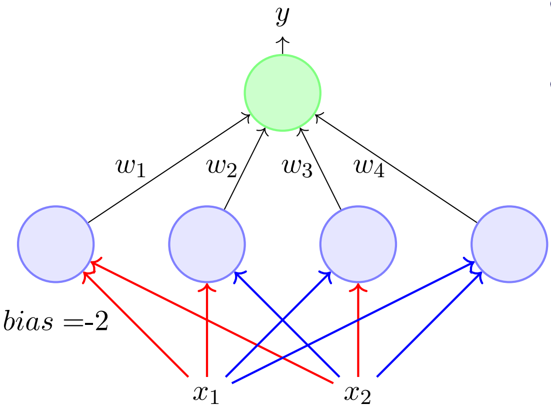
Terminology:

- This network contains 3 layers
- The layer containing the inputs (x_1, x_2) is called the **input layer**



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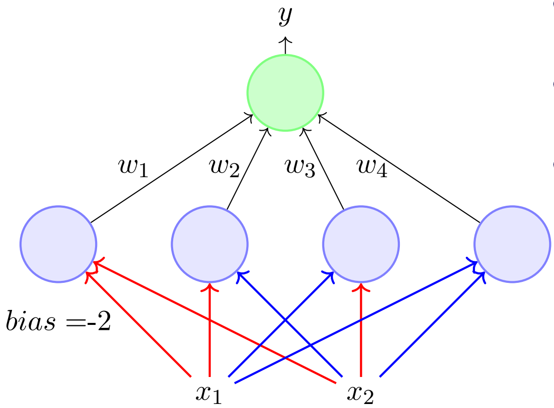
Terminology:

- This network contains 3 layers
- The layer containing the inputs (x_1, x_2) is called the **input layer**
- The middle layer containing the 4 perceptrons is called the **hidden layer**



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Terminology:

- This network contains 3 layers
- The layer containing the inputs (x_1, x_2) is called the **input layer**
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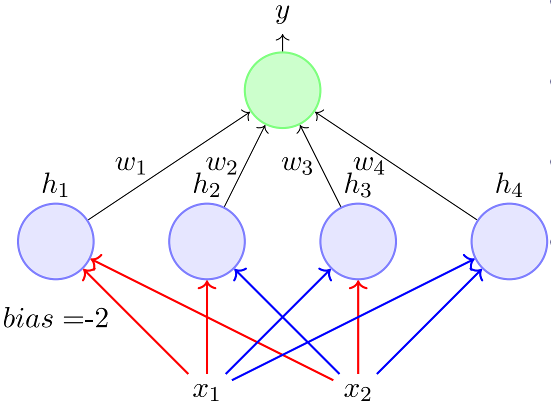

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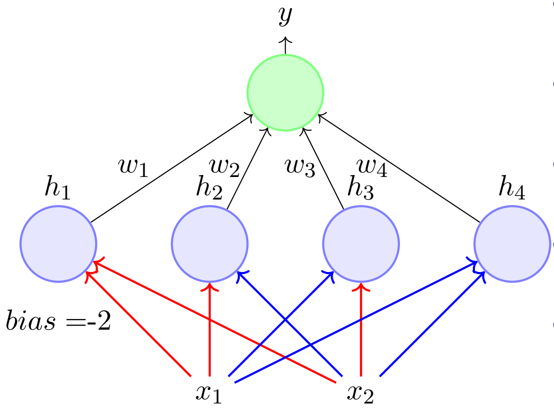
- The outputs of the 4 perceptrons in the hidden layer are denoted by h_1, h_2, h_3, h_4



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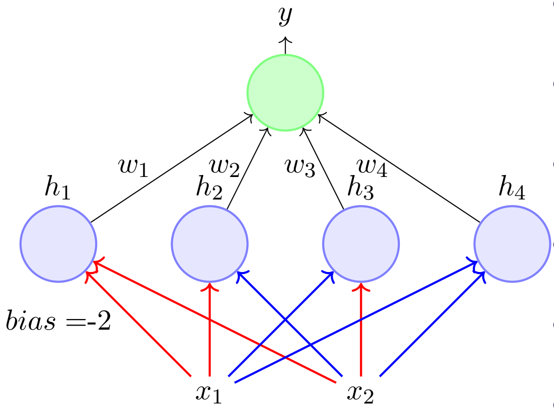
- The red and blue edges are called layer 1 weights



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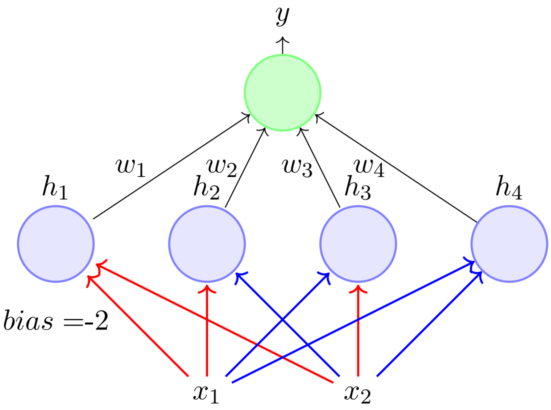
- The red and blue edges are called layer 1 weights
- w_1, w_2, w_3, w_4 are called layer 2 weights



red edge indicates w = -1
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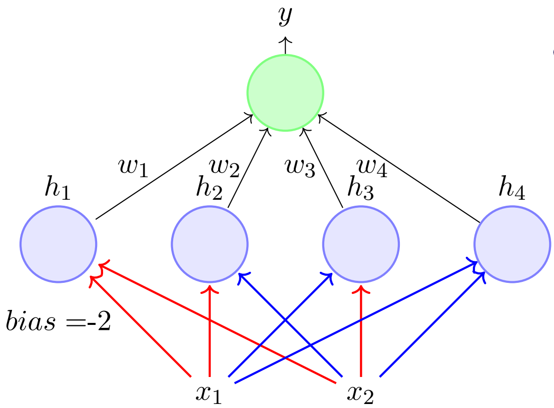
- We claim that this network can be used to implement **any** boolean function (linearly separable or not) !



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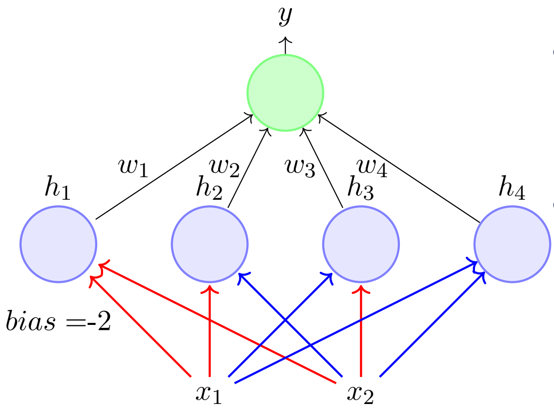
- In other words, we can find w_1, w_2, w_3, w_4 such that the truth table of any boolean function can be represented by this network



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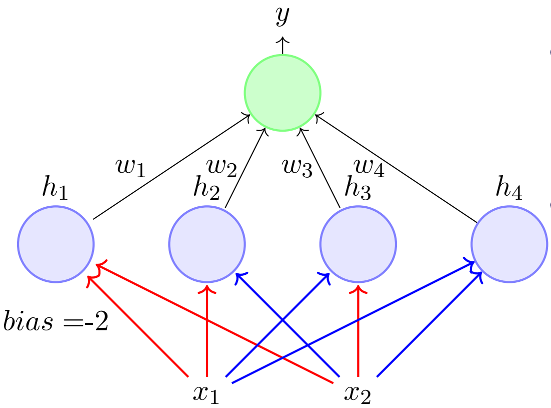
- Astonishing claim!



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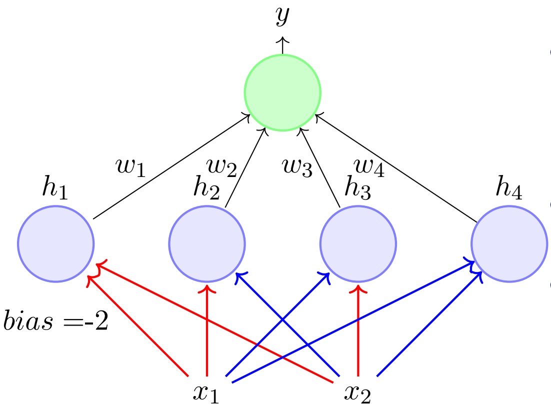
- Astonishing claim! Well, not really, if you understand what is going on



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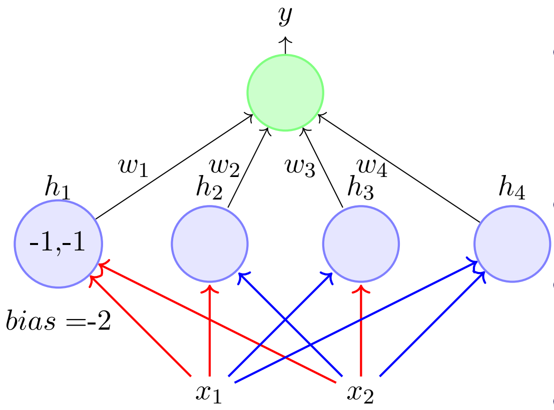
- Each perceptron in the middle layer fires only for a specific input (and no two perceptrons fire for the same input)



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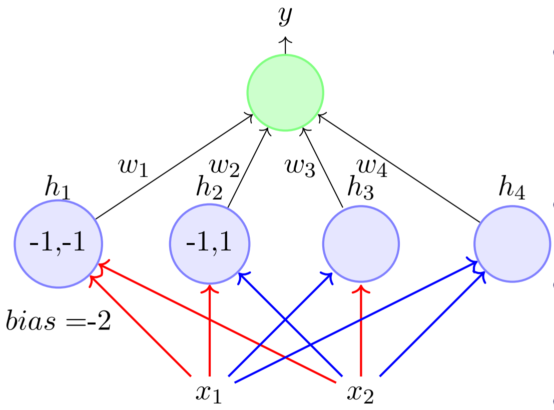
- Each perceptron in the middle layer fires only for a specific input (and no two perceptrons fire for the same input)
- the first perceptron fires for {-1,-1}



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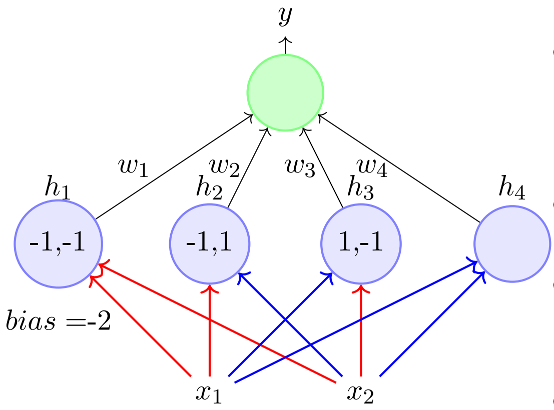
- the second perceptron fires for {-1,1}



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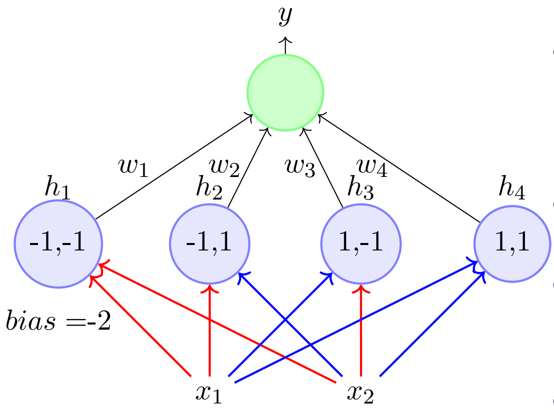
- Each perceptron in the middle layer fires only for a specific input (and no two perceptrons fire for the same input)
- the third perceptron fires for {1,-1}



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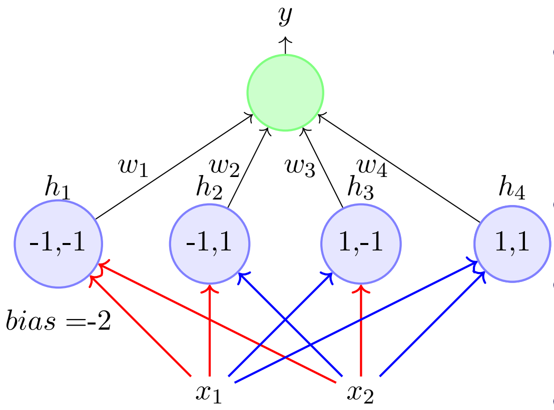

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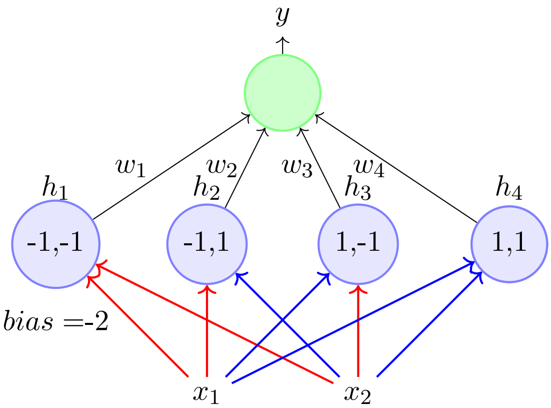
- Astonishing claim! Well, not really, if you understand what is going on
- Each perceptron in the middle layer fires only for a specific input (and no two perceptrons fire for the same input)
- Let us see why this network works by taking an example of the XOR function

- Let w_0 be the bias output of the neuron (*i.e.*, it will fire if $\sum_{i=1}^{4} w_i h_i \geq w_0$)



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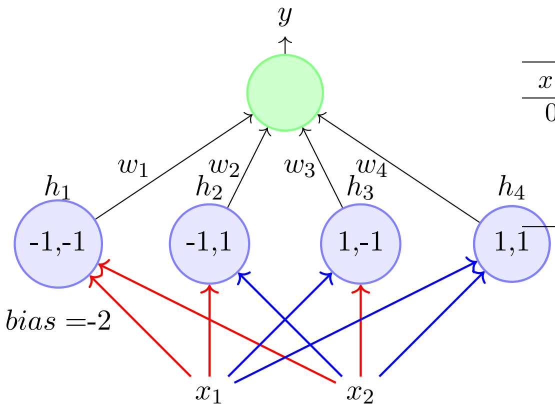

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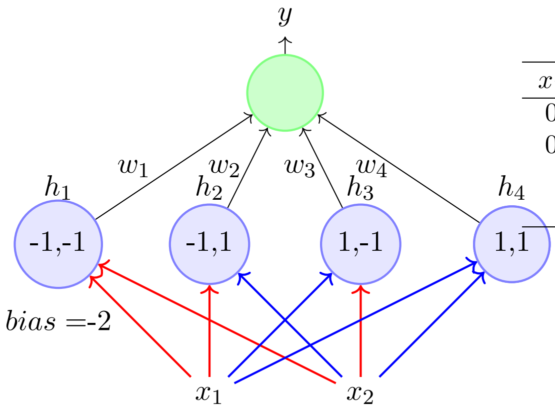
x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
0	0	0	1	0	0	0	w_1

- Let w_0 be the bias output of the neuron ($i.e.$, it will fire if $\sum_{i=1}^{4} w_i h_i \geq w_0$)



x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
0	0	0	1	0	0	0	w_1
0	1	1	0	1	0	0	w_2

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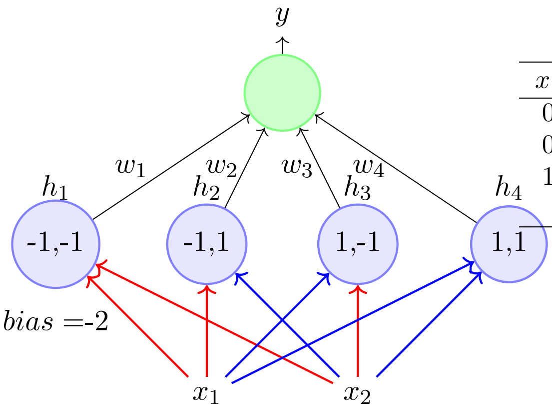

x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
0	0	0	1	0	0	0	w_1
0	1	1	0	1	0	0	w_2
1	0	1	0	0	1	0	w_3

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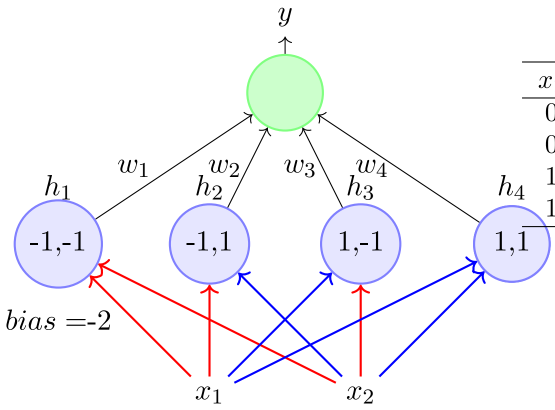
- Let w_0 be the bias output of the neuron (*i.e.*, it will fire if $\sum_{i=1}^{4} w_i h_i \geq w_0$)



x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
0	0	0	1	0	0	0	w_1
0	1	1	0	1	0	0	w_2
1	0	1	0	0	1	0	w_3
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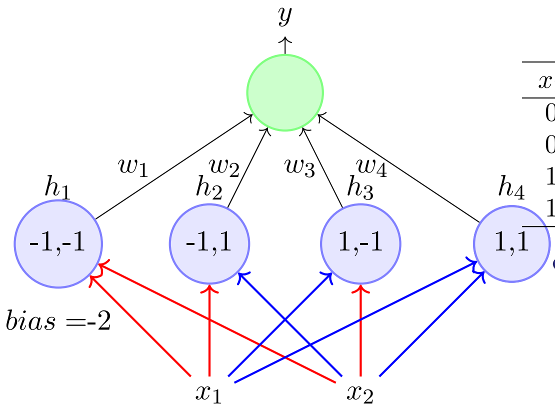

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x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
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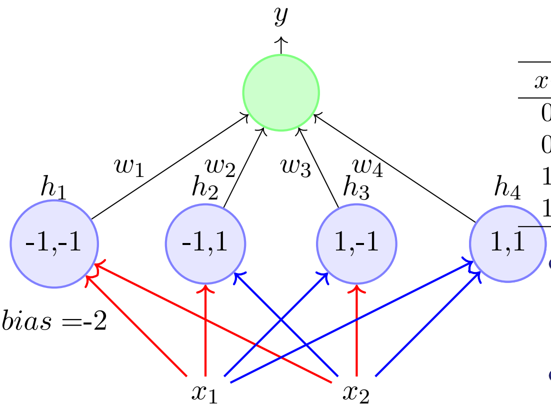
0	1	1	0	1	0	0	w_2
1	0	1	0	0	1	0	w_3
1	1	0	0	0	0	1	w_4

- This results in the following four conditions to implement XOR: $w_1 < w_0, w_2 \geq w_0, w_3 \geq w_0, w_4 < w_0$



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x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
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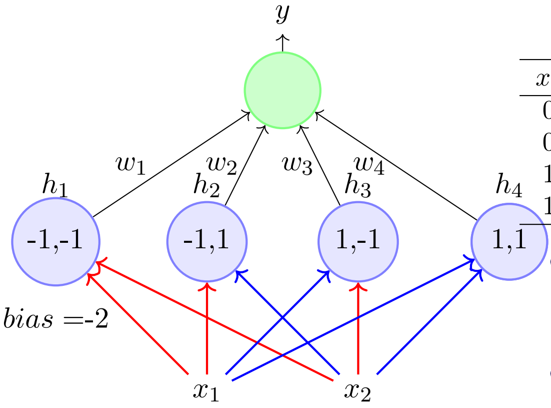
1	1	0	0	0	0	1	w_4

- This results in the following four conditions to implement XOR: $w_1 < w_0, w_2 \geq w_0, w_3 \geq w_0, w_4 < w_0$
- Unlike before, there are no contradictions now and the system of inequalities can be satisfied



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x_1	x_2	XOR	h_1	h_2	h_3	h_4	$\sum_{i=1}^{4} w_i h_i$
0	0	0	1	0	0	0	w_1
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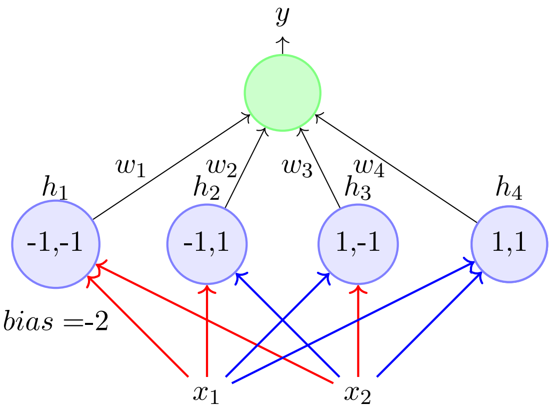
1	0	1	0	0	1	0	w_3
1	1	0	0	0	0	1	w_4

- This results in the following four conditions to implement XOR: $w_1 < w_0, w_2 \geq w_0, w_3 \geq w_0, w_4 < w_0$
- Unlike before, there are no contradictions now and the system of inequalities can be satisfied
- Essentially each w_i is now responsible for one of the 4 possible inputs and can be adjusted to get the desired output for that input



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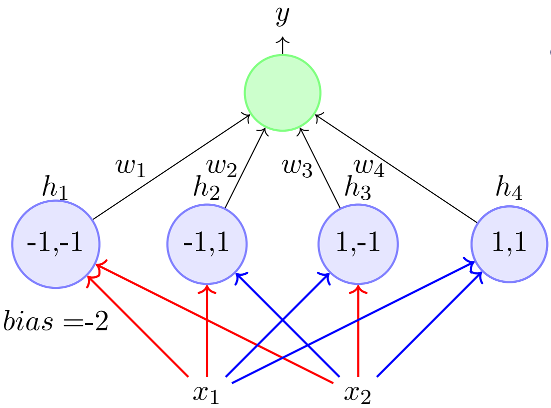
- It should be clear that the same network can be used to represent the remaining 15 boolean functions also



red edge indicates w = -1
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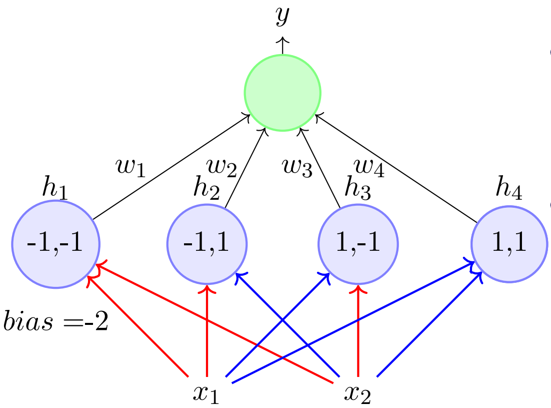
- It should be clear that the same network can be used to represent the remaining 15 boolean functions also
- Each boolean function will result in a different set of non-contradicting inequalities which can be satisfied by appropriately setting w_1, w_2, w_3, w_4



red edge indicates w = -1
blue edge indicates w = +1

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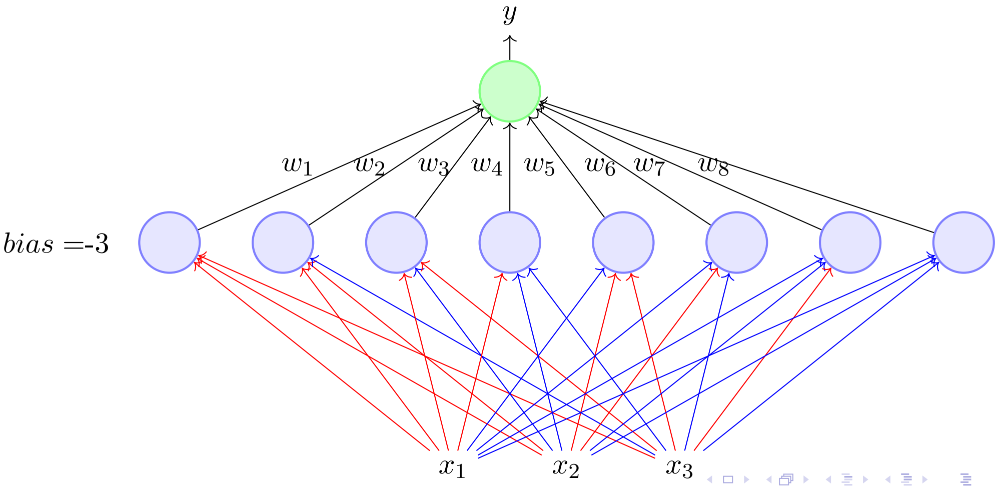
- Each boolean function will result in a different set of non-contradicting inequalities which can be satisfied by appropriately setting w_1, w_2, w_3, w_4
- Try it!

- What if we have more than 3 inputs ?

- Again each of the 8 perceptorns will fire only for one of the 8 inputs
- Each of the 8 weights in the second layer is responsible for one of the 8 inputs and can be adjusted to produce the desired output for that input



- What if we have n inputs ?

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Catch: As n increases the number of perceptrons in the hidden layers obviously increases exponentially

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- More appropriate terminology would be“Multilayered Network of Perceptrons” but MLP is the more commonly used name
- The theorem that we just saw gives us the representation power of a MLP with a single hidden layer
- Specifically, it tells us that a MLP with a single hidden layer can represent **any** boolean function

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- Enough about boolean functions!
- What about arbitrary functions of the form $y = f(x)$ where $x \in \mathbb{R}^n$ (instead of $\{0,1\}^n$) and $y \in \mathbb{R}$ (instead of $\{0,1\}$) ?
- Before answering the above question we will have to first graduate from *perceptrons* to *sigmoidal neurons* ...

Pre-requisites for Lecture 3 and Lecture 4

- Please do Assignment 1 sincerely (you will be able to understand the next two lectures better if you do so!)
- Some more reading material (if needed) will be posted on moodle