

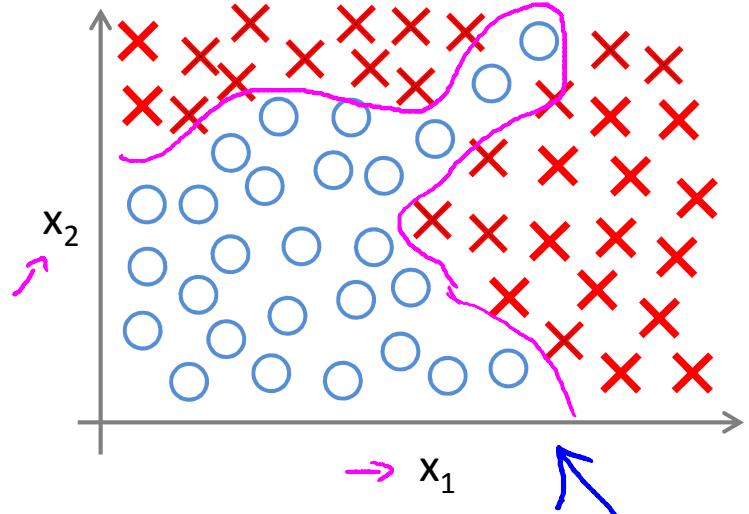
Machine Learning

# Neural Networks: Representation

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## Non-linear hypotheses

# Non-linear Classification



$\rightarrow \underline{x_1}$  = size  
 $\underline{x_2}$  = # bedrooms  
 $\underline{x_3}$  = # floors  
 $x_4$  = age  
 $\dots$   
 $x_{100}$  -

$\left. \right\} h=100$

$$\begin{aligned}
 & \downarrow \\
 & g(\theta_0 + \theta_1 x_1 + \theta_2 x_2 \\
 & + \theta_3 x_1 x_2 + \theta_4 x_1^2 x_2 \\
 & + \theta_5 x_1^3 x_2 + \underline{\theta_6 x_1 x_2^2} + \dots)
 \end{aligned}$$

$$\begin{aligned}
 & \rightarrow \underline{x_1^2}, \underline{x_1 x_2}, \underline{x_1 x_3}, \underline{x_1 x_4} \dots \underline{x_1 x_{100}} \\
 & \underline{x_2^2}, \underline{x_2 x_3} \dots
 \end{aligned}$$

$\approx 5000$  feature

$$\begin{aligned}
 & \mathcal{O}(n^2) \\
 & \frac{n^2}{2} \\
 & \cancel{10}
 \end{aligned}$$

$$\rightarrow \underline{x_1^2}, \underline{x_2^2}, \underline{x_3^2}, \dots, \underline{x_{100}^2}$$

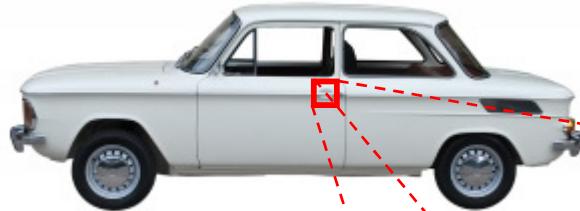
$$\rightarrow \underline{x_1 x_2 x_3}, \underline{x_1^2 x_2}, \underline{x_{10} x_{11} x_{12}}, \dots$$

$\mathcal{O}(n^3)$

170,000

# What is this?

You see this:



But the camera sees this:

194	210	201	212	199	213	215	195	178	158	182	209
180	189	190	221	209	205	191	167	147	115	129	163
114	126	140	188	176	165	152	140	170	106	78	88
87	103	115	154	143	142	149	153	173	101	57	57
102	112	106	131	122	138	152	147	128	84	58	66
94	95	79	104	105	124	129	113	107	87	69	67
68	71	69	98	89	92	98	95	89	88	76	67
41	56	68	99	63	45	60	82	58	76	75	65
20	43	69	75	56	41	51	73	55	70	63	44
50	50	57	69	75	75	73	74	53	68	59	37
72	59	53	66	84	92	84	74	57	72	63	42
67	61	58	65	75	78	76	73	59	75	69	50



# Computer Vision: Car detection



Cars

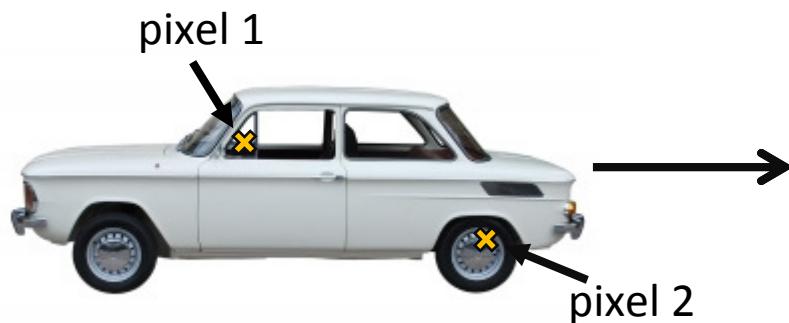


Not a car

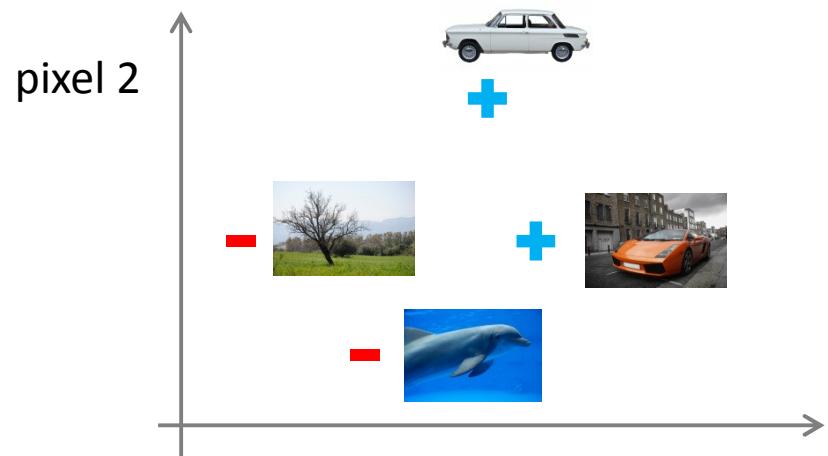
Testing:



What is this?

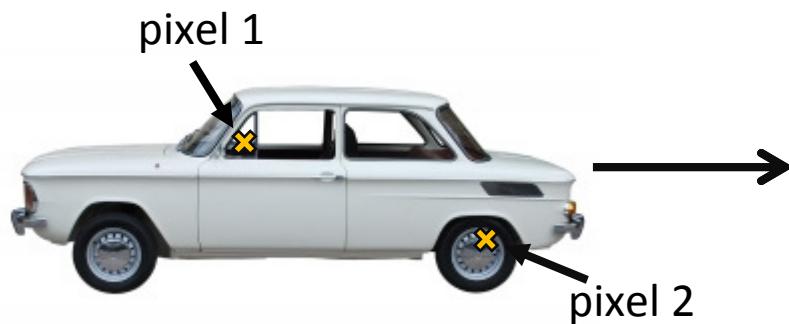


Learning  
Algorithm

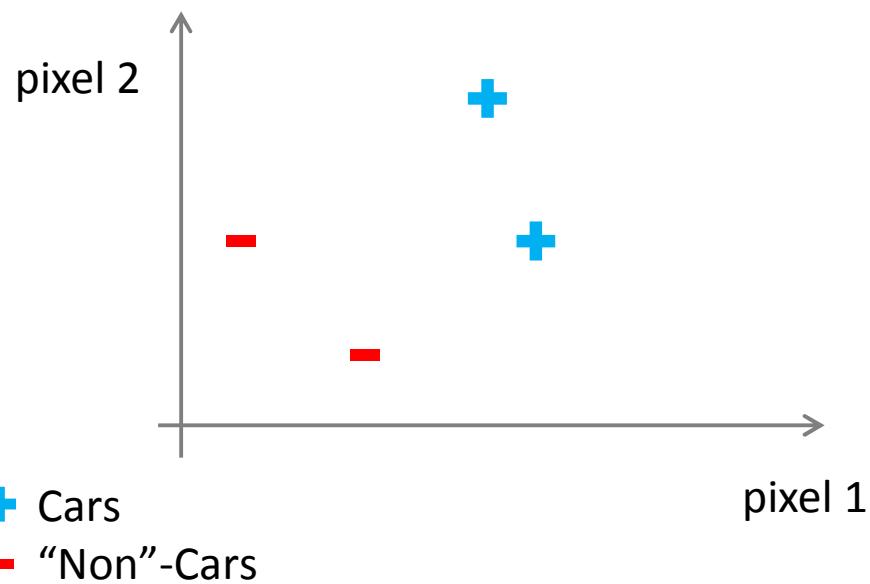


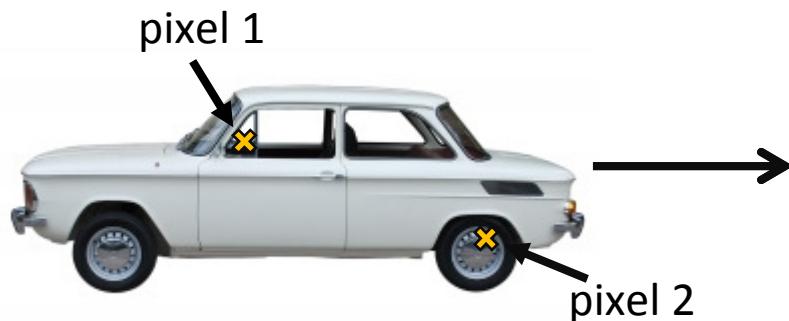
+ Cars

- "Non"-Cars

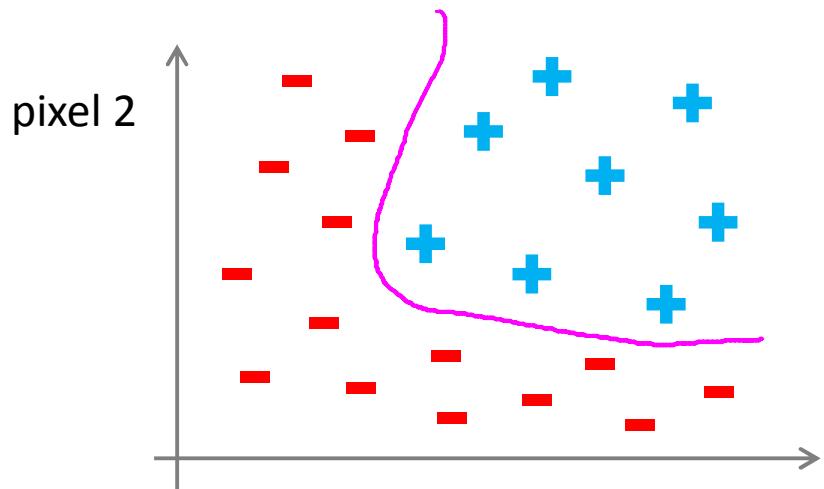


Learning  
Algorithm





Learning  
Algorithm



$50 \times 50$  pixel images  $\rightarrow$  2500 pixels  
 $n = 2500$  (7500 if RGB)

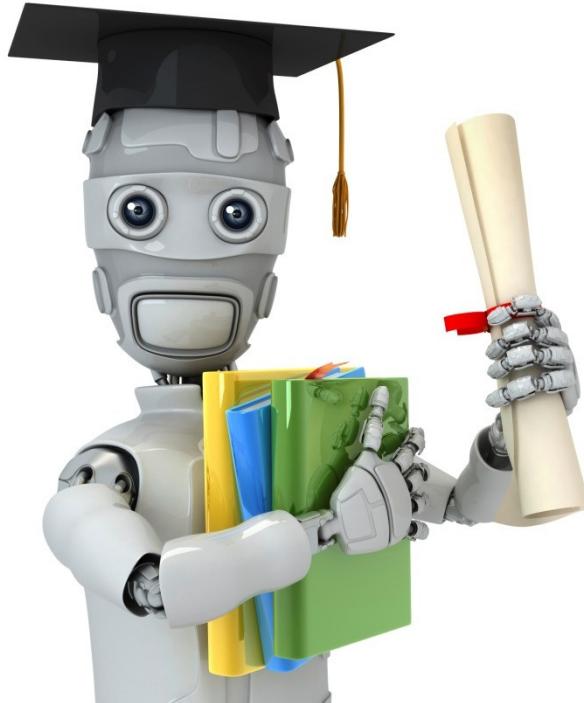
$$x = \begin{bmatrix} \text{pixel 1 intensity} \\ \text{pixel 2 intensity} \\ \vdots \\ \text{pixel 2500 intensity} \end{bmatrix}$$

$0 - 255$

$\text{Cars}$   
 $\text{---} \quad \text{"Non"-Cars}$

Quadratic features ( $x_i \times x_j$ ):  $\approx 3$  million features





Machine Learning

# Neural Networks: Representation

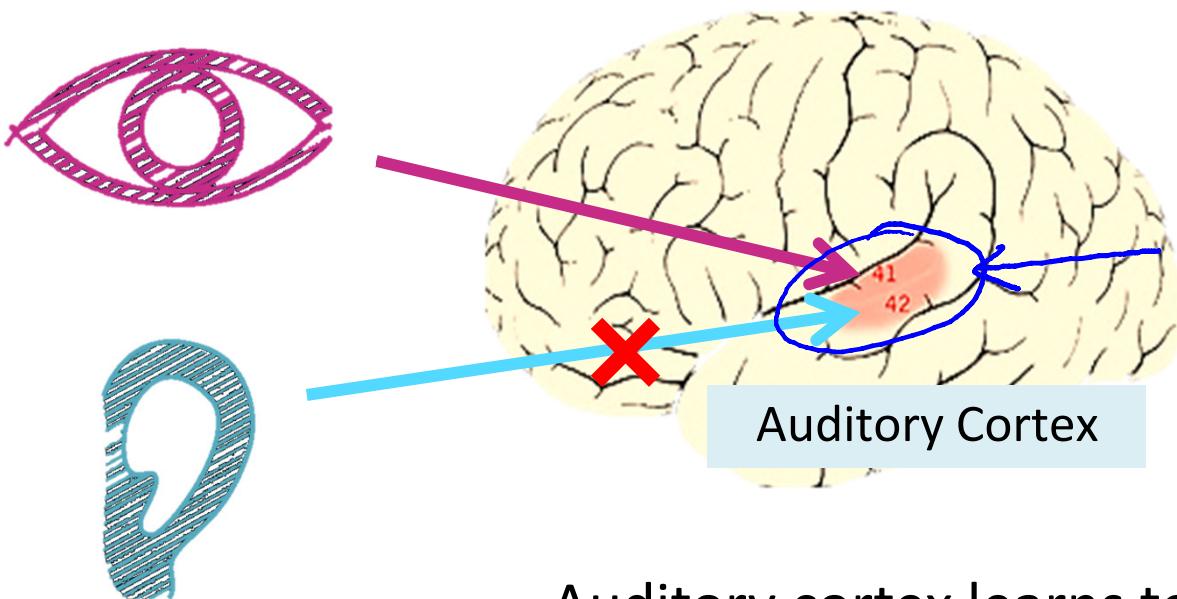
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## Neurons and the brain

# Neural Networks

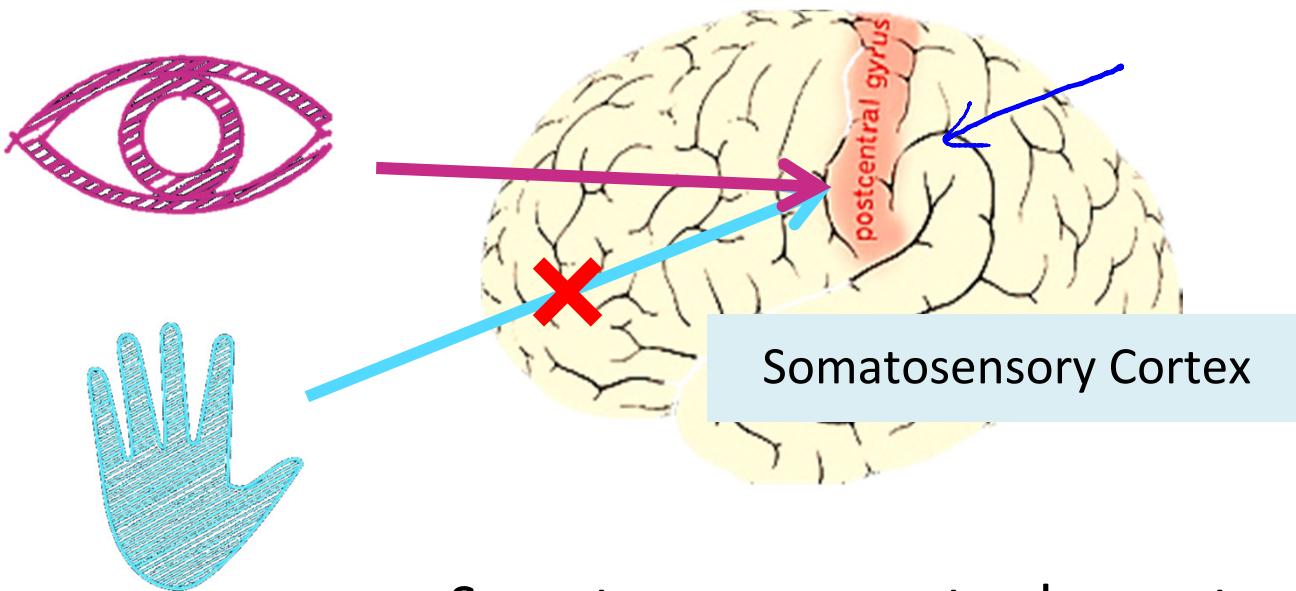
- Origins: Algorithms that try to mimic the brain.
- Was very widely used in 80s and early 90s; popularity diminished in late 90s.
- Recent resurgence: State-of-the-art technique for many applications

# The “one learning algorithm” hypothesis



Auditory cortex learns to see

# The “one learning algorithm” hypothesis



Somatosensory cortex learns to see

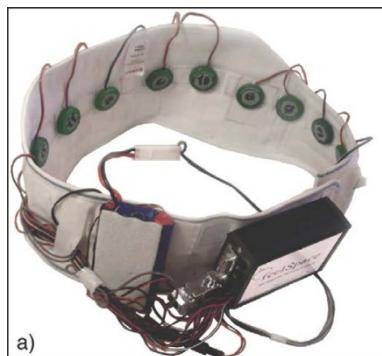
# Sensor representations in the brain



Seeing with your tongue



Human echolocation (sonar)

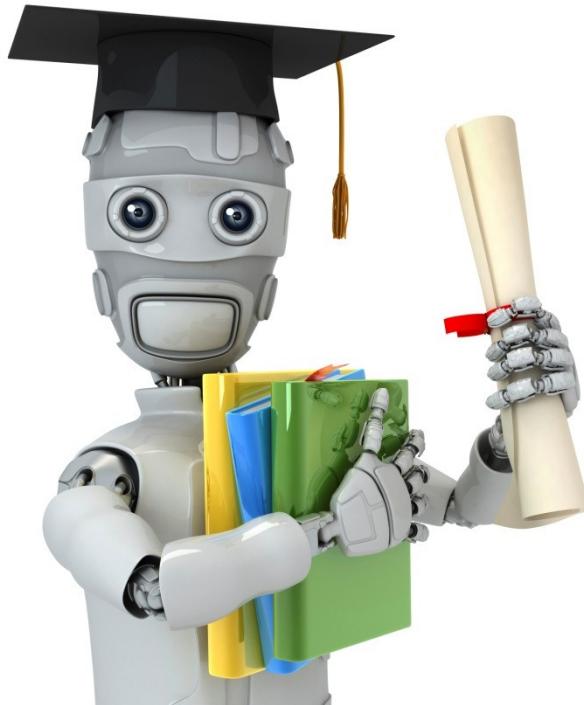


Haptic belt: Direction sense



Implanting a 3<sup>rd</sup> eye





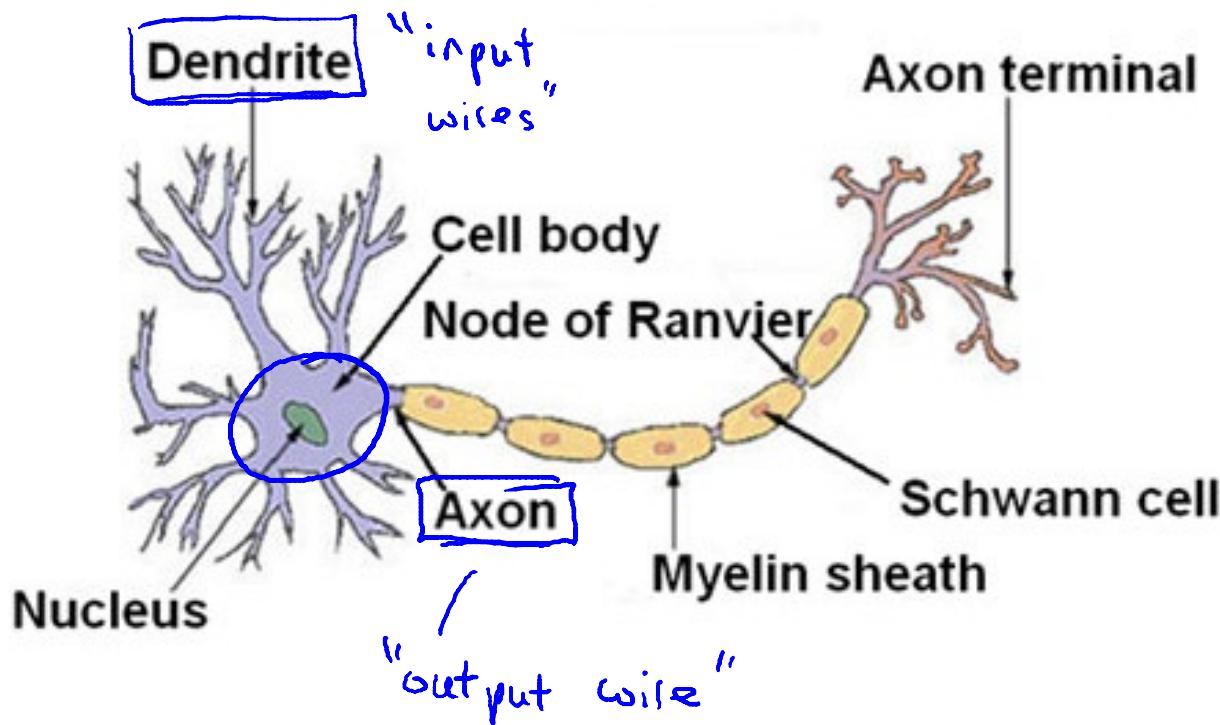
Machine Learning

# Neural Networks: Representation

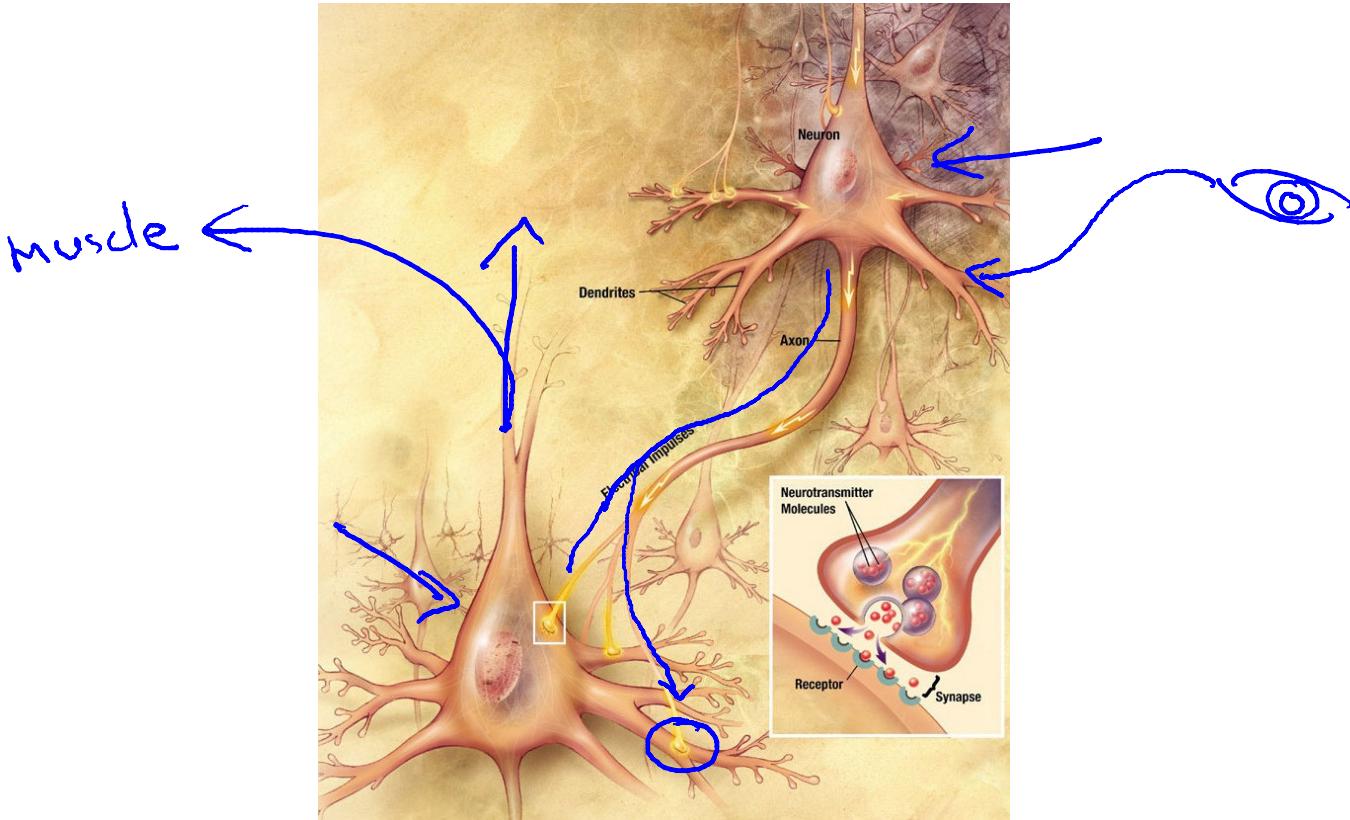
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## Model representation I

# Neuron in the brain



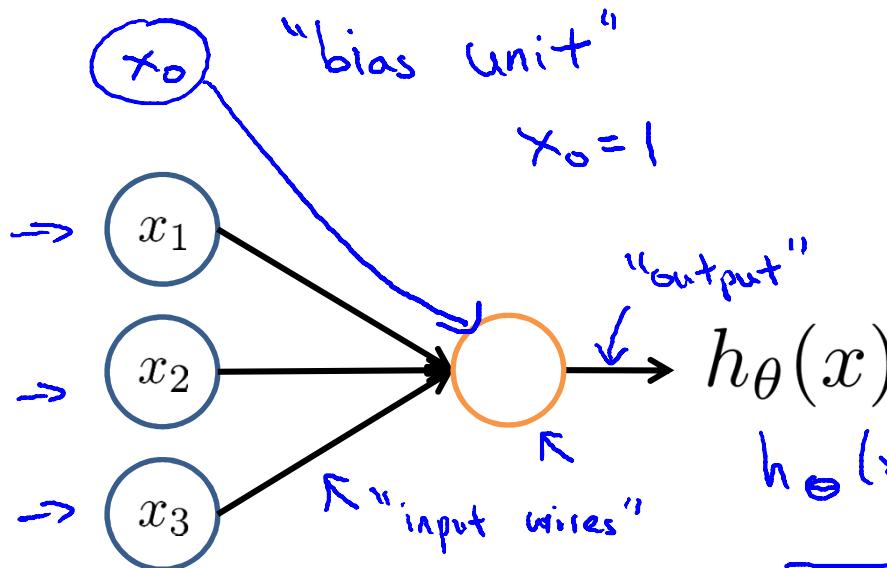
# Neurons in the brain



[Credit: US National Institutes of Health, National Institute on Aging]

Andrew Ng

## Neuron model: Logistic unit



$$x = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$\theta = \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

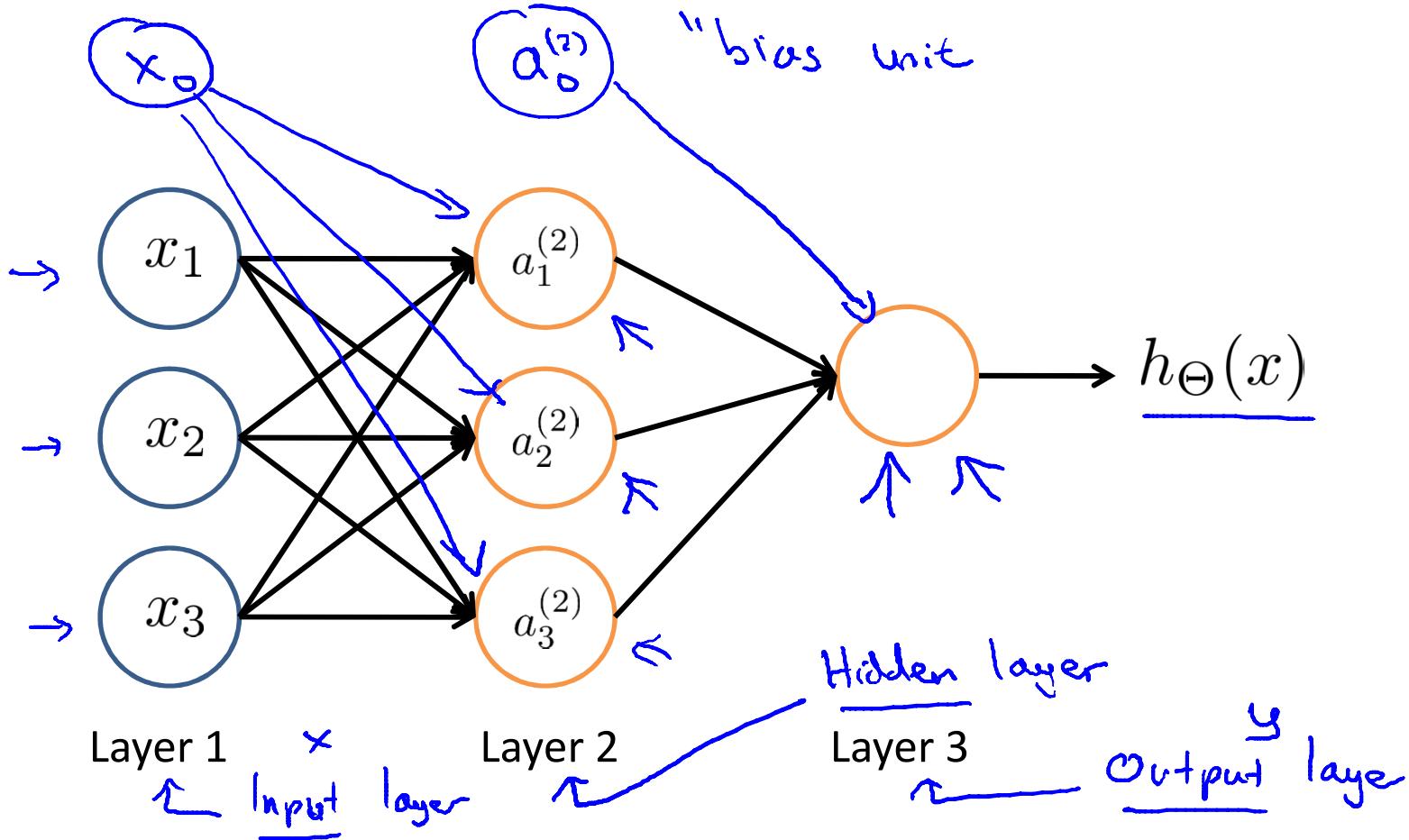
↑  
"weights" ←  
(parameters ←)

$$h_{\theta}(x) = \frac{1}{1+e^{-\theta^T x}}$$

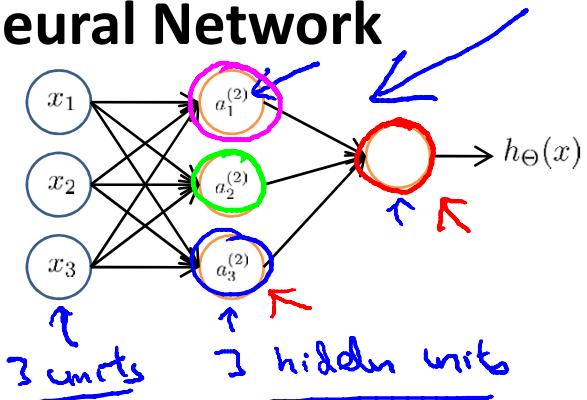
Sigmoid (logistic) activation function.

$$g(z) = \frac{1}{1+e^{-z}}$$

# Neural Network



# Neural Network



→  $a_i^{(j)}$  = “activation” of unit  $i$  in layer  $j$

→  $\Theta^{(j)}$  = matrix of weights controlling function mapping from layer  $j$  to layer  $j + 1$

$$\Theta^{(j)} \in \mathbb{R}^{3 \times 4}$$

$$h_{\Theta}(x)$$

$$\rightarrow a_1^{(2)} = g(\underline{\Theta_{10}^{(1)} x_0 + \Theta_{11}^{(1)} x_1 + \Theta_{12}^{(1)} x_2 + \Theta_{13}^{(1)} x_3})$$

$$\rightarrow a_2^{(2)} = g(\underline{\Theta_{20}^{(1)} x_0 + \Theta_{21}^{(1)} x_1 + \Theta_{22}^{(1)} x_2 + \Theta_{23}^{(1)} x_3})$$

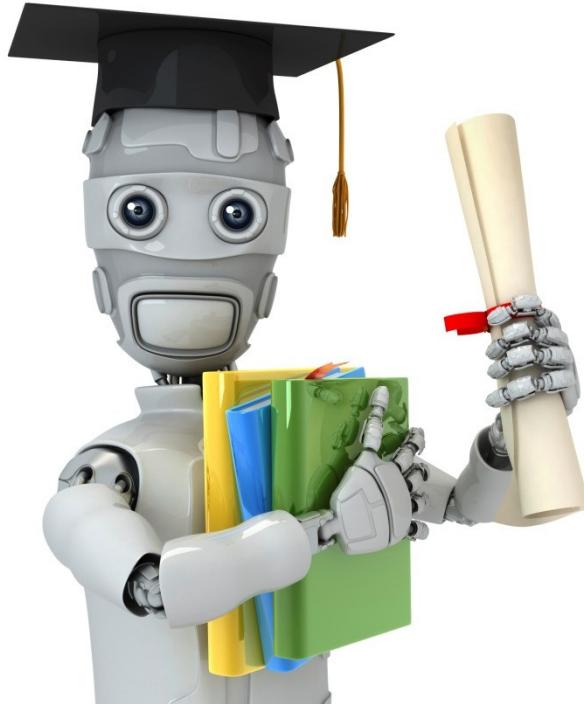
$$\rightarrow a_3^{(2)} = g(\underline{\Theta_{30}^{(1)} x_0 + \Theta_{31}^{(1)} x_1 + \Theta_{32}^{(1)} x_2 + \Theta_{33}^{(1)} x_3})$$

$$\rightarrow h_{\Theta}(x) = \underline{a_1^{(3)}} = g(\underline{\Theta_{10}^{(2)} a_0^{(2)} + \Theta_{11}^{(2)} a_1^{(2)} + \Theta_{12}^{(2)} a_2^{(2)} + \Theta_{13}^{(2)} a_3^{(2)}})$$

- If network has  $s_j$  units in layer  $j$ ,  $s_{j+1}$  units in layer  $j + 1$ , then  $\underline{\Theta^{(j)}}$  will be of dimension  $\underline{s_{j+1} \times (s_j + 1)}$ .

$$s_{j+1} \times (s_j + 1)$$

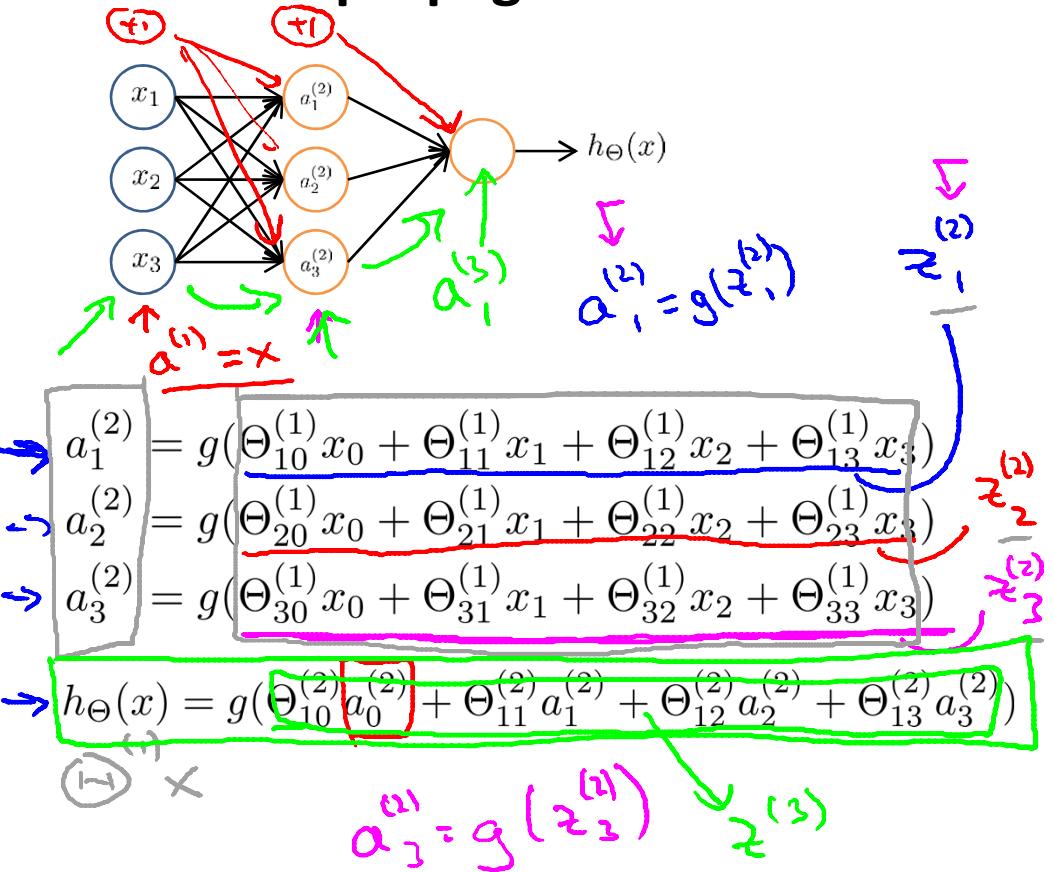




Machine Learning

# Neural Networks: Representation --- Model representation II

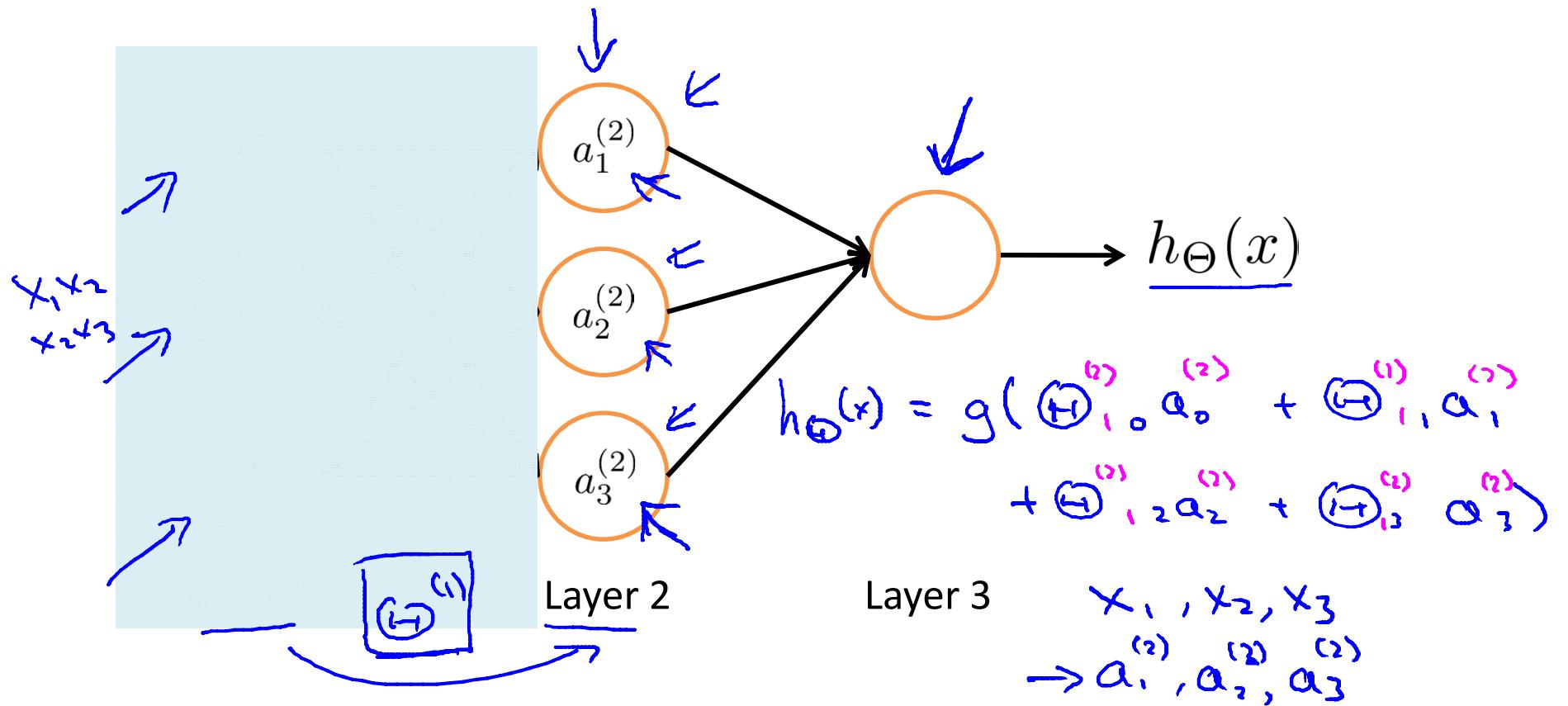
## Forward propagation: Vectorized implementation



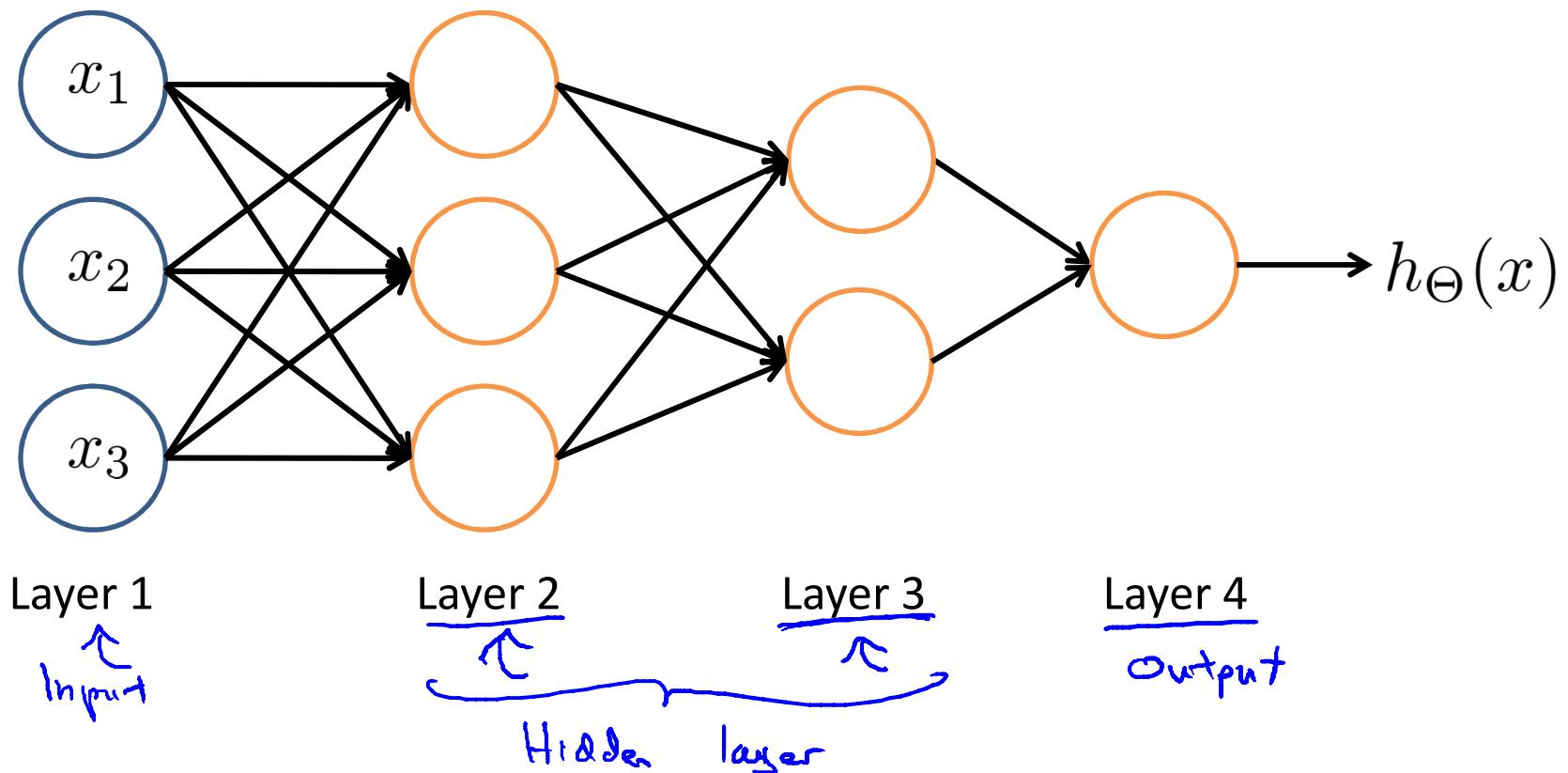
$$x = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad z^{(2)} = \begin{bmatrix} z_1^{(2)} \\ z_2^{(2)} \\ z_3^{(2)} \end{bmatrix}$$

$$\begin{aligned} z^{(2)} &= \Theta^{(1)} \cancel{x} \quad \vec{a}^{(2)} \\ a^{(2)} &= g(z^{(2)}) \quad \vec{z}^{(2)} \in \mathbb{R}^3 \\ \text{Add } a_0^{(2)} &= 1. \rightarrow \vec{a}^{(2)} \in \mathbb{R}^4 \\ z^{(3)} &= \Theta^{(2)} a^{(2)} \\ h_{\Theta}(x) &= \underline{a^{(3)}} = g(z^{(3)}) \end{aligned}$$

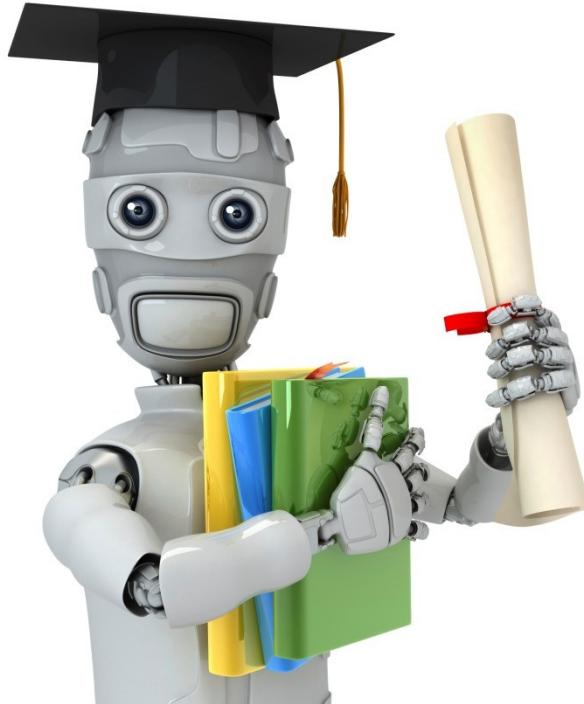
# Neural Network learning its own features



## Other network architectures







Machine Learning

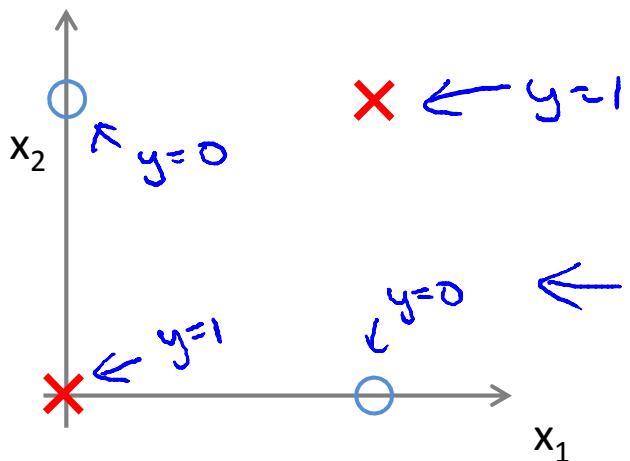
# Neural Networks: Representation

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## Examples and intuitions I

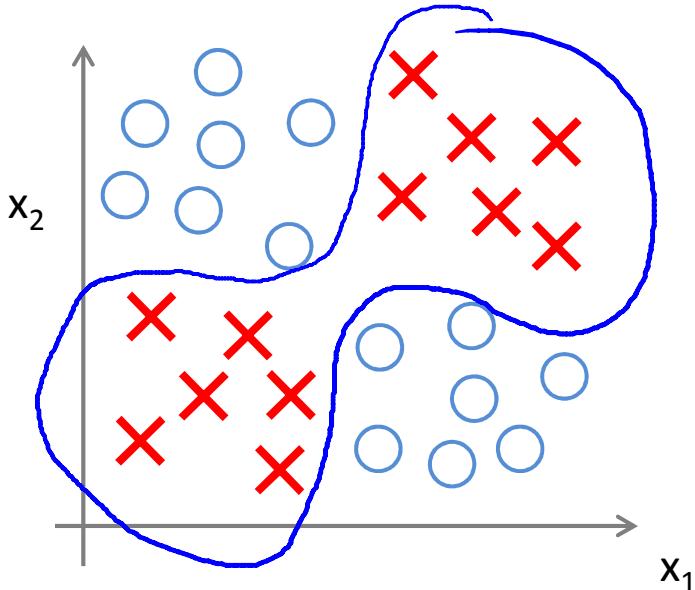
## Non-linear classification example: XOR/XNOR

→  $x_1, x_2$  are binary (0 or 1).



$$y = \underline{x_1 \text{ XOR } x_2}$$

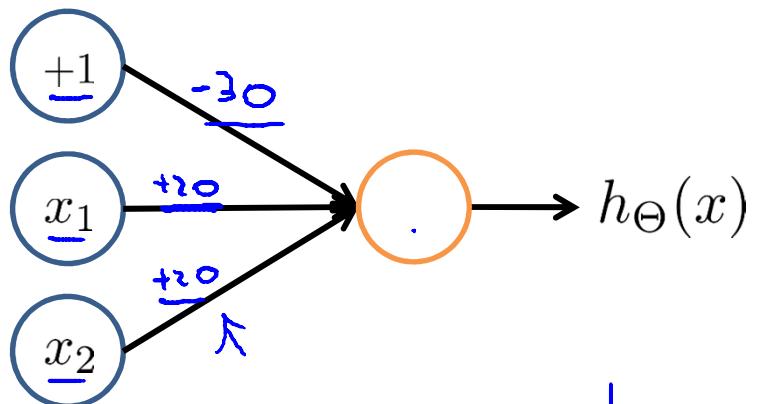
→  $\underline{x_1 \text{ XNOR } x_2}$  ←  
→ NOT (x<sub>1</sub> XOR x<sub>2</sub>)



## Simple example: AND

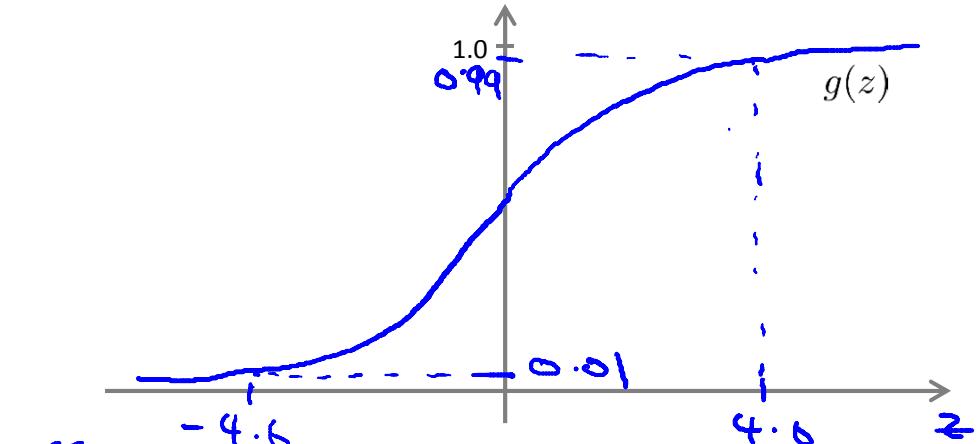
$$\rightarrow x_1, x_2 \in \{0, 1\}$$

$$\rightarrow y = x_1 \text{ AND } x_2$$



$$\rightarrow h_{\Theta}(x) = g\left(\frac{-30}{\pi} + \frac{20}{\pi}x_1 + \frac{20}{\pi}x_2\right)$$

$\Theta^{(1)}_{1,0}$        $\Theta^{(1)}_{1,1}$        $\Theta^{(1)}_{1,2}$

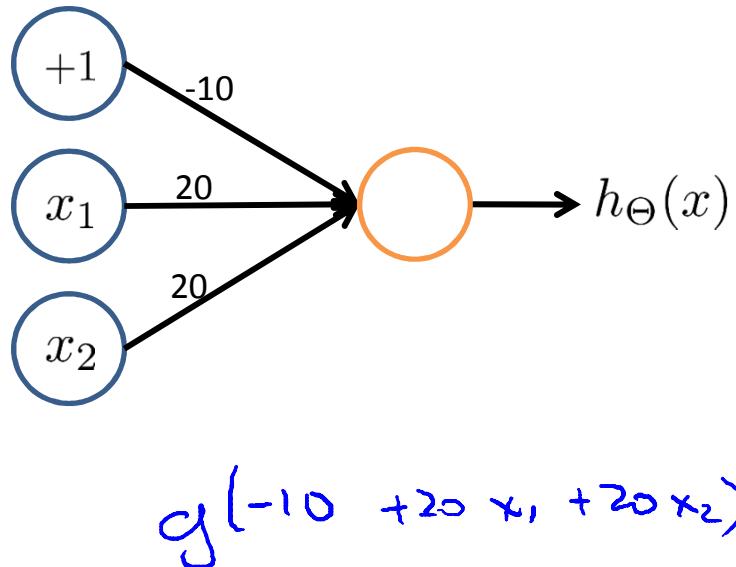


$\leftarrow$

$x_1$	$x_2$	$h_{\Theta}(x)$
0	0	$g(-30) \approx 0$
0	1	$g(-10) \approx 0$
1	0	$g(-10) \approx 0$
1	1	$g(10) \approx 1$

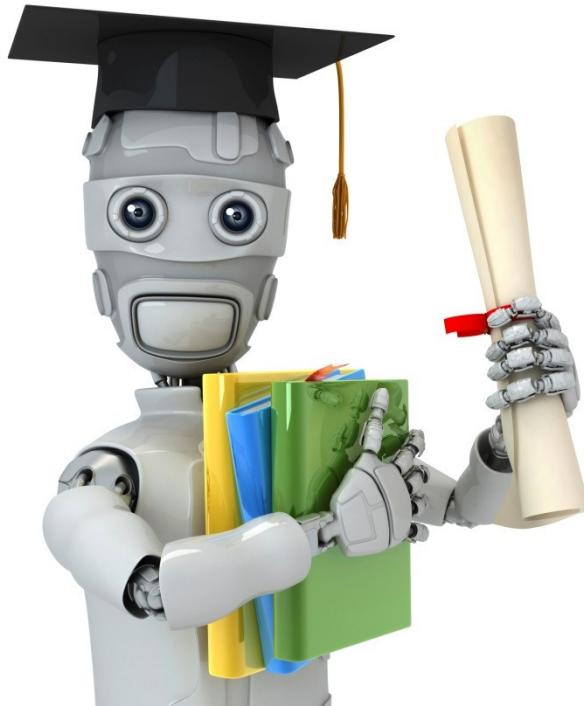
$h_{\Theta}(x) \approx x_1 \text{ AND } x_2$

## Example: OR function



$x_1$	$x_2$	$h_{\Theta}(x)$
0	0	$g(-10) \approx 0$
0	1	$g(10) \approx 1$
1	0	$\approx 1$
1	1	$\approx 1$





Machine Learning

# Neural Networks: Representation

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## Examples and intuitions II

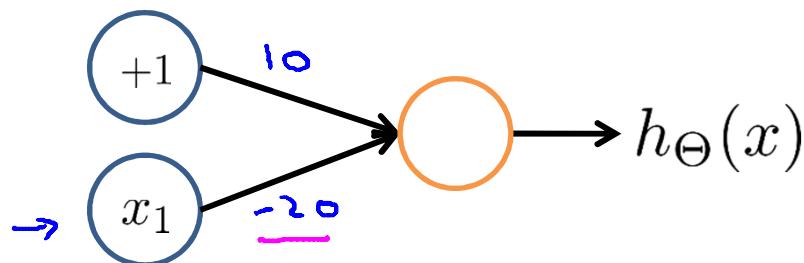
$\rightarrow x_1 \text{ AND } x_2$

$\rightarrow x_1 \text{ OR } x_2$

$\{0, 1\}$ .

## Negation:

NOT  $x_1$



$x_1$	$h_{\Theta}(x)$
0	$g(10) \approx 1$
1	$g(-20) \approx 0$

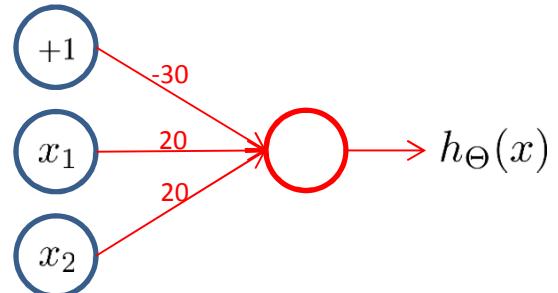
$$h_{\Theta}(x) = g(10 - 20x_1)$$

$\rightarrow (\text{NOT } x_1) \text{ AND } (\text{NOT } x_2)$

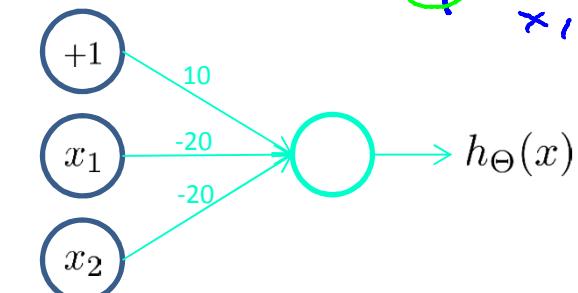
$\begin{cases} = 1 & \text{if and only if} \\ = 0 & \end{cases}$

$\rightarrow x_1 = x_2 = 0$

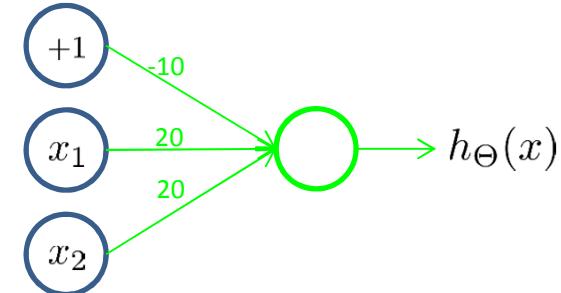
## Putting it together: $x_1$ XNOR $x_2$



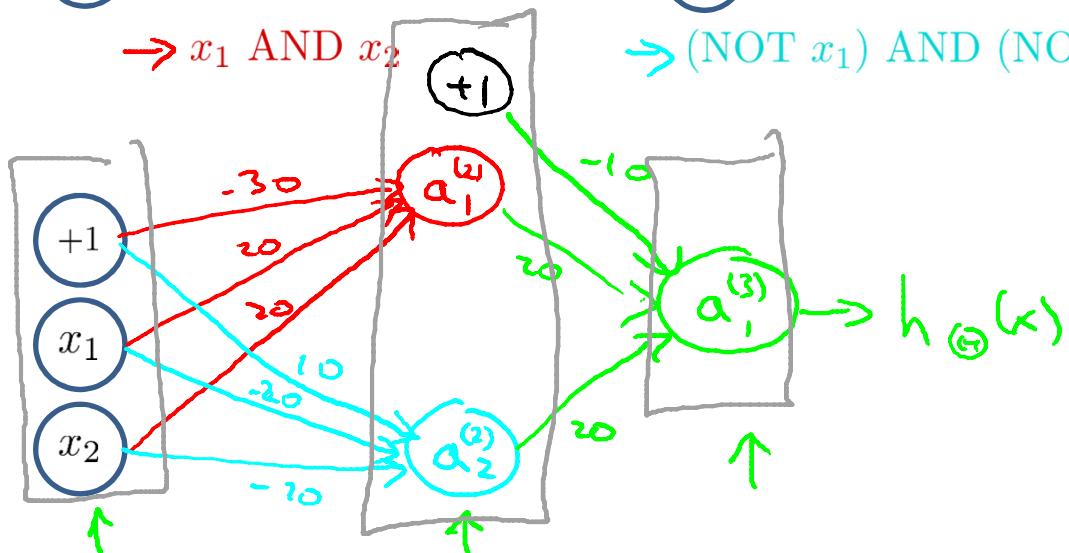
$\rightarrow x_1 \text{ AND } x_2$



$\rightarrow (\text{NOT } x_1) \text{ AND } (\text{NOT } x_2)$

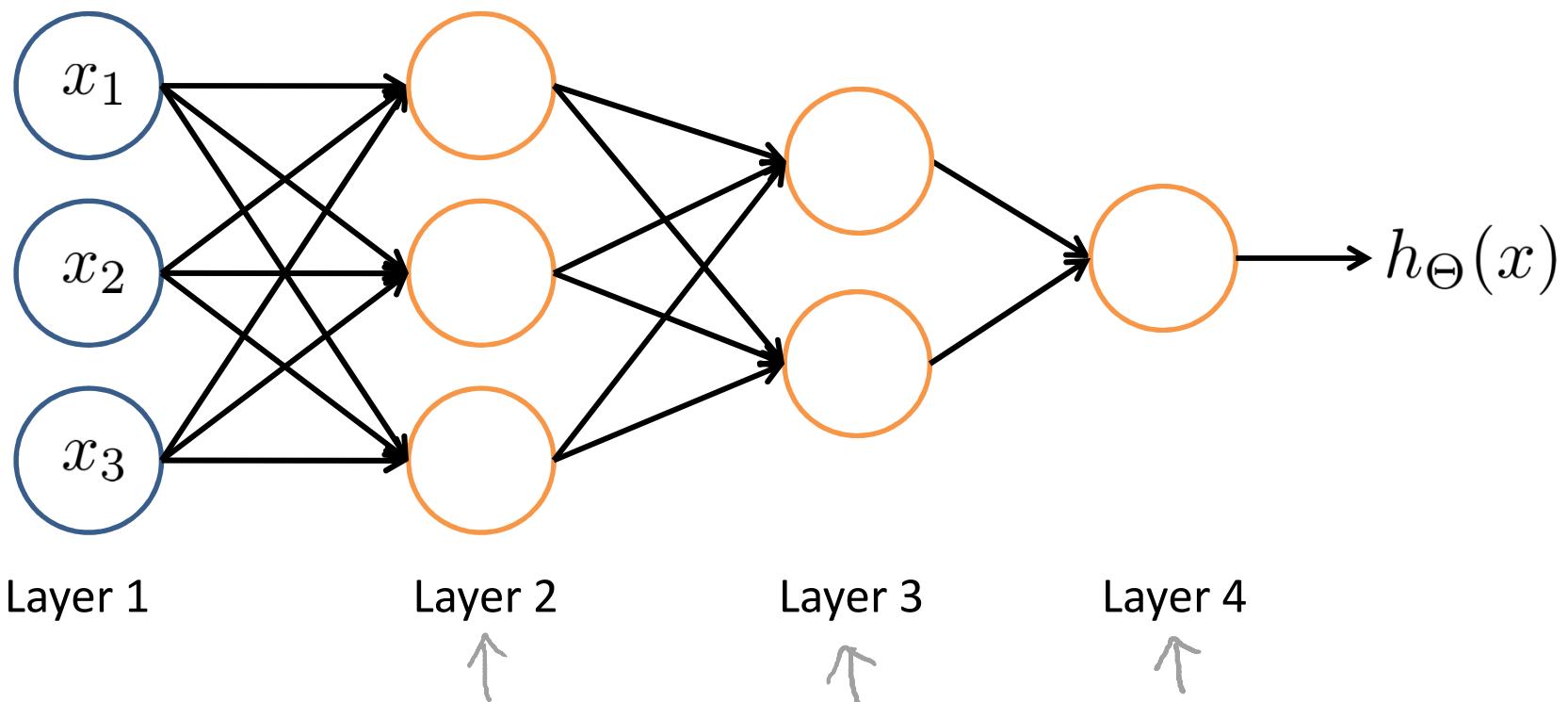


$\rightarrow x_1 \text{ OR } x_2$

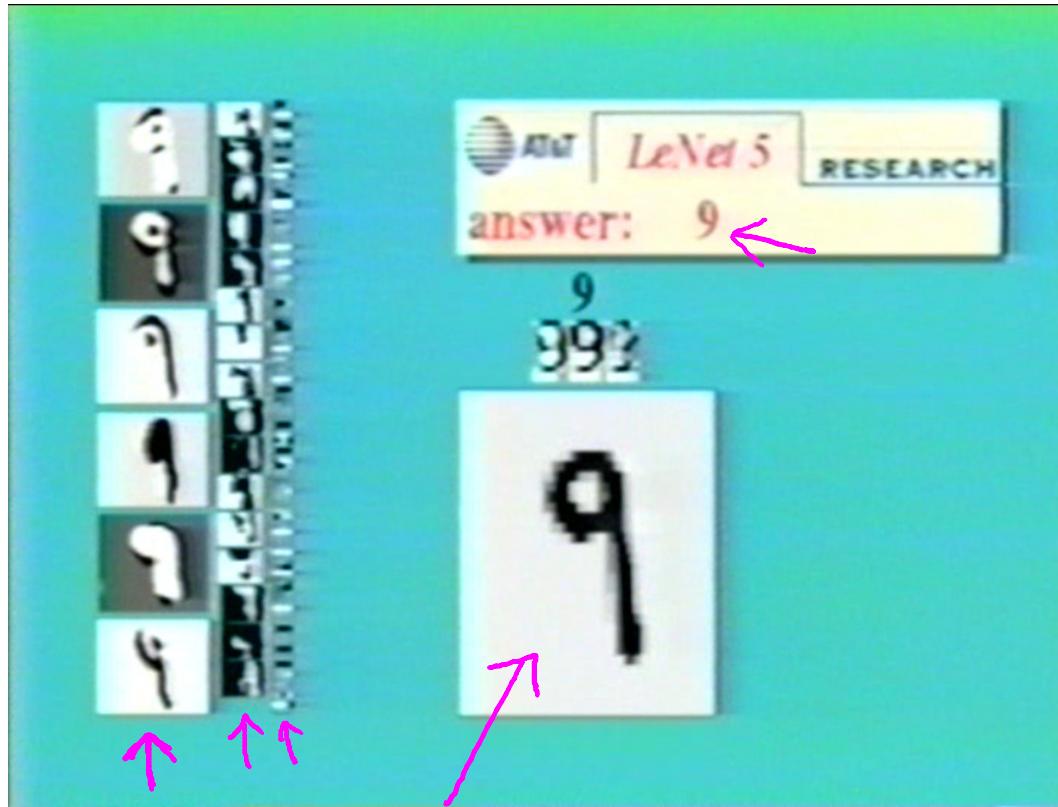


$x_1$	$x_2$	$a_1^{(2)}$	$a_2^{(2)}$	$h_{\Theta}(x)$
0	0	0	1	1 ↘
0	1	0	0	0 ↘
1	0	0	0	0 ↘
1	1	1	0	1 ↘

# Neural Network intuition



# Handwritten digit classification



[Courtesy of Yann LeCun]



Andrew Ng

# Handwritten digit classification







Machine Learning

# Neural Networks: Representation

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## Multi-class classification

# Multiple output units: One-vs-all.



Pedestrian



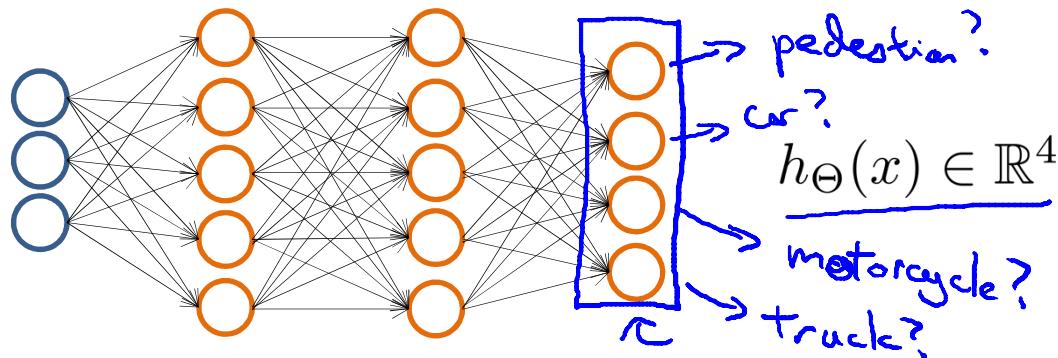
Car



Motorcycle



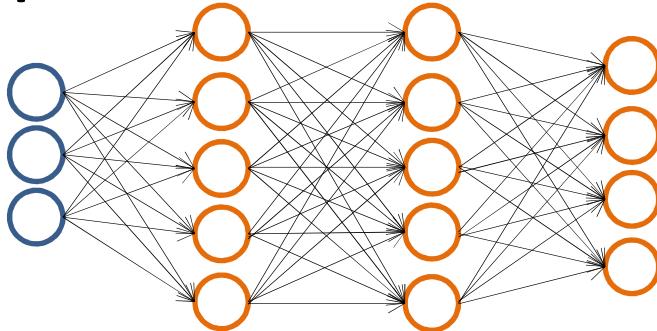
Truck



Want  $h_{\Theta}(x) \approx \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$ ,     $h_{\Theta}(x) \approx \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$ ,     $h_{\Theta}(x) \approx \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$ , etc.

when pedestrian                          when car                          when motorcycle

## Multiple output units: One-vs-all.



$$h_{\Theta}(x) \in \mathbb{R}^4$$

Want  $h_{\Theta}(x) \approx \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$ ,  $h_{\Theta}(x) \approx \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$ ,  $h_{\Theta}(x) \approx \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$ , etc.  
when pedestrian      when car      when motorcycle

Training set:  $(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \dots, (x^{(m)}, y^{(m)})$

→  $y^{(i)}$  one of  
pedestrian      car      motorcycle      truck

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

~~Previously~~  
 $y \in \{1, 2, 3, 4\}$   
 $\underline{h_{\Theta}(x^{(i)}) \approx y^{(i)}} \in \mathbb{R}^4$

