

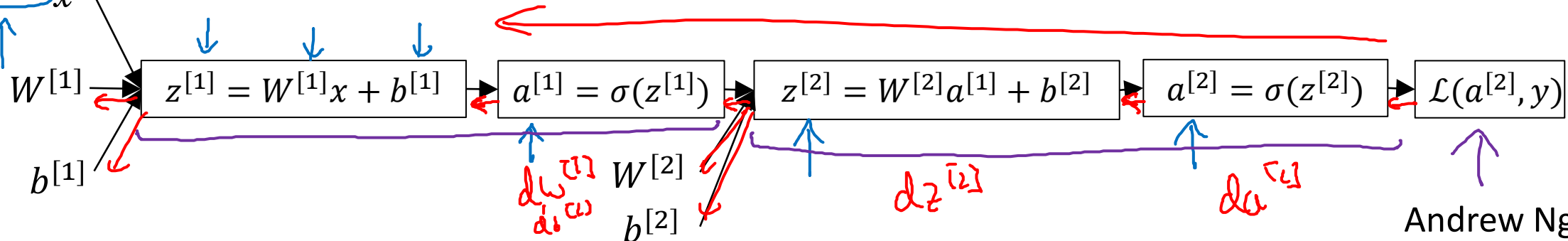
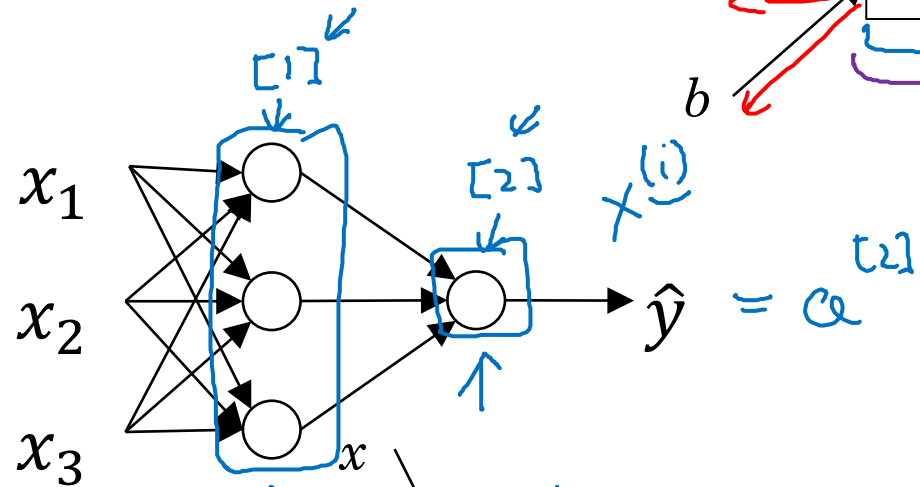
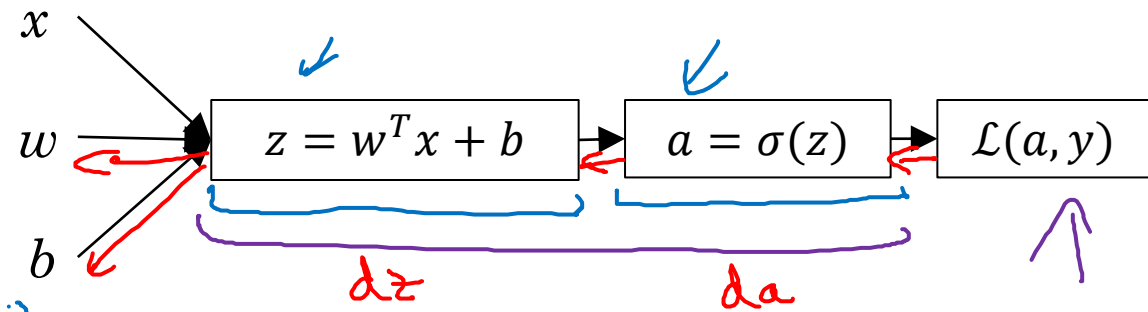
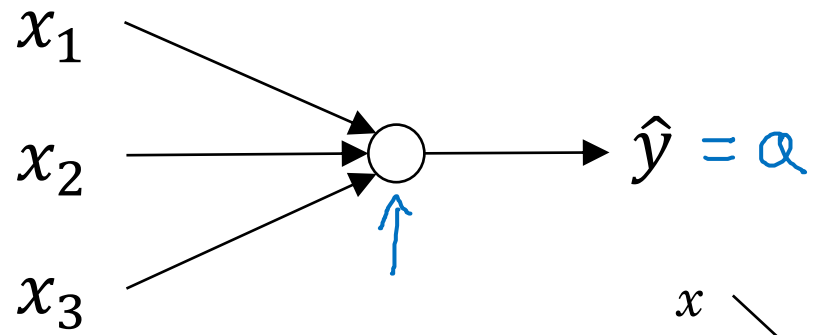


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One hidden layer
Neural Network

Neural Networks Overview

What is a Neural Network?



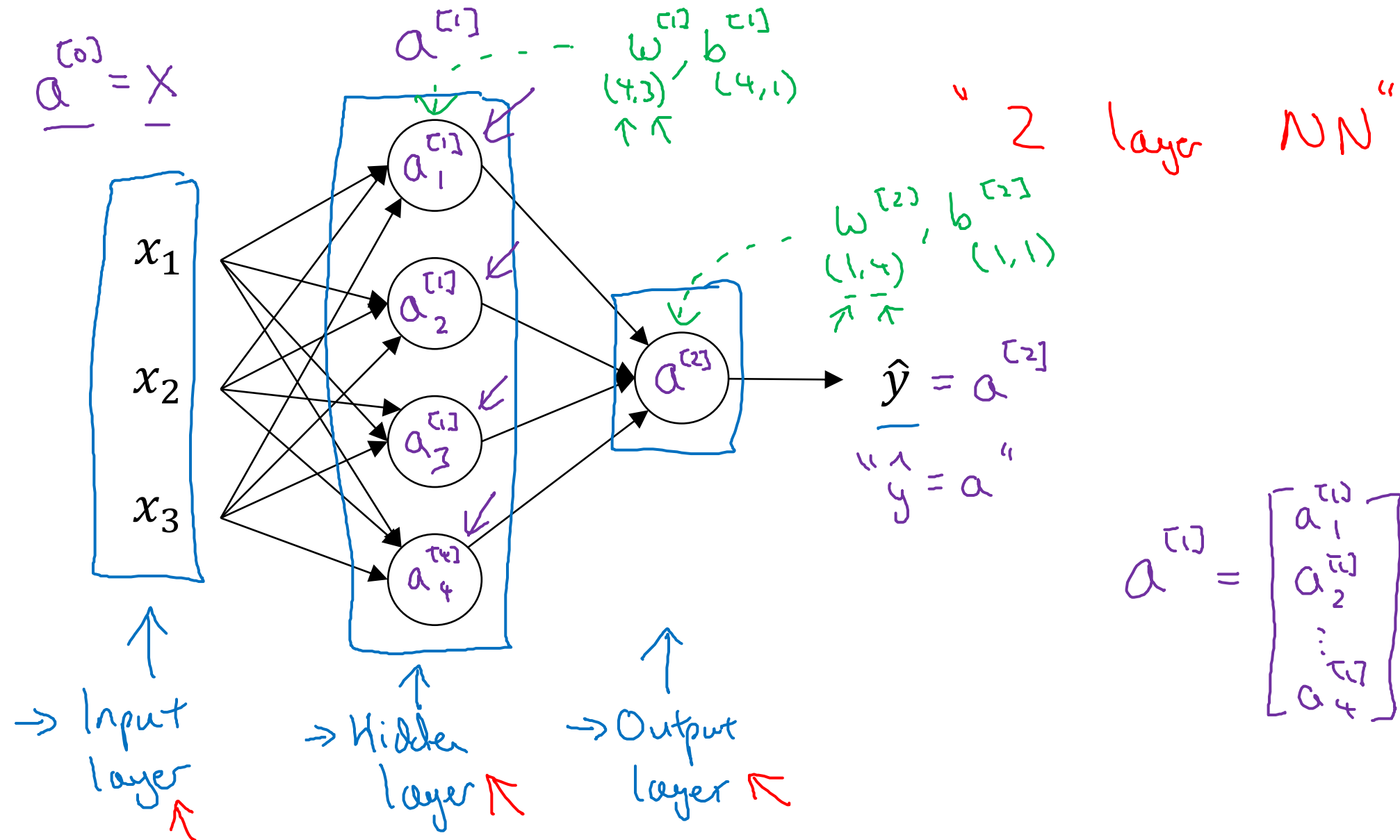


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One hidden layer
Neural Network

Neural Network
Representation

Neural Network Representation



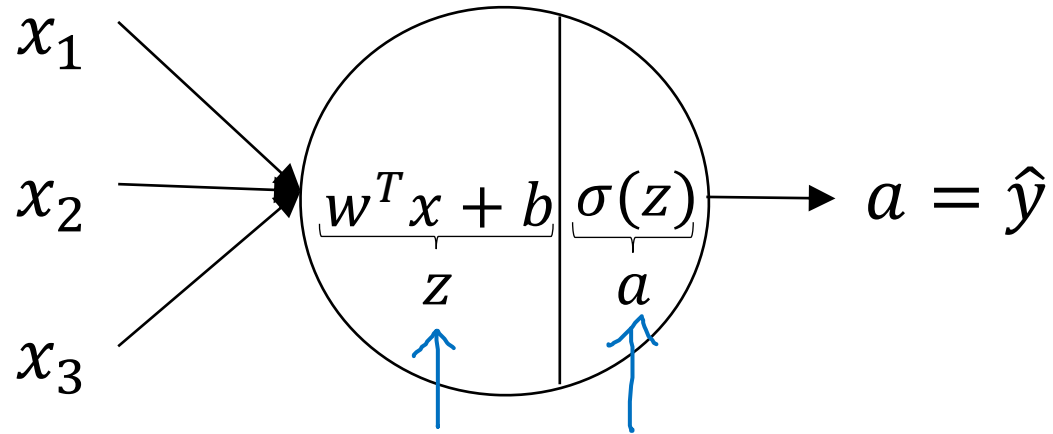


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One hidden layer Neural Network

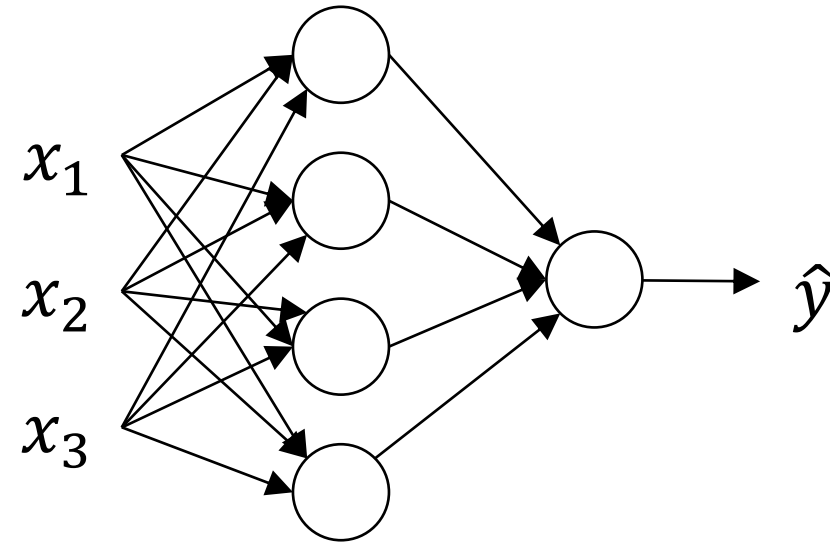
Computing a
Neural Network's
Output

Neural Network Representation

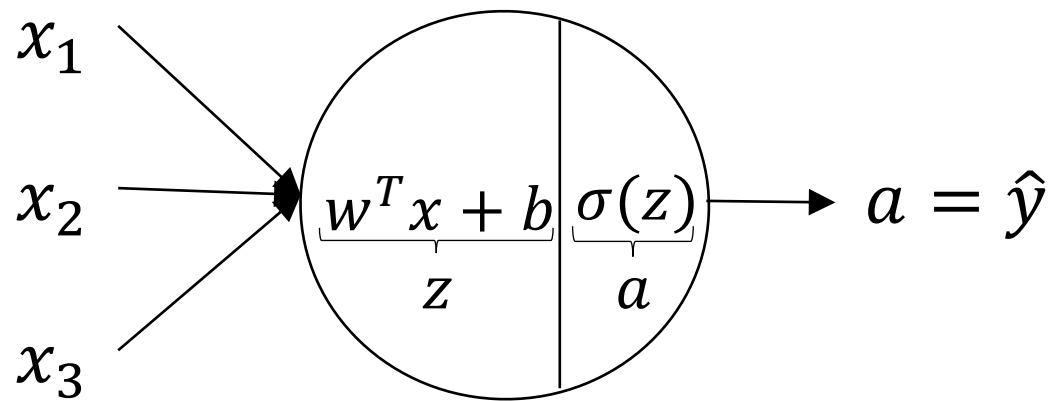


$$z = w^T x + b$$

$$a = \sigma(z)$$

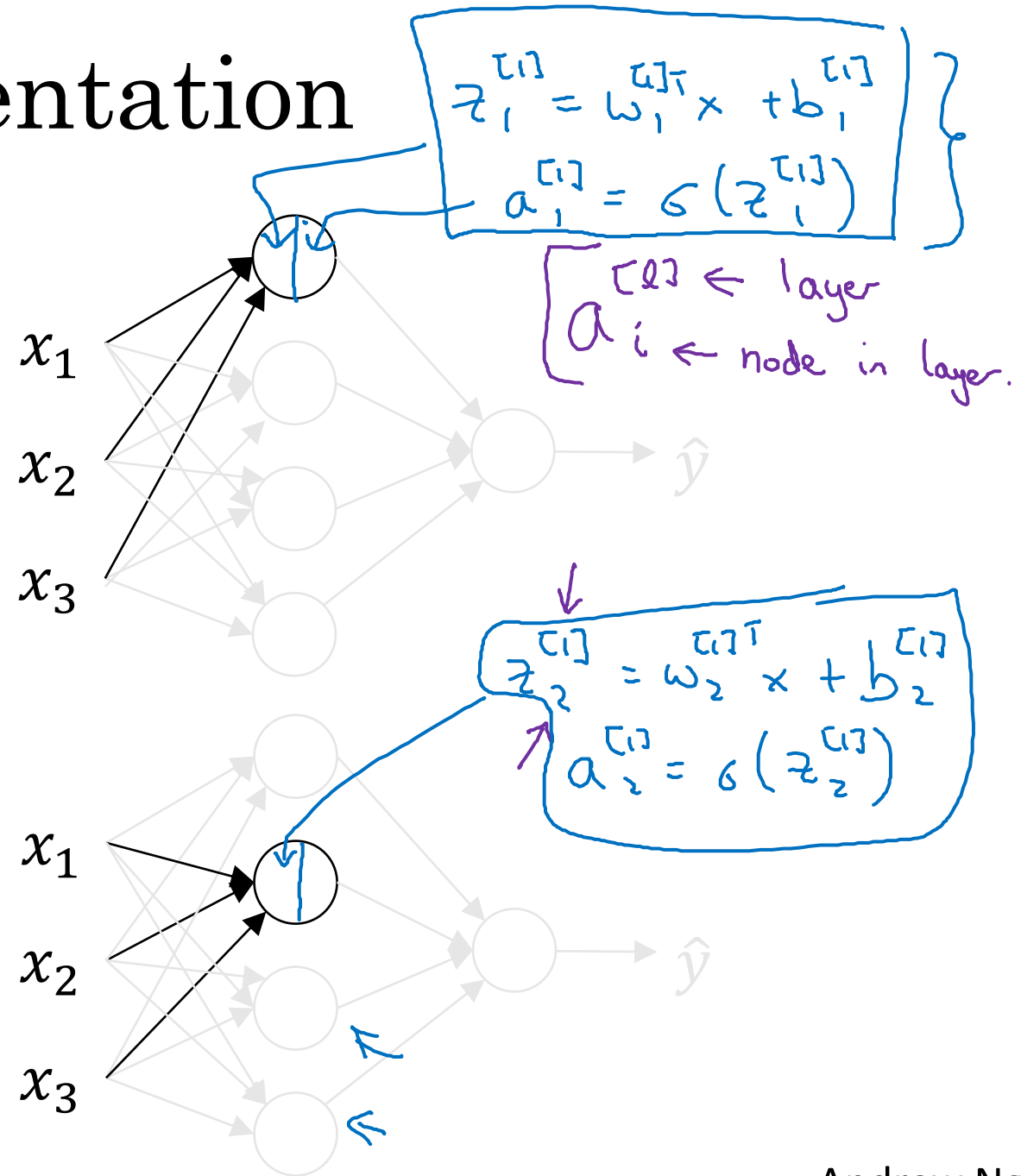


Neural Network Representation

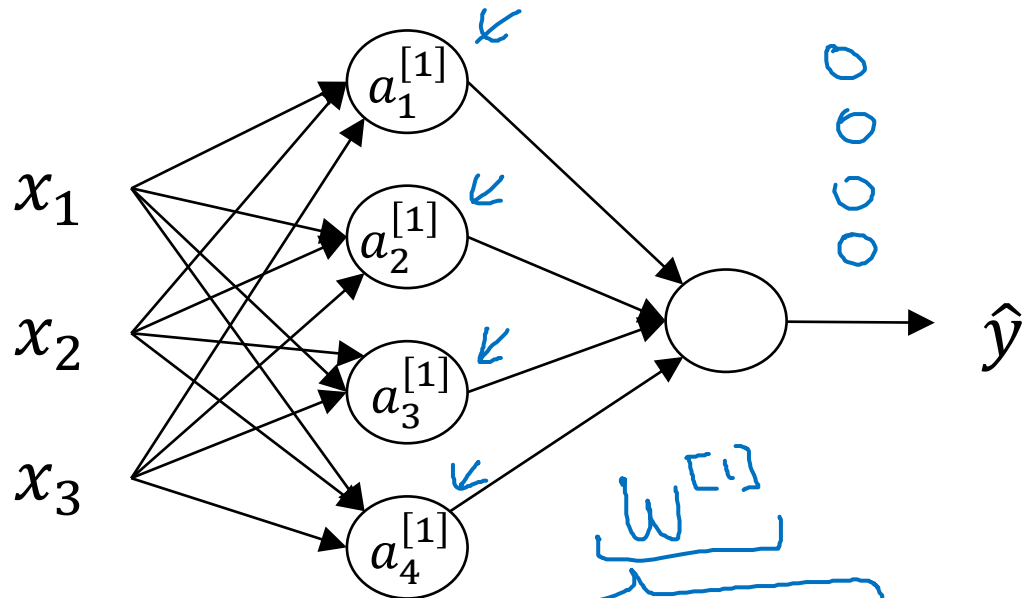


$$z = w^T x + b$$

$$a = \sigma(z)$$



Neural Network Representation



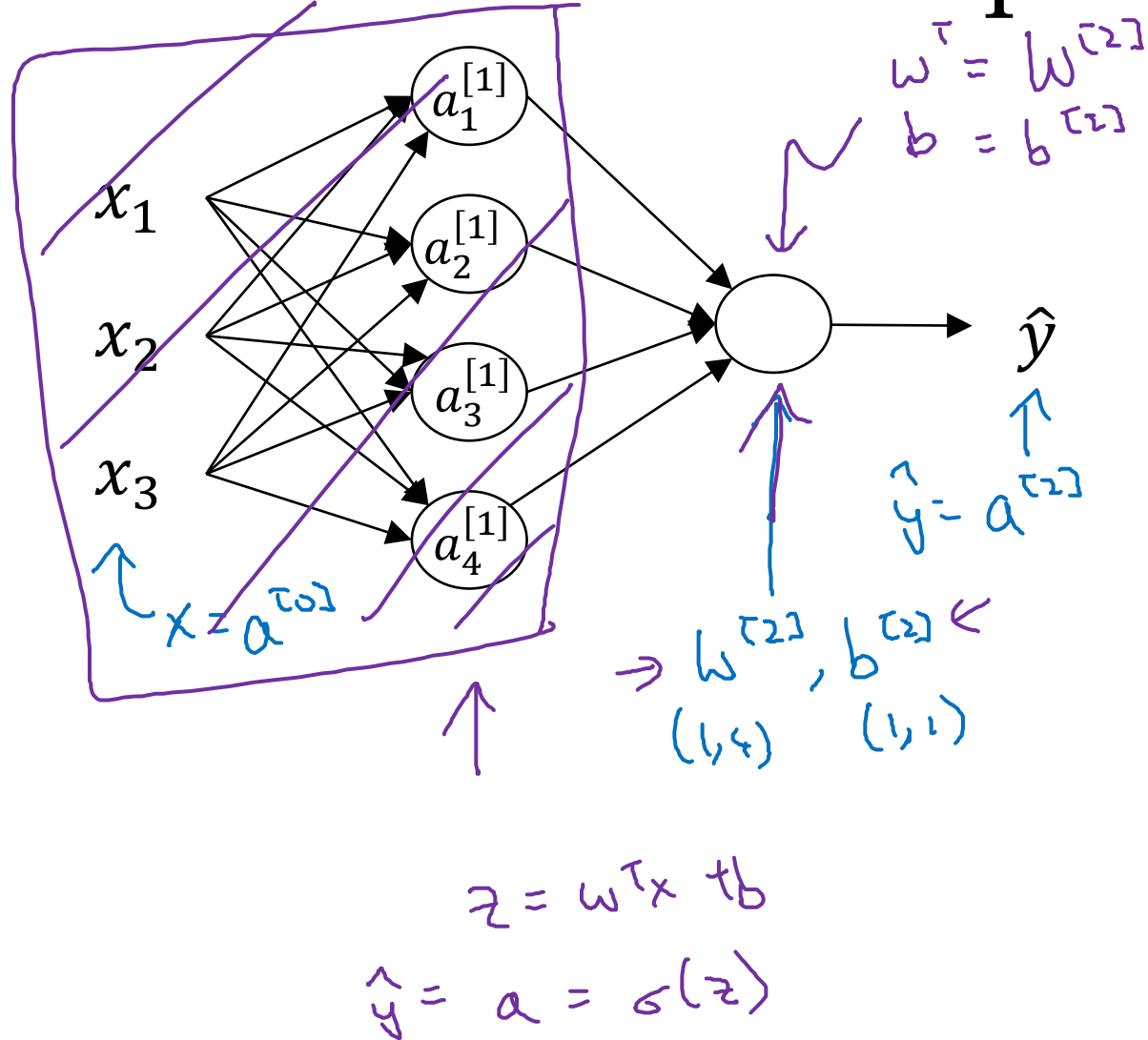
$$\begin{aligned}
 z_1^{[1]} &= w_1^{[1]T} x + b_1^{[1]} & a_1^{[1]} &= \sigma(z_1^{[1]}) \\
 z_2^{[1]} &= w_2^{[1]T} x + b_2^{[1]} & a_2^{[1]} &= \sigma(z_2^{[1]}) \\
 z_3^{[1]} &= w_3^{[1]T} x + b_3^{[1]} & a_3^{[1]} &= \sigma(z_3^{[1]}) \\
 z_4^{[1]} &= w_4^{[1]T} x + b_4^{[1]} & a_4^{[1]} &= \sigma(z_4^{[1]})
 \end{aligned}$$

Handwritten notes: $(w_1^{[1]})^T x$ and $Q^{[1]}$ are written above the first equation. A red box highlights the activation function part $a_i^{[1]} = \sigma(z_i^{[1]})$.

$$\begin{aligned}
 \rightarrow z^{[1]} &= \begin{bmatrix} w_1^{[1]T} \\ w_2^{[1]T} \\ w_3^{[1]T} \\ w_4^{[1]T} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} b_1^{[1]} \\ b_2^{[1]} \\ b_3^{[1]} \\ b_4^{[1]} \end{bmatrix} = \begin{bmatrix} w_1^{[1]T} x + b_1^{[1]} \\ w_2^{[1]T} x + b_2^{[1]} \\ w_3^{[1]T} x + b_3^{[1]} \\ w_4^{[1]T} x + b_4^{[1]} \end{bmatrix} = \begin{bmatrix} z_1^{[1]} \\ z_2^{[1]} \\ z_3^{[1]} \\ z_4^{[1]} \end{bmatrix} \\
 \rightarrow a^{[1]} &= \begin{bmatrix} a_1^{[1]} \\ \vdots \\ a_4^{[1]} \end{bmatrix} = \sigma(z^{[1]})
 \end{aligned}$$

Handwritten notes: $(4, 3)$ is written below the weight matrix. $b^{[1]} (4, 1)$ is written below the bias vector. A red box highlights the activation function part $a^{[1]} = \sigma(z^{[1]})$.

Neural Network Representation learning



Given input x :

$$\begin{aligned} \rightarrow z^{[1]} &= W^{[1]} a^{[0]} + b^{[1]} \\ &\quad (4,1) \quad (4,3) \quad (3,1) \quad (4,1) \\ \rightarrow a^{[1]} &= \sigma(z^{[1]}) \\ &\quad (4,1) \quad (4,1) \\ \rightarrow z^{[2]} &= W^{[2]} a^{[1]} + b^{[2]} \\ &\quad (1,1) \quad (1,4) \quad (4,1) \quad (1,1) \\ \rightarrow a^{[2]} &= \sigma(z^{[2]}) \\ &\quad (1,1) \quad (1,1) \end{aligned}$$

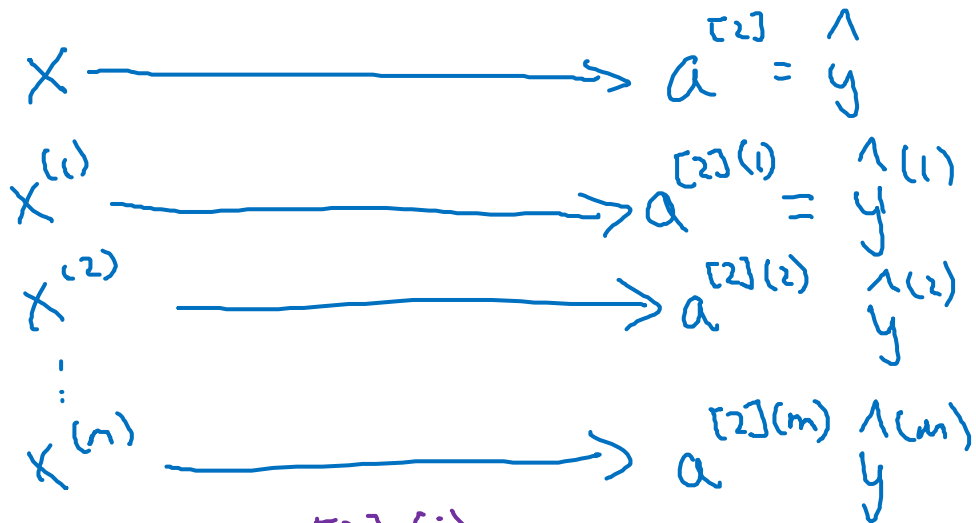
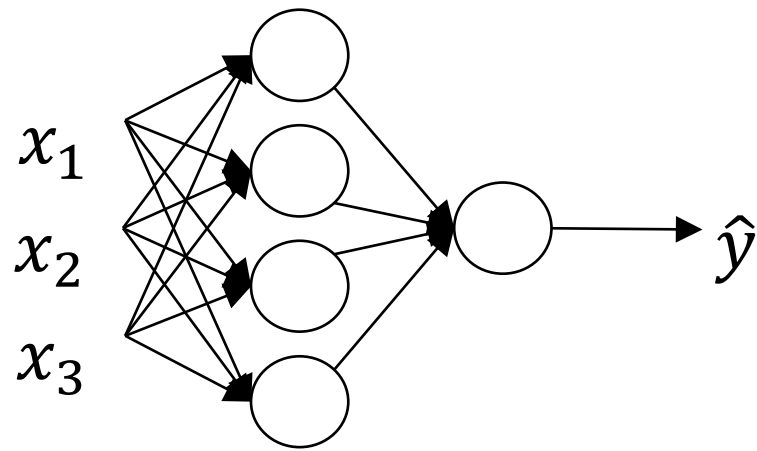


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One hidden layer Neural Network

Vectorizing across multiple examples

Vectorizing across multiple examples



$a^{[2](i)}$
 \nwarrow example i
 \swarrow layer 2

$$z^{[1]} = W^{[1]}x + b^{[1]}$$

$$a^{[1]} = \sigma(z^{[1]})$$

$$z^{[2]} = W^{[2]}a^{[1]} + b^{[2]}$$

$$a^{[2]} = \sigma(z^{[2]})$$

for $i = 1$ to m ,

$$z^{[1](i)} = W^{[1]}x^{(i)} + b^{[1]}$$

$$a^{[1](i)} = \sigma(z^{[1](i)})$$

$$z^{[2](i)} = W^{[2]}a^{[1](i)} + b^{[2]}$$

$$a^{[2](i)} = \sigma(z^{[2](i)})$$

Vectorizing across multiple examples

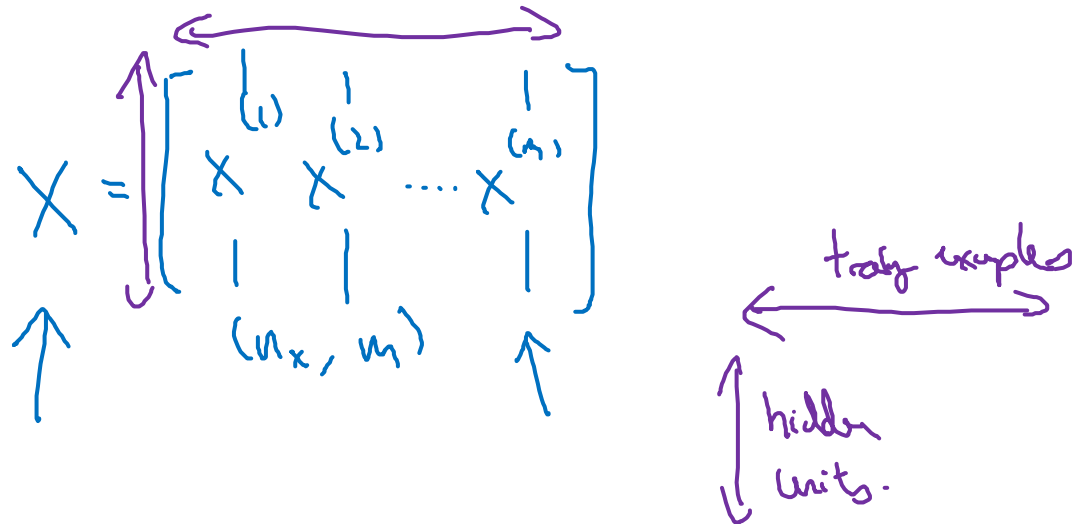
for $i = 1$ to m :

$$z^{[1]}(i) = W^{[1]}x^{(i)} + b^{[1]}$$

$$a^{[1]}(i) = \sigma(z^{[1]}(i))$$

$$z^{[2]}(i) = W^{[2]}a^{[1]}(i) + b^{[2]}$$

$$a^{[2]}(i) = \sigma(z^{[2]}(i))$$

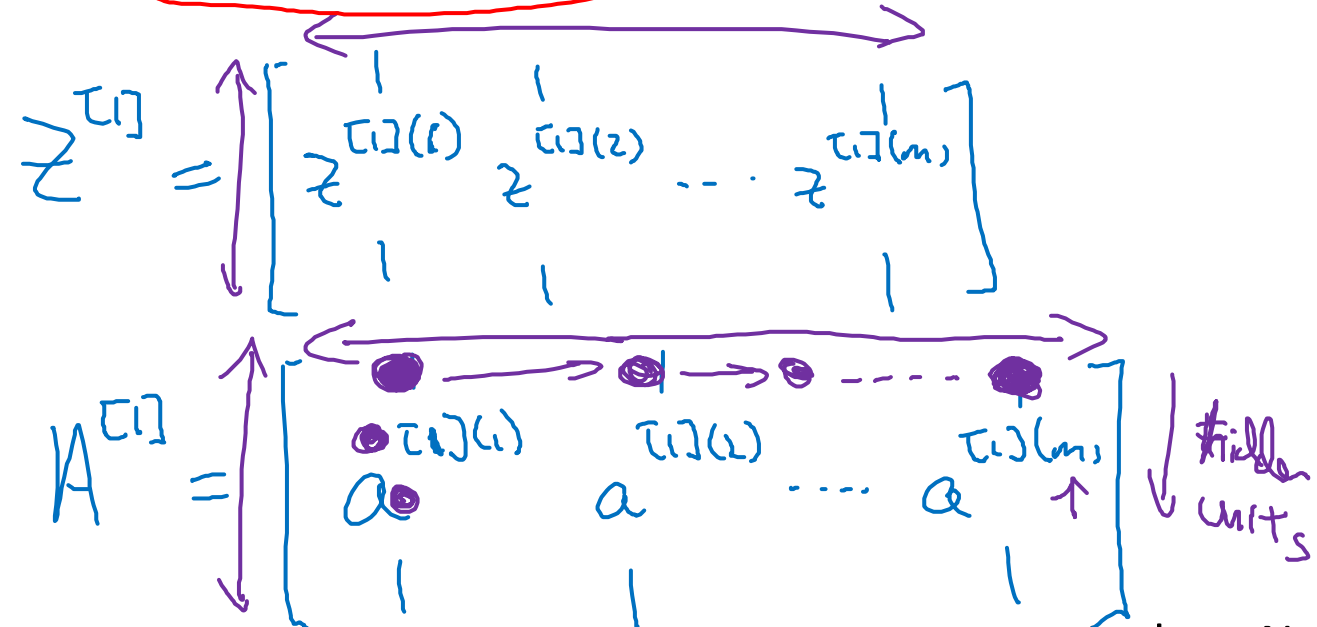


$$z^{[1]} = W^{[1]}X + b^{[1]}$$

$$\rightarrow A^{[1]} = \sigma(z^{[1]})$$

$$\rightarrow z^{[2]} = W^{[2]}A^{[1]} + b^{[2]}$$

$$\rightarrow A^{[2]} = \sigma(z^{[2]})$$





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One hidden layer Neural Network

Explanation
for vectorized
implementation

Justification for vectorized implementation

$$z^{1} = \omega^{[1]} x^{(1)} + \cancel{b^{[1]}} \quad , \quad z^{[1](2)} = \omega^{[1]} x^{(2)} + \cancel{b^{[1]}} \quad , \quad z^{[1](3)} = \omega^{[1]} x^{(3)} + \cancel{b^{[1]}}$$

↑ ↘ 0
↑ ↘ 0
↑ ↘ 0

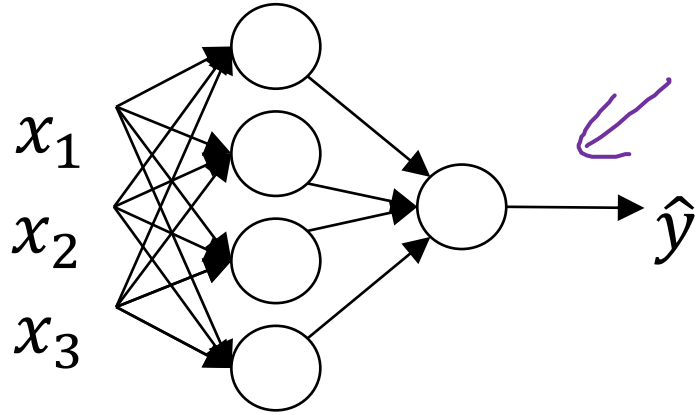
$$\omega^{[1]} = \begin{bmatrix} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{bmatrix} \quad \omega^{[1]} x^{(1)} = \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} \quad \omega^{[1]} x^{(2)} = \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} \quad \omega^{[1]} x^{(3)} = \begin{bmatrix} \bullet \\ \bullet \\ \bullet \\ \bullet \end{bmatrix}$$

$$\omega^{[1]} \begin{bmatrix} | & | & | & \dots \\ x^{(1)} & x^{(2)} & x^{(3)} & \dots \\ | & | & | & \dots \end{bmatrix} = \begin{bmatrix} \bullet & \bullet & \bullet & \dots \\ \bullet & \bullet & \bullet & \dots \\ \bullet & \bullet & \bullet & \dots \\ \bullet & \bullet & \bullet & \dots \end{bmatrix} = \begin{bmatrix} | & | & | & \dots \\ z^{1} & z^{[1](2)} & z^{[1](3)} & \dots \\ | & | & | & \dots \end{bmatrix} = z^{[1]}$$

↑ + b^[1]
↑ + b^[1]
↑ + b^[1]

$\hat{z} = \omega^{[1]} X + b^{[1]}$

Recap of vectorizing across multiple examples



$$X = \begin{bmatrix} | & | & \dots & | \\ x^{(1)} & x^{(2)} & \dots & x^{(m)} \\ | & | & \dots & | \end{bmatrix}$$

A purple arrow points from the matrix X towards the right.

$$\underline{A^{[1]}} = \begin{bmatrix} | & | & \dots & | \\ a^{[1]}(1) & a^{[1]}(2) & \dots & a^{[1]}(m) \\ | & | & \dots & | \end{bmatrix}$$

A purple arrow points from the matrix $A^{[1]}$ towards the right.

for $i = 1$ to m

$$\rightarrow z^{[1]}(i) = W^{[1]}x^{(i)} + b^{[1]}$$

$$\rightarrow a^{[1]}(i) = \sigma(z^{[1]}(i))$$

$$\rightarrow z^{[2]}(i) = W^{[2]}a^{[1]}(i) + b^{[2]}$$

$$\rightarrow a^{[2]}(i) = \sigma(z^{[2]}(i))$$

$$Z^{[1]} = W^{[1]}X + b^{[1]}$$

$$A^{[1]} = \sigma(Z^{[1]})$$

$$Z^{[2]} = W^{[2]}A^{[1]} + b^{[2]}$$

$$A^{[2]} = \sigma(Z^{[2]})$$

$$x = a^{[0]} \quad x^{(i)} = a^{[0]}(i)$$

$$W^{[1]}A^{[0]} + b^{[1]}$$

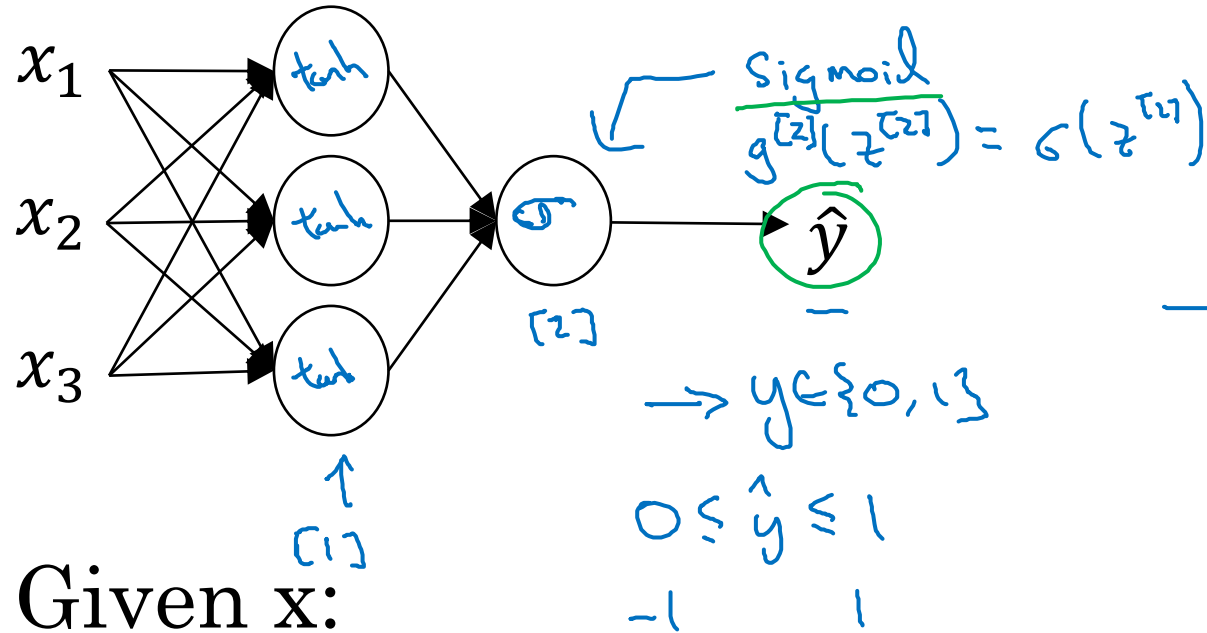


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One hidden layer
Neural Network

Activation functions

Activation functions



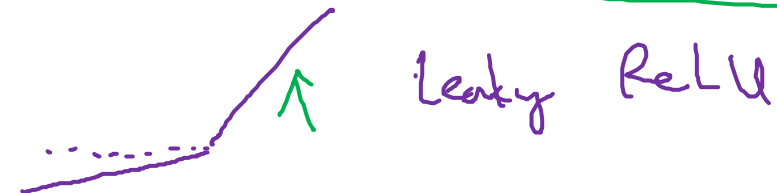
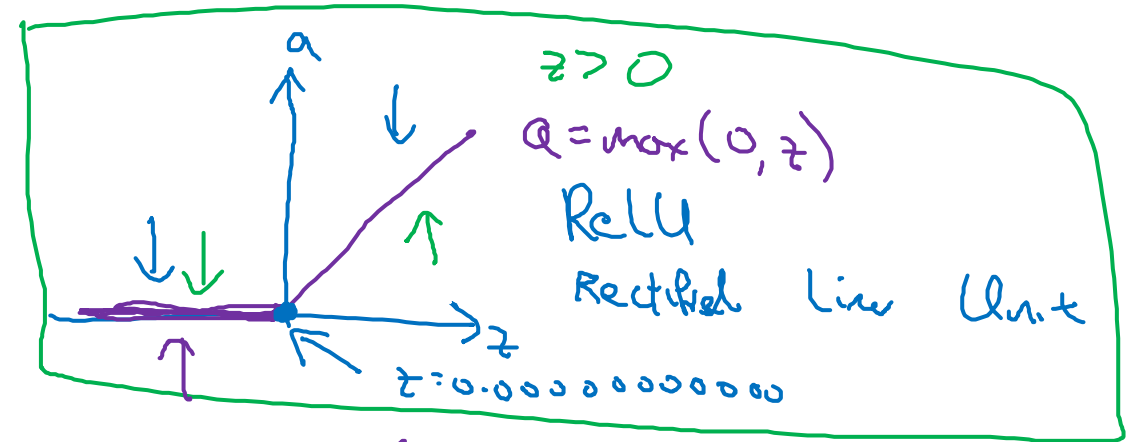
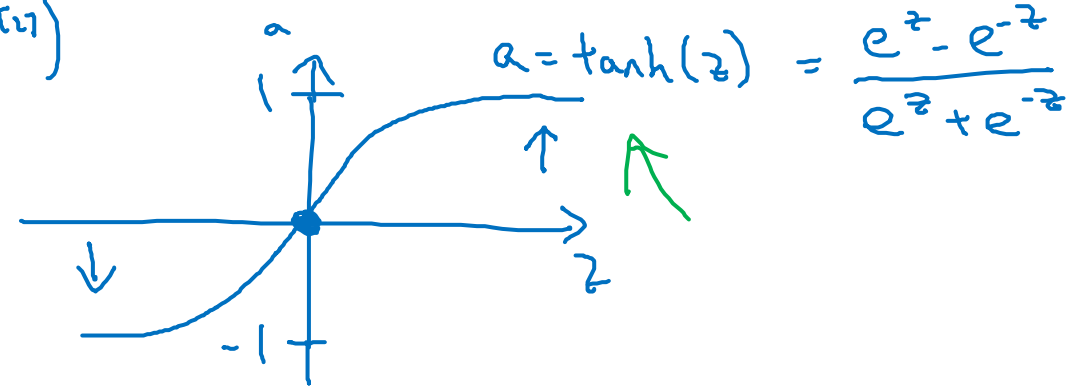
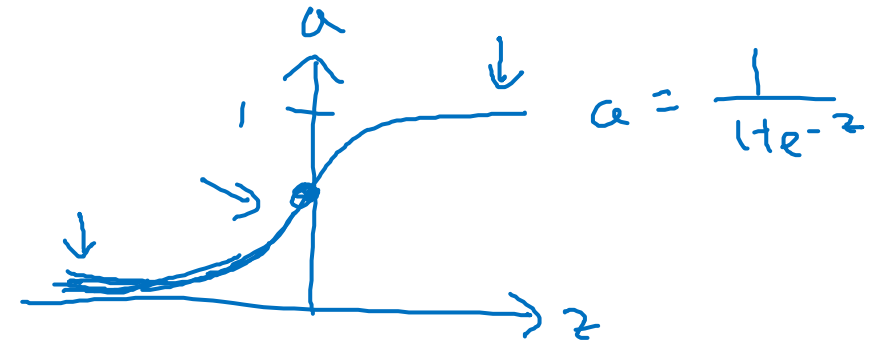
Given x :

$$z^{[1]} = W^{[1]}x + b^{[1]}$$

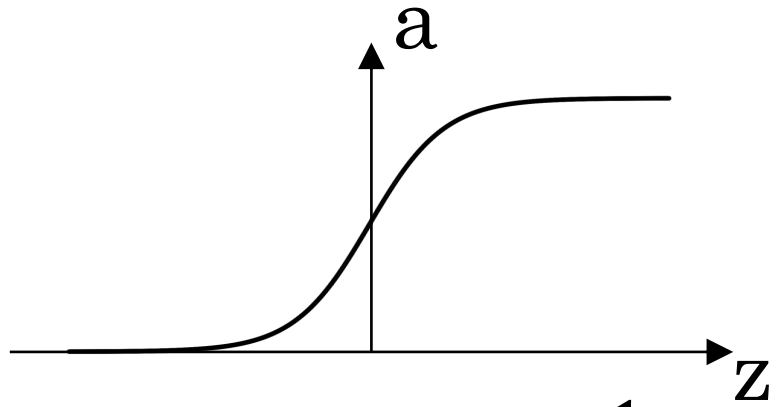
$$\rightarrow a^{[1]} = \cancel{\sigma(z^{[1]})} g^{(1)}(z^{(1)})$$

$$z^{[2]} = W^{[2]}a^{[1]} + b^{[2]}$$

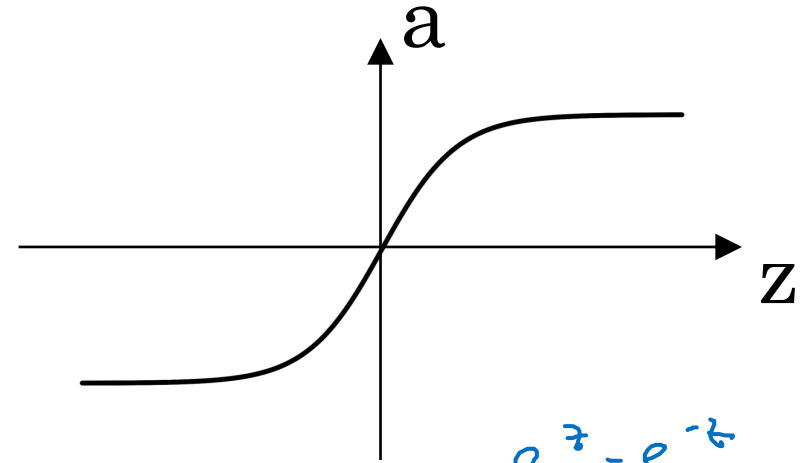
$$\rightarrow a^{[2]} = \cancel{\sigma(z^{[2]})} g^{(2)}(z^{(2)})$$



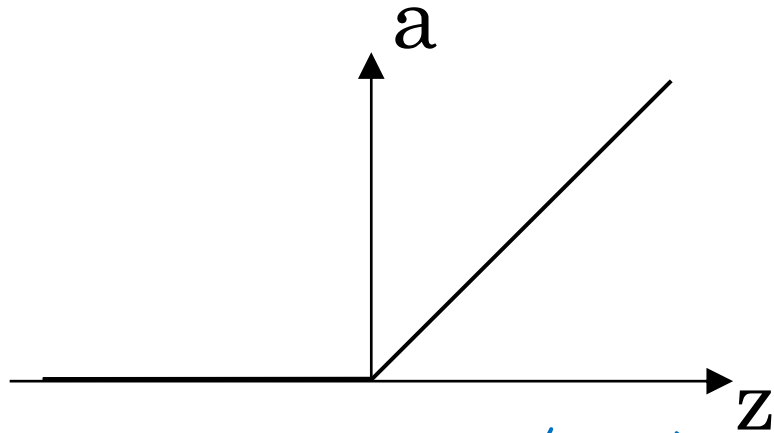
Pros and cons of activation functions



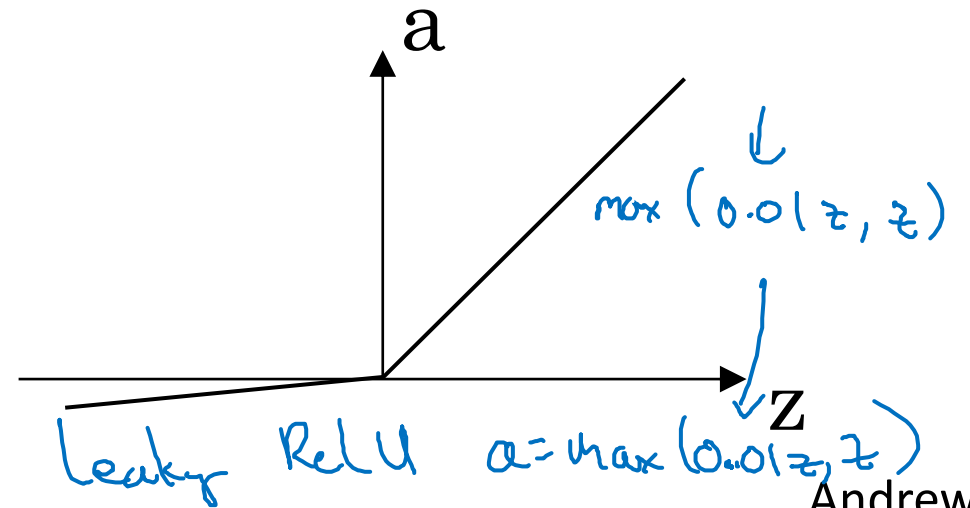
sigmoid: $a = \frac{1}{1 + e^{-z}}$



tanh: $a = \frac{e^z - e^{-z}}{e^z + e^{-z}}$



ReLU $a = \max(0, z)$



Leaky ReLU $a = \max(0.01z, z)$

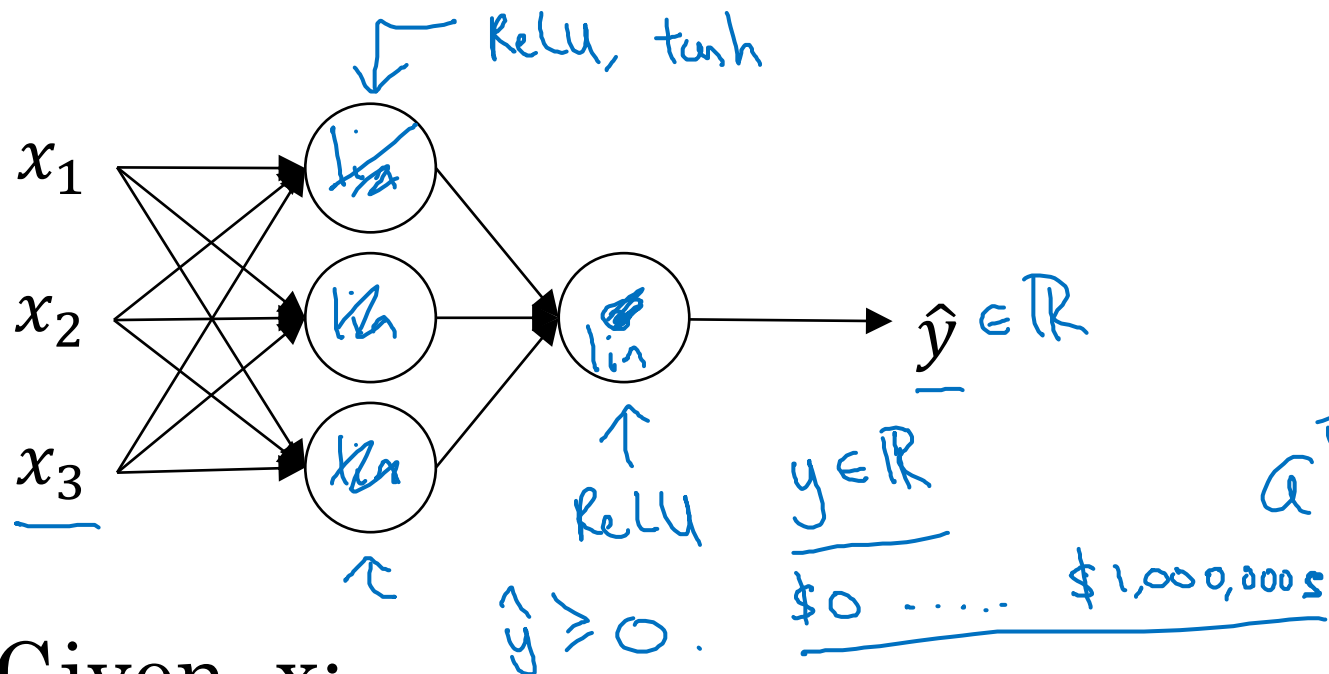


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One hidden layer Neural Network

Why do you
need non-linear
activation functions?

Activation function



Given x :

$$\begin{aligned} \rightarrow z^{[1]} &= W^{[1]}x + b^{[1]} \\ \rightarrow a^{[1]} &= \cancel{g^{[1]}(z^{[1]})} z^{[1]} \\ \rightarrow z^{[2]} &= W^{[2]}a^{[1]} + b^{[2]} \\ \rightarrow a^{[2]} &= \cancel{g^{[2]}(z^{[2]})} z^{[2]} \end{aligned}$$

$g(z) = z$
"linear activation function"

$$a^{[1]} = z^{[1]} = W^{[1]}x + b^{[1]}$$

$$a^{[2]} = z^{[2]} = W^{[2]}a^{[1]} + b^{[2]}$$

$$a^{[2]} = W^{[2]} \left(W^{[1]}x + b^{[1]} \right) + b^{[2]}$$

$$= \left(W^{[2]} W^{[1]} \right) x + \left(W^{[2]} b^{[1]} + b^{[2]} \right)$$

$$= W'x + b'$$

$$g(z) = z$$

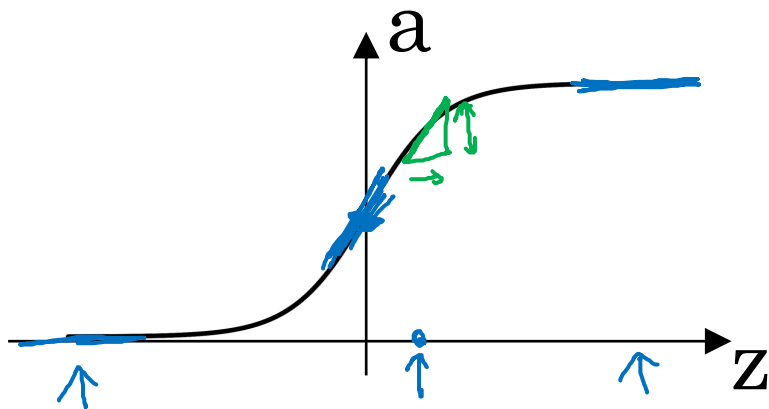


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One hidden layer
Neural Network

Derivatives of
activation functions

Sigmoid activation function



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

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

$$\boxed{g'(z)} = \boxed{\frac{d}{dz} g(z)} = \text{slope of } g(z) \text{ at } z$$

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

$$= g(z) (1 - g(z)) \leftarrow$$

$$= \boxed{a(1-a)} \quad \left| \begin{array}{l} g'(z) = a(1-a) \\ \uparrow \\ a \end{array} \right.$$

$$z = 10. \quad g(z) \approx 1$$

$$\frac{d}{dz} g(z) \approx 1(1-1) \approx 0$$

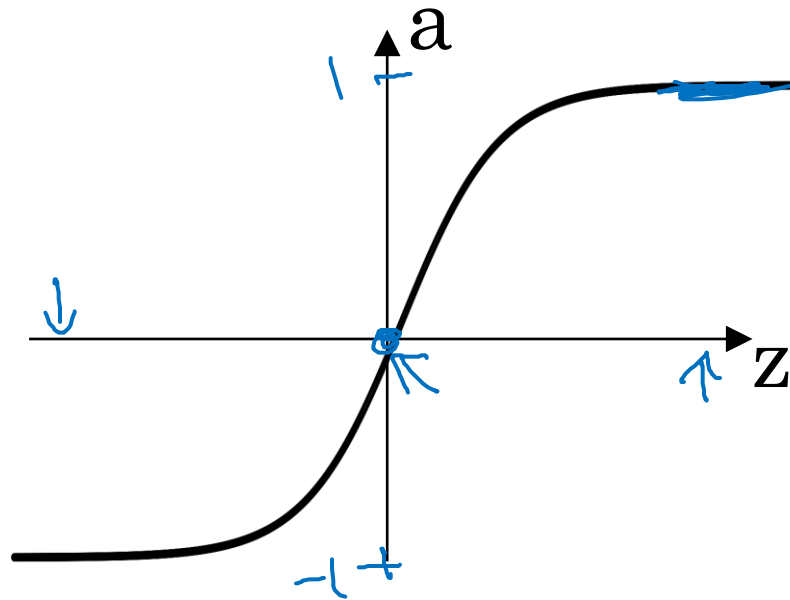
$$z = -10 \quad g(z) \approx 0$$

$$\frac{d}{dz} g(z) \approx 0 \cdot (1-0) \approx 0$$

$$z = 0 \quad g(z) = \frac{1}{2}$$

$$\frac{d}{dz} g(z) = \frac{1}{2} \left(1 - \frac{1}{2} \right) = \frac{1}{4}$$

Tanh activation function



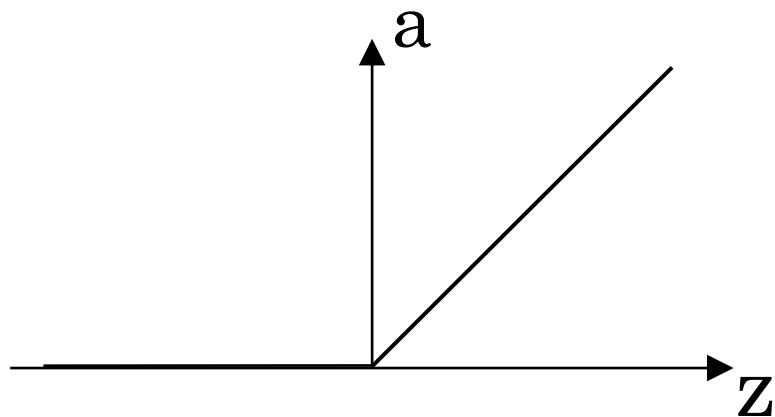
$$g(z) = \tanh(z) = \frac{e^z - e^{-z}}{e^z + e^{-z}}$$

$$g'(z) = \frac{d}{dz} g(z) = \text{slope of } g(z) \text{ at } z = \underline{1 - (\tanh(z))^2} \leftarrow$$

$$a = g(z), \quad g'(z) = 1 - a^2$$

$$\left| \begin{array}{ll} z=10 & \tanh(z) \approx 1 \\ & g'(z) \approx 0 \\ z=-10 & \tanh(z) \approx -1 \\ & g'(z) \approx 0 \\ z=0 & \tanh(z) = 0 \\ & g'(z) = 1 \end{array} \right.$$

ReLU and Leaky ReLU



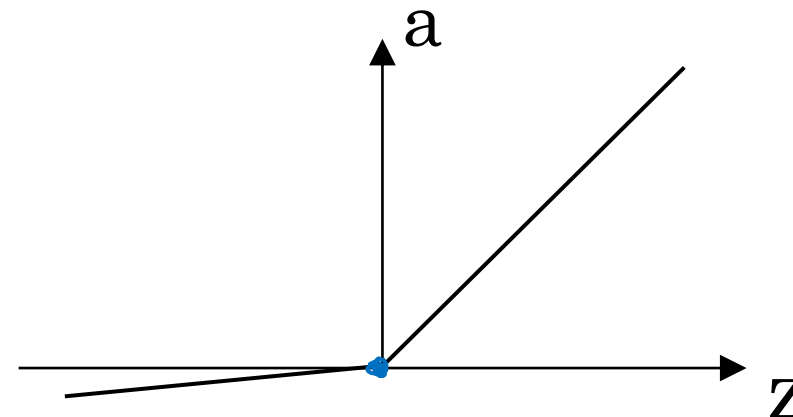
ReLU

$$g(z) = \max(0, z)$$

→ $g'(z) = \begin{cases} 0 & \text{if } z < 0 \\ 1 & \text{if } z \geq 0 \end{cases}$

~~undefined if $z = 0$~~

$z = 0.0000 \dots 0$



Leaky ReLU

$$g(z) = \max(0.01z, z)$$

$$g'(z) = \begin{cases} 0.01 & \text{if } z < 0 \\ 1 & \text{if } z \geq 0 \end{cases}$$



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One hidden layer
Neural Network

Gradient descent for
neural networks

Gradient descent for neural networks

Parameters: $W^{[1]}, b^{[1]}, W^{[2]}, b^{[2]}$
 $(n^{[1]}, n^{[0]})$ $(n^{[1]}, 1)$ $(n^{[2]}, n^{[1]})$ $(n^{[2]}, 1)$ $n_x = n^{[0]}, n^{[1]}, \underline{n^{[2]} = 1}$

Cost function: $J(W^{[1]}, b^{[1]}, \underline{W^{[2]}}, \underline{b^{[2]}}) = \frac{1}{m} \sum_{i=1}^m \ell(\hat{y}, y)$
 \uparrow \uparrow $\uparrow a^{[2]}$

Gradient descent:

→ Repeat {

→ Compute predictions $(\hat{y}^{(i)}, i=1, \dots, m)$

$$\underline{dW^{[1]}} = \frac{\partial J}{\partial W^{[1]}}, \quad \underline{db^{[1]}} = \frac{\partial J}{\partial b^{[1]}}, \dots$$

$$W^{[1]} := W^{[1]} - \alpha dW^{[1]}$$

$$b^{[1]} := b^{[1]} - \alpha db^{[1]}$$

$$W^{[2]} := \dots \quad b^{[2]} := \dots$$

Formulas for computing derivatives

Forward propagation:

$$z^{[1]} = w^{[1]}x + b^{[1]}$$

$$a^{[1]} = g^{[1]}(z^{[1]}) \leftarrow$$

$$z^{[2]} = w^{[2]}a^{[1]} + b^{[2]}$$

$$a^{[2]} = g^{[2]}(z^{[2]}) = \sigma(z^{[2]})$$

Back propagation:

$$dz^{[2]} = A^{[2]} - Y \leftarrow$$

$$dw^{[2]} = \frac{1}{m} dz^{[2]} A^{[1]T}$$

$$db^{[2]} = \frac{1}{m} \text{np.sum}(dz^{[2]}, \text{axis}=1, \text{keepdims}=\text{True})$$

$$dz^{[1]} = \underbrace{w^{[2]T} dz^{[2]}}_{(n^{[1]}, m)} \times \underbrace{g^{[1]'}(z^{[1]})}_{\text{element-wise product}} \quad (n^{[1]}, m)$$

$$dw^{[1]} = \frac{1}{m} dz^{[1]} x^T$$

$$db^{[1]} = \frac{1}{m} \text{np.sum}(dz^{[1]}, \text{axis}=1, \text{keepdims}=\text{True})$$

$(n^{[1]}, 1)$ $(n^{[1]},)$ \uparrow reshape

$$Y = [y^{(1)} \ y^{(2)} \ \dots \ y^{(m)}]$$

$$(n^{[2]}) \leftarrow$$

$$\downarrow (n^{[2]}, 1) \leftarrow$$



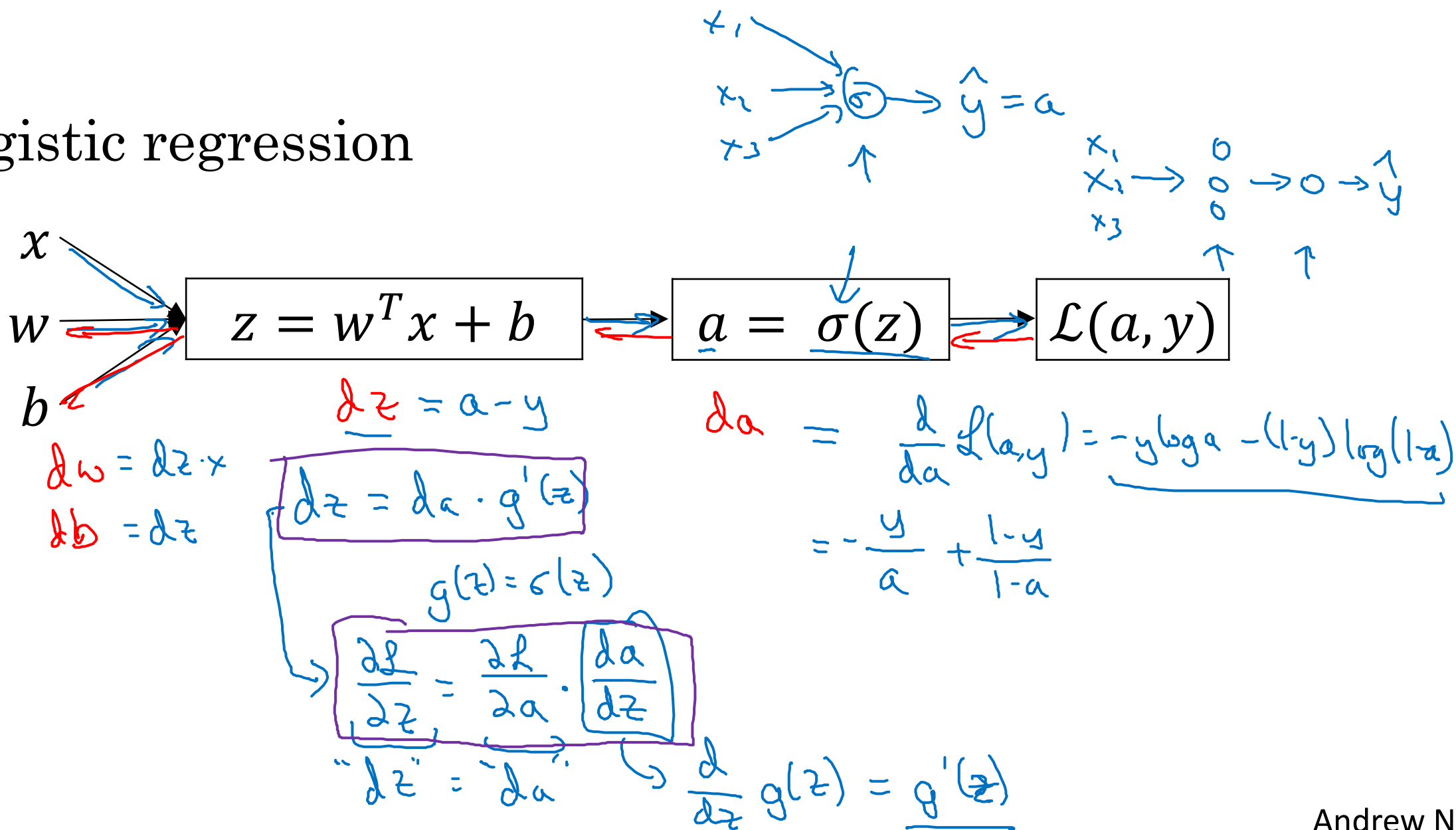
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One hidden layer
Neural Network

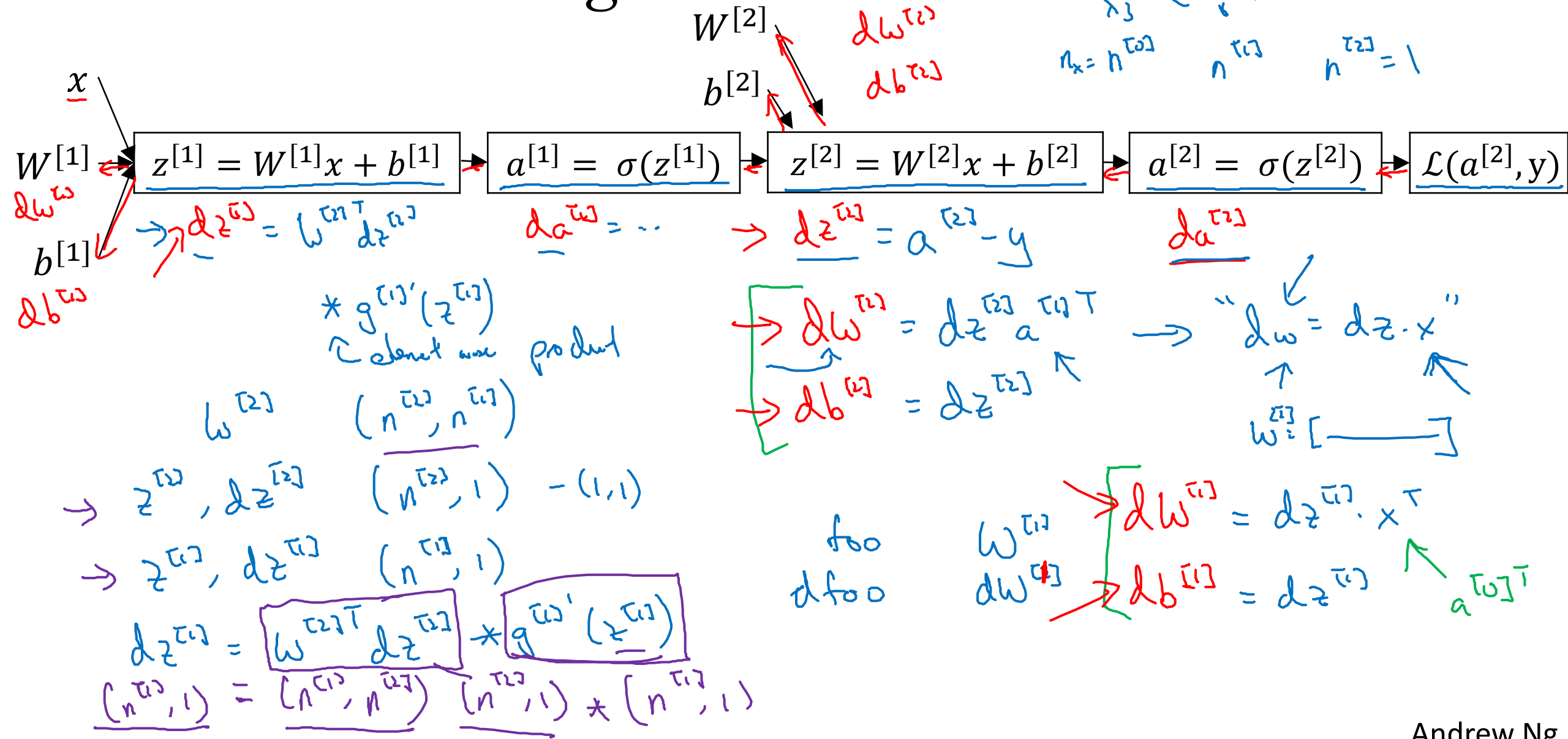
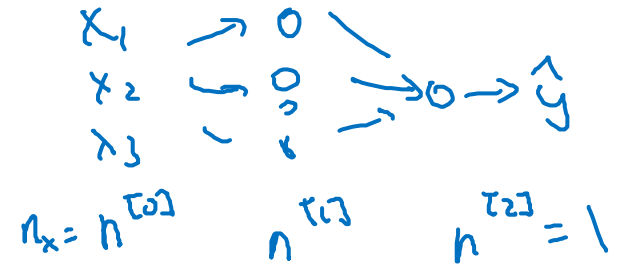
Backpropagation
intuition (Optional)

Computing gradients

Logistic regression



Neural network gradients



Summary of gradient descent

$$dz^{[2]} = a^{[2]} - y$$

$$dW^{[2]} = dz^{[2]} a^{[1]T}$$

$$db^{[2]} = dz^{[2]}$$

$$dz^{[1]} = W^{[2]T} dz^{[2]} * g^{[1]'}(z^{[1]})$$

$$dW^{[1]} = dz^{[1]} x^T$$

$$db^{[1]} = dz^{[1]}$$

Vectorized Implementation:

$$z^{[1]} = W^{[1]} x + b^{[1]}$$
$$a^{[1]} = g^{[1]}(z^{[1]})$$
$$z^{[1]} = \begin{bmatrix} z^{1} \\ z^{[1](2)} \\ \dots \\ z^{[1](n)} \end{bmatrix}$$
$$z^{[2]} = W^{[2]} x + b^{[2]}$$
$$A^{[2]} = g^{[2]}(z^{[2]})$$

Summary of gradient descent

$$\underline{dz^{[2]}} = \underline{a^{[2]}} - \underline{y}$$

$$dW^{[2]} = dz^{[2]} a^{[1]T}$$

$$db^{[2]} = dz^{[2]}$$

$$\underbrace{dz^{[1]}}_{(n^{[1]}, 1)} = W^{[2]T} dz^{[2]} * g^{[1]'}(z^{[1]})$$

$$dW^{[1]} = dz^{[1]} x^T$$

$$db^{[1]} = dz^{[1]}$$

$$\underline{dZ^{[2]}} = A^{[2]} - Y$$

$$dW^{[2]} = \frac{1}{m} dZ^{[2]} A^{[1]T}$$

$$db^{[2]} = \frac{1}{m} \text{np.sum}(dZ^{[2]}, \text{axis} = 1, \text{keepdims} = \text{True})$$

$$\underbrace{dZ^{[1]}}_{(n^{[1]}, m)} = \underbrace{W^{[2]T} dZ^{[2]}}_{(n^{[1]}, m)} * \underbrace{g^{[1]'}(Z^{[1]})}_{(n^{[1]}, m)}$$

elementwise product

$$dW^{[1]} = \frac{1}{m} dZ^{[1]} X^T$$

$$db^{[1]} = \frac{1}{m} \text{np.sum}(dZ^{[1]}, \text{axis} = 1, \text{keepdims} = \text{True})$$

$$J(\cdot) = \frac{1}{m} \sum_{i=1}^n \mathcal{L}(\hat{y}_i, y_i)$$

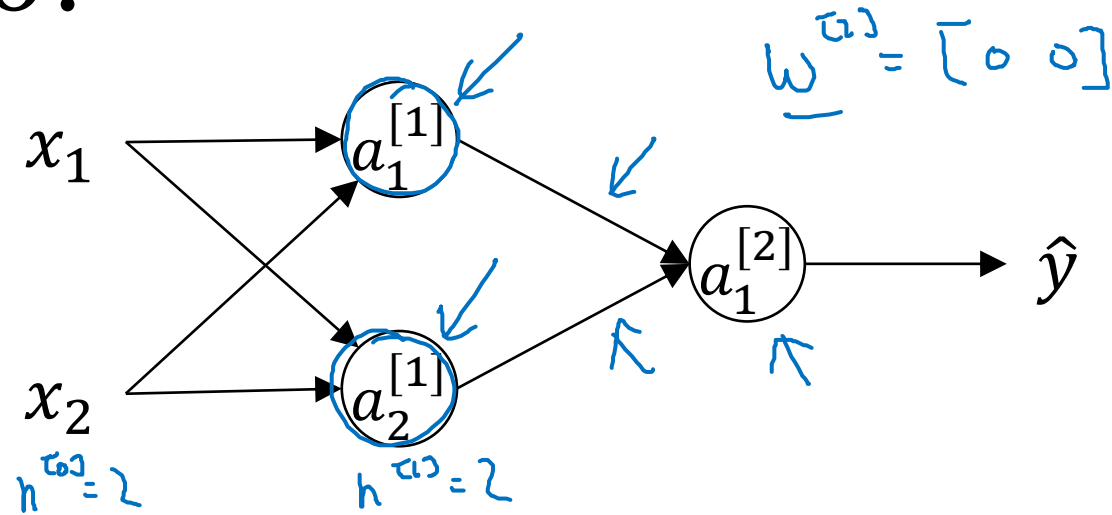


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One hidden layer
Neural Network

Random Initialization

What happens if you initialize weights to zero?



$$W_{\kappa}^{[1]} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

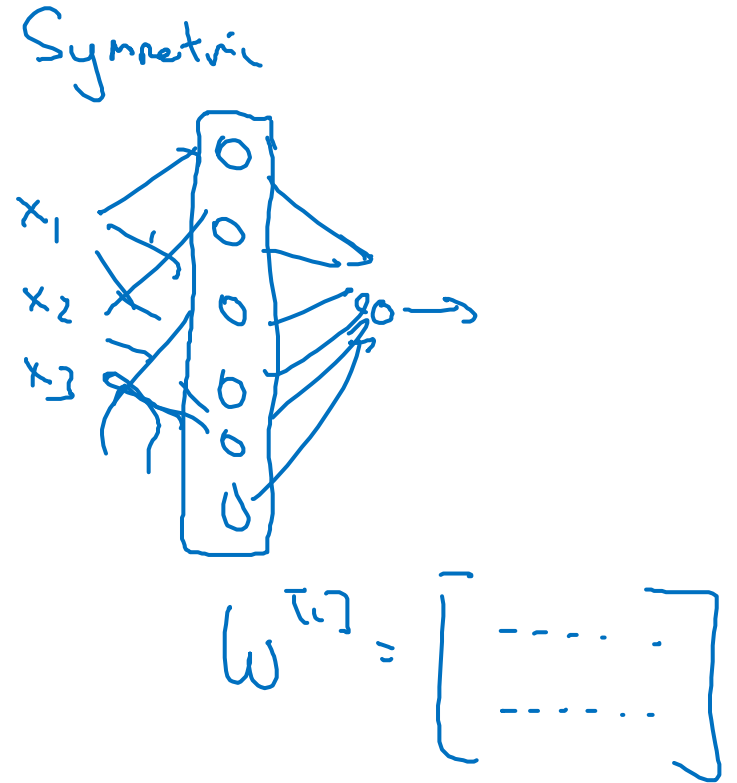
$$a_1^{[1]} = a_2^{[1]}$$

$$dW = \begin{bmatrix} u & v \\ u & v \end{bmatrix}$$

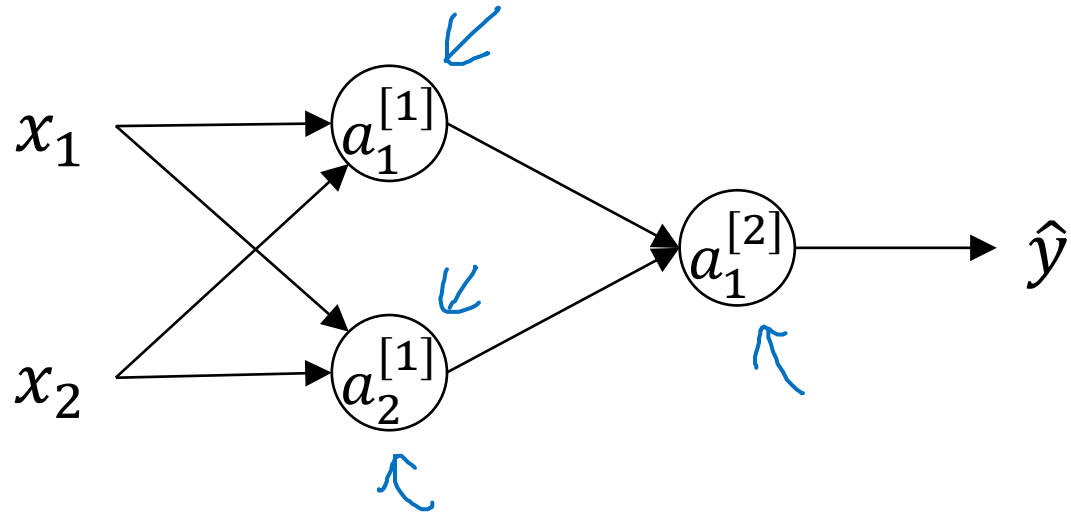
$$b_{\kappa}^{[1]} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$dz_1 = dz_2$$

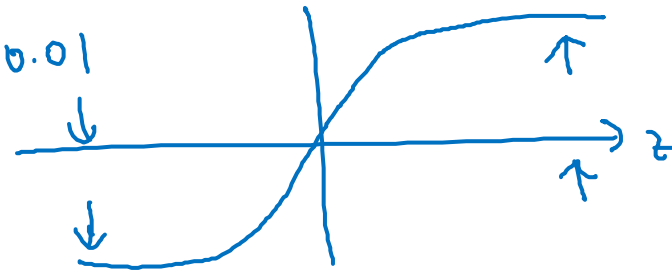
$$W^{[1]} = W^{[1]} - \alpha dW$$



Random initialization



→ $w^{[1]} = \text{np.random.randn}(2,2) * \frac{0.01}{100?}$
 $b^{[1]} = \text{np.zeros}(2,1)$
 $w^{[2]} = \text{np.random.randn}(1,2) * 0.01$
 $b^{[2]} = 0$



$$z^{[1]} = w^{[1]}x + b^{[1]}$$
$$a^{[1]} = g^{[1]}(z^{[1]})$$