lecture 5

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H/W Review - One layer

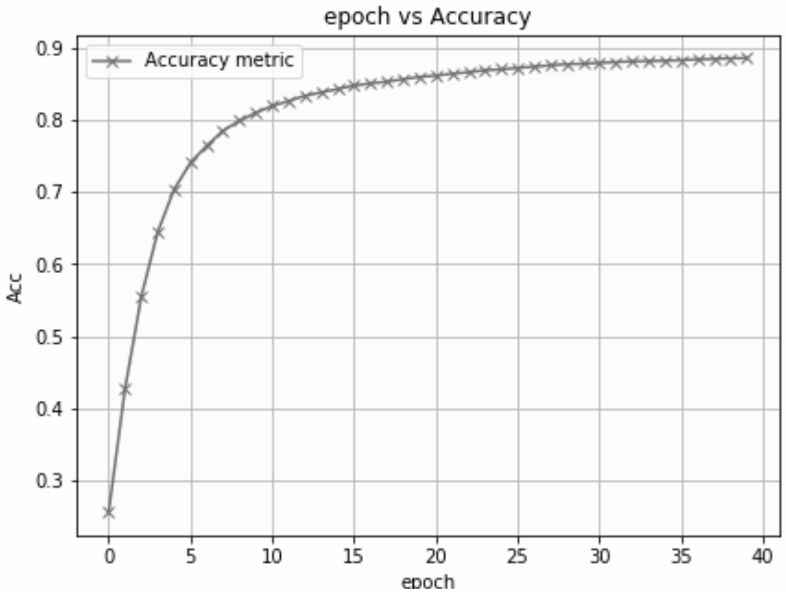
```
##########################################################################
# TODO:                                                                  #
# Stack linear layers for bast accuracy.                                 #
##########################################################################
class LinearModel(nn.Module):
    def __init__(self):
        super(LinearModel, self).__init__()
        self.linear1_1 = nn.Linear(in_features=784, out_features=10, bias=True)
       # self.linear1_2 = nn.Linear(in_features=, out_features=, bias=True)
       # self.linear1_3 = nn.Linear(in_features=, out_features=, bias=True)

        self.sigmoid = nn.LogSigmoid()
       # self.softmax = nn.Softmax(dim=1)

    def forward(self, x):
        x = self.linear1_1(x)
        x = self.sigmoid(x)
       # x = self.linear1_2(x)
       # x = self.sigmoid(x)
       # x = self.linear1_3(x)
       # x = self.sigmoid(x)
       # x = self.softmax(x)

        return x
```

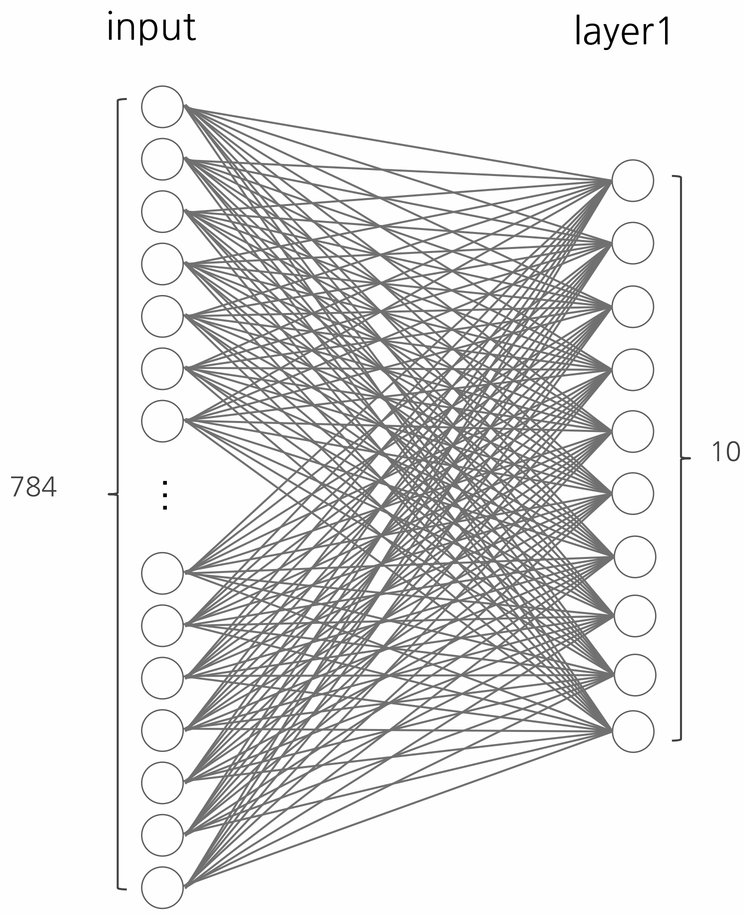
H/W Review - One layer

Layer 1:

input: 784
output: 10

best Acc: 88%





Params: 7850

H/W Review - Two layers

```
class LinearModel(nn.Module):
    def __init__(self):
        super(LinearModel, self).__init__()
        self.linear1_1 = nn.Linear(in_features=784, out_features=128, bias=True)
        self.linear1_2 = nn.Linear(in_features=128, out_features=10, bias=True)

        self.sigmoid = nn.LogSigmoid()

    def forward(self, x):
        x = self.linear1_1(x)
        x = self.sigmoid(x)
        x = self.linear1_2(x)
        x = self.sigmoid(x)

        return x
```

H/W Review - Two layers

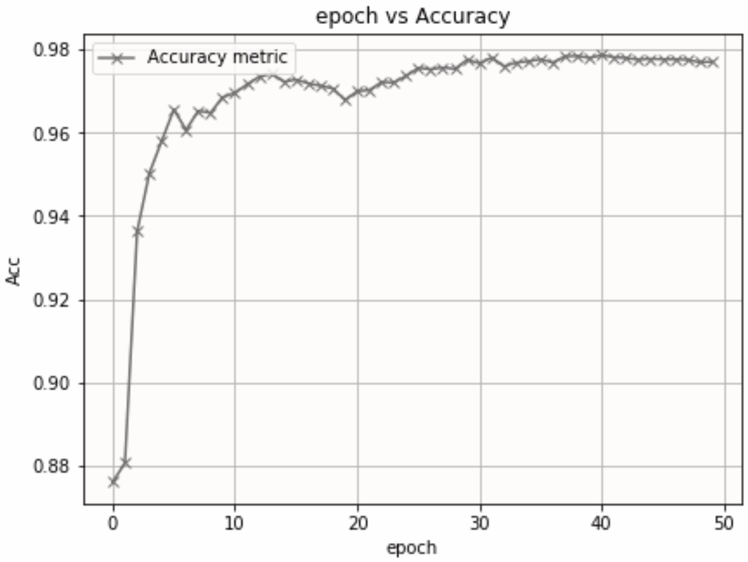
Layer 1:

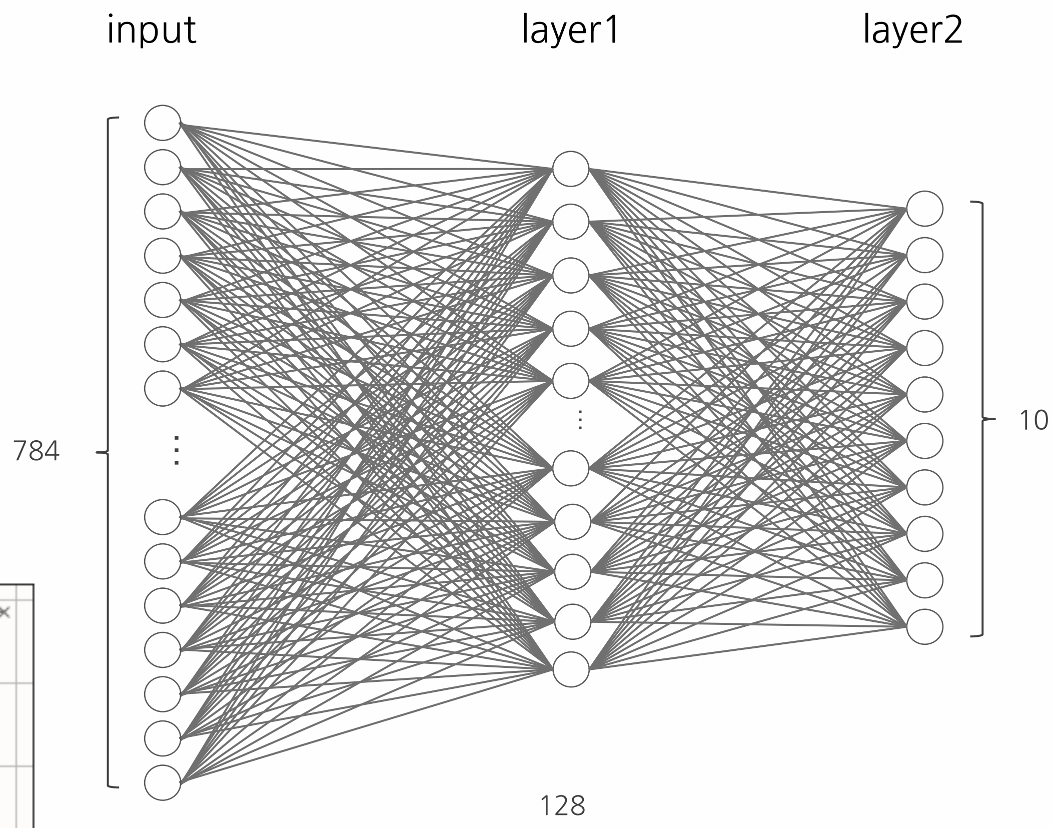
input: 784
output: 128

Layer 2:

input: 128
output: 10

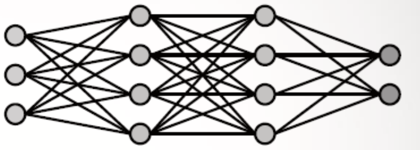
best Acc: 97.9%





Params: 7850 → 101770

H/W Review - Three layers



Layer 1:

input: 784
output: 512

Layer 2:

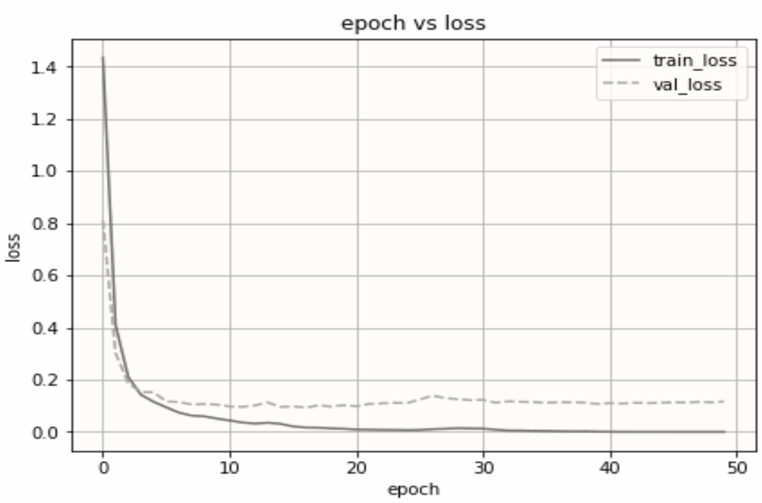
input: 784
output: 256

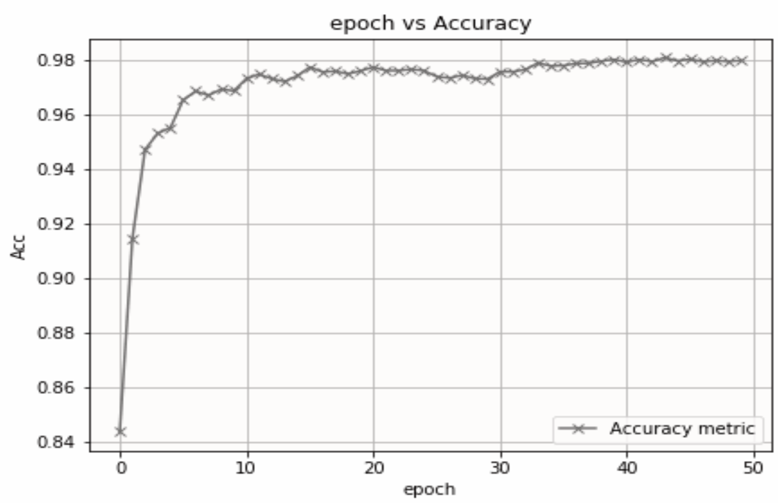
Layer 3:

input: 784
output: 10

best Acc: 98.4%

```
class LinearModel(nn.Module):
    def __init__(self):
        super(LinearModel, self).__init__()
        self.linear1_1 = nn.Linear(in_features=784, out_features=512, bias=True)
        self.linear1_2 = nn.Linear(in_features=512, out_features=256, bias=True)
        self.linear1_3 = nn.Linear(in_features=256, out_features=10, bias=True)

        self.sigmoid = nn.LogSigmoid()

    def forward(self, x):
        x = self.linear1_1(x)
        x = self.sigmoid(x)
        x = self.linear1_2(x)
        x = self.sigmoid(x)
        x = self.linear1_3(x)
        x = self.sigmoid(x)

        return x
```





Params: 7850 → 101770 → 535818

H/W Review - Three layers, More params

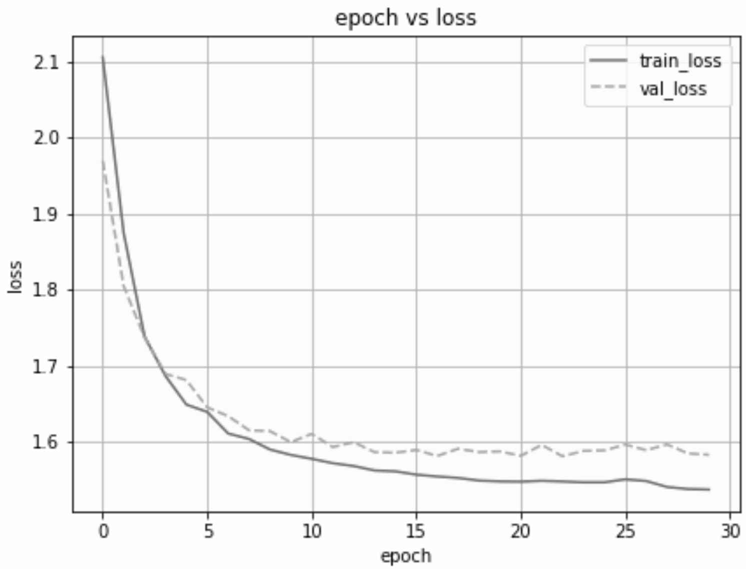
```
class LinearModel(nn.Module):
    def __init__(self):
        super(LinearModel, self).__init__()
        self.linear1_1 = nn.Linear(in_features=784, out_features=1024, bias=True)
        self.linear1_2 = nn.Linear(in_features=1024, out_features=2048, bias=True)
        self.linear1_3 = nn.Linear(in_features=2048, out_features=10, bias=True)

        self.sigmoid = nn.LogSigmoid()

    def forward(self, x):
        x = self.linear1_1(x)
        x = self.sigmoid(x)
        x = self.linear1_2(x)
        x = self.sigmoid(x)
        x = self.linear1_3(x)
        x = self.sigmoid(x)

        return x
```

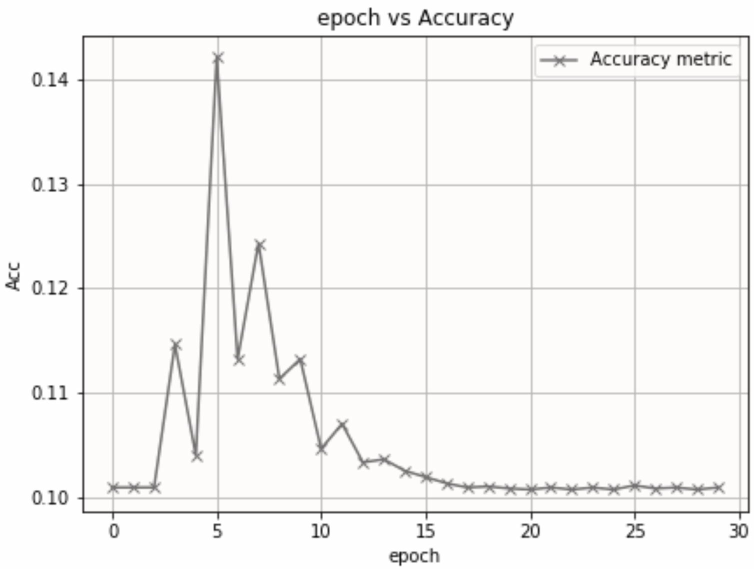
Layer 1:
input: 784
output: 1024

Layer 2:
input: 1024
output: 2048

Layer 3:
input: 2048
output: 10

Best Acc: 14.2%





Params: 7850 → 101770 → 535818 → 2923530

H/W Review - Three layers, More, more params

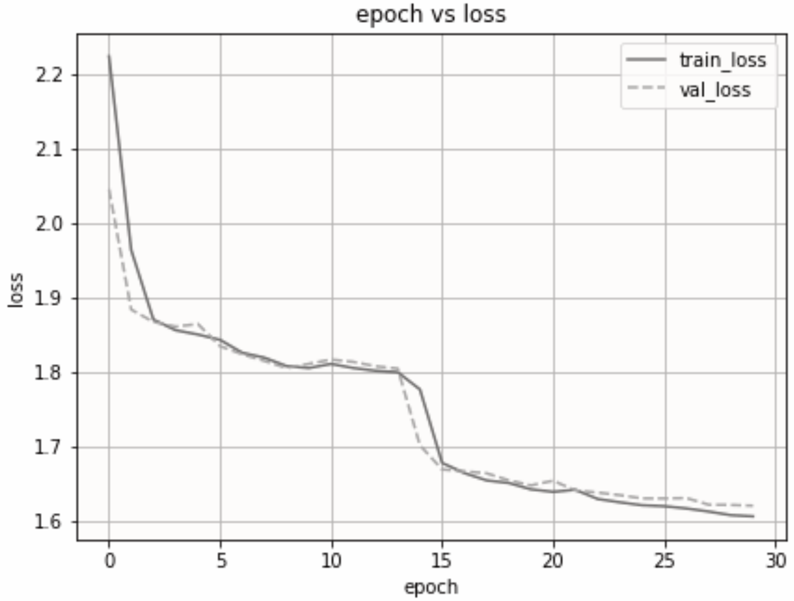
```python
class LinearModel(nn.Module):
    def __init__(self):
        super(LinearModel, self).__init__()
        self.linear1_1 = nn.Linear(in_features=784, out_features=2048, bias=True)
        self.linear1_2 = nn.Linear(in_features=2048, out_features=4096, bias=True)
        self.linear1_3 = nn.Linear(in_features=4096, out_features=10, bias=True)

        self.sigmoid = nn.LogSigmoid()

    def forward(self, x):
        x = self.linear1_1(x)
        x = self.sigmoid(x)
        x = self.linear1_2(x)
        x = self.sigmoid(x)
        x = self.linear1_3(x)
        x = self.sigmoid(x)

        return x
```

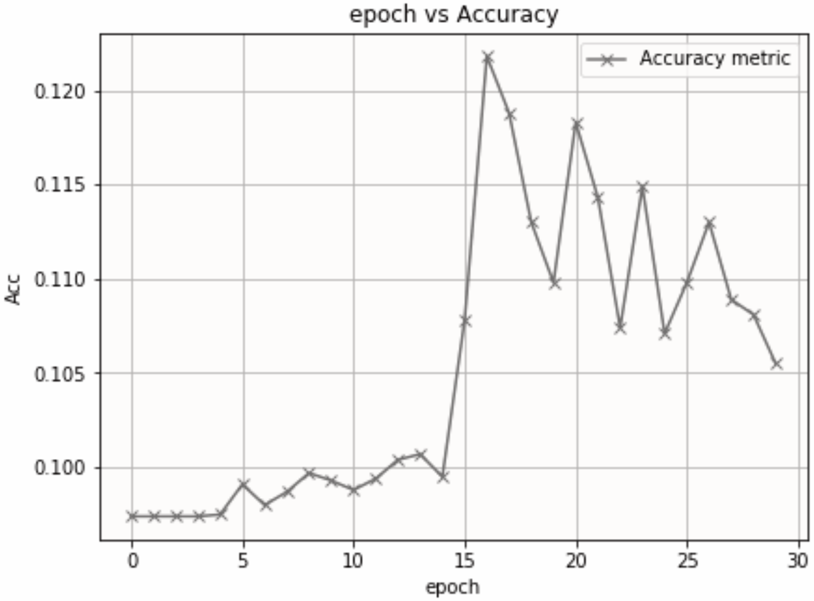
Layer 1:
input: 784
output: 2048

Layer 2:
input: 2048
output: 4096

Layer 3:
input: 4096
output: 10

best Acc: 12.5%





Params: 7850 → 101770 → 535818 → 2923530 → 10041354

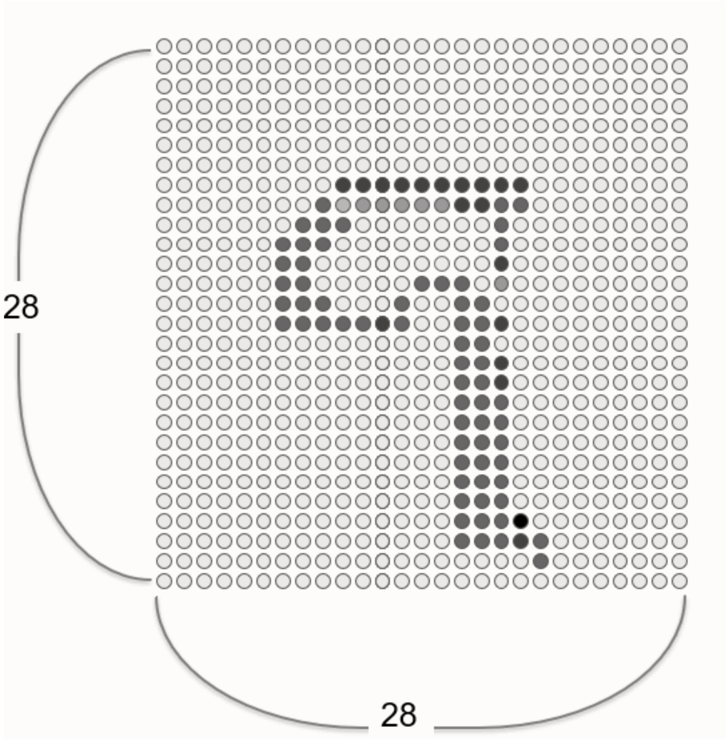
H/W Summary

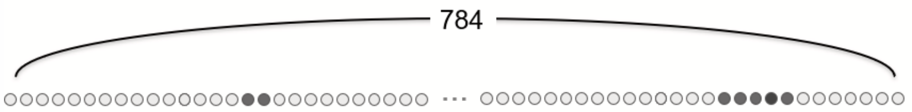
1. Stacking multiple layers deepens the network for higher accuracy.

2. Adjust the dimensions properly to get good accuracy.

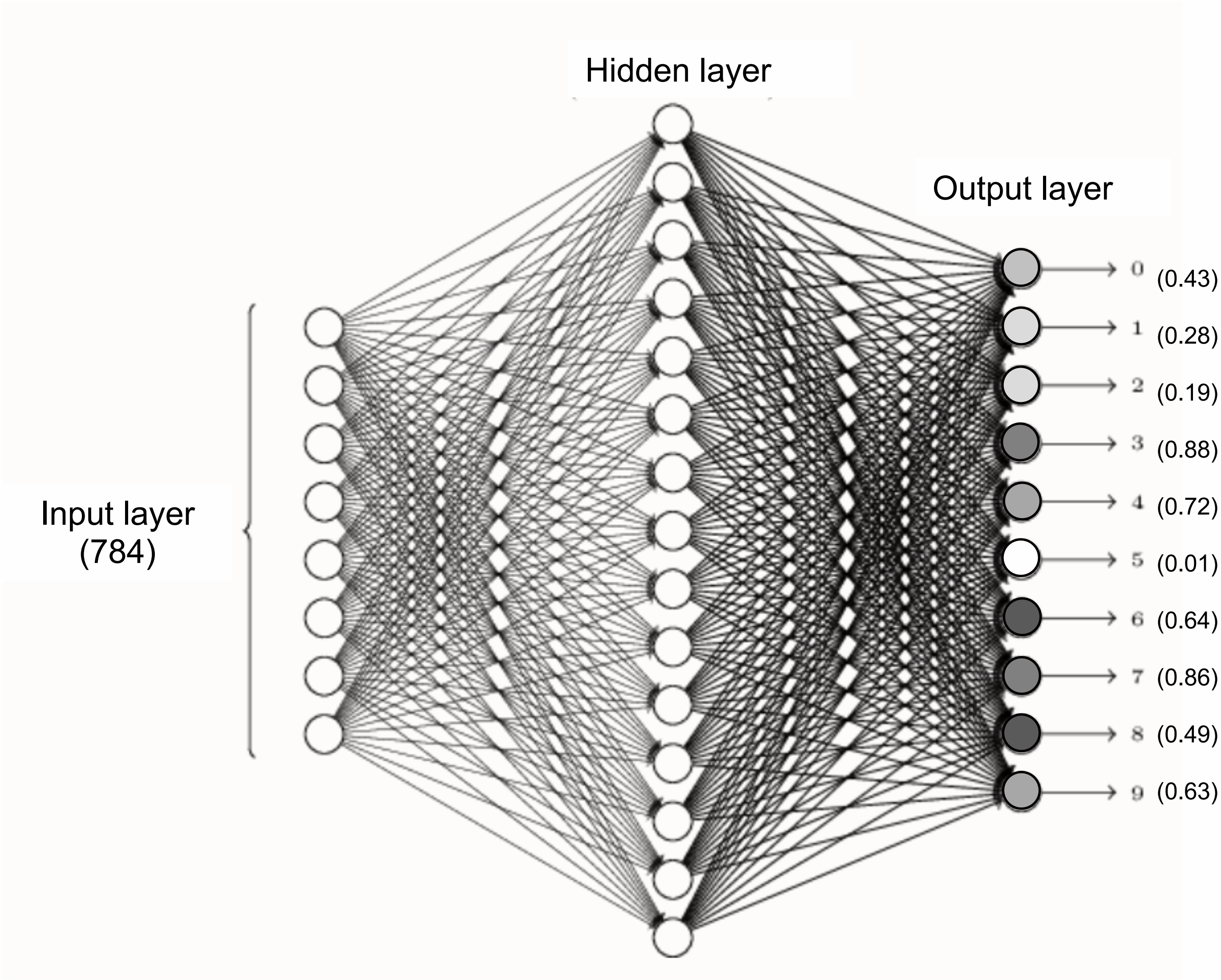
3. If the number of dimensions in the network is too large, the curse of the dimensions will make learning difficult.

Remind – Forward propagation

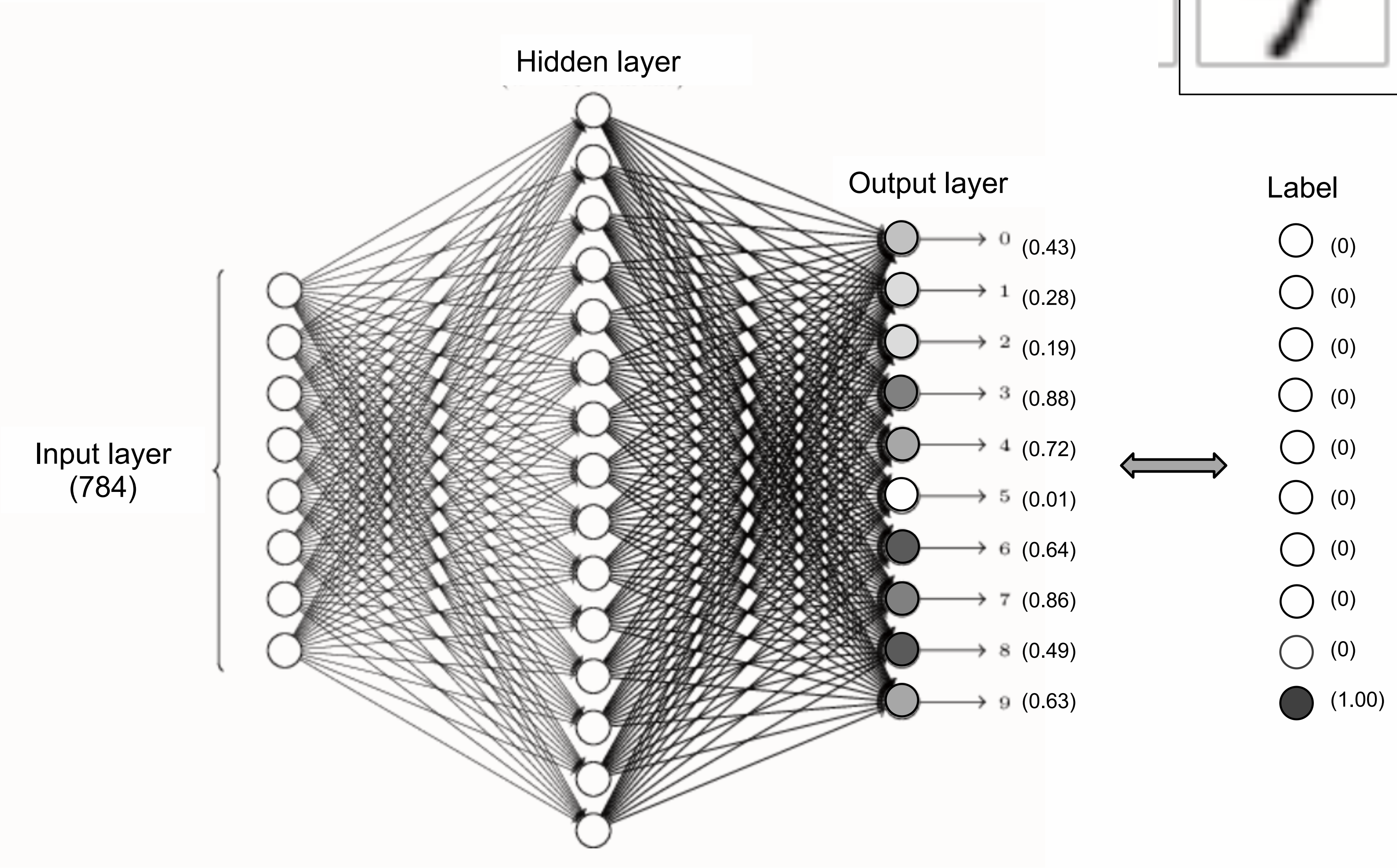




Remind – Forward propagation



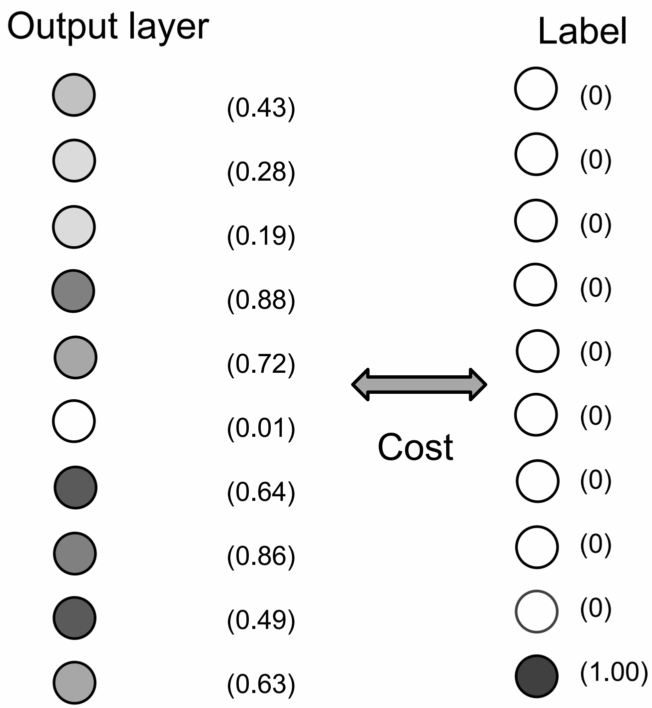
Remind – Forward propagation



Remind – Forward propagation

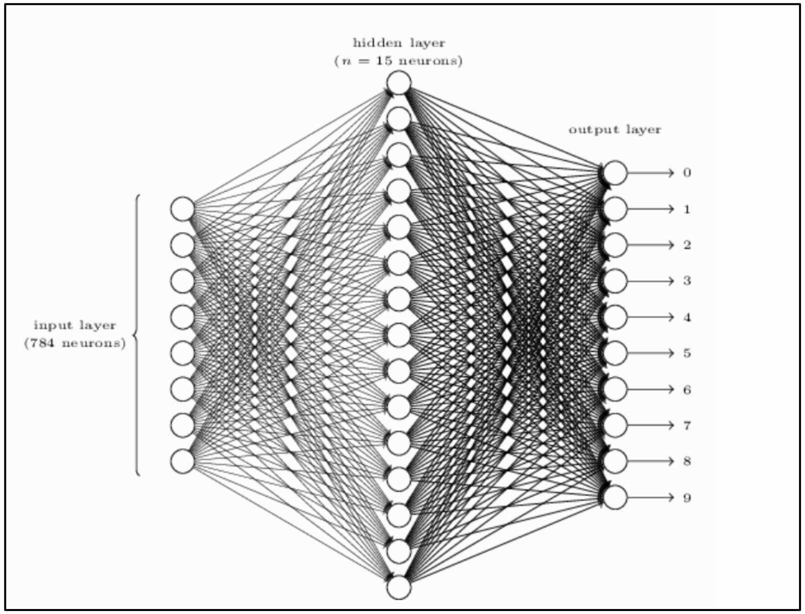
Cost of 

$$
\left\{
\begin{aligned}
&(0.43 - 0)^2 + \\
&(0.28 - 0)^2 + \\
&(0.19 - 0)^2 + \\
&(0.88 - 0)^2 + \\
&(0.72 - 0)^2 + \\
&(0.01 - 0)^2 + \\
&(0.64 - 0)^2 + \\
&(0.86 - 0)^2 + \\
&(0.49 - 0)^2 + \\
&\mathbf{(0.63 - 1)^2}
\end{aligned}
\right.
$$



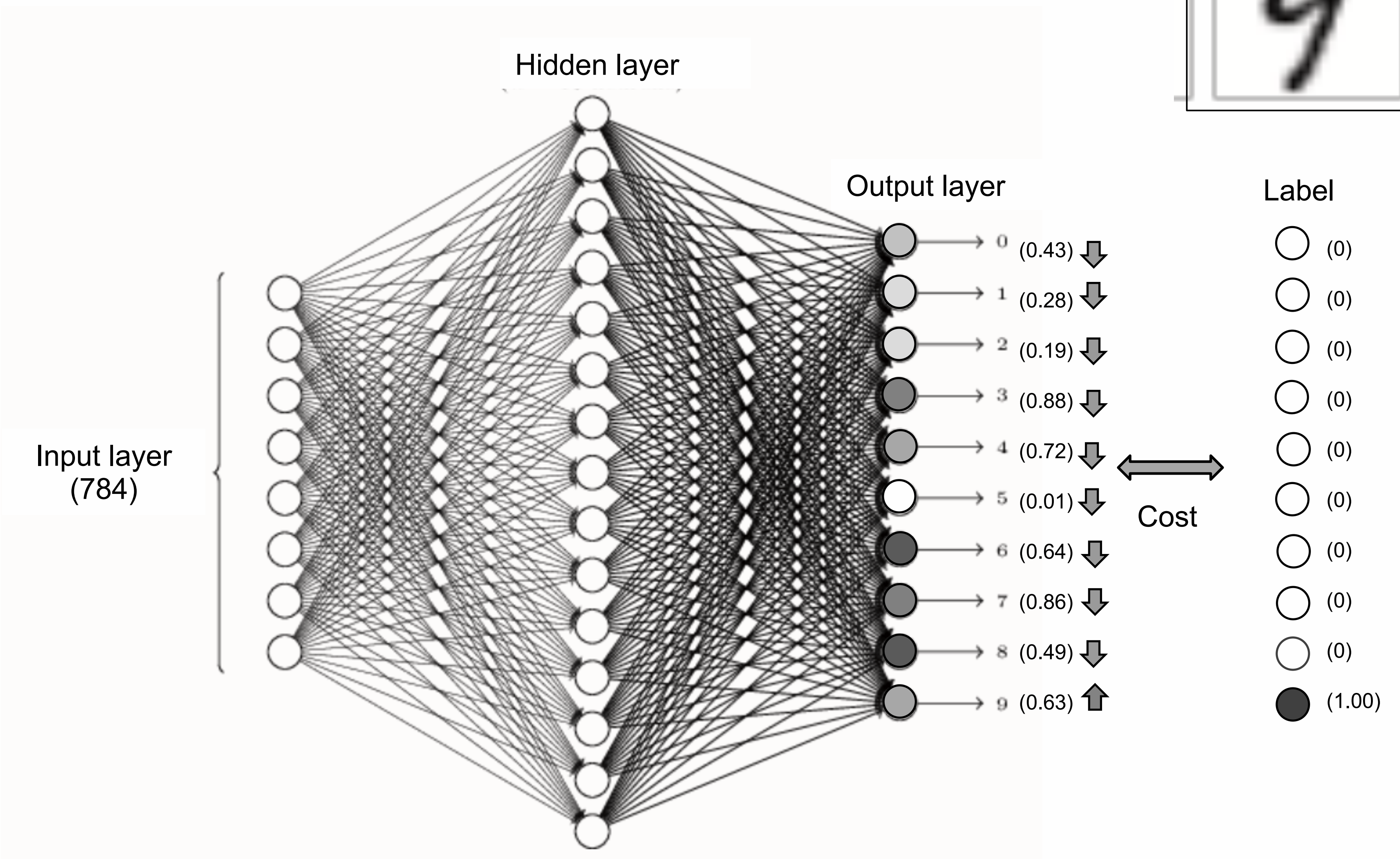
Remind – Forward propagation

$$-\nabla C(\underbrace{\ldots}_{\text{All weights and biases}}) = \begin{matrix}(0.43-0)^2 + \\ (0.28-0)^2 + \\ (0.19-0)^2 + \\ (0.88-0)^2 + \\ (0.72-0)^2 + \\ (0.01-0)^2 + \\ (0.64-0)^2 + \\ (0.86-0)^2 + \\ (0.49-0)^2 + \\ (0.63-1)^2\end{matrix} = \begin{bmatrix}0.19 \\ 0.86 \\ -0.85 \\ . \\ . \\ . \\ -0.05 \\ 0.24 \\ 0.13\end{bmatrix}$$

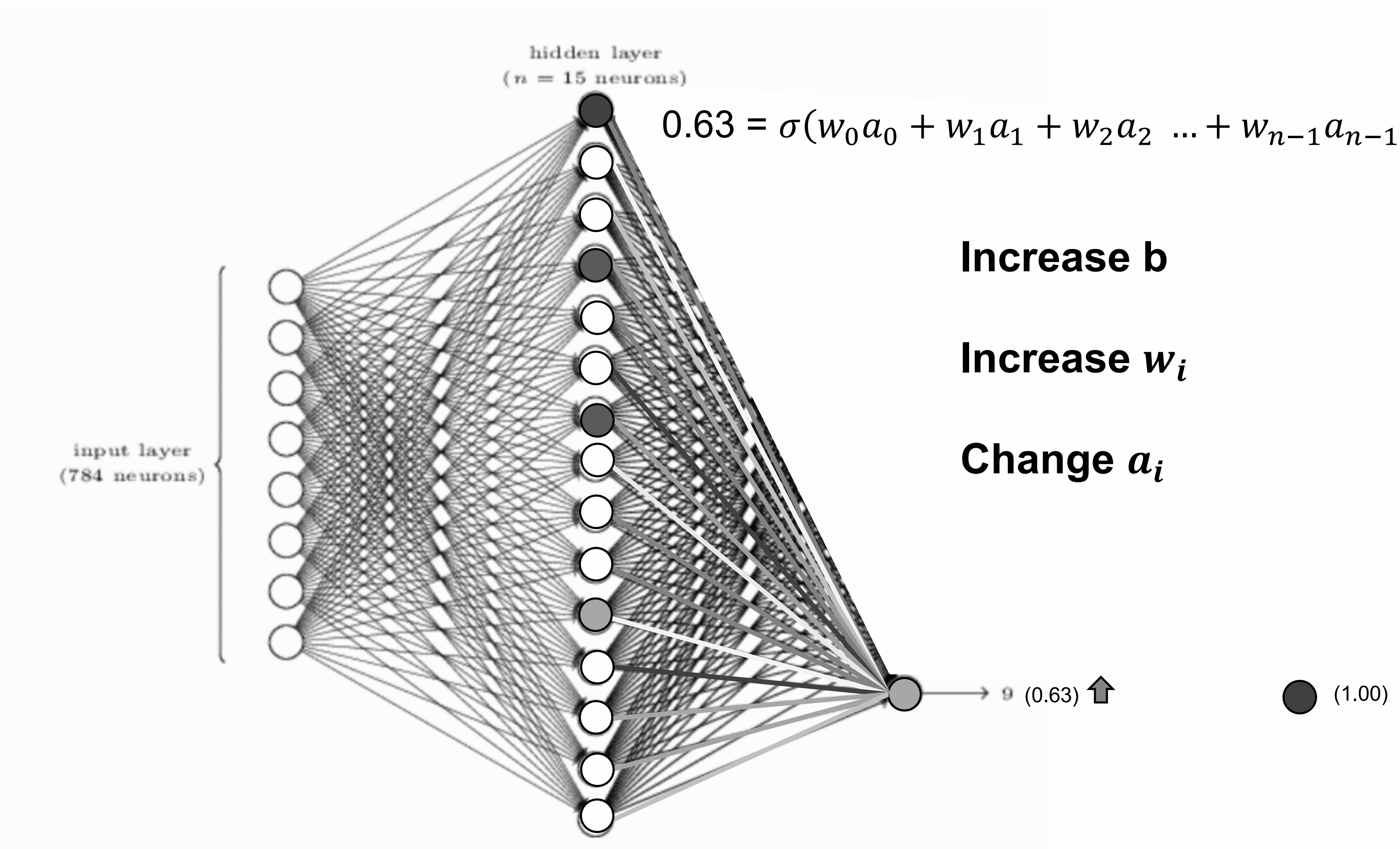


C(W_0 ,W_1, W_2, W_3, W_4,… W_{11910}) = 3.27

Remind – Forward propagation



Remind – Forward propagation



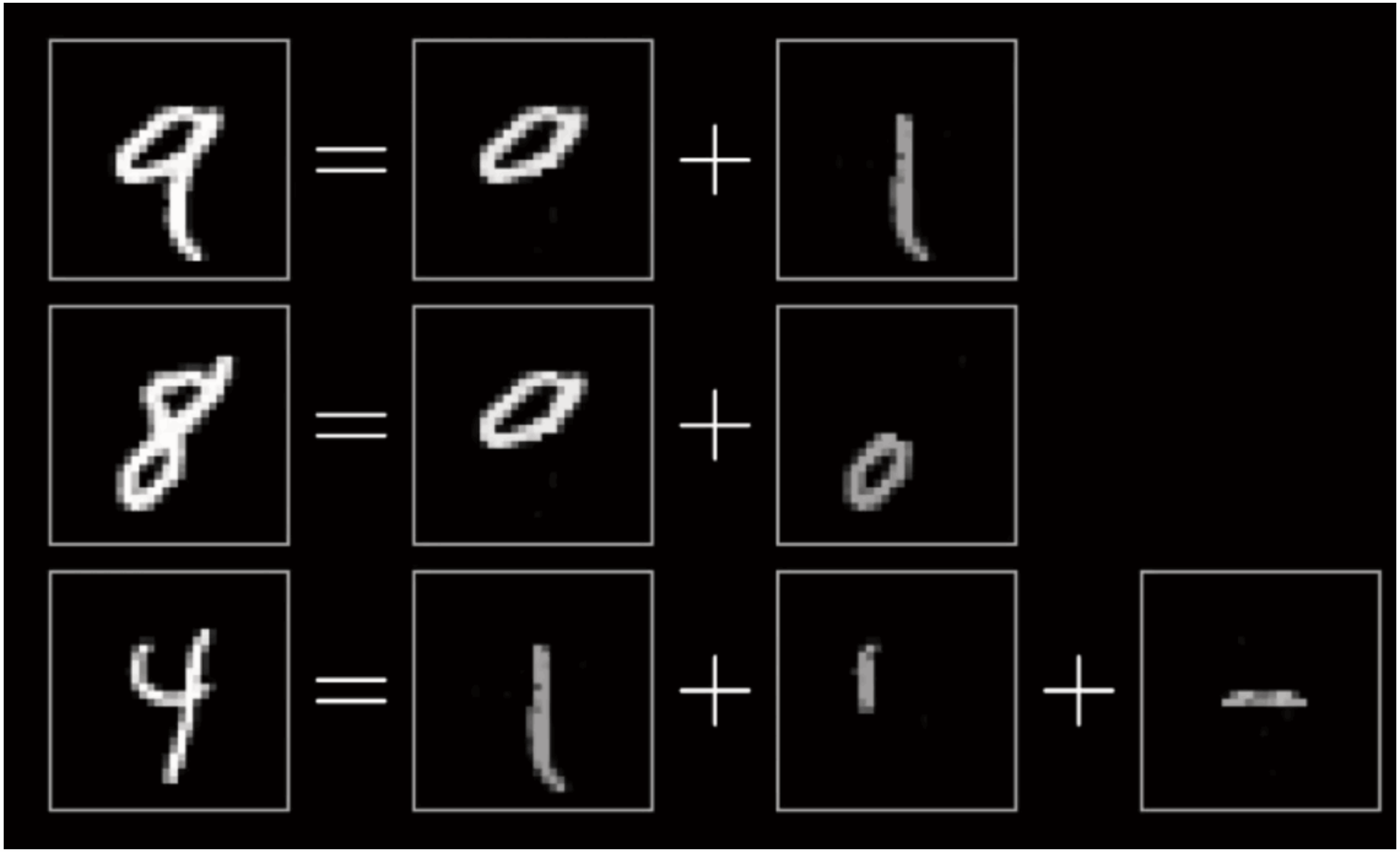
$0.63 = \sigma(w_0 a_0 + w_1 a_1 + w_2 a_2 \; ... + w_{n-1} a_{n-1} + b)$

Increase b

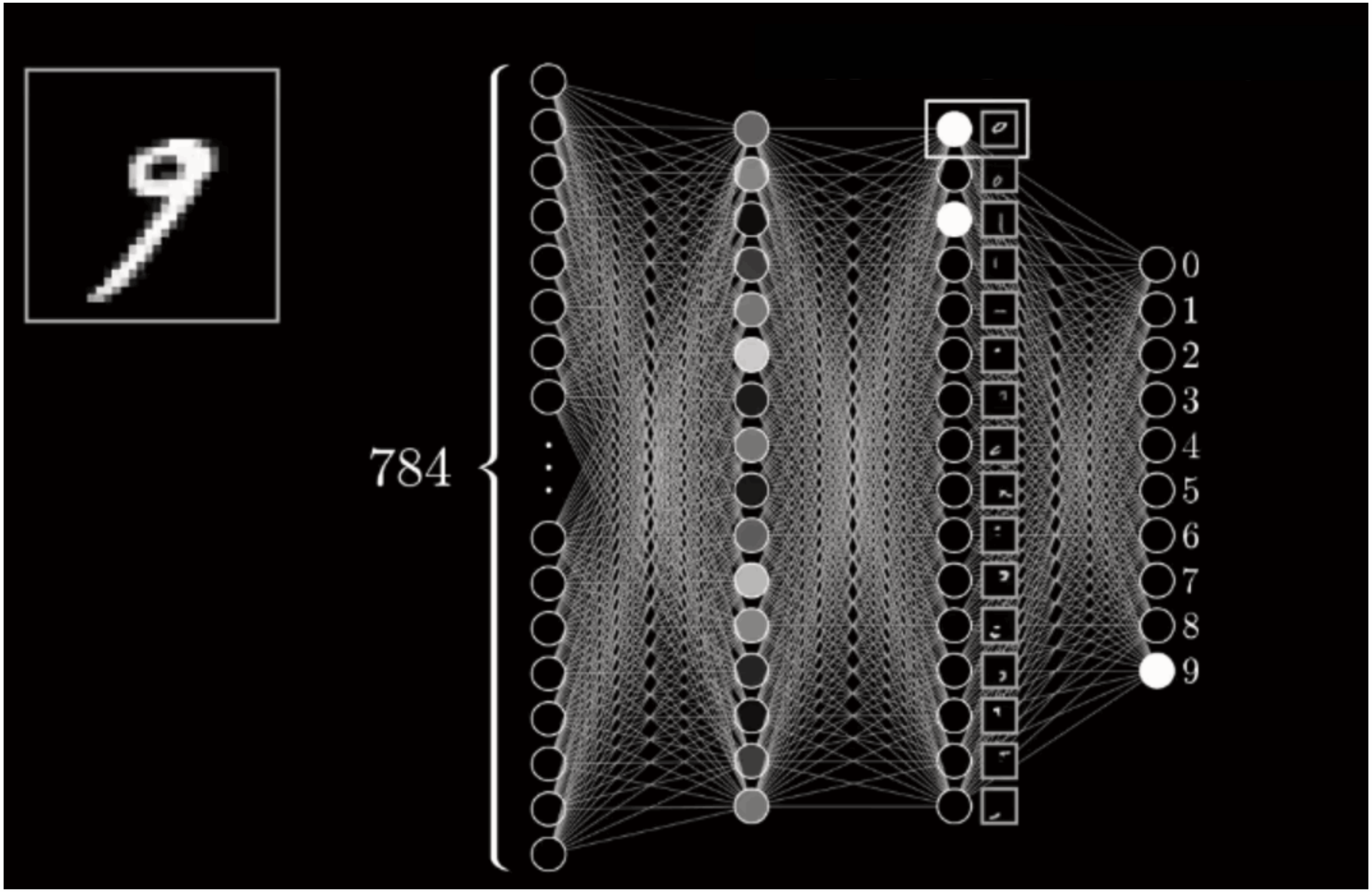
Increase w_i

Change a_i

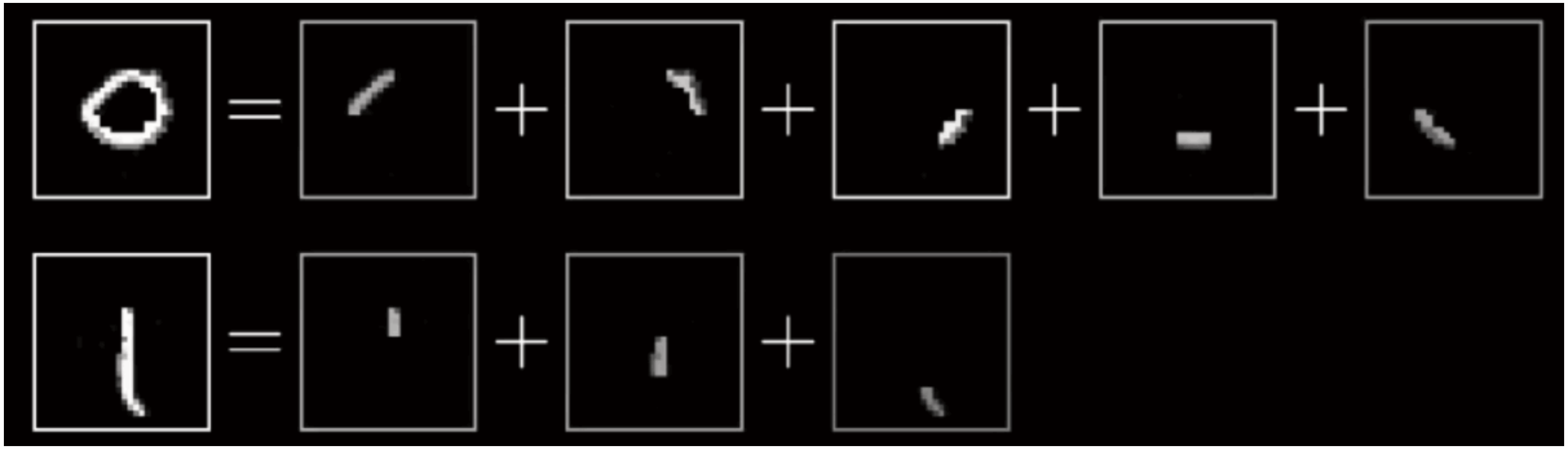
Backpropagation



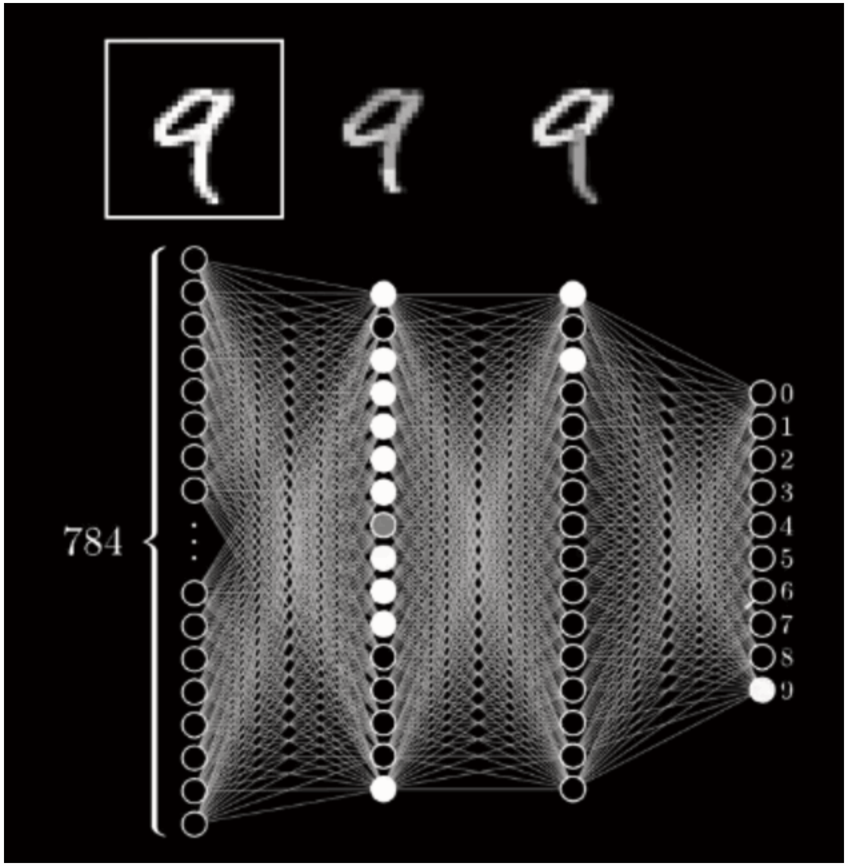
Backpropagation



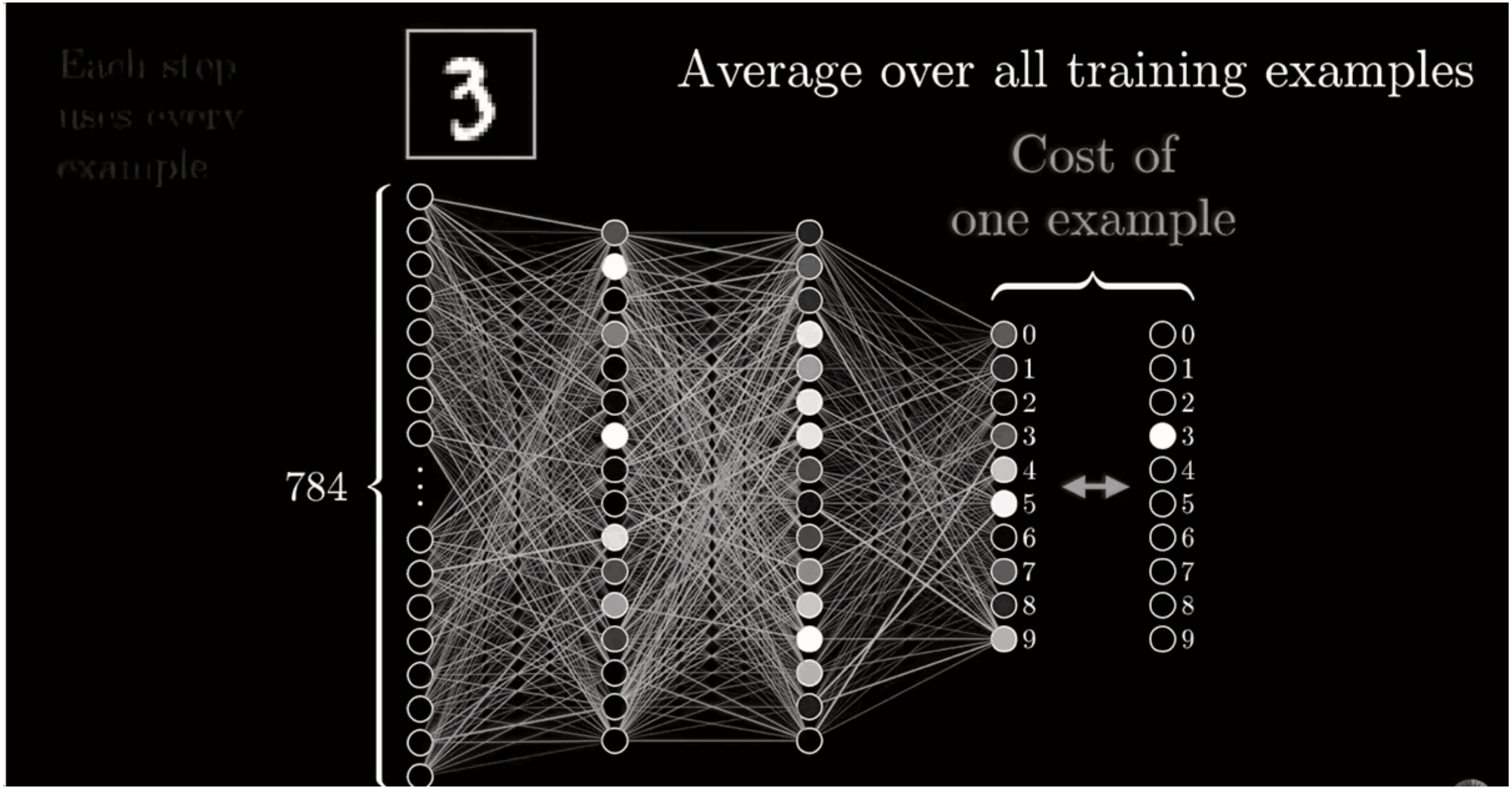
Backpropagation



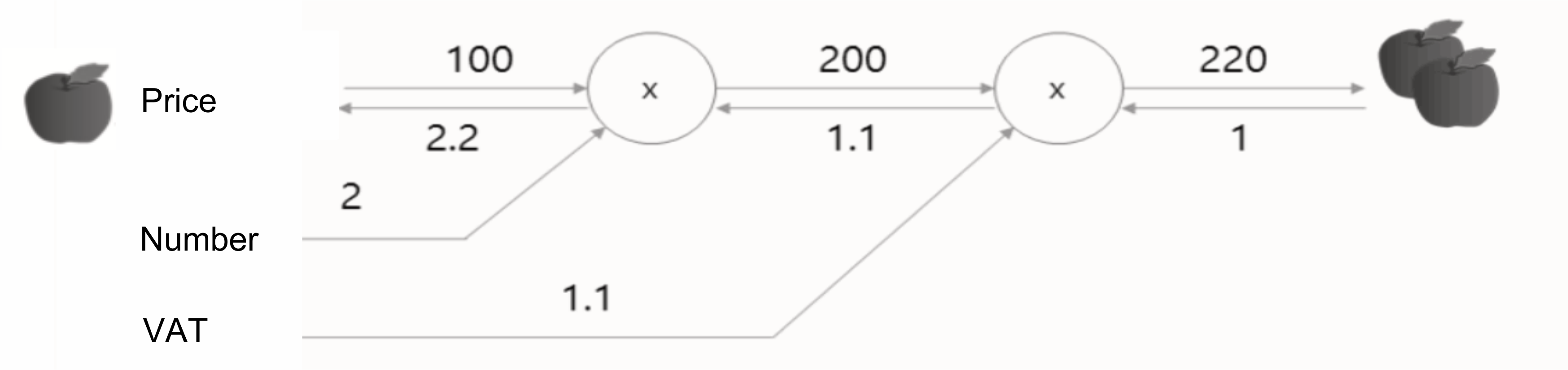
Backpropagation



Backpropagation



Backpropagation

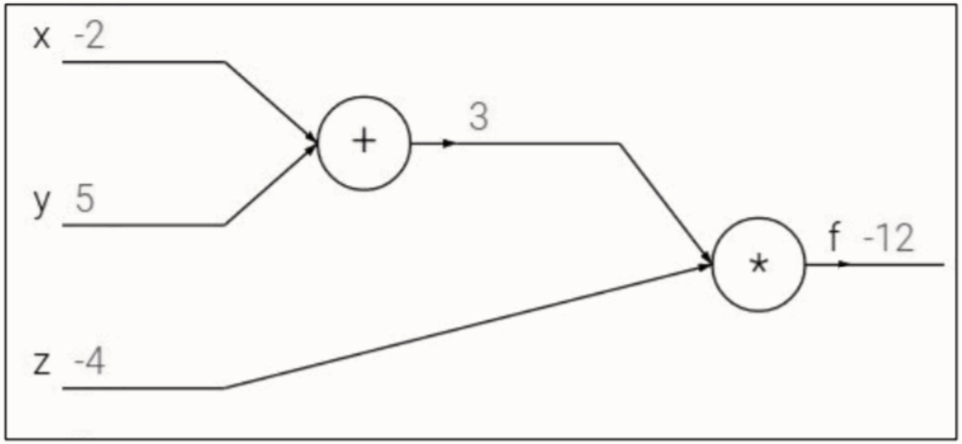


Backpropagation

Backpropagation: a simple example

$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4



Backpropagation

Backpropagation: a simple example

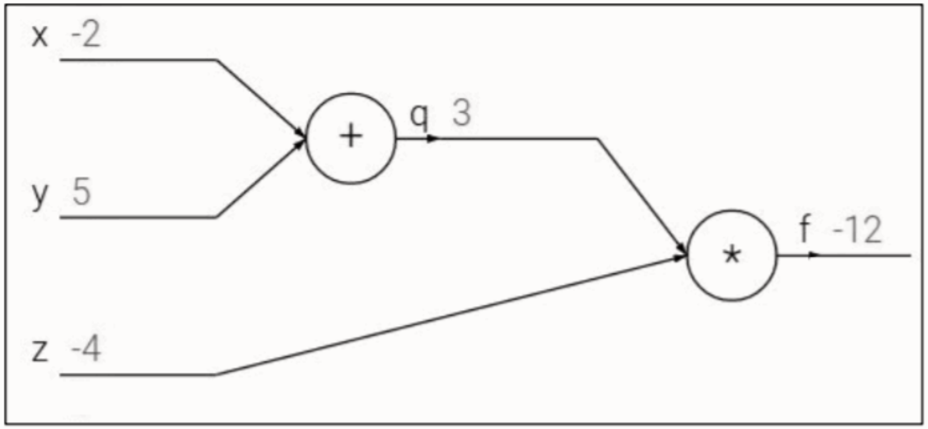
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation

Backpropagation: a simple example

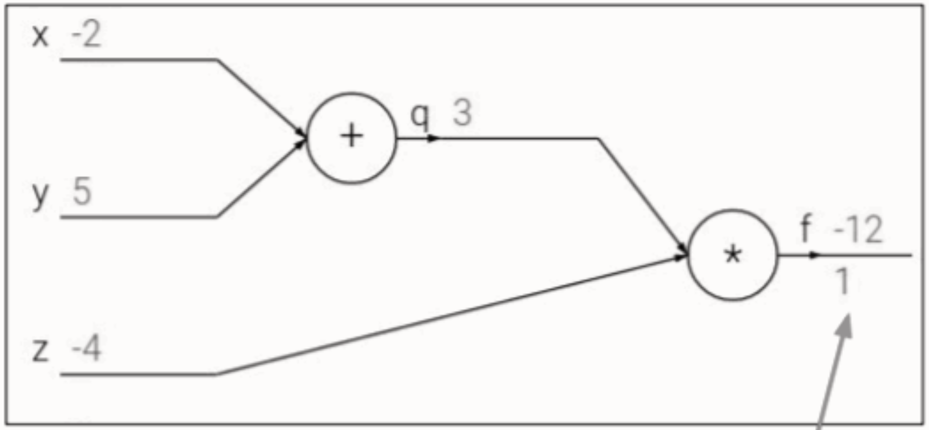
$$f(x,y,z) = (x+y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



$$\frac{\partial f}{\partial f}$$

Backpropagation

Backpropagation: a simple example

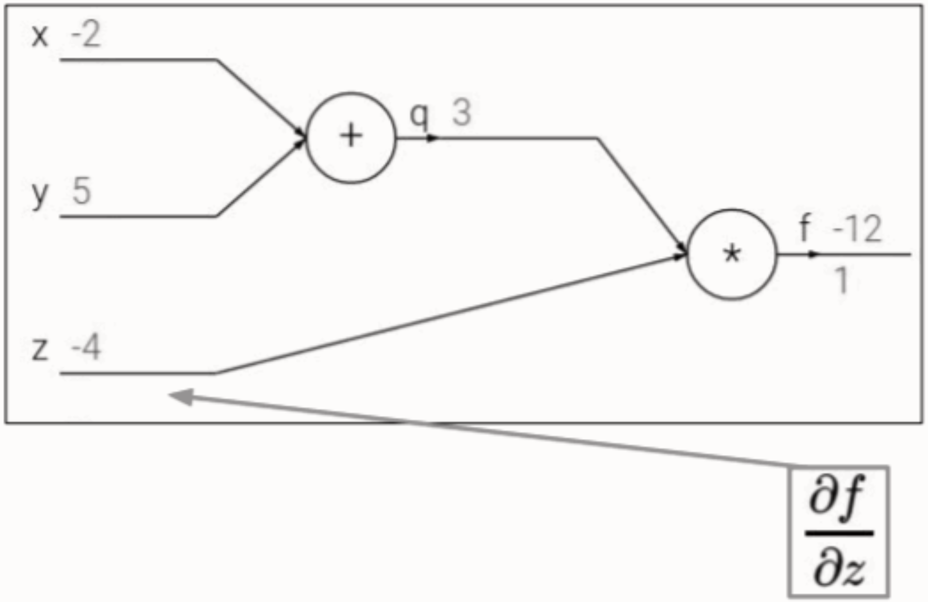
$$f(x,y,z) = (x+y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation

Backpropagation: a simple example

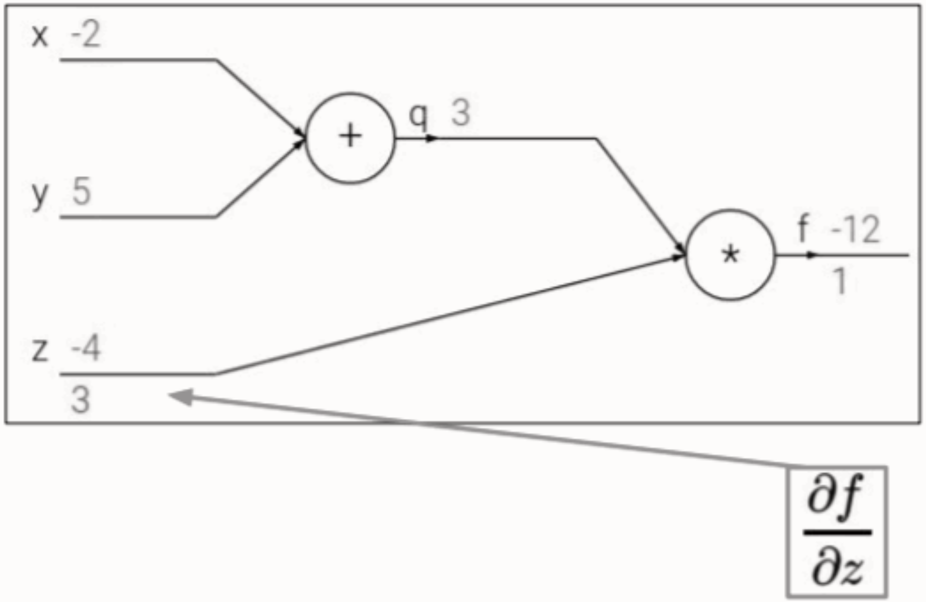
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation

Backpropagation: a simple example

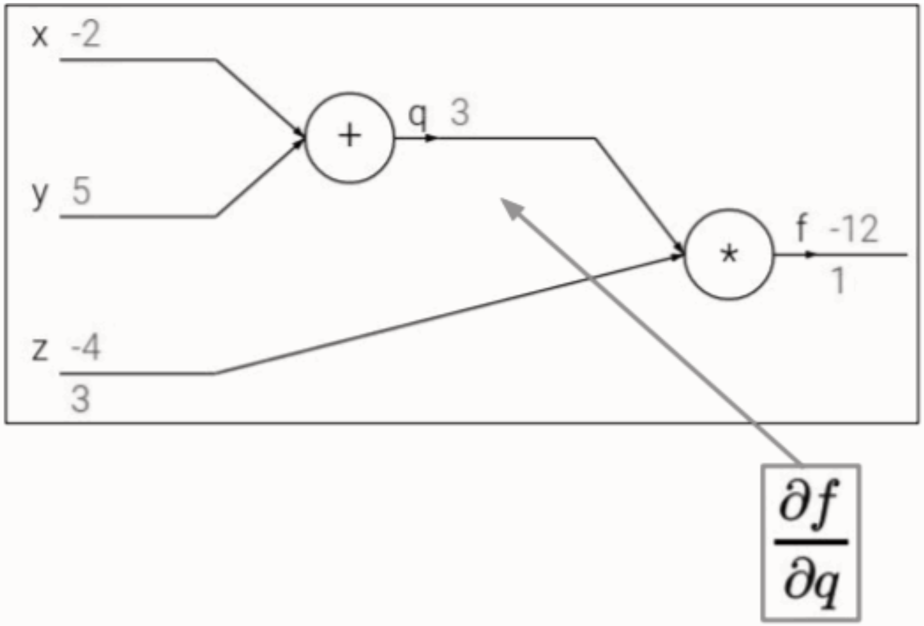
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation

Backpropagation: a simple example

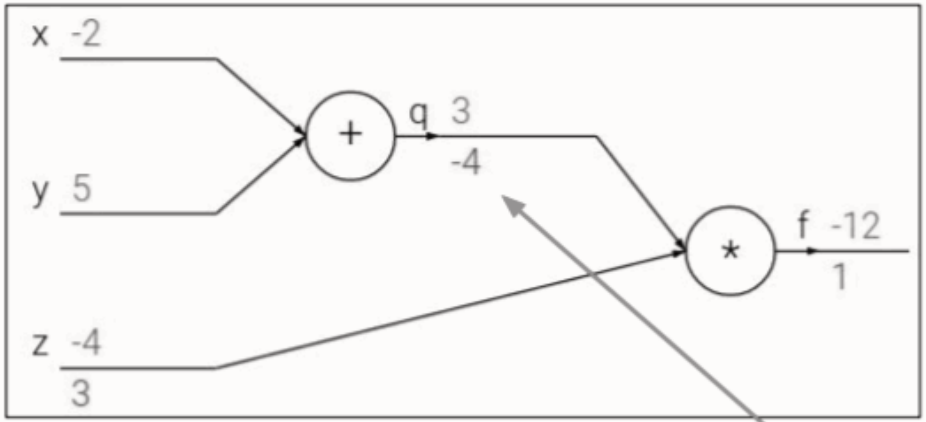
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



$$\frac{\partial f}{\partial q}$$

Backpropagation

Backpropagation: a simple example

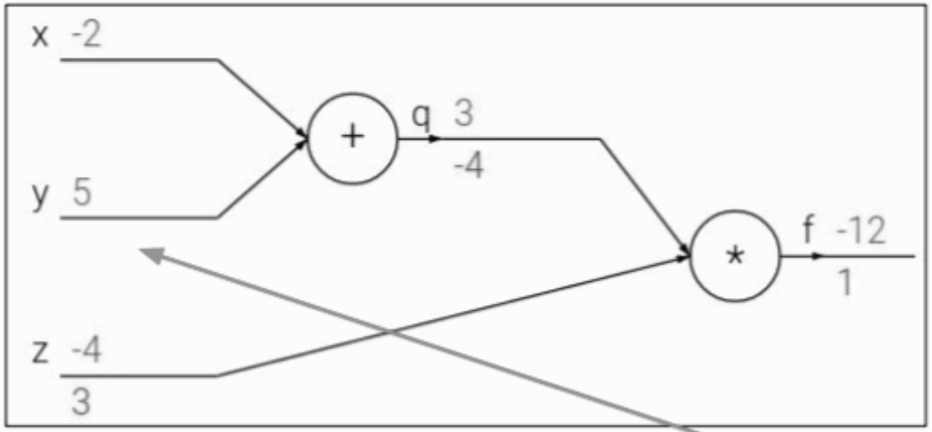
$$f(x,y,z) = (x+y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



$$\frac{\partial f}{\partial y}$$

Backpropagation

Backpropagation: a simple example

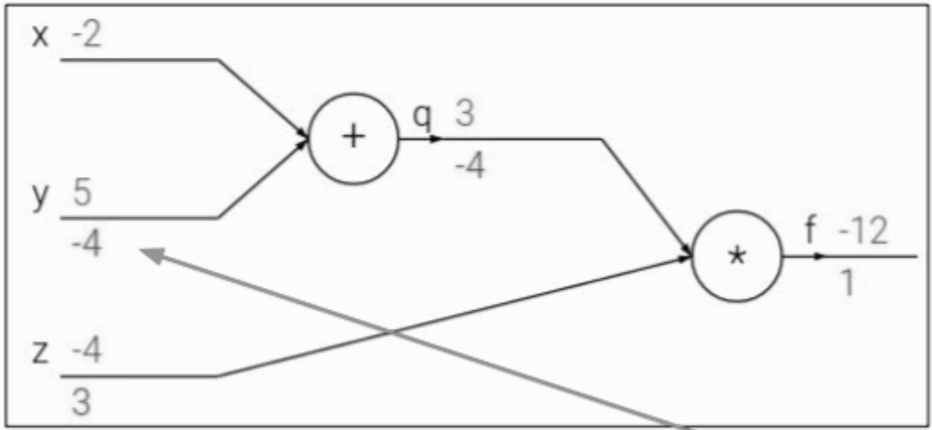
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



$$\frac{\partial f}{\partial y}$$

Chain rule:

$$\frac{\partial f}{\partial y} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial y}$$

Backpropagation

Backpropagation: a simple example

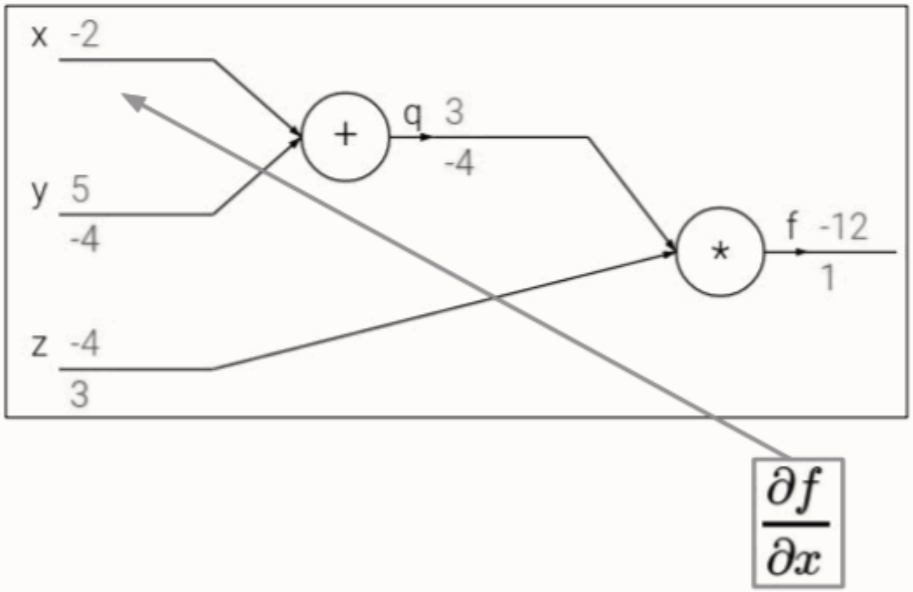
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$



Backpropagation

Backpropagation: a simple example

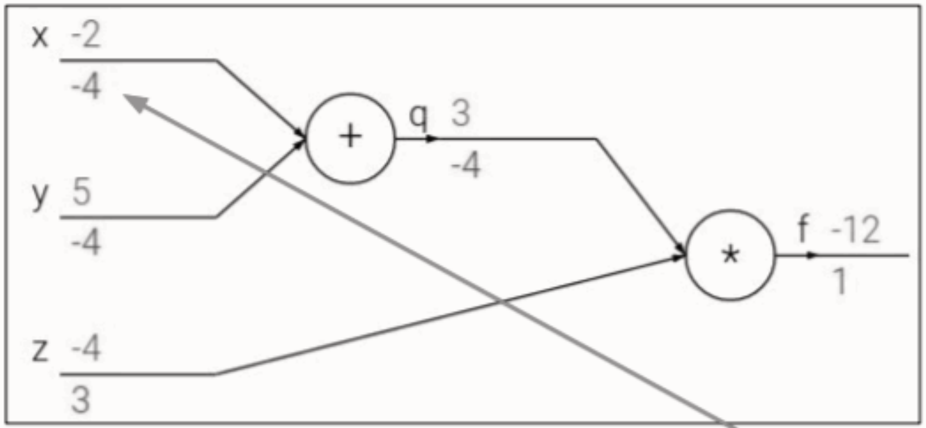
$$f(x, y, z) = (x + y)z$$

e.g. x = -2, y = 5, z = -4

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

$$f = qz \qquad \frac{\partial f}{\partial q} = z, \frac{\partial f}{\partial z} = q$$

Want: $\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}$

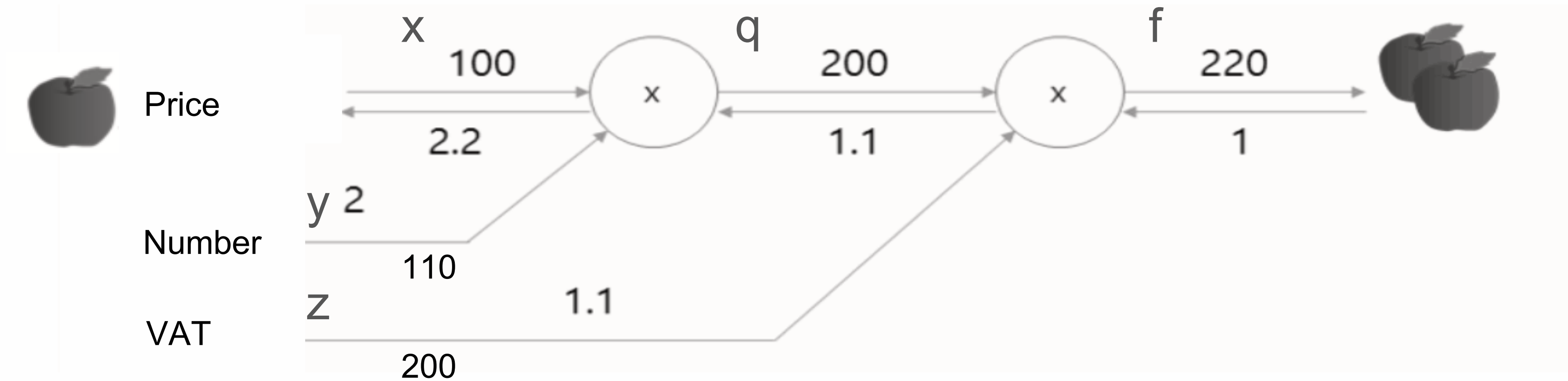


$$\boxed{\frac{\partial f}{\partial x}}$$

Chain rule:

$$\frac{\partial f}{\partial x} = \frac{\partial f}{\partial q} \frac{\partial q}{\partial x}$$

Backpropagation



$$q = x \times y$$

$$f = q \times z$$

$$\frac{\partial q}{\partial x} = y, \ \frac{\partial q}{\partial y} = x$$

$$\frac{\partial f}{\partial q} = z, \ \boxed{\frac{\partial f}{\partial z}} = q$$

$$\boxed{\frac{\partial f}{\partial x}} = \frac{\partial f}{\partial q}\frac{\partial q}{\partial x} = z \times y, \ \boxed{\frac{\partial f}{\partial y}} = \frac{\partial f}{\partial q}\frac{\partial q}{\partial y} = z \times x$$

$if \ \ x = 100 + 1 = 101, \quad then \ \ f = 220 + 2.2 = 222.2$

$prof. \ 101 \times 2 \times 1.1 = 222.2$

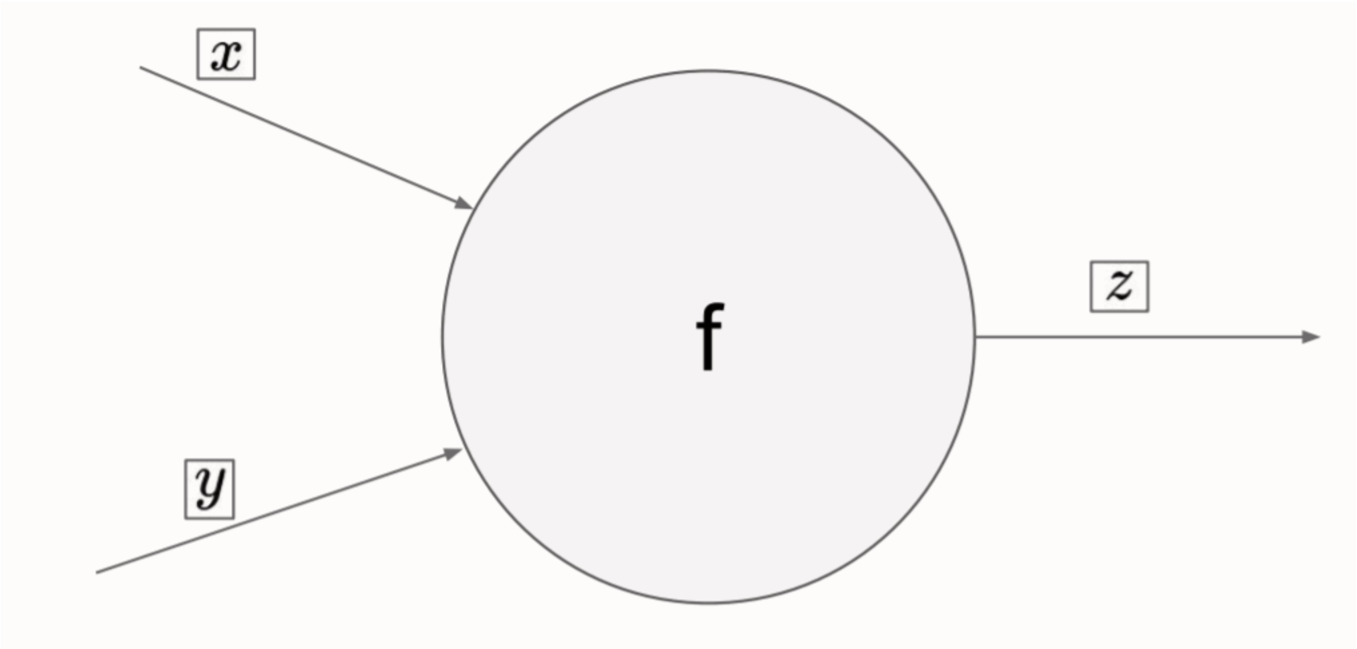
$if \ \ y = 2 + 1 = 3, \quad then \ \ f = 220 + 110 = 330$

$prof. \ 100 \times 3 \times 1.1 = 330$

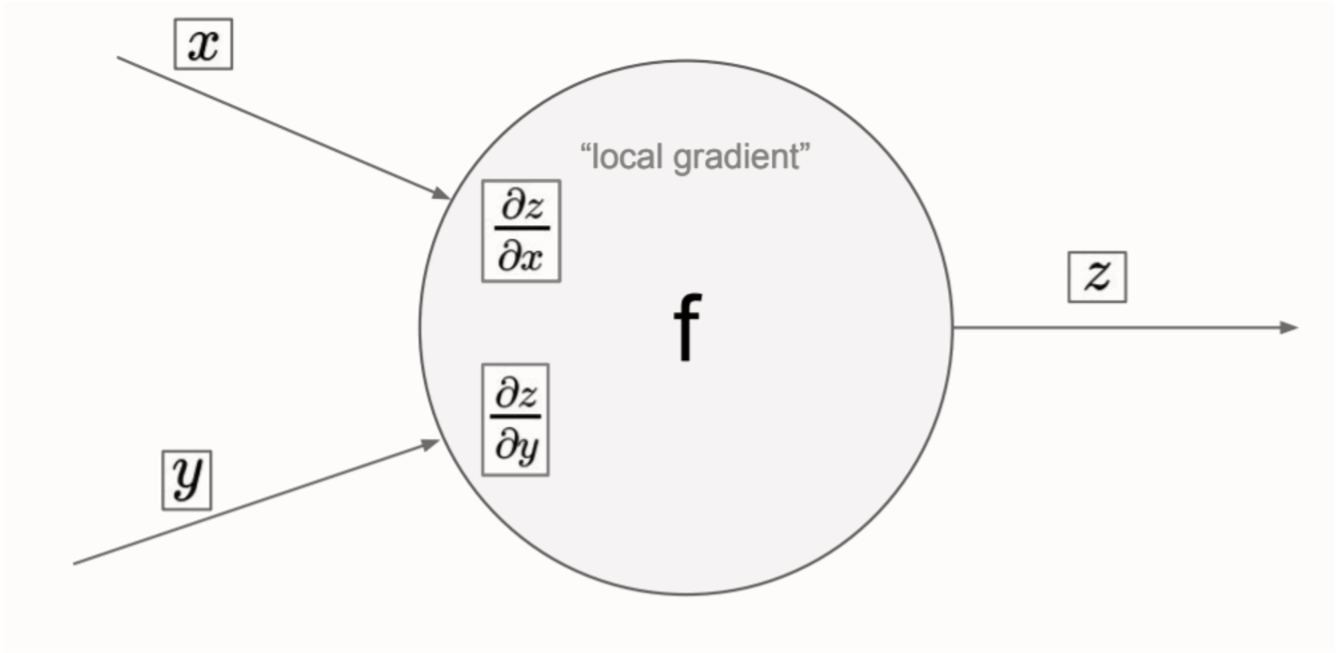
$if \ \ z = 1.1 + 1 = 2.1, \quad then \ \ f = 220 + 200 = 420$

$prof. \ 100 \times 2 \times 2.1 = 420$

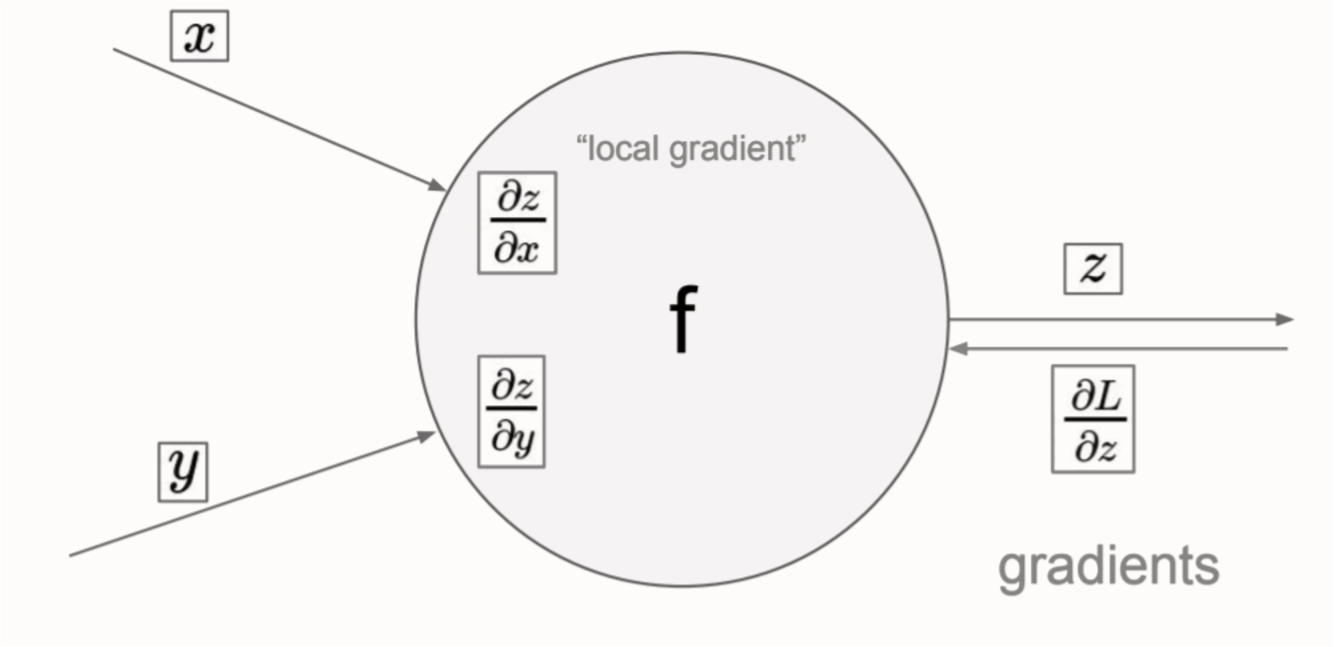
Backpropagation



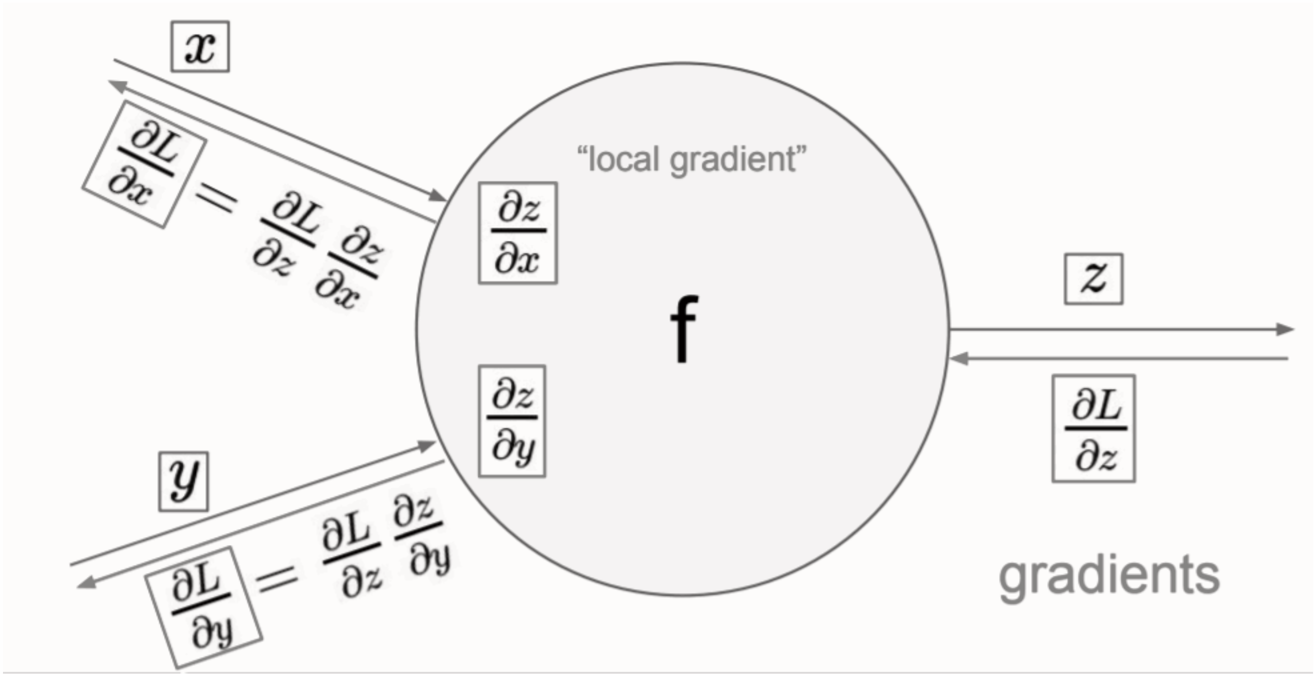
Backpropagation



Backpropagation

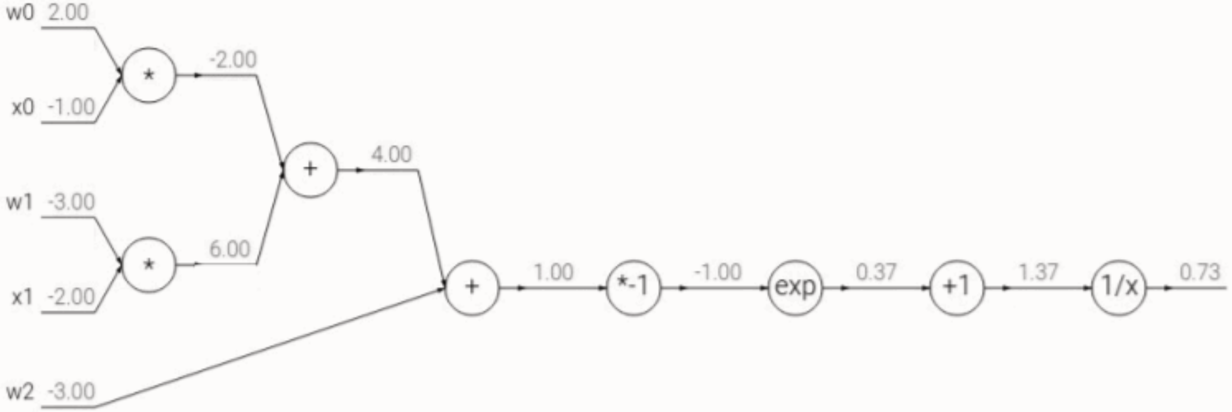


Backpropagation



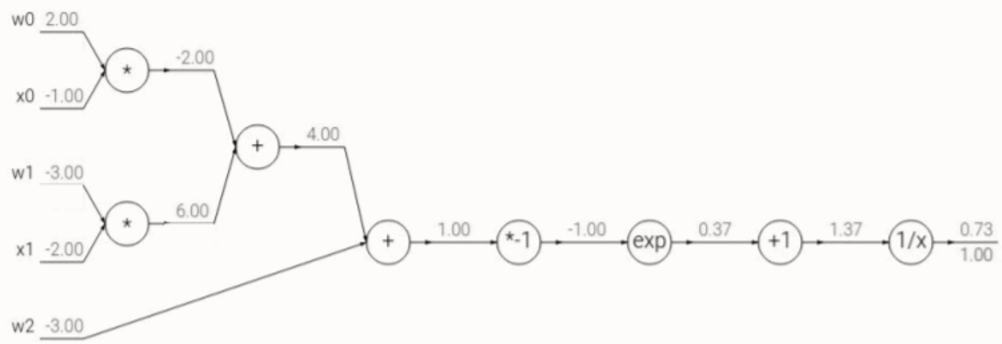
Backpropagation

Another example: $f(w,x) = \frac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$



Backpropagation

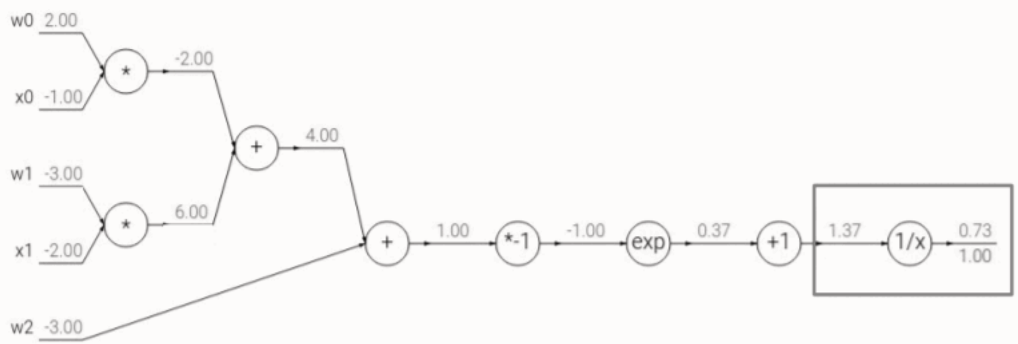
Another example: $f(w,x) = \dfrac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$



$f(x) = e^x$	$\rightarrow$	$\dfrac{df}{dx} = e^x$	$f(x) = \dfrac{1}{x}$	$\rightarrow$	$\dfrac{df}{dx} = -1/x^2$
$f_a(x) = ax$	$\rightarrow$	$\dfrac{df}{dx} = a$	$f_c(x) = c + x$	$\rightarrow$	$\dfrac{df}{dx} = 1$

Backpropagation

Another example: $$f(w,x) = \frac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$$



$$f(x) = e^x \quad \rightarrow \quad \frac{df}{dx} = e^x$$

$$f_a(x) = ax \quad \rightarrow \quad \frac{df}{dx} = a$$

$$\boxed{f(x) = \frac{1}{x} \quad \rightarrow \quad \frac{df}{dx} = -1/x^2}$$

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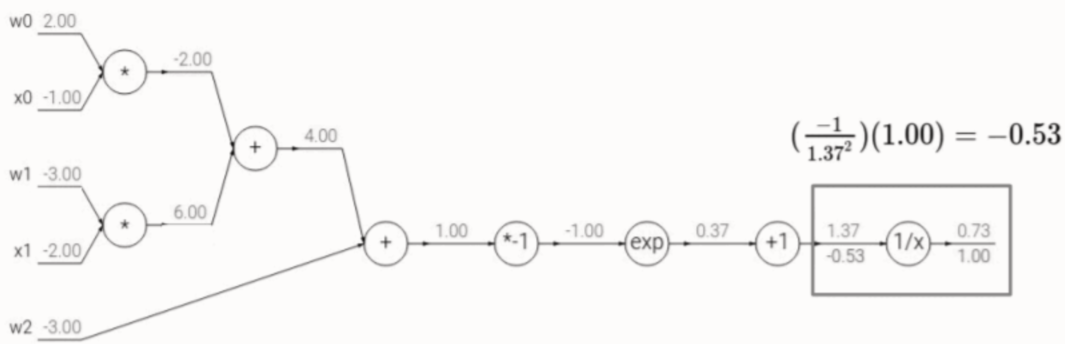

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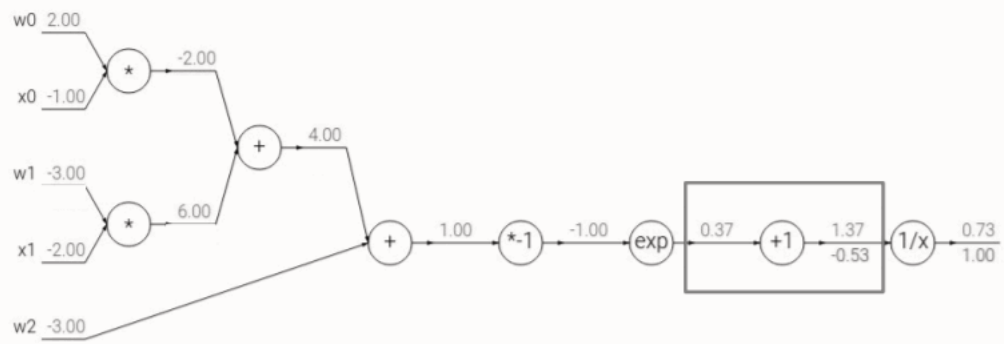

$$f(x) = e^x \quad \rightarrow \quad \frac{df}{dx} = e^x$$

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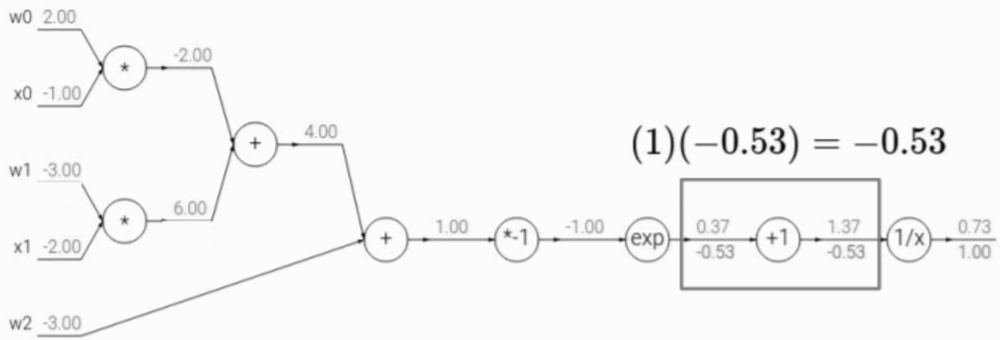

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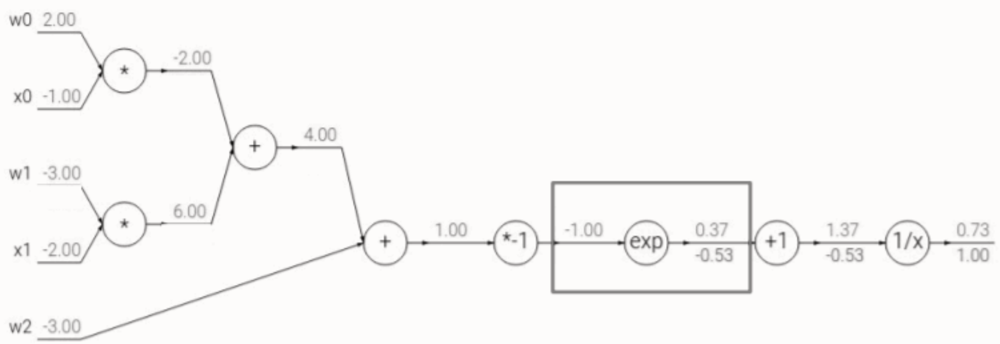

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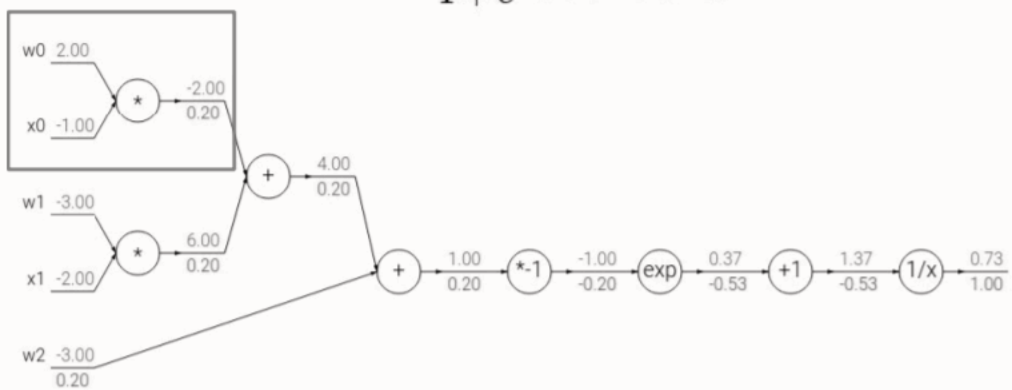

$$f(x) = e^x \quad \rightarrow \quad \frac{df}{dx} = e^x \qquad\qquad f(x) = \frac{1}{x} \quad \rightarrow \quad \frac{df}{dx} = -1/x^2$$

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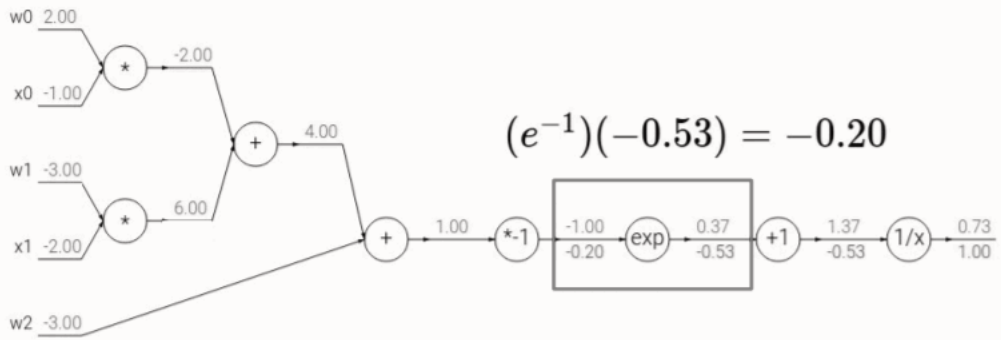
Backpropagation

Another example: $f(w,x) = \dfrac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$

$$(e^{-1})(-0.53) = -0.20$$



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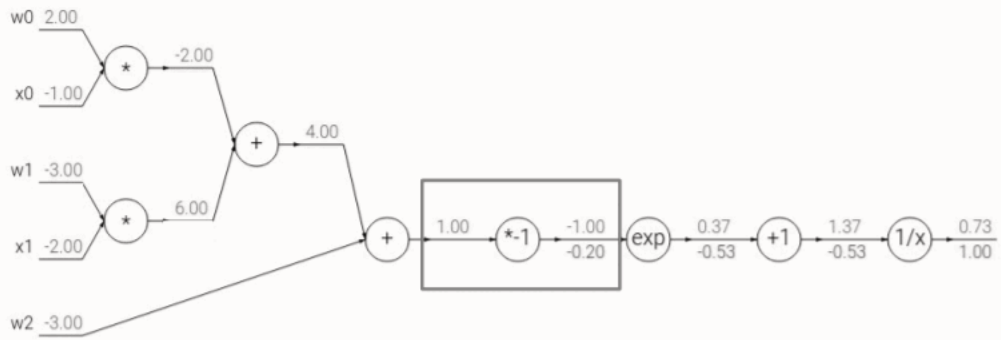

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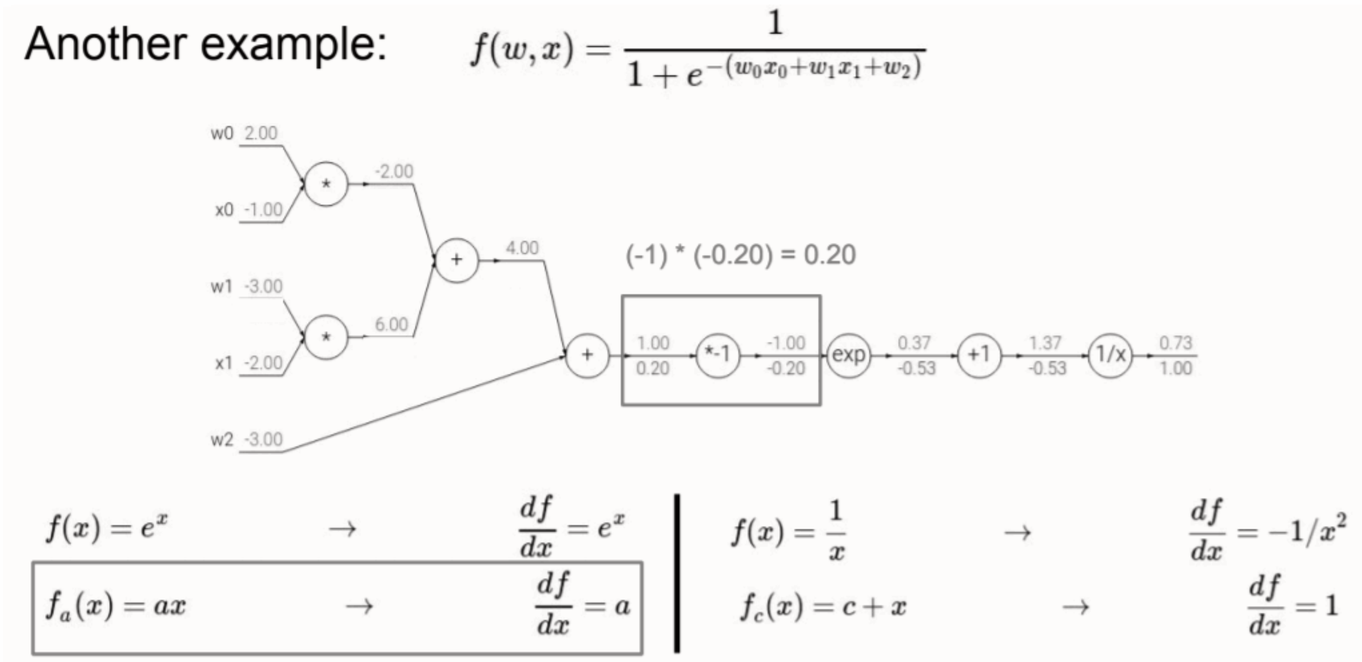
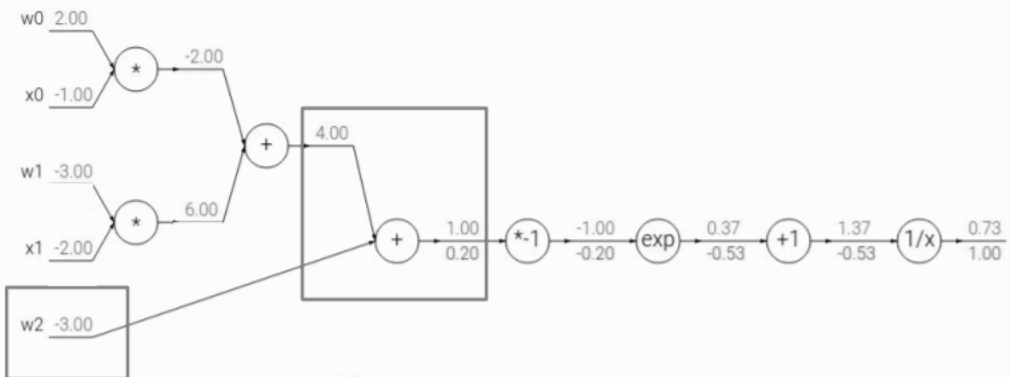
Backpropagation



Backpropagation

Another example: $f(w,x) = \dfrac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$



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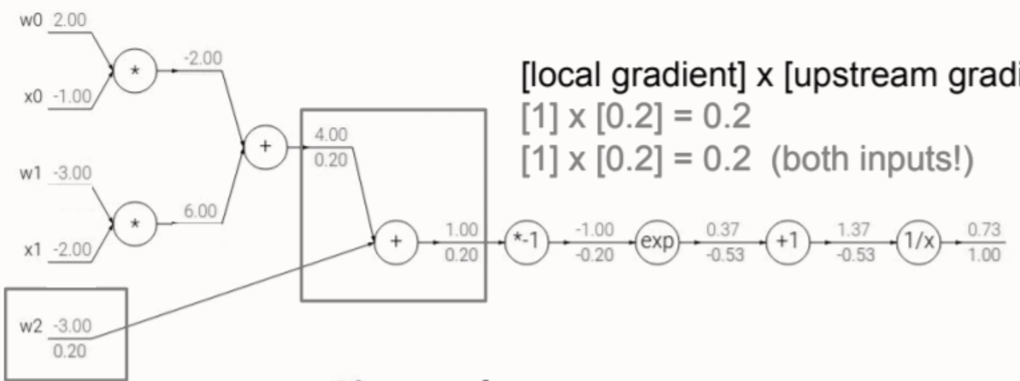

[local gradient] x [upstream gradient]
[1] x [0.2] = 0.2
[1] x [0.2] = 0.2 (both inputs!)

$f(x) = e^x \quad \rightarrow \quad \dfrac{df}{dx} = e^x$

$f_a(x) = ax \quad \rightarrow \quad \dfrac{df}{dx} = a$

$f(x) = \dfrac{1}{x} \quad \rightarrow \quad \dfrac{df}{dx} = -1/x^2$

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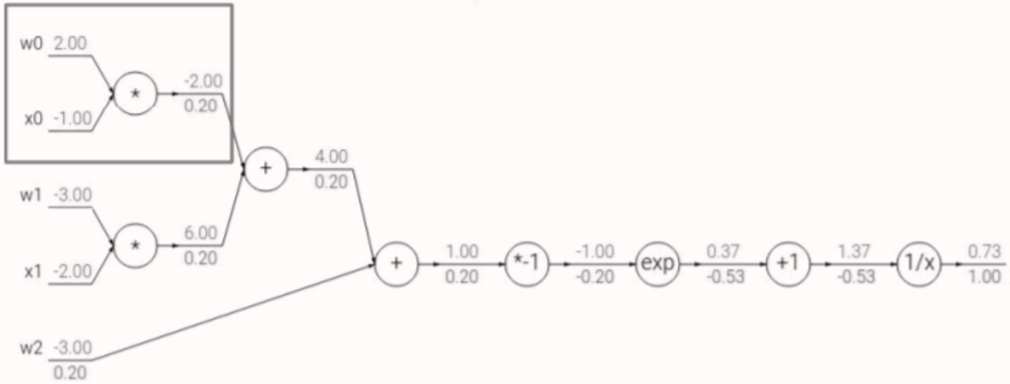

$f(x) = e^x \quad \rightarrow \quad \frac{df}{dx} = e^x$

$f_a(x) = ax \quad \rightarrow \quad \frac{df}{dx} = a$

$f(x) = \frac{1}{x} \quad \rightarrow \quad \frac{df}{dx} = -1/x^2$

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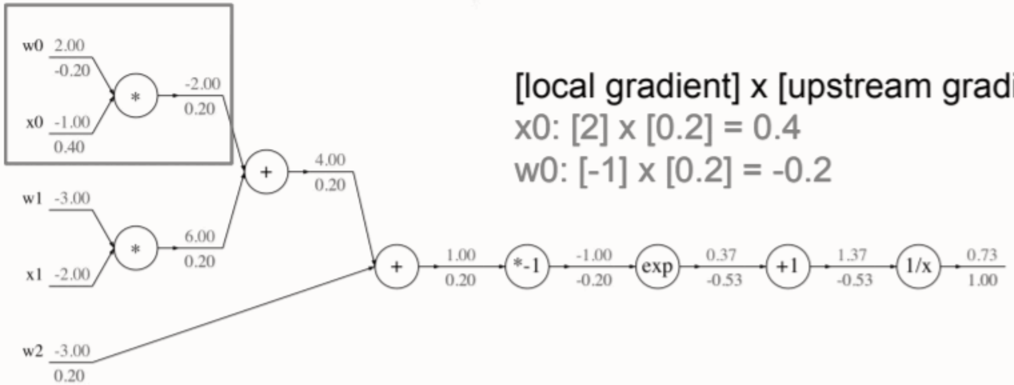
Backpropagation

Another example: $f(w,x) = \frac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$

[local gradient] x [upstream gradient]
x0: [2] x [0.2] = 0.4
w0: [-1] x [0.2] = -0.2



$f(x) = e^x \rightarrow \frac{df}{dx} = e^x$ | $f(x) = \frac{1}{x} \rightarrow \frac{df}{dx} = -1/x^2$

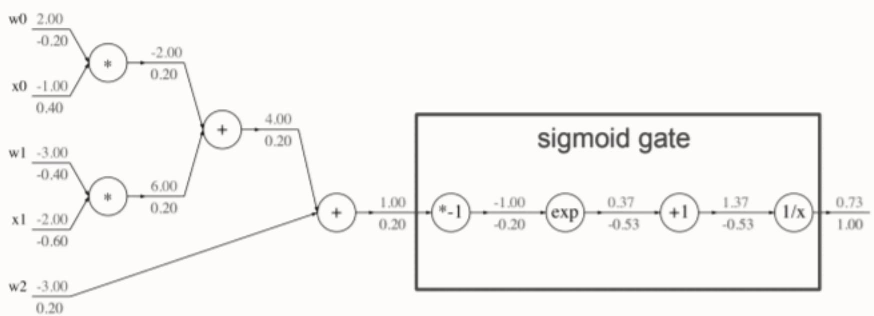
$f_a(x) = ax \rightarrow \frac{df}{dx} = a$ | $f_c(x) = c + x \rightarrow \frac{df}{dx} = 1$

Backpropagation

$$f(w,x) = \frac{1}{1+e^{-(w_0x_0+w_1x_1+w_2)}}$$

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

$$\frac{d\sigma(x)}{dx} = \frac{e^{-x}}{(1+e^{-x})^2} = \left(\frac{1+e^{-x}-1}{1+e^{-x}}\right)\left(\frac{1}{1+e^{-x}}\right) = (1-\sigma(x))\,\sigma(x)$$



Backpropagation

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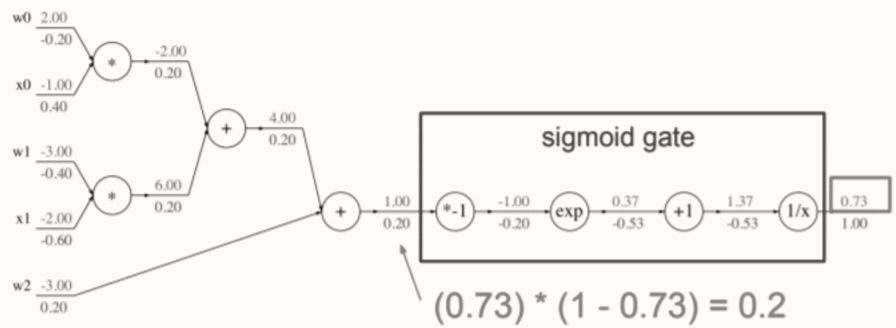
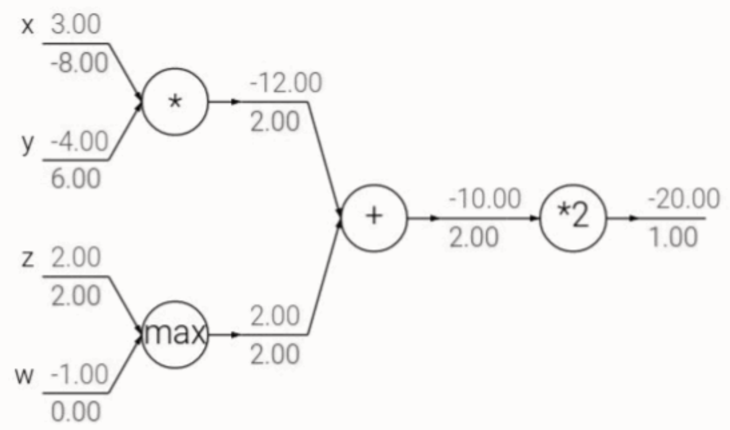


Backpropagation

Patterns in backward flow

add gate: gradient distributor

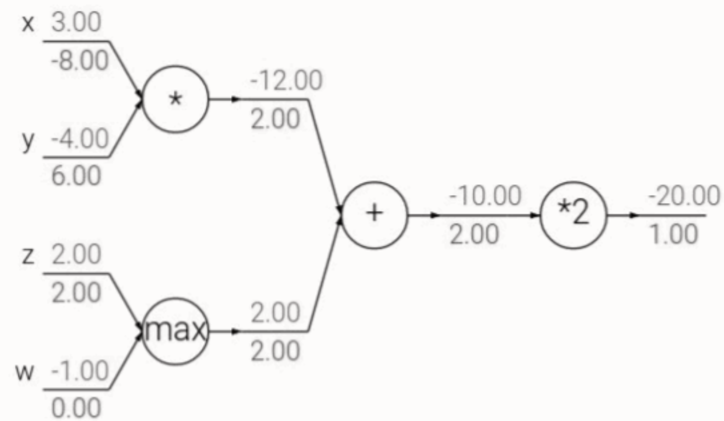


Backpropagation

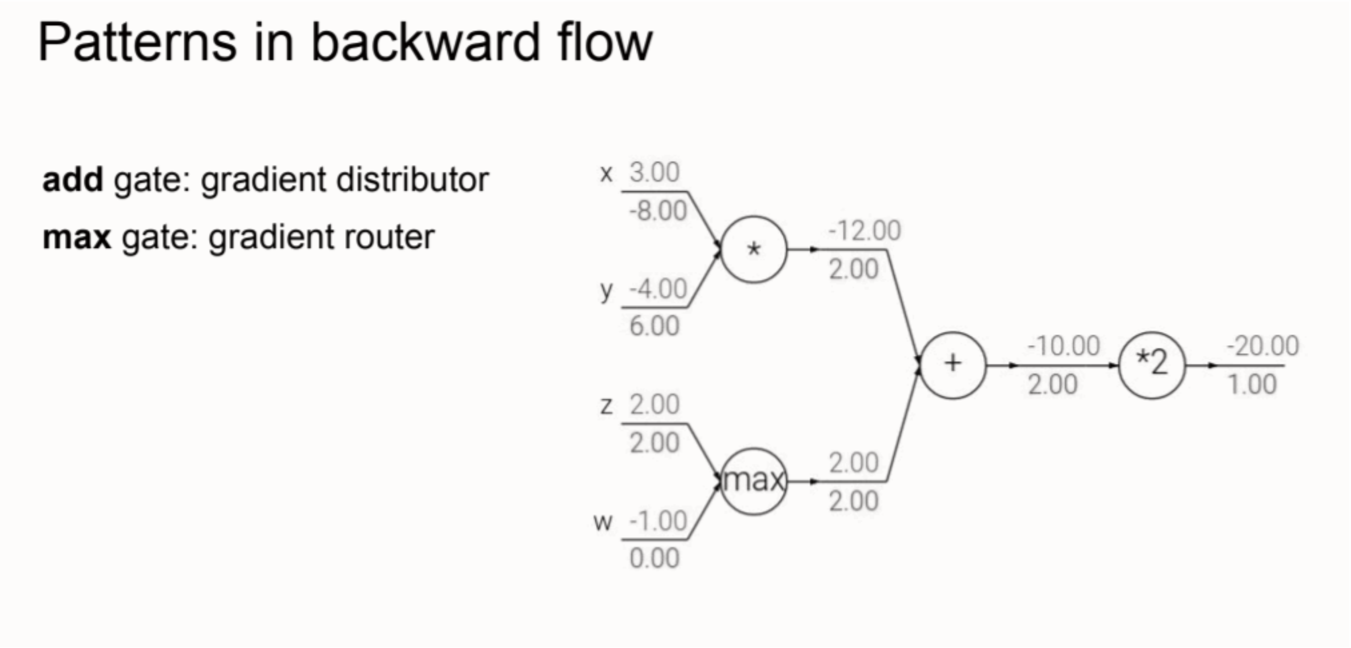
Patterns in backward flow

add gate: gradient distributor

Q: What is a **max** gate?



Backpropagation



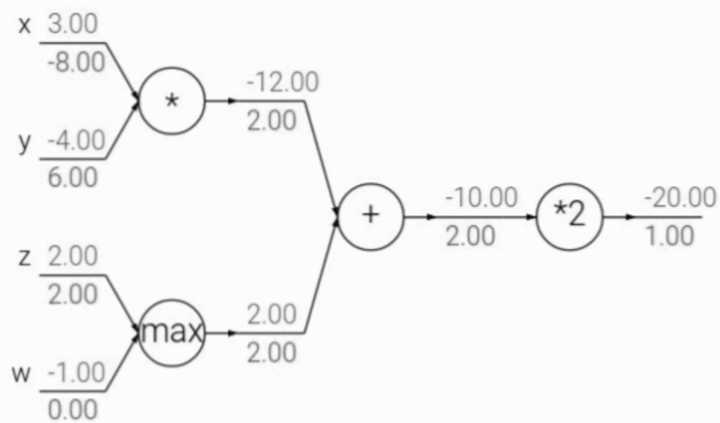
Backpropagation

Patterns in backward flow

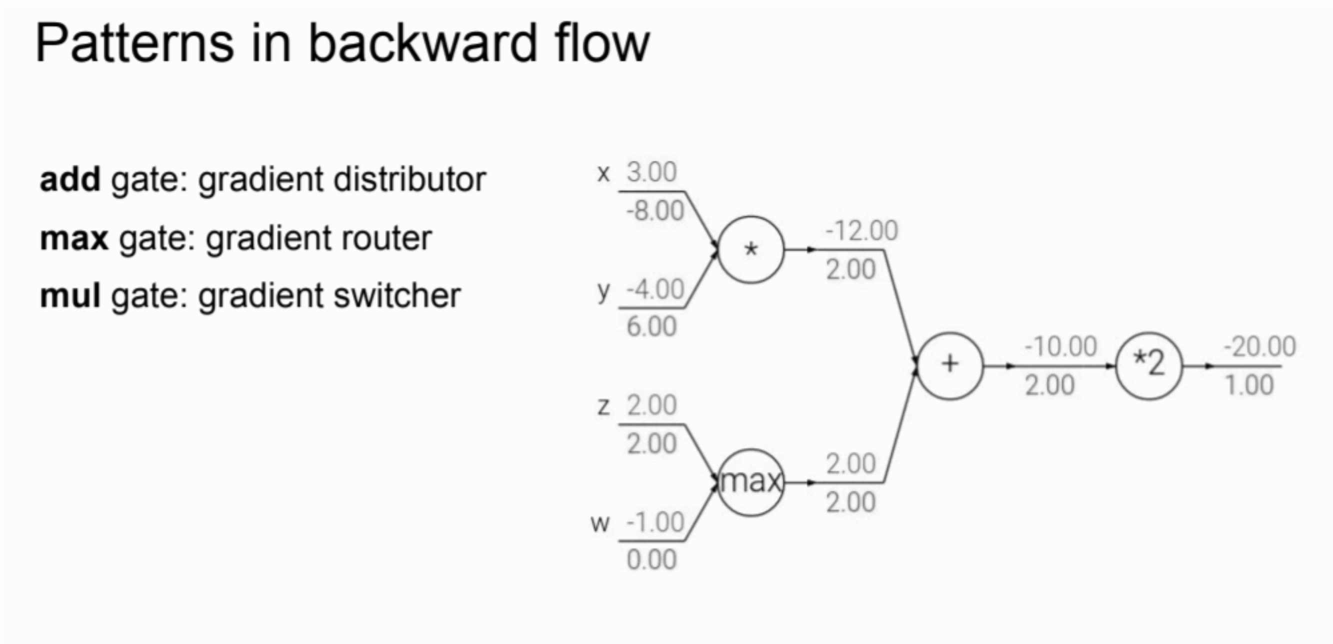
add gate: gradient distributor

max gate: gradient router

Q: What is a **mul** gate?



Backpropagation

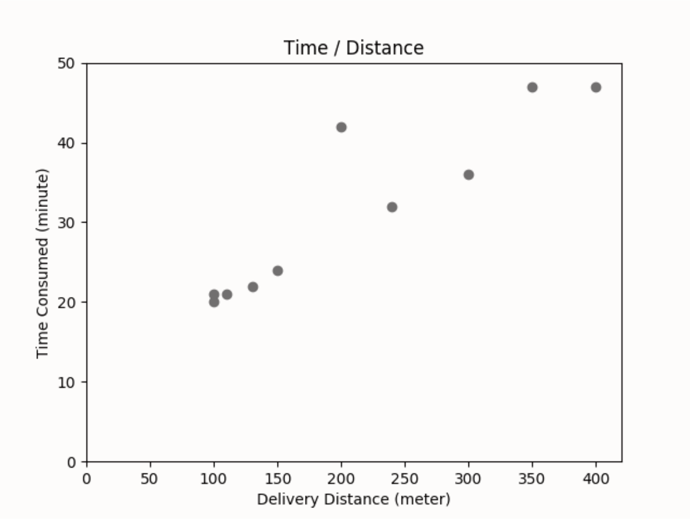


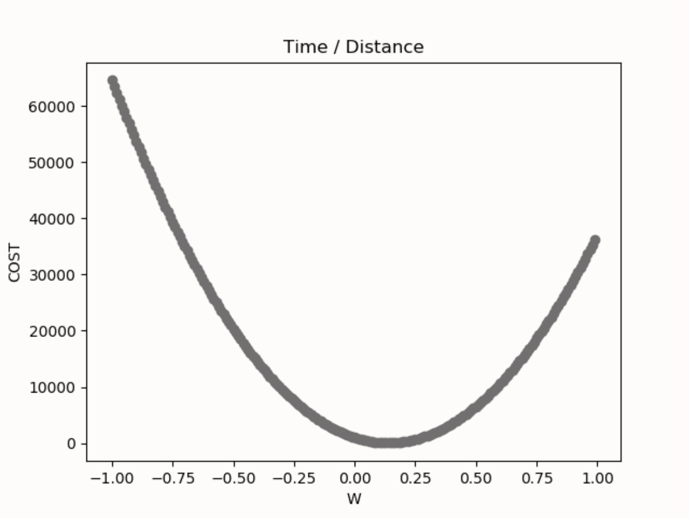
SUMMARY

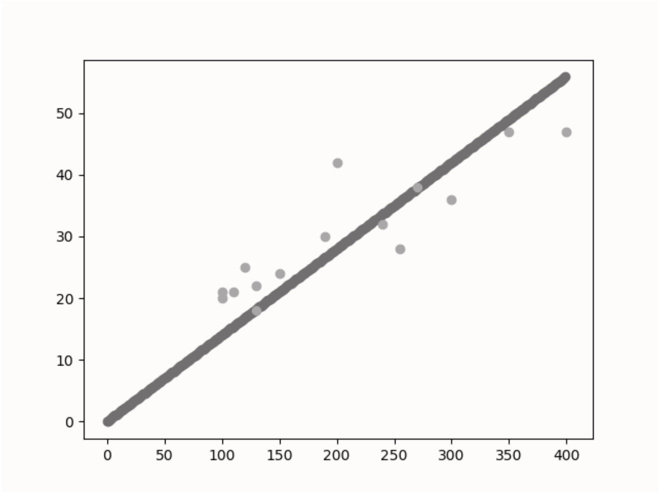
1. Linear regression
2. Multi input Linear regression
3. Logistic Classification
4. Back Propagation

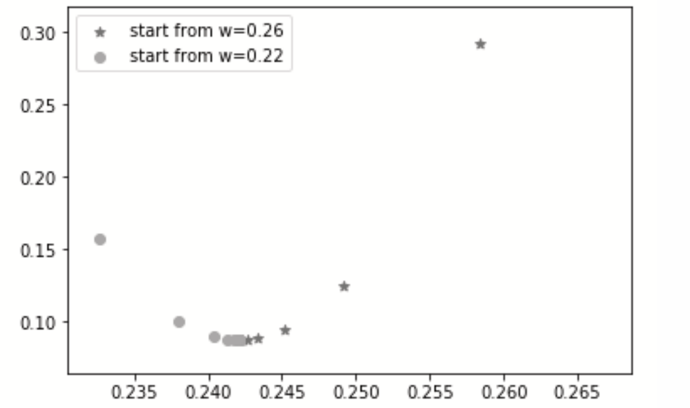
SUMMARY

1. Linear regression





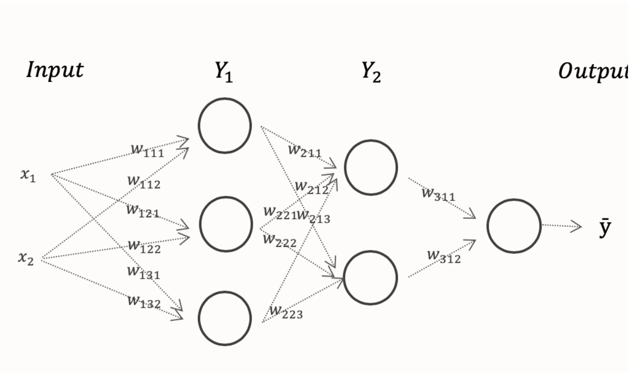




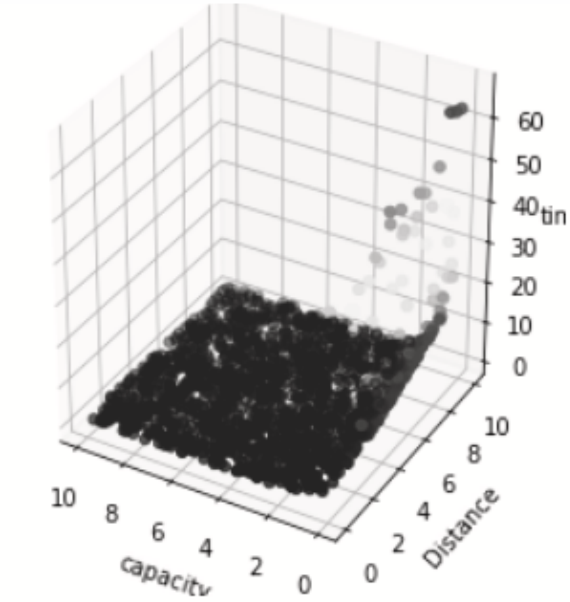
SUMMARY

2. Multi input Linear regression

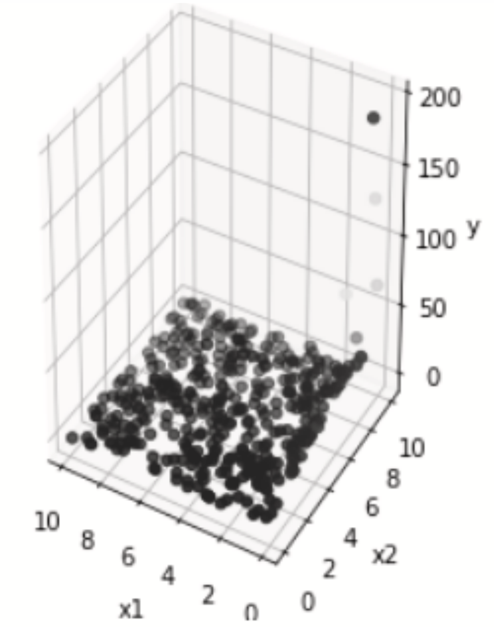
model



model predicted

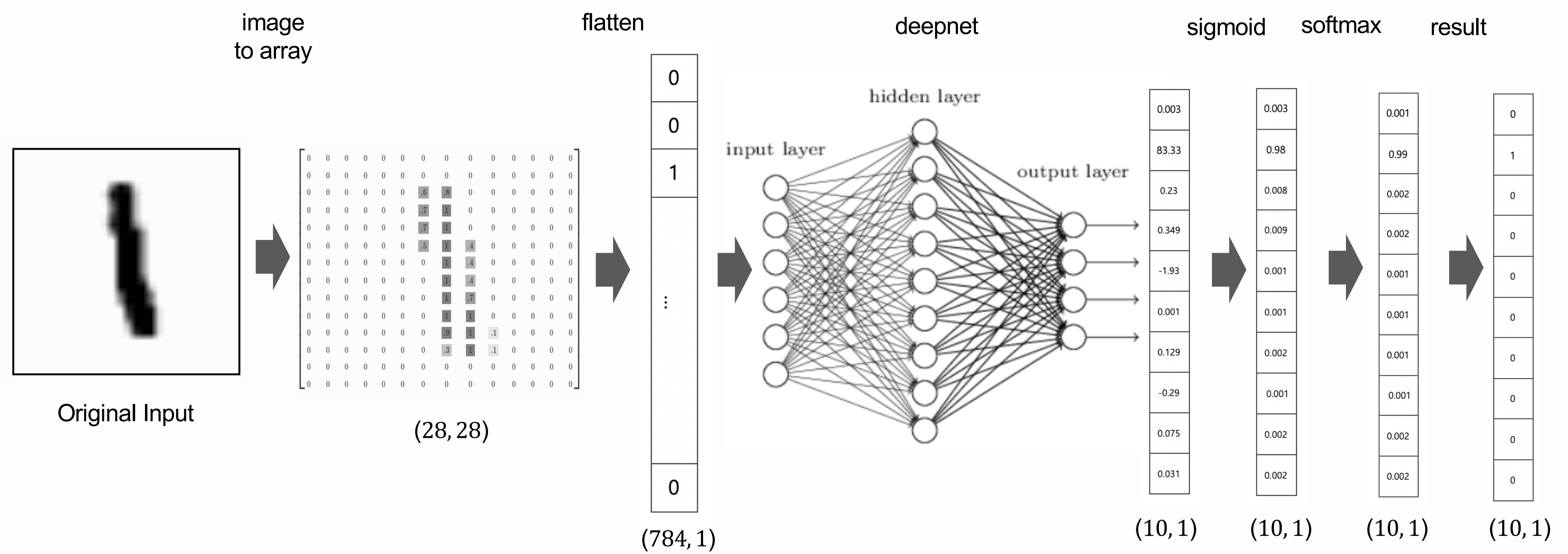


real data



SUMMARY

3. Logistic Classification



SUMMARY

4. Back Propagation