

# Redes Neurais e Deep Learning

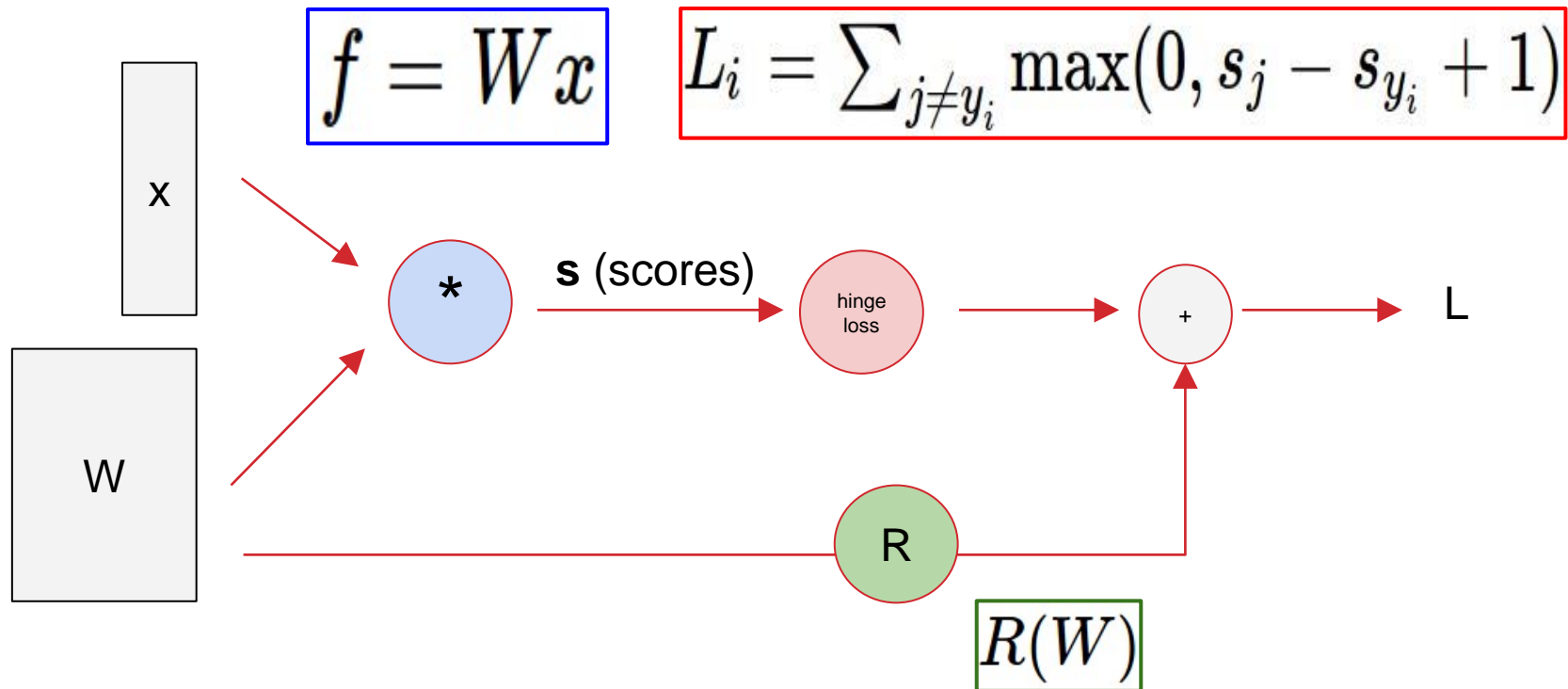
## PROPAGACÃO RETRÓGRADA

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Zenilton K. G. Patrocínio Jr

[zenilton@pucminas.br](mailto:zenilton@pucminas.br)

# Grafo de Computação da Função de Perda

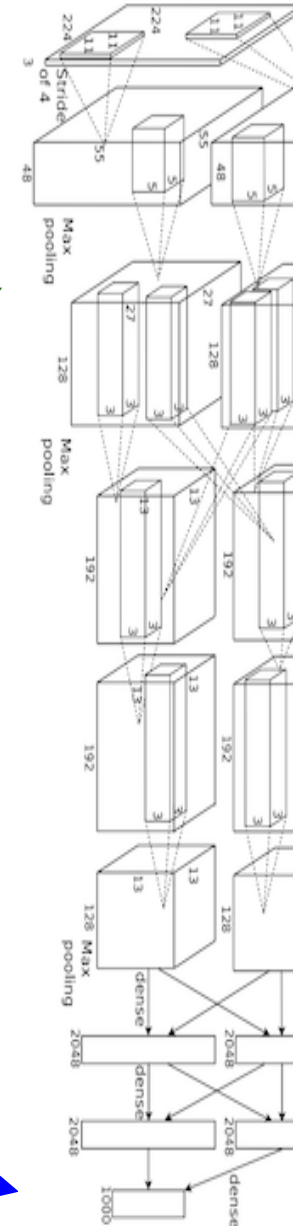


# Rede Convolutucional (AlexNet)

Imagem de entrada

Pesos

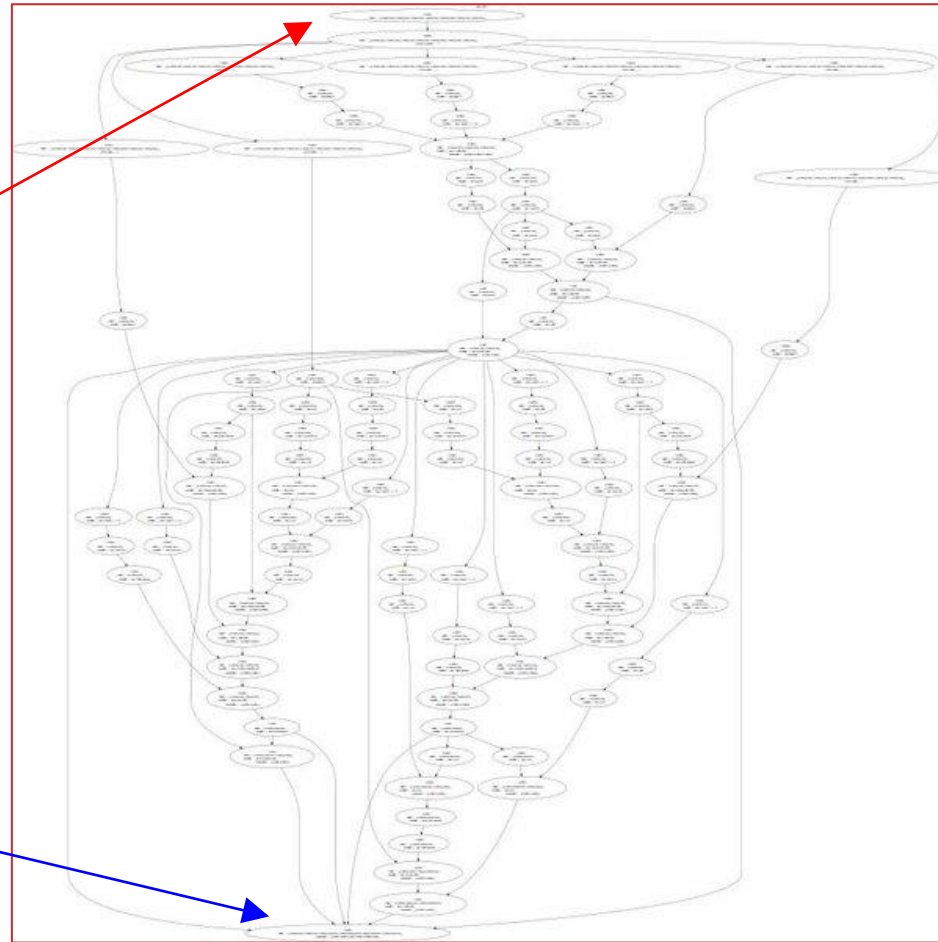
Perda



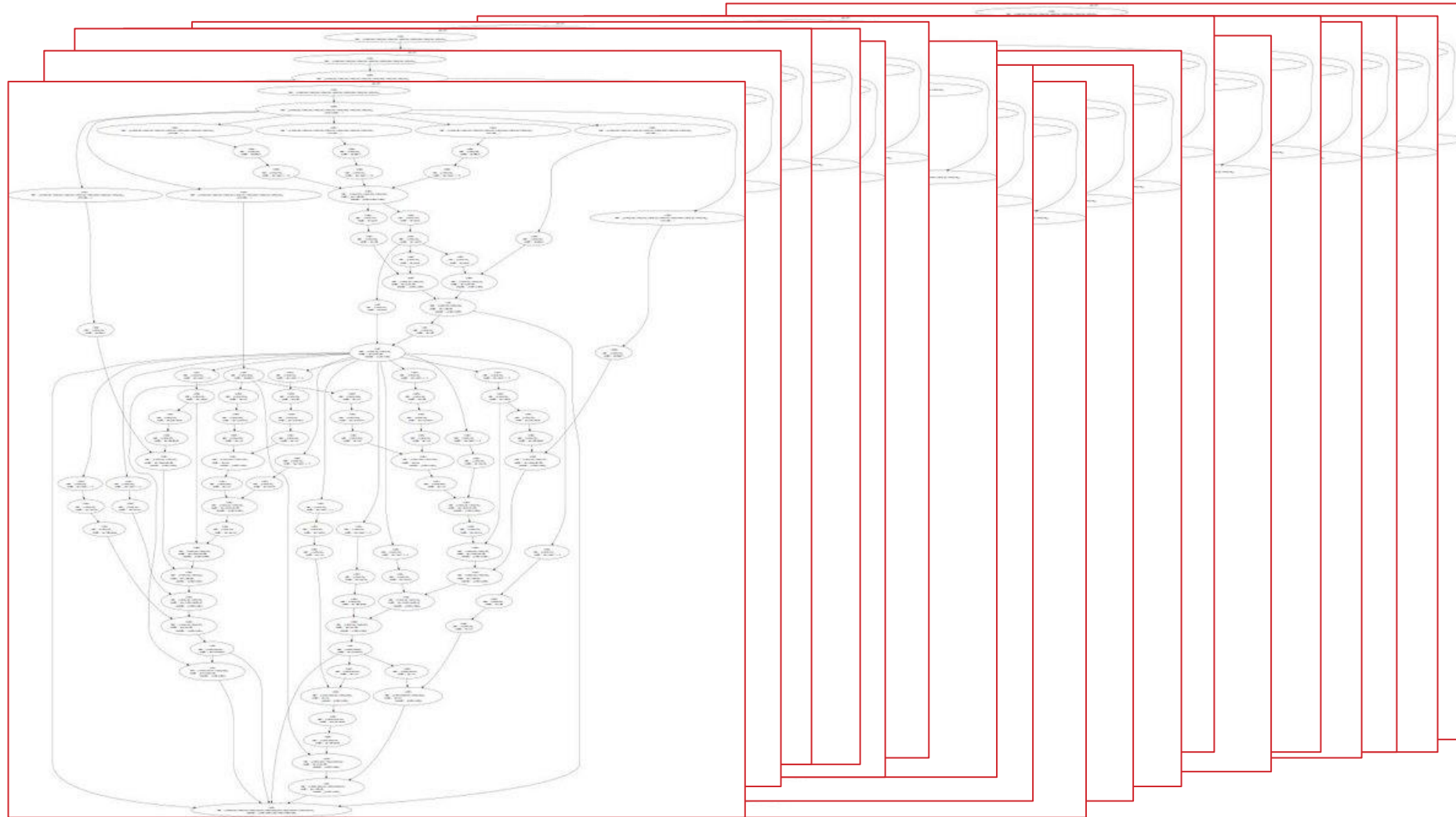
# Máquina Neural de Turing

Fita de entrada

Perda

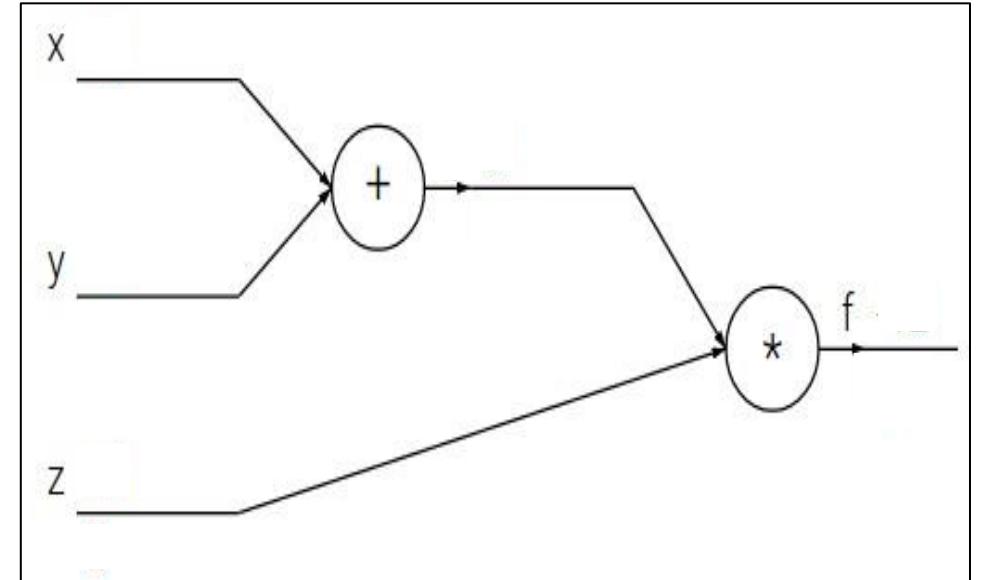


# Neural Turing Machine



# Diferenciação de um Grafo de Computação

Seja  $f(x, y, z) = (x + y) \times z$

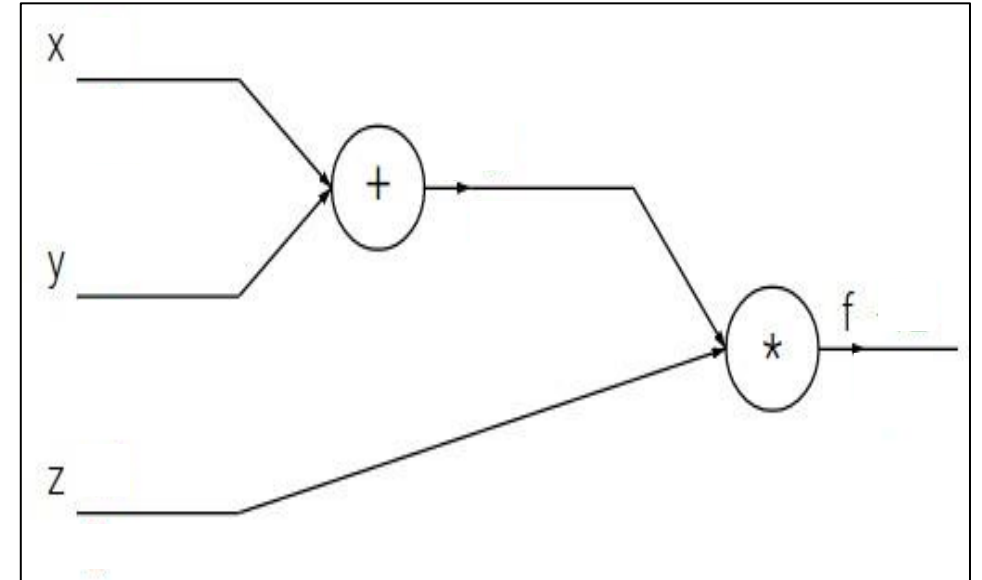


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Então, pode-se dizer que

$$f(x, y, z) = g(h(x, y), z)$$



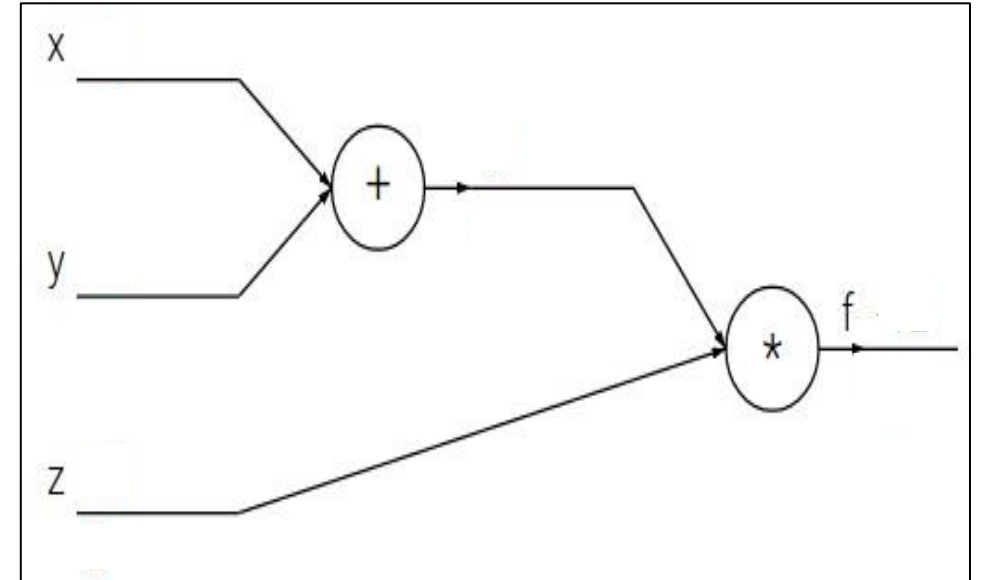
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em  $h(x, y) = x + y$





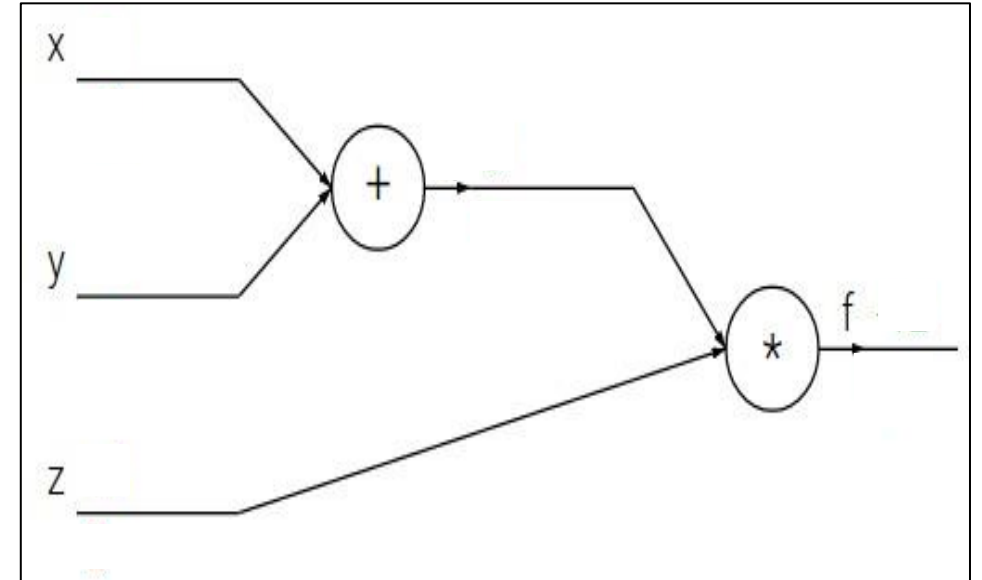
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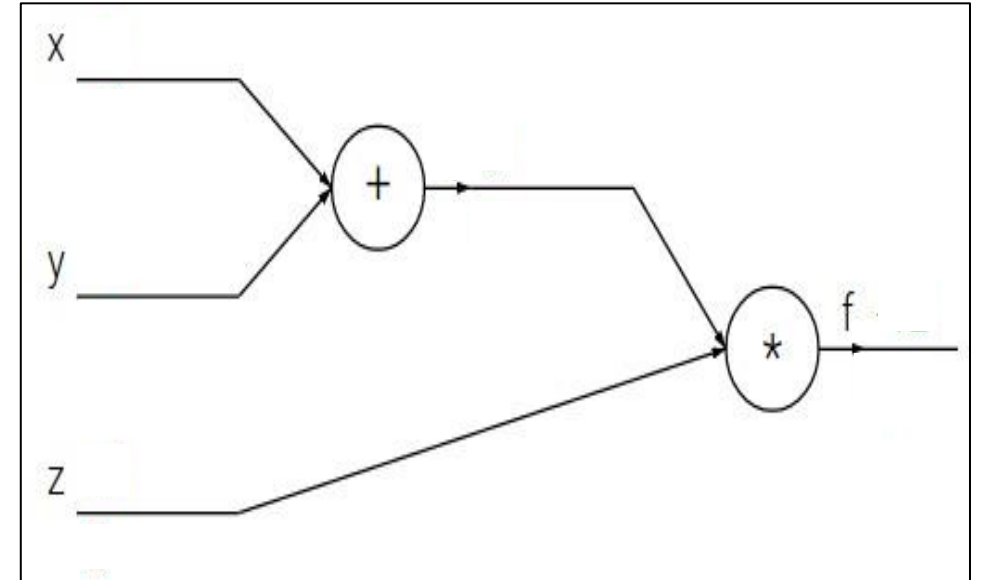
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$$\frac{df}{dx} = \frac{dg}{dh} \times \frac{dh}{dx}$$



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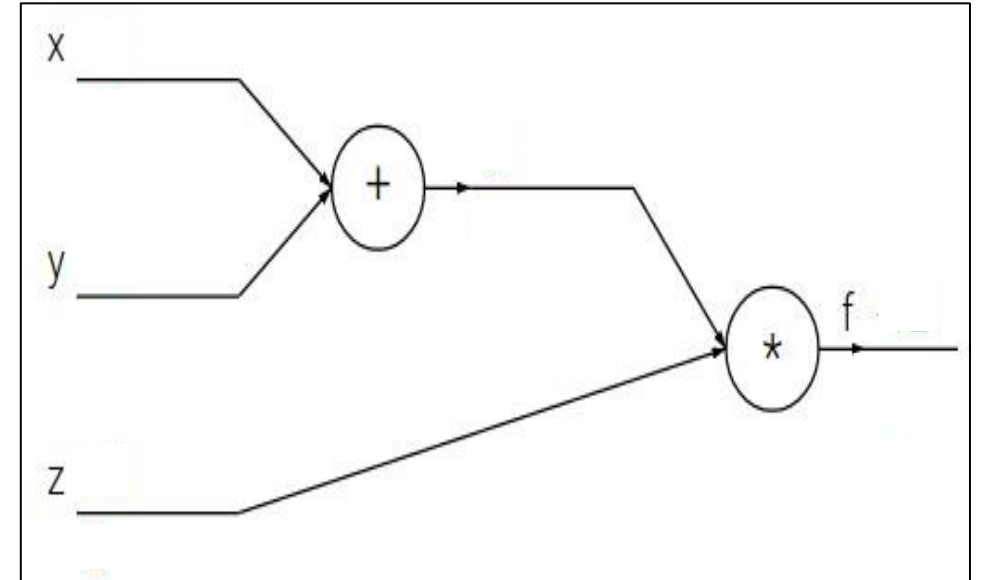
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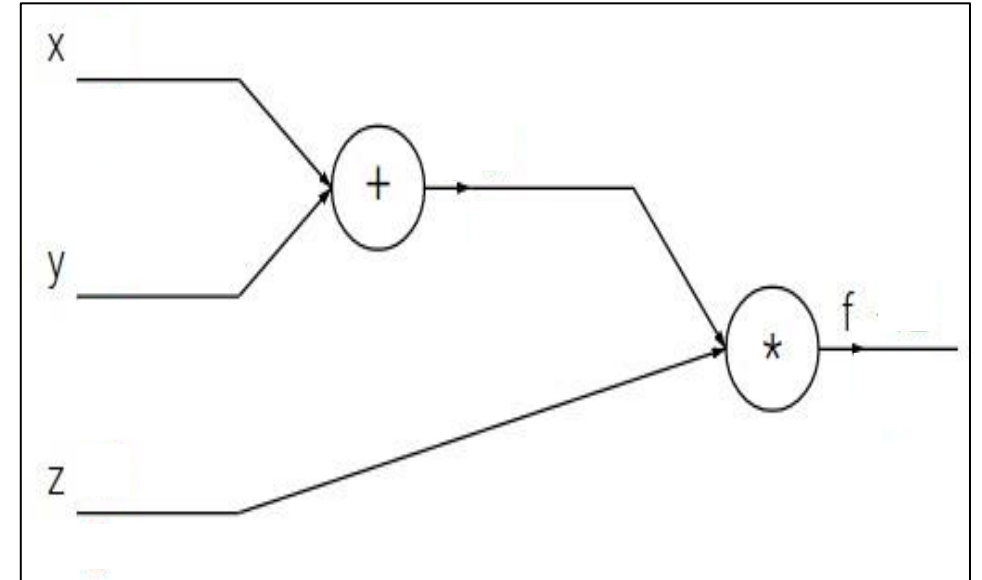
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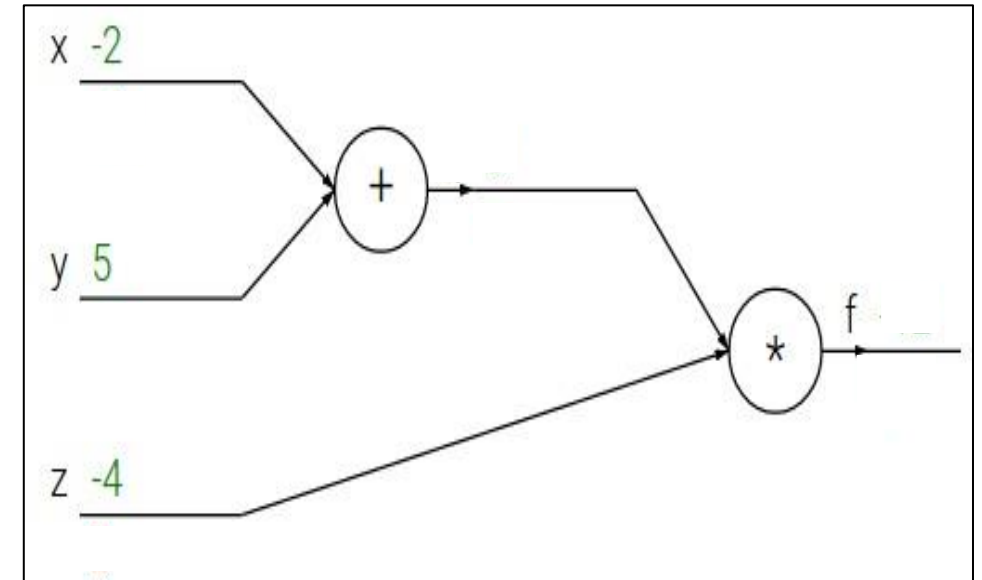
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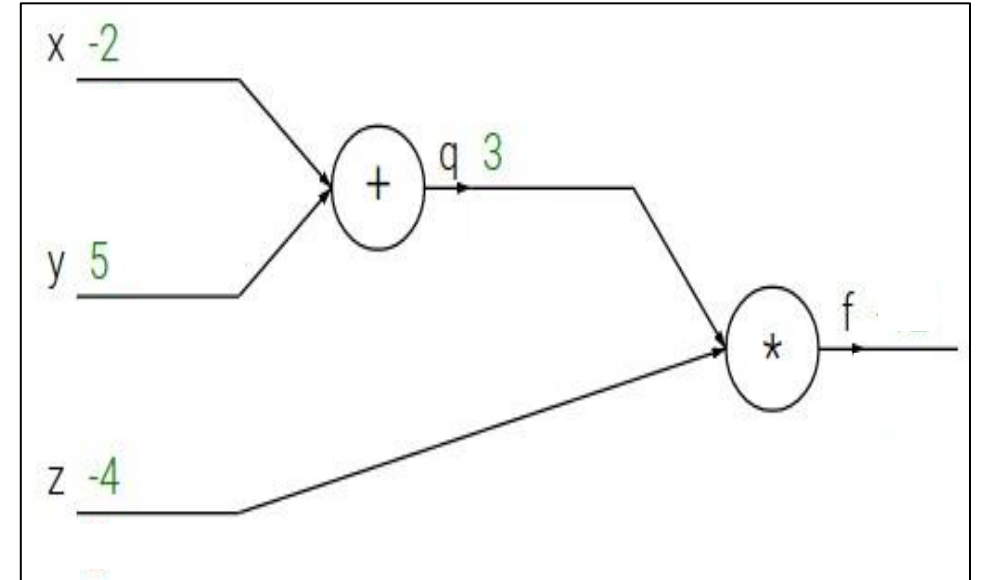


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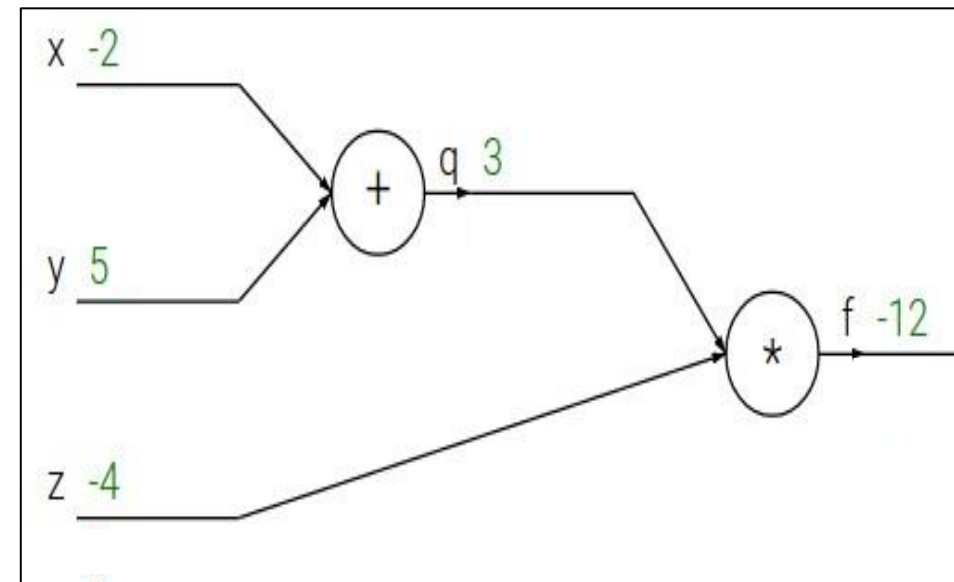
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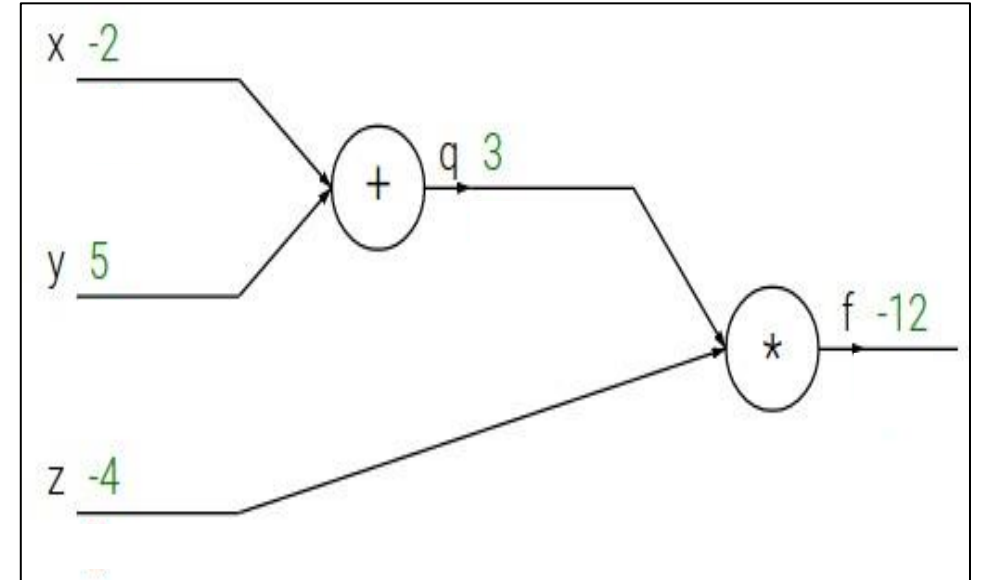
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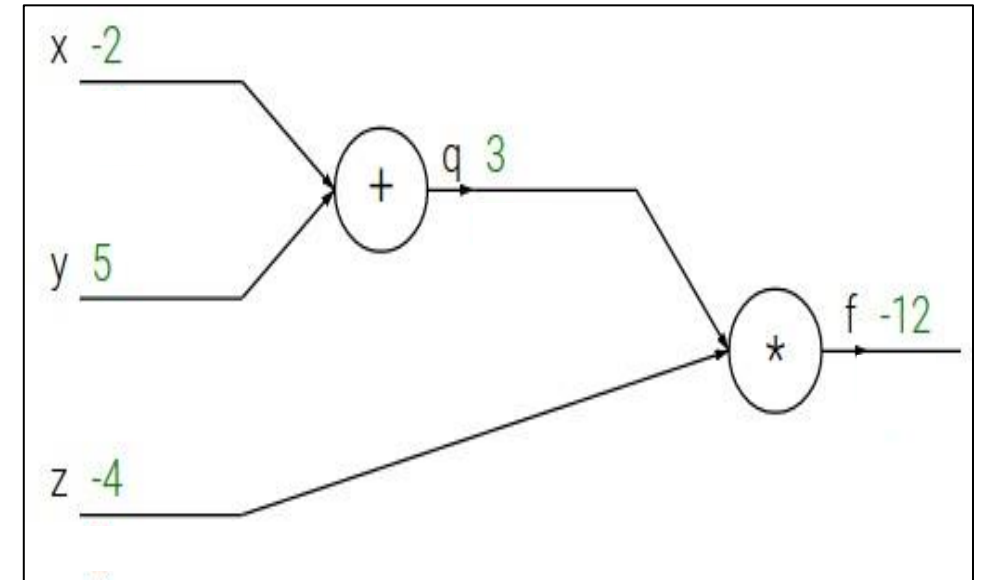
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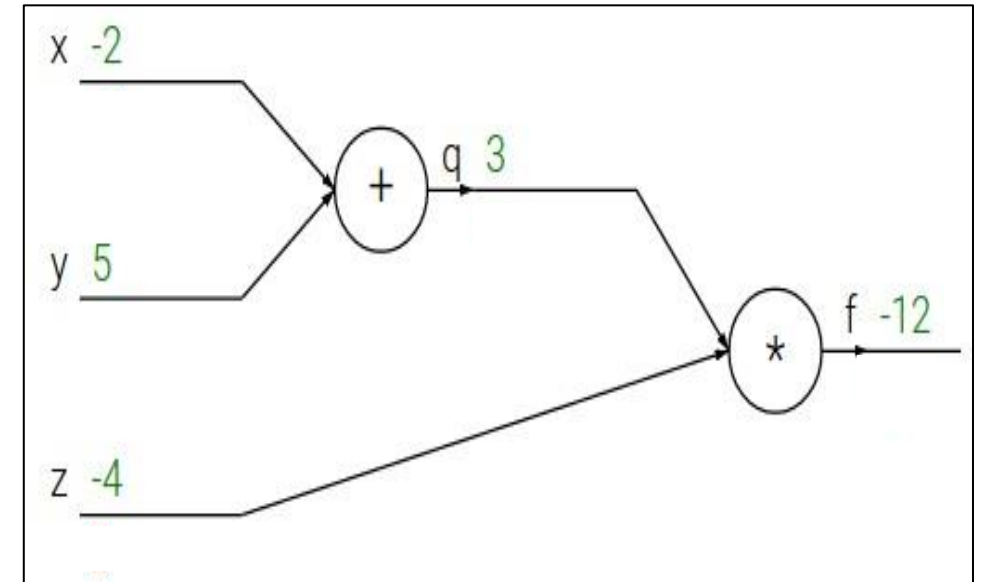
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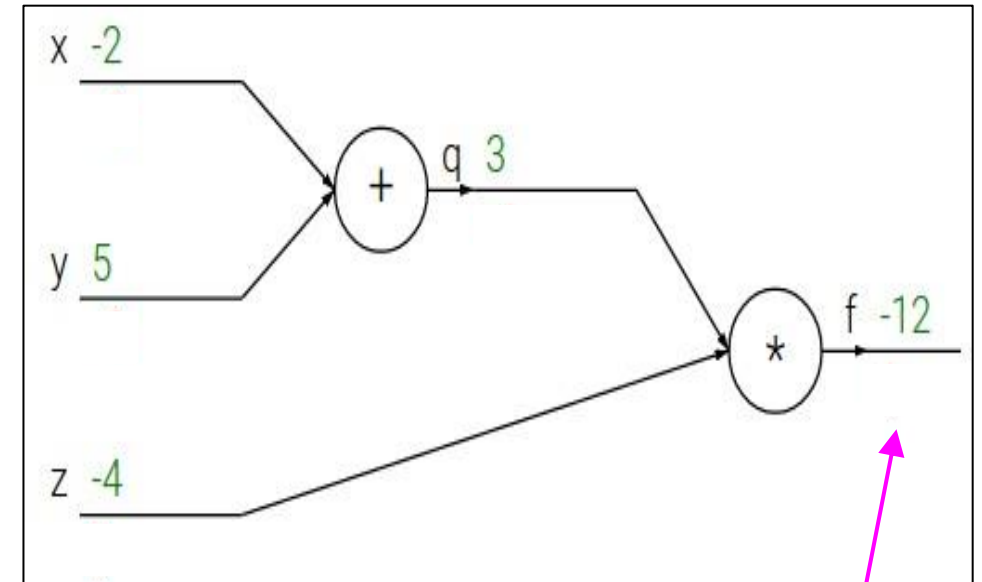
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$$\frac{\partial f}{\partial f}$$

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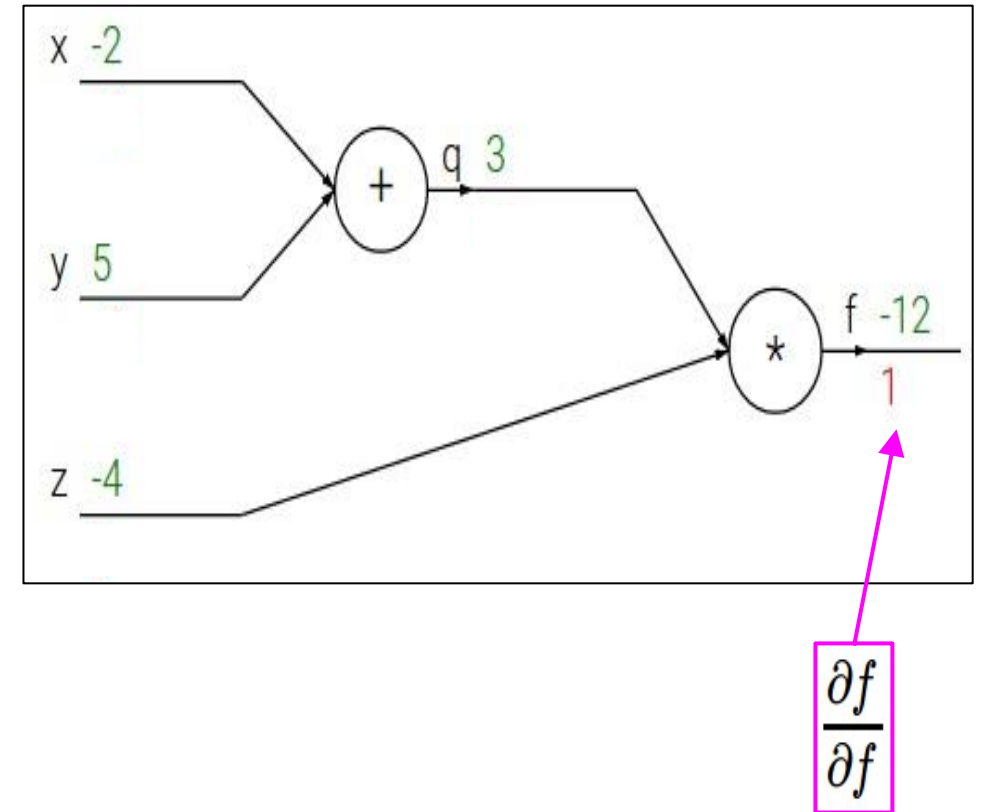
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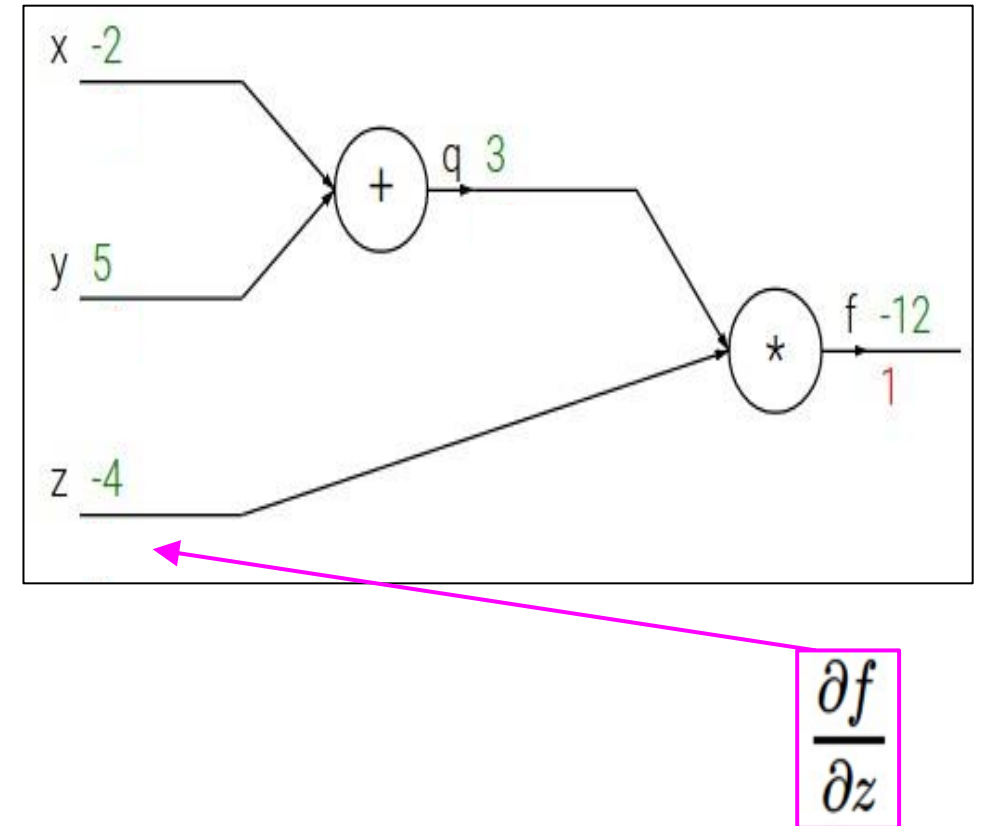
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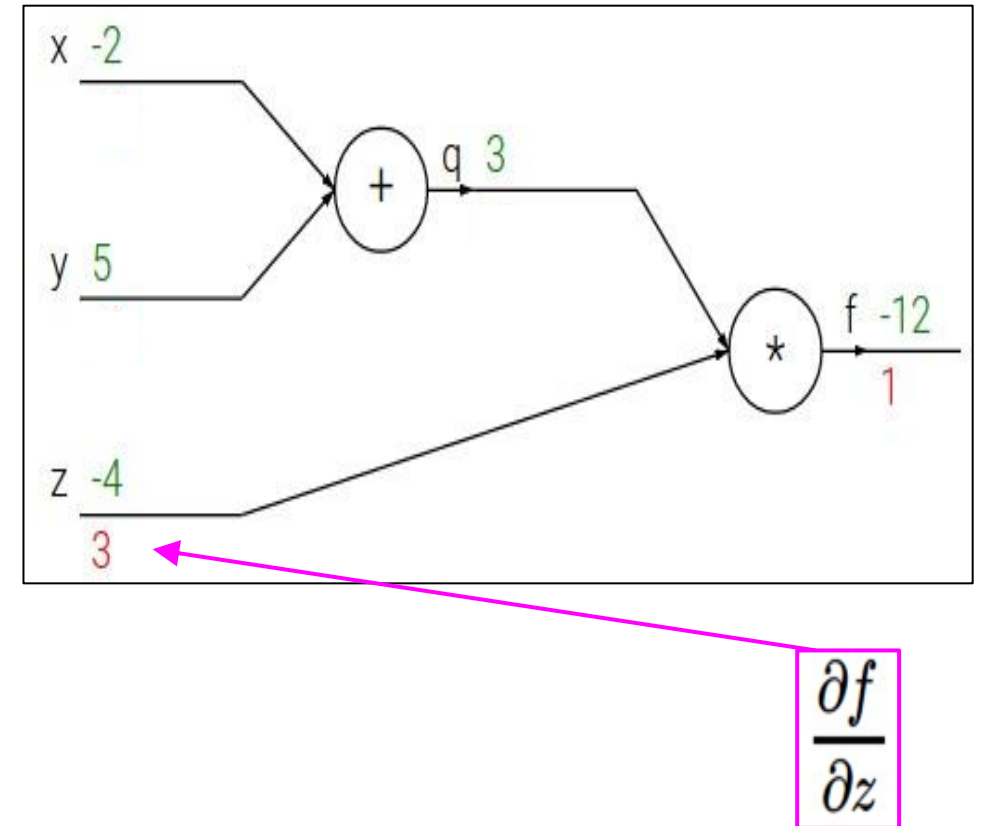
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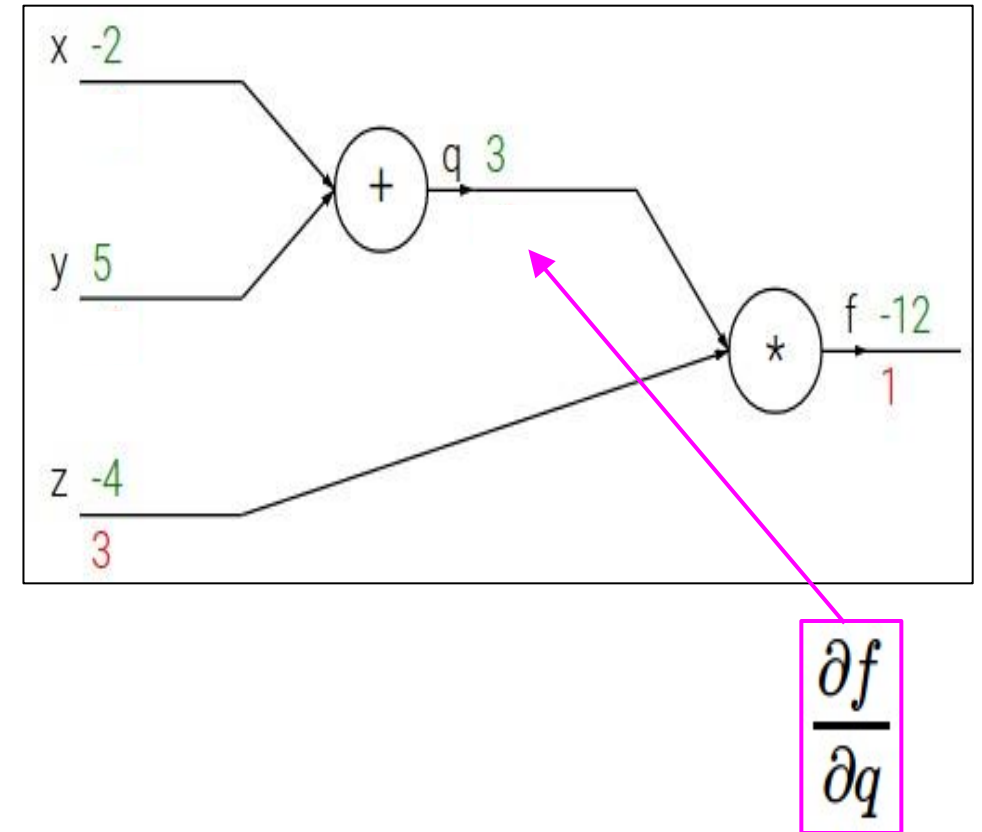
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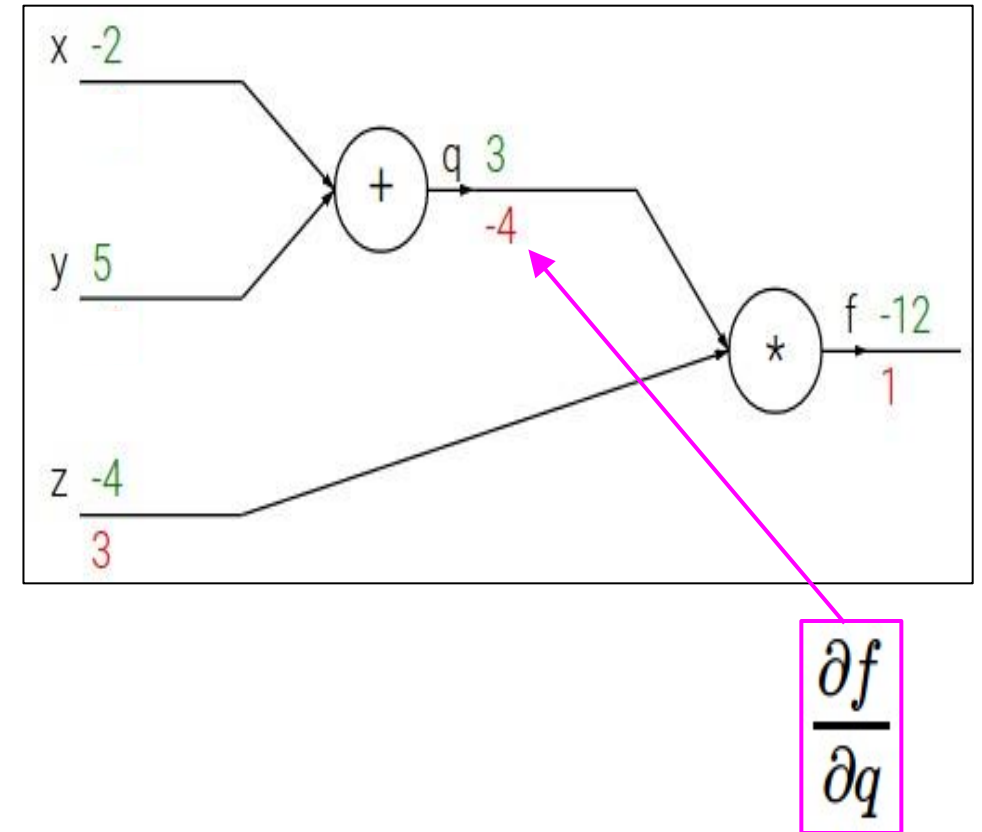
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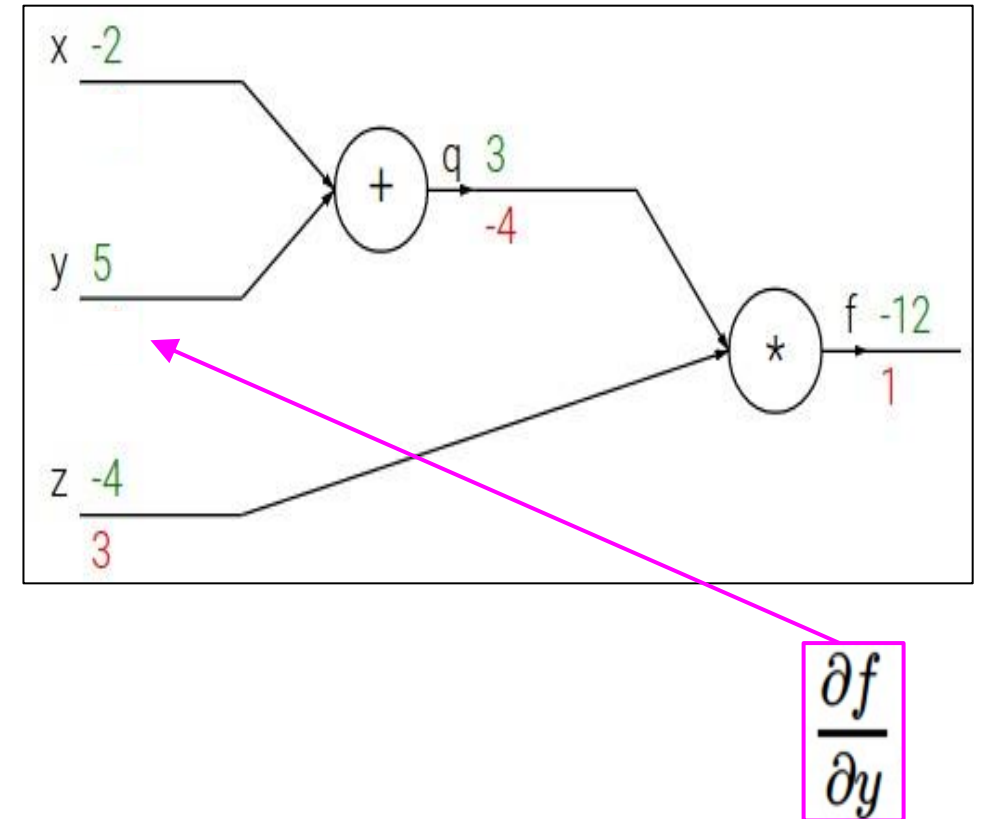
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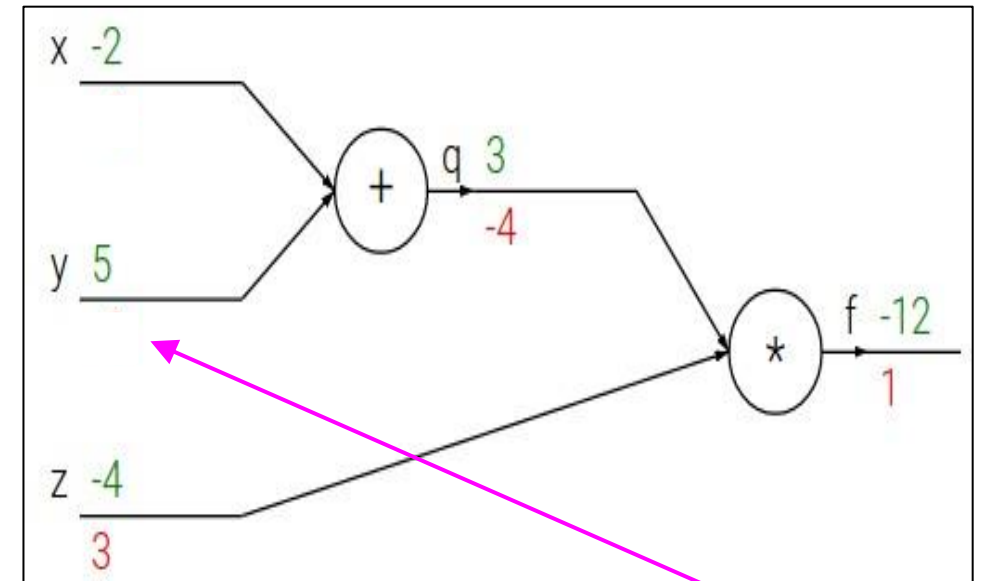
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Regra da Cadeia:

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

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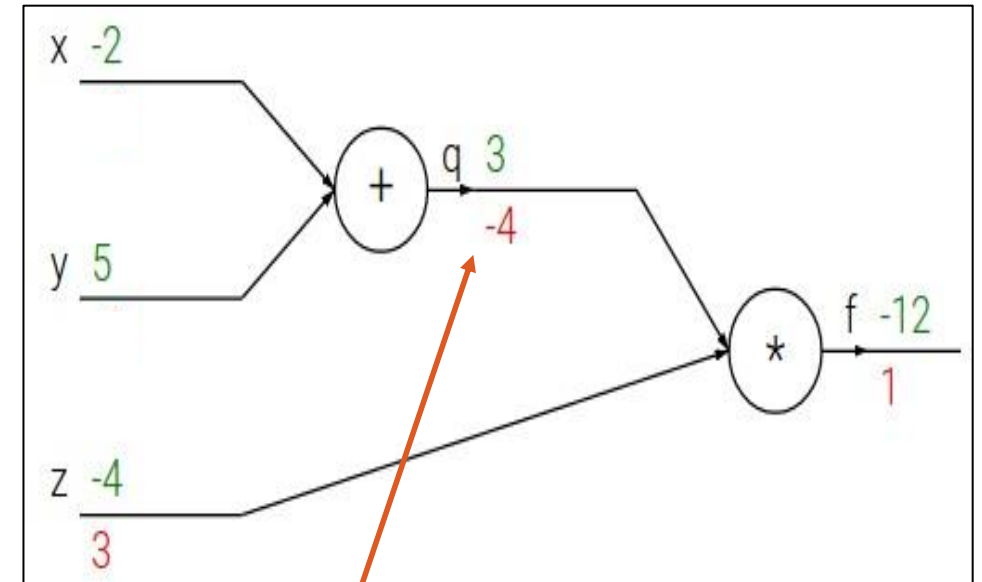
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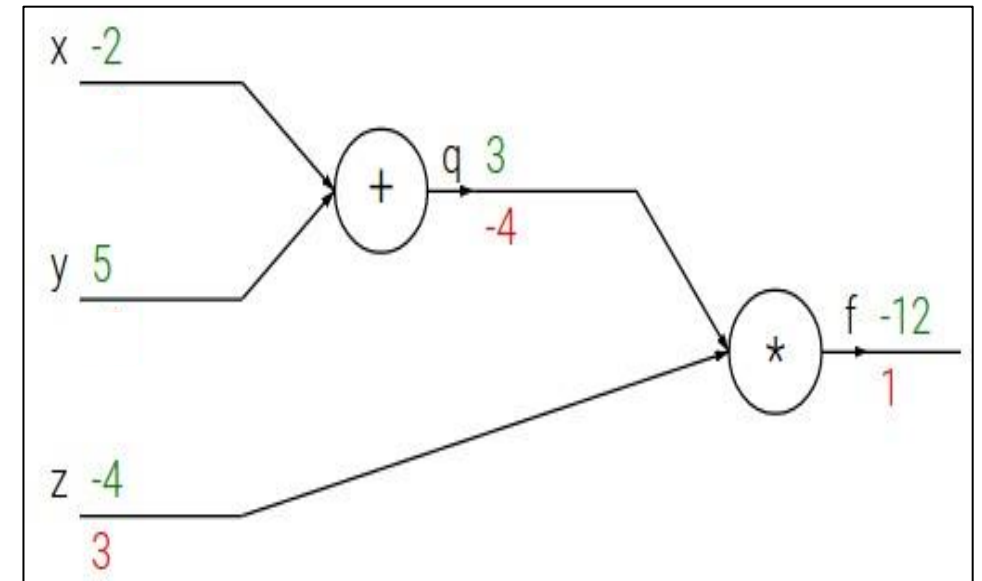
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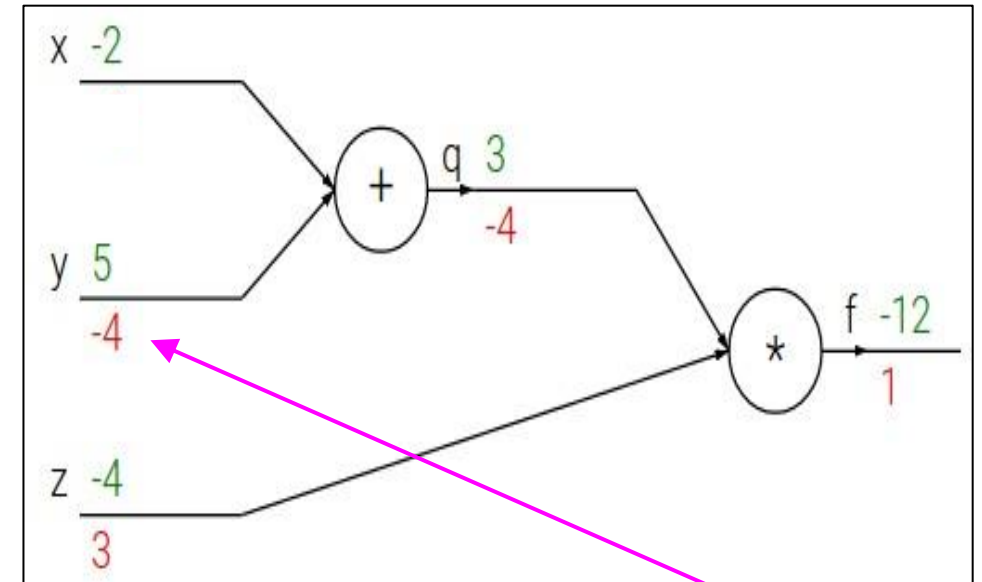
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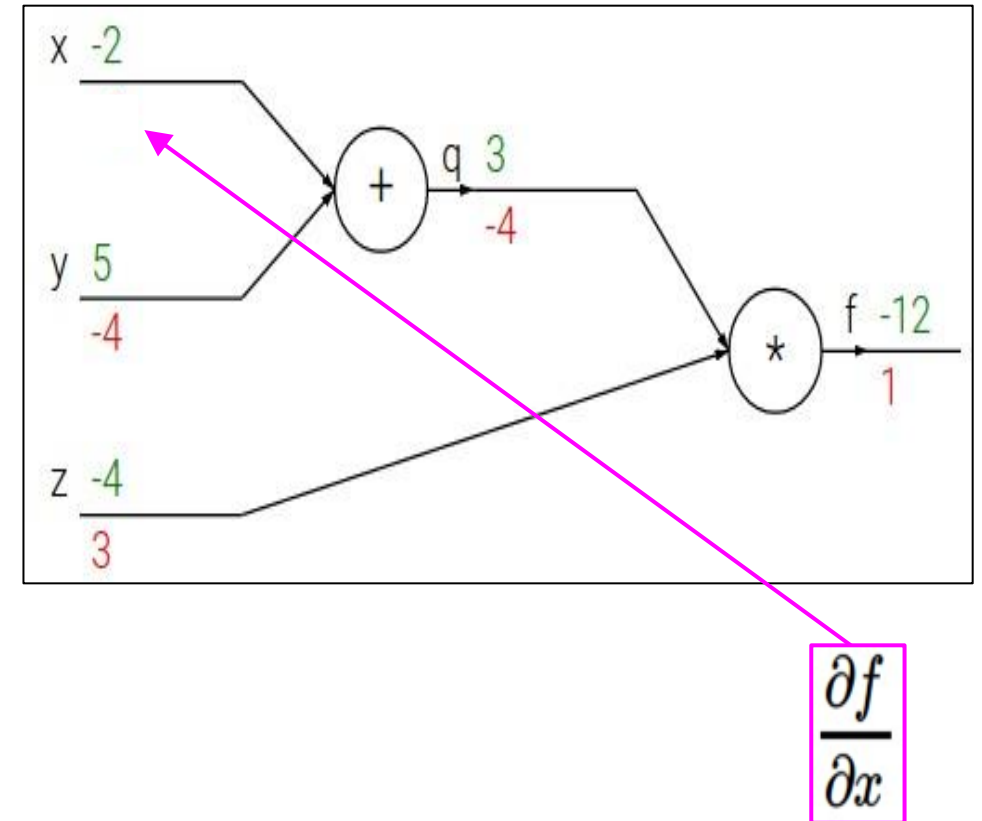
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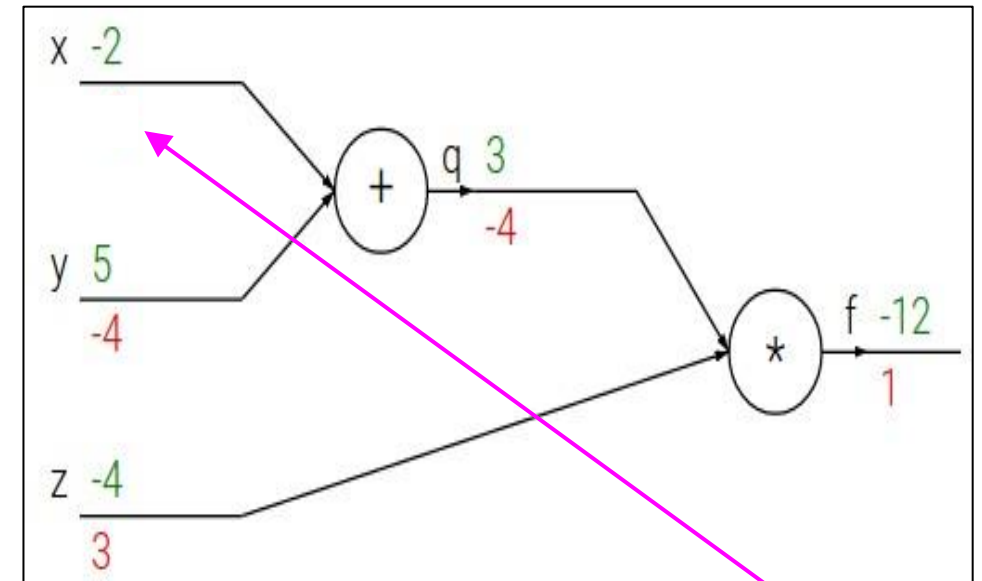
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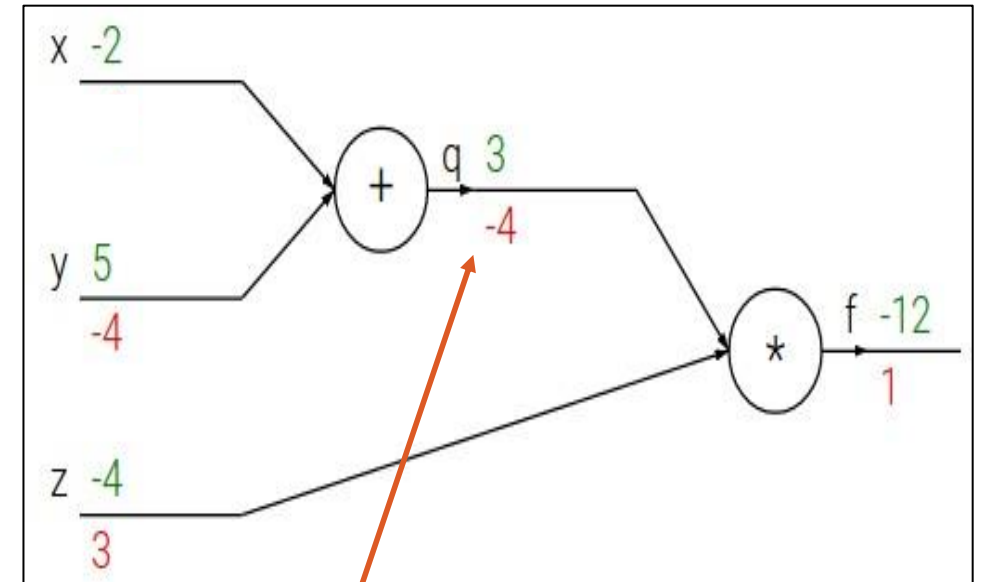
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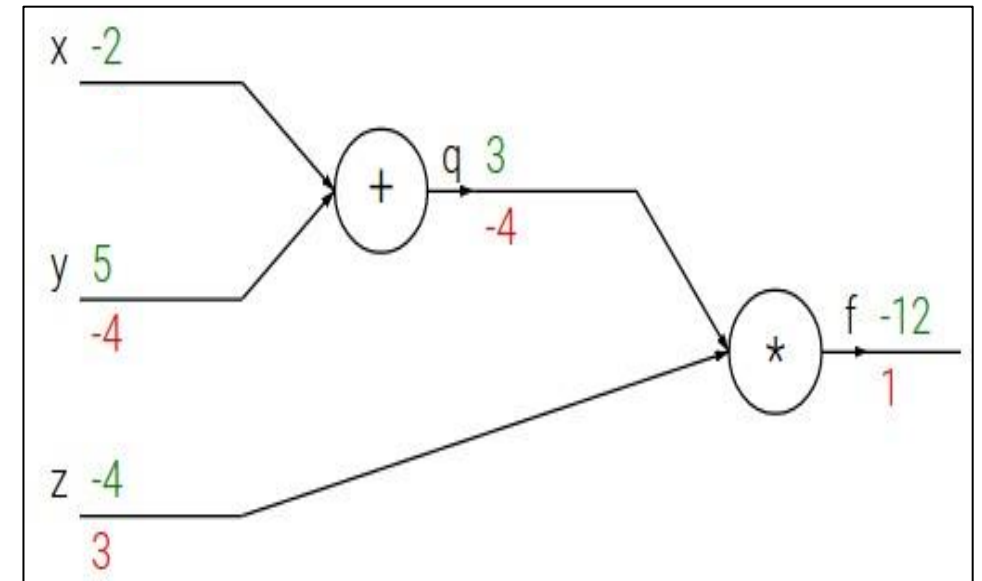
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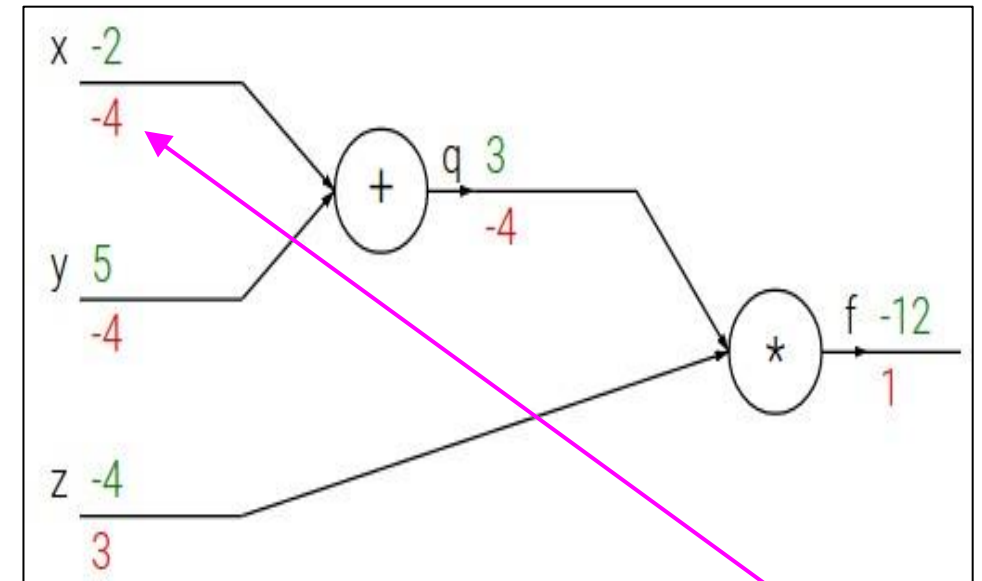
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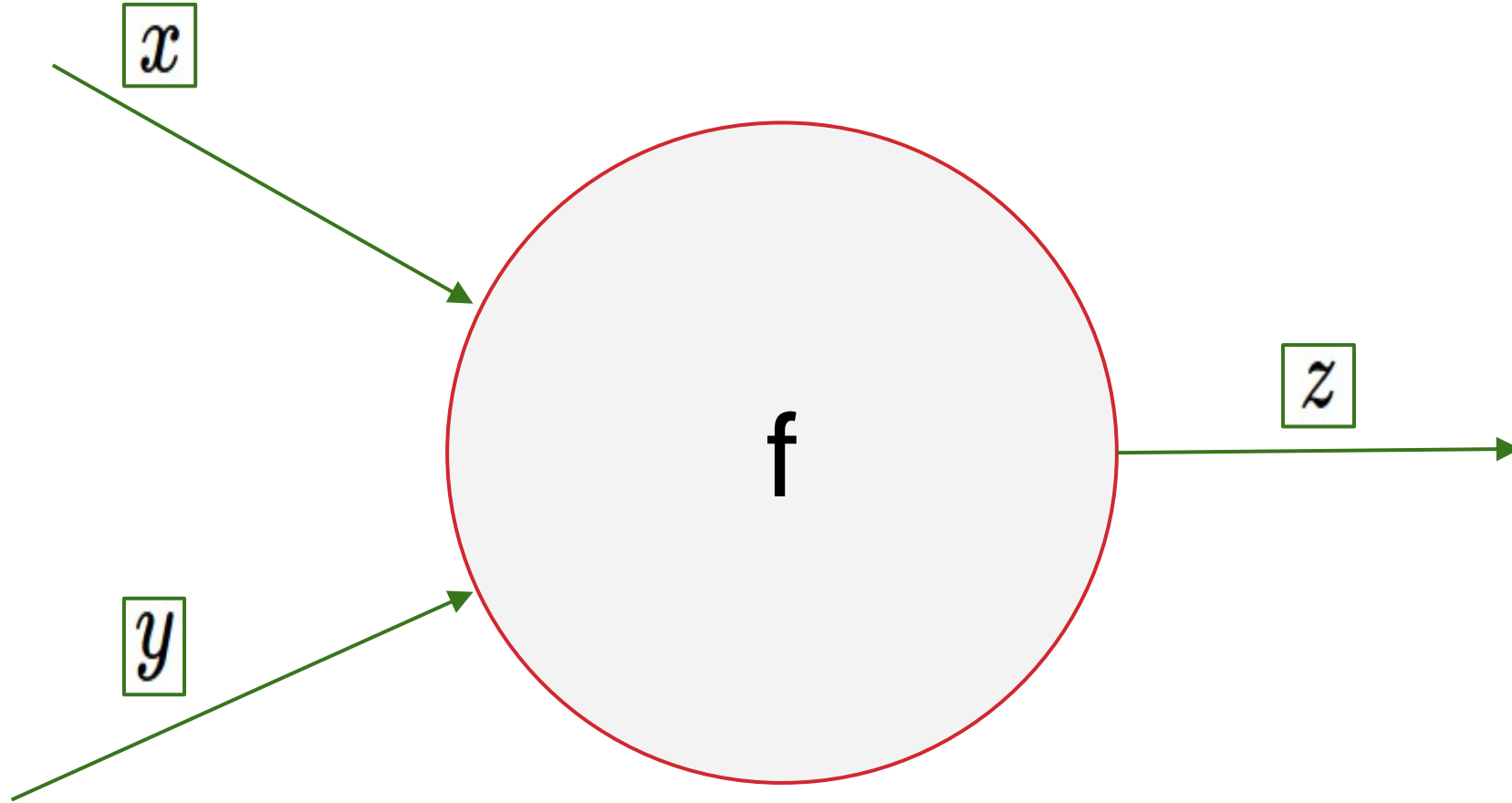


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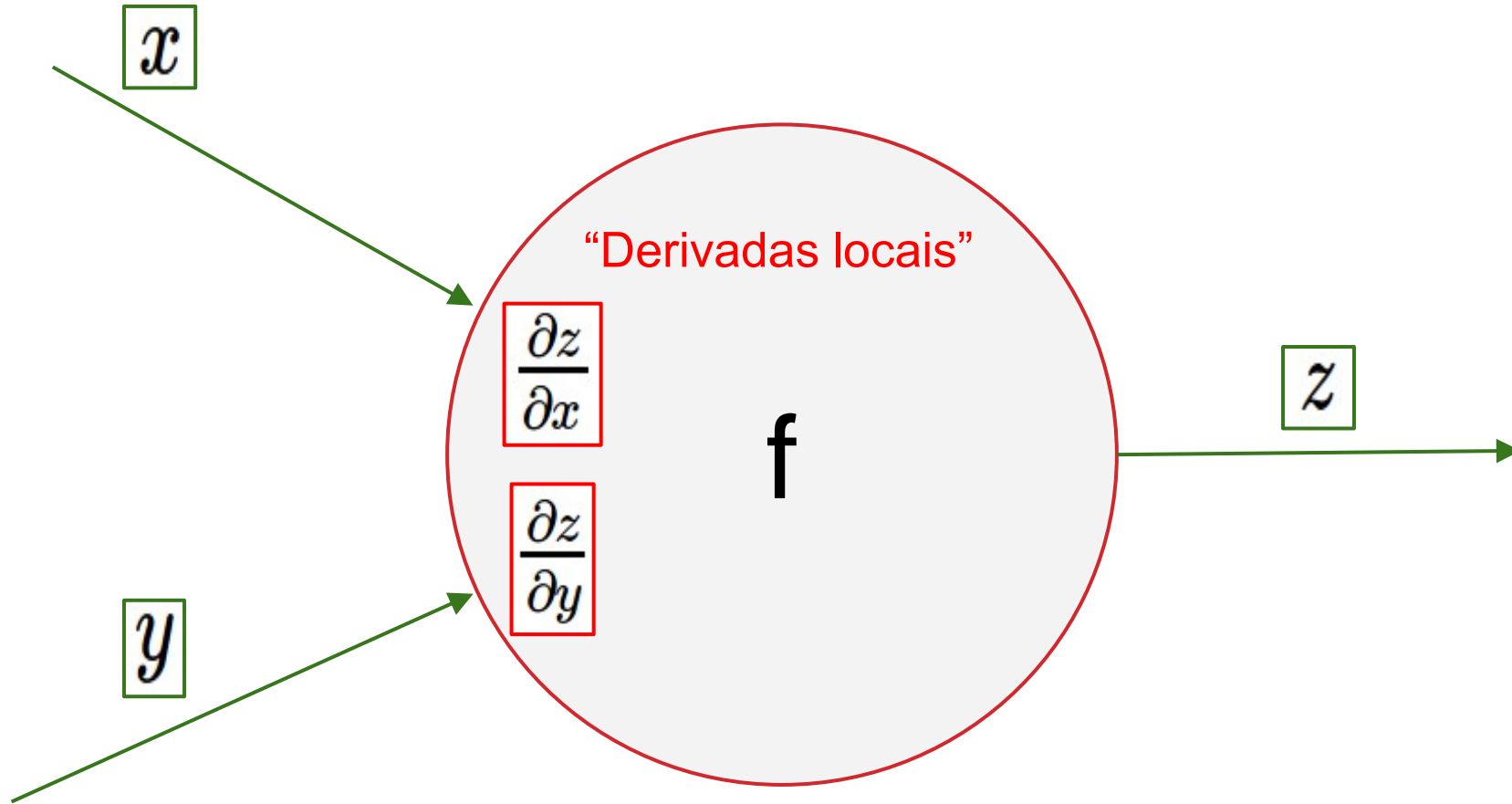
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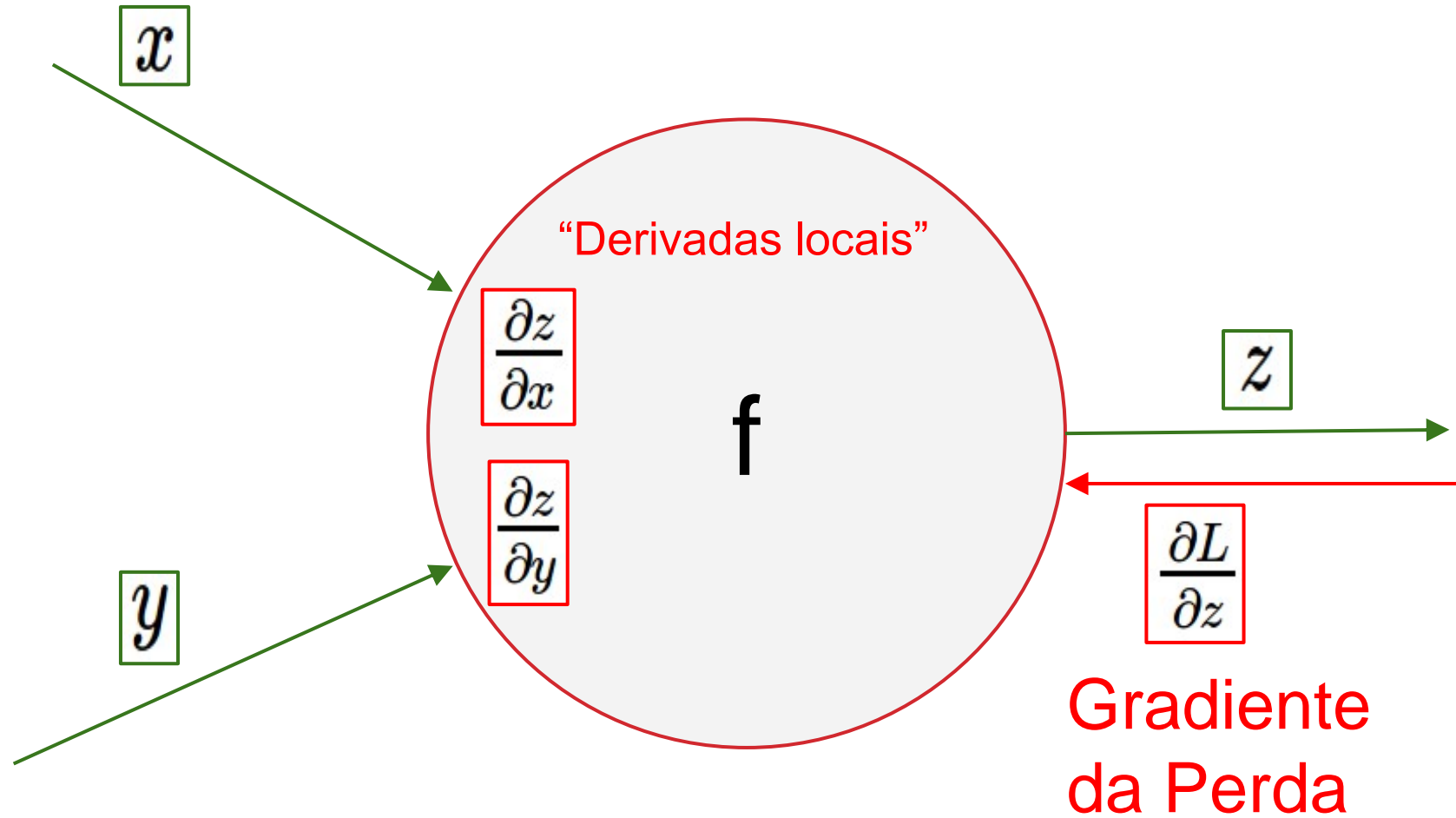
# Passo Retrógrado (*Backward Pass*)



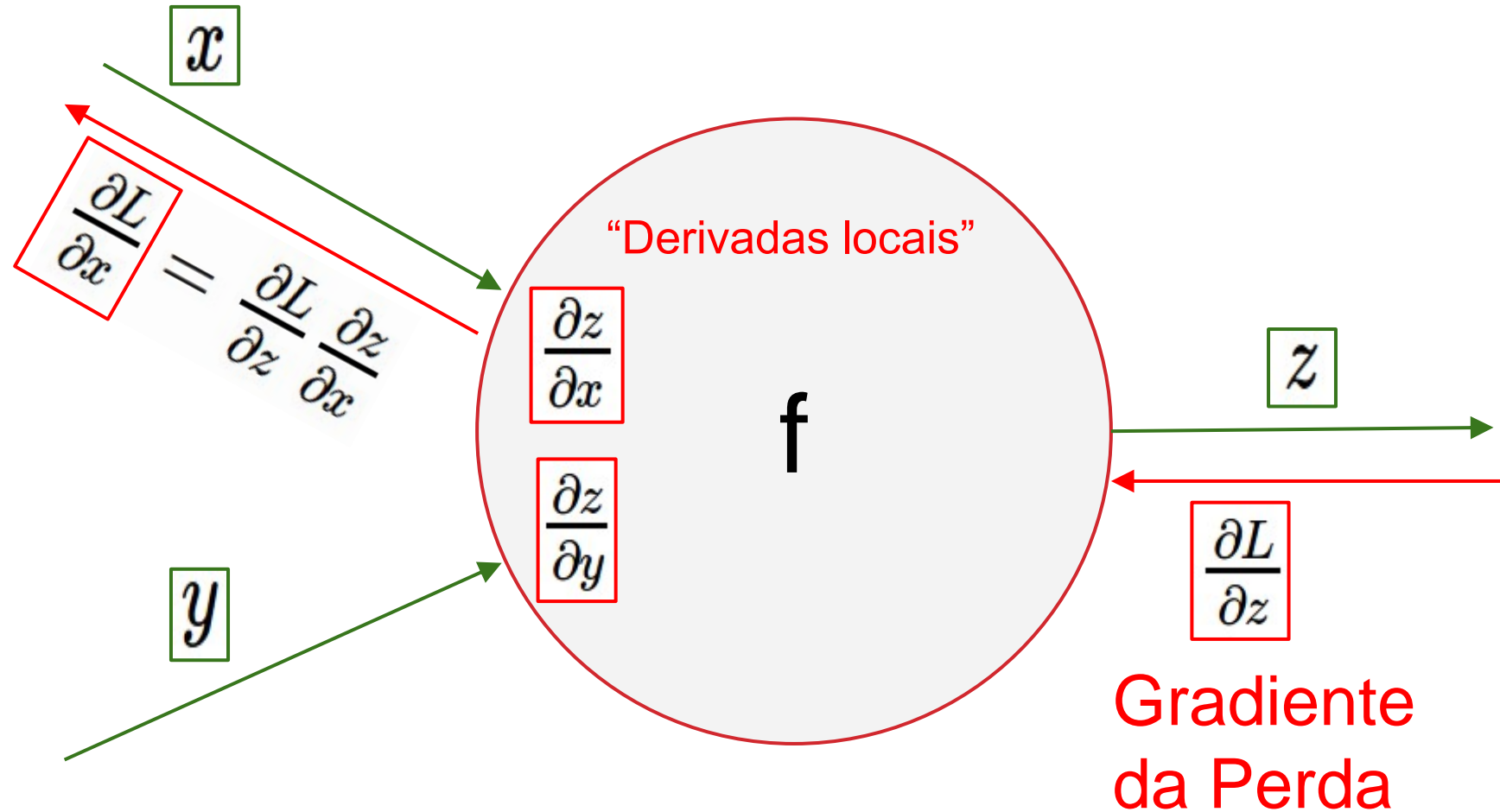
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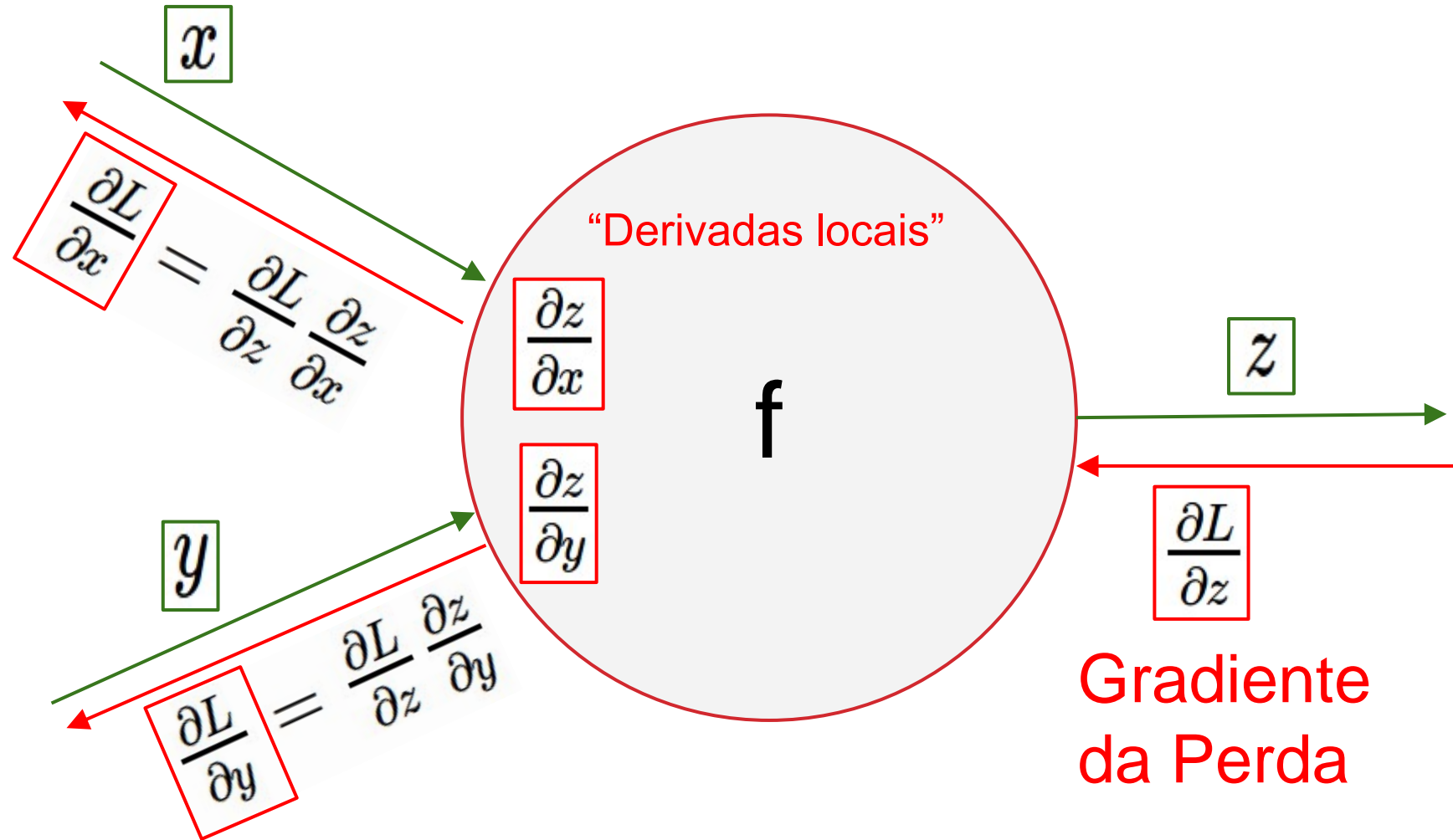
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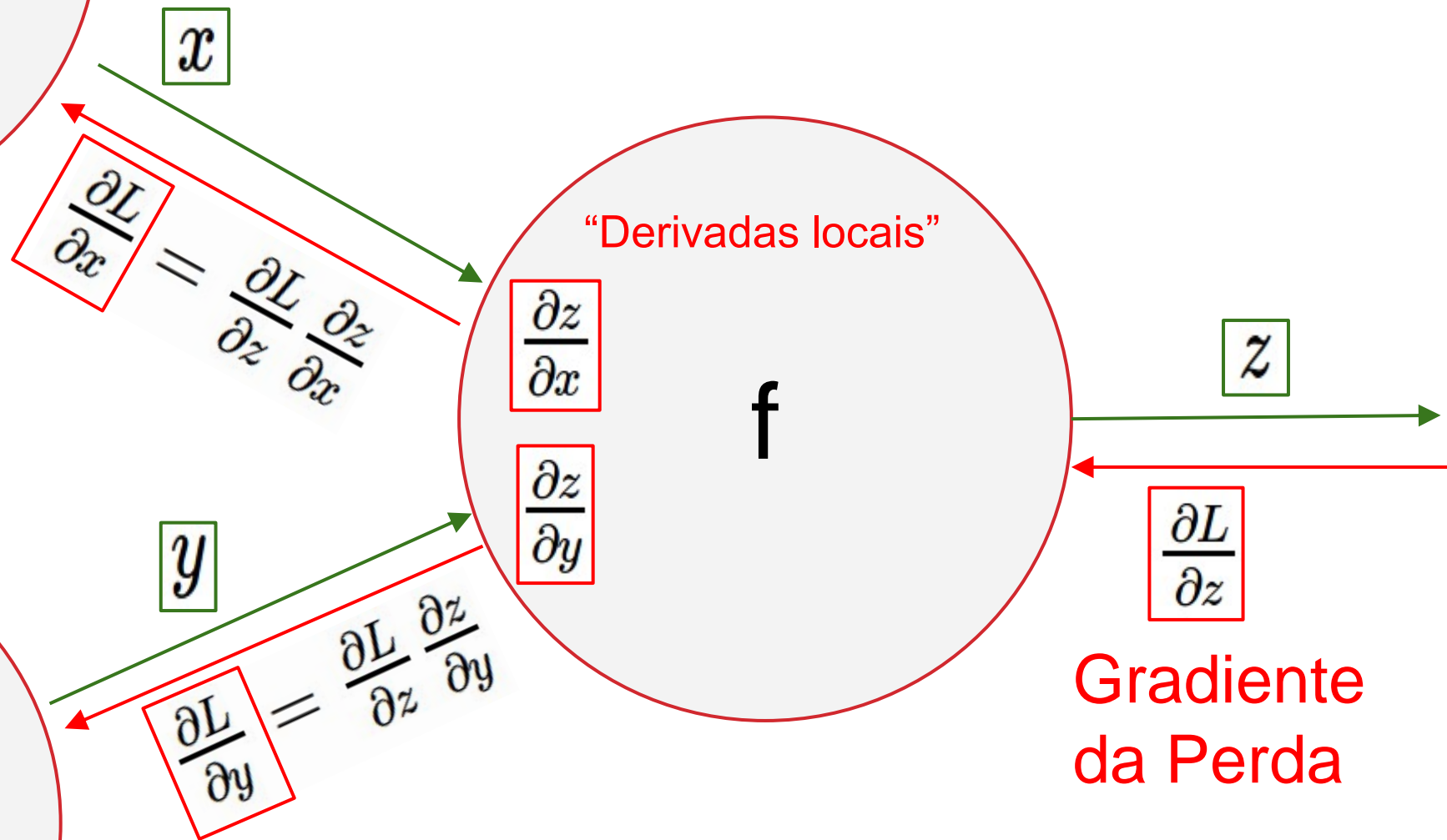
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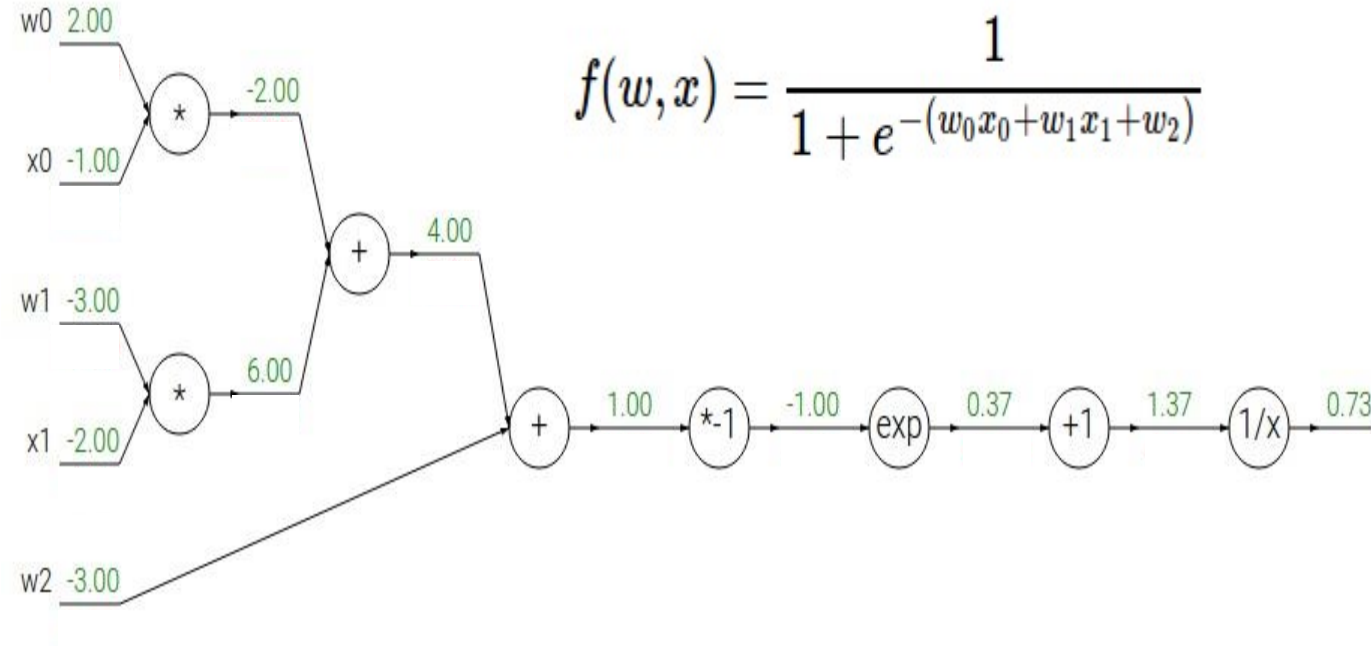


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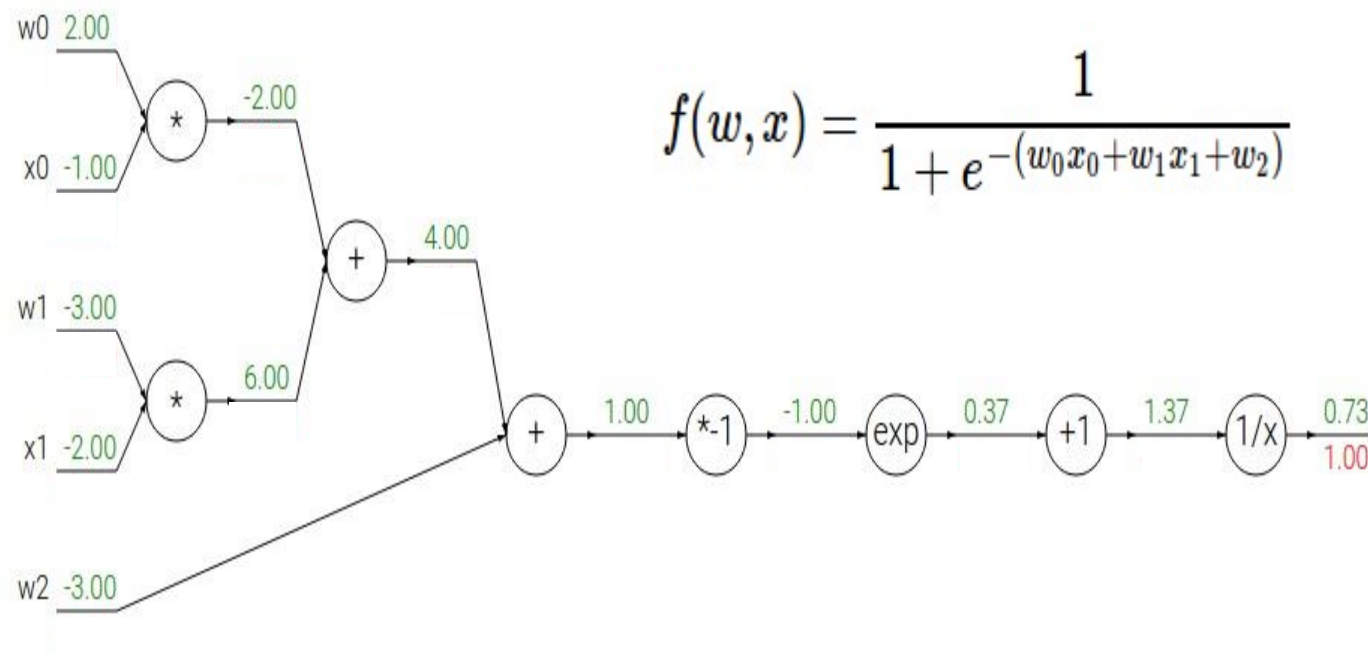




# Outro Exemplo – Passo Retrógrado

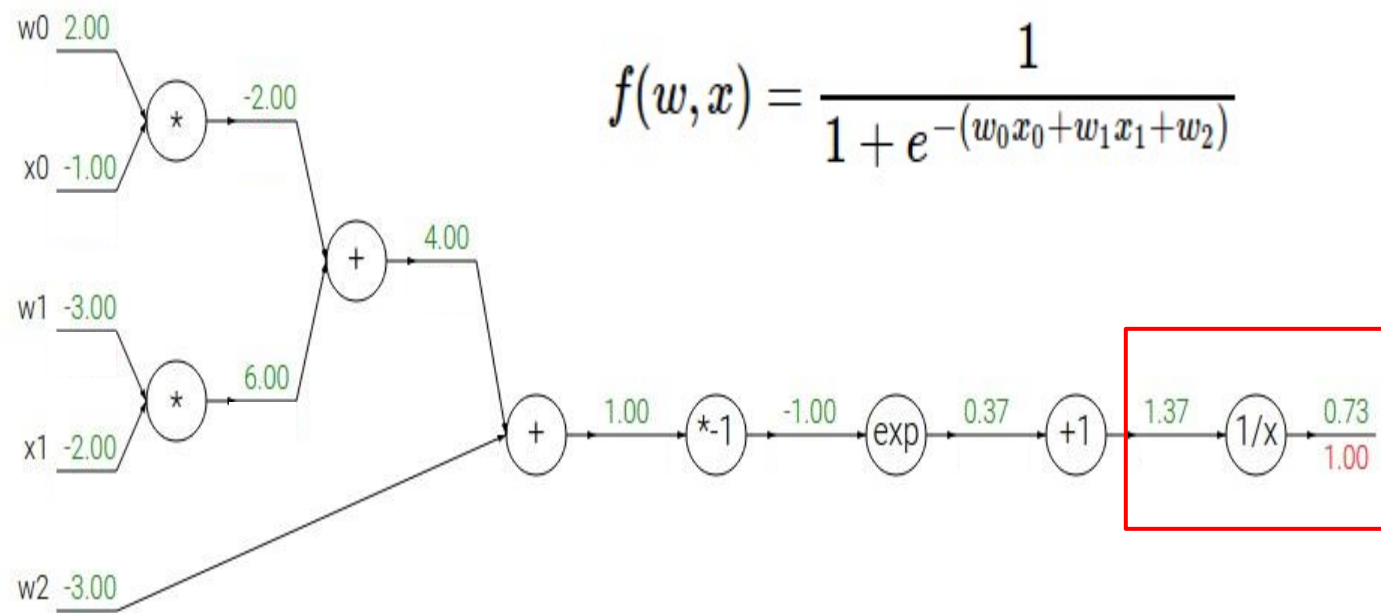


# Outro Exemplo – Passo Retrógrado



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

# Outro Exemplo – Passo Retrógrado



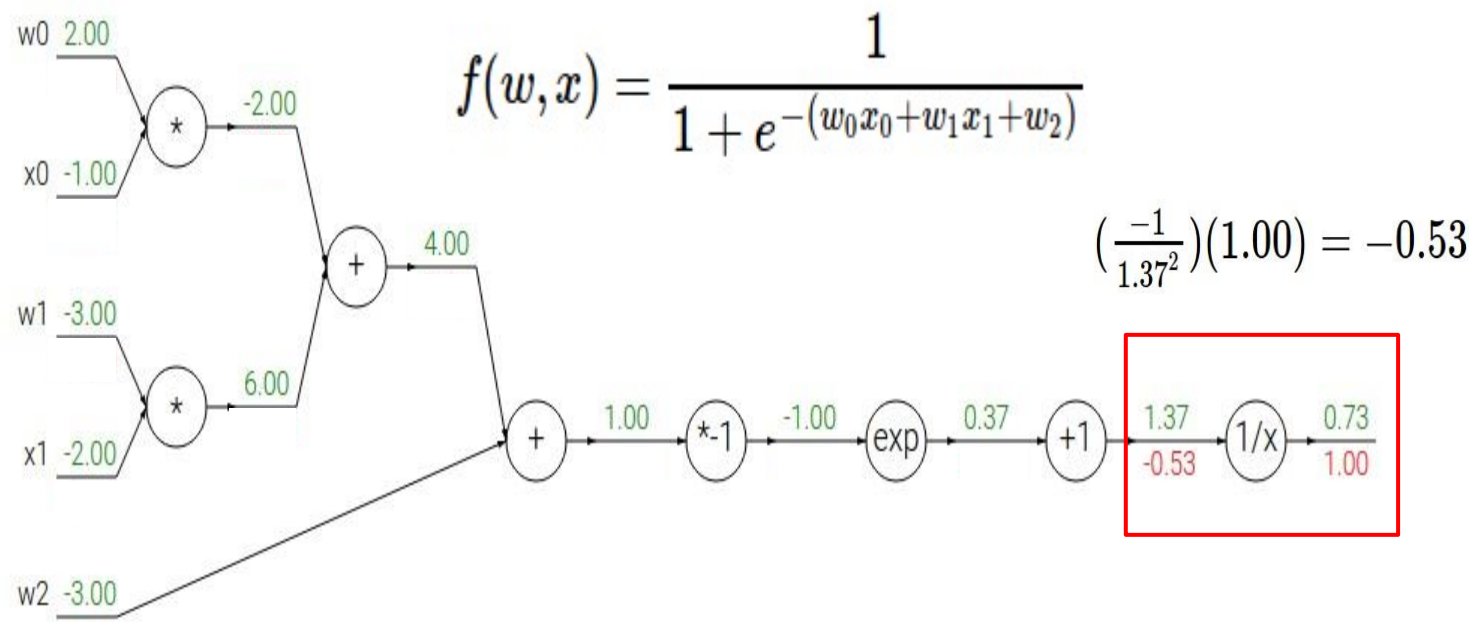
$$f(x) = e^x \rightarrow \frac{df}{dx} = e^x$$

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

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

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

# Outro Exemplo – Passo Retrógrado



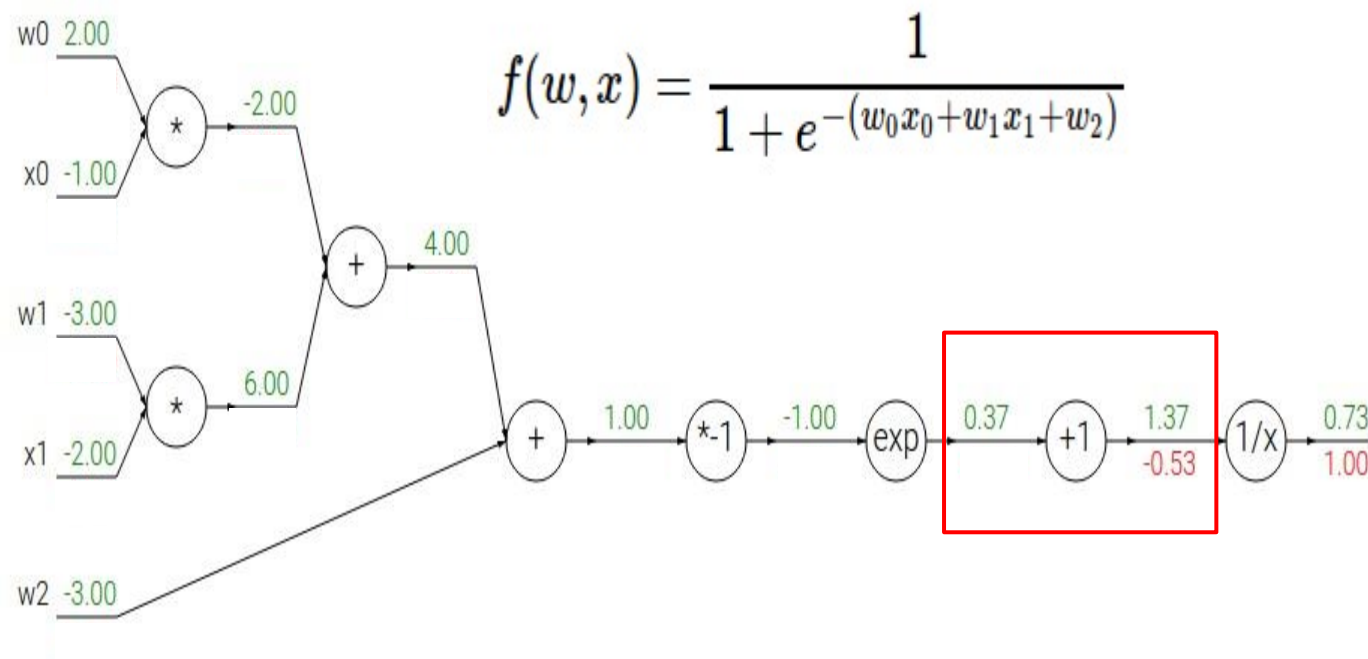
$$f(x) = e^x \rightarrow \frac{df}{dx} = e^x$$

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

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

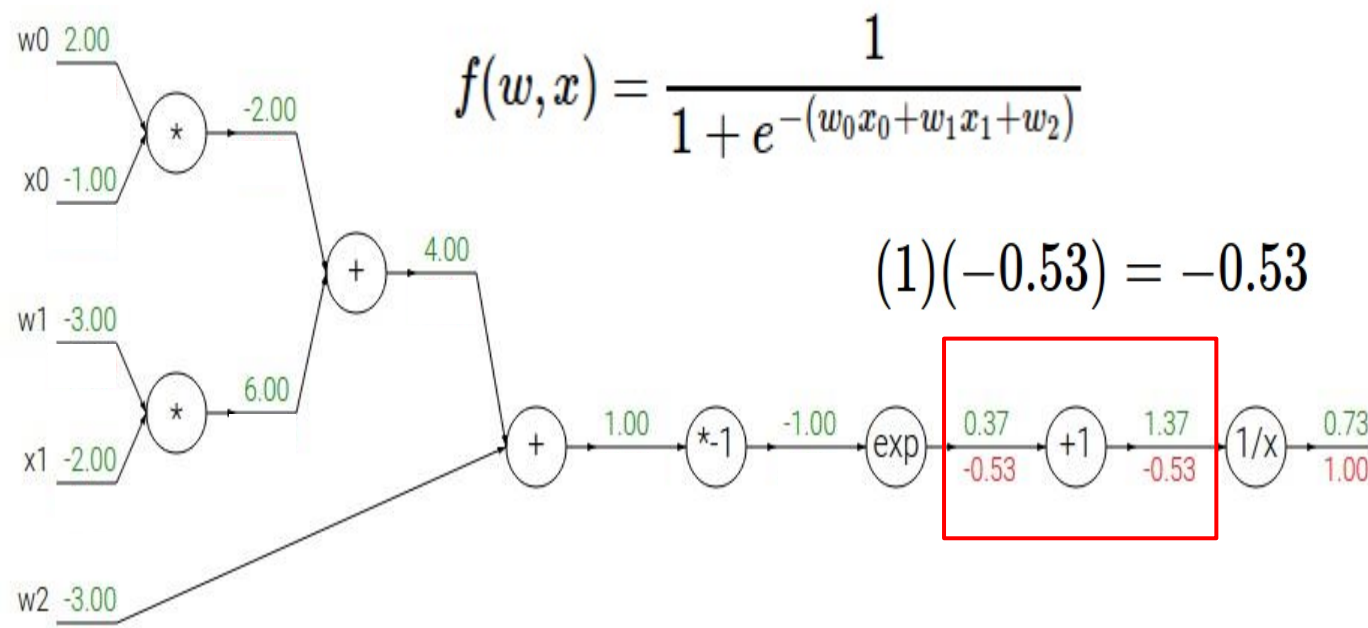
$$f_c(x) = c + x \rightarrow \frac{df}{dx} = 1$$

# Outro Exemplo – Passo Retrógrado



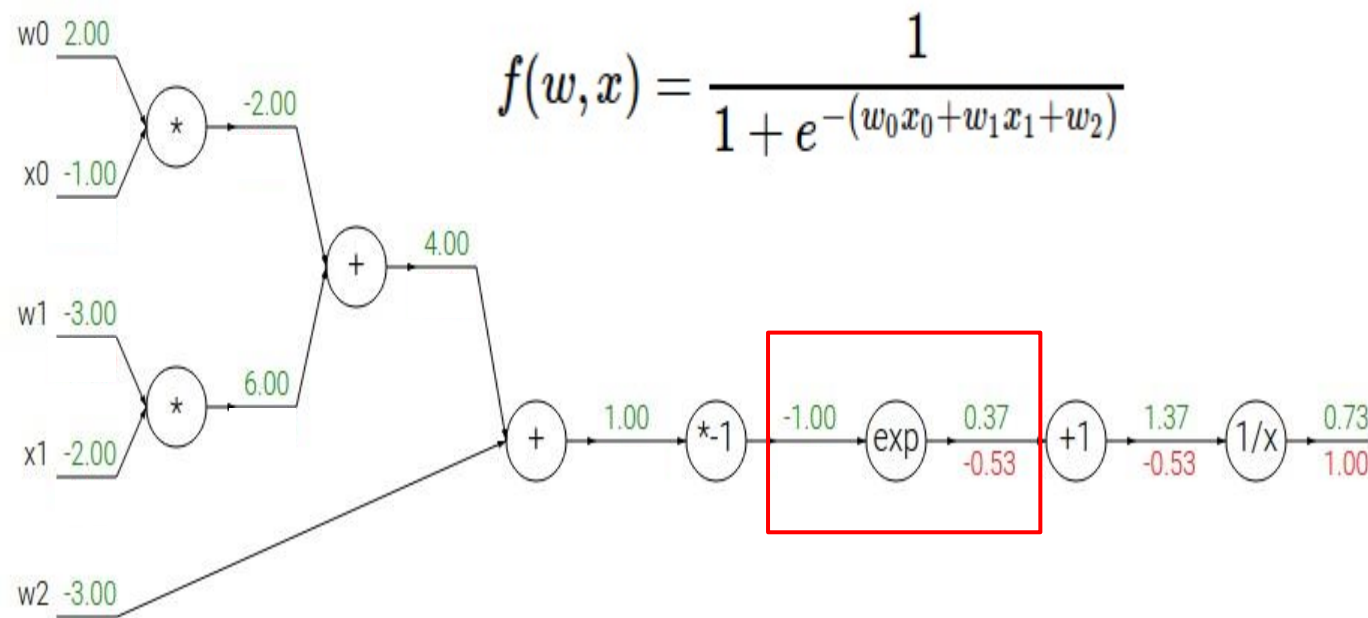
$f(x) = e^x$	$\rightarrow$	$\frac{df}{dx} = e^x$		$f(x) = \frac{1}{x}$	$\rightarrow$	$\frac{df}{dx} = -1/x^2$
$f_a(x) = ax$	$\rightarrow$	$\frac{df}{dx} = a$		$f_c(x) = c + x$	$\rightarrow$	$\frac{df}{dx} = 1$

# Outro Exemplo – Passo Retrógrado



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

# Outro Exemplo – Passo Retrógrado



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

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

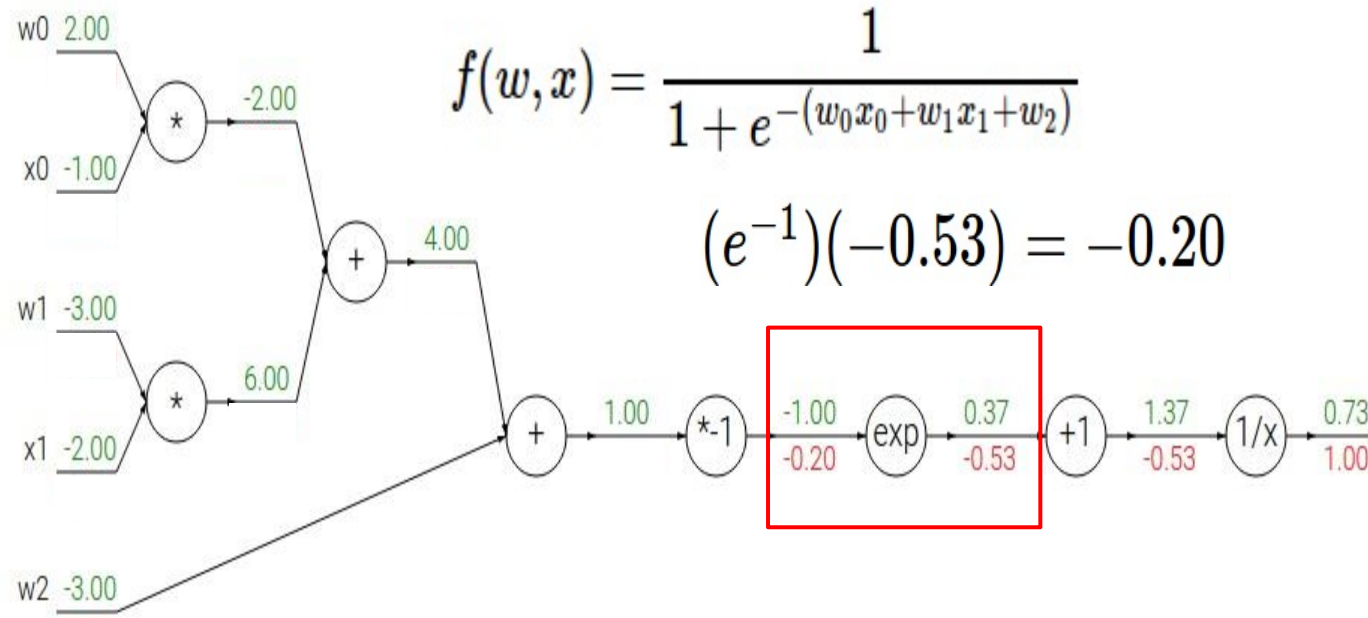
$$f(x) = \frac{1}{x}$$

$$f_c(x) = c + x$$

$$\rightarrow \frac{df}{dx} = -1/x^2$$

$$\rightarrow \frac{df}{dx} = 1$$

# Outro Exemplo – Passo Retrógrado



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

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

$$f(x) = \frac{1}{x}$$

$$f_c(x) = c + x$$

→

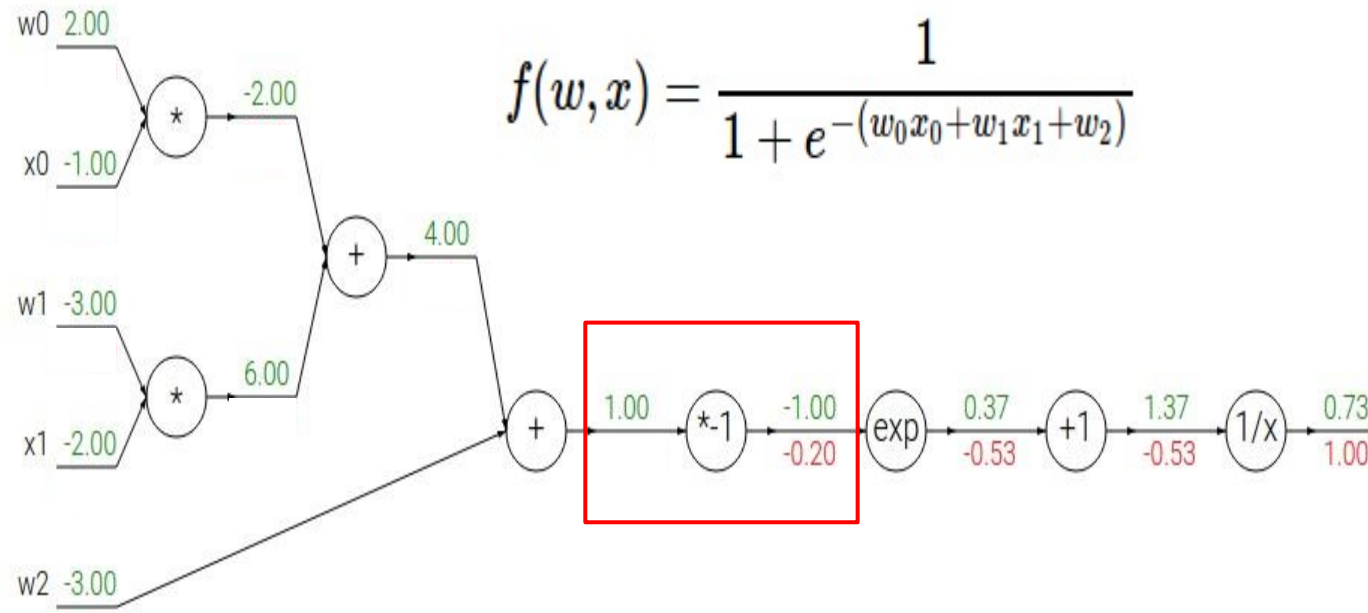
$$\frac{df}{dx} = -1/x^2$$

→

$$\frac{df}{dx} = 1$$



# Outro Exemplo – Passo Retrógrado



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

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

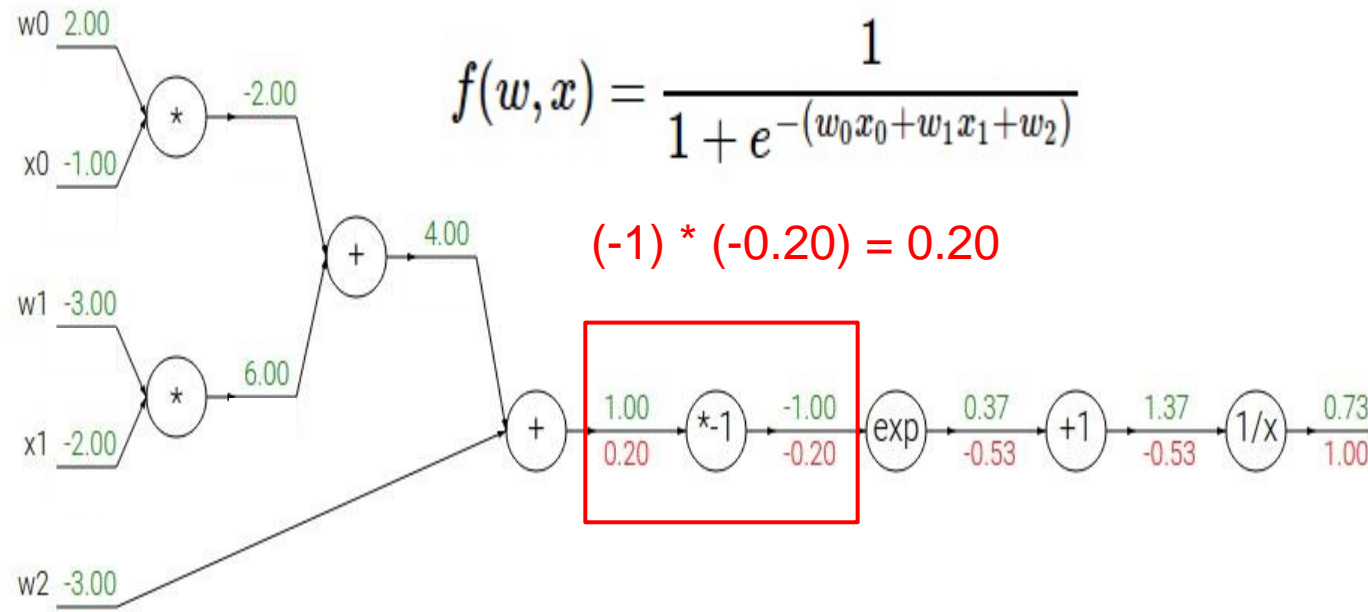
$$f(x) = \frac{1}{x}$$

$$f_c(x) = c + x$$

$$\rightarrow \frac{df}{dx} = -1/x^2$$

$$\rightarrow \frac{df}{dx} = 1$$

# Outro Exemplo – Passo Retrógrado



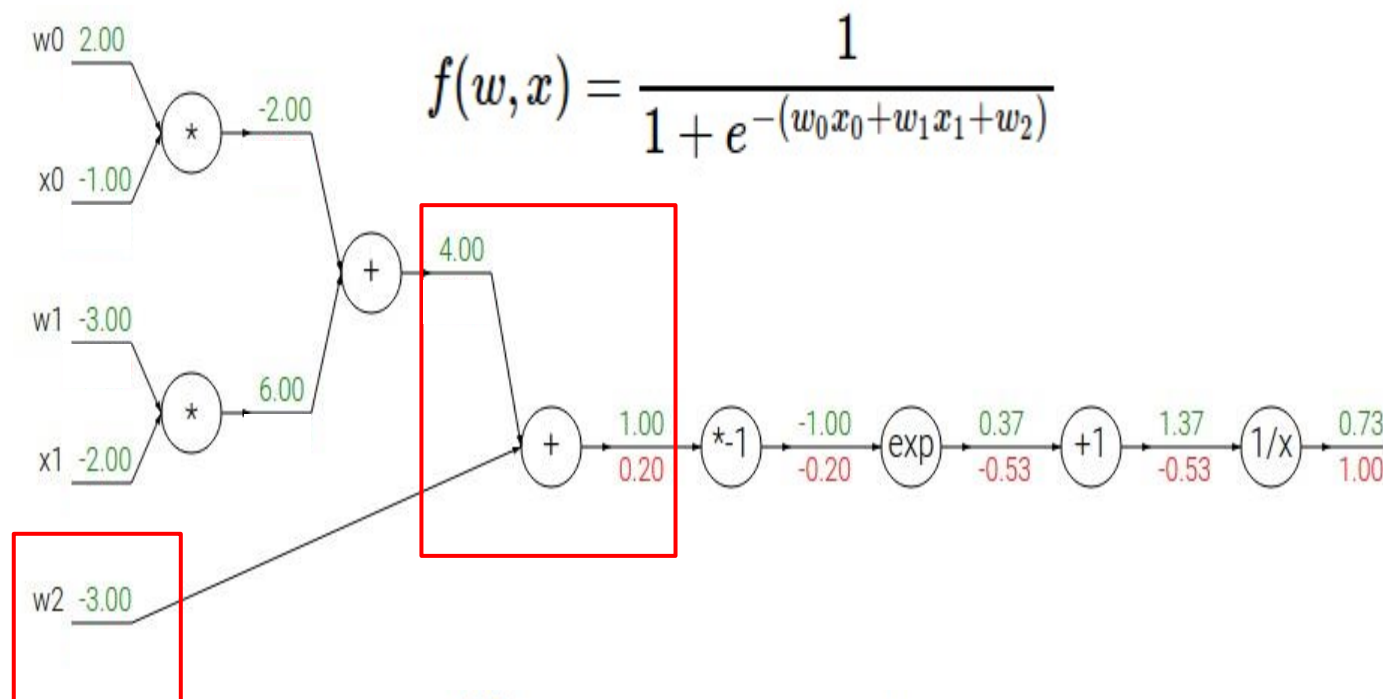
$$f(x) = e^x \rightarrow \frac{df}{dx} = e^x$$

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

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

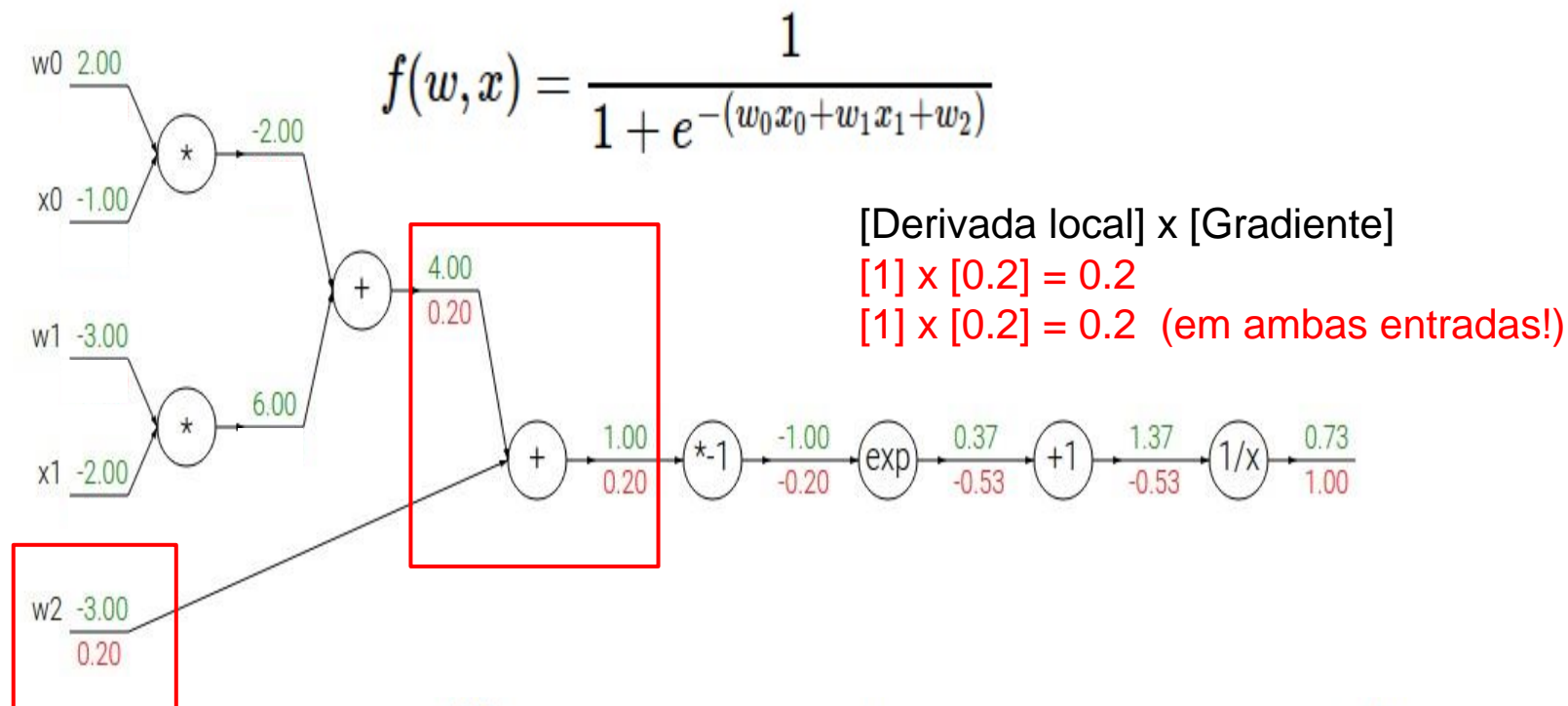
$$f_c(x) = c + x \rightarrow \frac{df}{dx} = 1$$

# Outro Exemplo – Passo Retrógrado



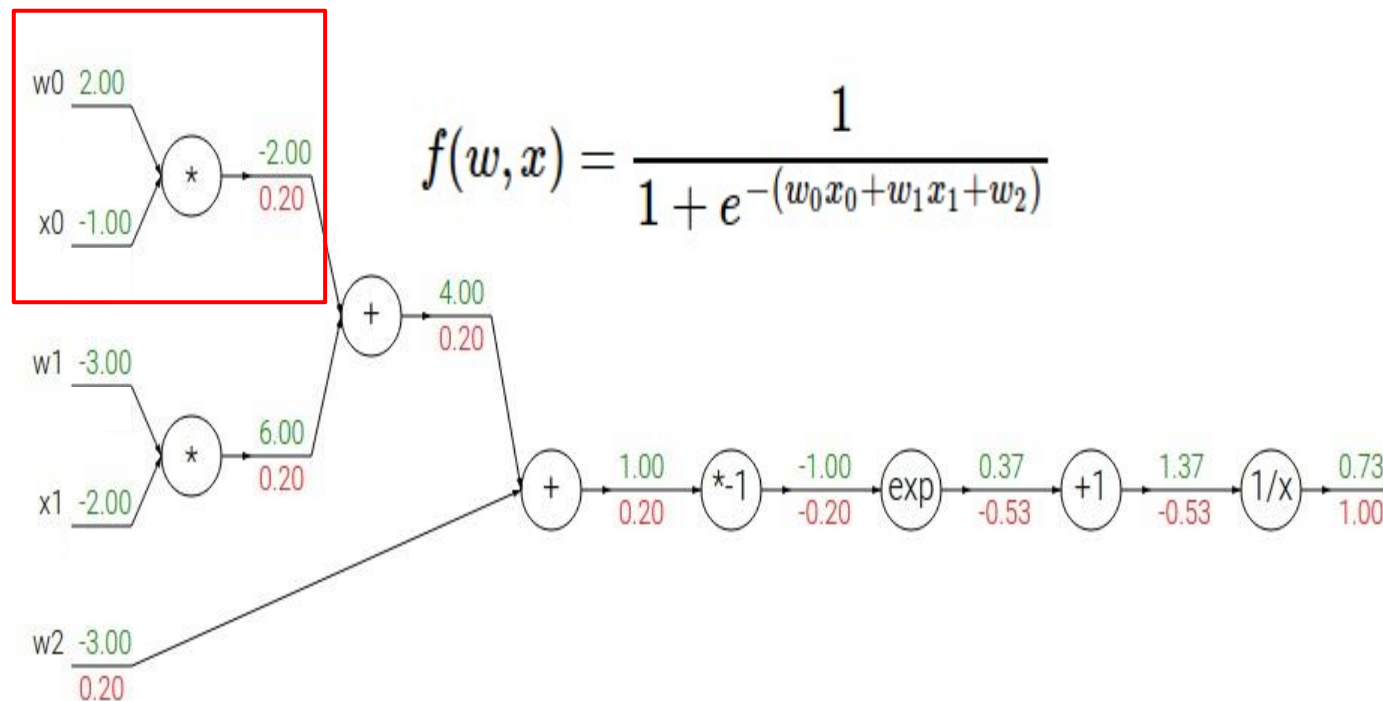
$f(x) = e^x$	$\rightarrow$	$\frac{df}{dx} = e^x$		$f(x) = \frac{1}{x}$	$\rightarrow$	$\frac{df}{dx} = -1/x^2$
$f_a(x) = ax$	$\rightarrow$	$\frac{df}{dx} = a$		$f_c(x) = c + x$	$\rightarrow$	$\frac{df}{dx} = 1$

# Outro Exemplo – Passo Retrógrado



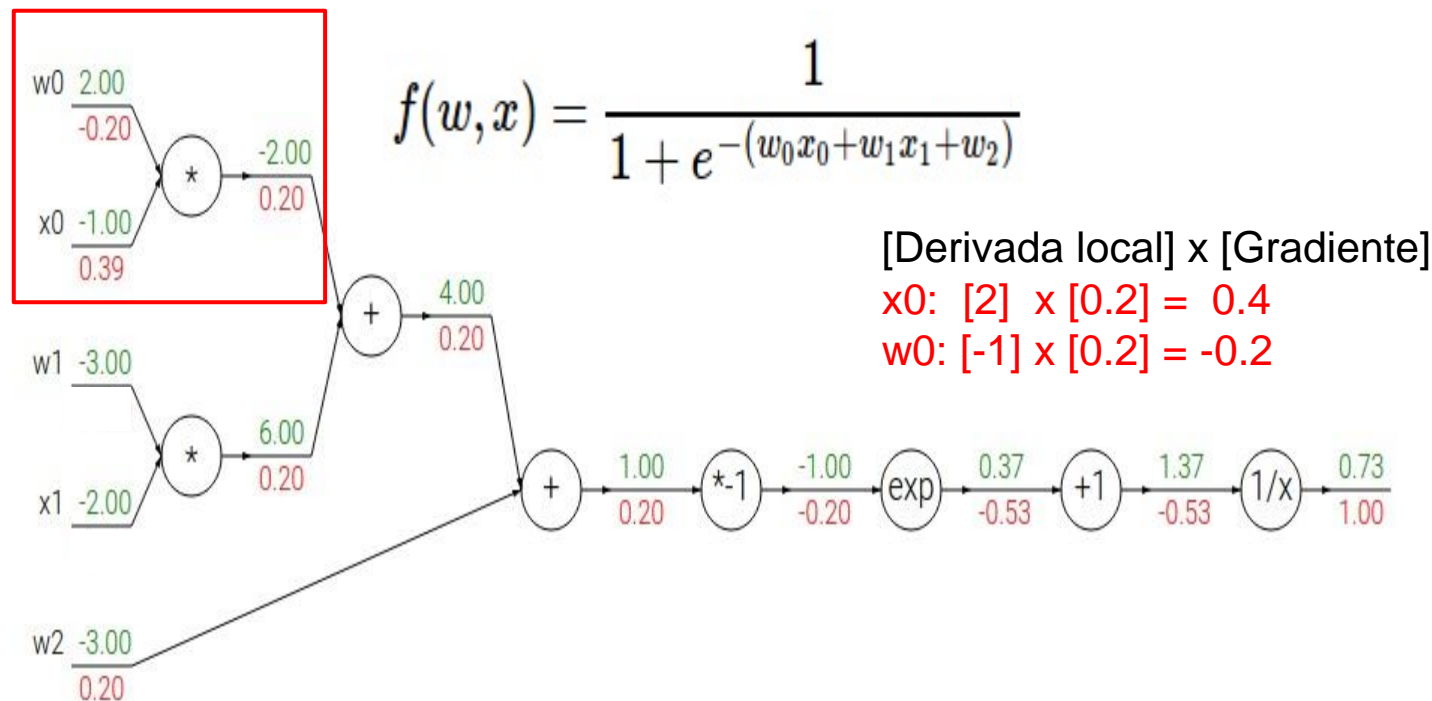
$f(x) = e^x$	$\rightarrow$	$\frac{df}{dx} = e^x$		$f(x) = \frac{1}{x}$	$\rightarrow$	$\frac{df}{dx} = -1/x^2$
$f_a(x) = ax$	$\rightarrow$	$\frac{df}{dx} = a$		$f_c(x) = c + x$	$\rightarrow$	$\frac{df}{dx} = 1$

# Outro Exemplo – Passo Retrógrado



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

# Outro Exemplo – Passo Retrógrado



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

# Outro Exemplo – Passo Retrógrado

$$f(w, x) = \frac{1}{1 + e^{-(w_0 x_0 + w_1 x_1 + w_2)}}$$

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

Função sigmoide

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

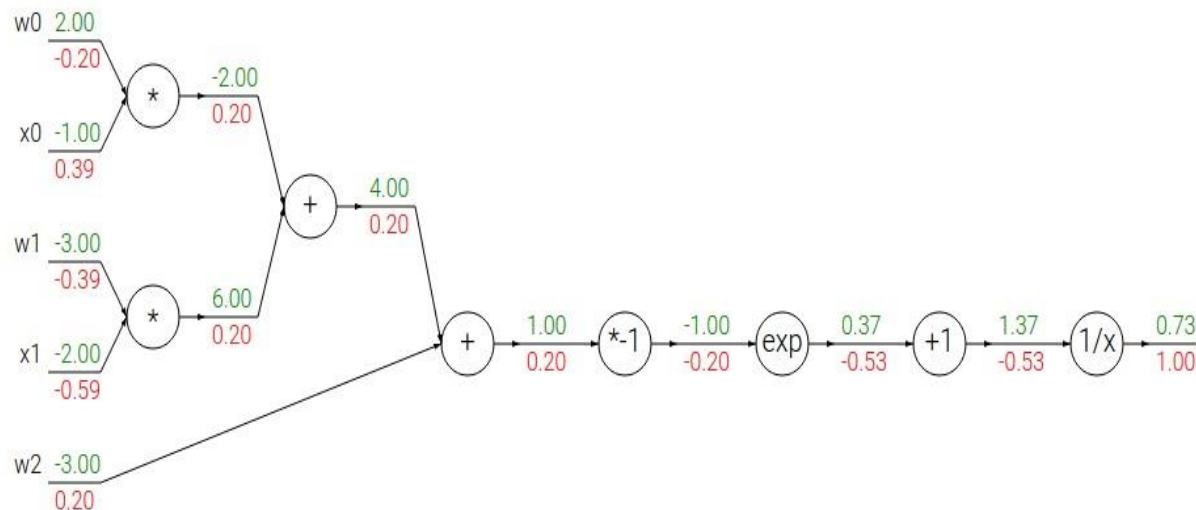
# Outro Exemplo – Passo Retrógrado

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2x_2)}}$$

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

Função sigmoide

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





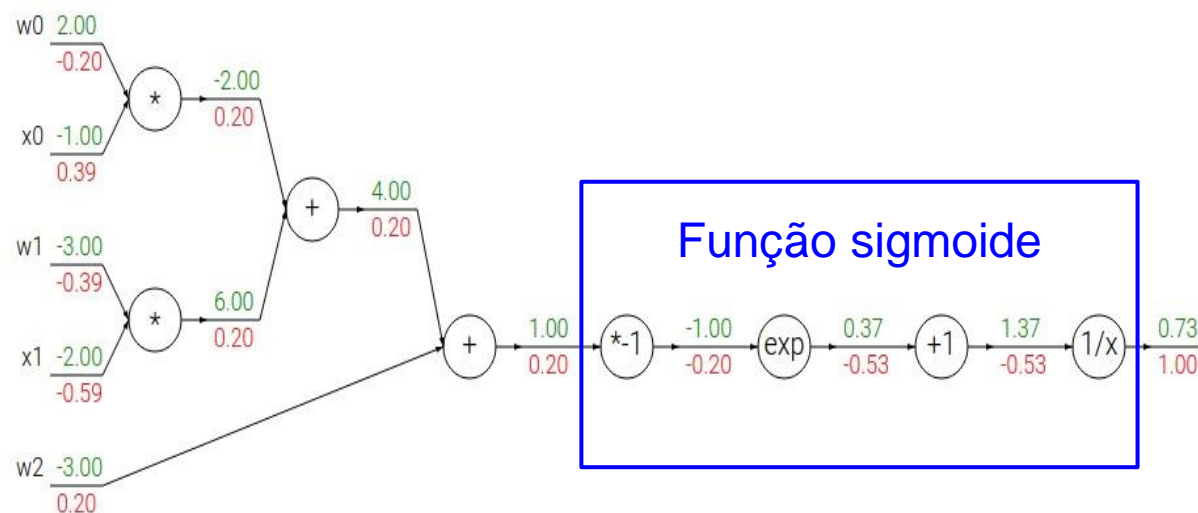
# Outro Exemplo – Passo Retrógrado

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2x_2)}}$$

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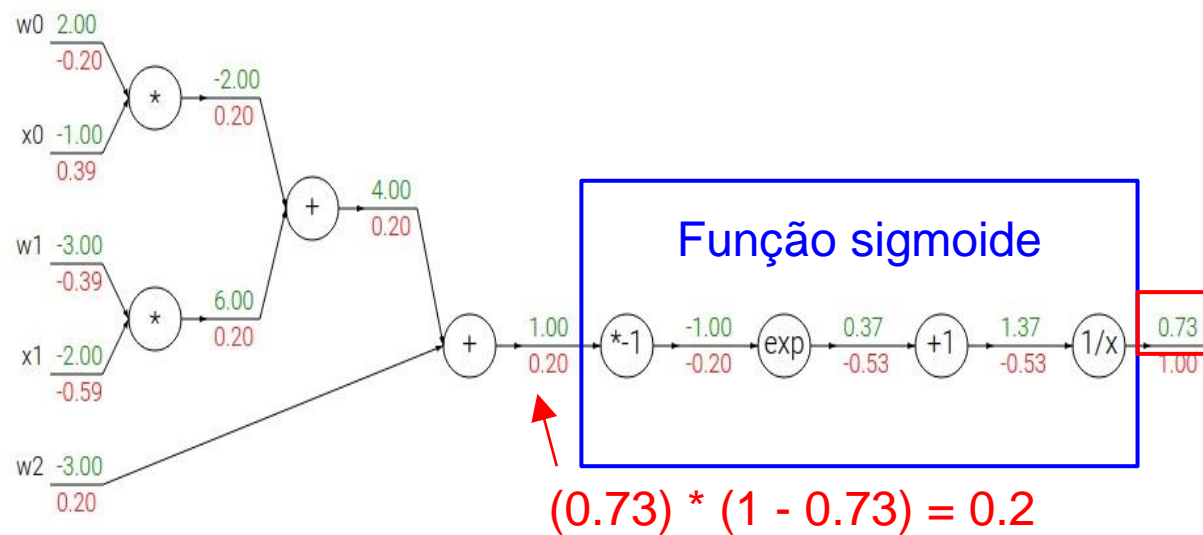
# Outro Exemplo – Passo Retrógrado

$$f(w, x) = \frac{1}{1 + e^{-(w_0x_0 + w_1x_1 + w_2x_2)}}$$

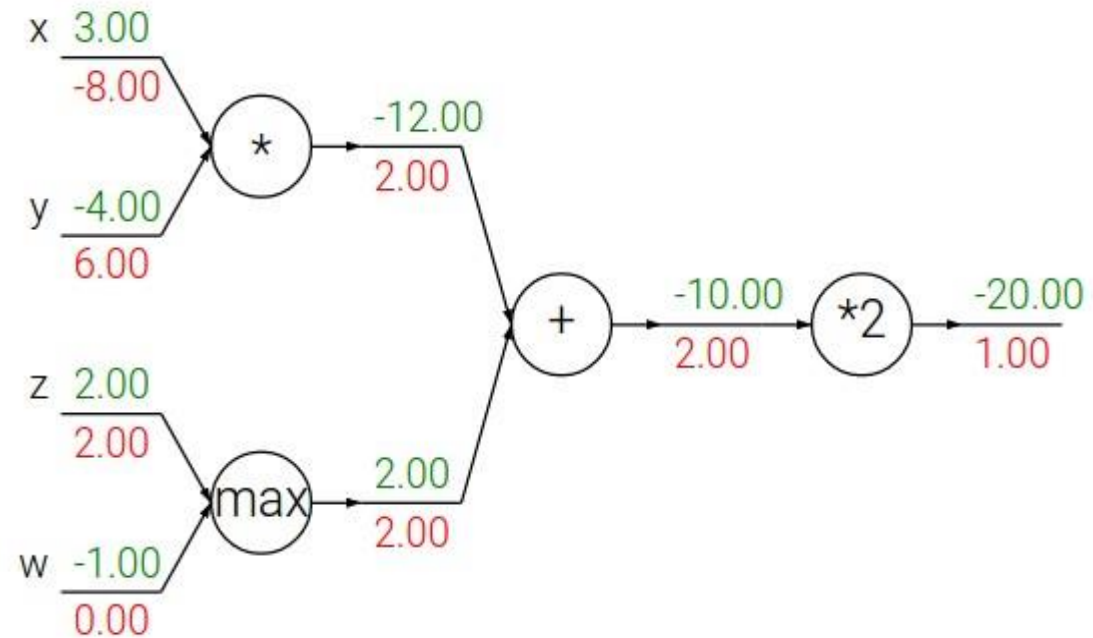
$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

Função sigmoide

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

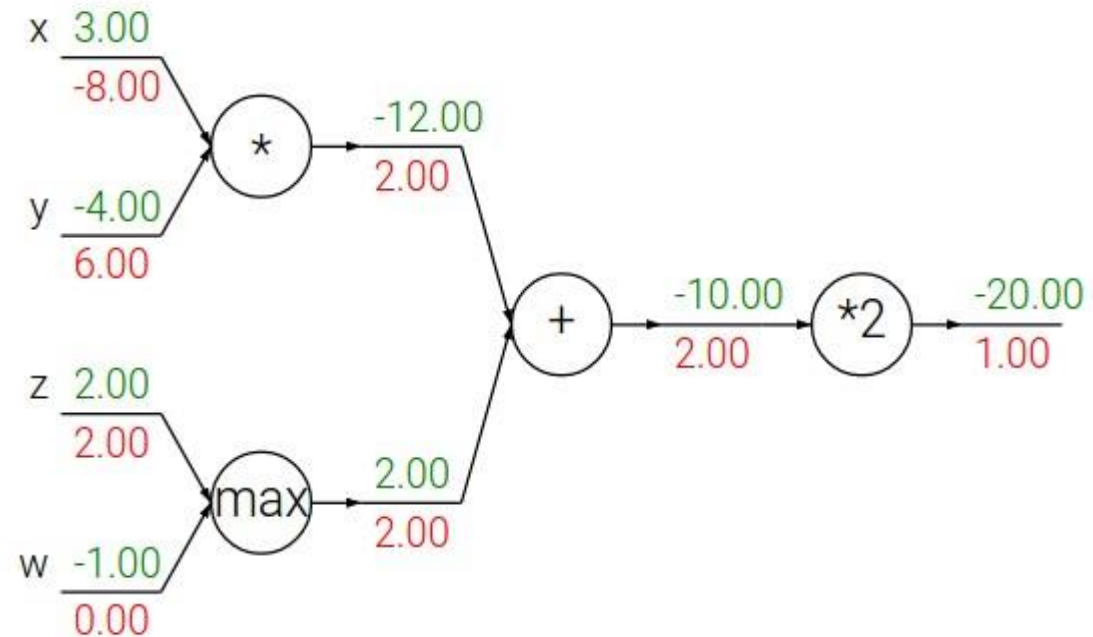


# Padrões no Fluxo Reverso



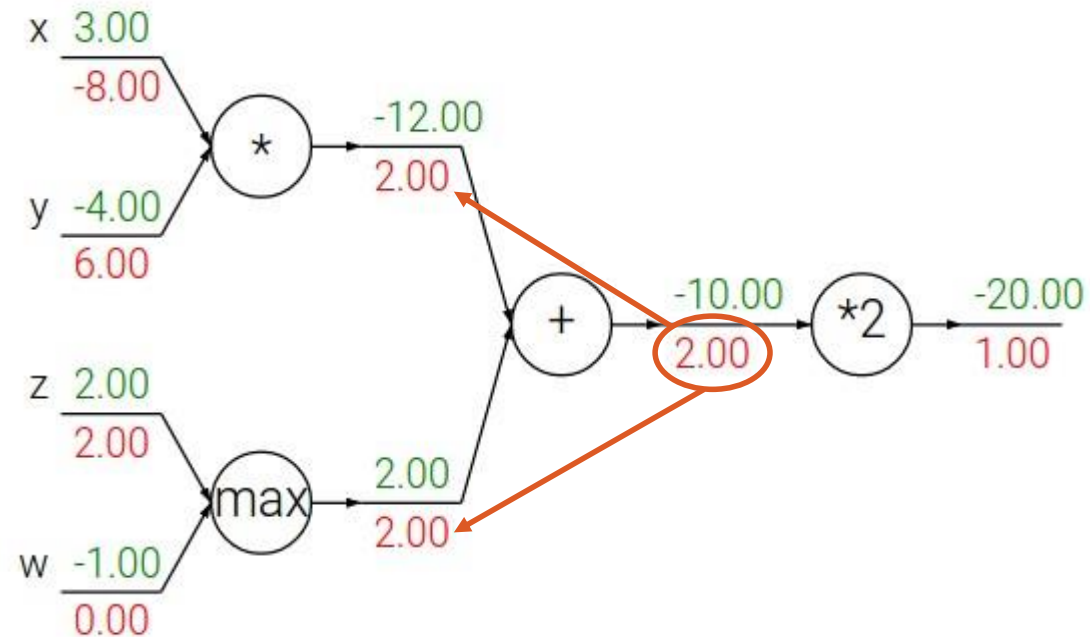
# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente



# Padrões no Fluxo Reverso

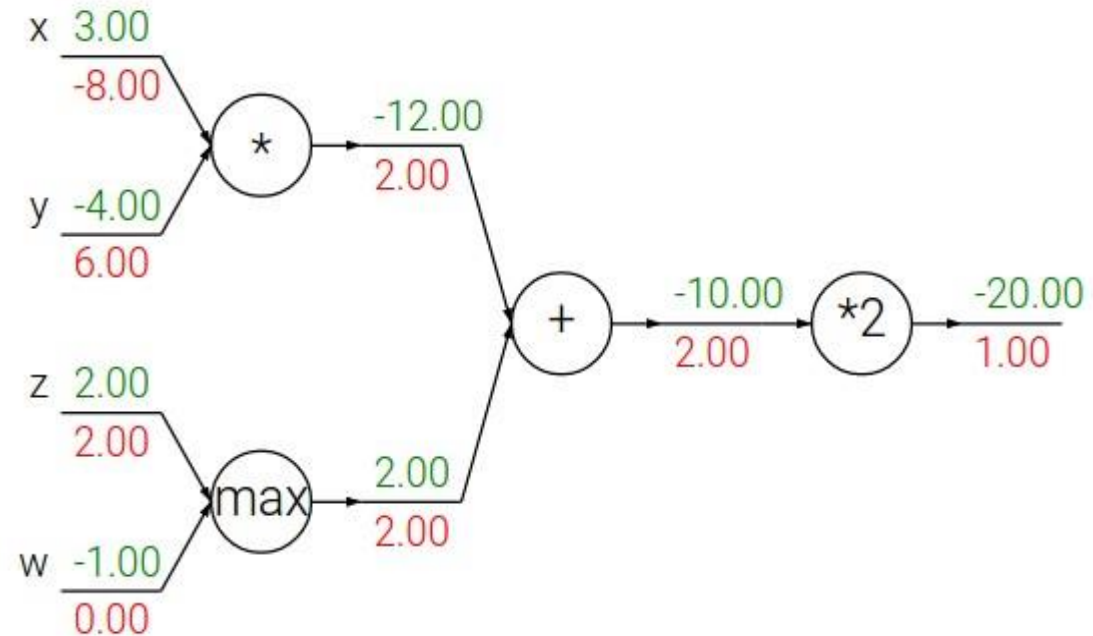
**Adição** : distribuidor de gradiente



# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente

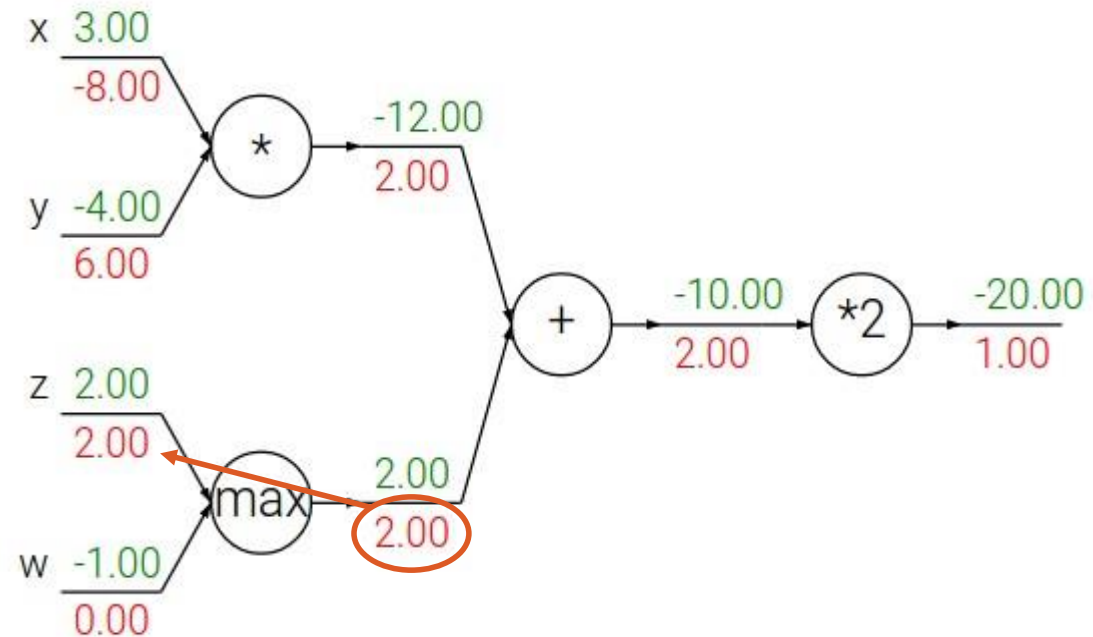
**Max** : direcionador de gradiente



# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente

**Max** : direcionador de gradiente

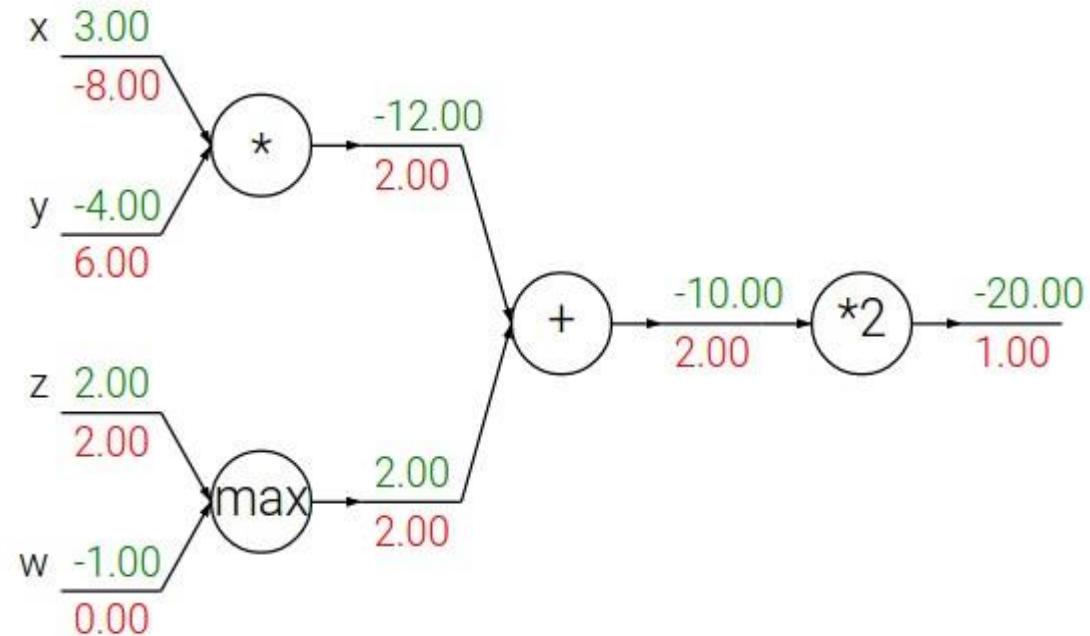


# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente

**Max** : direcionador de gradiente

**Produto**: “comutador” de gradiente



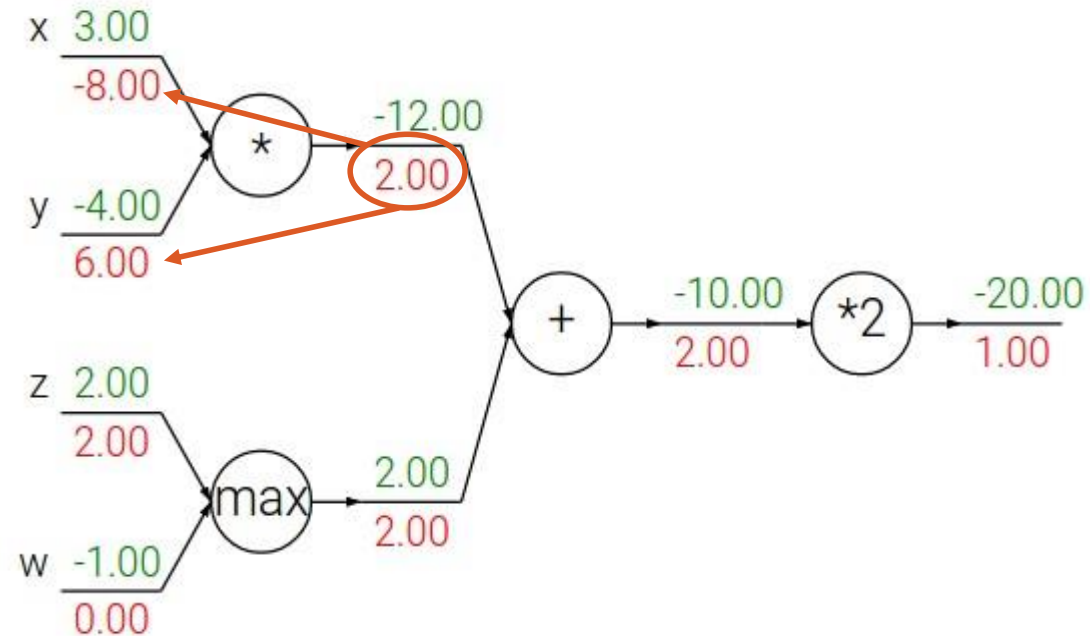


# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente

**Max** : direcionador de gradiente

**Produto**: “comutador” de gradiente

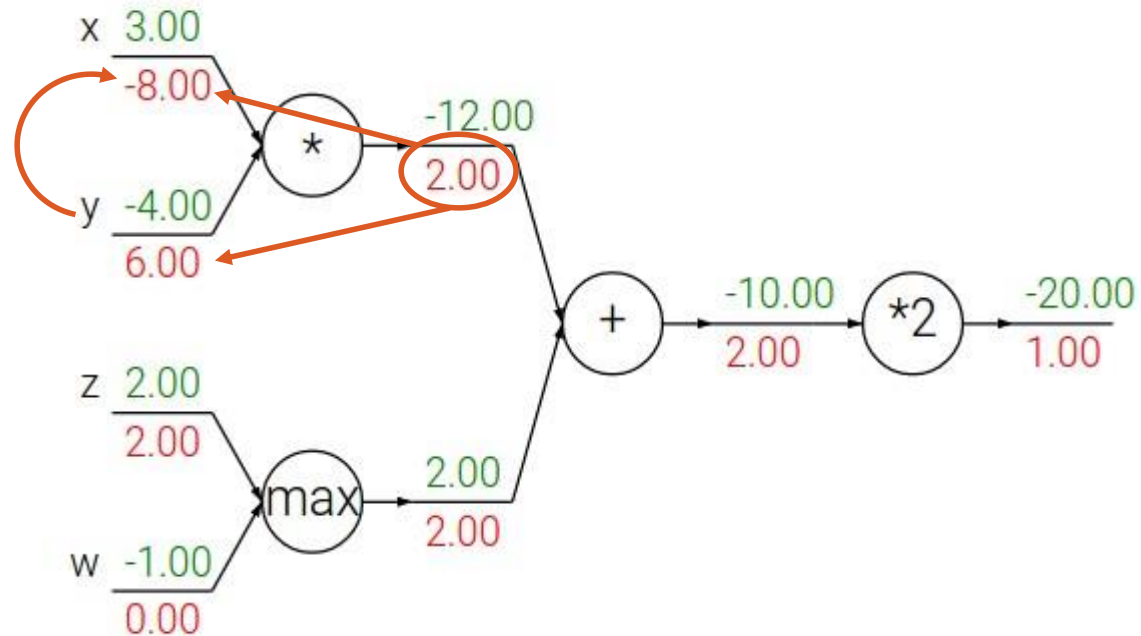


# Padrões no Fluxo Reverso

**Adição** : distribuidor de gradiente

**Max** : direcionador de gradiente

**Produto**: “comutador” de gradiente

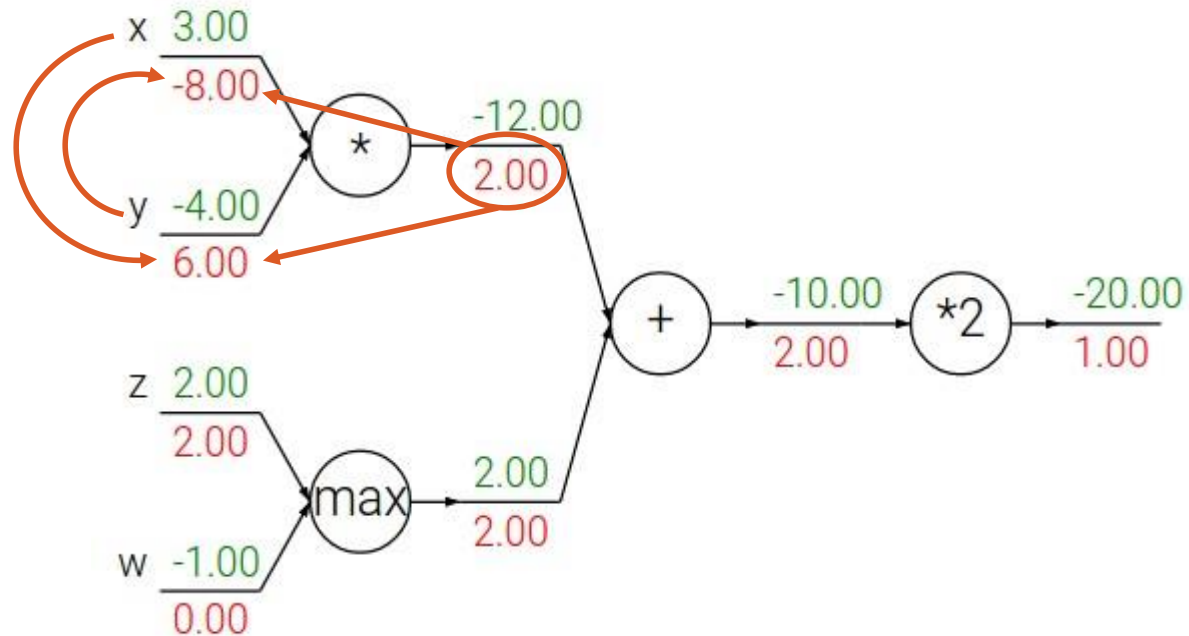


# Padrões no Fluxo Reverso

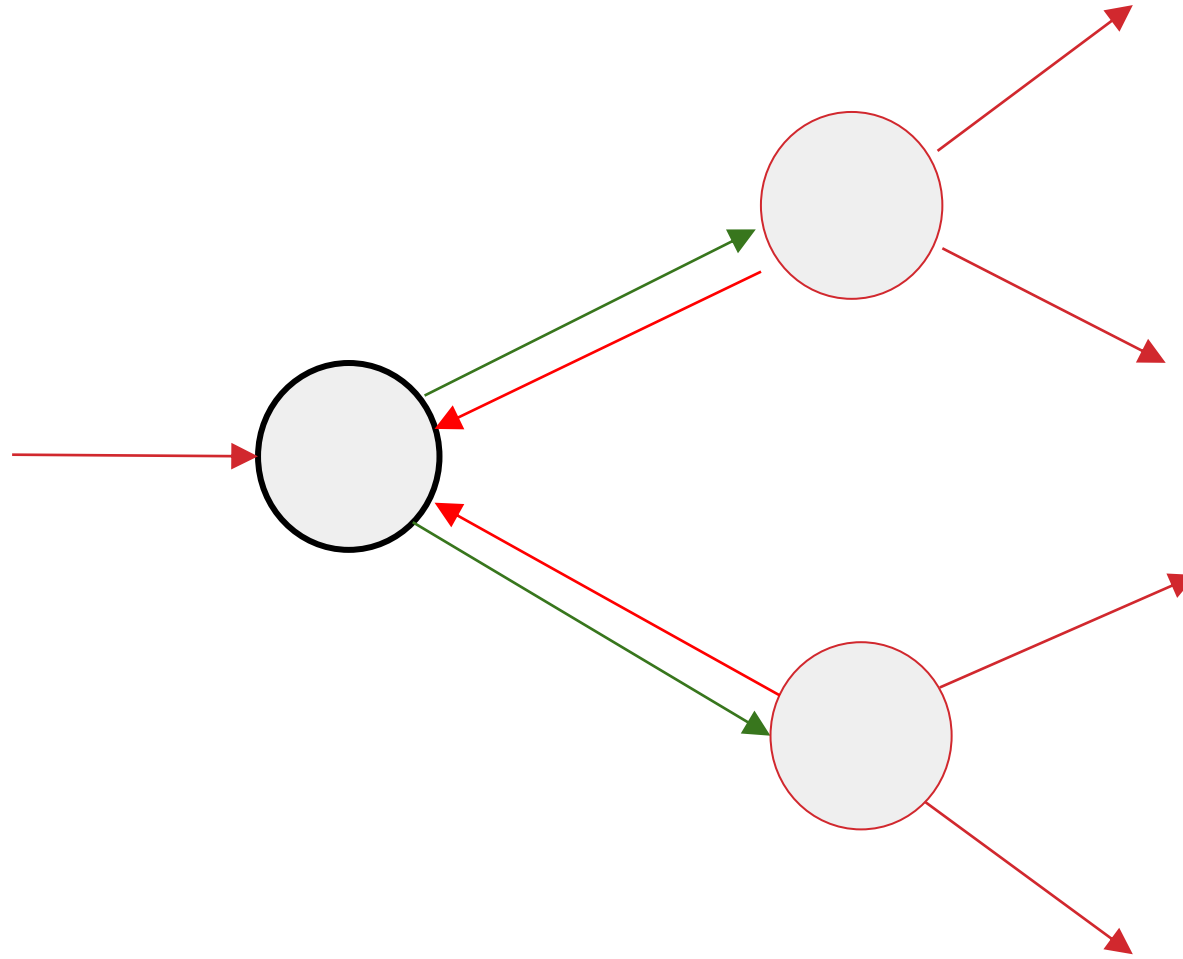
**Adição** : distribuidor de gradiente

**Max** : direcionador de gradiente

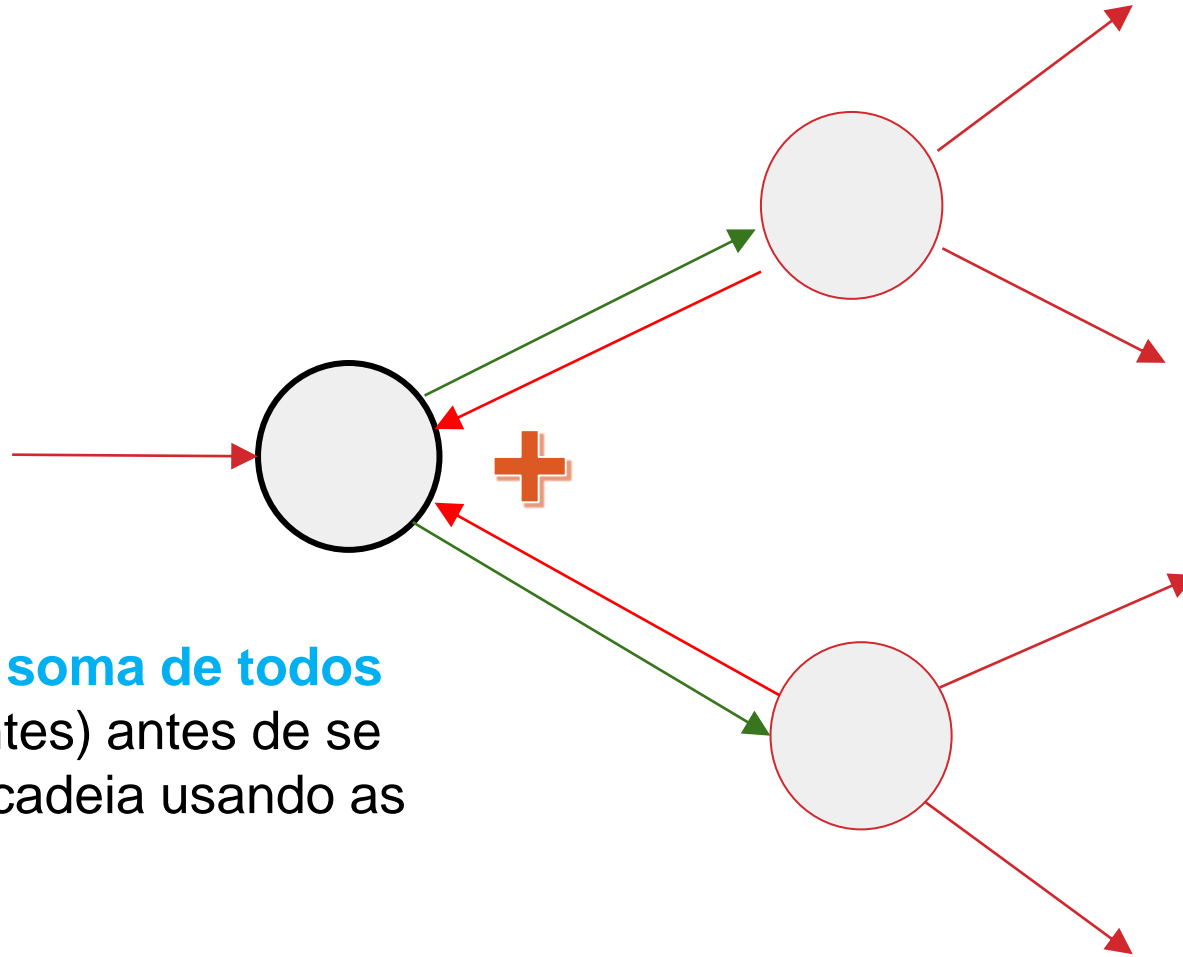
**Produto**: “comutador” de gradiente



# Gradientes nas Ramificações

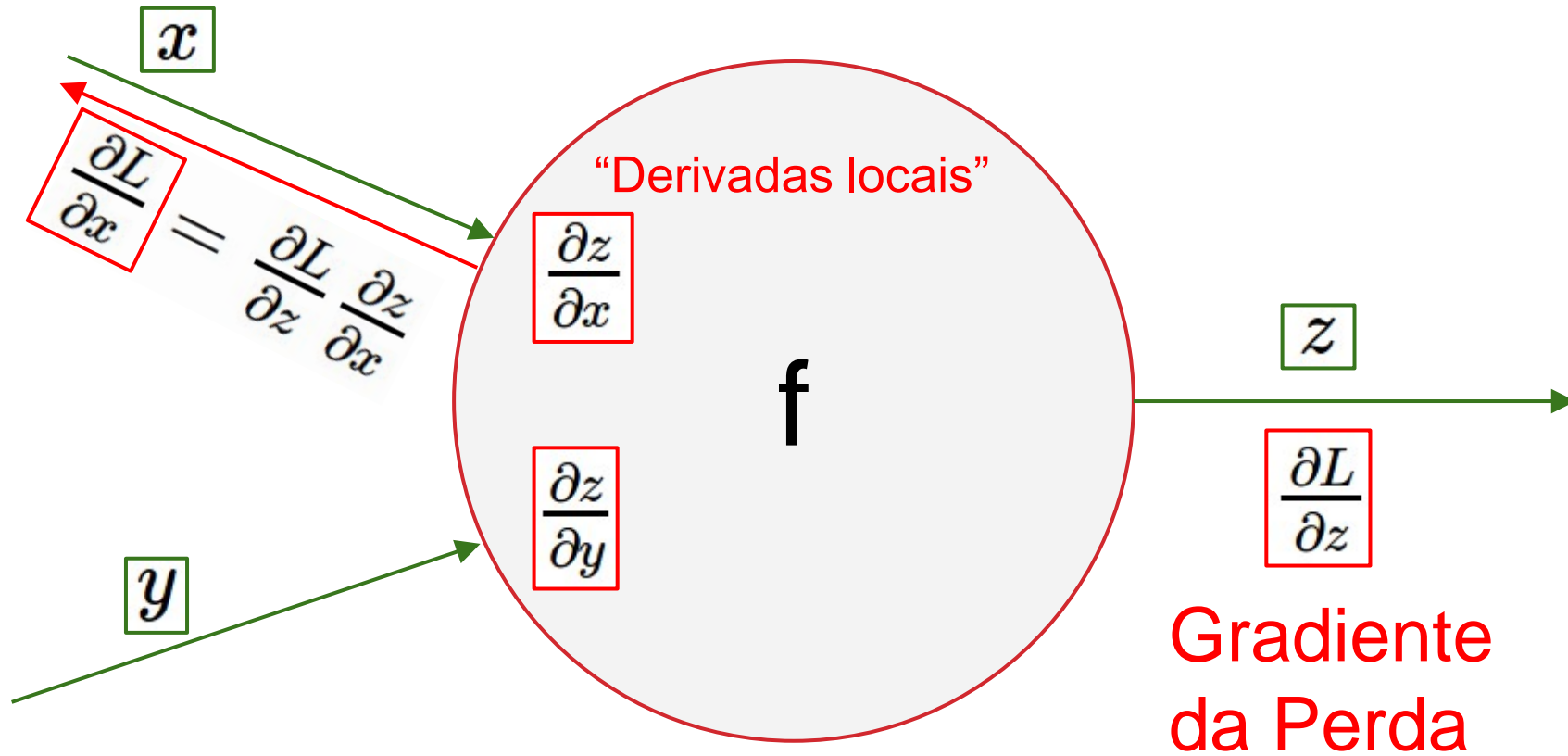


# Gradientes nas Ramificações

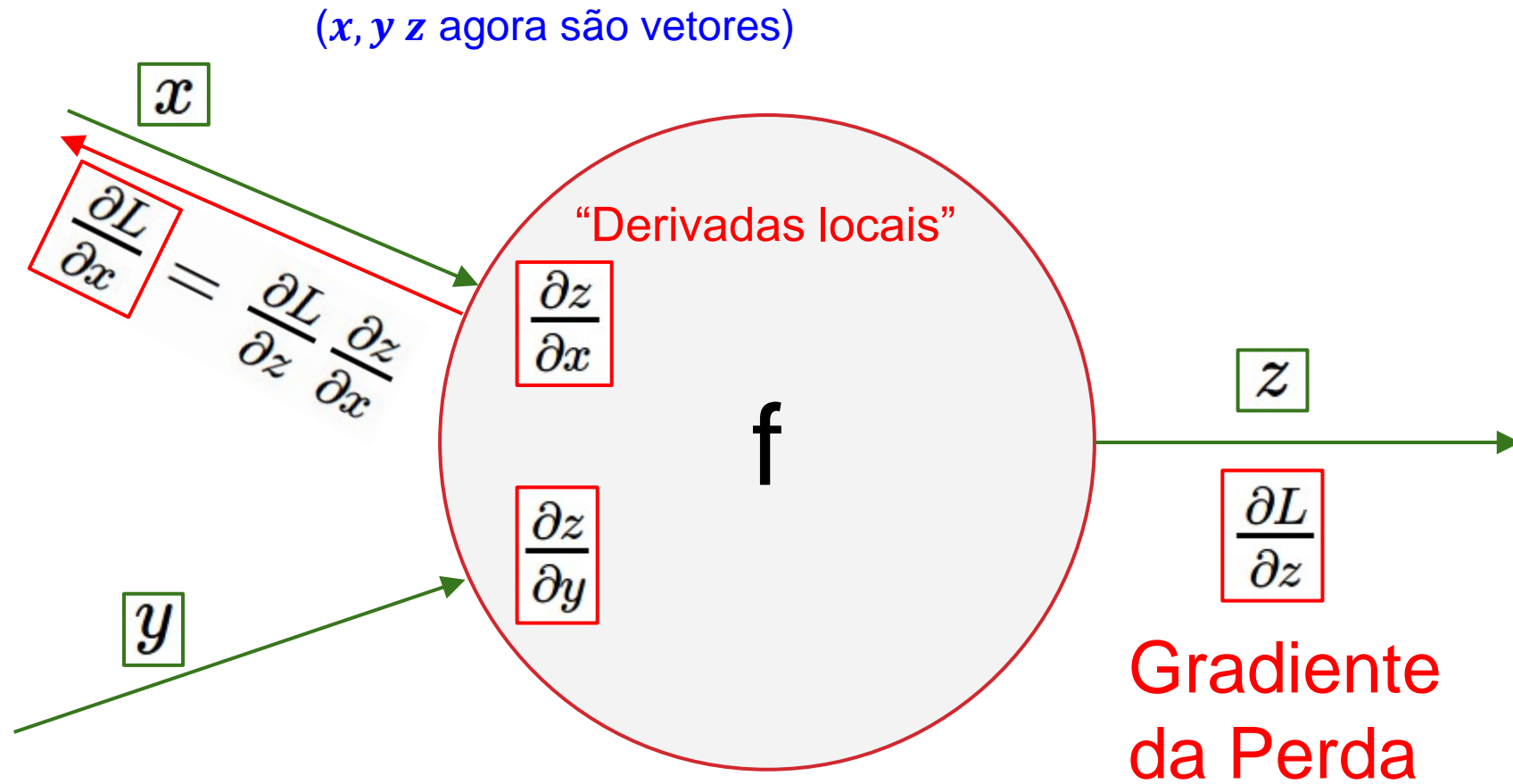


Deve-se realizar a **soma de todos os fluxos** (gradientes) antes de se aplicar a regra da cadeia usando as derivadas locais

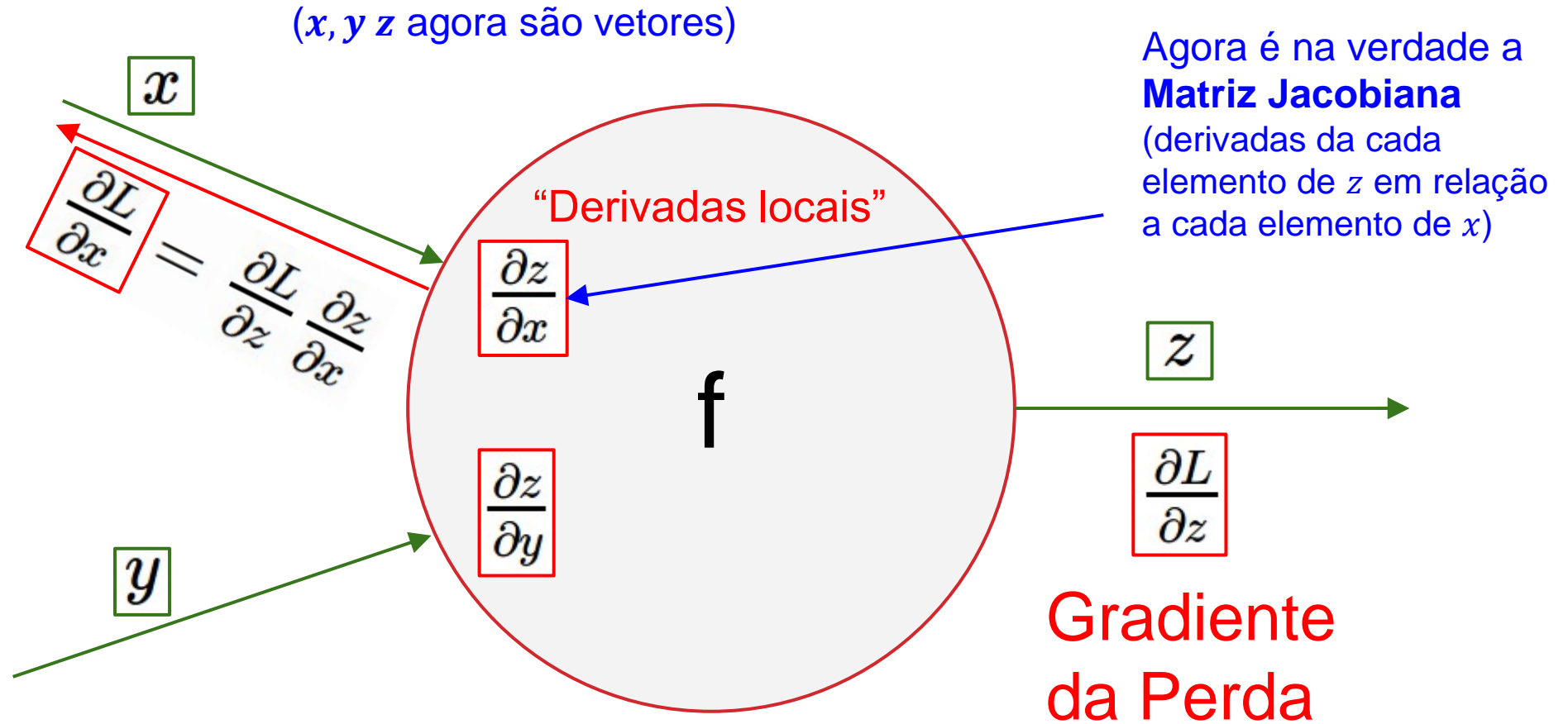
# Gradientes para Dados Multidimensionais



# Gradientes para Dados Multidimensionais

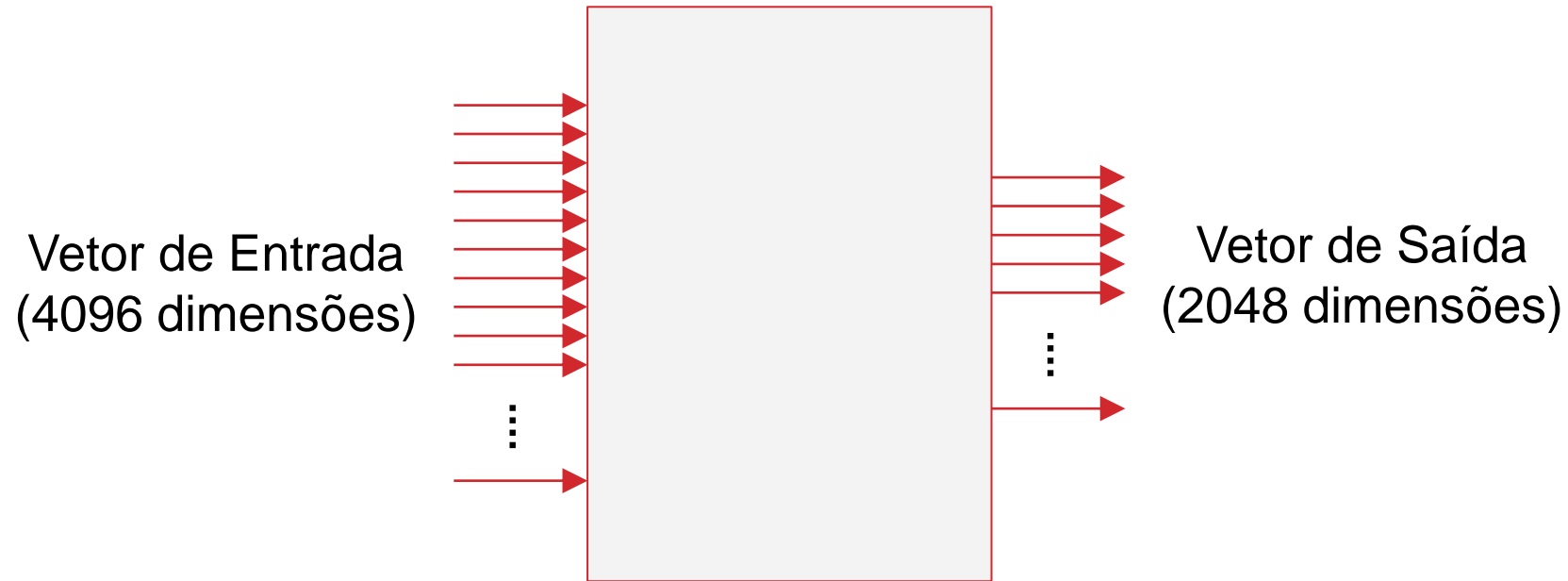


# Gradientes para Dados Multidimensionais

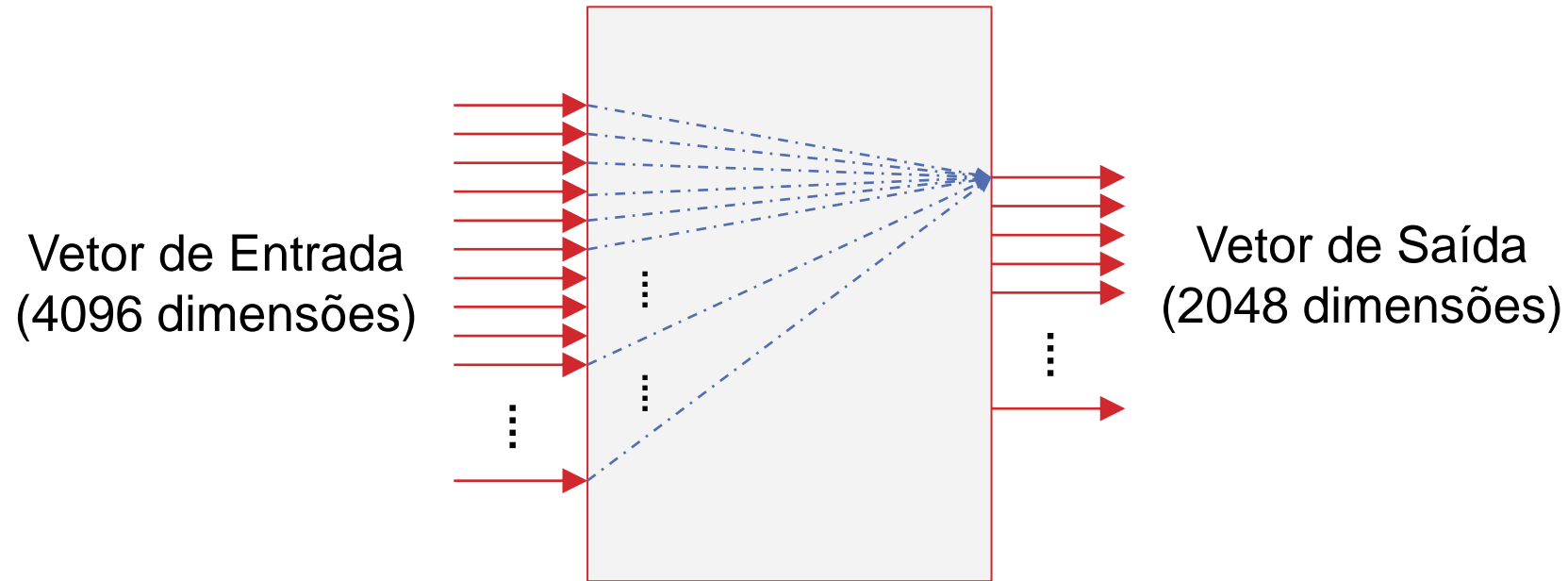




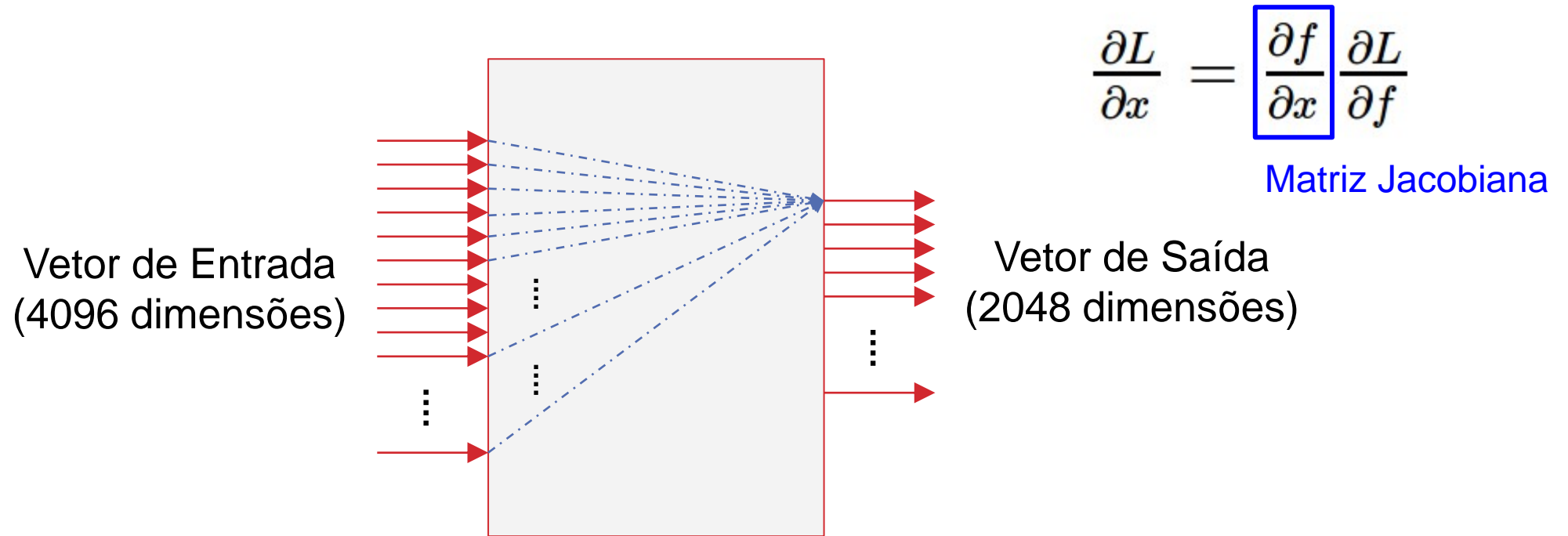
# Gradientes para Dados Multidimensionais



# Gradientes para Dados Multidimensionais



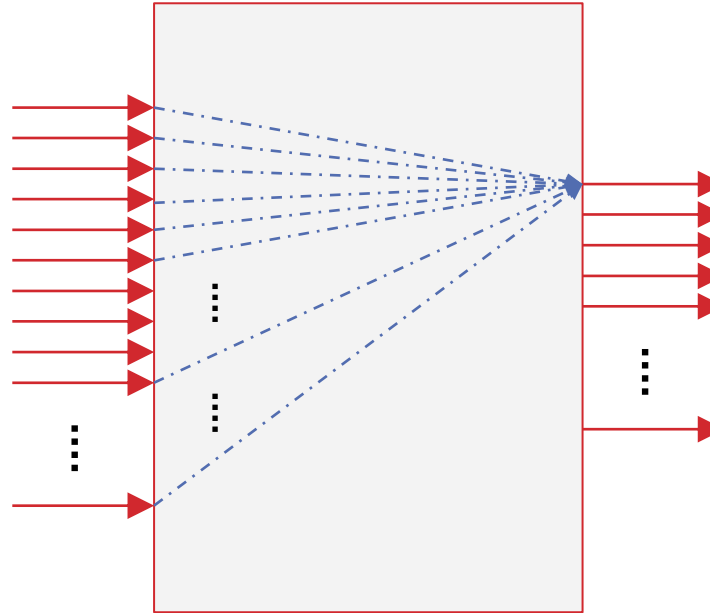
# Gradientes para Dados Multidimensionais



# Gradientes para Dados Multidimensionais

P1: qual o tamanho  
da matriz Jacobiana?

Vetor de Entrada  
(4096 dimensões)



Vetor de Saída  
(2048 dimensões)

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

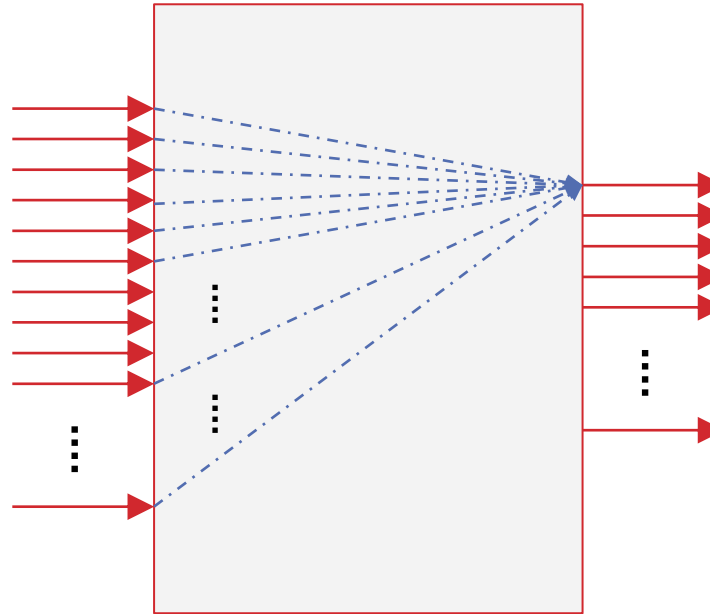
Matriz Jacobiana

# Gradientes para Dados Multidimensionais

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

Matriz Jacobiana

Vetor de Entrada  
(4096 dimensões)



Vetor de Saída  
(2048 dimensões)

P1: qual o tamanho  
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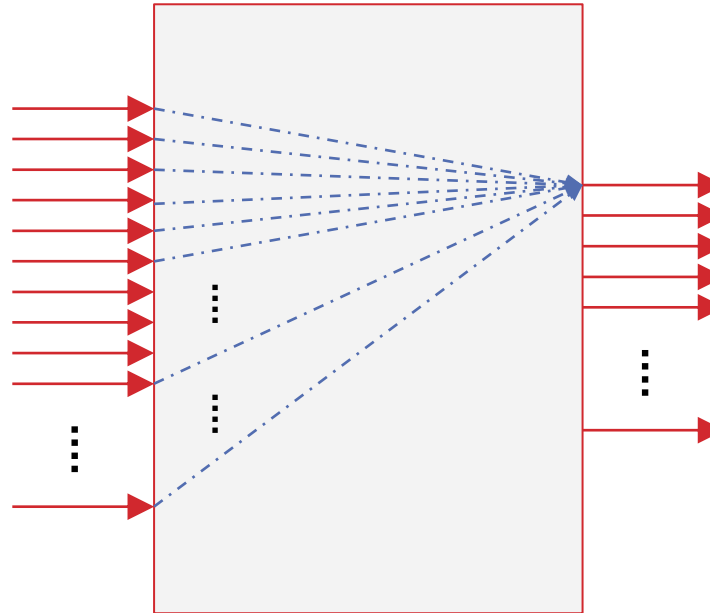
⇒ 2048 × 4096 !

# Gradientes para Dados Multidimensionais

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

Matriz Jacobiana

Vetor de Entrada  
(4096 dimensões)



Vetor de Saída  
(2048 dimensões)

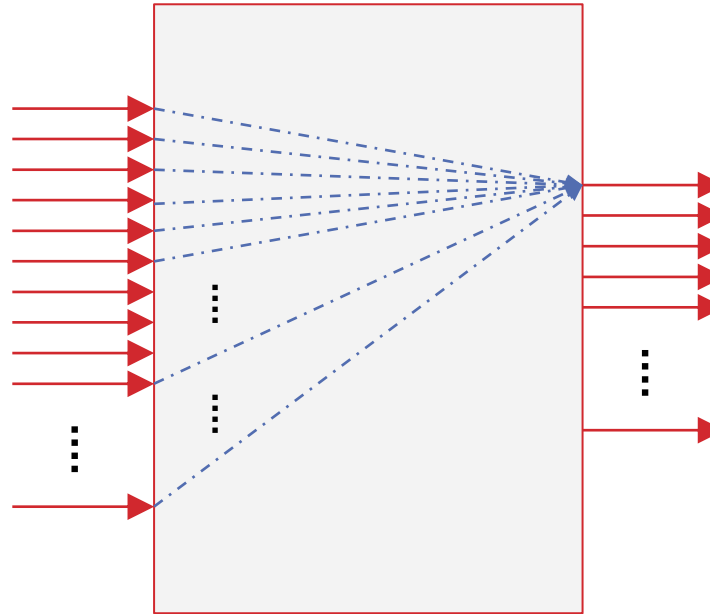
P1: qual o tamanho  
da matriz Jacobiana?

⇒ 2048 × 4096 !

P2: qual a aparência  
dessa matriz?

# Gradientes para Dados Multidimensionais

Vetor de Entrada  
(4096 dimensões)



P1: qual o tamanho  
da matriz Jacobiana?

⇒ 2048 × 4096 !

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

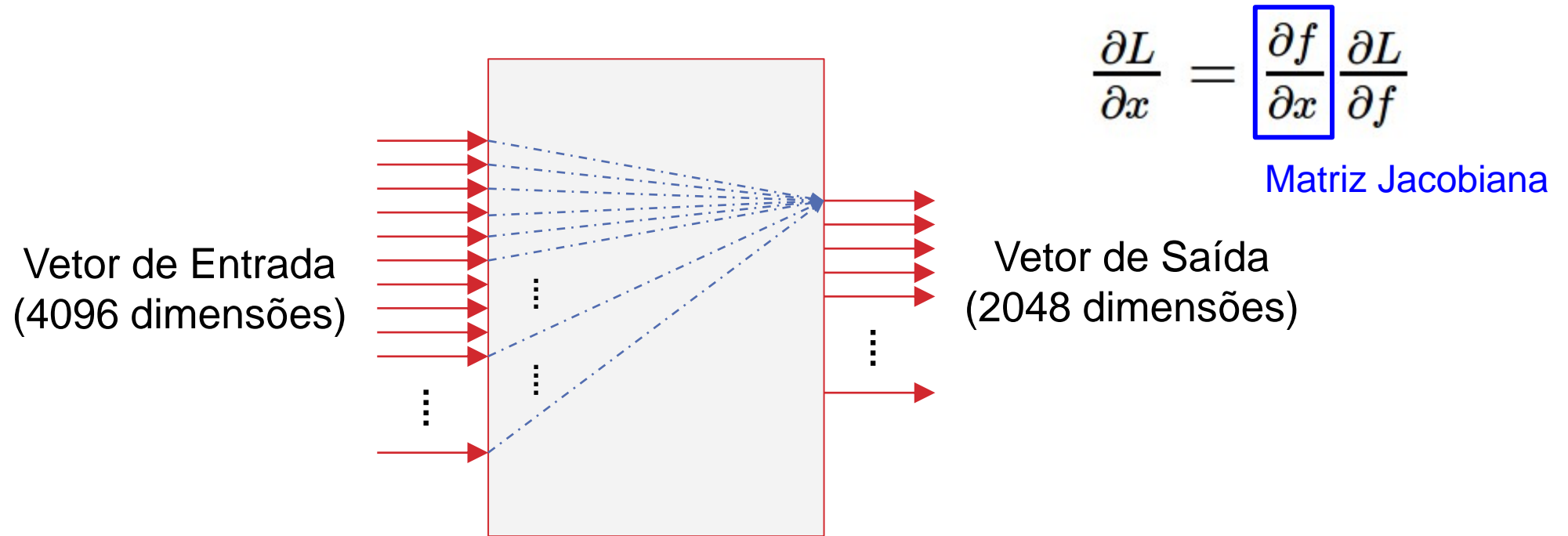
Matriz Jacobiana

Vetor de Saída  
(2048 dimensões)

P2: qual a aparência  
dessa matriz?

$$\begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_m} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \dots & \frac{\partial f_2}{\partial x_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_k}{\partial x_1} & \frac{\partial f_k}{\partial x_2} & \dots & \frac{\partial f_k}{\partial x_m} \end{bmatrix}$$

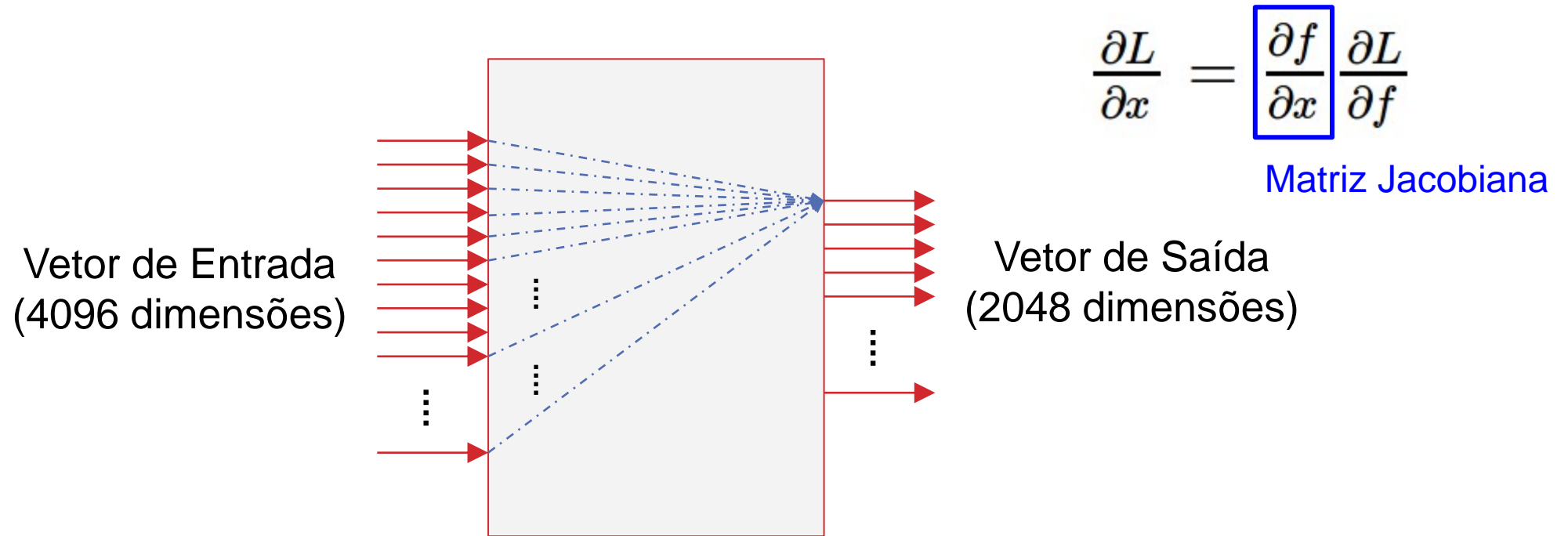
# Gradientes para Dados Multidimensionais



Na prática, processa-se todo um lote ou “*minibatch*” (p.ex. 100 amostras) de uma só vez



# Gradientes para Dados Multidimensionais



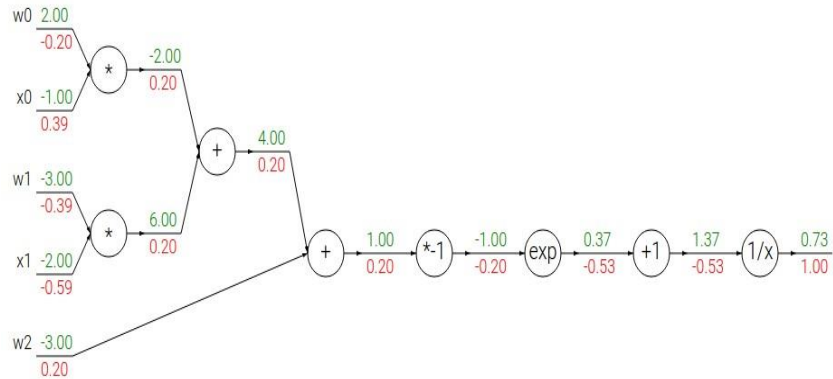
Na prática, processa-se todo um lote ou “*minibatch*” (p.ex. 100 amostras) de uma só vez

Assim, as dimensões da matriz Jacobiana desse exemplo seriam

$$2.048 \times 4.096 \times 100$$

$\approx 839$  milhões de pesos :(

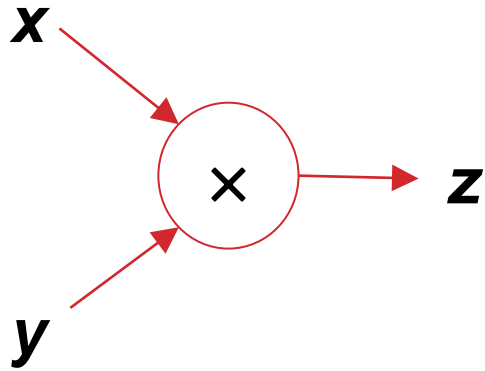
# Implementação – Forward / Backward API



Para um grafo ou rede (*pseudocódigo*)

```
class ComputationalGraph(object):  
    #...  
    def forward(inputs):  
        # 1. [pass inputs to input gates...]  
        # 2. forward the computational graph:  
        for gate in self.graph.nodes_topologically_sorted():  
            gate.forward()  
        return loss # the final gate in the graph outputs the loss  
    def backward():  
        for gate in reversed(self.graph.nodes_topologically_sorted()):  
            gate.backward() # little piece of backprop (chain rule applied)  
        return inputs_gradients
```

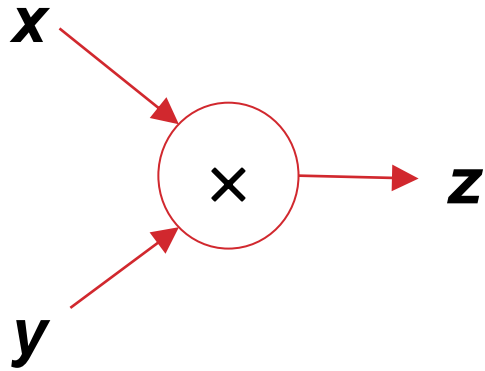
# Implementação – Forward / Backward API



( $x$ ,  $y$ ,  $z$  escalares)

```
class MultiplyGate(object):  
    def forward(x,y):  
        z = x*y  
        return z  
    def backward(dz):  
        # dx = ... #todo  
        # dy = ... #todo  
        return [dx, dy]
```

# Implementação – Forward / Backward API



( $x$ ,  $y$ ,  $z$  escalares)

```
class MultiplyGate(object):
```

```
    def forward(x,y):
```

```
        z = x*y
```

```
        return z
```

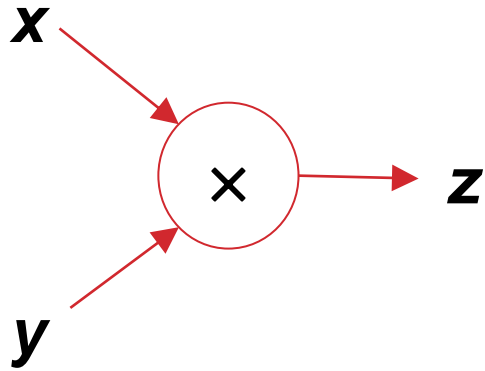
```
    def backward(dz):
```

```
        # dx = ... #todo
```

```
        # dy = ... #todo
```

```
        return [dx, dy]
```

# Implementação – Forward / Backward API



( $x$ ,  $y$ ,  $z$  escalares)

```
class MultiplyGate(object):
```

```
    def forward(x,y):
```

```
        z = x*y
```

```
        return z
```

```
    def backward(dz):
```

```
        # dx = ... #todo
```

```
        # dy = ... #todo
```

```
        return [dx, dy]
```

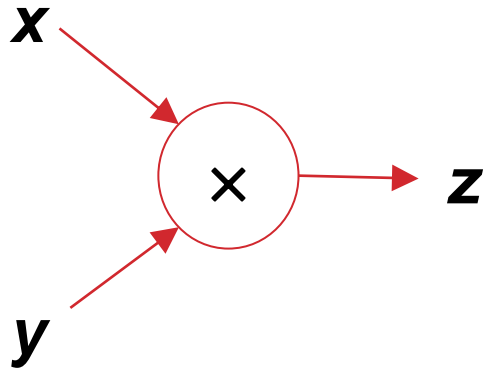
$$\frac{\partial L}{\partial z}$$

An arrow points from this box to the `dz` parameter in the `backward` method definition.

$$\frac{\partial L}{\partial x}$$


An arrow points from this box to the `dx` element in the `return` statement of the `backward` method.

# Implementação – Forward / Backward API

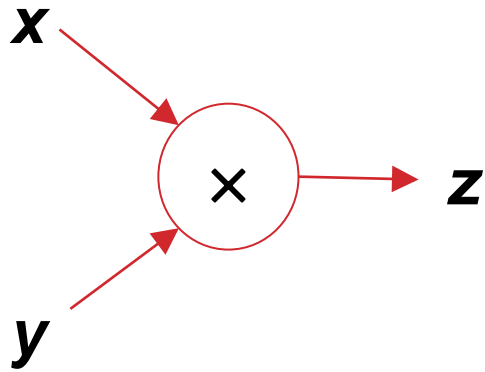


( $x$ ,  $y$ ,  $z$  escalares)

```
class MultiplyGate(object):  
    def forward(x,y):  
        z = x*y  
        self.x = x # must keep these around!  
        self.y = y  
        return z  
    def backward(dz):  
        dx = self.y * dz # [dz/dx * dL/dz]  
        dy = self.x * dz # [dz/dy * dL/dz]  
        return [dx, dy]
```



# Implementação – Forward / Backward API



( $x$ ,  $y$ ,  $z$  escalares)

```
class MultiplyGate(object):  
    def forward(x,y):  
        z = x*y  
        self.x = x # must keep these around!  
        self.y = y  
        return z  
    def backward(dz):  
        dx = self.y * dz # [dz/dx * dL/dz]  
        dy = self.x * dz # [dz/dy * dL/dz]  
        return [dx, dy]
```



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1,139 commits		377 branches		79 releases		88 contributors		
Search master	View pull requests	New file	Find file	HTTPS	https://github.com/torch	Download ZIP		
nnvectors Merge pull request #955 from torchresearch/nnvectors								
Latest commit 2385176		15 hours ago						
nn	Fix batch mode in MergeRankingCriterion	4 days ago						
nnvectors	Improve error message in SpatialConvolutionMM	4 days ago						
nn	THNN: add missing OpenMP include	2 days ago						
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