Lecture 4:

Backpropagation and Neural Networks part 1

Administrative

A1 is due Jan 20 (Wednesday). ~150 hours left
Warning: Jan 18 (Monday) is Holiday (no class/office hours)

Also note:
Lectures are non-exhaustive.
Read course notes for completeness.

I'll hold make up office hours on Wed Jan20, 5pm @ Gates 259

Where we are...

$$s = f(x; W) = Wx$$

scores function

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

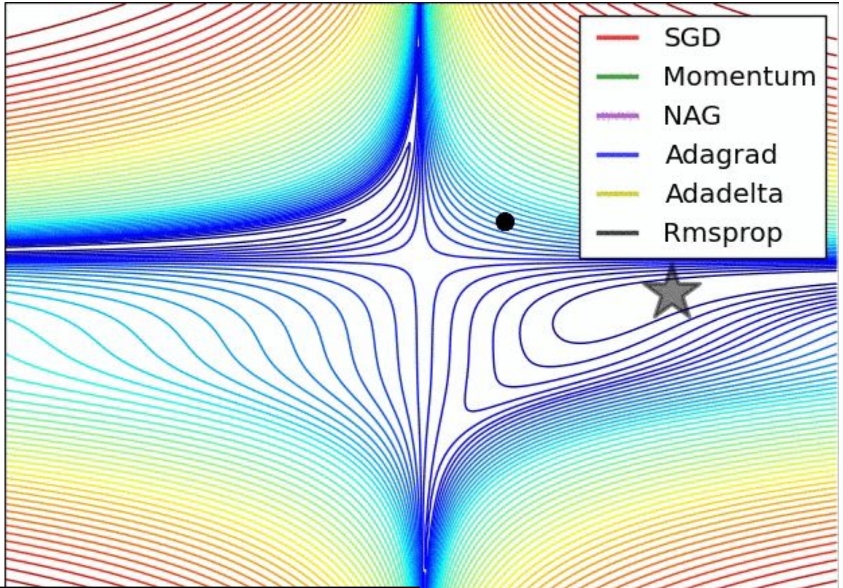
SVM loss

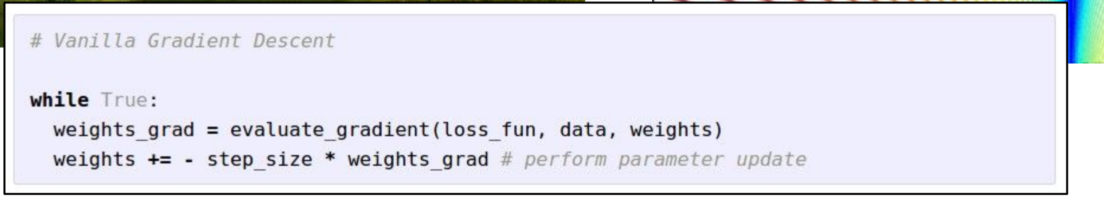
$$L = \frac{1}{N} \sum_{i=1}^{N} L_i + \sum_k W_k^2$$

data loss + regularization

want $\boxed{\nabla_W L}$

Optimization





```
# Vanilla Gradient Descent

while True:
  weights_grad = evaluate_gradient(loss_fun, data, weights)
  weights += - step_size * weights_grad # perform parameter update
```

(image credits
to Alec Radford)

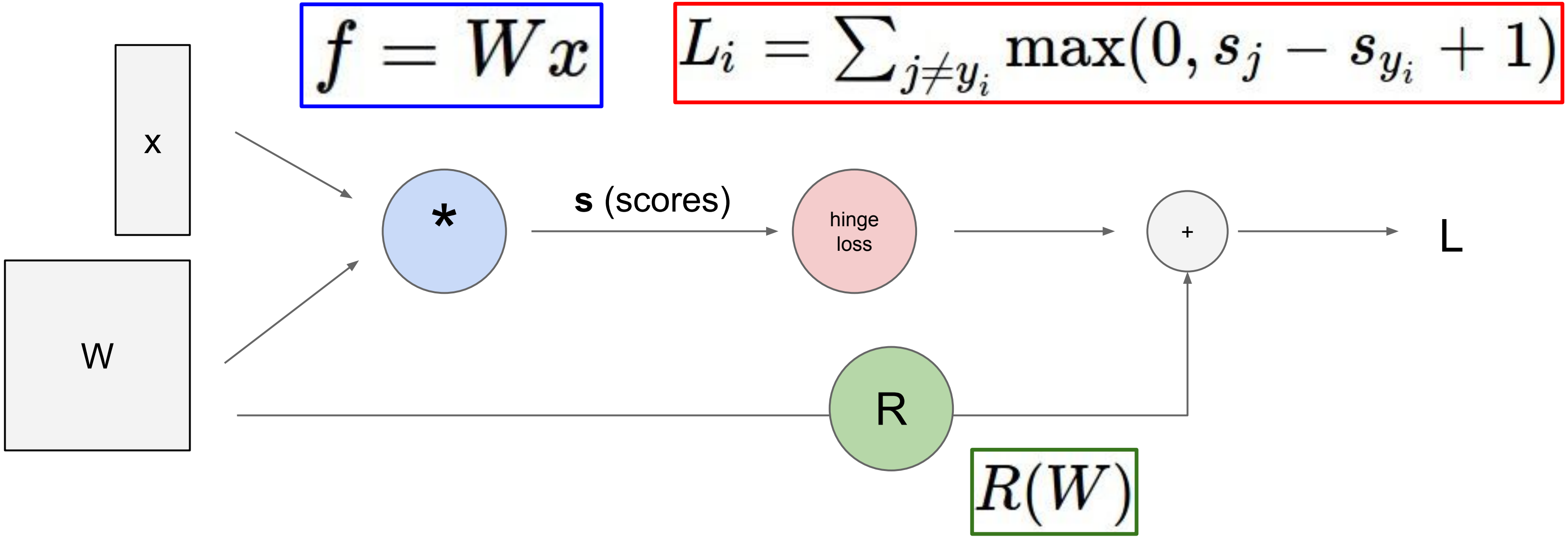
Gradient Descent

$$\frac{df(x)}{dx} = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$$

Numerical gradient: slow :(, approximate :(, easy to write :)
Analytic gradient: fast :), exact :), error-prone :(

In practice: Derive analytic gradient, check your implementation with numerical gradient

Computational Graph

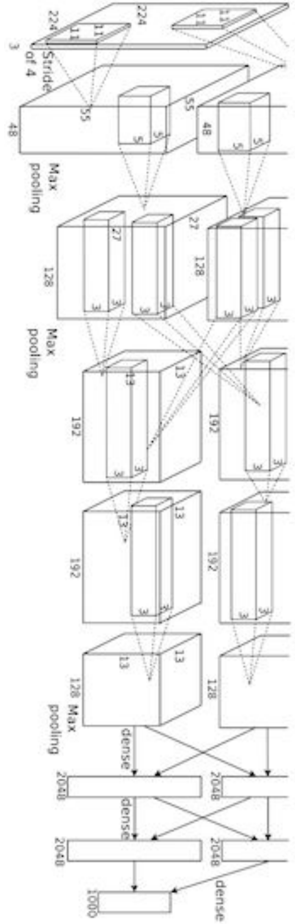


$$f = Wx$$

$$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$$

$$R(W)$$

Convolutional Network (AlexNet)

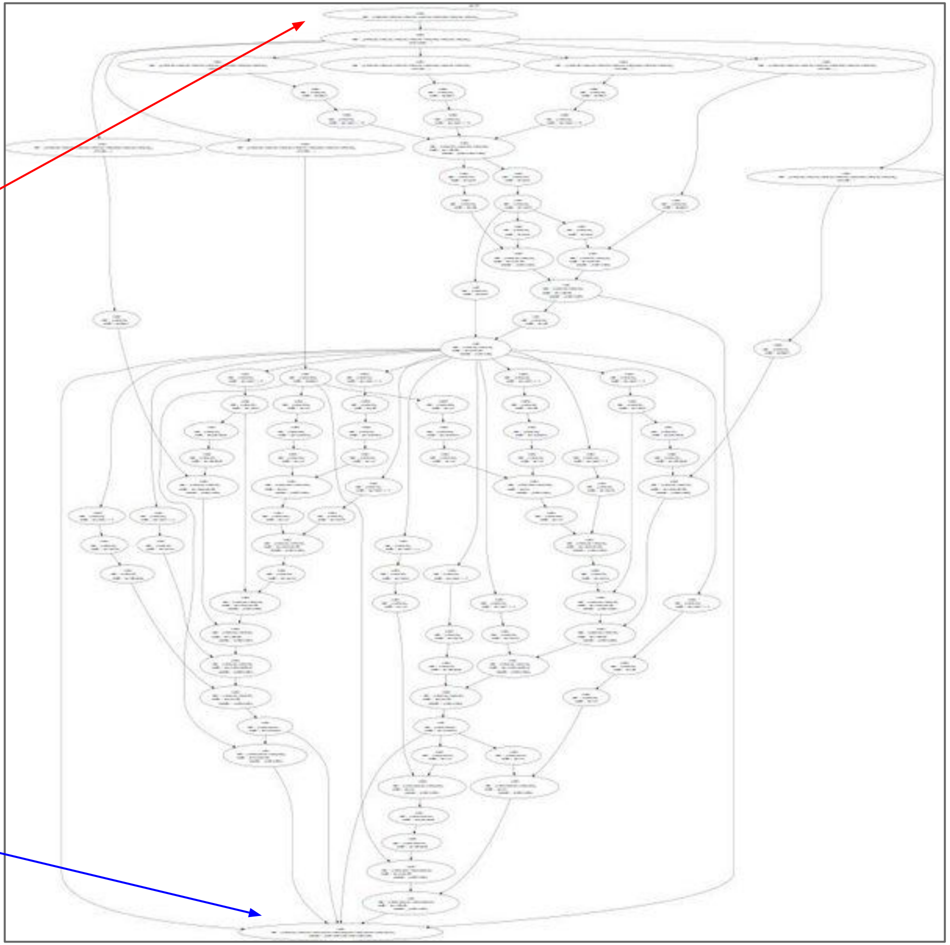


input image

weights

loss

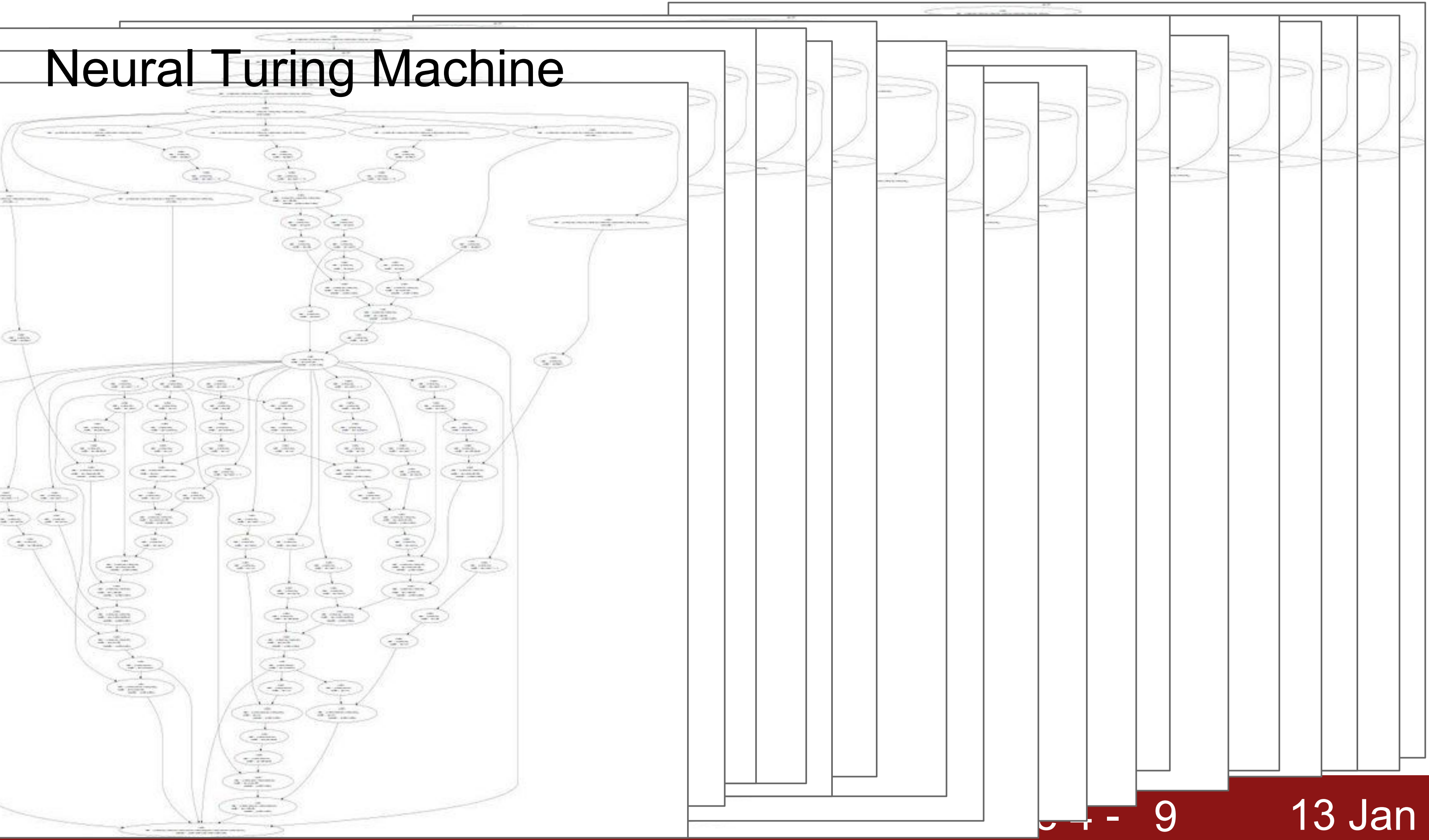
Neural Turing Machine



input tape

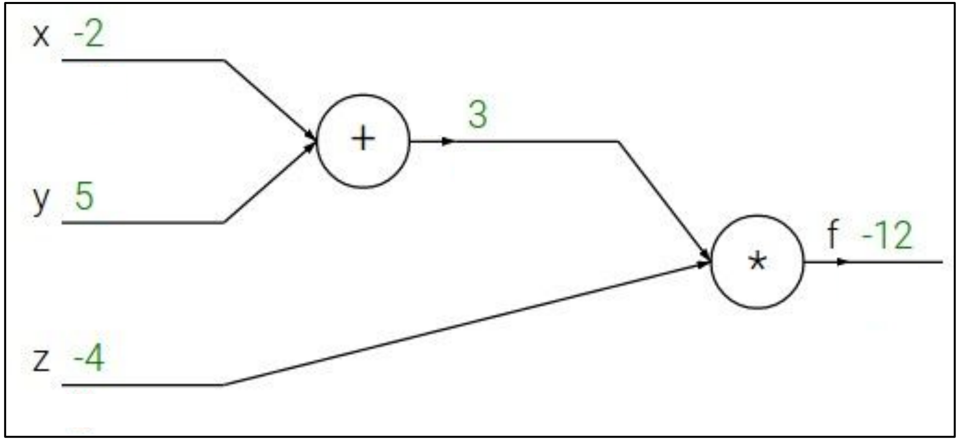
loss

Neural Turing Machine



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

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



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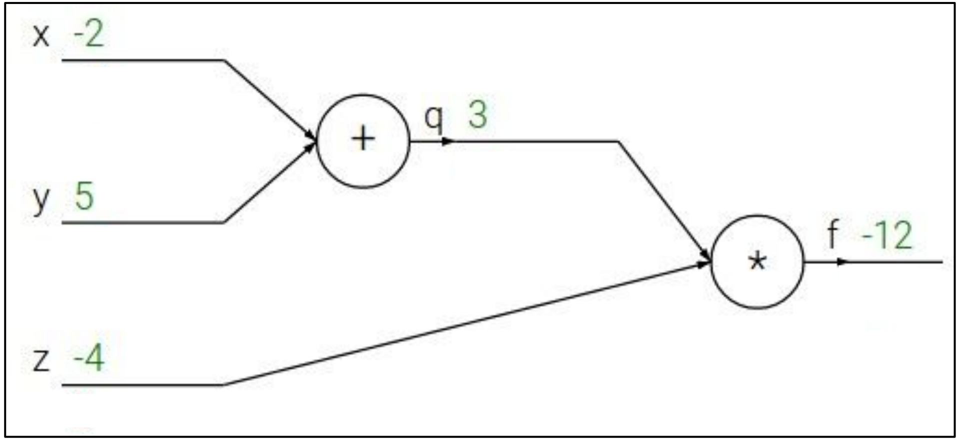

$$q = x + y \qquad \frac{\partial q}{\partial x} = 1, \frac{\partial q}{\partial y} = 1$$

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

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

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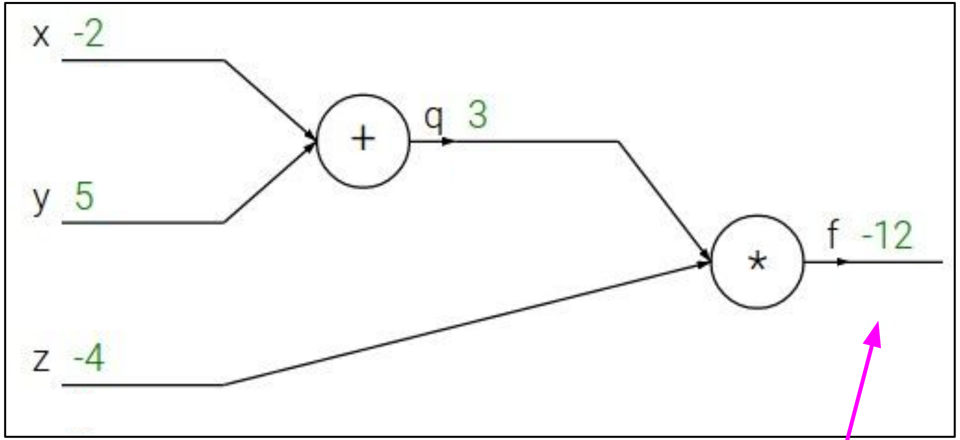

$\frac{\partial f}{\partial f}$

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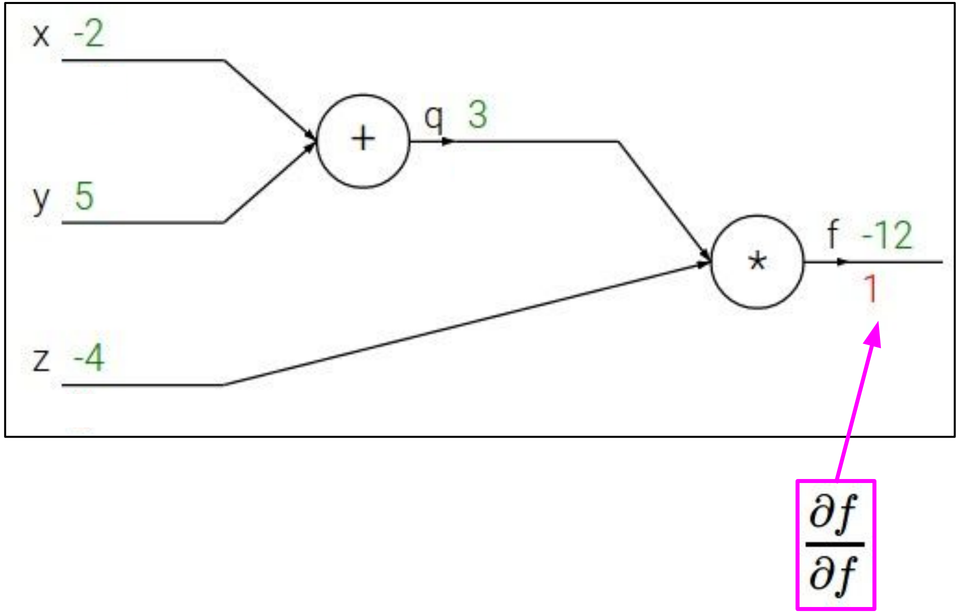

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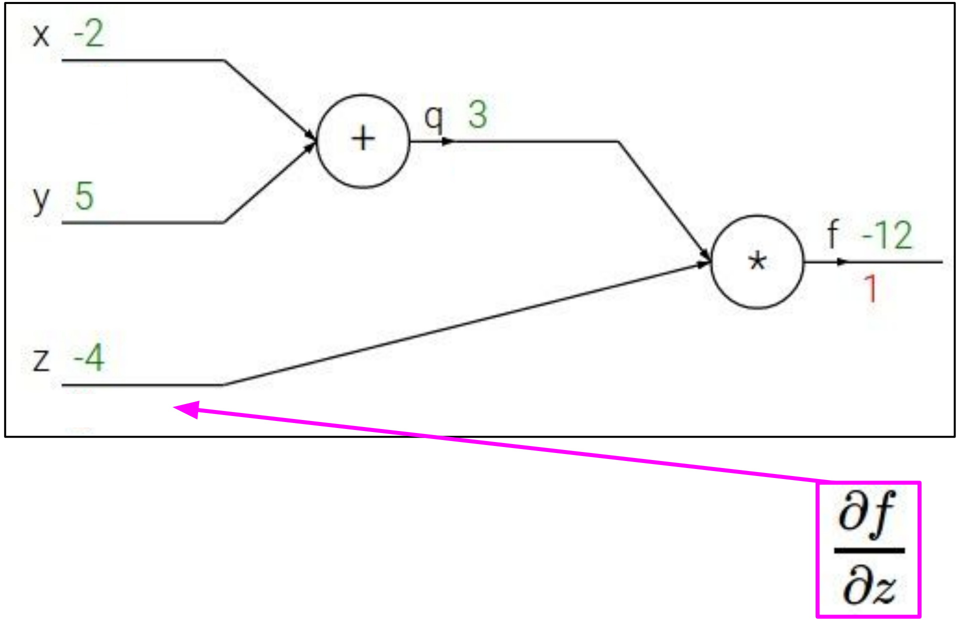

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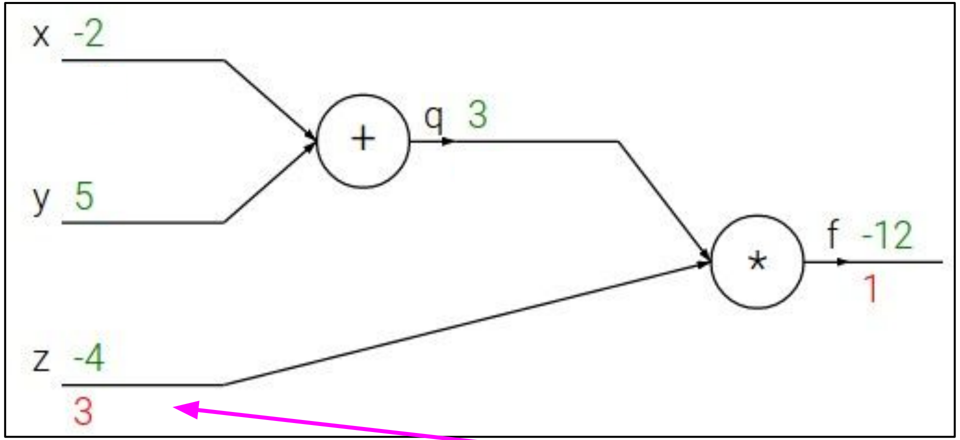

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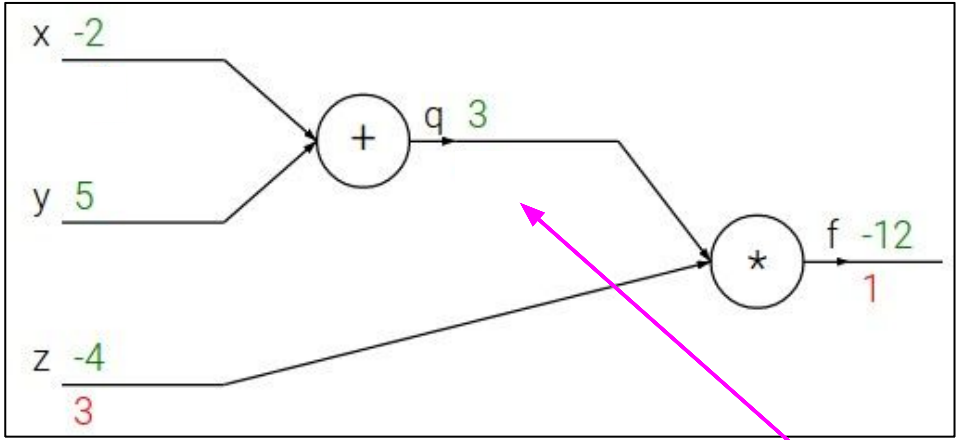

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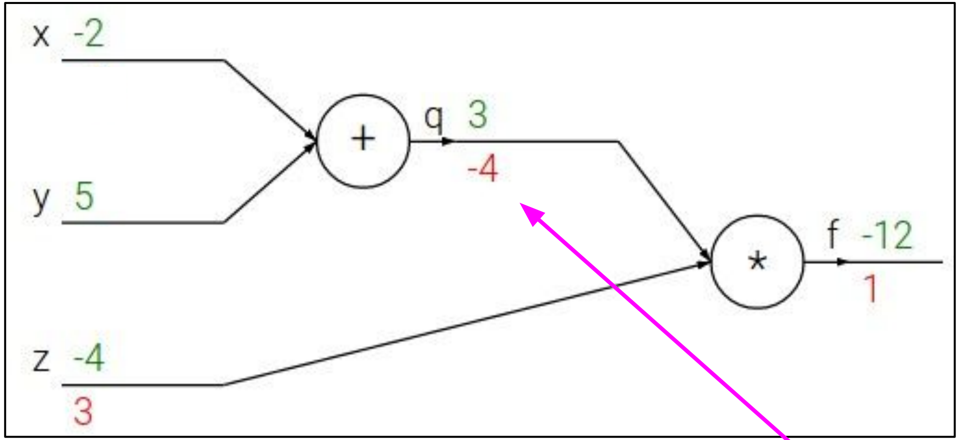

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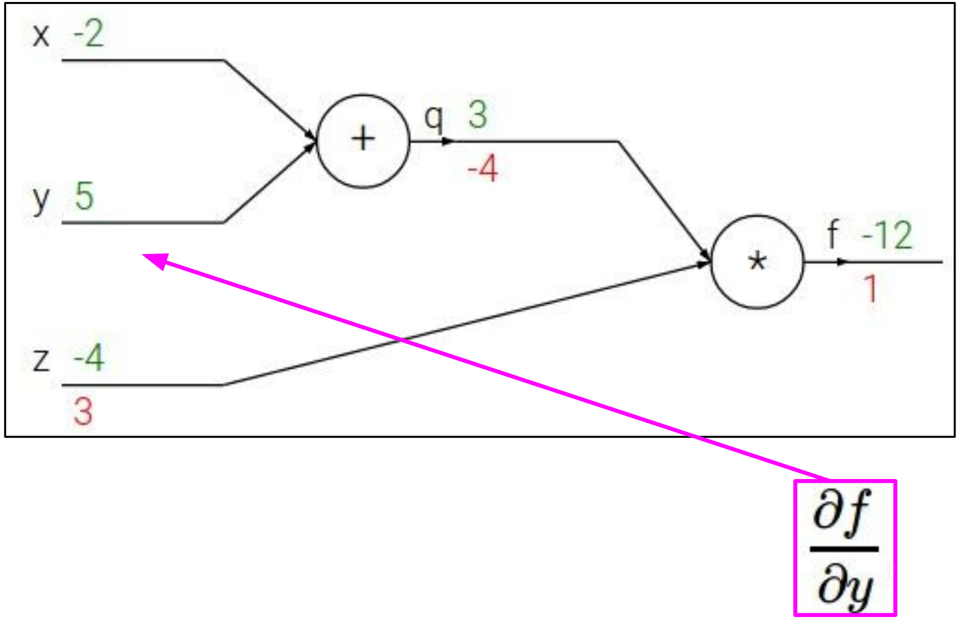

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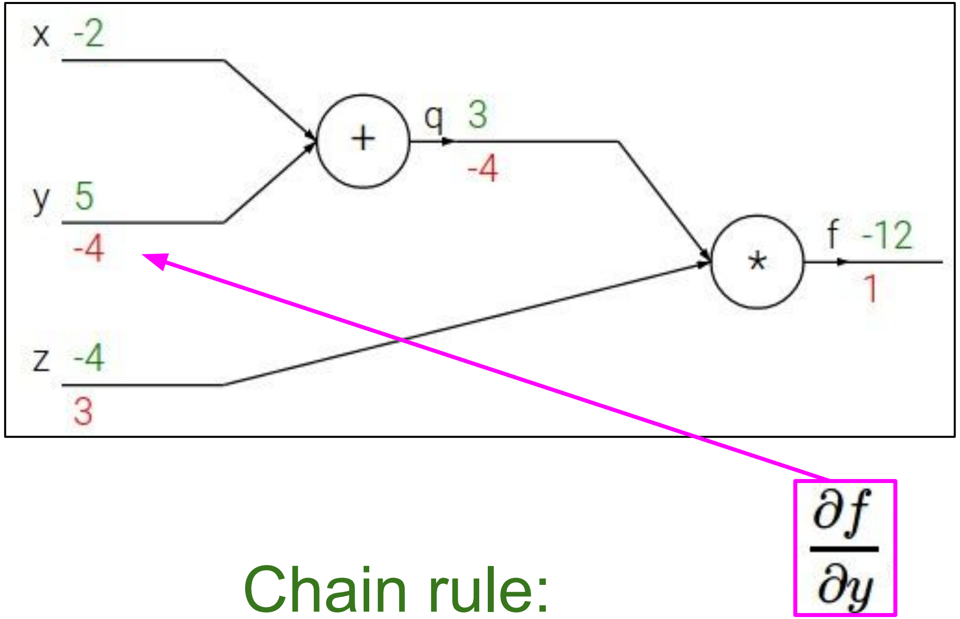

Chain rule:

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

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

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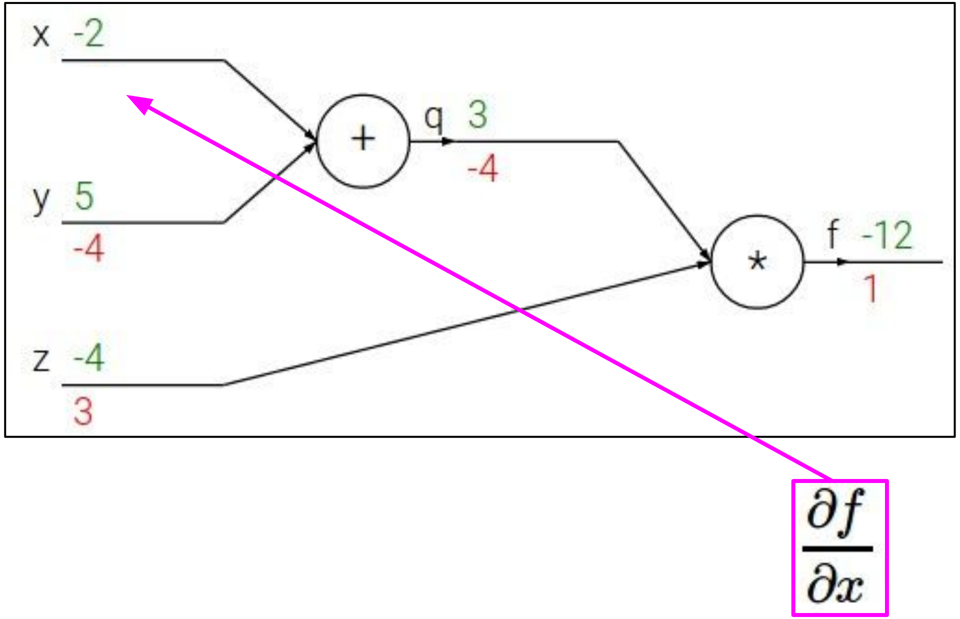

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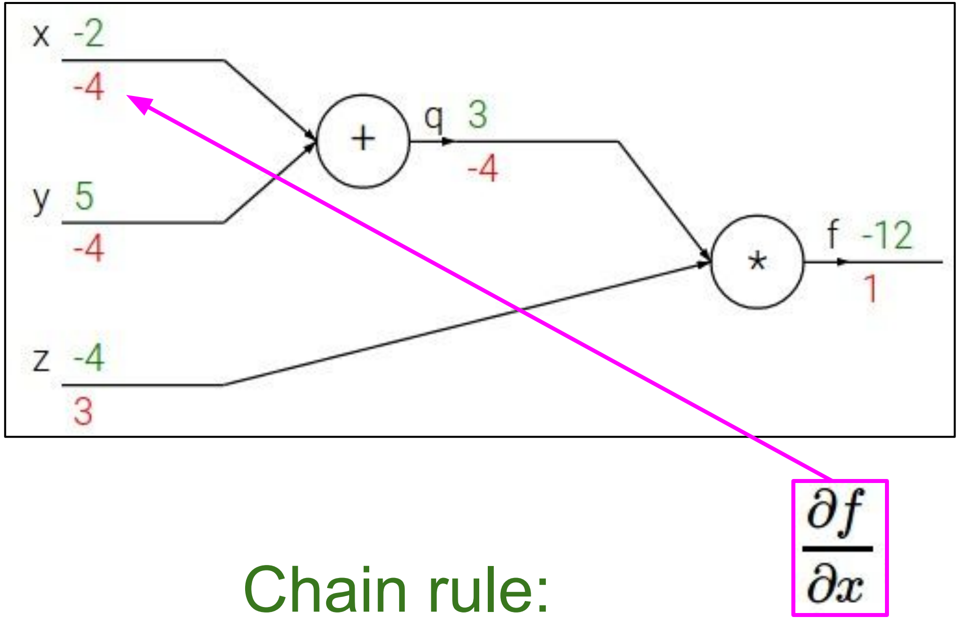

$$\boxed{\frac{\partial f}{\partial x}}$$

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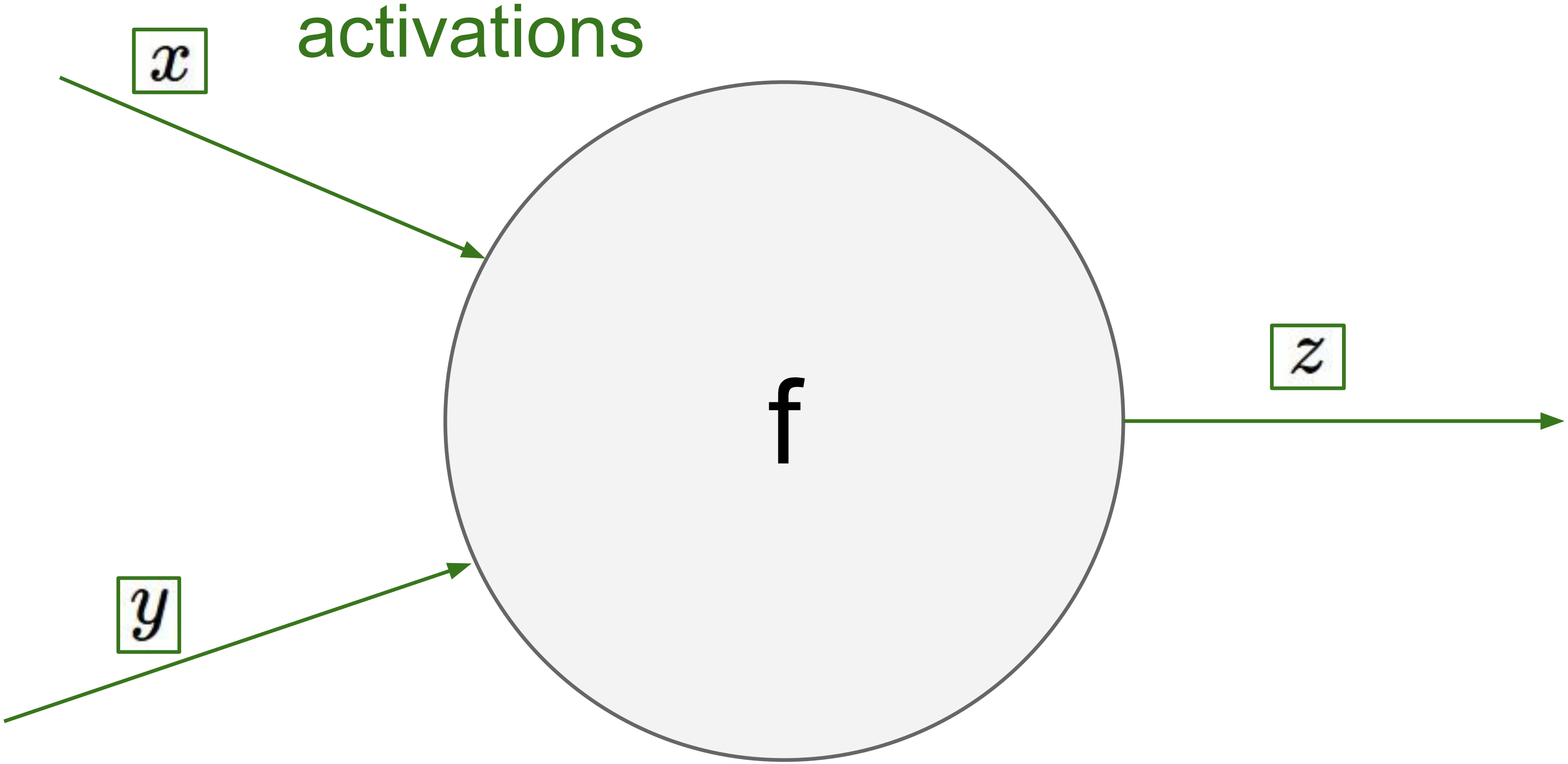
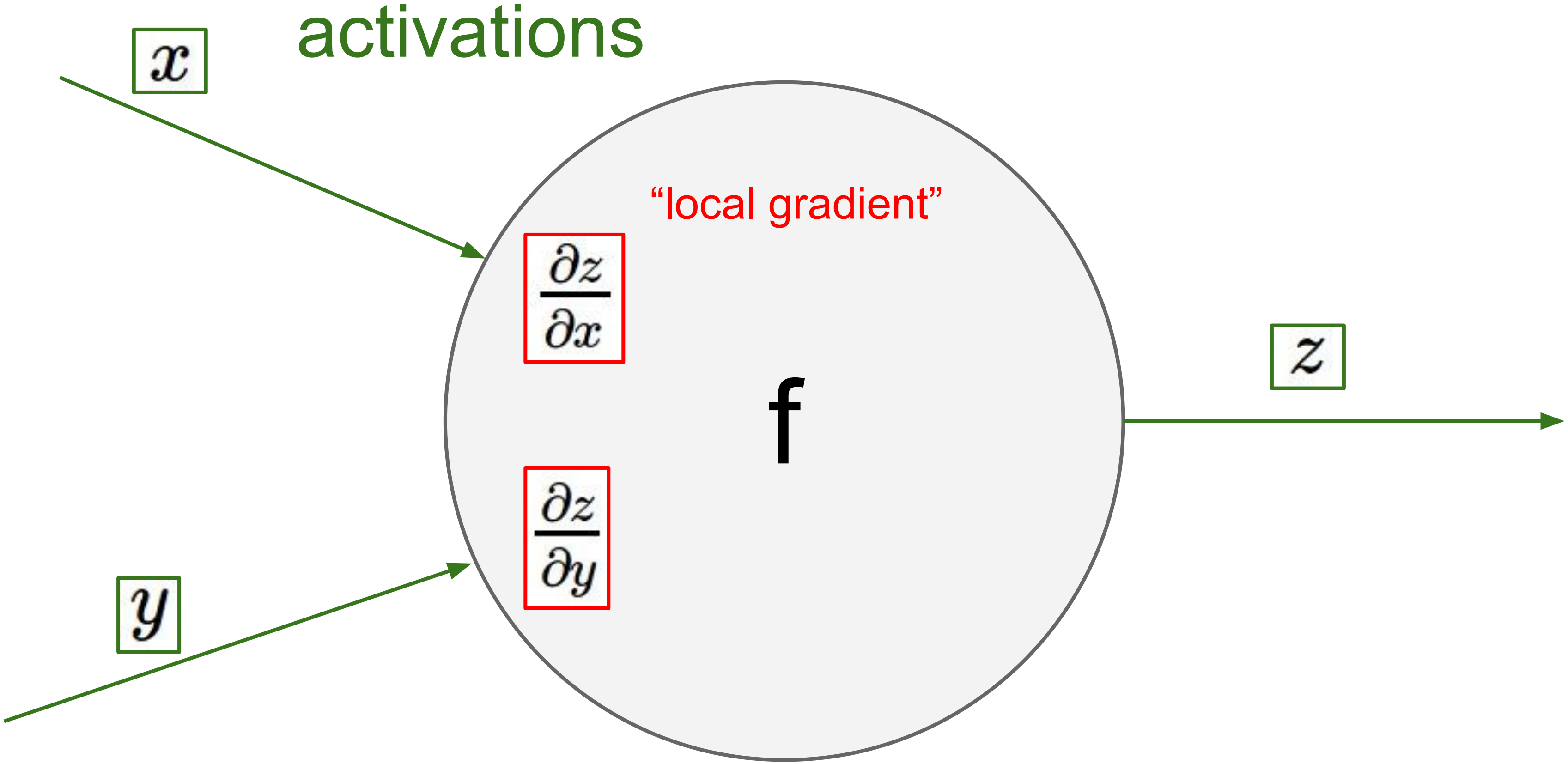

activations
x
y
f
z



activations

x

y

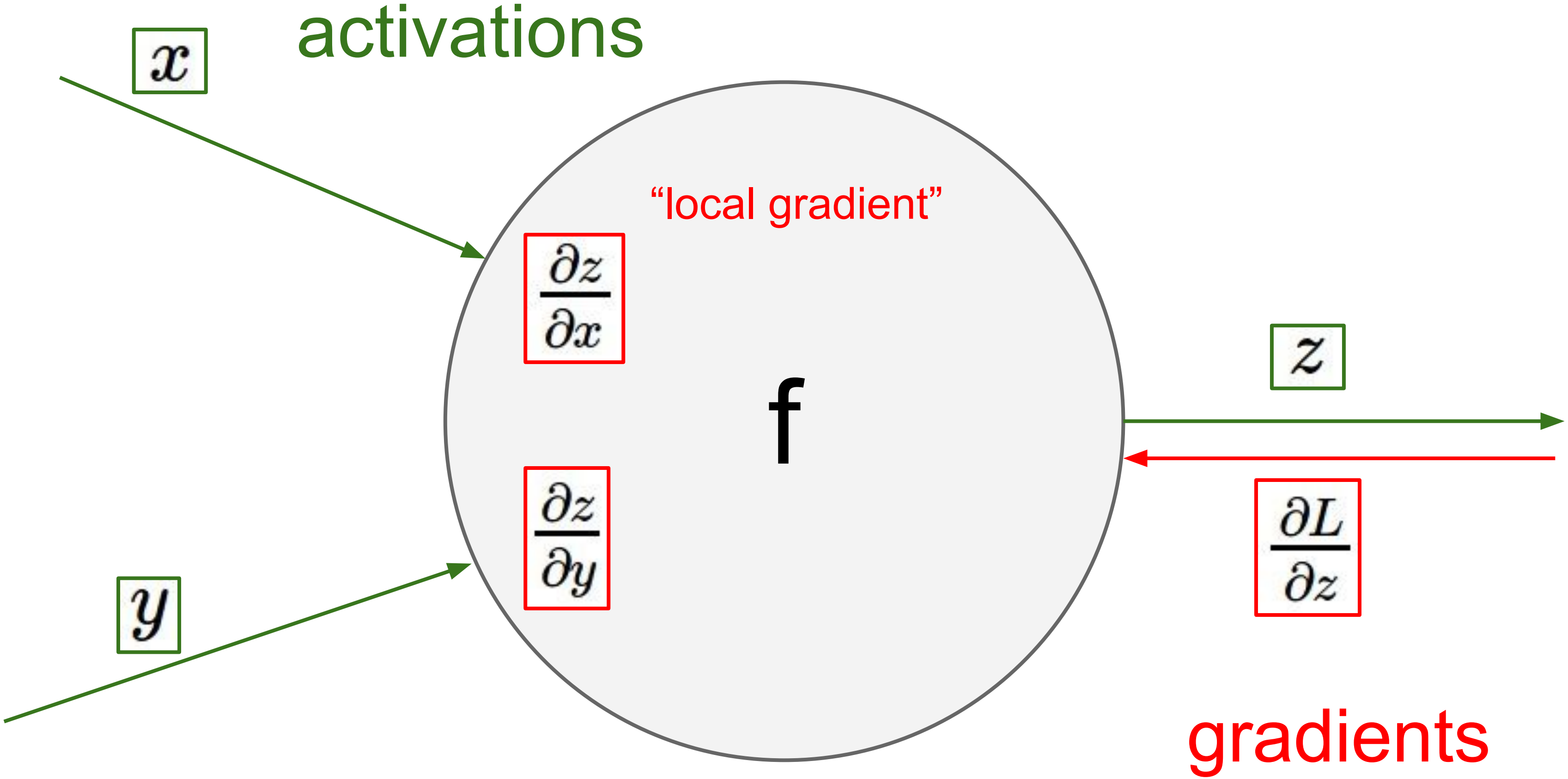
z

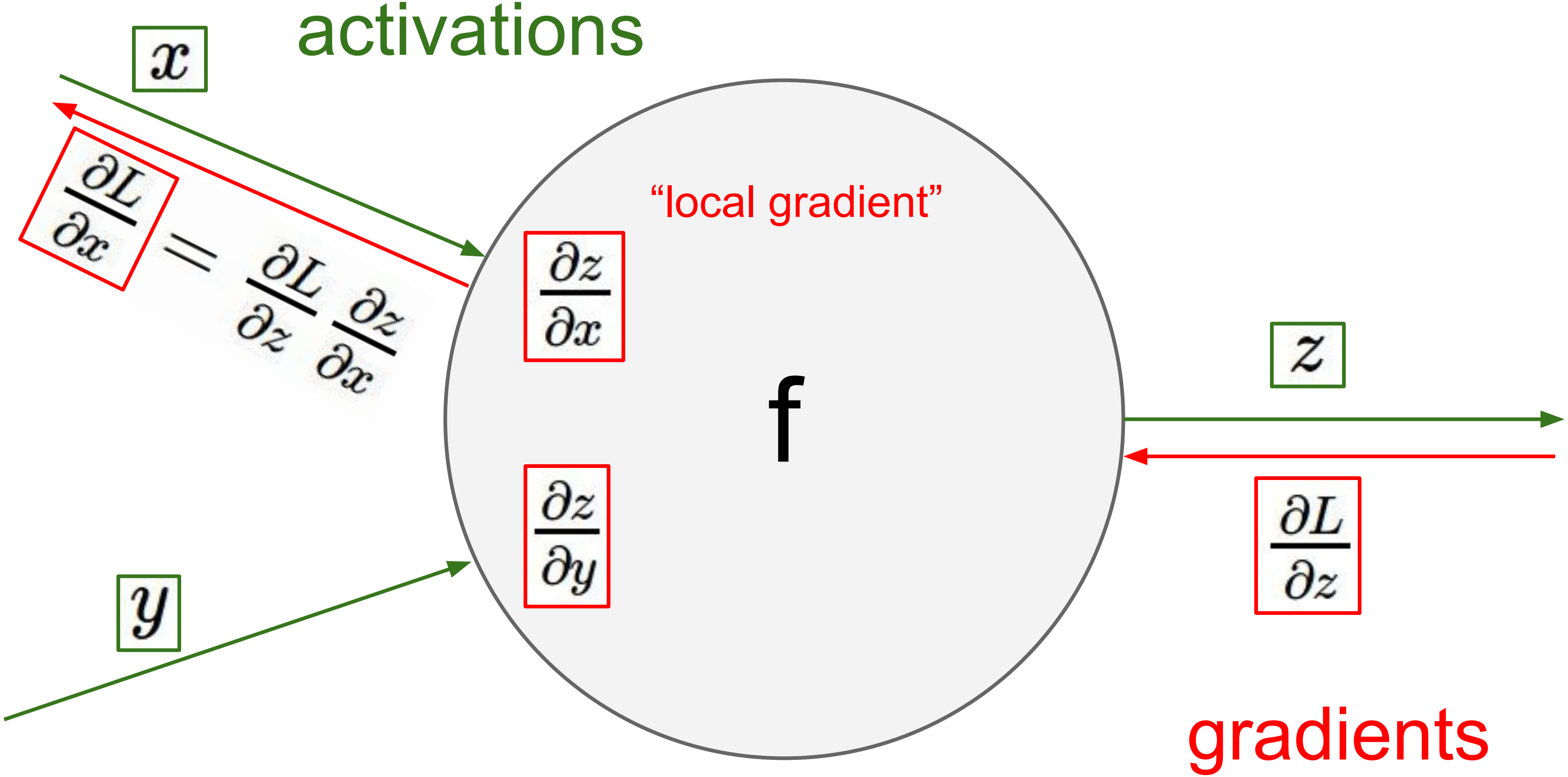
f

“local gradient”

$\frac{\partial z}{\partial x}$

$\frac{\partial z}{\partial y}$


x
activations
"local gradient"
$\frac{\partial z}{\partial x}$
f
z
$\frac{\partial z}{\partial y}$
$\frac{\partial L}{\partial z}$
y
gradients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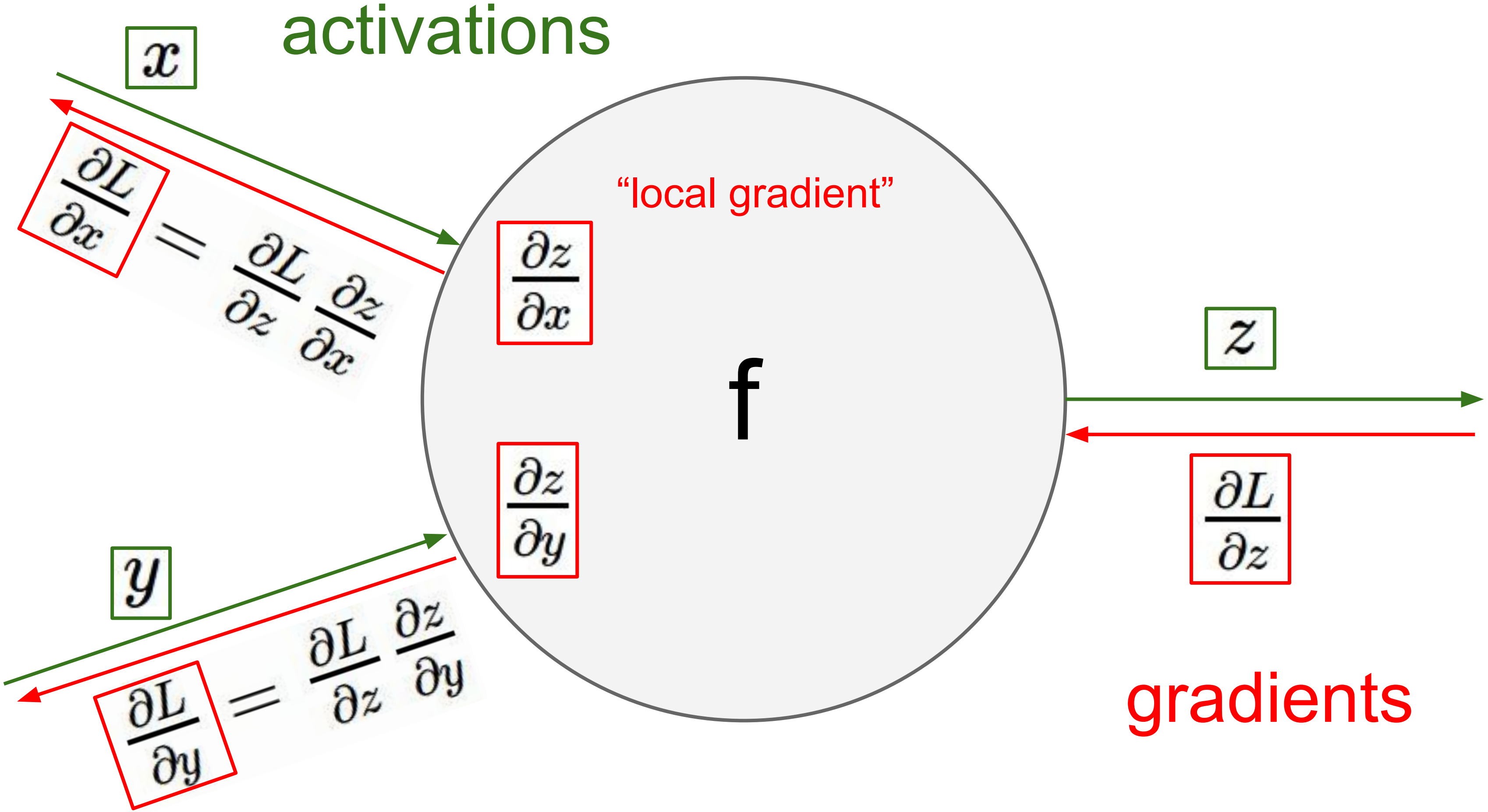


activations

x

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

“local gradient”

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

$$\boxed{\frac{\partial z}{\partial y}}$$

f

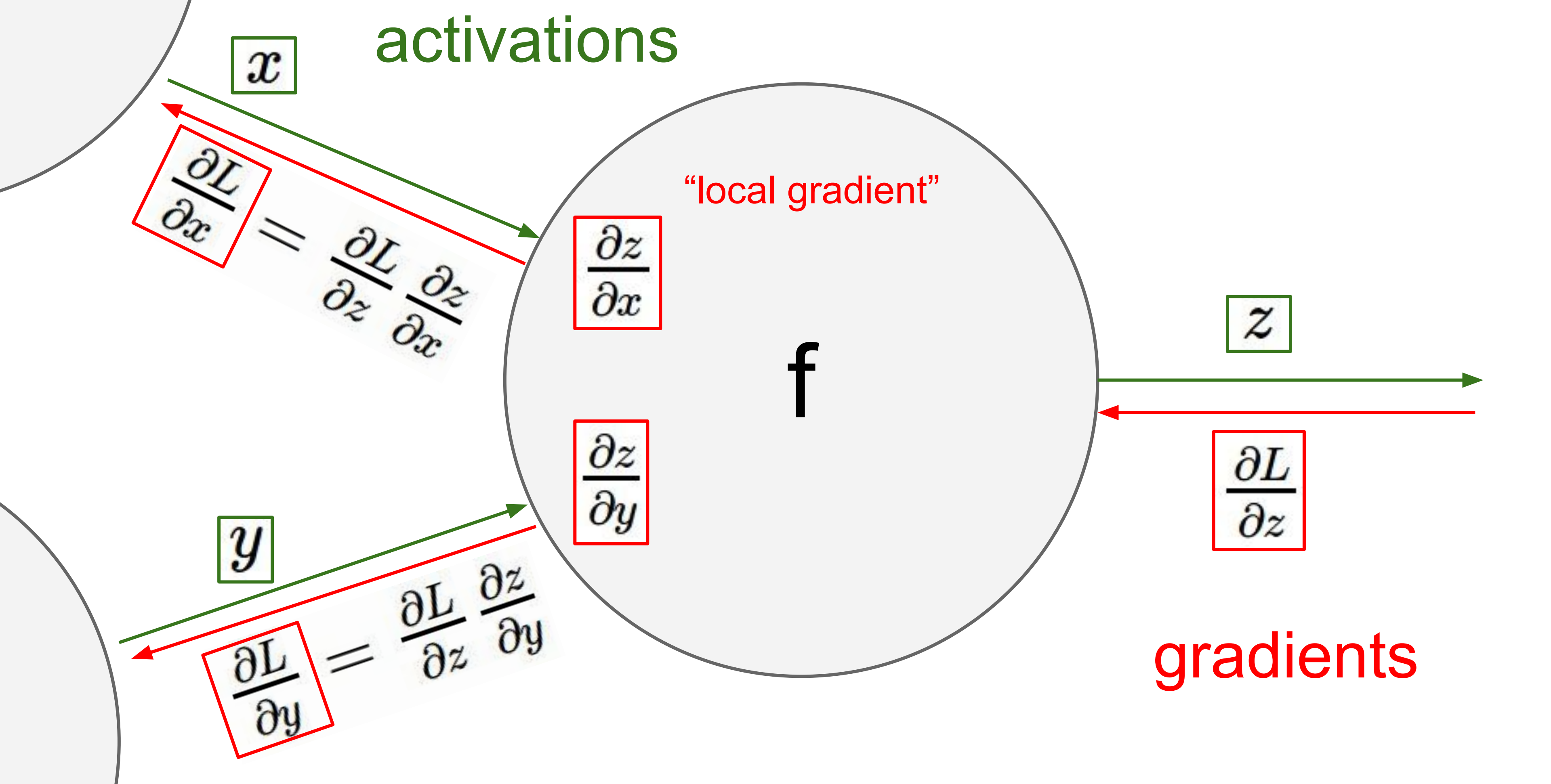
z

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

y

$$\boxed{\frac{\partial L}{\partial y}} = \frac{\partial L}{\partial z}\frac{\partial z}{\partial y}$$

gradients



activations

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“local gradient”

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

f

$\boxed{\frac{\partial z}{\partial y}}$

z

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

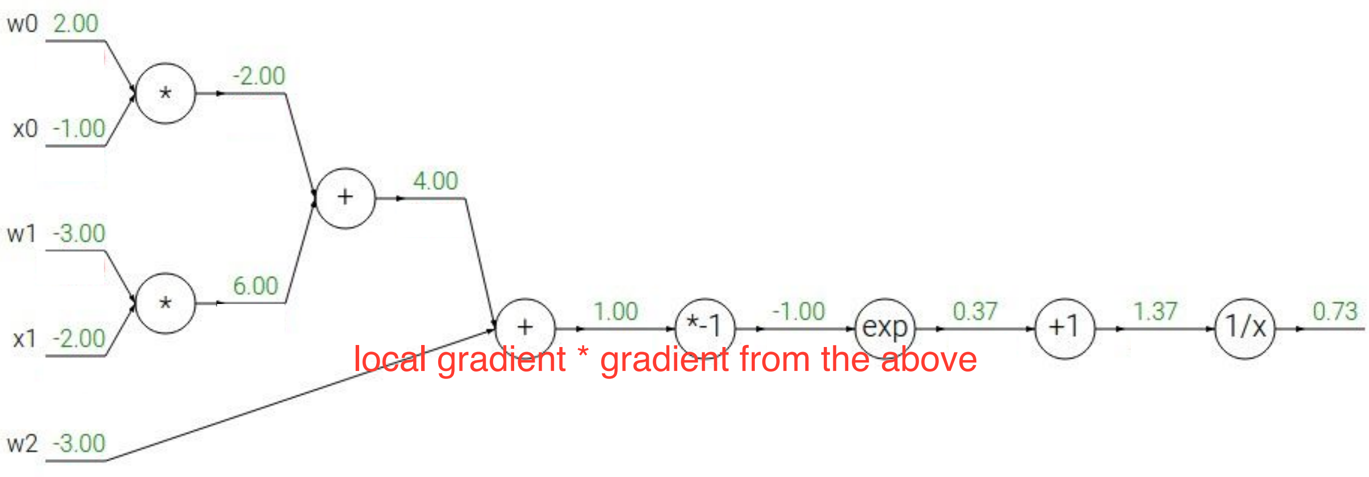
y

$$\boxed{\frac{\partial L}{\partial y}} = \frac{\partial L}{\partial z}\frac{\partial z}{\partial y}$$

gradients

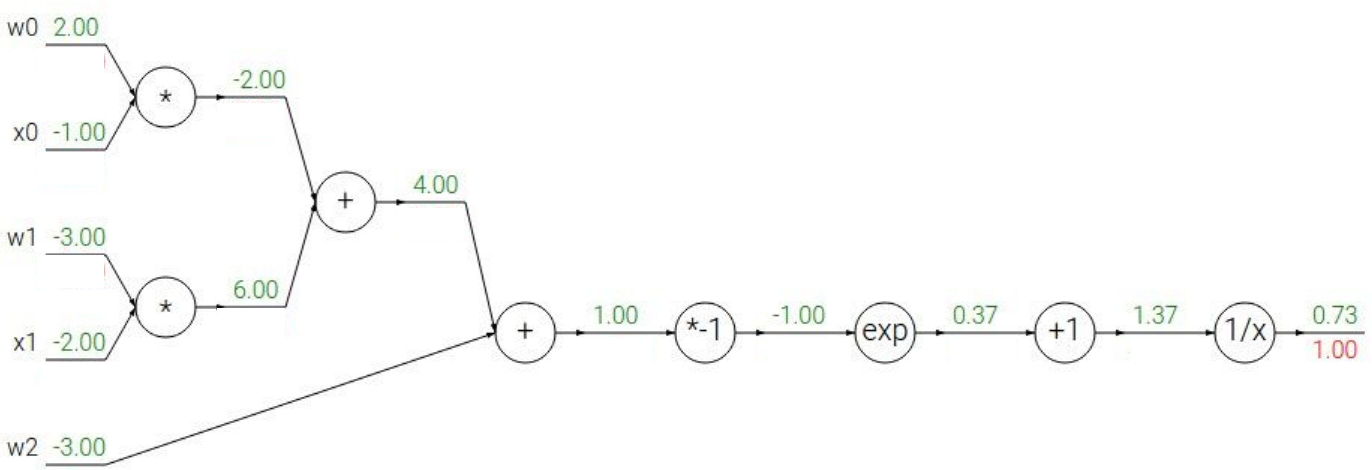
Another example:

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



local gradient * gradient from the above

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



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

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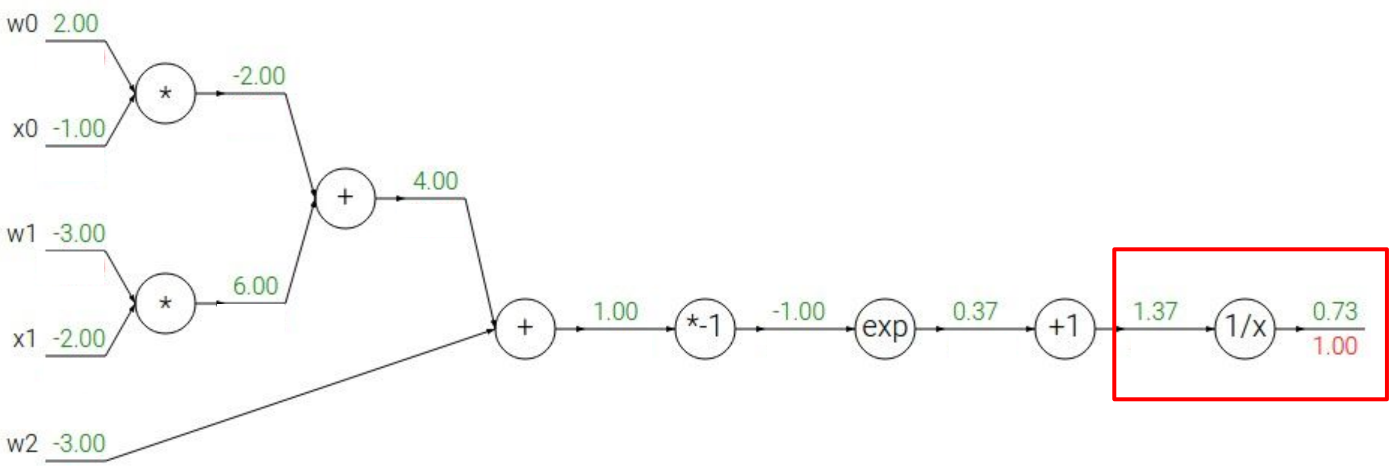

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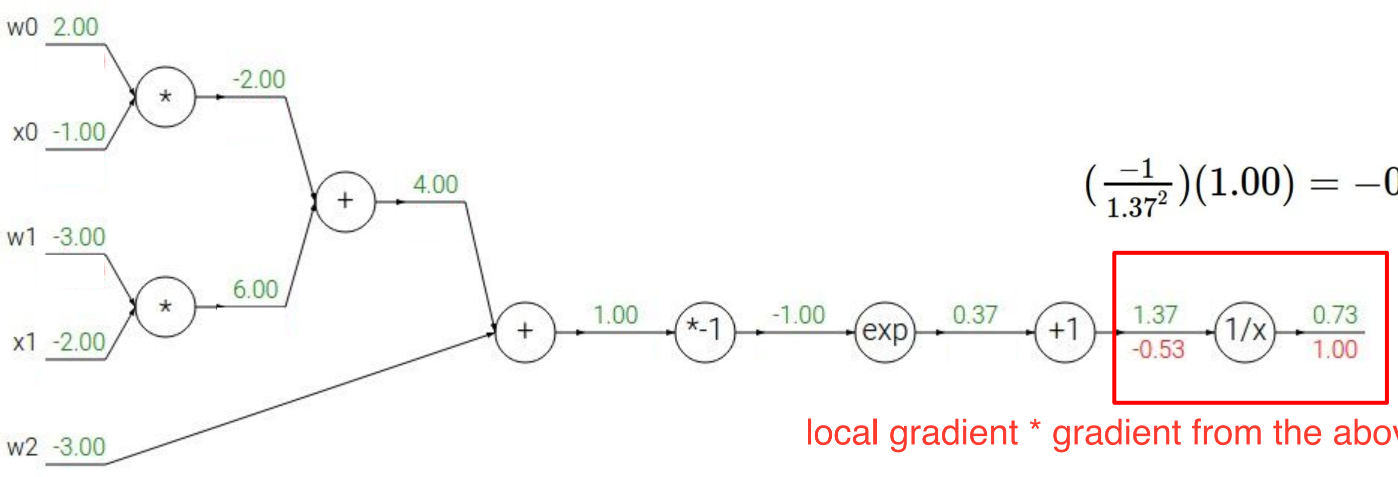

$$\left(\frac{-1}{1.37^2}\right)(1.00) = -0.53$$

local gradient * gradient from the above

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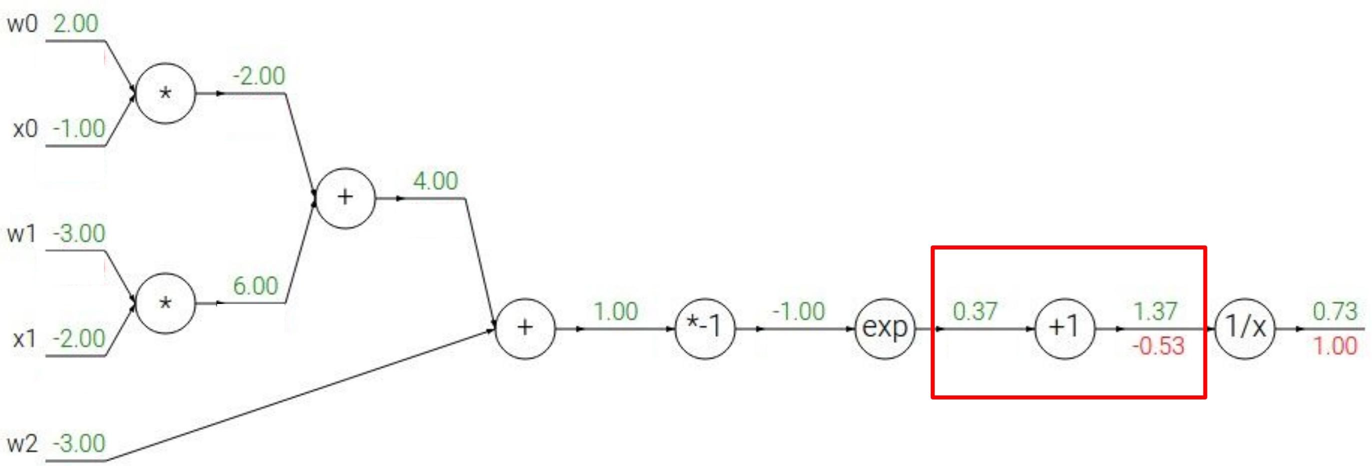

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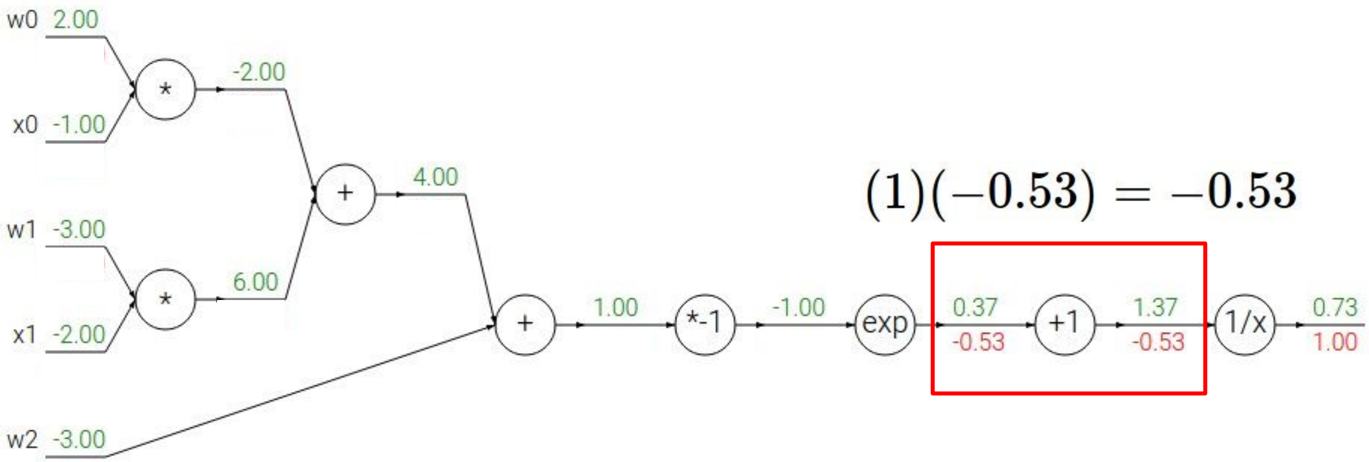

$$(1)(-0.53) = -0.53$$

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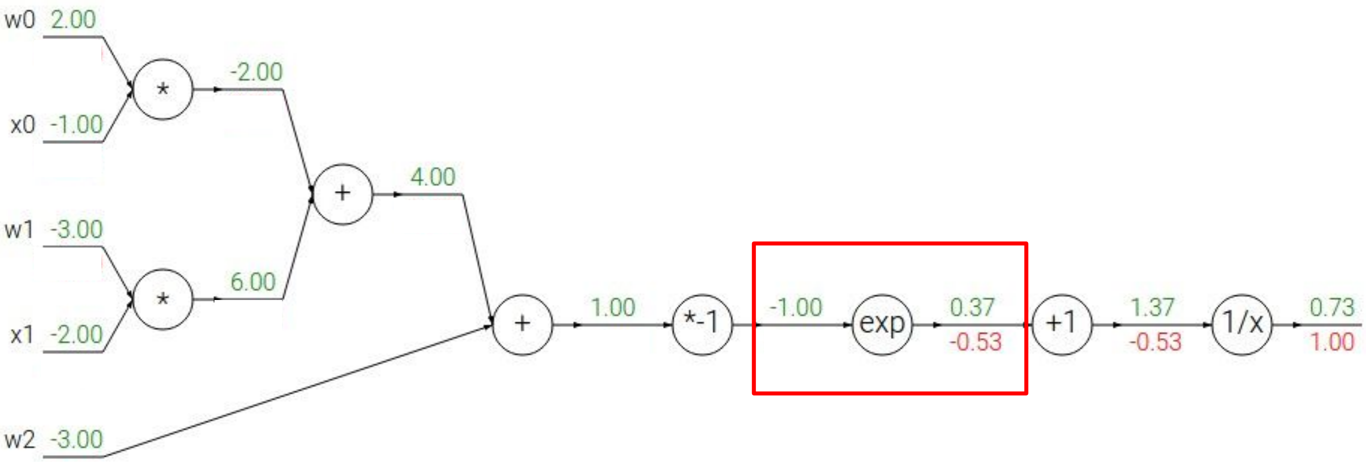

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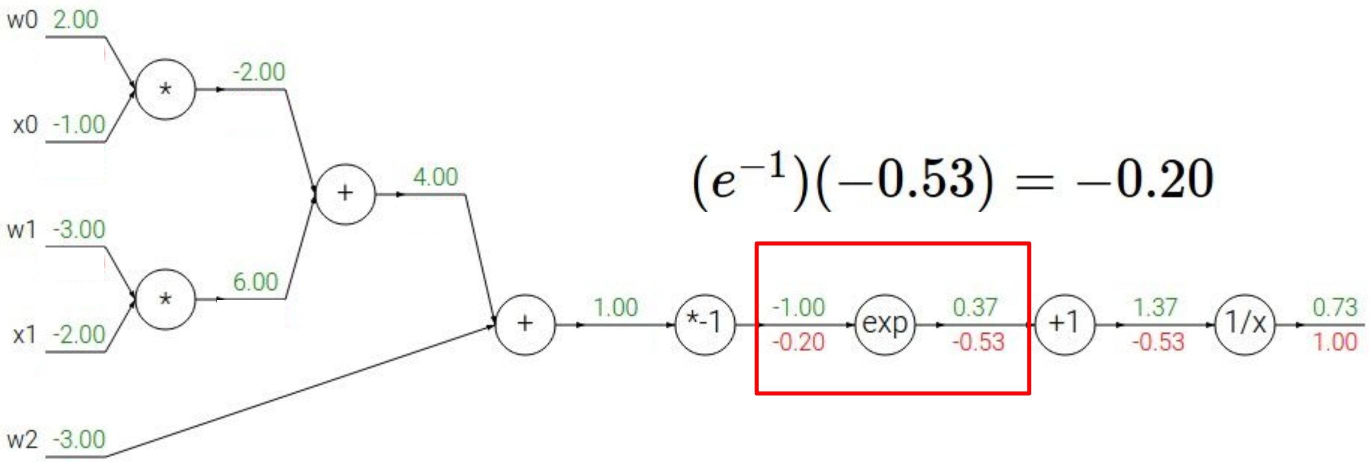

$$(e^{-1})(-0.53) = -0.20$$

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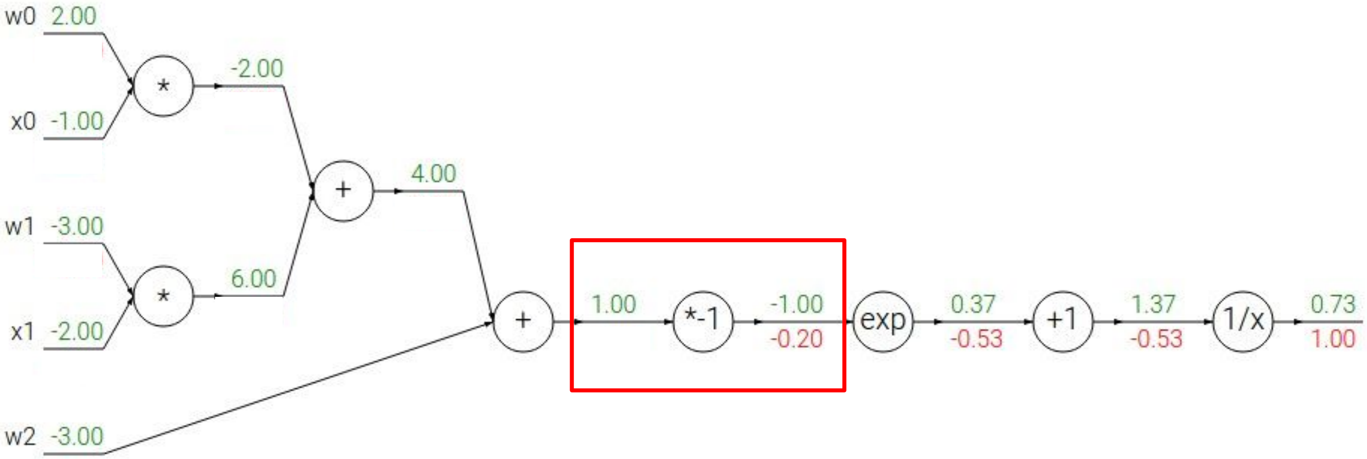

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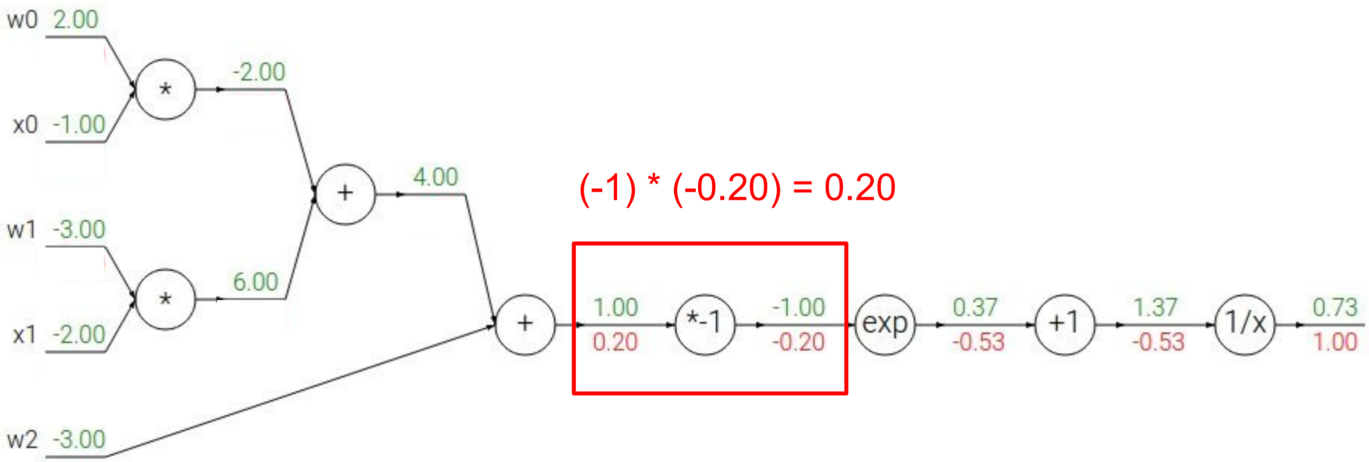

(-1) * (-0.20) = 0.20

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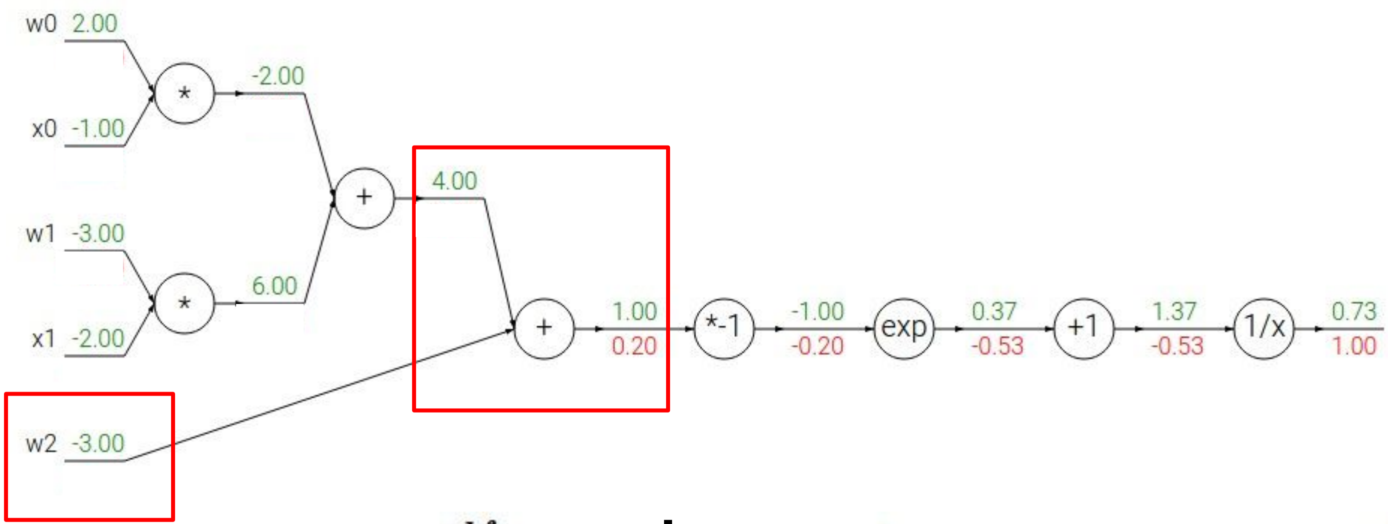

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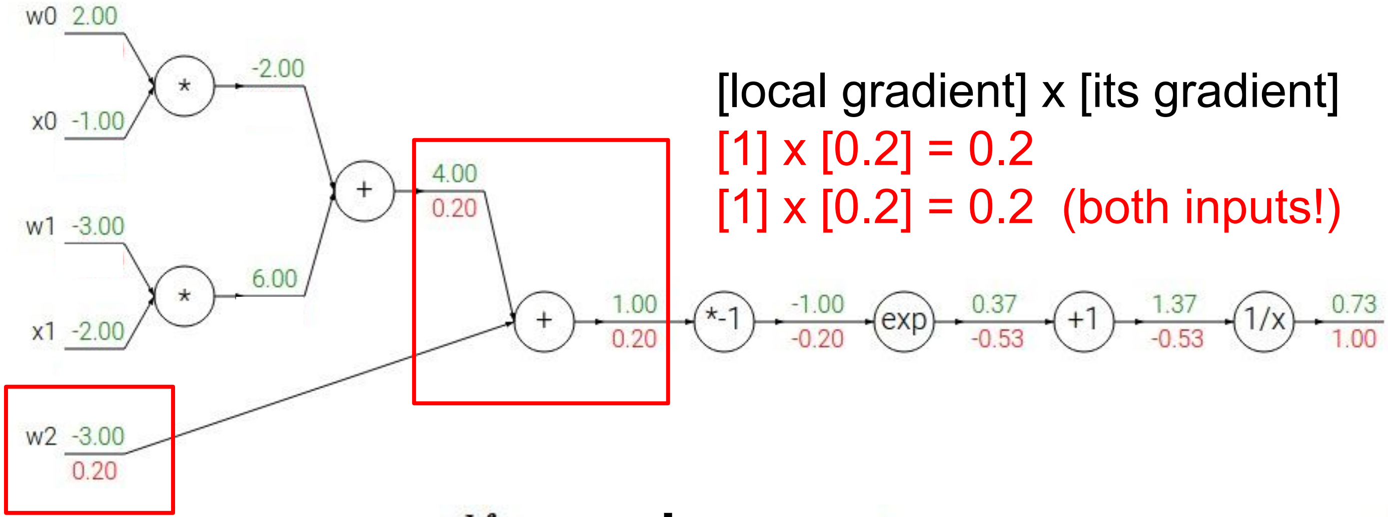

[local gradient] x [its gradient]

[1] x [0.2] = 0.2

[1] x [0.2] = 0.2 (both inputs!)

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

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

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

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

Another example:

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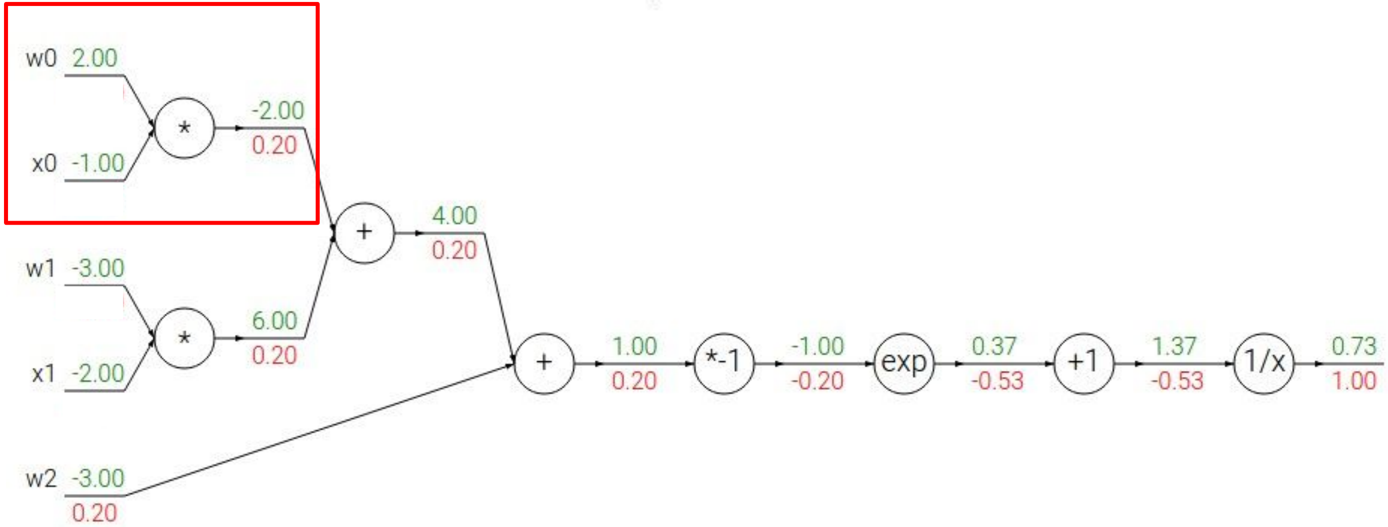

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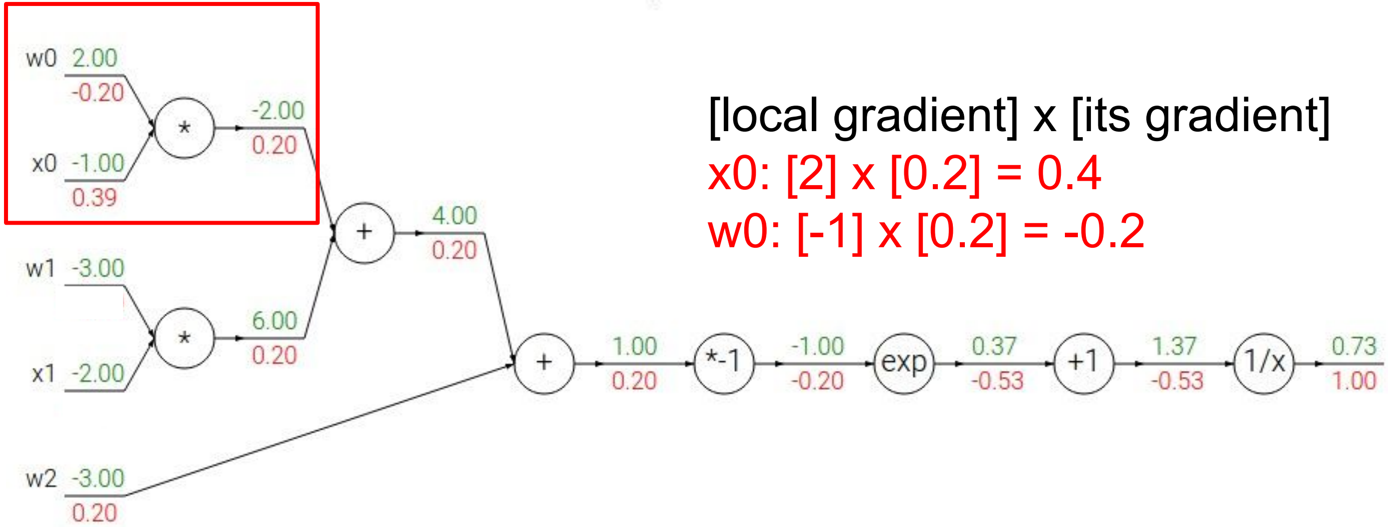


[local gradient] x [its gradient]

x0: [2] x [0.2] = 0.4

w0: [-1] x [0.2] = -0.2

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

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

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

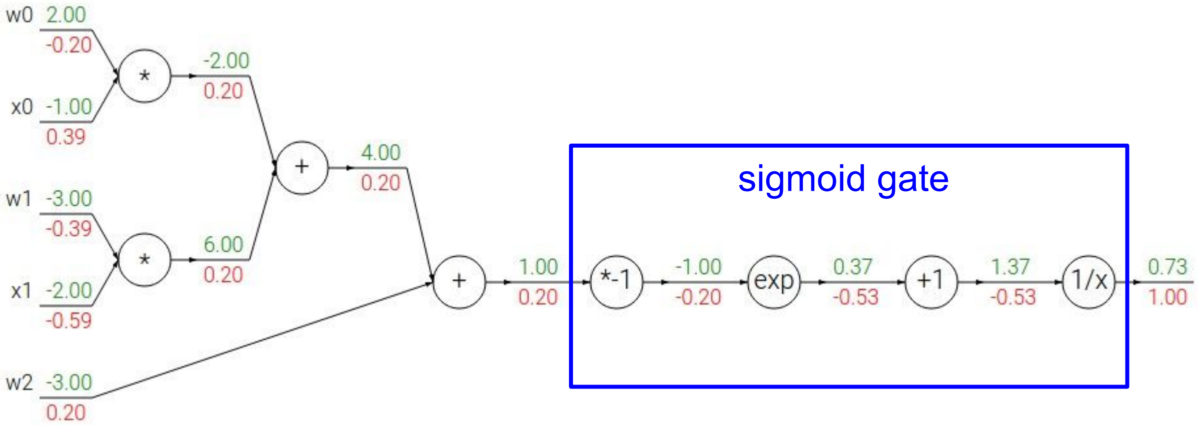
$$f_c(x) = c + x \quad \rightarrow \quad \frac{df}{dx} = 1$$

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

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

sigmoid function

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



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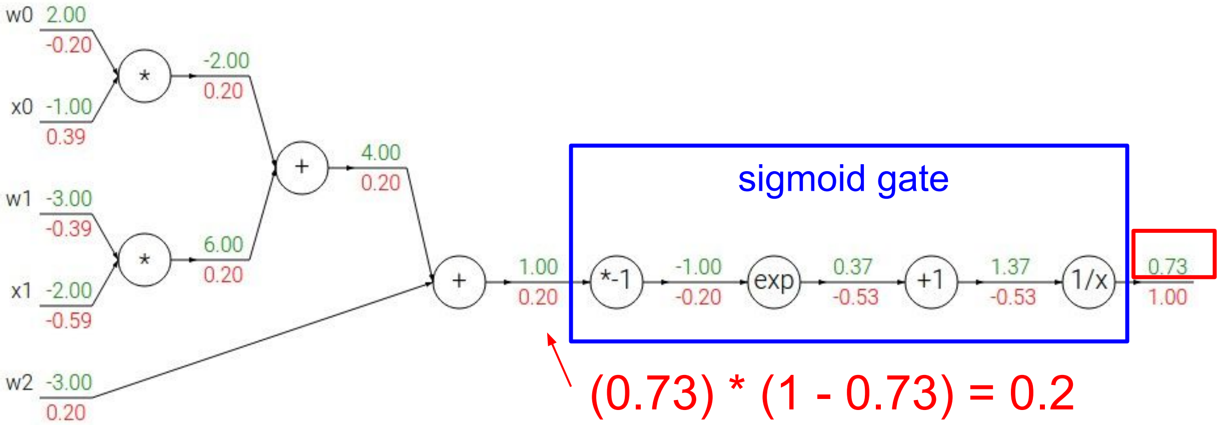


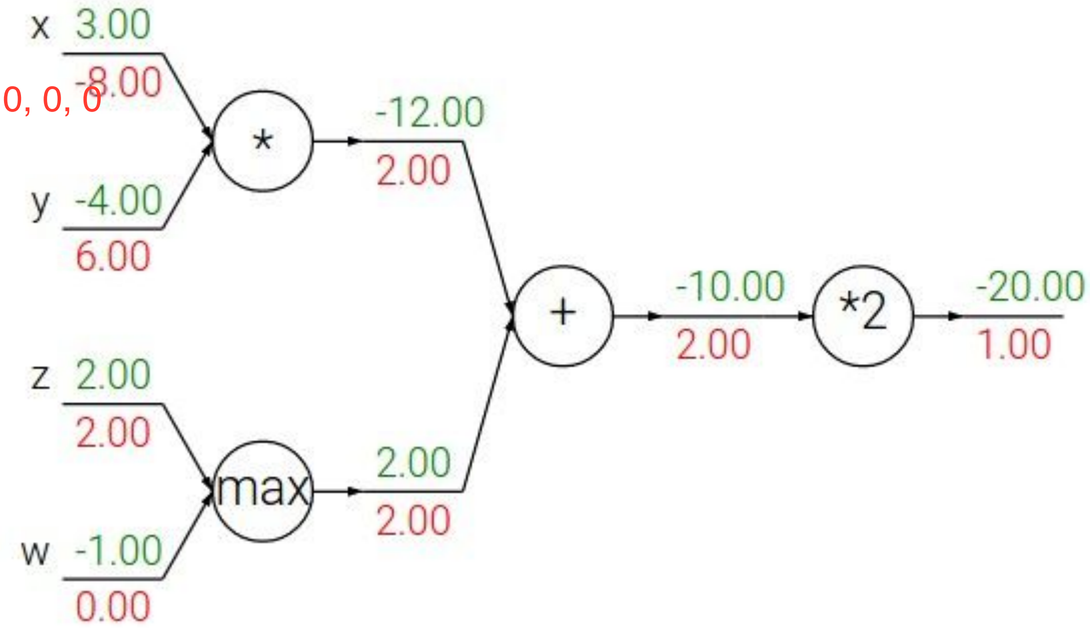
(0.73) * (1 - 0.73) = 0.2

Patterns in backward flow

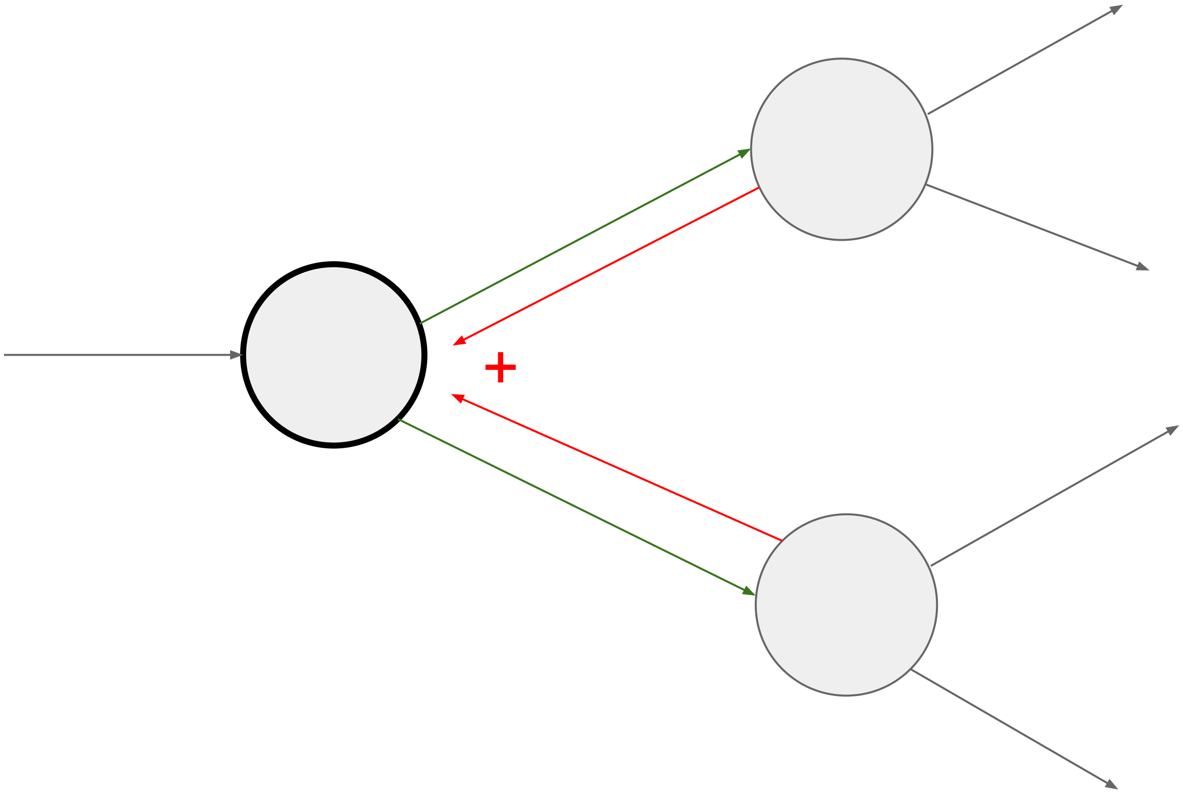
add gate: gradient distributor

max gate: gradient router 1(largest), 0, 0, 0

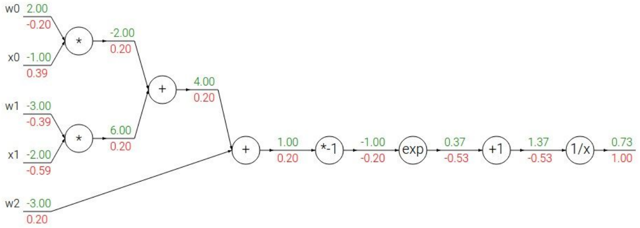
mul gate: gradient… “switcher”?



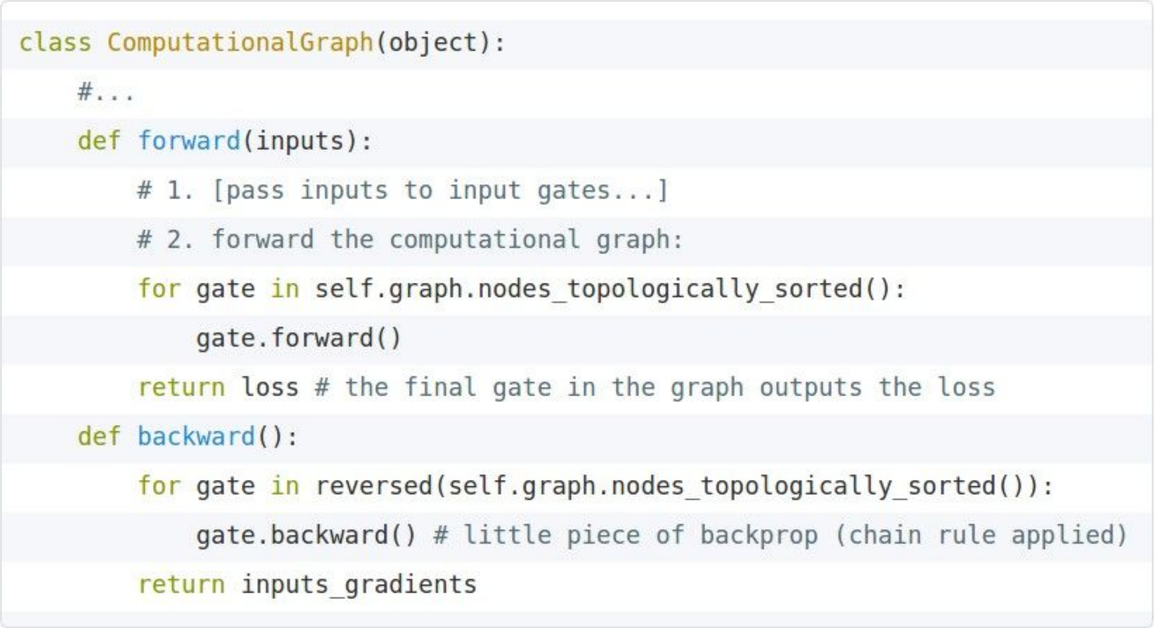
Gradients add at branches



Implementation: forward/backward API

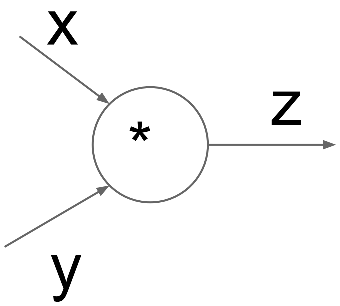


Graph (or Net) object. *(Rough psuedo code)*

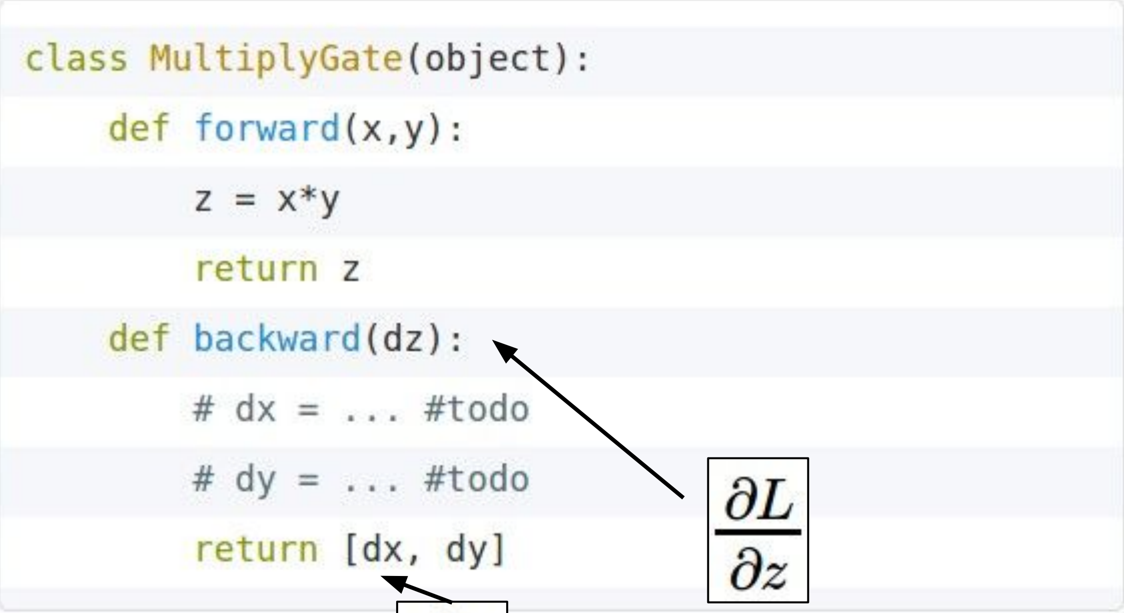


```
class ComputationalGraph(object):
    #...
    def forward(inputs):
        # 1. [pass inputs to input gates...]
        # 2. forward the computational graph:
        for gate in self.graph.nodes_topologically_sorted():
            gate.forward()
        return loss # the final gate in the graph 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
```

Implementation: forward/backward API



(x,y,z are scalars)

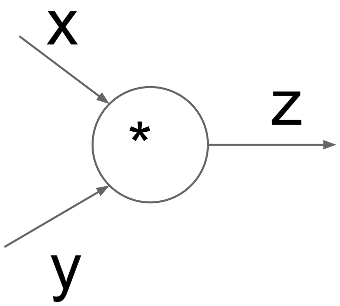


```
class MultiplyGate(object):
    def forward(x,y):
        z = x*y
        return z
    def backward(dz):
        # dx = ... #todo
        # dy = ... #todo
        return [dx, dy]
```

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

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

Implementation: forward/backward API



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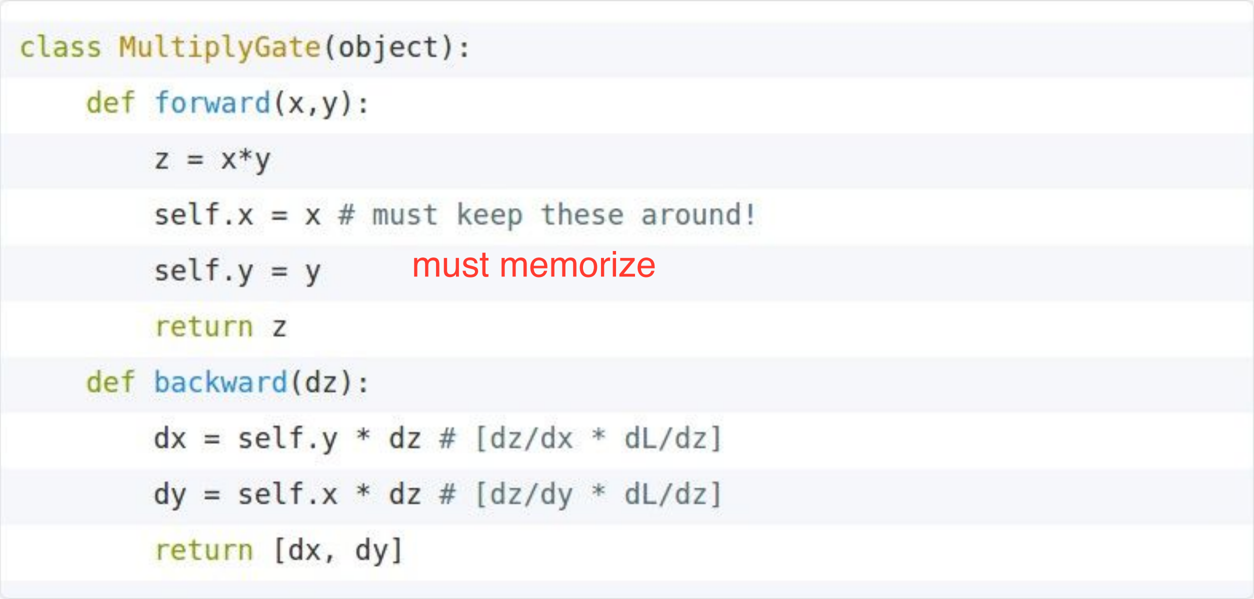
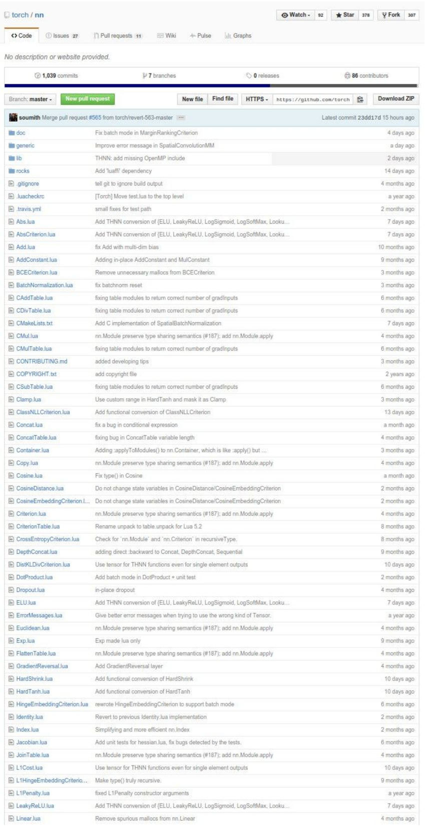


```
class MultiplyGate(object):
    def forward(x,y):
        z = x*y
        self.x = x # must keep these around!
        self.y = y
        return z
    def backward(dz):
        dx = self.y * dz # [dz/dx * dL/dz]
        dy = self.x * dz # [dz/dy * dL/dz]
        return [dx, dy]
```

must memorize

Example: Torch Layers



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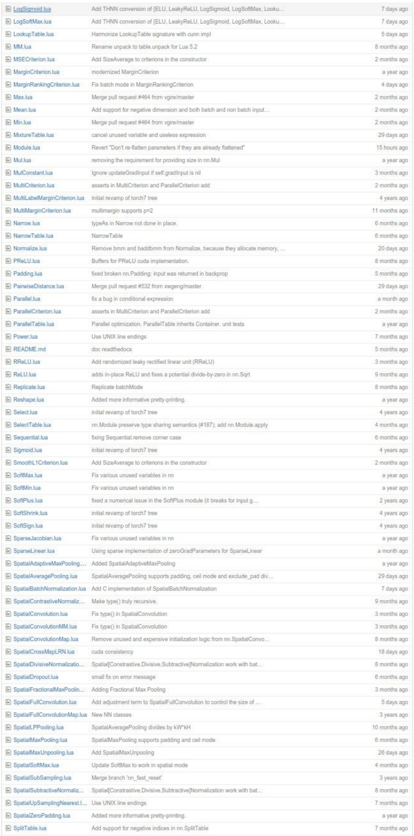

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SmoothL1Criterion.lua	Add SizeAverage to criterions in the constructor	2 months ago
SoftMax.lua	Fix various unused variables in nn	a year ago
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SoftPlus.lua	fixed a numerical issue in the SoftPlus module (it breaks for input g...	2 years ago
SoftShrink.lua	initial revamp of torch7 tree	4 years ago
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SparseJacobian.lua	Fix various unused variables in nn	a year ago
SparseLinear.lua	Using sparse implementation of zeroGradParameters for SparseLinear	a month ago
SpatialAdaptiveMaxPooling....	Added SpatialAdaptiveMaxPooling	a year ago
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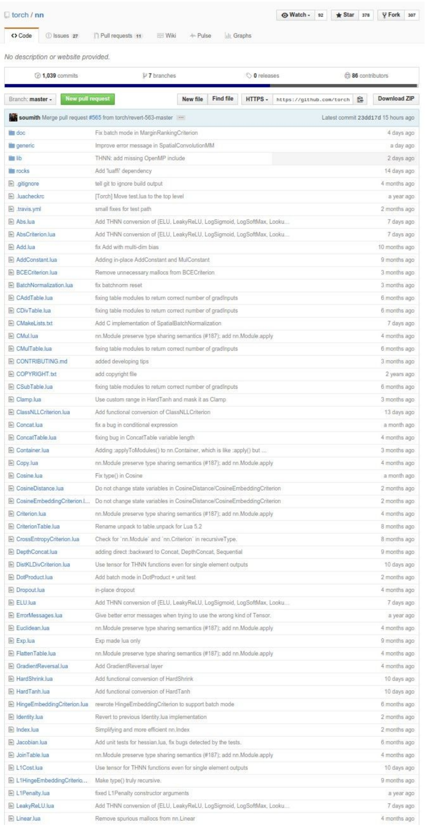

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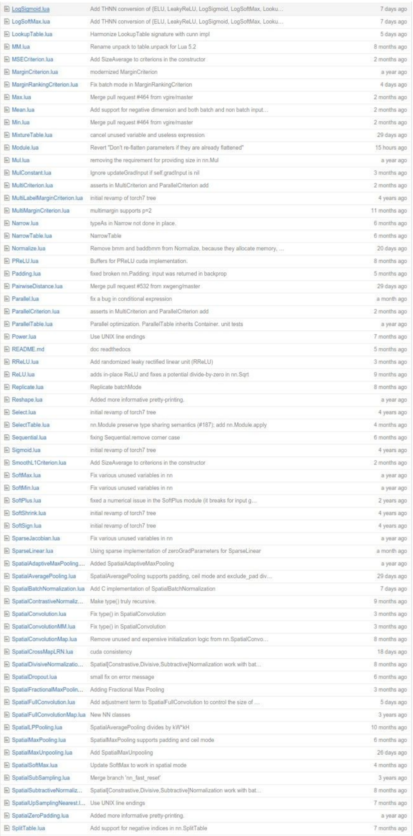

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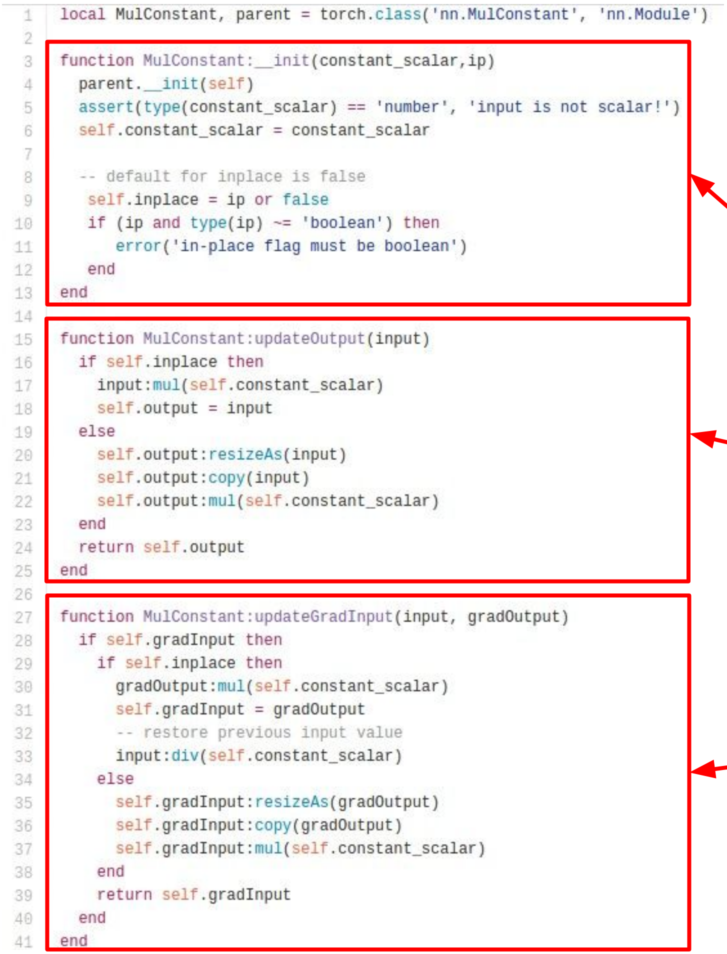
Sequential.lua	fixing Sequential.remove corner case	6 months ago
Sigmoid.lua	initial revamp of torch7 tree	4 years ago
SmoothL1Criterion.lua	Add SizeAverage to criterions in the constructor	2 months ago
SoftMax.lua	Fix various unused variables in nn	a year ago
SoftMin.lua	Fix various unused variables in nn	a year ago
SoftPlus.lua	fixed a numerical issue in the SoftPlus module (it breaks for input g...	2 years ago
SoftShrink.lua	initial revamp of torch7 tree	4 years ago
SoftSign.lua	initial revamp of torch7 tree	4 years ago
SparseJacobian.lua	Fix various unused variables in nn	a year ago
SparseLinear.lua	Using sparse implementation of zeroGradParameters for SparseLinear	a month ago
SpatialAdaptiveMaxPooling....	Added SpatialAdaptiveMaxPooling	a year ago
SpatialAveragePooling.lua	SpatialAveragePooling supports padding, ceil mode and exclude_pad div...	29 days ago
SpatialBatchNormalization.lua	Add C implementation of SpatialBatchNormalization	7 days ago
SpatialContrastiveNormaliz...	Make type() truly recursive.	9 months ago
SpatialConvolution.lua	Fix type() in SpatialConvolution	3 months ago
SpatialConvolutionMM.lua	Fix type() in SpatialConvolution	3 months ago
SpatialConvolutionMap.lua	Remove unused and expensive initialization logic from nn.SpatialConvo...	8 months ago
SpatialCrossMapLRN.lua	cuda consistency	18 days ago
SpatialDivisiveNormalizatio...	Spatial[Constrastive,Divisive,Subtractive]Normalization work with bat...	8 months ago
SpatialDropout.lua	small fix on error message	6 months ago
SpatialFractionalMaxPoolin...	Adding Fractional Max Pooling	3 months ago
SpatialFullConvolution.lua	Add adjustment term to SpatialFullConvolution to control the size of ...	5 days ago
SpatialFullConvolutionMap.lua	New NN classes	3 years ago
SpatialLPPooling.lua	SpatialAveragePooling divides by kW*kH	10 months ago
SpatialMaxPooling.lua	SpatialMaxPooling supports padding and ceil mode	6 months ago
SpatialMaxUnpooling.lua	Add SpatialMaxUnpooling	26 days ago
SpatialSoftMax.lua	Update SoftMax to work in spatial mode	4 months ago
SpatialSubSampling.lua	Merge branch 'nn_fast_reset'	3 years ago
SpatialSubtractiveNormaliz...	Spatial[Constrastive,Divisive,Subtractive]Normalization work with bat...	8 months ago
SpatialUpSamplingNearest.l...	Use UNIX line endings	7 months ago
SpatialZeroPadding.lua	Added more informative pretty-printing.	a year ago
SplitTable.lua	Add support for negative indices in nn.SplitTable	7 months ago

=

Example: Torch MulConstant



```lua
local MulConstant, parent = torch.class('nn.MulConstant', 'nn.Module')

function MulConstant:__init(constant_scalar,ip)
  parent.__init(self)
  assert(type(constant_scalar) == 'number', 'input is not scalar!')
  self.constant_scalar = constant_scalar

  -- default for inplace is false
   self.inplace = ip or false
   if (ip and type(ip) ~= 'boolean') then
      error('in-place flag must be boolean')
   end
end

function MulConstant:updateOutput(input)
  if self.inplace then
    input:mul(self.constant_scalar)
    self.output = input
  else
    self.output:resizeAs(input)
    self.output:copy(input)
    self.output:mul(self.constant_scalar)
  end
  return self.output
end

function MulConstant:updateGradInput(input, gradOutput)
  if self.gradInput then
    if self.inplace then
      gradOutput:mul(self.constant_scalar)
      self.gradInput = gradOutput
      -- restore previous input value
      input:div(self.constant_scalar)
    else
      self.gradInput:resizeAs(gradOutput)
      self.gradInput:copy(gradOutput)
      self.gradInput:mul(self.constant_scalar)
    end
    return self.gradInput
  end
end
```

$$f(X) = aX$$

scalar

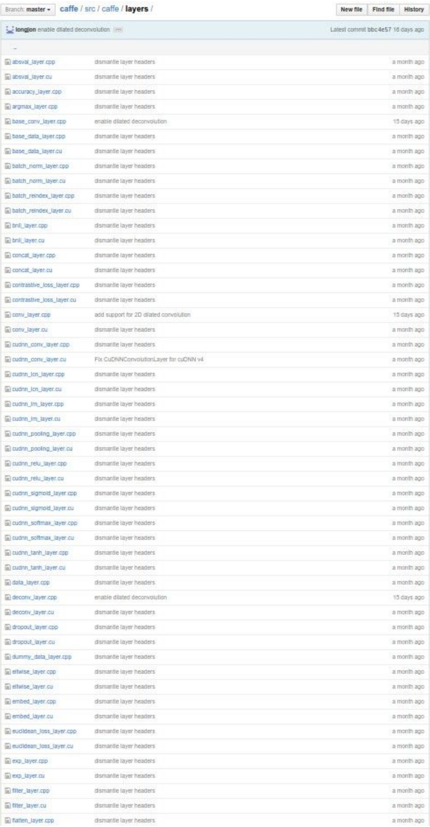
tensor

initialization

forward()

backward()

Example: Caffe Layers



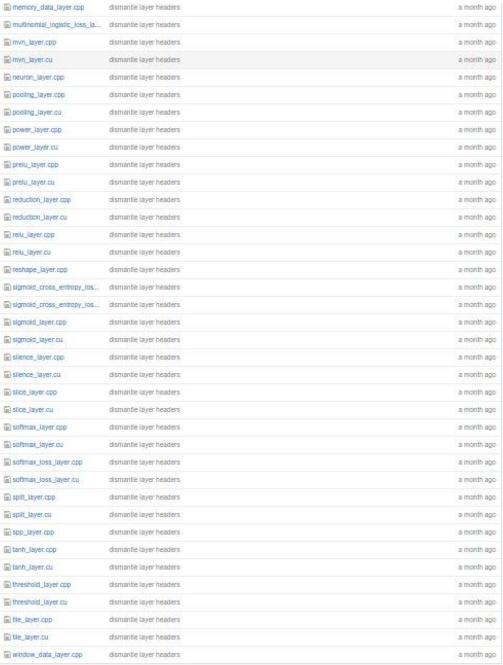
Branch: master ▾ caffe / src / caffe / layers /

New file | Find file | History

longjon enable dilated deconvolution … Latest commit bbc4e57 16 days ago

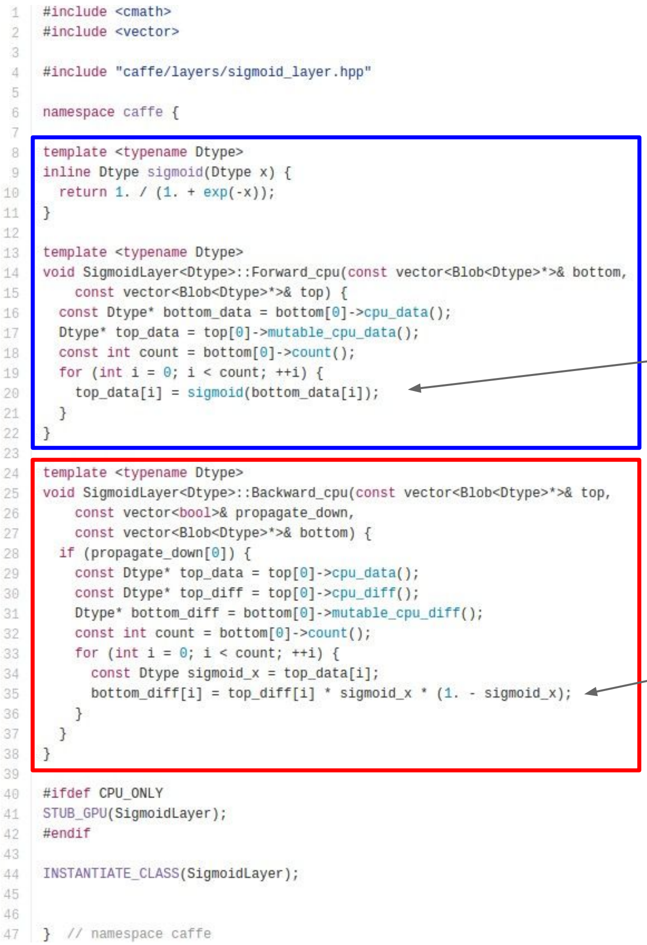
..

absval_layer.cpp	dismantle layer headers	a month ago
absval_layer.cu	dismantle layer headers	a month ago
accuracy_layer.cpp	dismantle layer headers	a month ago
argmax_layer.cpp	dismantle layer headers	a month ago
base_conv_layer.cpp	enable dilated deconvolution	15 days ago
base_data_layer.cpp	dismantle layer headers	a month ago
base_data_layer.cu	dismantle layer headers	a month ago
batch_norm_layer.cpp	dismantle layer headers	a month ago
batch_norm_layer.cu	dismantle layer headers	a month ago
batch_reindex_layer.cpp	dismantle layer headers	a month ago
batch_reindex_layer.cu	dismantle layer headers	a month ago
bnll_layer.cpp	dismantle layer headers	a month ago
bnll_layer.cu	dismantle layer headers	a month ago
concat_layer.cpp	dismantle layer headers	a month ago
concat_layer.cu	dismantle layer headers	a month ago
contrastive_loss_layer.cpp	dismantle layer headers	a month ago
contrastive_loss_layer.cu	dismantle layer headers	a month ago
conv_layer.cpp	add support for 2D dilated convolution	15 days ago
conv_layer.cu	dismantle layer headers	a month ago
cudnn_conv_layer.cpp	dismantle layer headers	a month ago
cudnn_conv_layer.cu	Fix CuDNNConvolutionLayer for cuDNN v4	a month ago
cudnn_lcn_layer.cpp	dismantle layer headers	a month ago
cudnn_lcn_layer.cu	dismantle layer headers	a month ago
cudnn_lrn_layer.cpp	dismantle layer headers	a month ago
cudnn_lrn_layer.cu	dismantle layer headers	a month ago
cudnn_pooling_layer.cpp	dismantle layer headers	a month ago
cudnn_pooling_layer.cu	dismantle layer headers	a month ago
cudnn_relu_layer.cpp	dismantle layer headers	a month ago
cudnn_relu_layer.cu	dismantle layer headers	a month ago
cudnn_sigmoid_layer.cpp	dismantle layer headers	a month ago
cudnn_sigmoid_layer.cu	dismantle layer headers	a month ago
cudnn_softmax_layer.cpp	dismantle layer headers	a month ago
cudnn_softmax_layer.cu	dismantle layer headers	a month ago
cudnn_tanh_layer.cpp	dismantle layer headers	a month ago
cudnn_tanh_layer.cu	dismantle layer headers	a month ago
data_layer.cpp	dismantle layer headers	a month ago
deconv_layer.cpp	enable dilated deconvolution	15 days ago
deconv_layer.cu	dismantle layer headers	a month ago
dropout_layer.cpp	dismantle layer headers	a month ago
dropout_layer.cu	dismantle layer headers	a month ago
dummy_data_layer.cpp	dismantle layer headers	a month ago
eltwise_layer.cpp	dismantle layer headers	a month ago
eltwise_layer.cu	dismantle layer headers	a month ago
embed_layer.cpp	dismantle layer headers	a month ago
embed_layer.cu	dismantle layer headers	a month ago
euclidean_loss_layer.cpp	dismantle layer headers	a month ago
euclidean_loss_layer.cu	dismantle layer headers	a month ago
exp_layer.cpp	dismantle layer headers	a month ago
exp_layer.cu	dismantle layer headers	a month ago
filter_layer.cpp	dismantle layer headers	a month ago
filter_layer.cu	dismantle layer headers	a month ago
flatten_layer.cpp	dismantle layer headers	a month ago



memory_data_layer.cpp	dismantle layer headers	a month ago
multinomial_logistic_loss_la…	dismantle layer headers	a month ago
mvn_layer.cpp	dismantle layer headers	a month ago
mvn_layer.cu	dismantle layer headers	a month ago
neuron_layer.cpp	dismantle layer headers	a month ago
pooling_layer.cpp	dismantle layer headers	a month ago
pooling_layer.cu	dismantle layer headers	a month ago
power_layer.cpp	dismantle layer headers	a month ago
power_layer.cu	dismantle layer headers	a month ago
prelu_layer.cpp	dismantle layer headers	a month ago
prelu_layer.cu	dismantle layer headers	a month ago
reduction_layer.cpp	dismantle layer headers	a month ago
reduction_layer.cu	dismantle layer headers	a month ago
relu_layer.cpp	dismantle layer headers	a month ago
relu_layer.cu	dismantle layer headers	a month ago
reshape_layer.cpp	dismantle layer headers	a month ago
sigmoid_cross_entropy_los…	dismantle layer headers	a month ago
sigmoid_cross_entropy_los…	dismantle layer headers	a month ago
sigmoid_layer.cpp	dismantle layer headers	a month ago
sigmoid_layer.cu	dismantle layer headers	a month ago
silence_layer.cpp	dismantle layer headers	a month ago
silence_layer.cu	dismantle layer headers	a month ago
slice_layer.cpp	dismantle layer headers	a month ago
slice_layer.cu	dismantle layer headers	a month ago
softmax_layer.cpp	dismantle layer headers	a month ago
softmax_layer.cu	dismantle layer headers	a month ago
softmax_loss_layer.cpp	dismantle layer headers	a month ago
softmax_loss_layer.cu	dismantle layer headers	a month ago
split_layer.cpp	dismantle layer headers	a month ago
split_layer.cu	dismantle layer headers	a month ago
spp_layer.cpp	dismantle layer headers	a month ago
tanh_layer.cpp	dismantle layer headers	a month ago
tanh_layer.cu	dismantle layer headers	a month ago
threshold_layer.cpp	dismantle layer headers	a month ago
threshold_layer.cu	dismantle layer headers	a month ago
tile_layer.cpp	dismantle layer headers	a month ago
tile_layer.cu	dismantle layer headers	a month ago
window_data_layer.cpp	dismantle layer headers	a month ago

Caffe Sigmoid Layer



```
#include <cmath>
#include <vector>

#include "caffe/layers/sigmoid_layer.hpp"

namespace caffe {

template <typename Dtype>
inline Dtype sigmoid(Dtype x) {
  return 1. / (1. + exp(-x));
}

template <typename Dtype>
void SigmoidLayer<Dtype>::Forward_cpu(const vector<Blob<Dtype>*>& bottom,
    const vector<Blob<Dtype>*>& top) {
  const Dtype* bottom_data = bottom[0]->cpu_data();
  Dtype* top_data = top[0]->mutable_cpu_data();
  const int count = bottom[0]->count();
  for (int i = 0; i < count; ++i) {
    top_data[i] = sigmoid(bottom_data[i]);
  }
}

template <typename Dtype>
void SigmoidLayer<Dtype>::Backward_cpu(const vector<Blob<Dtype>*>& top,
    const vector<bool>& propagate_down,
    const vector<Blob<Dtype>*>& bottom) {
  if (propagate_down[0]) {
    const Dtype* top_data = top[0]->cpu_data();
    const Dtype* top_diff = top[0]->cpu_diff();
    Dtype* bottom_diff = bottom[0]->mutable_cpu_diff();
    const int count = bottom[0]->count();
    for (int i = 0; i < count; ++i) {
      const Dtype sigmoid_x = top_data[i];
      bottom_diff[i] = top_diff[i] * sigmoid_x * (1. - sigmoid_x);
    }
  }
}

#ifdef CPU_ONLY
STUB_GPU(SigmoidLayer);
#endif

INSTANTIATE_CLASS(SigmoidLayer);


}  // namespace caffe
```

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

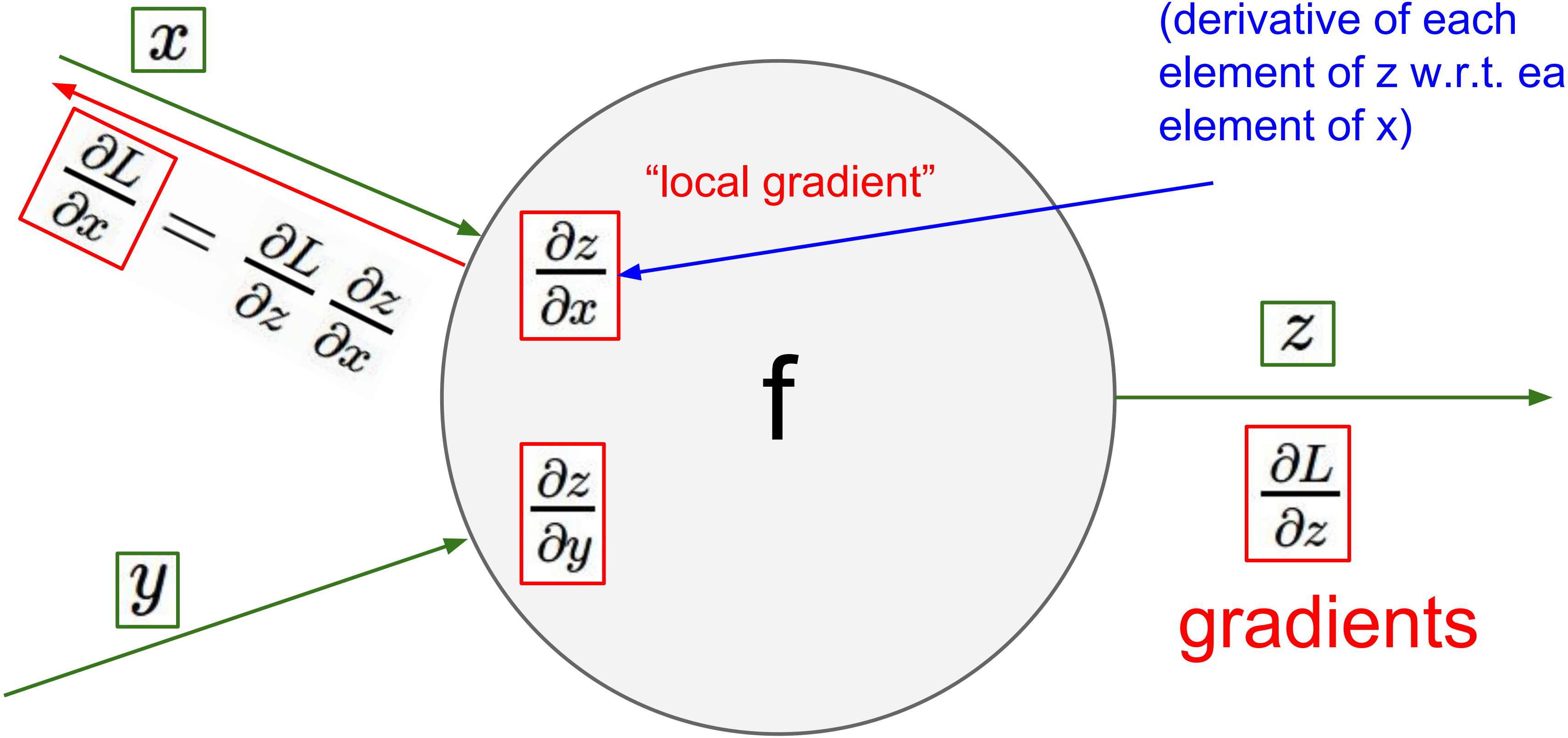
forward - backward - upgrade for W

$$\boxed{(1-\sigma(x))\sigma(x)} \quad \text{*top\_diff} \quad \text{(chain rule)}$$

Gradients for vectorized code

(x,y,z are now vectors)

This is now the **Jacobian matrix** (derivative of each element of z w.r.t. each element of x)



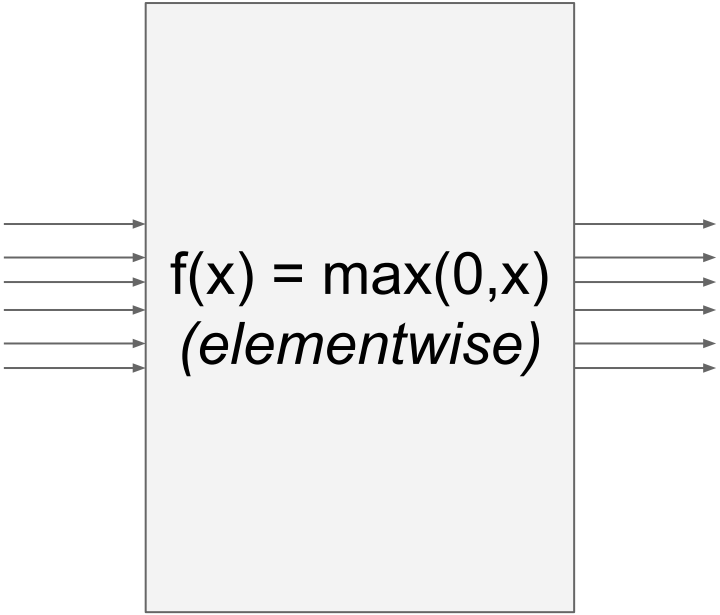
x
y
z
f
$\frac{\partial L}{\partial x} = \frac{\partial L}{\partial z}\frac{\partial z}{\partial x}$
$\frac{\partial z}{\partial x}$
$\frac{\partial z}{\partial y}$
$\frac{\partial L}{\partial z}$

“local gradient”

gradients

Vectorized operations

4096-d
input vector



f(x) = max(0,x)
(elementwise)

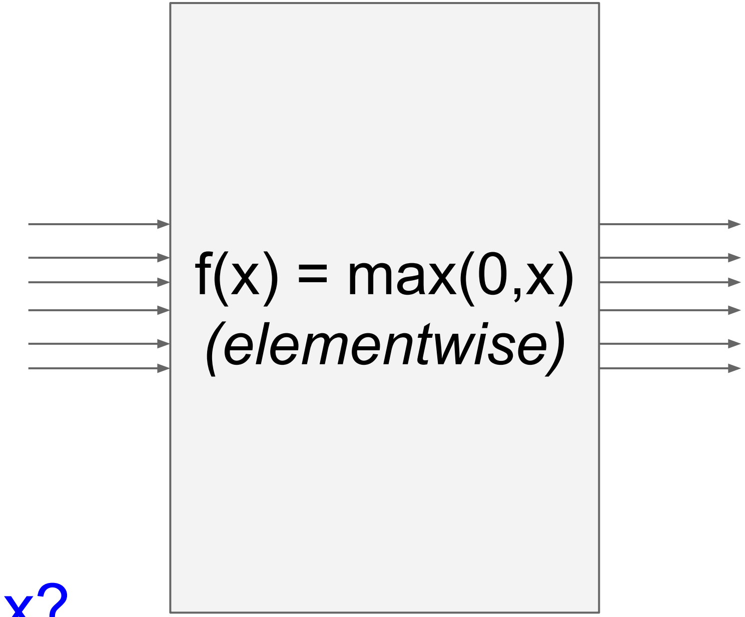
4096-d
output vector

Vectorized operations

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

Jacobian matrix

4096-d
input vector



4096-d
output vector

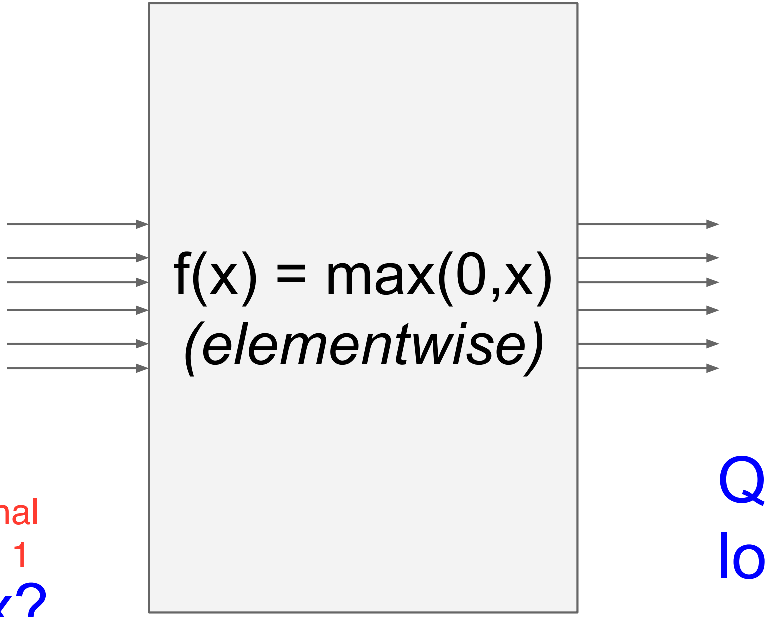
Q: what is the size of the Jacobian matrix?

Vectorized operations

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

Jacobian matrix

4096-d
input vector



4096-d
output vector

Q: what is the size of the Jacobian matrix?
[4096 x 4096!]

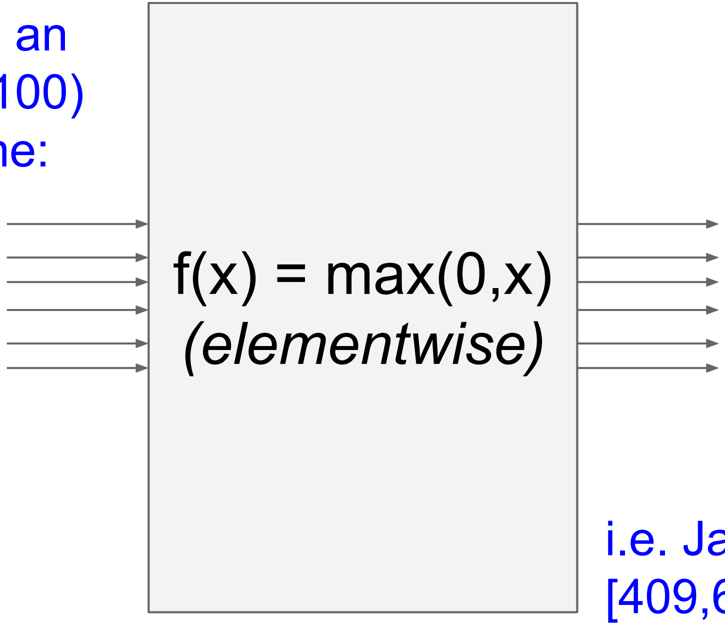
diagonal
0 and 1

Q2: what does it look like?

Vectorized operations

in practice we process an entire minibatch (e.g. 100) of examples at one time:

100 4096-d
input vectors



f(x) = max(0,x)
(elementwise)

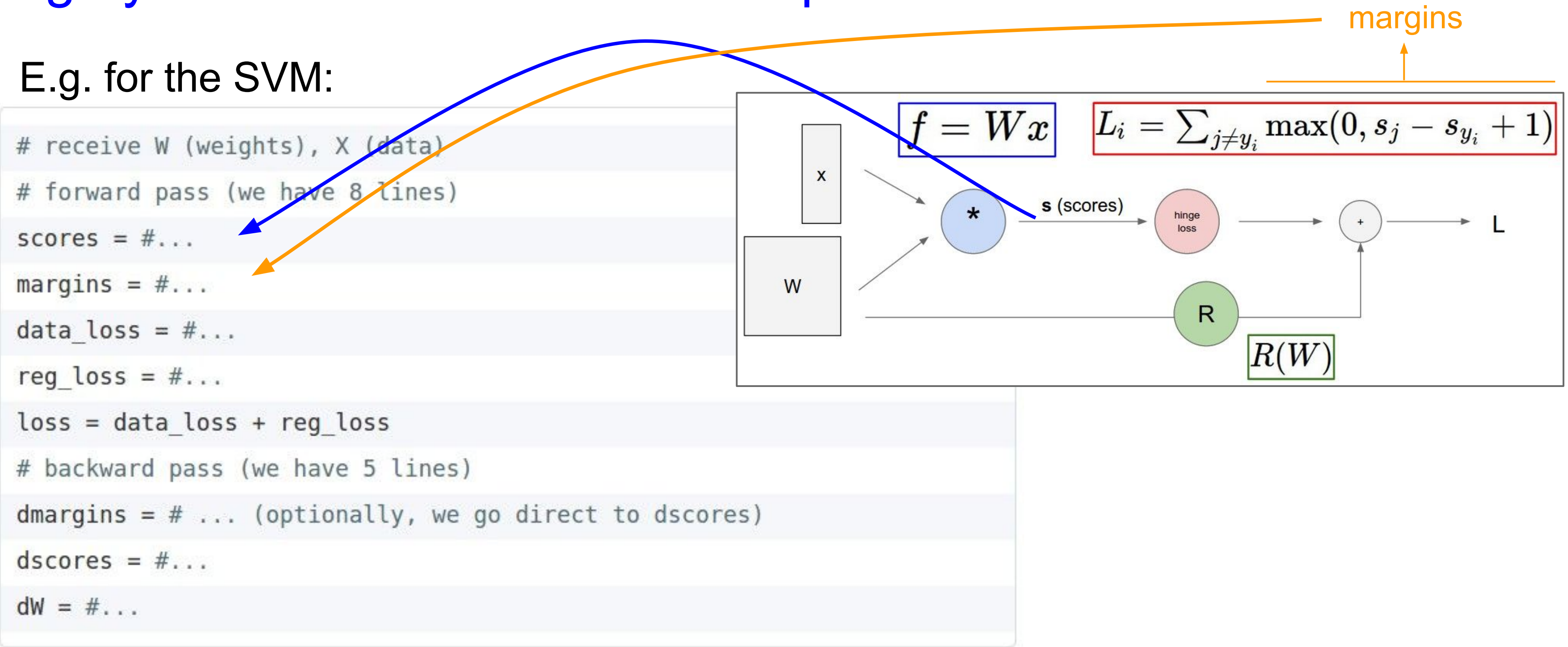
100 4096-d
output vectors

i.e. Jacobian would technically be a [409,600 x 409,600] matrix :\

Assignment: Writing SVM/Softmax

Stage your forward/backward computation!

E.g. for the SVM:



```
# receive W (weights), X (data)
# forward pass (we have 8 lines)
scores = #...
margins = #...
data_loss = #...
reg_loss = #...
loss = data_loss + reg_loss
# backward pass (we have 5 lines)
dmargins = # ... (optionally, we go direct to dscores)
dscores = #...
dW = #...
```

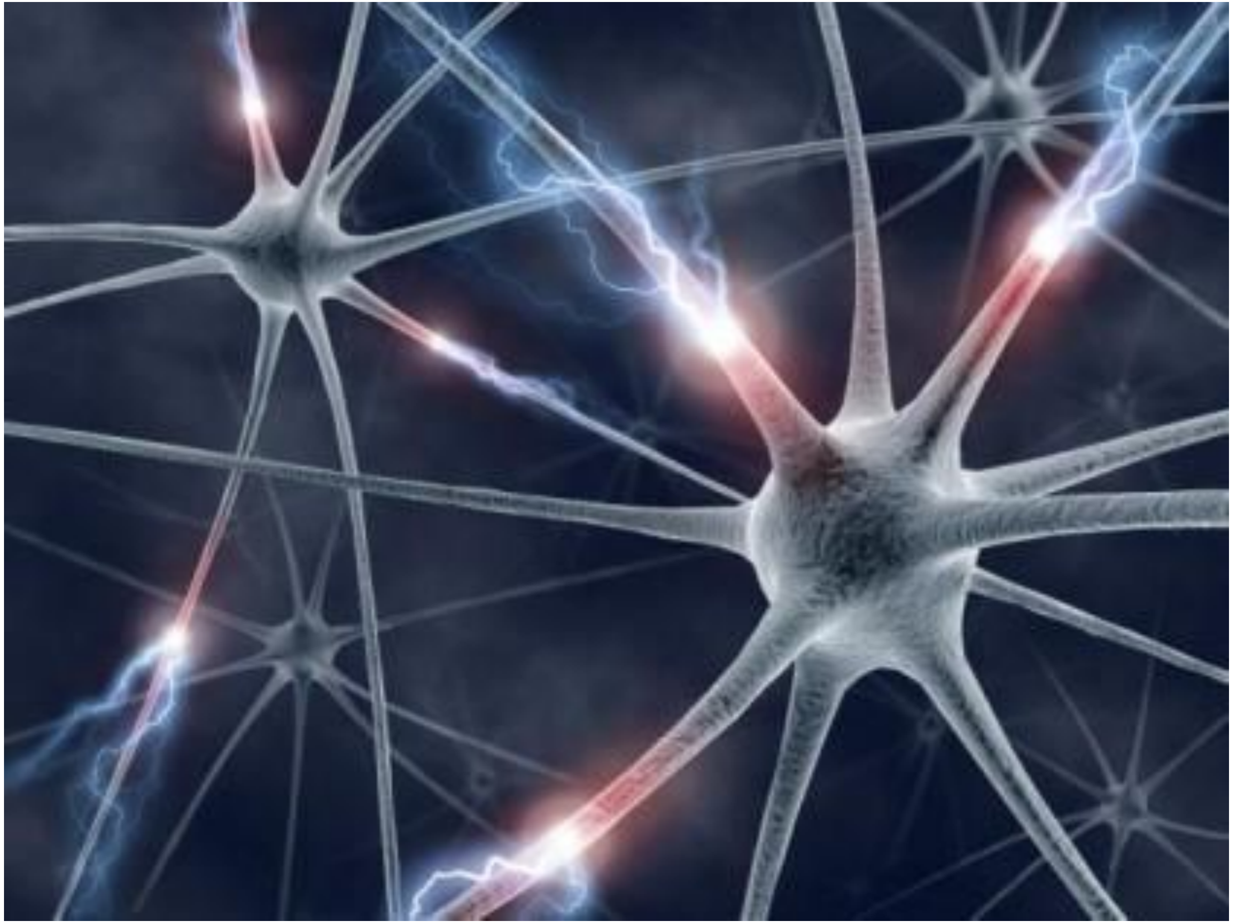
$f = Wx$

$L_i = \sum_{j \neq y_i} \max(0, s_j - s_{y_i} + 1)$

$R(W)$

Summary so far

- neural nets will be very large: no hope of writing down gradient formula by hand for all parameters
- **backpropagation** = recursive application of the chain rule along a computational graph to compute the gradients of all inputs/parameters/intermediates
- implementations maintain a graph structure, where the nodes implement the **forward**() / **backward**() API.
- **forward**: compute result of an operation and save any intermediates needed for gradient computation in memory
- **backward**: apply the chain rule to compute the gradient of the loss function with respect to the inputs.



Neural Network: without the brain stuff

(**Before**) Linear score function: $f = Wx$

Neural Network: without the brain stuff

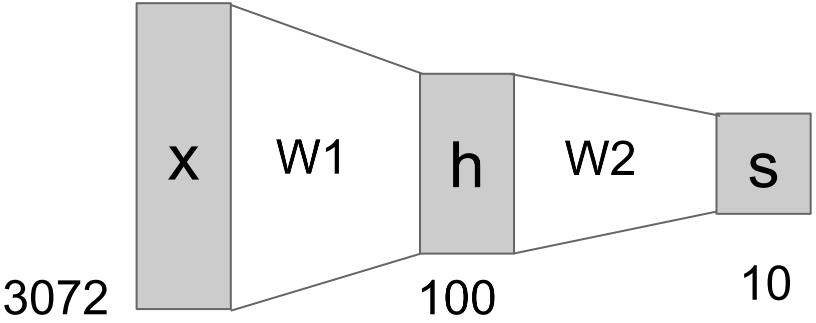
(**Before**) Linear score function: $f = Wx$

(**Now**) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

Neural Network: without the brain stuff

(**Before**) Linear score function: $f = Wx$

(**Now**) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$

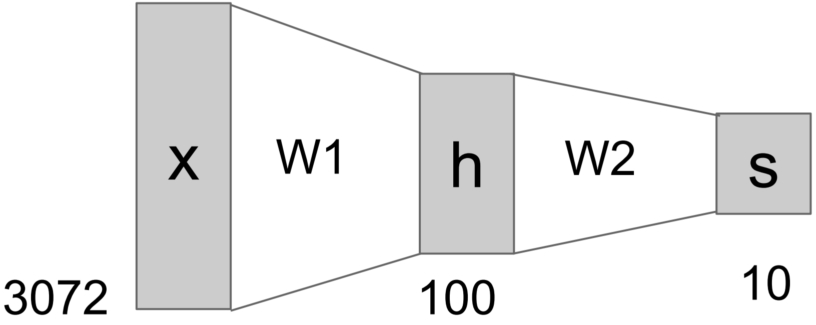


Neural Network: without the brain stuff

plane
car
bird
cat
deer
dog
frog
horse
ship
truck

(**Before**) Linear score function: $f = Wx$

(**Now**) 2-layer Neural Network $f = W_2 \max(0, W_1 x)$



Neural Network: without the brain stuff

(**Before**) Linear score function:

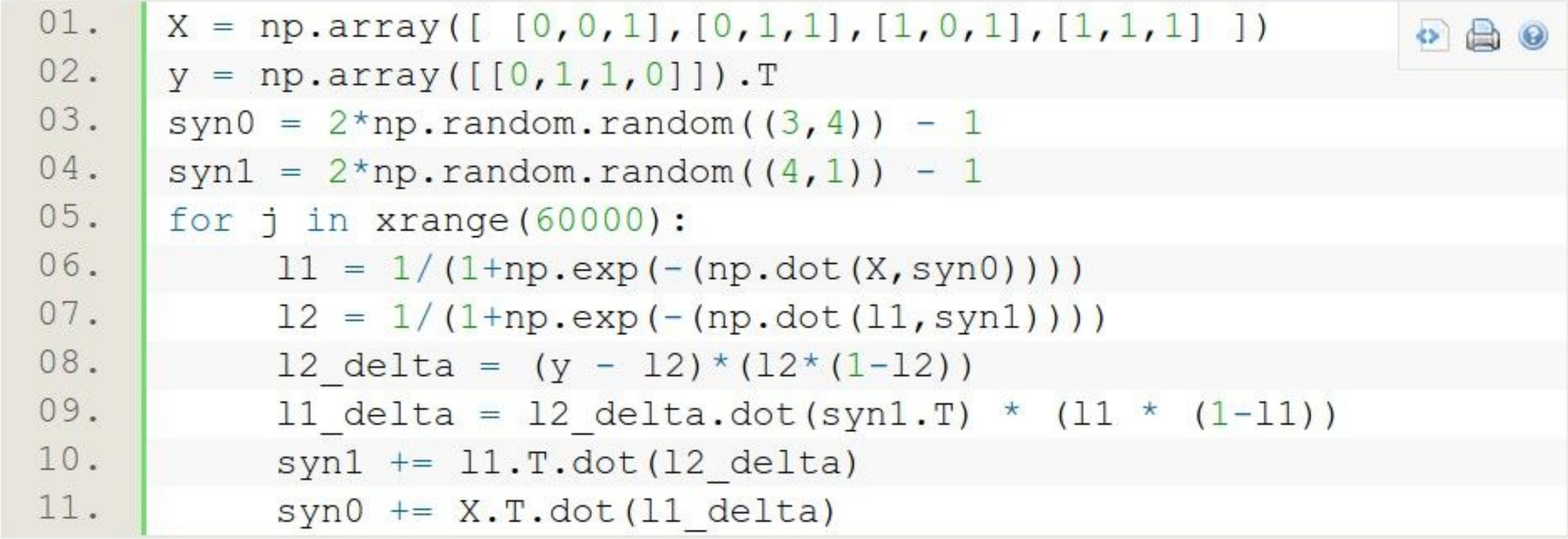
$$f = Wx$$

(**Now**) 2-layer Neural Network
or 3-layer Neural Network

$$f = W_2 \max(0, W_1 x)$$

$$f = W_3 \max(0, W_2 \max(0, W_1 x))$$

Full implementation of training a 2-layer Neural Network needs ~11 lines:

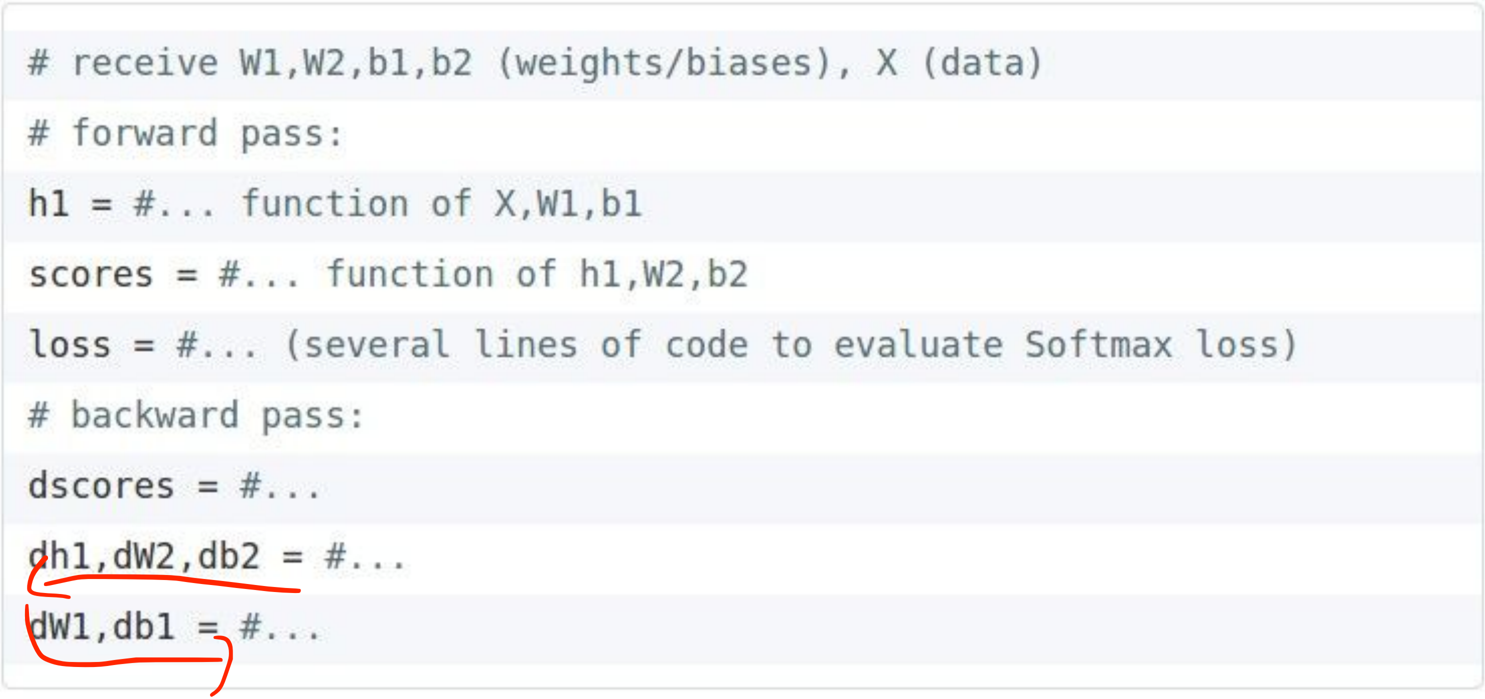


```
X = np.array([ [0,0,1],[0,1,1],[1,0,1],[1,1,1] ])
y = np.array([[0,1,1,0]]).T
syn0 = 2*np.random.random((3,4)) - 1
syn1 = 2*np.random.random((4,1)) - 1
for j in xrange(60000):
    l1 = 1/(1+np.exp(-(np.dot(X,syn0))))
    l2 = 1/(1+np.exp(-(np.dot(l1,syn1))))
    l2_delta = (y - l2)*(l2*(1-l2))
    l1_delta = l2_delta.dot(syn1.T) * (l1 * (1-l1))
    syn1 += l1.T.dot(l2_delta)
    syn0 += X.T.dot(l1_delta)
```

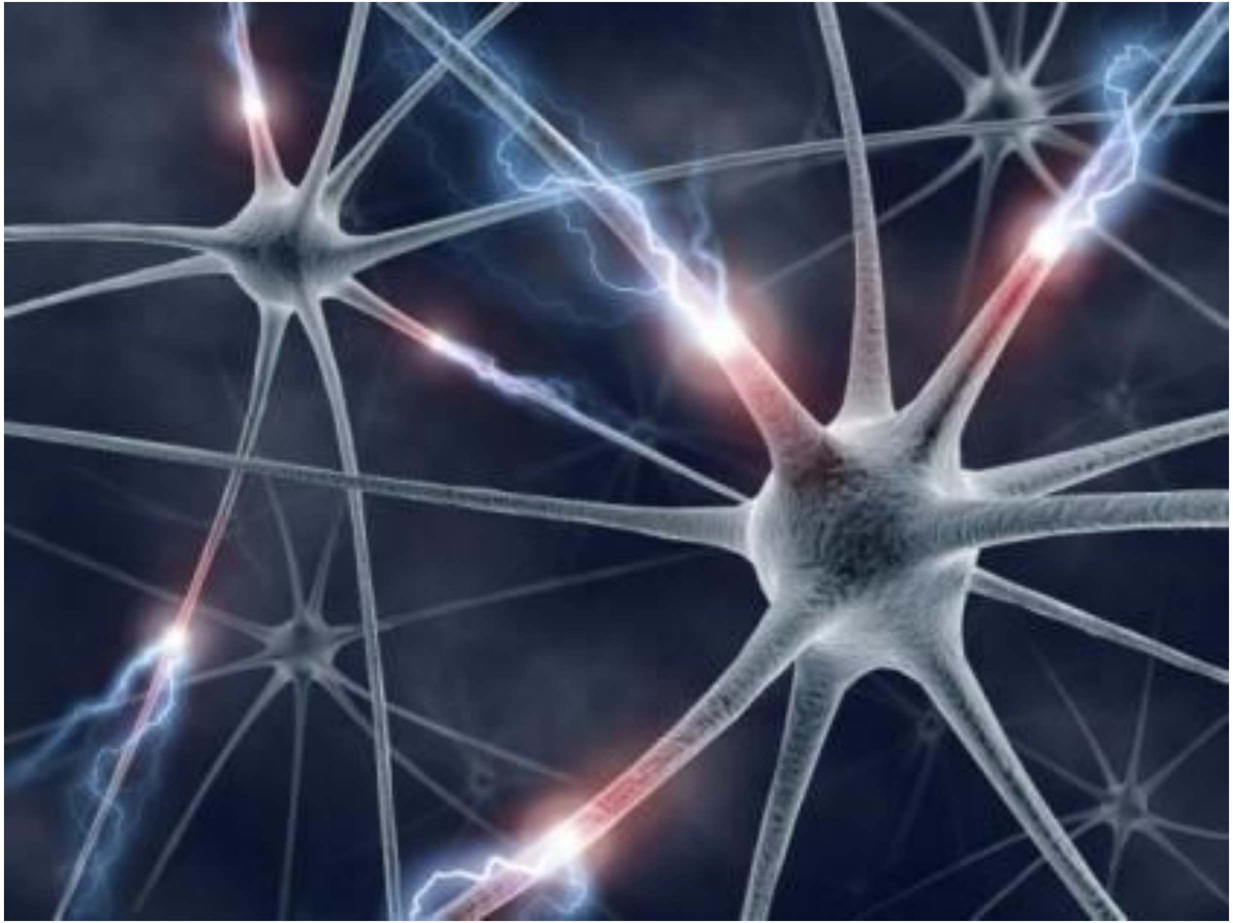
from @iamtrask, http://iamtrask.github.io/2015/07/12/basic-python-network/

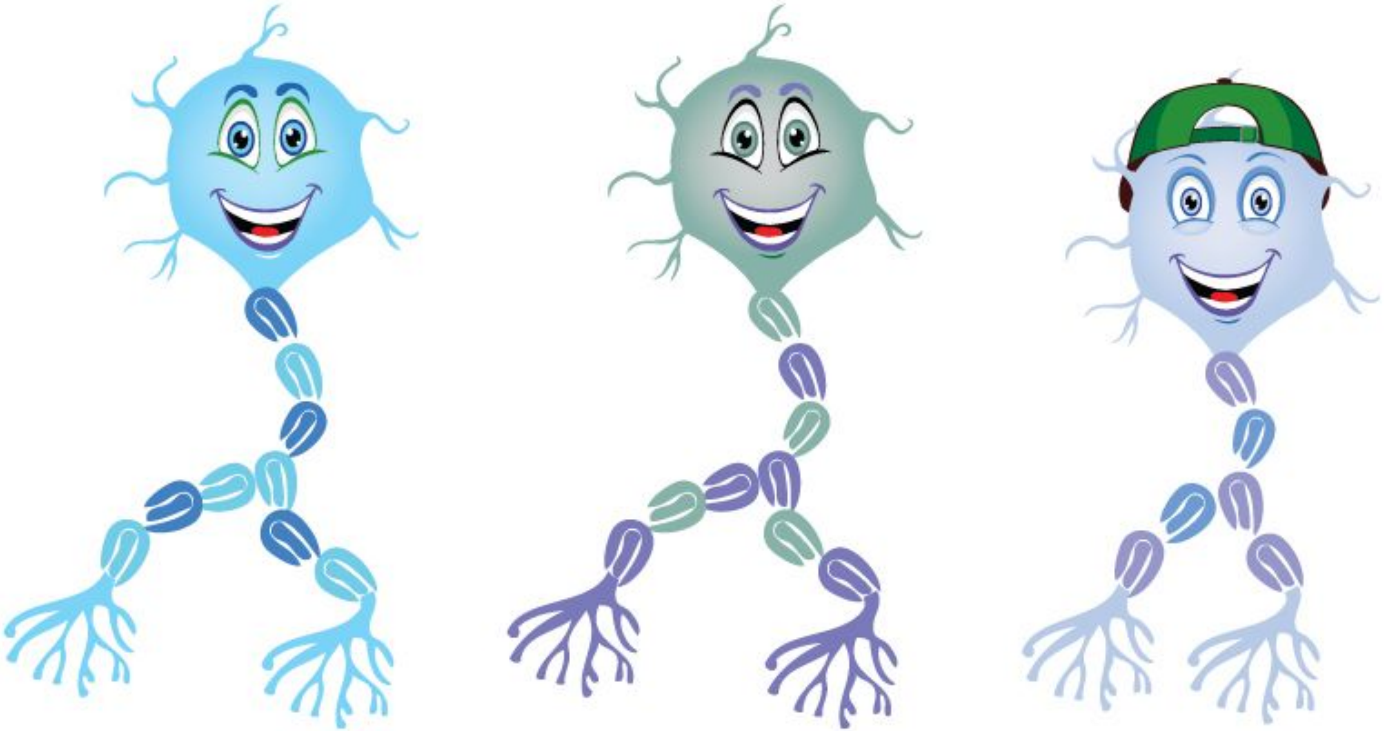
Assignment: Writing 2layer Net

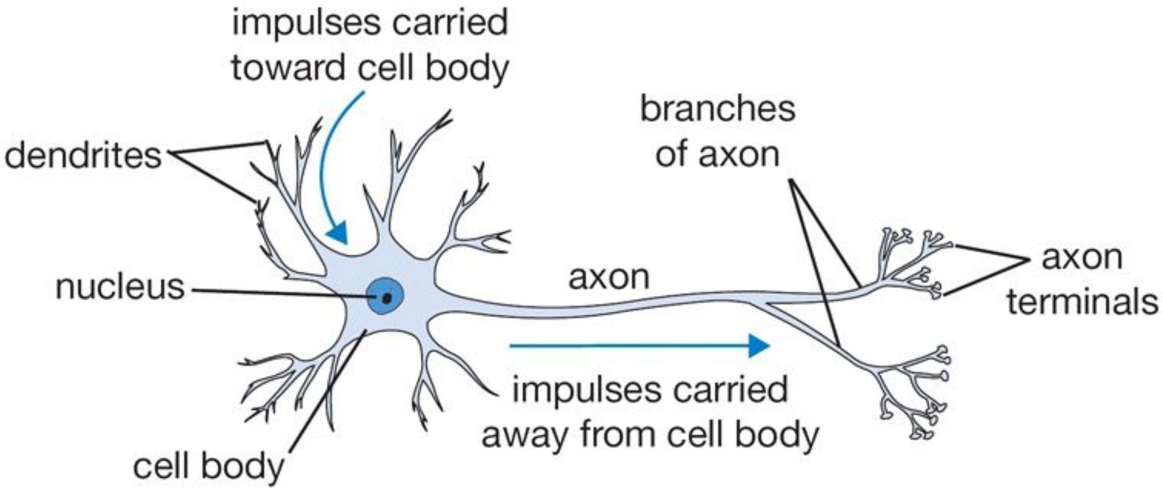
Stage your forward/backward computation!

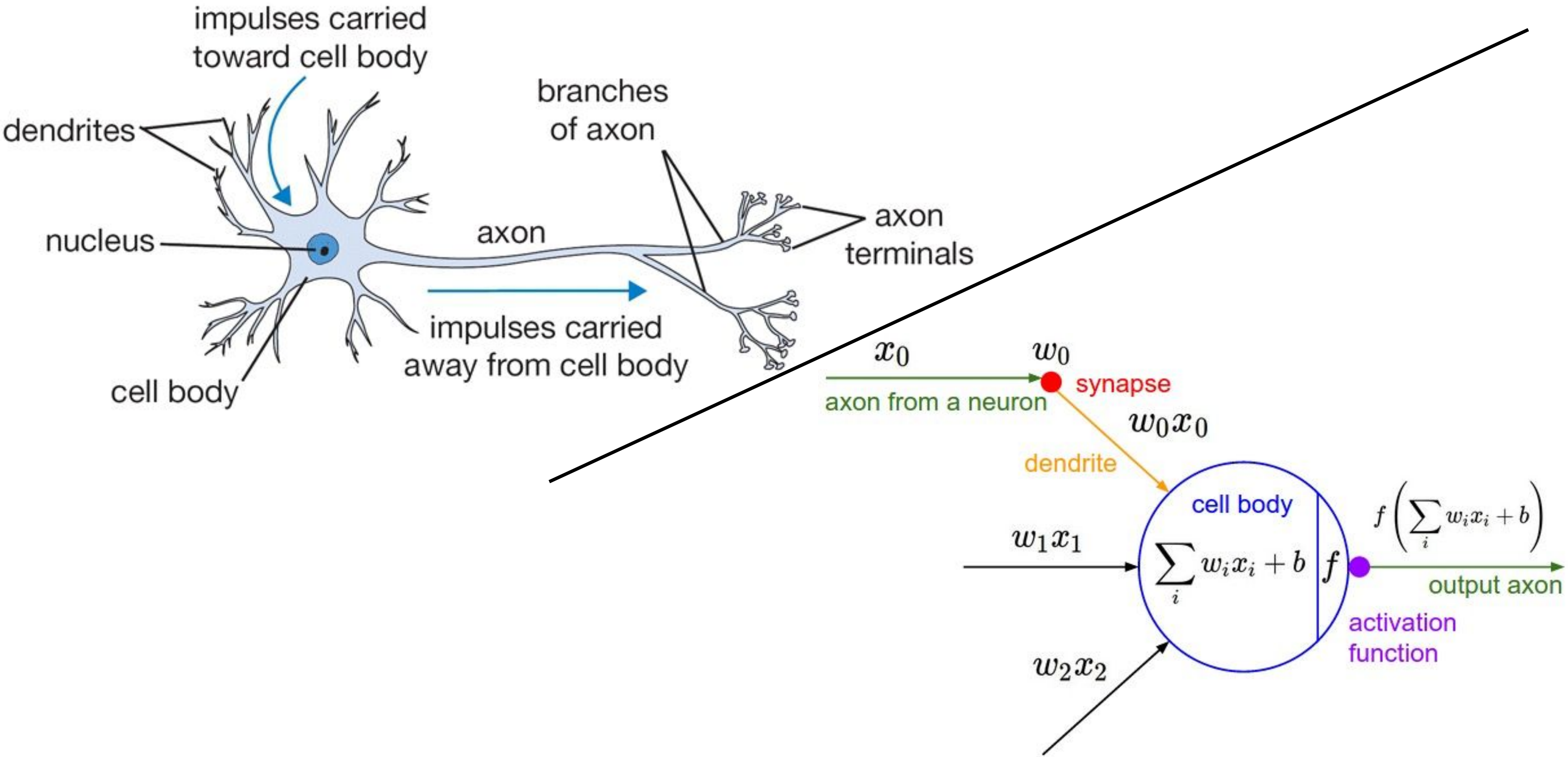


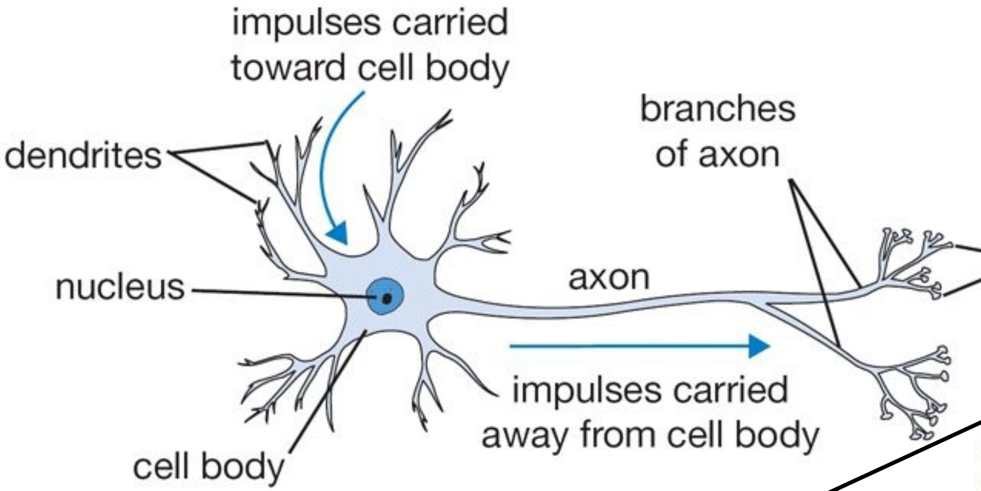
```
# receive W1,W2,b1,b2 (weights/biases), X (data)
# forward pass:
h1 = #... function of X,W1,b1
scores = #... function of h1,W2,b2
loss = #... (several lines of code to evaluate Softmax loss)
# backward pass:
dscores = #...
dh1,dW2,db2 = #...
dW1,db1 = #...
```

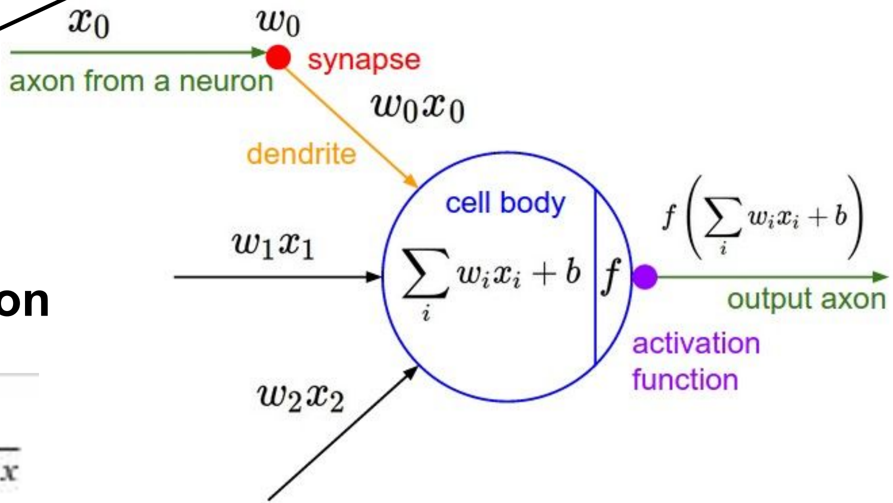


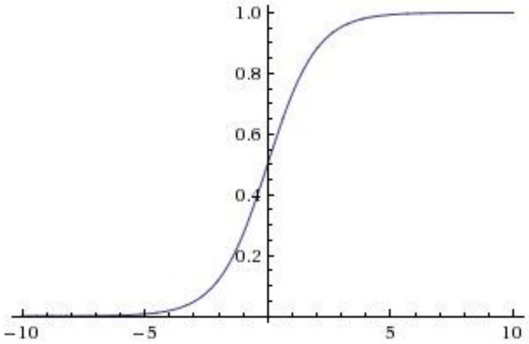



impulses carried toward cell body
dendrites
branches of axon
nucleus
axon
axon terminals
impulses carried away from cell body
cell body


impulses carried toward cell body
dendrites
branches of axon
nucleus
axon
axon terminals
impulses carried away from cell body
cell body
x_0
w_0
synapse
axon from a neuron
$w_0 x_0$
dendrite
cell body
$f\left(\sum_i w_i x_i + b\right)$
$w_1 x_1$
$\sum_i w_i x_i + b$
f
output axon
activation function
$w_2 x_2$

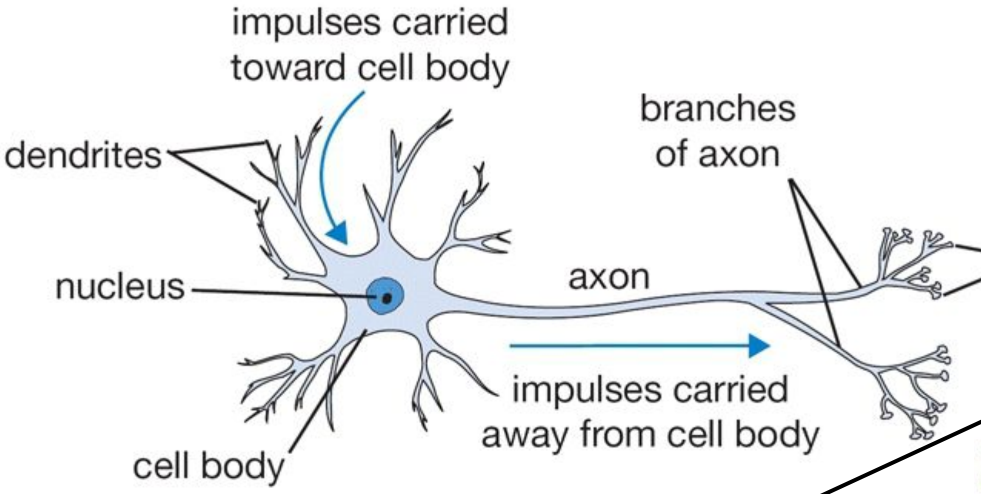

impulses carried toward cell body
dendrites
branches of axon
axon
axon terminals
nucleus
impulses carried away from cell body
cell body

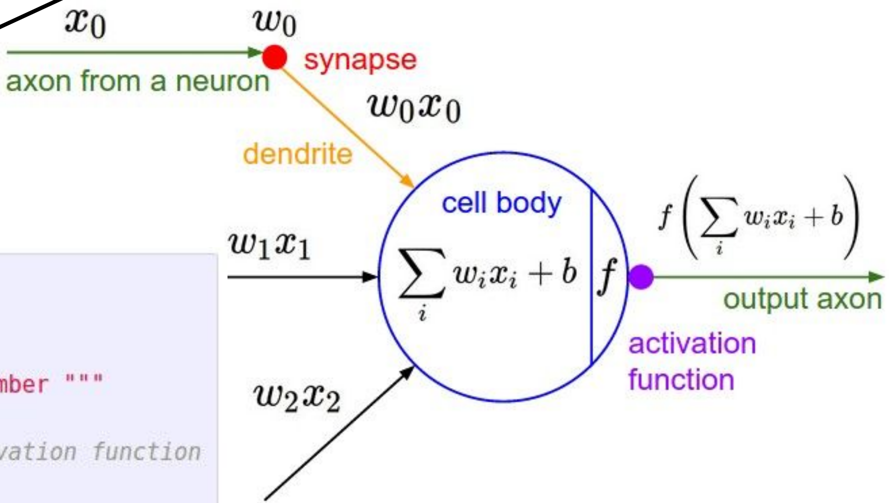




sigmoid activation function

$$\frac{1}{1+e^{-x}}$$


impulses carried toward cell body
dendrites
branches of axon
nucleus
axon
axon terminals
impulses carried away from cell body
cell body

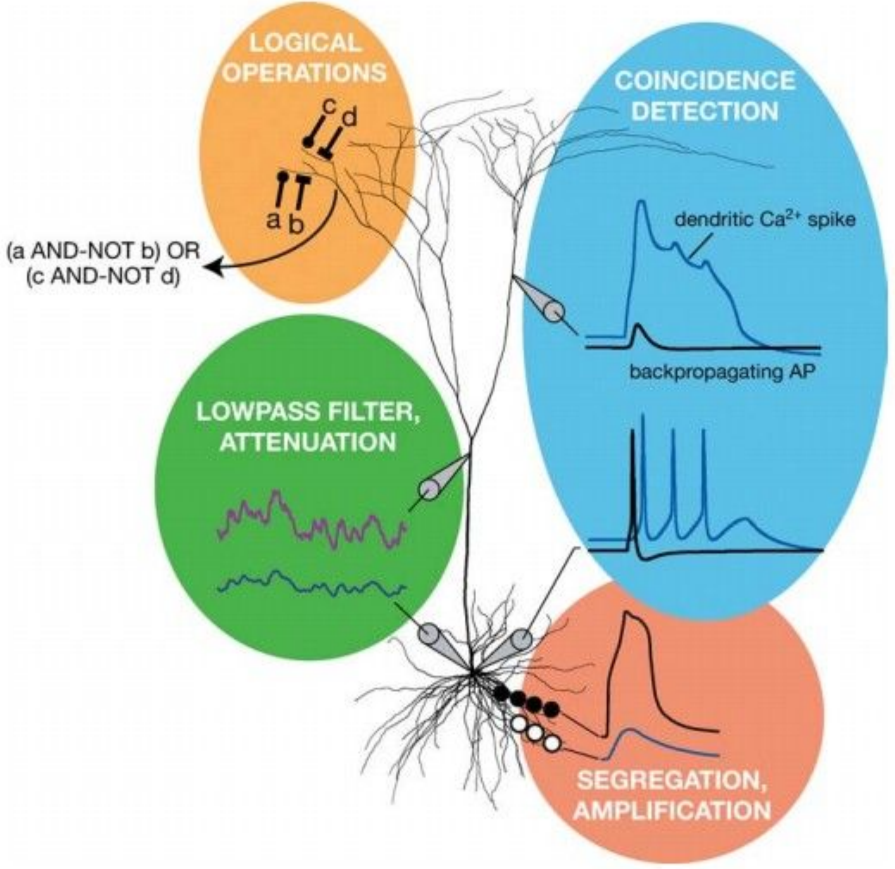


```
class Neuron:
  # ...
  def neuron_tick(inputs):
    """ assume inputs and weights are 1-D numpy arrays and bias is a number """
    cell_body_sum = np.sum(inputs * self.weights) + self.bias
    firing_rate = 1.0 / (1.0 + math.exp(-cell_body_sum)) # sigmoid activation function
    return firing_rate
```

Be very careful with your Brain analogies:

Biological Neurons:

- Many different types
- Dendrites can perform complex non-linear computations
- Synapses are not a single weight but a complex non-linear dynamical system
- Rate code may not be adequate

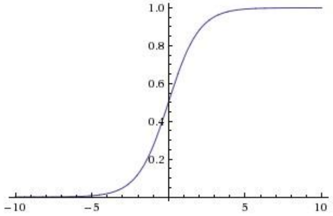

LOGICAL OPERATIONS
c d
a b
(a AND-NOT b) OR (c AND-NOT d)
COINCIDENCE DETECTION
dendritic Ca^{2+} spike
backpropagating AP
LOWPASS FILTER, ATTENUATION
SEGREGATION, AMPLIFICATION

[Dendritic Computation. London and Hausser]

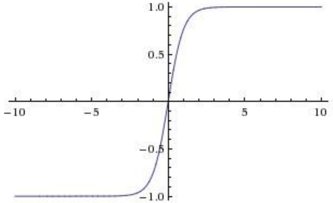
Activation Functions

Sigmoid

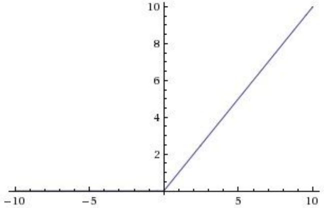
$$\sigma(x) = 1/(1+e^{-x})$$



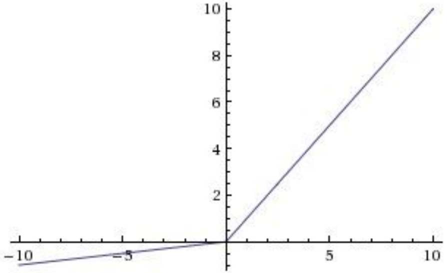
tanh tanh(x)



ReLU max(0,x)



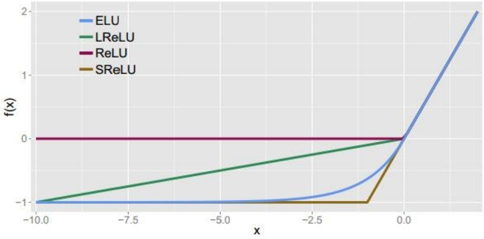
Leaky ReLU
max(0.1x, x)



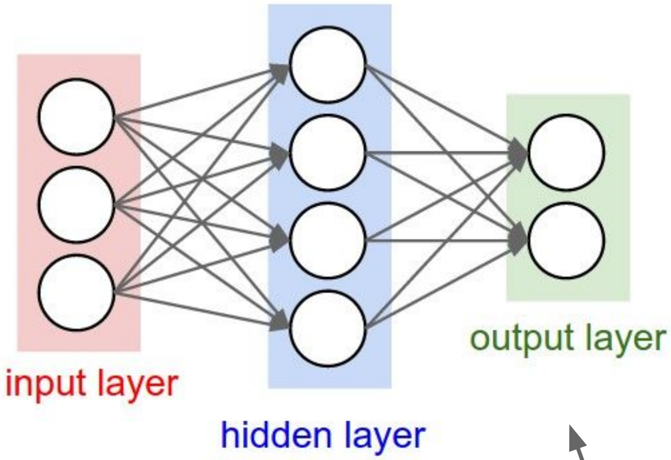
Maxout $\max(w_1^T x + b_1, w_2^T x + b_2)$

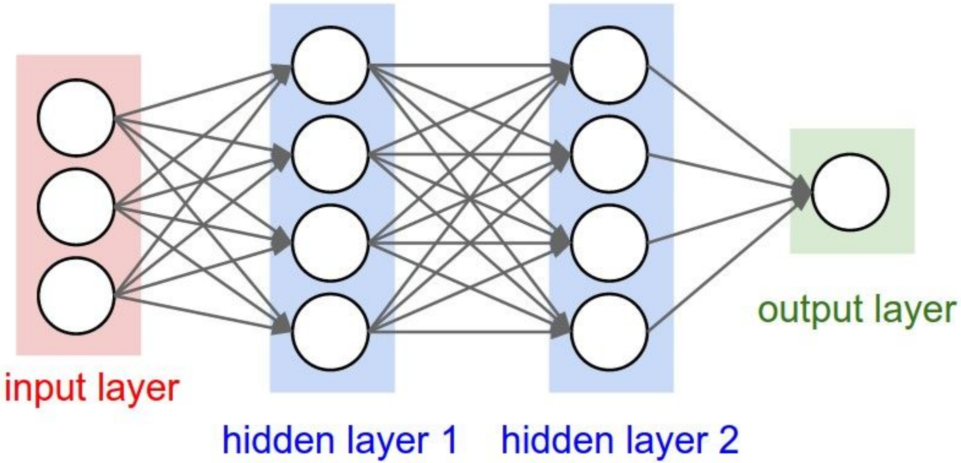
ELU

$$f(x) = \begin{cases} x & \text{if } x > 0 \\ \alpha\,(\exp(x) - 1) & \text{if } x \leq 0 \end{cases}$$



Neural Networks: Architectures



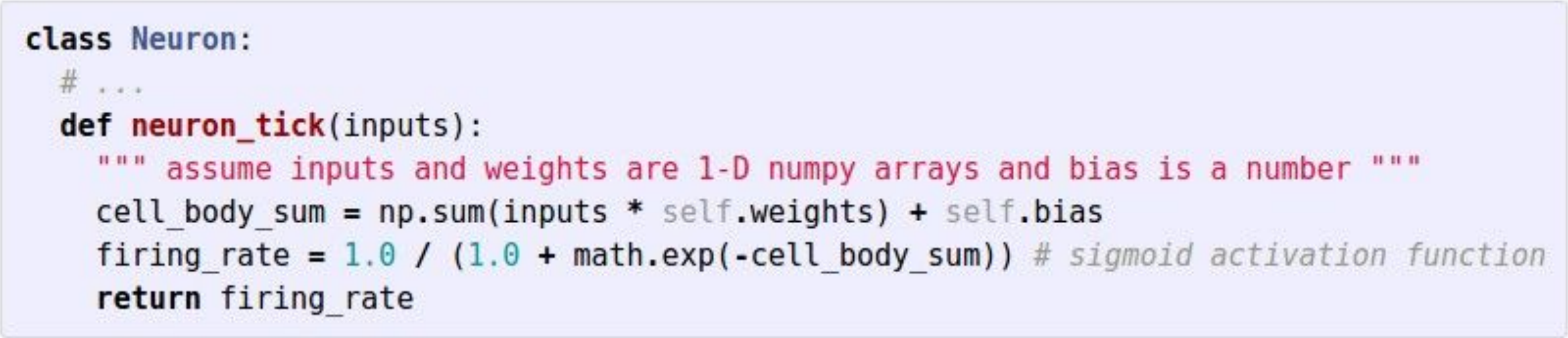


"2-layer Neural Net", or
"1-hidden-layer Neural Net"

"3-layer Neural Net", or
"2-hidden-layer Neural Net"

"Fully-connected" layers

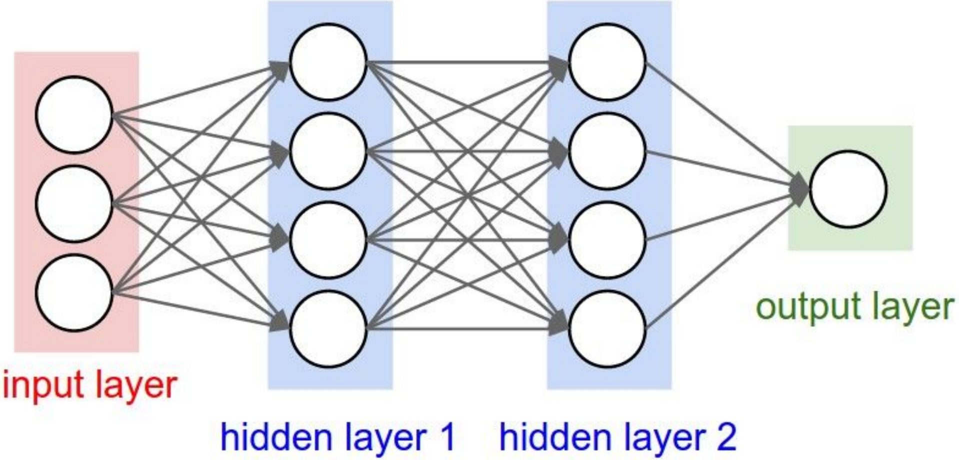
Example Feed-forward computation of a Neural Network

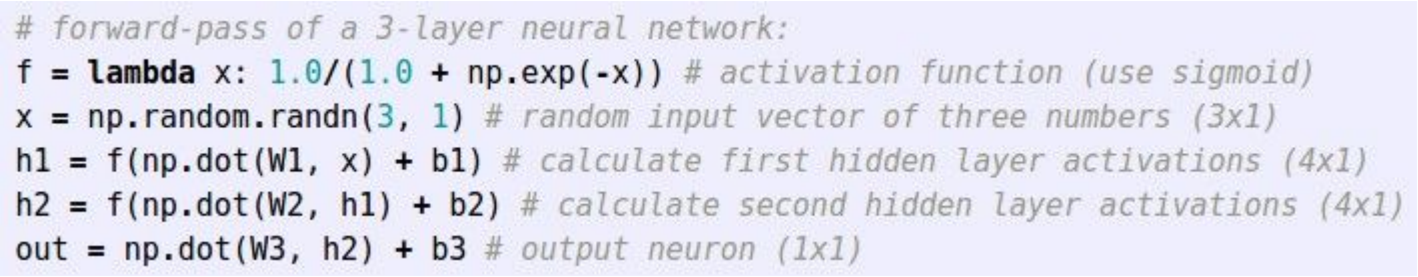


```
class Neuron:
  # ...
  def neuron_tick(inputs):
    """ assume inputs and weights are 1-D numpy arrays and bias is a number """
    cell_body_sum = np.sum(inputs * self.weights) + self.bias
    firing_rate = 1.0 / (1.0 + math.exp(-cell_body_sum)) # sigmoid activation function
    return firing_rate
```

We can efficiently evaluate an entire layer of neurons.

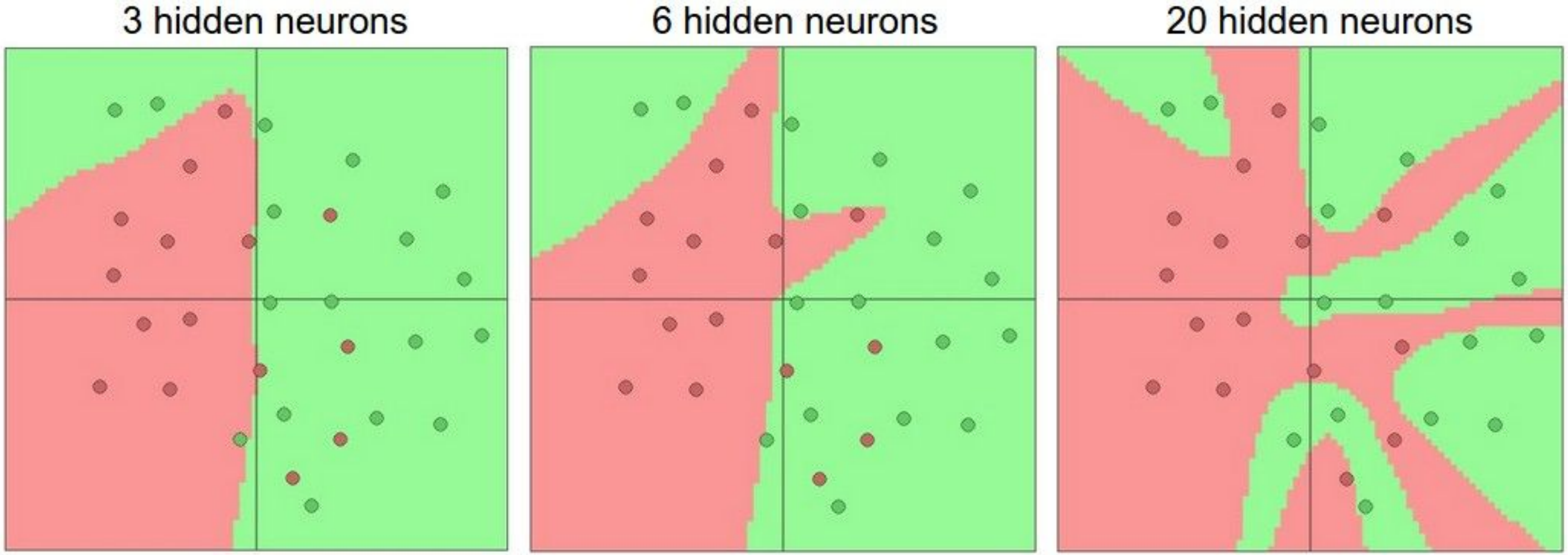
Example Feed-forward computation of a Neural Network





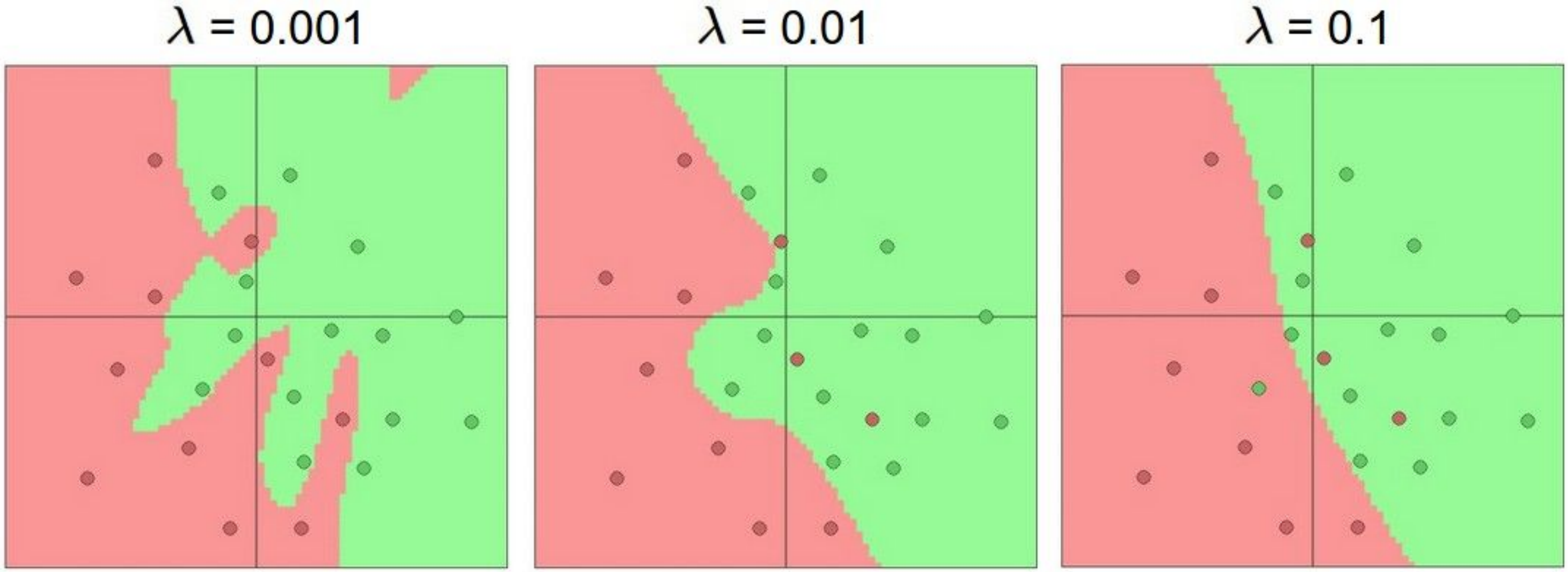
```
# forward-pass of a 3-layer neural network:
f = lambda x: 1.0/(1.0 + np.exp(-x)) # activation function (use sigmoid)
x = np.random.randn(3, 1) # random input vector of three numbers (3x1)
h1 = f(np.dot(W1, x) + b1) # calculate first hidden layer activations (4x1)
h2 = f(np.dot(W2, h1) + b2) # calculate second hidden layer activations (4x1)
out = np.dot(W3, h2) + b3 # output neuron (1x1)
```

Setting the number of layers and their sizes



more neurons = more capacity

Do not use size of neural network as a regularizer. Use stronger regularization instead:



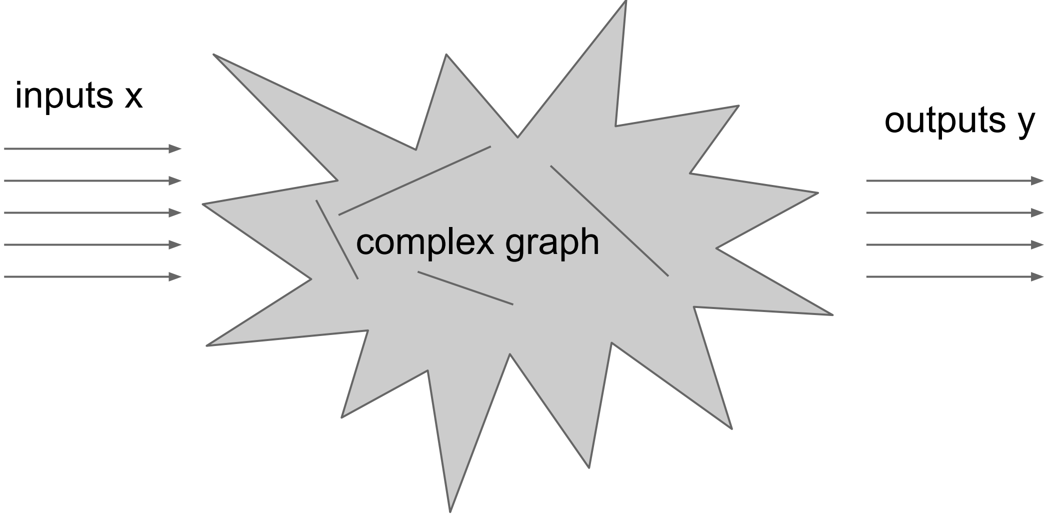
(you can play with this demo over at ConvNetJS: http://cs.stanford.edu/people/karpathy/convnetjs/demo/classify2d.html)

Summary

- we arrange neurons into fully-connected layers
- the abstraction of a **layer** has the nice property that it allows us to use efficient vectorized code (e.g. matrix multiplies)
- neural networks are not really *neural*
- neural networks: bigger = better (but might have to regularize more strongly)

Next Lecture:

More than you ever wanted to know about Neural Networks and how to train them.



reverse-mode differentiation (if you want effect of many things on one thing)

$\frac{\partial y}{\partial x}$ for many different x

forward-mode differentiation (if you want effect of one thing on many things)

$\frac{\partial y}{\partial x}$ for many different y