Lecture Nov 1

> halfway to midterm project reports


VOGUE
THE TRENDS ISSUE
SVMs:
the HOTTEST black box method you haven't even heard of yet!
Linear regression:
Talks sex, Justin Bieber, and doing the dishes
Spice up your null model- 32 ways how!
Exclusive
Black and Scholes
How this iconic duo became THE name in statistical finance
Are you a frequentist or a Bayesian?
Take our quiz and find out!

Deep Learning (continued)

Recap of ANNs: so far

- History/overview of ANNs
- ANN utility, scalability, and trainability
  - ANNs are expressive (especially if you can vary the architecture ands sets of computational units you can use)
  - ANNs are fast for large datasets (especially if you can use GPUs and parallel processing for matrix operations)
- Modern ANNs
  - …

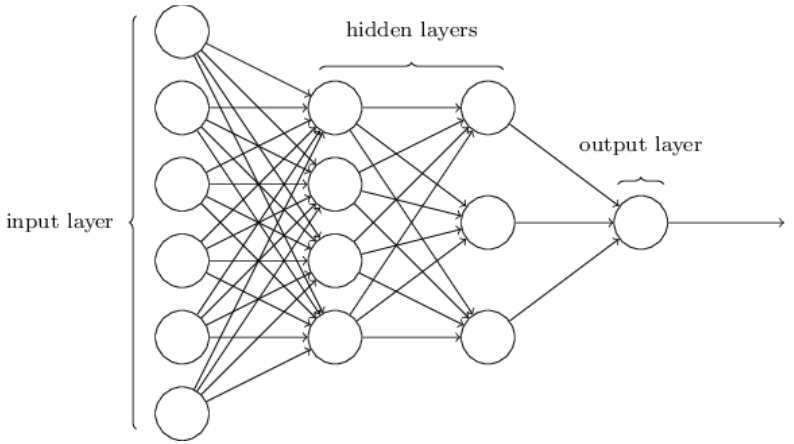
BackProp: summary

$$\delta^L = \nabla_a C \odot \sigma'(z^L)$$

$$\delta^l = ((w^{l+1})^T \delta^{l+1}) \odot \sigma'(z^l)$$

$$\frac{\partial C}{\partial b^l_j} = \delta^l_j$$

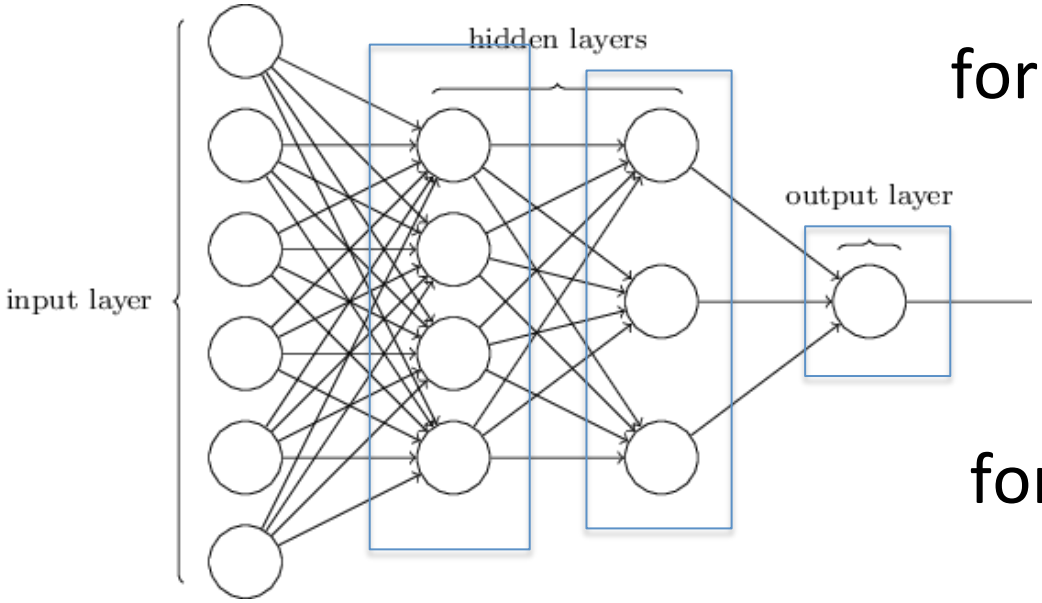
$$\frac{\partial C}{\partial w^l_{j\,k}} = a^{l-1}_k \delta^l_j$$



Level *l* for *l=1,…,L*
Matrix: w^l
Vectors*:*

- bias b^l
- activation a^l
- pre-sigmoid activ: z^l
- target output *y*
- "local error" δ^l

Computation propagates errors backward



for *l=1, 2, … L:*

$$a^l = \sigma(w^l a^{l-1} + b^l).$$

for *l=L,L-1,…1:*

$$\delta^l = ((w^{l+1})^T \delta^{l+1}) \odot \sigma'(z^l)$$

$$\frac{\partial C}{\partial b^l_j} = \delta^l_j$$

$$\frac{\partial C}{\partial w^l_{jk}} = a^{l-1}_k \delta^l_j$$

Modern ANNs

- Use of softmax and entropic loss instead of quadratic loss.
- Use of alternate non-linearities
  - reLU and hyperbolic tangent
- Better understanding of weight initialization
- Ability to explore architectures rapidly

How can we generalize BackProp to other ANNs?

Deep Neural Network Toolkits: What's Under the Hood?

Recap: weight updates for multilayer ANN

How can we generalize BackProp to other ANNs?

For nodes k in output layer:

$$\delta_k \equiv (t_k - a_k)\ a_k(1 - a_k)$$

For nodes j in hidden layer:

$$\delta_j \equiv \sum_k (\delta_k w_{kj})\ a_j(1 - a_j)$$

For all weights:

$$w_{kj} = w_{kj} - \varepsilon\ \delta_k a_j$$

$$w_{ji} = w_{ji} - \varepsilon\ \delta_j a_i$$

"Propagate errors backward" BACKPROP

Can carry this recursion out further if you have multiple hidden layers

$$f(x_1, x_2) \equiv (2x_1 + x_2)^2$$

$$\begin{aligned} z_1 &= \texttt{add}(x_1, x_1) \\ z_2 &= \texttt{add}(z_1, x_2) \\ f &= \texttt{square}(z_2) \end{aligned}$$

$$\begin{aligned} f(x_1, x_2) &= (2x_1 + x_2)^2 = 4x_1^2 + 4x_1x_2 + x_2^2 \\ \frac{df}{dx_1} &= 8x_1 + 4x_2 \\ \frac{df}{dx_2} &= 4x_1 + 2x_2 \end{aligned}$$

$$f(x_1, x_2) \equiv (2x_1 + x_2)^2$$

$$\begin{aligned} z_1 &= \texttt{add}(x_1, x_1) \\ z_2 &= \texttt{add}(z_1, x_2) \\ f &= \texttt{square}(z_2) \end{aligned}$$

Derivation Step	Reason
$\frac{df}{dx_1} = \frac{dz_2^2}{dz_2} \cdot \frac{dz_2}{dx_1}$	$f = z_2^2$
$\frac{df}{dx_1} = 2z_2 \cdot \frac{dz_2}{dx_1}$	$\frac{d(a^2)}{da} = 2a$
$\frac{df}{dx_1} = 2z_2 \cdot \frac{d(z_1+x_2)}{dx_1}$	$z_2 = z_1 + x_2$
$\frac{df}{dx_1} = 2z_2 \cdot \left(1 \cdot \frac{dz_1}{dx_1} + 1 \cdot \frac{dx_2}{dx_1}\right)$	$\frac{d(a+b)}{da} = \frac{d(a+b)}{db} = 1$

…

$$f(x_1, x_2) \equiv (2x_1 + x_2)^2$$

$$\begin{aligned} z_1 &= \texttt{add}(x_1, x_1) \\ z_2 &= \texttt{add}(z_1, x_2) \\ f &= \texttt{square}(z_2) \end{aligned}$$

Derivation Step	
$\frac{df}{dx_1} = \frac{dz_2^2}{dz_2} \cdot \frac{dz_2}{dx_1}$	$f = z_2^2$
$\frac{df}{dx_1} = 2z_2 \cdot \frac{dz_2}{dx_1}$	$\frac{d(a^2)}{da} = 2a$
$\frac{df}{dx_1} = 2z_2 \cdot \frac{d(z_1+x_2)}{dx_1}$	$z_2 = z_1 + x_2$
$\frac{df}{dx_1} = 2z_2 \cdot \left(1 \cdot \frac{dz_1}{dx_1} + 1 \cdot \frac{dx_2}{dx_1}\right)$	$\frac{d(a+b)}{da} = \frac{d(a+b)}{db} = 1$
$\frac{df}{dx_1} = 2z_2 \cdot \left(1 \cdot \frac{d(x_1+x_1)}{dx_1} + 1 \cdot \frac{dx_2}{dx_1}\right)$	$z_1 = x_1 + x_1$
$\frac{df}{dx_1} = 2z_2 \cdot \left(1 \cdot \left(1 \cdot \frac{dx_1}{dx_1} + 1 \cdot \frac{dx_1}{dx_1}\right) + 1 \cdot \frac{dx_2}{dx_1}\right)$	$\frac{d(a+b)}{da} = \frac{d(a+b)}{db} = 1$
$\frac{df}{dx_1} = 2z_2 \cdot (1 \cdot (1 \cdot 1 + 1 \cdot 1) + 1 \cdot 0)$	$\frac{da}{da} = 1$ and $\frac{da}{db} = 0$ for inputs a, b
$\frac{df}{dx_1} = 2z_2 \cdot 2 = 8x_1 + 4x_2$	simplify

https://justindomke.wordpress.com/

Generalizing backprop

- Starting point: a function of *n* variables
- Step 1: code your function as a series of assignments Wengert list
- Step 2: back propagate by going thru the list in reverse order, starting with… $\frac{dx_N}{dx_N} \leftarrow 1$
- …and using the chain rule

$$\frac{dx_N}{dx_i} = \sum_{j:i \in \pi(j)} \frac{dx_N}{dx_j} \frac{\partial x_j}{\partial x_i}$$

e.g.

$$x_7 = x_2 + x_5$$
$$\pi(7) = (2, 5)$$
$$f_7 = \text{add}$$

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

A function

Step 1: backprop

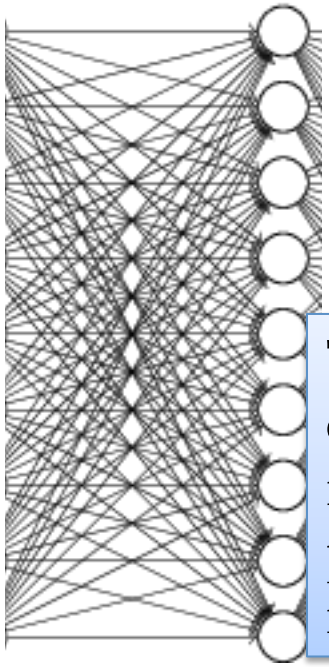
for $i = N-1, N-2, \ldots, 1$

$$\frac{dx_N}{dx_i} \leftarrow \sum_{j:i \in \pi(j)} \frac{dx_N}{dx_j} \frac{\partial f_j}{\partial x_i}$$

Computed in previous step

Recap: logistic regression with SGD

Let X be a matrix with *k* examples
Let $\mathbf{w}_i$ be the input weights for the i-th hidden unit
Then Z = X W is output (pre-sigmoid) for all *m* units for all *k* examples



x_1	1	0	1	1
x_2	…			
…				
x_k				

w_1	w_2	w_3	…	w_m
0.1	-0.3	…		
-1.7	…			
0.3	…			
1.2				

There's a *lot* of chances to do this in parallel…. with parallel matrix multiplication

XW =

$x_1.w_1$	$x_1.w_2$	…	$x_1.w_m$
$x_k.w_1$	…	…	$x_k.w_m$

Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, ..., N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

Step 1: backprop

for $i = N-1, N-2, ..., 1$

$$\frac{dx_N}{dx_i} \leftarrow \sum_{j:i\in\pi(j)} \frac{dx_N}{dx_j}\frac{\partial f_j}{\partial x_i}$$

```
Inputs: X,W1,B1,W2,B2
Z1a = mul(X,W1)        // matrix mult
Z1b = add*(Z1a,B1)     // add bias vec
A1 = tanh(Z1b)         //element-wise
Z2a = mul(A1,W2)
Z2b = add*(Z2a,B2)
A2 = tanh(Z2b)         // element-wise
P = softMax(A2)        // vec to vec
C = crossEnt_Y(P)      // cost function
```

X is *N*D*, W1 is *D*H*, B1 is *1*H*, W2 is *H*K*, …

Z1a is *N*H*

Z1b is *N*H*

A1 is *N*H*

Z2a is *N*K*

Z2b is *N*K*

A2 is *N*K*

P is *N*K*

C is a scalar

Target Y; *N* examples; *K* outs; *D* feats, *H* hidden

Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, ..., N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

Step 1: backprop

for $i = N-1, N-2, ..., 1$

$$\frac{dx_N}{dx_i} \leftarrow \sum_{j:i\in\pi(j)} \frac{dx_N}{dx_j}\frac{\partial f_j}{\partial x_i}$$

```
Inputs: X,W1,B1,W2,B2
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Z2b = add*(Z2a,B2)
A2 = tanh(Z2b)         // element-wise
P = softMax(A2)        // vec to vec
C = crossEnt_Y(P)      // cost function
```

N*H

```
dC/dC = 1
dC/dP = dC/dC * dCrossEnt_Y/dP
dC/dA2 = dC/dP * dsoftmax/dA2
dC/dZ2b = dC/dA2 * dtanh/dZ2b
dC/dZ2a = dC/dZ2b * dadd*/dZ2a
dC/dB2 = dC/dZ2b * dadd*/dB2
dC/dA1 = ...
```

N*K

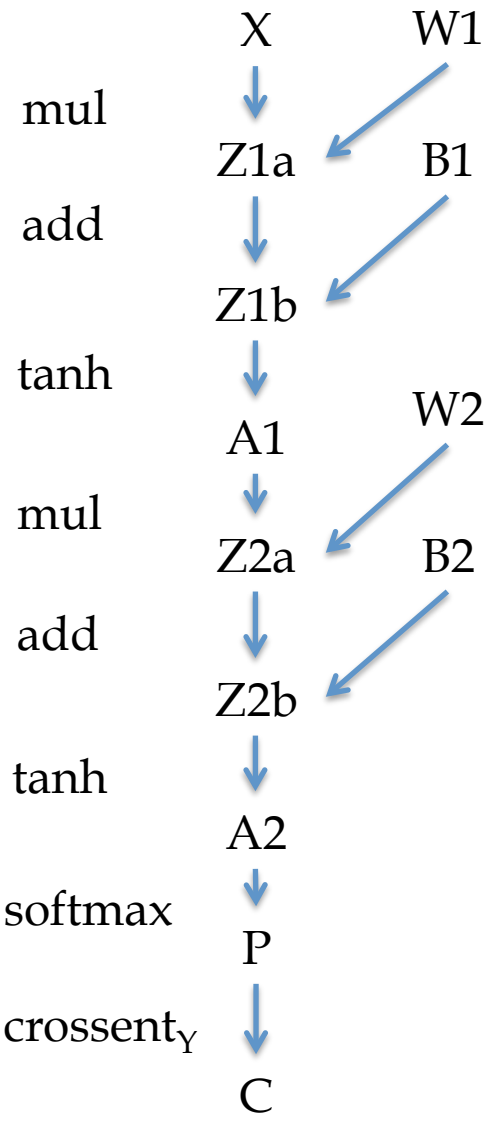
(N*K) * (K*K)

(N*K)

$$a_j^L = \frac{e^{z_j^L}}{\sum_k e^{z_k^L}}, \qquad -\frac{1}{N}\sum_i \left(\frac{\mathbf{p}_i - \mathbf{y}_i}{\mathbf{y}_i(1-\mathbf{y}_i)} \right)$$

Target Y; *N* rows; *K* outs; *D* feats, *H* hidden

Example: 2-layer neural network



dC/dC = 1
dC/dP = dC/dC * dCrossEnt$_Y$/dP
dC/dA2 = dC/dP * dsoftmax/dA2
dC/dZ2b = dC/dA2 * dtanh/dZ2b
dC/dZ2a = dC/dZ2b * dadd*/dZ2a
- dC/dB2 = dC/dZ2b * dadd*/dB2 →

dC/dA1 = dC/dZ2a *dmul/dA1
- dC/dW2 = dC/dZ2a *dmul/dW2 →

dC/dZ1b = dC/dA1 * dtanh/dZ1b
dC/dZ1a = dC/dZ1b * dadd*/dZ1a
- dC/dB1 = dC/dZ1b * dadd*/dB1

dC/dX = dC/dZ1a * dmul*/dZ1a
- dC/dW1 = dC/dZ1a * dmul*/dW1 →

Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

Step 1: backprop

for $i = N-1, N-2, \ldots, 1$

$$\frac{dx_N}{dx_i} \leftarrow \sum_{j:i\in\pi(j)} \frac{dx_N}{dx_j}\frac{\partial f_j}{\partial x_i}$$

```
Inputs: X,W1,B1,W2,B2
Z1a = mul(X,W1)        // matrix mult
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A1 = tanh(Z1b)         //element-wise
Z2a = mul(A1,W2)       N*H
Z2b = add(Z2a,B2)
A2 = tanh(Z2b)         // element-wise
P = softMax(A2)        // vec to vec
C = crossEnt_Y(P)      // cost function
```

```
dC/dC = 1
dC/dP = dC/dC * dCrossEnt_Y/dP
dC/dA2 = dC/dP * dsoftmax/dA2
dC/Z2b = dC/dA2 * dtanh/dZ2b
dC/dZ2a = dC/dZ2b * dadd*/dZ2a
dC/dB2 = dC/dZ2b * dadd*/dB2
dC/dA1 = …
```

*N*K*

Need a backward form for each matrix operation used in forward

$$-\frac{1}{N}\sum_i\left(\frac{\mathbf{p}_i - \mathbf{y}_i}{\mathbf{y}_i(1-\mathbf{y}_i)}\right)$$

Target Y; *N* rows; *K* outs; *D* feats, *H* hidden

Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

Step 1: backprop

for $i = N-1, N-2, \ldots, 1$

$$\frac{dx_N}{dx_i} \leftarrow \sum_{j:i\in\pi(j)} \frac{dx_N}{dx_j}\frac{\partial f_j}{\partial x_i}$$

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Z2b = add(Z2a,B2)
A2 = tanh(Z2b)        // element-wise
P = softMax(A2)       // vec to vec
C = crossEnt_Y(P)     // cost function
```

```
dC/dC = 1
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dC/dZ2a = dC/dZ2b * dadd*/dZ2a
dC/dB2 = dC/dZ2b * dadd*/dB2
dC/dA1 = ...
```

N*K

Need a backward form for each matrix operation used in forward, **with respect to each argument**

Target Y; *N* rows; *K* outs; *D* feats, *H* hidden

Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

```
Inputs: X,W1,B1,W2,B2
Z1a = mul(X,W1)      // matrix mult
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Z2b = add(Z2a,B2)
A2 = tanh(Z2b)       // element-wise
P = softMax(A2)      // vec to vec
C = crossEnt(P)      // cost function
```

Need a backward form for each matrix operation used in forward, **with respect to each argument**

An autodiff package usually includes

- A collection of matrix-oriented operations (mul, add*, …)
- For each operation
  - A forward implementation
  - A backward implementation for each argument

- It's still a little awkward to program with a list of assignments so….

Target Y; *N* rows; *K* outs; *D* feats, *H* hidden

https://justindomke.wordpress.com/

Generalizing backprop

- Starting point: a function of *n* variables
- Step 1: code your function as a series of assignments

Wengert list

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

- Better plan: overload your matrix operators so that when you use them in-line they build an **expression graph**
- Convert the expression graph to a Wengert list when necessary

Some autodiff systems

Example: Theano

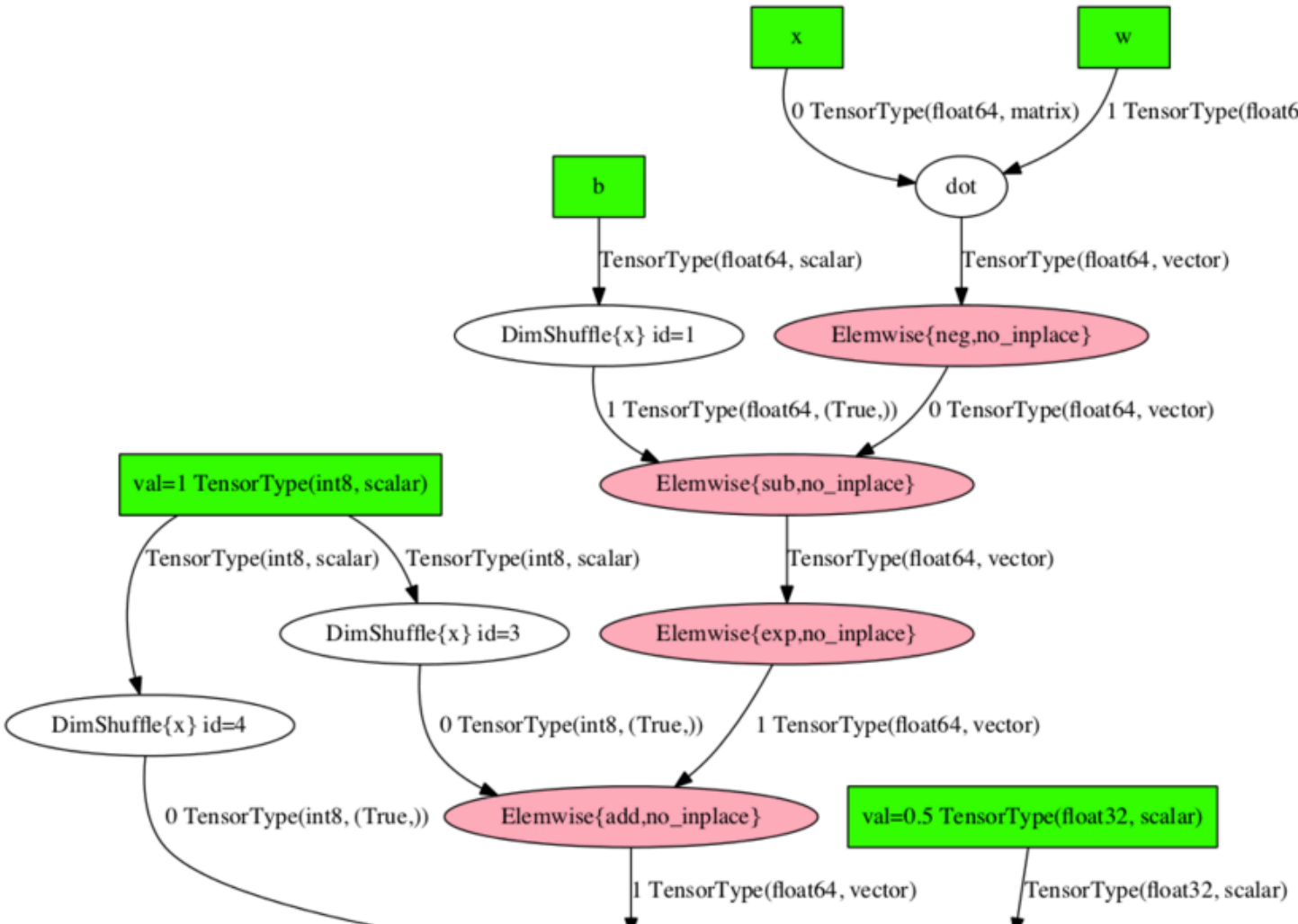
```
> import numpy
> import theano
> import theano.tensor as T
> rng = numpy.random
> # Training data
> N = 400
> feats = 784
> D = … # generate some training data
> training_steps = 10000
> # Declare Theano symbolic variables
> x = T.matrix("x")
> y = T.vector("y")
> w = theano.shared(rng.randn(feats).astype(theano.config.floatX), name="w")
> b = theano.shared(numpy.asarray(0., dtype=theano.config.floatX), name="b")
> x.tag.test_value = D[0]
> y.tag.test_value = D[1]
> # Construct Theano expression graph
> p_1 = 1 / (1 + T.exp(-T.dot(x, w)-b)) # Probability of having a one
> pre
> # C
> xen
> cos
> gw,
```

```
p_1 = 1 / (1 + T.exp(-T.dot(x, w)-b))
prediction = p_1 > 0.5
```

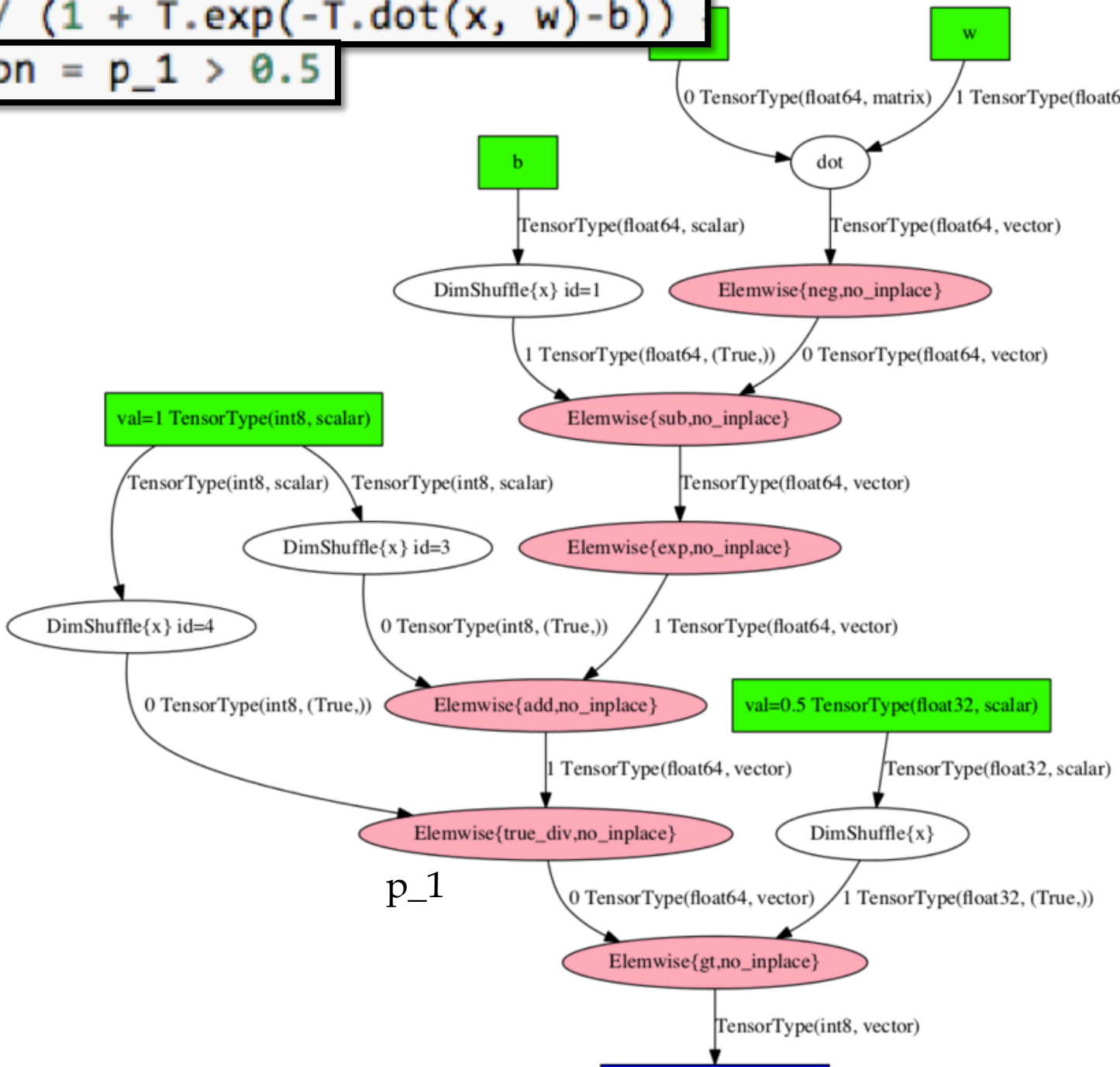
```
xent = -y*T.log(p_1) - (1-y)*T.log(1-p_1)
cost = xent.mean() + 0.01*(w**2).sum() #
gw,gb = T.grad(cost, [w,b])
```

Example: Theano

```
p_1 = 1 / (1 + T.exp(-T.dot(x, w)-b))
prediction = p_1 > 0.5
```



```
p_1 = 1 / (1 + T.exp(-T.dot(x, w)-b))
prediction = p_1 > 0.5
```



Example: 2-layer neural network

Step 1: forward

inputs: $x_1, x_2, \ldots, x_n$

for $i = n+1, n+2, \ldots, N$

$$x_i \leftarrow f_i(\mathbf{x}_{\pi(i)})$$

return x_N

```
Inputs: X,W1,B1,W2,B2
Z1a = mul(X,W1)        // matrix mult
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P = softMax(A2)        // vec to vec
C = crossEnt_Y(P)      // cost function
```

An autodiff package usually includes

- A collection of matrix-oriented operations (mul, add*, …)
- For each operation
  - A **forward** implementation
  - A **backward implementation** for each argument

- A way of composing operations into expressions (often using operator overloading) which evaluate to **expression trees**
- Expression simplification/ compilation

Some tools that use autodiff

- Theano:
  - Univ Montreal system, Python-based, first version 2007 now v0.8, integrated with GPUs
  - Many libraries build over Theano (Lasagne, Keras, Blocks..)
- Torch:
  - Collobert et al, used heavily at Facebook, based on Lua. Similar performance-wise to Theano
- TensorFlow:
  - Google system
  - Also supported by Keras
- Autograd
  - New system which is very Pythonic, doesn't support GPUs (yet)
- …

Breaking down autodiff

Walkthru of an Autodiff Program

Matrix and vector operations are very useful

$$f(\mathbf{x}, \mathbf{y}, W) \equiv \texttt{crossEntropy}(\texttt{softmax}(\mathbf{x} \cdot W), \mathbf{y}) + \texttt{frobeniusNorm}(W)$$

$$\begin{aligned}
\mathbf{z}_1 &= \texttt{dot}(\mathbf{x}, W) \\
\mathbf{z}_2 &= \texttt{softmax}(\mathbf{z}_1) \\
z_3 &= \texttt{crossEntropy}(\mathbf{z}_2, \mathbf{y}) \\
z_4 &= \texttt{frobeniusNorm}(W) \\
f &= \texttt{add}(z_3, z_4)
\end{aligned}$$

Walkthru of an Autodiff Program

Matrix and vector operations are very useful

$$f(\mathbf{x}, \mathbf{y}, W) \equiv \texttt{crossEntropy}(\texttt{softmax}(\mathbf{x} \cdot W), \mathbf{y}) + \texttt{frobeniusNorm}(W)$$

$$\texttt{softmax}(\langle a_1, \ldots, a_d \rangle) \equiv \langle \frac{e^{a_1}}{\sum_{i=1}^{d} e^{a}_{i}}, \ldots, \frac{e^{a_d}}{\sum_{i=1}^{d} e^{a}_{i}} \rangle$$

$$\texttt{crossEntropy}(\langle a_1, \ldots, a_d \rangle, \langle b_1, \ldots, b_d \rangle) \equiv -\sum_{i=1}^{d} a_i \log b_i$$

$$\texttt{frobeniusNorm}(A) \equiv \sqrt{\sum_{i=1}^{d} \sum_{j=1}^{k} a_{i,j}^2}$$

Walkthru of an Autodiff Program

Matrix and vector operations are very useful…but lets start with some simple scalar operations.

$$f(x_1, x_2) \equiv (2x_1 + x_2)^2$$

$$G = \{\texttt{add}, \texttt{multiply}, \texttt{square}\}$$

$$\begin{aligned} z_1 &= \texttt{add}(x_1, x_1) \\ z_2 &= \texttt{add}(z_1, x_2) \\ f &= \texttt{square}(z_2) \end{aligned}$$

Python encoding

```
[ ("z1", "add", ("x1","x1")),
  ("z2", "add", ("z1","x2")),
  ("f", "square", ("z2")) ]
```

The Interesting Part: Evaluation and Differentiation of a Wengert list

$$f(x_1, x_2) \equiv (2x_1 + x_2)^2$$

$$\begin{aligned} z_1 &= \texttt{add}(x_1, x_1) \\ z_2 &= \texttt{add}(z_1, x_2) \\ f &= \texttt{square}(z_2) \end{aligned}$$

```
G = { "add" : lambda a,b: a+b,
      "square": lambda a:a*a }

[ ("z1", "add", ("x1","x1")),
  ("z2", "add", ("z1","x2")),
  ("f", "square", ("z2")) ]
```

To compute f(3,7):

```
def eval(f)
    initialize val = { "x1" : 3, "x2" : 7 }
    for (z, g, (y_1, ..., y_k)) in the list:
        op = G[g]
        val[z] = op(val[y_1],...,val[y_k])
    return the last entry stored in val.
```

The Interesting Part: Evaluation and Differentiation of a Wengert list

$f(x_1, x_2$

$z_1 =$

$z_2 =$

$f = \texttt{square}(z_2)$

```
DG = { "add" : [ (lambda a,b: 1),  (lambda a,b: 1) ],
       "square": [ lambda a:2*a ] }
```

```
[ ("z1", "add", ("x1","x1")),
  ("z2", "add", ("z1","x2")),
  ("f", "square", ("z2")) ]
```

To compute f(3,7):

Populated with call to "eval"

```
def backprop(f,val)
    initialize delta: delta[f] = 1
    for (z,g,(y_1,...,y_k)) in the list, in reverse order:
        for i = 1,...,k:
            op_i = DG[g][i]
            if delta[y_i] is not defined set delta[y_i] = 0
            delta[y_i] = delta[y_i] + delta[z] * op_i(val[y_1],...,val[y_k])
```

Differentiating a Wengert list: a simple case

$$
\begin{aligned}
z_1 &= f_1(z_0) \\
z_2 &= f_2(z_1) \\
&\cdots \\
z_m &= f_m(z_{m-1})
\end{aligned}
\qquad
\begin{aligned}
\frac{dz_m}{dz_0} &= \frac{dz_m}{dz_{m-1}}\frac{dz_{m-1}}{dz_0} \\
&= \frac{dz_m}{dz_{m-1}}\frac{dz_{m-1}}{dz_{m-2}}\frac{dz_{m-2}}{dz_0} \\
&\cdots \\
&= \frac{dz_m}{dz_{m-1}}\frac{dz_{m-1}}{dz_{m-2}}\cdots\frac{dz_1}{dz_0}
\end{aligned}
$$

Notation: $h_{i,j} \rightarrow \frac{dz_i}{dz_j}$

Differentiating a Wengert list: a simple case

$$
\begin{aligned}
z_1 &= f_1(z_0) & a_1 &= f_1(a) \\
z_2 &= f_2(z_1) & a_2 &= f_2(f_1(a)) \\
&\dots & &\dots \\
z_m &= f_m(z_{m-1}) & a_m &= f_m(f_{m-1}(f_{m-2}(\dots f_1(a)\dots)))
\end{aligned}
$$

Notation: $h_{i,j} \rightarrow \frac{dz_i}{dz_j}$ *a_i is the i-th ouput on input a*

Differentiating a Wengert list: a simple case

$$
\begin{aligned}
z_1 &= f_1(z_0) \\
z_2 &= f_2(z_1) \\
&\cdots \\
z_m &= f_m(z_{m-1})
\end{aligned}
$$

$$
\frac{dz_m}{dz_0} = \frac{dz_m}{dz_{m-1}} \frac{dz_{m-1}}{dz_0}
$$

for all a

$$
h_{m,0}(a) = f'_m(a_m) \cdot h_{m-1,1}(a)
$$

Notation: $h_{i,j} \rightarrow \frac{dz_i}{dz_j}$

Differentiating a Wengert list: a simple case

$$
\begin{aligned}
z_1 &= f_1(z_0) \\
z_2 &= f_2(z_1) \\
&\cdots \\
z_m &= f_m(z_{m-1})
\end{aligned}
\qquad
\frac{dz_m}{dz_0} = \frac{dz_m}{dz_{m-1}}\frac{dz_{m-1}}{dz_{m-2}}\cdots\frac{dz_1}{dz_0}
$$

for all a

$$h_{m,0}(a) = f'_m(a_m) \cdot f'_{m-1}(a_{m-1}) \cdots f'_2(a_1) \cdot f'_1(a)$$

Notation: $h_{i,j} \rightarrow \frac{dz_i}{dz_j}$

Differentiating a Wengert list: a simple case

$$\frac{dz_m}{dz_0} = \frac{dz_m}{dz_{m-1}} \frac{dz_{m-1}}{dz_{m-2}} \cdots \frac{dz_1}{dz_0}$$

for all a

$$h_{m,0}(a) = f'_m(a_m) \cdot f'_{m-1}(a_{m-1}) \cdots f'_2(a_1) \cdot f'_1(a)$$

backprop routine compute order

$$h_{m,0}(a) = \Big(\Big(\Big((f'_m(a_m) \cdot f'_{m-1}(a_{m-1})\Big) \cdot f'_{m-2}(a_{m-2})\Big) \cdots f'_2(a_1)\Big)\Big) \cdot f'_1(a)$$

$$\texttt{delta}[z_i] = f'_m(a_m) \cdots f'_i(a_i)$$

Differentiating a Wengert list

```
DG = { "add" : [ (lambda a,b: 1),  (lambda a,b: 1) ],
       "square": [ lambda a:2*a ] }
```

```
[ ("z1", "add", ("x1","x1")),
  ("z2", "add", ("z1","x2")),
  ("f", "square", ("z2")) ]
```

```
def backprop(f,val)
    initialize delta: delta[f] = 1
    for (z,g,(y_1,...,y_k)) in the list, in reverse order:
        for i = 1,...,k:
            op_i = DG[g][i]
            if delta[y_i] is not defined set delta[y_i] = 0
            delta[y_i] = delta[y_i] + delta[z] * op_i(val[y_1],...,val[y_k])
```

The Tricky Part: Constructing a List

Goal: write code like this:

```
from xman import *
...
class f(XManFunctions):
    @staticmethod
    def half(a):
        ...
class Triangle(XMan):
    h = f.input()
    w = f.input()
    area = f.half(h*w)
...
xm = Triangle().setup()
print xm.operationSequence(xm.area)
```

Add your problem-specific functions: but just the syntax, not the G and DG definitions

Define the function to optimize with gradient descent

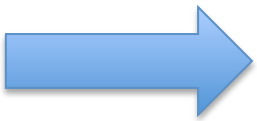
Use your function

Python code to create a Wengert list

```
from xman import *
...
class f(XManFunctions):
    @staticmethod
    def half(a):
        ...
class Triangle(XMan):
    h = f.input()
    w = f.input()
    area = f.half(h*w)
...
xm = Triangle().setup()
print xm.operationSequence(xm.area)
```

h, w, area are *registers*

also an automaticall y-named register z1 to hold h*w



```
[('z1', 'mul', ['h', 'w']),
 ('area', 'half', ['z1'])]
```

Python code to create a Wengert list

```
from xman import *
...
class f(XManFunctions):
    @staticmethod
    def half(a):
        ...
class Triangle(XMan):
    h = f.input()
    w = f.input()
    area = f.half(h*w)
...
xm = Triangle().setup()
print xm.operationSequence(xm.area)
```

some Python hacking can use the class variable name 'area' and insert it into the 'name' field of a register

and invert names for the others at setup()

name	"h"
role	"input"

name	"w"
role	"input"

name	z1
role	"opOut"
defAs	01

name	"area"
role	"opOut"
defAs	02

Python code to create a Wengert list

```
from xman import *
...
class f(XManFunctions):
    @staticmethod
    def half(a):
        ...
class Triangle(XMan):
    h = f.input()
    w = f.input()
    area = f.half(h*w)
...
xm = Triangle().setup()
print xm.operationSequence(xm.area)
```

"half" is an operator

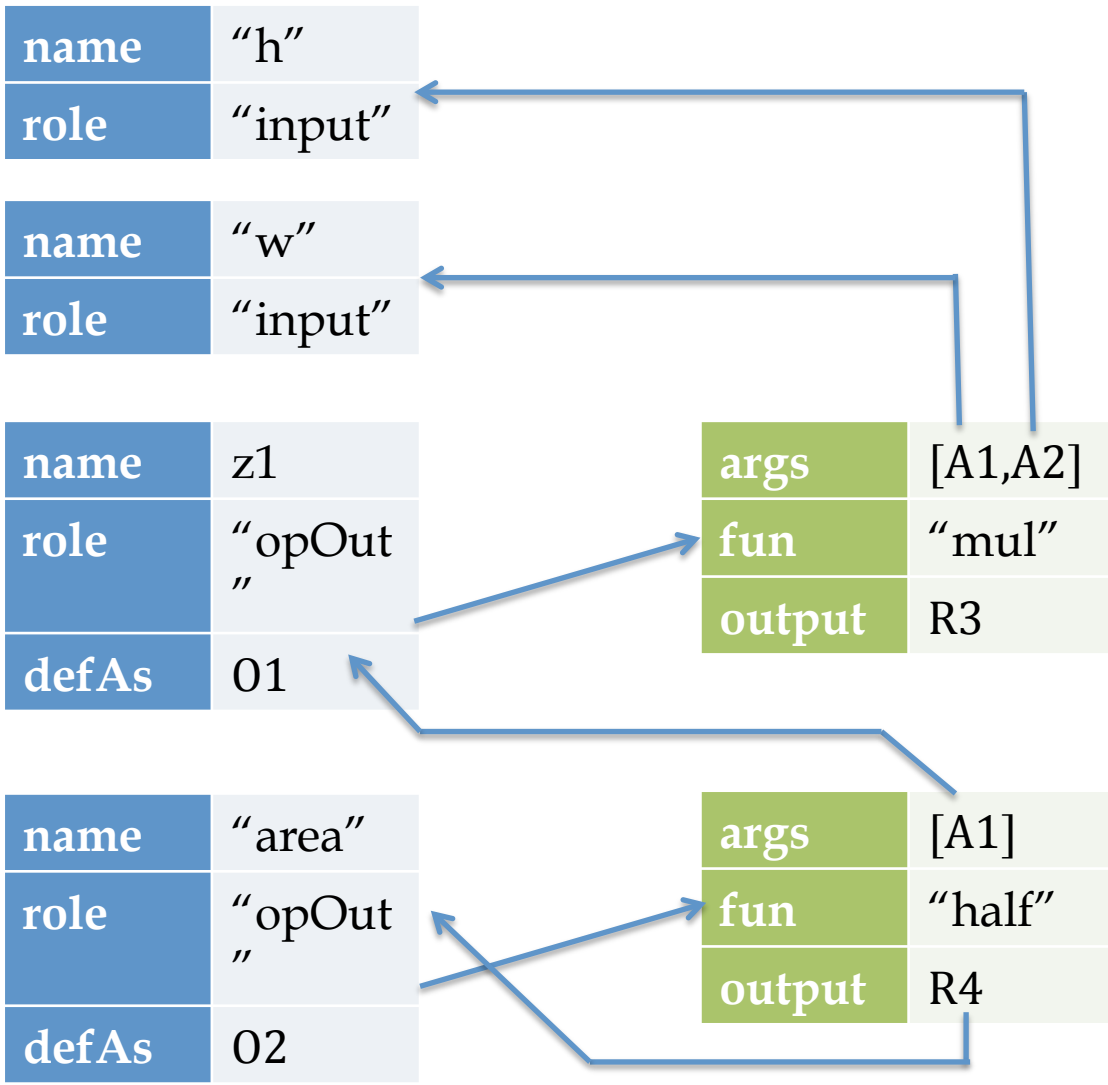
so is "mul" --- h*w → mul(h,w)

each instance of an operator points to registers that are arguments and outputs

Python code to create a Wengert list

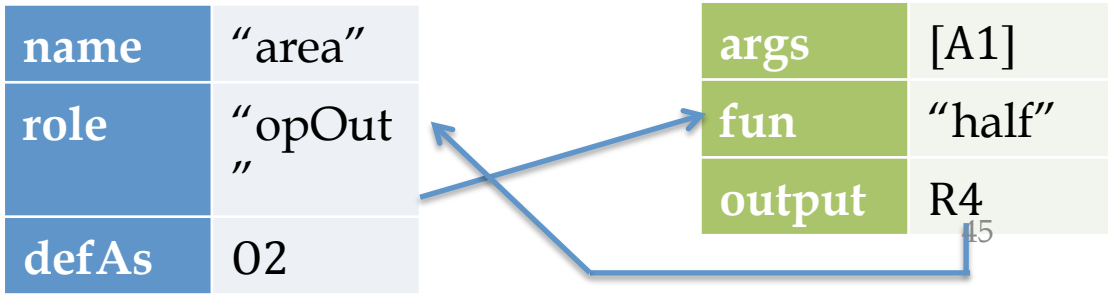
h, w are registers;
mul() generates an operator

```
class f(XManFunctions):
    @staticmethod
    def half(a):
        ...
class Triangle(XMan):
    h = f.input()
    w = f.input()
    area = f.half(h*w)
```



Python code to create a Wengert list

```
class XManFunctions(object):
    @staticmethod
    def input(default=None):
        return Register(role='input',default=default)
    ...
    @staticmethod
    def mul(a,b):
        return XManFunctions.registerDefinedByOperator('mul',a,b)
    ...
    @staticmethod
    def registerDefinedByOperator(fun,*args):
        reg = Register(role='operationOutput')
        op = Operation(fun,*args)
        reg.definedAs = op
        op.outputReg = reg
        return reg
```



Even more detail….

More detail: xman.py

```
class Operation(object):
    """ An operation encodes a single step of a differentiable
    computation, eg y=f(x1,...,xk). It contains a function, arguments,
    and a pointer to the register that is defined as the output of
    this operation.
    """

    def __init__(self,fun,*args):
        self.fun = fun
        self.args = args
        self.outputReg = None

    def asStringTuple(self):
        """ Return a nested tuple of encoding the operation y=f(x1,...xk) of
        the form (y,f,(x1,...,xk)) where y,f, and x1...xk are strings.
        """
        dstName = self.outputReg.name if (self.outputReg and self.outputReg.name) else "???"
        argNames = map(lambda reg:reg.name or "???", self.args)
        return (dstName,self.fun,argNames)

    def __str__(self):
        """ Human readable representation """
        (dstName,fun,argNames) = self.asStringTuple()
        return dstName + " = f." + fun + "(" + ",".join(argNames) + ")"
```

```
class Register(object):
    """ Registers are like variables - they are used as the inputs to and
    outputs of Operations.  The 'name' of each register should be unique,
    as it will be used as a key in storing outputs, and
    """
    _validRoles = set("input param operationOutput".split())

    def __init__(self,role=None,default=None):
        assert role in Register._validRoles
        self.role = role
        self.name = None
        self.definedAs = None
        self.default = default

    def inputsTo(self):
        """ Trace back through the definition of this register, if it exists,
        to find a list of all other registers that this register
        depends on.  This method is needed to find the
        operationSequence that is needed to construct the value of a
        register, and also to assign names to otherwise unnamed
        registers.
        """
        if self.definedAs:
            assert isinstance(self.definedAs,Operation)
            return self.definedAs.args
        else:
            return []
    # operator overloading
    def __add__(self,other):
        return XManFunctions.add(self,other)
    def __sub__(self,other):
        return XManFunctions.subtract(self,other)
    def __mul__(self,other):
        return XManFunctions.mul(self,other)
```

```
class XManFunctions(object):
    """ Encapsulates the static methods that are used in a subclass of
    XMan.  Each of these generates an OperationOutput register that is
    definedBy an Operation, with the operations outputReg field
    pointing back to the register.

    You will usually subclass this so you can
    add your own functions, and give the subclass
    a short name

    """

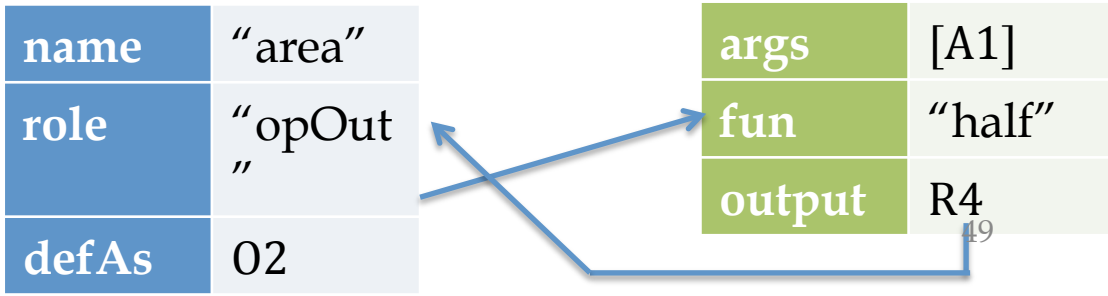
    @staticmethod
    def input(default=None):
        return Register(role='input',default=default)
    @staticmethod
    def param(default=None):
        return Register(role='param',default=default)

    @staticmethod
    def add(a,b):
        return XManFunctions.registerDefinedByOperator('add',a,b)
    @staticmethod
    def subtract(a,b):

    …


    @staticmethod
    def registerDefinedByOperator(fun,*args):

        …
```



```
class XMan(object):

    def __init__(self):
        self._nextTmp = 1
        self._setupComplete = False
        self._registers = {}

    def setup(self):
        """ Must call this before you do any other operations with an
        expression manager """
        # use available python variable names for register names
        for regName,reg in self.namedRegisterItems():
            if not reg.name:
                reg.name = regName
                self._registers[regName] = reg
        # give names to any other registers used in subexpressions
        def _recursivelyLabelUnnamedRegisters(reg):
            if not reg.name:
                reg.name = 'z%d' % self._nextTmp
                self._nextTmp += 1
                self._registers[reg.name] = reg
            for child in reg.inputsTo():
                _recursivelyLabelUnnamedRegisters(child)
        for regName,reg in self.namedRegisterItems():
            _recursivelyLabelUnnamedRegisters(reg)
        self._setupComplete = True
        # convenient return value so we can say net = FooNet().setup()
        return self

 def namedRegisterItems(self):
     """ Returns a list of all pairs (name,registerObject) where some
     python class/instance variable with the given name is bound to
     a Register object.  These are sorted by name to make tests
     easier.
     """
     keys = sorted(self.__dict__.keys() + self.__class__.__dict__.keys())
     vals = [self.__dict__.get(k) or self.__class__.__dict__.get(k) for k in keys]
     return filter(lambda (reg,regObj):isinstance(regObj,Register), zip(keys,vals))
```

```
class XMan(object):

    ...

    def operationSequence(self,reg):
        """ Traverse the expression tree to find the sequence of operations
        needed to compute the values associated with this register.
        """
        assert self._setupComplete, 'operationSequence() called before setup()'
        # pre-order traversal of the expression tree
        previouslyDefined = set()
        buf = []
        for child in reg.inputsTo():
            if child.name not in previouslyDefined:
                buf += self.operationSequence(child)
                previouslyDefined.add(child.name)
        if reg.definedAs and (not reg.name in previouslyDefined):
            buf.append(reg.definedAs.asStringTuple())
        return buf
```

Using xman.py

```
from xman import *

# functions I'll use for this problem

class f(XManFunctions):
    @staticmethod
    def half(a):
        return XManFunctions.registerDefinedByOperator('half',a)
    @staticmethod
    def square(a):
        return XManFunctions.registerDefinedByOperator('square',a)
    @staticmethod
    def alias(a):
        """ This will just make a copy of a register that
        has a different name."""
        return XManFunctions.registerDefinedByOperator('alias',a)
```

Using xman.py

```
EVAL_FUNS = {
    'add':      lambda x1,x2: x1+x2,
    'subtract': lambda x1,x2: x1-x2,
    'mul':      lambda x1,x2: x1*x2,
    'half':     lambda x: 0.5*x,
    'square':   lambda x: x*x,
    'alias':    lambda x: x,
    }

BP_FUNS = {
    'add':      [lambda delta,out,x1,x2: delta,    lambda delta,out,x1,x2: delta],
    'subtract': [lambda delta,out,x1,x2: delta,    lambda delta,out,x1,x2: -delta],
    'mul':      [lambda delta,out,x1,x2: delta*x2, lambda delta,out,x1,x2: delta*x1],
    'half':     [lambda delta,out,x: delta*0.5],
    'square':   [lambda delta,out,x: delta*2*x],
    'alias':    [lambda delta,out,x: delta],
    }
```

Using xman.py

```
class Autograd(object):
    """ Automatically compute partial derivatives.
    """

    def __init__(self,xman):
        self.xman = xman

    def eval(self,opseq,valueDict):
        """ Evaluate the function specified by the wengart list (aka operation
        sequence). Here valueDict is a dict holding the values of any
        inputs/parameters that are needed (indexed by register name,
        which is a string).  Returns the augmented valueDict.
        """
        for (dstName,funName,inputNames) in opseq:
            inputValues = map(lambda a:valueDict[a], inputNames)
            fun = EVAL_FUNS[funName]
            result = fun(*inputValues)
            valueDict[dstName] = result
        return valueDict
```

Using xman.py

```
class Autograd(object):
    """ Automatically compute partial derivatives.
    """


    def bprop(self,opseq,valueDict,**deltaDict):
        """ For each intermediate register g used in computing the function f
        computed by the operation sequence, find df/dg.  Here
        valueDict is a dict holding the values of any
        inputs/parameters that are needed for the gradient (indexed by
        register name), as populated by eval.
        """
        for (dstName,funName,inputNames) in reversed(opseq):
            delta = deltaDict[dstName]
            # values is extended to include the next-level delta and
            # the function output, and these will be passed as
            # arguments
            values = [delta] + map(lambda a:valueDict[a], [dstName]+list(inputNames))
            for i in range(len(inputNames)):
                result = (BP_FUNS[funName][i])(*values)
                # increment a running sum of all the delta's that are
                # pushed back to the i-th parameter, initializing to
                # zero if needed.
                self._incrementBy(deltaDict, inputNames[i], result)
        return deltaDict
```

Using xman.py – like Guinea Pig

```
class House(XMan):
    """ A toy task that has parameters and a loss function.
    First you compute the area of a simple shape, a 'house',
    which is a triangle on top of a rectangle.
    """

    # define some macros
    def rectArea(h,w): return h*w
    def roofHeight(wallHeight): return f.half(wallHeight)
    def triangleArea(h,w): return f.half(h*w)

    # height and width of rectangle are inputs
    h = f.param()
    w = f.param()
    # so is the target height and the target area, these inputs have
    # defaults
    targetArea = f.input()
    targetHeight = f.input(8.0)
    heightFactor = f.input(100.0)

    # compute area of the house
    area = rectArea(h,w) + triangleArea(roofHeight(h), w)

    # loss to optimize is weighted sum of square loss of area relative
    # to the targetArea, plus same for height
    loss = f.square(area - targetArea) + f.square(h - targetHeight) * heightFactor
```

```
# build your dream house with gradient descent

h = House().setup()
autograd = Autograd(h)
rate = 0.001
epochs = 20

# this fills in default values for inputs with defaults, like
# targetHeight and heightFactor
initDict = h.inputDict(h=5,w=10,targetArea=200)

# form wengart list to compute the loss
opseq = h.operationSequence(h.loss)

for i in range(epochs):

    # find gradient of loss wrt parameters
    gradientDict = autograd.bprop(opseq,valueDict,loss=1.0)

    # update the parameters appropriately
    for rname in gradientDict:
        if h.isParam(rname):
            initDict[rname] = initDict[rname] - rate*gradientDict[rname]
```

An Xman instance and a loop

```
def Skyscraper(numFloors):
    """ Another toy task - optimize area of a stack of several rectangles
    """

    x = XMan()
    # height and width of rectangle are inputs
    x.h = f.param(default=30.0)
    x.w = f.param(default=20.0)
    x.targetArea = f.input(default=0.0)
    x.targetHeight = f.input(default=8.0)
    x.heightFactor = f.input(default=100.0)

    # compute area of the skyscraper
    x.zero = f.input(default=0.0)

    # here areaRegister popints to a different
    # register in each iteration of the loop
    areaRegister = x.zero
    for i in range(numFloors):
        floorRegister = (x.h * x.w)
        floorRegister.name = 'floor_%d' % (i+1)
        areaRegister = areaRegister + floorRegister
    # when the loop finishes, we give it the register a name, in this
    # case by having an instance variable point to the register.
    # we could also execute: areaRegister.name = 'area'
    x.area = areaRegister

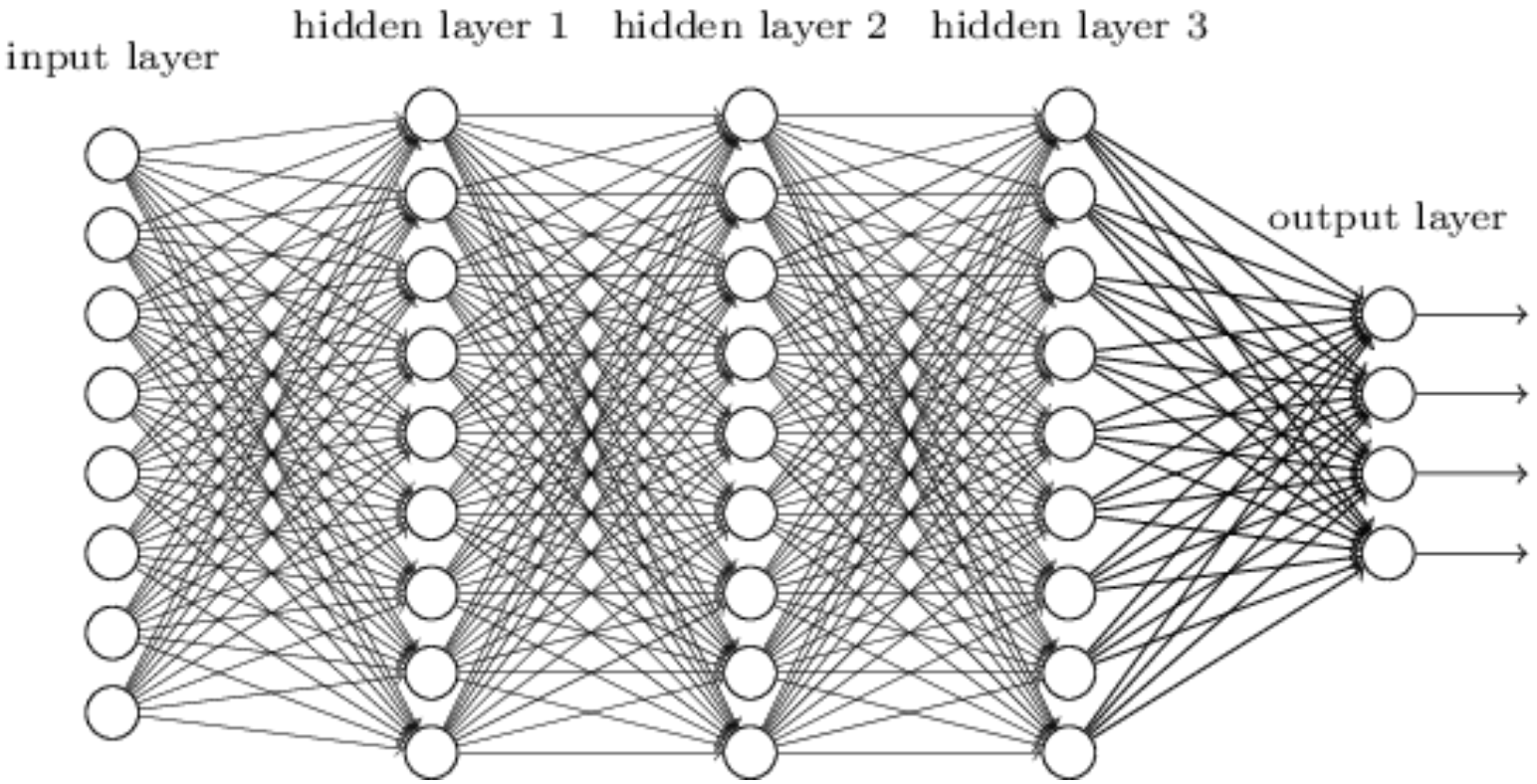
    x.loss = f.square(x.area - x.targetArea) + f.square(x.h - x.targetHeight) * x.heightFactor
    return x
```

Modern ANNs

- Use of softmax and entropic loss instead of quadratic loss.
- Use of alternate non-linearities
  - reLU and hyperbolic tangent
- Better understanding of weight initialization
- Ability to explore architectures rapidly

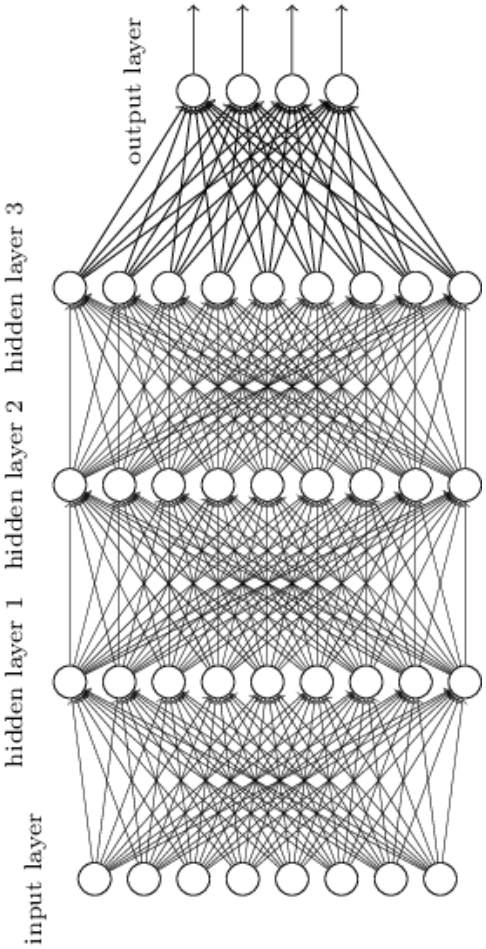
RECURRENT NEURAL NETWORKS

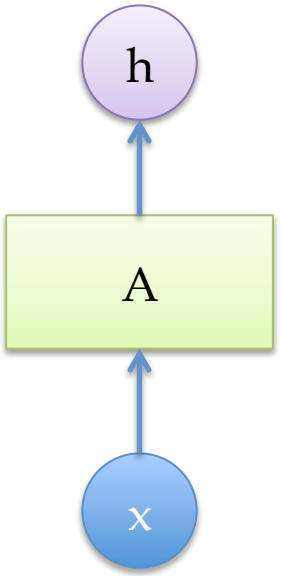
Motivation: what about sequence prediction?



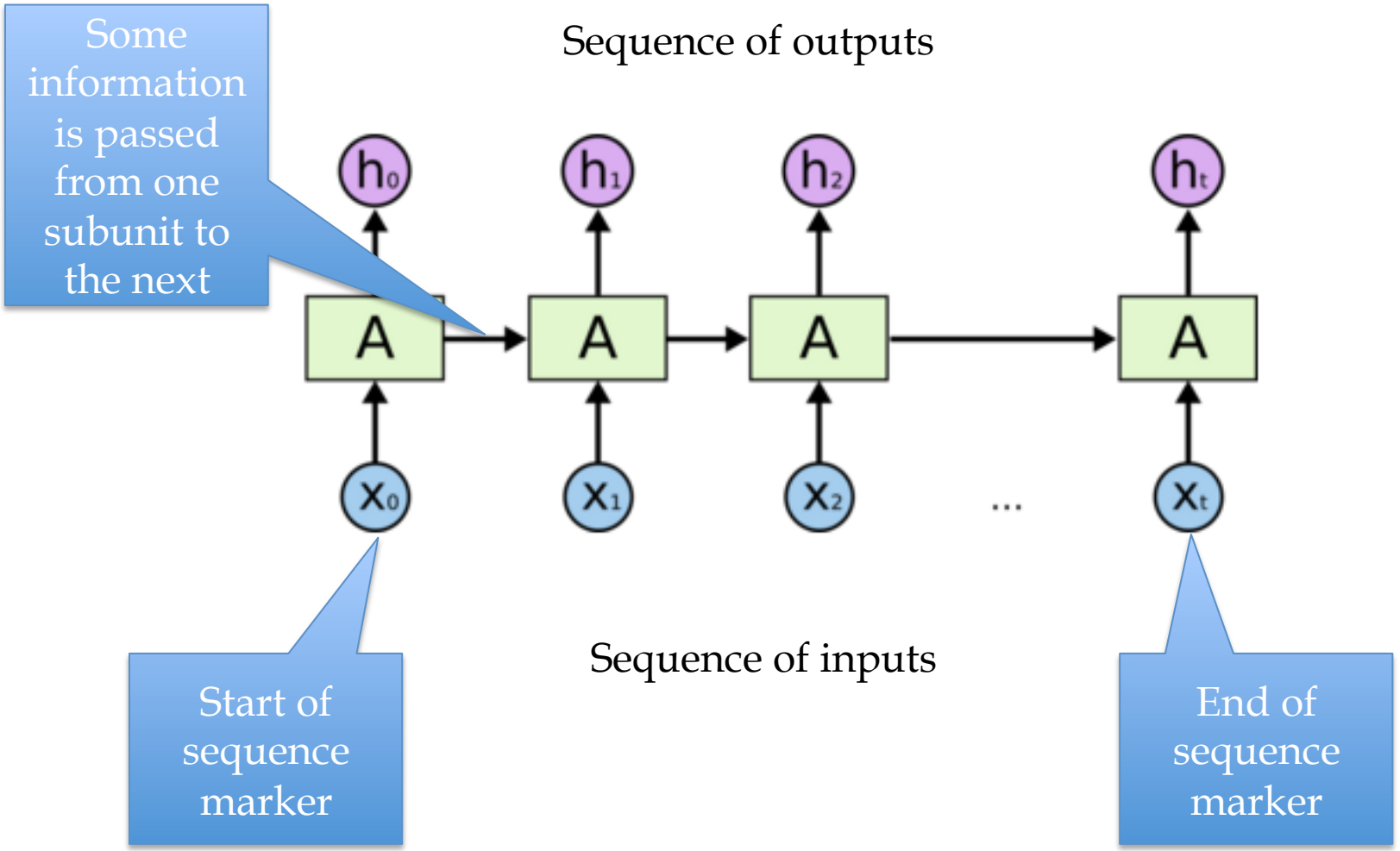
What can I do when input size and output size vary?

Motivation: what about sequence prediction?



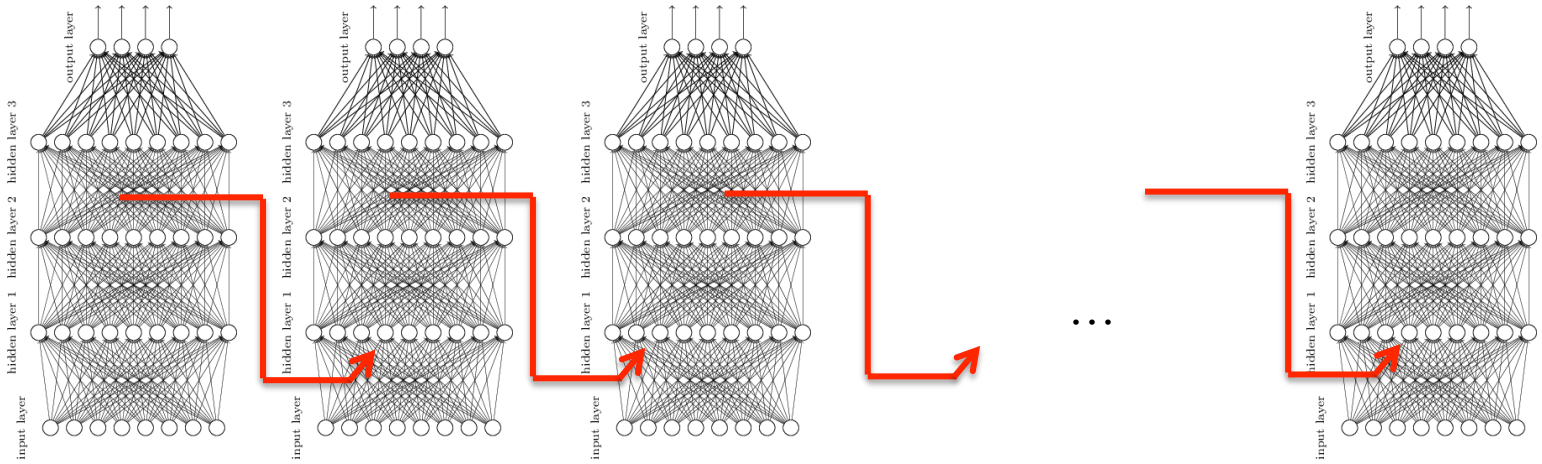


Architecture for an RNN

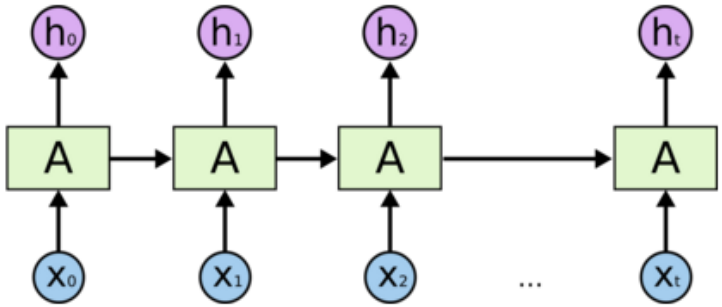


http://colah.github.io/posts/2015-08-Understanding-LSTMs/

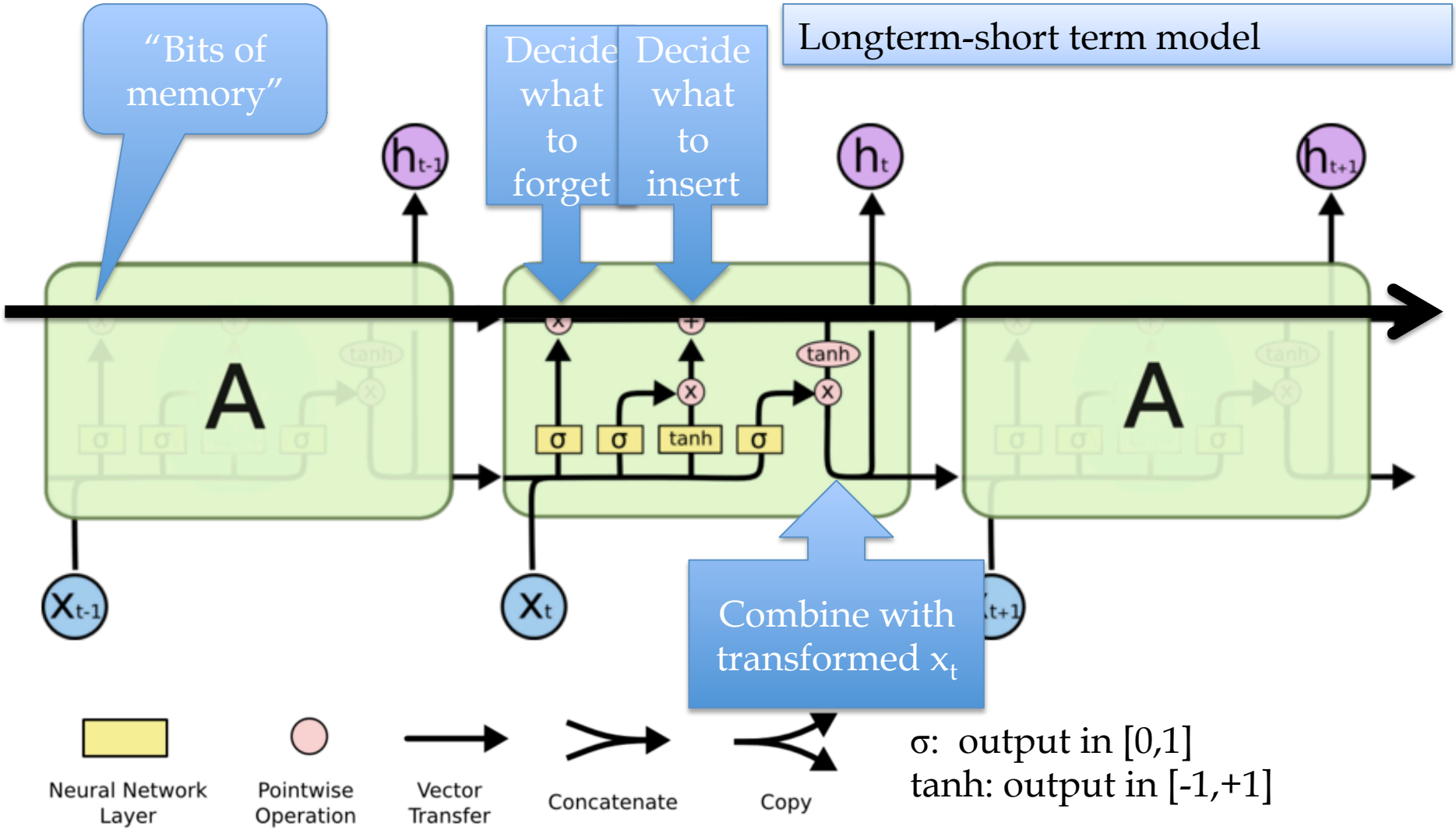
Architecture for an 1980's RNN



Problem with this: it's extremely deep and very hard to train

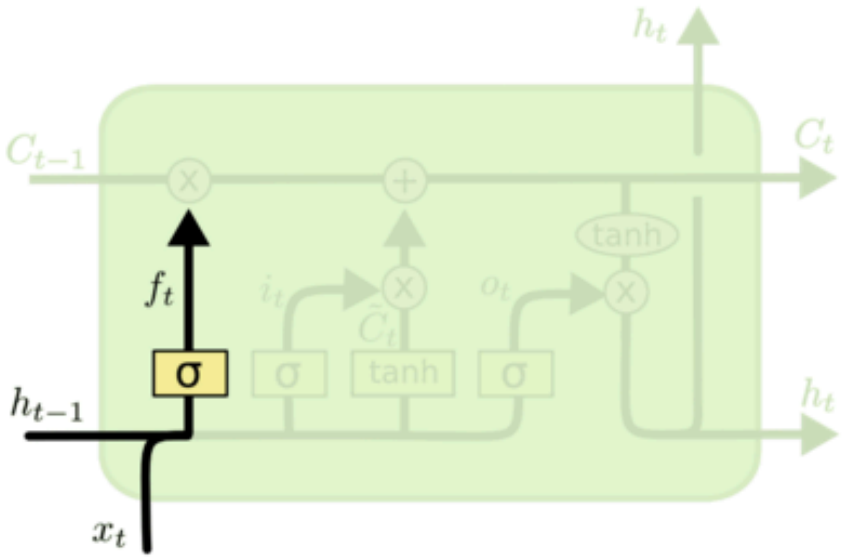


Architecture for an LSTM



http://colah.github.io/posts/2015-08-Understanding-LSTMs/

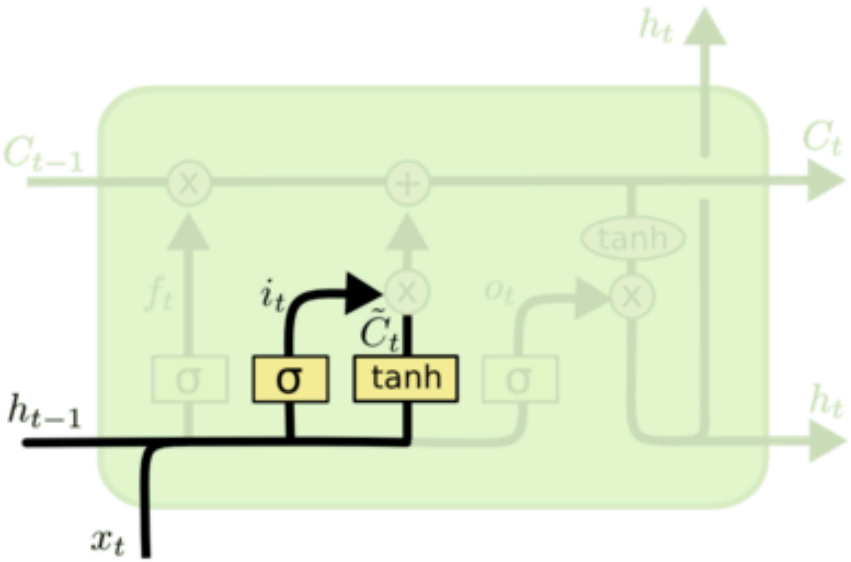
Walkthrough



What part of memory to "forget" – zero means forget this bit

$$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] \; + \; b_f\right)$$

Walkthrough



What bits to insert into the next states

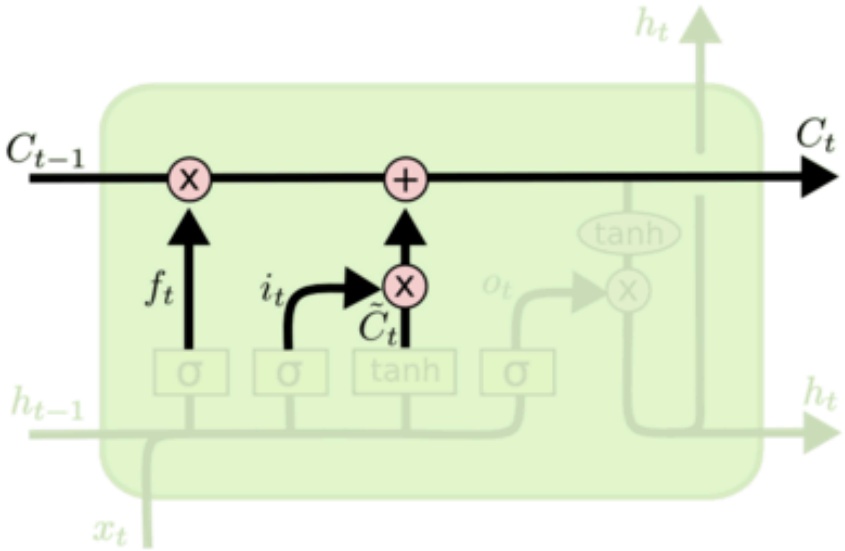
$$i_t = \sigma\left(W_i \cdot [h_{t-1}, x_t] \; + \; b_i\right)$$

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] \; + \; b_C)$$

What content to store into the next state

http://colah.github.io/posts/2015-08-Understanding-LSTMs/

Walkthrough

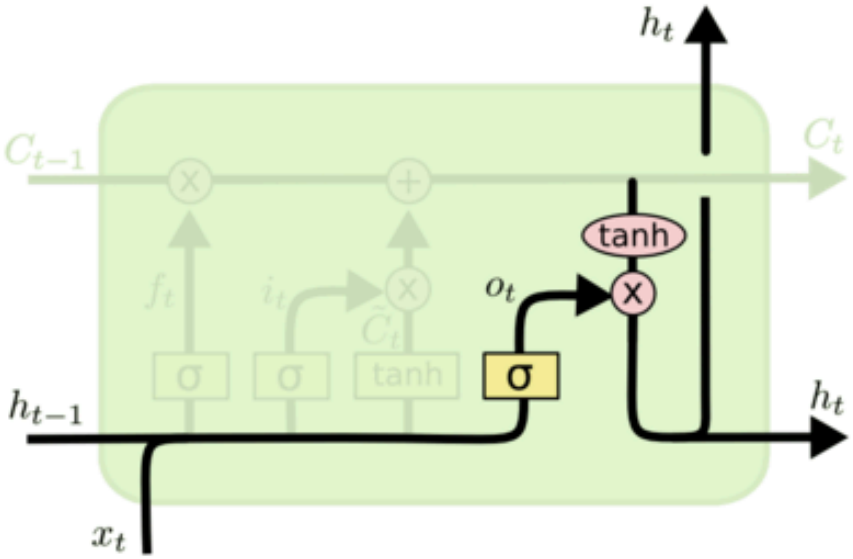


Next memory cell content – mixture of not-forgotten part of previous cell and insertion

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$$

http://colah.github.io/posts/2015-08-Understanding-LSTMs/

Walkthrough



What part of cell to output

$$o_t = \sigma\left(W_o\left[h_{t-1}, x_t\right] + b_o\right)$$

$$h_t = o_t * \tanh\left(C_t\right)$$

tanh maps bits to [-1,+1] range

http://colah.github.io/posts/2015-08-Understanding-LSTMs/

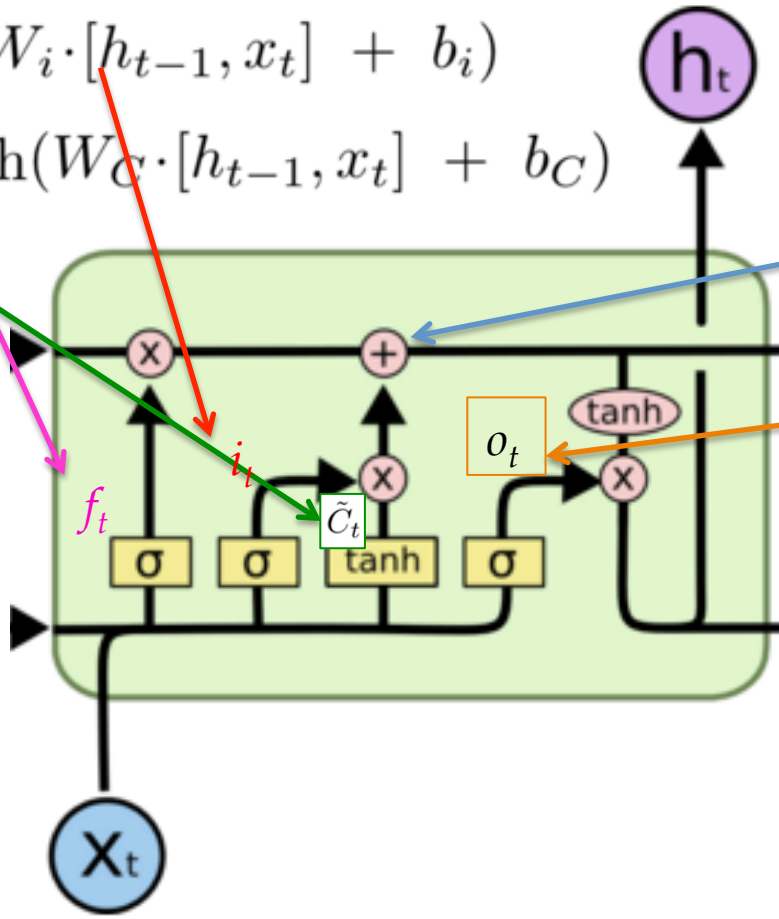
Architecture for an LSTM

(1)

$$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] \; + \; b_f\right)$$

$$i_t = \sigma\left(W_i \cdot [h_{t-1}, x_t] \; + \; b_i\right)$$

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] \; + \; b_C)$$



(2)

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$$

(3)

$$o_t = \sigma\left(W_o \; [h_{t-1}, x_t] \; + \; b_o\right)$$

$$h_t = o_t * \tanh\left(C_t\right)$$

http://colah.github.io/posts/2015-08-Understanding-LSTMs/

Implementing an LSTM

For $t = 1,\ldots,T$:

(1) $$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] \; + \; b_f\right)$$

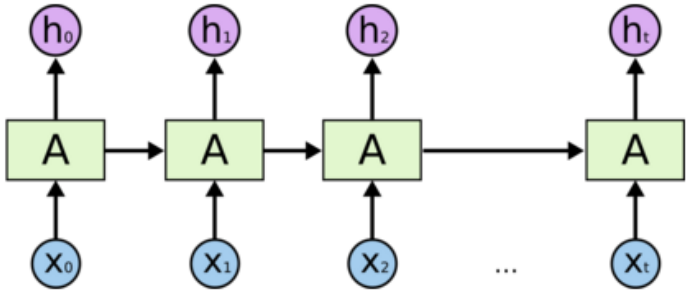
$$i_t = \sigma\left(W_i \cdot [h_{t-1}, x_t] \; + \; b_i\right)$$

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] \; + \; b_C)$$

(2) $$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$$

(3) $$o_t = \sigma\left(W_o \; [h_{t-1}, x_t] \; + \; b_o\right)$$

$$h_t = o_t * \tanh\left(C_t\right)$$



http://colah.github.io/posts/2015-08-Understanding-LSTMs/

SOME FUN LSTM EXAMPLES

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

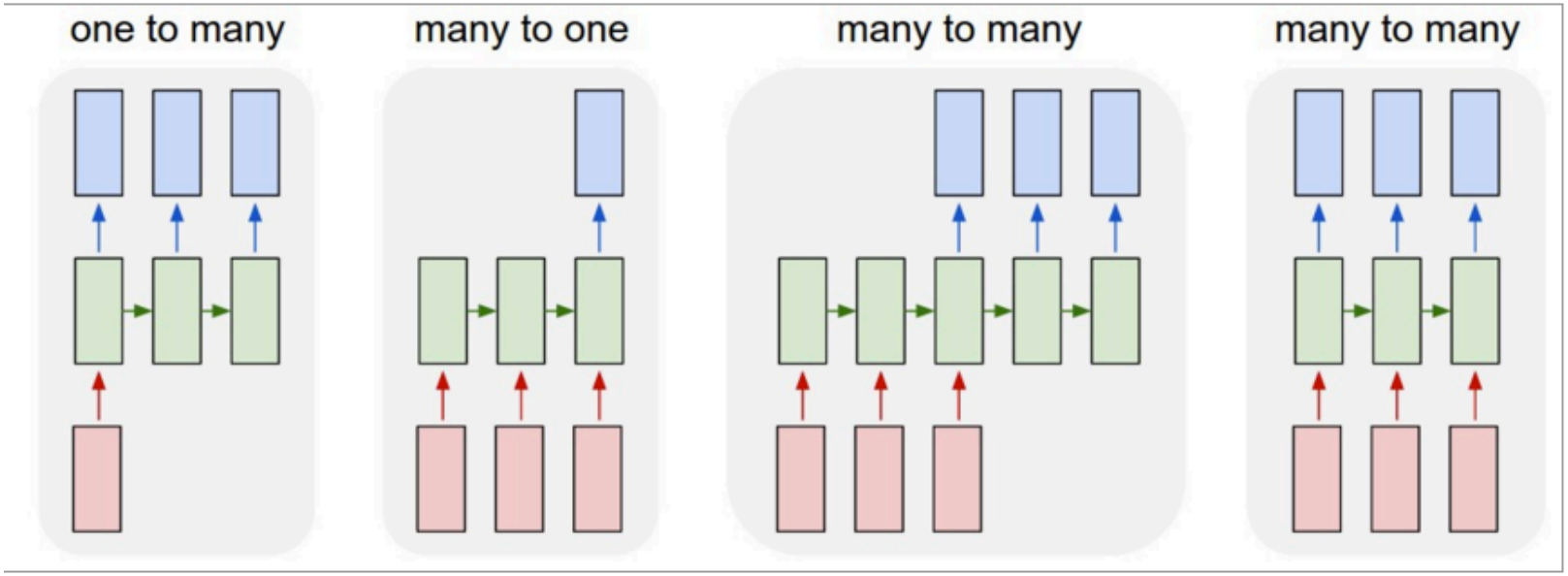
LSTMs can be used for other sequence tasks

image captioning

sequence classification

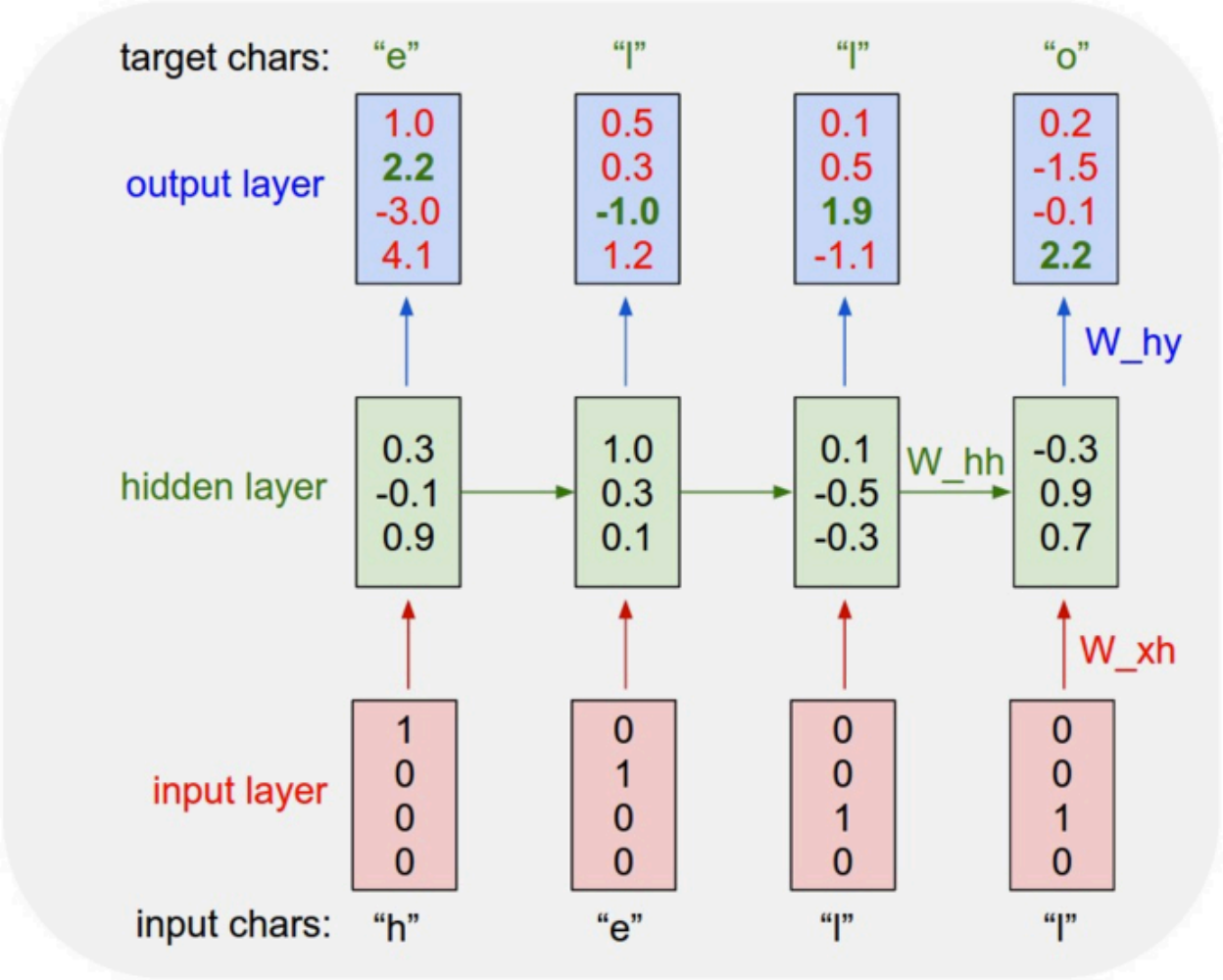
translation

named entity recognition



http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model



Test time:

- pick a seed character sequence
- generate the next character
- then the next
- then the next …

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model

```
PANDARUS:
Alas, I think he shall be come approached and the day
When little srain would be attain'd into being never fed,
And who is but a chain and subjects of his death,
I should not sleep.

Second Senator:
They are away this miseries, produced upon my soul,
Breaking and strongly should be buried, when I perish
The earth and thoughts of many states.

DUKE VINCENTIO:
Well, your wit is in the care of side and that.

Second Lord:
They would be ruled after this chamber, and
my fair nues begun out of the fact, to be conveyed,
Whose noble souls I'll have the heart of the wars.
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model

```
First Citizen:
Nay, then, that was hers,
It speaks against your other service:
But since the
youth of the circumstance be spoken:
Your uncle and one Baptista's daughter.

SEBASTIAN:
Do I stand till the break off.

BIRON:
Hide thy head.

VENTIDIUS:
He purposeth to Athens: whither, with the vow
I made to handle you.

FALSTAFF:
My good knave.
```

Yoav Goldberg: order-10 unsmoothed character n-grams

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model

```
MMMMM----- Recipe via Meal-Master (tm) v8.05

      Title: BARBECUE RIBS
 Categories: Chinese, Appetizers
      Yield: 4 Servings

      1 pk Seasoned rice
      1    Beer -- cut into
           -cubes
      1 ts Sugar
    3/4 c  Water
           Chopped finels,
           -up to 4 tblsp of chopped
      2 pk Yeast Bread/over

MMMMM-------------------------FILLIN
      2 c  Pineapple, chopped
    1/3 c  Milk
    1/2 c  Pecans
           Cream of each
      2 tb Balsamic cocoa
      2 tb Flour
      2 ts Lemon juice
           Granulated sugar
      2 tb Orange juice
      1 c  Sherry wheated curdup
      1    Onion; sliced
      1 ts Salt
      2 c  Sugar
   1/4 ts Salt
   1/2 ts White pepper, freshly ground
          Sesame seeds
      1 c  Sugar
    1/4 c  Shredded coconut
    1/4 ts Cumin seeds

Preheat oven to 350.  In a medium bowl, combine milk,
flour and water and then cornstarch. add tomatoes, or
nutmeg; serve.
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model

For $\bigoplus_{n=1,\ldots,m}$ where $\mathcal{L}_{m_\bullet} = 0$, hence we can find a closed subset $\mathcal{H}$ in $\mathcal{H}$ and any sets $\mathcal{F}$ on X, U is a closed immersion of S, then $U \to T$ is a separated algebraic space.

Proof. Proof of (1). It also start we get

$$S = \mathrm{Spec}(R) = U \times_X U \times_X U$$

and the compariciol y in the fibre product covering we have to prove the lemma generated by $\coprod Z \times_U U \to V$. Consider the maps M along the set of points Sch_{fppf} and $U \to U$ is the fibre category of S in U in Section, ?? and the fact that any U affine, see Morphisms, Lemma ??. Hence we obtain a scheme S and any open subset $W \subset U$ in $Sh(G)$ such that $\mathrm{Spec}(R') \to S$ is smooth or an

$$U = \bigcup U_i \times_{S_i} U_i$$

which has a nonzero morphism we may assume that f_i is of finite presentation over S. We claim that $\mathcal{O}_{X,x}$ is a scheme where $x, x', s'' \in S'$ such that $\mathcal{O}_{X,x'} \to \mathcal{O}'_{X',x'}$ is separated. By Algebra, Lemma ?? we can define a map of complexes $\mathrm{GL}_{S'}(x'/S'')$ and we win. □

To prove study we see that $\mathcal{F}|_U$ is a covering of $\mathcal{X}'$, and $\mathcal{T}_i$ is an object of $\mathcal{F}_{X/S}$ for $i > 0$ and $\mathcal{F}_p$ exists and let $\mathcal{F}_i$ be a presheaf of $\mathcal{O}_X$-modules on $\mathcal{C}$ as a $\mathcal{F}$-module. In particular $\mathcal{F} = U/\mathcal{F}$ we have to show that

$$\widetilde{M^\bullet} = \mathcal{I}^\bullet \otimes_{\mathrm{Spec}(k)} \mathcal{O}_{S,s} - i_X^{-1}\mathcal{F})$$

is a unique morphism of algebraic stacks. Note that

$$\mathrm{Arrows} = (Sch/S)^{opp}_{fppf}, (Sch/S)_{fppf}$$

and

$$V = \Gamma(S, \mathcal{O}) \longmapsto (U, \mathrm{Spec}(A))$$

LaTeX "almost compiles"

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Character-level language model

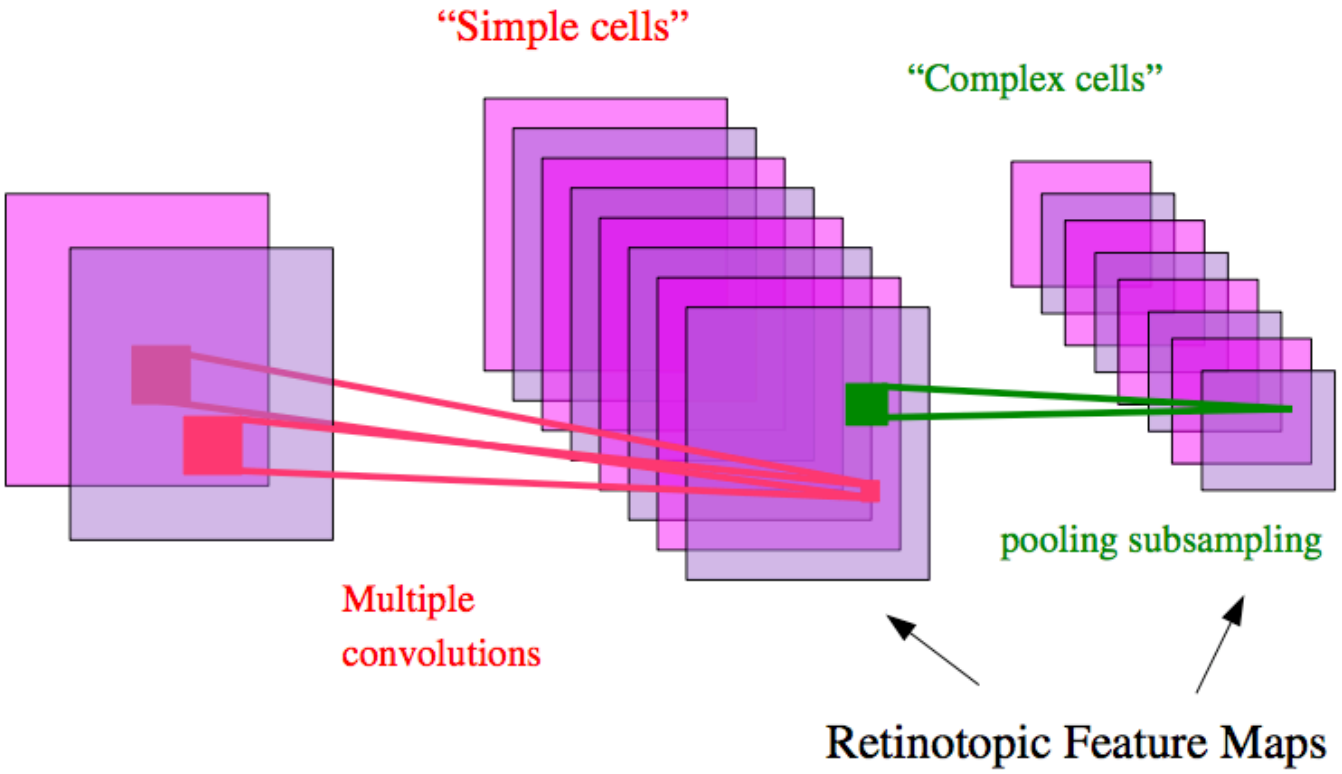
```
/*
 * Increment the size file of the new incorrect UI_FILTER group information
 * of the size generatively.
 */
static int indicate_policy(void)
{
  int error;
  if (fd == MARN_EPT) {
    /*
     * The kernel blank will coeld it to userspace.
     */
    if (ss->segment < mem_total)
      unblock_graph_and_set_blocked();
    else
      ret = 1;
    goto bail;
  }
  segaddr = in_SB(in.addr);
  selector = seg / 16;
  setup_works = true;
  for (i = 0; i < blocks; i++) {
    seq = buf[i++];
    bpf = bd->bd.next + i * search;
    if (fd) {
      current = blocked;
    }
  }
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

CONVOLUTIONAL NEURAL NETWORKS

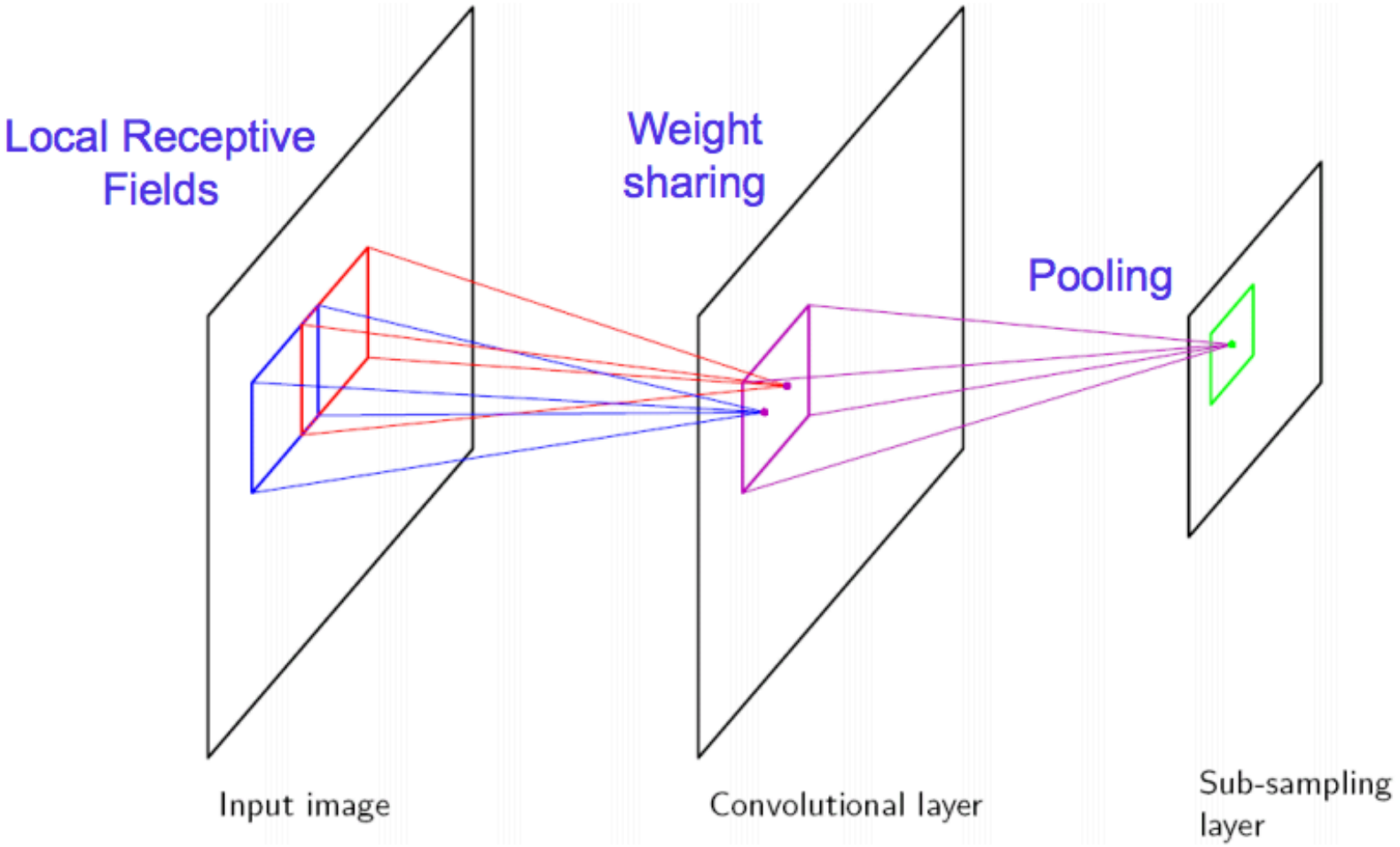
Model of vision in animals

- **[Hubel & Wiesel 1962]:**
  - simple cells detect local features
  - complex cells "pool" the outputs of simple cells within a retinotopic neighborhood.



Vision with ANNs

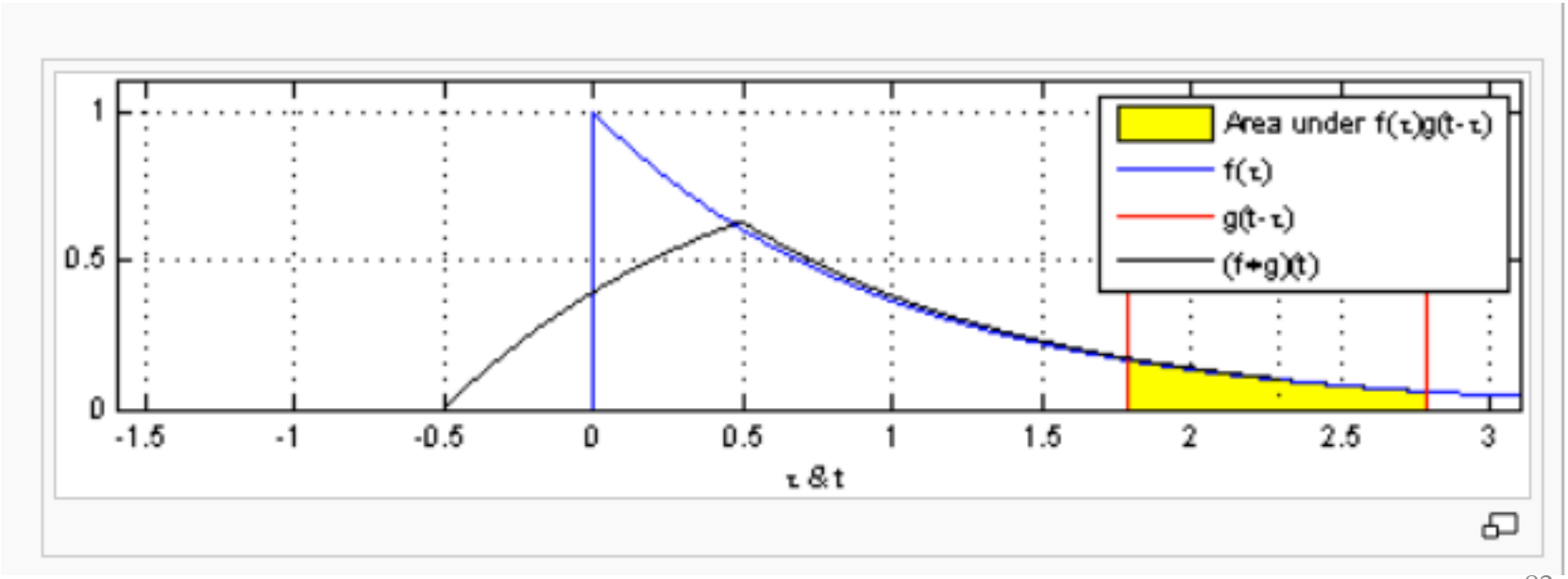
(LeCun et al., 1989)



What's a convolution?

https://en.wikipedia.org/wiki/Convolution

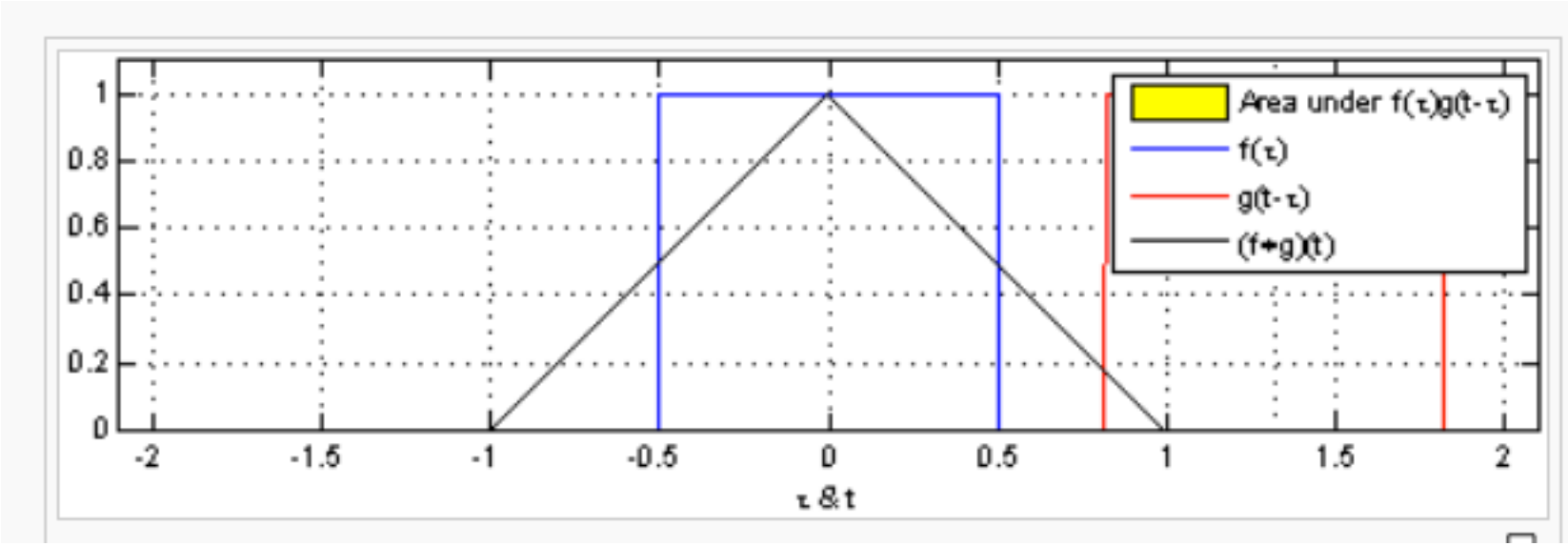
1-D $$(f * g)(t) \ \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau = \int_{-\infty}^{\infty} f(t-\tau)\, g(\tau)\, d\tau.$$



What's a convolution?

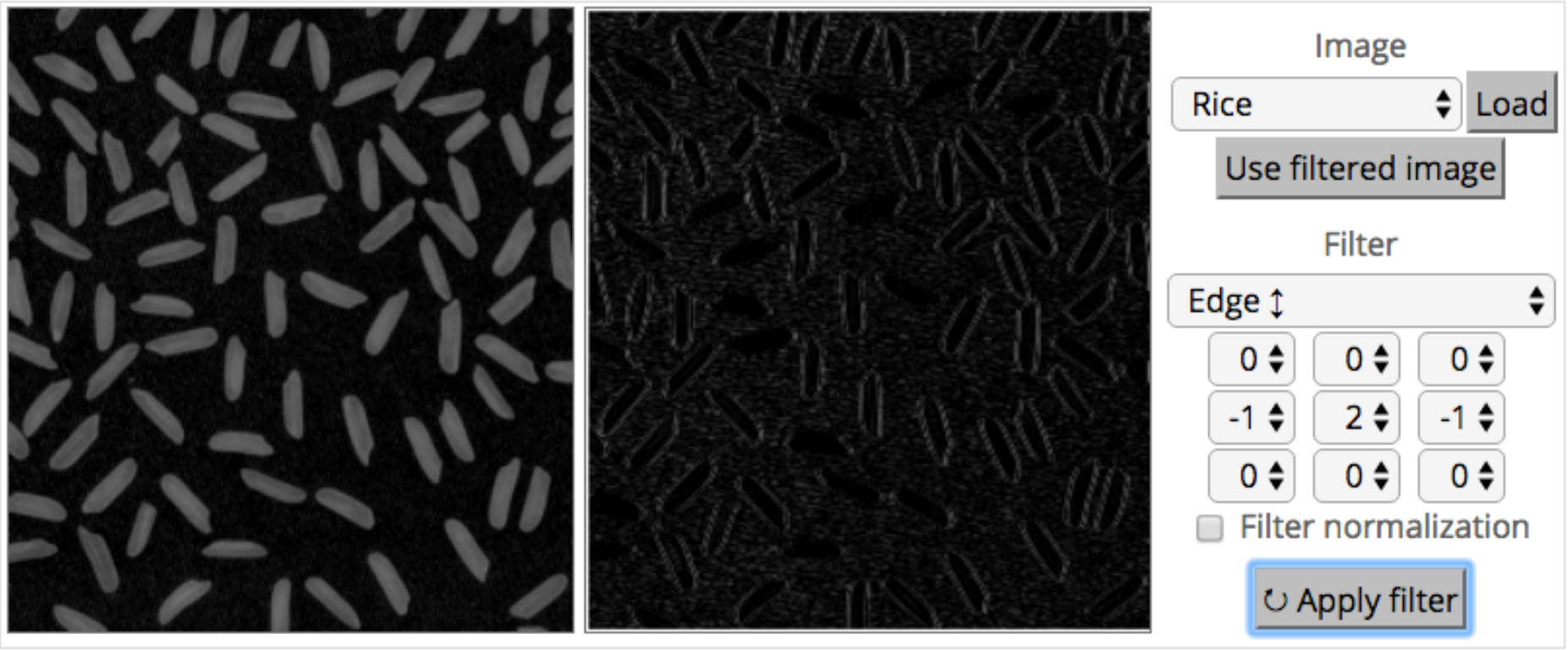
https://en.wikipedia.org/wiki/Convolution

1-D $$(f * g)(t) \ \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau$$
$$= \int_{-\infty}^{\infty} f(t-\tau)\, g(\tau)\, d\tau.$$



What's a convolution?

http://matlabtricks.com/post-5/3x3-convolution-kernels-with-online-demo



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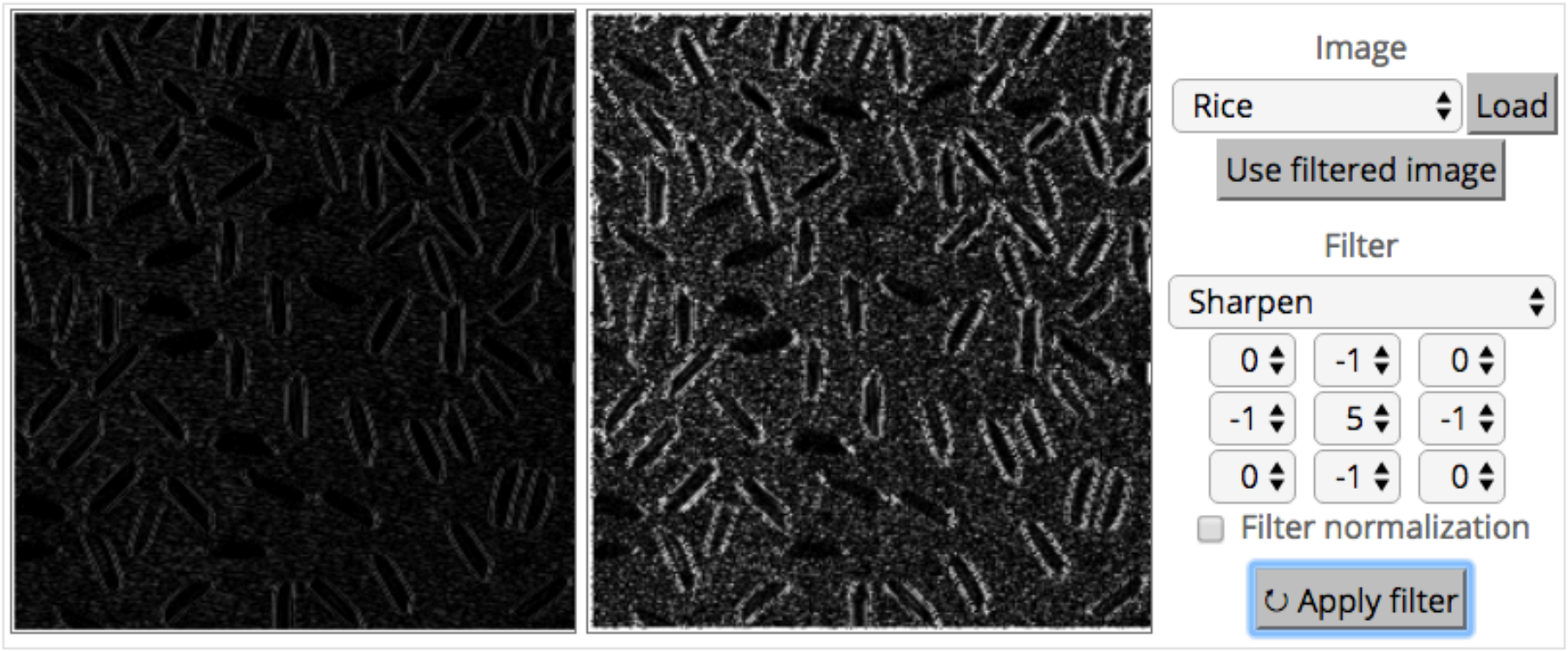

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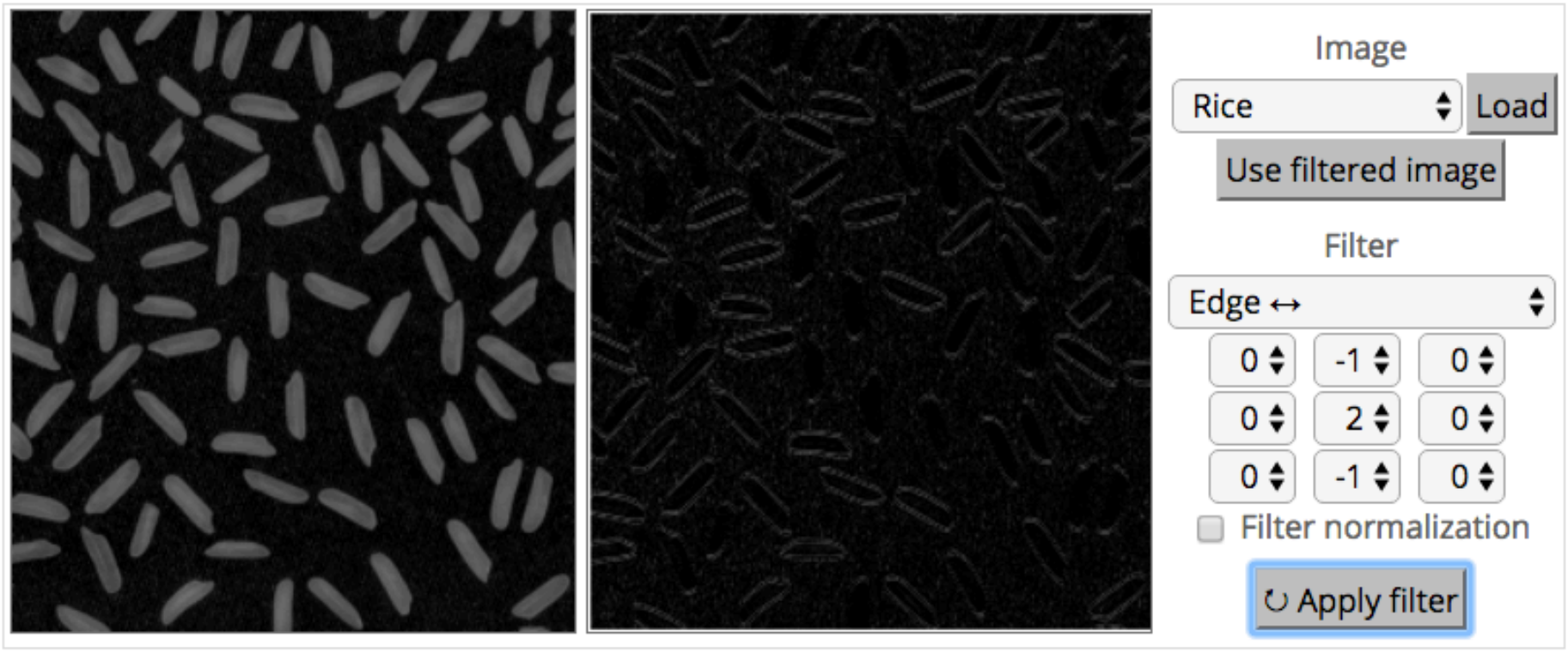
http://matlabtricks.com/post-5/3x3-convolution-kernels-with-online-demo



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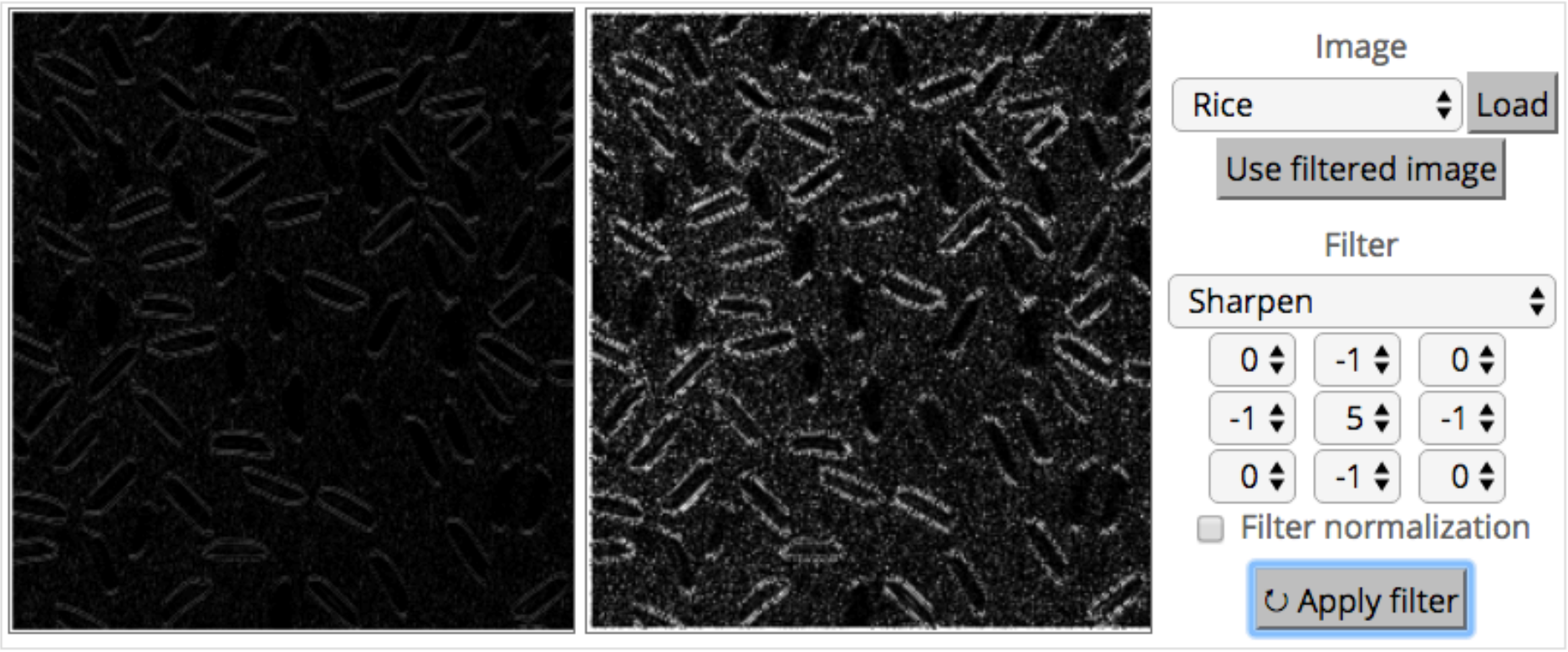

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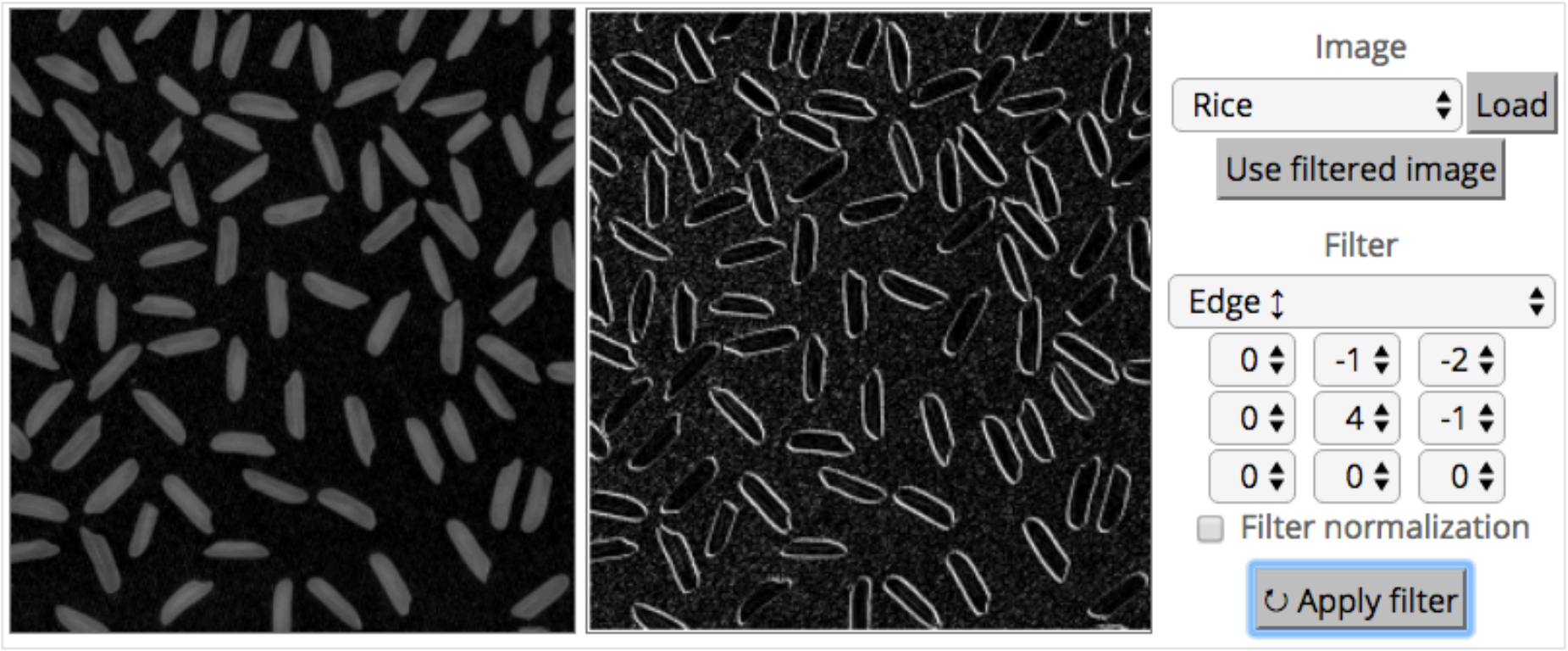

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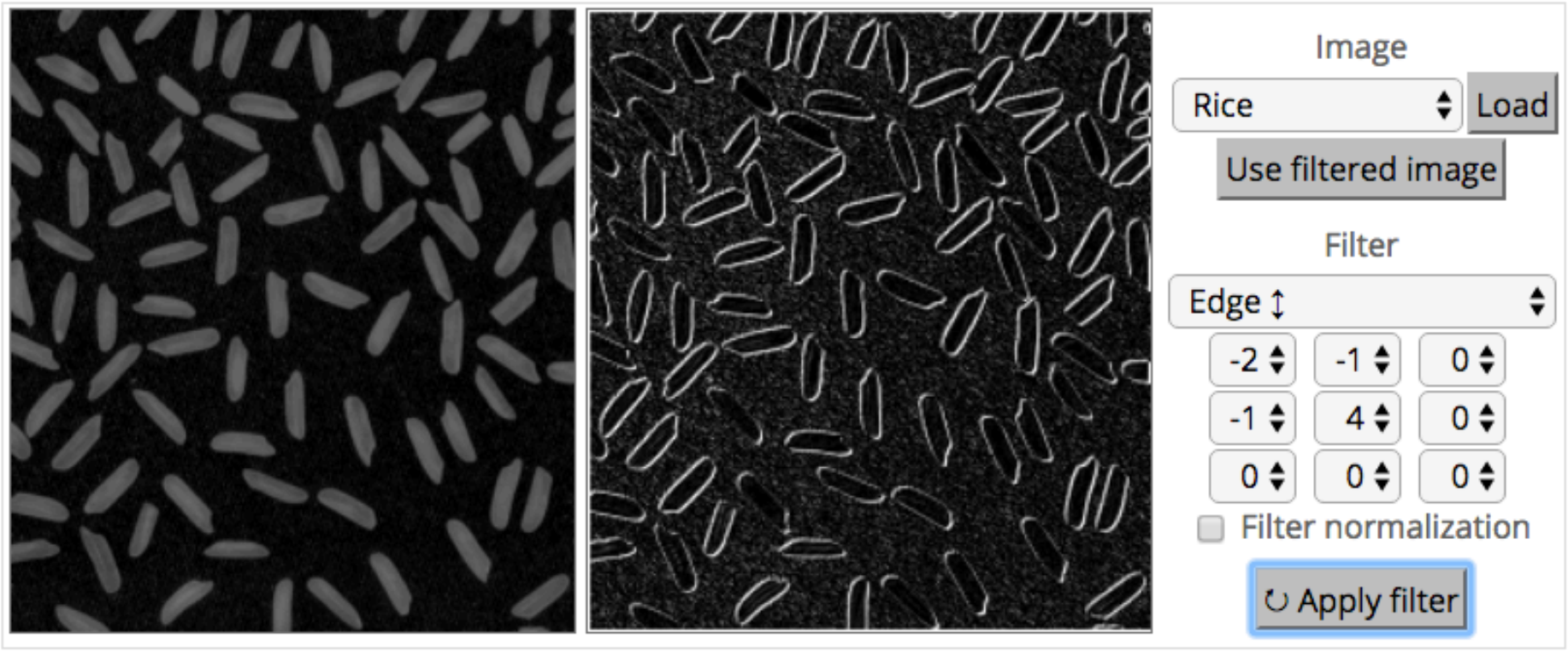
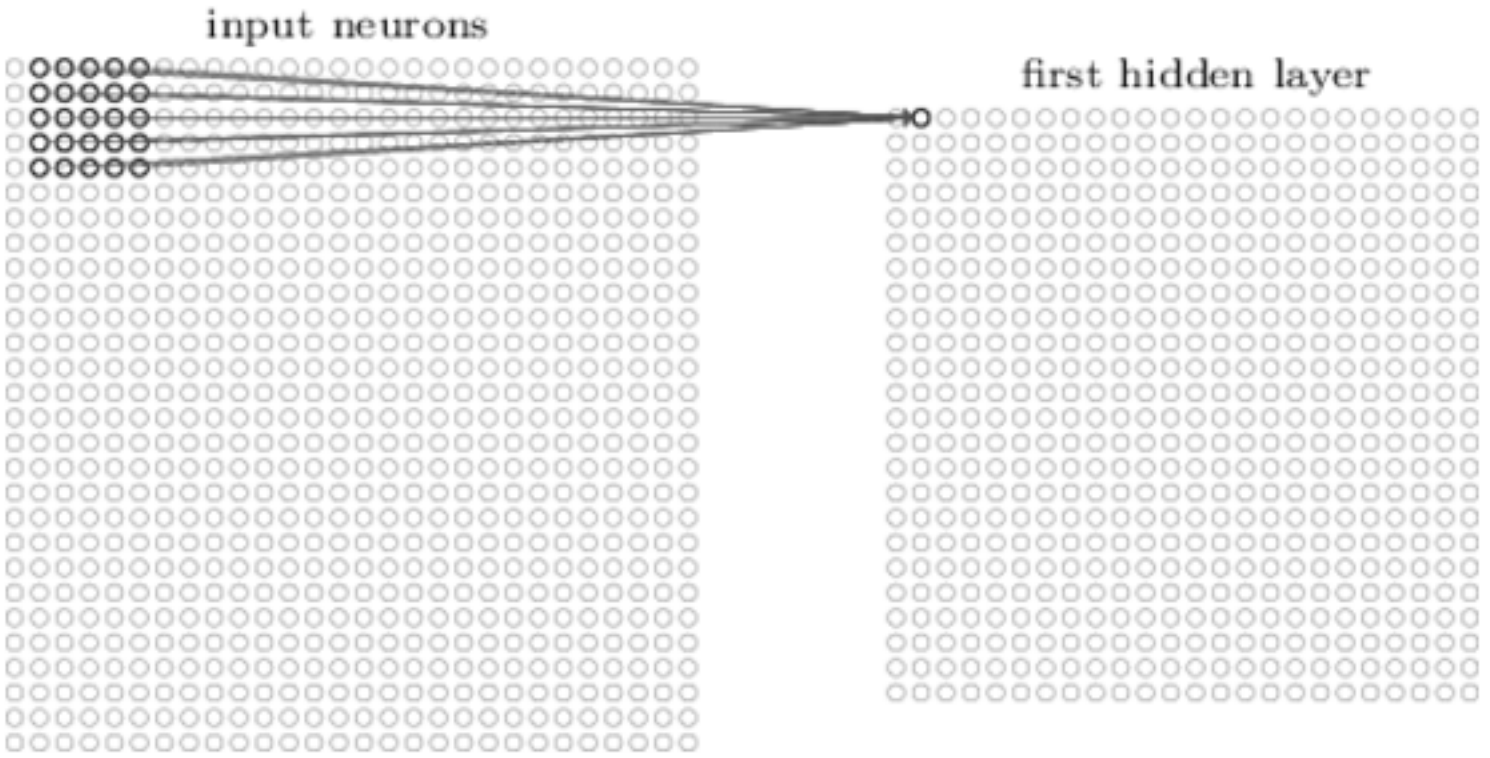


What's a convolution?

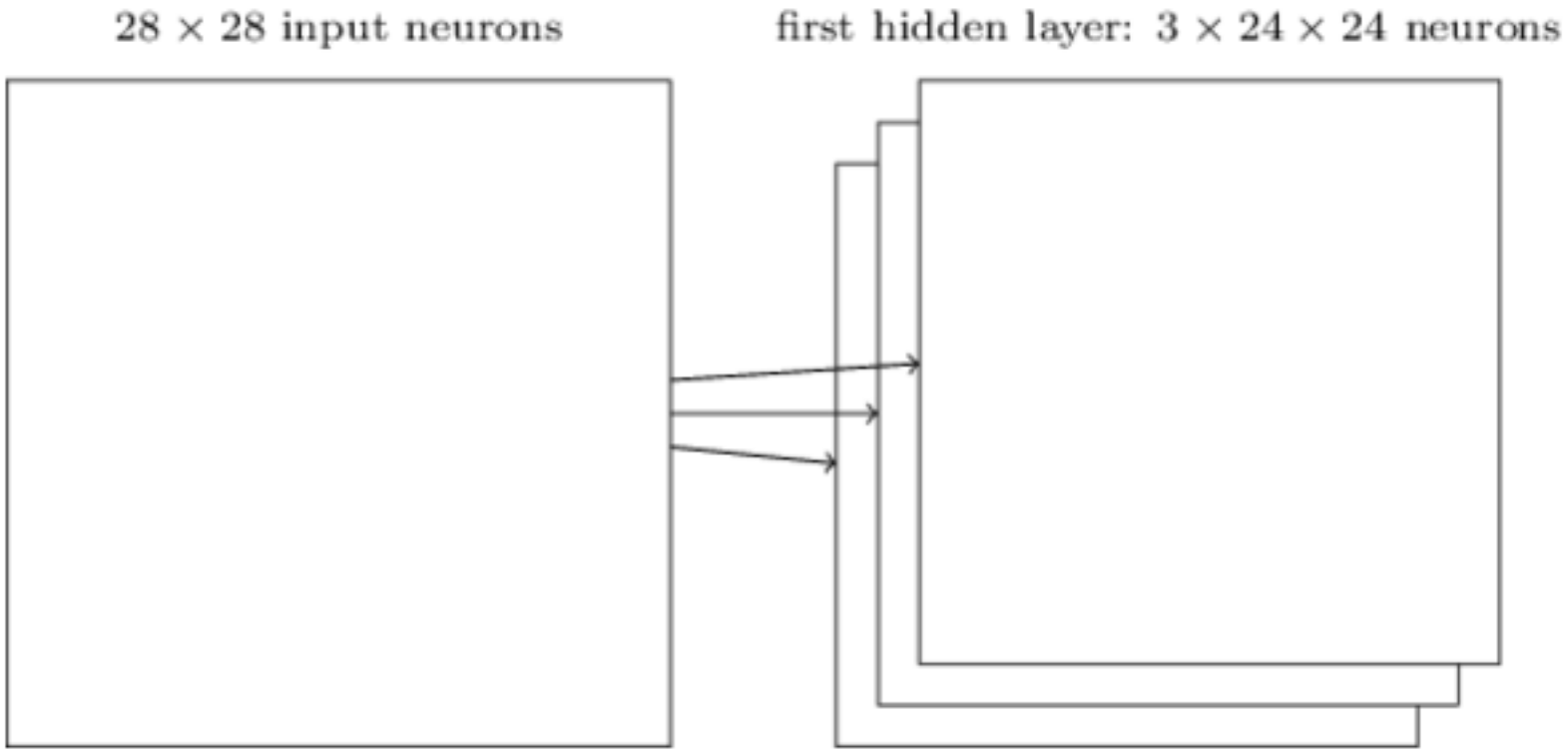
- Basic idea:
  - Pick a 3-3 matrix F of weights
  - Slide this over an image and compute the "inner product" (similarity) of F and the corresponding field of the image, and replace the pixel in the center of the field with the output of the inner product operation
- Key point:
  - Different convolutions extract different types of low-level "features" from an image
  - All that we need to vary to generate these different features is the weights of F

How do we convolve an image with an ANN?

Note that the parameters in the matrix defining the convolution are **tied** across all places that it is used

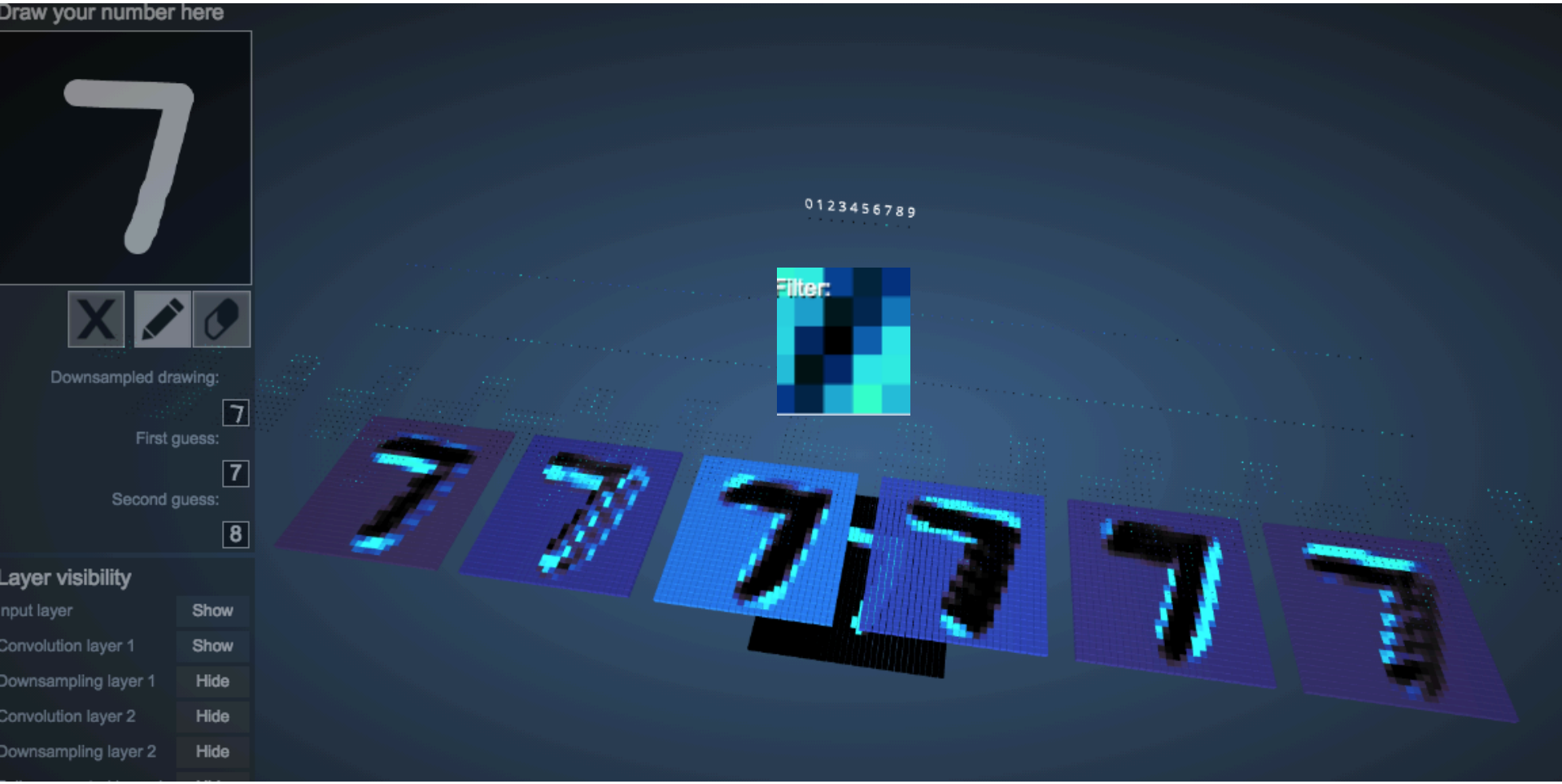


How do we do many convolutions of an image with an ANN?



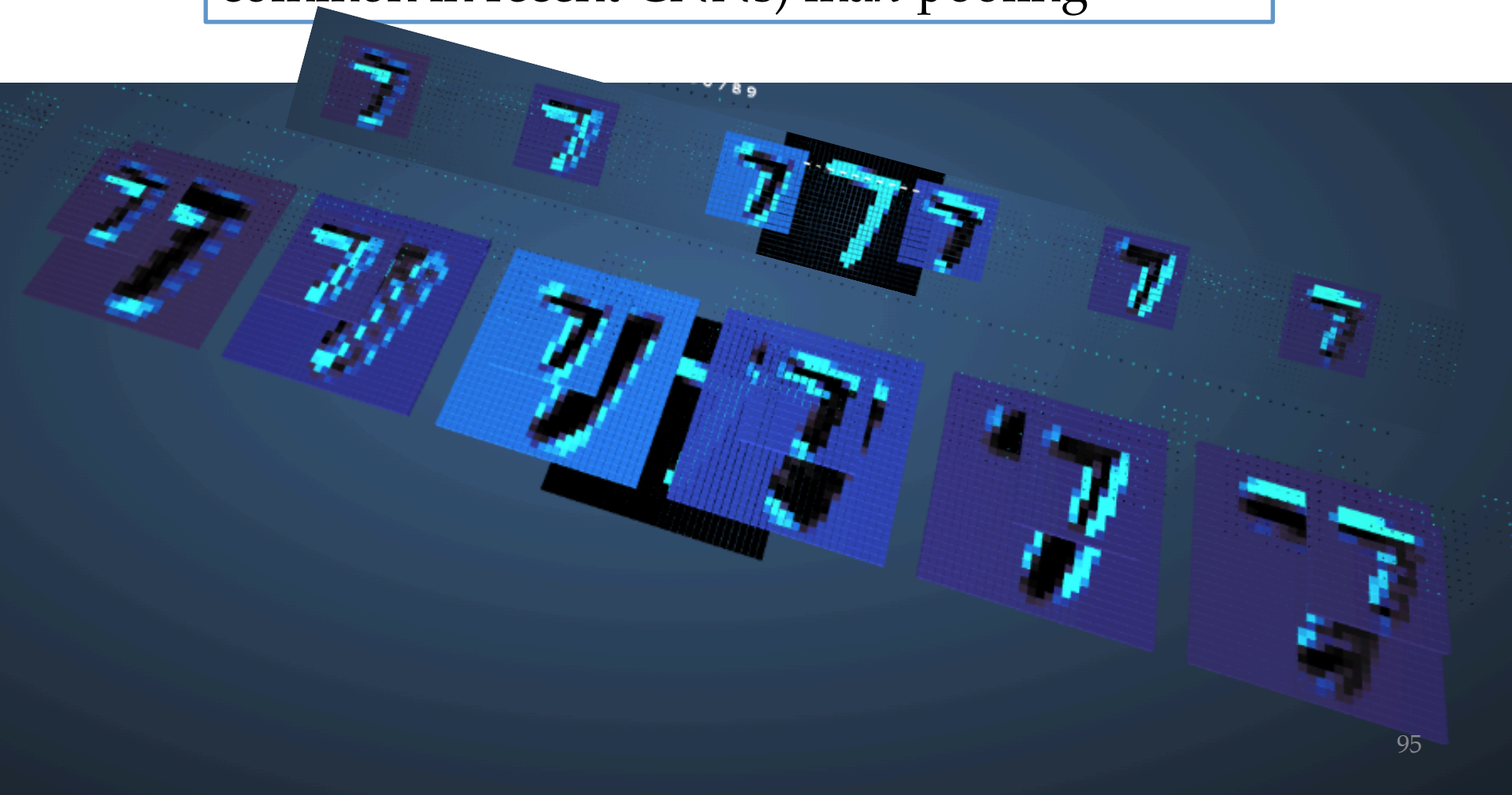
Example: 6 convolutions of a digit

http://scs.ryerson.ca/~aharley/vis/conv/



CNNs typically alternate convolutions, non-linearity, and then downsampling

Downsampling is usually averaging or (more common in recent CNNs) max-pooling



Why do max-pooling?

- Saves space
- Reduces overfitting?
- Because I'm going to add *more* convolutions after it!
  - Allows the short-range convolutions to extend over larger subfields of the images
    - So we can spot larger objects
    - Eg, a long horizontal line, or a corner, or …

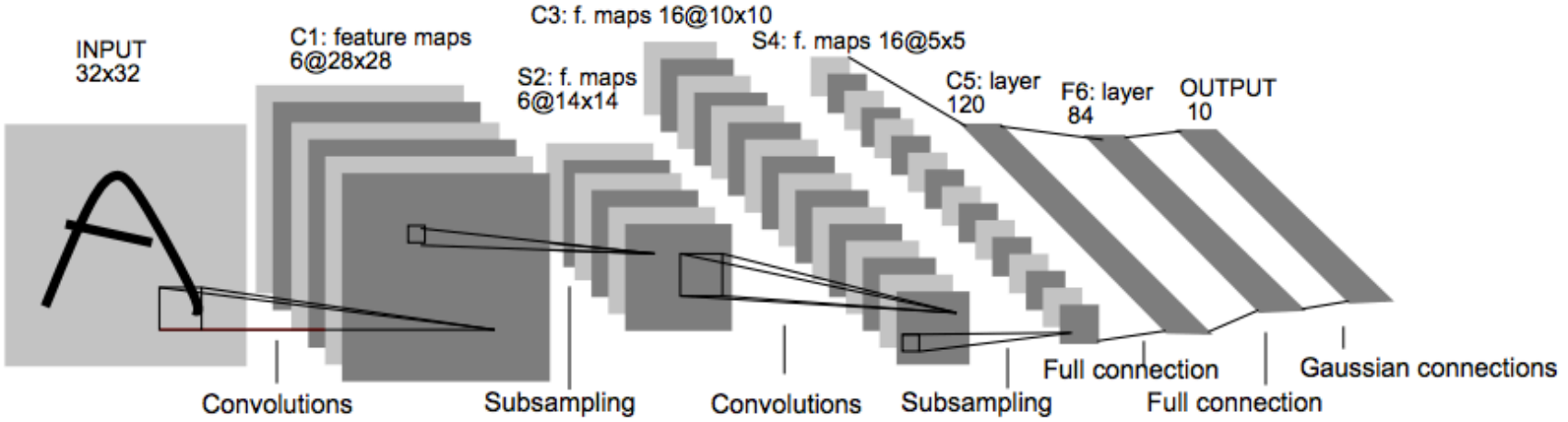


Fig. 2. Architecture of LeNet-5, a Convolutional Neural Network, here for digits recognition. Each plane is a feature map, i.e. a set of units whose weights are constrained to be identical.

Another CNN visualization

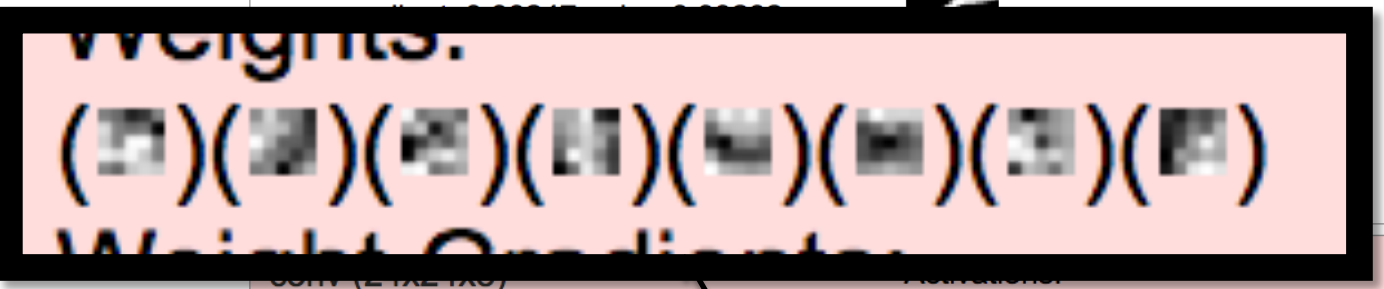
https://cs.stanford.edu/people/karpathy/convnetjs/demo/mnist.html

Network Visualization

input (24x24x1)
max activation: 0.99607, min: 0

Activations:

Weights:

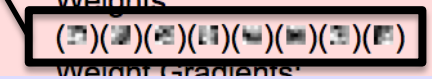


filter size 5x5x1, stride 1
max activation: 2.96187, min: -5.43735
max gradient: 0.00068, min: -0.00102
parameters: 8x5x5x1+8 = 208

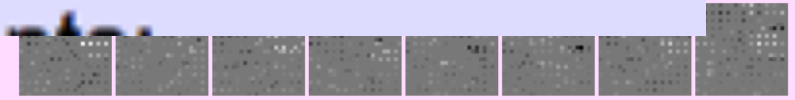
Activations:

Activation Gradients:

Weights:



Activations:



pool (12x12x8)
pooling size 2x2, stride 2
max activation: 2.96187, min: 0
max gradient: 0.00106, min: -0.00102

Activations:

Activation Gradients:

conv (12x12x16)
filter size 5x5x8, stride 1
max activation: 5.58937, min: -11.45423
max gradient: 0.00053, min: -0.00106
parameters: 16x5x5x8+16 = 3216

Activations:

Activation Gradients:

Weights:

relu (12x12x16)
max activation: 5.58937, min: 0
max gradient: 0.0007, min: -0.0011

Activations:

Activation Gradients:

softmax (1x1x10)
max activation: 0.99864, min: 0
max gradient: 0, min: 0

Activations:

Why do max-pooling?

- Saves space
- Reduces overfitting?
- Because I'm going to add *more* convolutions after it!
  - Allows the short-range convolutions to extend over larger subfields of the images
    - So we can spot larger objects
    - Eg, a long horizontal line, or a corner, or …
- At some point the feature maps start to get very sparse and blobby – they are indicators of some semantic property, not a recognizable transformation of the image
- Then just use them as features in a "normal" ANN

Why do max-pooling?

- Saves space
- Reduces overfitting?
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    - So we can spot larger objects
    - Eg, a long horizontal line, or a corner, or …

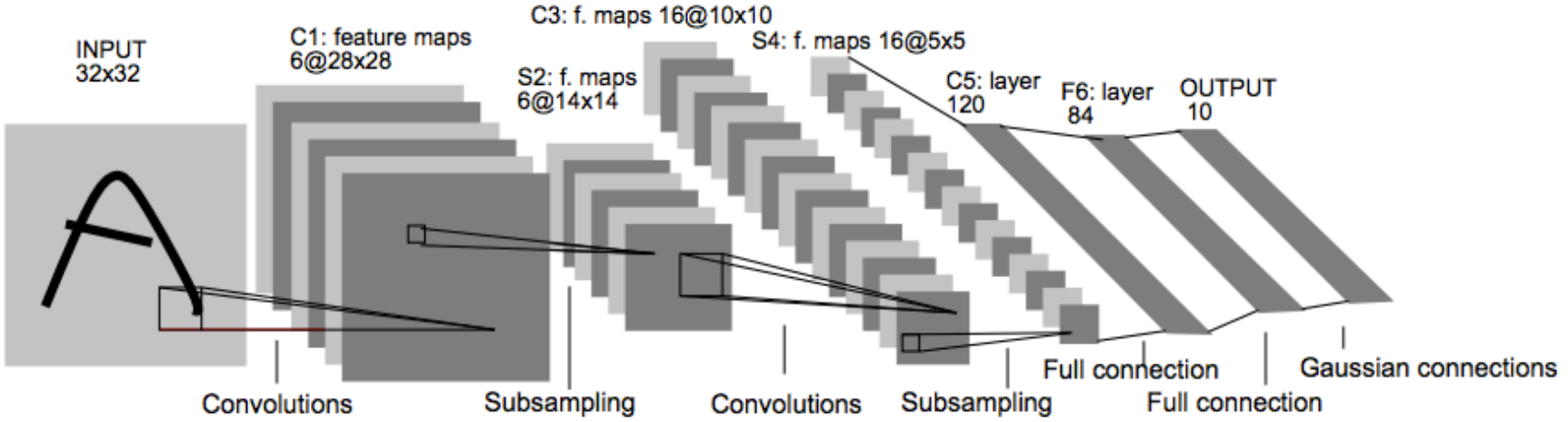
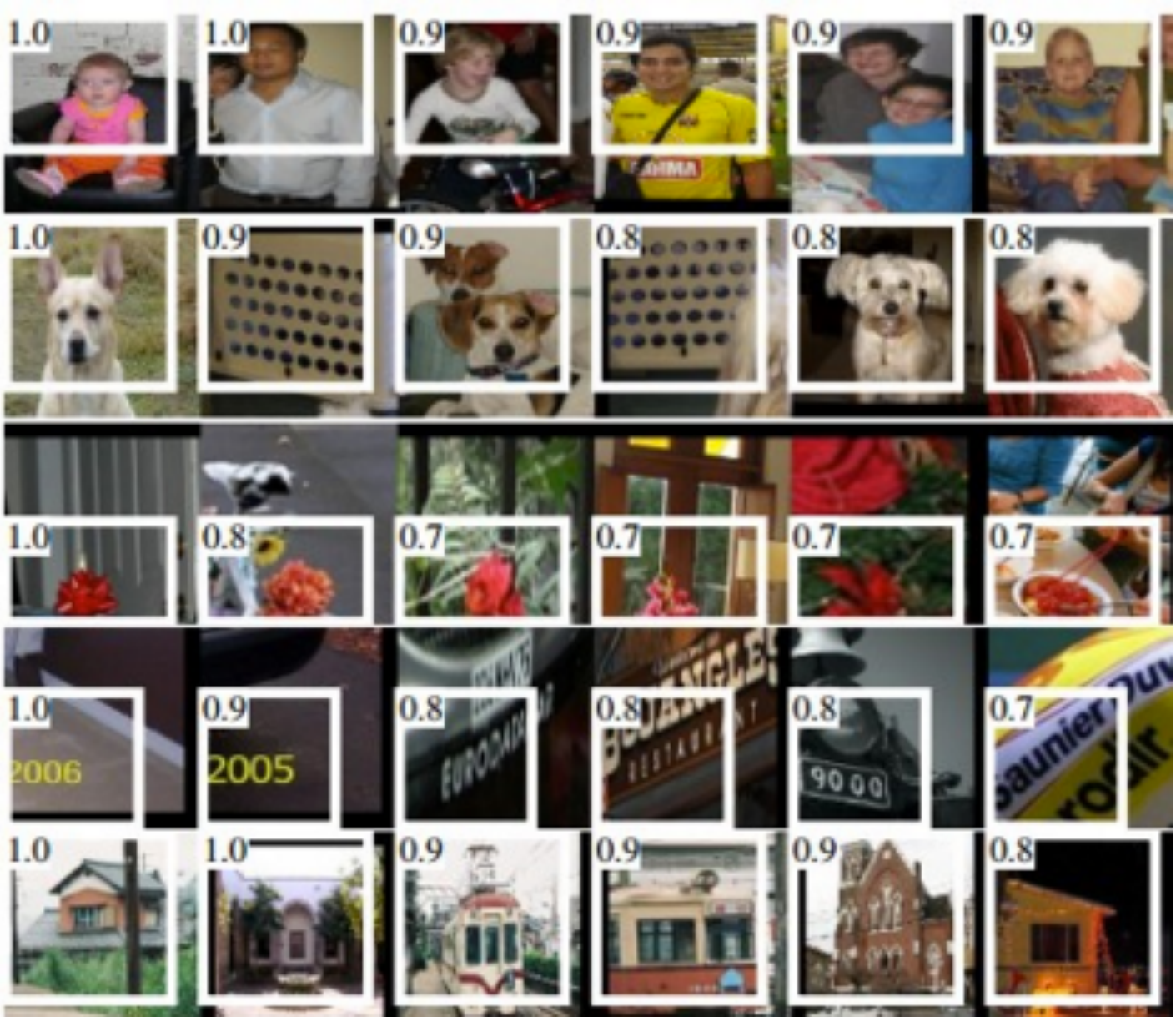


Fig. 2. Architecture of LeNet-5, a Convolutional Neural Network, here for digits recognition. Each plane is a feature map, i.e. a set of units whose weights are constrained to be identical.

Alternating convolution and downsampling



5 layers up

The subfield in a large dataset that gives the strongest output for a neuron