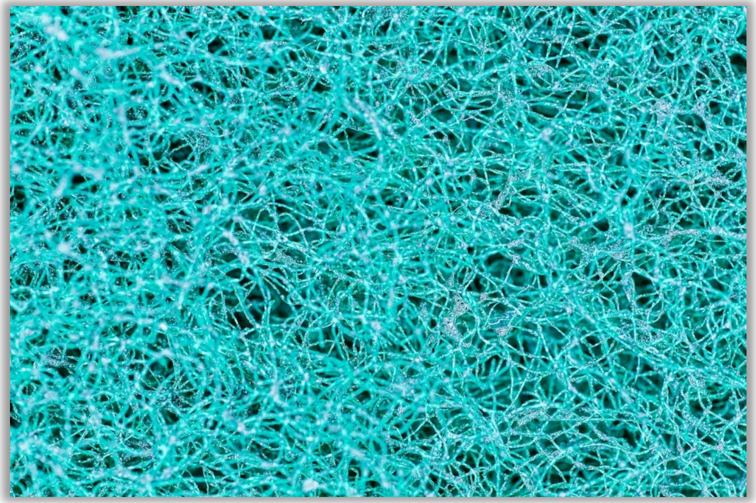
Introduction to Neural Networks

MLPs, CNNs, Backpropagation, Learned Image Processing



CSC2529

David Lindell

University of Toronto

cs.toronto.edu/~lindell/teaching/2529

*slides adapted from CS231n at Stanford

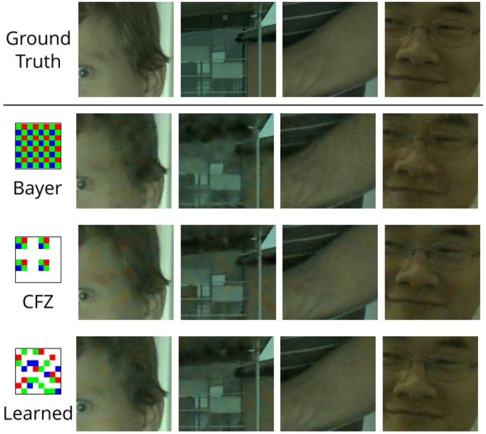
Announcements

- HW4 due Wednesday 25/10
- HW5 is out

- Problem session for HW5 tomorrow

Neural Networks in Computational Imaging

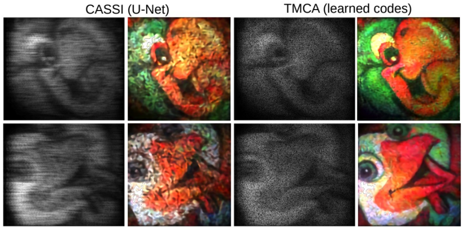
- Now: learned pipelines for computational imaging



Learning CFAs

(b) Raw data via traditional pipeline (c) Our result

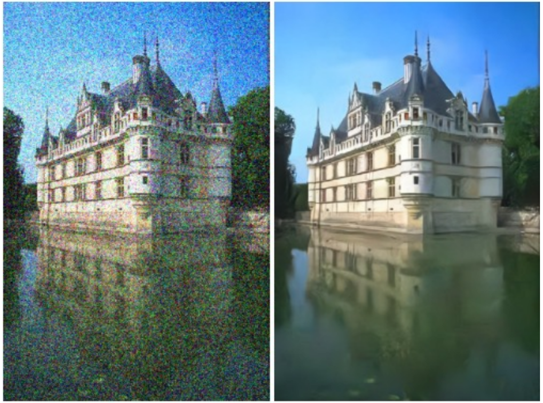
Learning ISPs



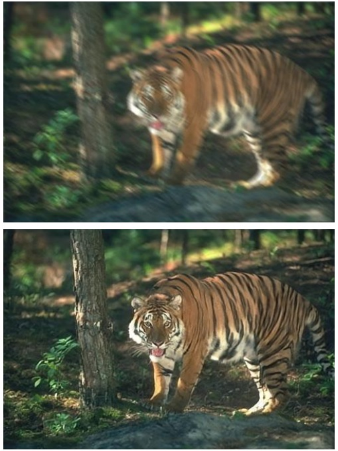
Learning coded apertures

Neural Networks in Computational Imaging

- Now: learned pipelines for computational imaging



Learned denoising



Learned deblurring

HDR Imaging

Today

- What is a neural network?
- Training/optimizing neural nets
- Why “neural”?
- Convolutional neural networks
- Applications & inverse problems

What is a neural network?

- Image classification example

Image Classification

- Image classification example

Images

MNIST Dataset

Image Classification

- Image classification example

Images

Class

“zero”
“one”

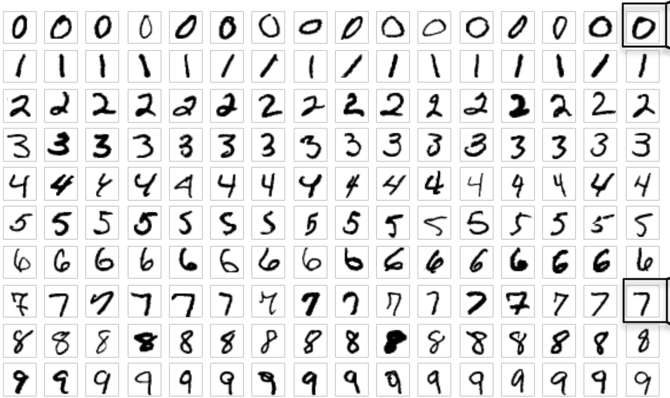
…

“nine”

Image Classification

- Image classification example

Images



What the computer "sees"

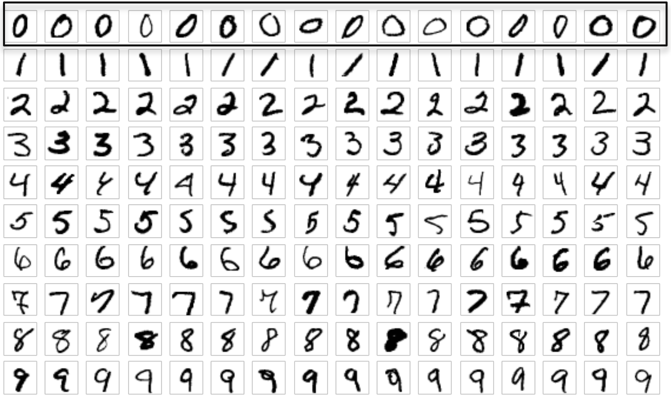
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	019	146	146	018	000	000	000	000
000	000	000	000	000	000	000	023	188	248	236	115	003	000	000	000
000	000	000	000	000	000	059	192	249	246	112	236	086	000	000	000
000	000	000	000	000	017	214	243	145	223	064	180	113	000	000	000
000	000	000	000	014	161	232	137	006	014	000	156	209	003	000	000
000	000	000	000	108	230	042	009	000	000	000	155	227	004	000	000
000	000	000	020	223	138	000	000	000	000	000	156	220	003	000	000
000	000	000	054	237	023	000	000	000	000	024	206	111	000	000	000
000	000	000	055	210	003	000	000	001	057	216	088	006	000	000	000
000	000	000	055	242	085	022	089	160	219	108	001	000	000	000	000
000	000	000	040	233	246	226	242	175	070	001	000	000	000	000	000
000	000	000	000	058	211	212	069	001	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000

000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	000	000	000	000	000	000	000
000	000	000	000	000	000	000	000	000	001	003	002	000	000	000	000
000	000	000	000	000	001	002	035	101	171	239	229	052	000	000	000
000	000	000	000	026	195	223	242	202	219	243	250	134	000	000	000
000	000	000	002	195	249	239	096	005	024	231	229	028	000	000	000
000	000	000	086	245	200	037	000	004	079	243	138	001	000	000	000
000	000	000	033	120	016	000	000	082	245	176	007	000	000	000	000
000	000	000	000	000	000	000	015	245	227	015	000	000	000	000	000
000	000	000	000	000	000	000	112	248	110	001	000	000	000	000	000
000	000	000	000	000	001	095	225	124	006	000	000	000	000	000	000
000	000	000	000	000	026	224	177	002	000	000	000	000	000	000	000
000	000	000	000	003	172	234	038	000	000	000	000	000	000	000	000
000	000	000	000	046	234	076	002	000	000	000	000	000	000	000	000
000	000	000	000	010	087	005	000	000	000	000	000	000	000	000	000

Image Classification

- Image classification example

Images



Challenges

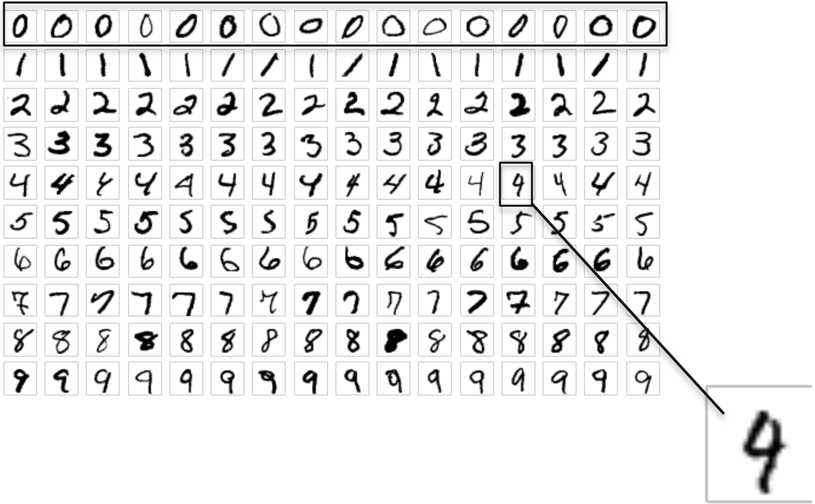
Intra-class variation

- stroke widths
- alignment
- writing styles

Image Classification

- Image classification example

Images



Challenges

Intra-class variation

- stroke widths
- alignment
- writing styles

Inter-class similarities

- “four” or “nine”?

Image Classification

- Image classification example

Images

Implementation?

```
def classify_digit(image):
    # ???
    return image_class
```

Can't hardcode solution!

Image Classification

- Data-driven approach
  - Collect training images and labels
  - Train a classifier using machine learning
  - Evaluate the classifier on unseen images

Implementation?

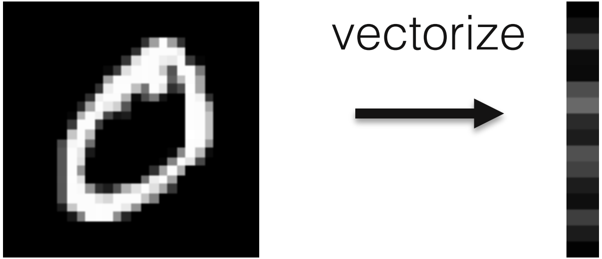
```
def train(images, labels):
    # machine learning model
    return image_class

def evaluate(model, test_images):
    # machine learning model
    return test_labels

```

Image Classification

- Linear Model $$f(x, W) = Wx$$



$$x$$

Image Classification

- Linear Model $$f(x, W) = Wx$$

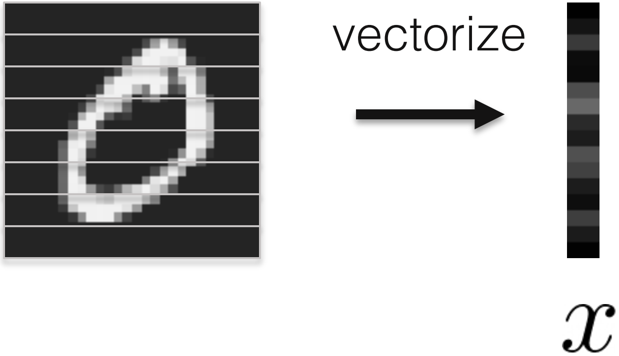
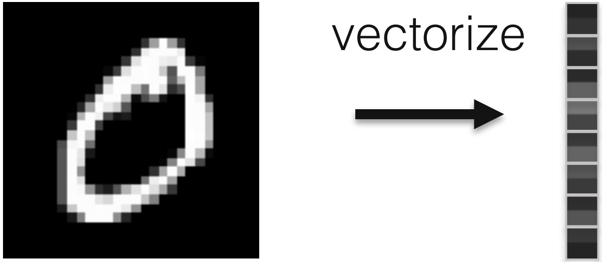


Image Classification

- Linear Model

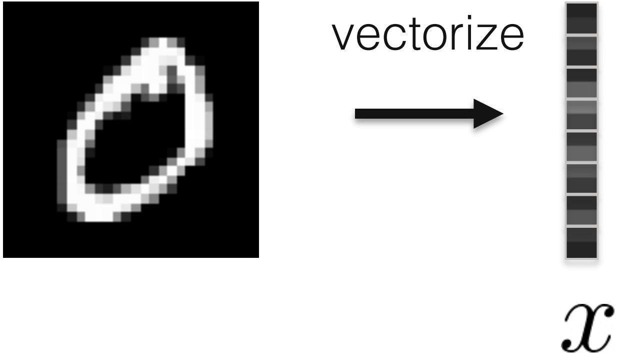
$$f(x, W) = Wx$$



x

Image Classification

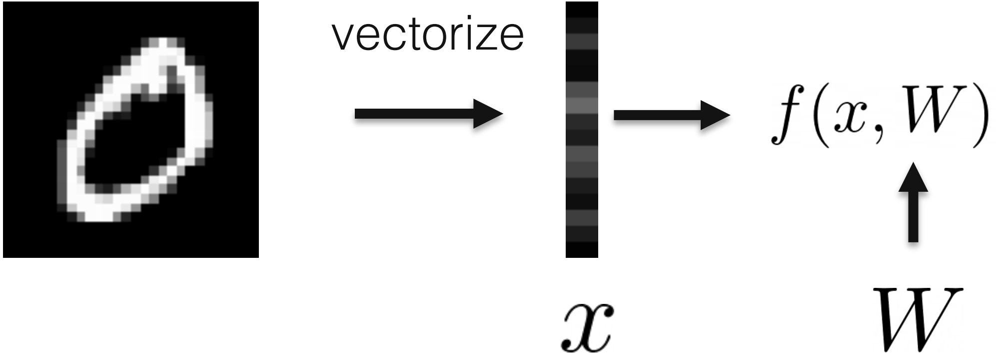
- Linear Model $$f(x, W) = Wx$$



Length of this vector is the "dimensionality" of our problem!

Image Classification

- Linear Model $f(x, W) = Wx$



In general: $Wx + b$

Image Classification

- Linear Model $f(x, W) = Wx$

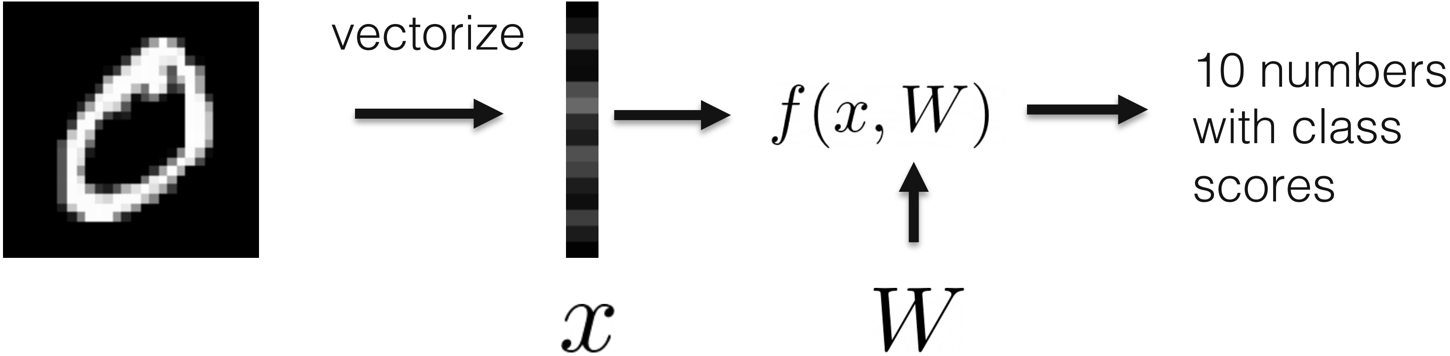
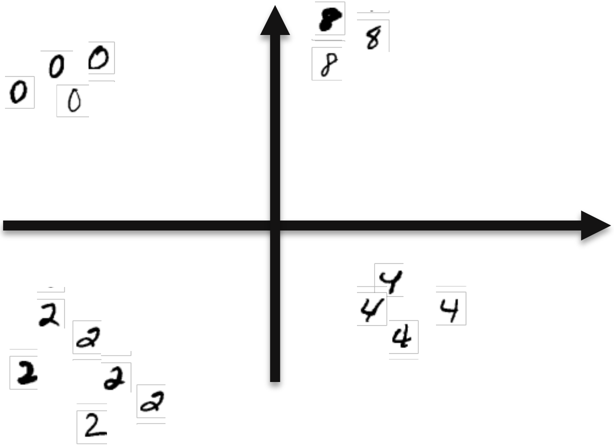


Image Classification

- Linear model: geometric intrepretation

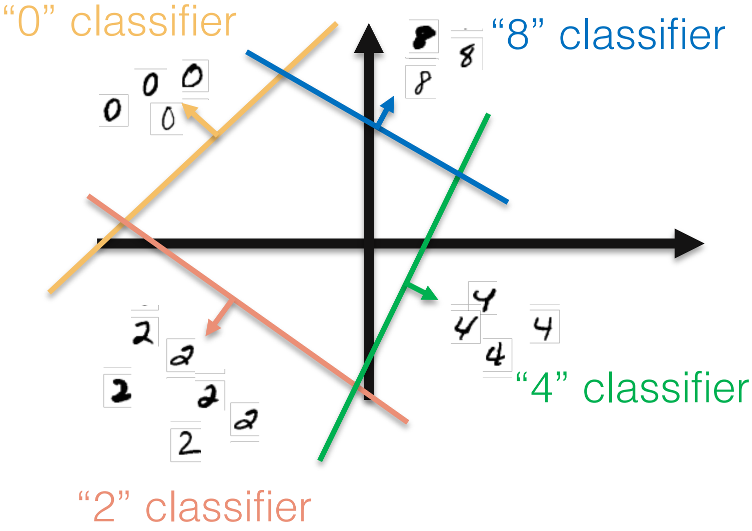


Each image is a point in an N-dimensional space

- N is the number of pixels

Image Classification

- Linear model: geometric interpretation



$$f(x, W) = Wx$$

Computes inner product between rows of W and x!

- Each row of W is a hyperplane
- Sign of inner product tells you which side of the hyperplane
- "separates" the digits

Image Classification

- Linear model (visual interpretation)

Learned filters (rows of W)

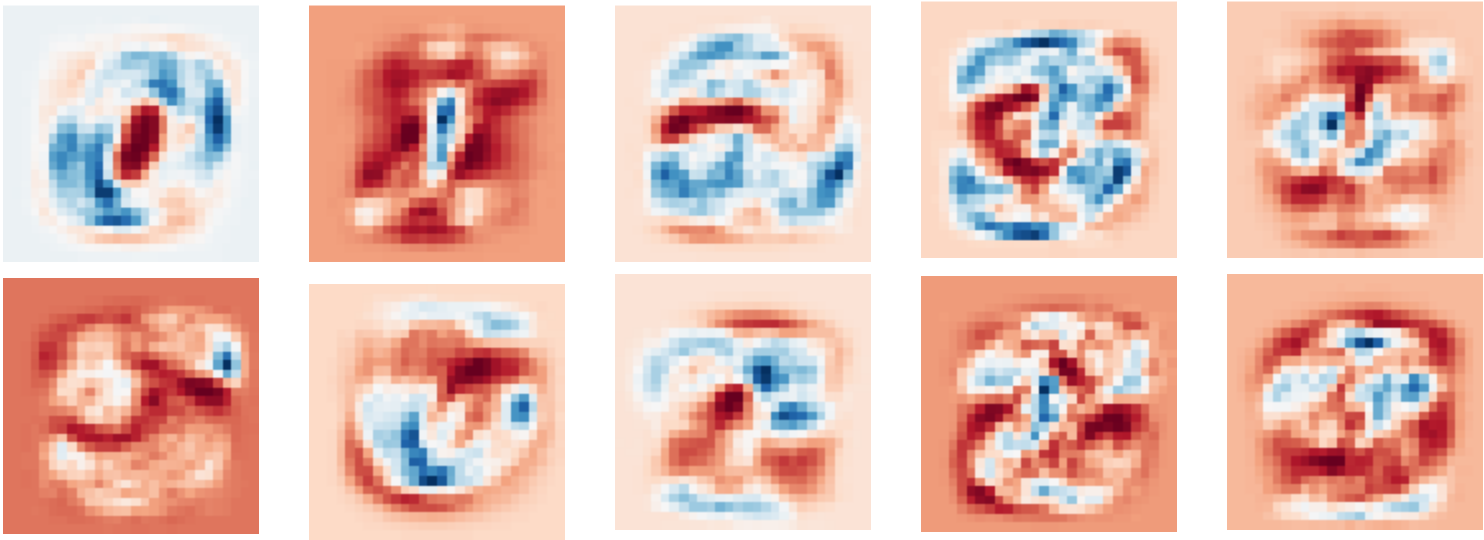
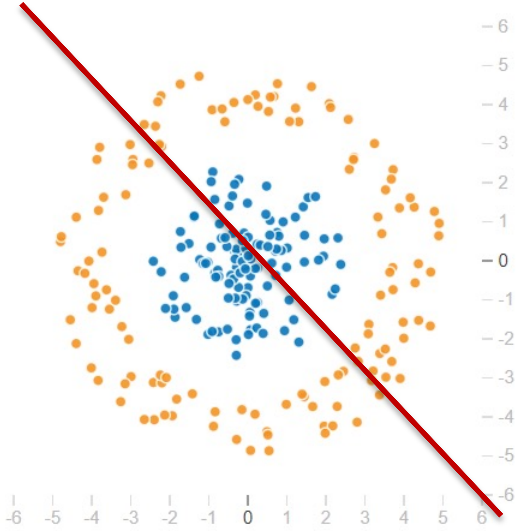


Image Classification

- Limits of linear classifiers

Linear classifiers learn linear decision planes

What if dataset is not linearly separable?



Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$

Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$
- 3-layer MLP $f = W_3 \max(0, W_2 \max(0, W_1 x))$

Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$
- 3-layer MLP $f = W_3 \max(0, W_2 \max(0, W_1 x))$

Non-linearity/activation function between linear layers

Multilayer Perceptrons (MLPs)

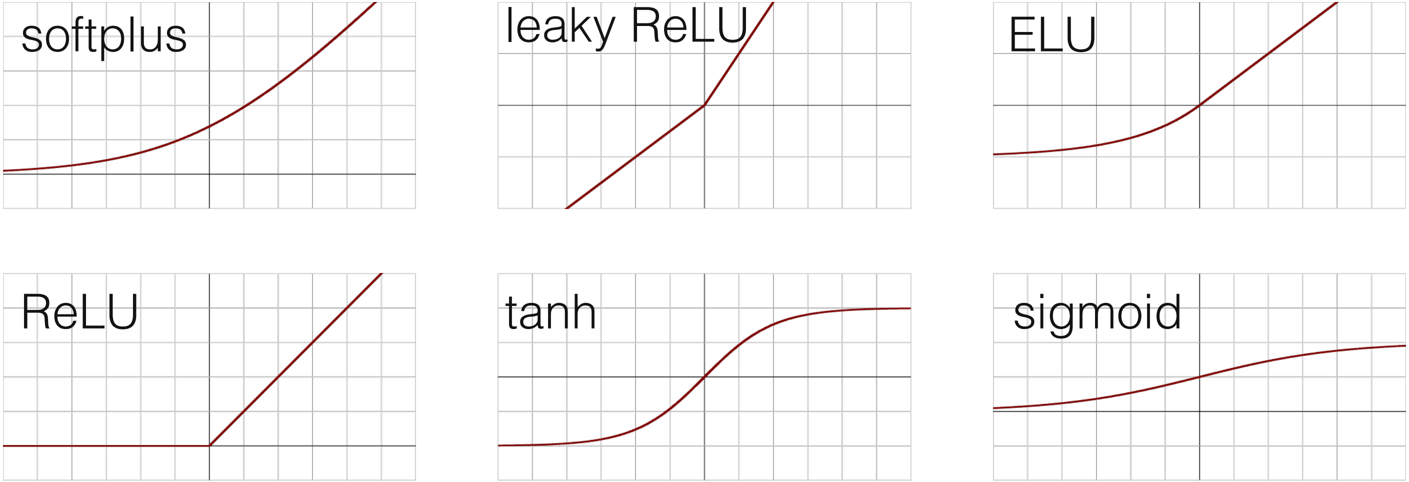
- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$
- 3-layer MLP $f = W_3 \max(0, W_2 \max(0, W_1 x))$

Otherwise we have:

$$f = W_3 W_2 W_1 x$$

Activation Functions

…many to choose from

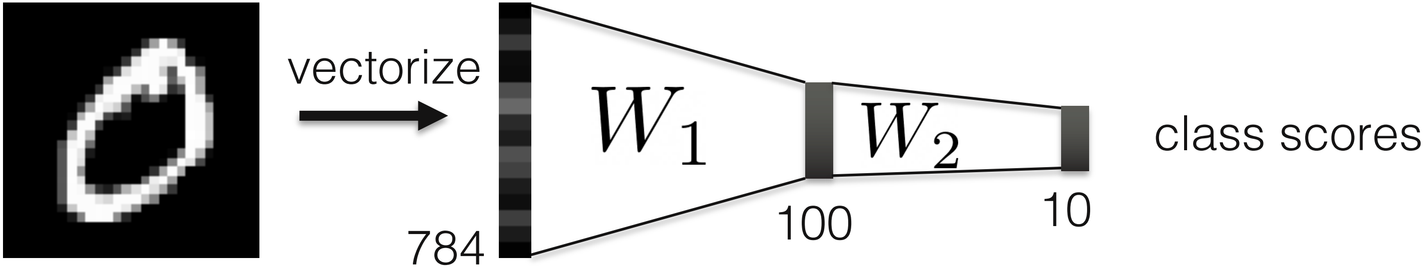


… ReLU is a good general-purpose choice: ReLU(x) = max(0, x)

Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$

Back to our classification example…

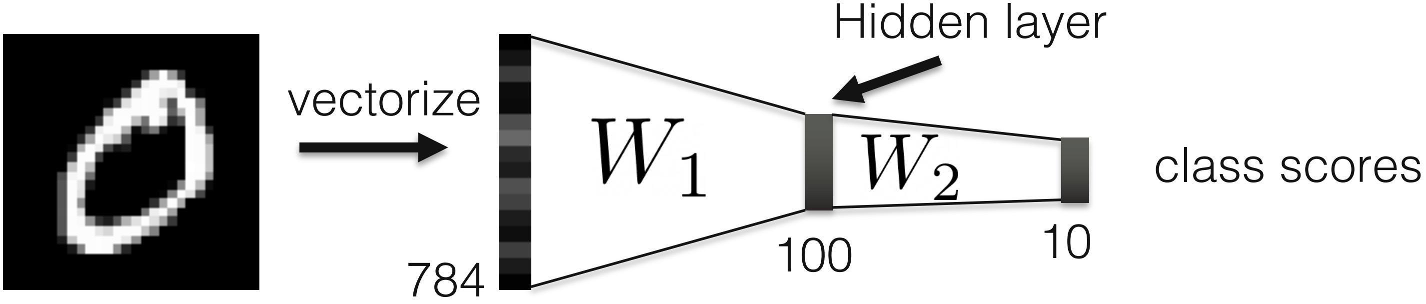


$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$

Back to our classification example…

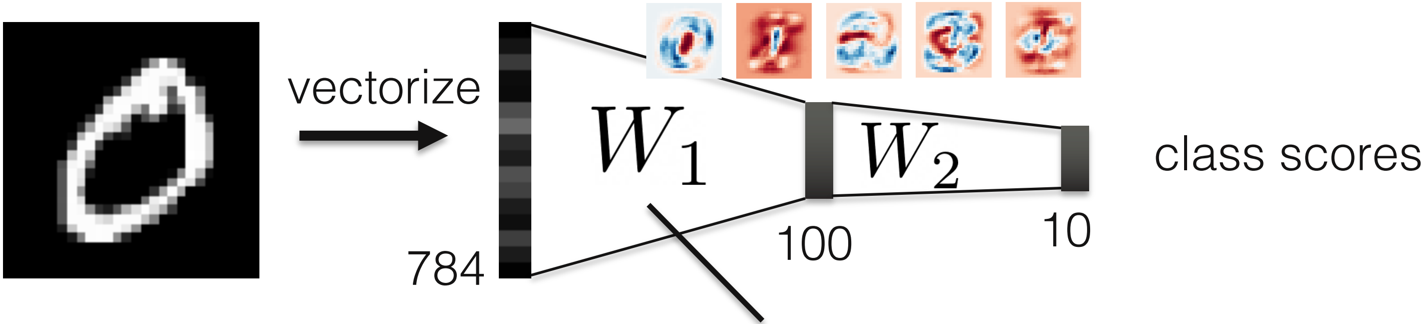


$$x \in \mathbb{R}^D, W_1 \in \mathbb{R}^{H \times D}, W_2 \in \mathbb{R}^{C \times H}$$

Multilayer Perceptrons (MLPs)

- Linear Model $f = Wx$
- 2-layer MLP $f = W_2 \max(0, W_1 x)$

Back to our classification example…



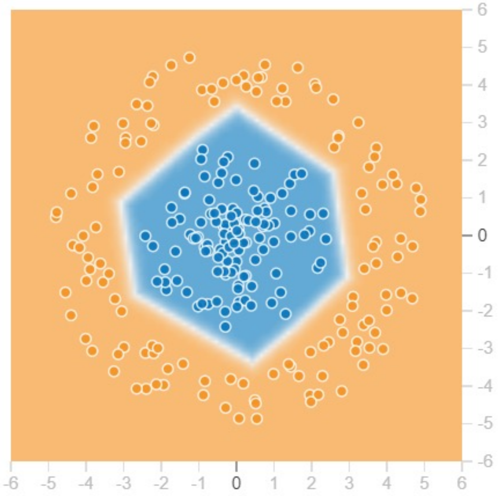
Now we have 100 shape templates, shared between classes

Multilayer Perceptrons (MLPs)

- Overcomes limits of linear classifiers

    - Can learn non-linear decision boundaries

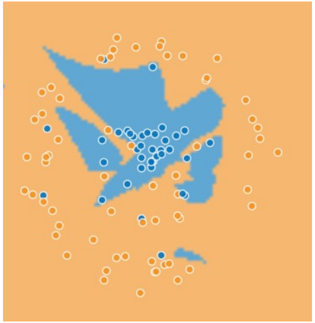
    - Complexity scales with the number of neurons/hidden layers



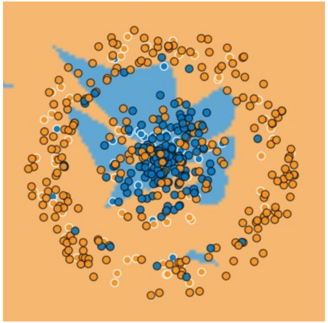
Multilayer Perceptrons (MLPs)

- More parameters is not always better!
  - Can lead to overfitting the training data
  - Performance on test data is worse

train

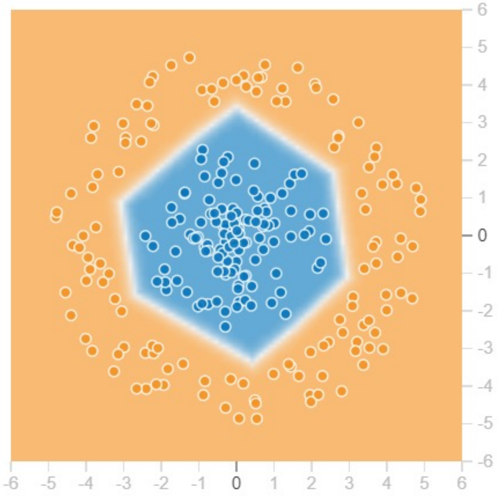


test



Multilayer Perceptrons (MLPs)

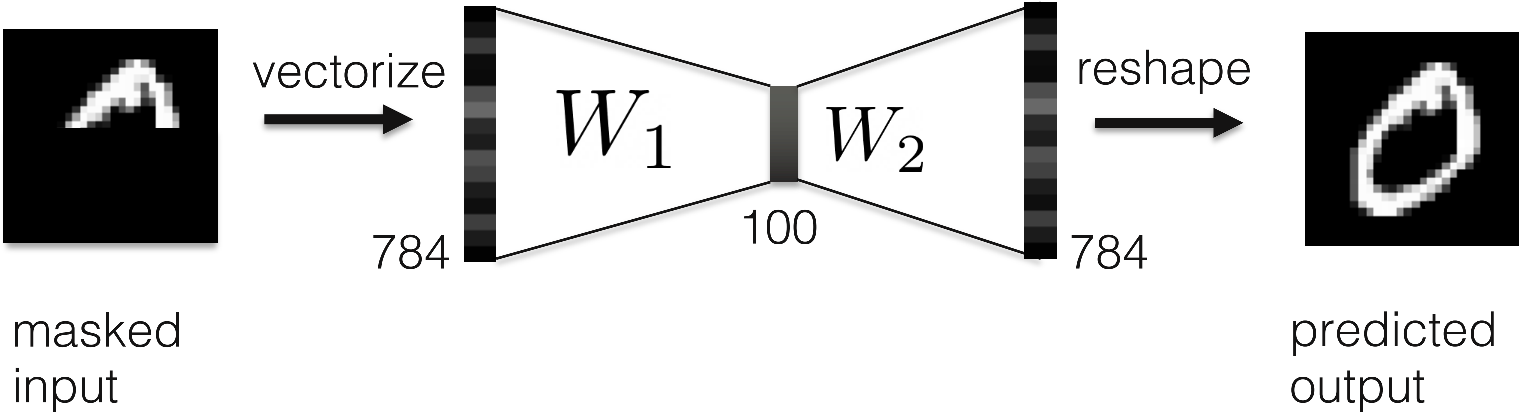
- More on classification…
  - https://cs231n.github.io/linear-classify/
  - https://csc413-uoft.github.io/



Today

- What is a neural network?
- Training/optimizing neural nets
- Why "neural"?
- Convolutional neural networks
- Applications & inverse problems

Image Inpainting



Training the MLP

Image inpainting example

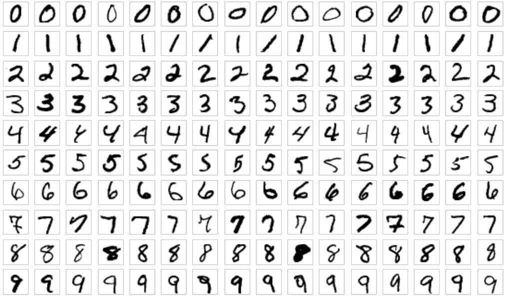
Training dataset:

- masked and complete image pairs

- train network to predict the complete image

masked images

ground truth



Training the MLP

Train the network to minimize the loss function

$$\mathcal{L}_\theta = \frac{1}{2}||y - \hat{y}||_2^2$$

network parameters

$\theta = \{W_1, W_2\}$

Training the MLP

Train the network to minimize the loss function

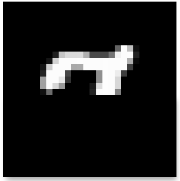
$$\mathcal{L}_\theta = \frac{1}{2}||y - \hat{y}||_2^2$$

network parameters

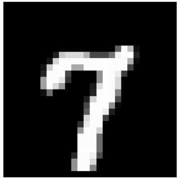
$\theta = \{W_1, W_2\}$

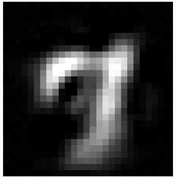
ground truth image

network prediction



input





Training the MLP

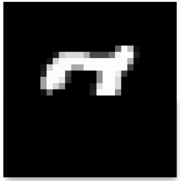
How do we figure out θ?

$$\mathcal{L}_\theta = \frac{1}{2}||y - \hat{y}||_2^2$$

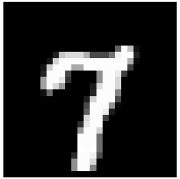
network parameters
$\theta = \{W_1, W_2\}$

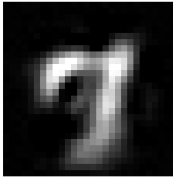
ground truth image

network prediction



input

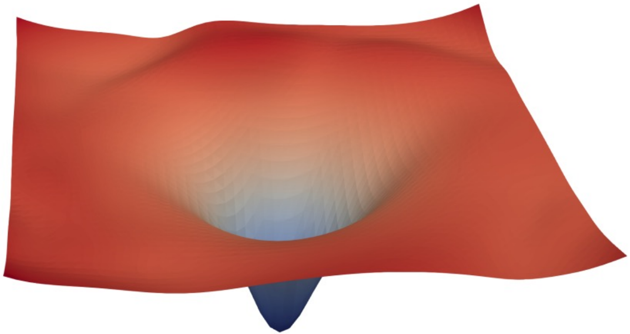




Training the MLP

Gradient-based optimization

$$\nabla_\theta \mathcal{L}_\theta$$



Loss Landscape

[Li et al. '18]

Training the MLP

$$\frac{\partial}{\partial W_1}\mathcal{L}_\theta = \frac{\partial}{\partial W_1}\frac{1}{2}\|y - \hat{y}\|_2^2$$

$$\frac{\partial}{\partial W_2}\mathcal{L}_\theta = \frac{\partial}{\partial W_2}\frac{1}{2}\|y - \hat{y}\|_2^2$$

Need to calculate the partial derivative with respect to each parameter

Training the MLP

Generally there are 3 options

1. Numerical differentiation
2. Symbolic differentiation
3. “Automatic” differentiation

Numerical Differentiation

$$\frac{\partial f(x)}{\partial x} \approx \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$$

Not very accurate, computationally expensive

Easy to implement! Can be used to check your analytical answers..

Symbolic Differentiation

$$
\begin{aligned}
\frac{\partial \mathcal{L}_\theta}{\partial W_1} &= \frac{\partial}{\partial W_1} \frac{1}{2} \|y - \hat{y}\|_2^2 \\
&= \frac{\partial}{\partial W_1} \frac{1}{2} \left(W_2 \sigma(W_1 x)\right)^T \left(W_2 \sigma(W_1 x)\right) \\
&= \frac{\partial}{\partial W_1} \frac{1}{2} \sigma(W_1 x)^T W_2^T W_2 \sigma(W_1 x) \\
&= \ldots \quad \text{chain rule, product rule…}
\end{aligned}
$$

Accurate, but must be manually calculated for each term
Tedious!

Automatic Differentiation

Think about the problem as a "computational graph"

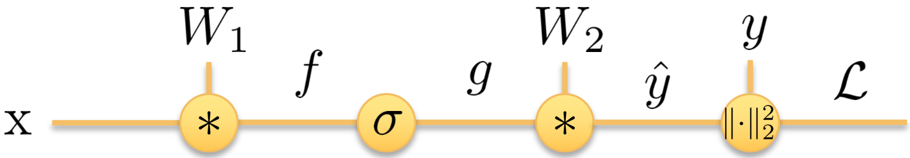
Divide and conquer using the chain rule

Enables "backpropagation" – an efficient way to take derivatives of all parameters in a computational graph

Automatic Differentiation

Think about the problem as a "computational graph"

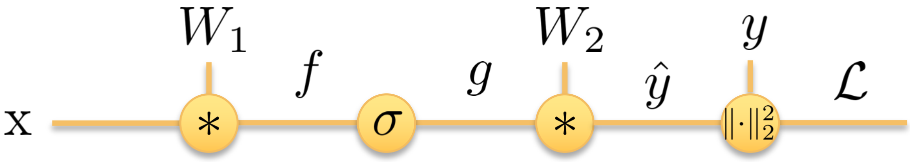
Divide and conquer using the chain rule



Automatic Differentiation

Think about the problem as a "computational graph"

Divide and conquer using the chain rule

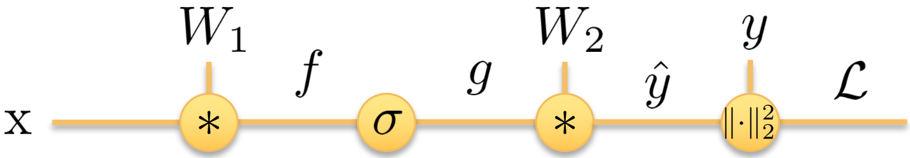


$$\frac{\partial \mathcal{L}}{\partial W_2} = \frac{\partial \hat{y}}{\partial W_2} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Automatic Differentiation

Think about the problem as a "computational graph"

Divide and conquer using the chain rule

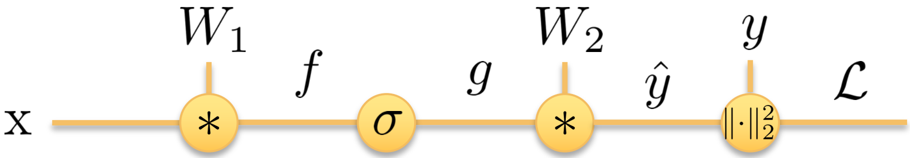


$$\frac{\partial \mathcal{L}}{\partial W_1} = \frac{\partial f}{\partial W_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Automatic Differentiation

Think about the problem as a "computational graph"

Divide and conquer using the chain rule

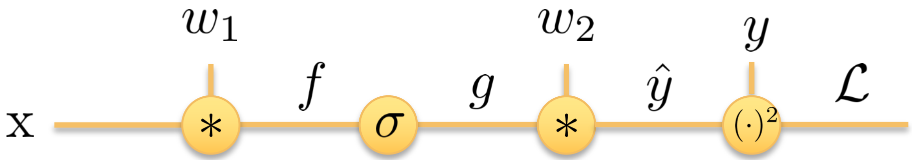


$$\frac{\partial \mathcal{L}}{\partial W_1} = \frac{\partial f}{\partial W_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

We can calculate analytical expressions for each of these terms and then plug in our values

Autodiff Example

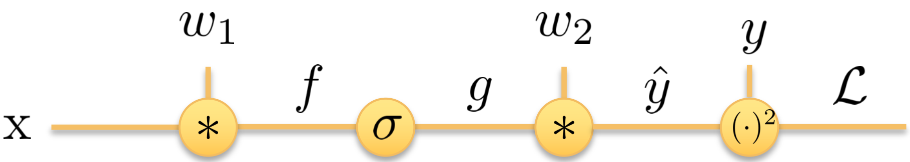
(assume scalar values for now)



$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \boxed{\frac{\partial \mathcal{L}}{\partial \hat{y}}}$$

Autodiff Example

(assume scalar values for now)

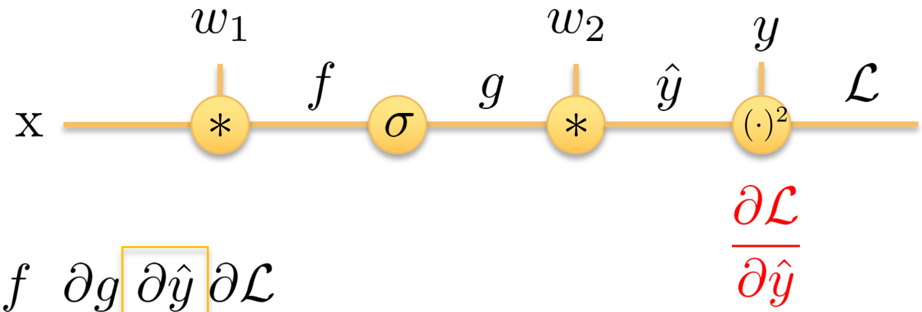


$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \boxed{\frac{\partial \mathcal{L}}{\partial \hat{y}}}$$

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \frac{\partial}{\partial \hat{y}} \frac{1}{2} (\hat{y} - y)^2 = \hat{y} - y$$

Autodiff Example

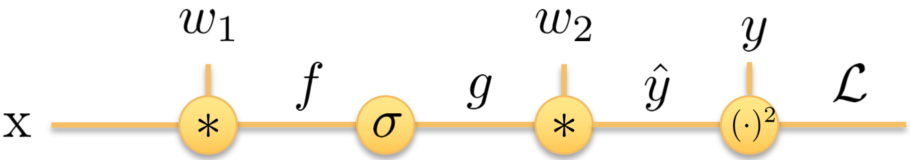
(assume scalar values for now)



$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \boxed{\frac{\partial \hat{y}}{\partial g}} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example

(assume scalar values for now)



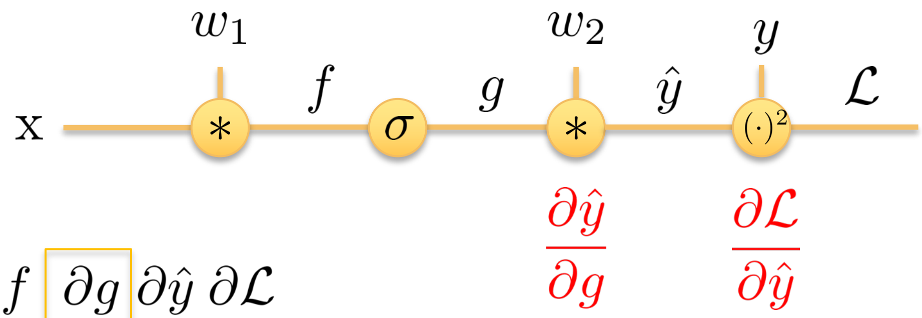
$$\frac{\partial \mathcal{L}}{\partial \hat{y}}$$

$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} w_2 \cdot g = w_2$$

Autodiff Example

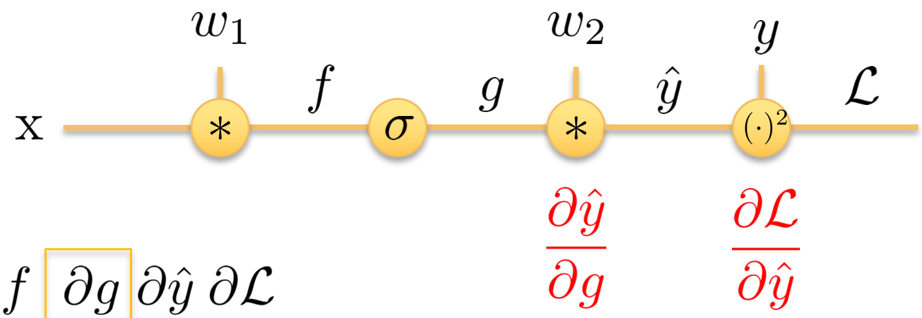
(assume scalar values for now)



$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \boxed{\frac{\partial g}{\partial f}} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example

(assume scalar values for now)

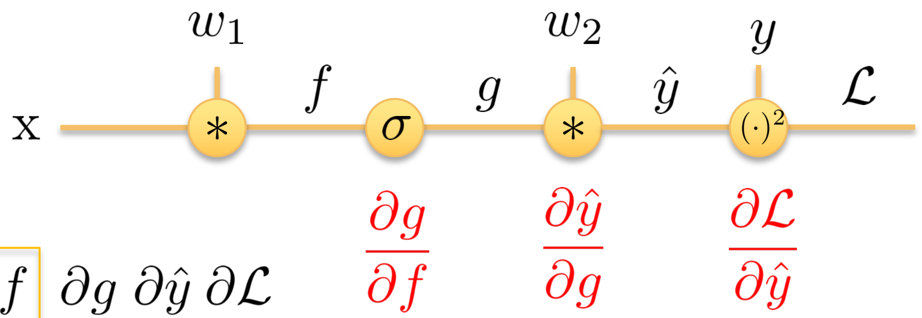


$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

$$\frac{\partial g}{\partial f} = \frac{\partial}{\partial f}\sigma(f) = \frac{\partial}{\partial f}\max(0, f) = \begin{cases} 0, & f < 0 \\ 1 & \text{else} \end{cases}$$

Autodiff Example

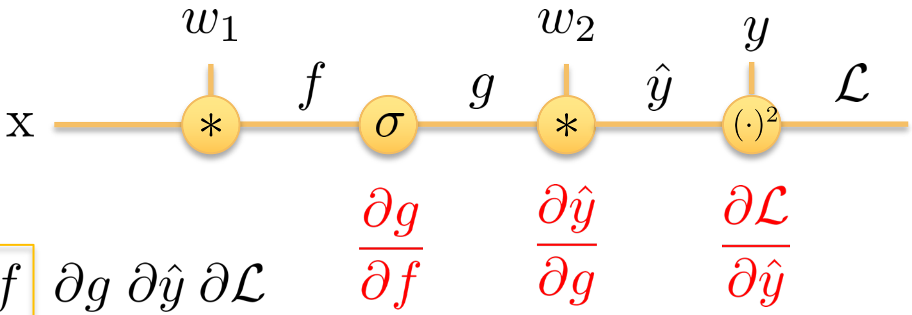
(assume scalar values for now)



$$\frac{\partial \mathcal{L}}{\partial w_1} = \boxed{\frac{\partial f}{\partial w_1}} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example

(assume scalar values for now)

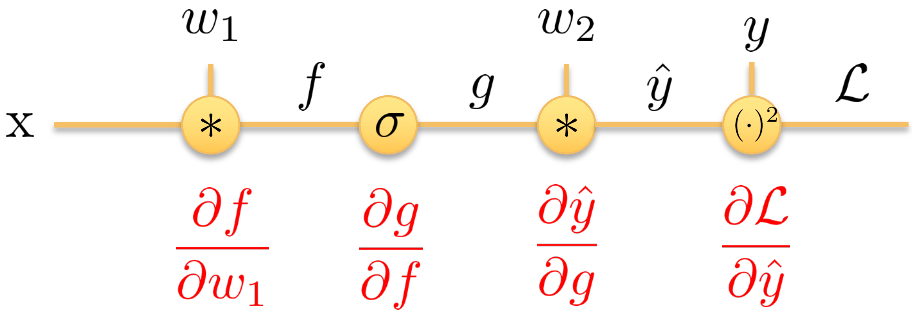


$$\frac{\partial \mathcal{L}}{\partial w_1} = \frac{\partial f}{\partial w_1} \frac{\partial g}{\partial f} \frac{\partial \hat{y}}{\partial g} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

$$\frac{\partial f}{\partial w_1} = \frac{\partial}{\partial w_1} w_1 \cdot x = x$$

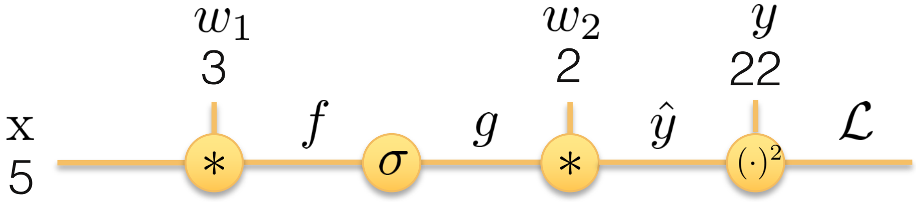
Autodiff Example

(assume scalar values for now)



Autodiff Example

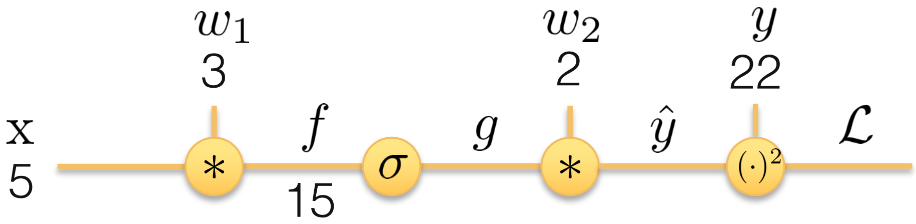
Let's plug in the values now…



$$\frac{\partial f}{\partial w_1} \quad \frac{\partial g}{\partial f} \quad \frac{\partial \hat{y}}{\partial g} \quad \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example

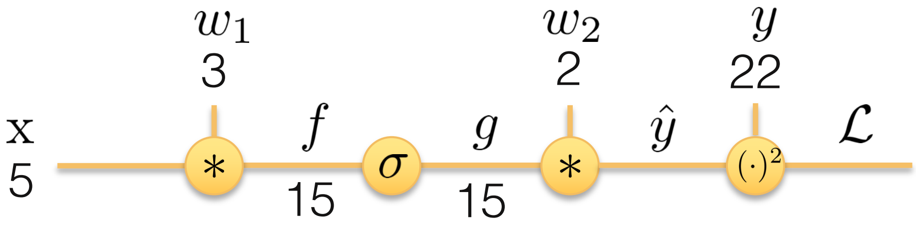
Let's plug in the values now…



$$\frac{\partial f}{\partial w_1} \quad \frac{\partial g}{\partial f} \quad \frac{\partial \hat{y}}{\partial g} \quad \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example

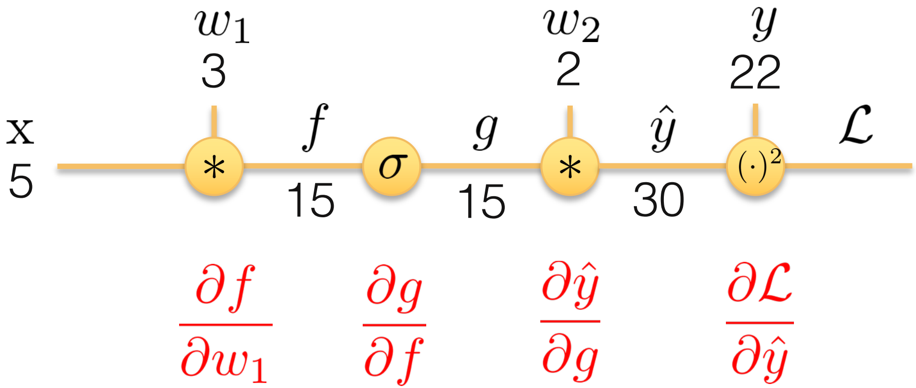
Let's plug in the values now…



$$\frac{\partial f}{\partial w_1} \quad \frac{\partial g}{\partial f} \quad \frac{\partial \hat{y}}{\partial g} \quad \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

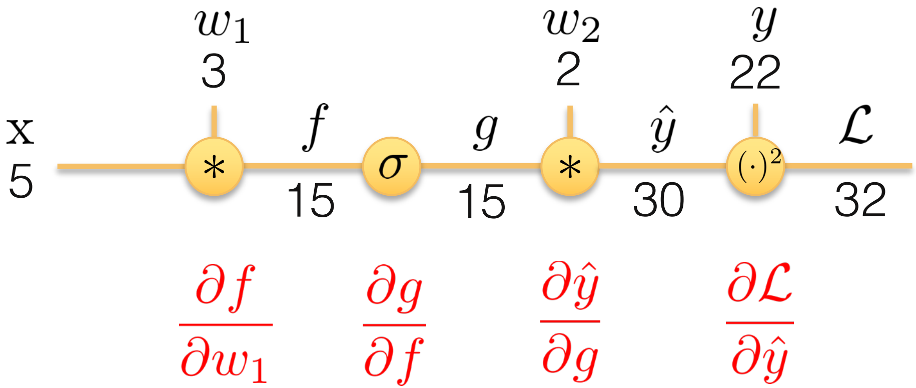
Autodiff Example

Let's plug in the values now…



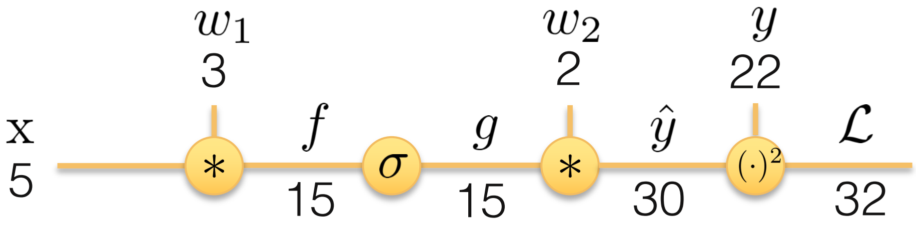
Autodiff Example

Let's plug in the values now…



Autodiff Example

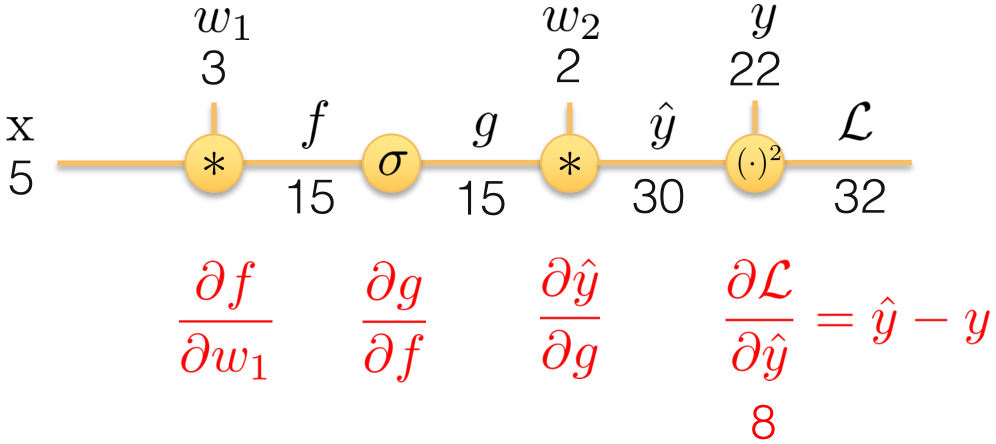
Let's plug in the values now…



$$\frac{\partial f}{\partial w_1} \qquad \frac{\partial g}{\partial f} \qquad \frac{\partial \hat{y}}{\partial g} \qquad \frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$

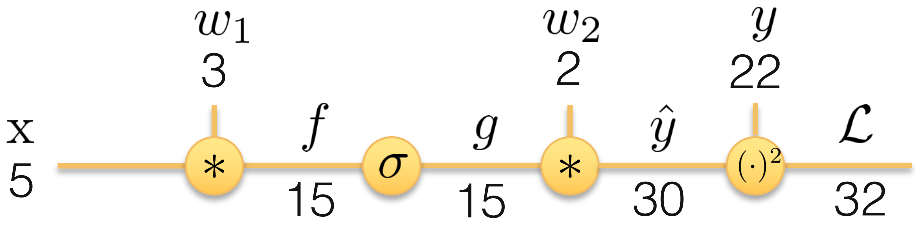
Autodiff Example

Let's plug in the values now…



Autodiff Example

Let's plug in the values now…



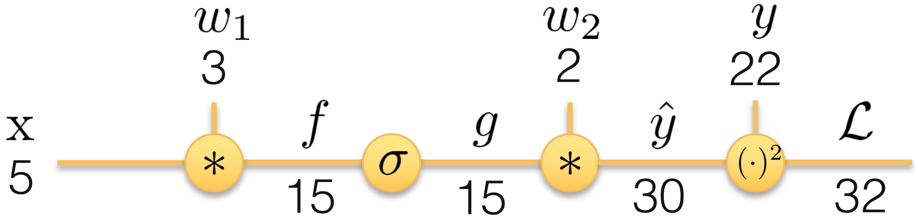
$$\frac{\partial f}{\partial w_1} \quad \frac{\partial g}{\partial f} \quad \frac{\partial \hat{y}}{\partial g} \quad \frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$

2

8

Autodiff Example

Let’s plug in the values now…

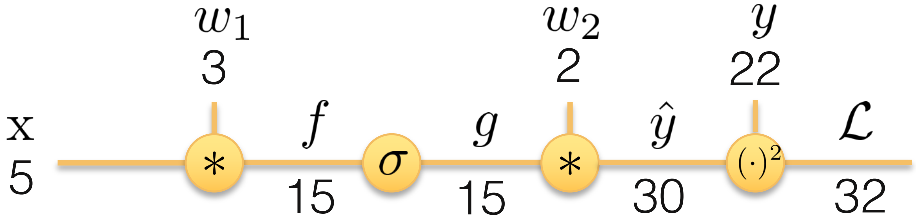


$$\frac{\partial f}{\partial w_1} \qquad \frac{\partial g}{\partial f} \qquad \frac{\partial \hat{y}}{\partial g} \qquad \frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$

1   2   8

Autodiff Example

Let's plug in the values now…

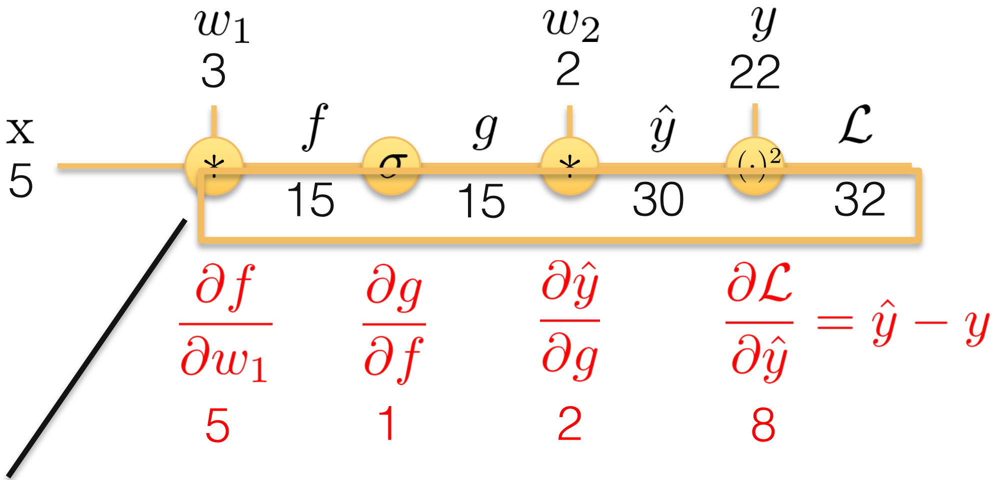


$$\frac{\partial f}{\partial w_1} \quad \frac{\partial g}{\partial f} \quad \frac{\partial \hat{y}}{\partial g} \quad \frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$

5   1   2   8

Autodiff Example

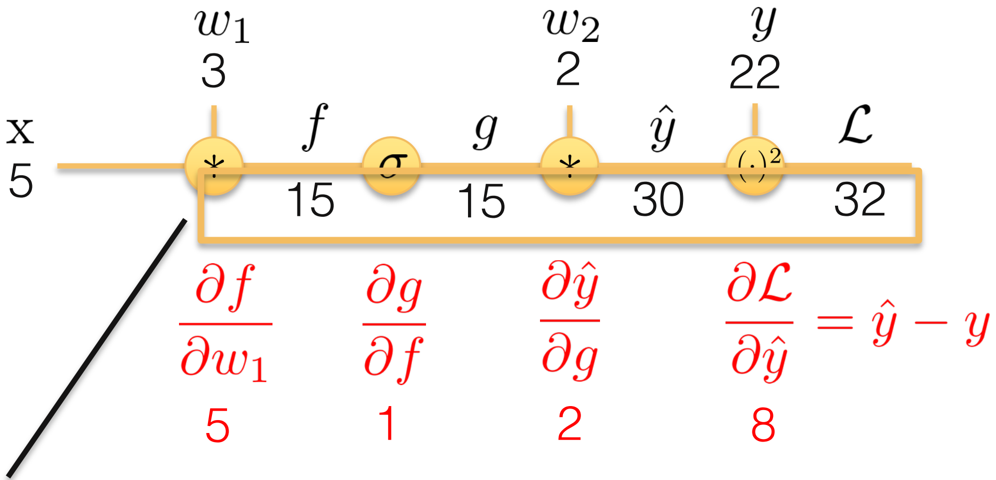
What is backpropagation?



Save these intermediate values during forward computation

Autodiff Example

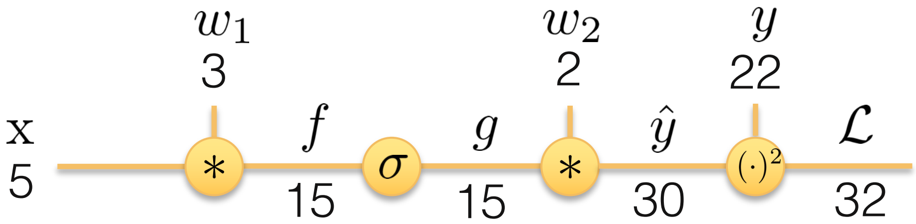
What is backpropagation?



Then we perform a "backward pass"

Autodiff Example

What is backpropagation?



$$\frac{\partial f}{\partial w_1}$$
5

$$\frac{\partial g}{\partial f}$$
1

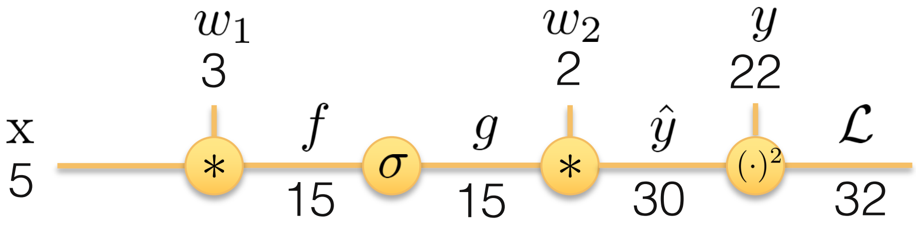
$$\frac{\partial \hat{y}}{\partial g}$$
2

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$
8

$$\frac{\partial \mathcal{L}}{\partial g}$$

Autodiff Example

What is backpropagation?



$$\frac{\partial f}{\partial w_1}$$
5

$$\frac{\partial g}{\partial f}$$
1

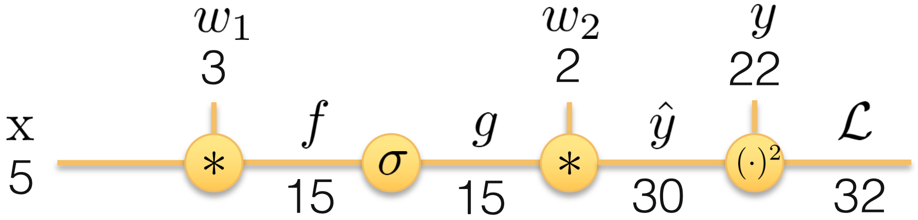
$$\frac{\partial \hat{y}}{\partial g}$$
2

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$
8

$$\frac{\partial \mathcal{L}}{\partial g}$$
16

Autodiff Example

What is backpropagation?



$\frac{\partial f}{\partial w_1}$ 5

$\frac{\partial g}{\partial f}$ 1

$\frac{\partial \mathcal{L}}{\partial f}$

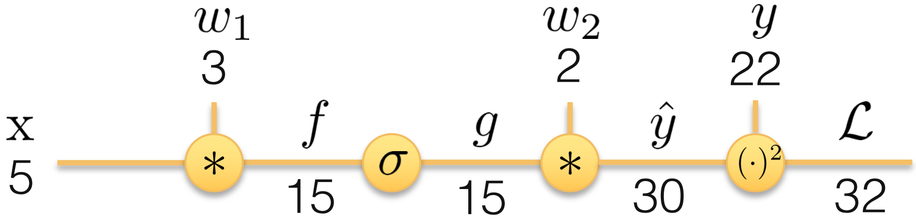
$\frac{\partial \hat{y}}{\partial g}$ 2

$\frac{\partial \mathcal{L}}{\partial g}$ 16

$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$ 8

Autodiff Example

What is backpropagation?



$$\frac{\partial f}{\partial w_1}$$
5

$$\frac{\partial g}{\partial f}$$
1

$$\frac{\partial \mathcal{L}}{\partial f}$$
16

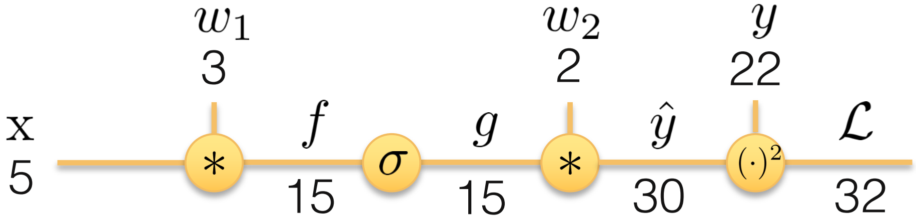
$$\frac{\partial \hat{y}}{\partial g}$$
2

$$\frac{\partial \mathcal{L}}{\partial g}$$
16

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$
8

Autodiff Example

What is backpropagation?



$$\frac{\partial f}{\partial w_1}$$
5

$$\frac{\partial g}{\partial f}$$
1

$$\frac{\partial \hat{y}}{\partial g}$$
2

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$
8

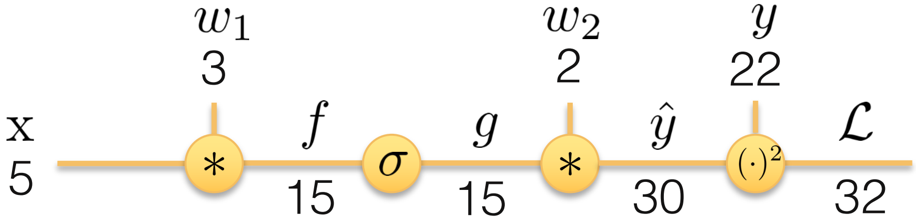
$$\frac{\partial \mathcal{L}}{\partial w_1}$$

$$\frac{\partial \mathcal{L}}{\partial f}$$
16

$$\frac{\partial \mathcal{L}}{\partial g}$$
16

Autodiff Example

What is backpropagation?



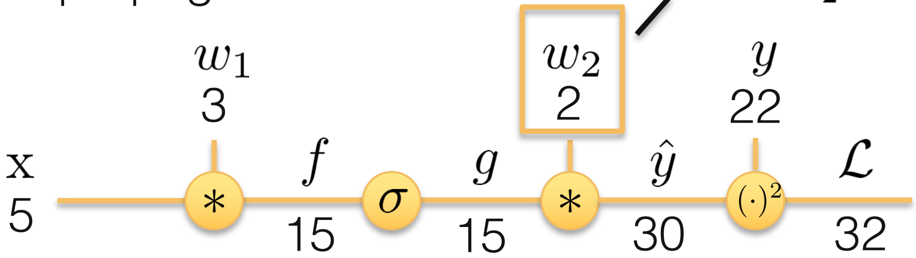
$$\frac{\partial f}{\partial w_1} \quad 5 \qquad \frac{\partial g}{\partial f} \quad 1 \qquad \frac{\partial \hat{y}}{\partial g} \quad 2 \qquad \frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y \quad 8$$

$$\frac{\partial \mathcal{L}}{\partial w_1} \quad 80 \qquad \frac{\partial \mathcal{L}}{\partial f} \quad 16 \qquad \frac{\partial \mathcal{L}}{\partial g} \quad 16$$

Autodiff Example

What is backpropagation?

What about $\frac{\partial \mathcal{L}}{\partial w_2}$?



$$\frac{\partial f}{\partial w_1}$$
5

$$\frac{\partial g}{\partial f}$$
1

$$\frac{\partial \hat{y}}{\partial g}$$
2

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$
8

$$\frac{\partial \mathcal{L}}{\partial w_1}$$
80

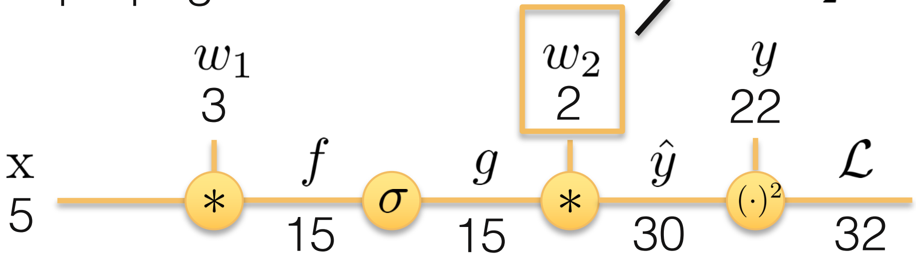
$$\frac{\partial \mathcal{L}}{\partial f}$$
16

$$\frac{\partial \mathcal{L}}{\partial g}$$
16

Autodiff Example

What is backpropagation?

What about $\frac{\partial \mathcal{L}}{\partial w_2}$?



$$\frac{\partial f}{\partial w_1} \quad 5 \qquad \frac{\partial g}{\partial f} \quad 1 \qquad \frac{\partial \hat{y}}{\partial g} \quad 2$$

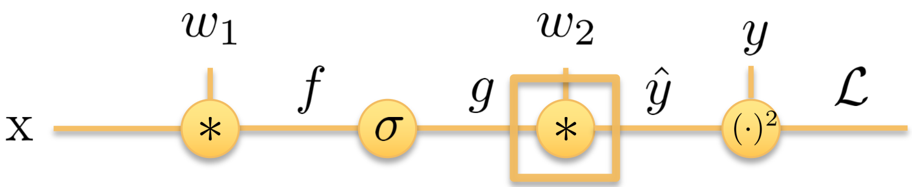
$$\frac{\partial \mathcal{L}}{\partial w_1} \quad 80 \qquad \frac{\partial \mathcal{L}}{\partial f} \quad 16 \qquad \frac{\partial \mathcal{L}}{\partial g} \quad 16$$

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = \hat{y} - y$$

We can re-use computation!

$$\frac{\partial \mathcal{L}}{\partial w_2} = \frac{\partial \hat{y}}{\partial w_2} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

Autodiff Example



PyTorch Code:

```
class Multiply(torch.autograd.Function):
  @staticmethod
  def forward(ctx, x, y):
    ctx.save_for_backward(x, y)
    z = x * y
    return z
  @staticmethod
  def backward(ctx, grad_z):
    x, y = ctx.saved_tensors
    grad_x = y * grad_z    # dz/dx * dL/dz
    grad_y = x * grad_z    # dz/dy * dL/dz
    return grad_x, grad_y
```

Need to stash some values for use in backward

Upstream gradient

Multiply upstream and local gradients

Image Inpainting Training Loop

1. Sample batch of images from dataset

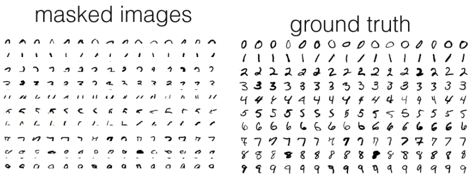
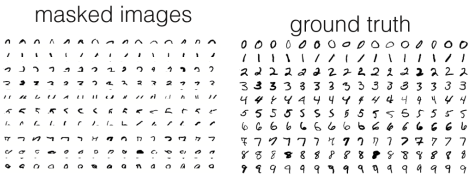


Image Inpainting Training Loop

1. Sample batch of images from dataset



2. Run forward pass to calculate network output for each image

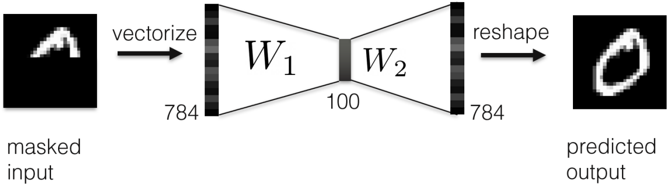
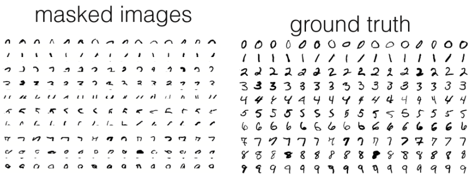
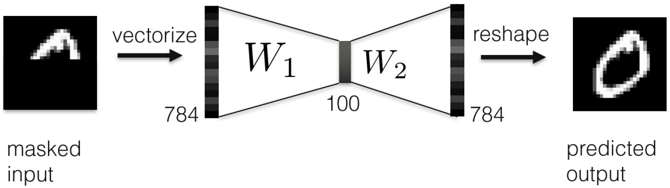


Image Inpainting Training Loop

1. Sample batch of images from dataset



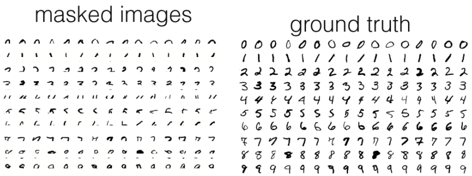
2. Run forward pass to calculate network output for each image



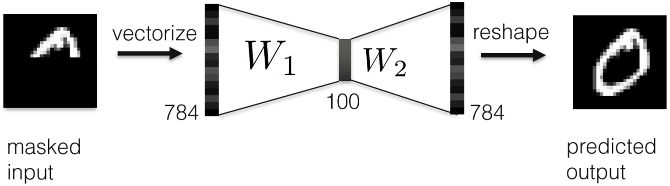
3. Run backward pass to calculate gradients with backpropagation

Image Inpainting Training Loop

1. Sample batch of images from dataset



2. Run forward pass to calculate network output for each image



3. Run backward pass to calculate gradients with backpropagation

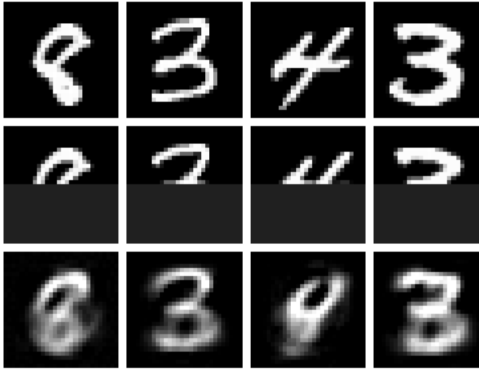
4. Update parameters with stochastic gradient descent

4. Update parameters with stochastic gradient descent

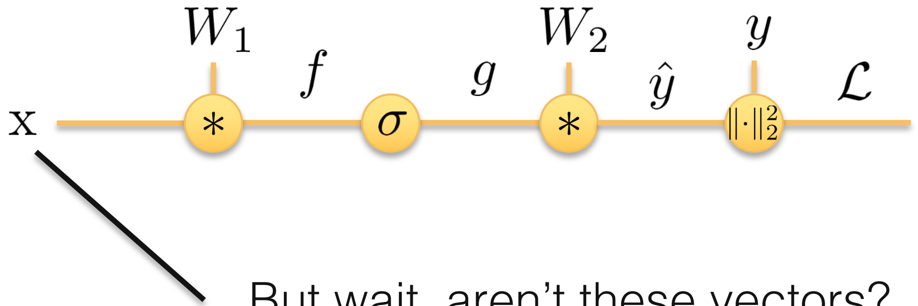
$$\mathcal{L}_\theta = \|y - \hat{y}\|_2^2$$

$$W_2^{(k+1)} = W_2^{(k)} - \alpha \frac{\partial \mathcal{L}}{\partial W_2}$$

$$W_1^{(k+1)} = W_1^{(k)} - \alpha \frac{\partial \mathcal{L}}{\partial W_1}$$

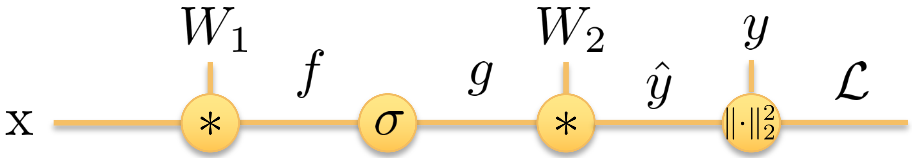


Vector Differentiation



But wait, aren't these vectors?

Vector Differentiation



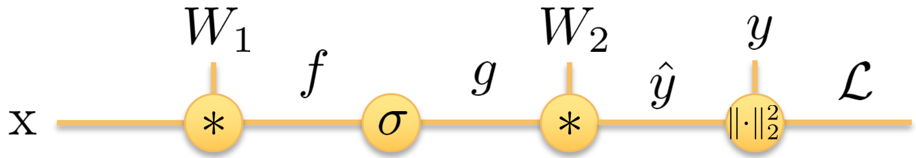
Recap: vector differentiation

Scalar by Scalar

$$x, y \in \mathbb{R}$$

$$\frac{\partial y}{\partial x} \in ?$$

Vector Differentiation



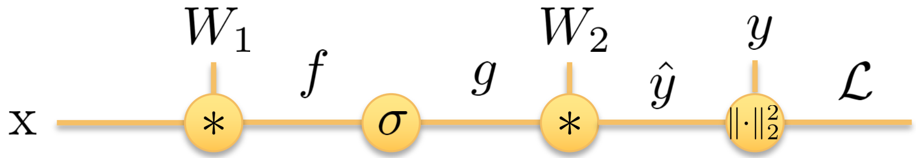
Recap: vector differentiation

Scalar by Scalar

$$x, y \in \mathbb{R}$$

$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

Vector Differentiation



Recap: vector differentiation

Scalar by Scalar

$$x, y \in \mathbb{R}$$

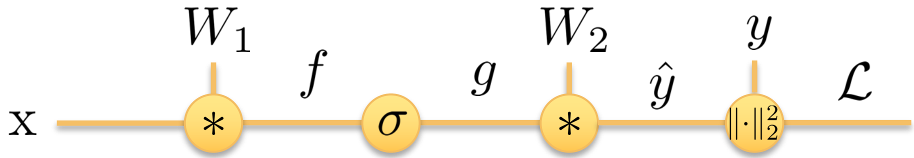
$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

Scalar by Vector

$$x \in \mathbb{R}^N, y \in \mathbb{R}$$

$$\frac{\partial y}{\partial x} \in \ ?$$

Vector Differentiation



Recap: vector differentiation

Scalar by Scalar

$$x, y \in \mathbb{R}$$

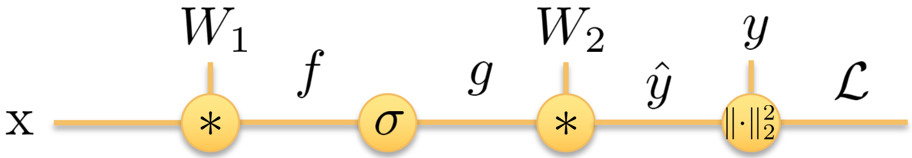
$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

Scalar by Vector

$$x \in \mathbb{R}^N, y \in \mathbb{R}$$

$$\frac{\partial y}{\partial x} \in \mathbb{R}^N$$

Vector Differentiation



Recap: vector differentiation

Scalar by Scalar

$$x, y \in \mathbb{R}$$

$$\frac{\partial y}{\partial x} \in \mathbb{R}$$

Scalar by Vector

$$x \in \mathbb{R}^N, y \in \mathbb{R}$$

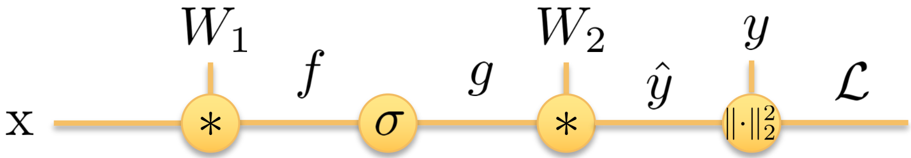
$$\frac{\partial y}{\partial x} \in \mathbb{R}^N$$

Vector by Vector

$$x \in \mathbb{R}^N, y \in \mathbb{R}^M$$

$$\frac{\partial y}{\partial x} \in \quad ?$$

Vector Differentiation



Recap: vector differentiation

Scalar by Scalar	Scalar by Vector	Vector by Vector
$x, y \in \mathbb{R}$	$x \in \mathbb{R}^N, y \in \mathbb{R}$	$x \in \mathbb{R}^N, y \in \mathbb{R}^M$
$\frac{\partial y}{\partial x} \in \mathbb{R}$	$\frac{\partial y}{\partial x} \in \mathbb{R}^N$	$\frac{\partial y}{\partial x} \in \mathbb{R}^{N \times M}$

Vector Differentiation

$$\underset{\in \mathbb{R}^P}{w} \longrightarrow \underset{\in \mathbb{R}^N}{x} \longrightarrow \underset{\in \mathbb{R}^M}{y}$$

$$\frac{\partial x}{\partial w} \in \mathbb{R}^{P \times N} \qquad \frac{\partial y}{\partial x} \in \mathbb{R}^{N \times M}$$

Vector Differentiation

$$w \in \mathbb{R}^P \longrightarrow x \in \mathbb{R}^N \longrightarrow y \in \mathbb{R}^M$$

$$\frac{\partial x}{\partial w} \in \mathbb{R}^{P \times N} \qquad \frac{\partial y}{\partial x} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial y}{\partial w} = \frac{\partial x}{\partial w}\frac{\partial y}{\partial x} \in \mathbb{R}^{P \times M}$$

Vector Differentiation

$$\underset{\in \mathbb{R}^P}{w} \longrightarrow \underset{\in \mathbb{R}^N}{x} \longrightarrow \underset{\in \mathbb{R}^M}{y}$$

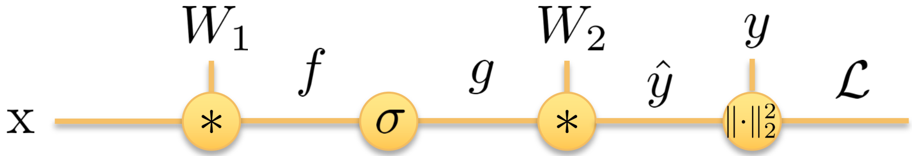
$$\frac{\partial x}{\partial w} \in \mathbb{R}^{P \times N} \qquad \frac{\partial y}{\partial x} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial y}{\partial w} = \frac{\partial x}{\partial w}\frac{\partial y}{\partial x} \in \mathbb{R}^{P \times M}$$

sometimes the Jacobian is defined as the transpose of this, depending on whether you left or right multiply

(I like to left multiply because it aligns with the direction of the computational graph)

Recap: vector differentiation



Example 1: matrix multiply

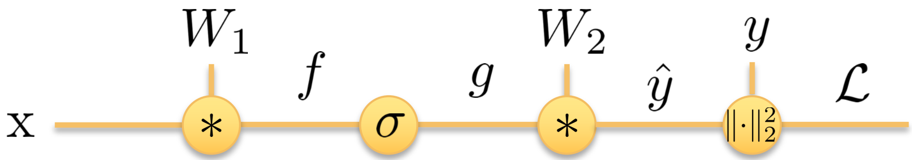
$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} W_2 g$$

$$W_2 \in \mathbb{R}^{M \times N}$$

$$g \in \mathbb{R}^N$$

$$\frac{\partial \hat{y}}{\partial g} \in \mathbb{R}^{N \times M}$$

Recap: vector differentiation



Example 1: matrix multiply

$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} W_2 g$$

$$W_2 \in \mathbb{R}^{M \times N}$$

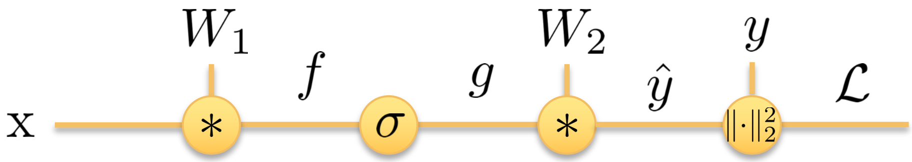
$$g \in \mathbb{R}^N$$

$$\frac{\partial \hat{y}}{\partial g} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial}{\partial g} W_2 g$$

$$= \frac{\partial}{\partial g} \begin{bmatrix} w_{11} g_1 + \cdots + w_{1n} g_n \\ \vdots \quad \ddots \quad \vdots \\ w_{m1} g_1 + \cdots + w_{mn} g_n \end{bmatrix}$$

Recap: vector differentiation



Example 1: matrix multiply

$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} W_2 g$$

$$W_2 \in \mathbb{R}^{M \times N}$$

$$g \in \mathbb{R}^{N}$$

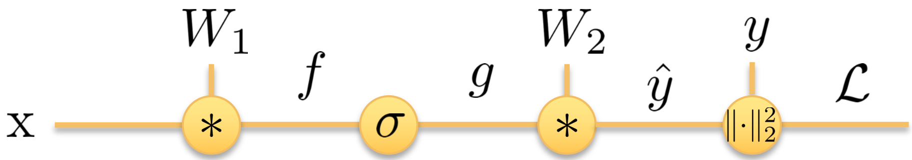
$$\frac{\partial \hat{y}}{\partial g} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial \hat{y}}{\partial g} = \begin{bmatrix} \frac{\partial \hat{y}_1}{\partial g_1} & \cdots & \frac{\partial \hat{y}_m}{\partial g_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \hat{y}_1}{\partial g_n} & \cdots & \frac{\partial \hat{y}_m}{\partial g_n} \end{bmatrix}$$

$$\frac{\partial}{\partial g} W_2 g$$

$$= \frac{\partial}{\partial g} \begin{bmatrix} w_{11} g_1 + \cdots + w_{1n} g_n \\ \vdots \quad \ddots \quad \vdots \\ w_{m1} g_1 + \cdots + w_{mn} g_n \end{bmatrix}$$

Recap: vector differentiation



$$\frac{\partial \hat{y}}{\partial g} = \begin{bmatrix} \frac{\partial \hat{y}_1}{\partial g_1} & \cdots & \frac{\partial \hat{y}_m}{\partial g_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \hat{y}_1}{\partial g_n} & \cdots & \frac{\partial \hat{y}_m}{\partial g_n} \end{bmatrix}$$

Example 1: matrix multiply

$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} W_2 g$$

$$W_2 \in \mathbb{R}^{M \times N}$$

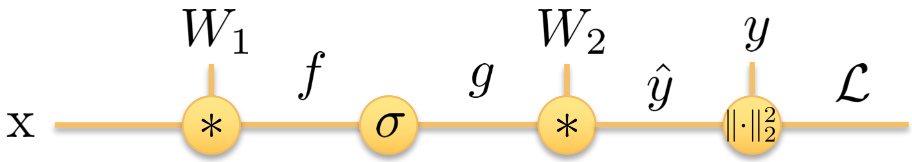
$$g \in \mathbb{R}^{N}$$

$$\frac{\partial \hat{y}}{\partial g} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial}{\partial g} W_2 g$$

$$= \frac{\partial}{\partial g} \begin{bmatrix} w_{11} g_1 + \cdots + w_{1n} g_n \\ \vdots \quad \ddots \quad \vdots \\ w_{m1} g_1 + \cdots + w_{mn} g_n \end{bmatrix} = \begin{bmatrix} w_{11} & \cdots & w_{m1} \\ \vdots & \ddots & \vdots \\ w_{1n} & \cdots & w_{mn} \end{bmatrix}$$

Recap: vector differentiation



$$\frac{\partial \hat{y}}{\partial g} = \begin{bmatrix} \frac{\partial \hat{y}_1}{\partial g_1} & \cdots & \frac{\partial \hat{y}_m}{\partial g_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \hat{y}_1}{\partial g_n} & \cdots & \frac{\partial \hat{y}_m}{\partial g_n} \end{bmatrix}$$

Example 1: matrix multiply

$$\frac{\partial \hat{y}}{\partial g} = \frac{\partial}{\partial g} W_2 g$$

$$W_2 \in \mathbb{R}^{M \times N}$$

$$g \in \mathbb{R}^N$$

$$\frac{\partial \hat{y}}{\partial g} \in \mathbb{R}^{N \times M}$$

$$\frac{\partial}{\partial g} W_2 g$$

$$= \frac{\partial}{\partial g} \begin{bmatrix} w_{11} g_1 + \cdots + w_{1n} g_n \\ \vdots \quad \ddots \quad \vdots \\ w_{m1} g_1 + \cdots + w_{mn} g_n \end{bmatrix} = \begin{bmatrix} w_{11} & \cdots & w_{m1} \\ \vdots & \ddots & \vdots \\ w_{1n} & \cdots & w_{mn} \end{bmatrix}$$

$$= \boxed{W_2^T}$$

Recap: vector differentiation

Example 2: elementwise functions

$$h = f \odot g$$

$$f \in \mathbb{R}^N$$

$$g \in \mathbb{R}^N$$

$$\frac{\partial h}{\partial f} \in \mathbb{R}^{N \times N}$$

Recap: vector differentiation

Example 2: elementwise functions

$$h = f \odot g$$

$$f \in \mathbb{R}^N$$

$$g \in \mathbb{R}^N$$

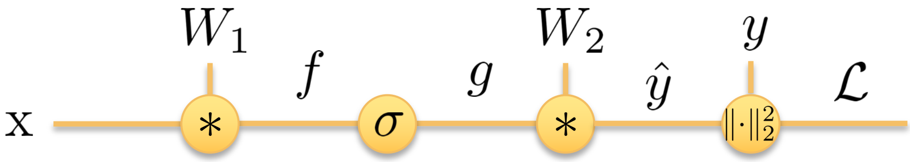
$$\frac{\partial h}{\partial f} \in \mathbb{R}^{N \times N}$$

$$\frac{\partial h}{\partial f} = \begin{bmatrix} \frac{\partial h_1}{\partial f_1} & \cdots & \frac{\partial h_n}{\partial f_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial h_1}{\partial f_n} & \cdots & \frac{\partial h_n}{\partial f_n} \end{bmatrix}$$

$$\frac{\partial h}{\partial f} = \begin{bmatrix} g_1 & & 0 \\ & \ddots & \\ 0 & & g_n \end{bmatrix} = \mathrm{diag}(g)$$

Recap: vector differentiation

Final hint: dimensions should always match up!



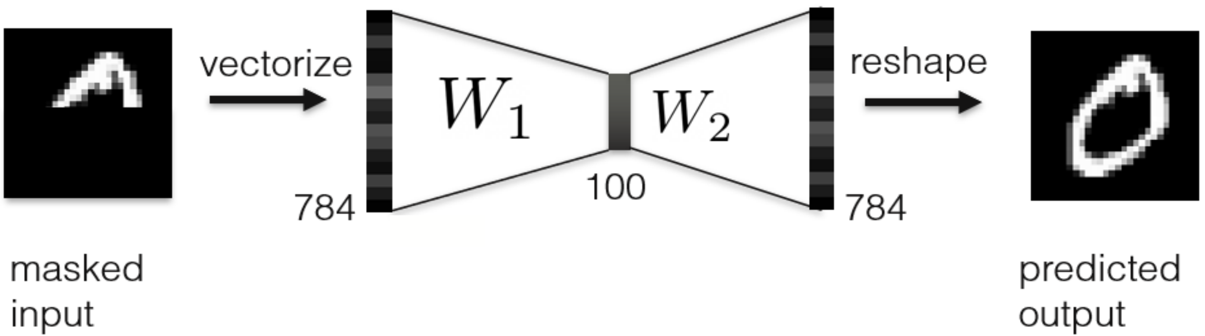
$$\frac{\partial \mathcal{L}}{\partial W_1} = \frac{\partial f}{\partial W_1}\frac{\partial g}{\partial f}\frac{\partial \hat{y}}{\partial g}\frac{\partial \mathcal{L}}{\partial \hat{y}}$$

You should be able to calculate derivatives of each of these terms and then perform matrix multiplications without issues

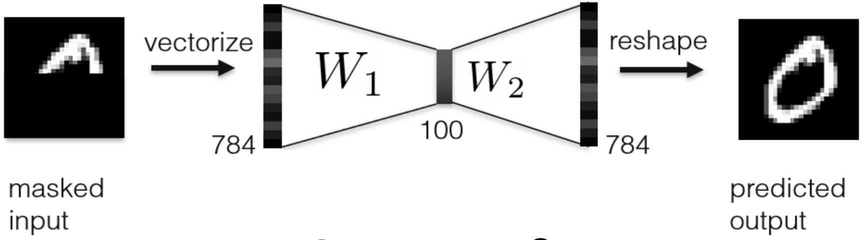
Today

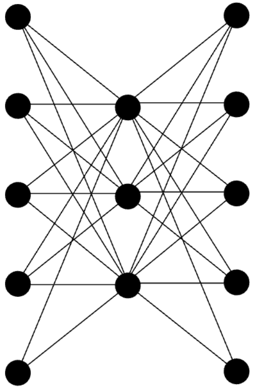
- What is a neural network?
- Training/optimizing neural nets
- Why “neural”?
- Convolutional neural networks
- Applications & inverse problems

Why “neural” network?

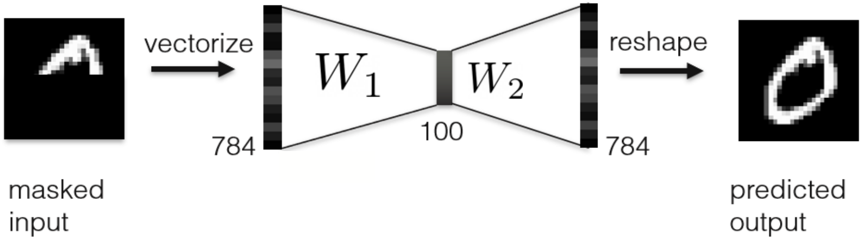


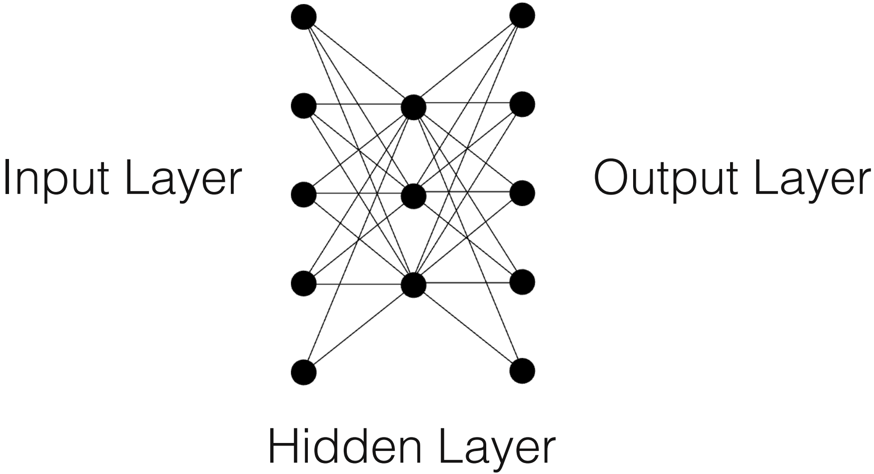
Why "neural" network?



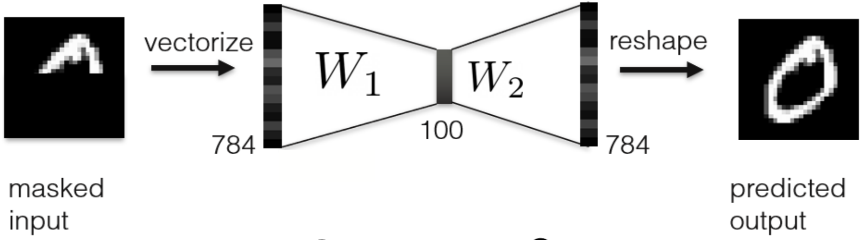


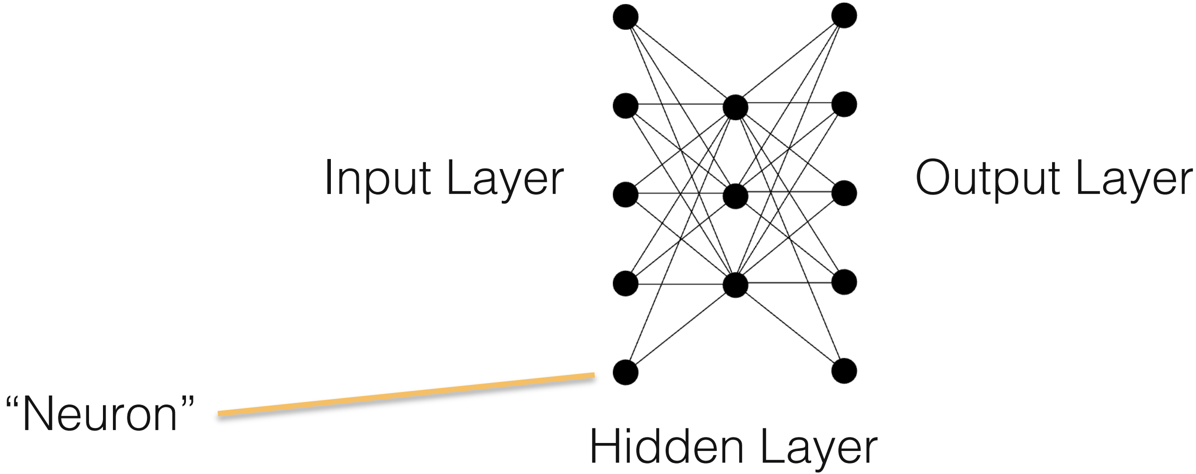
Why “neural” network?



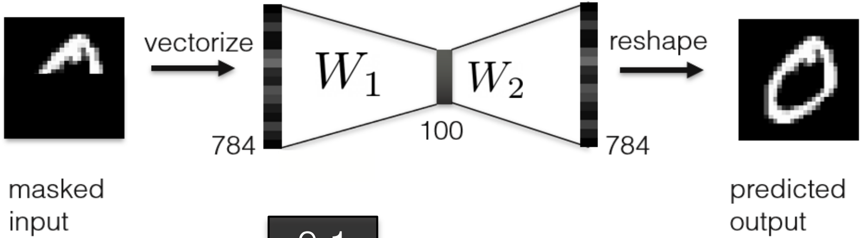


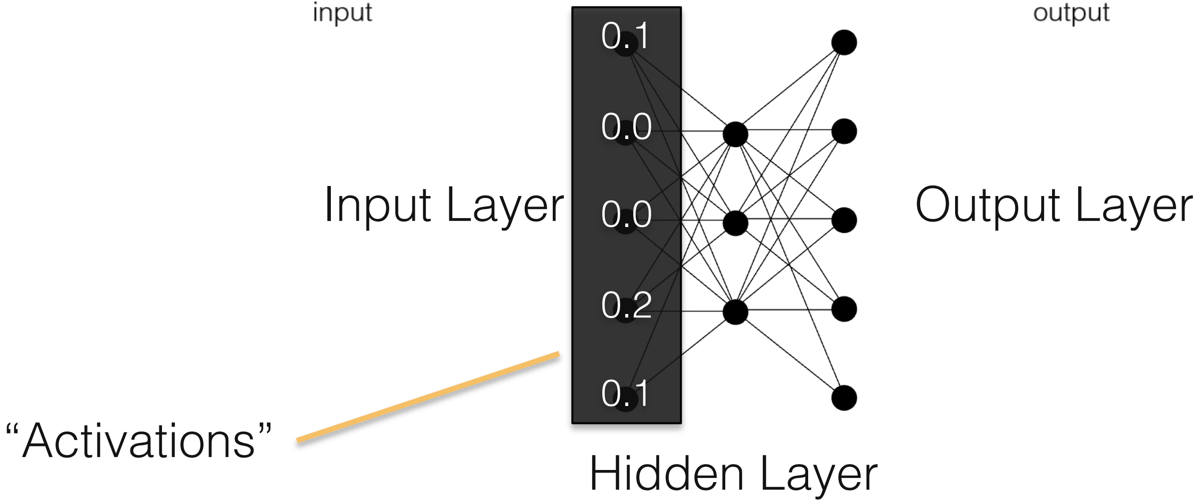
Why “neural” network?



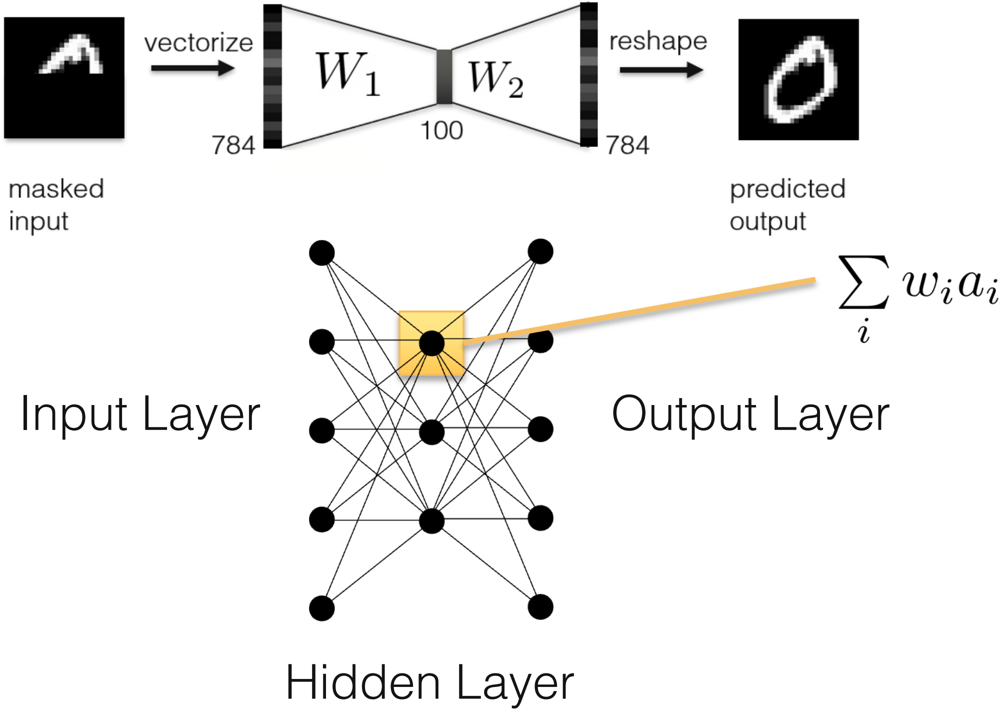


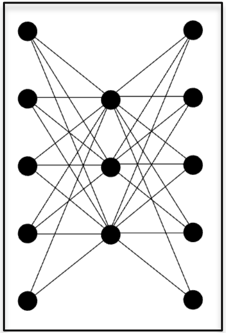
Why “neural” network?

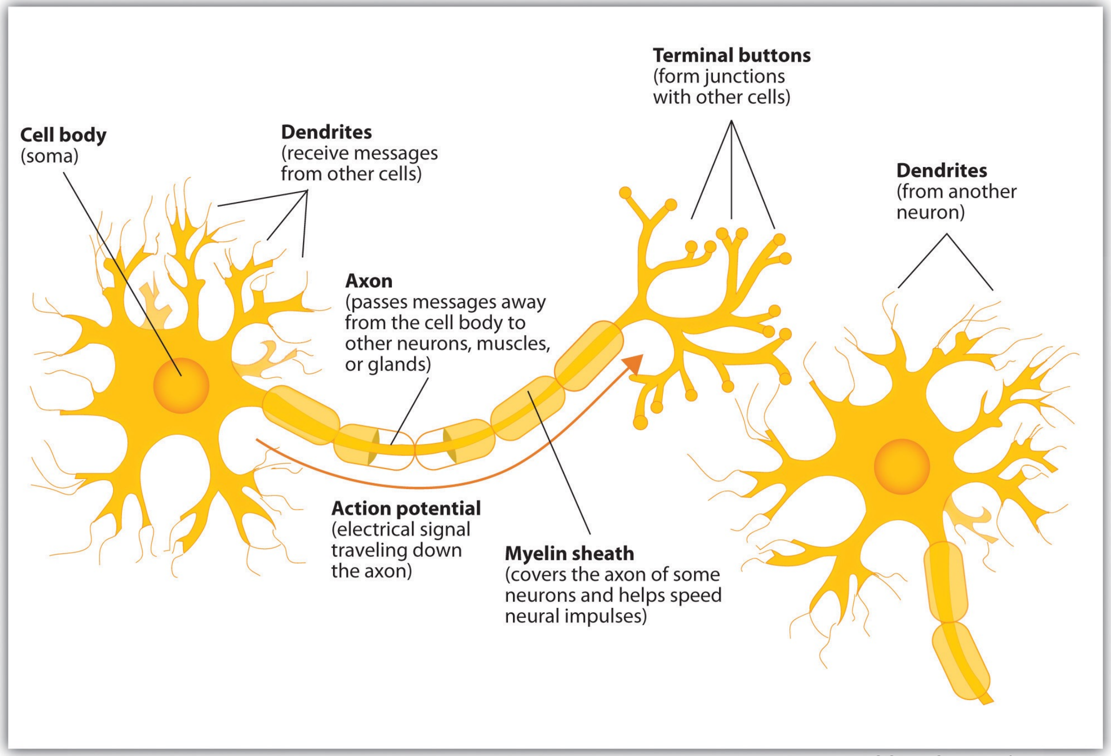




Why “neural” network?





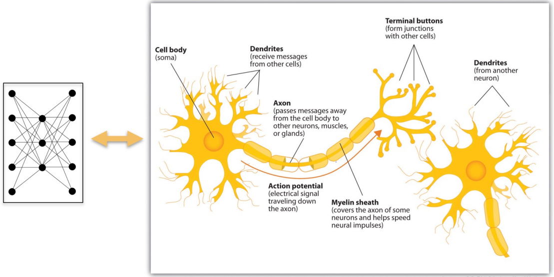

Terminal buttons
(form junctions
with other cells)
Cell body
(soma)
Dendrites
(receive messages
from other cells)
Dendrites
(from another
neuron)
Axon
(passes messages away
from the cell body to
other neurons, muscles,
or glands)
Action potential
(electrical signal
traveling down
the axon)
Myelin sheath
(covers the axon of some
neurons and helps speed
neural impulses)

Loose analogy!

- Neurons have activation potentials, all-or-none firing behavior

- Interconnectivity between actual neurons is dense and complicated

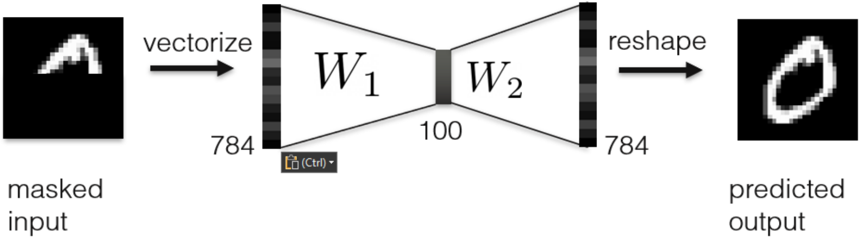
- Connection between neurons is complex non-linear dynamical system



Today

- What is a neural network?
- Training/optimizing neural nets
- Why “neural”?
- Convolutional neural networks
- Applications & inverse problems

Drawbacks of fully-connected networks



- spatial structure is destroyed
- fully-connected weights do not scale

Convolutional Neural Networks

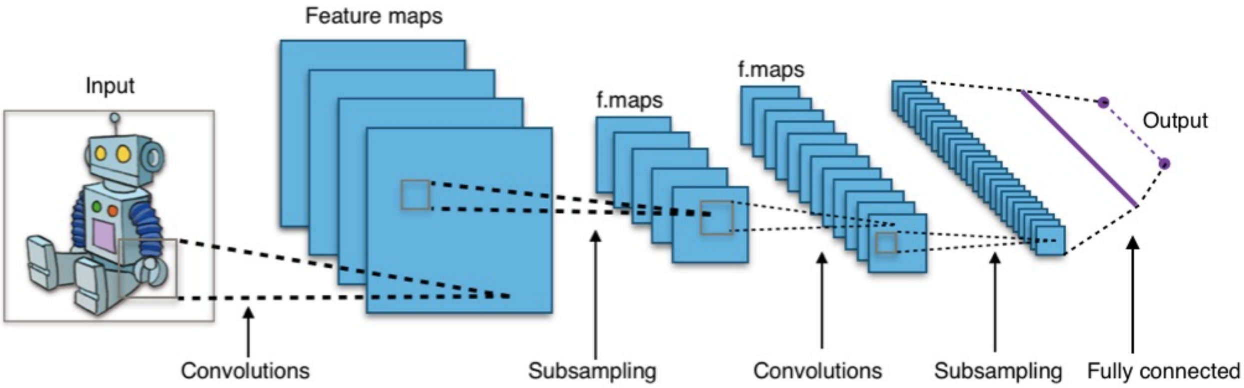


Image: CC Aphex34

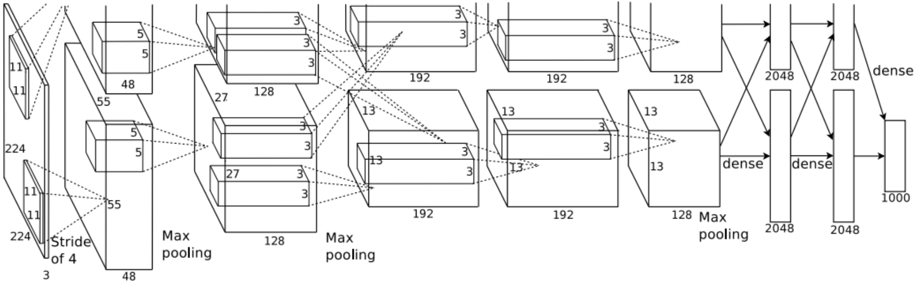
- Exploit spatial structure
- Scale to large inputs with fewer parameters
- Remarkable performance for processing visual data

AlexNet & surge in popularity

2010: ImageNet Large Scale Visual Recognition Challenge

- 10 million labeled images

First convolutional network for image classification



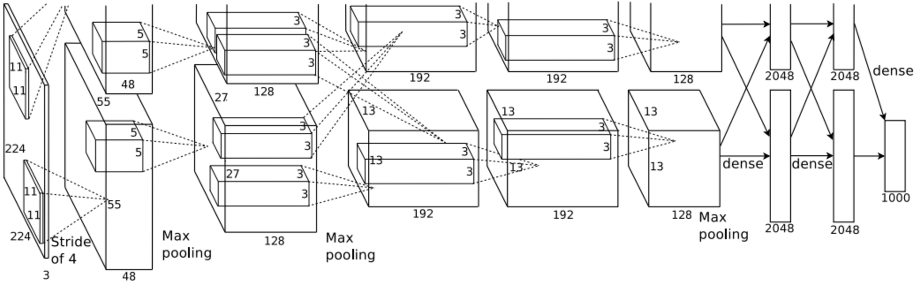
AlexNet [Krizhevsky ‘12]

AlexNet & surge in popularity

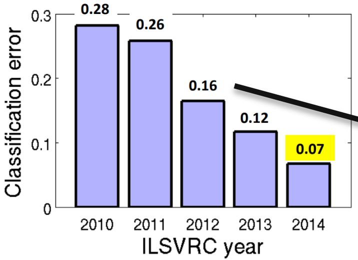
2010: ImageNet Large Scale Visual Recognition Challenge

- 10 million labeled images

First convolutional network for image classification



AlexNet [Krizhevsky ‘12]



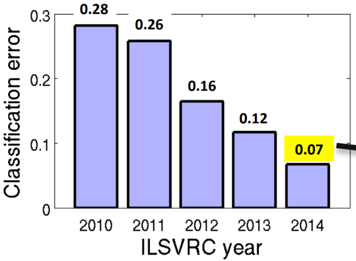
[Russakovsky ’15]

CNNs

AlexNet & surge in popularity

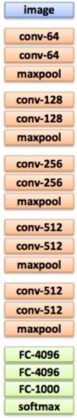
2010: ImageNet Large Scale Visual Recognition Challenge

- 10 million labeled images



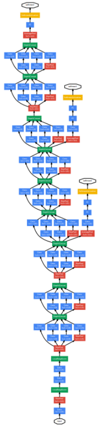
[Russakovsky '15]

Deep networks



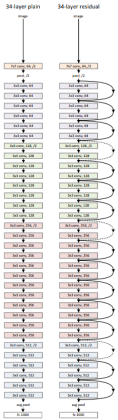
VGG

[Simonyan '14]



GoogLeNet

[Szegedy '14]

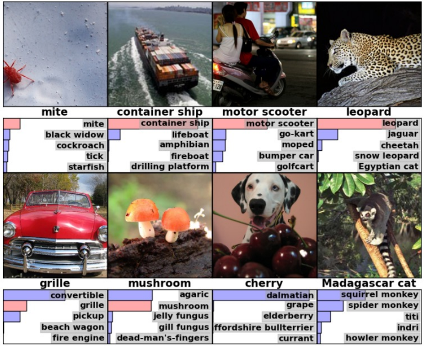


ResNet

[He '15]

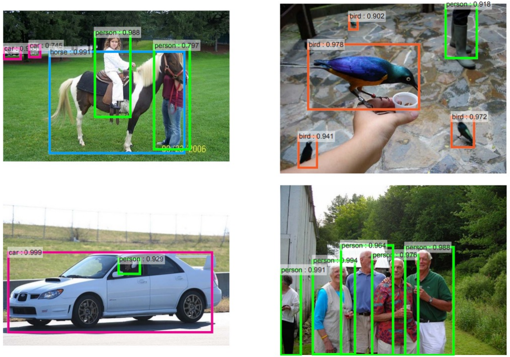
Image Classification

[Krizhevsky '12]



Object Detection

[Ren '16]

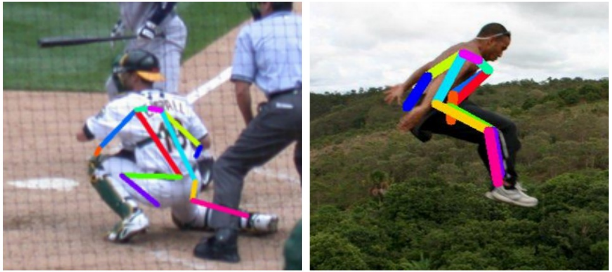


Segmentation

[Farabet '13]

Pose estimation

[Toshev '14]



Imaging & Image processing

Image Denoising

[Zhang '17]

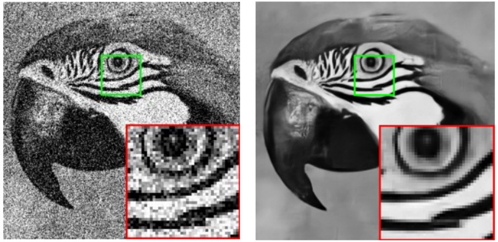


Image Deblurring

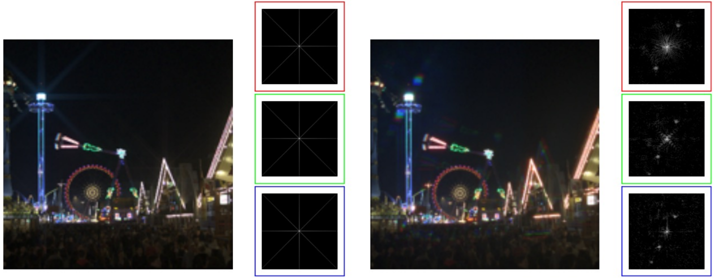
[Nah '17]

Learned ISPs

[Chen '18]

End-to-End Optimization

[Metzler '19]



Imaging & Image processing

Monocular Depth Estimation

[Eigen '14]

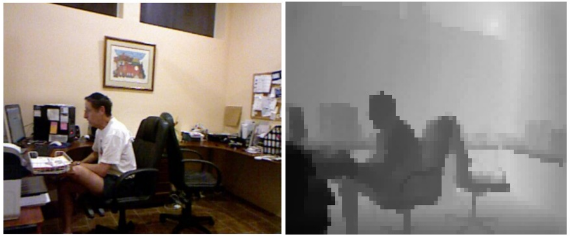
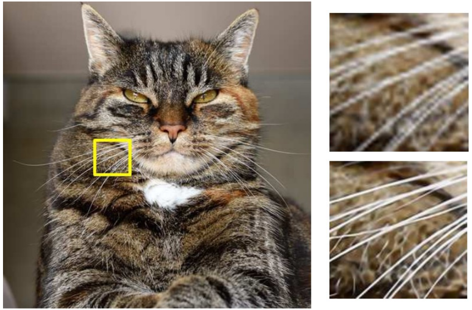


Image Relighting

[Sun '19]

Image Super-resolution

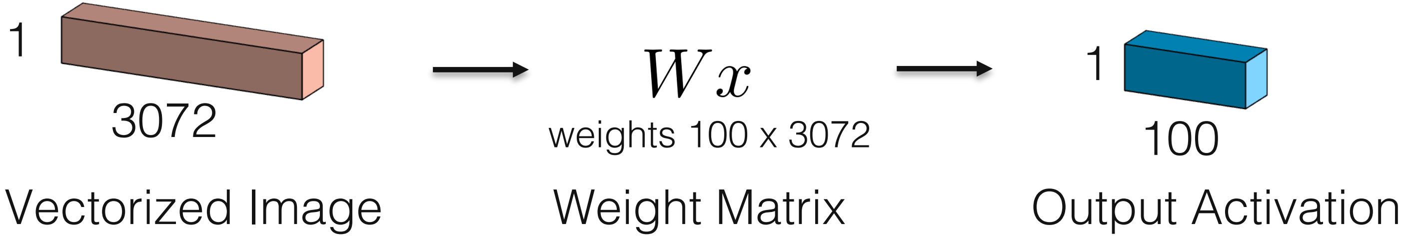
[Lim '17]



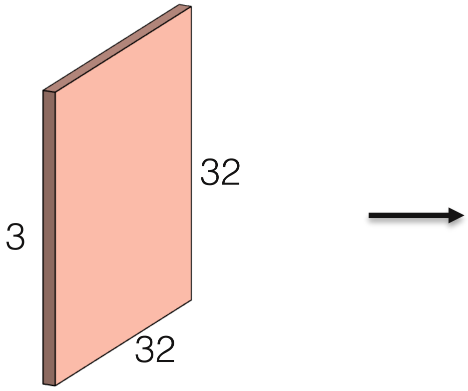
Synthetic Depth-of-Field

ai.googleblog.com

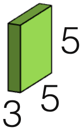
Fully-Connected Layer



Convolutional Layer

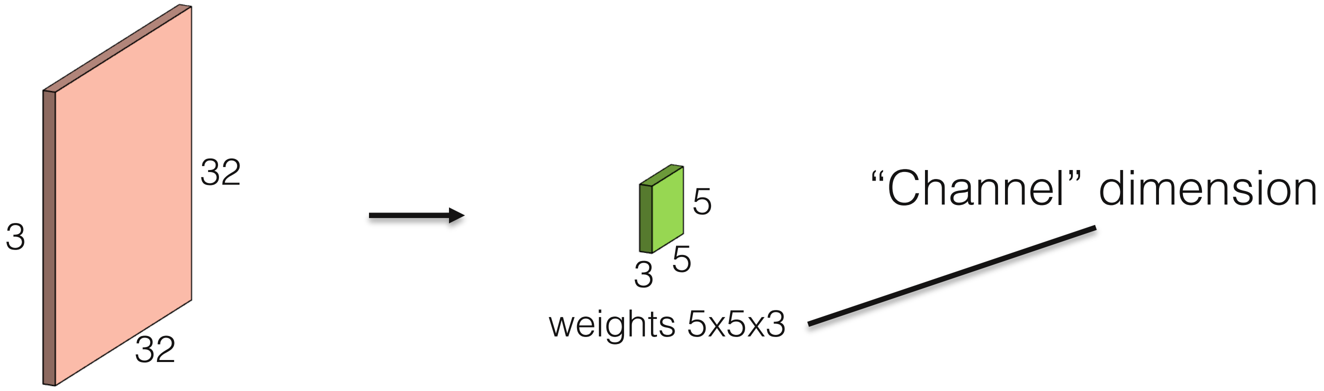


Input Image



Filter

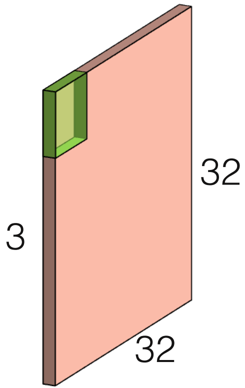
Convolutional Layer



Input Image

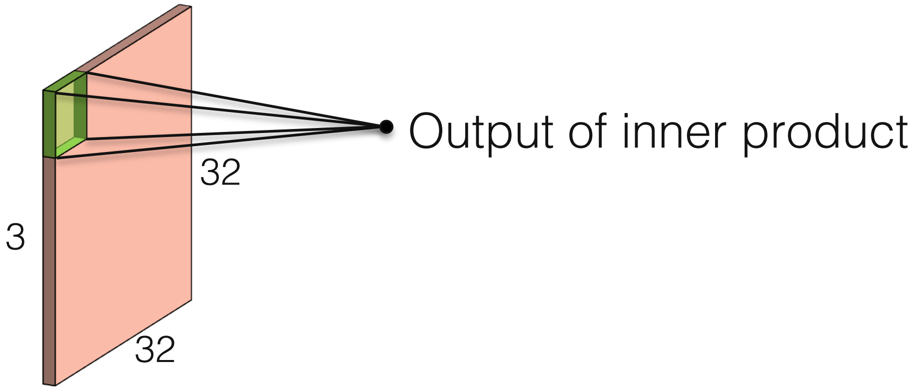
Filter

Convolutional Layer



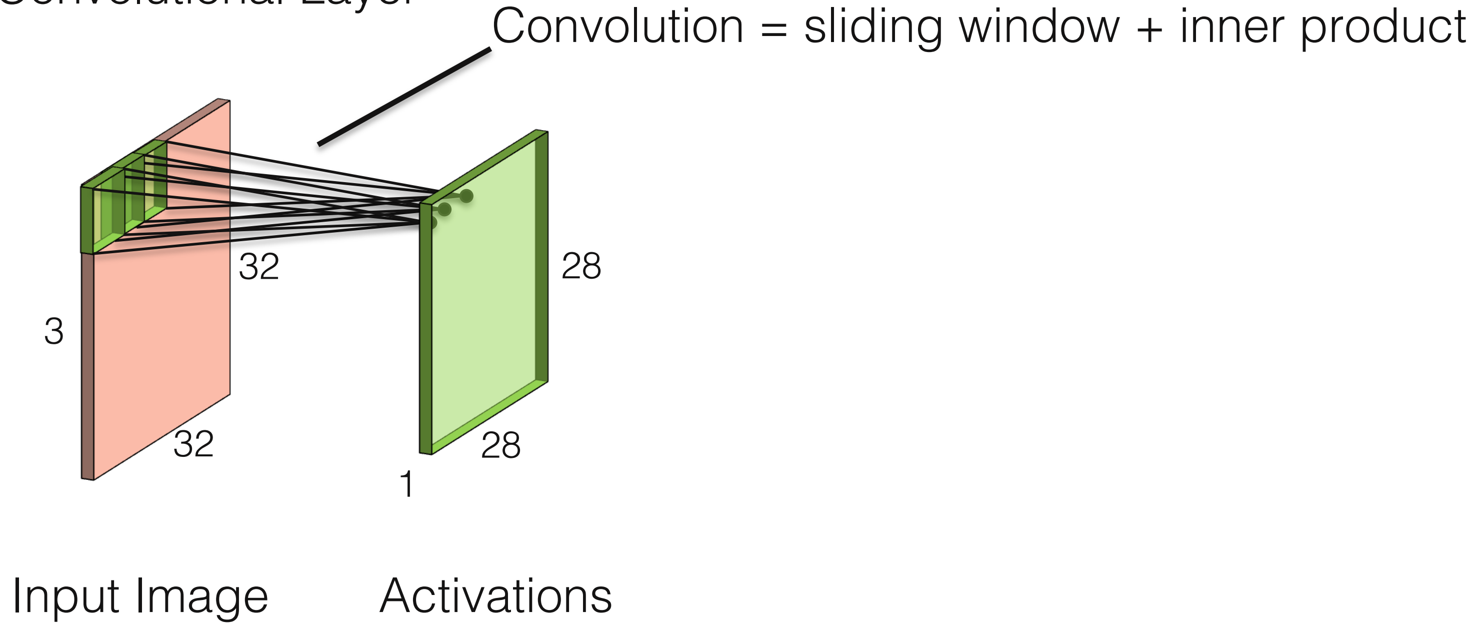
Input Image

Convolutional Layer

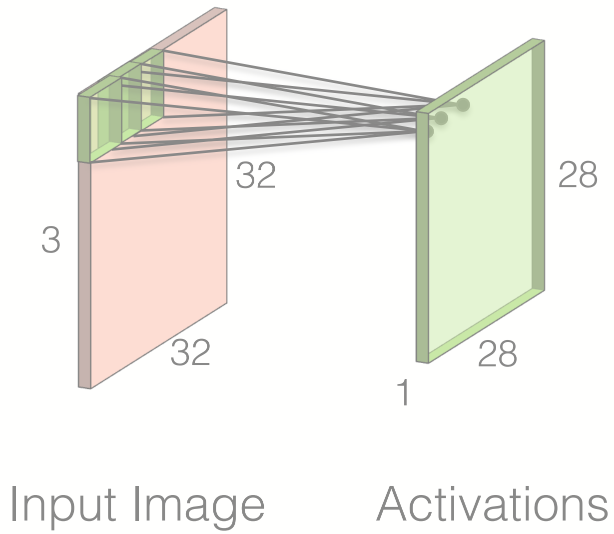


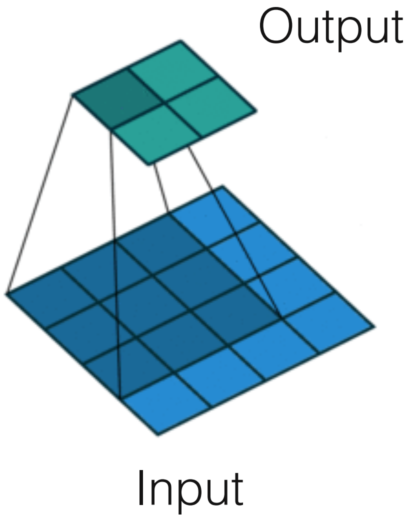
Input Image

Convolutional Layer



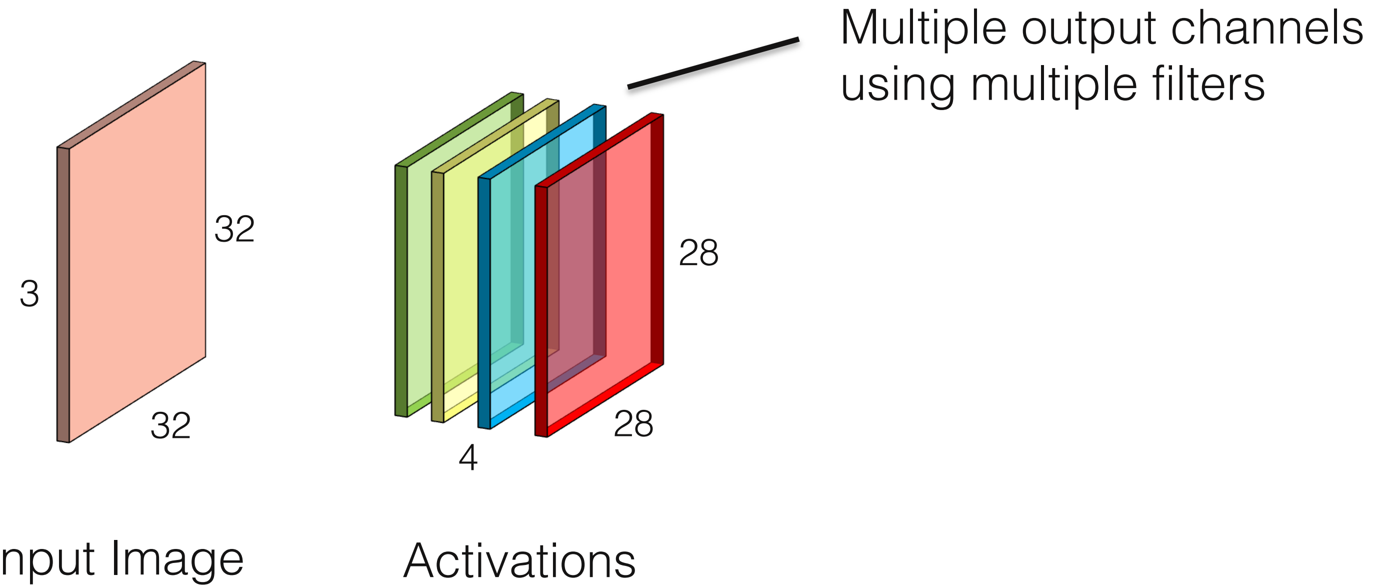
Convolutional Layer



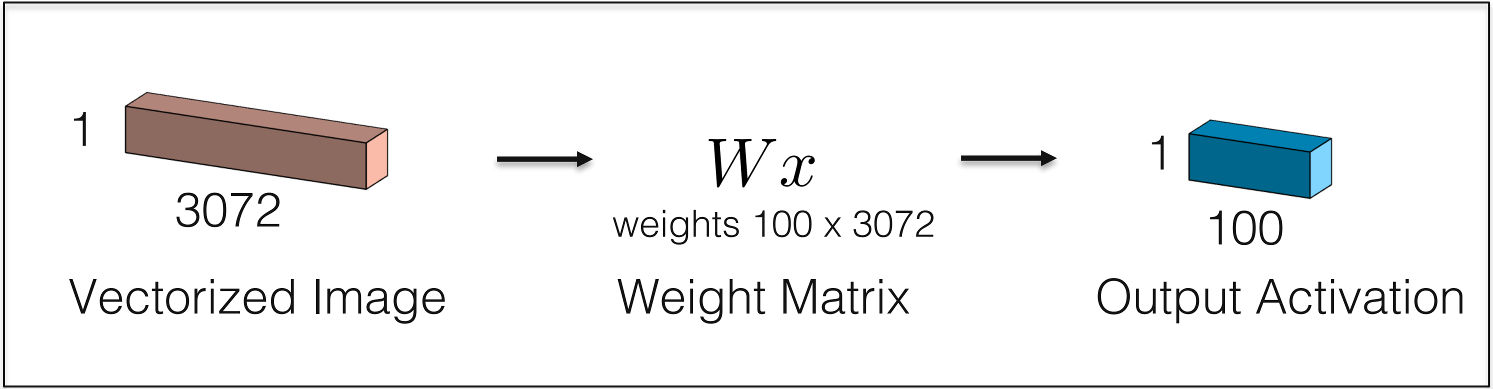


https://github.com/vdumoulin/conv_arithmetic

Convolutional Layer

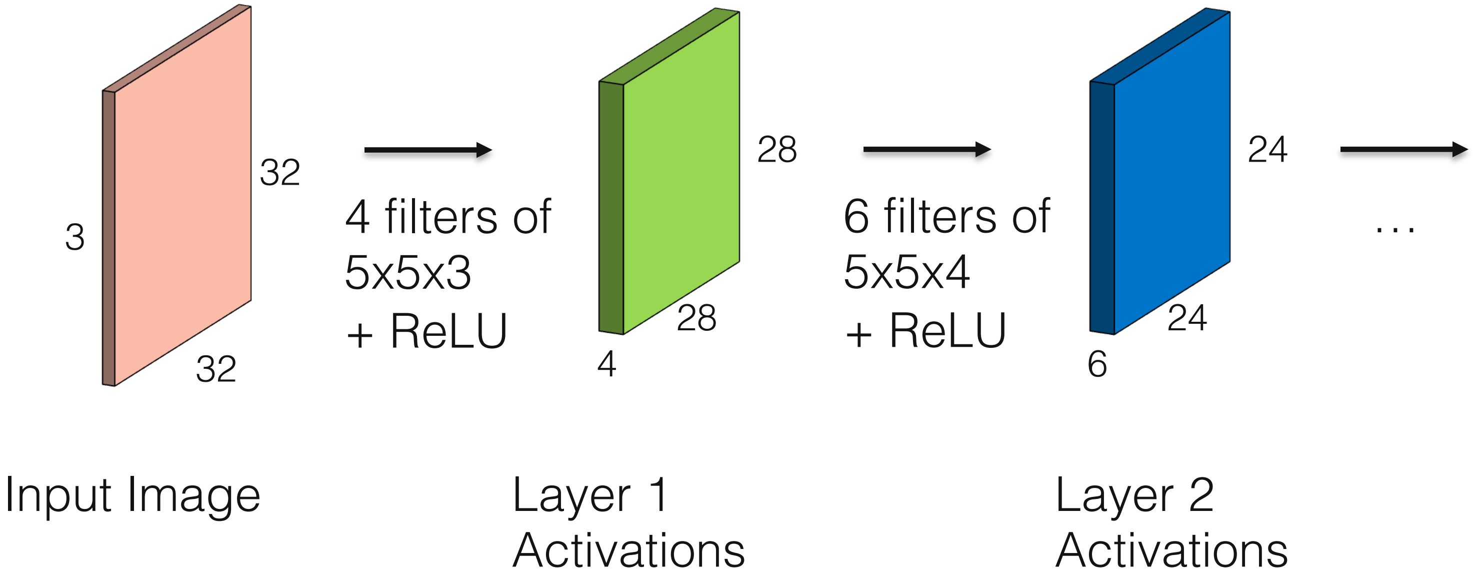


Fully-Connected Layer



Special case of convolutional layer when filter size = input size!

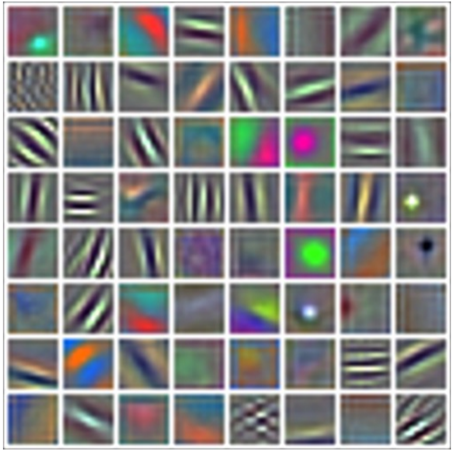
Convolutional Neural Network



Case Study: AlexNet

Input Image

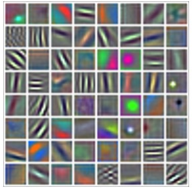
First-layer Filters

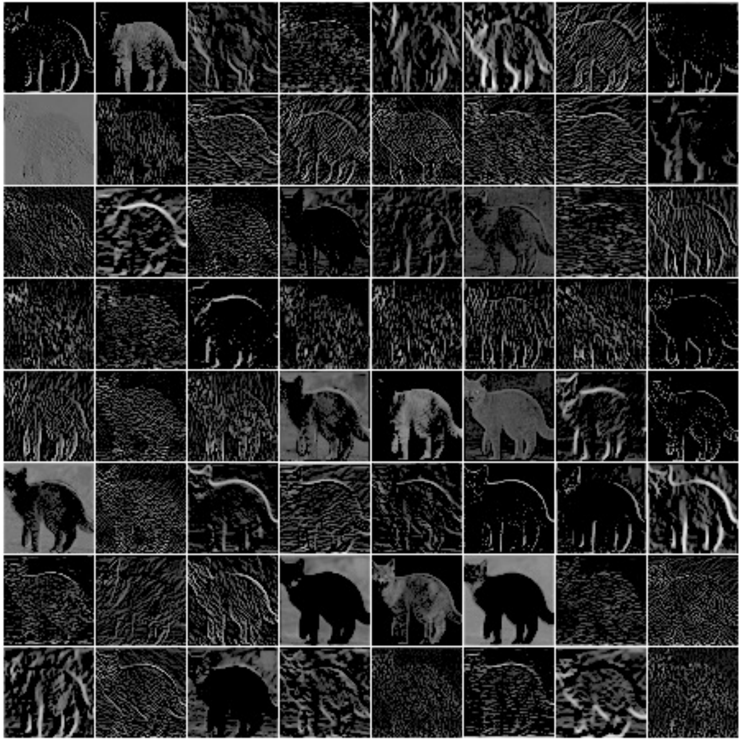


Case Study: AlexNet

Input Image

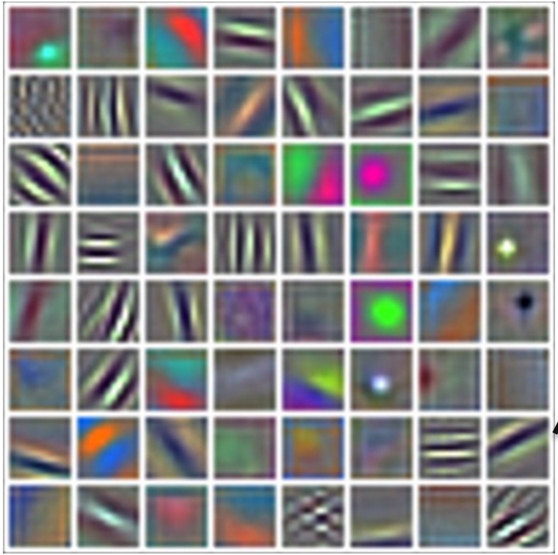
First-layer Filters





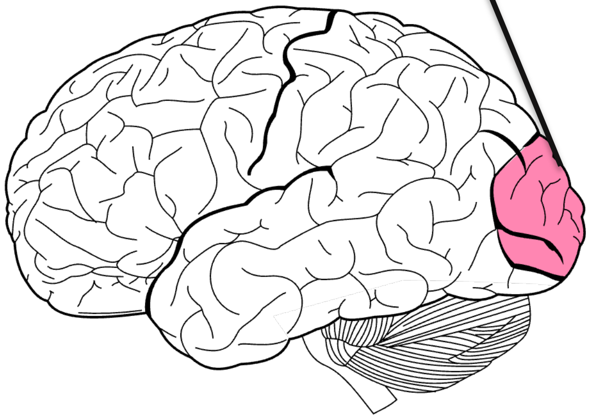
Activations

Case Study: AlexNet



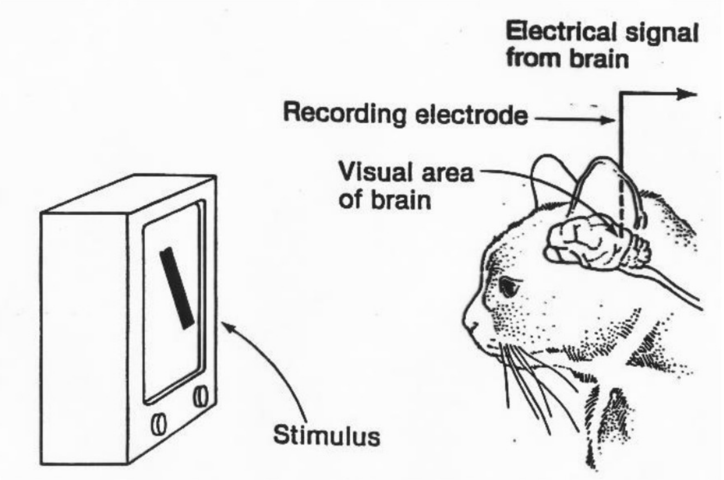
First-layer Filters

Similar to simple cells in visual cortex!
- Edge detectors



Case Study: AlexNet

[Hubel & Wiesel 1959]



Simple cells in visual cortex detect edges, complex cells compose earlier responses

CNN higher layer filters

[Olah '17]

Dataset examples that maximize neuron outputs

CNN Building Blocks

Design choices:

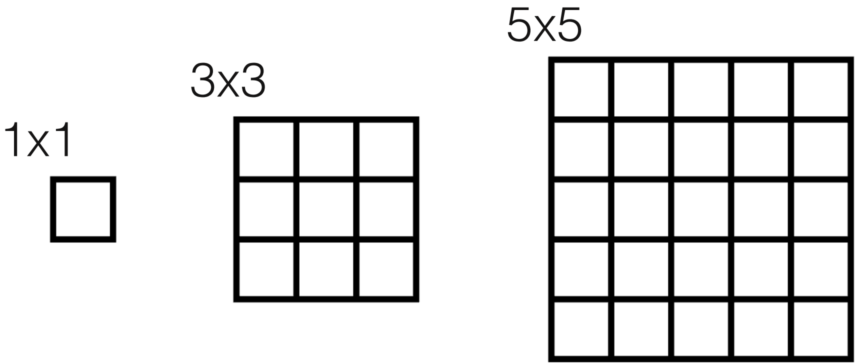
- filter size
- number of filters
- padding
- stride

Layer types:

- pooling
- transpose convolutions
- upsampling layers

CNN Building Blocks

Filter size



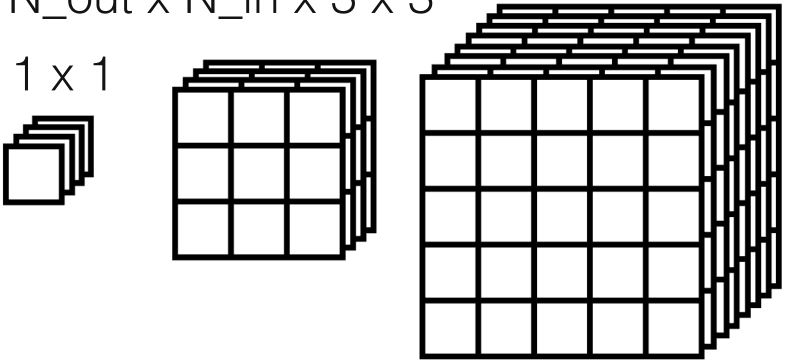
CNN Building Blocks

Number of channels

N_out x N_in x 5 x 5

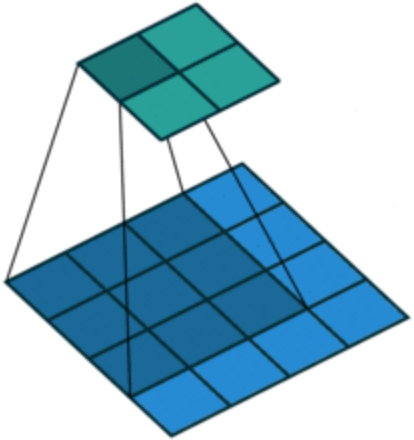
N_out x N_in x 3 x 3

N_out x N_in x 1 x 1

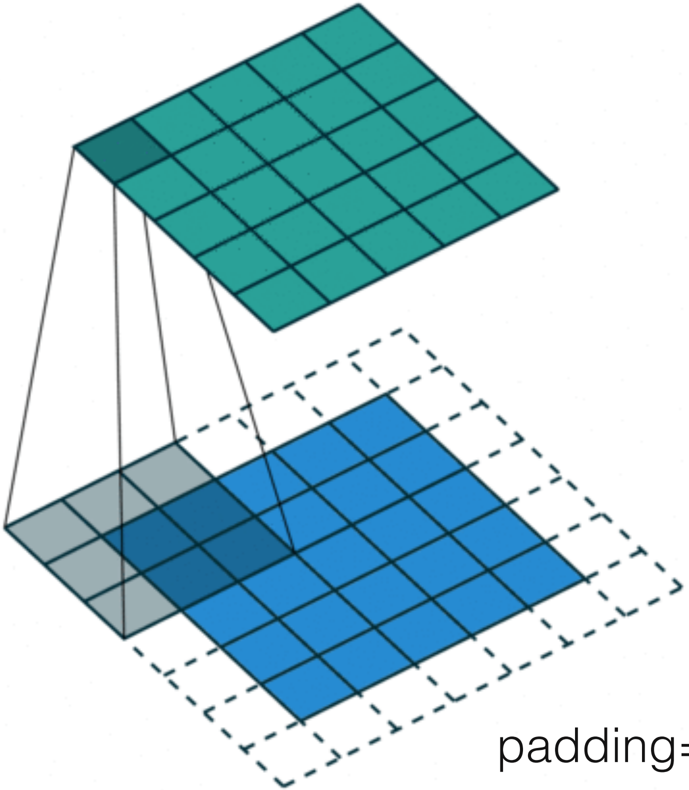


CNN Building Blocks

padding



No padding

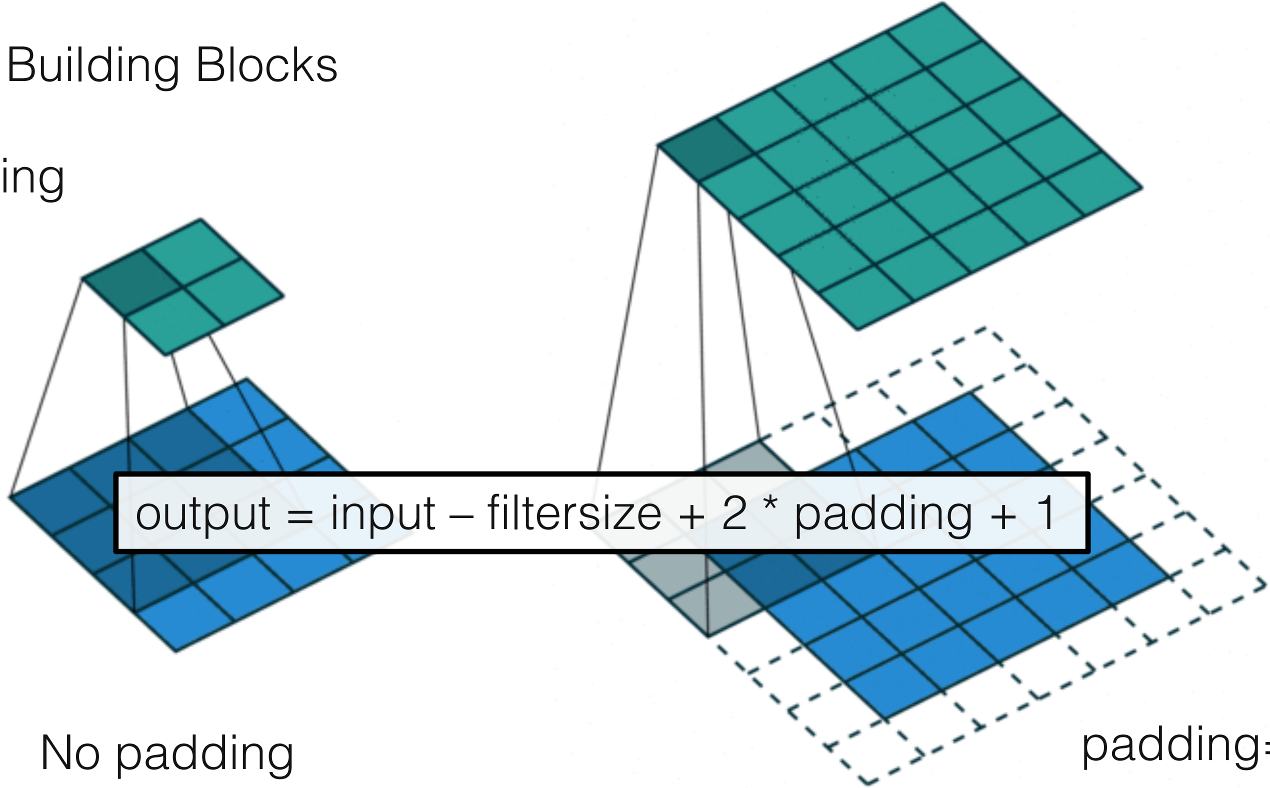


padding=1

https://github.com/vdumoulin/conv_arithmetic

CNN Building Blocks

padding

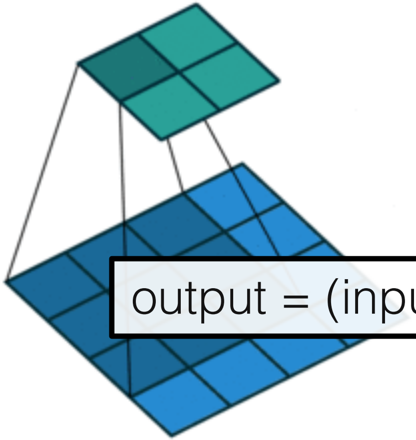


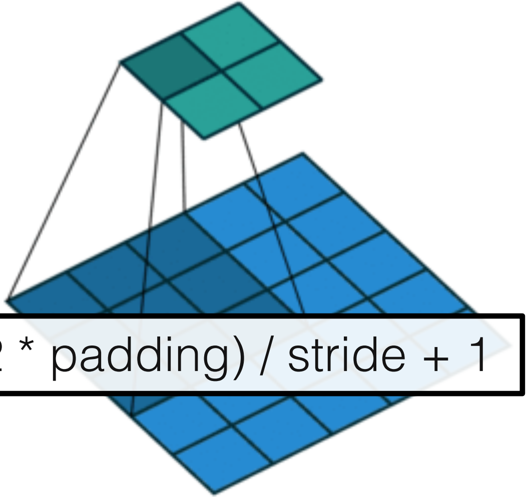
output = input – filtersize + 2 * padding + 1

https://github.com/vdumoulin/conv_arithmetic

CNN Building Blocks

stride





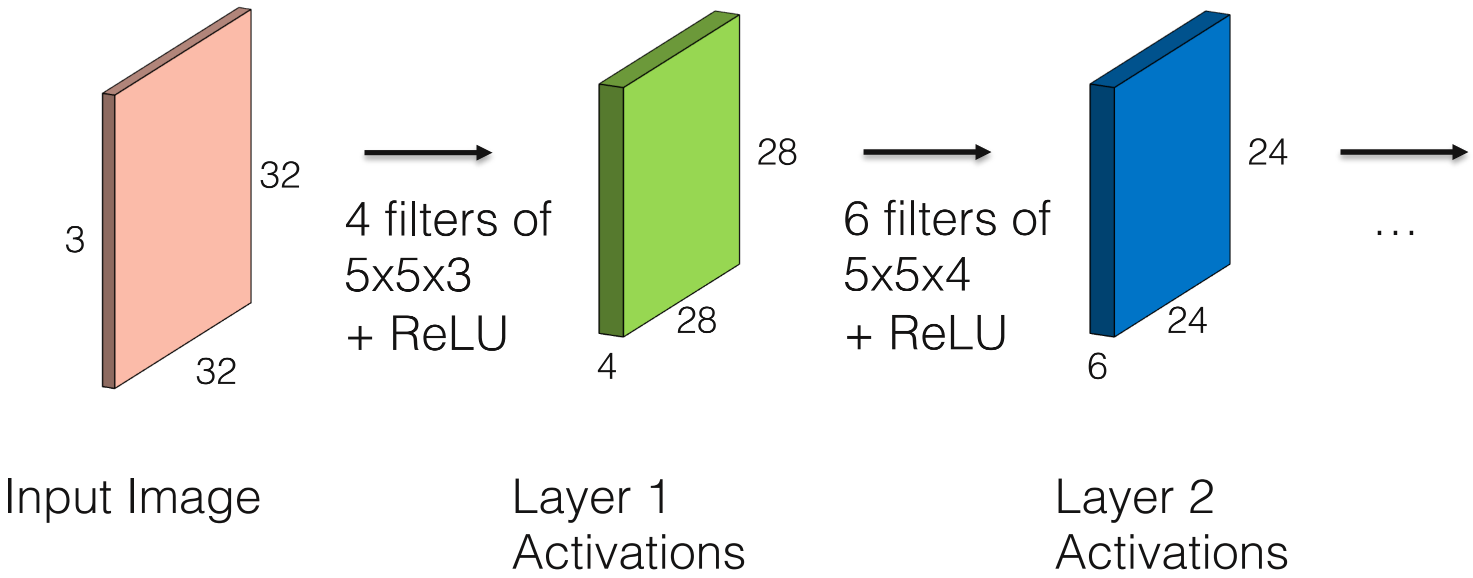
output = (input – filtersize + 2 * padding) / stride + 1

stride = 1

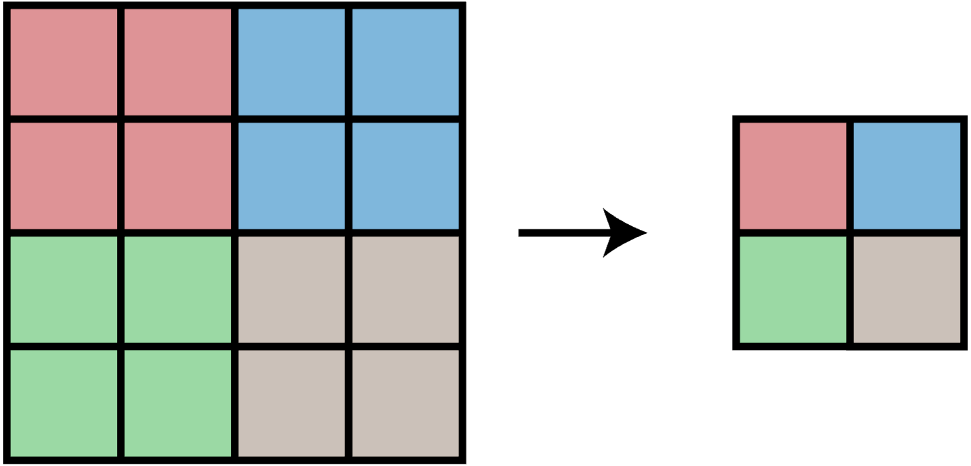
stride = 2

https://github.com/vdumoulin/conv_arithmetic

Convolutional Neural Network

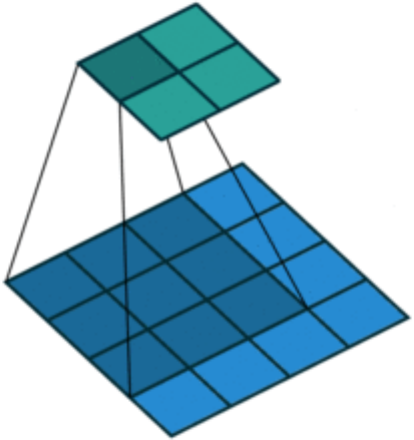


Layer types: Pooling

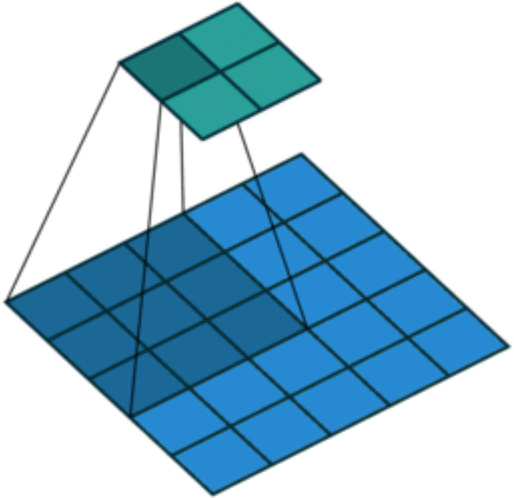


e.g., max pool size=2, stride=2

Transpose Convolution



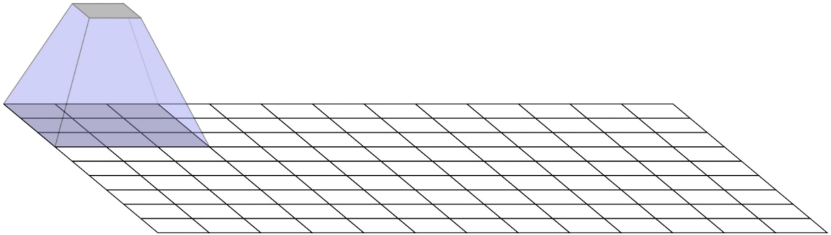
stride=1



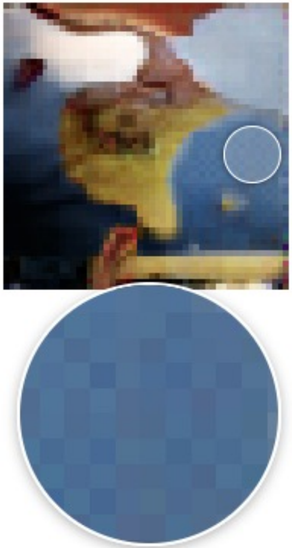
stride=2

https://github.com/vdumoulin/conv_arithmetic

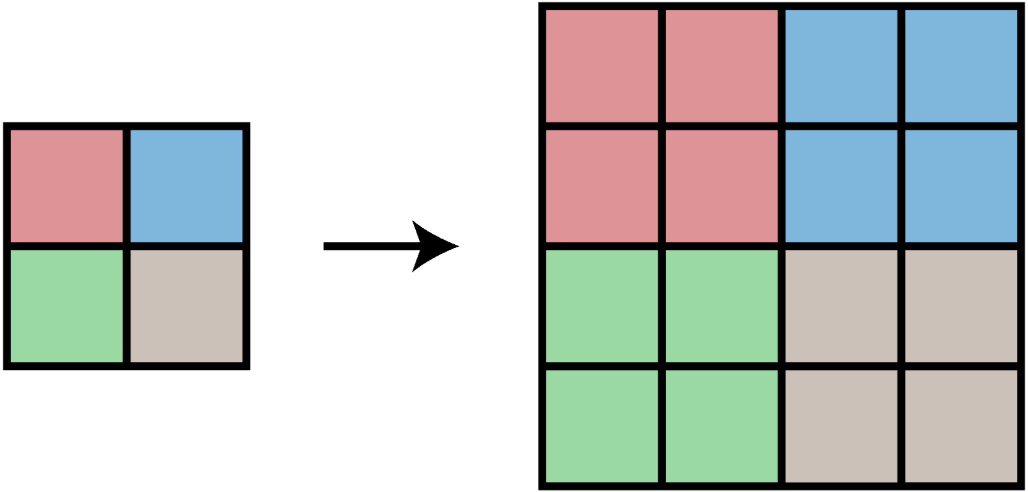
Transpose Convolution (checkerboard artifacts)



[Odena '16]

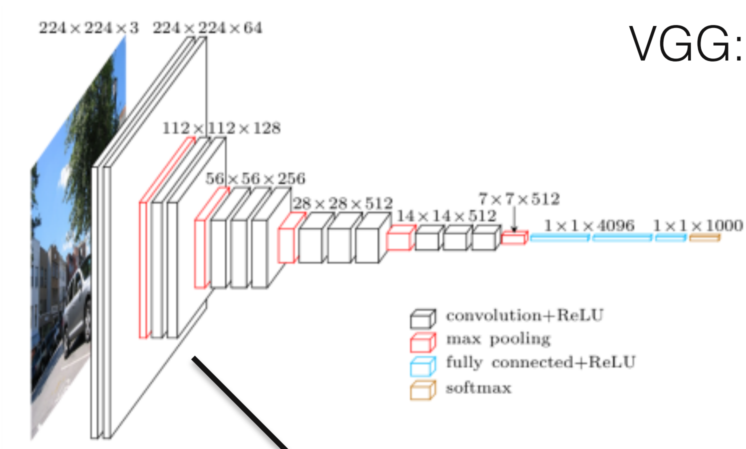


Upsampling layers



e.g., bilinear upsampling, nearest neighbor upsampling

Common Network Architectures



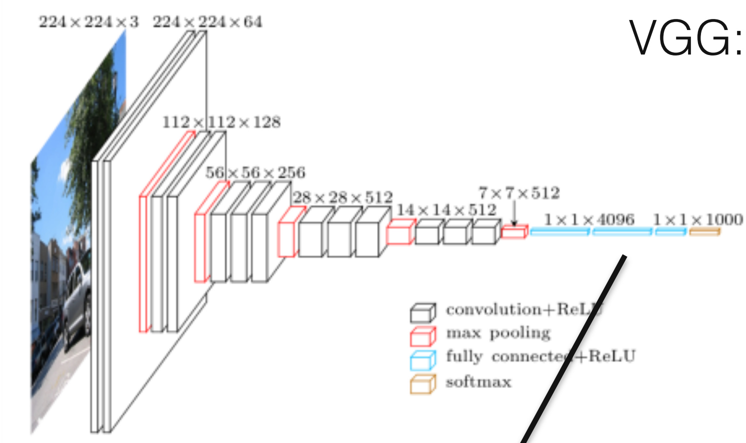
VGG: one of the first “deep” CNNs

downsampling with max pooling

Image: Davi Frossard

Common Network Architectures

VGG: one of the first "deep" CNNs

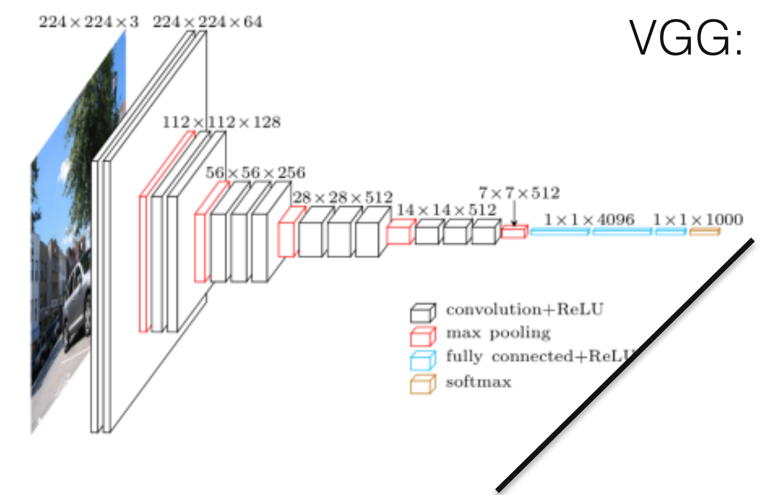


Classification scores output with fully-connected layers

Image: Davi Frossard

Common Network Architectures

VGG: one of the first "deep" CNNs



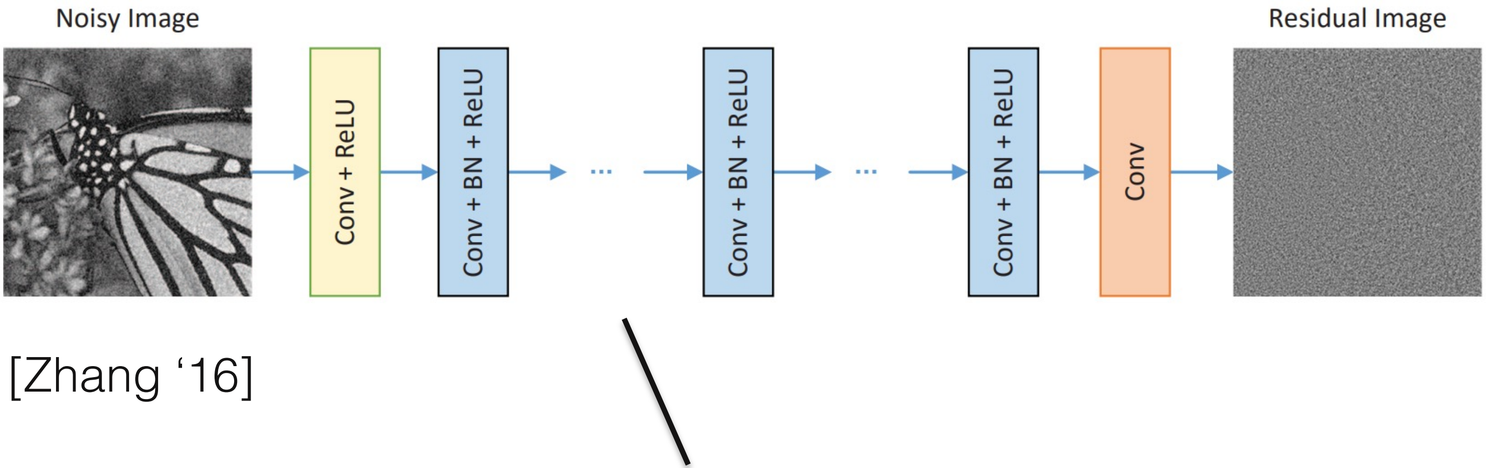
Not suitable for image processing…

Image: Davi Frossard

Today

- What is a neural network?
- Training/optimizing neural nets
- Why “neural”?
- Convolutional neural networks
- Applications & inverse problems

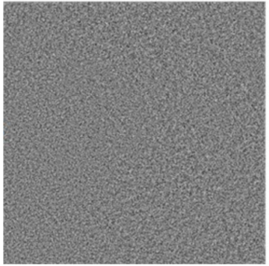
Image denoising with DnCNN



[Zhang '16]

Key ideas: residual learning & batch normalization

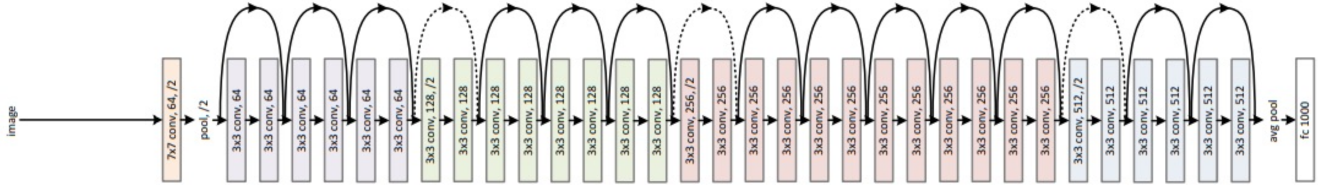
Residual Learning



Clean image = noisy image - estimated noise

[Zhang ‘16]

Residual Learning



[He ‘15]

Popularized by residual nets “ResNets” for image classification

- Usually easier to optimize
- Better classification accuracy, good for many tasks!

Batch Normalization

Normalizes layer activations to zero mean, unit variance, preventing distribution shifts during training

- can speed up and stabilize training
- seems to smooth out loss landscape

BATCHNORM2D

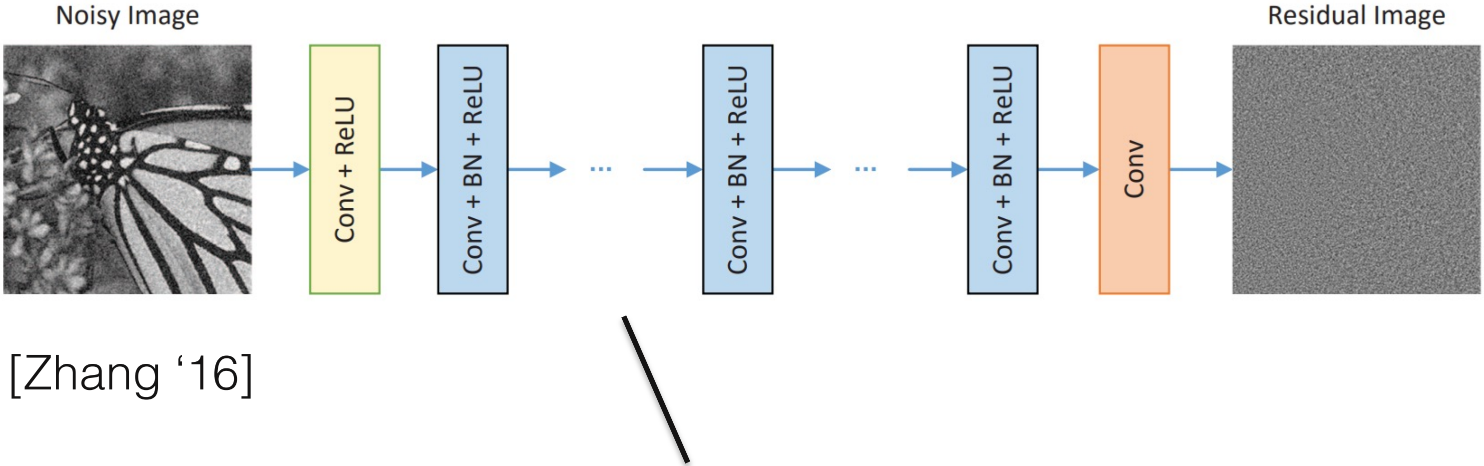
CLASS `torch.nn.BatchNorm2d(`*`num_features, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True, device=None, dtype=None`*`)` [SOURCE]

Applies Batch Normalization over a 4D input (a mini-batch of 2D inputs with additional channel dimension) as described in the paper Batch Normalization: Accelerating Deep Network Training by Reducing Internal Covariate Shift .

$$y = \frac{x - \mathrm{E}[x]}{\sqrt{\mathrm{Var}[x] + \epsilon}} * \gamma + \beta$$

https://pytorch.org/docs/stable/generated/torch.nn.BatchNorm2d.html

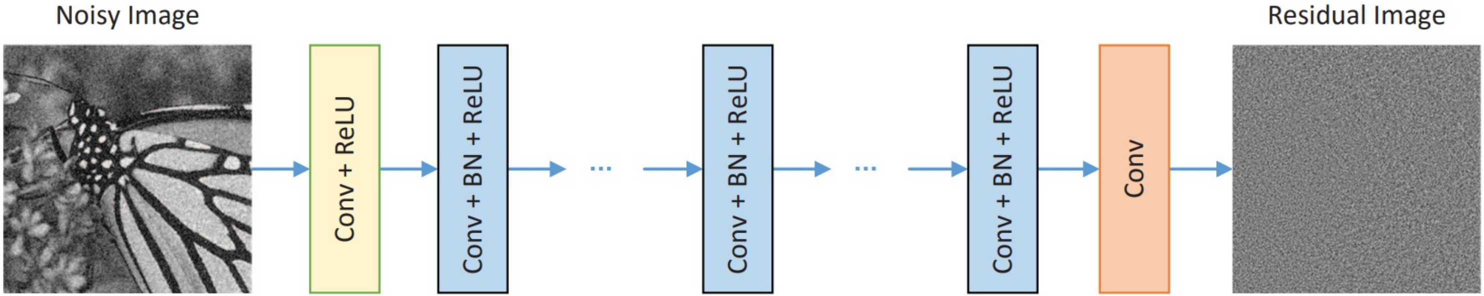
Image denoising with DnCNN



[Zhang '16]

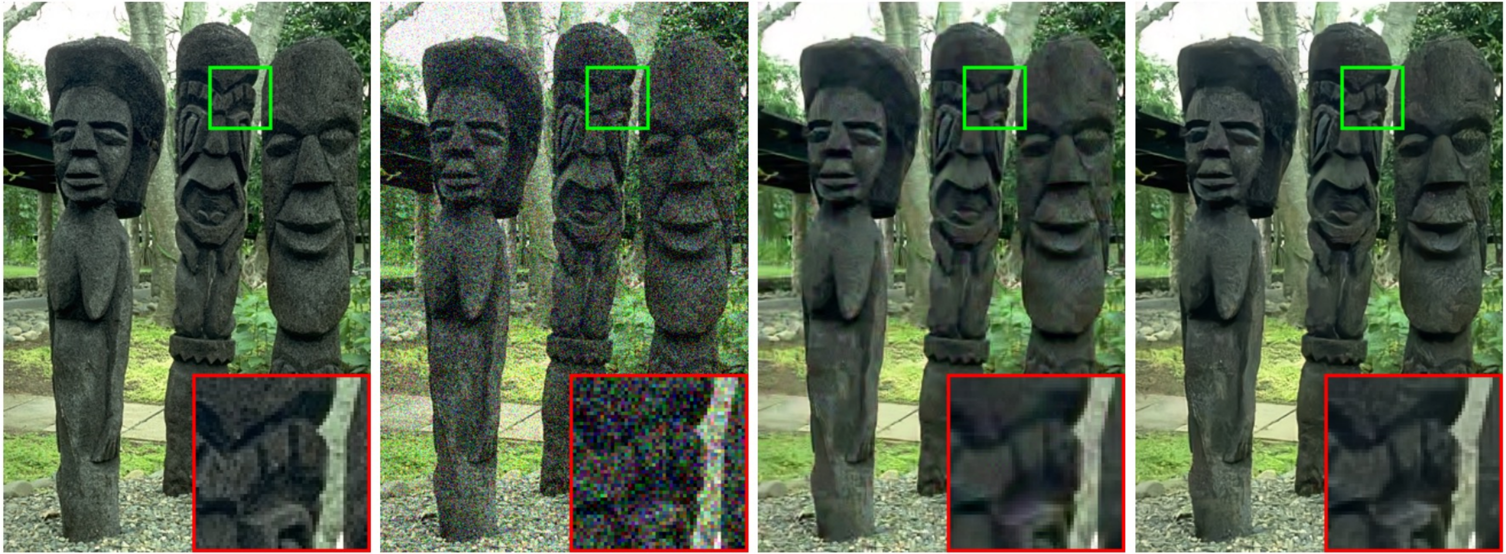
(Remember to disable the bias in your conv layer)

Image denoising with DnCNN



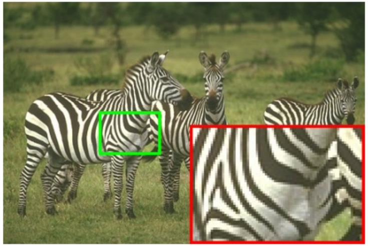
[Zhang ‘16]

No fully connected layers – can be applied to any input size

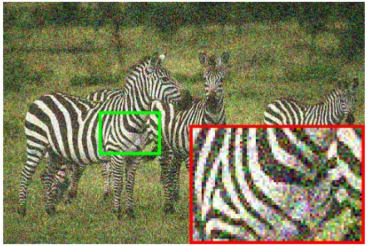


(a) Ground-truth (b) Noisy / 17.25dB (c) CBM3D / 25.93dB (d) CDnCNN-B / 26.58dB

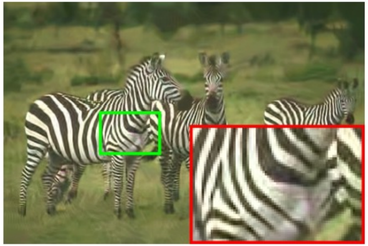
[Zhang ‘16]



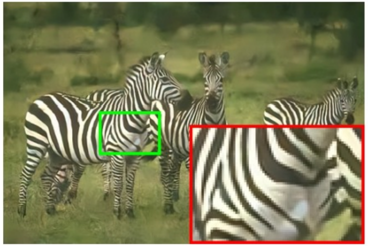
(a) Ground-truth



(b) Noisy / 15.07dB



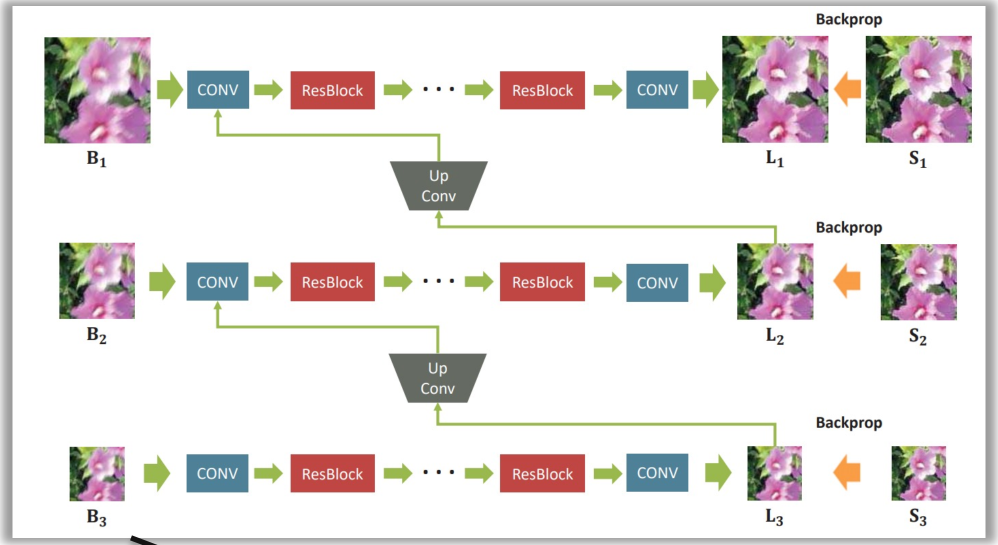
(c) CBM3D / 26.97dB



(d) CDnCNN-B / 27.87dB

[Zhang ‘16]

Multi-Scale Architectures



[Nah '18]

Uses image pyramid to process & deblur

Multi-Scale Architectures

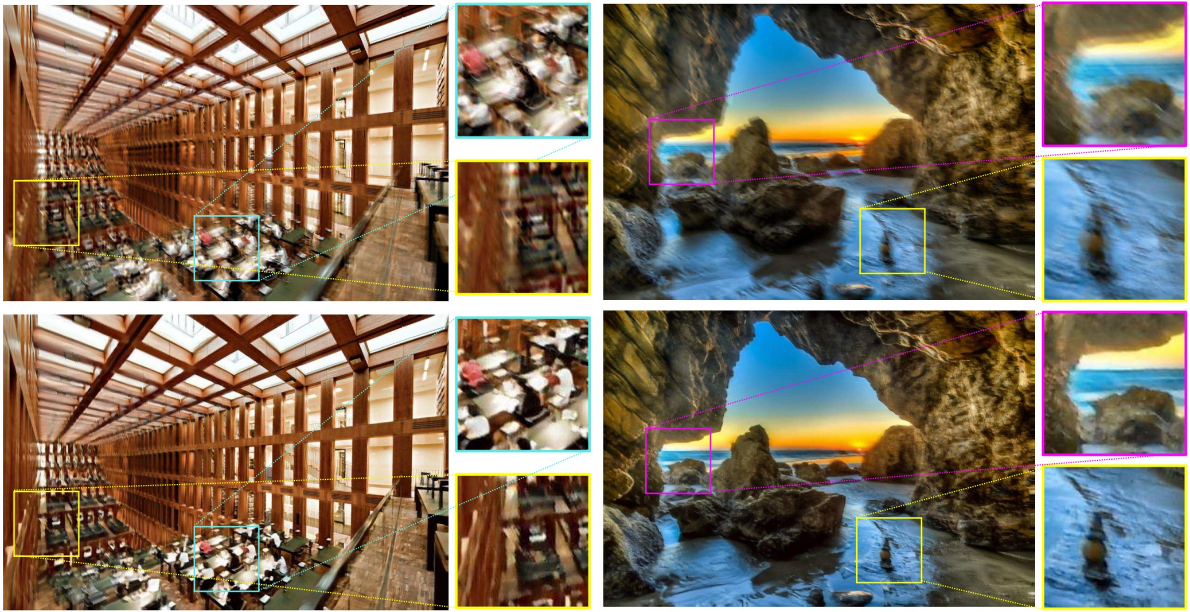
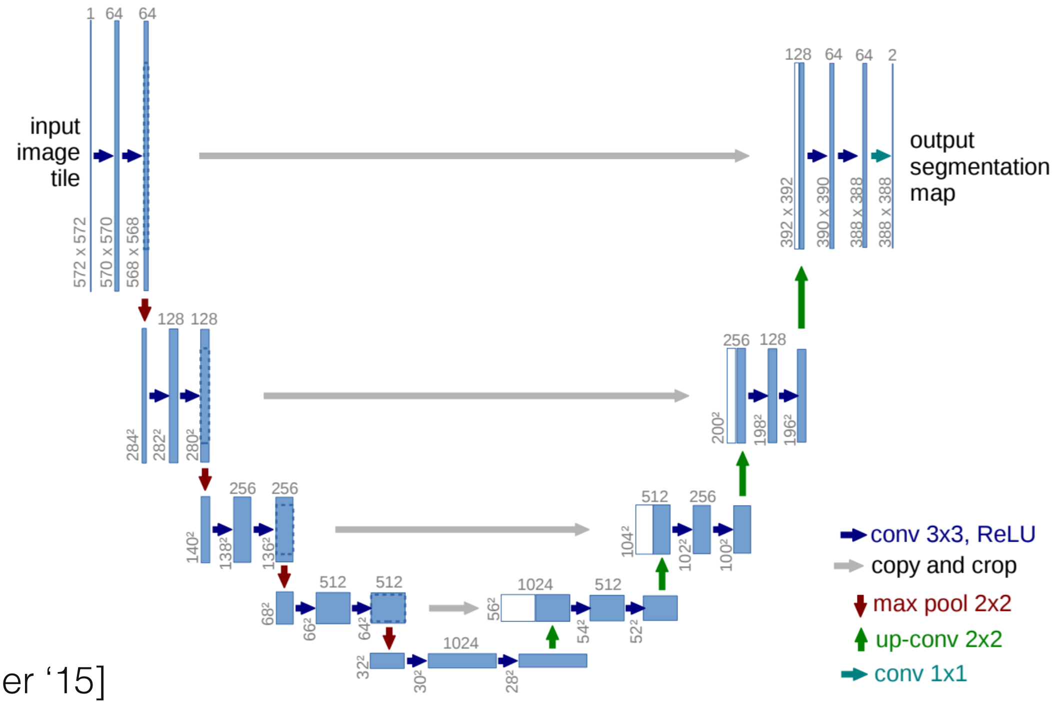


Figure 6. Deblurring results on the dataset [20]. The top row shows results of results of Sun et al. [26] and the bottom row shows our results.

[Nah '18]

U-Net: General-purpose architecture

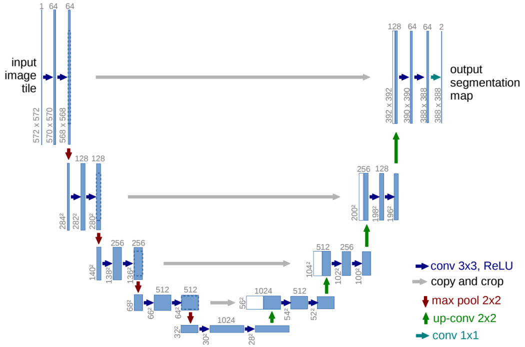


[Ronneberger '15]

U-Net: General-purpose architecture

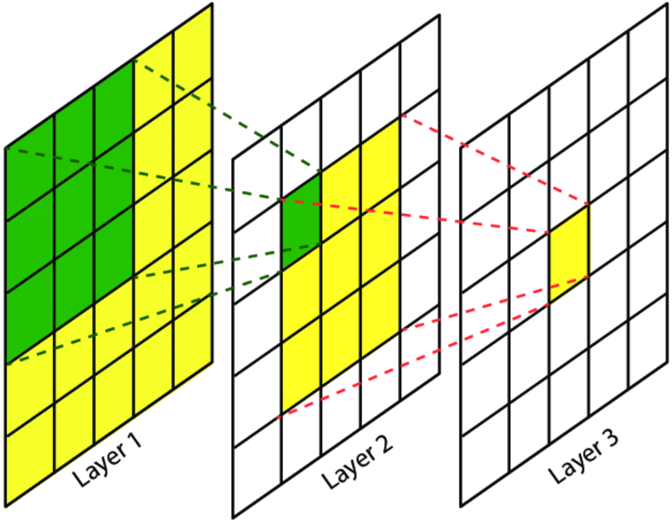
Introduced for biomedical image segmentation

- Uses residual connections
- Multi-scale processing (captures details at different scales)
- Large receptive field!



U-Net: General-purpose architecture

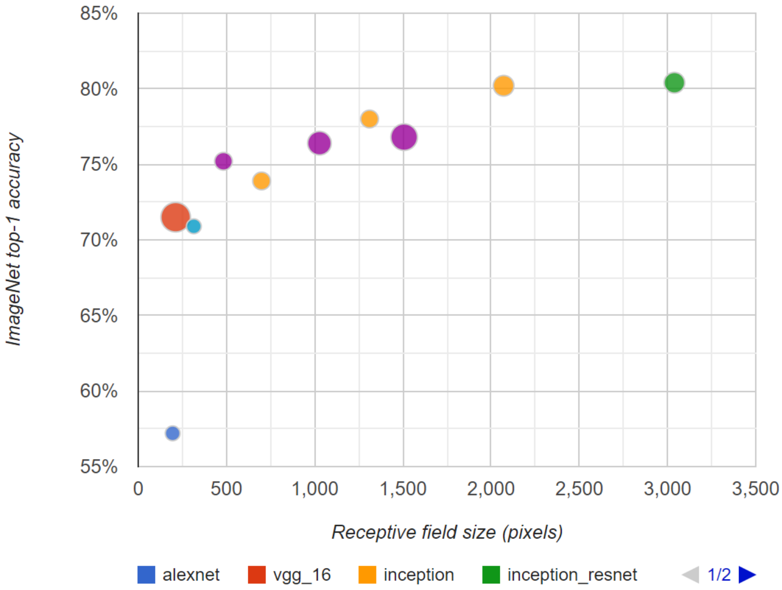
Receptive field: size of the input that contributes to the activation/output value



[Lin '17]

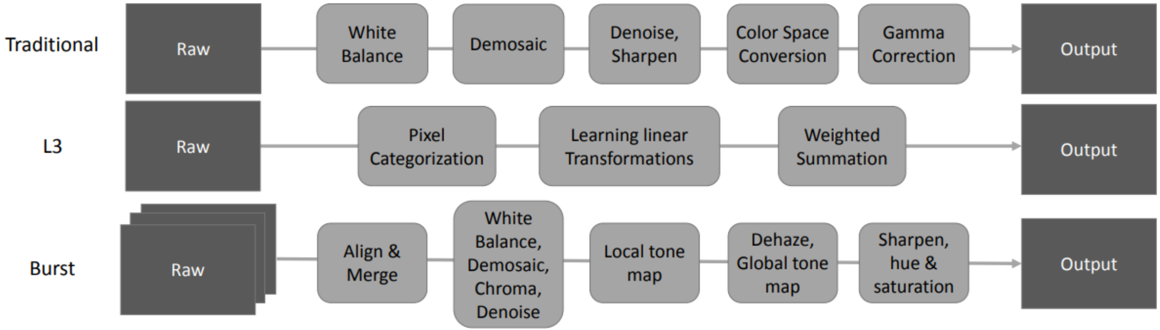
U-Net: General-purpose architecture

Large receptive field is important for high-level vision tasks and semantic understanding

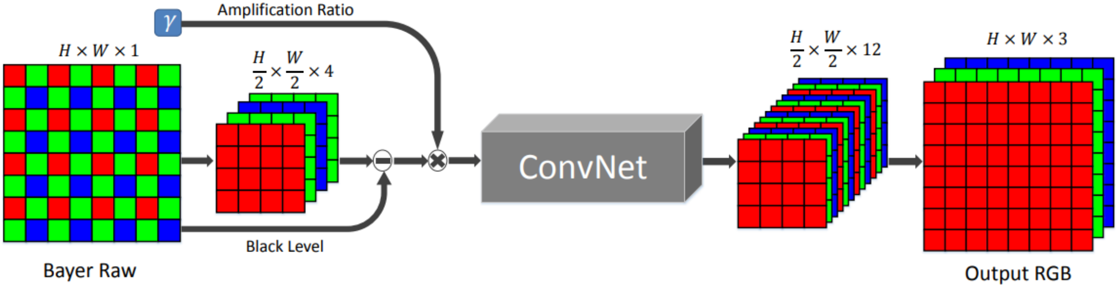


[Araujo '19]

Learned ISP

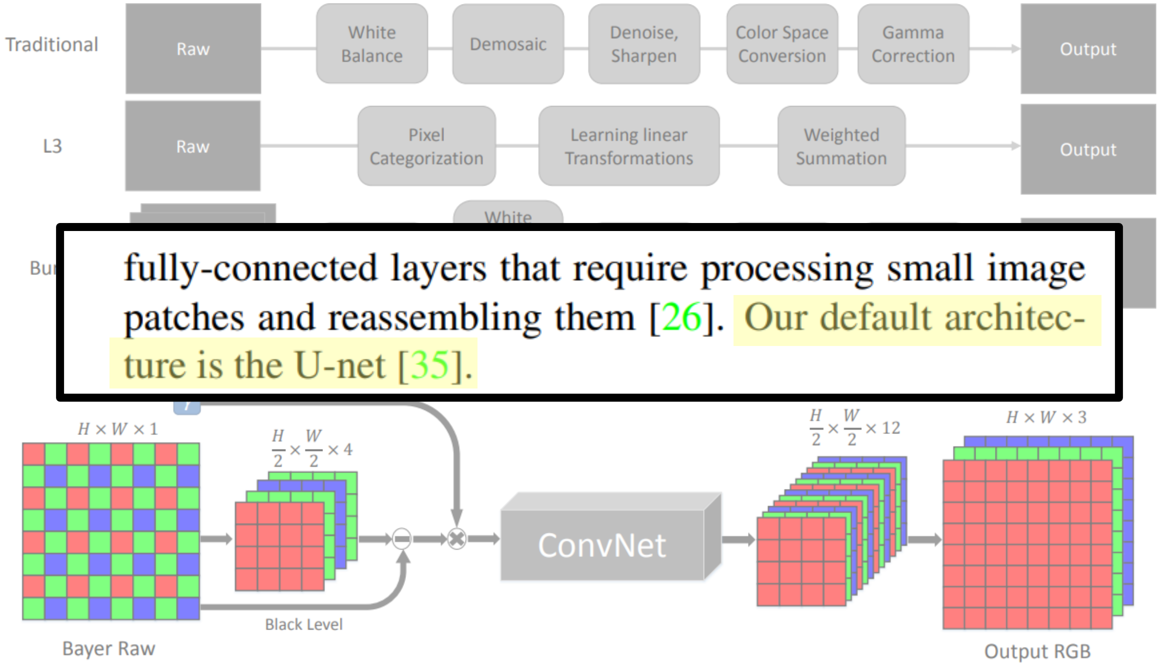


(a)



[Chen '18]

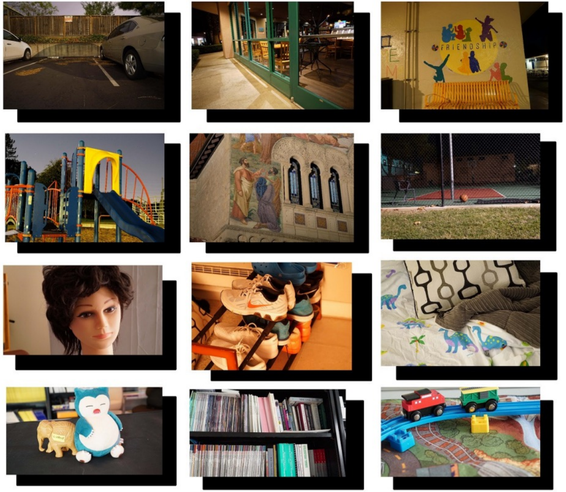
Learned ISP

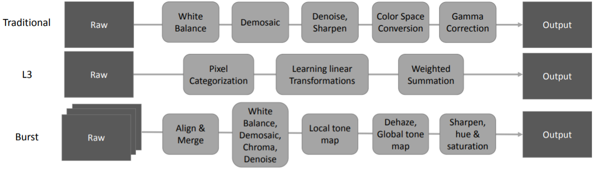


fully-connected layers that require processing small image patches and reassembling them [26]. Our default architecture is the U-net [35].

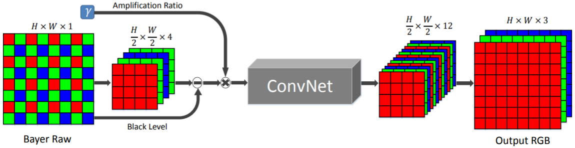
[Chen '18]

Learned ISP





(a)

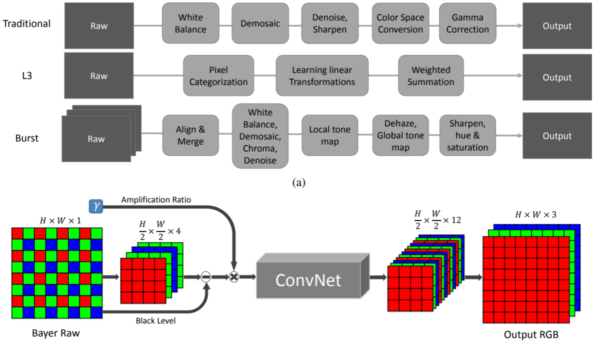


Trained on short-exposure (noisy) / long-exposure image pairs

[Chen ‘18]

Learned ISP

(a) Traditional pipeline (b) Our result



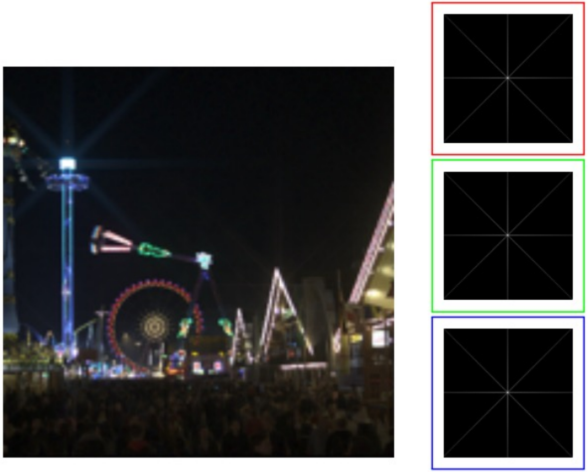
[Chen ‘18]

Deep optics for HDR imaging

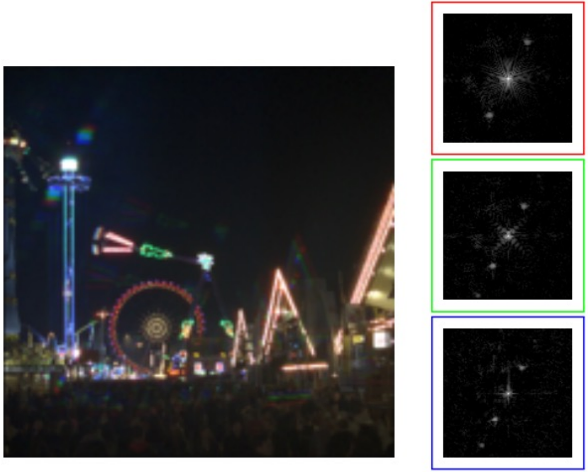
What kind of PSF would be good for HDR imaging?

- Should preserve fine details
- Should help to avoid saturation

Deep optics for HDR imaging



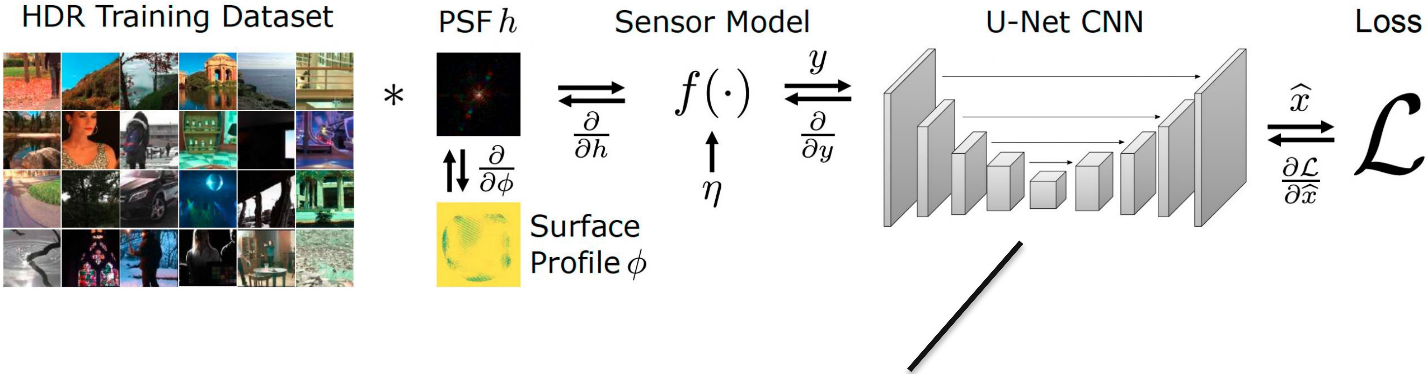
(a) Star PSF



(b) E2E PSF

[Metzler '20]

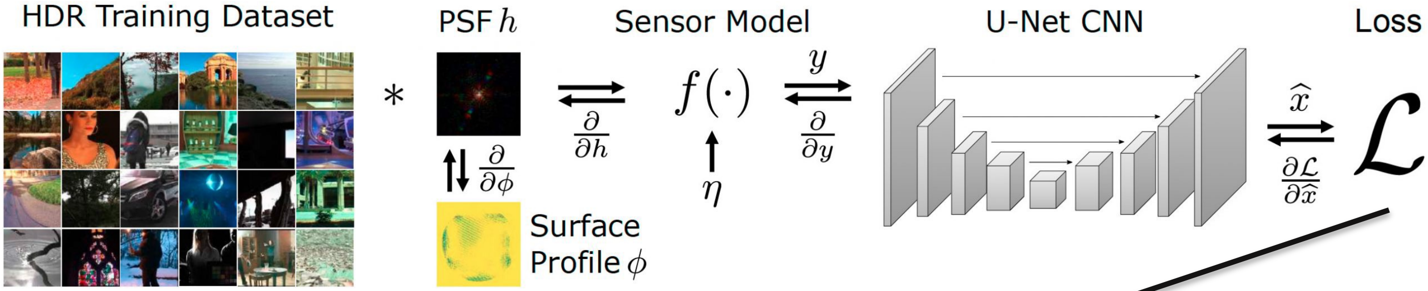
Deep optics for HDR imaging



U-Net again

[Metzler '20]

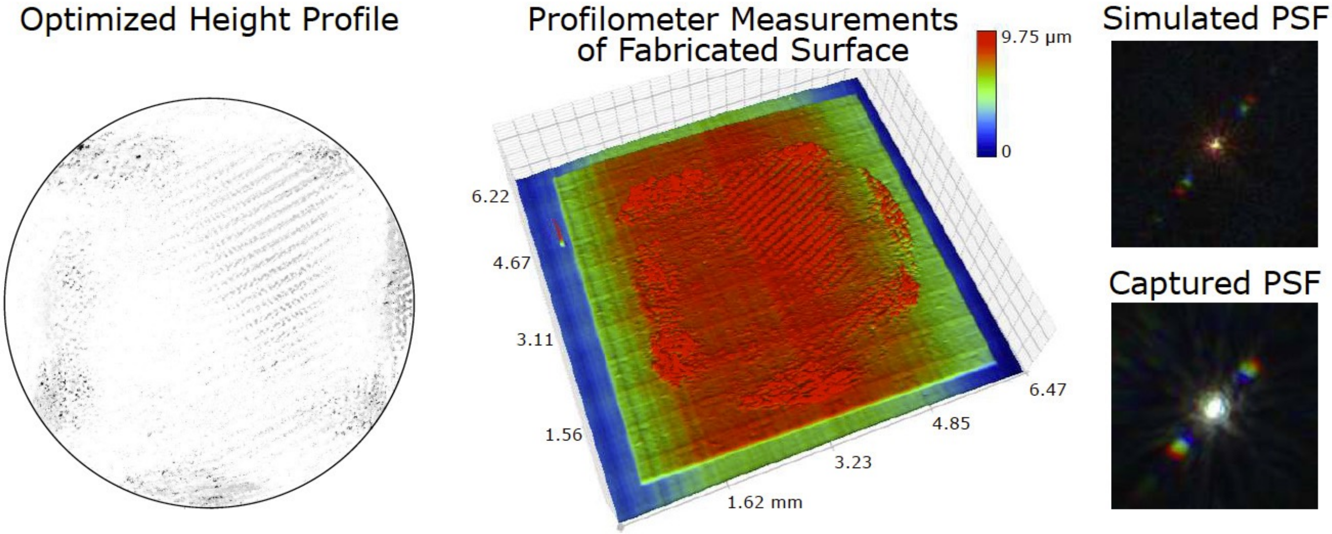
Deep optics for HDR imaging



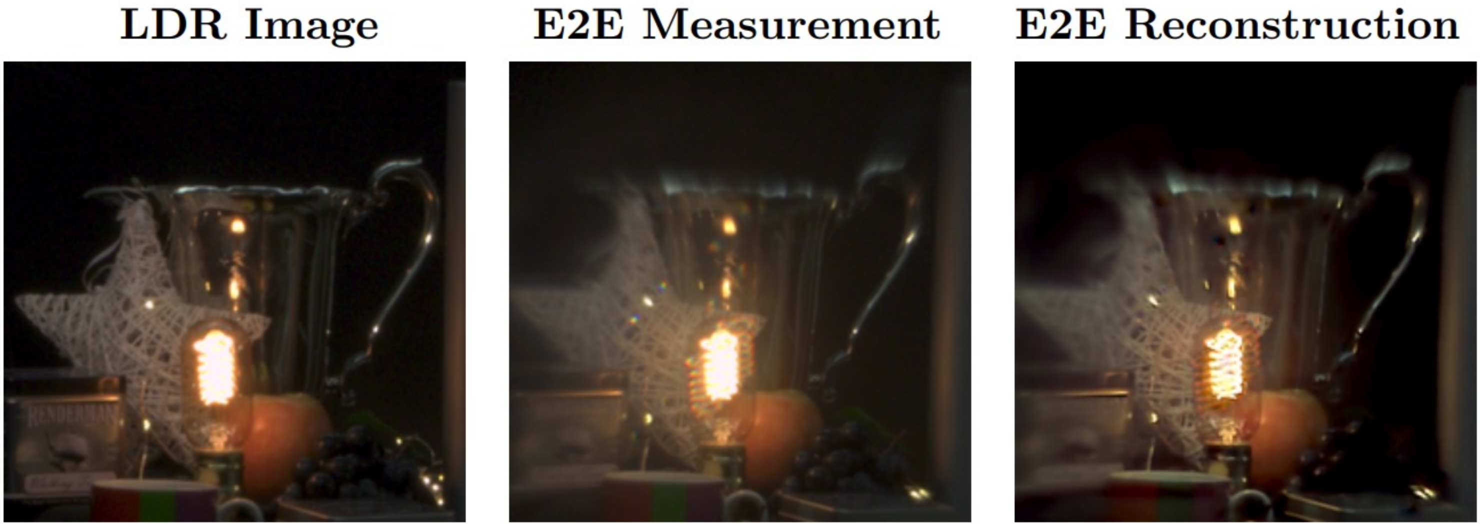
Minimize difference between reconstruction and tone-mapped GT images

[Metzler '20]

Deep optics for HDR imaging

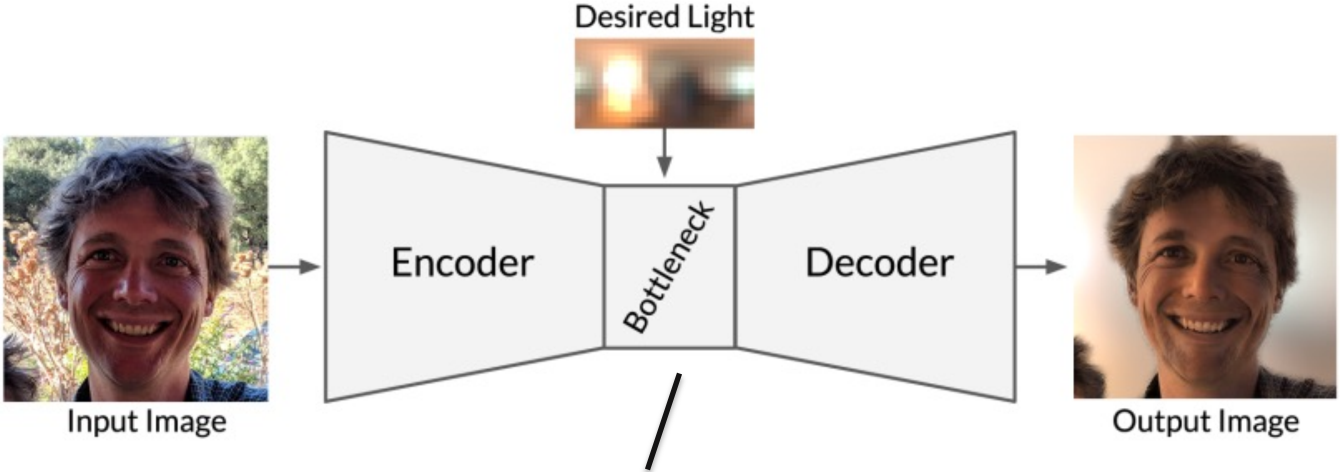


[Metzler '20]



[Metzler '20]

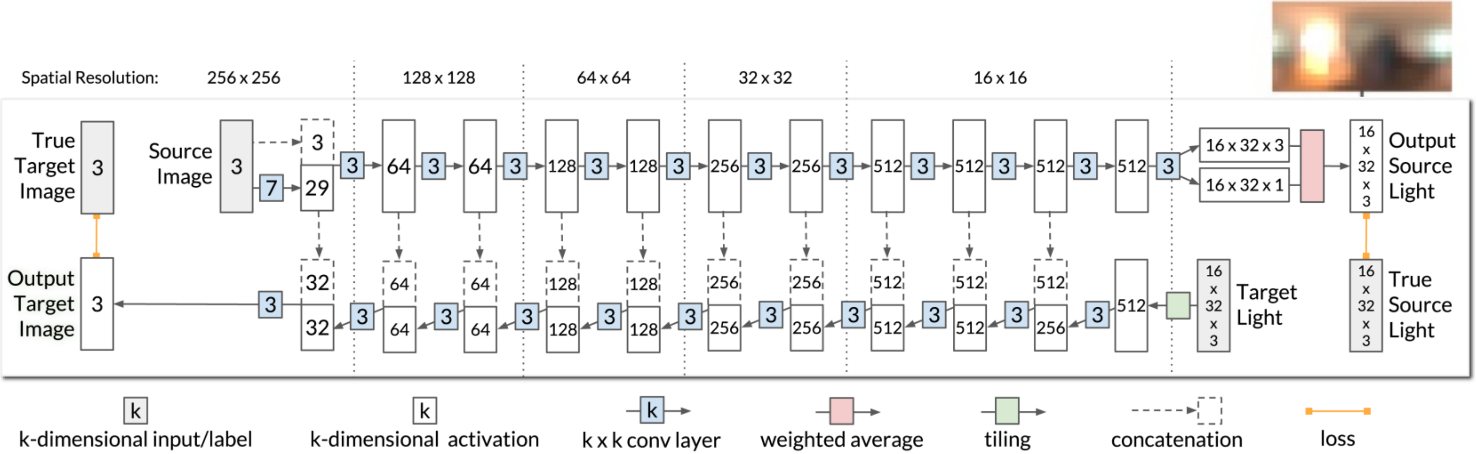
Image Relighting



U-Net

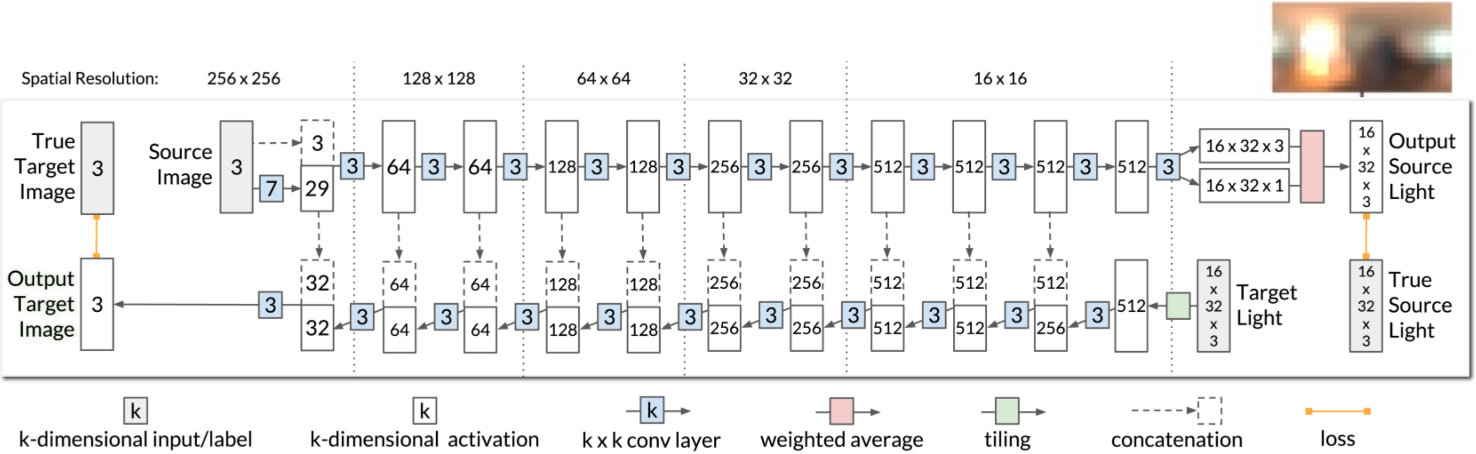
[Sun '19]

Image Relighting



[Sun '19]

Image Relighting



How would you train this network?

[Sun '19]

Image Relighting

Light-stage dataset capture (Google)

[Sun ‘19]

Image Relighting

OLAT photos (columns)

$$b = Ax$$

Re-rendered image

Environment map

(a) OLAT images (7 cameras). (b) Ground-truth renderings.

[Sun ‘19]

Image Relighting

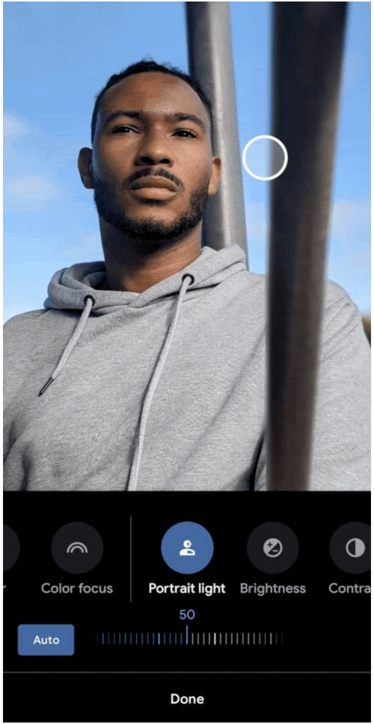
(a) Input image and estimated lighting

(b) Rendered images from our method under three novel illuminations

[Sun ‘19]

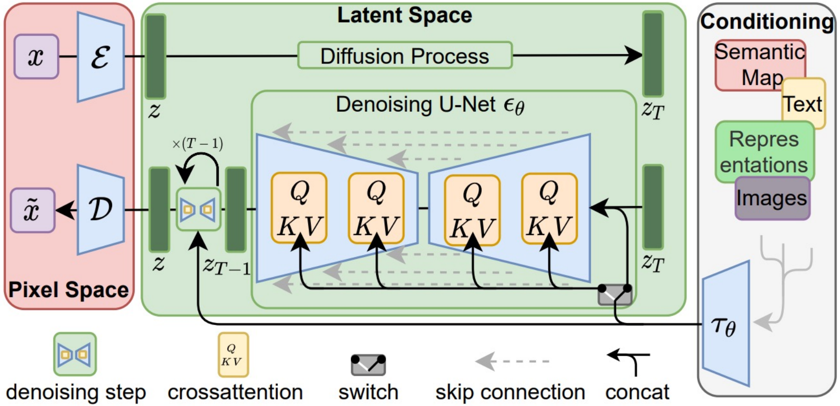
Image Relighting

Now a feature in pixel phones



[Sun ‘19]

Image Generation



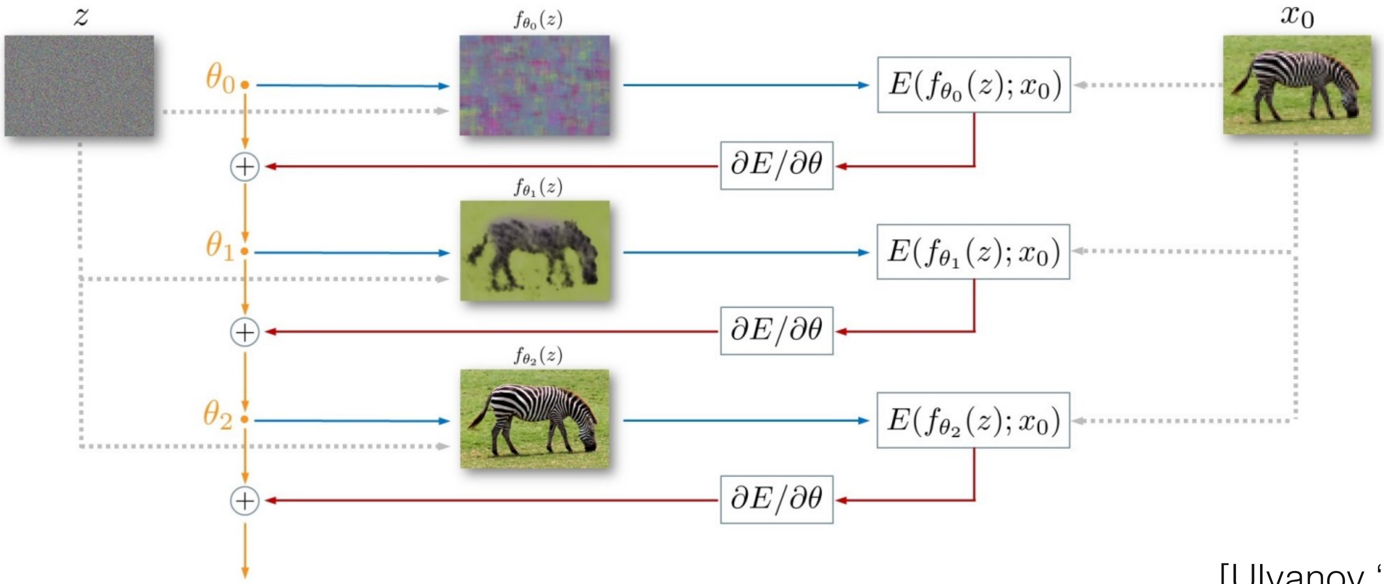
Text-to-Image Synthesis on LAION. 1.45B Model.

'A street sign that reads "Latent Diffusion" '	'A zombie in the style of Picasso'	'An image of an animal half mouse half octopus'	'An illustration of a slightly conscious neural network'	'A painting of a squirrel eating a burger'	'A watercolor painting of a chair that looks like an octopus'	'A shirt with the inscription: "I love generative models!" '

Do we always need training datasets?

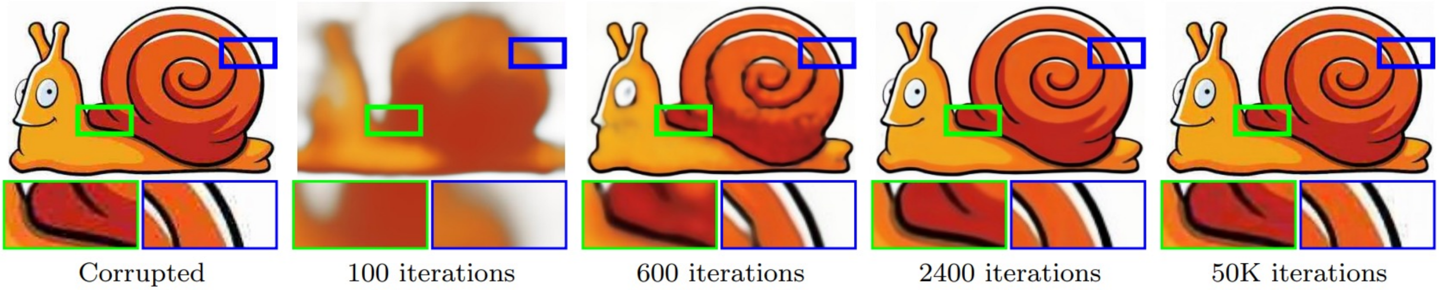
Deep image prior

Idea: Overfit a U-Net to a noisy image, but stop training early



[Ulyanov '20]

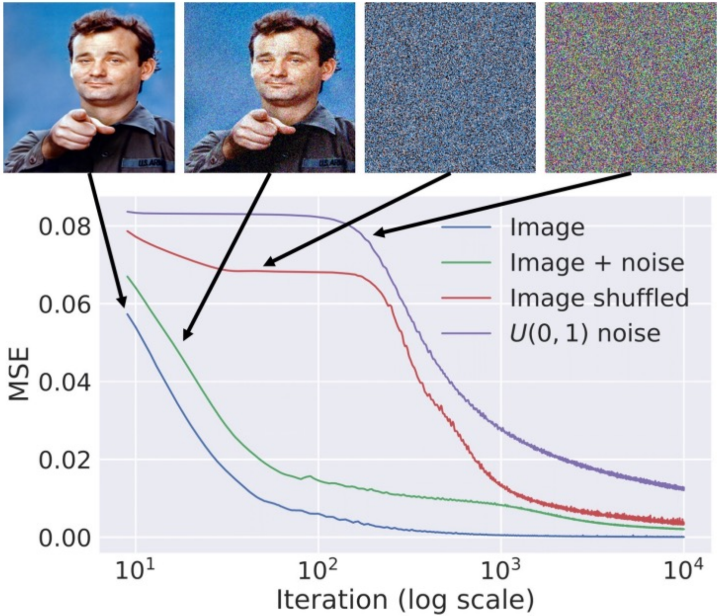
Deep image prior



The CNN itself is a good prior for natural images

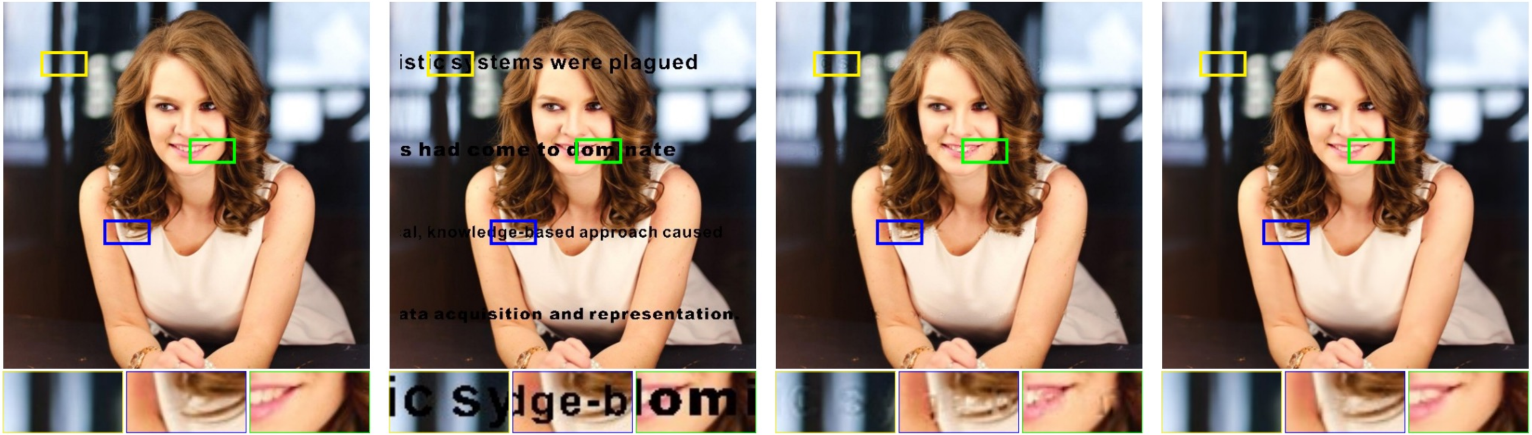
[Ulyanov '20]

Deep image prior



During training, the network fits the image before noise [Ulyanov '20]

Deep image prior



GT | Corrupted | Trained CNN | DIP

[Ulyanov '20]

Summary

- “Neural” Networks & CNNs
- Building blocks of CNNs and deep networks
- Applications & inverse problems
- Just scratches the surface!
    - GANs, diffusion models, neural fields, neural rendering, text-to-image models, autoregressive models, transformers…

Next Time

- Optimization using alternating direction method of multipliers
- Hybrid techniques!

References and Further Reading

slides adapted from Stanford CS231N: http://cs231n.stanford.edu/slides/

CS229/CS231n notes on linear classifiers

https://cs231n.github.io/linear-classify/

https://cs229.stanford.edu/notes2021fall/cs229-notes1.pdf

CS231n Notes on backprop

http://cs231n.stanford.edu/handouts/linear-backprop.pdf

https://cs231n.github.io/optimization-2/

Intro to pytorch autograd

https://pytorch.org/tutorials/beginner/blitz/autograd_tutorial.html

Extending pytorch autograd functions

https://pytorch.org/docs/stable/notes/extending.html

References and Further Reading

slides adapted from Stanford CS231N: http://cs231n.stanford.edu/slides/

Araujo, André, Wade Norris, and Jack Sim. "Computing receptive fields of convolutional neural networks." *Distill* 4.11 (2019)

Chen, Chen, et al. "Learning to see in the dark." *Proc. CVPR*. 2018.

Eigen, David, Christian Puhrsch, and Rob Fergus. "Depth map prediction from a single image using a multi-scale deep network." *Proc. NeurIPS.* (2014).

Farabet, Clement, et al. "Learning hierarchical features for scene labeling." *IEEE TPAMI.* 35.8 (2012): 1915-1929.

He, Kaiming, et al. "Deep residual learning for image recognition." Proc. CVPR. 2016.

Hubel, David H., and Torsten N. Wiesel. "Receptive fields of single neurones in the cat's striate cortex." *The Journal of physiology* 148.3 (1959): 574-591.

Krizhevsky, Alex, Ilya Sutskever, and Geoffrey E. Hinton. "Imagenet classification with deep convolutional neural networks." *Proc. NeurIPS* 25 (2012): 1097-1105.

Lim, Bee, et al. "Enhanced deep residual networks for single image super-resolution." *Proc. CVPR Workshops*. 2017.

Lin, Haoning, Zhenwei Shi, and Zhengxia Zou. "Maritime semantic labeling of optical remote sensing images with multi-scale fully convolutional network." *Remote sens.* 9.5 (2017): 480.

Metzler, Christopher A., et al. "Deep optics for single-shot high-dynamic-range imaging." Proc. CVPR. 2020.

Nah, Seungjun, Tae Hyun Kim, and Kyoung Mu Lee. "Deep multi-scale convolutional neural network for dynamic scene deblurring." *Proc. CVPR*. 2017.

Odena, Augustus, Vincent Dumoulin, and Chris Olah. "Deconvolution and checkerboard artifacts." *Distill* 1.10 (2016)

Olah, Chris, Alexander Mordvintsev, and Ludwig Schubert. "Feature visualization." *Distill* 2.11 (2017)

Ronneberger, Olaf, Philipp Fischer, and Thomas Brox. "U-net: Convolutional networks for biomedical image segmentation." *International Conference on Medical image computing and computer-assisted intervention*. 2015.

Ren, Shaoqing, et al. "Faster R-CNN: towards real-time object detection with region proposal networks." *IEEE TPAMI.* 39.6 (2016): 1137-1149.

Russakovsky, Olga, et al. "Imagenet large scale visual recognition challenge." *IJCV* 115.3 (2015): 211-252.

Simonyan, Karen, and Andrew Zisserman. "Very deep convolutional networks for large-scale image recognition." *Proc. ICLR* (2014).

Sun, Tiancheng, et al. "Single image portrait relighting." *ACM Trans. Graph.* 38.4 (2019): 79-1.

Toshev, Alexander, and Christian Szegedy. "Deeppose: Human pose estimation via deep neural networks." *Proc. CVPR*. 2014.

Ulyanov, Dmitry, Andrea Vedaldi, and Victor Lempitsky. "Deep image prior." *Proc. CVPR.* 2018.

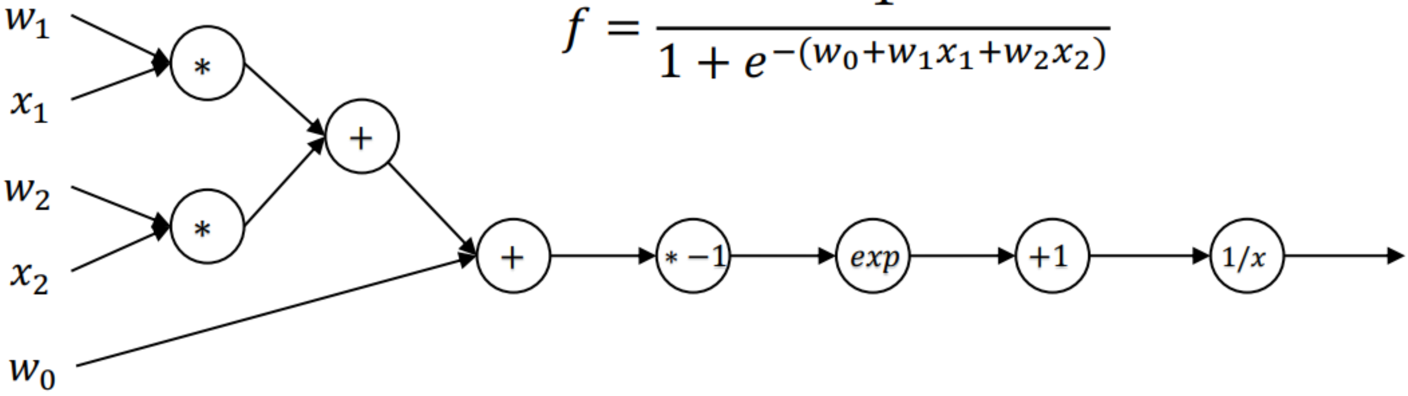
Zhang, Kai, et al. "Beyond a gaussian denoiser: Residual learning of deep cnn for image denoising." *IEEE Trans. Imag. Proc.* 26.7 (2017): 3142-3155.

Extra backpropagation example (from Stanford CS231n)

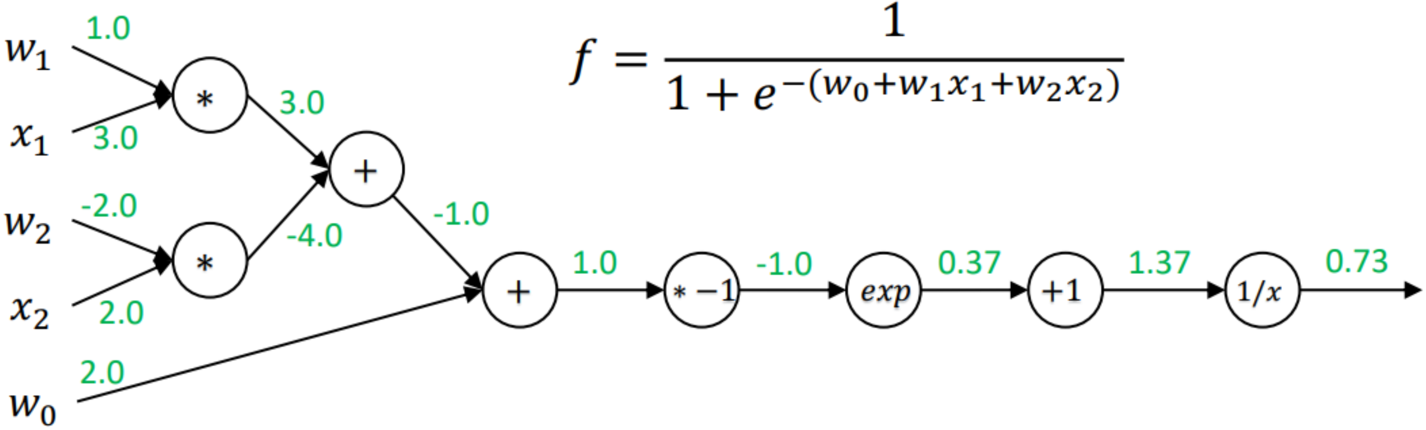
$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$

Extra backpropagation example

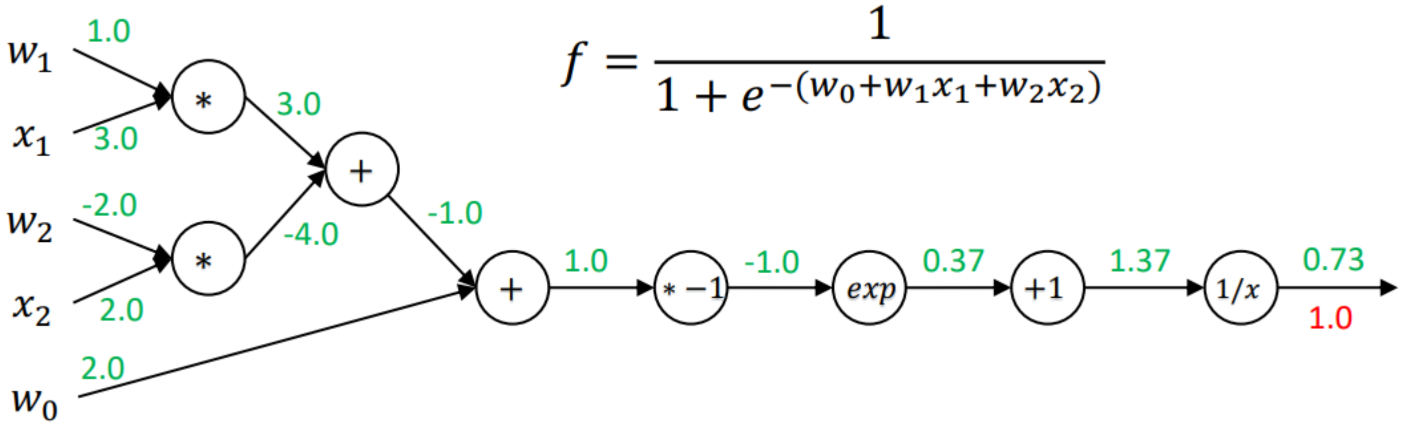
$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$



Extra backpropagation example

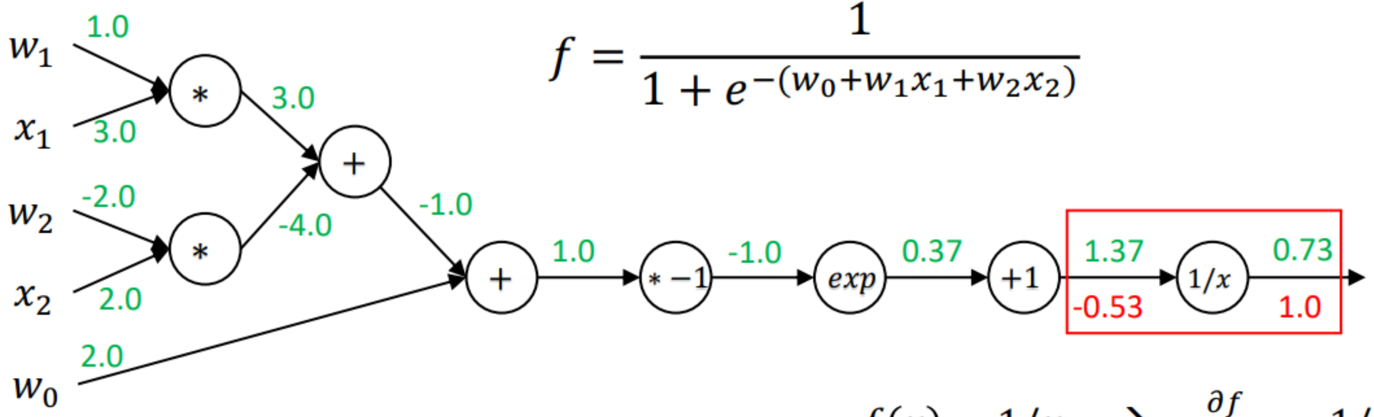


Extra backpropagation example



Extra backpropagation example

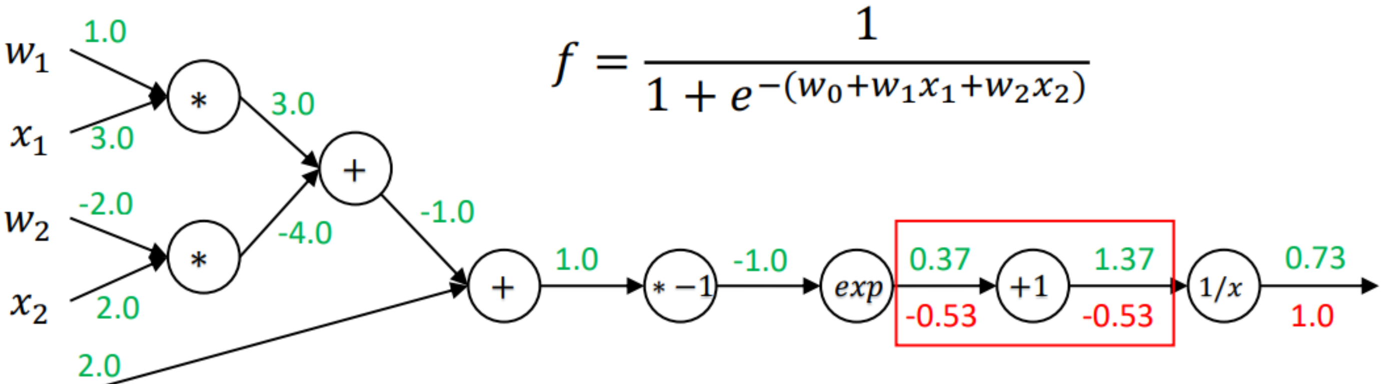
$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$



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

$$\frac{\partial J}{\partial x} = \frac{\partial J}{\partial f}\frac{\partial f}{\partial x} = -1/x^2$$

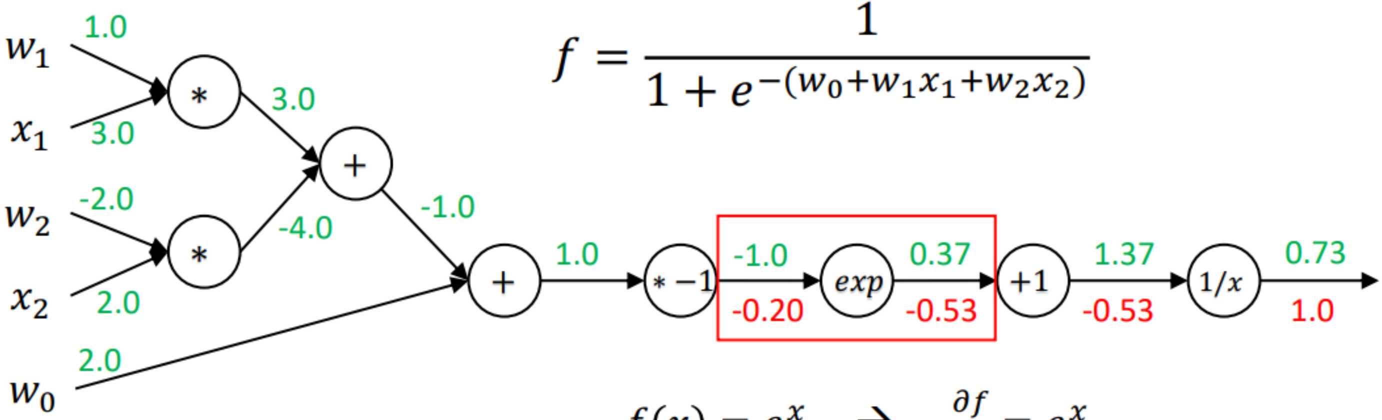
Extra backpropagation example



$$f(x) = x + 1 \quad \rightarrow \quad \frac{\partial f}{\partial x} = 1$$

Extra backpropagation example

$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$

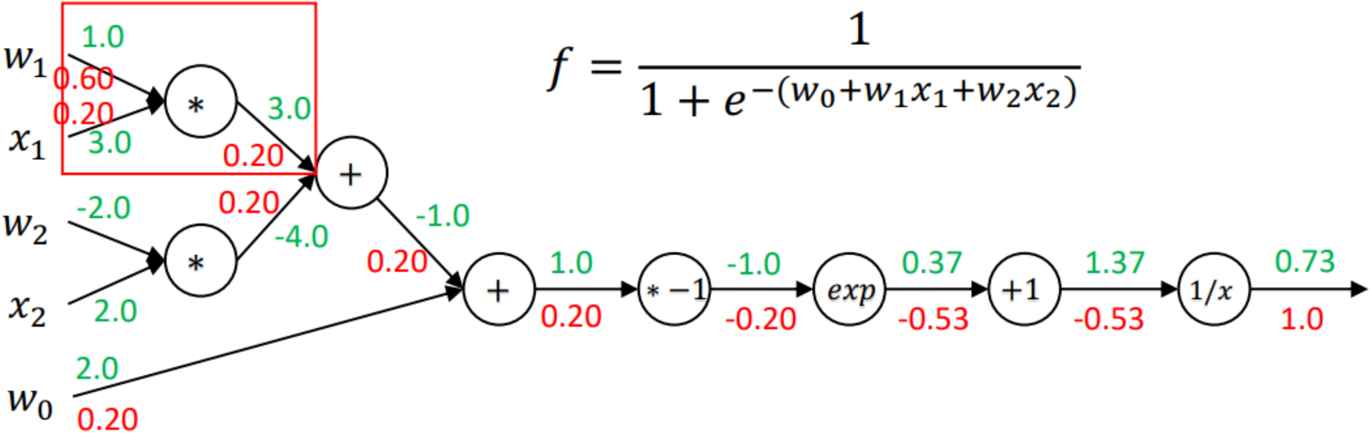


$$f(x) = e^x \quad \rightarrow \quad \frac{\partial f}{\partial x} = e^x$$

$$\frac{\partial J}{\partial x} = \frac{\partial J}{\partial f}\frac{\partial f}{\partial x} = \frac{\partial J}{\partial f} \cdot e^x$$

Extra backpropagation example

$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$



$$f(x, w) = xw \quad \rightarrow \quad \frac{\partial f}{\partial x} = w, \; \frac{\partial f}{\partial w} = x$$

Extra backpropagation example

$$f = \frac{1}{1 + e^{-(w_0 + w_1 x_1 + w_2 x_2)}}$$