BOSTON UNIVERSITY

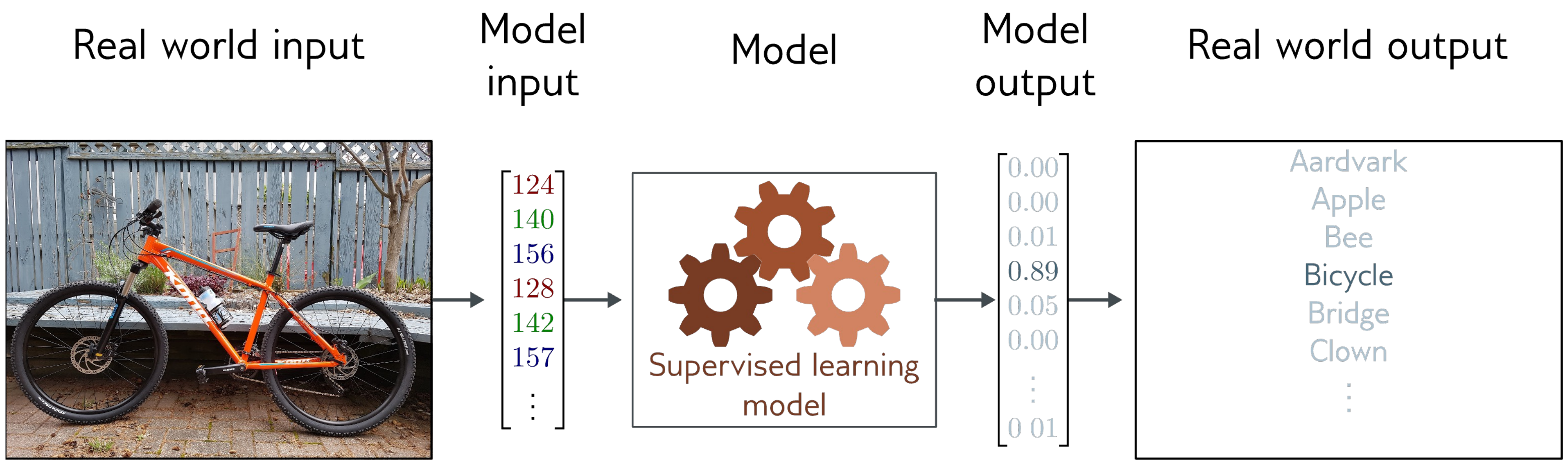
Convolutional Networks

DL4DS – Spring 2026

Convolutional networks

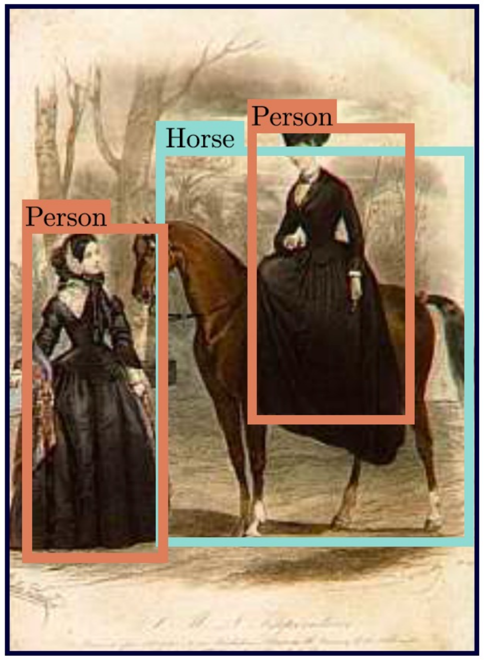
- Networks for images
- Invariance and equivariance
- 1D convolution
- Convolutional layers
- Channels
- Receptive fields
- Convolutional network for MNIST 1D

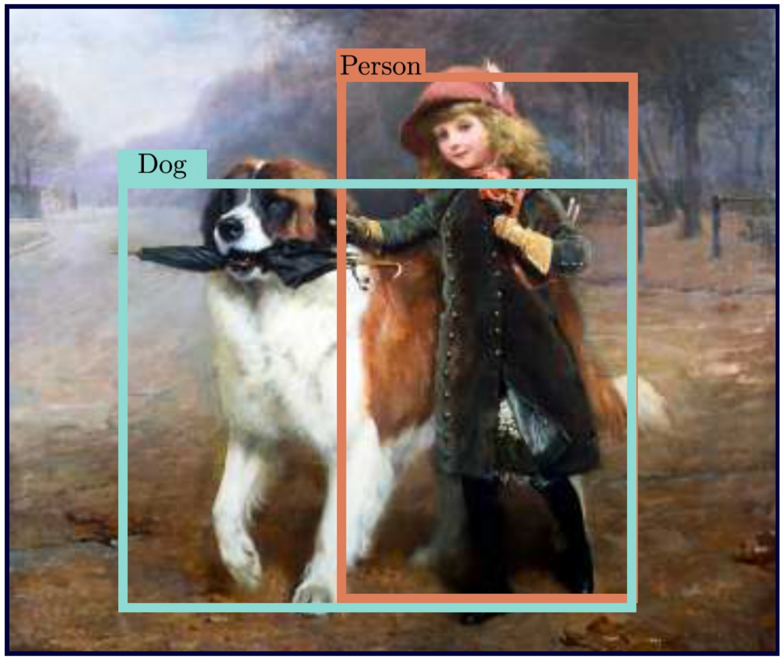
Image classification



- Multiclass classification problem (discrete classes, >2 possible classes)
- Convolutional network

Object detection (+ classification)





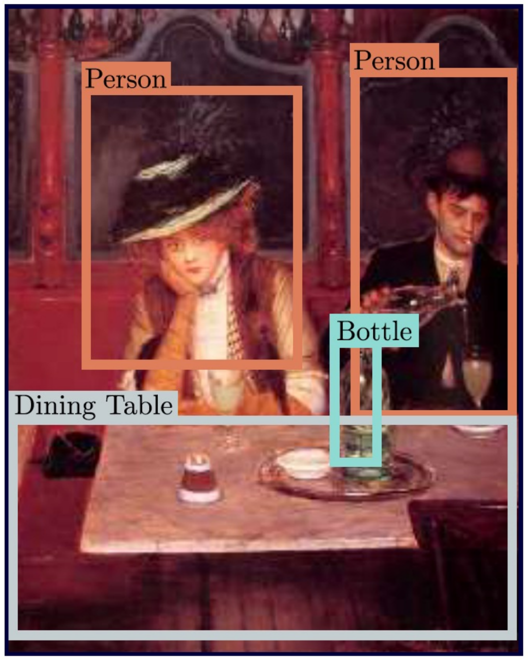
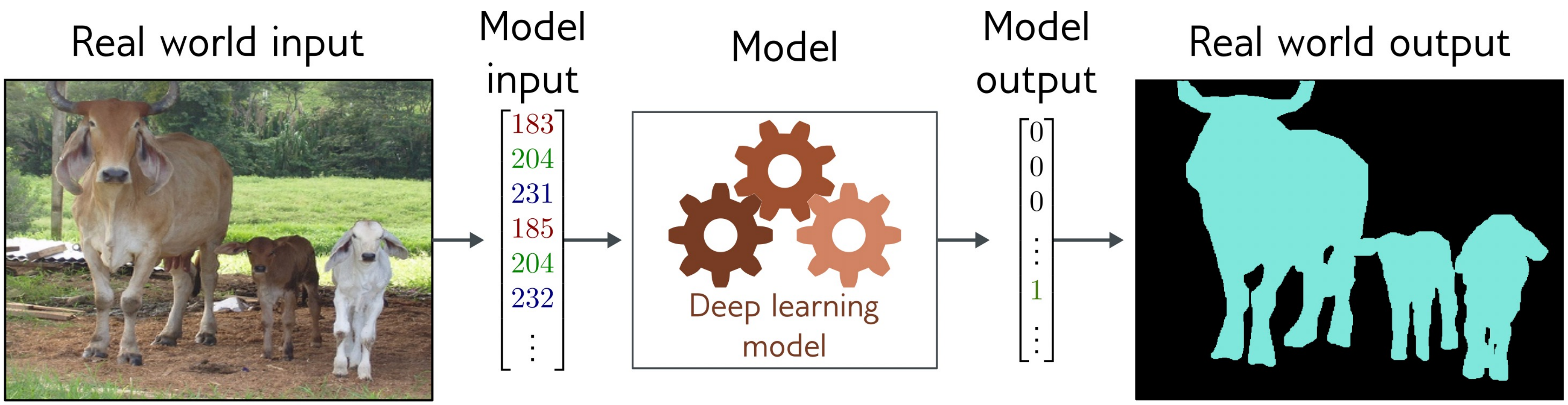


Image segmentation



- Multivariate binary classification problem (many outputs, two discrete classes)
- Convolutional encoder-decoder network

Networks for images

- Problems with fully-connected networks

1. Size
    - 224x224 RGB image = 150,528 dimensions
    - Hidden layers generally larger than inputs
    - One hidden layer = 150,520x150,528 weights -- 22 billion
2. Nearby pixels statistically related
    - But could permute pixels and relearn and get same results with FC
3. Should be stable under transformations
    - Don’t want to re-learn appearance at different parts of image

Convolutional networks

- Parameters only look at local image patches
- Share parameters across image

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Invariance

- A function f[x] is invariant to a transformation t[] if:

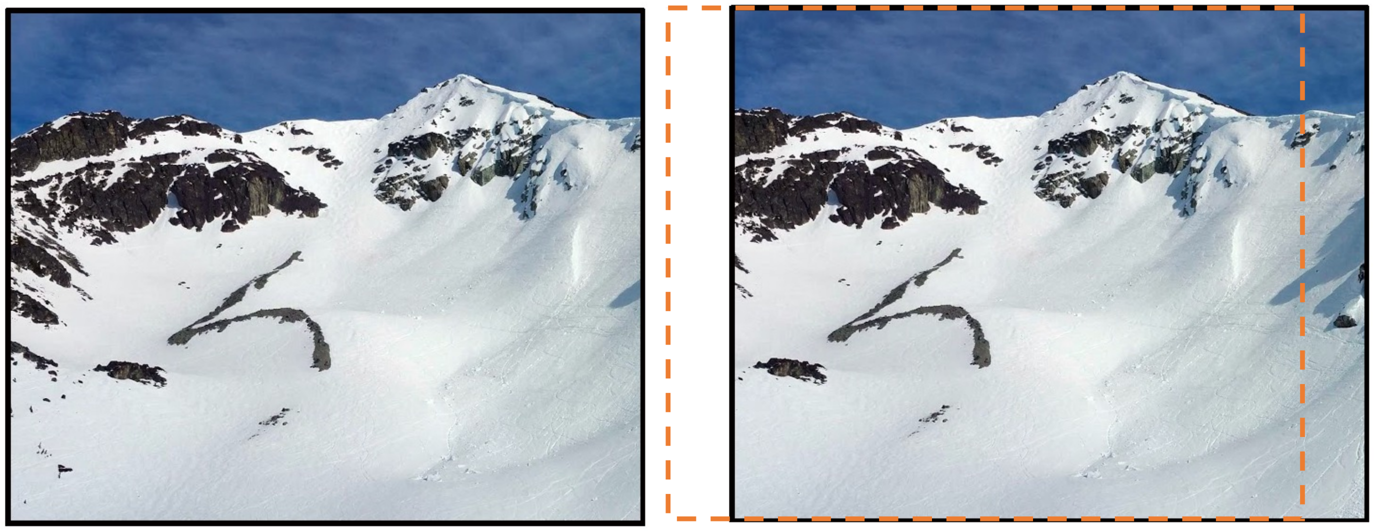
$$\mathbf{f}\left[\mathbf{t}[\mathbf{x}]\right] = \mathbf{f}[\mathbf{x}]$$

i.e., the function output is the same even after the transformation is applied.

Invariance example

e.g., Image classification

- Image has been translated, but we want our classifier to give the same result



Equivariance

- A function f[x] is equivariant to a transformation t[] if:

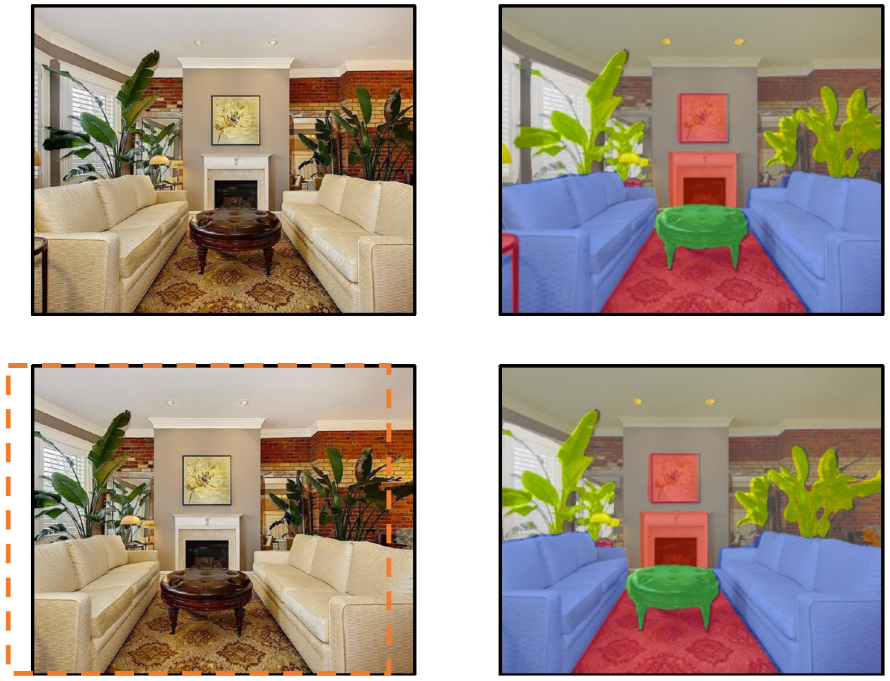
$$\mathbf{f}\left[\mathbf{t}[\mathbf{x}]\right] = \mathbf{t}\left[\mathbf{f}[\mathbf{x}]\right]$$

i.e., the output is transformed in the same way as the input

Equivariance example

e.g., Image segmentation

- Image has been translated and we want segmentation to translate with it



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Convolution* in 1D

- Input vector **x:**

$$\mathbf{x} = [x_1, x_2, \ldots, x_I]$$

- Output is weighted sum of neighbors:

$$z_i = \omega_1 x_{i-1} + \omega_2 x_i + \omega_3 x_{i+1}$$

- Convolutional kernel or filter:

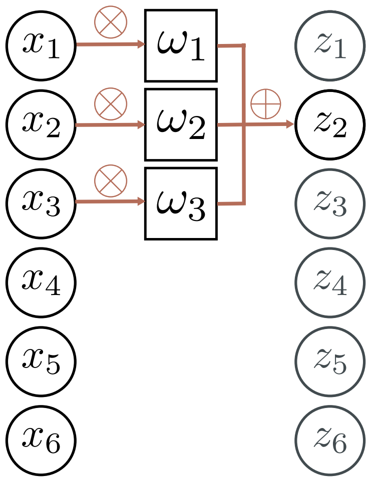
$$\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]^T$$

Kernel size = 3

** Not technically convolution because weights order is not reversed*

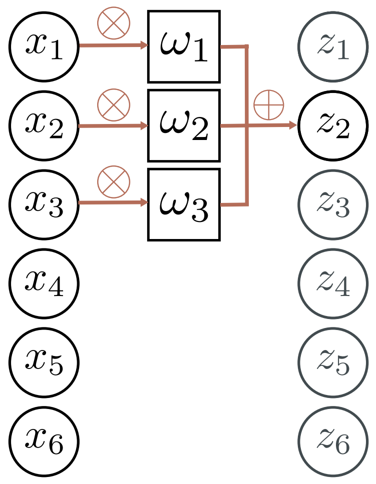
Convolution with kernel size 3

a)

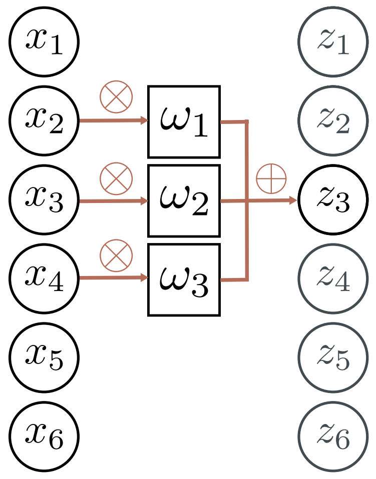


Convolution with kernel size 3

a)

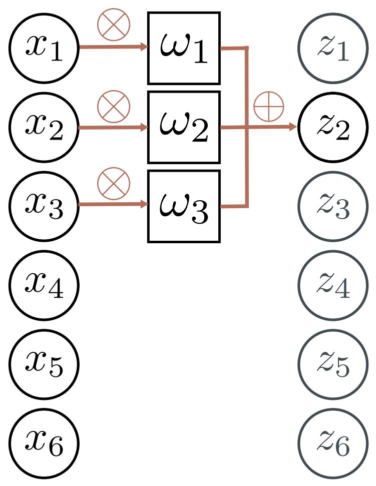


b)

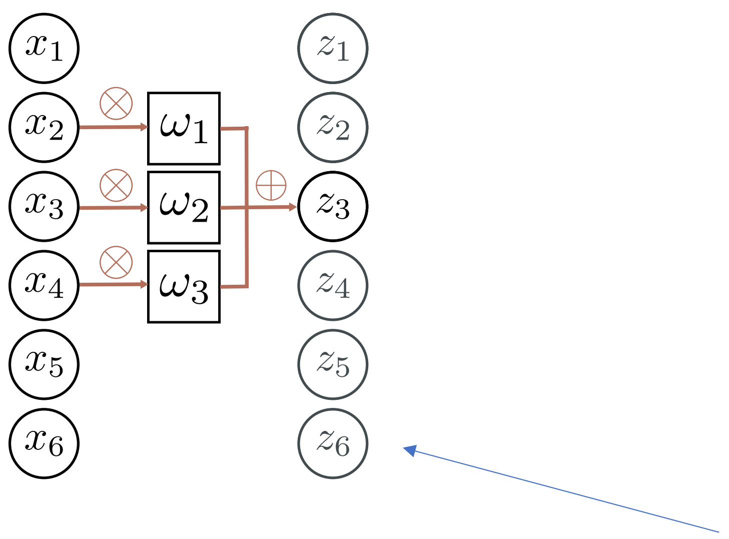


Convolution with kernel size 3

a)



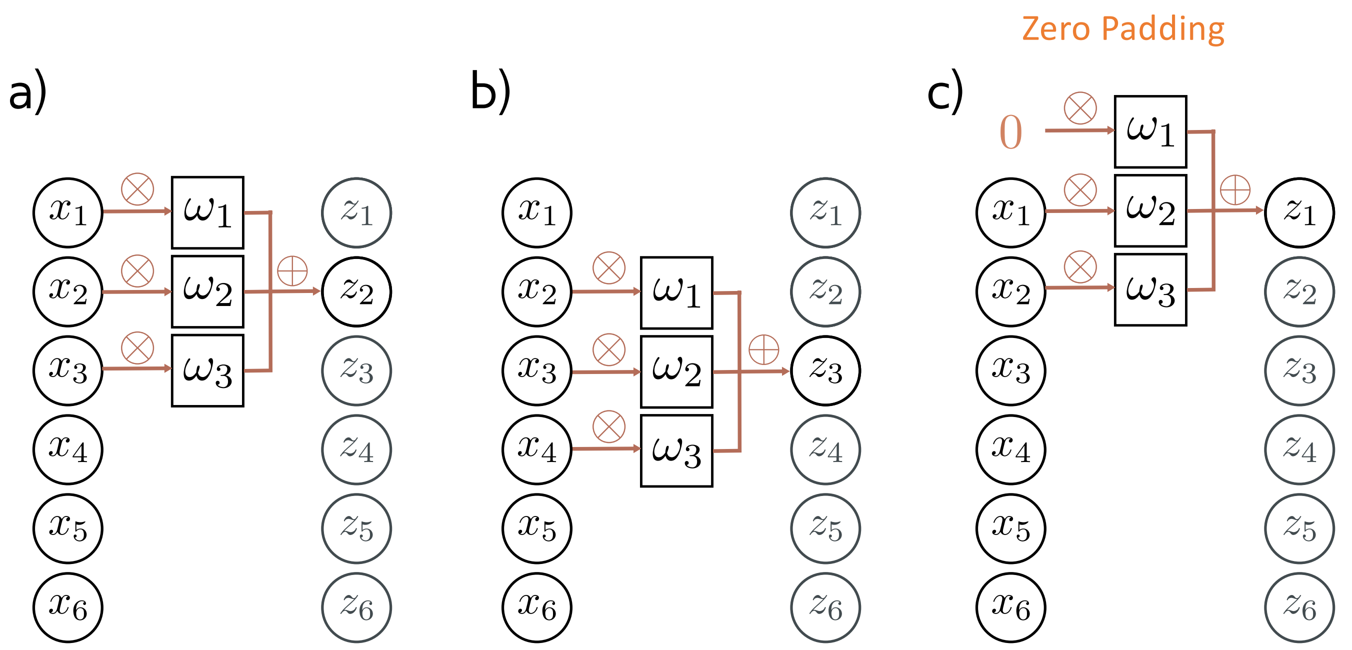
b)



Equivariant to translation of input

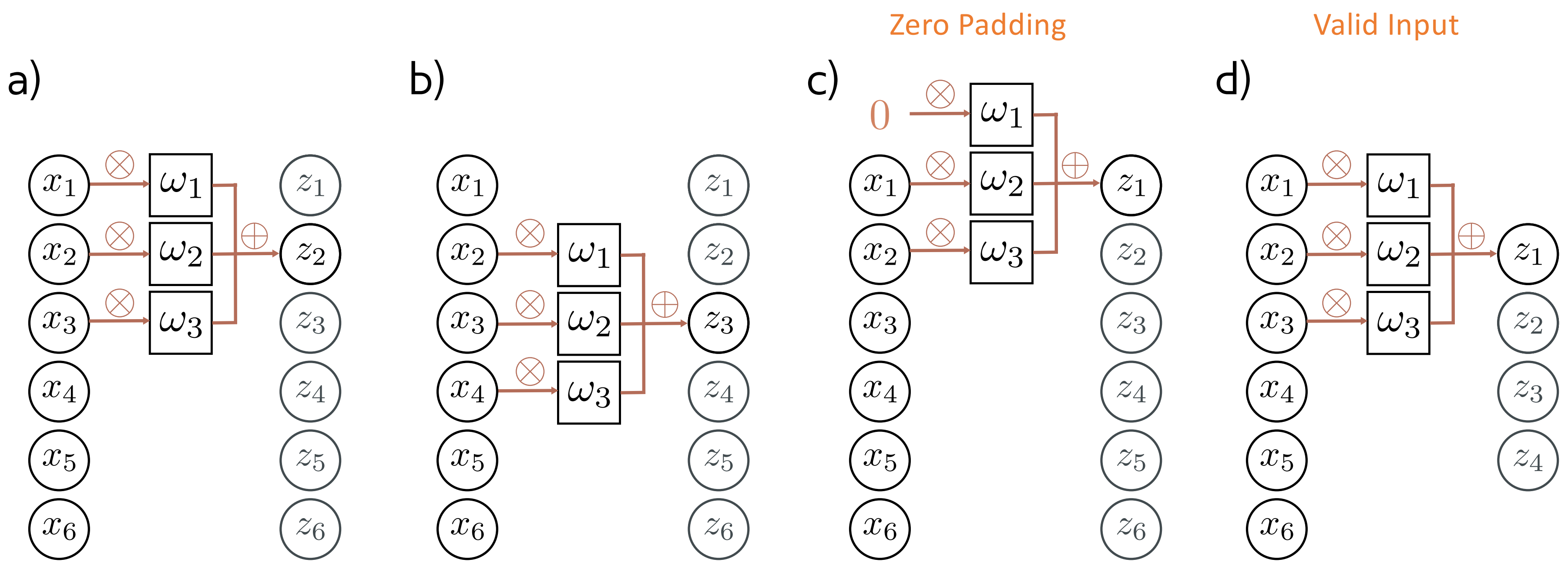
$$\mathbf{f}\left[\mathbf{t}[\mathbf{x}]\right] = \mathbf{t}\left[\mathbf{f}[\mathbf{x}]\right]$$

Zero padding



Treat positions that are beyond end of the input as zero.

“Valid” convolutions

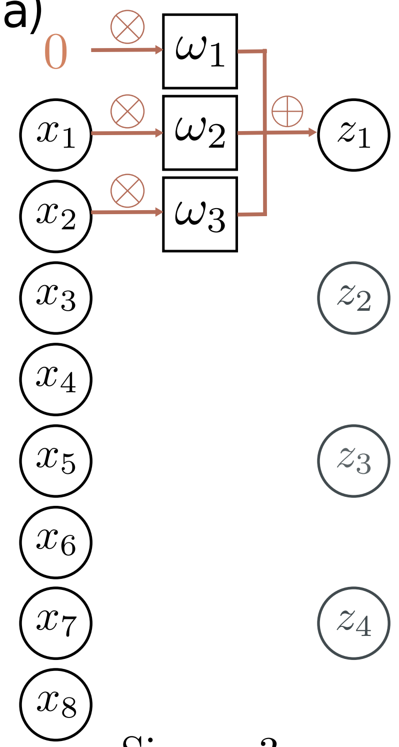


Only process positions where kernel falls in image (smaller output).

Stride, kernel size, and dilation

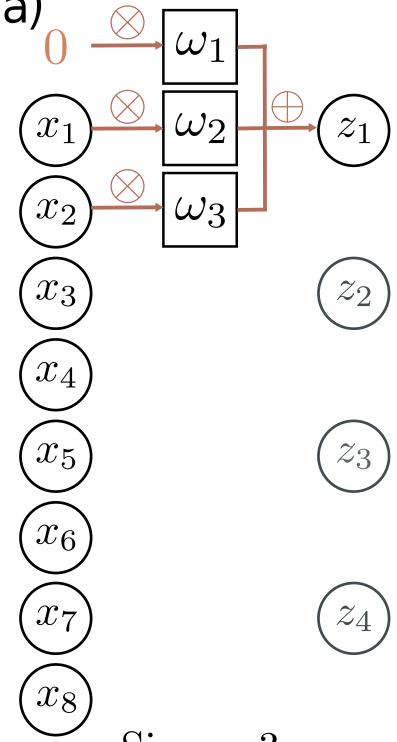
- Stride = shift by k positions for each output
  - Decreases size of output relative to input
- Kernel size = weight a different number of inputs for each output
  - Combine information from a larger area
  - But kernel size 5 uses 5 parameters
- Dilated or atrous convolutions = intersperse kernel values with zeros
  - Combine information from a larger area
  - Fewer parameters

a)



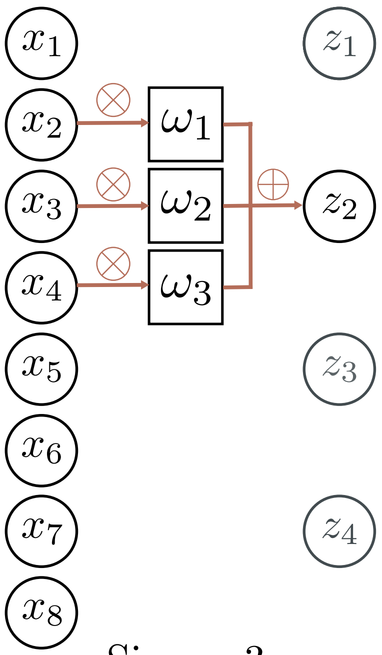
$\text{Size} = 3$
$\text{Stride} = 2$
$\text{Dilation} = 1$

a)

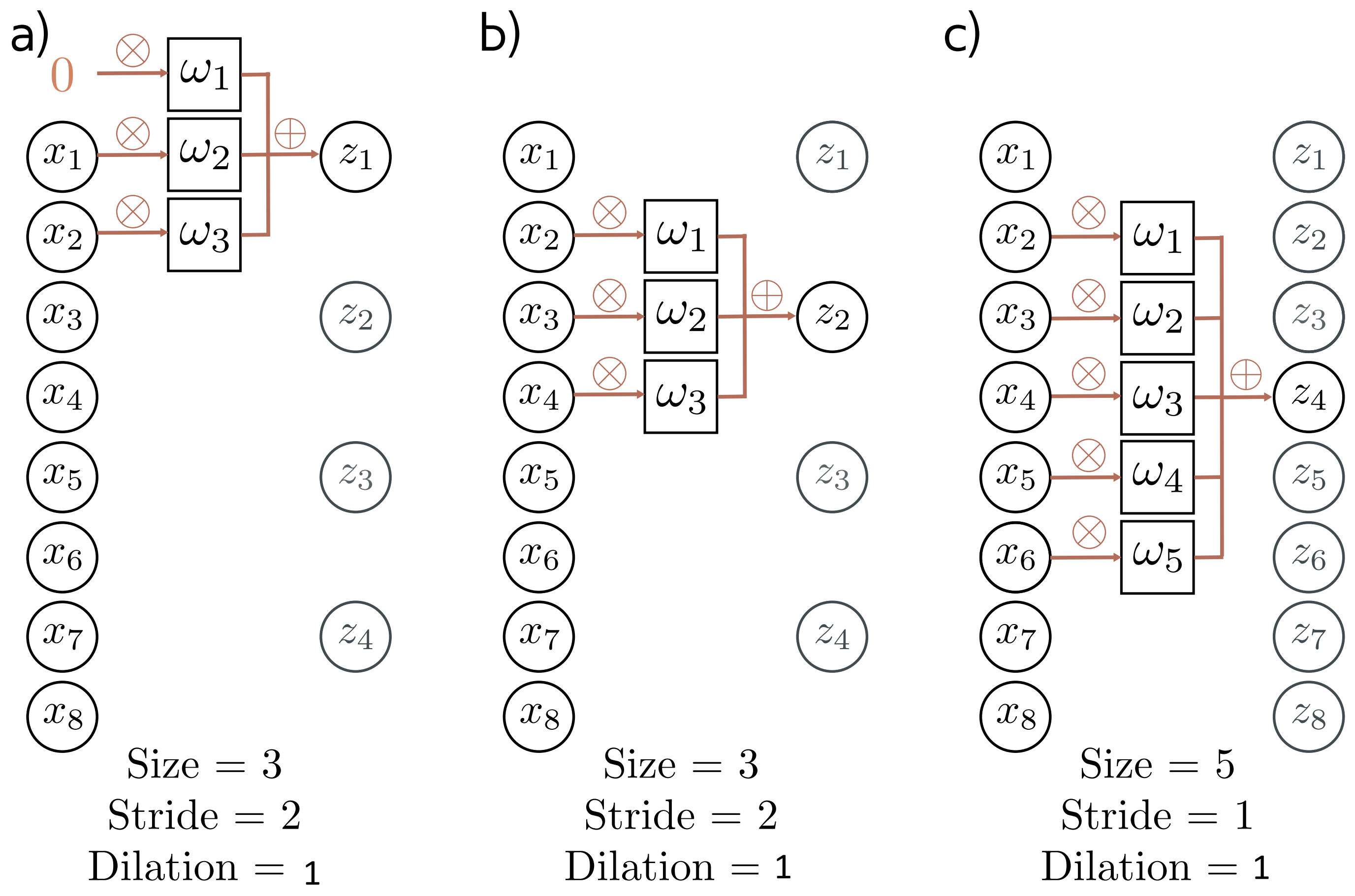


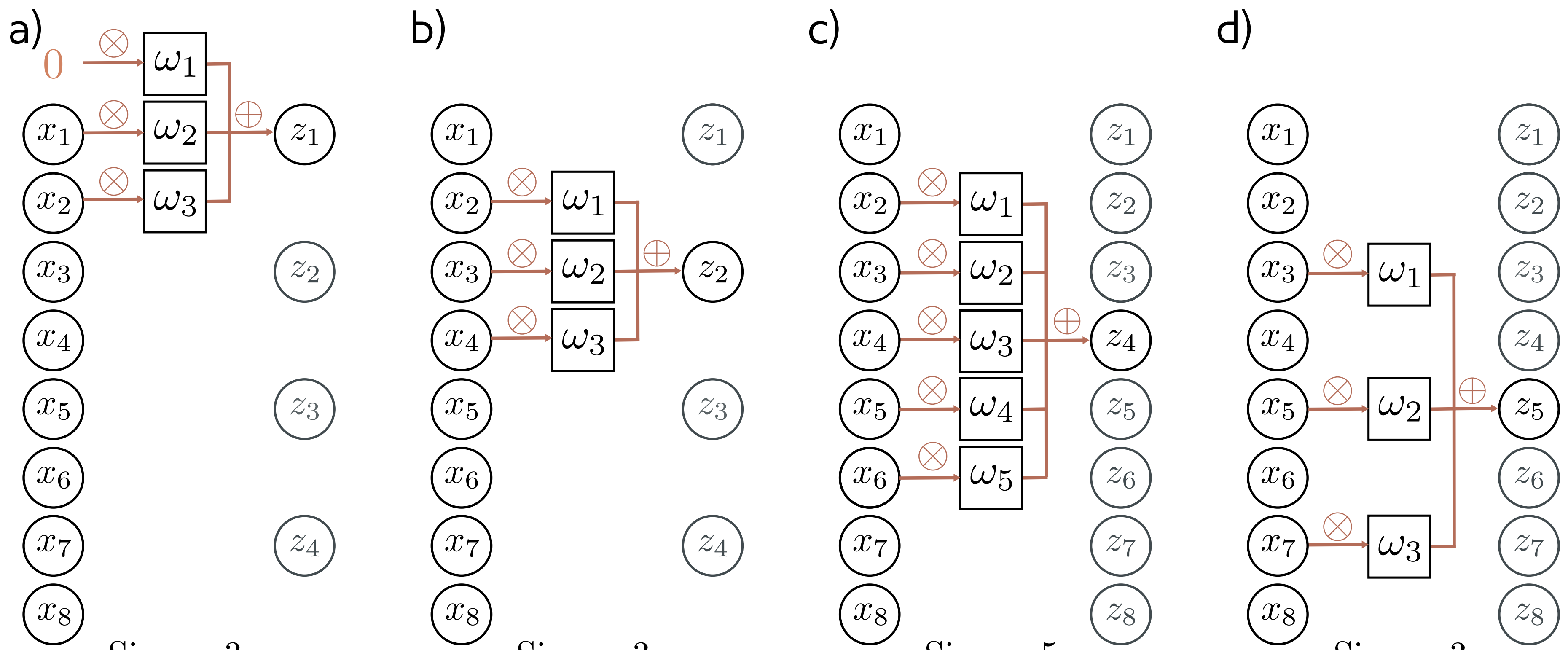
Size = 3
Stride = 2
Dilation = 1

b)



Size = 3
Stride = 2
Dilation = 1


a)
0
x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8
ω_1 ω_2 ω_3
z_1 z_2 z_3 z_4
Size $= 3$
Stride $= 2$
Dilation $= 1$
b)
x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8
ω_1 ω_2 ω_3
z_1 z_2 z_3 z_4
Size $= 3$
Stride $= 2$
Dilation $= 1$
c)
x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8
ω_1 ω_2 ω_3 ω_4 ω_5
z_1 z_2 z_3 z_4 z_5 z_6 z_7 z_8
Size $= 5$
Stride $= 1$
Dilation $= 1$



Size $=3$
Stride $=2$
Dilation $=1$

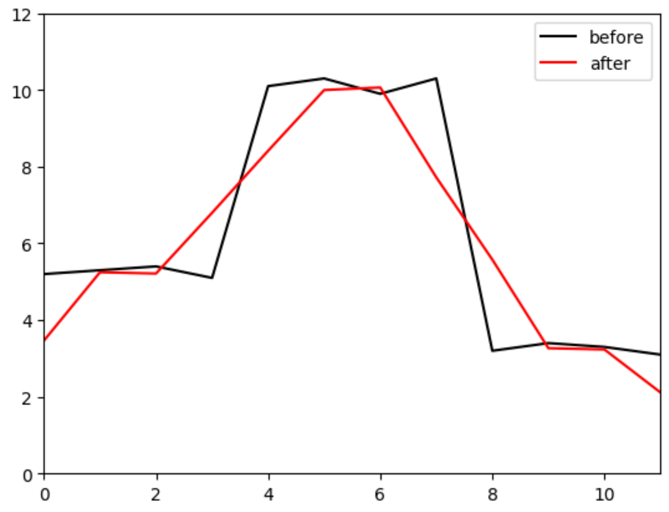
Size $=3$
Stride $=2$
Dilation $=1$

Size $=5$
Stride $=1$
Dilation $=1$

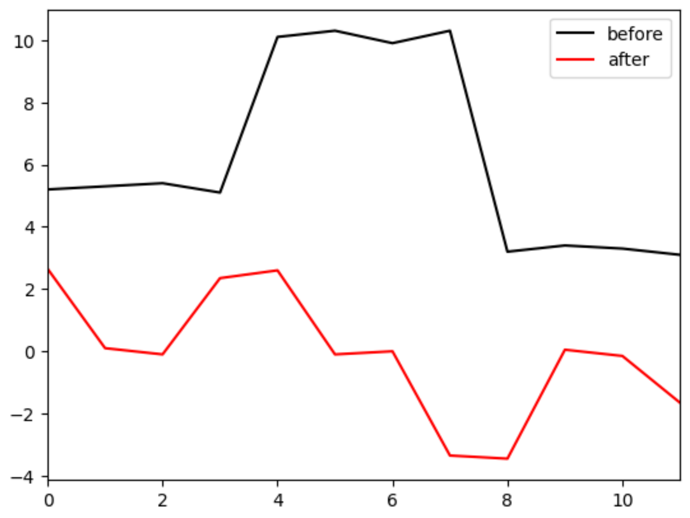
Size $=3$
Stride $=1$
Dilation $=2$.

1-D Convolution Example

```
# Define a signal that we can apply convolution to
x = [5.2, 5.3, 5.4, 5.1, 10.1, 10.3, 9.9, 10.3, 3.2, 3.4, 3.3, 3.1]
```



```
omega = [0.33,0.33,0.33]
```



```
omega = [-0.5,0,0.5]
```

```
length=3, stride=1, dilation=1, zero padding
```

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Convolutional layer – Output at Position i

(size: 3, stride: 1, dilation: 1)

$$\begin{aligned} h_i &= \mathrm{a}\left[\beta + \omega_1 x_{i-1} + \omega_2 x_i + \omega_3 x_{i+1}\right] \\ &= \mathrm{a}\left[\beta + \sum_{j=1}^{3} \omega_j x_{i+j-2}\right] \end{aligned}$$

Special case of fully-connected network

Convolutional network:

$$
\begin{aligned}
h_i &= \mathrm{a}\left[\beta + \omega_1 x_{i-1} + \omega_2 x_i + \omega_3 x_{i+1}\right] \\
&= \mathrm{a}\left[\beta + \sum_{j=1}^{3} \omega_j x_{i+j-2}\right]
\end{aligned}
$$

Fully connected network:
(D inputs, D hidden units)

$$
h_i = \mathrm{a}\left[\beta_i + \sum_{j=1}^{D} \omega_{ij} x_j\right]
$$

Special case of fully-connected network

Convolutional network:

$$\begin{aligned} h_i &= \mathrm{a}\left[\beta + \omega_1 x_{i-1} + \omega_2 x_i + \omega_3 x_{i+1}\right] \\ &= \mathrm{a}\left[\beta + \sum_{j=1}^{3} \omega_j x_{i+j-2}\right] \end{aligned}$$

3 weights, 1 bias for all i: 1 … D

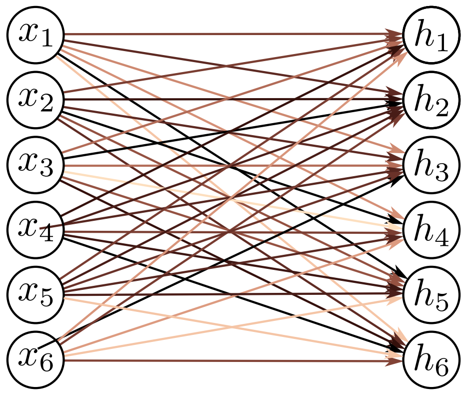
Fully connected network:
(D inputs, D hidden units)

$$h_i = \mathrm{a}\left[\beta_i + \sum_{j=1}^{D} \omega_{ij} x_j\right]$$

D^2 weights, D biases for all i: 1 … D

Special case of fully-connected network

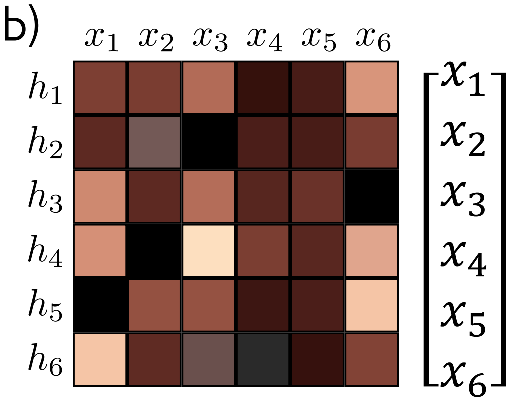
a)



6 inputs to each hidden unit

b)

Weight Matrix



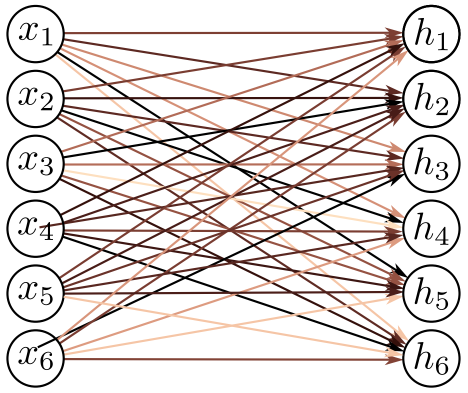
$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix}$$

Fully connected network

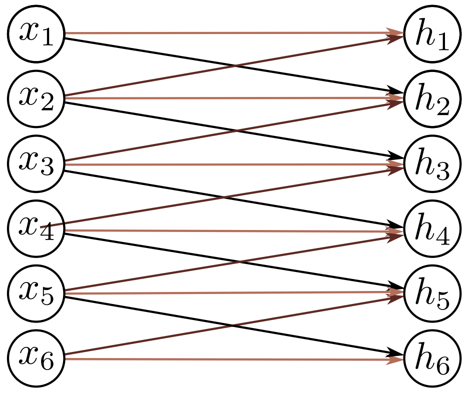
Bias is implied

Special case of fully-connected network

a)



c)

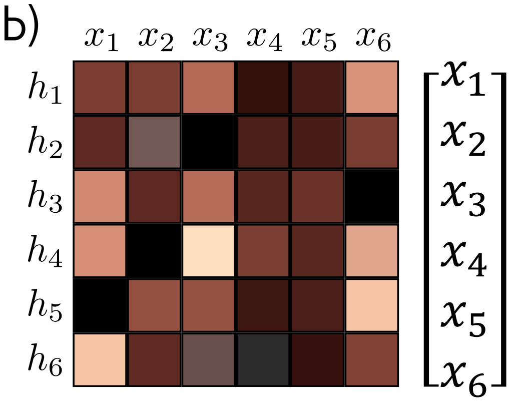


3 inputs to each hidden unit

Bias is implied

b)

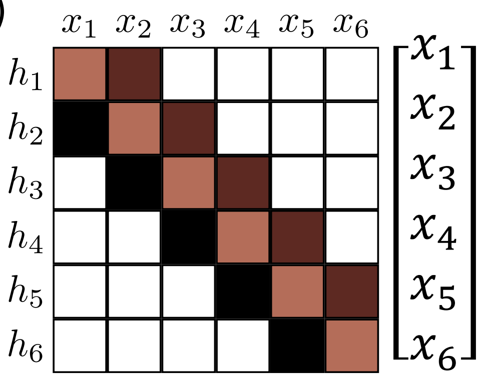
Weight Matrices



x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6
x_1 x_2 x_3 x_4 x_5 x_6

Fully connected network

d)

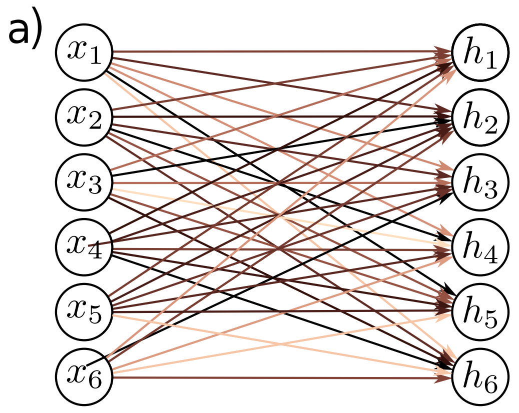


x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6
x_1 x_2 x_3 x_4 x_5 x_6

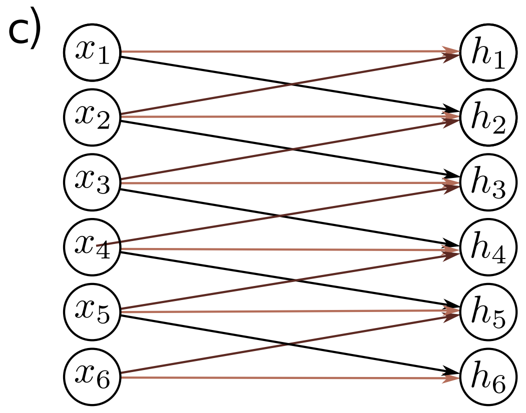
Convolution, kernel 3, stride 1, dilation 1

Special case of fully-connected network

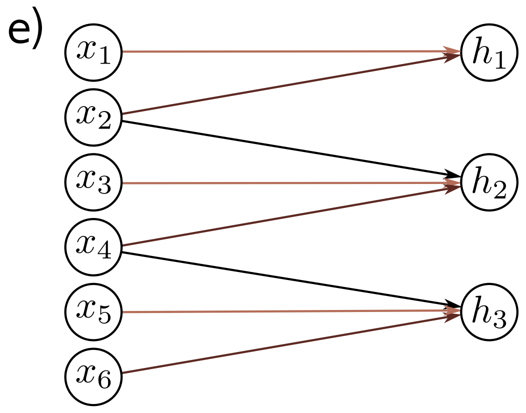
Bias is implied



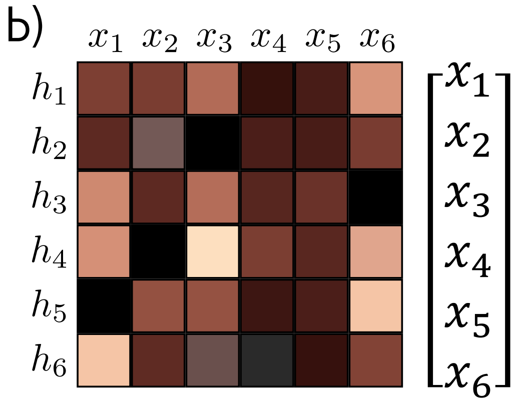
a)
x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6



c)
x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6

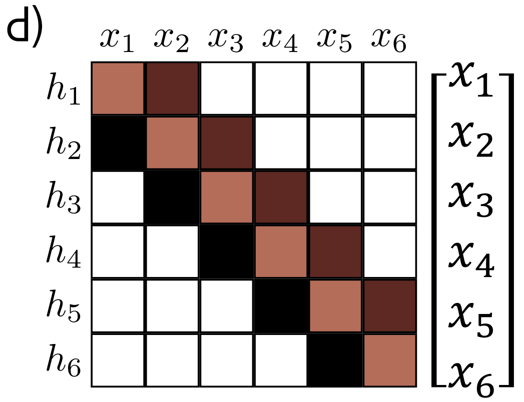


Weight Matrices



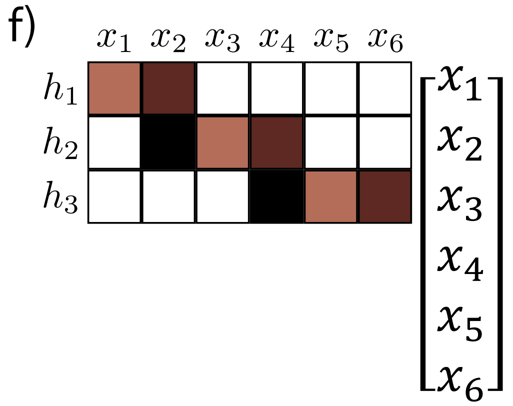
b)
x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6
x_1 x_2 x_3 x_4 x_5 x_6

Fully connected network



d)
x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3 h_4 h_5 h_6
x_1 x_2 x_3 x_4 x_5 x_6

Convolution, size 3, stride 1, dilation 1, zero padding



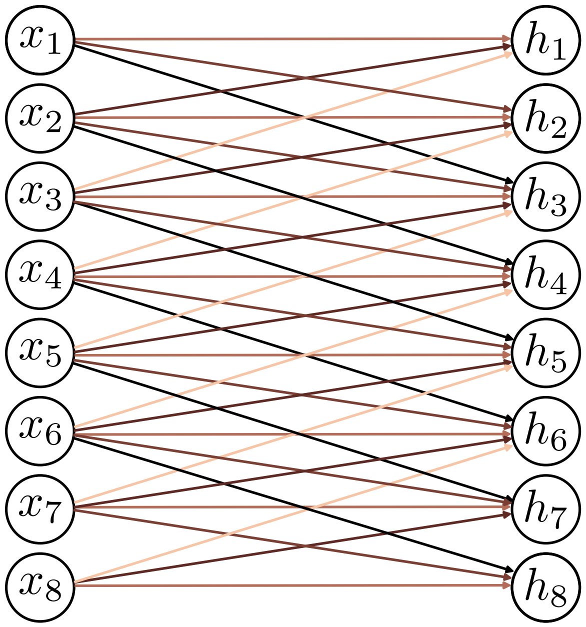
f)
x_1 x_2 x_3 x_4 x_5 x_6
h_1 h_2 h_3
x_1 x_2 x_3 x_4 x_5 x_6

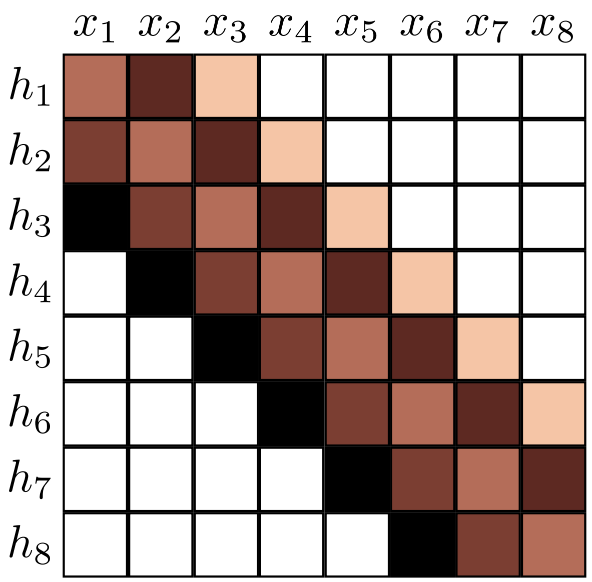
Convolution, size 3, stride 2, dilation 1, zero padding

Question 1

Bias is implied

- Kernel size?
- Stride?
- Dilation?
- Zero padding / valid?



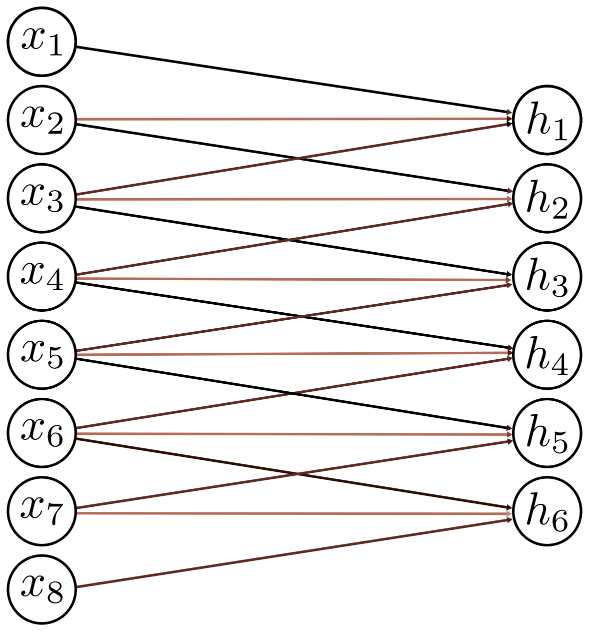


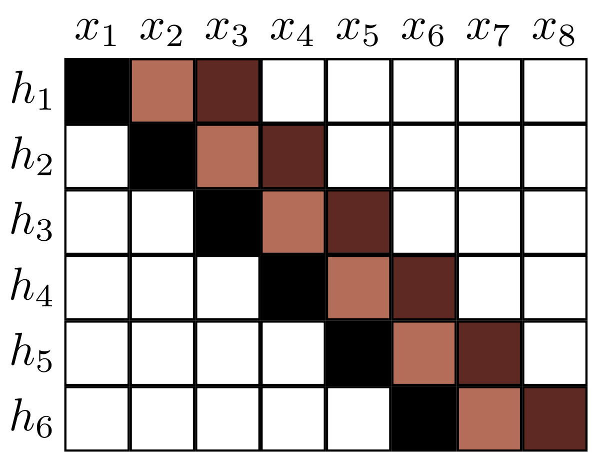
Convolution Configuration

Bias is implied

Question 2

- Kernel size?
- Stride?
- Dilation?
- Zero padding / valid?





Do not edit
How to change the design

Conv Config 2

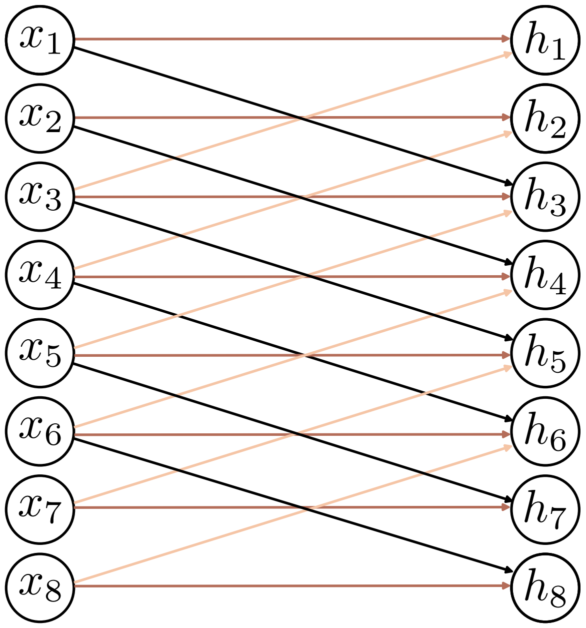
ⓘ The Slido app must be installed on every computer you're presenting from

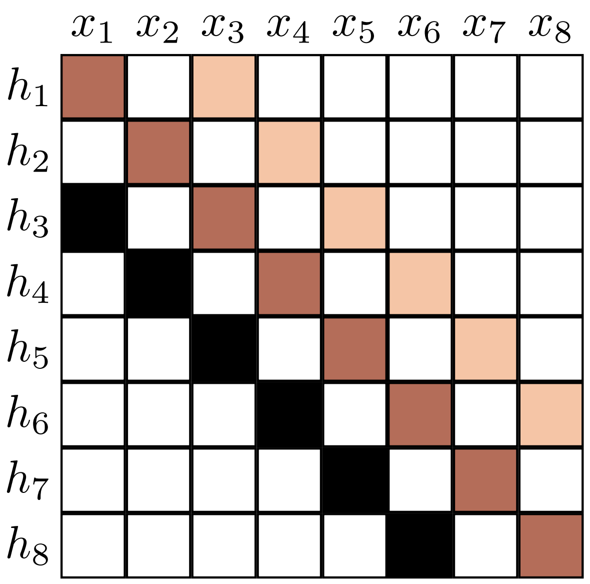
slido

Question 3

Bias is implied

- Kernel size?
- Stride?
- Dilation?
- Zero padding / valid?





Conv Config 3

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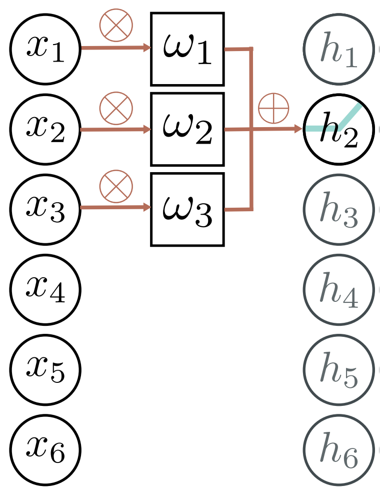
Channels

- The convolutional operation averages together the inputs
- Then passes through ReLU function
- Result is loss of information
- Solution:
  - apply several convolutions and stack them in channels
  - Sometimes also called feature maps

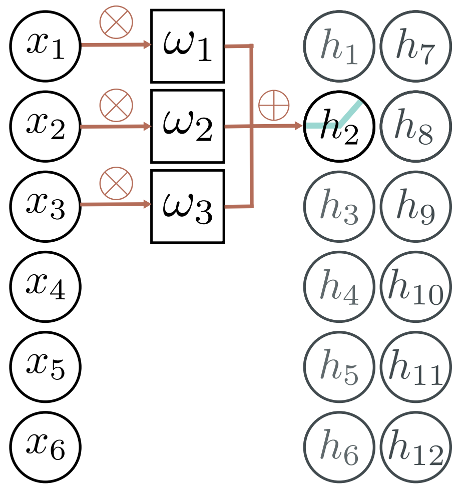
Two output channels, one input channel

a)

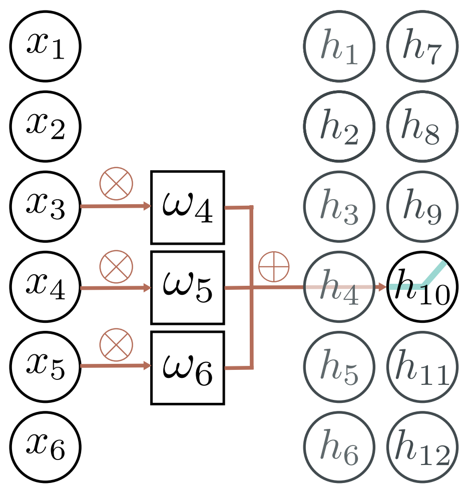


Two output channels, one input channel

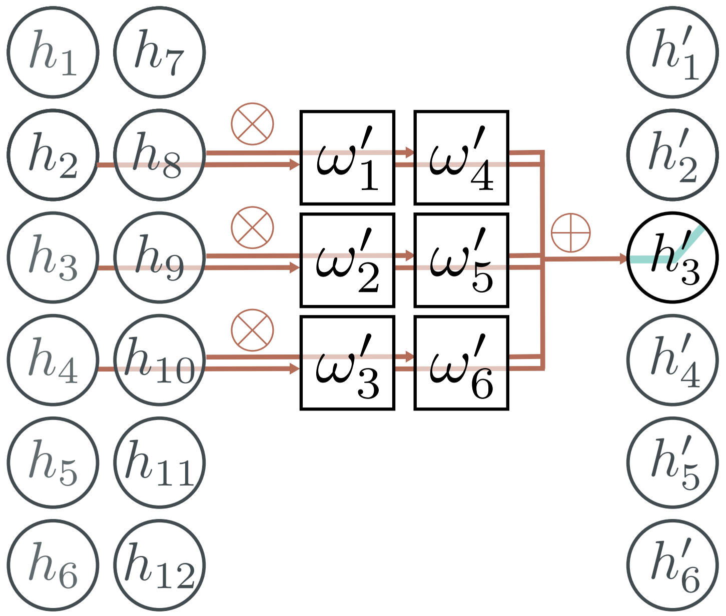
a)



b)



Two input channels, one output channel



How many parameters?

- If there are C_i input channels and kernel size K

$$\boldsymbol{\Omega} \in \mathbb{R}^{C_i \times K} \qquad \boldsymbol{\beta} \in \mathbb{R}$$

- If there are C_i input channels and C_o output channels

$$\boldsymbol{\Omega} \in \mathbb{R}^{C_i \times C_o \times K} \qquad \boldsymbol{\beta} \in \mathbb{R}^{C_o}$$

A 2D convolutional layer has an input with 3 channels, 16 output channels, and a 5×5 kernel. How many learnable parameters does it have (including bias)?

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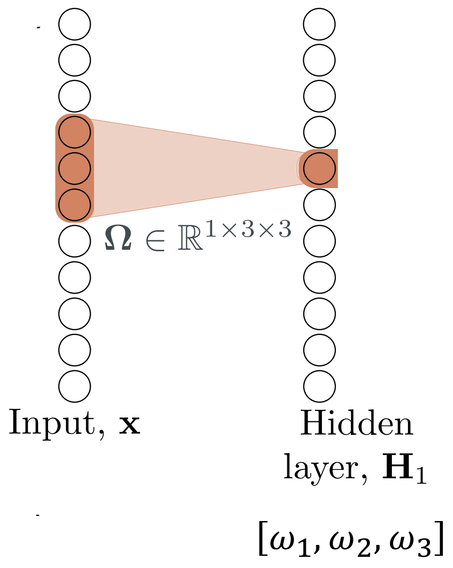
Receptive fields

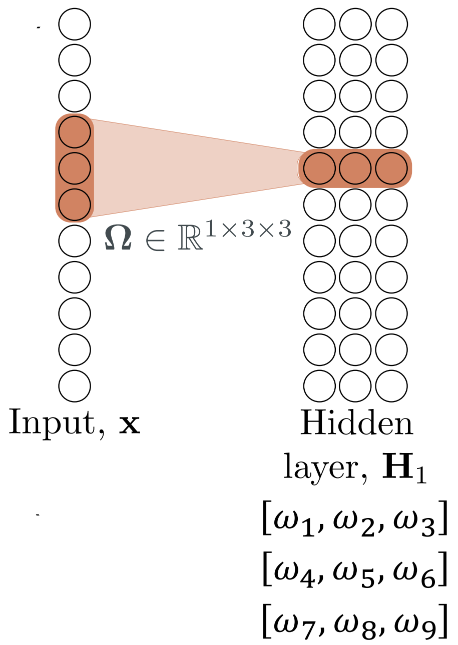
$\mathbb{R}^{C_i \times C_o \times K}$


$\boldsymbol{\Omega} \in \mathbb{R}^{1\times3\times3}$
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
$[\omega_1, \omega_2, \omega_3]$

Indicates how many neighboring pixels influence the current output.

Receptive fields

$\mathbb{R}^{C_i \times C_o \times K}$

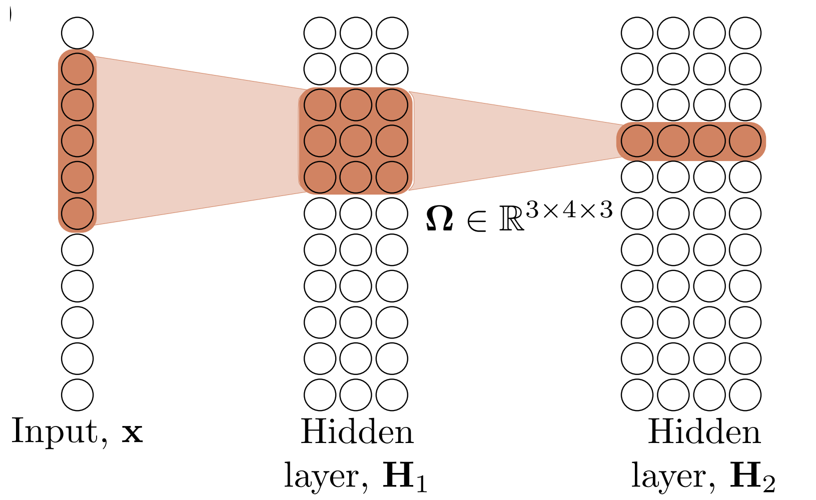

$\mathbf{\Omega} \in \mathbb{R}^{1\times 3\times 3}$
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
$[\omega_1, \omega_2, \omega_3]$
$[\omega_4, \omega_5, \omega_6]$
$[\omega_7, \omega_8, \omega_9]$

Receptive field only dependent on filter size, not number of channels

Each channel has a different set of filter weights.

Receptive fields

$\mathbb{R}^{C_i \times C_o \times K}$

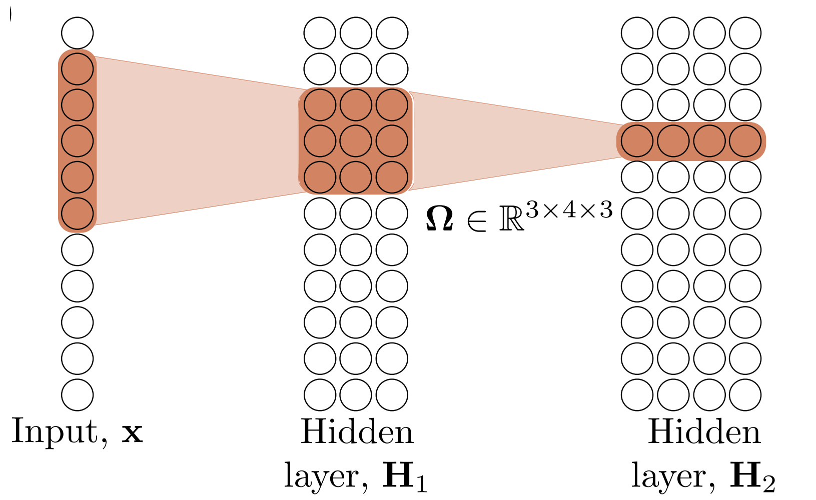

$\mathbf{\Omega} \in \mathbb{R}^{3\times4\times3}$
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
Hidden layer, $\mathbf{H}_2$

Influence compounds in subsequent layers.

$[\omega_1, \omega_2, \omega_3]$
$[\omega_4, \omega_5, \omega_6]$
$[\omega_7, \omega_8, \omega_9]$

$[\omega_1, \omega_2, \omega_3]$
$[\omega_4, \omega_5, \omega_6]$
$[\omega_7, \omega_8, \omega_9]$
$[\omega_{10}, \omega_{11}, \omega_{12}]$

Receptive fields $\mathbb{R}^{C_i \times C_o \times K}$


$\mathbf{\Omega} \in \mathbb{R}^{3\times4\times3}$
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
Hidden layer, $\mathbf{H}_2$

The area of support is equivalent to the area of support of convolution.

$$[\omega_1, \omega_2, \omega_3] \otimes [\omega_4, \omega_5, \omega_6] = [\omega_1, \omega_2, \omega_3, \omega_4, \omega_5]$$

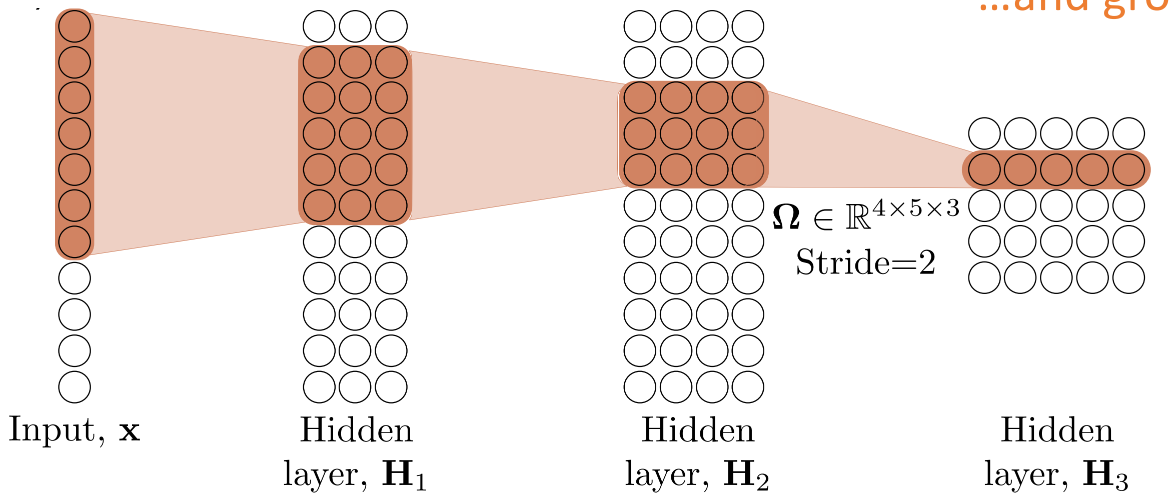
$[\omega_1, \omega_2, \omega_3]$
$[\omega_4, \omega_5, \omega_6]$
$[\omega_7, \omega_8, \omega_9]$

$[\omega_1, \omega_2, \omega_3]$
$[\omega_4, \omega_5, \omega_6]$
$[\omega_7, \omega_8, \omega_9]$
$[\omega_{10}, \omega_{11}, \omega_{12}]$

Receptive fields $\mathbb{R}^{C_i \times C_o \times K}$

$$[\omega_1, \omega_2, \omega_3, \omega_4, \omega_5] \otimes [\omega_1, \omega_2, \omega_3] = [\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6, \omega_7]$$

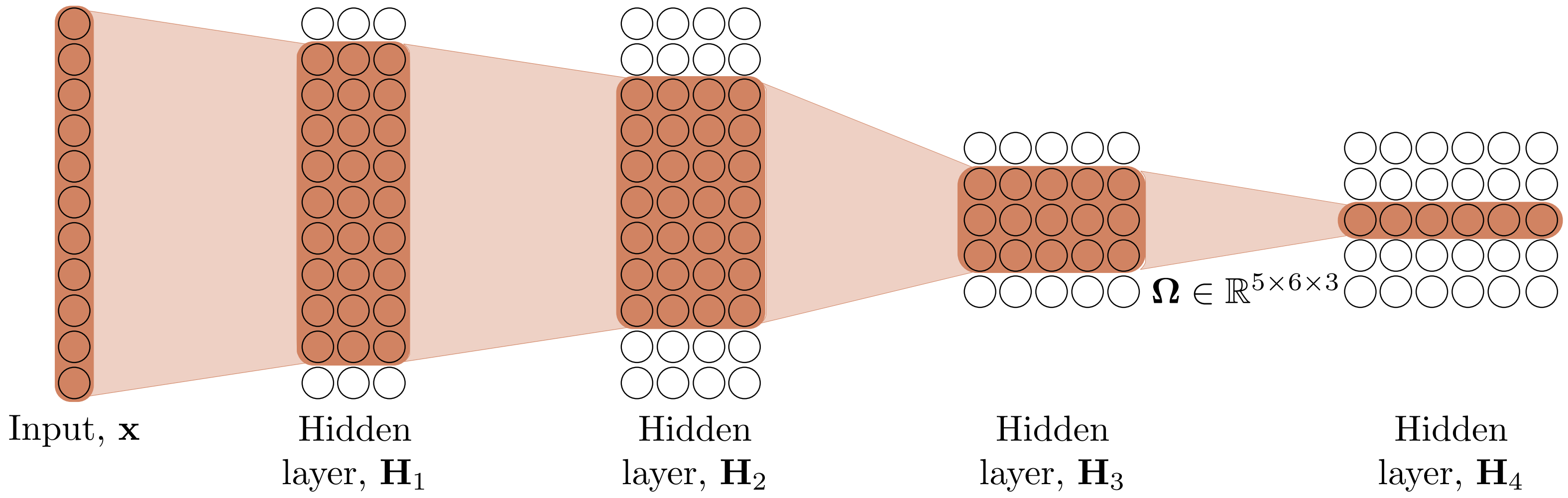
…and grows with each layer



$\mathbf{\Omega} \in \mathbb{R}^{4\times5\times3}$
Stride=2
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
Hidden layer, $\mathbf{H}_2$
Hidden layer, $\mathbf{H}_3$

Receptive fields

$\mathbb{R}^{C_i \times C_o \times K}$

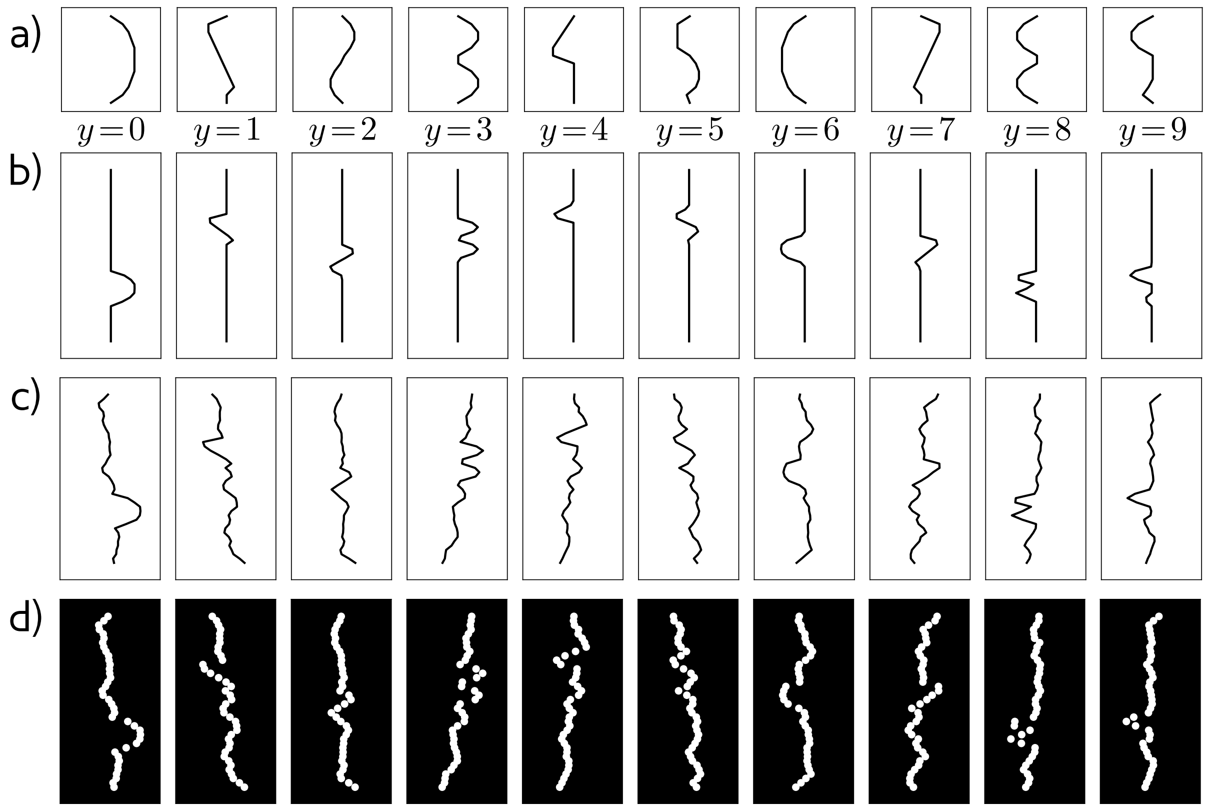

$\boldsymbol{\Omega} \in \mathbb{R}^{5\times6\times3}$
Input, $\mathbf{x}$
Hidden layer, $\mathbf{H}_1$
Hidden layer, $\mathbf{H}_2$
Hidden layer, $\mathbf{H}_3$
Hidden layer, $\mathbf{H}_4$

Reminder: Receptive field only dependent on filter size, not number of channels.

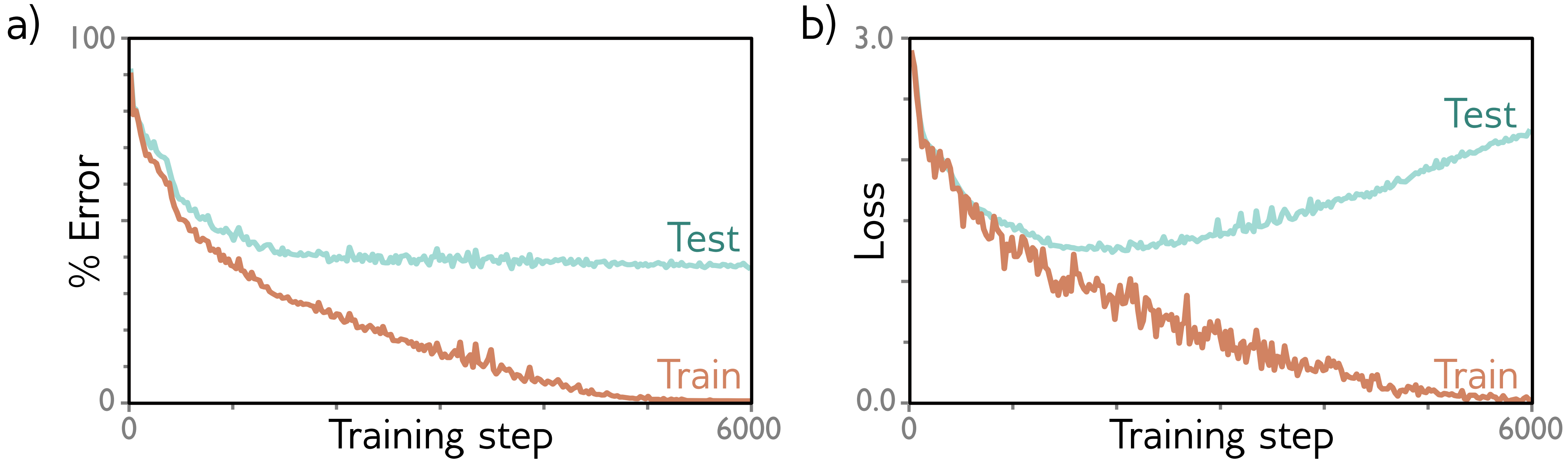
Convolutional networks

- Networks for images
- Invariance and equivariance
- 1D convolution
- Convolutional layers
- Channels
- Receptive fields
- Convolutional network for MNIST 1D

MNIST 1D Dataset



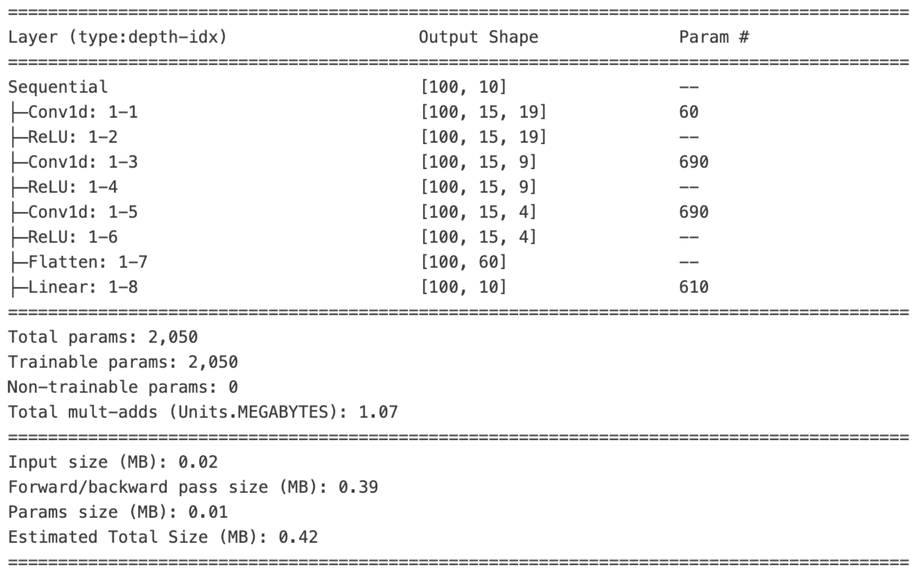
MNIST-1D results for fully-connected network



Total parameters = 150,185

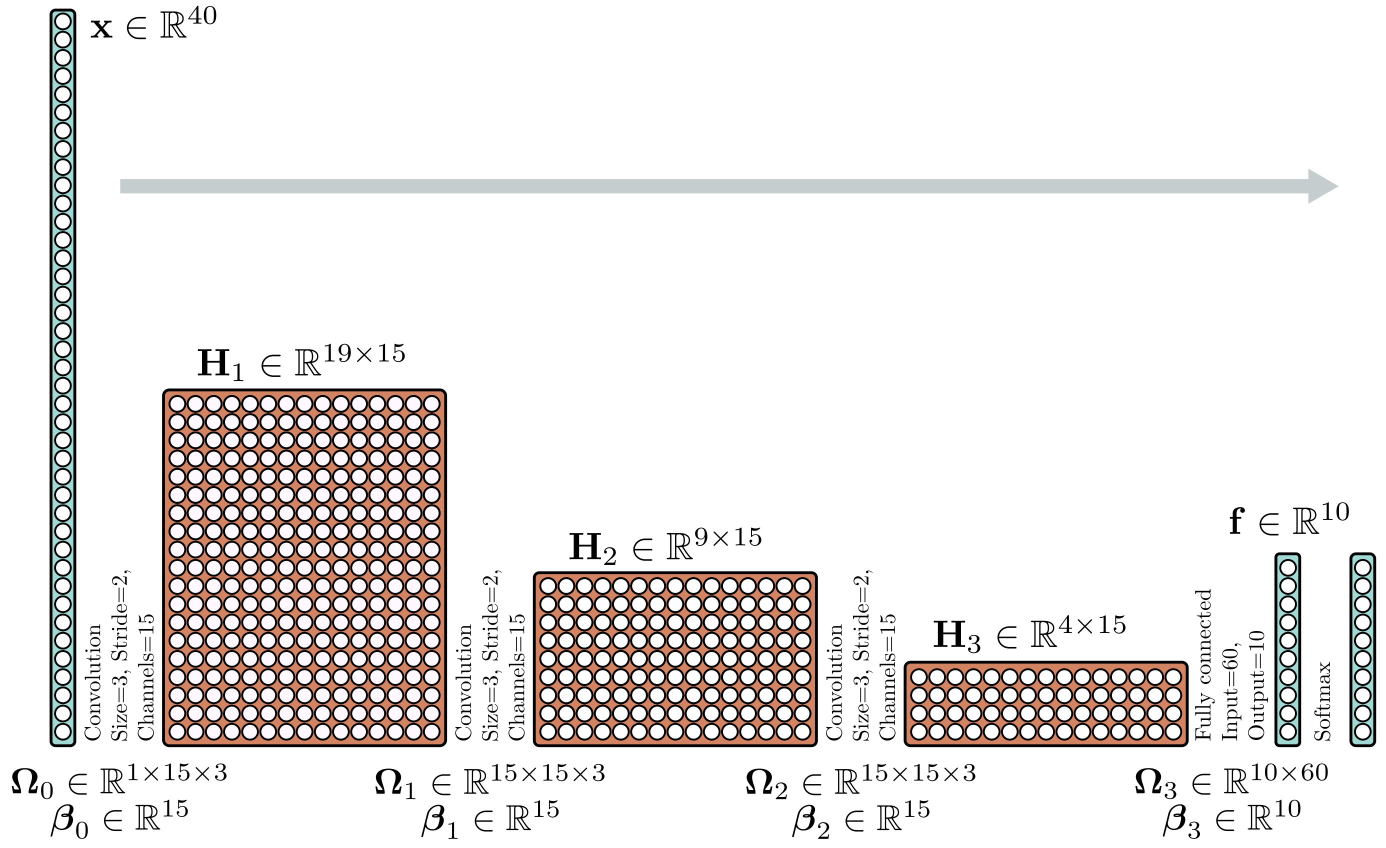
Convolutional network

- Four hidden layers
- Three convolutional layers
- One fully-connected layer
- Softmax at end
- Total parameters = 2050
- Trained for 100,000 steps with SGD, LR = 0.01, batch size 100

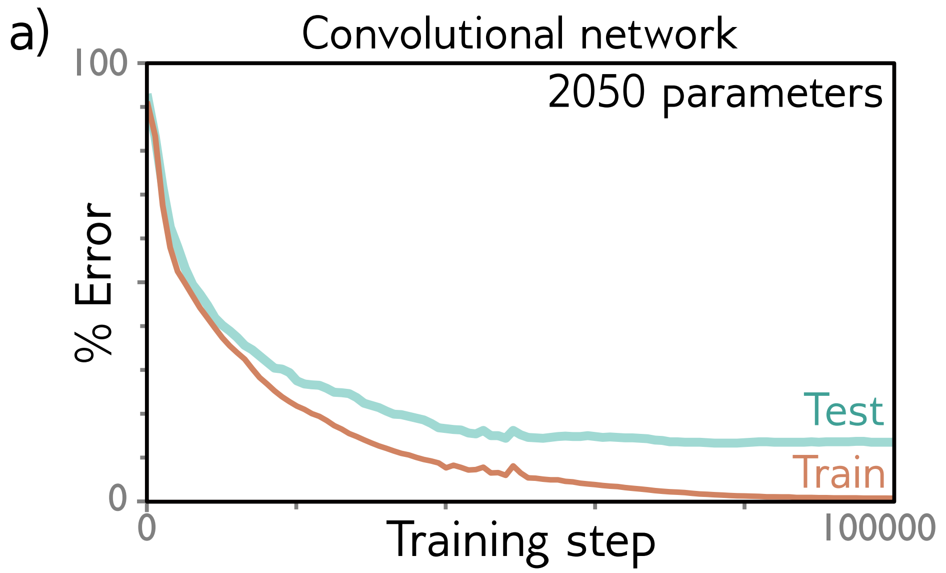


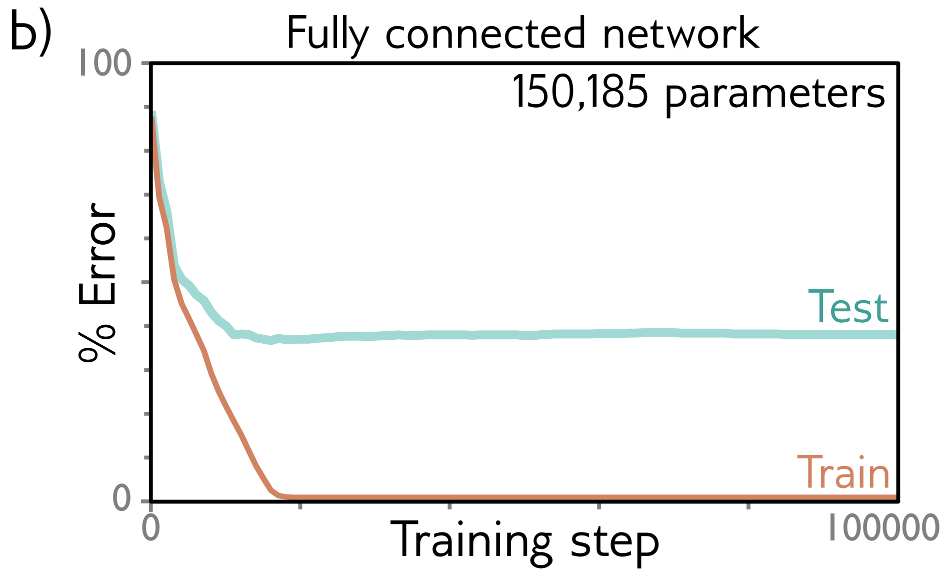
```
==========================================================================================
Layer (type:depth-idx)                   Output Shape              Param #
==========================================================================================
Sequential                               [100, 10]                 --
├─Conv1d: 1-1                            [100, 15, 19]             60
├─ReLU: 1-2                              [100, 15, 19]             --
├─Conv1d: 1-3                            [100, 15, 9]              690
├─ReLU: 1-4                              [100, 15, 9]              --
├─Conv1d: 1-5                            [100, 15, 4]              690
├─ReLU: 1-6                              [100, 15, 4]              --
├─Flatten: 1-7                           [100, 60]                 --
├─Linear: 1-8                            [100, 10]                 610
==========================================================================================
Total params: 2,050
Trainable params: 2,050
Non-trainable params: 0
Total mult-adds (Units.MEGABYTES): 1.07
==========================================================================================
Input size (MB): 0.02
Forward/backward pass size (MB): 0.39
Params size (MB): 0.01
Estimated Total Size (MB): 0.42
==========================================================================================
```

MNIST-1D convolutional network


$\mathbf{x} \in \mathbb{R}^{40}$
Convolution Size=3, Stride=2, Channels=15
$\mathbf{H}_1 \in \mathbb{R}^{19\times15}$
Convolution Size=3, Stride=2, Channels=15
$\mathbf{H}_2 \in \mathbb{R}^{9\times15}$
Convolution Size=3, Stride=2, Channels=15
$\mathbf{H}_3 \in \mathbb{R}^{4\times15}$
Fully connected Input=60, Output=10
$\mathbf{f} \in \mathbb{R}^{10}$
Softmax
$\boldsymbol{\Omega}_0 \in \mathbb{R}^{1\times15\times3}$
$\boldsymbol{\beta}_0 \in \mathbb{R}^{15}$
$\boldsymbol{\Omega}_1 \in \mathbb{R}^{15\times15\times3}$
$\boldsymbol{\beta}_1 \in \mathbb{R}^{15}$
$\boldsymbol{\Omega}_2 \in \mathbb{R}^{15\times15\times3}$
$\boldsymbol{\beta}_2 \in \mathbb{R}^{15}$
$\boldsymbol{\Omega}_3 \in \mathbb{R}^{10\times60}$
$\boldsymbol{\beta}_3 \in \mathbb{R}^{10}$

Performance





Why?

- Better inductive bias
- Forced the network to process each location similarly
- Shares information across locations
- Search through a smaller family of input/ouput mappings, all of which are plausible

2D Convolution

Convolution #2

- 2D Convolution
- Downsampling and upsampling, 1x1 convolution
- Image classification
- Object detection
- Semantic segmentation
- Residual networks
- U-Nets and hourglass networks

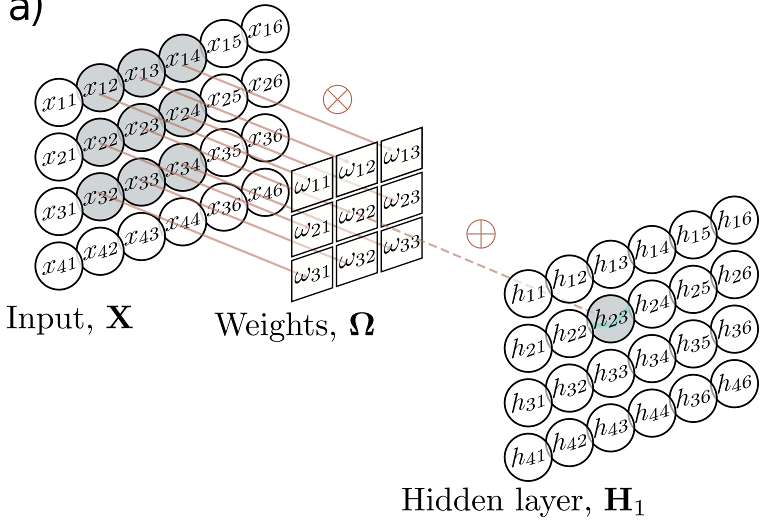
2D Convolution

- Convolution in 2D
  - Weighted sum over a K x K region
  - K x K weights
- Build into a convolutional layer by adding bias and passing through activation function

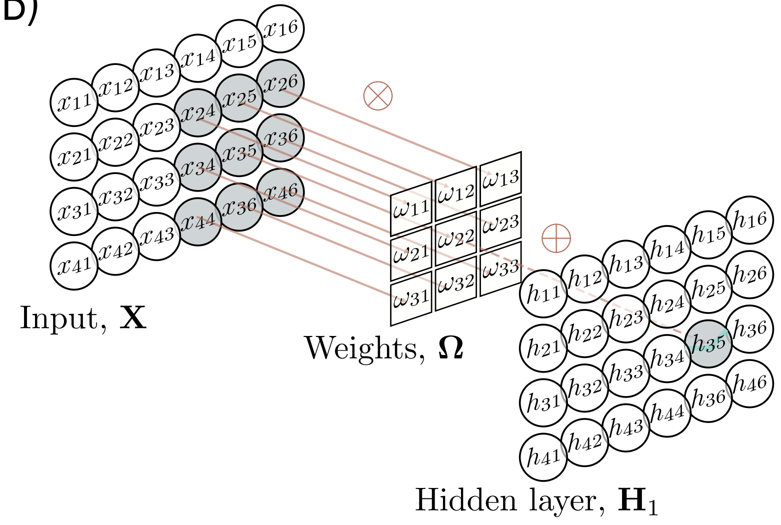
$$h_{i,j} = \mathrm{a}\left[\beta + \sum_{m=1}^{3}\sum_{n=1}^{3}\omega_{m,n}x_{i+m-2,j+n-2}\right]$$

2D Convolution

a)

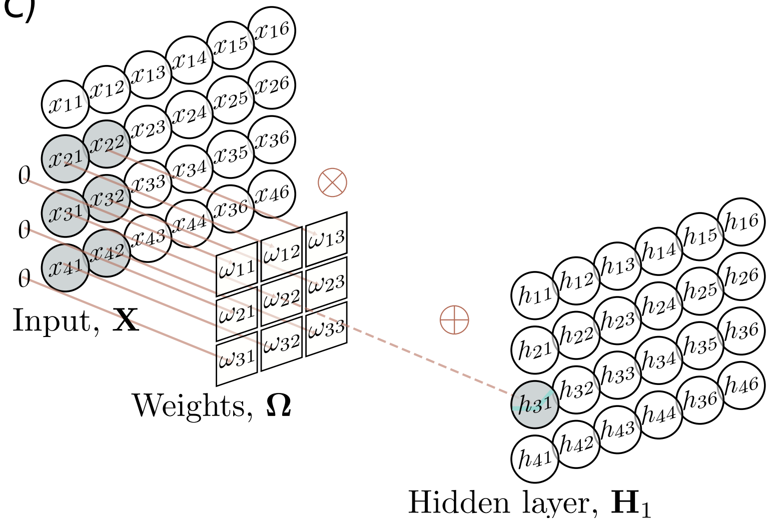


b)



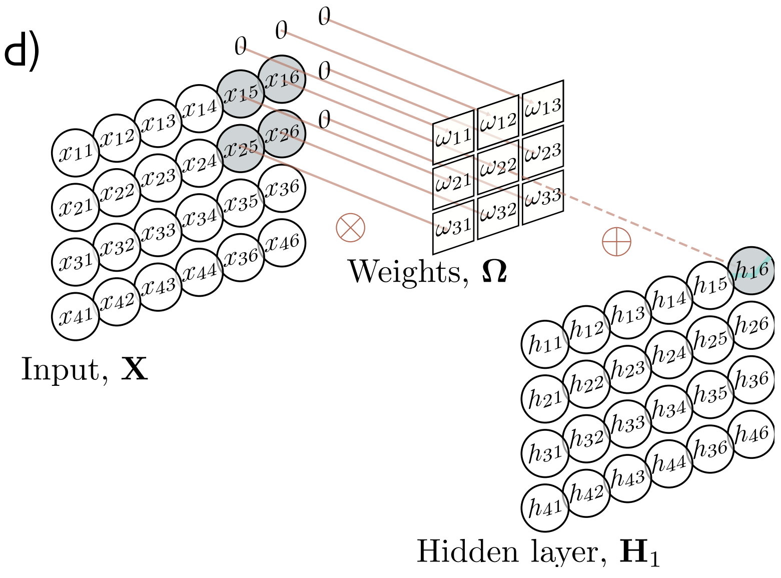
2D Convolution with Zero Padding

c)



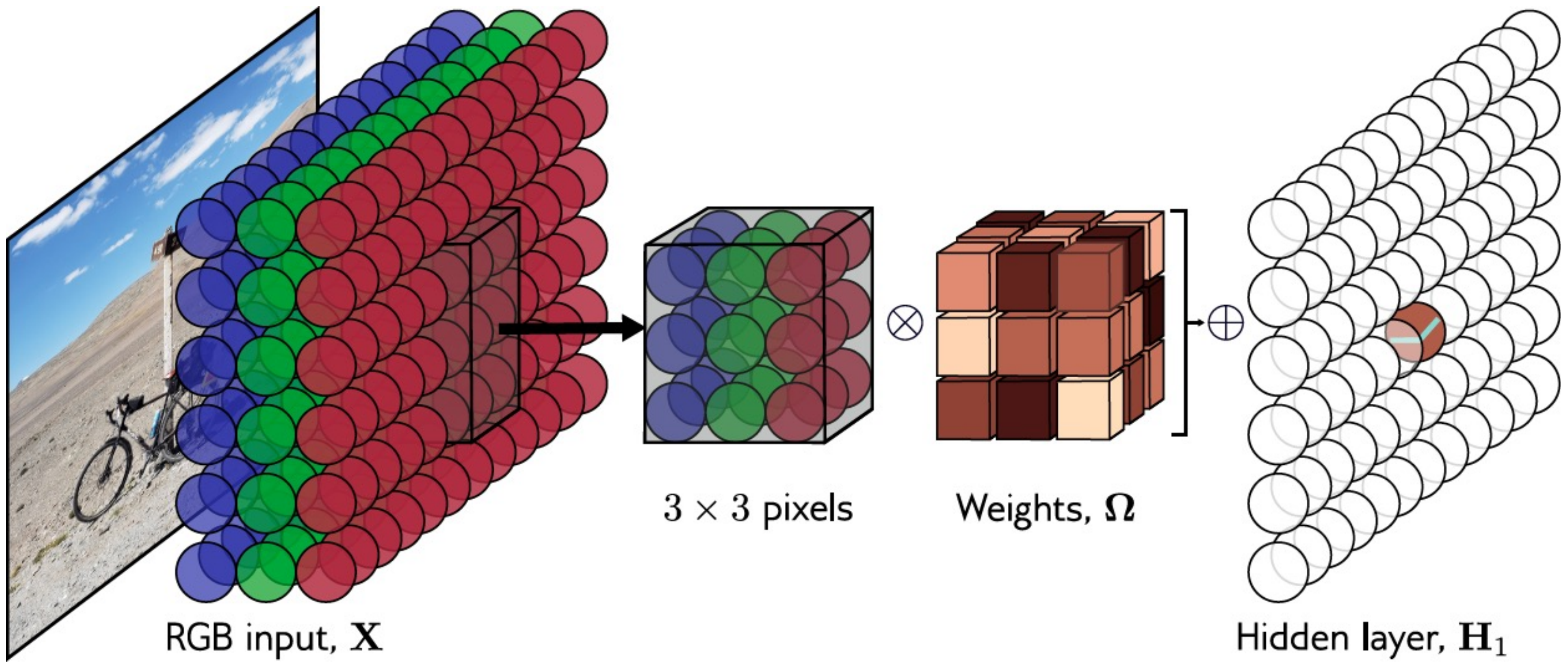
x_{11} x_{12} x_{13} x_{14} x_{15} x_{16}
x_{21} x_{22} x_{23} x_{24} x_{25} x_{26}
x_{31} x_{32} x_{33} x_{34} x_{35} x_{36}
x_{41} x_{42} x_{43} x_{44} x_{36} x_{46}
0
0
0
$\otimes$
ω_{11} ω_{12} ω_{13}
ω_{21} ω_{22} ω_{23}
ω_{31} ω_{32} ω_{33}
$\oplus$
Input, $\mathbf{X}$
Weights, $\mathbf{\Omega}$
h_{11} h_{12} h_{13} h_{14} h_{15} h_{16}
h_{21} h_{22} h_{23} h_{24} h_{25} h_{26}
h_{31} h_{32} h_{33} h_{34} h_{35} h_{36}
h_{41} h_{42} h_{43} h_{44} h_{36} h_{46}
Hidden layer, $\mathbf{H}_1$

d)



0 0 0
0
0
x_{11} x_{12} x_{13} x_{14} x_{15} x_{16}
x_{21} x_{22} x_{23} x_{24} x_{25} x_{26}
x_{31} x_{32} x_{33} x_{34} x_{35} x_{36}
x_{41} x_{42} x_{43} x_{44} x_{36} x_{46}
$\otimes$
ω_{11} ω_{12} ω_{13}
ω_{21} ω_{22} ω_{23}
ω_{31} ω_{32} ω_{33}
$\oplus$
Input, $\mathbf{X}$
Weights, $\mathbf{\Omega}$
h_{11} h_{12} h_{13} h_{14} h_{15} h_{16}
h_{21} h_{22} h_{23} h_{24} h_{25} h_{26}
h_{31} h_{32} h_{33} h_{34} h_{35} h_{36}
h_{41} h_{42} h_{43} h_{44} h_{36} h_{46}
Hidden layer, $\mathbf{H}_1$

Channels in 2D convolution



Kernel size, stride, dilation all
work as you would expect

How many parameters?

- If there are C_i input channels and kernel size K x K

$$\boldsymbol{\omega} \in \mathbb{R}^{C_i \times K \times K} \qquad \boldsymbol{\beta} \in \mathbb{R}$$

- If there are C_i input channels and C_o output channels

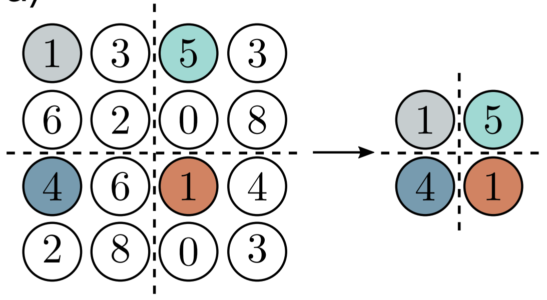
$$\boldsymbol{\omega} \in \mathbb{R}^{C_i \times C_o \times K \times K} \qquad \boldsymbol{\beta} \in \mathbb{R}^{C_o}$$

Convolution #2

- 2D Convolution
- Downsampling and upsampling, 1x1 convolution
- Image classification
- Object detection
- Semantic segmentation
- Residual networks
- U-Nets and hourglass networks

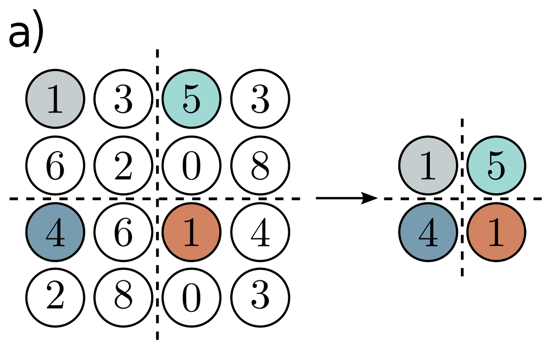
Downsampling

a)

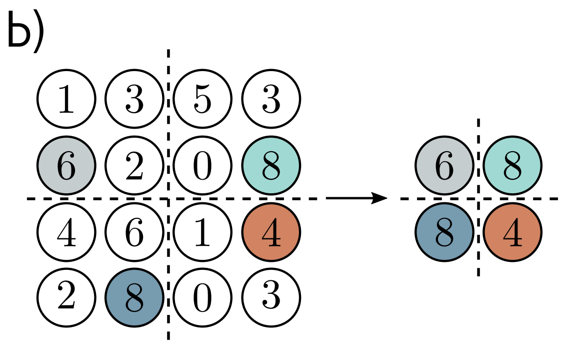


Sample every other position (equivalent to stride two)

Downsampling

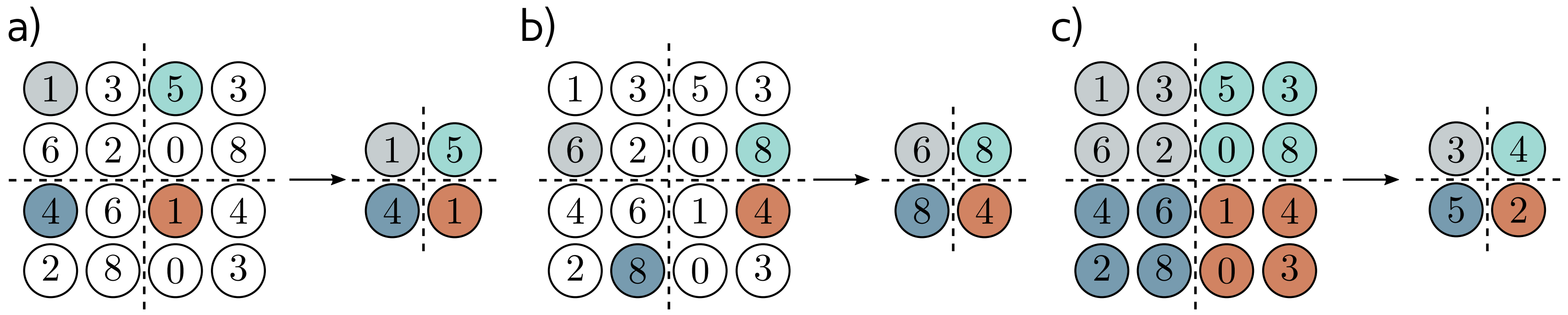


Sample every other position (equivalent to stride two)



Max pooling (partial invariance to translation)

Downsampling



Sample every other position (equivalent to stride two)

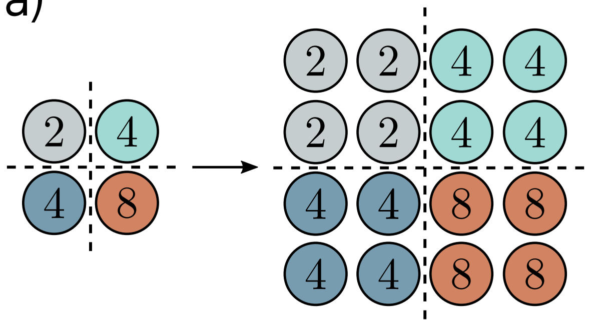
Max pooling (partial invariance to translation)

Mean pooling

You apply a 2×2 max pooling layer to a feature map. An object shifts by 1 pixel. What happens to the pooled output?

Upsampling

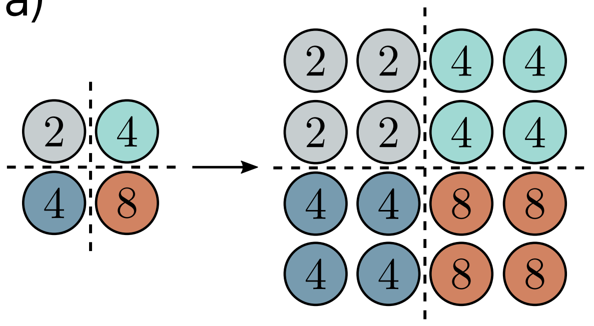
a)



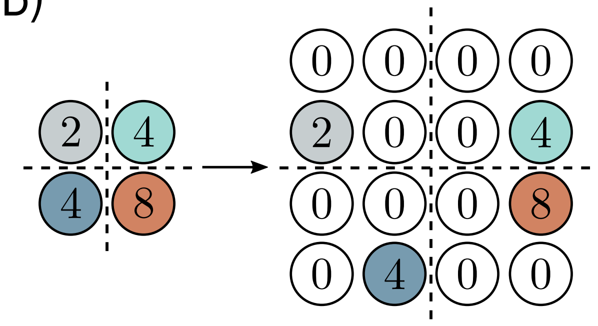
Duplicate

Upsampling

a)



b)

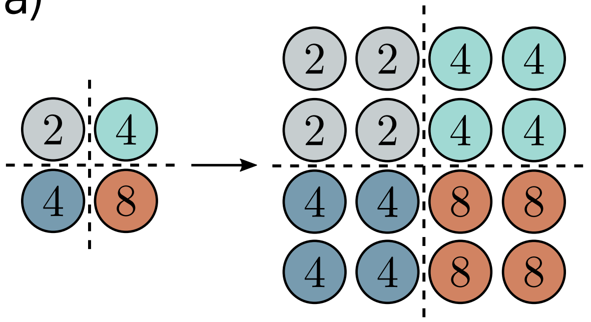


Duplicate

Max-upsampling

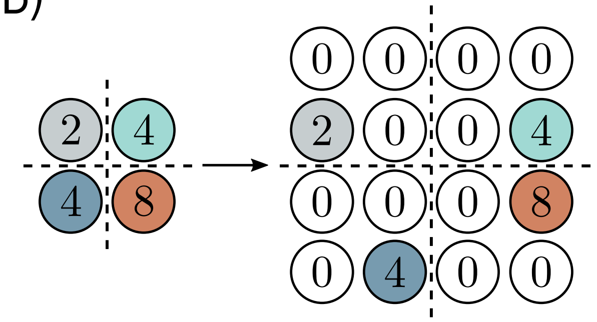
Upsampling

a)



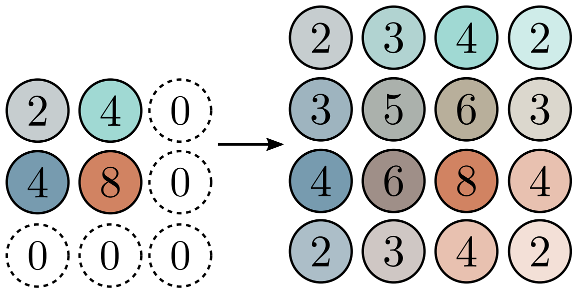
Duplicate

b)



Max-upsampling

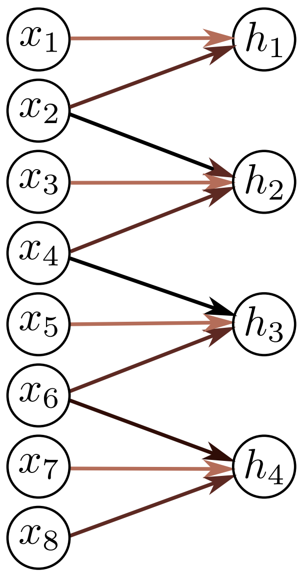
c)



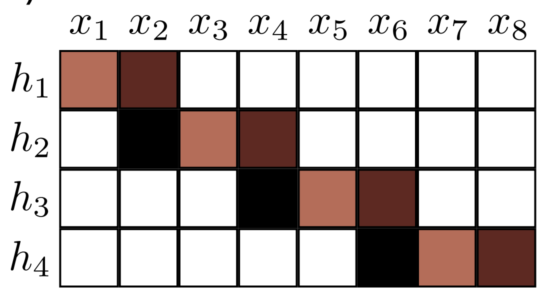
Bilinear interpolation

Transposed convolutions

a)

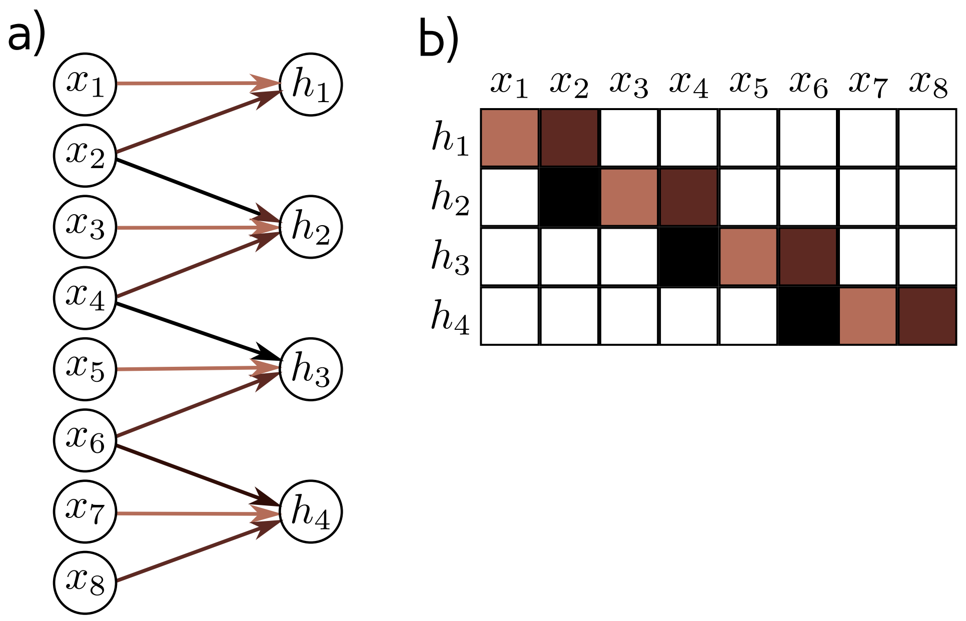


b)

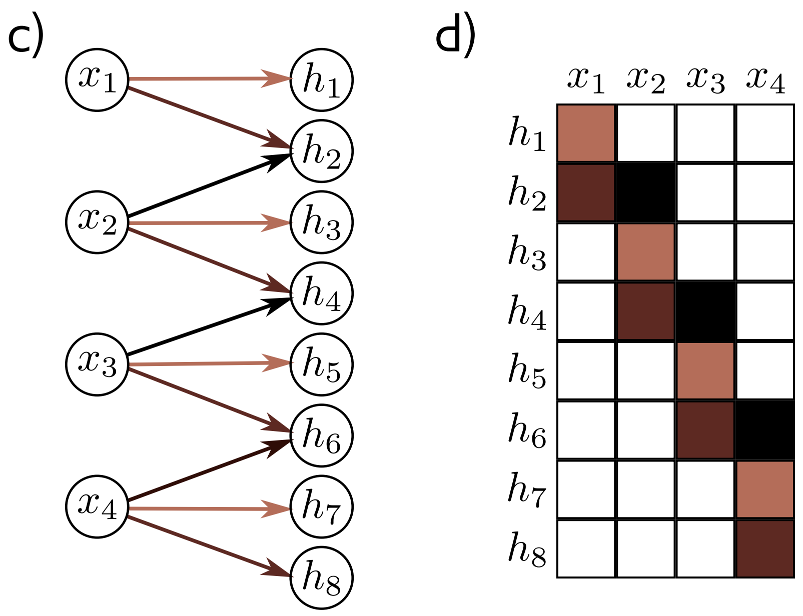


Kernel size 3, Stride 2 convolution

Transposed convolutions

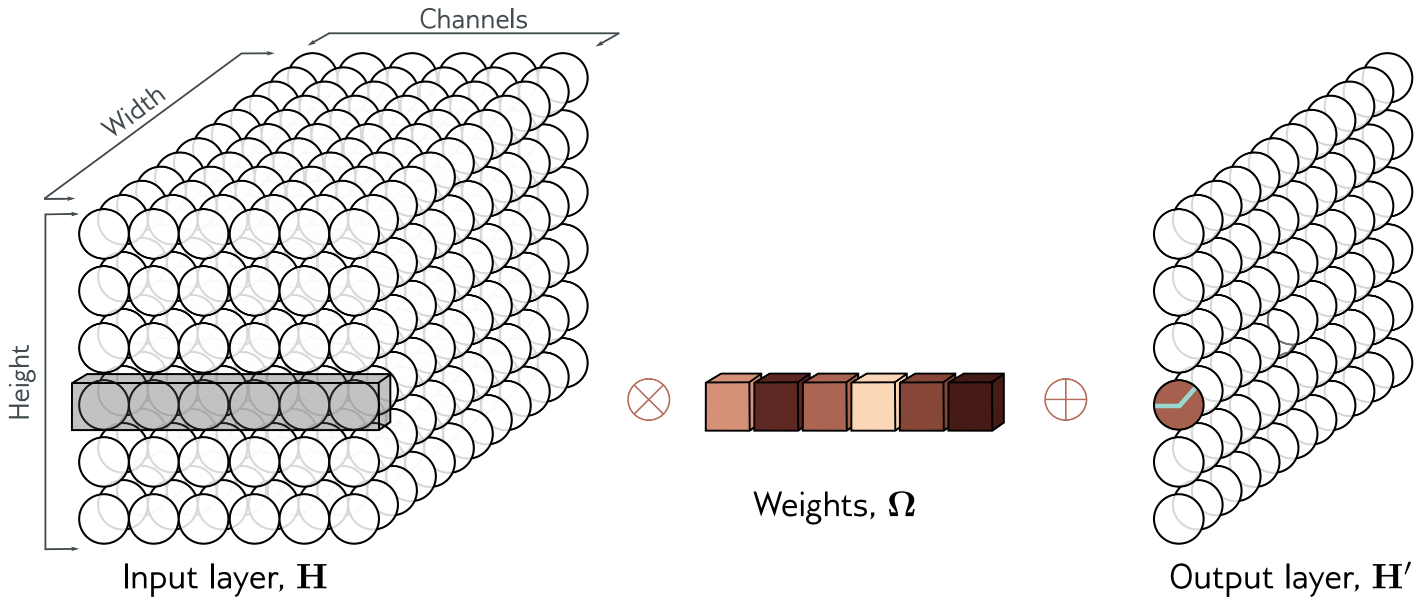

a)
x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8
h_1 h_2 h_3 h_4
b)
x_1 x_2 x_3 x_4 x_5 x_6 x_7 x_8
h_1 h_2 h_3 h_4

Kernel size 3, Stride 2 convolution


c)
x_1 x_2 x_3 x_4
h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8
d)
x_1 x_2 x_3 x_4
h_1 h_2 h_3 h_4 h_5 h_6 h_7 h_8

Transposed convolution

1x1 convolution


Channels
Width
Height
Input layer, $\mathbf{H}$
Weights, $\boldsymbol{\Omega}$
Output layer, $\mathbf{H}'$

- Mixes channels
- Can change number of channels
- Equivalent to running same fully connected network at each position

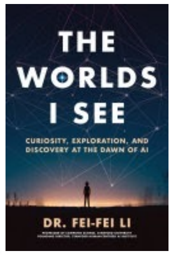
What does a 1×1 convolution primarily accomplish that a standard 3×3 convolution does not?

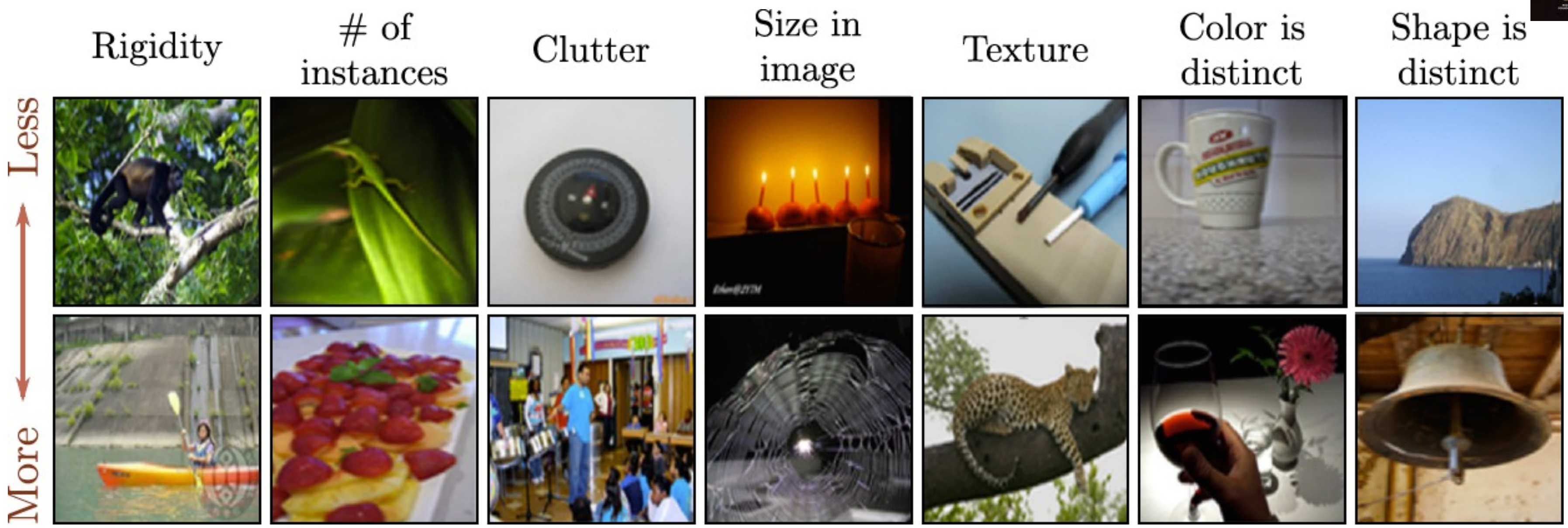
Convolution #2

- 2D Convolution
- Downsampling and upsampling, 1x1 convolution
- Image classification
- Object detection
- Semantic segmentation
- Residual networks
- U-Nets and hourglass networks

ImageNet 1K database

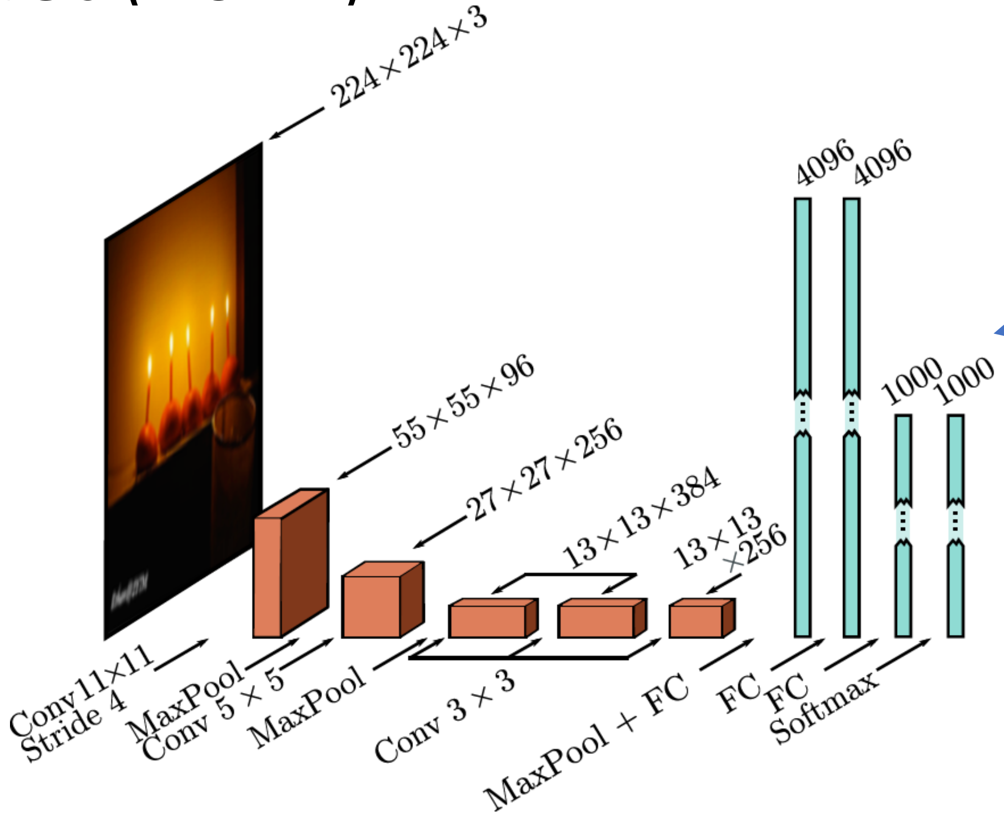
Fei-Fei Li





- 224 x 224 images
- 1,281,167 training images, 50,000 validation images, and 100,000 test images
- 1000 classes

AlexNet (2012)



Almost all the 60 million parameters
parameters are in fully connected layers

A. Krizhevsky, I. Sutskever, and G. E. Hinton, "ImageNet classification with deep convolutional neural networks," *Commun. ACM*, vol. 60, no. 6, pp. 84–90, May 2012, doi: 10.1145/3065386.

AlexNet (2012)

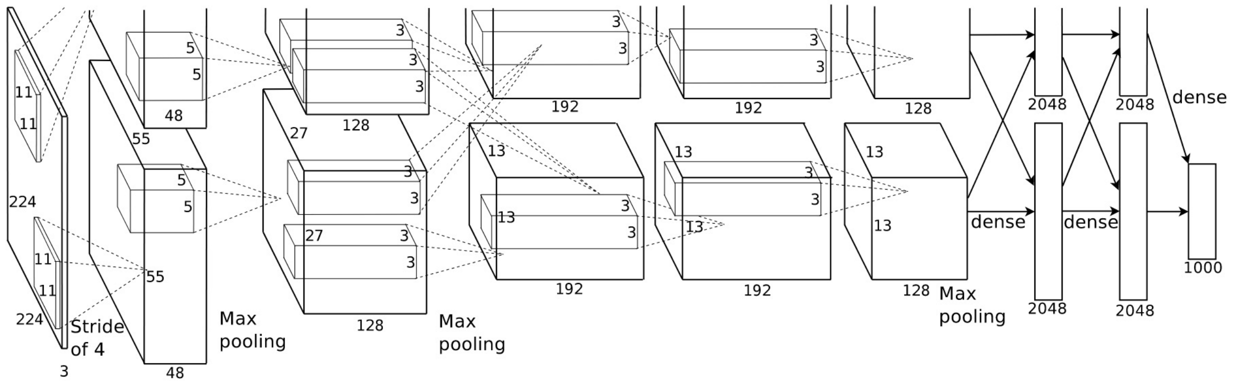


Figure 2: An illustration of the architecture of our CNN, explicitly showing the delineation of responsibilities between the two GPUs. One GPU runs the layer-parts at the top of the figure while the other runs the layer-parts at the bottom. The GPUs communicate only at certain layers. The network's input is 150,528-dimensional, and the number of neurons in the network's remaining layers is given by 253,440–186,624–64,896–64,896–43,264–4096–4096–1000.

Won the 2012 Large-Scale Vision Recognition Challenge (ILSVRC) by a big margin.

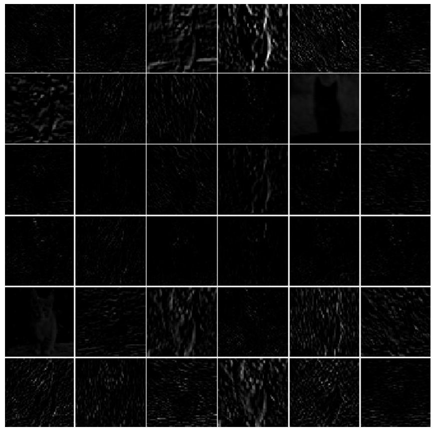
Took between five and six days to train on two GTX 580 3GB GPUs with manually optimized compute kernels.

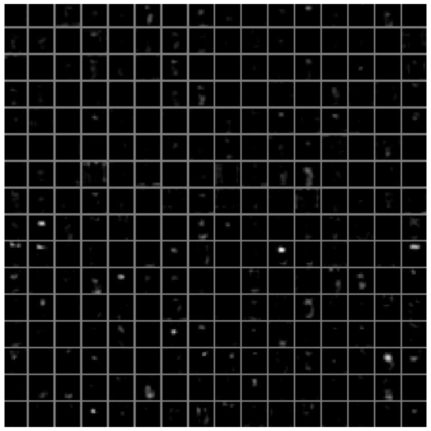
A. Krizhevsky, I. Sutskever, and G. E. Hinton, "ImageNet classification with deep convolutional neural networks," *Commun. ACM*, vol. 60, no. 6, pp. 84–90, May 2012, doi: 10.1145/3065386.

AlexNet

Cat image input
(not actual image)

Activations
(feature maps)





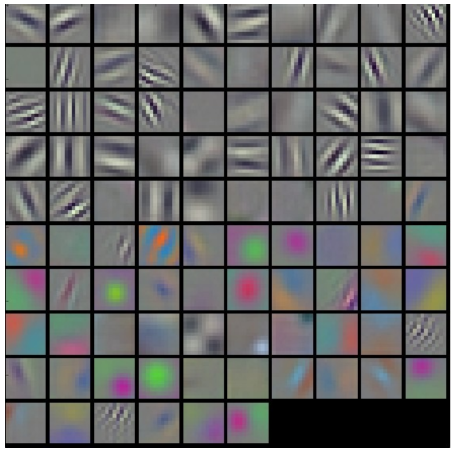
• • •

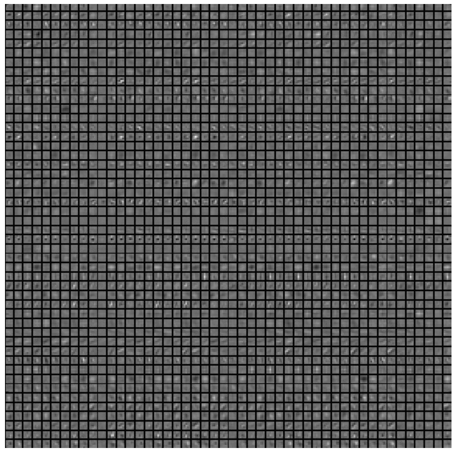
1st Layer

2nd Layer

5th Layer

Filter Kernels



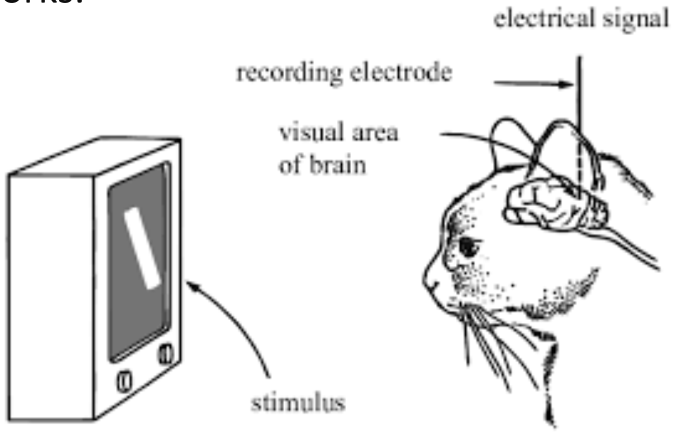


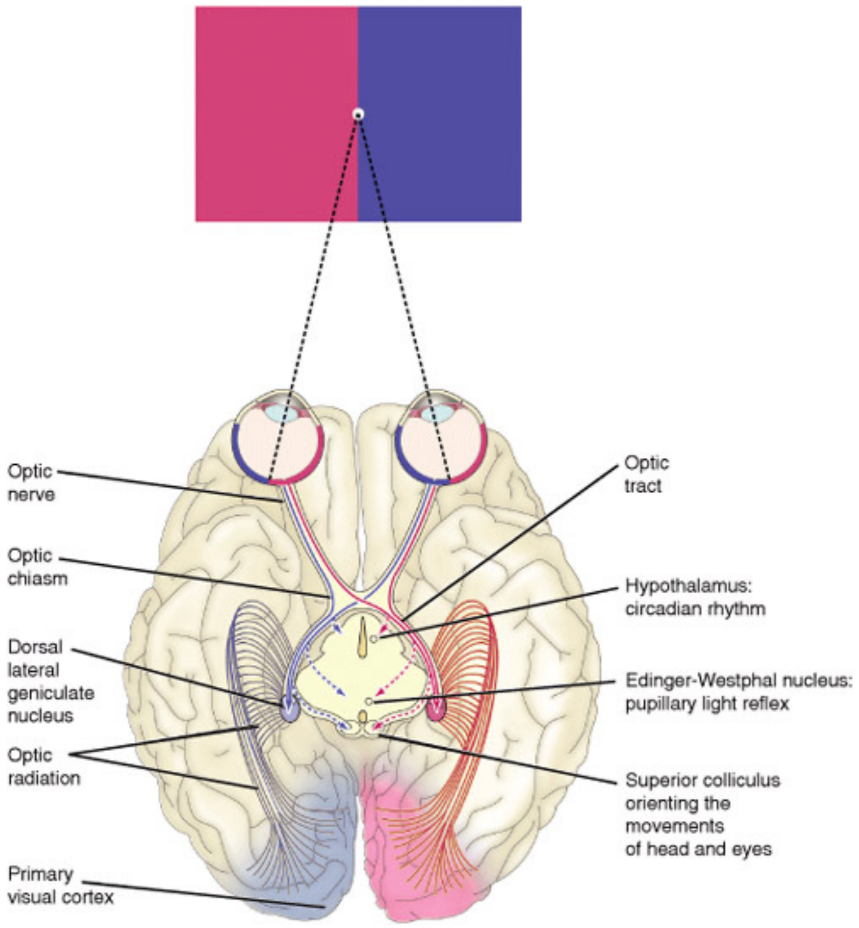
• • •

https://cs231n.github.io/understanding-cnn/

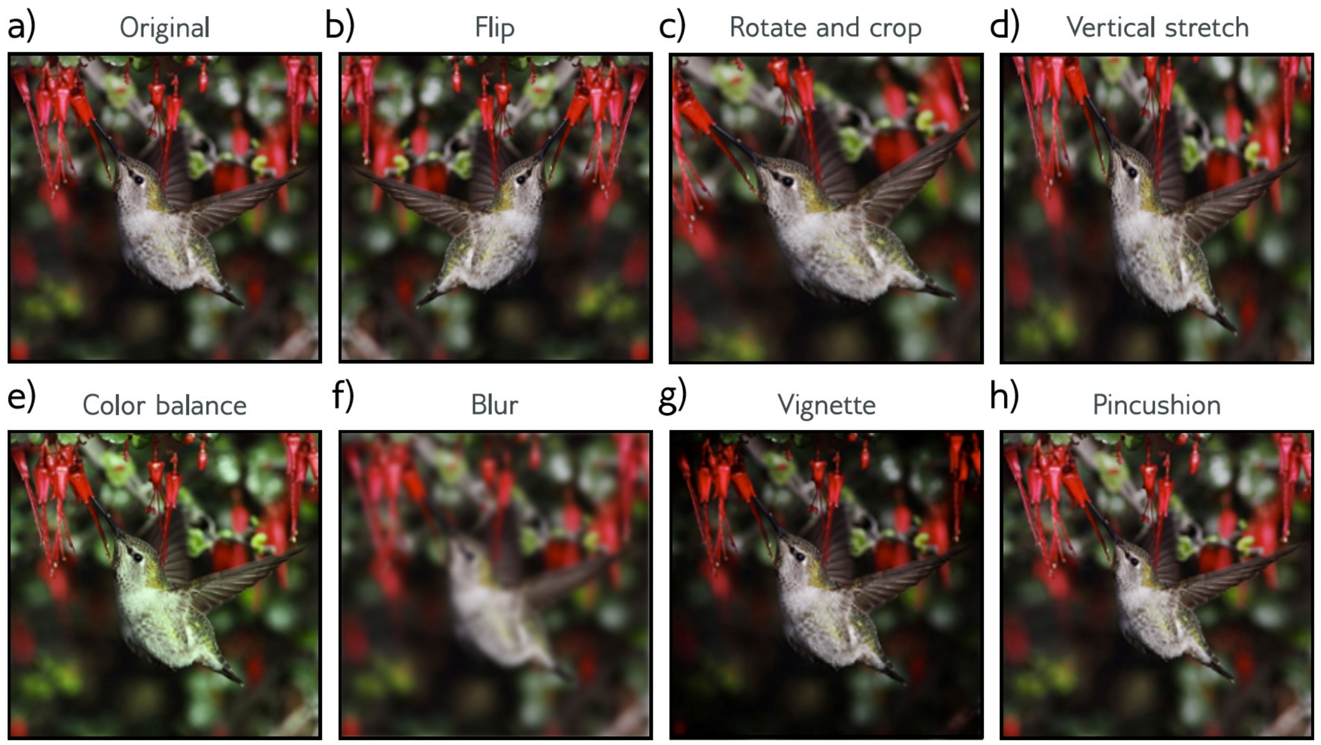
~1959: Hubel & Wiesel – Visual cortex and receptive fields

David Hubel and Torsten Wiesel discovered how neurons in the visual cortex respond to specific patterns of light, such as edges and orientations. Their work on receptive fields provided key insights into hierarchical processing in vision, influencing the design of modern convolutional neural networks.



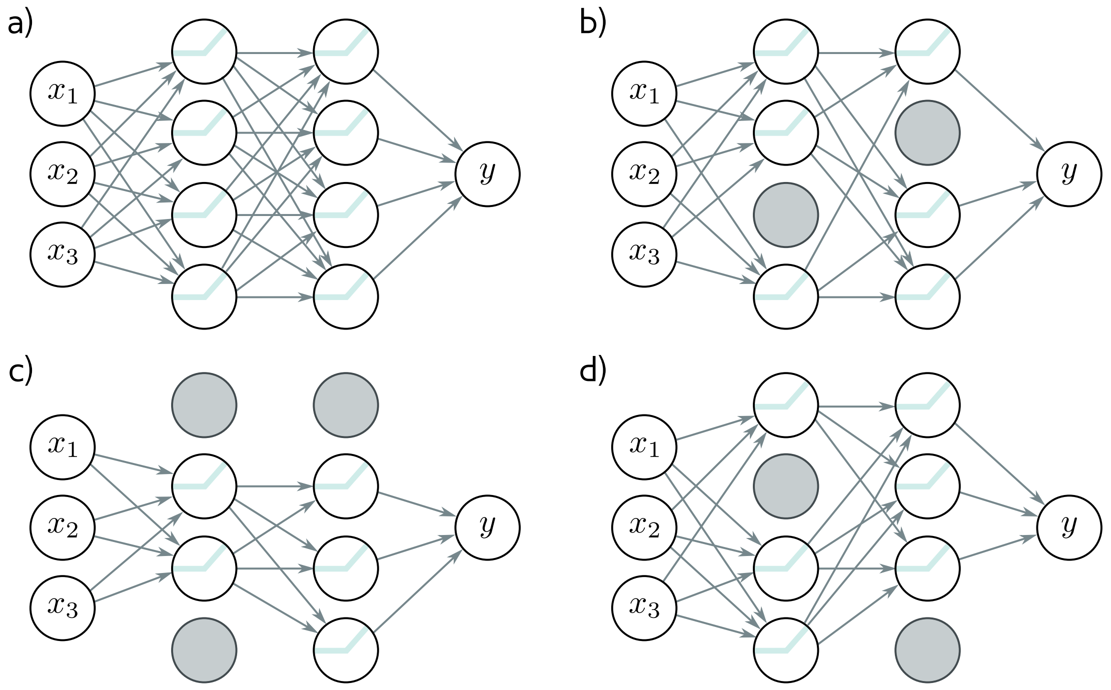

Optic nerve
Optic chiasm
Dorsal lateral geniculate nucleus
Optic radiation
Primary visual cortex
Optic tract
Hypothalamus: circadian rhythm
Edinger-Westphal nucleus: pupillary light reflex
Superior colliculus orienting the movements of head and eyes

Data augmentation



- Data augmentation a factor of 2048 using (i) spatial transformations and (ii) modifications of the input intensities.

Dropout

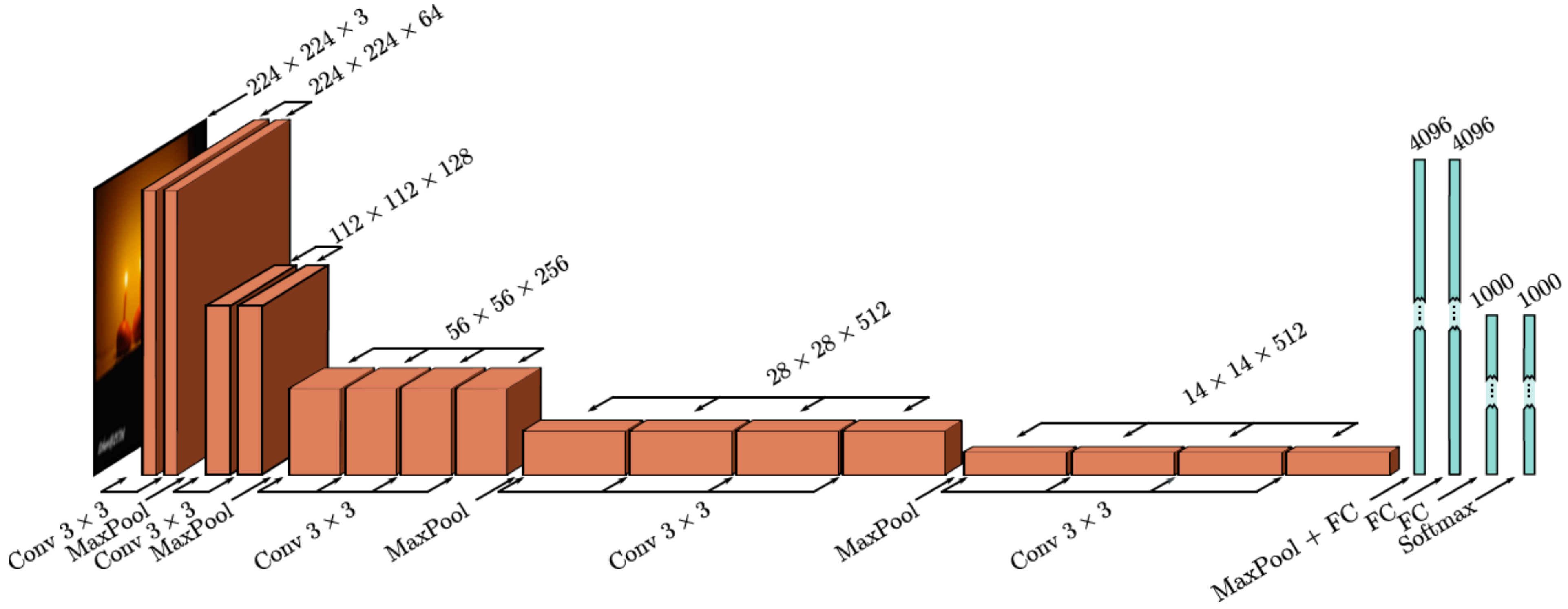


- Dropout was applied in the fully connected layers

Details

- At test time average results from five different cropped and mirrored versions of the image
- SGD with a momentum coefficient of 0.9 and batch size of 128.
- L2 (weight decay) regularizer used.
- This system achieved a 16.4% top-5 error rate and a 38.1% top-1 error rate.

VGG (2015)

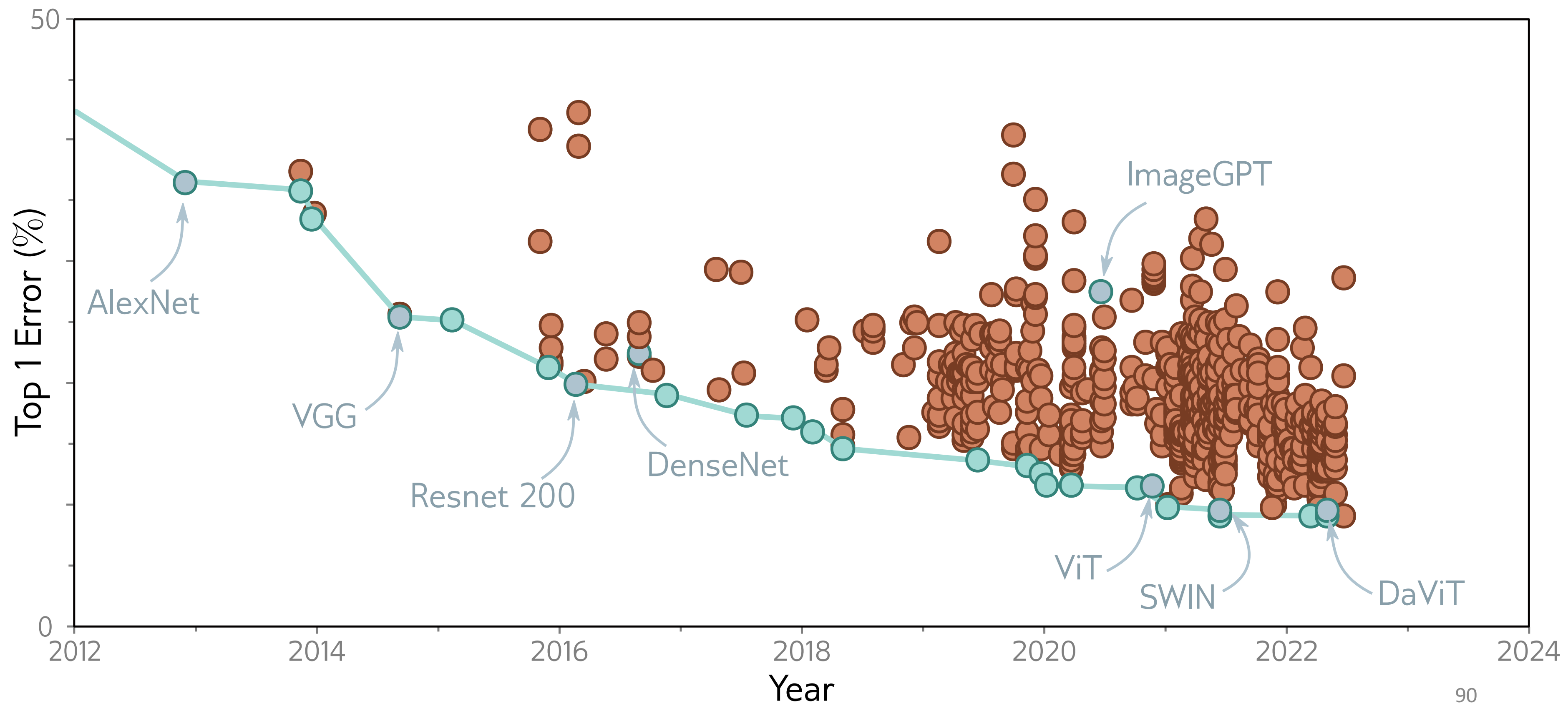


$224 \times 224 \times 3$
$224 \times 224 \times 64$
$112 \times 112 \times 128$
$56 \times 56 \times 256$
$28 \times 28 \times 512$
$14 \times 14 \times 512$
4096
4096
1000
1000
Conv 3×3
MaxPool
Conv 3×3
MaxPool
Conv 3×3
MaxPool
Conv 3×3
MaxPool
Conv 3×3
MaxPool + FC
FC
FC
Softmax

Details

- 19 hidden layers
- 144 million parameters
- 6.8% top-5 error rate, 23.7% top-1 error rate

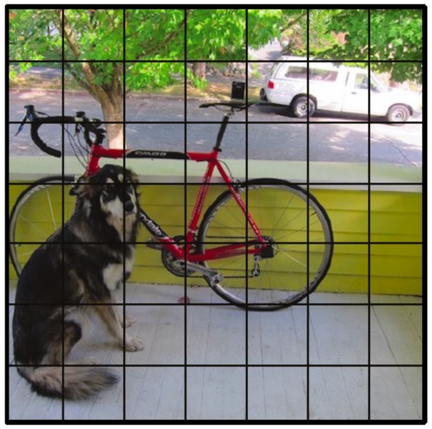
ImageNet History



Convolution #2

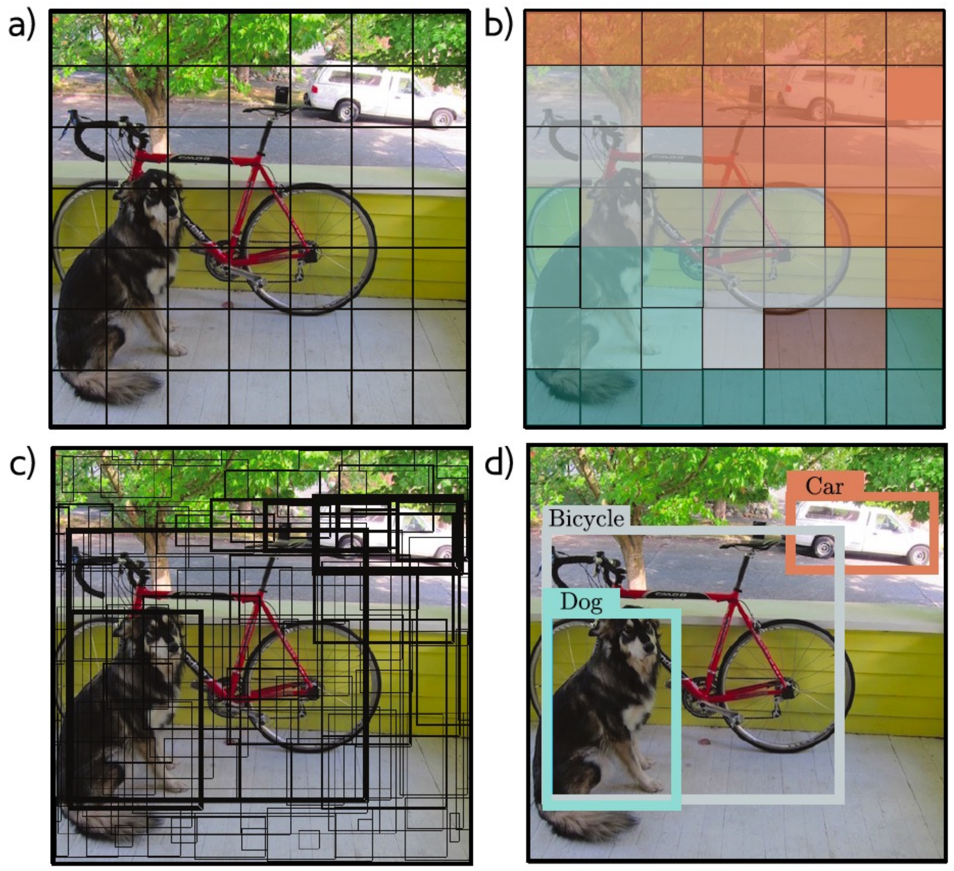
- 2D Convolution
- Downsampling and upsampling, 1x1 convolution
- Image classification
- Object detection
- Semantic segmentation
- Residual networks
- U-Nets and hourglass networks

You Only Look Once (YOLO)

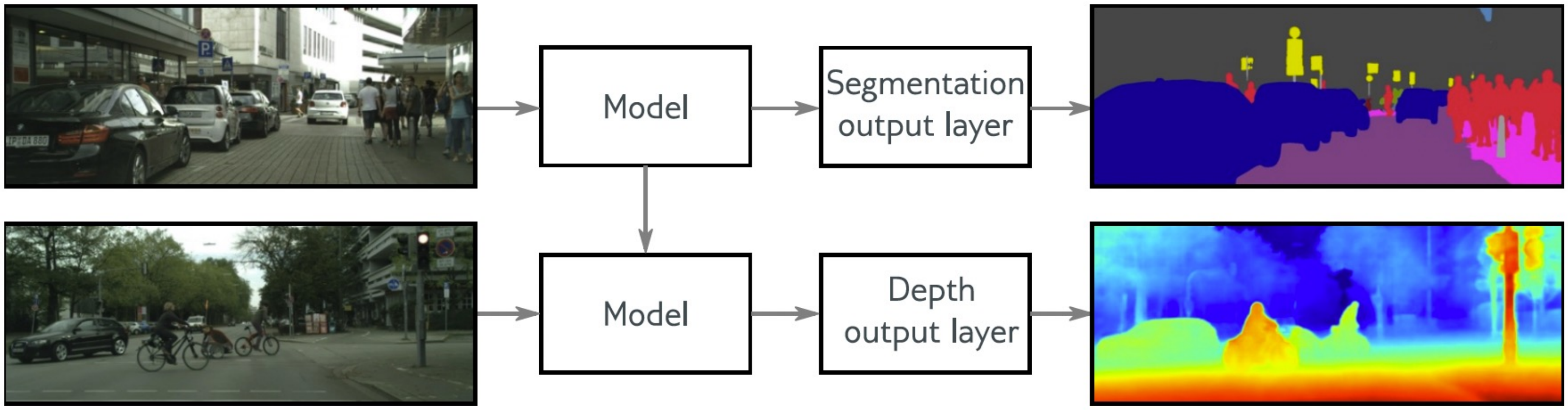


- Network similar to VGG (448x448 input)
- 7×7 grid of locations
- Predict class at each location
- Predict 2 bounding boxes at each location
  - Five parameters –x,y, height, width, and confidence
- Momentum, weight decay, dropout, and data augmentation
- Heuristic at the end to threshold and decide final boxes – (non maximum suppression)

Object detection (YOLO)

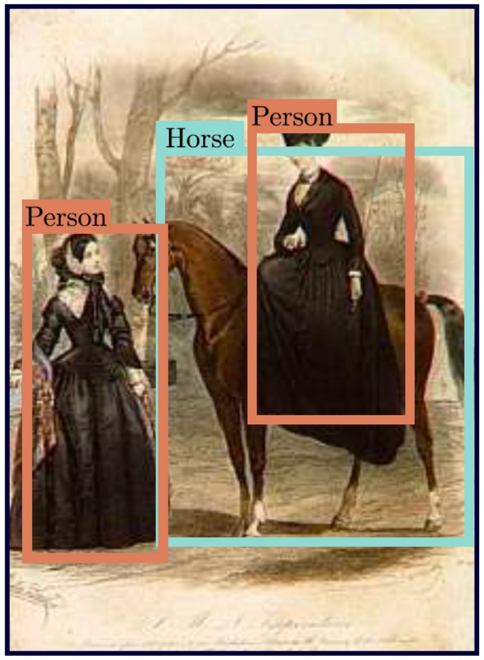


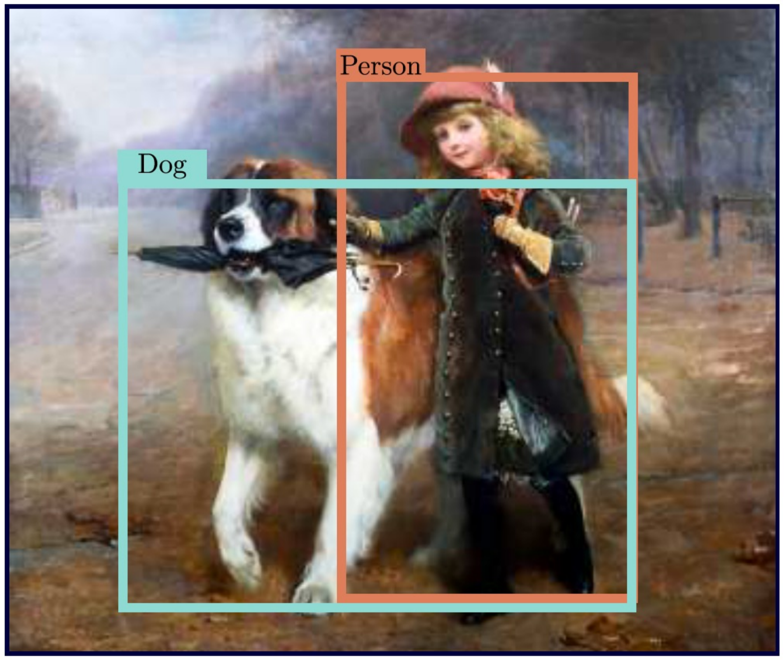
Transfer learning

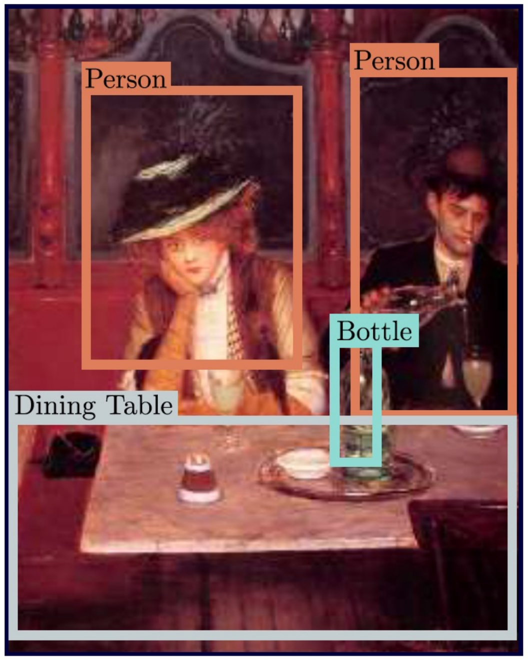


Transfer learning from ImageNet classification

Results


Horse
Person
Person

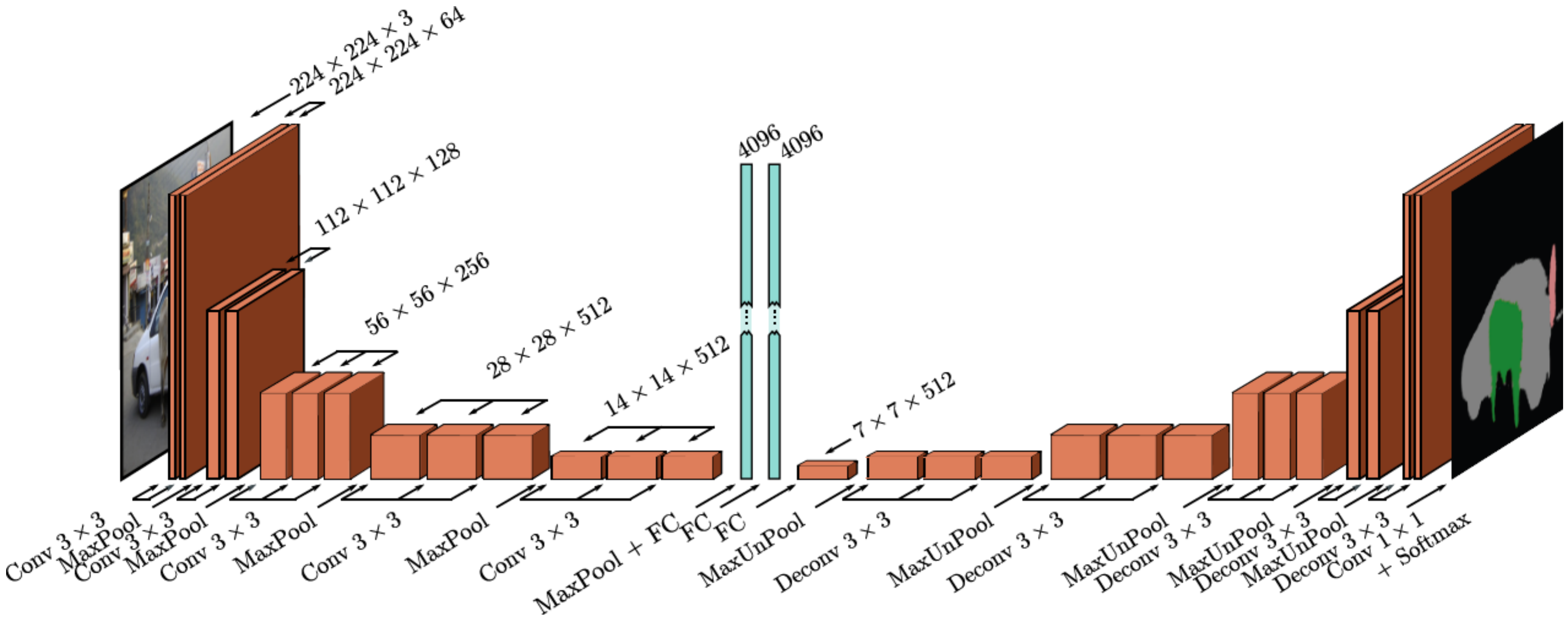

Person
Dog


Person
Person
Bottle
Dining Table

Convolution #2

- 2D Convolution
- Downsampling and upsampling, 1x1 convolution
- Image classification
- Object detection
- Semantic segmentation
- Residual networks
- U-Nets and hourglass networks

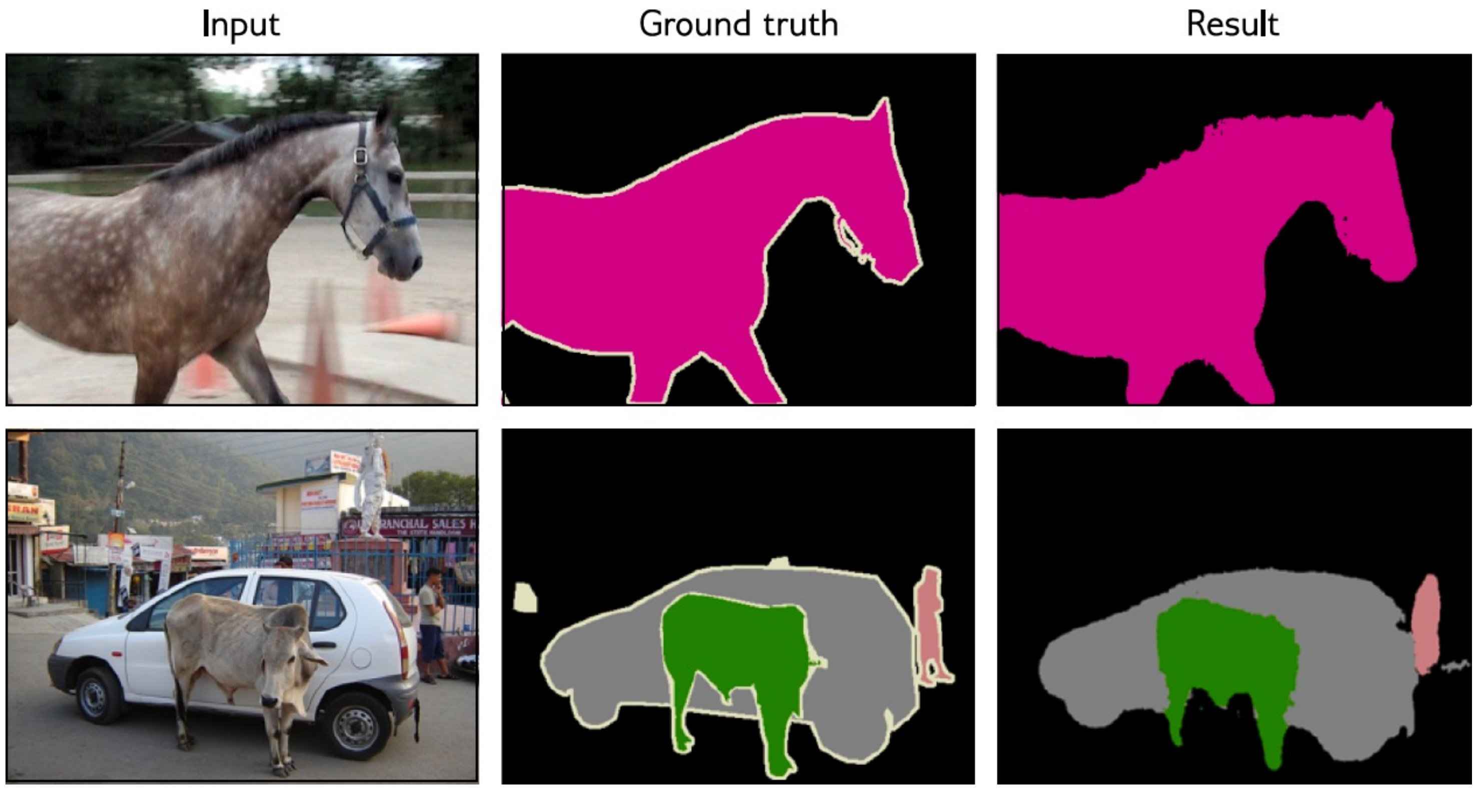
Semantic Segmentation (2015)



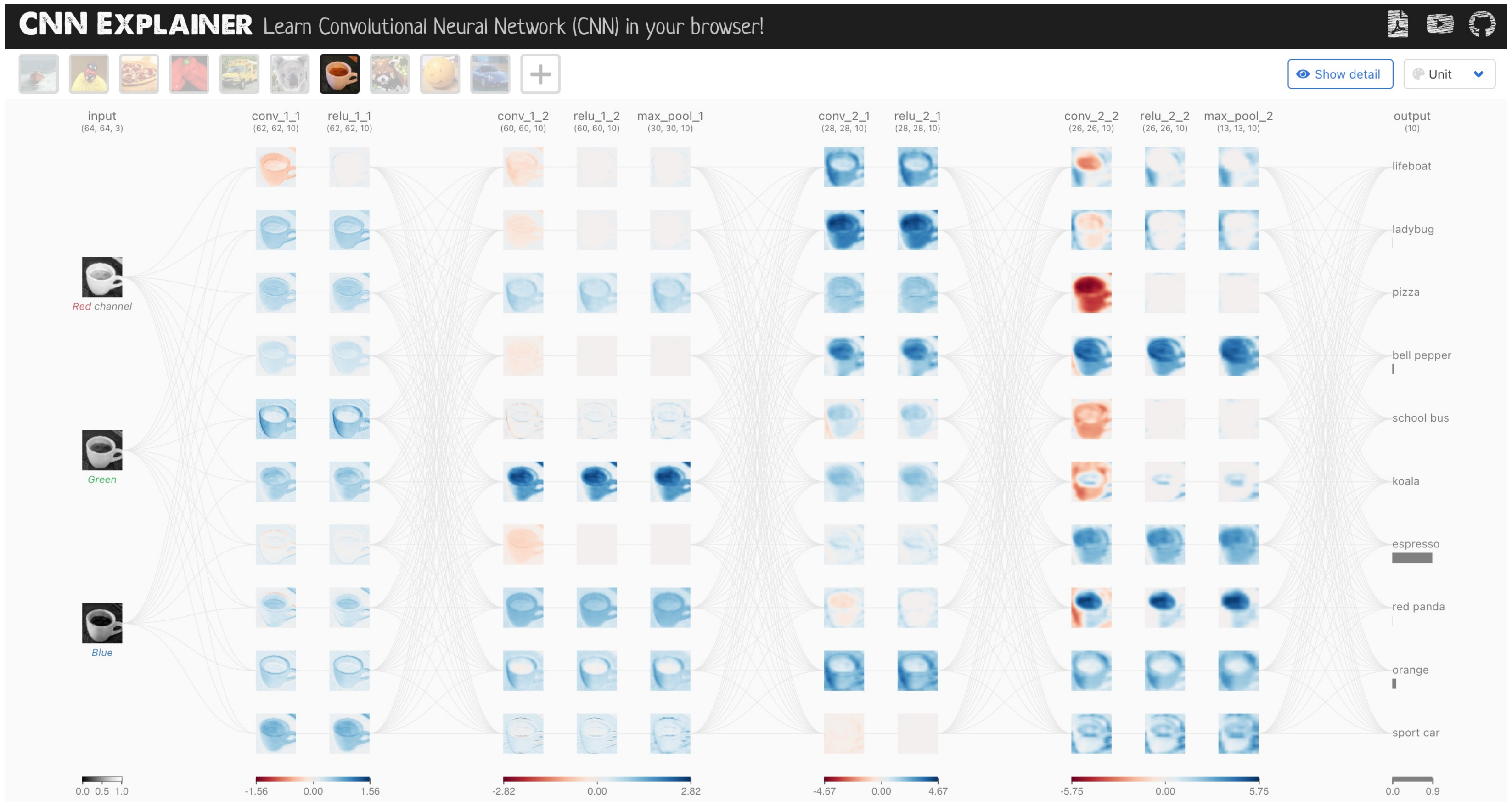
Encoder

Decoder

Semantic segmentation results



In an encoder-decoder segmentation network, why is it beneficial to use skip connections that pass feature maps from encoder layers directly to corresponding decoder layers?



https://poloclub.github.io/cnn-explainer/

Feedback?

https://forms.gle/pXHM5nx1Ti9aFmpw6