



# Convolutional Neural Network

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Risman Adnan  
Telkom University

## Classification



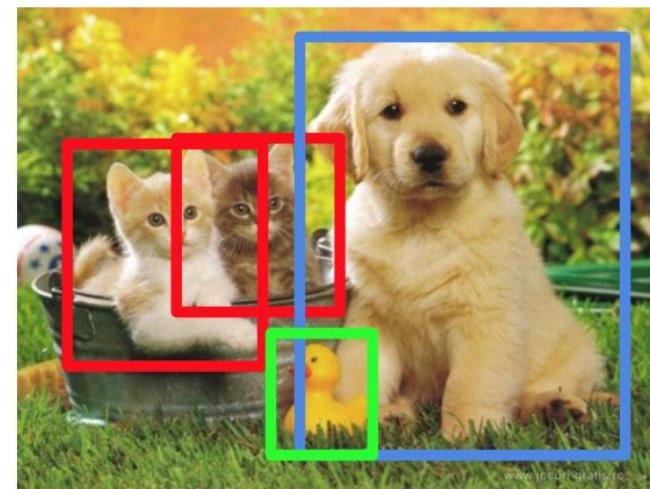
CAT

## Classification + Localization



CAT

## Object Detection



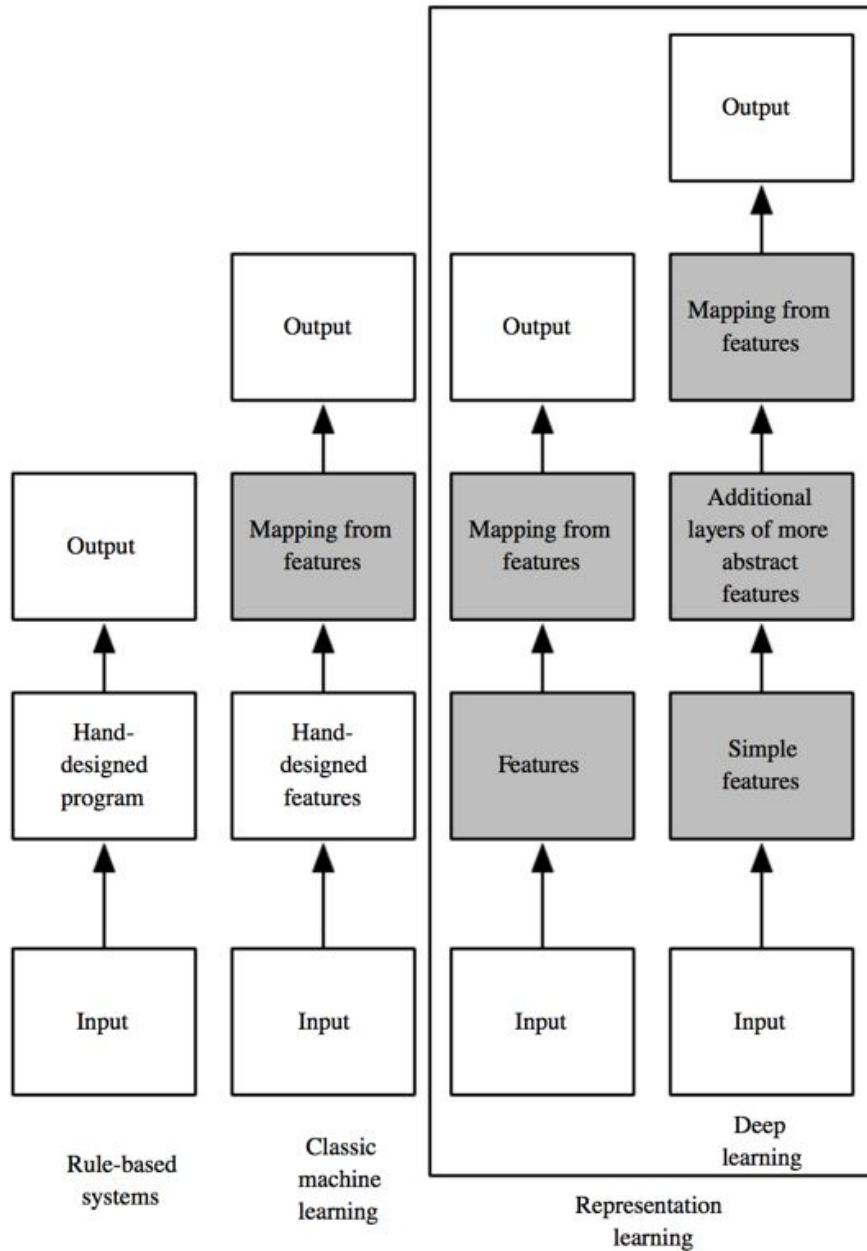
CAT, DOG, DUCK

## Instance Segmentation



CAT, DOG, DUCK

Computer Vision Tasks



THEORY	TECHNIQUES		PARADIGMS
	MODELS	METHODS	
VC	Linear	Regularization	Supervised
Bias-Variance	Neural Networks	Validation	Unsupervised
Complexity	SVM	Aggregation	Reinforcement
Bayesian	Nearest Neighbors	Input Processing	Active
	RBF		Online
	Gaussian Processes		
	SVD		

# Machine Learning vs Deep Learning



[www.image-net.org](http://www.image-net.org)

**22K** categories and **14M** images

- Animals
  - Bird
  - Fish
  - Mammal
  - Invertebrate
- Plants
  - Tree
  - Flower
  - Food
  - Materials
- Structures
  - Artifact
  - Tools
  - Appliances
  - Structures
- Person
- Scenes
  - Indoor
  - Geological Formations
  - Sport Activities



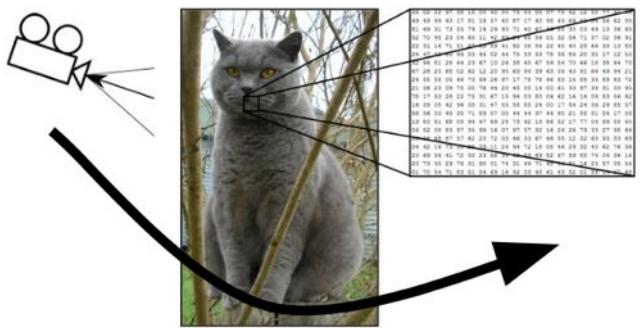
98	02	22	97	38	15	00	40	00	75	04	05	07	78	52	12	50	77	91	00
49	49	99	40	17	81	18	57	60	87	17	40	98	43	68	44	55	56	62	00
81	49	31	73	55	79	14	29	93	71	40	67	53	05	30	03	49	13	36	91
82	70	95	23	04	60	11	42	63	11	65	56	01	32	56	71	37	02	36	91
22	31	16	71	51	67	05	89	41	92	36	54	22	40	40	28	66	33	13	80
24	47	39	00	99	03	45	02	44	75	33	53	78	36	84	20	35	17	12	50
82	98	81	28	64	23	67	10	26	38	30	67	59	54	70	66	18	38	64	70
67	26	20	68	02	62	12	20	95	63	94	39	63	08	40	91	66	49	94	21
24	55	58	05	66	73	99	26	97	17	78	78	96	83	14	08	34	89	63	72
21	36	23	09	75	00	76	44	20	45	35	14	00	61	33	97	34	31	33	95
78	17	53	28	22	75	31	67	15	94	03	80	04	62	16	14	09	53	56	92
16	39	05	42	96	35	31	47	55	58	88	24	00	17	54	24	36	29	85	57
86	56	00	48	35	71	89	07	05	44	44	37	44	60	21	58	51	54	17	59
19	80	81	68	05	95	47	69	28	73	92	13	86	52	17	77	06	89	55	40
04	52	08	83	97	35	99	16	07	97	57	32	16	26	26	79	33	27	98	66
93	44	48	87	57	62	20	72	03	46	33	67	46	55	12	32	63	93	53	69
04	42	16	73	31	05	39	11	24	94	72	18	08	46	29	32	40	62	76	36
20	69	36	41	72	30	23	88	37	60	92	69	82	67	59	85	74	04	36	16
20	73	35	29	78	31	90	01	74	31	49	71	48	04	61	16	23	57	05	54
01	70	54	71	83	51	54	69	16	92	33	48	61	43	52	01	89	21	67	46

What the computer sees

## Image Classification Problem

- Core task in computer vision: can we recognize object?
- Image represented as 3D array or simply vector.
- Supervised learning with labeled dataset.
- Datasets: ImageNet, CIFAR-10, etc.

## Camera pose



## Illumination



## Deformation



## Occlusion



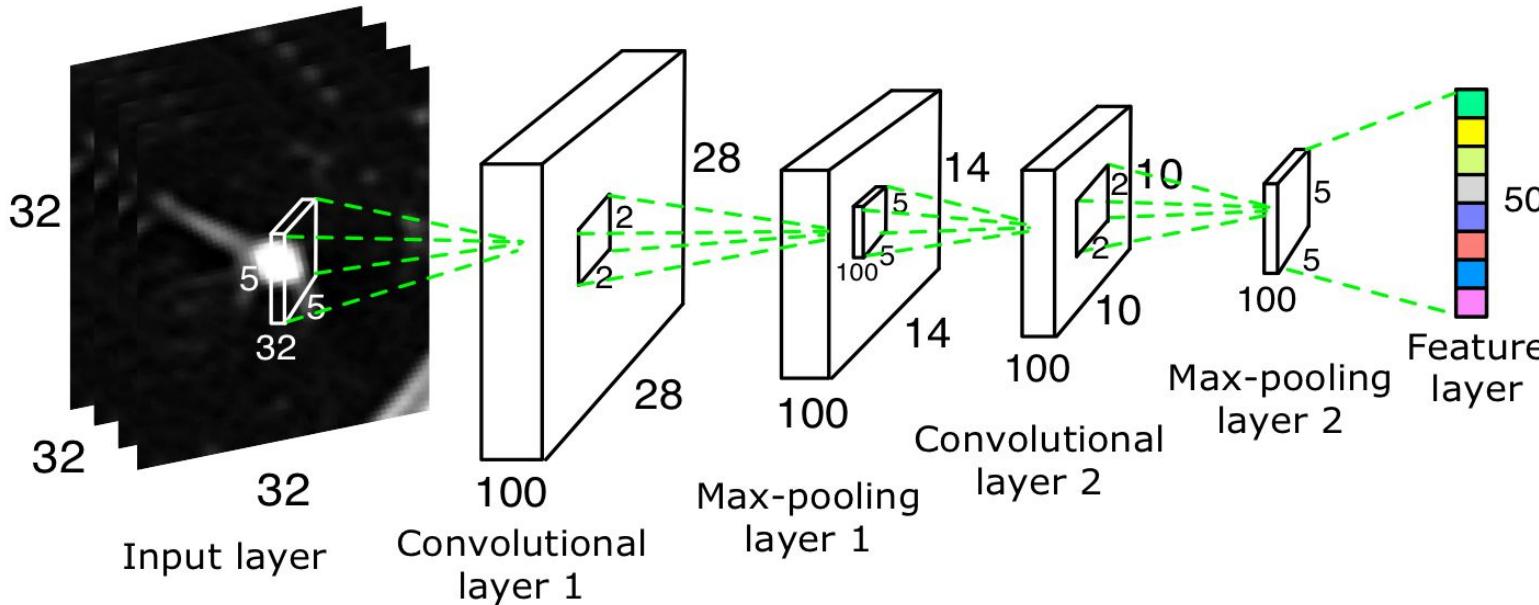
## Background clutter



## Intraclass variation



# Key Challenges |



```

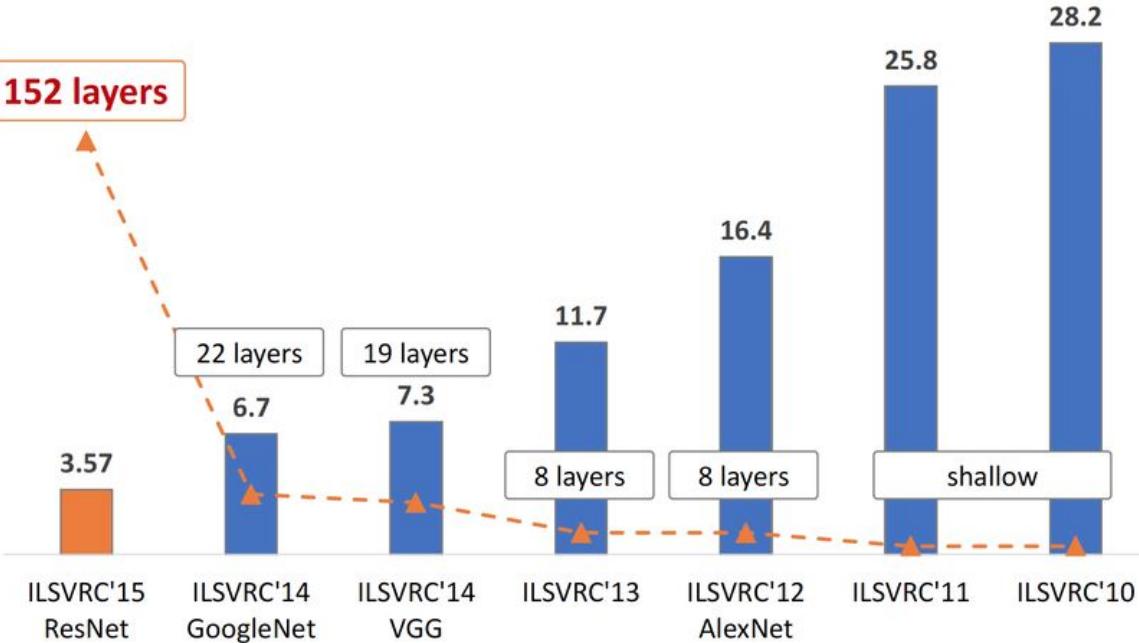
def train(train_images, train_labels):
    # build a model for images -> labels...
    return model

def predict(model, test_images):
    # predict test_labels using the model...
    return test_labels

```

## Convolutional Neural Network

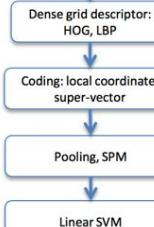
- Supervised Learning Approach
  - Collect a dataset of images and labels
  - Use **CNN** model to train an image classifier
  - **CNN** has automatic feature extraction
  - Evaluate the classifier on a withheld set of test images



## IMAGENET Large Scale Visual Recognition Challenge

Year 2010

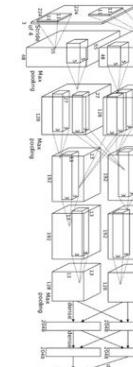
NEC-UIUC



[Lin CVPR 2011]

Year 2012

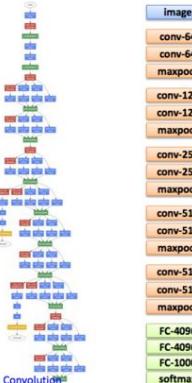
SuperVision



[Krizhevsky NIPS 2012]

Year 2014

GoogLeNet VGG



[Szegedy arxiv 2014] [Simonyan arxiv 2014]

Year 2015

MSRA



# Image Classification State-of-Arts

# History of Convolutional Neural Network

A bit of history:

**Hubel & Wiesel,**

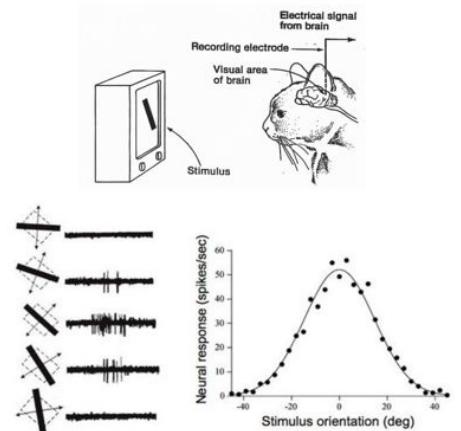
1959

RECEPTIVE FIELDS OF SINGLE NEURONES IN THE CAT'S STRIATE CORTEX

1962

RECEPTIVE FIELDS, BINOCULAR INTERACTION AND FUNCTIONAL ARCHITECTURE IN THE CAT'S VISUAL CORTEX

1968...

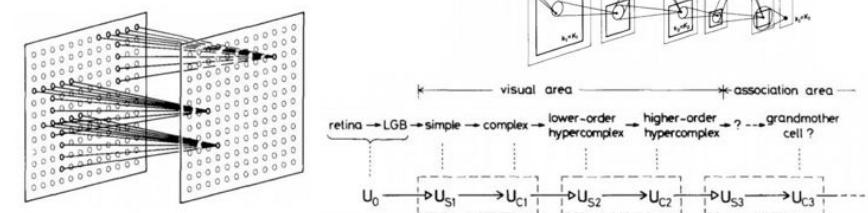


A bit of history:

**Neurocognitron**

[Fukushima 1980]

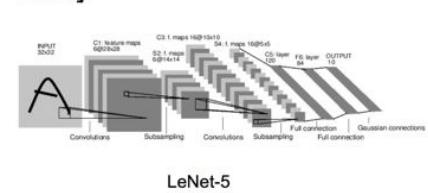
"sandwich" architecture (SCSCSC...)  
simple cells: modifiable parameters  
complex cells: perform pooling



A bit of history:

**Gradient-based learning applied to document recognition**

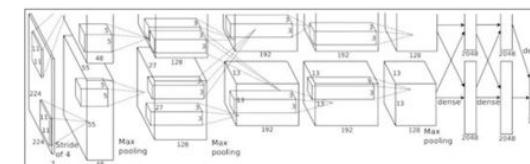
[LeCun, Bottou, Bengio, Haffner 1998]



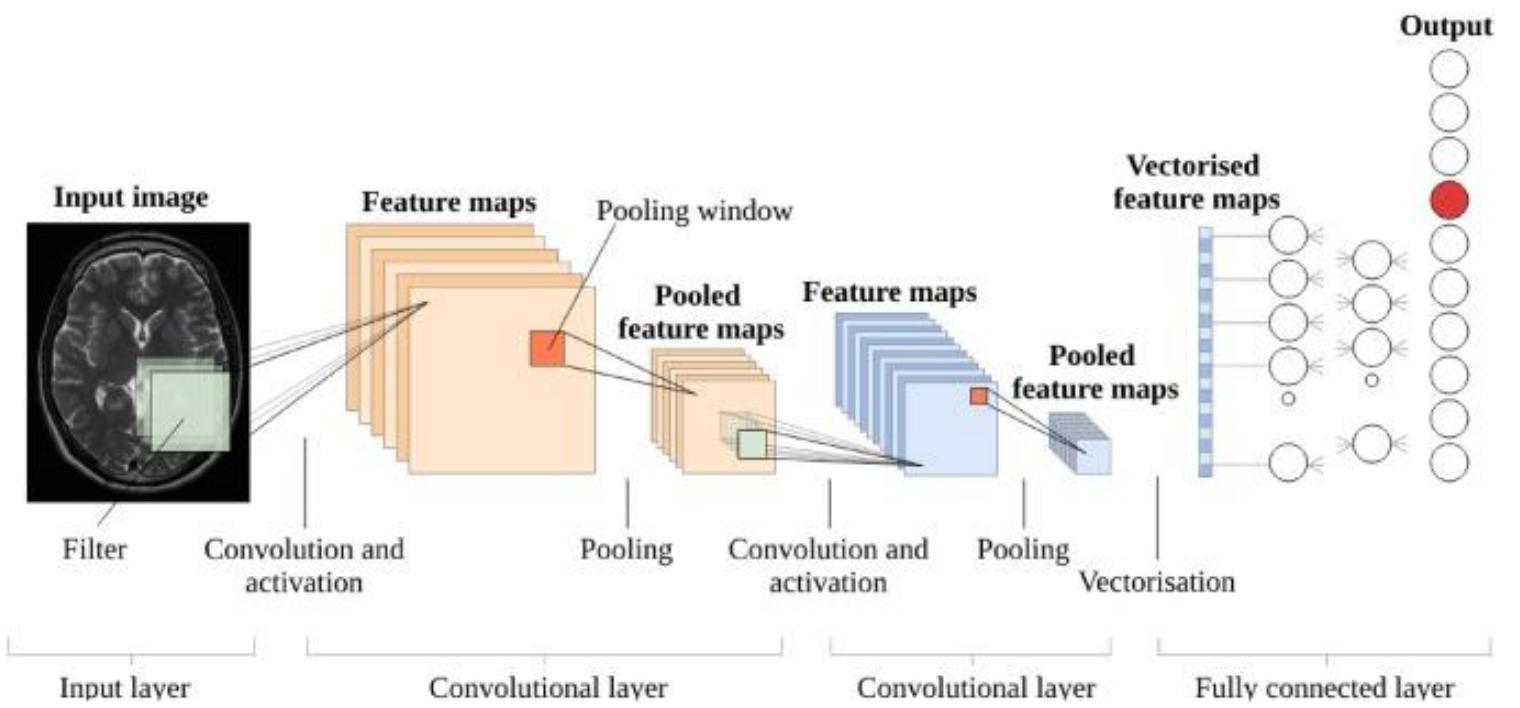
A bit of history:

**ImageNet Classification with Deep Convolutional Neural Networks**

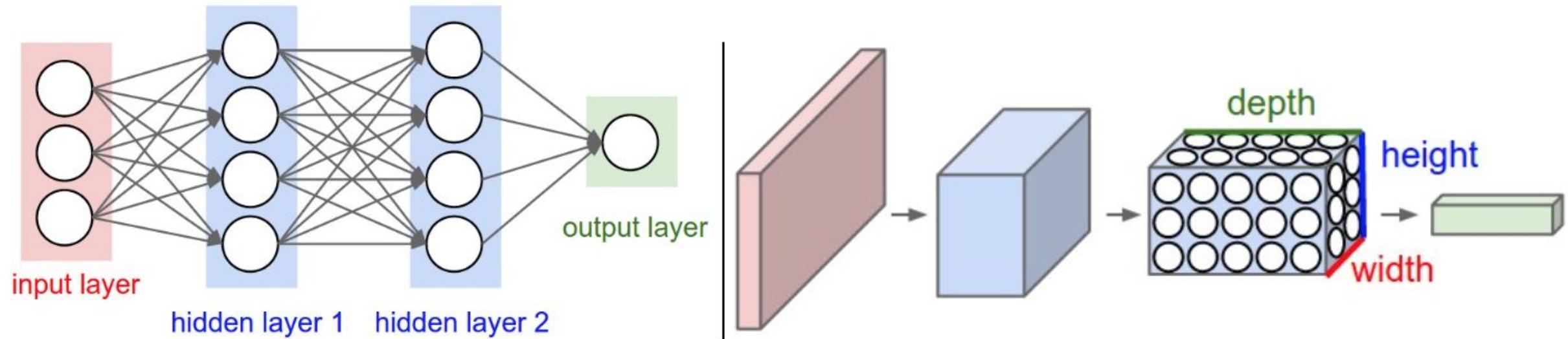
[Krizhevsky, Sutskever, Hinton, 2012]



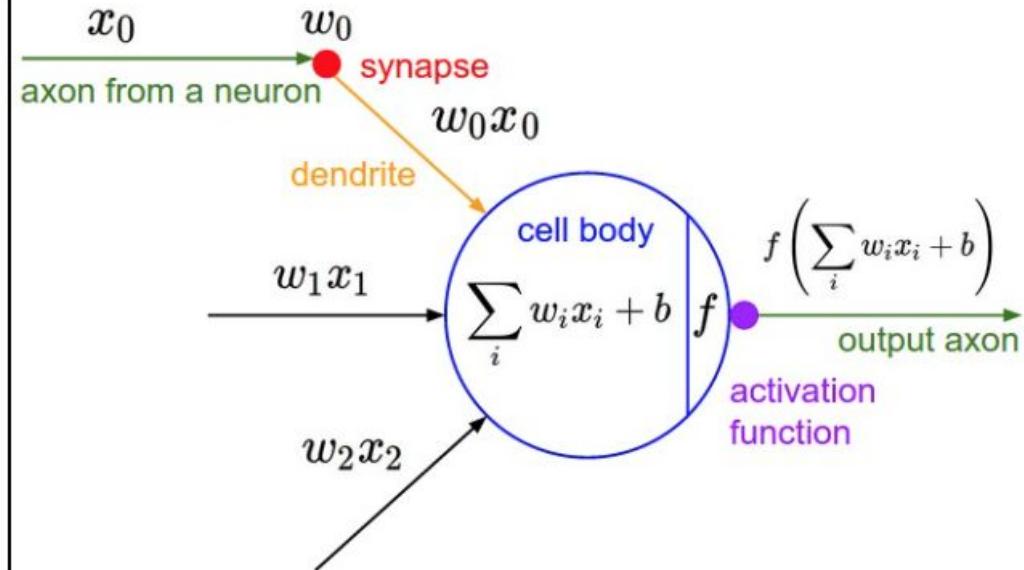
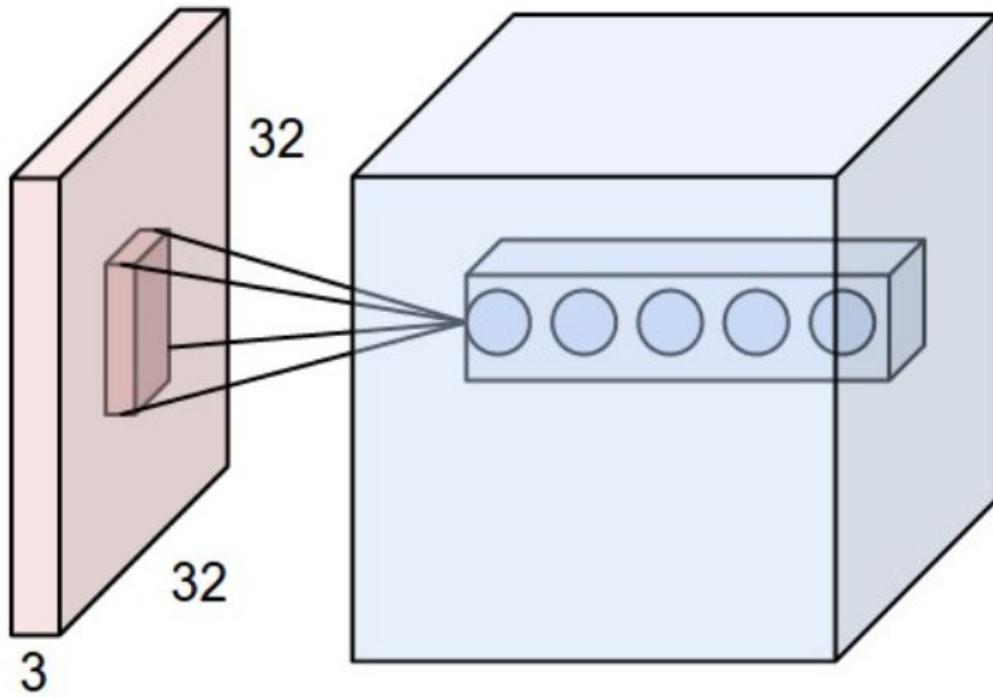
“AlexNet”



# Convolutional Neural Network (ConvNets)

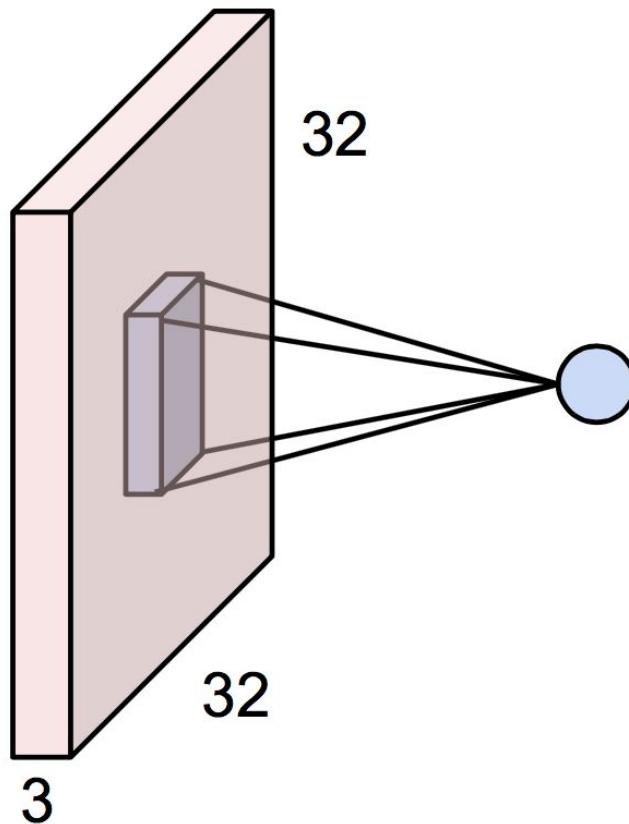


# ConvNets Architecture



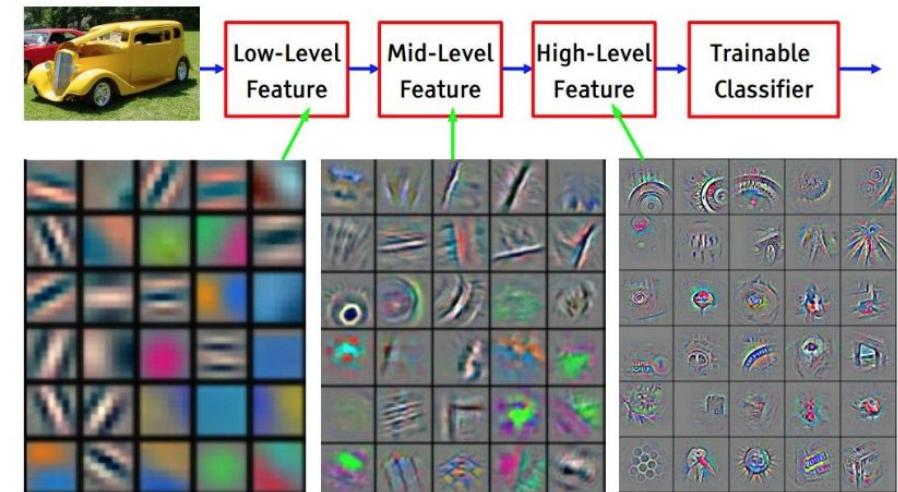
# ConvNets Architecture

# Convolution



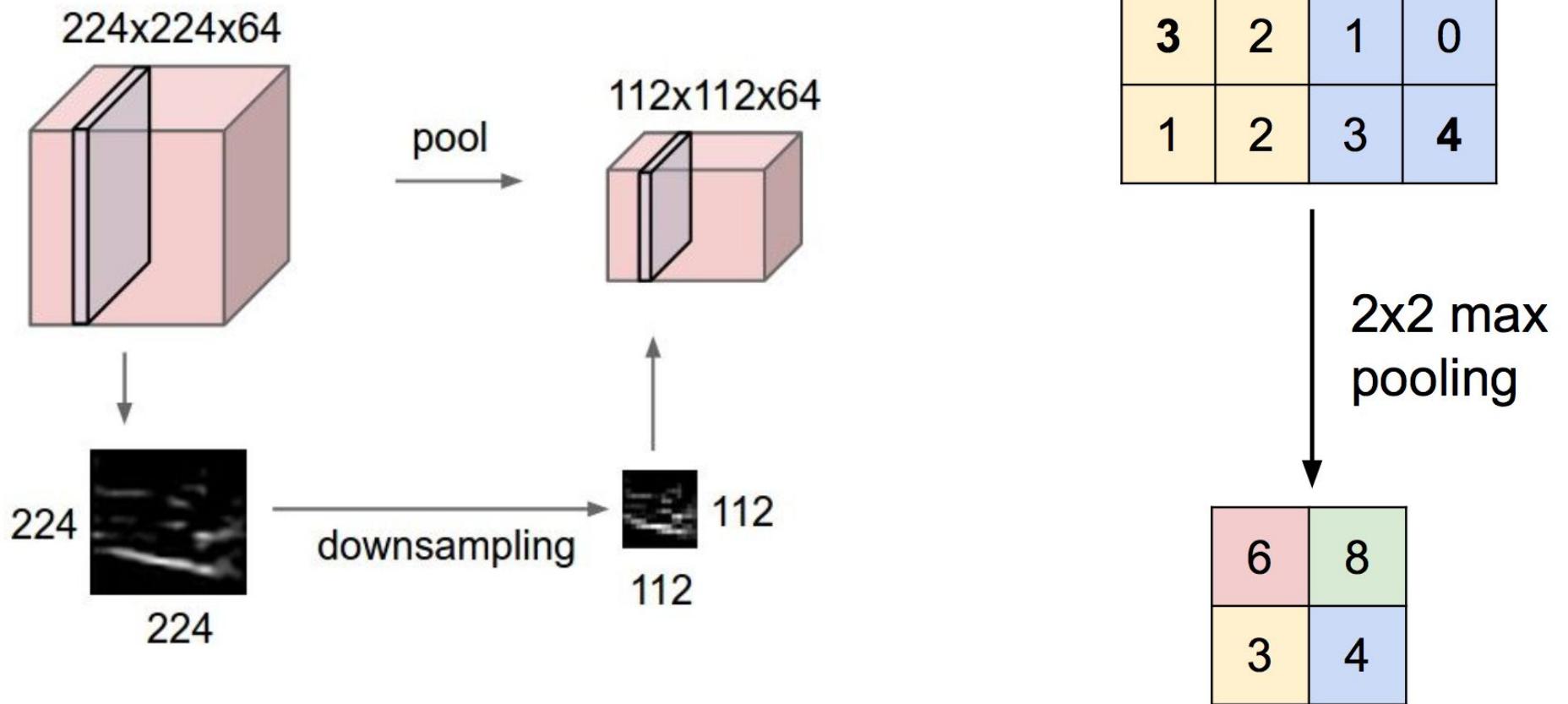
**Summary.** To summarize, the Conv Layer:

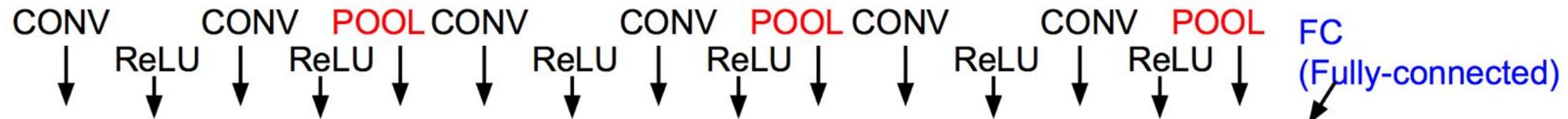
- Accepts a volume of size  $W_1 \times H_1 \times D_1$
- Requires four hyperparameters:
  - Number of filters  $K$ ,
  - their spatial extent  $F$ ,
  - the stride  $S$ ,
  - the amount of zero padding  $P$ .



Feature visualization of convolutional net trained on ImageNet from [Zeiler & Fergus 2013]

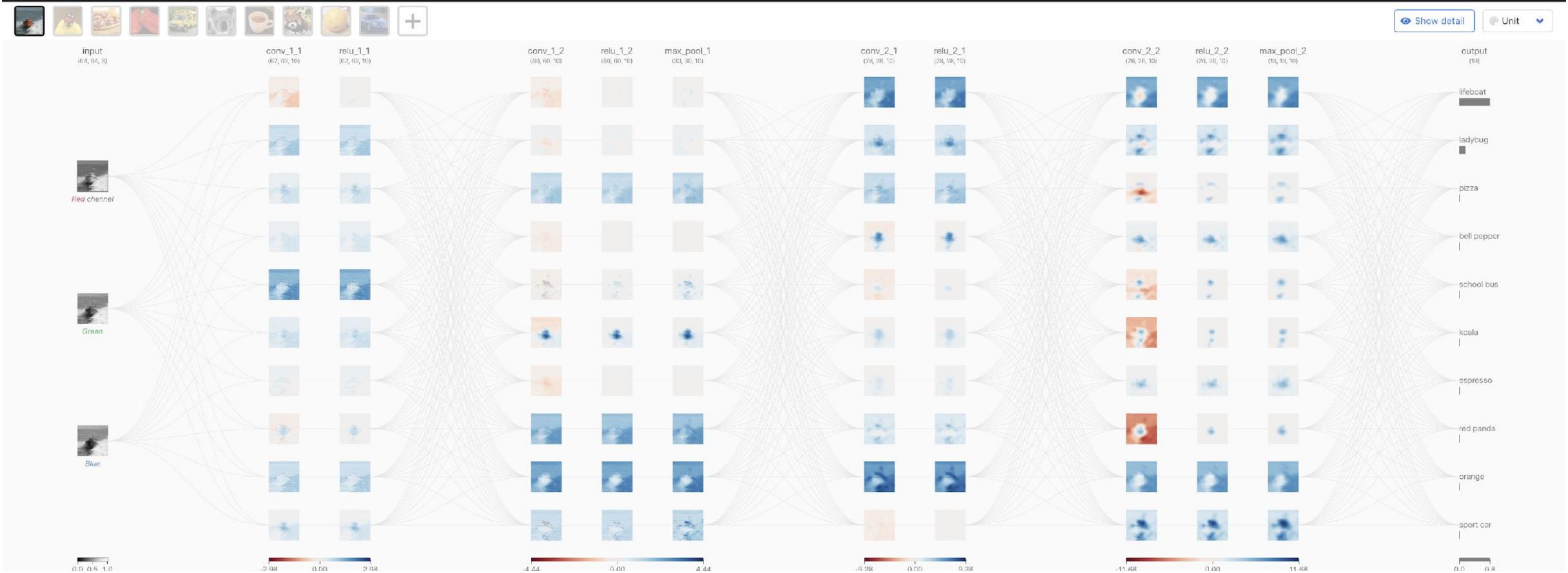
# Pooling





truck  
car  
airplane  
ship  
horse

# ConvNets Architecture



# How ConvNets Works

# APPENDIX

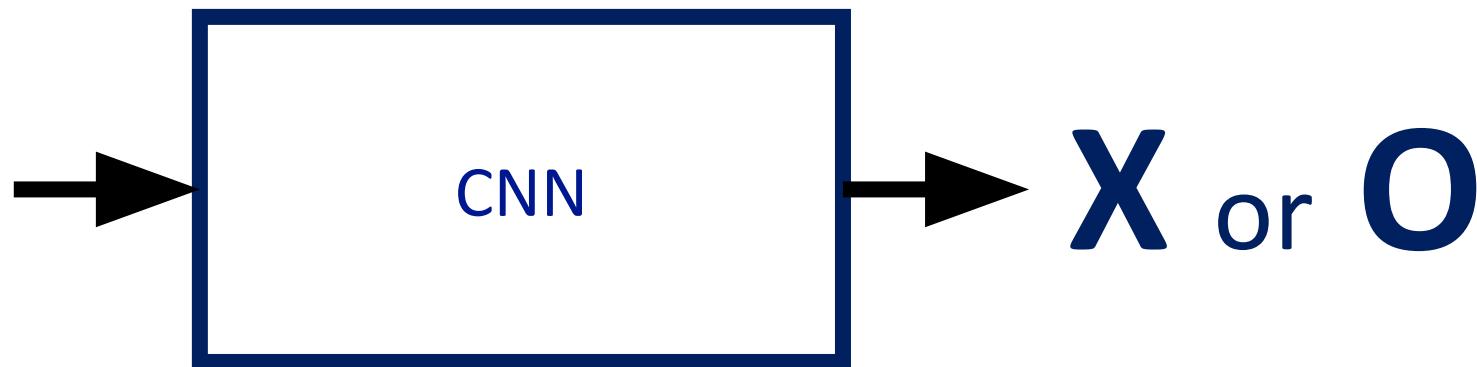
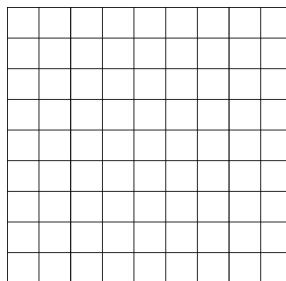
## How ConvNets Work

Telkom University

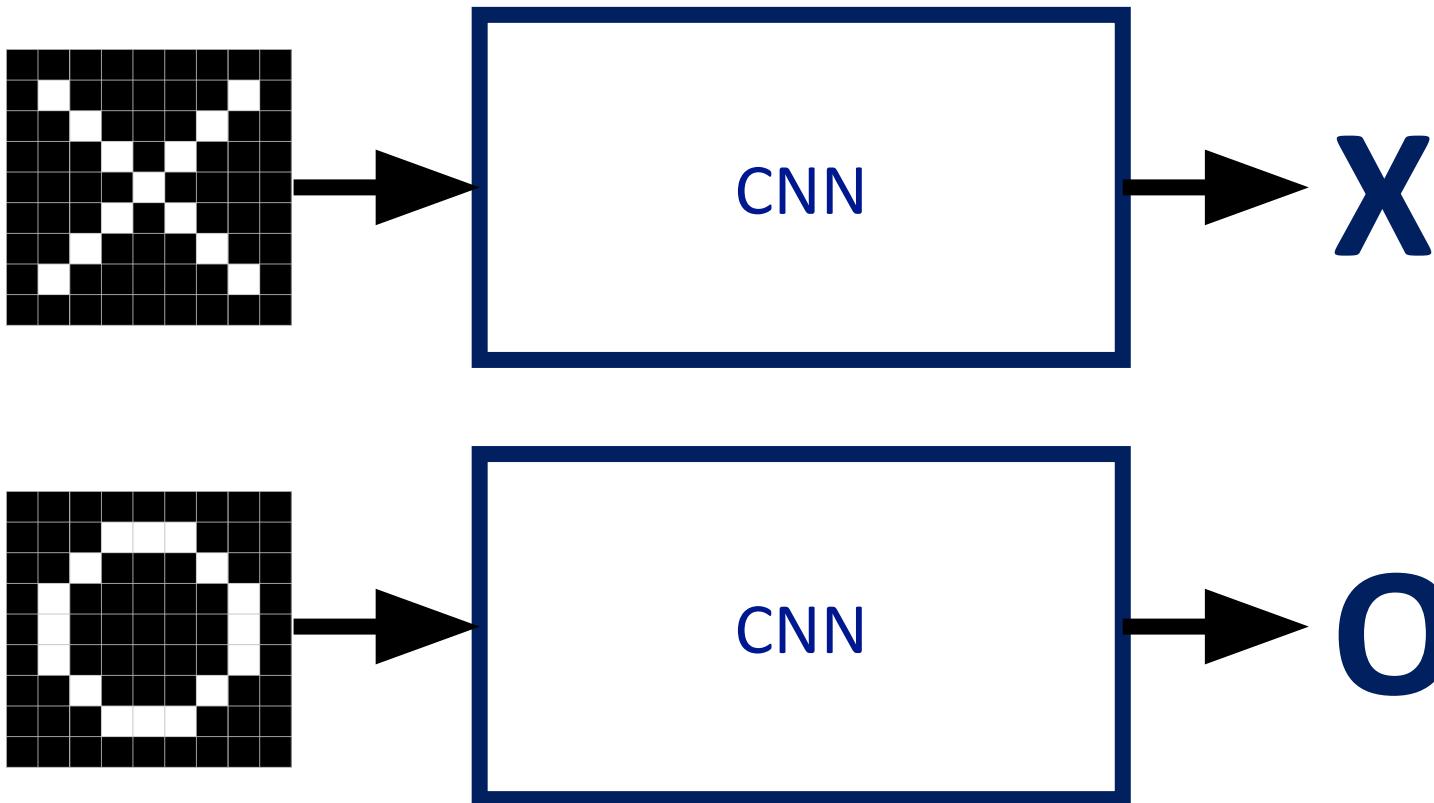
# A Toy ConvNet: X's and O's

Says whether a picture is of an X or an O

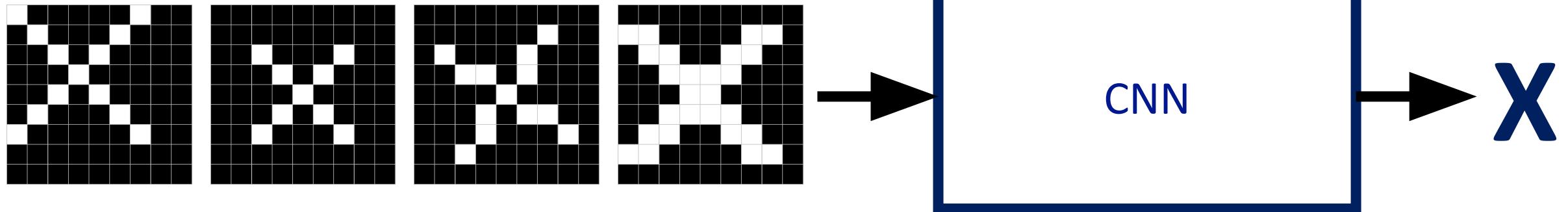
A two-dimensional  
array of pixels



# For Example



# Trickier Cases

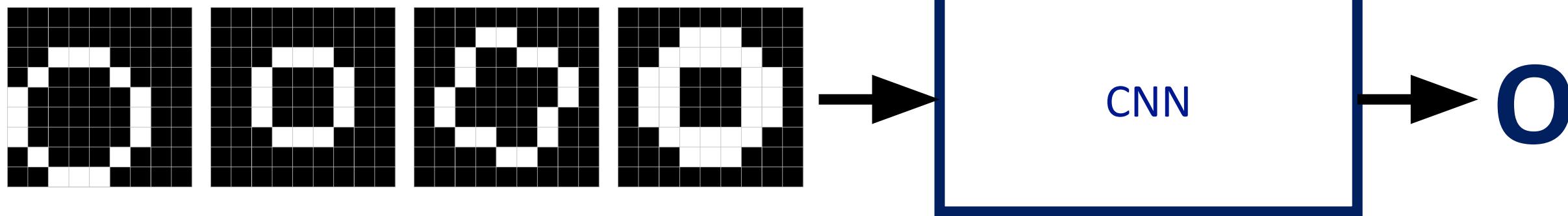


translation

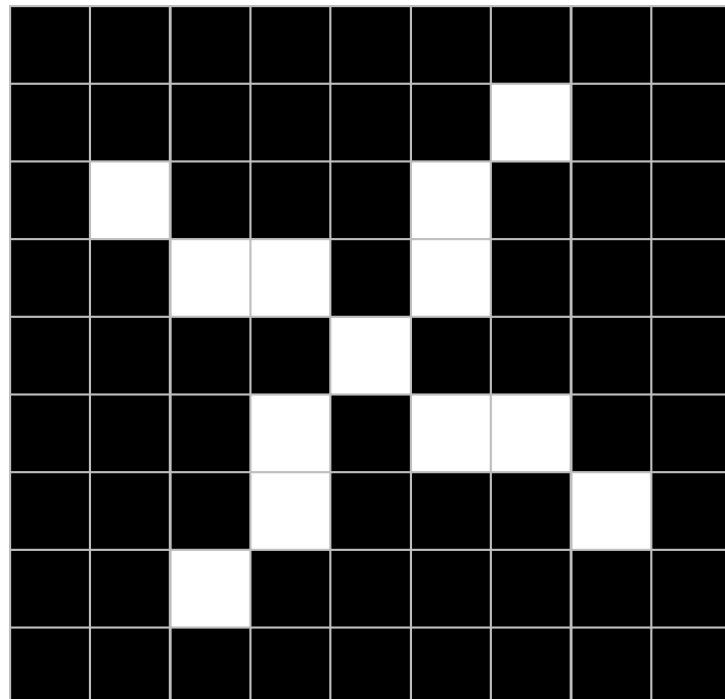
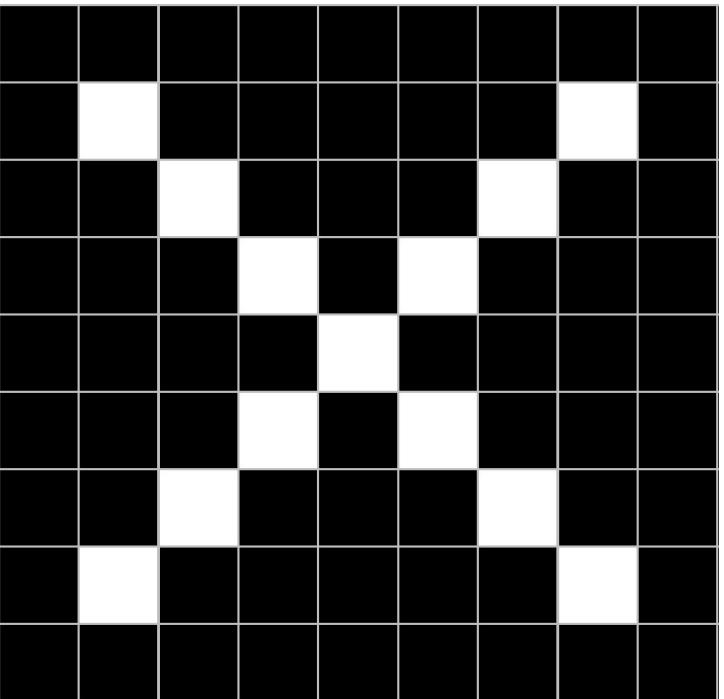
scaling

rotation

weight



# Deciding is Hard



# What Computers See



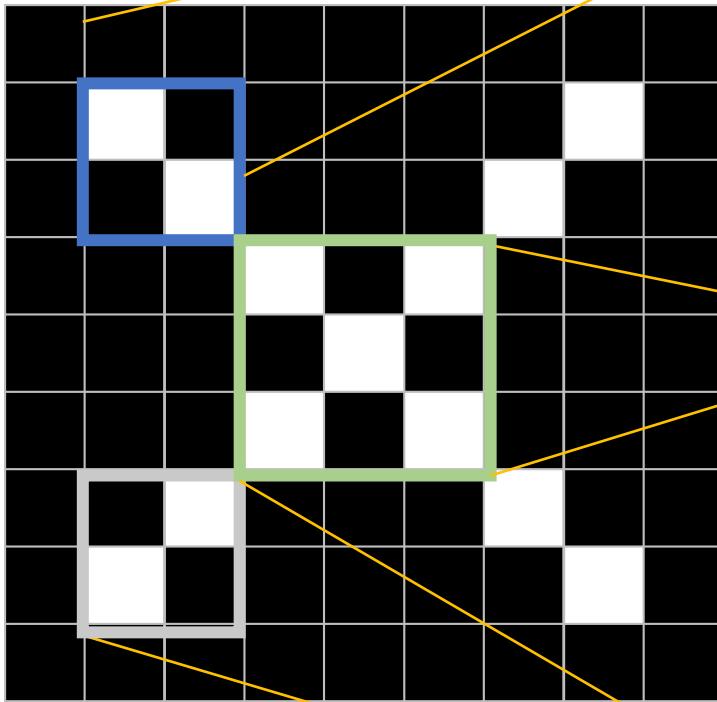
# What Computers See

# Computers are Literal

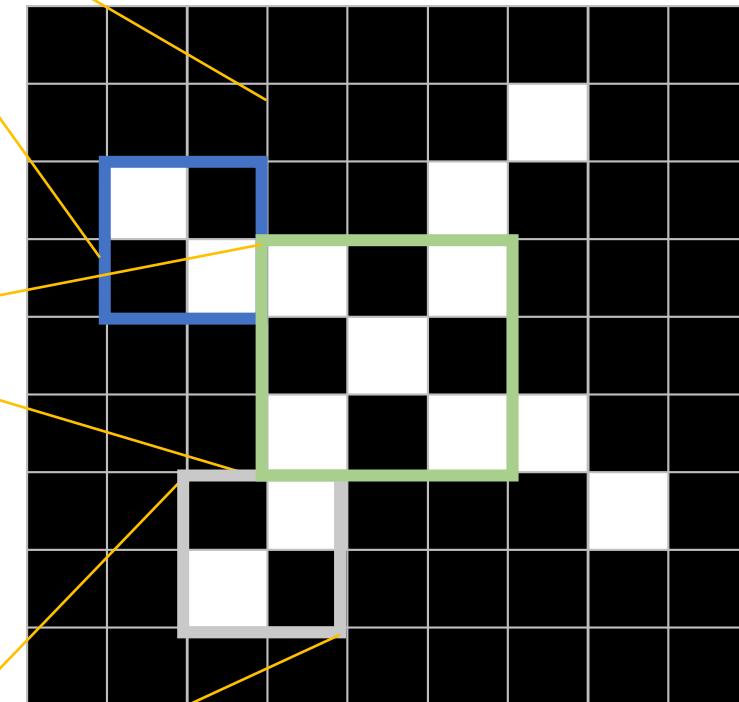


# ConvNets Match Pieces of the Image

=



=



=

# Features Match Pieces of the Image

1	-1	-1
-1	1	-1
-1	-1	1

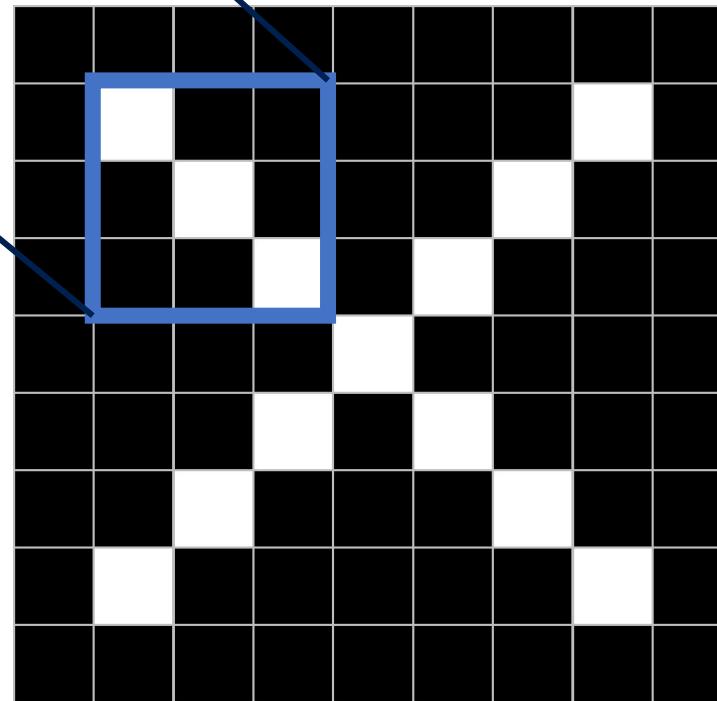
1	-1	1
-1	1	-1
1	-1	1

-1	-1	1
-1	1	-1
1	-1	-1

1	-1	-1
-1	1	-1
-1	-1	1

1	-1	1
-1	1	-1
1	-1	1

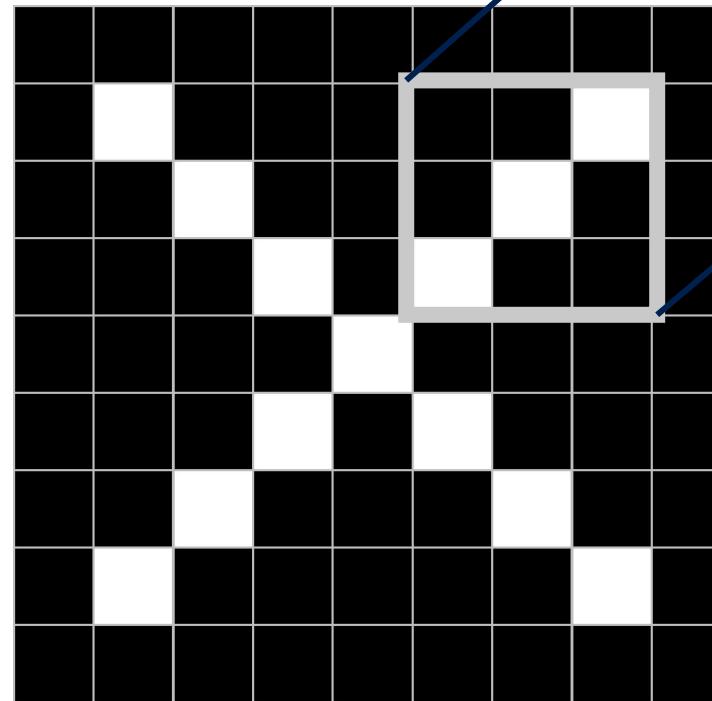
-1	-1	1
-1	1	-1
1	-1	-1



1	-1	-1
-1	1	-1
-1	-1	1

1	-1	1
-1	1	-1
1	-1	1

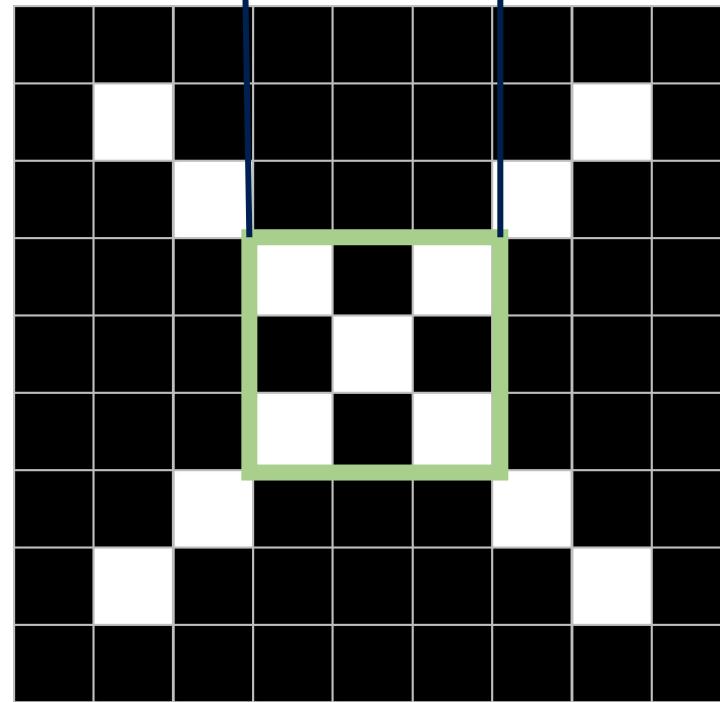
-1	-1	1
-1	1	-1
1	-1	-1



1	-1	-1
-1	1	-1
-1	-1	1

1	-1	1
-1	1	-1
1	-1	1

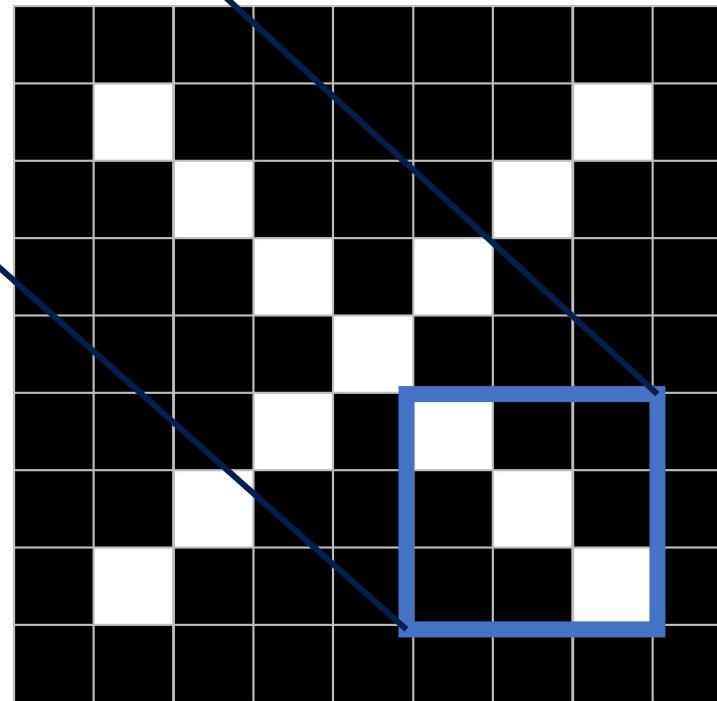
-1	-1	1
-1	1	-1
1	-1	-1



1	-1	-1
-1	1	-1
-1	-1	1

1	-1	1
-1	1	-1
1	-1	1

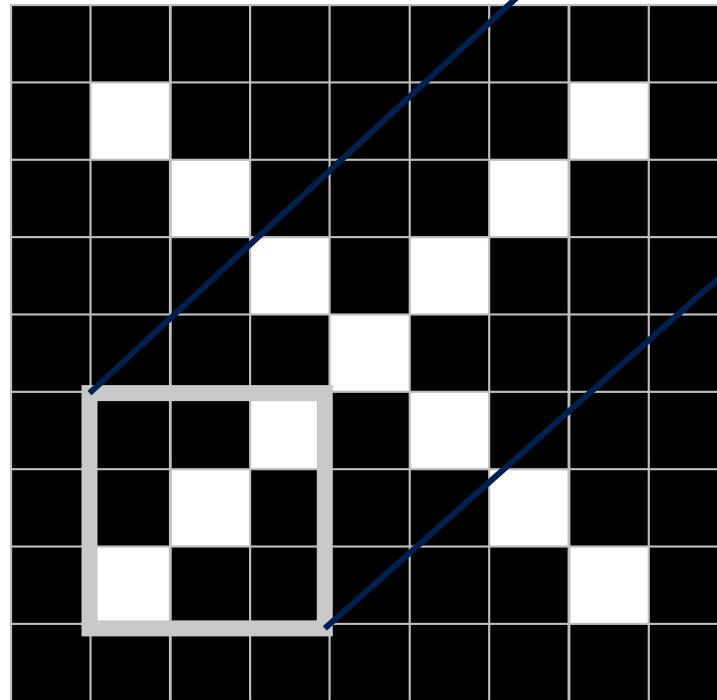
-1	-1	1
-1	1	-1
1	-1	-1



1	-1	-1
-1	1	-1
-1	-1	1

1	-1	1
-1	1	-1
1	-1	1

-1	-1	1
-1	1	-1
1	-1	-1



# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

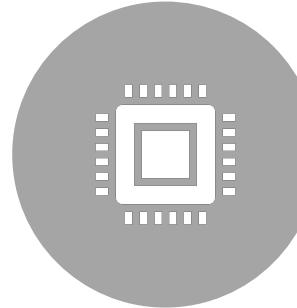


DON'T PANIC

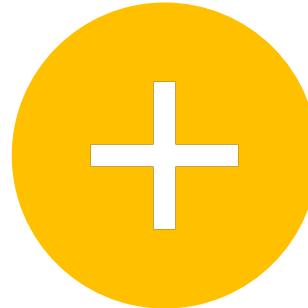
# Filtering: The Math Behind the Match



LINE UP THE FEATURE AND THE IMAGE PATCH.



MULTIPLY EACH IMAGE PIXEL BY THE CORRESPONDING FEATURE PIXEL.

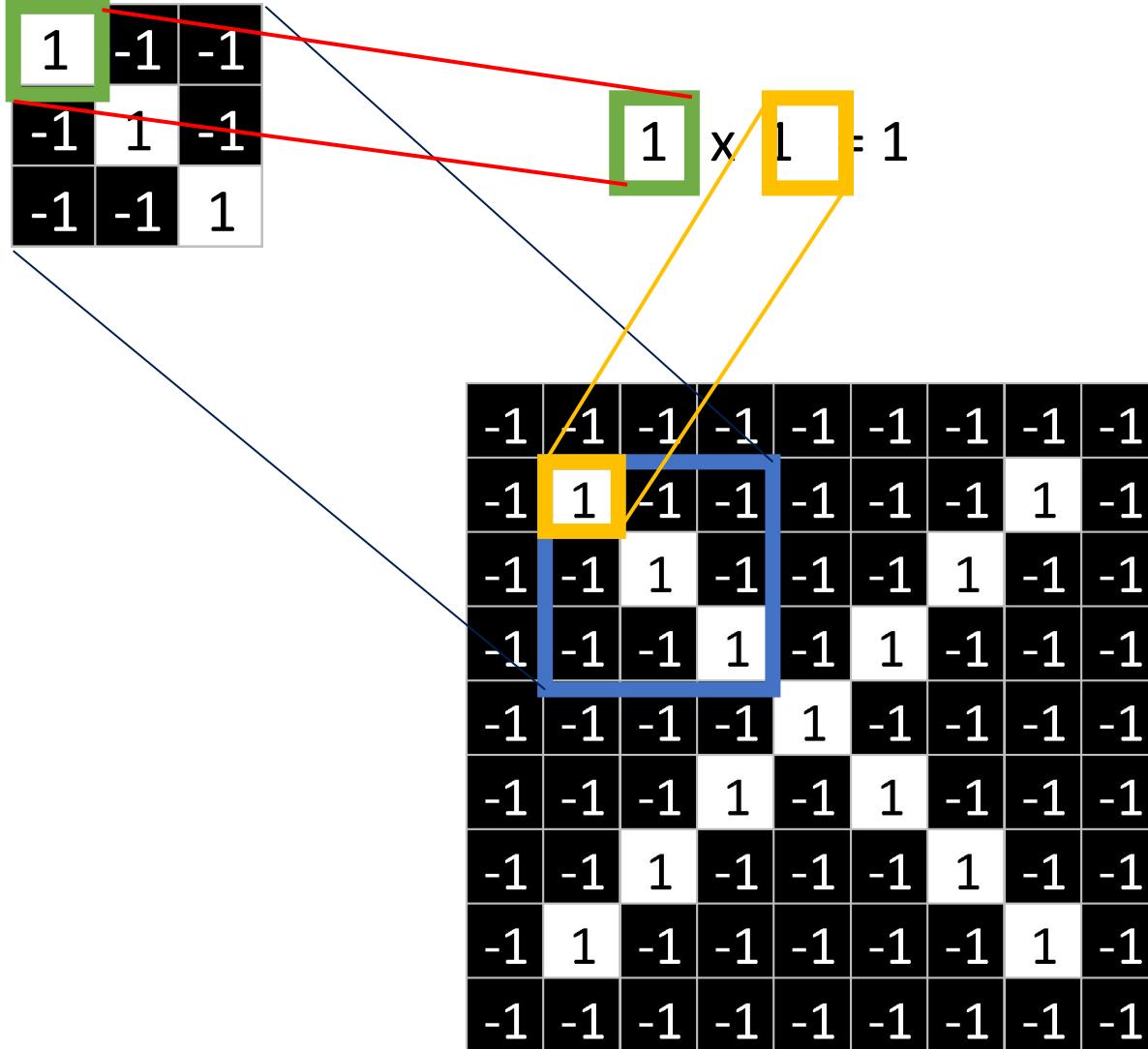


ADD THEM UP.

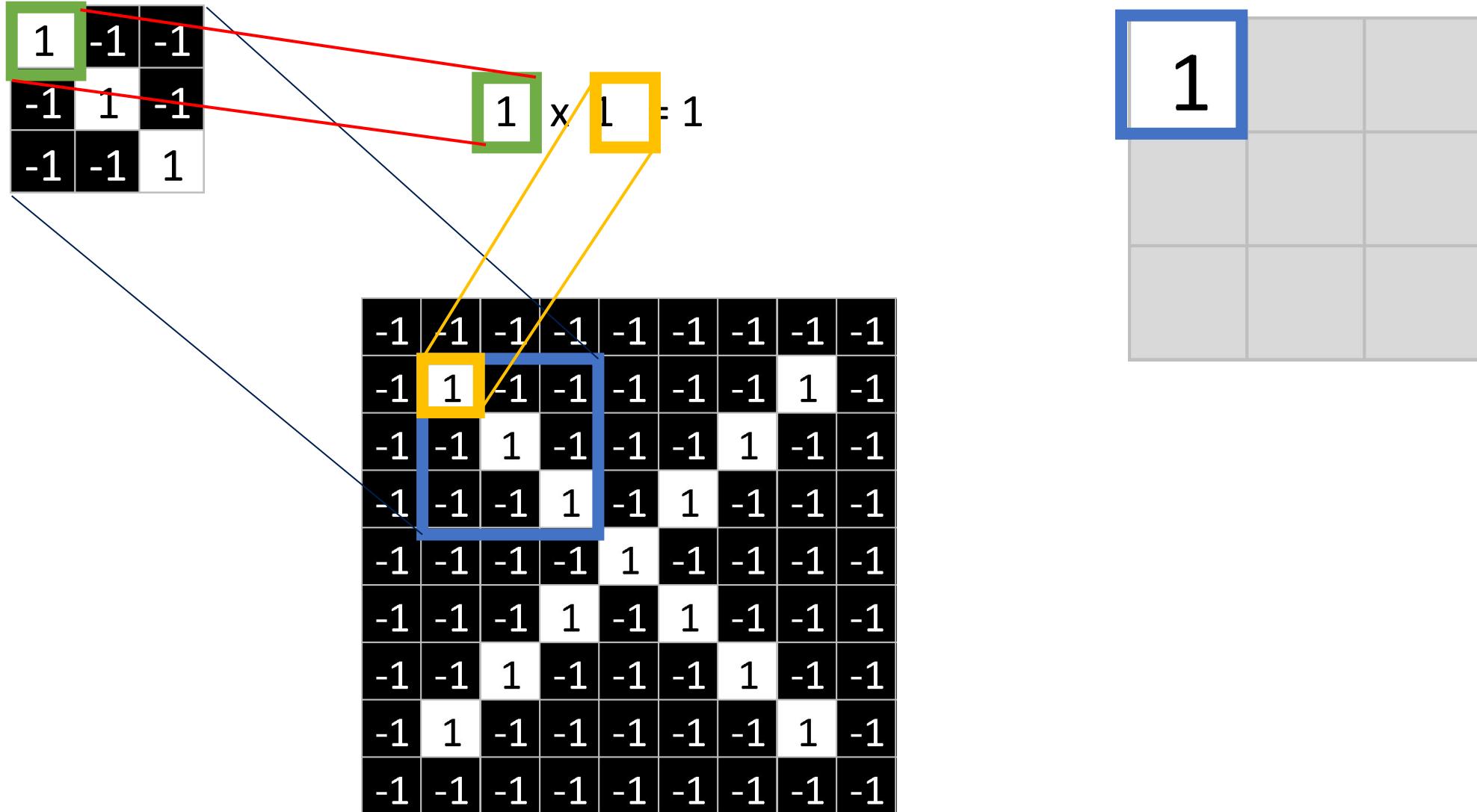


DIVIDE BY THE TOTAL NUMBER OF PIXELS IN THE FEATURE.

# Filtering: The Math Behind the Match



# Filtering: The Math Behind the Match



# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

$$-1 \times -1 = 1$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1

# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

$$-1 \times -1 = 1$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1	1

# Filtering: The Math Behind the Match

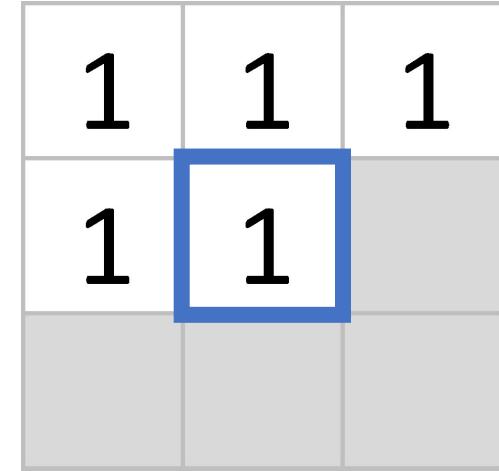
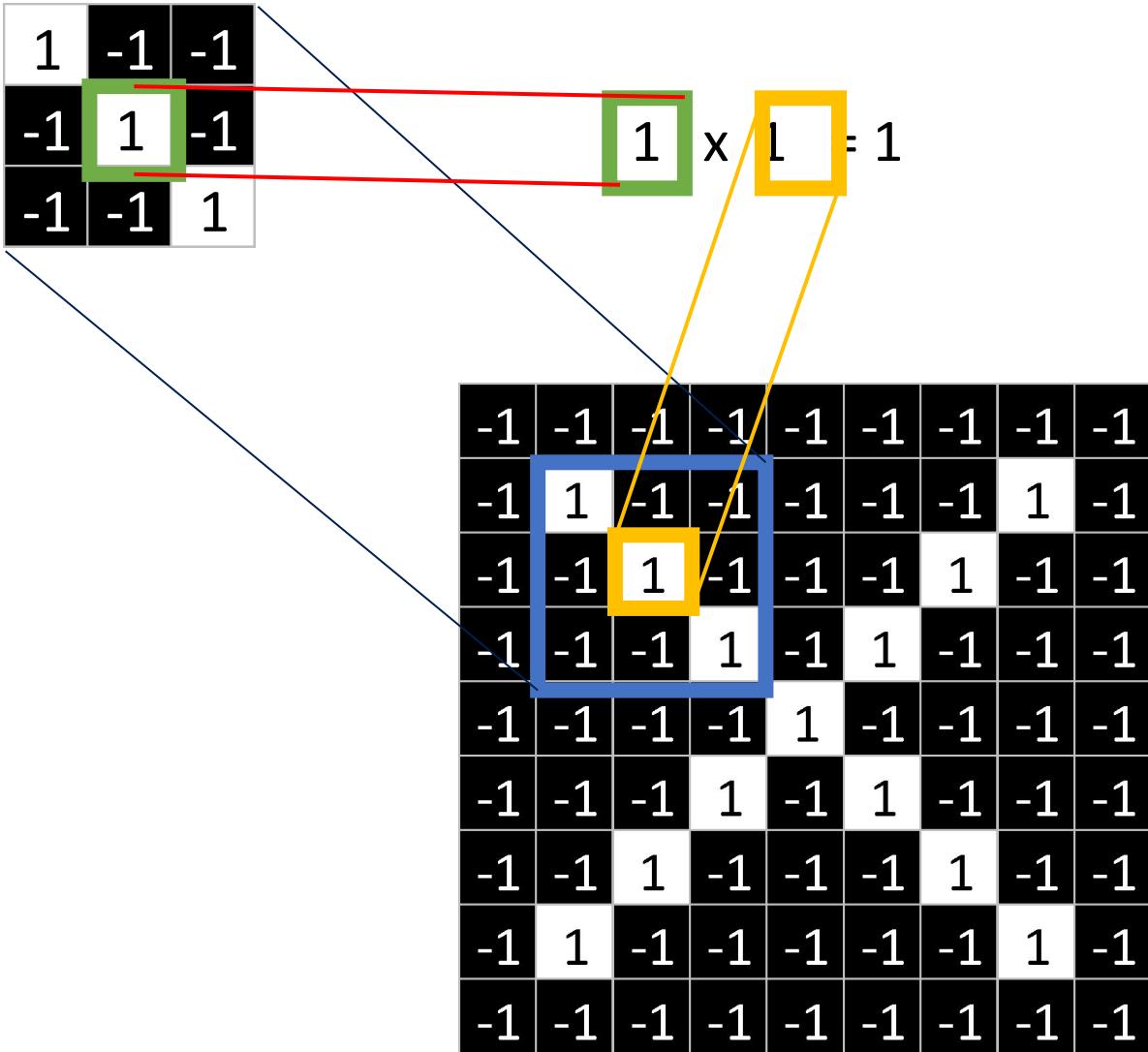
1	-1	-1
-1	1	-1
-1	-1	1

$$-1 \times -1 = 1$$

-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1	1
1		

# Filtering: The Math Behind the Match



# Filtering: The Math Behind the Match

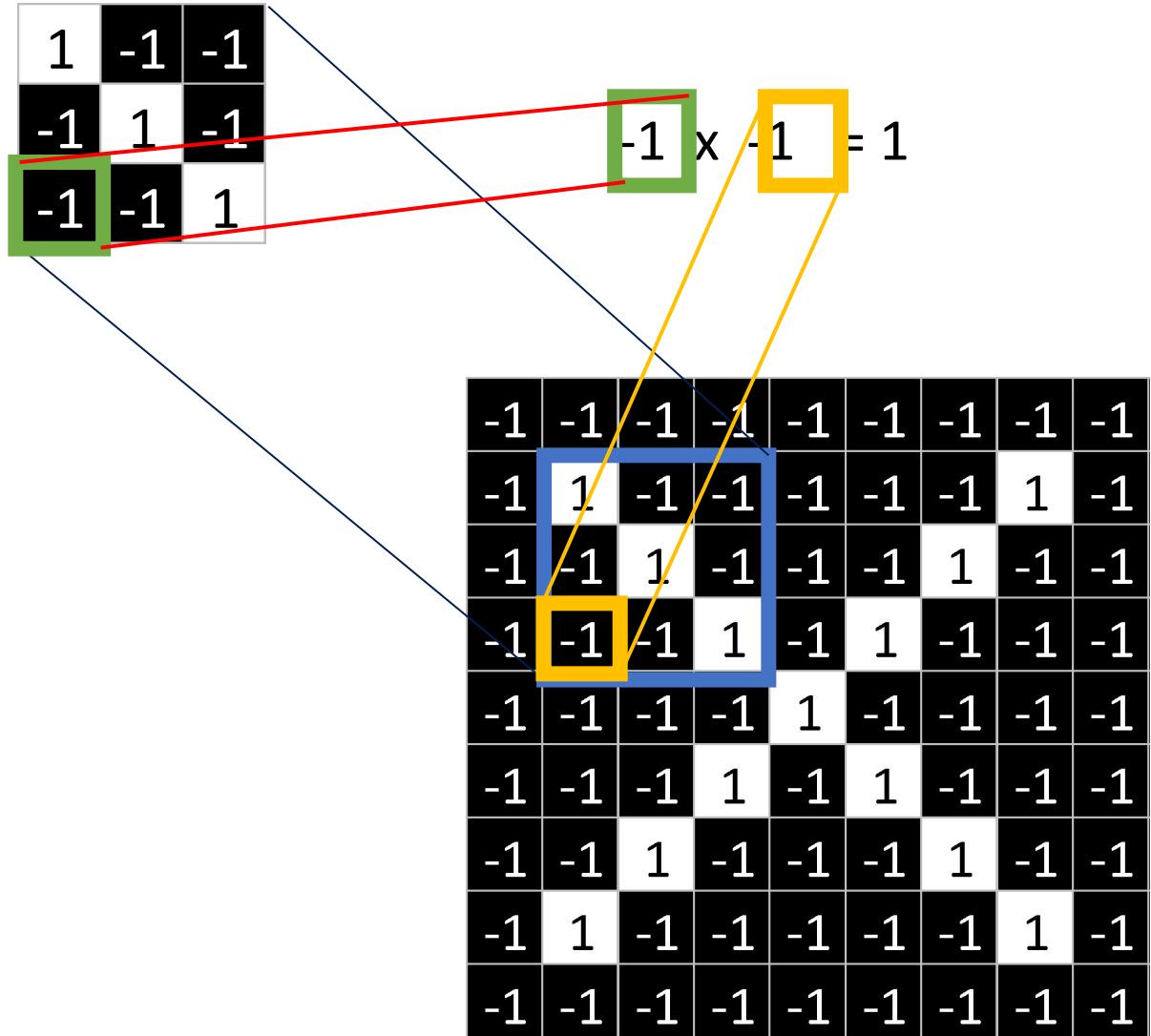
1	-1	-1
-1	1	-1
-1	-1	1

$$-1 \times -1 = 1$$

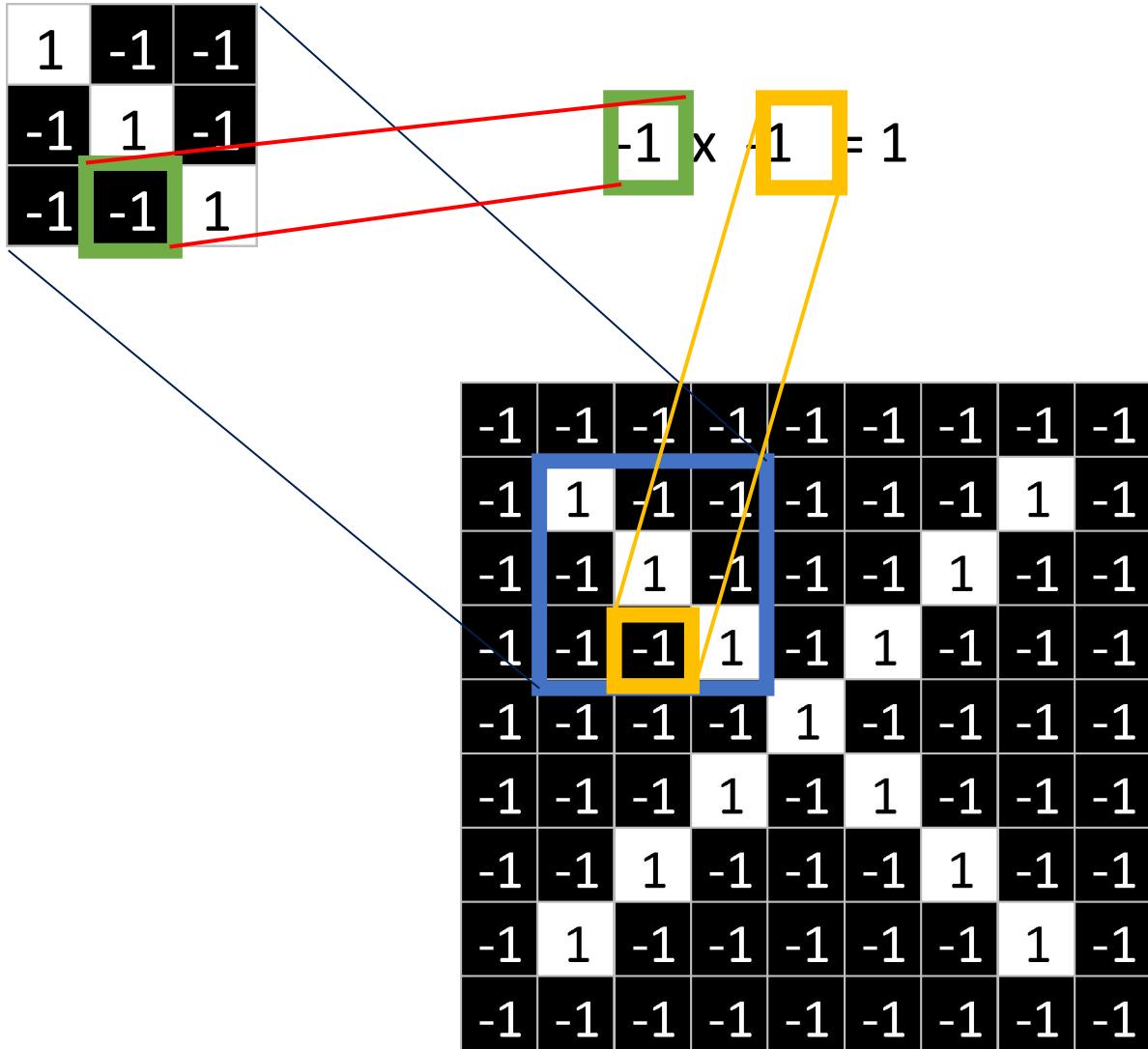
-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1	1
1	1	1
1	1	1

# Filtering: The Math Behind the Match

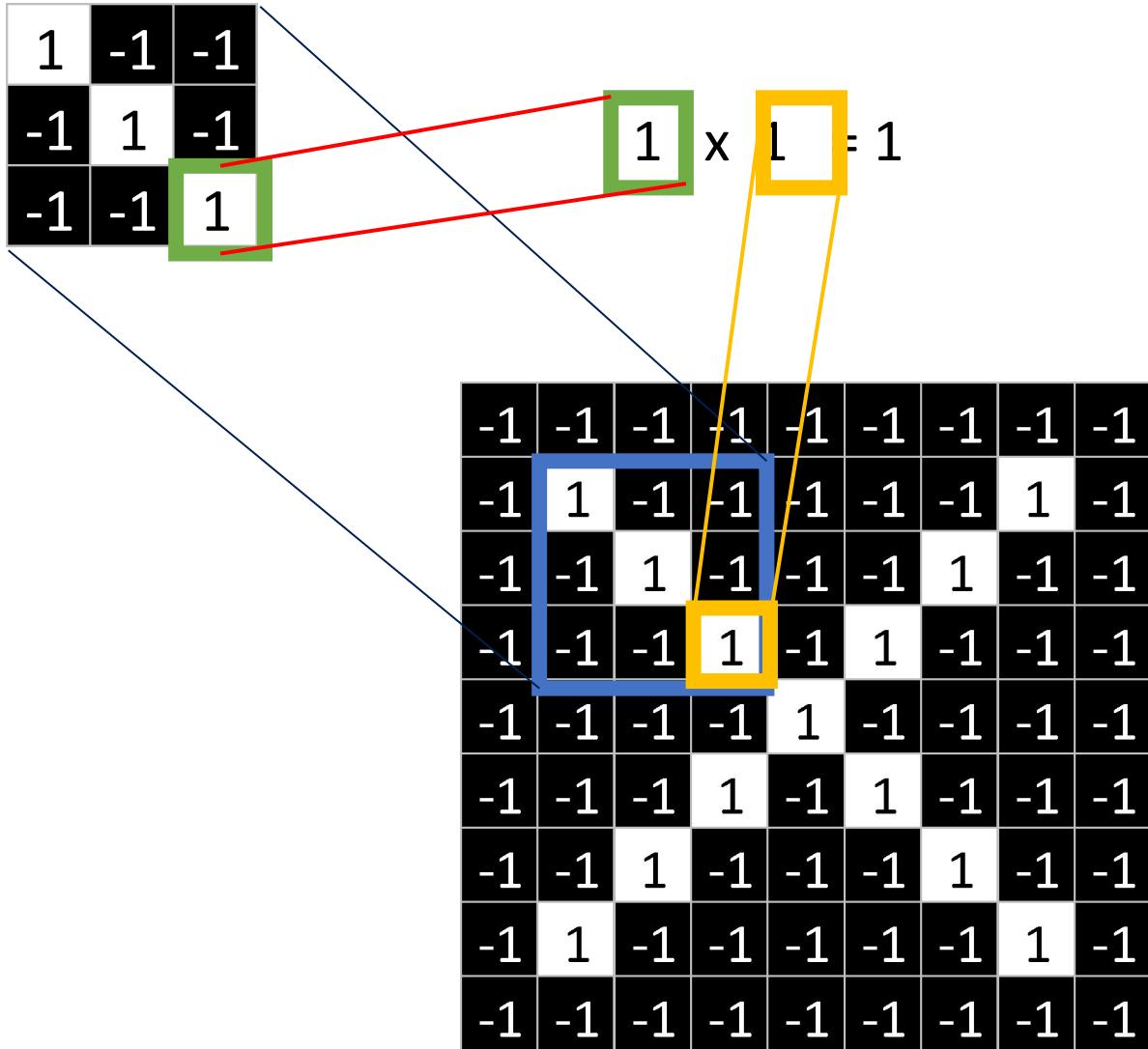


# Filtering: The Math Behind the Match



1	1	1
1	1	1
1	1	

# Filtering: The Math Behind the Match



1	1	1
1	1	1
1	1	1

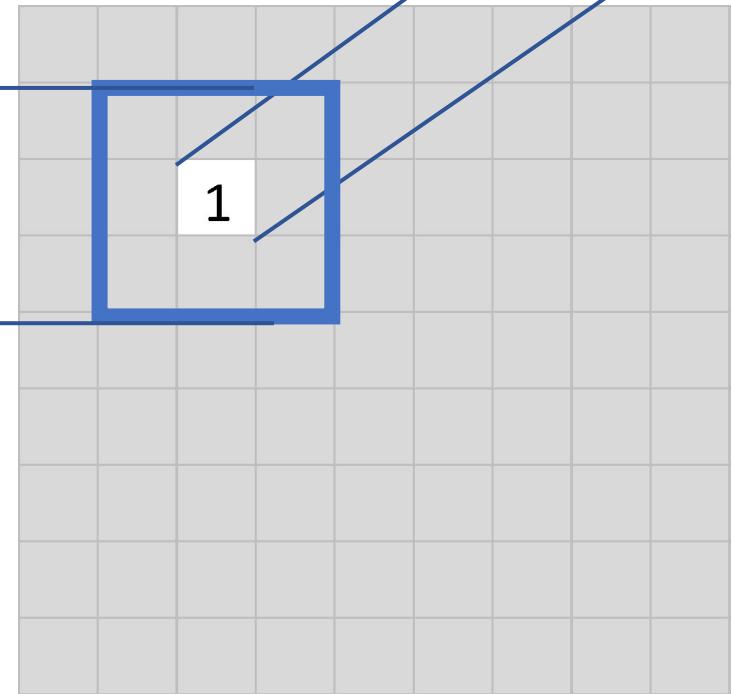
# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

1	1	1
1	1	1
1	1	1

$$\begin{array}{r} 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 \\ \hline 9 \end{array} = 1$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



# Filtering: The Math Behind the Match

$$\begin{bmatrix} 1 & -1 & -1 \\ -1 & 1 & -1 \\ -1 & -1 & 1 \end{bmatrix}$$

$$1 \times 1 = 1$$

$$\boxed{1}$$

$$\begin{bmatrix} -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ -1 & 1 & -1 & -1 & -1 & -1 & -1 & 1 & -1 \\ -1 & -1 & 1 & -1 & -1 & -1 & 1 & -1 & -1 \\ -1 & -1 & -1 & 1 & -1 & 1 & -1 & -1 & -1 \\ -1 & -1 & -1 & -1 & 1 & -1 & -1 & -1 & -1 \\ -1 & -1 & -1 & 1 & -1 & 1 & -1 & -1 & -1 \\ -1 & -1 & 1 & -1 & -1 & -1 & 1 & -1 & -1 \\ -1 & 1 & -1 & -1 & -1 & -1 & -1 & 1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix}$$

# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

$$-1 \times 1 = -1$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1	-1

# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

1	1	-1
1	1	1
-1	1	1

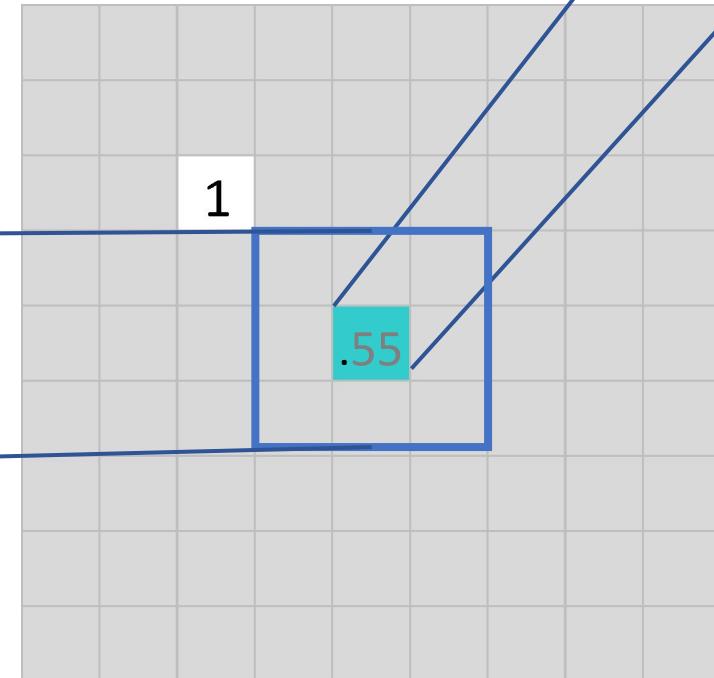
# Filtering: The Math Behind the Match

1	-1	-1
-1	1	-1
-1	-1	1

1	1	-1
1	1	1
-1	1	1

$$\frac{1 + 1 - 1 + 1 + 1 + 1 - 1 + 1}{9} = .55$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



# Convolution: Trying Every Possible Match

1	-1	-1
-1	1	-1
-1	-1	1

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

# Convolution: Trying Every Possible Match

-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	
-1	-1	1	-1	-1	-1	1	-1	-1	
-1	-1	-1	1	-1	1	-1	-1	-1	
-1	-1	-1	-1	1	-1	-1	-1	-1	
-1	-1	-1	-1	1	-1	-1	-1	-1	
-1	-1	-1	1	-1	1	-1	-1	-1	
-1	-1	1	-1	-1	-1	1	-1	-1	
-1	1	-1	-1	-1	-1	-1	1	-1	
-1	-1	-1	-1	-1	-1	-1	-1	-1	



$$\begin{matrix} 1 & -1 & -1 \\ -1 & 1 & -1 \\ -1 & -1 & 1 \end{matrix} =$$

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



1	-1	-1
-1	1	-1
-1	-1	1

=

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



1	-1	1
-1	1	-1
1	-1	1

=

0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.11	0.33	-0.77	1.00	-0.77	0.33	-0.11
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



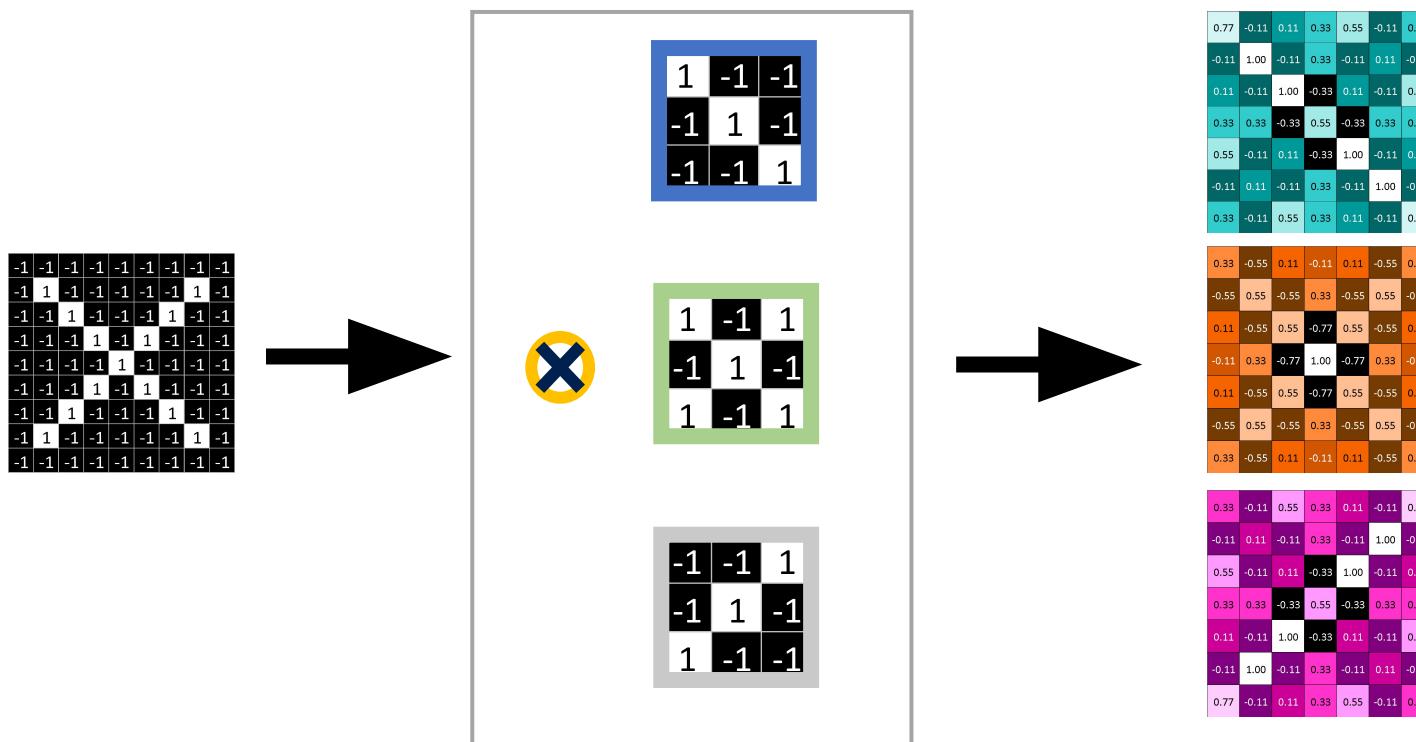
-1	-1	1
-1	1	-1
1	-1	-1

=

0.33	-0.11	0.55	0.33	0.11	-0.11	0.77
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.77	-0.11	0.11	0.33	0.55	-0.11	0.33

# Convolution Layer

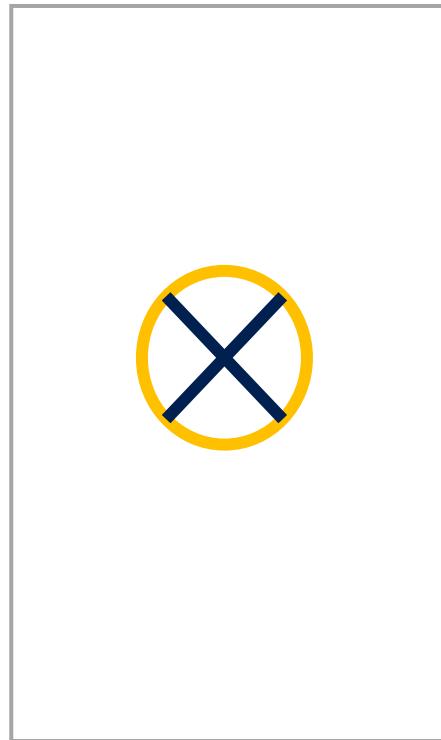
One image becomes a stack of filtered images



# Convolution Layer

One image becomes a stack of filtered images

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	-1	1	-1	-1	-1
-1	-1	-1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	1	-1	-1
-1	-1	-1	-1	-1	-1	-1	1	-1

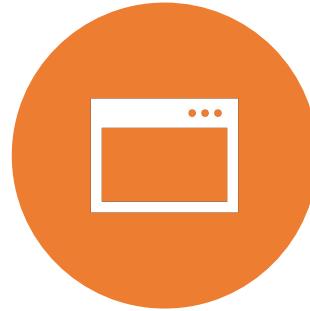


0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.11	0.33	-0.77	1.00	-0.77	0.33	-0.11
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33

0.33	-0.11	0.55	0.33	0.11	-0.11	0.77
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.77	-0.11	0.11	0.33	0.55	-0.11	0.33

# Pooling: Shrinking the Image Stack



PICK A WINDOW SIZE  
(USUALLY 2 OR 3).



PICK A STRIDE (USUALLY 2).

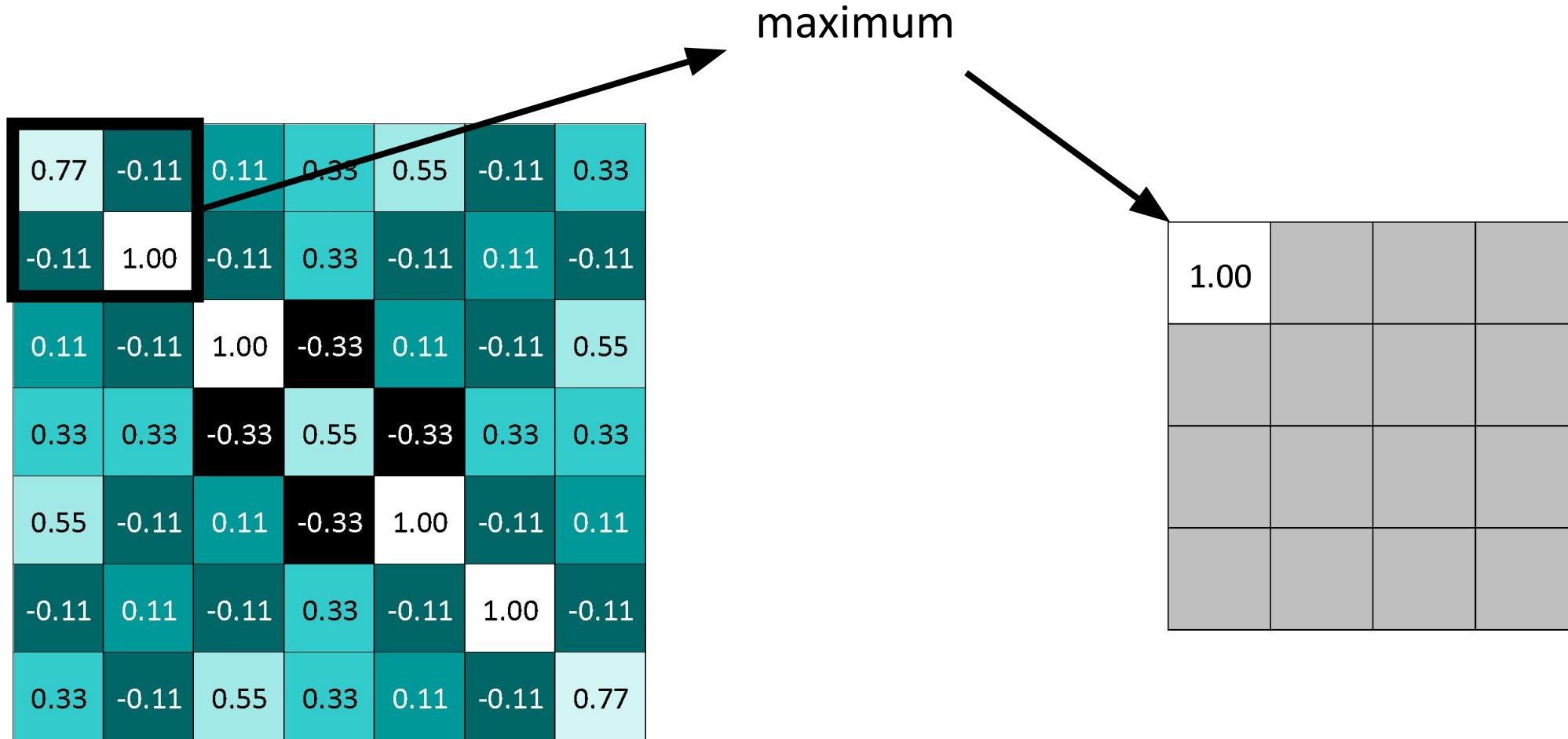


WALK YOUR WINDOW  
ACROSS YOUR FILTERED  
IMAGES.

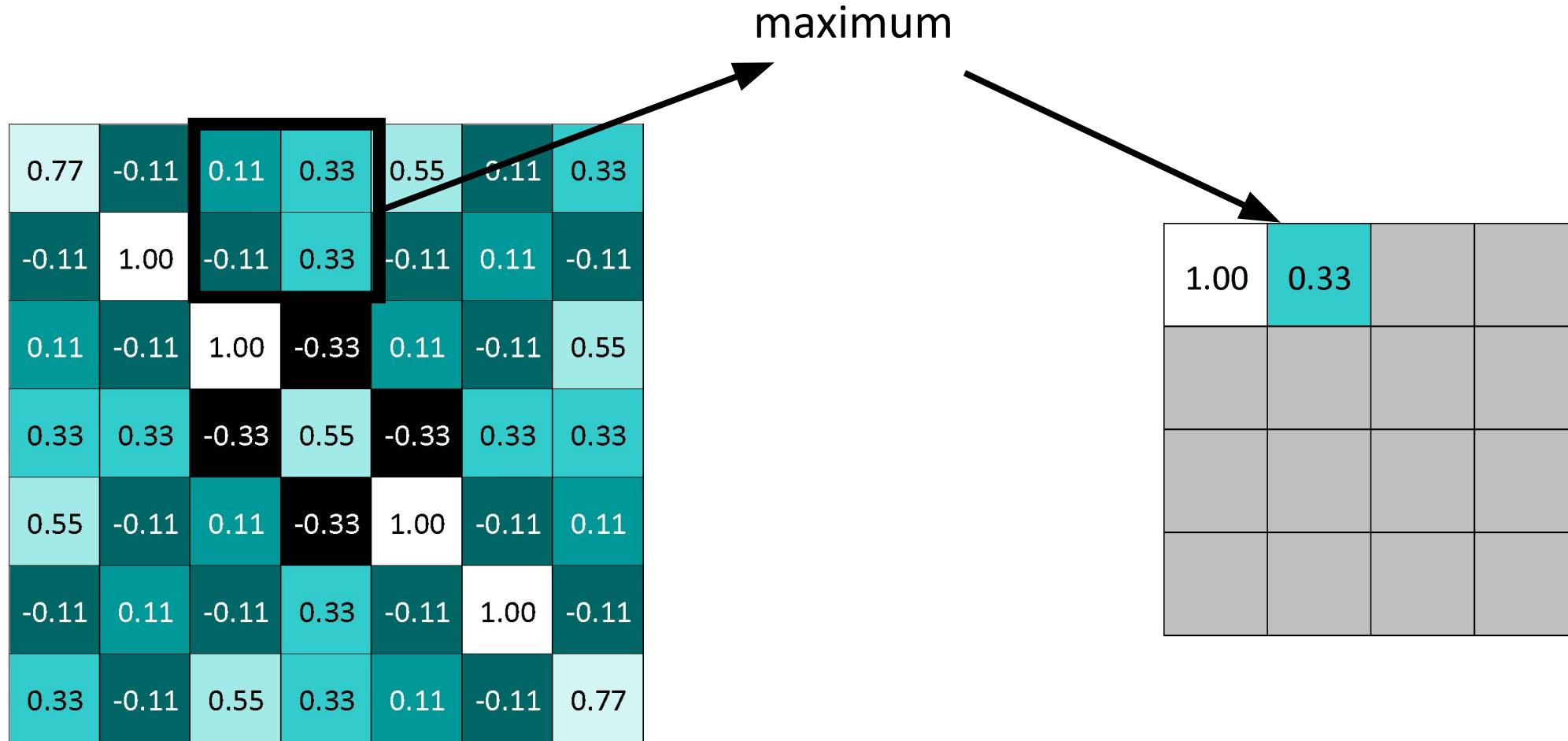


FROM EACH WINDOW,  
TAKE THE MAXIMUM  
VALUE.

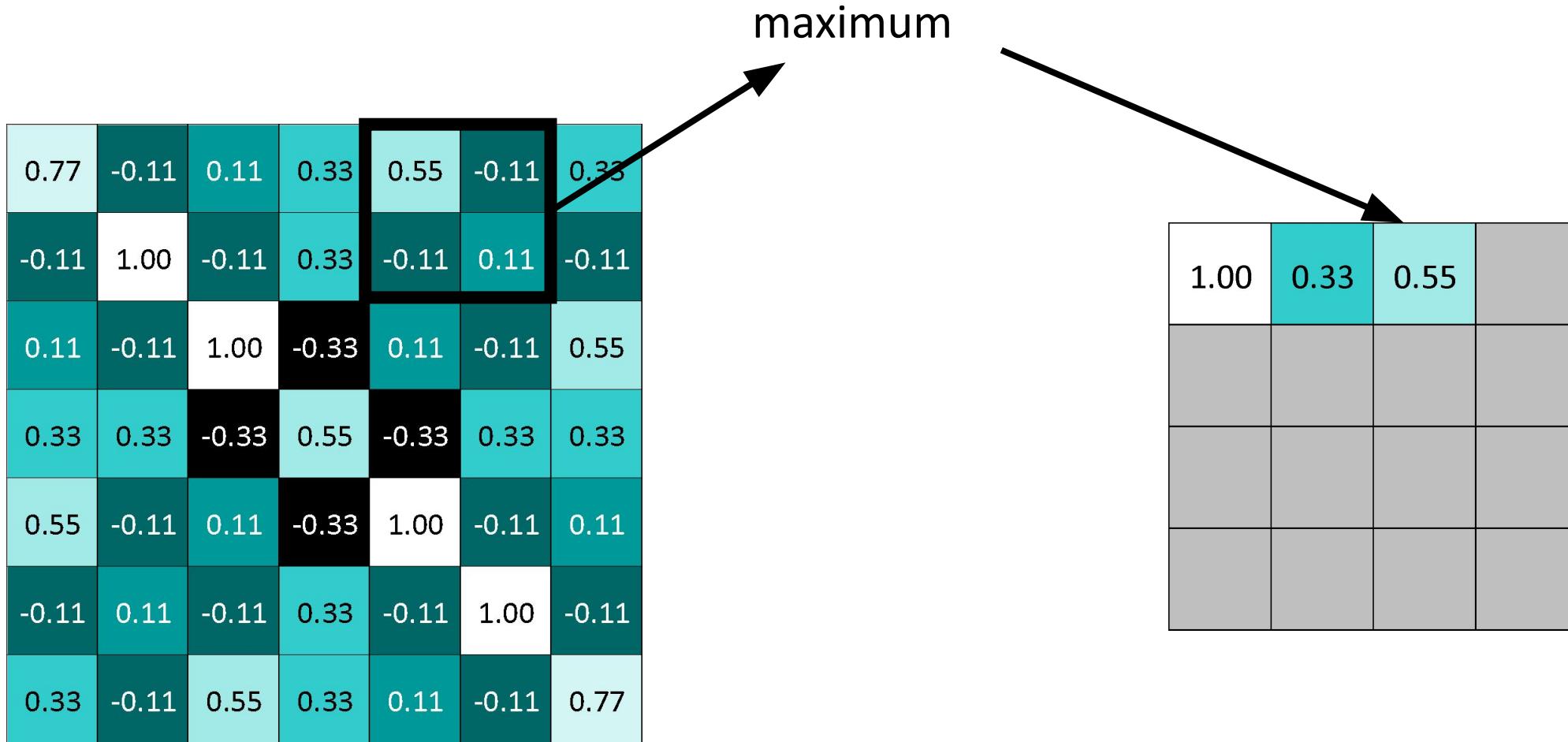
# Pooling



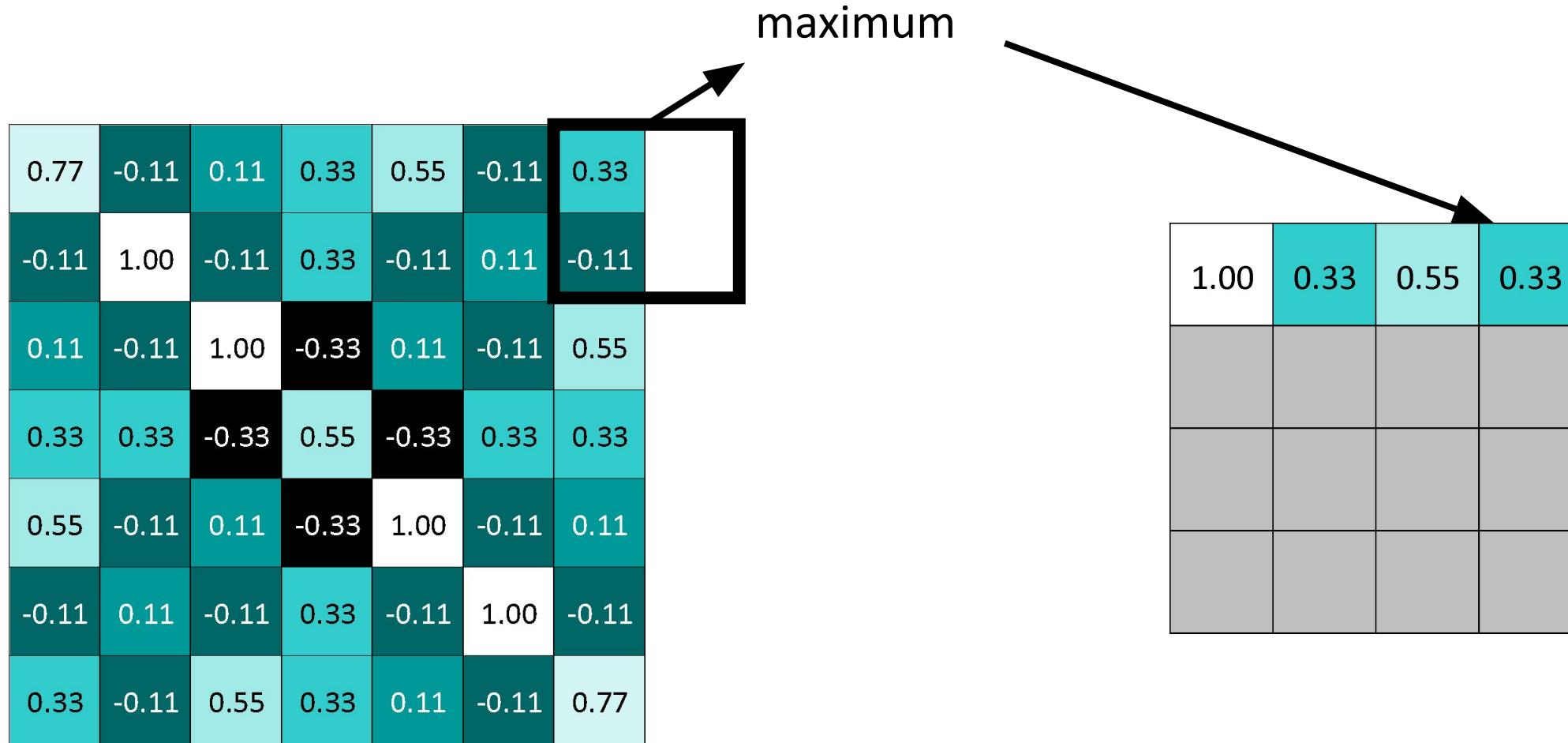
# Pooling



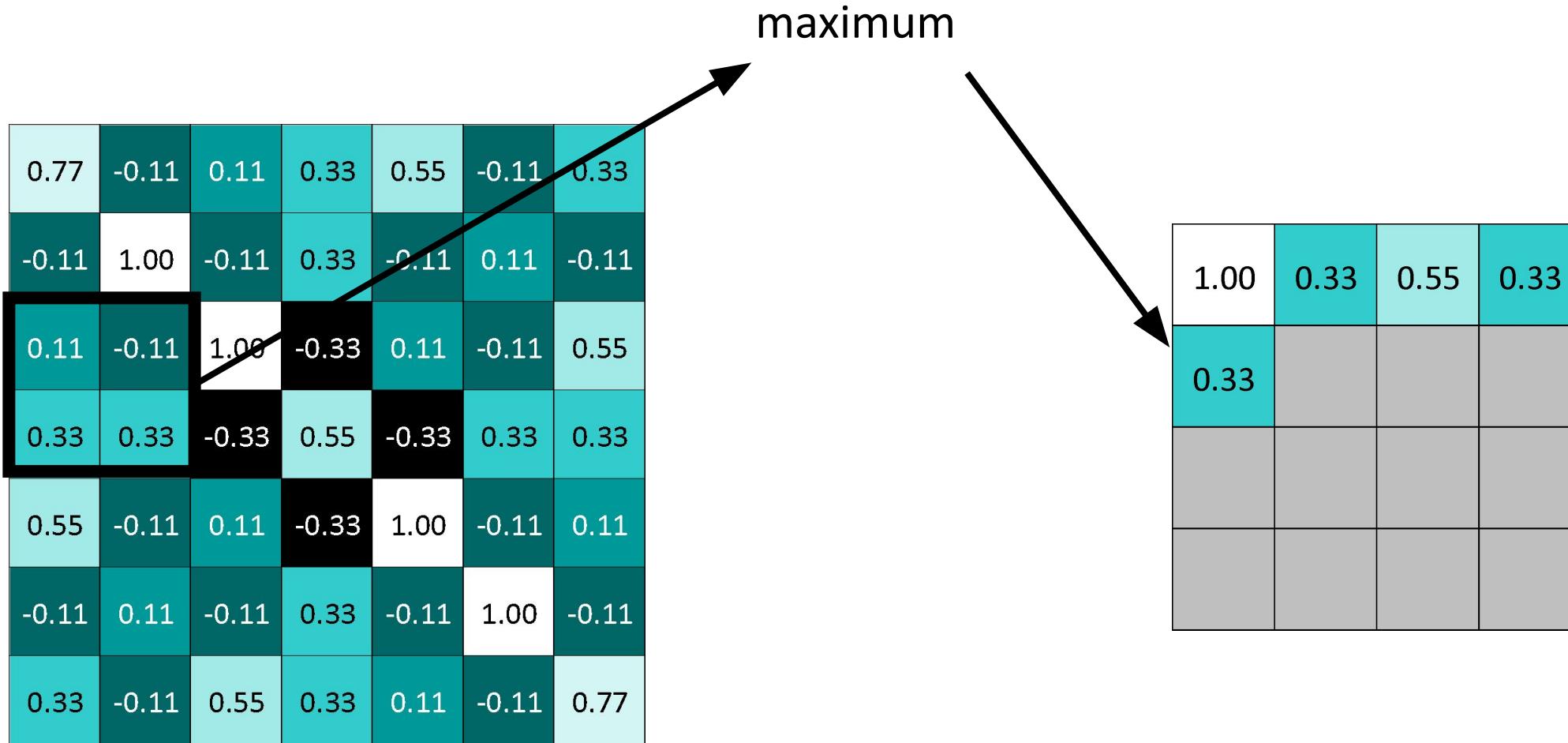
# Pooling



# Pooling



# Pooling



# Pooling

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

max pooling



1.00	0.33	0.55	0.33
0.33	1.00	0.33	0.55
0.55	0.33	1.00	0.11
0.33	0.55	0.11	0.77

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77



1.00	0.33	0.55	0.33
0.33	1.00	0.33	0.55
0.55	0.33	1.00	0.11
0.33	0.55	0.11	0.77

0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.11	0.33	-0.77	1.00	-0.77	0.33	-0.11
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33



0.55	0.33	0.55	0.33
0.33	1.00	0.55	0.11
0.55	0.55	0.55	0.11
0.33	0.11	0.11	0.33

0.33	-0.11	0.55	0.33	0.11	-0.11	0.77
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.77	-0.11	0.11	0.33	0.55	-0.11	0.33



0.33	0.55	1.00	0.77
0.55	0.55	1.00	0.33
1.00	1.00	0.11	0.55
0.77	0.33	0.55	0.33

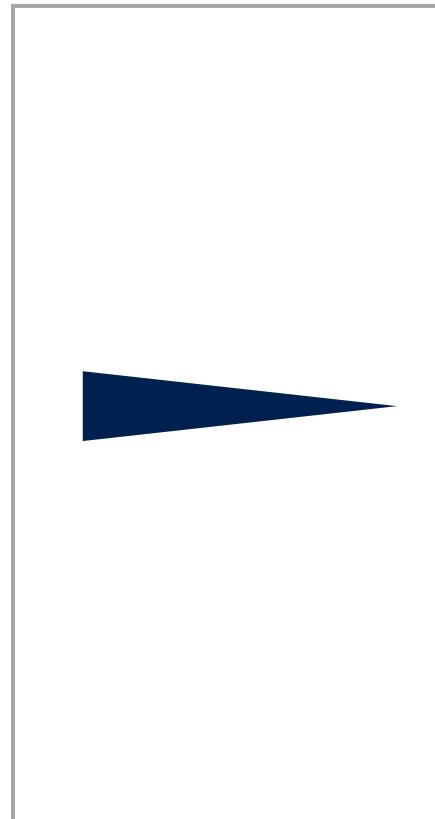
# Pooling Layer

A stack of images becomes a stack of smaller images.

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.11	0.33	-0.77	1.00	-0.77	0.33	-0.11
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33

0.33	-0.11	0.55	0.33	0.11	-0.11	0.77
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.77	-0.11	0.11	0.33	0.55	-0.11	0.33



1.00	0.33	0.55	0.33
0.33	1.00	0.33	0.55
0.55	0.33	1.00	0.11
0.33	0.55	0.11	0.77

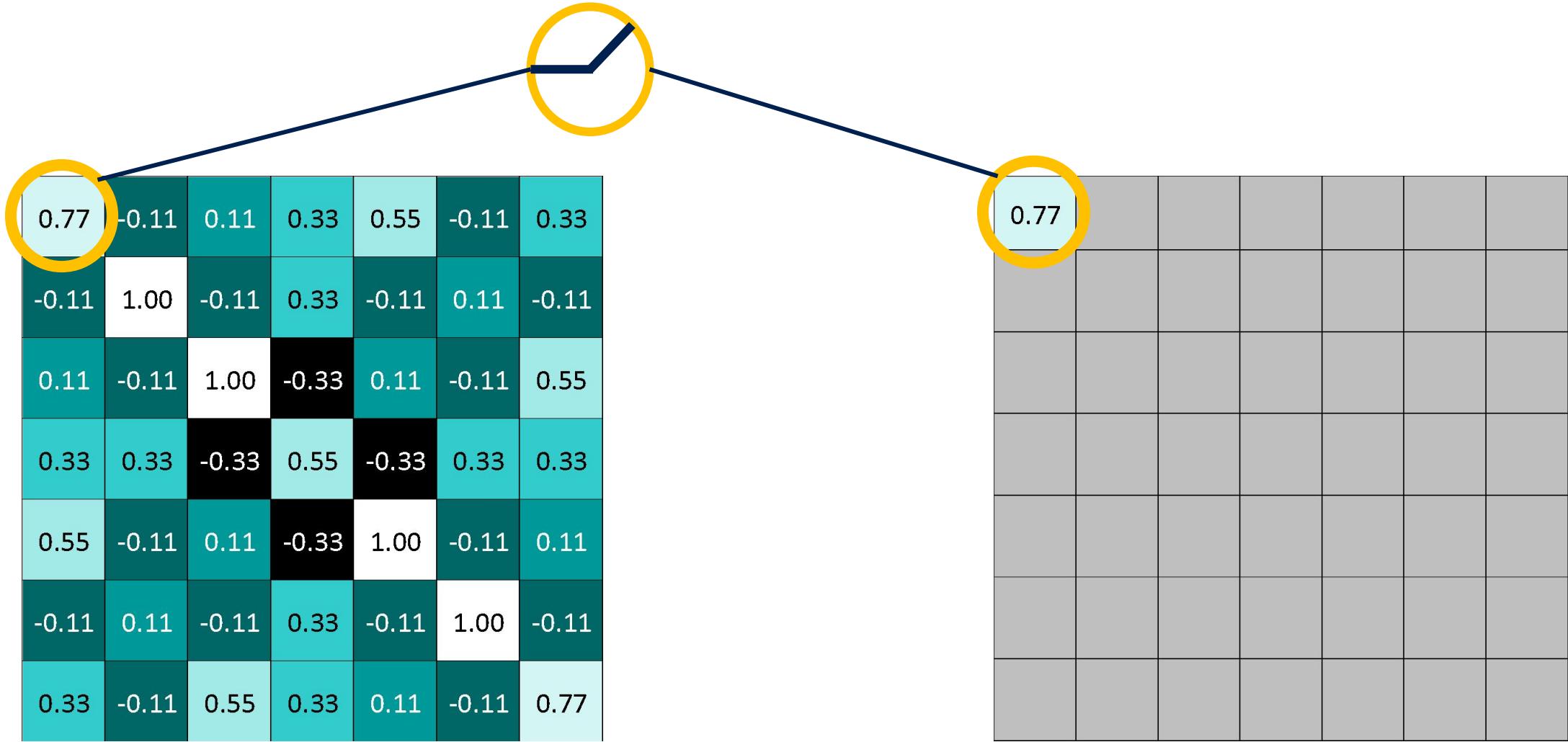
0.55	0.33	0.55	0.33
0.33	1.00	0.55	0.11
0.55	0.55	0.55	0.11
0.33	0.11	0.11	0.33

0.33	0.55	1.00	0.77
0.55	0.55	1.00	0.33
1.00	1.00	0.11	0.55
0.77	0.33	0.55	0.33

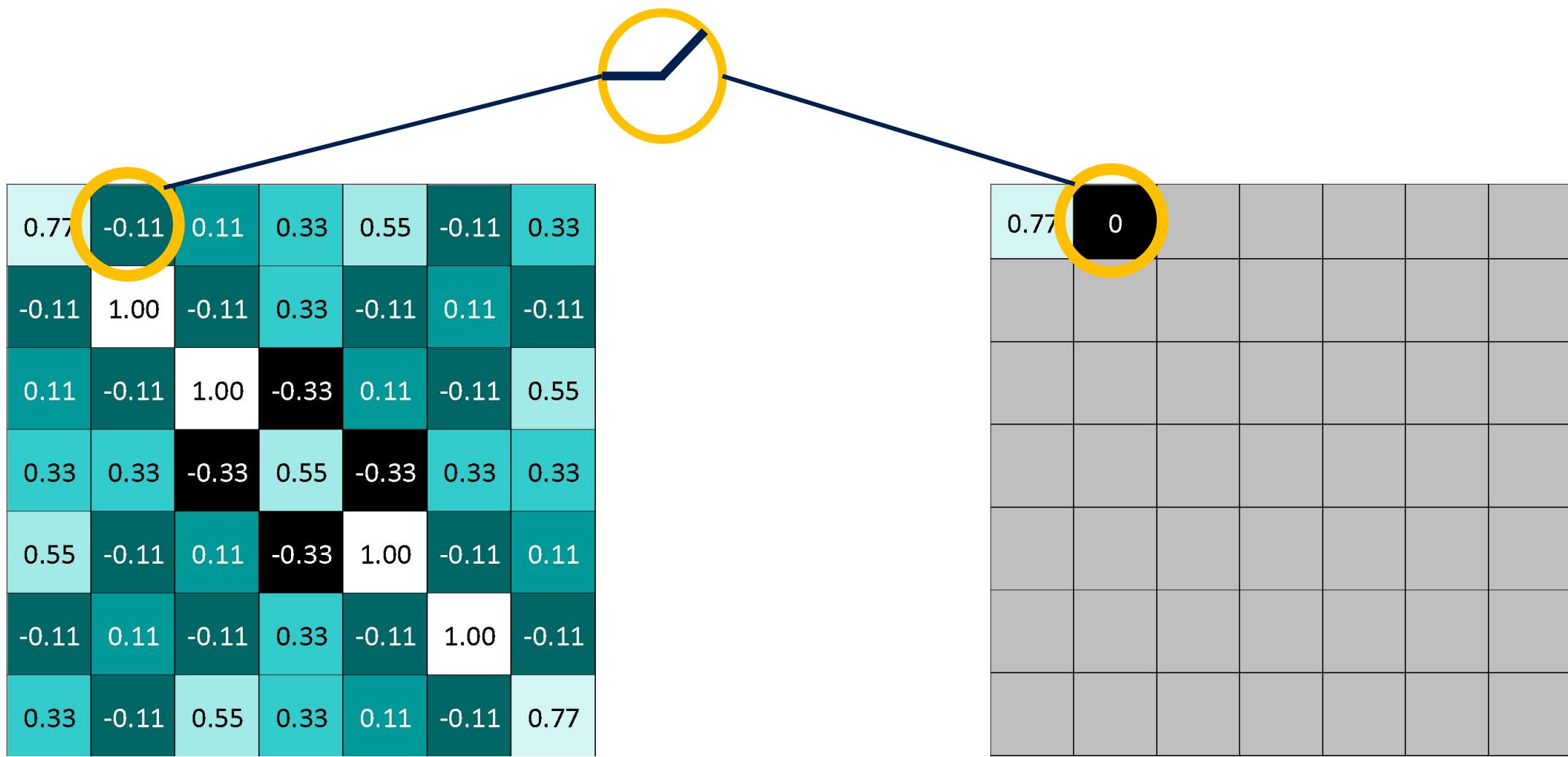
## Normalization

- Keep the math from breaking by tweaking each of the values just a bit.
- Change everything negative to zero.

# Rectified Linear Units (ReLUs)

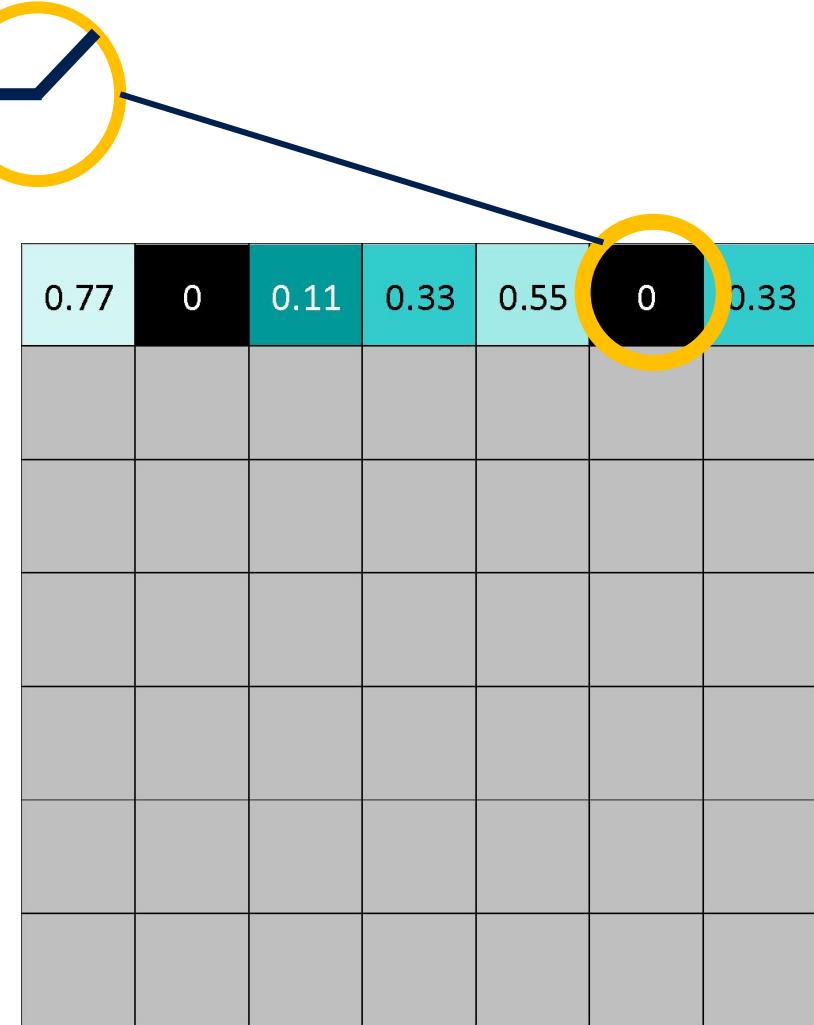


# Rectified Linear Units (ReLUs)



# Rectified Linear Units (ReLUs)

0.77	-0.11	0.11	0.33	0.55	<b>-0.11</b>	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77



# Rectified Linear Units (ReLUs)

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33	
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11	
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55	
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33	
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11	
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11	
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77	



0.77	0	0.11	0.33	0.55	0	0.33	
0	1.00	0	0.33	0	0.11	0	
0.11	0	1.00	0	0.11	0	0.55	
0.33	0.33	0	0.55	0	0.33	0.33	
0.55	0	0.11	0	1.00	0	0.11	
0	0.11	0	0.33	0	1.00	0	
0.33	0	0.55	0.33	0.11	0	0.77	

# ReLU Layer

A stack of images becomes a stack of images with no negative values.

0.77	-0.11	0.11	0.33	0.55	-0.11	0.33
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.33	-0.11	0.55	0.33	0.11	-0.11	0.77

0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.11	0.33	-0.77	1.00	-0.77	0.33	-0.11
0.11	-0.55	0.55	-0.77	0.55	-0.55	0.11
-0.55	0.55	-0.55	0.33	-0.55	0.55	-0.55
0.33	-0.55	0.11	-0.11	0.11	-0.55	0.33

0.33	-0.11	0.55	0.33	0.11	-0.11	0.77
-0.11	0.11	-0.11	0.33	-0.11	1.00	-0.11
0.55	-0.11	0.11	-0.33	1.00	-0.11	0.11
0.33	0.33	-0.33	0.55	-0.33	0.33	0.33
0.11	-0.11	1.00	-0.33	0.11	-0.11	0.55
-0.11	1.00	-0.11	0.33	-0.11	0.11	-0.11
0.77	-0.11	0.11	0.33	0.55	-0.11	0.33



0.77	0	0.11	0.33	0.55	0	0.33
0	1.00	0	0.33	0	0.11	0
0.11	0	1.00	0	0.11	0	0.55
0.33	0.33	0	0.55	0	0.33	0.33
0.55	0	0.11	0	1.00	0	0.11
0	0.11	0	0.33	0	1.00	0
0.33	0	0.55	0.33	0.11	0	0.77

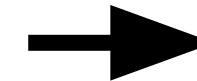
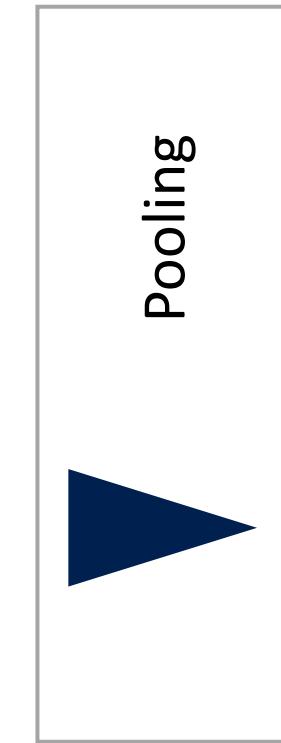
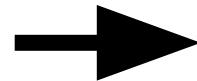
0.33	0	0.11	0	0.11	0	0.33
0	0.55	0	0.33	0	0.55	0
0.11	0	0.55	0	0.55	0	0.11
0	0.33	0	1.00	0	0.33	0
0.11	0	0.55	0	0.55	0	0.11
0	0.55	0	0.33	0	0.55	0
0.33	0	0.11	0	0.11	0	0.33

0.33	0	0.55	0.33	0.11	0	0.77
0	0.11	0	0.33	0	1.00	0
0.55	0	0.11	0	1.00	0	0.11
0.33	0.33	0	0.55	0	0.33	0.33
0.11	0	1.00	0	0.11	0	0.55
0	1.00	0	0.33	0	0.11	0
0.77	0	0.11	0.33	0.55	0	0.33

# Layers get stacked

The output of one becomes the input of the next.

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	1	1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1



1.00	0.33	0.55	0.33
0.33	1.00	0.33	0.55
0.55	0.33	1.00	0.11
0.33	0.55	0.11	0.77

0.55	0.33	0.55	0.33
0.33	1.00	0.55	0.11
0.55	0.55	0.55	0.11
0.33	0.11	0.11	0.33

0.33	0.55	1.00	0.77
0.55	0.55	1.00	0.33
1.00	1.00	0.11	0.55
0.77	0.33	0.55	0.33

# Deep stacking

Layers can be repeated several (or many) times.

-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	
-1	-1	1	-1	-1	-1	1	-1	-1	
-1	-1	-1	1	1	-1	1	-1	-1	
-1	-1	-1	-1	1	-1	-1	-1	-1	
-1	-1	-1	-1	1	-1	-1	-1	-1	
-1	-1	-1	1	-1	1	-1	-1	-1	
-1	-1	1	-1	-1	-1	1	-1	-1	
-1	1	-1	-1	-1	-1	-1	1	-1	
-1	-1	-1	-1	-1	-1	-1	-1	-1	



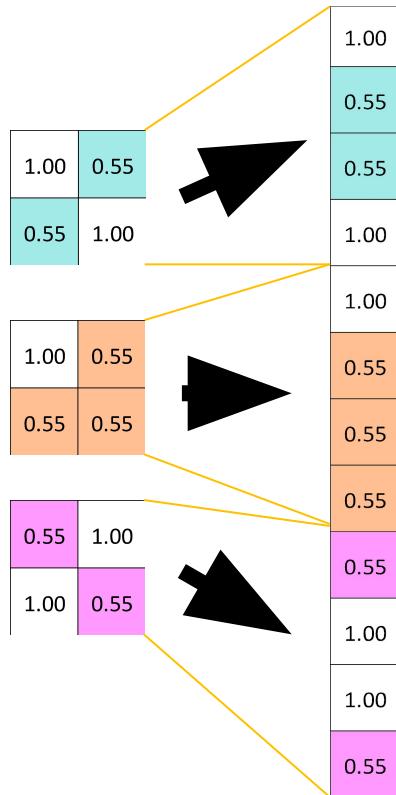
1.00	0.55
0.55	1.00

1.00	0.55
0.55	0.55

0.55	1.00
1.00	0.55

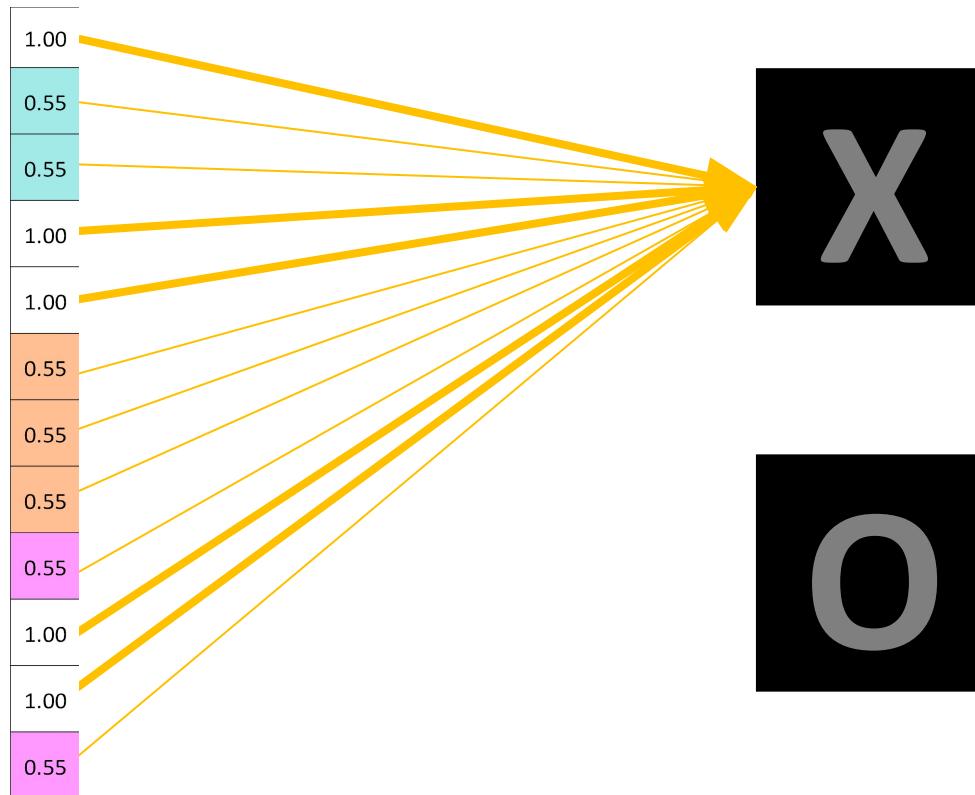
# Fully Connected Layer

Every value gets a vote



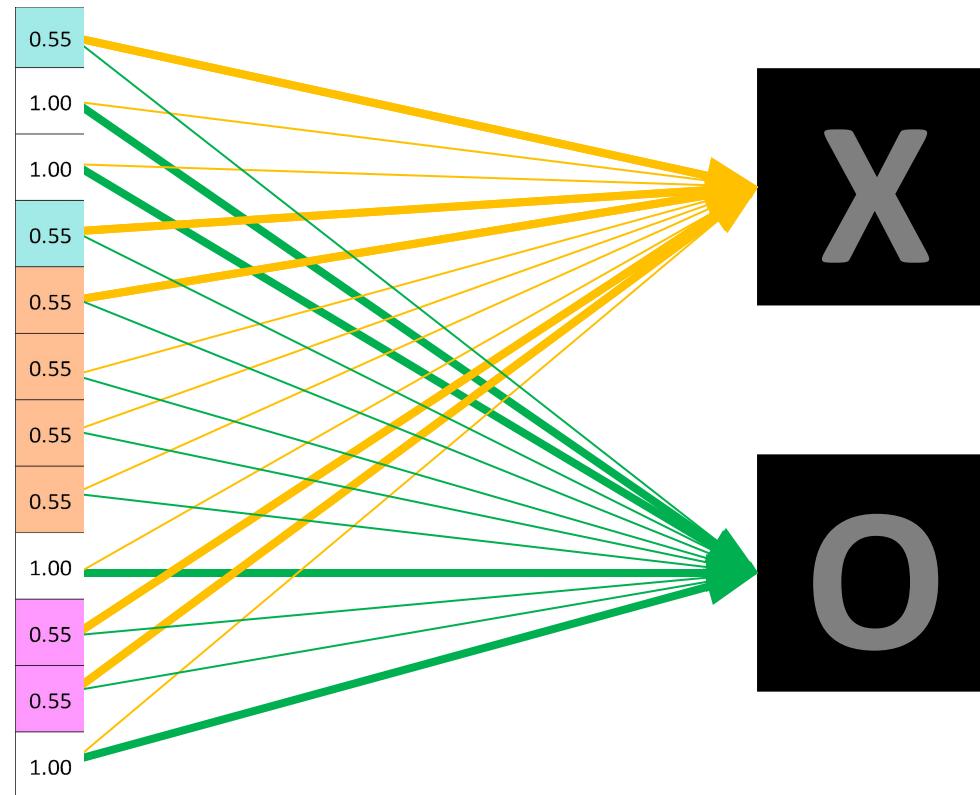
# Fully Connected Layer

Vote depends on how strongly a value predicts X or O



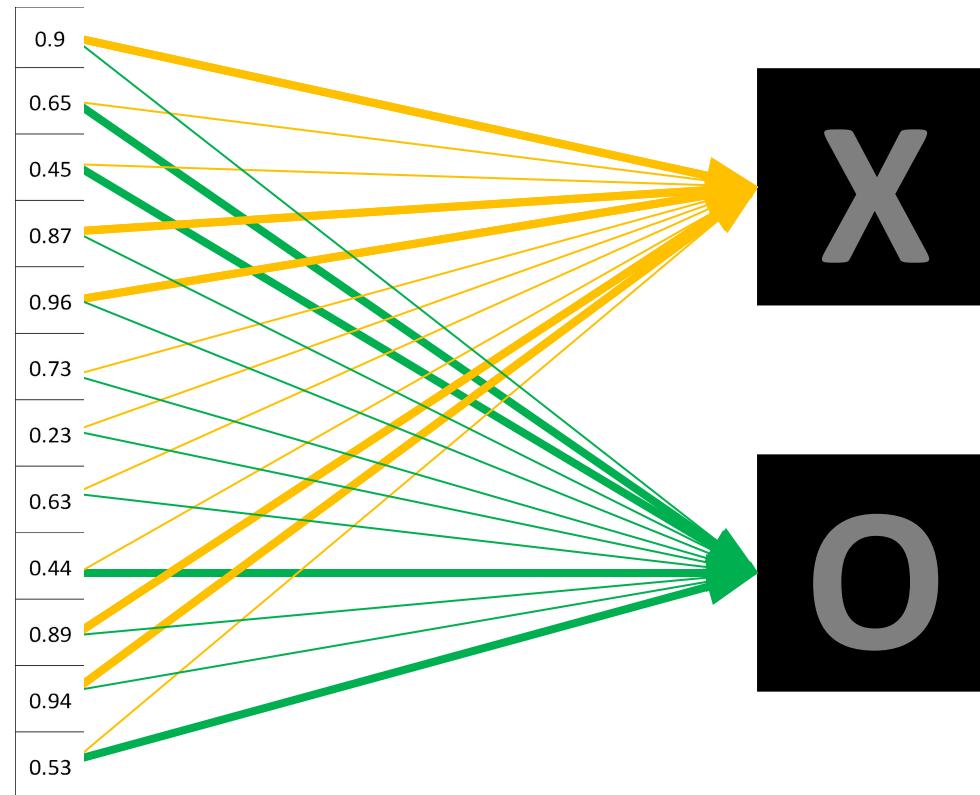
# Fully Connected Layer

Vote depends on how strongly a value predicts X or O



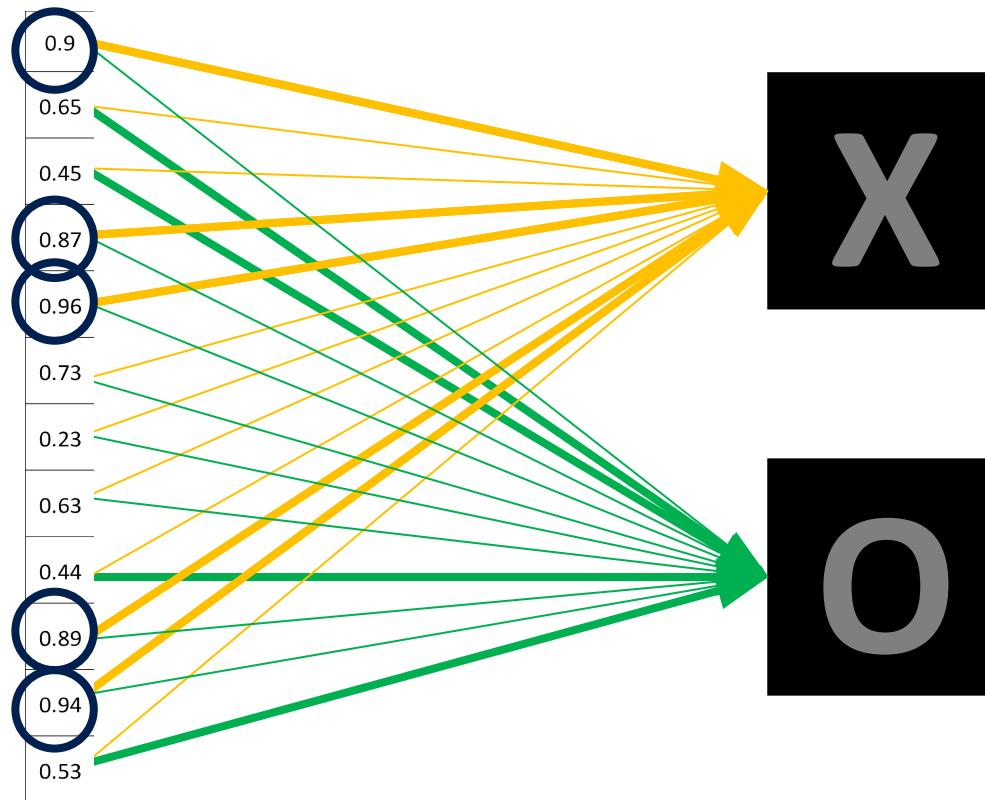
# Fully Connected Layer

Future values vote on X or O



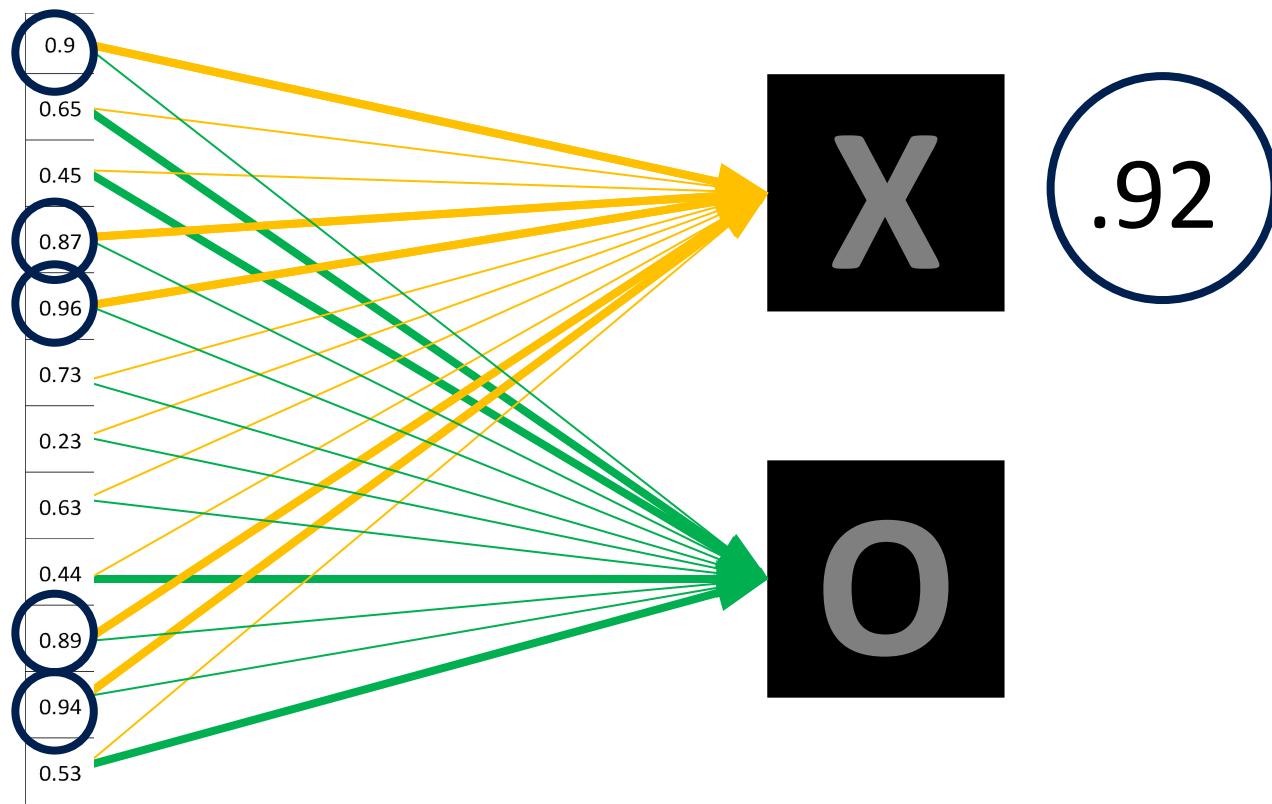
# Fully Connected Layer

Future values vote on X or O



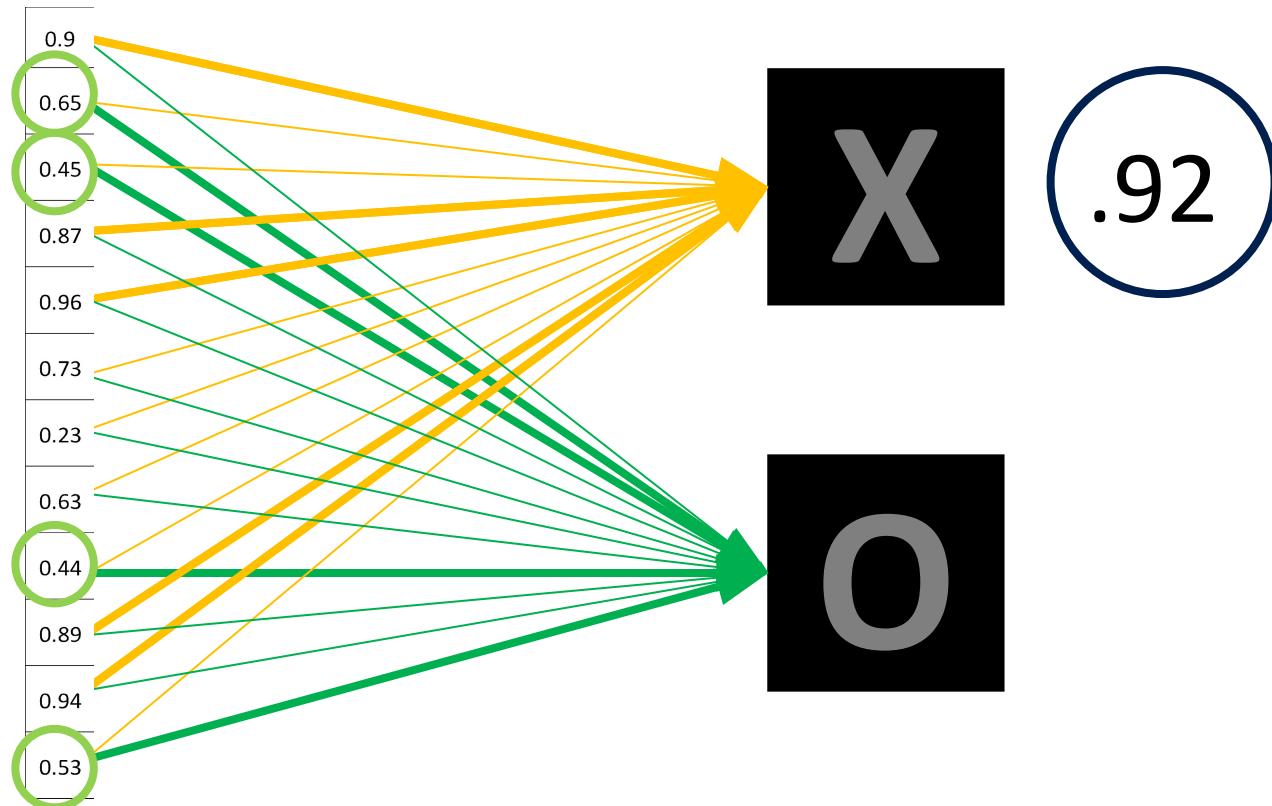
# Fully Connected Layer

Future values vote on X or O



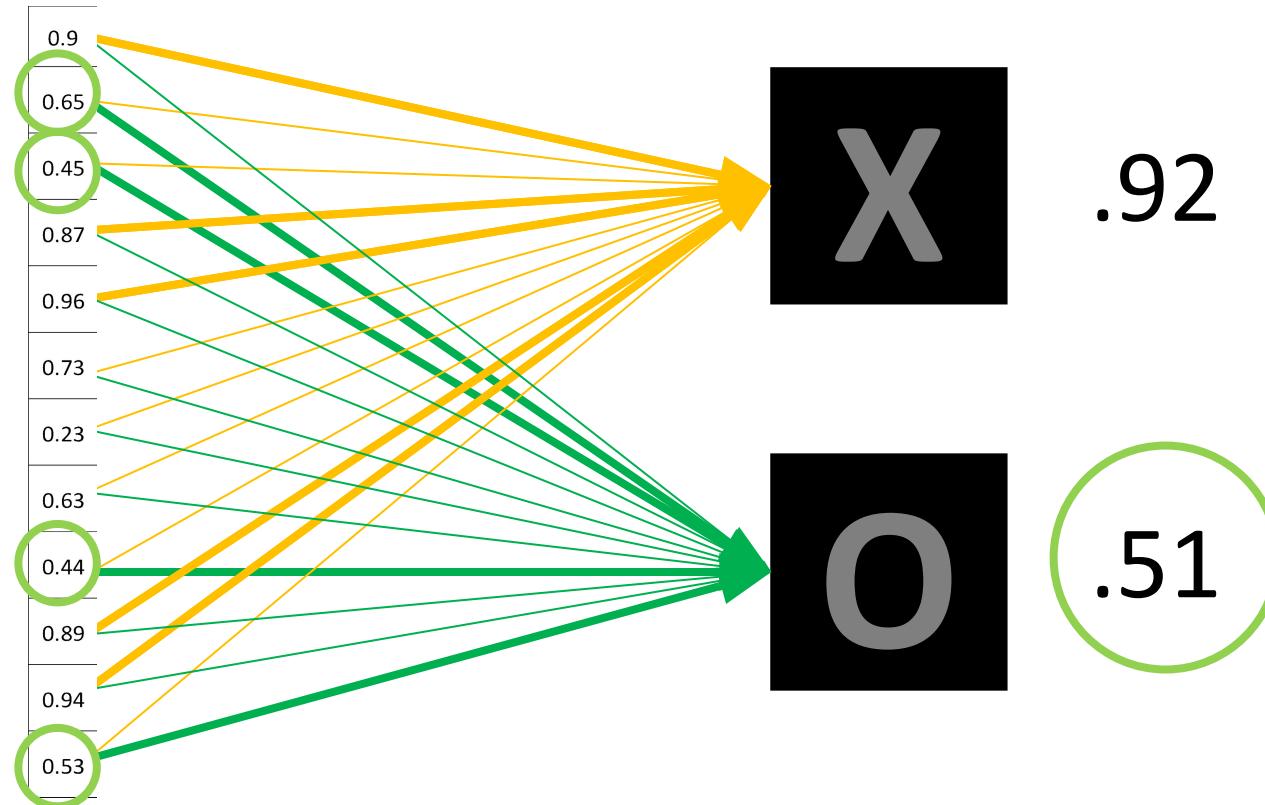
# Fully Connected Layer

Future values vote on X or O



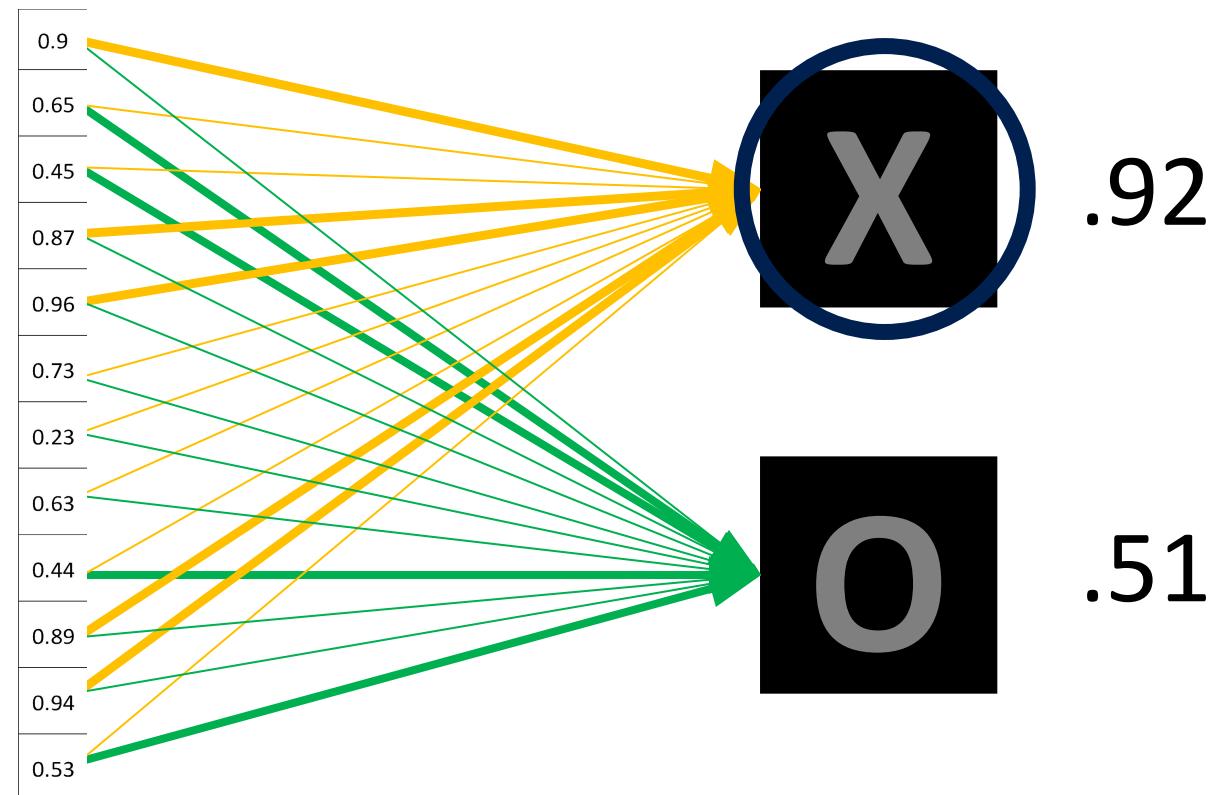
# Fully Connected Layer

Future values vote on X or O



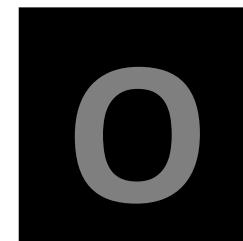
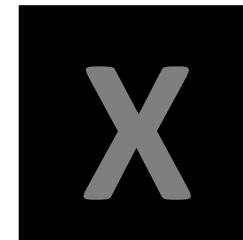
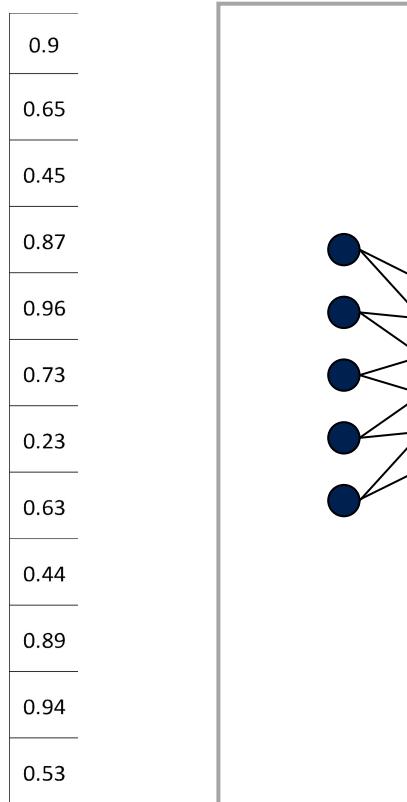
# Fully Connected Layer

Future values vote on X or O



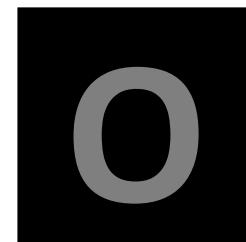
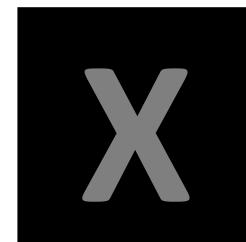
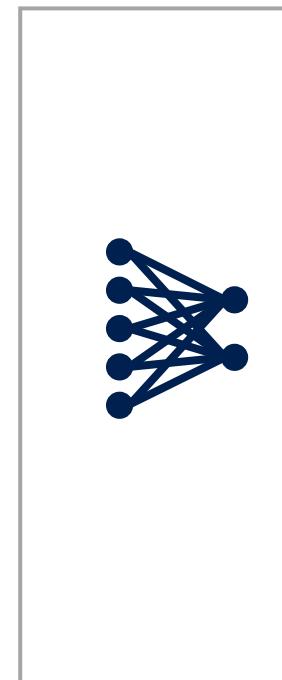
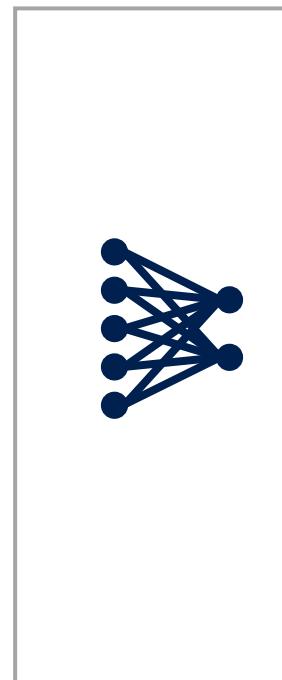
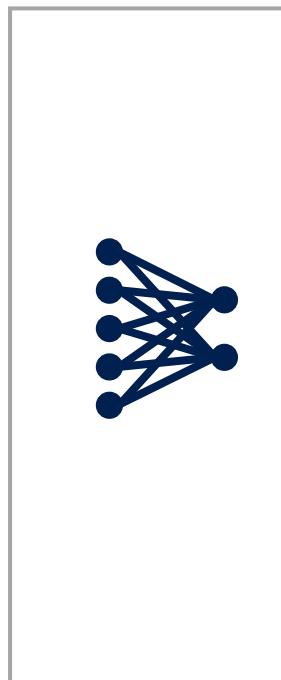
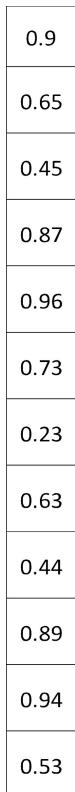
# Fully Connected Layer

A list of feature values becomes a list of votes.



# Fully Connected Layer

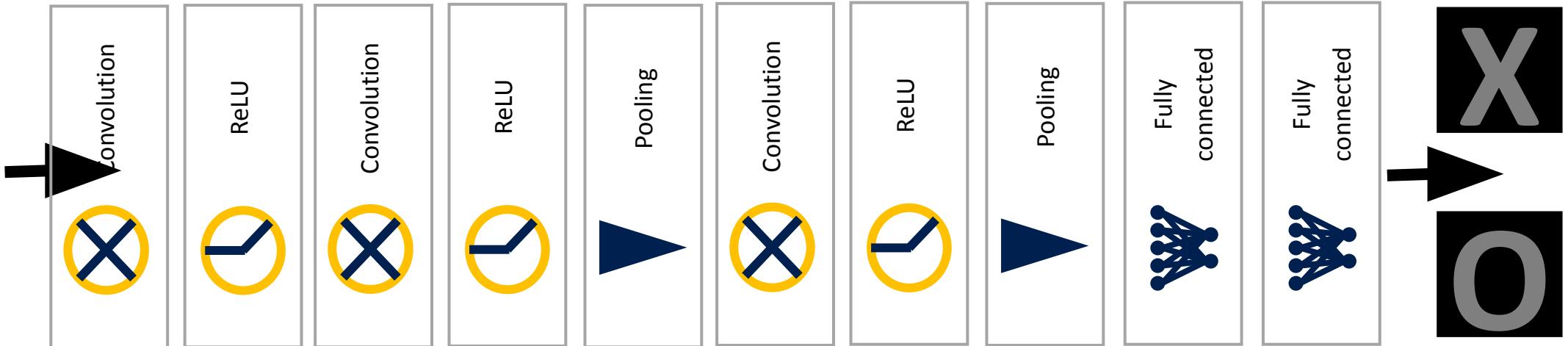
These can also be stacked.



# Putting it All Together

A set of pixels becomes a set of votes.

-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	1	-1	-1	1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1



.92

.51

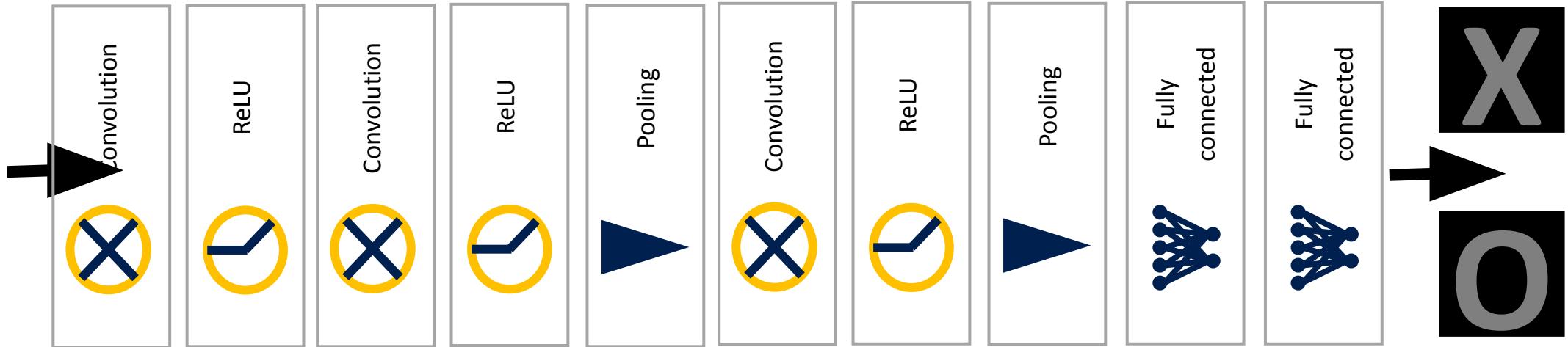
# Learning

- **Question:** Where do all the magic numbers come from?
  - Features in convolutional layers
  - Voting weights in fully connected layers
- **Answer:** Backpropagation Algorithm

# Backprop

Error = right answer – actual answer

-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	1	1	-1	-1	-1	-1	-1	-1	-1
-1	-1	1	-1	-1	1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

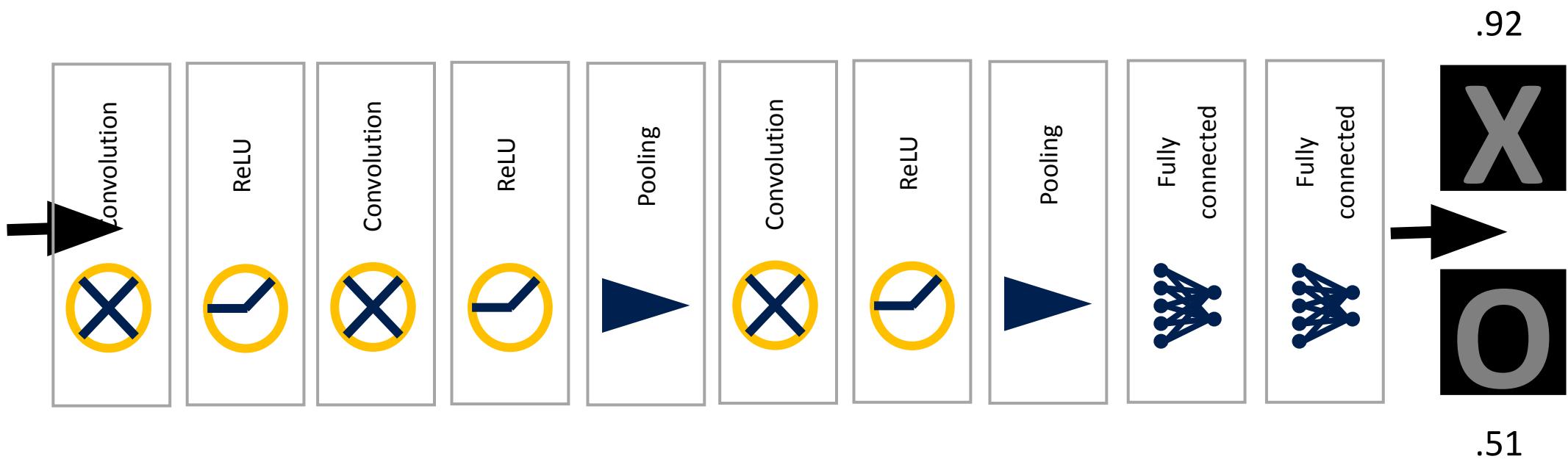
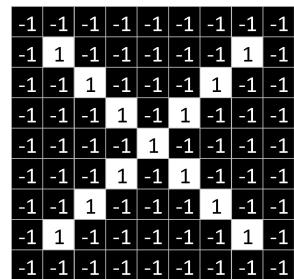


.92

.51

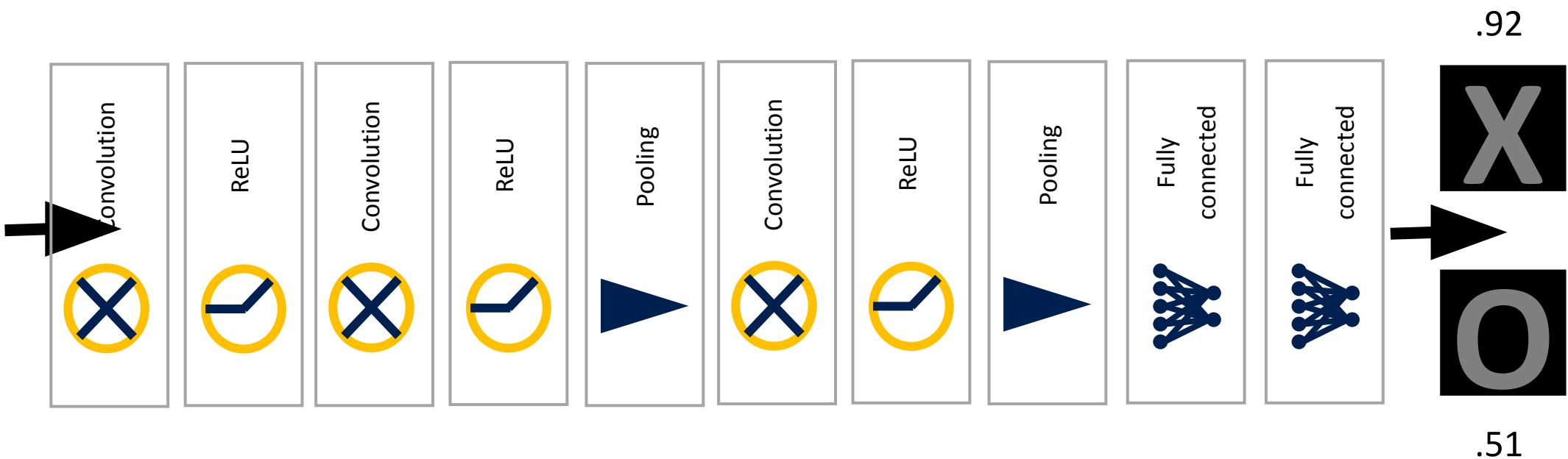
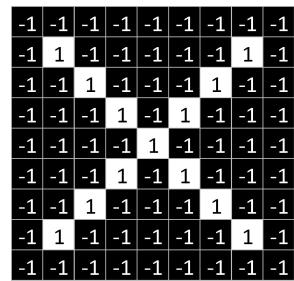
# Backprop

	Right answer	Actual answer	Error
X	1		
O			



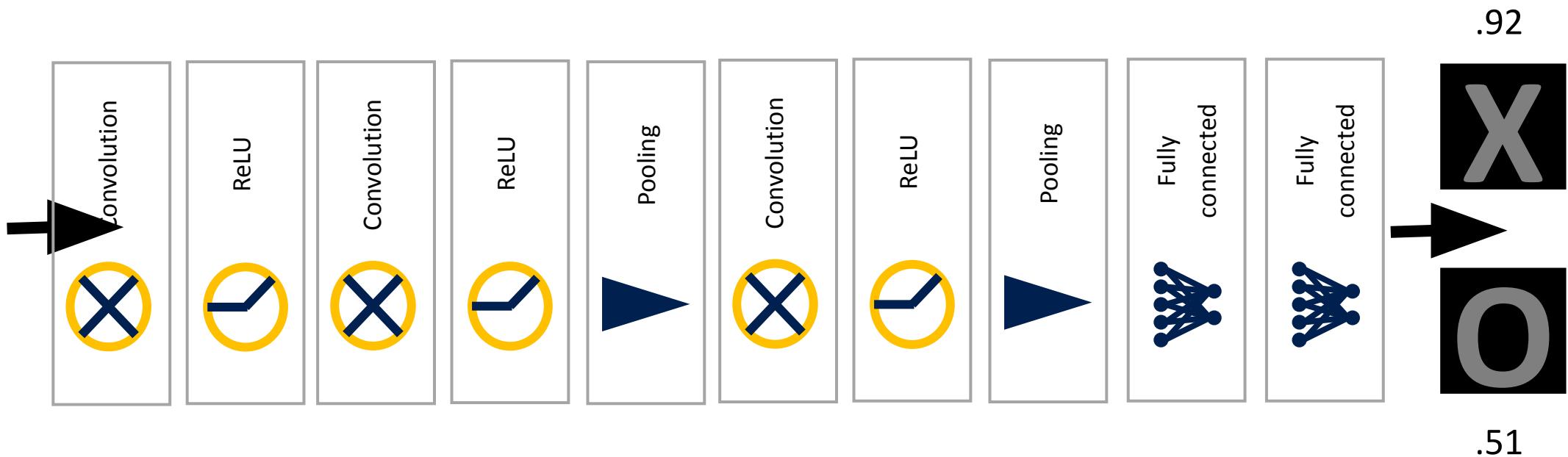
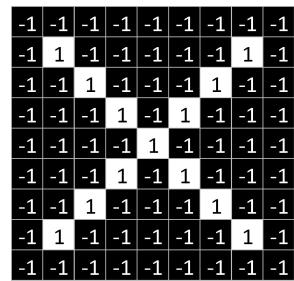
# Backprop

	Right answer	Actual answer	Error
X	1	0.92	
O			



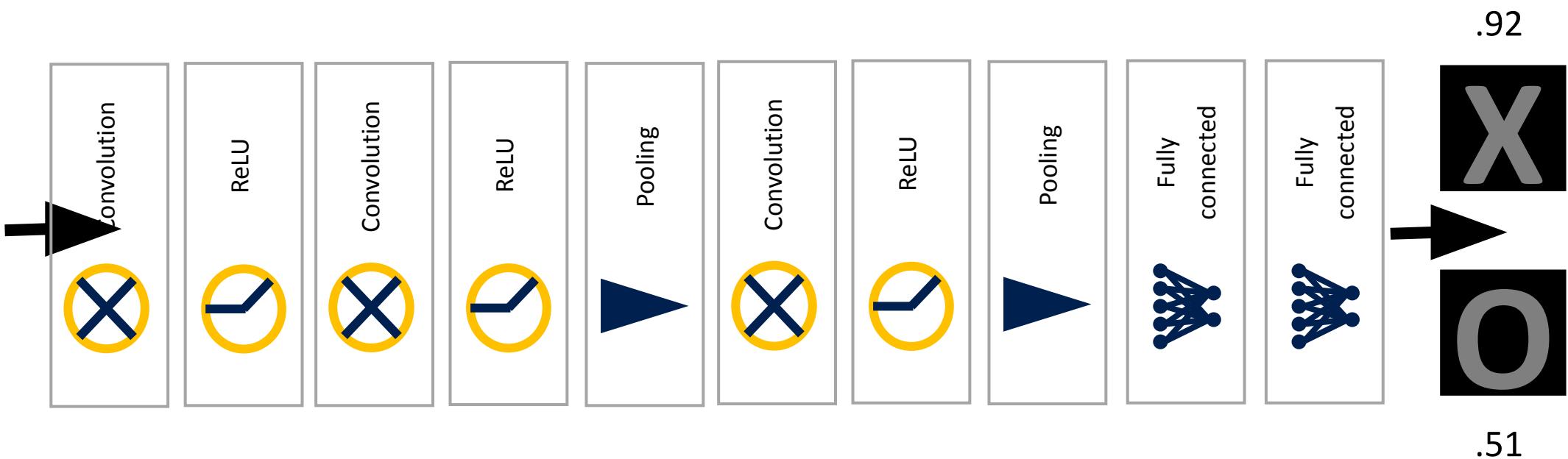
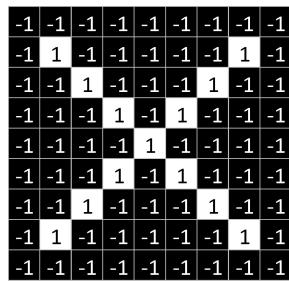
# Backprop

	Right answer	Actual answer	Error
X	1	0.92	0.08
O			



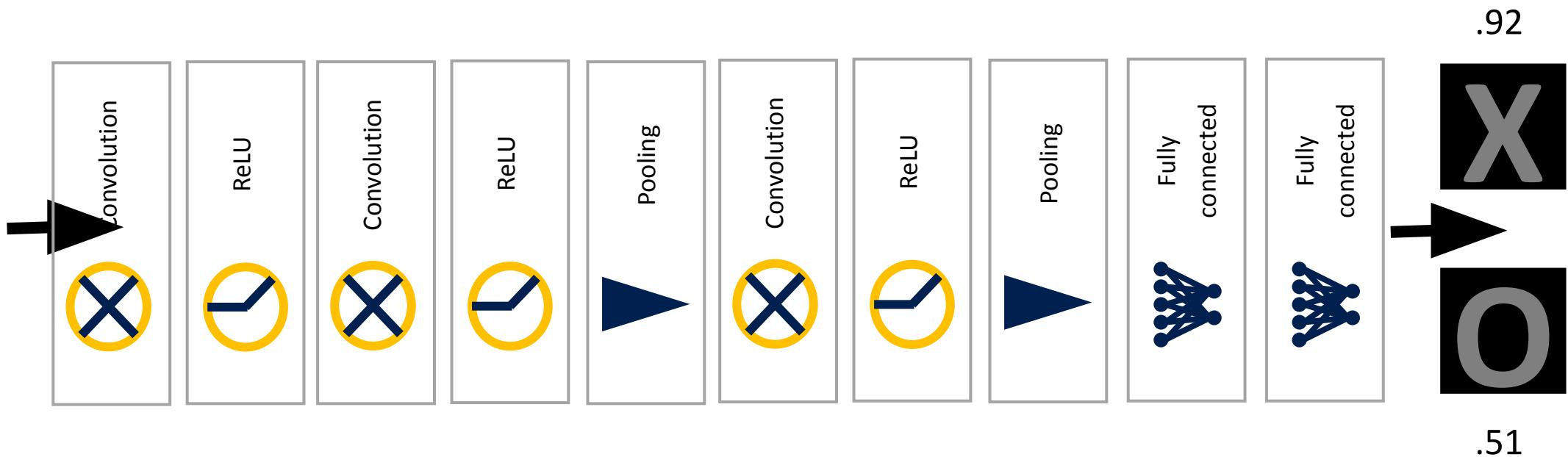
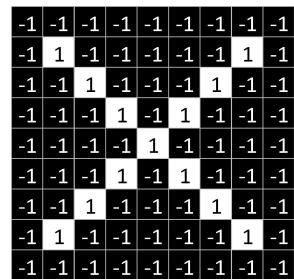
# Backprop

	Right answer	Actual answer	Error
X	1	0.92	0.08
O	0	0.51	0.49



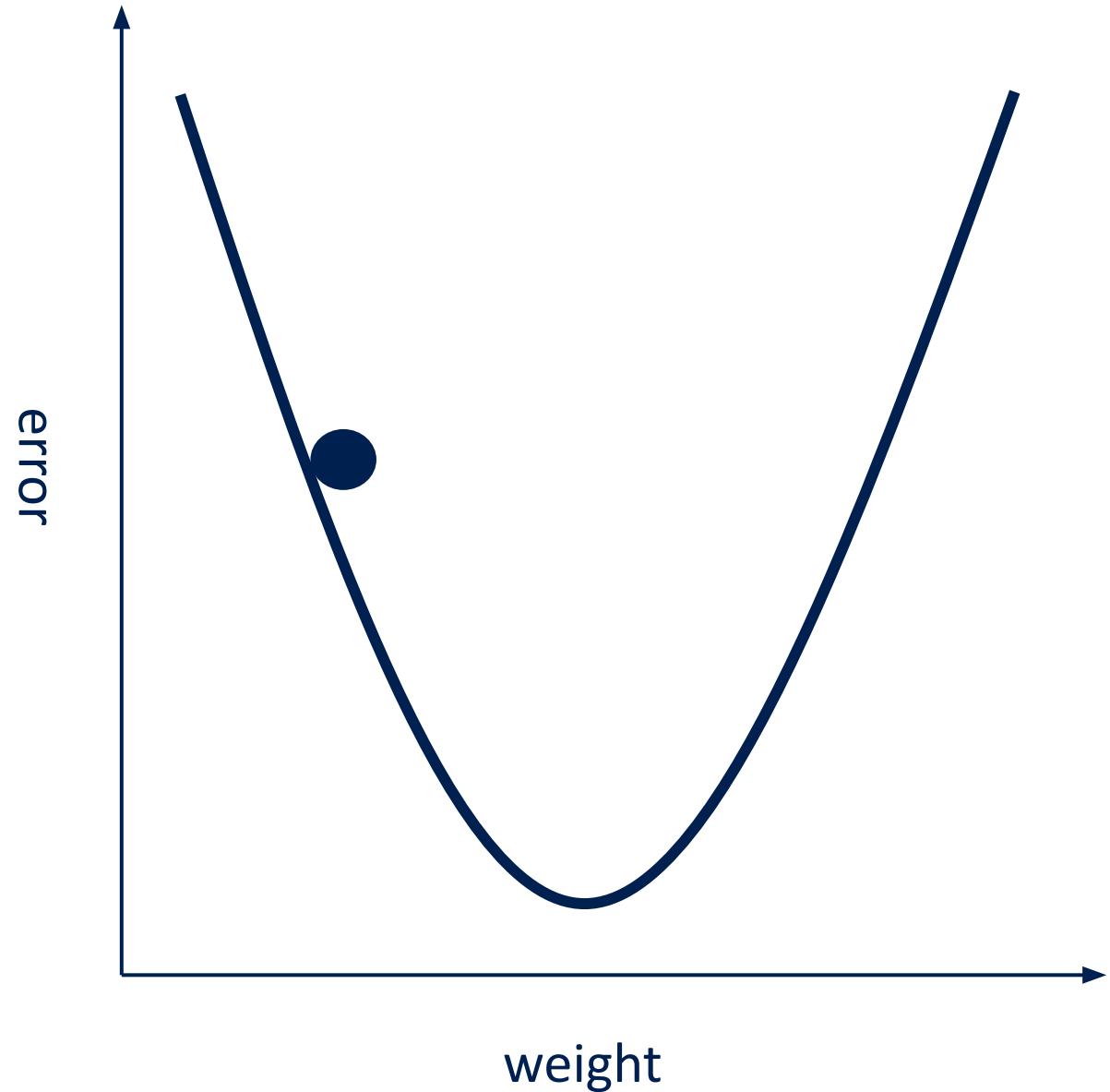
# Backprop

	Right answer	Actual answer	Error
X	1	0.92	0.08
O	0	0.51	0.49
Total			0.57



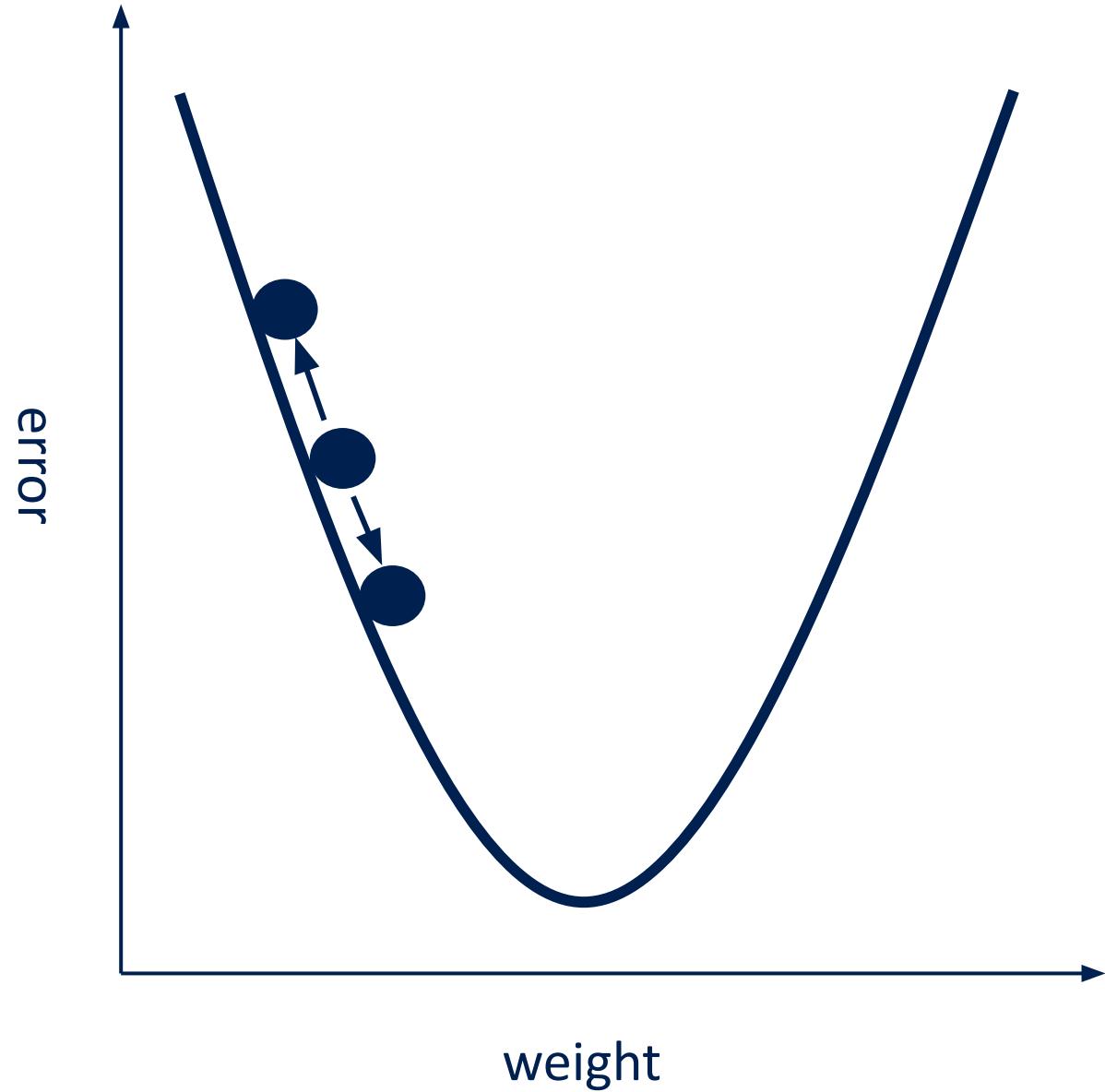
# Gradient descent

For each feature pixel and voting weight, adjust it up and down a bit and see how the error changes.



# Gradient descent

For each feature pixel and voting weight, adjust it up and down a bit and see how the error changes.



# Hyperparameters

- **Convolution**

- Number of features

- Size of features

- **Pooling**

- Window size

- Window stride

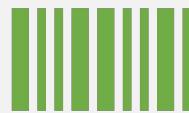
- **Fully Connected**

- Number of neurons

# Architecture



How many of each type of layer?



In what order?

# Not Just Images

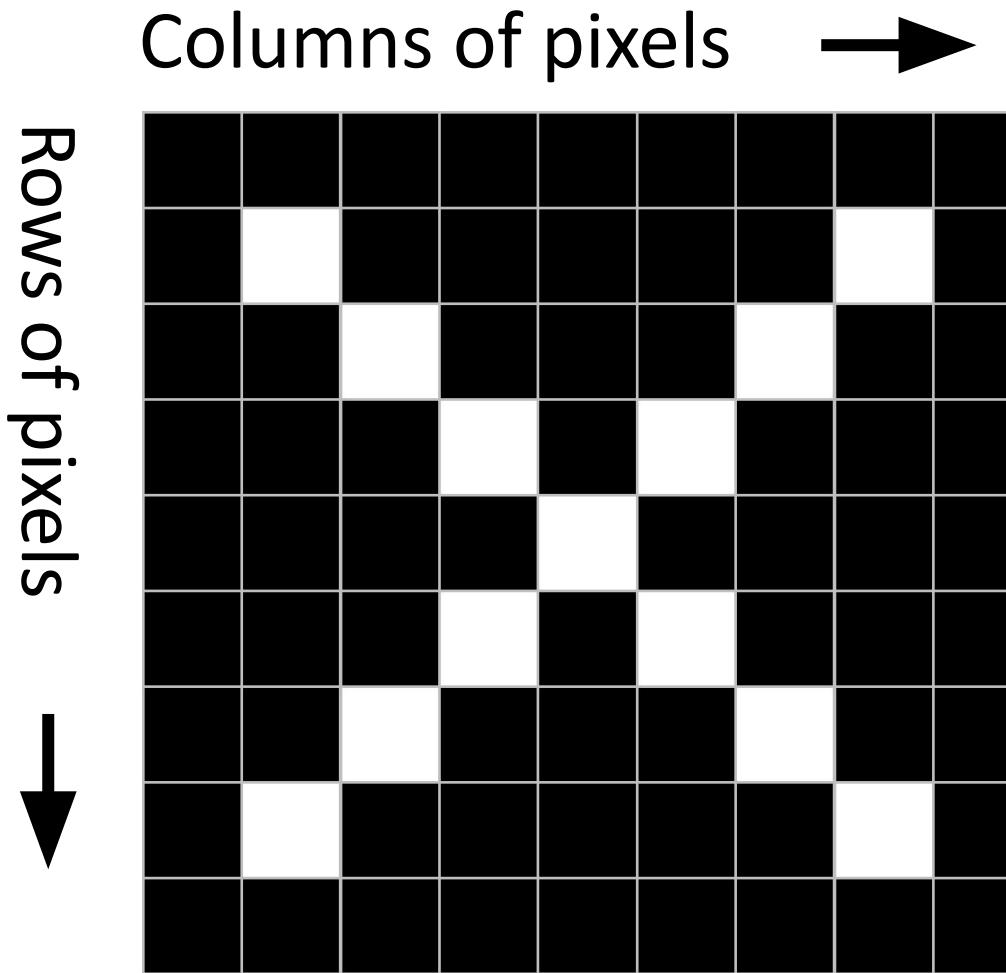


Any 2D (or 3D) data.

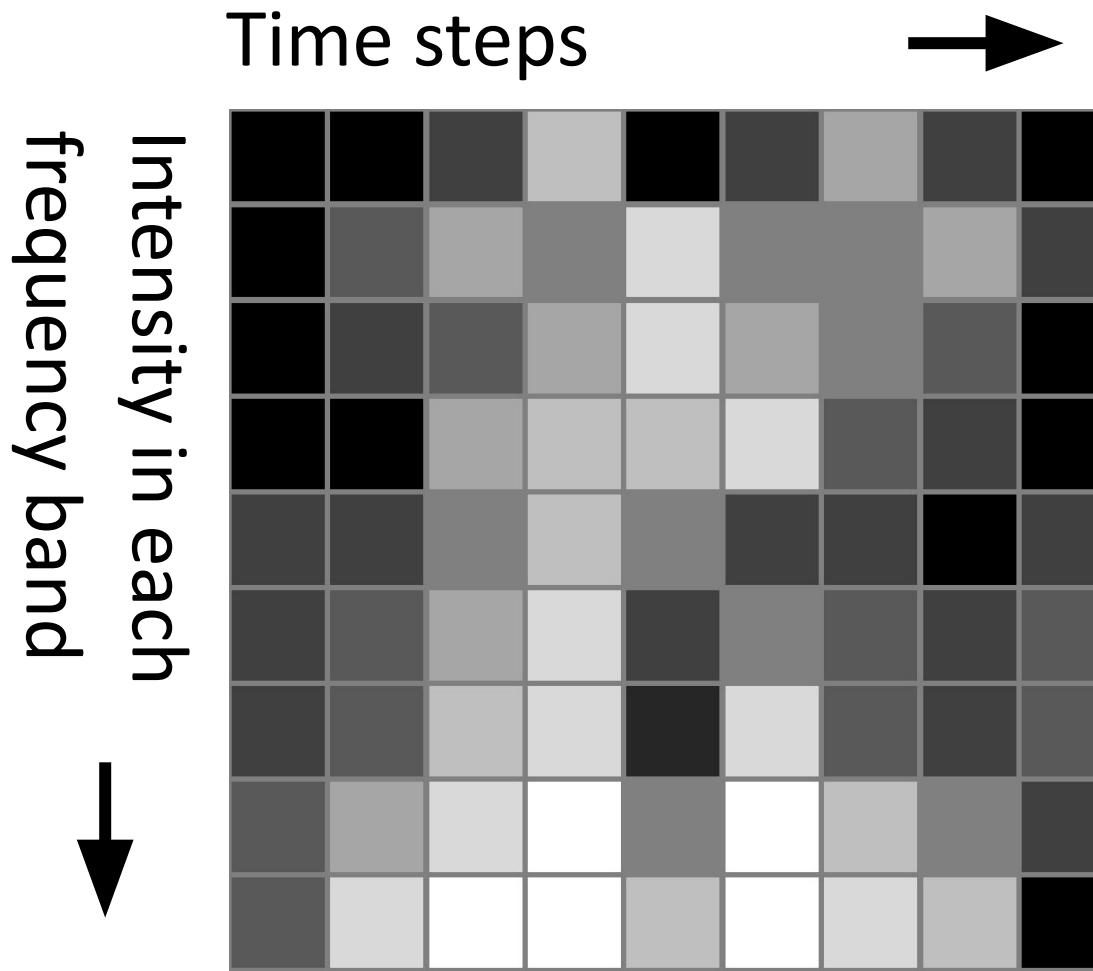


Things closer together are more closely related than things far away.

# Images

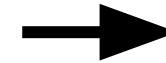


Sound

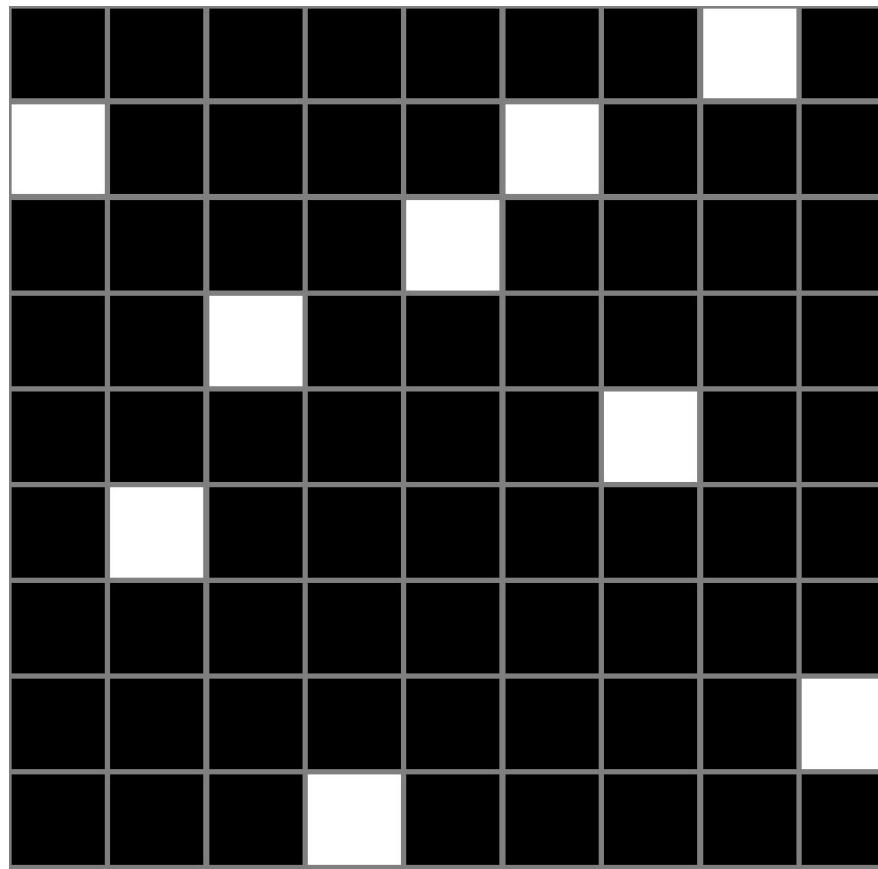
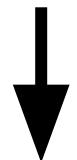


Text

Position in  
sentence



Words in  
dictionary



# Limitations



ConvNets only capture local  
**“spatial”** patterns in data.



If the data can't be made to look like an image, ConvNets are less useful.

” ”

## Rule of Thumb

- If your data is just as useful after swapping any of your columns with each other, then you can't use Convolutional Neural Networks.
- ConvNets are great at finding patterns and using them to classify images.