

Lecture 5: Convolutional Neural Networks

Topic Overview

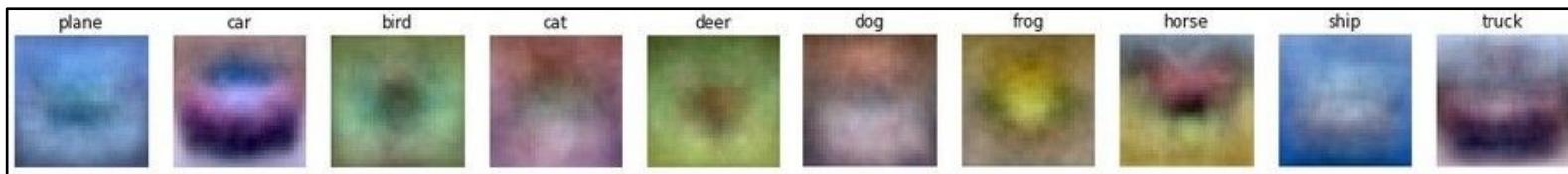
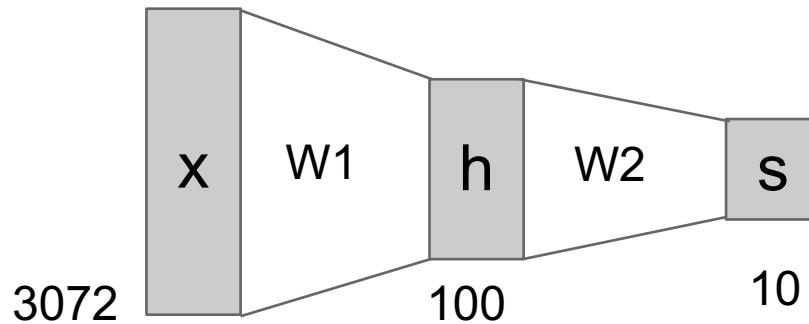
- Convolutional Neural Networks Overview
- CNN Architectures
- CNN Applications

Last time: Neural Networks

Linear score function: 2-layer Neural Network

$$f = Wx$$

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



Next: Convolutional Neural Networks

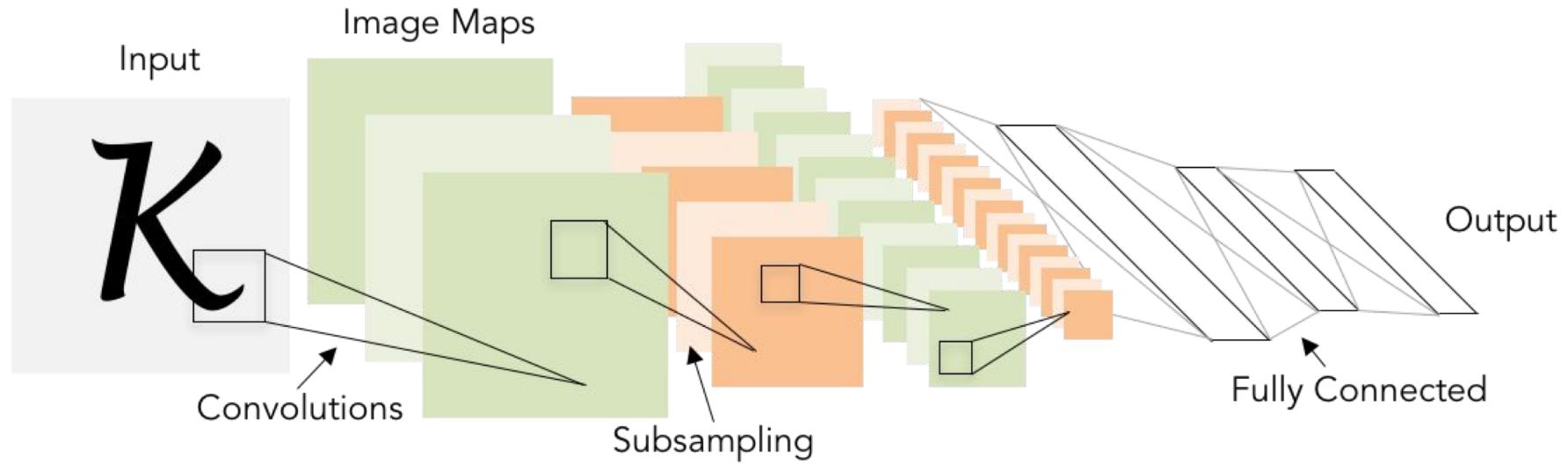


Illustration of LeCun et al. 1998 from CS231n 2017 Lecture 1

A bit of history...

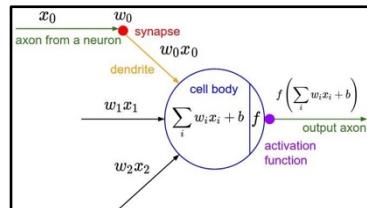
The **Mark I Perceptron** machine was the first implementation of the perceptron algorithm.

The machine was connected to a camera that used 20×20 cadmium sulfide photocells to produce a 400-pixel image.

recognized
letters of the alphabet

update rule:

$$w_i(t+1) = w_i(t) + \alpha(d_j - y_j(t))x_{j,i}$$

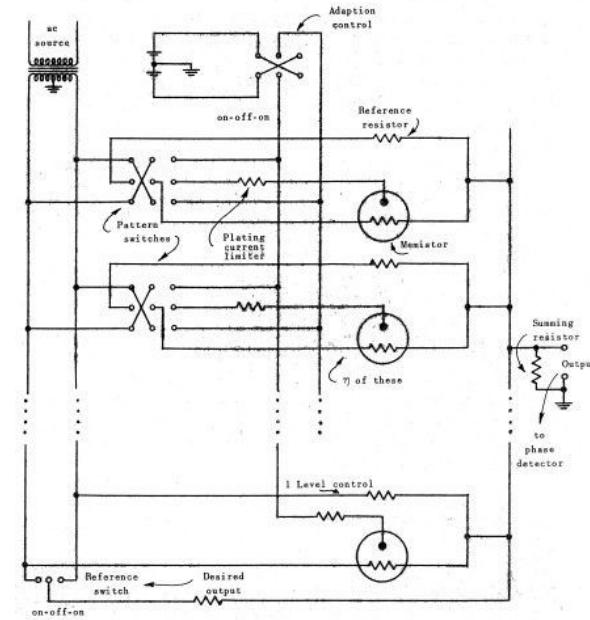
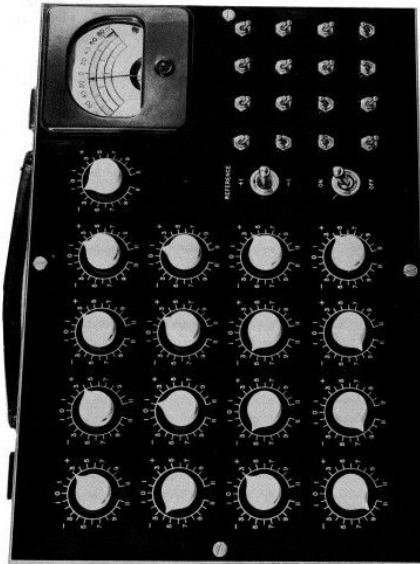
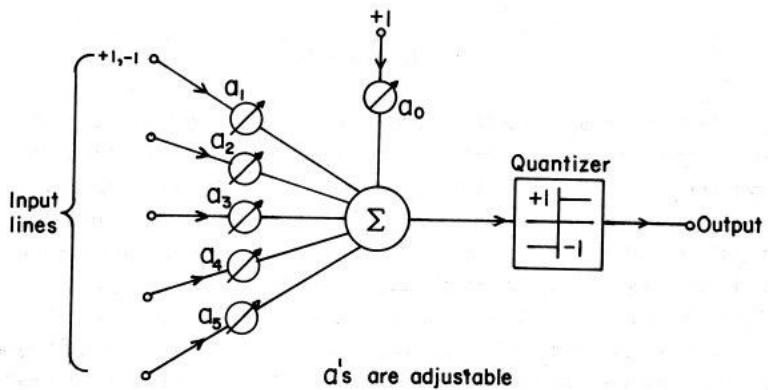


Frank Rosenblatt, ~1957: Perceptron



[This image](#) by Rocky Acosta is licensed under [CC-BY 3.0](#)

A bit of history...

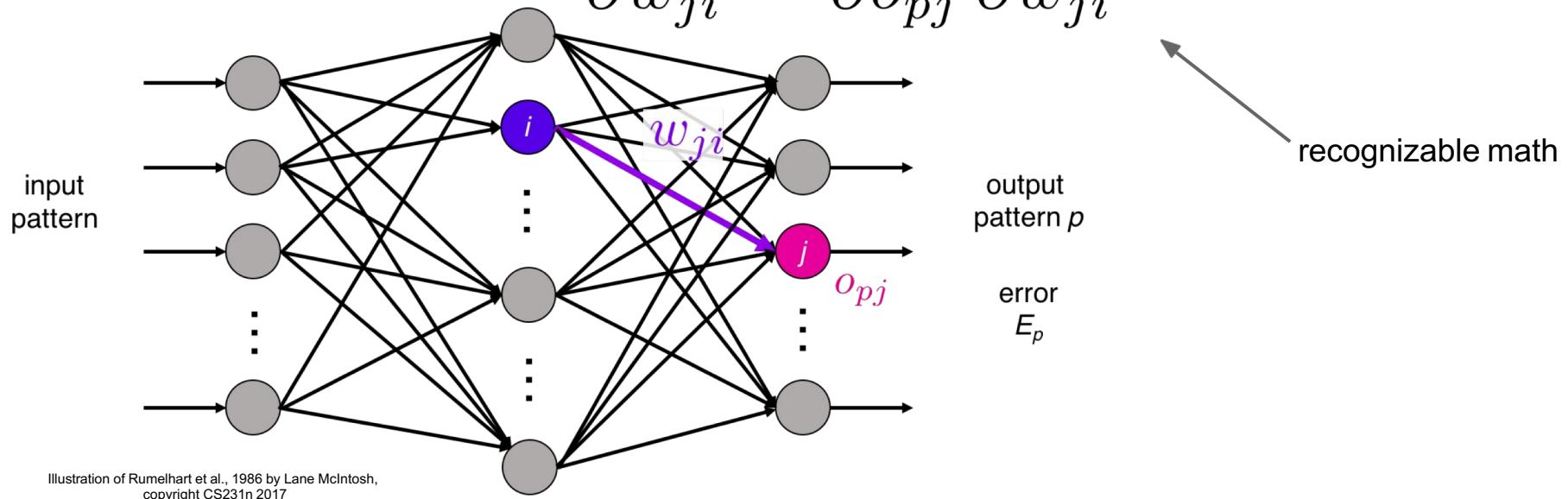


Widrow and Hoff, ~1960: Adaline/Madaline

These figures are reproduced from [Widrow 1960, Stanford Electronics Laboratories Technical Report](#) with permission from [Stanford University Special Collections](#).

A bit of history...

$$\frac{\partial E_p}{\partial w_{ji}} = \frac{\partial E_p}{\partial o_{pj}} \frac{\partial o_{pj}}{\partial w_{ji}}$$



Rumelhart et al., 1986: First time back-propagation became popular

A bit of history...

[Hinton and Salakhutdinov 2006]

Reinvigorated research in Deep Learning

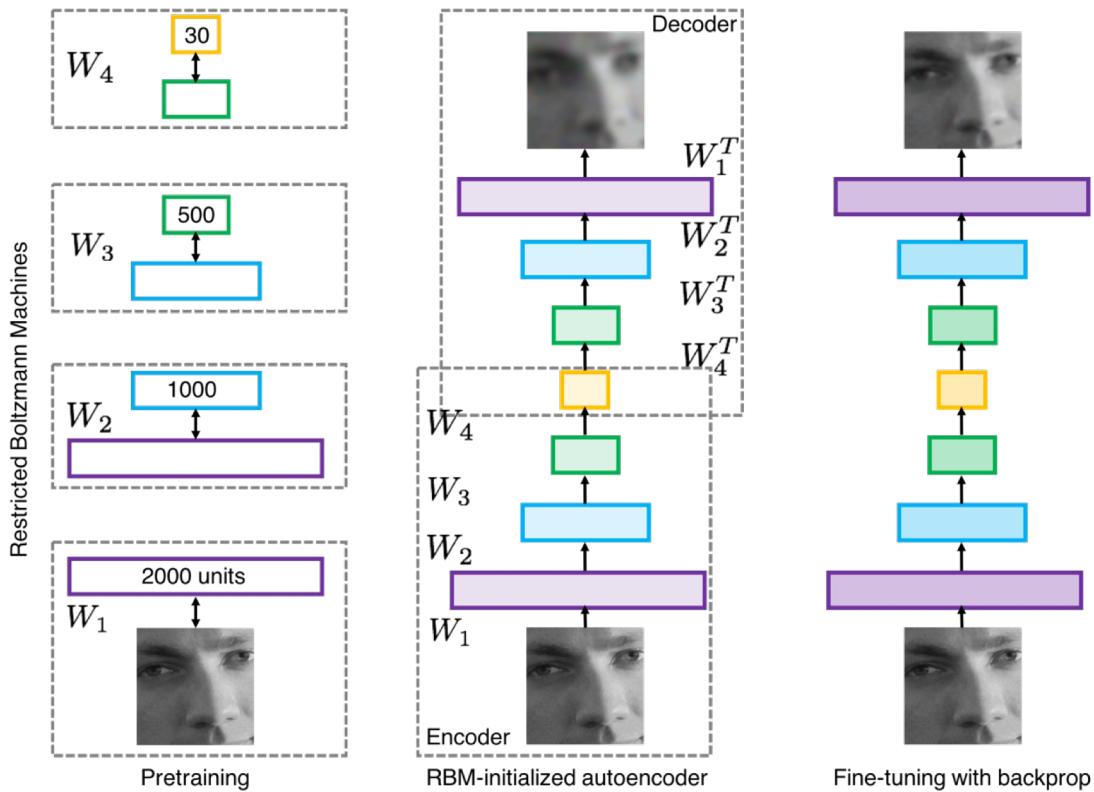


Illustration of Hinton and Salakhutdinov 2006 by Lane McIntosh, copyright CS231n 2017

First strong results

Acoustic Modeling using Deep Belief Networks

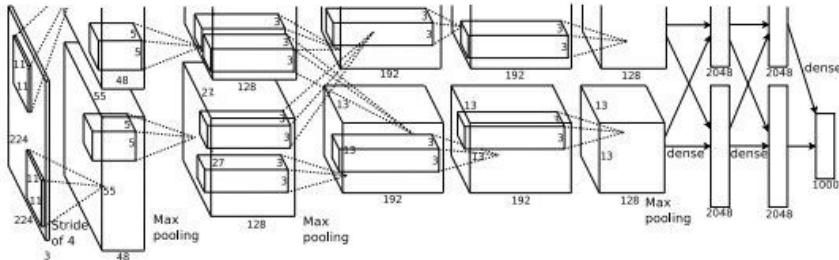
Abdel-rahman Mohamed, George Dahl, Geoffrey Hinton, 2010

Context-Dependent Pre-trained Deep Neural Networks for Large Vocabulary Speech Recognition

George Dahl, Dong Yu, Li Deng, Alex Acero, 2012

Imagenet classification with deep convolutional neural networks

Alex Krizhevsky, Ilya Sutskever, Geoffrey E Hinton, 2012



Figures copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

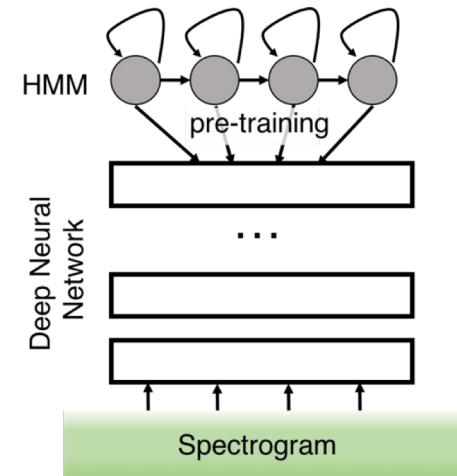


Illustration of Dahl et al. 2012 by Lane McIntosh, copyright CS231n 2017

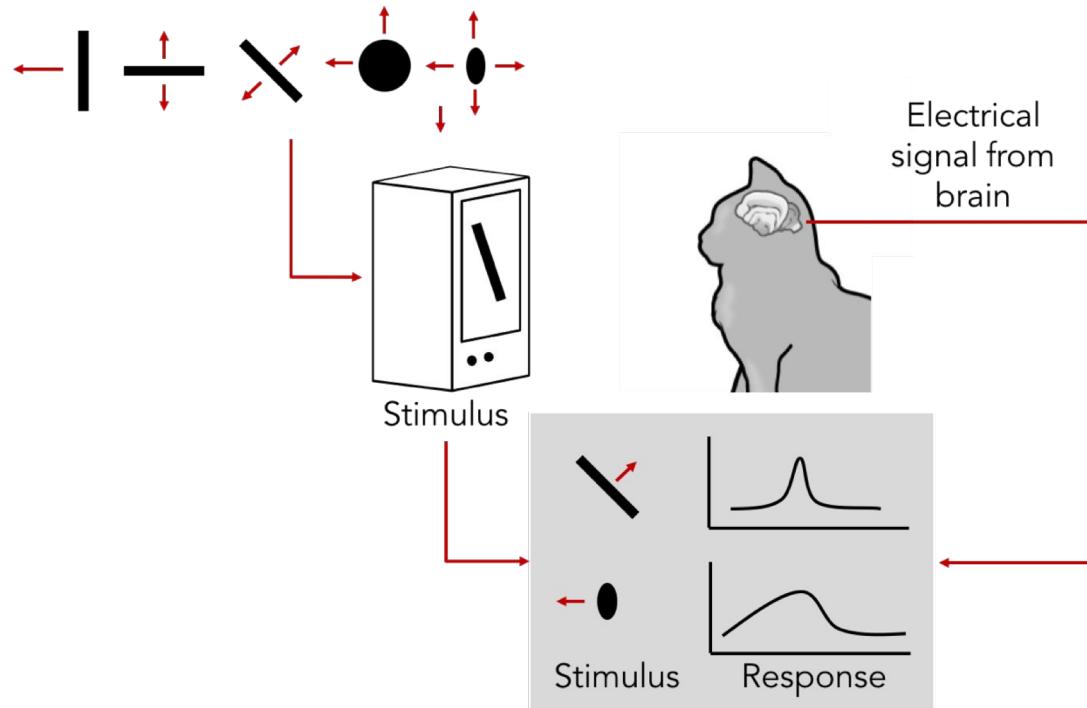
A bit of history: **Hubel & Wiesel, 1959**

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

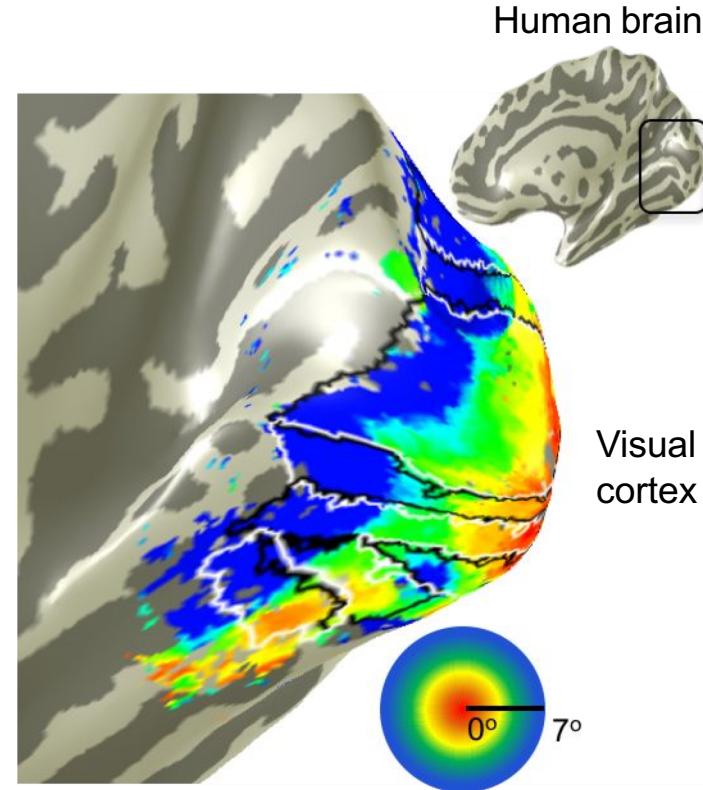
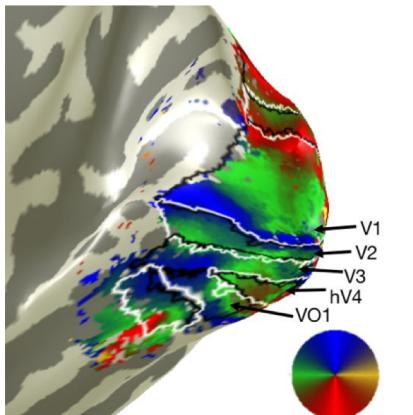
1968...



[Cat image](#) by CNXOpenStax is licensed
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A bit of history

Topographical mapping in the cortex:
nearby cells in cortex represent
nearby regions in the visual field



Retinotopy images courtesy of Jesse Gomez in the
Stanford Vision & Perception Neuroscience Lab.

Hierarchical organization

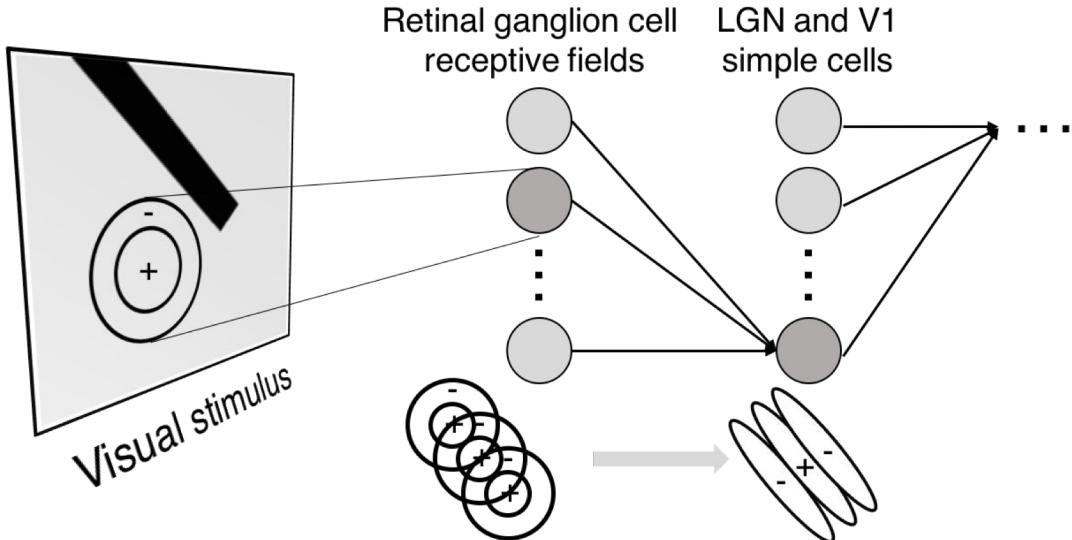
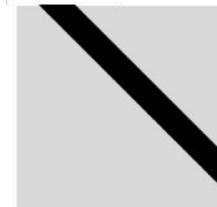


Illustration of hierarchical organization in early visual pathways by Lane McIntosh, copyright CS231n 2017

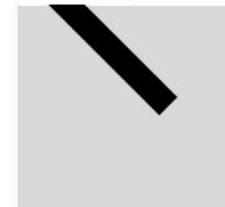
Simple cells:
Response to light orientation

Complex cells:
Response to light orientation and movement

Hypercomplex cells:
response to movement with an end point



No response



Response
(end point)

A bit of history:

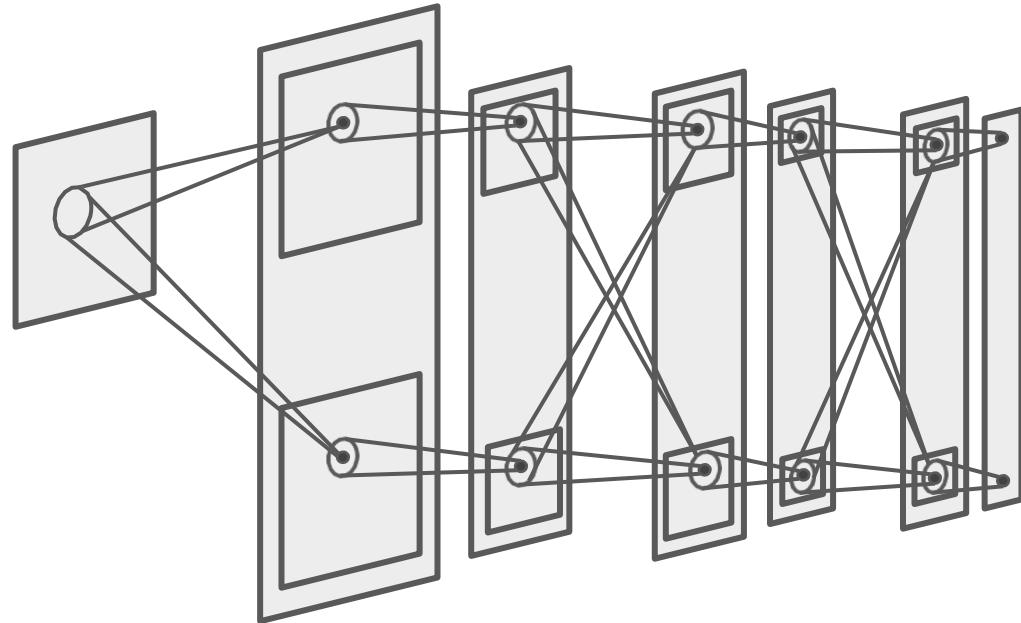
Neocognitron

[Fukushima 1980]

“sandwich” architecture (SCSCSC...)

simple cells: modifiable parameters

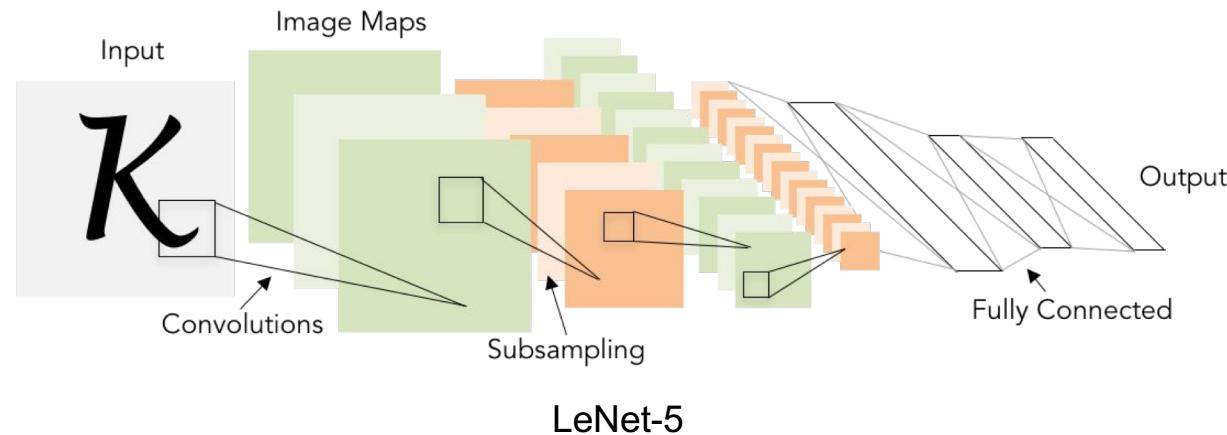
complex cells: perform pooling



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]

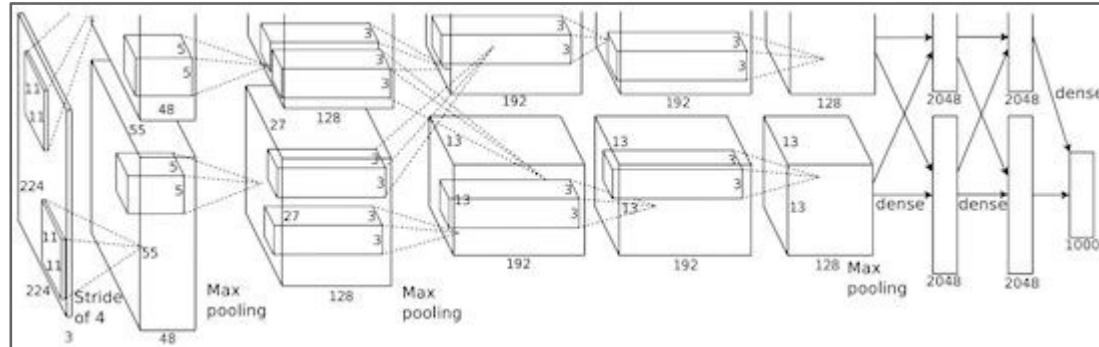


Figure copyright Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton, 2012. Reproduced with permission.

“AlexNet”

Fast-forward to today: ConvNets are everywhere

Classification



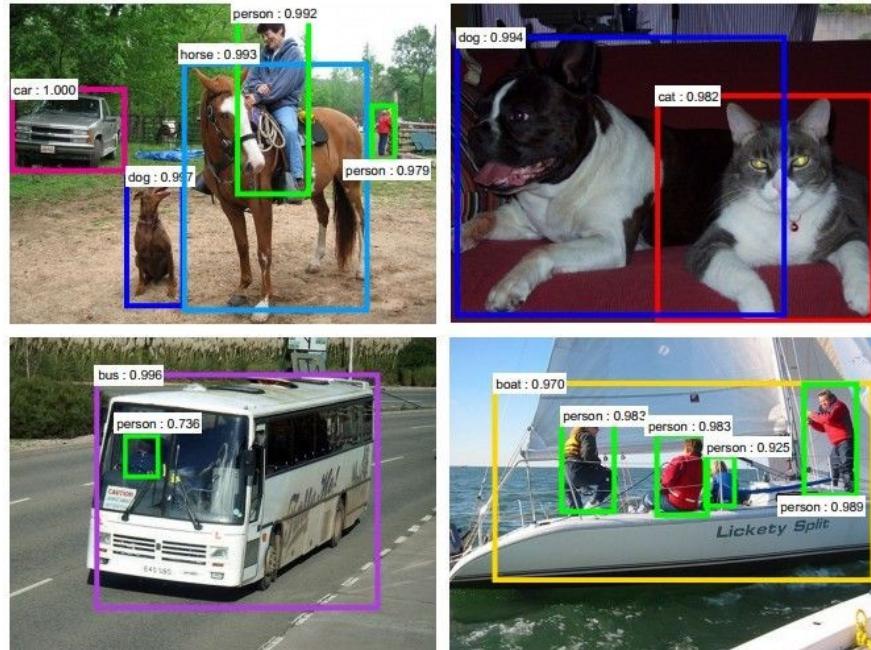
Retrieval



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Fast-forward to today: ConvNets are everywhere

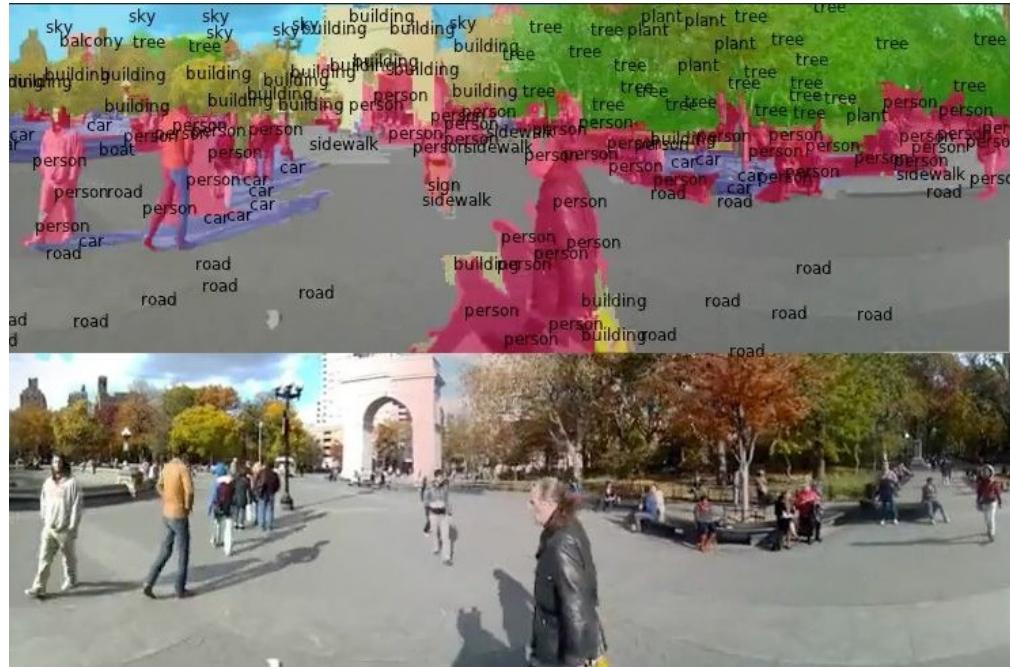
Detection



Figures copyright Shaoqing Ren, Kaiming He, Ross Girshick, Jian Sun, 2015. Reproduced with permission.

[Faster R-CNN: Ren, He, Girshick, Sun 2015]

Segmentation



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[Farabet et al., 2012]

Fast-forward to today: ConvNets are everywhere



self-driving cars

Photo by Lane McIntosh. Copyright CS231n 2017.



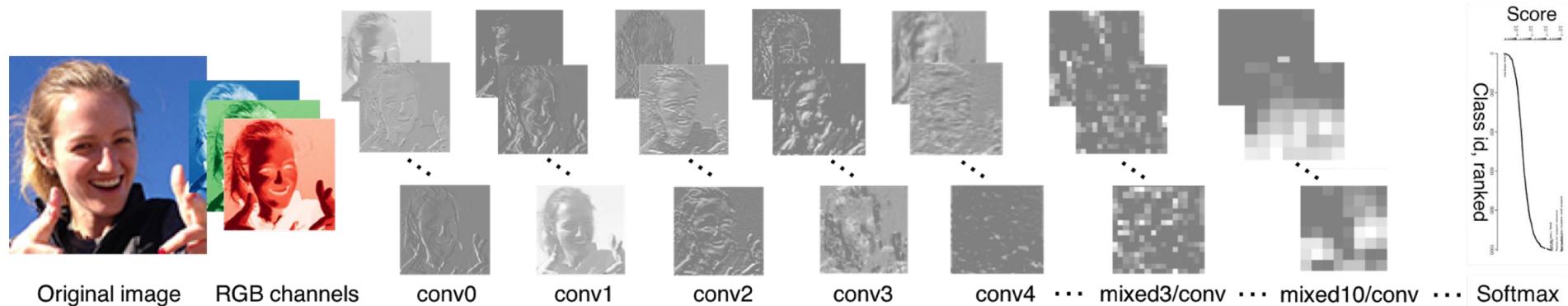
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NVIDIA Tesla line

(these are the GPUs on rye01.stanford.edu)

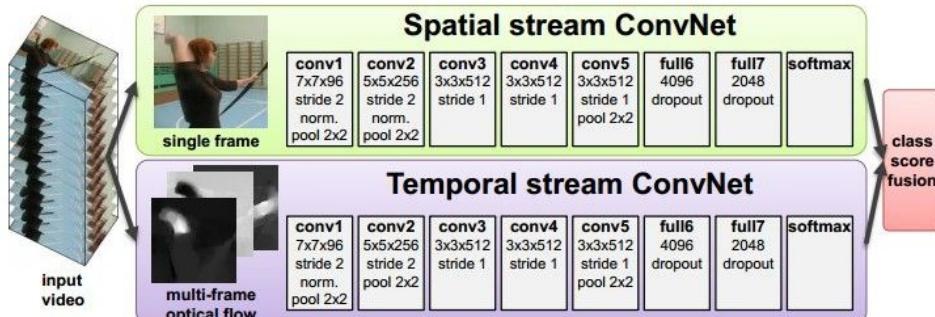
Note that for embedded systems a typical setup would involve NVIDIA Tegras, with integrated GPU and ARM-based CPU cores.

Fast-forward to today: ConvNets are everywhere



[Taigman et al. 2014]

Activations of [inception-v3 architecture](#) [Szegedy et al. 2015] to image of Emma McIntosh, used with permission. Figure and architecture not from Taigman et al. 2014.



[Simonyan et al. 2014]

Figures copyright Simonyan et al., 2014.
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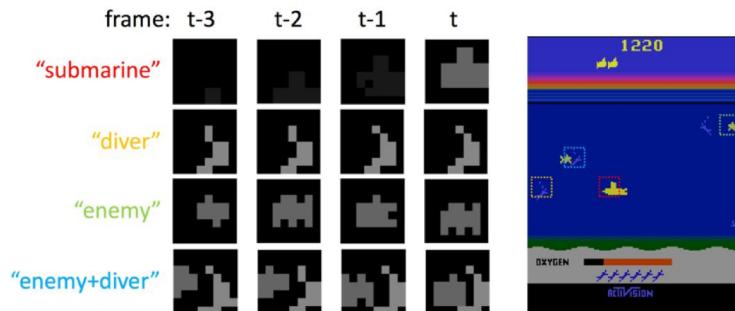
Illustration by Lane McIntosh,
photos of Katie Cumnock
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Fast-forward to today: ConvNets are everywhere

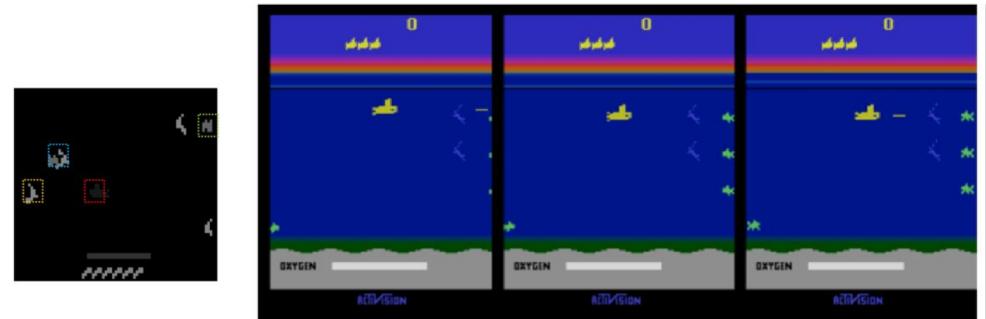


Images are examples of pose estimation, not actually from Toshev & Szegedy 2014. Copyright Lane McIntosh.

[Toshev, Szegedy 2014]

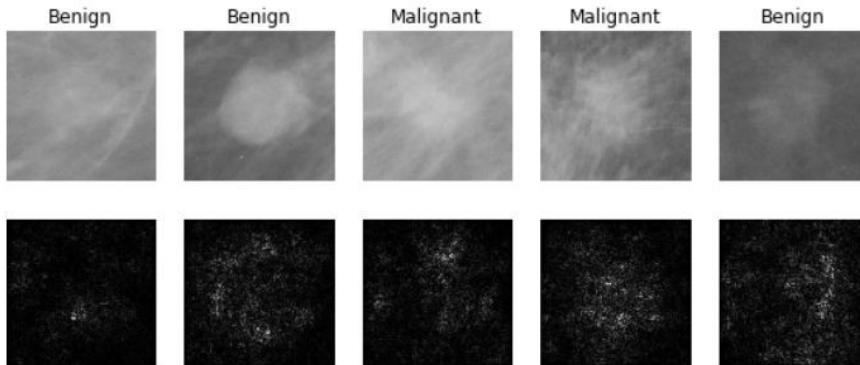


[Guo et al. 2014]



Figures copyright Xiaoxiao Guo, Satinder Singh, Honglak Lee, Richard Lewis, and Xiaoshi Wang, 2014. Reproduced with permission.

Fast-forward to today: ConvNets are everywhere



[Levy et al. 2016]

Figure copyright Levy et al. 2016.
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[Dieleman et al. 2014]

From left to right: [public domain by NASA](#), usage [permitted](#) by
ESA/Hubble, [public domain by NASA](#), and [public domain](#).



Photos by Lane McIntosh.
Copyright CS231n 2017.

[Sermanet et al. 2011]
[Ciresan et al.]

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Whale recognition, Kaggle Challenge

Photo and figure by Lane McIntosh; not actual example from Mnih and Hinton, 2010 paper.



Mnih and Hinton, 2010

No errors



A white teddy bear sitting in the grass



A man riding a wave on top of a surfboard

Minor errors



A man in a baseball uniform throwing a ball



A cat sitting on a suitcase on the floor

Somewhat related



A woman is holding a cat in her hand



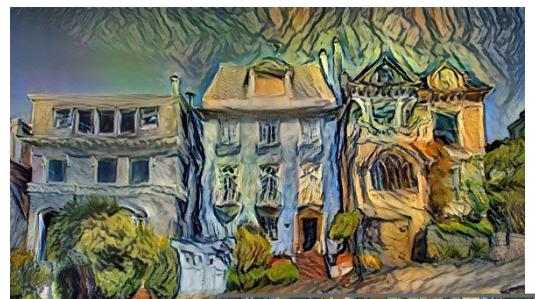
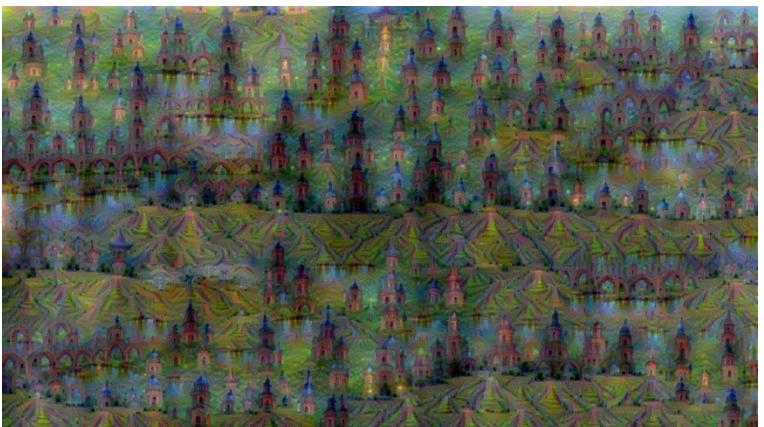
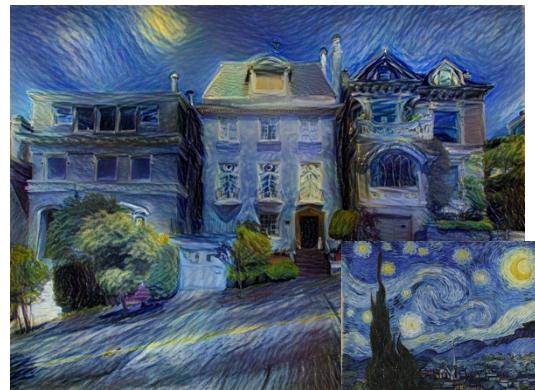
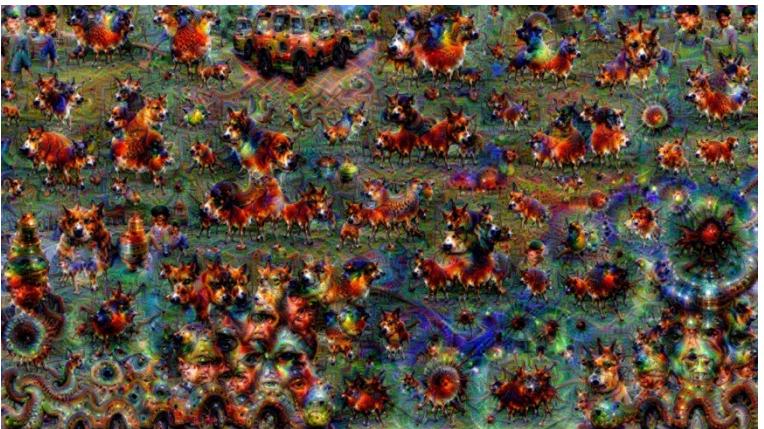
A woman standing on a beach holding a surfboard

Image Captioning

[Vinyals et al., 2015]
[Karpathy and Fei-Fei, 2015]

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Captions generated by Justin Johnson using [Neuraltalk2](#)



Figures copyright Justin Johnson, 2015. Reproduced with permission. Generated using the Inceptionism approach from a [blog post](#) by Google Research.

[Original image](#) is CC0 public domain
[Starry Night](#) and [Tree Roots](#) by Van Gogh are in the public domain

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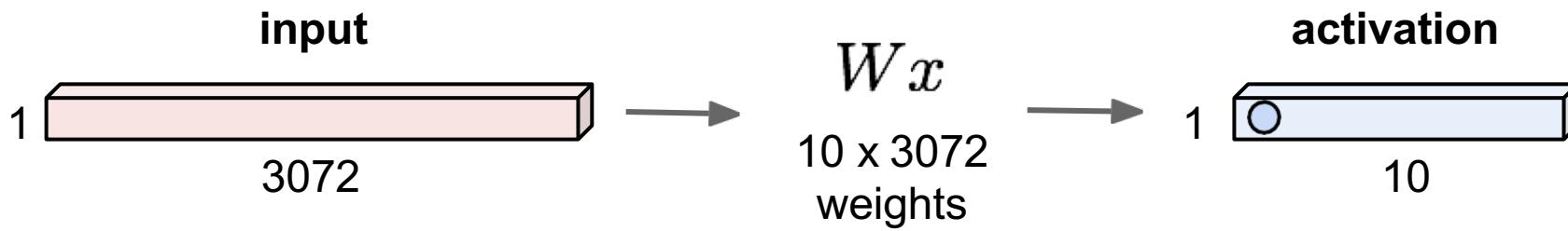
Gatys et al, "Image Style Transfer using Convolutional Neural Networks", CVPR2016
Gatys et al, "Controlling Perceptual Factors in Neural Style Transfer", CVPR2017

Convolutional Neural Networks

(First without the brain stuff)

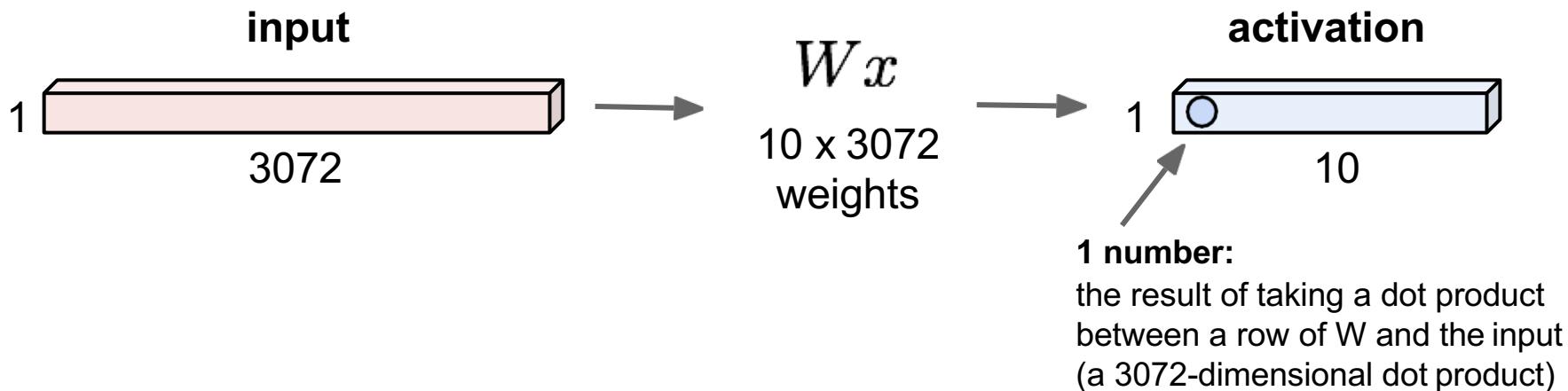
Fully Connected Layer

32x32x3 image -> stretch to 3072 x 1



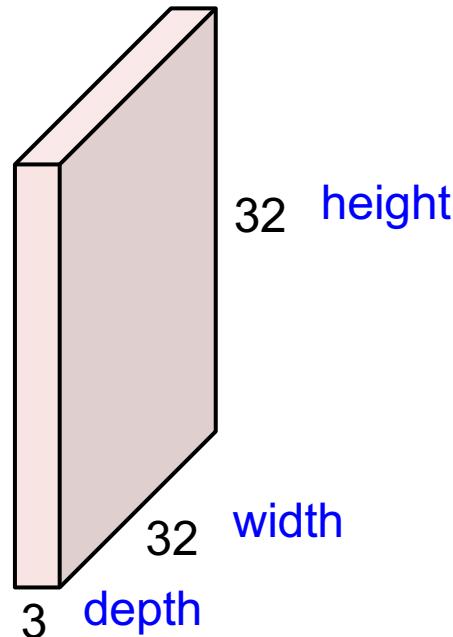
Fully Connected Layer

32x32x3 image -> stretch to 3072 x 1

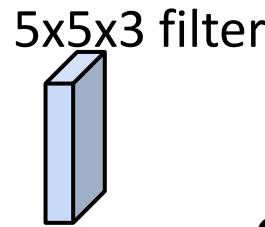
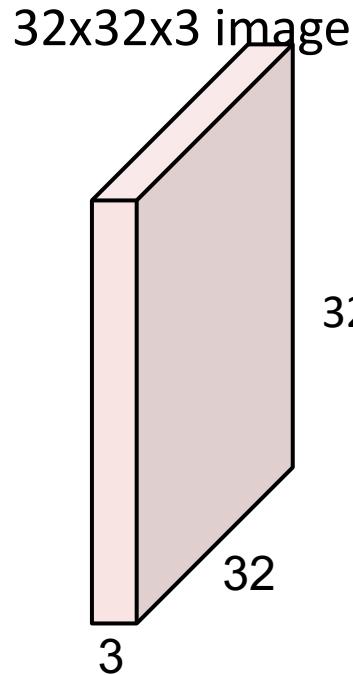


Convolution Layer

32x32x3 image -> preserve spatial structure



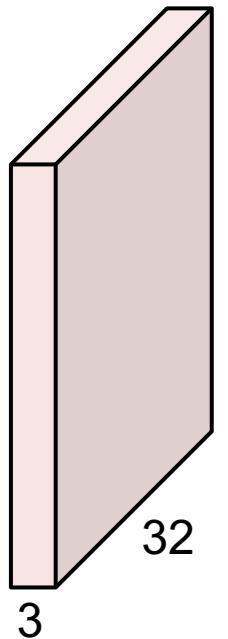
Convolution Layer



- **Convolve** the filter with the image
- i.e. “slide over the image spatially, computing dot products”

Convolution Layer

32x32x3 image



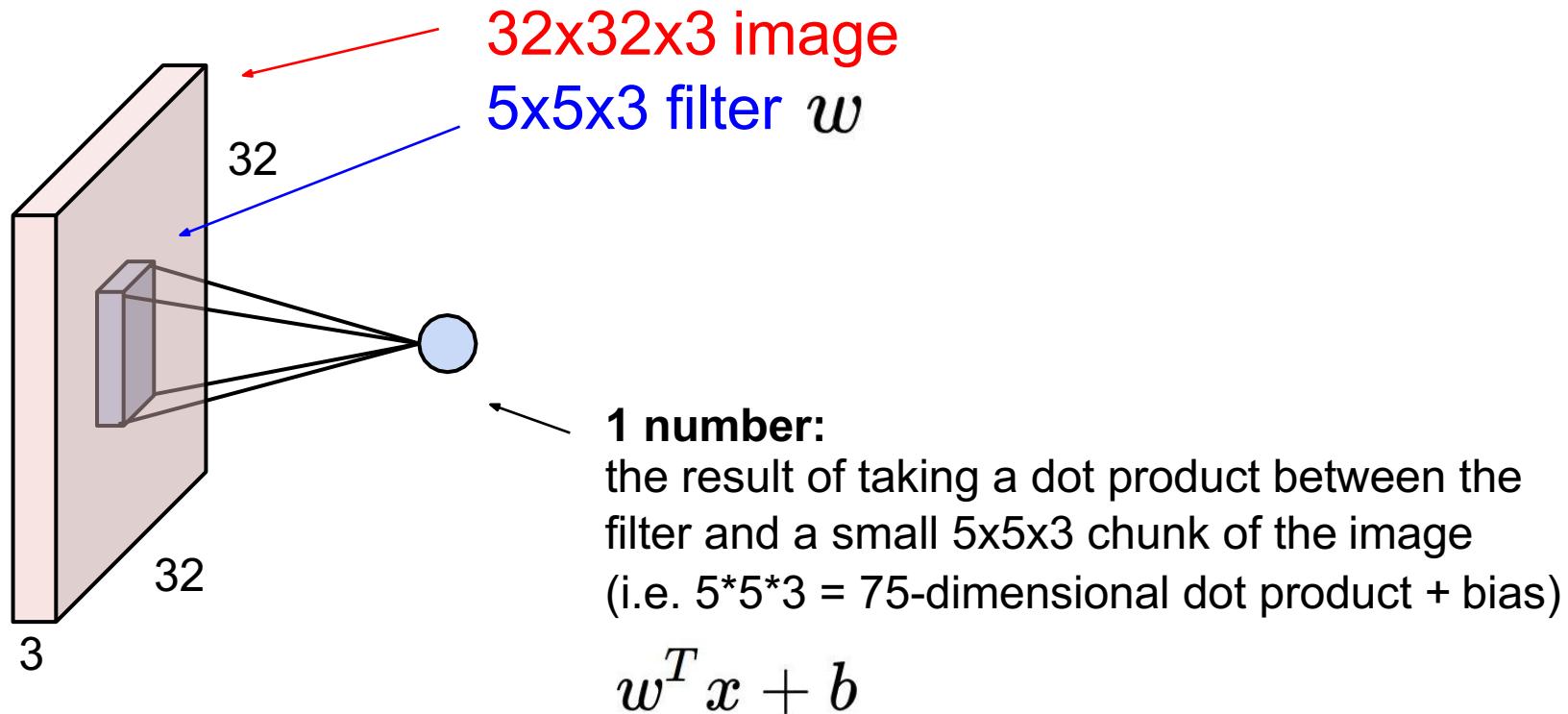
5x5x3 filter



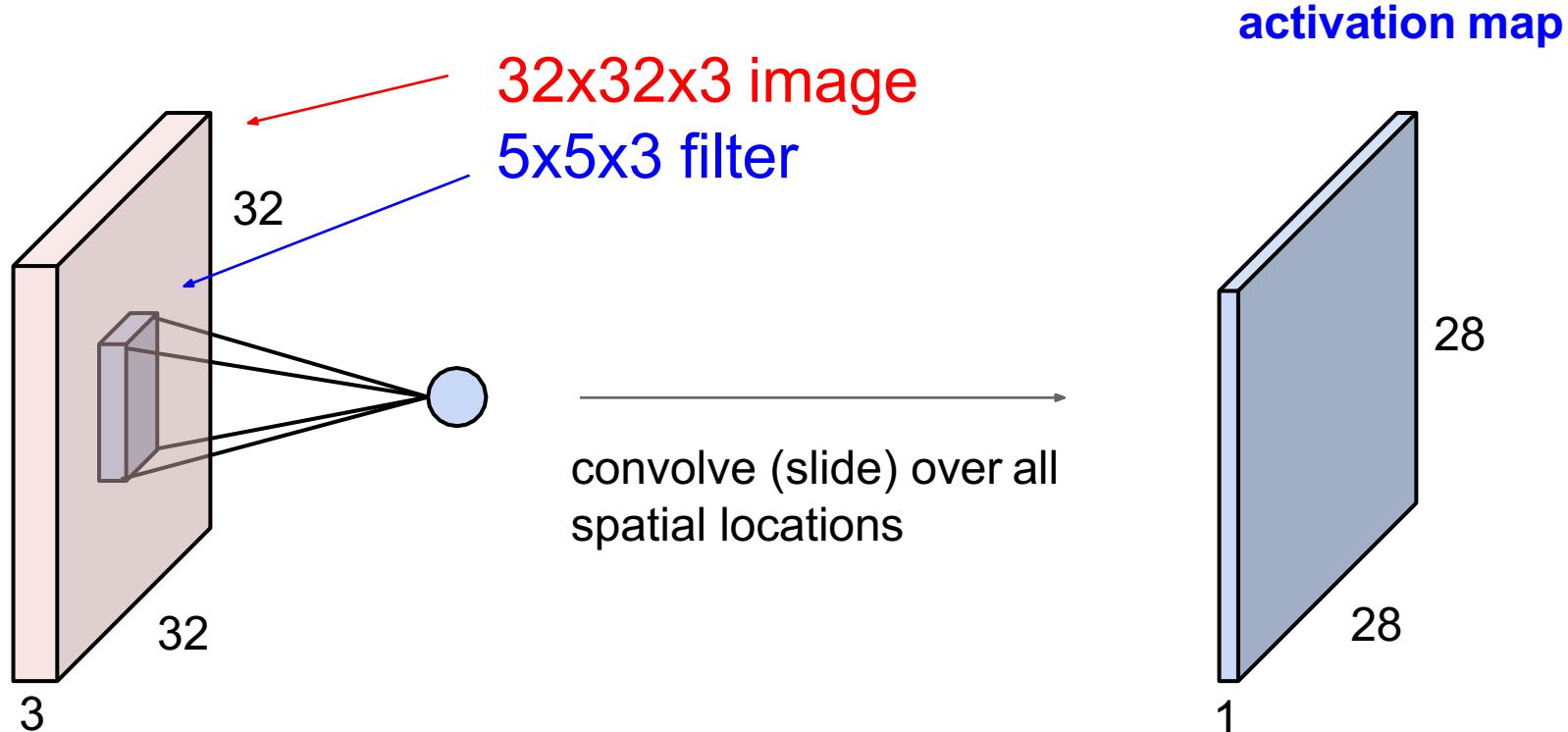
Filters always extend the full depth of the input volume

- **Convolve** the filter with the image
- i.e. “slide over the image spatially, computing dot products”

Convolution Layer

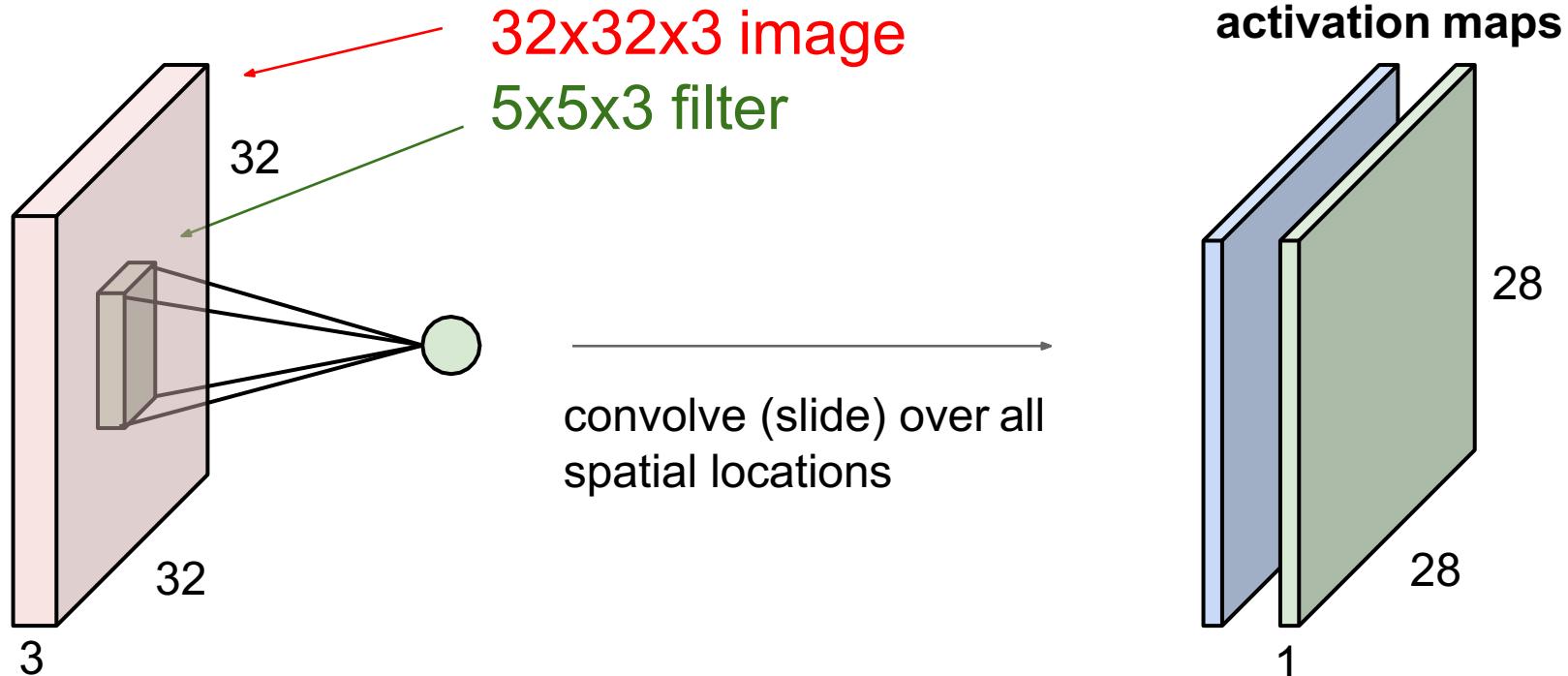


Convolution Layer

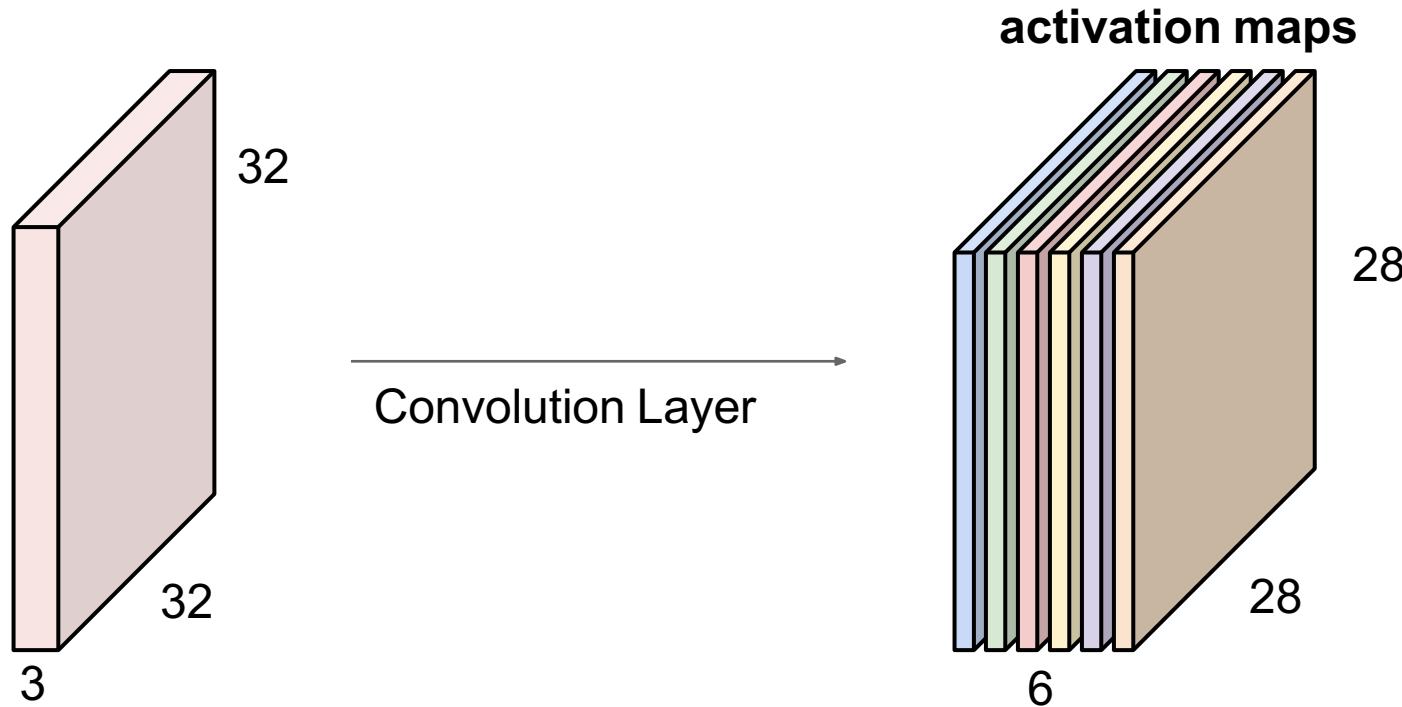


Convolution Layer

consider a second, green filter

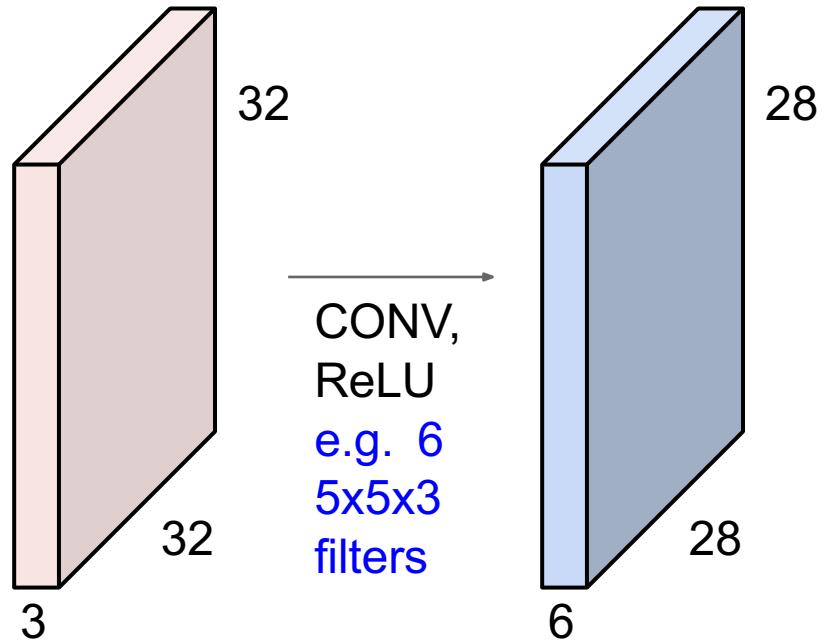


For example, if we had 6 5x5 filters, we'll get 6 separate activation maps:

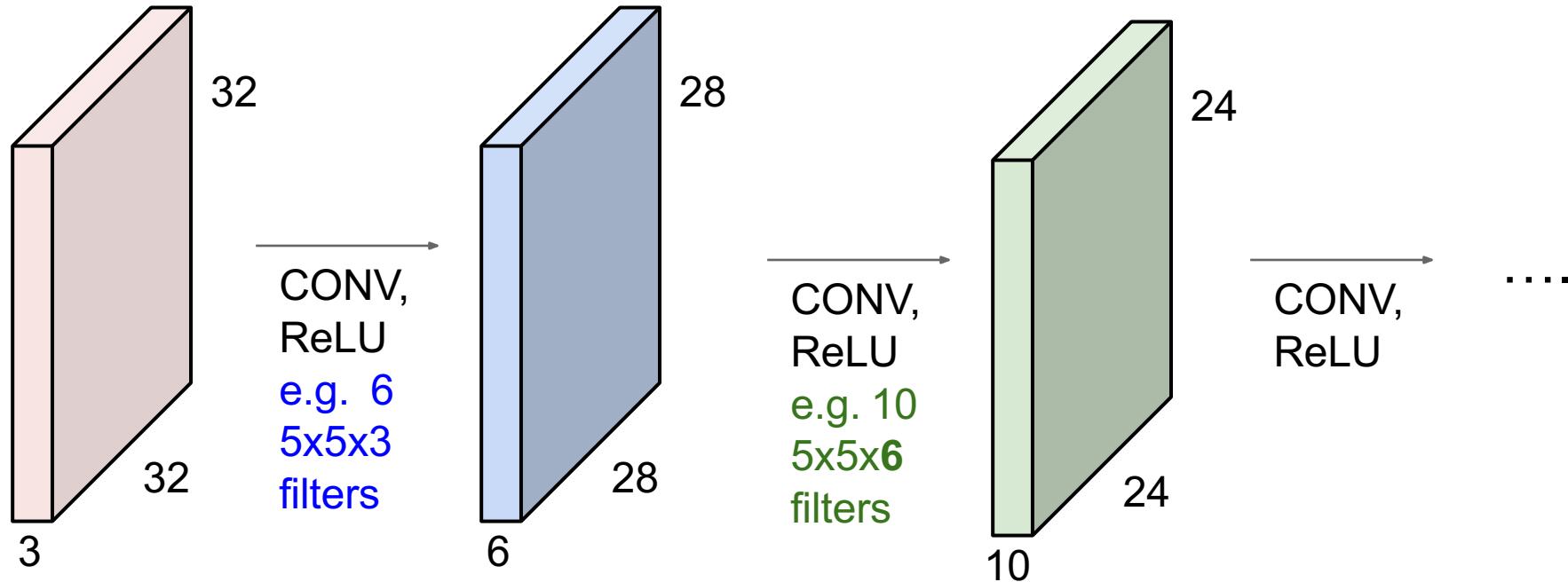


We stack these up to get a “new image” of size $28 \times 28 \times 6$!

Preview: ConvNet is a sequence of Convolution Layers, interspersed with activation functions



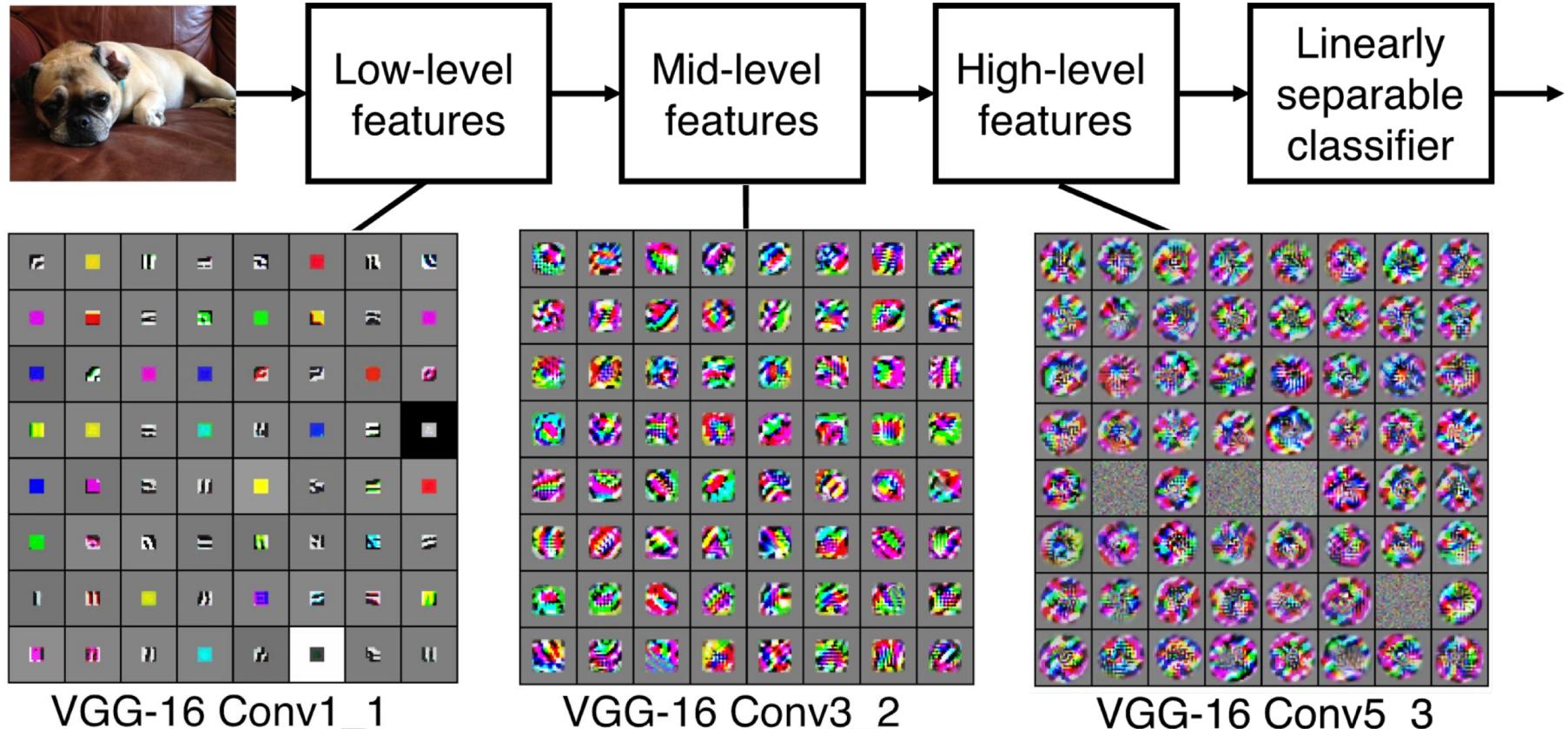
Preview: ConvNet is a sequence of Convolution Layers, interspersed with activation functions



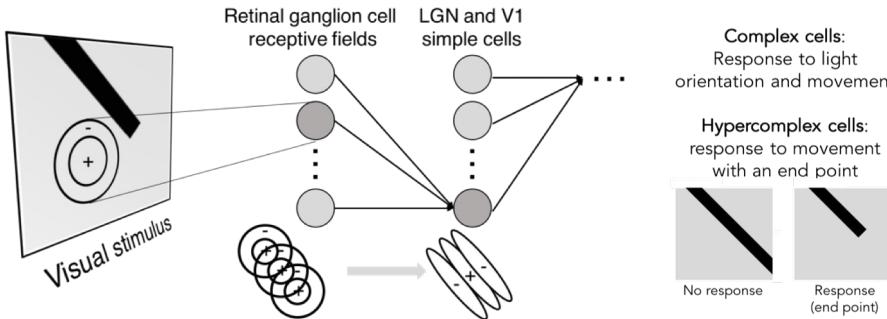
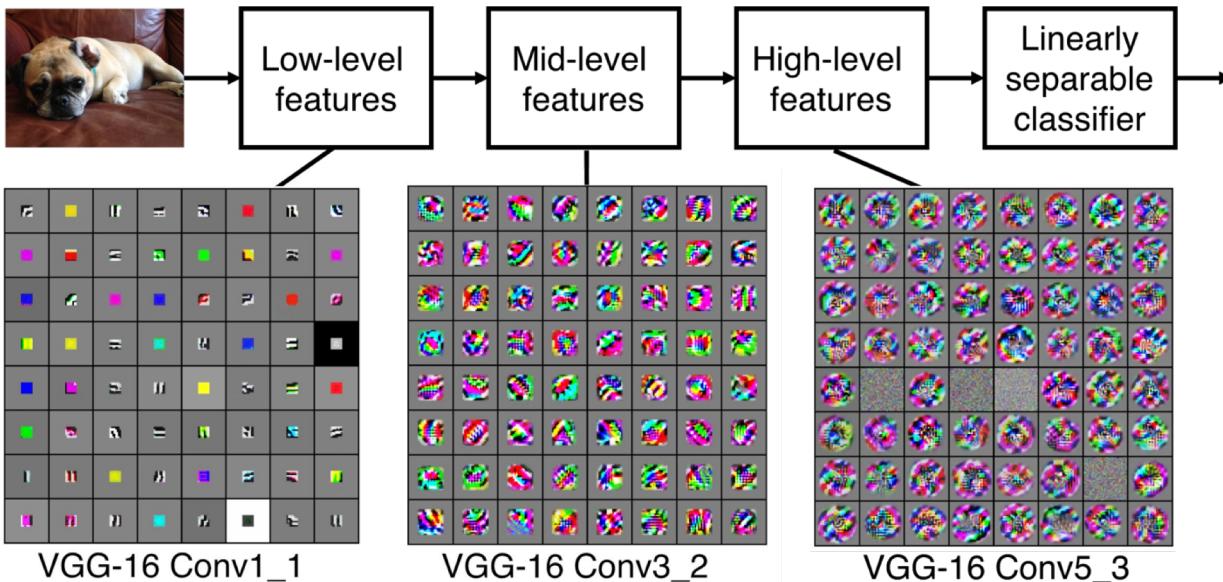
Preview

[Zeiler and Fergus 2013]

Visualization of VGG-16 by Lane McIntosh. VGG-16 architecture from [Simonyan and Zisserman 2014].

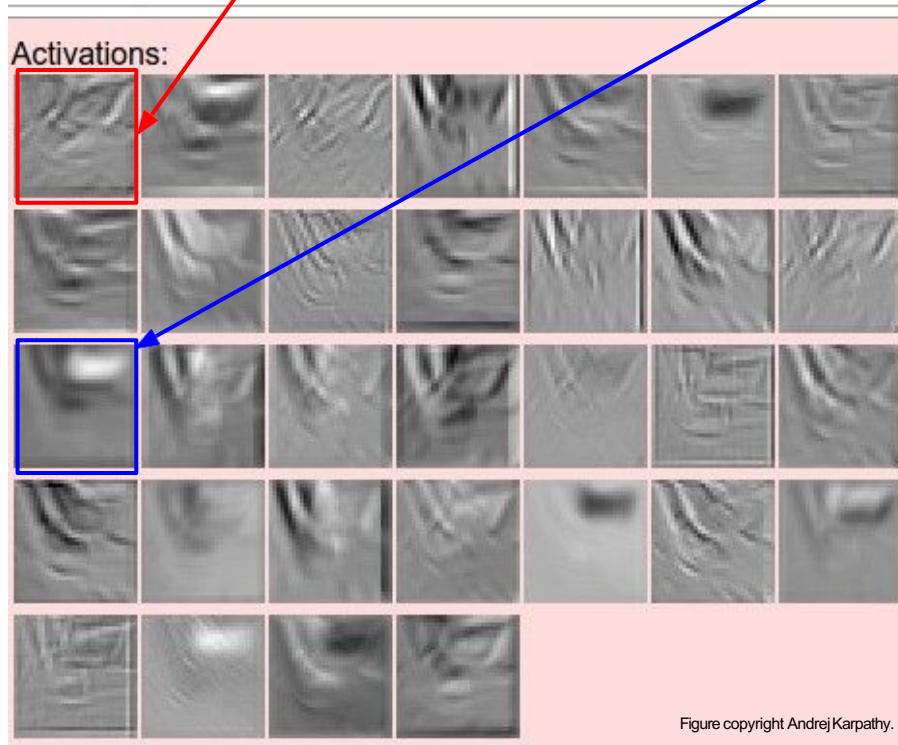


Preview





one filter =>
one activation map



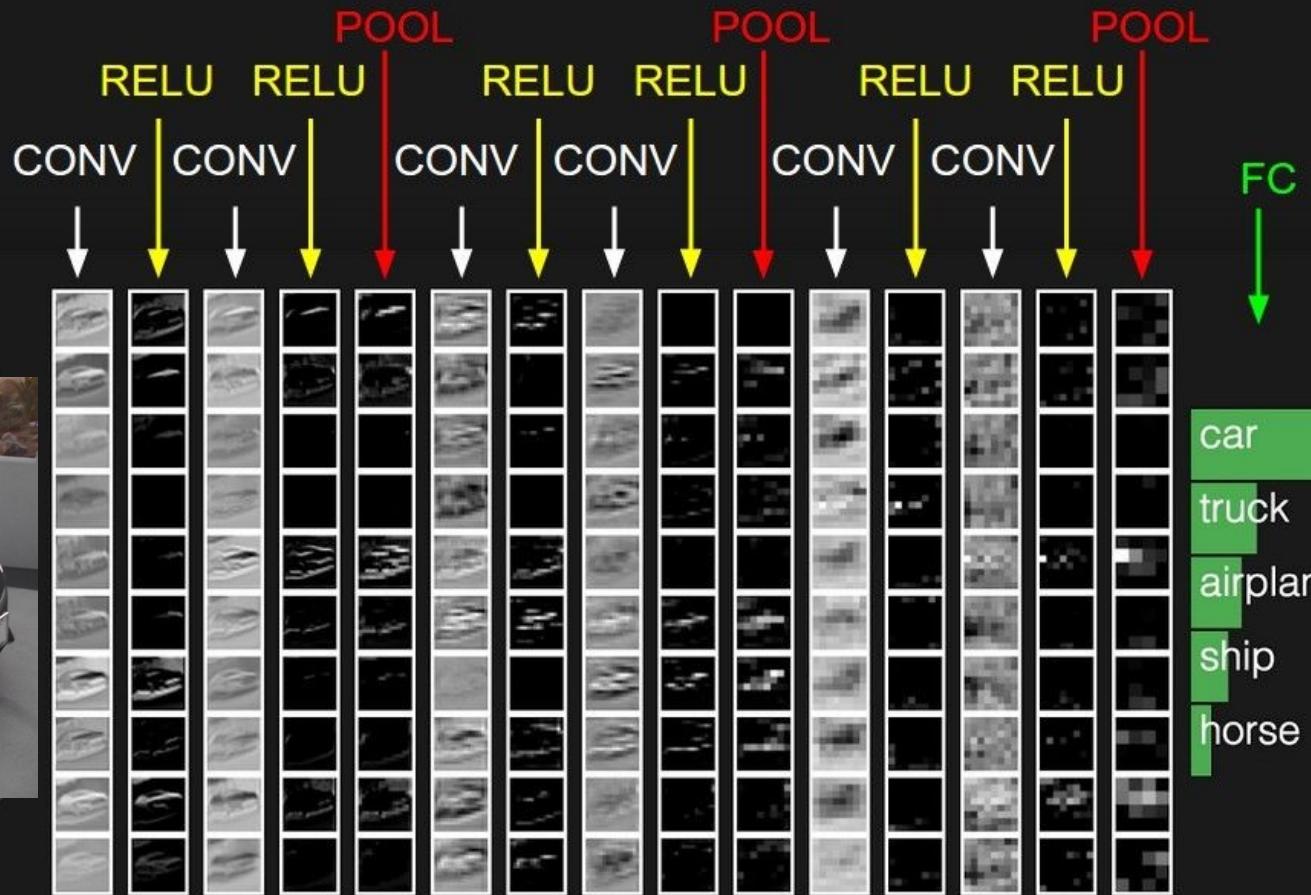
example 5x5 filters
(32 total)

We call the layer convolutional
because it is related to convolution
of two signals:

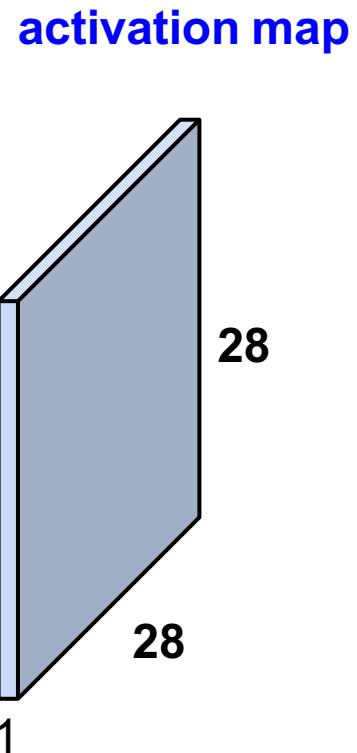
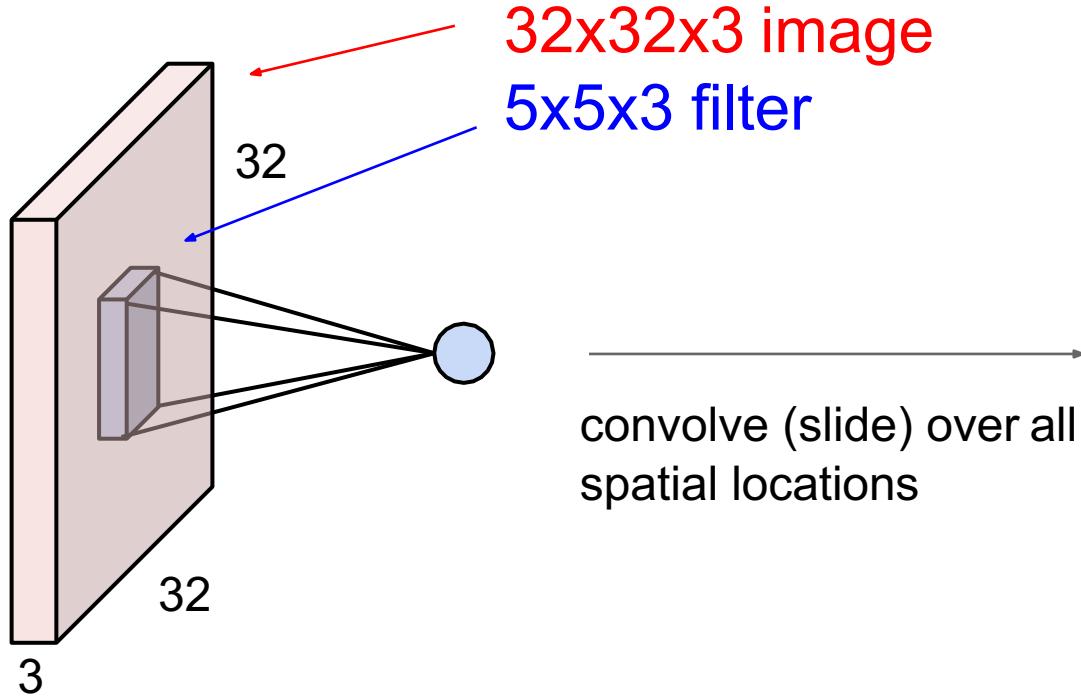
$$f[x,y] * g[x,y] = \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} f[n_1, n_2] \cdot g[x - n_1, y - n_2]$$

elementwise multiplication and sum of
a filter and the signal (image)

preview:

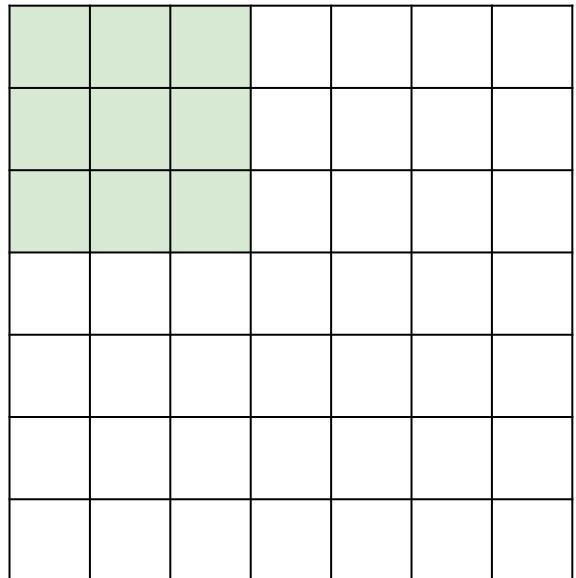


A closer look at spatial dimensions:



A closer look at spatial dimensions:

7



7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

7

7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

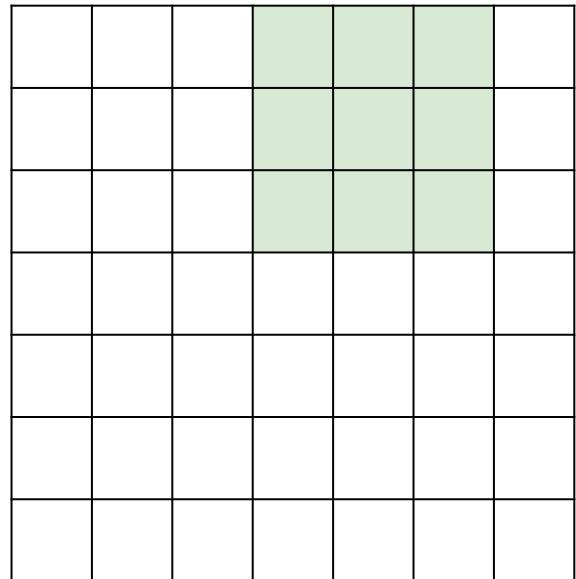
7

7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

7

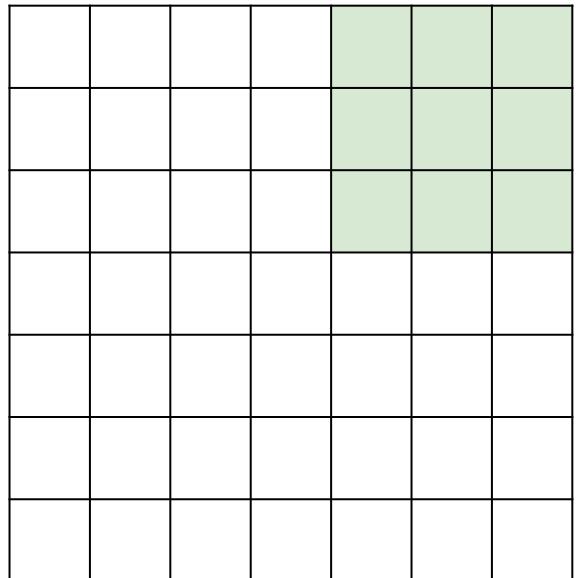


7x7 input (spatially)
assume 3x3 filter

7

A closer look at spatial dimensions:

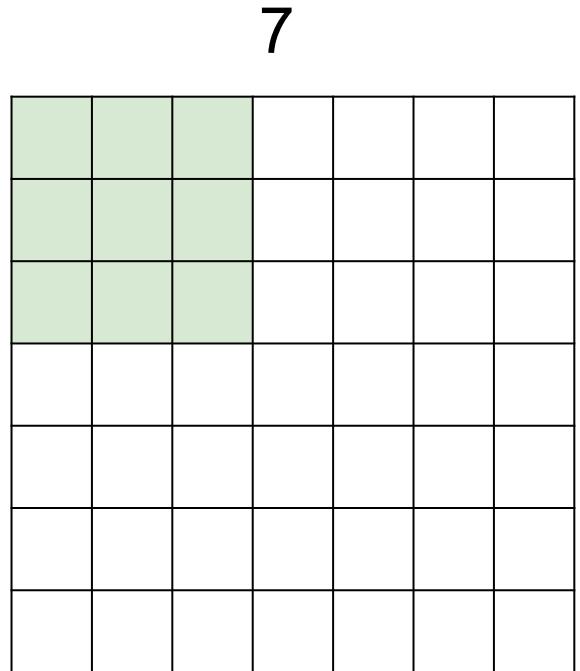
7



7x7 input (spatially)
assume 3x3 filter

=> 5x5 output

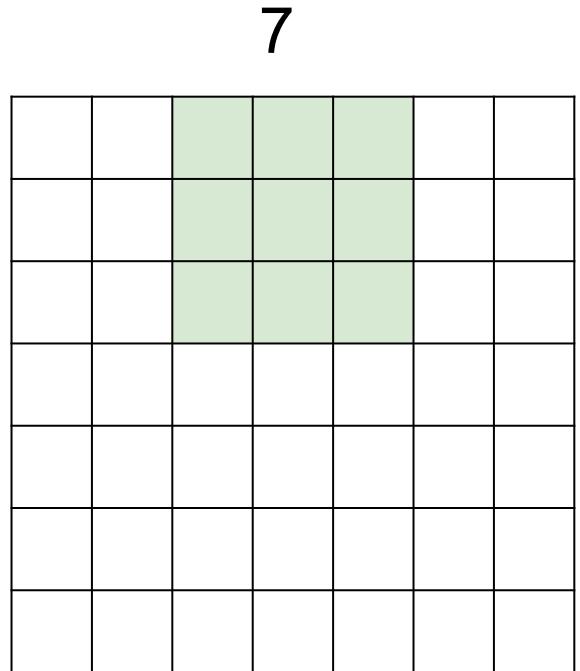
A closer look at spatial dimensions:



7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

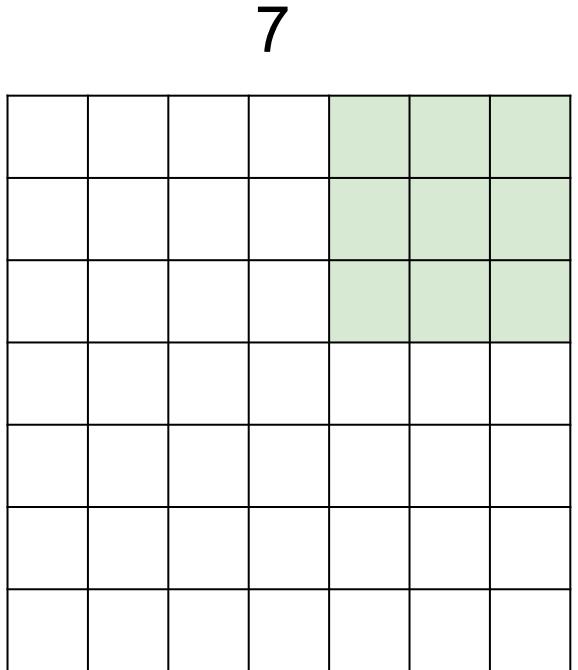
A closer look at spatial dimensions:



7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

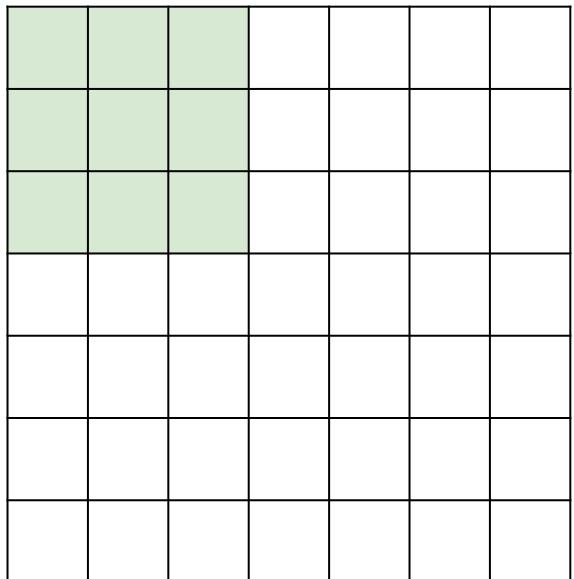
A closer look at spatial dimensions:



7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**
=> 3x3 output!

A closer look at spatial dimensions:

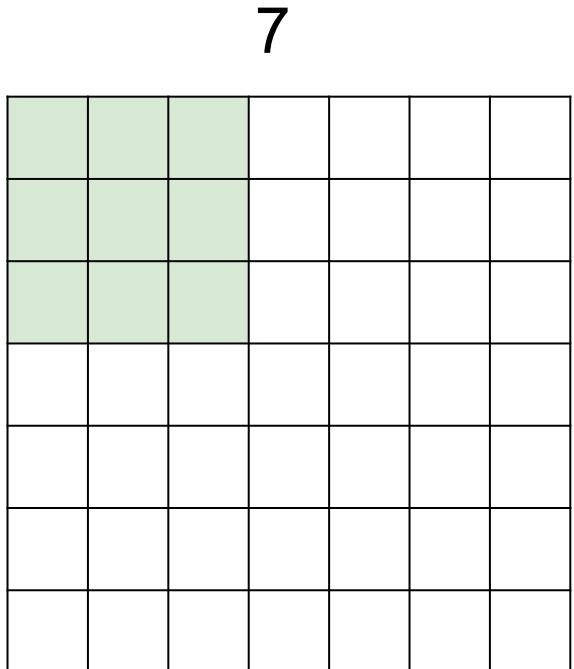
7



7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 3?**

A closer look at spatial dimensions:



7

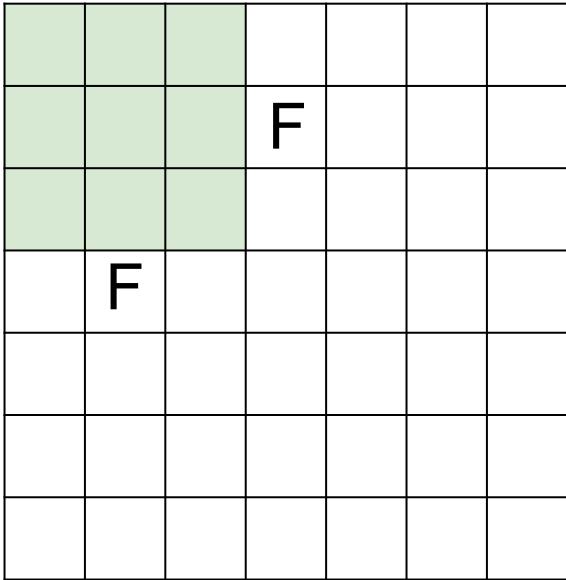
7

7x7 input (spatially)
assume 3x3 filter
applied **with stride 3?**

doesn't fit!

cannot apply 3x3 filter on
7x7 input with stride 3.

N



N

Output size:

$$(N - F) / \text{stride} + 1$$

e.g. $N = 7, F = 3$:

$$\text{stride } 1 \Rightarrow (7 - 3)/1 + 1 = 5$$

$$\text{stride } 2 \Rightarrow (7 - 3)/2 + 1 = 3$$

$$\text{stride } 3 \Rightarrow (7 - 3)/3 + 1 = 2.33 :\backslash$$

In practice: Common to zero pad the border

0	0	0	0	0	0		
0							
0							
0							
0							

e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

(recall:)

$$(N - F) / \text{stride} + 1$$

In practice: Common to zero pad the border

0	0	0	0	0	0		
0							
0							
0							
0							

e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

7x7 output!

In practice: Common to zero pad the border

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0							
0							
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e.g. input 7x7

3x3 filter, applied with stride 1

pad with 1 pixel border => what is the output?

7x7 output!

in general, common to see CONV layers with stride 1, filters of size FxF, and zero-padding with $(F-1)/2$. (will preserve size spatially)

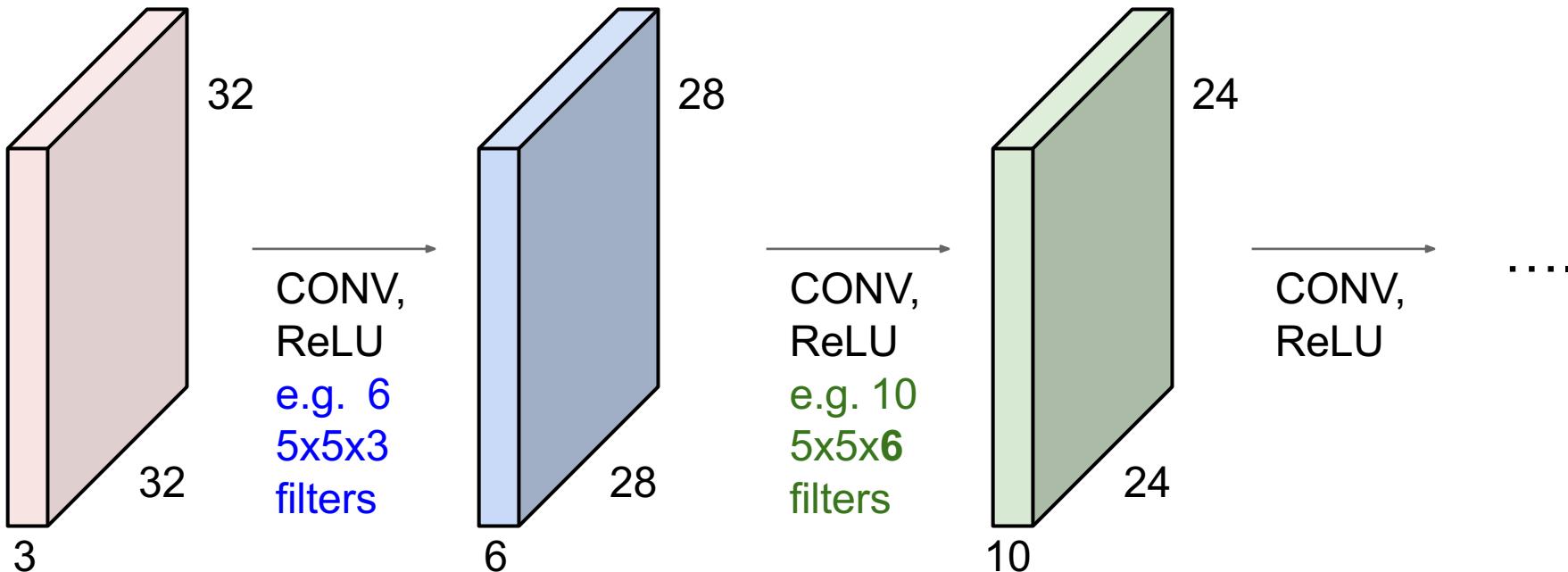
e.g. $F = 3 \Rightarrow$ zero pad with 1

$F = 5 \Rightarrow$ zero pad with 2

$F = 7 \Rightarrow$ zero pad with 3

Remember back to...

E.g. 32x32 input convolved repeatedly with 5x5 filters shrinks volumes spatially!
(32 -> 28 -> 24 ...). Shrinking too fast is not good, doesn't work well.

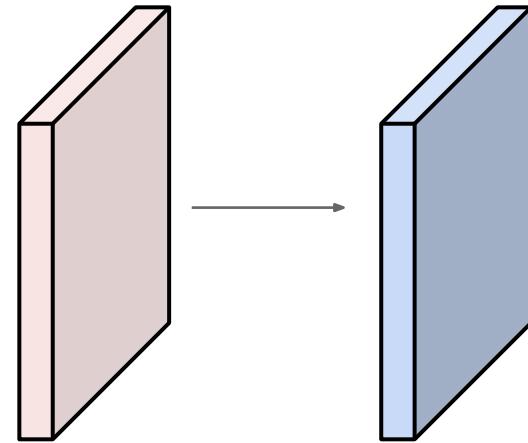


Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2

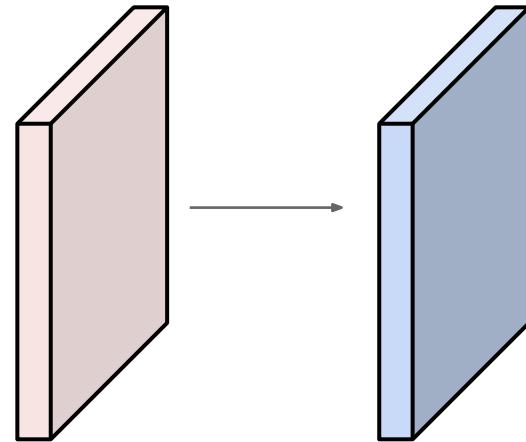
Output volume size: ?



Examples time:

Input volume: **32x32x3**

10 **5x5** filters with stride 1, pad **2**



Output volume size:

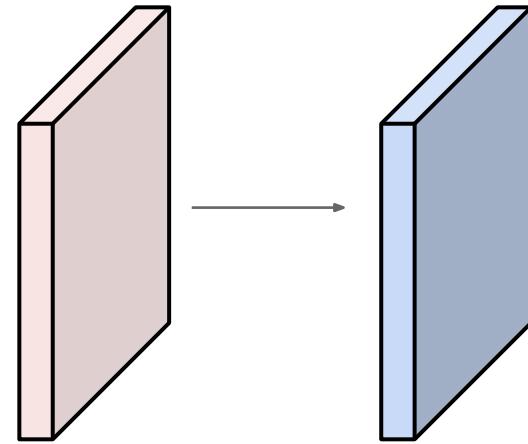
$(32+2*2-5)/1+1 = 32$ spatially, so

32x32x10

Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2

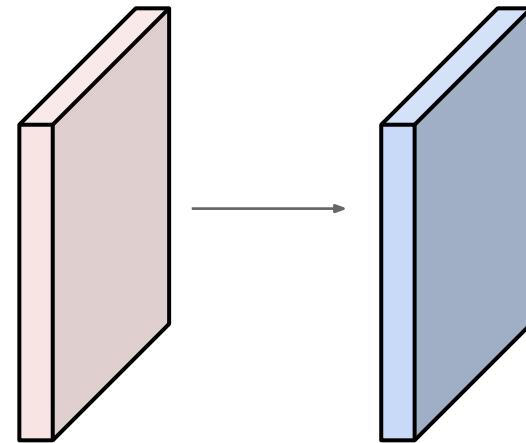


Number of parameters in this layer?

Examples time:

Input volume: **32x32x3**

10 5x5 filters with stride 1, pad 2



Number of parameters in this layer?

each filter has $5*5*3 + 1 = 76$ params (+1 for bias)
 $\Rightarrow 76*10 = 760$

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 .
- Produces a volume of size $W_2 \times H_2 \times D_2$ where:
 - $W_2 = (W_1 - F + 2P)/S + 1$
 - $H_2 = (H_1 - F + 2P)/S + 1$ (i.e. width and height are computed equally by symmetry)
 - $D_2 = K$
- With parameter sharing, it introduces $F \cdot F \cdot D_1$ weights per filter, for a total of $(F \cdot F \cdot D_1) \cdot K$ weights and K biases.
- In the output volume, the d -th depth slice (of size $W_2 \times H_2$) is the result of performing a valid convolution of the d -th filter over the input volume with a stride of S , and then offset by d -th bias.

Common settings:

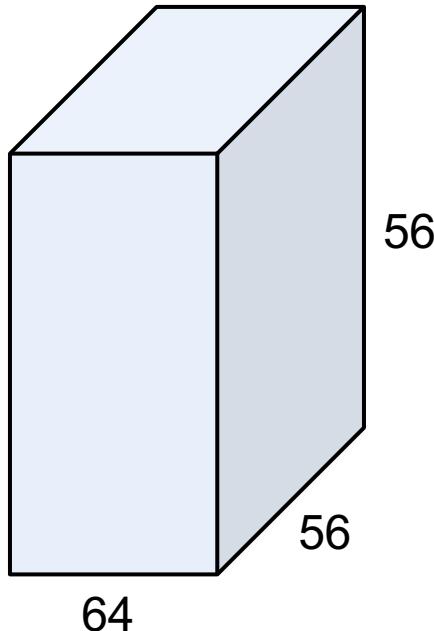
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$$K = (\text{powers of 2, e.g. } 32, 64, 128, 512)$$

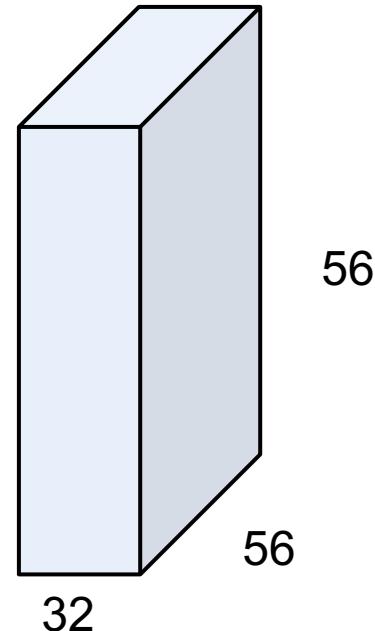
- $F = 3, S = 1, P = 1$
- $F = 5, S = 1, P = 2$
- $F = 5, S = 2, P = ? \text{ (whatever fits)}$
- $F = 1, S = 1, P = 0$

(btw, 1x1 convolution layers make perfect sense)

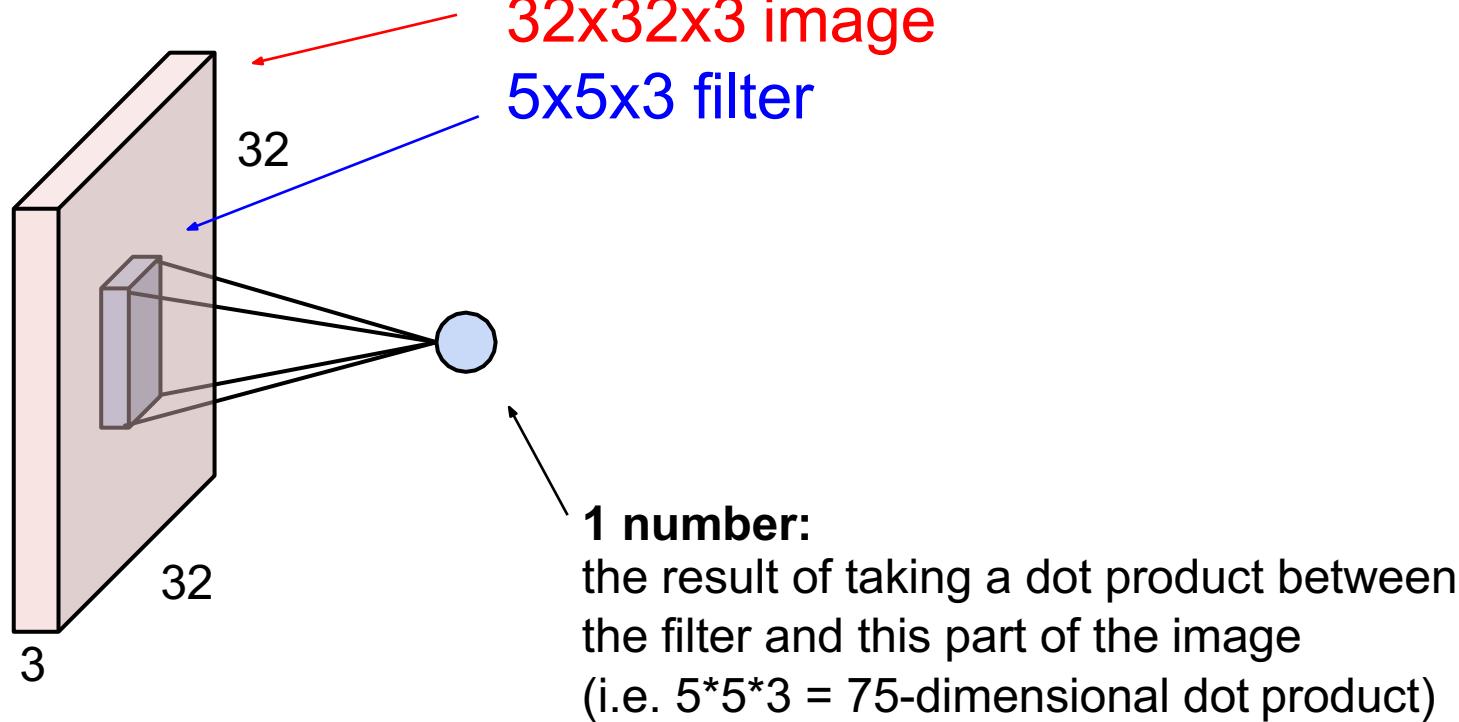


1x1 CONV
with 32 filters

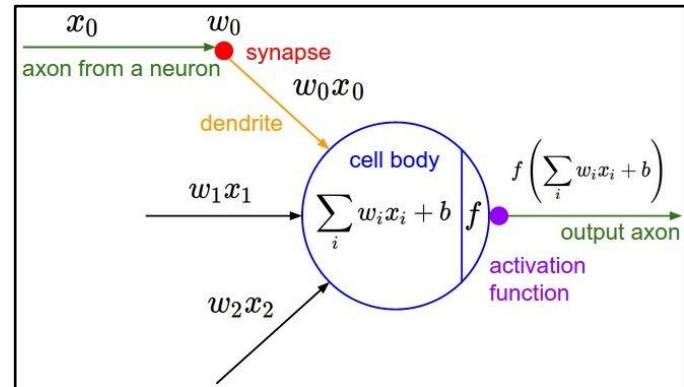
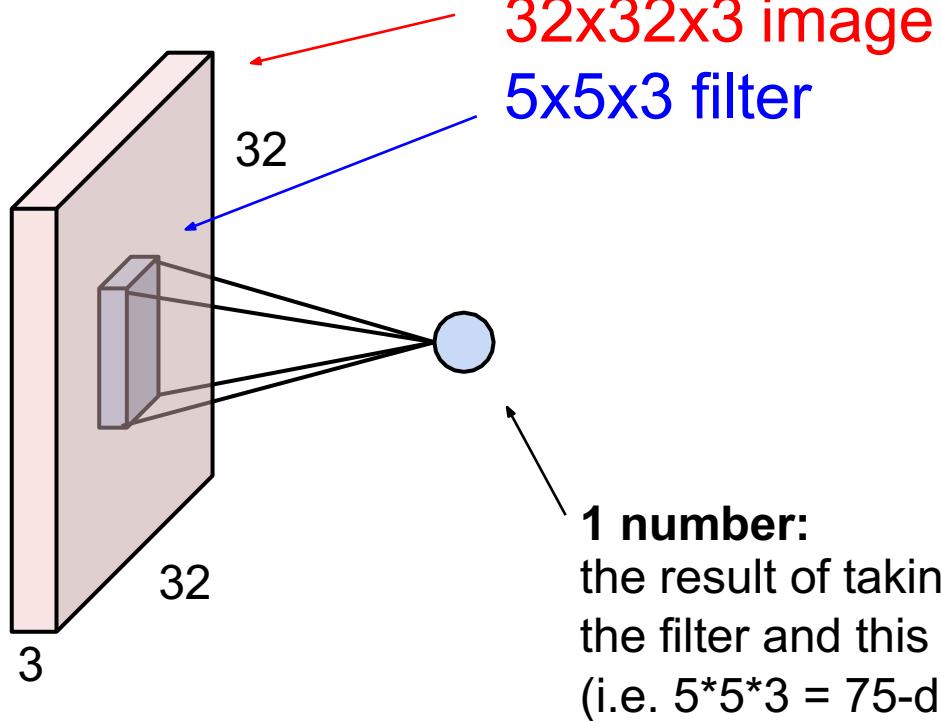
(each filter has size
1x1x64, and performs a
64-dimensional dot
product)



The brain/neuron view of CONV Layer

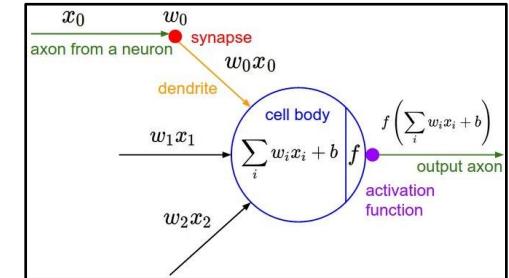
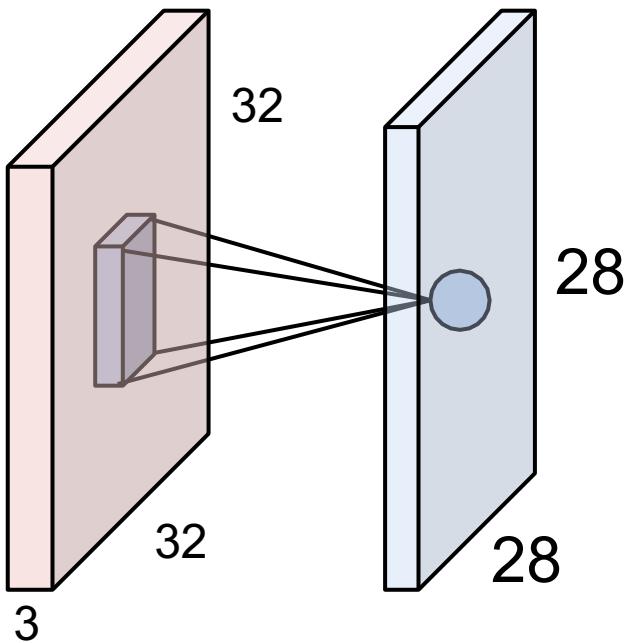


The brain/neuron view of CONV Layer



It's just a neuron with local connectivity...

The brain/neuron view of CONV Layer

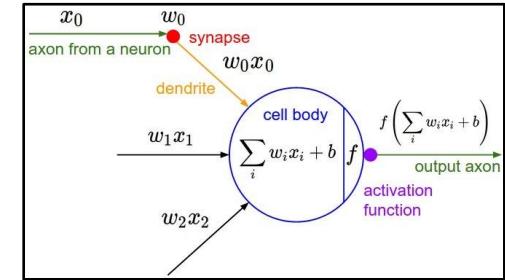
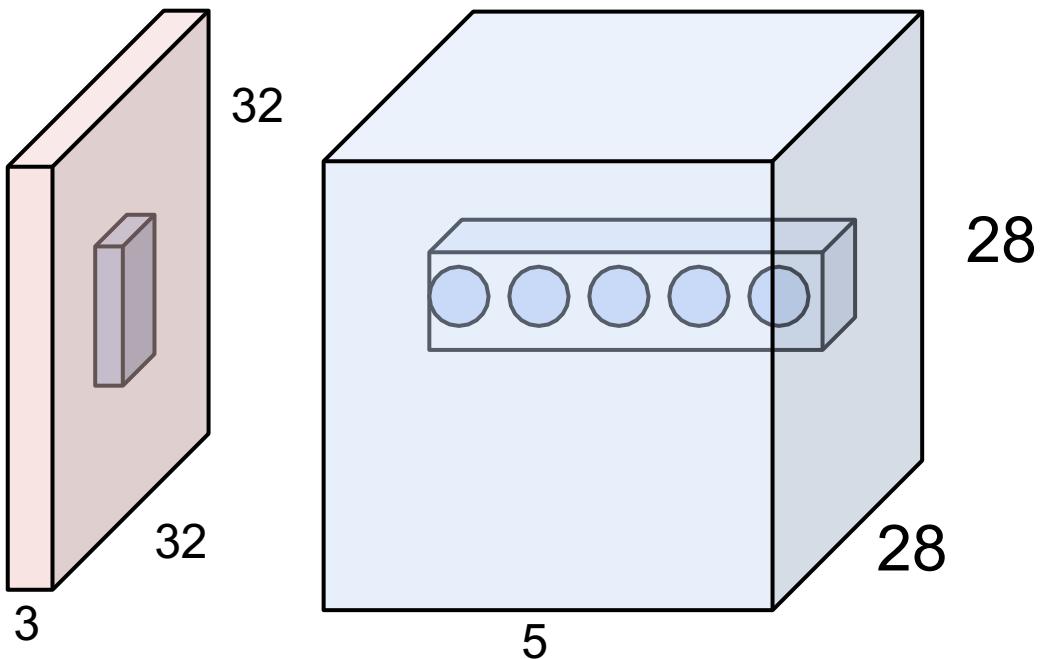


An activation map is a 28x28 sheet of neuron outputs:

1. Each is connected to a small region in the input
2. All of them share parameters

“5x5 filter” -> “5x5 receptive field for each neuron”

The brain/neuron view of CONV Layer



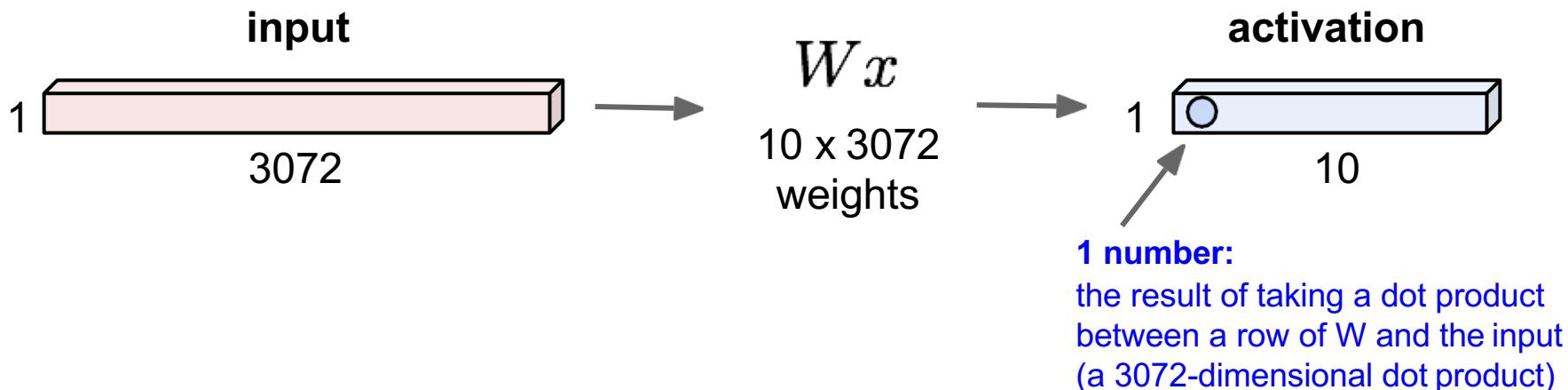
E.g. with 5 filters,
CONV layer consists of
neurons arranged in a 3D grid
($28 \times 28 \times 5$)

There will be 5 different
neurons all looking at the same
region in the input volume

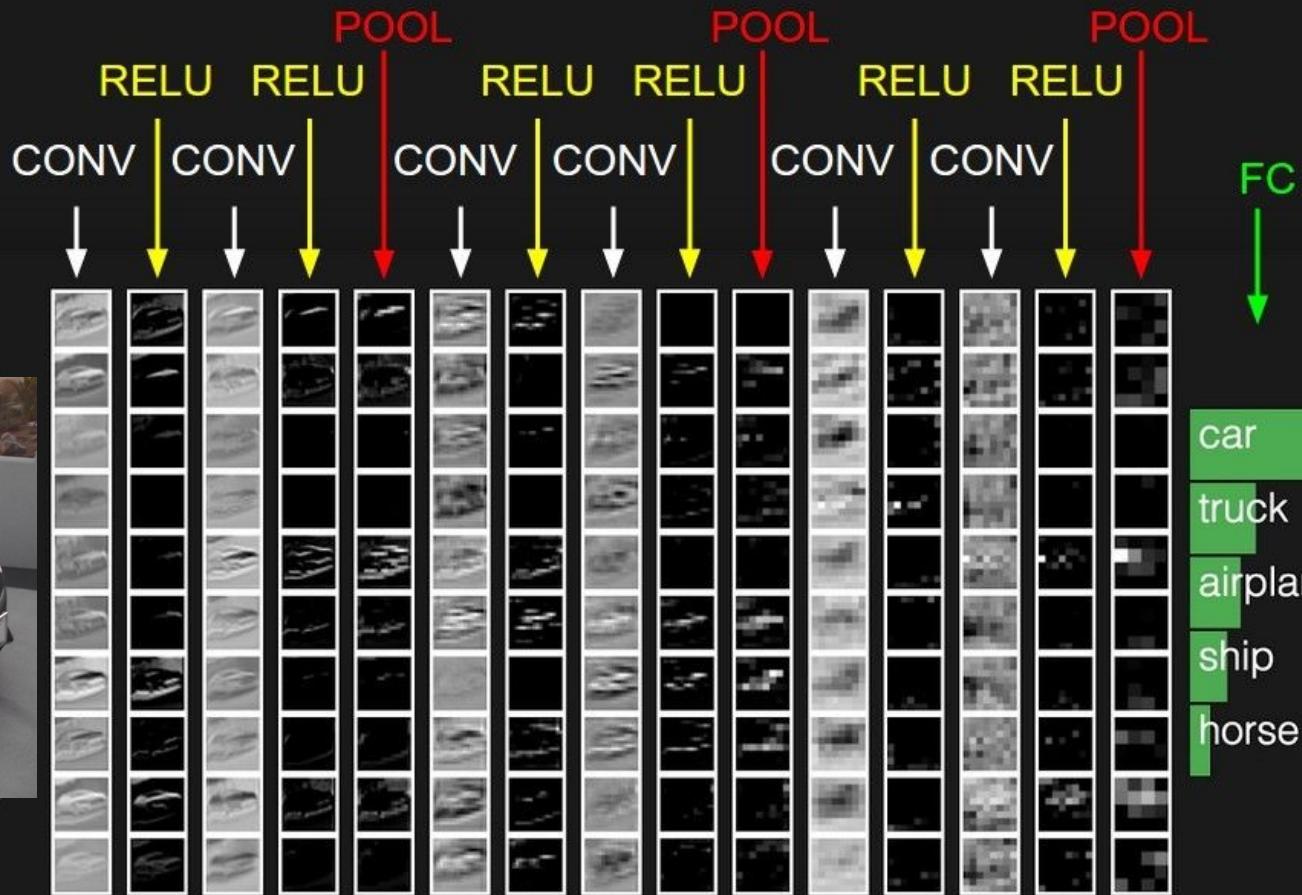
Reminder: Fully Connected Layer

32x32x3 image -> stretch to 3072 x 1

Each neuron
looks at the full
input volume

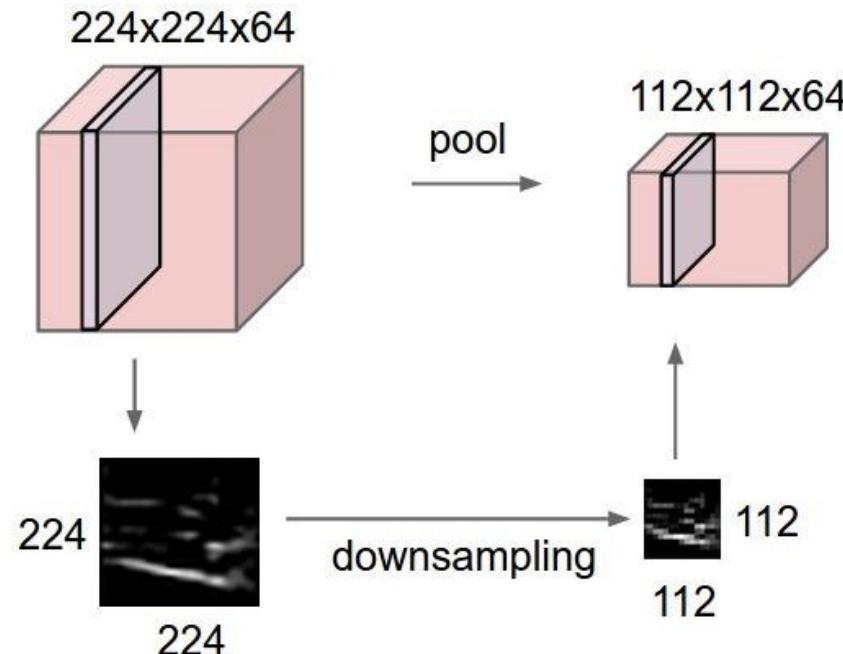


two more layers to go: POOL/FC



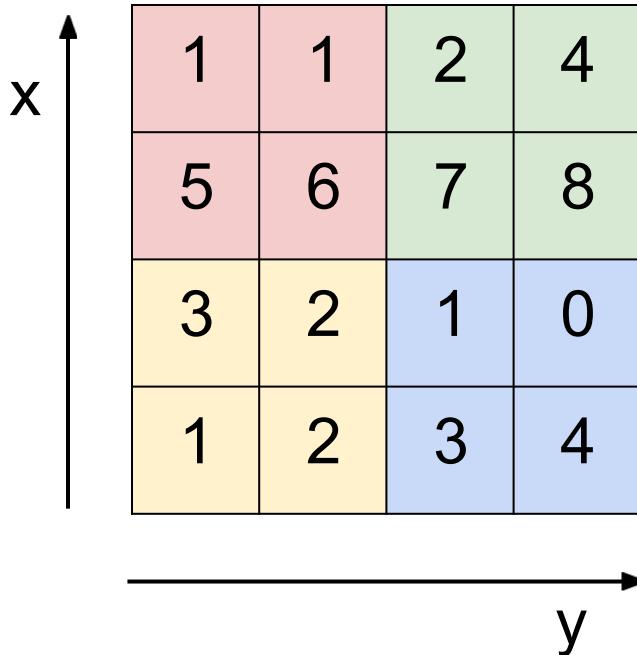
Pooling layer

- makes the representations smaller and more manageable
- operates over each activation map independently:



MAX POOLING

Single depth slice



max pool with 2x2 filters
and stride 2

6	8
3	4

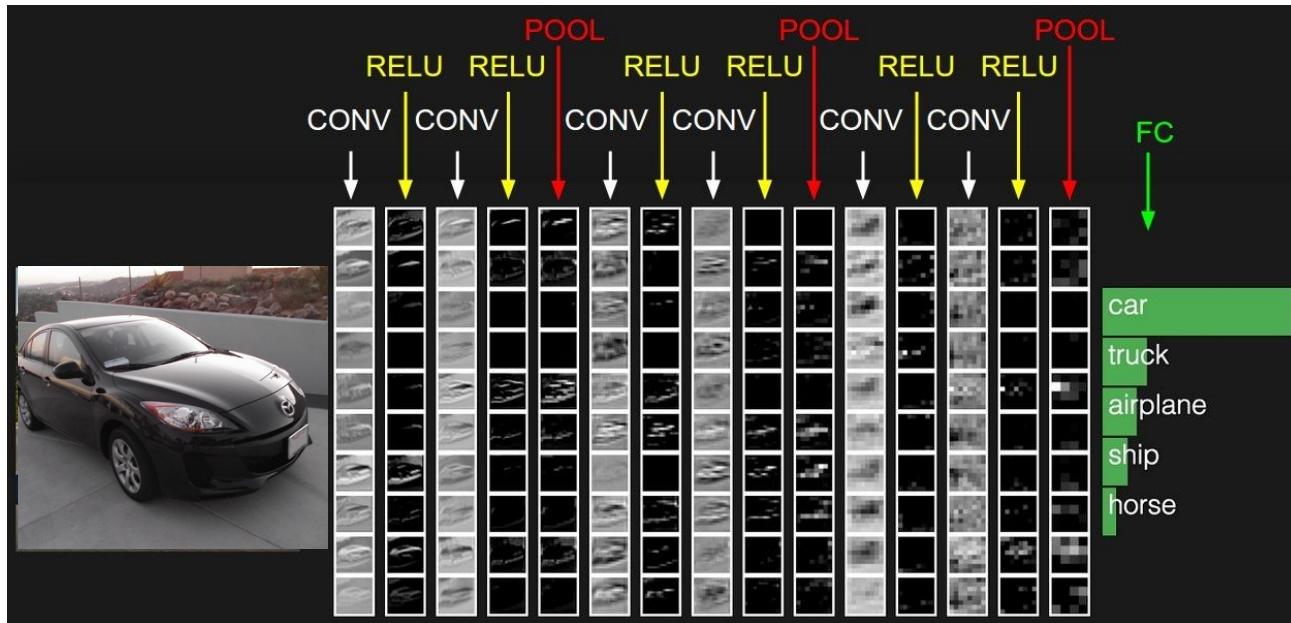
- Accepts a volume of size $W_1 \times H_1 \times D_1$
- Requires three hyperparameters:
 - their spatial extent F ,
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- Produces a volume of size $W_2 \times H_2 \times D_2$ where:
 - $W_2 = (W_1 - F)/S + 1$
 - $H_2 = (H_1 - F)/S + 1$
 - $D_2 = D_1$
- Introduces zero parameters since it computes a fixed function of the input
- Note that it is not common to use zero-padding for Pooling layers

Common settings:

- Accepts a volume of size $W_1 \times H_1 \times D_1$ $F = 2, S = 2$
- Requires three hyperparameters:
 - their spatial extent F ,
 - the stride S , $F = 3, S = 2$
- Produces a volume of size $W_2 \times H_2 \times D_2$ where:
 - $W_2 = (W_1 - F)/S + 1$
 - $H_2 = (H_1 - F)/S + 1$
 - $D_2 = D_1$
- Introduces zero parameters since it computes a fixed function of the input
- Note that it is not common to use zero-padding for Pooling layers

Fully Connected Layer (FC layer)

- Contains neurons that connect to the entire input volume, as in ordinary Neural Networks



Summary

- ConvNets stack CONV,POOL,FC layers
- Trend towards smaller filters and deeper architectures
- Trend towards getting rid of POOL/FC layers (just CONV)
- Historically architectures looked like
 $[(CONV-RELU)^*N-POOL?]^*M-(FC-RELU)^*K, SOFTMAX$
where N is usually up to ~5, M is large, $0 \leq K \leq 2$.
 - but recent advances such as ResNet/GoogLeNet have challenged this paradigm