CS7GV1: Computer Vision

Convolutional neural networks (CNNs)

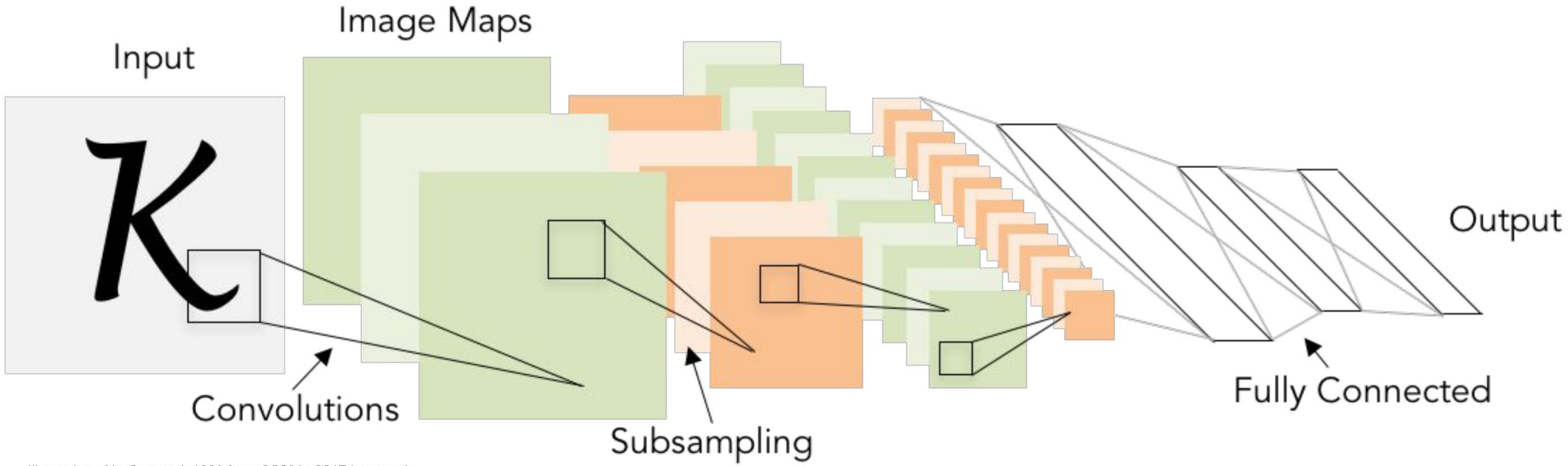


Illustration of LeCun et al. 1998 from CS231n 2017 Lecture 1

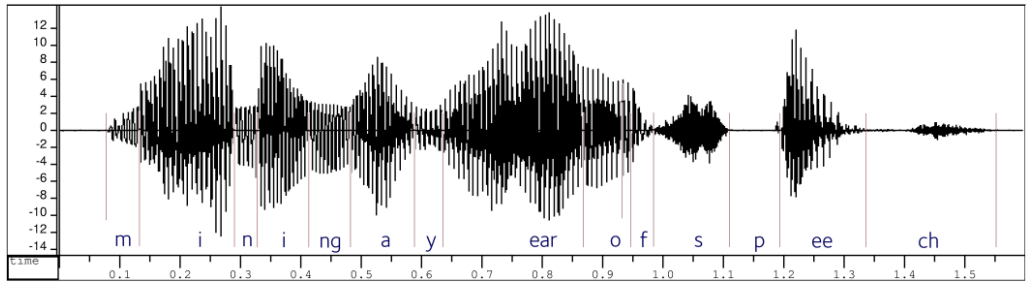
Credits: Some Slides from Noah Snavely (Cornell)
and Fei-Fei Li, Justin Johnson, Serena Yeung (Stanford)
http://vision.stanford.edu/teaching/cs231n/

Readings

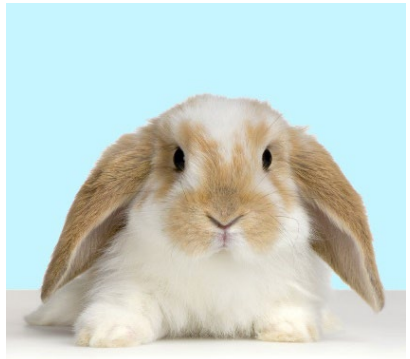
- Convolutional neural networks
  - http://cs231n.github.io/convolutional-networks/

Convolutional neural networks

- Version of deep neural networks designed for signals
  - 1D signals (e.g., speech waveforms)

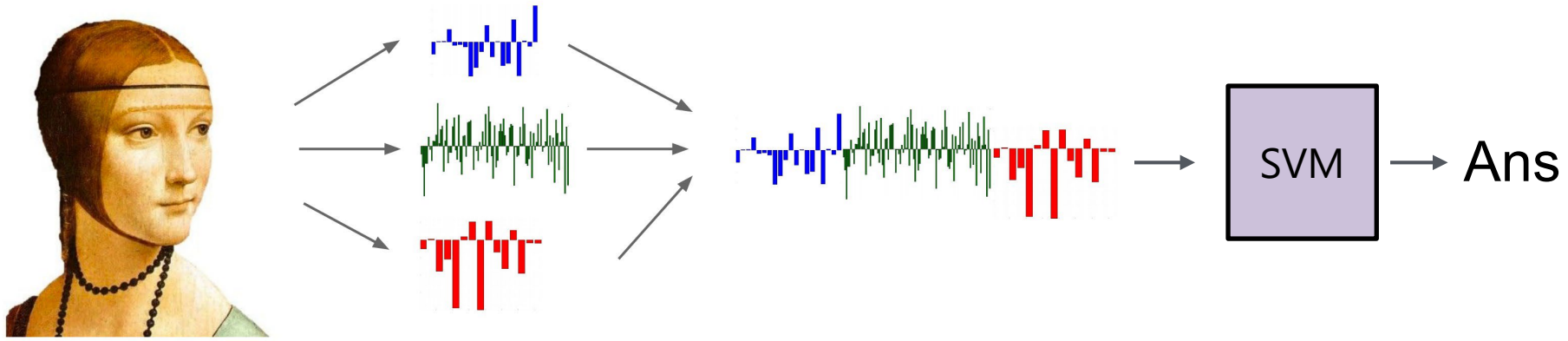


  - 2D signals (e.g., images)



Motivation – Feature Learning

Life Before Deep Learning



Input Pixels

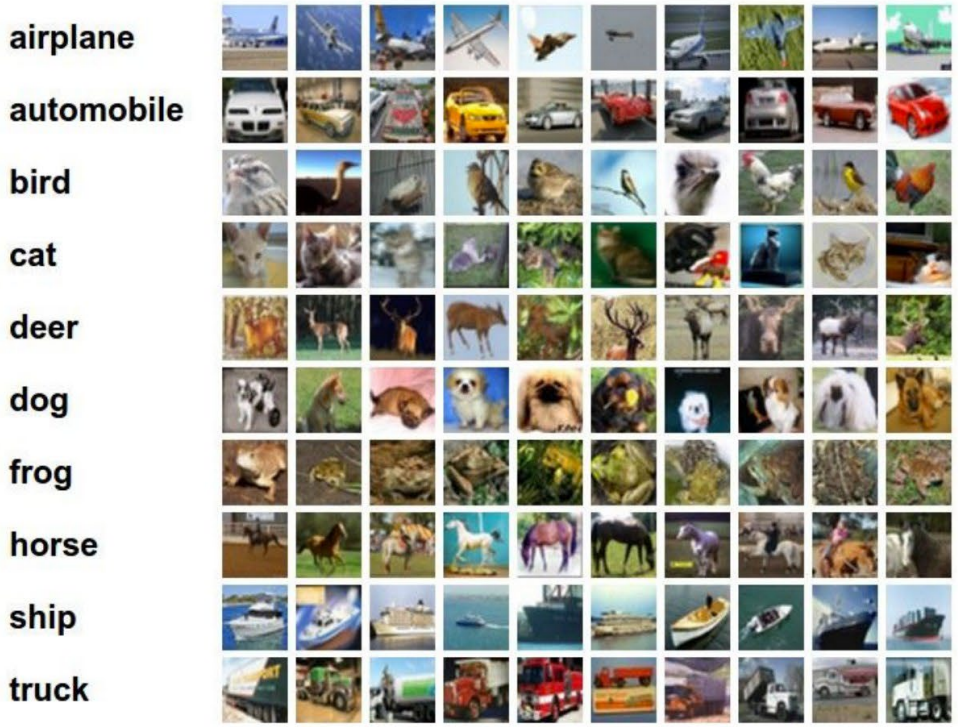
Extract Hand-Crafted Features

Concatenate into a vector ***x***

Linear Classifier

Figure: Karpathy 2016

Why use features? Why not pixels?



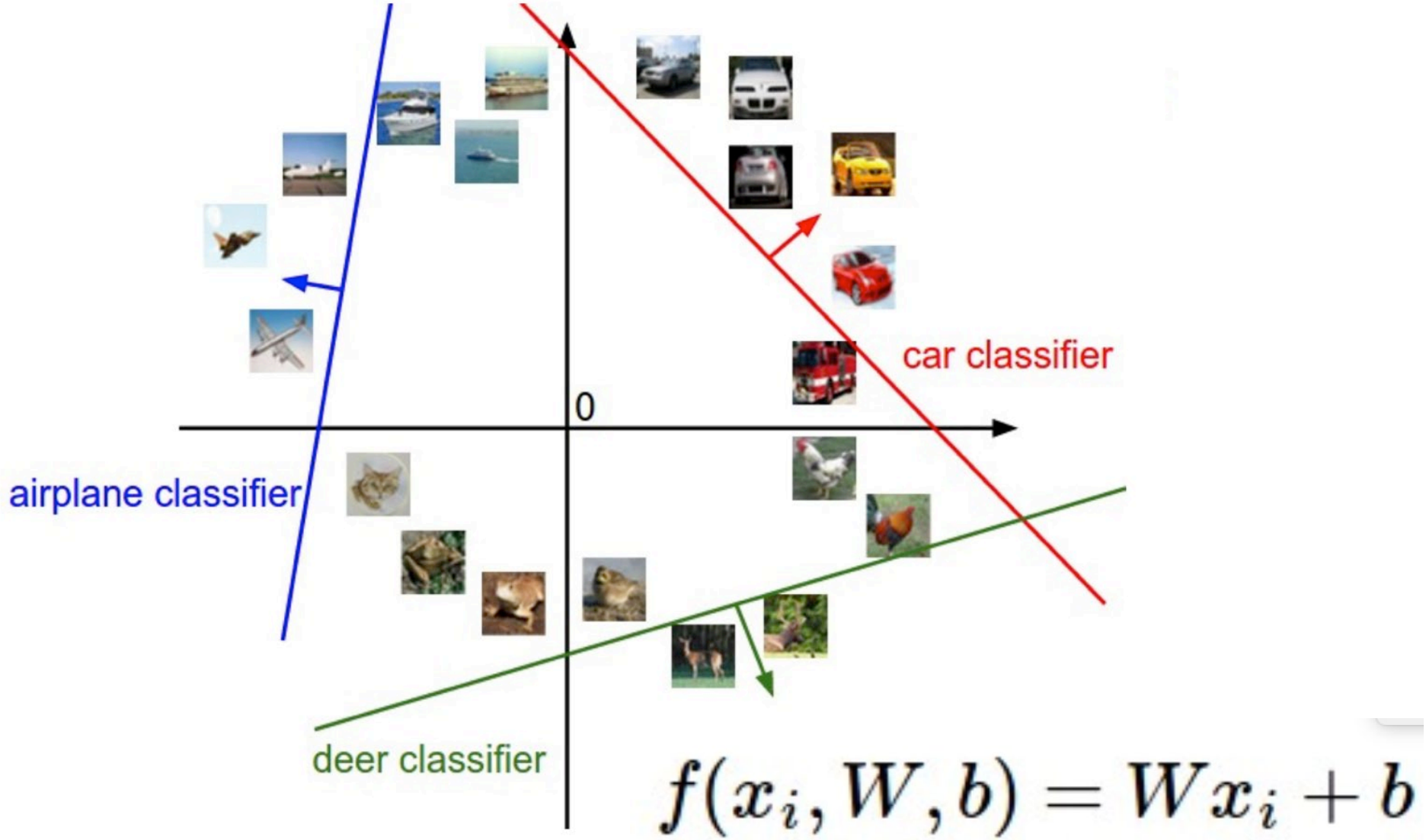
$$f(x_i, W, b) = Wx_i + b$$

Q: What would be a very hard set of classes for a linear classifier to distinguish?

(assuming x = pixels)

Slide from Karpathy 2016

Linearly separable classes



$$f(x_i, W, b) = Wx_i + b$$

Aside: Image Features

Class scores

$$f(x) = Wx$$

Aside: Image Features

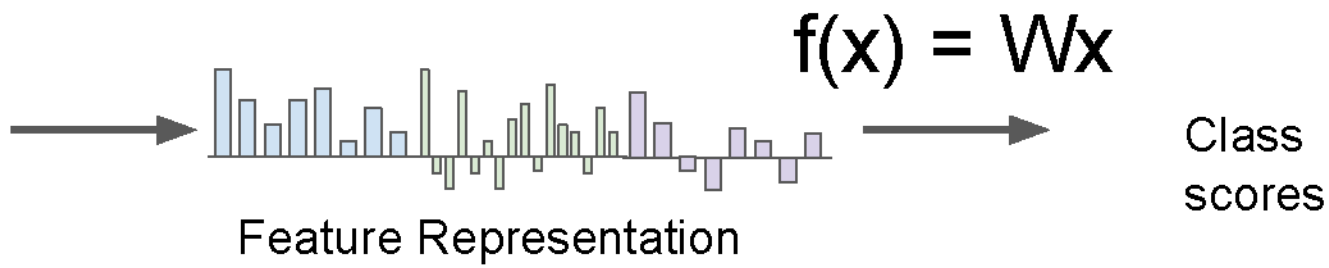
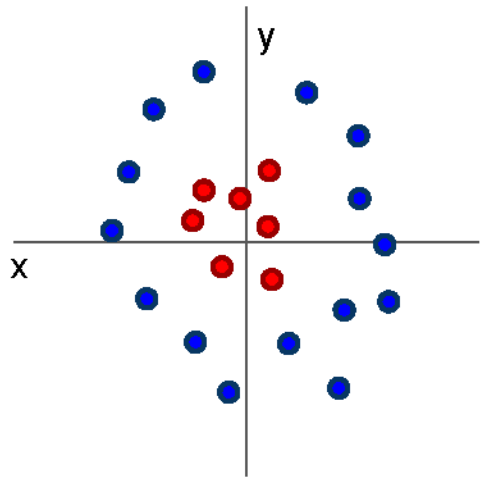
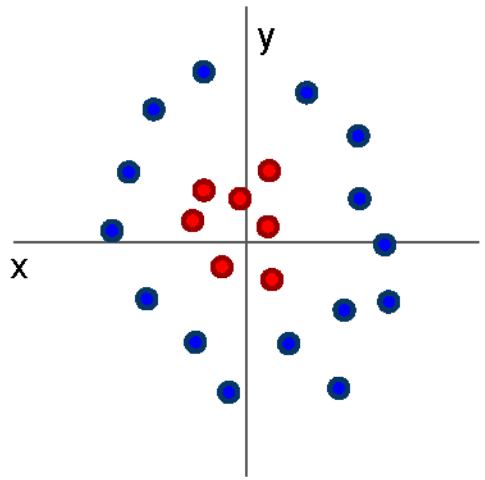


Image Features: Motivation



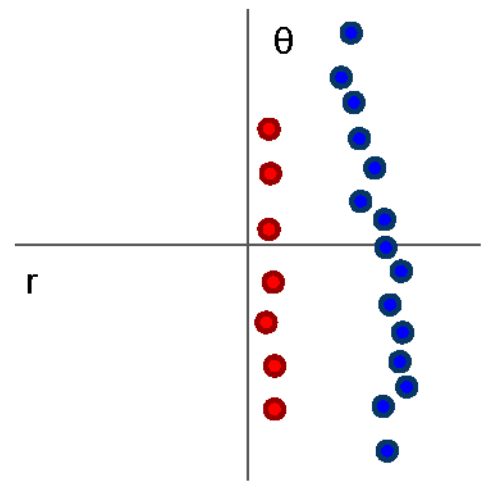
Cannot separate red and blue points with linear classifier

Image Features: Motivation



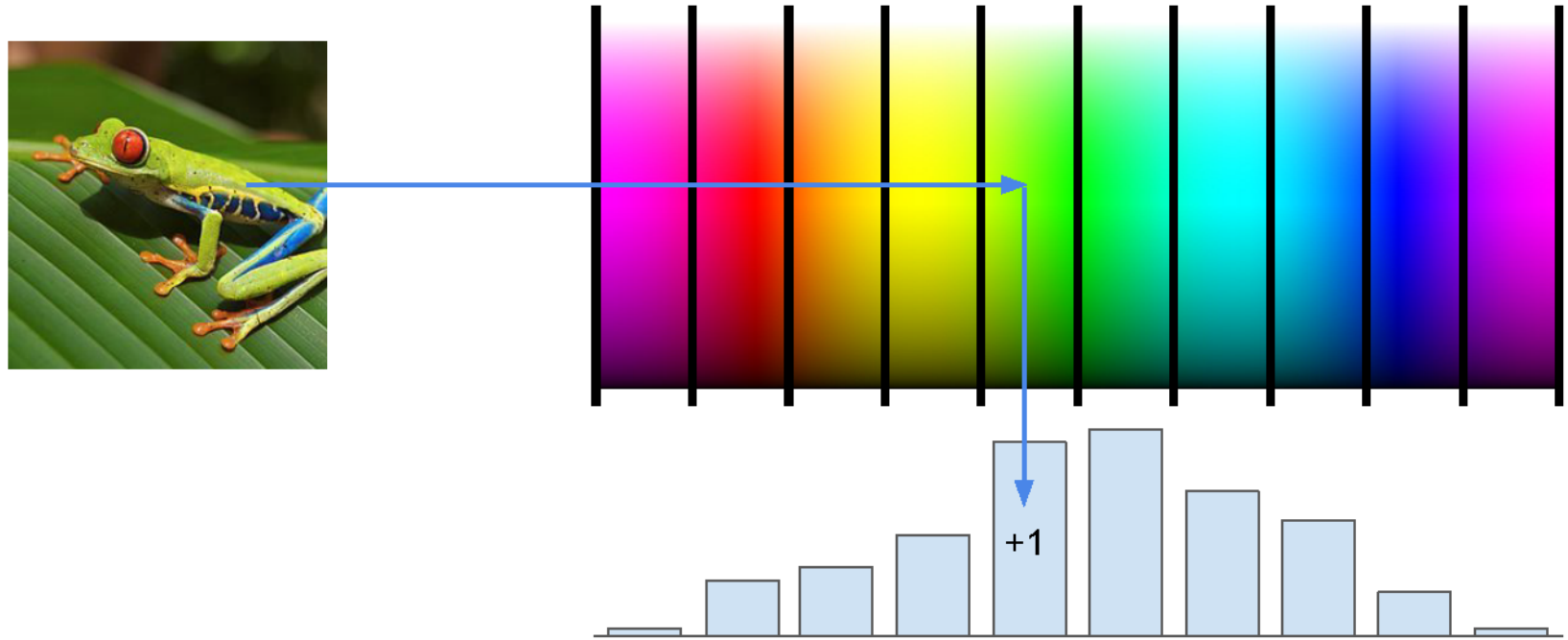
Cannot separate red and blue points with linear classifier

$f(x, y) = (r(x, y), \theta(x, y))$



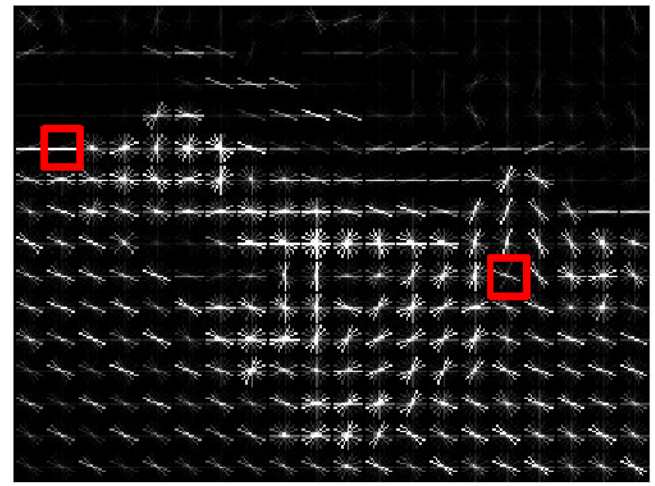
After applying feature transform, points can be separated by linear classifier

Example: Color Histogram



Example: Histogram of Oriented Gradients (HoG)

Divide image into 8x8 pixel regions
Within each region quantize edge direction into 9 bins



Example: 320x240 image gets divided into 40x30 bins; in each bin there are 9 numbers so feature vector has 30*40*9 = 10,800 numbers

Lowe, "Object recognition from local scale-invariant features", ICCV 1999
Dalal and Triggs, "Histograms of oriented gradients for human detection," CVPR 2005

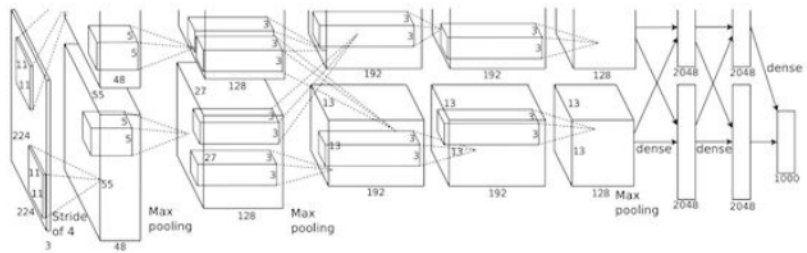
Image features vs ConvNets

Feature Extraction

f

10 numbers giving scores for classes

training

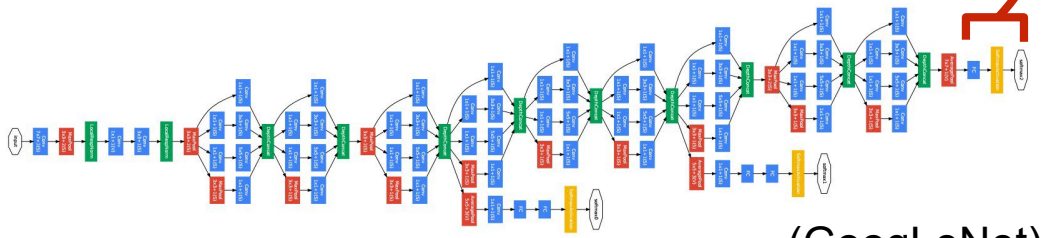


Krizhevsky, Sutskever, and Hinton, "Imagenet classification with deep convolutional neural networks", NIPS 2012. Figure copyright Krizhevsky, Sutskever, and Hinton, 2012. Reproduced with permission.

10 numbers giving scores for classes

training

Last layer of most CNNs is a linear classifier



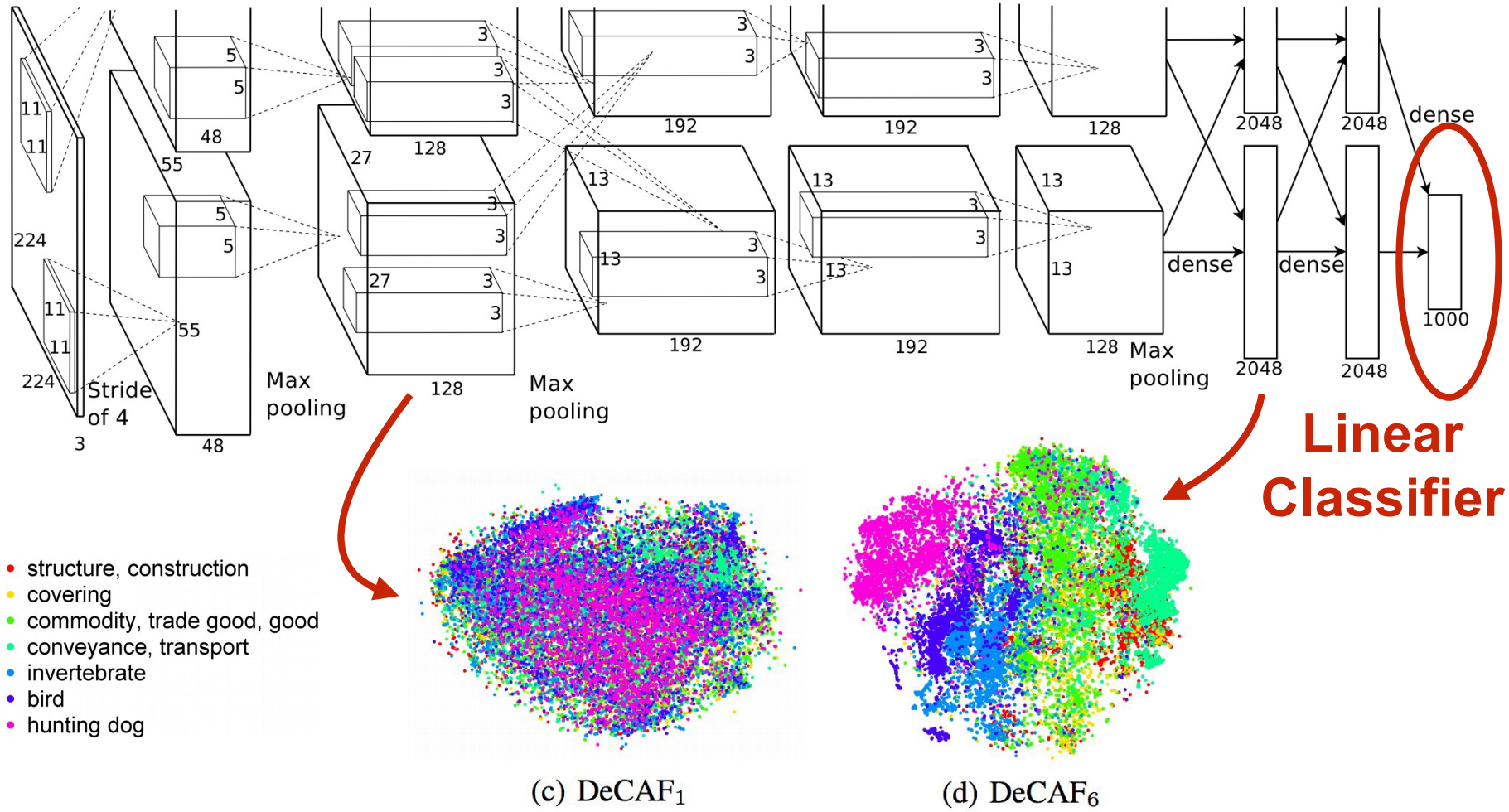
Ans

Input Pixels

Perform everything with a big neural network, trained end-to-end

Key: perform enough processing so that by the time you get to the end of the network, the classes are linearly separable

Visualizing AlexNet in 2D with t-SNE



(2D visualization using t-SNE)

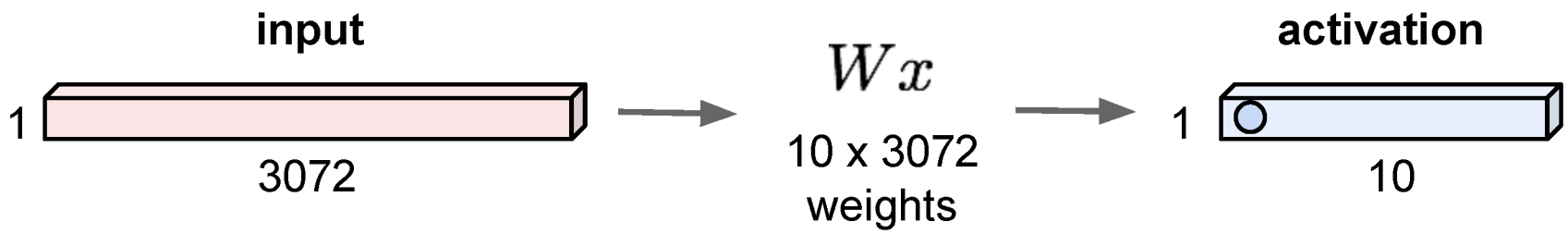
[Donahue, "DeCAF: DeCAF: A Deep Convolutional …", arXiv 2013]

Convolutional neural networks

- Layer types:
  - Fully-connected layer
  - *Convolutional layer*
  - Pooling layer

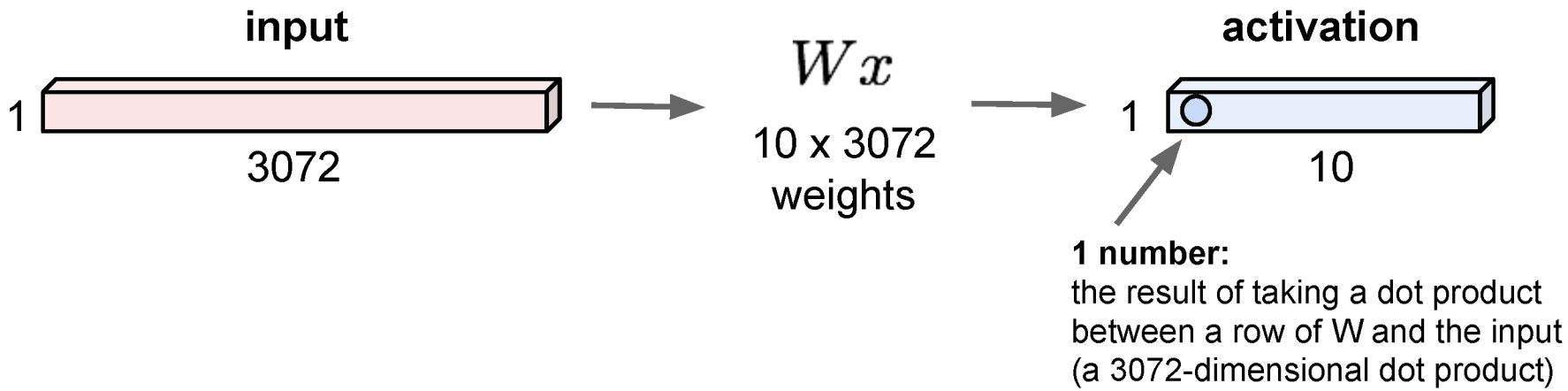
Fully Connected Layer

32x32x3 image -> stretch to 3072 x 1



Fully Connected Layer

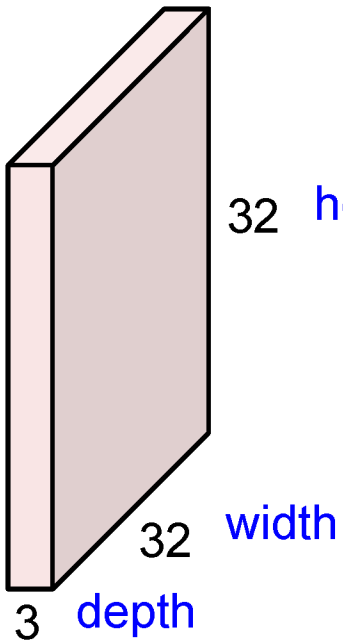
32x32x3 image -> stretch to 3072 x 1



Same as a linear classifer!

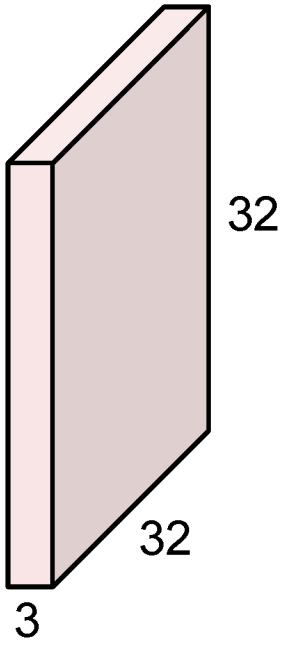
Convolution Layer

32x32x3 image -> preserve spatial structure

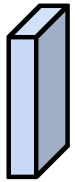


Convolution Layer

32x32x3 image



5x5x3 filter

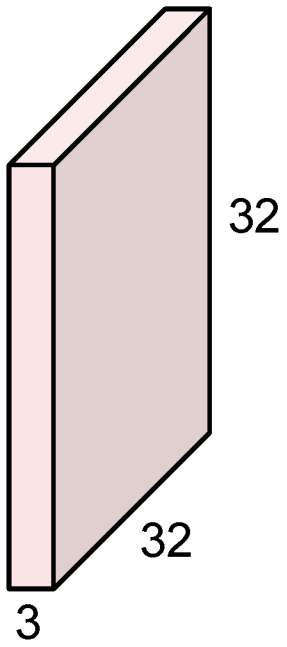


Convolve the filter with the image
i.e. “slide over the image spatially,
computing dot products”

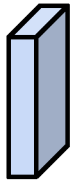
Convolution Layer

Filters always extend the full depth of the input volume

32x32x3 image



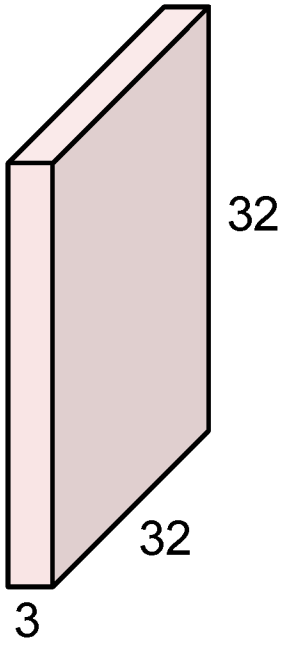
5x5x3 filter



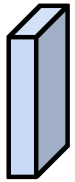
Convolve the filter with the image i.e. “slide over the image spatially, computing dot products”

Convolution Layer

32x32x3 image



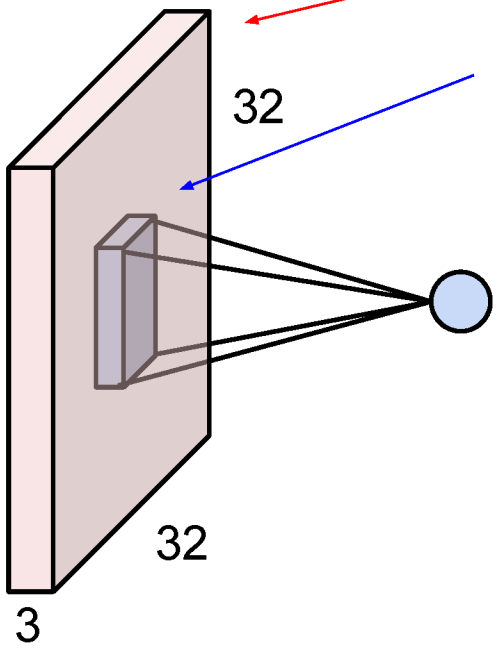
5x5x3 filter



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

Number of weights: 5 x 5 x 3 + 1 = **76**
(vs. 3072 for a fully-connected layer)
(+1 for bias)

Convolution Layer



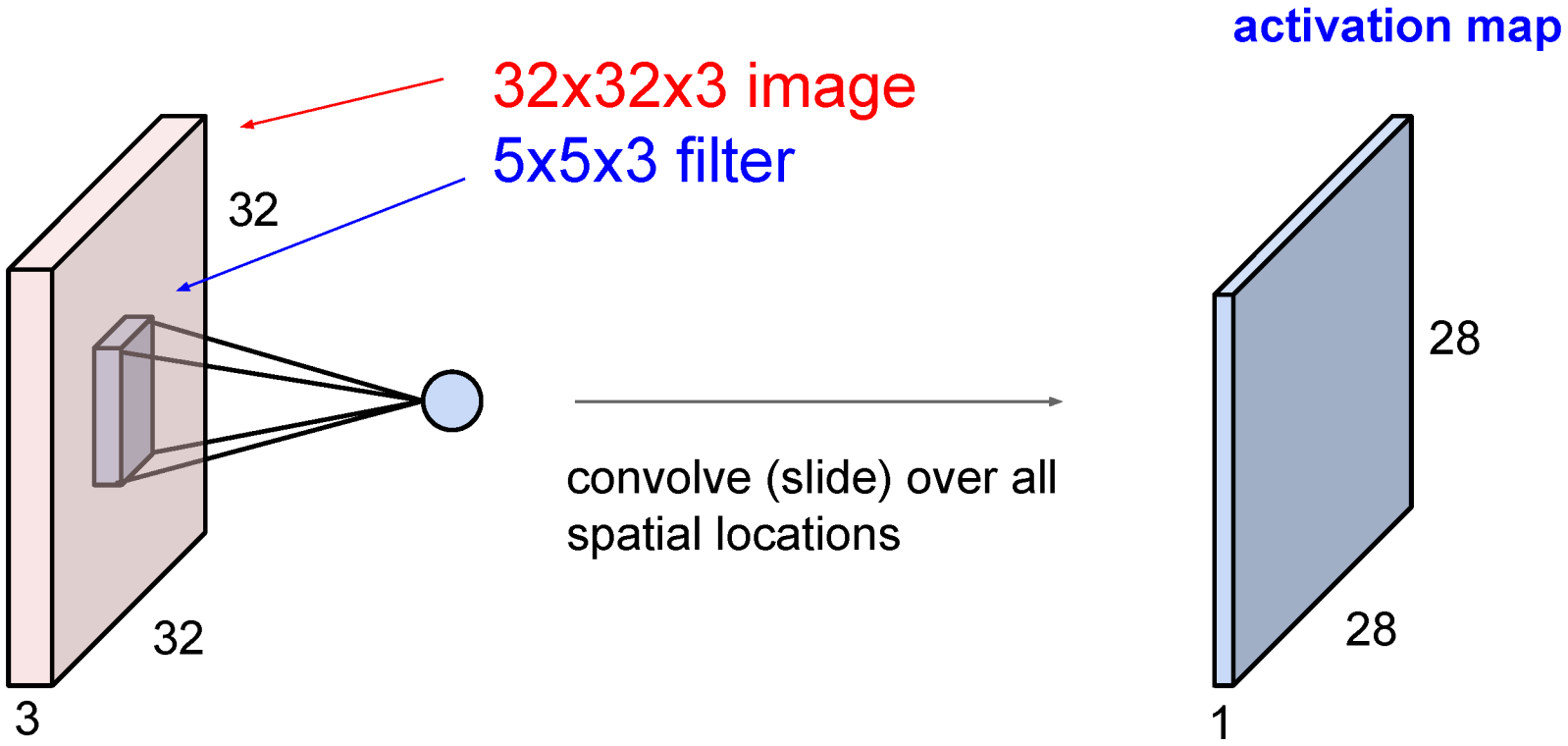
32x32x3 image

5x5x3 filter w

1 number:
the result of taking a dot product between the filter and a small 5x5x3 chunk of the image
(i.e. 5*5*3 = 75-dimensional dot product + bias)

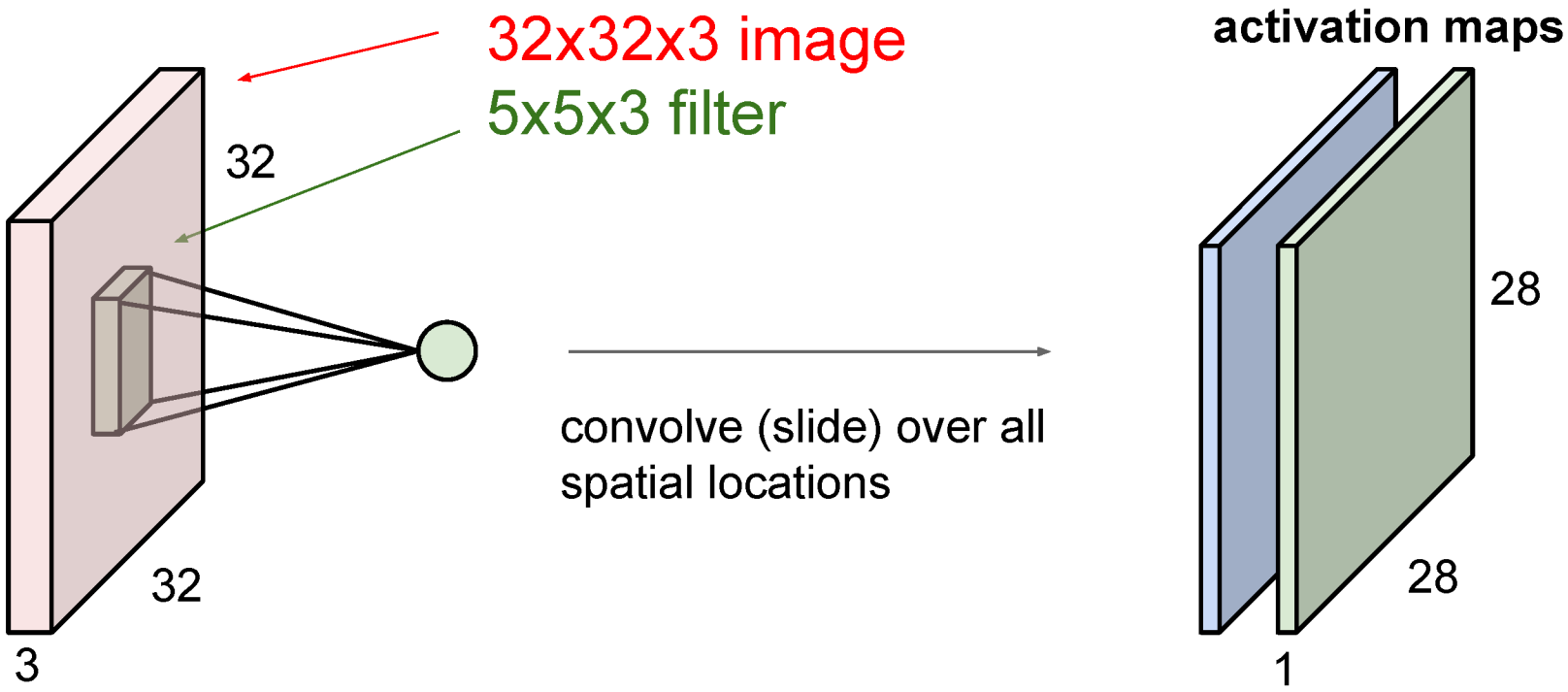
$$w^T x + b$$

Convolution Layer

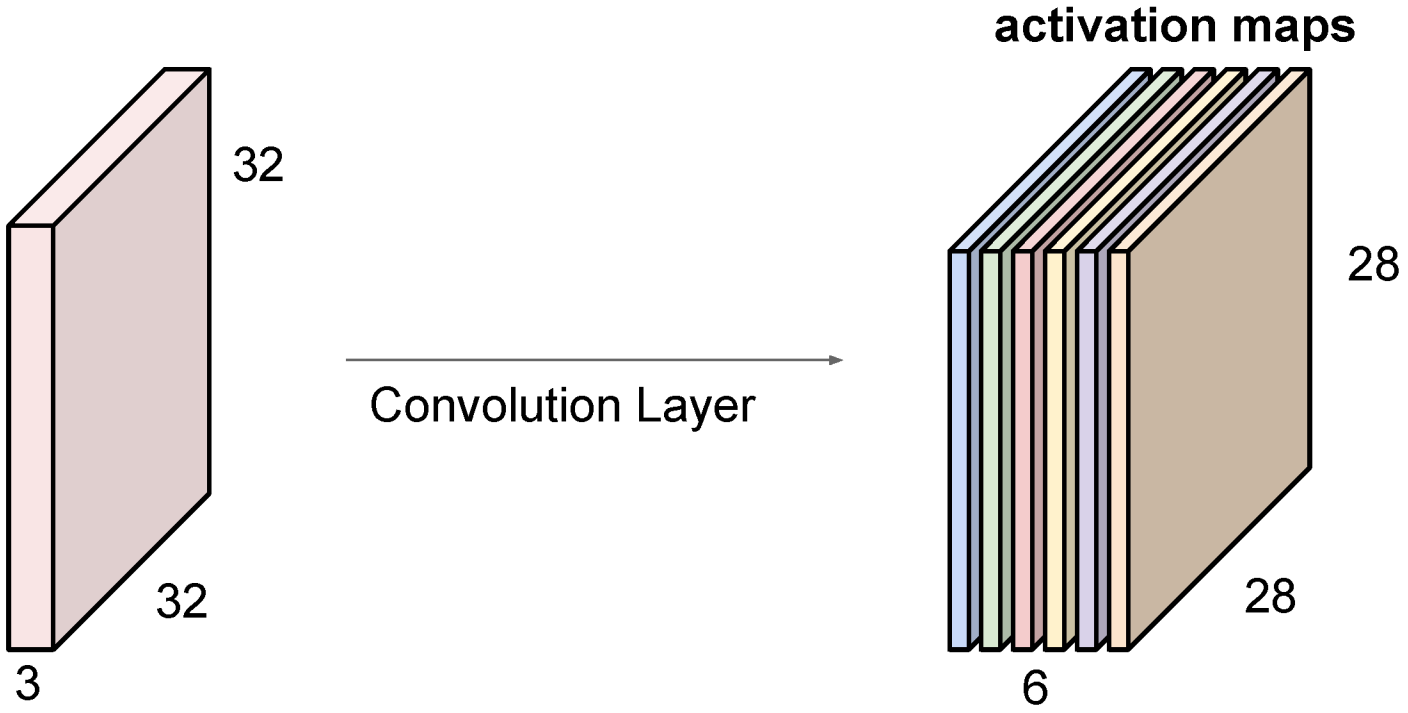


Convolution Layer

consider a second, green filter



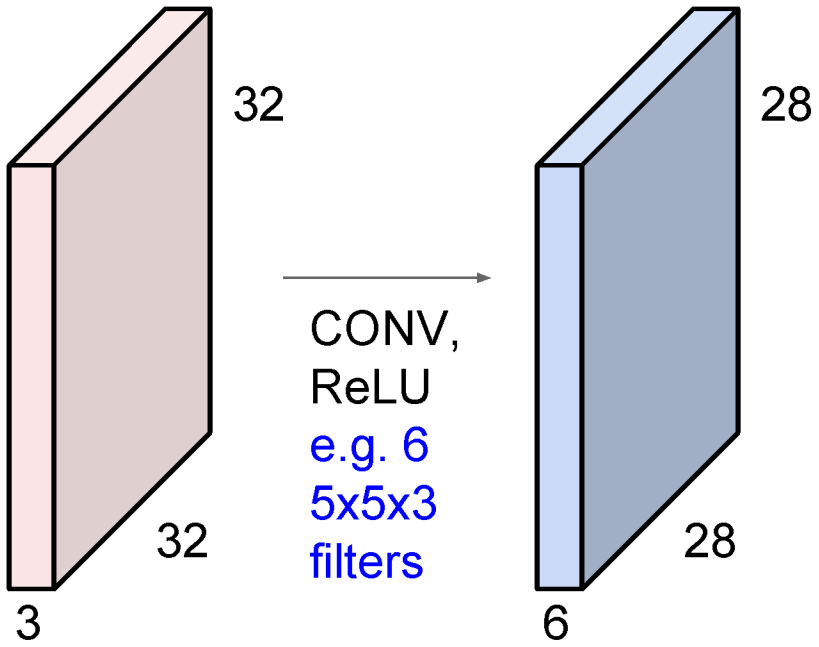
For example, if we had 6 5x5 filters, we'll get 6 separate activation maps:



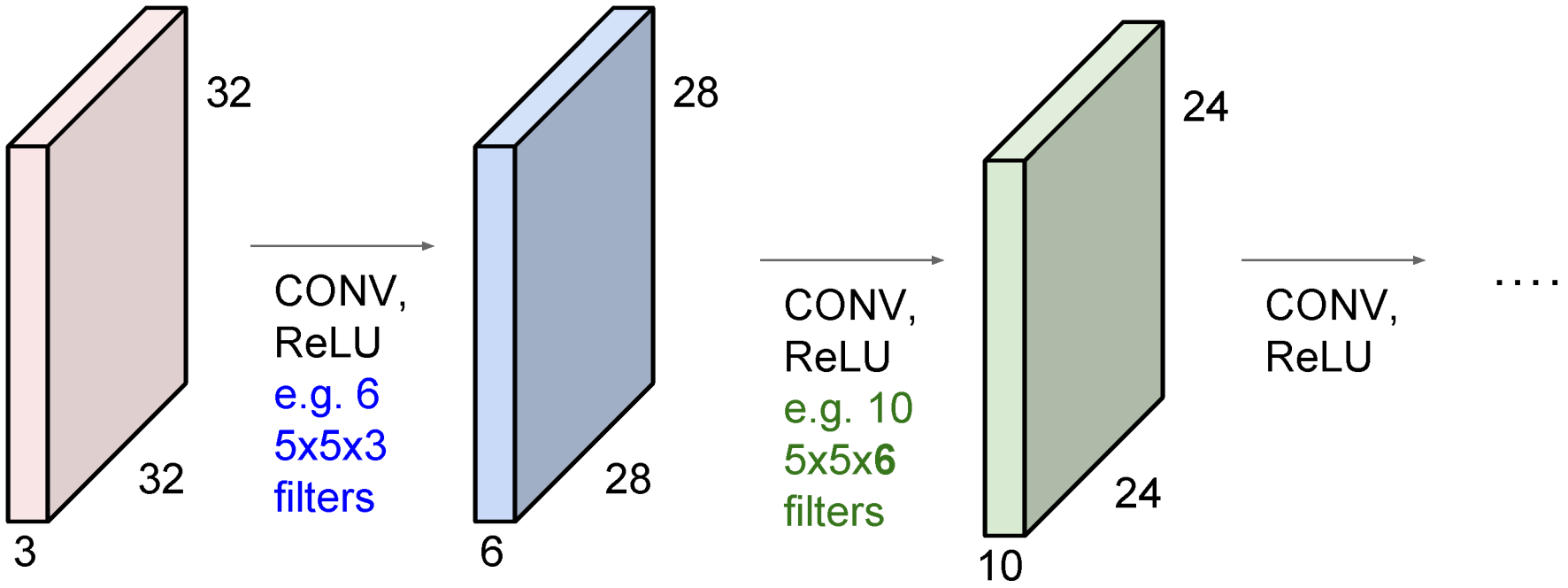
We stack these up to get a "new image" of size 28x28x6!

(total number of parameters: 6 x (75 + 1) = **456**)

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



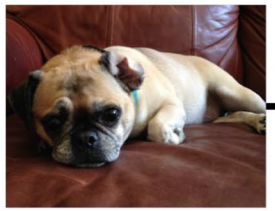
Preview: ConvNet is a sequence of Convolution Layers, interspersed with activation functions



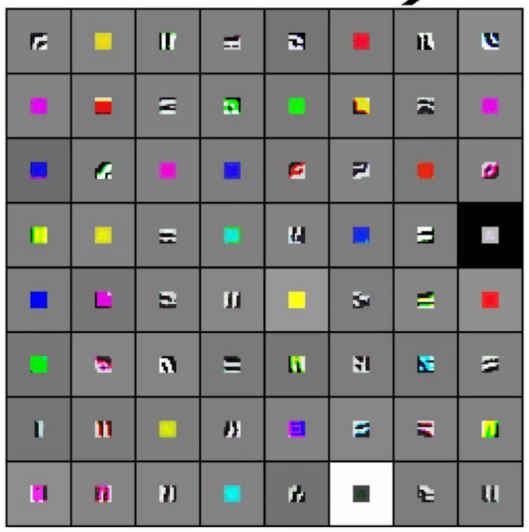
Preview

[Zeiler and Fergus 2013]

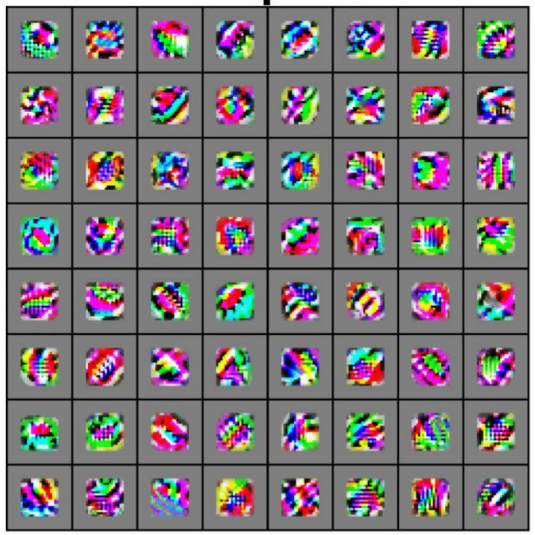
Visualization of VGG-16 by Lane McIntosh. VGG-16 architecture from [Simonyan and Zisserman 2014].



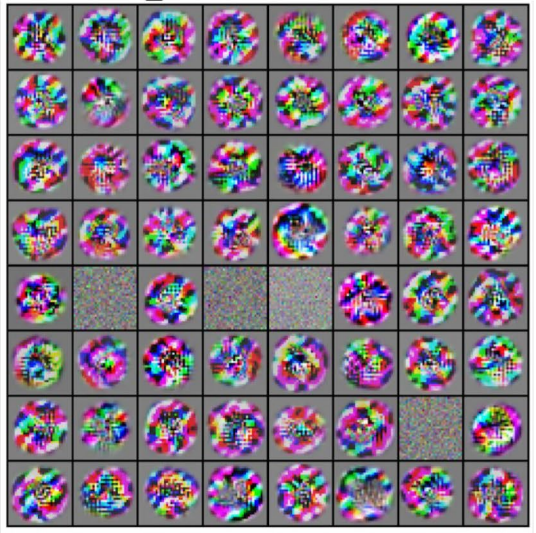
Low-level features → Mid-level features → High-level features → Linearly separable classifier



VGG-16 Conv1_1

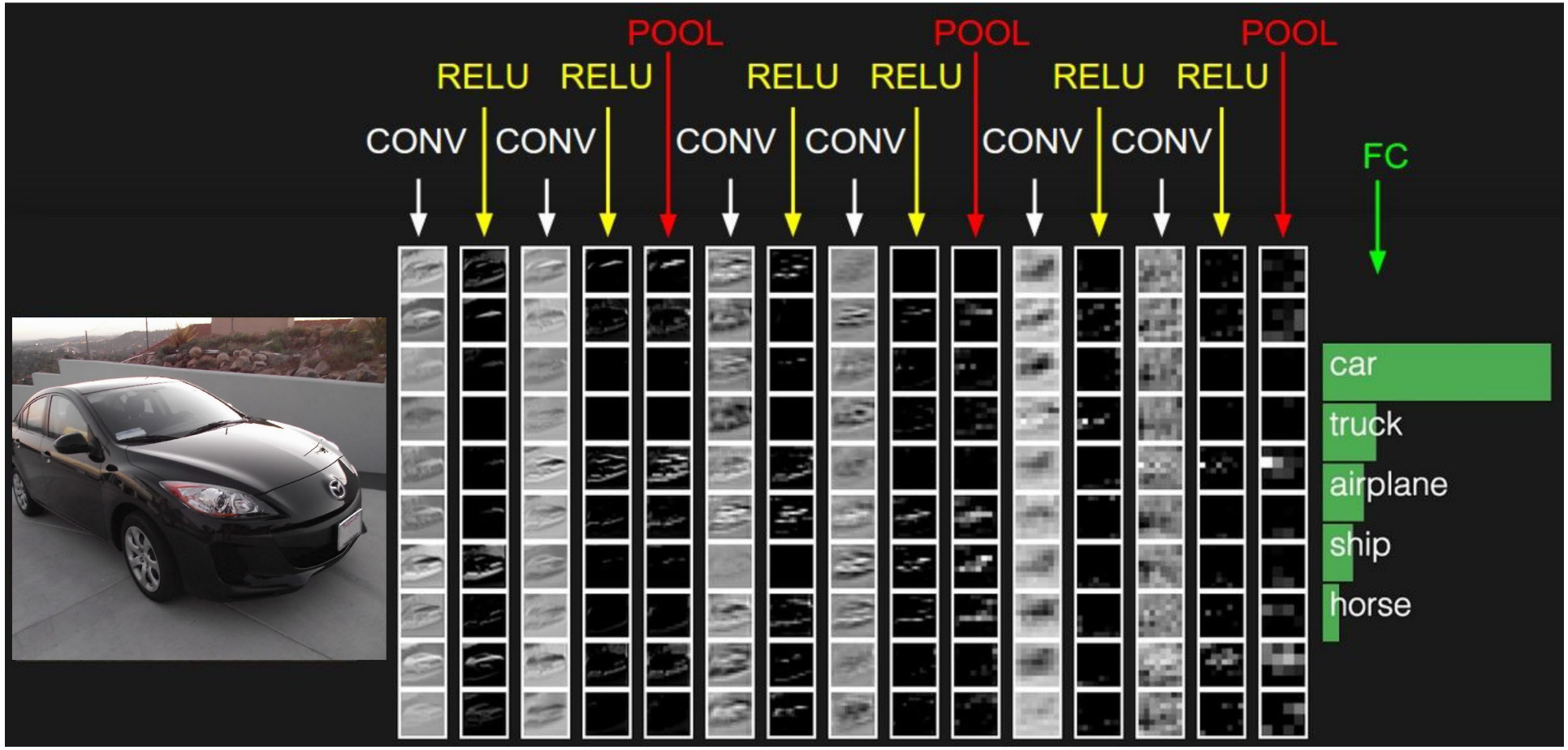


VGG-16 Conv3_2

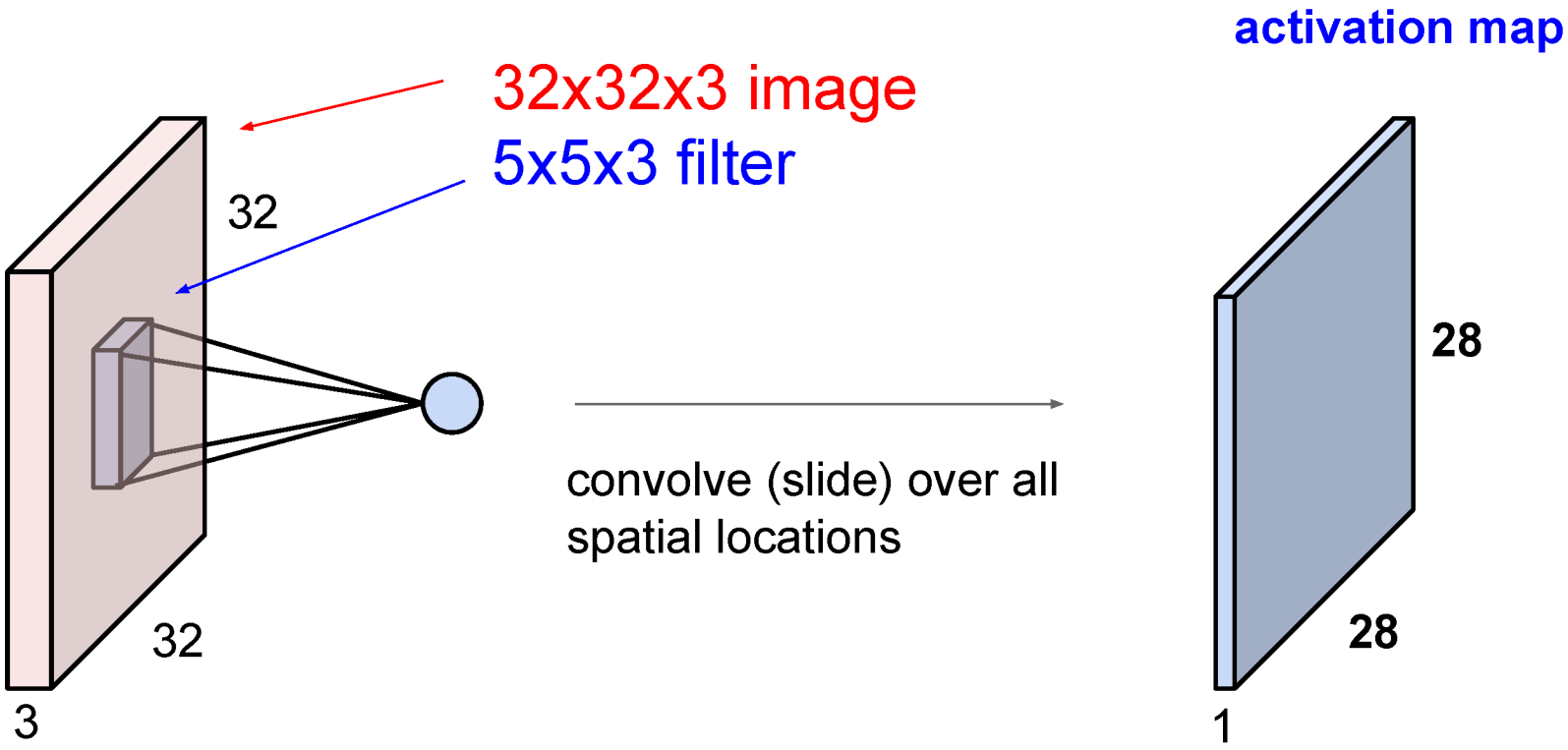


VGG-16 Conv5_3

preview:


POOL
POOL
POOL
RELU
RELU
RELU
RELU
RELU
RELU
CONV
CONV
CONV
CONV
CONV
CONV
FC
car
truck
airplane
ship
horse

A closer look at spatial dimensions:



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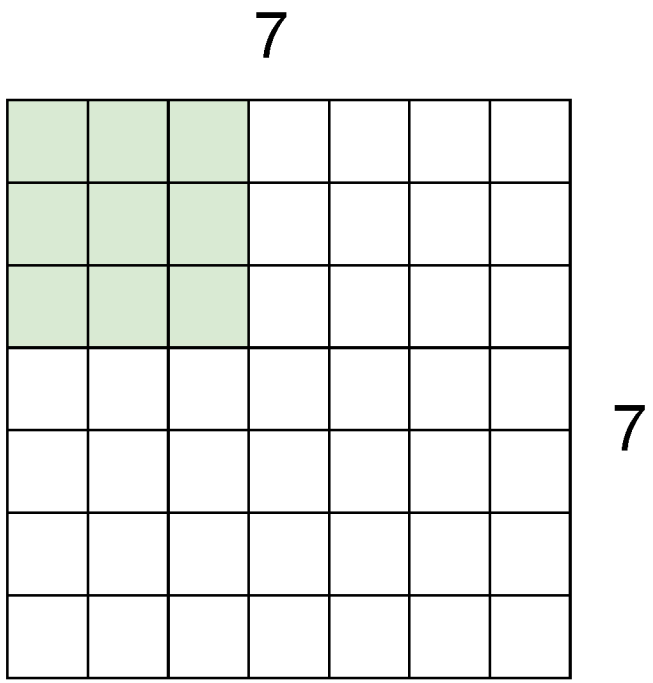
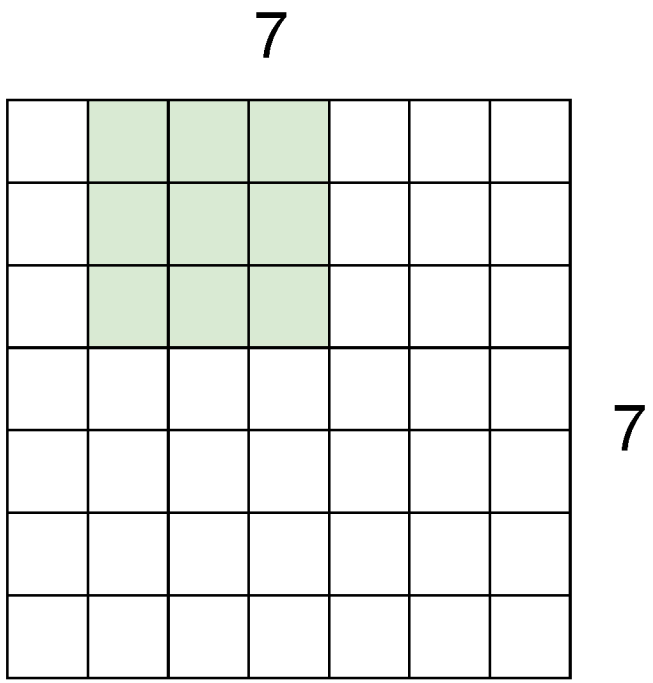


7x7 input (spatially)
assume 3x3 filter

A closer look at spatial dimensions:



7x7 input (spatially)
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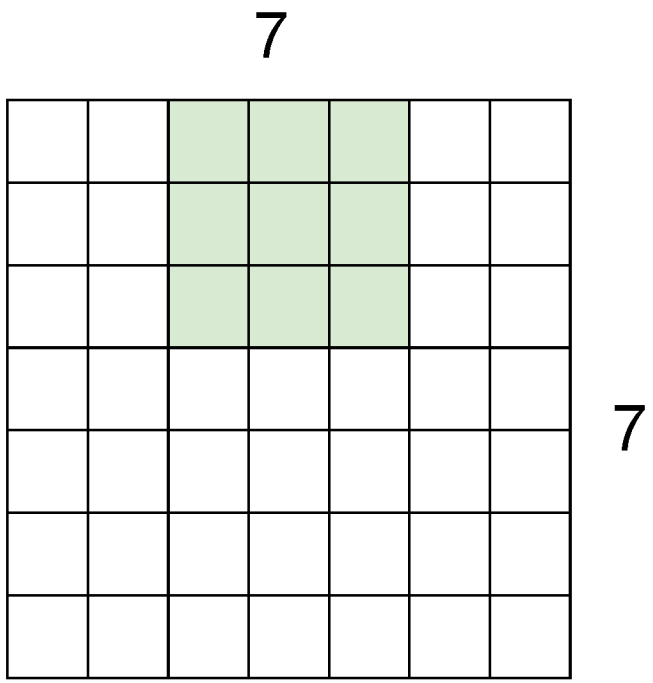
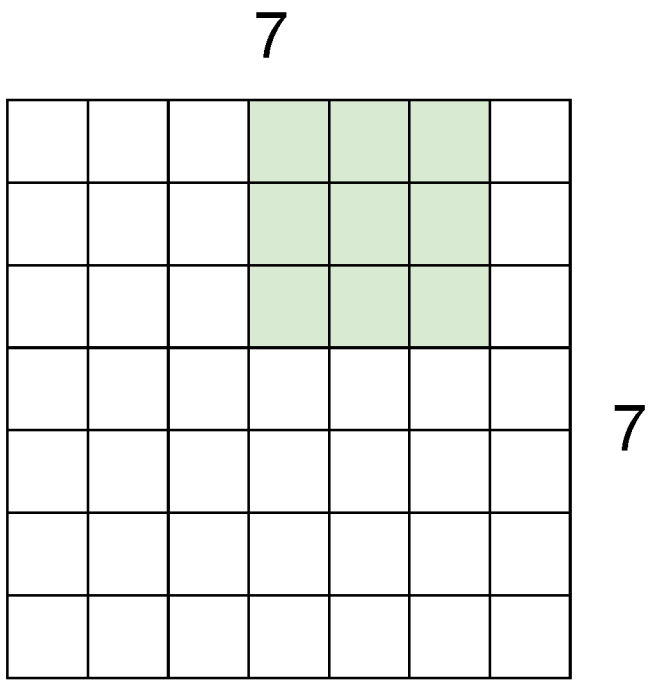
A closer look at spatial dimensions:



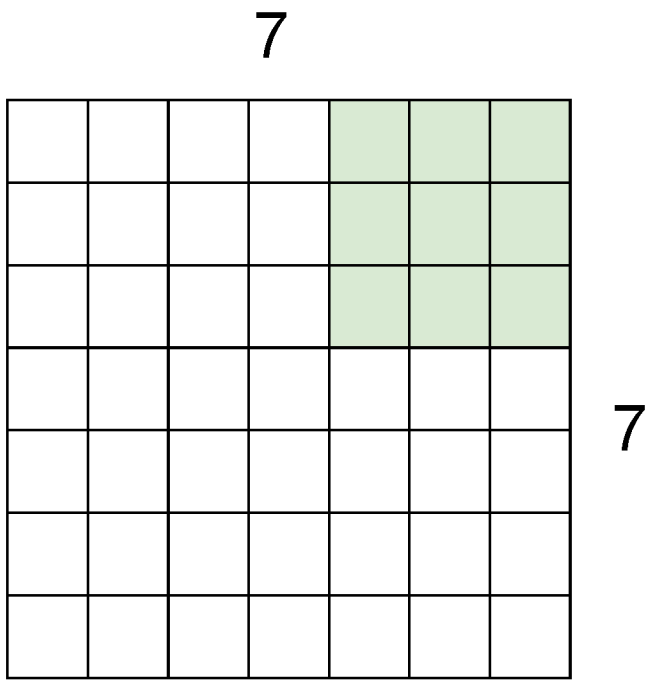
7x7 input (spatially)
assume 3x3 filter

A closer look at spatial dimensions:



7x7 input (spatially)
assume 3x3 filter

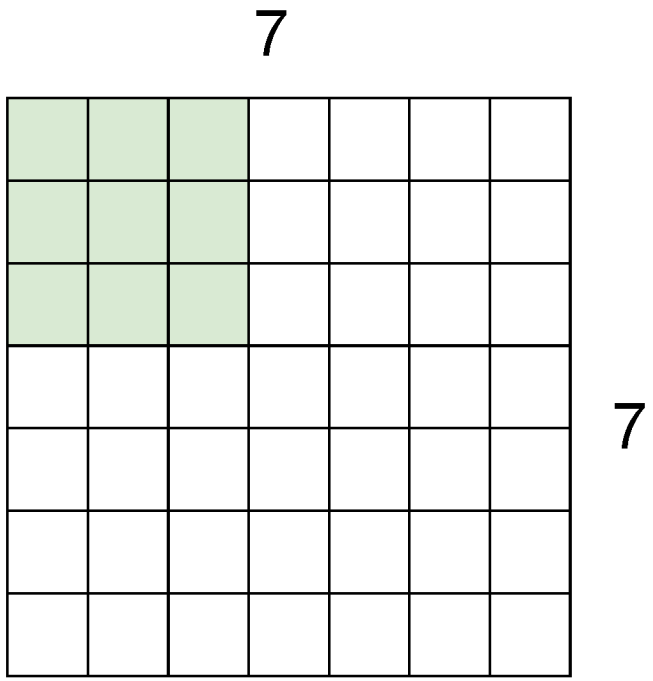
A closer look at spatial dimensions:



7x7 input (spatially)
assume 3x3 filter

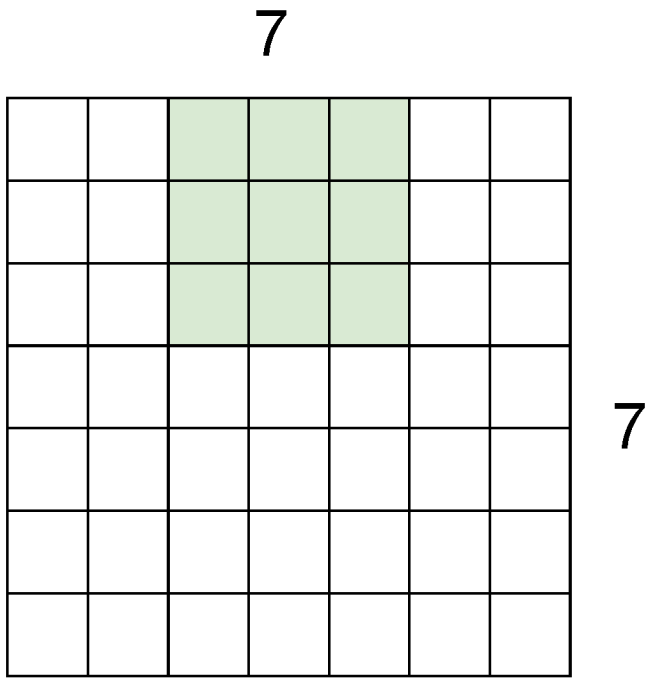
=> 5x5 output

A closer look at spatial dimensions:



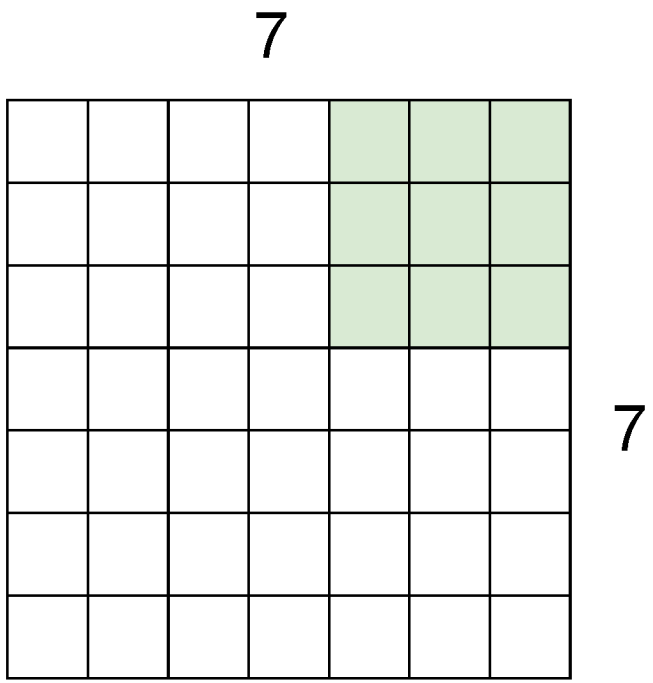
7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

A closer look at spatial dimensions:



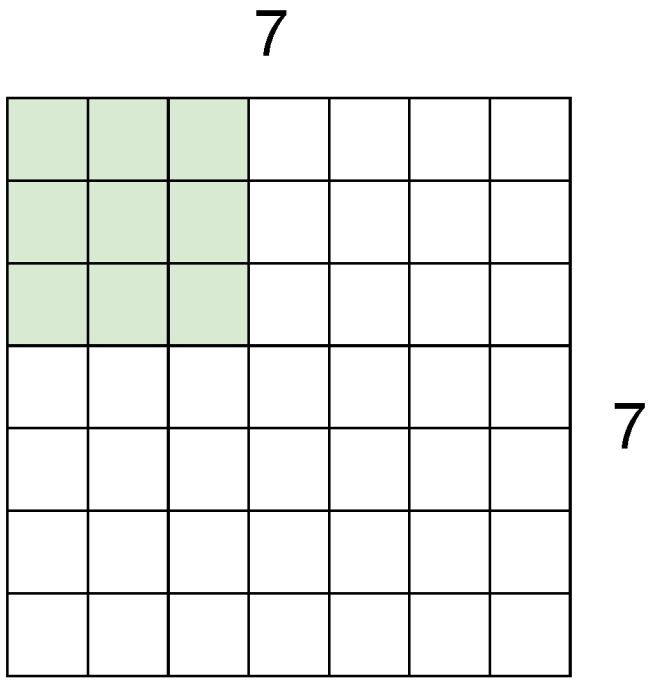
7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**

A closer look at spatial dimensions:



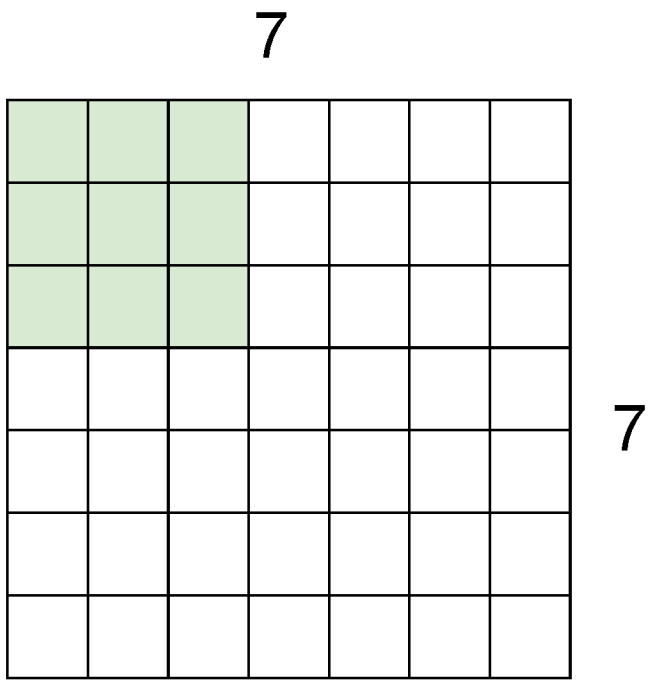
7x7 input (spatially)
assume 3x3 filter
applied **with stride 2**
=> 3x3 output!

A closer look at spatial dimensions:



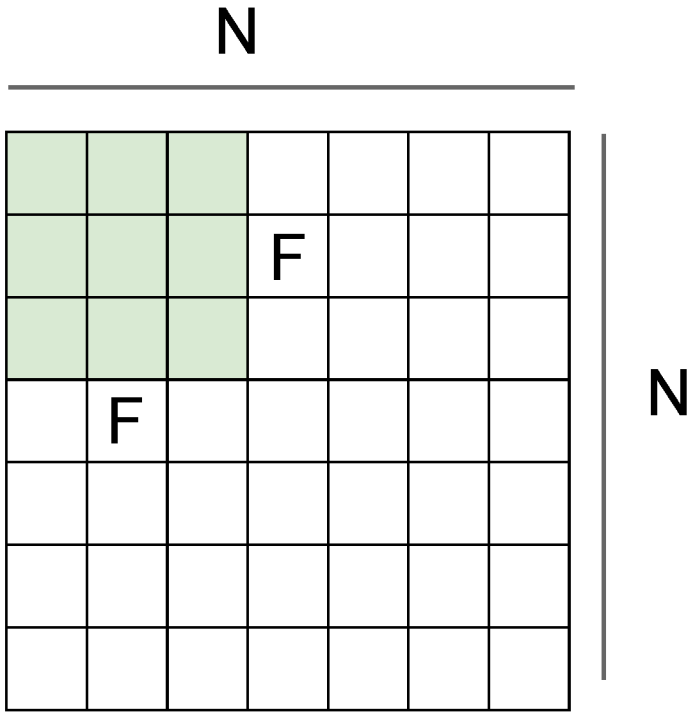
7x7 input (spatially)
assume 3x3 filter
applied **with stride 3?**

A closer look at spatial dimensions:



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

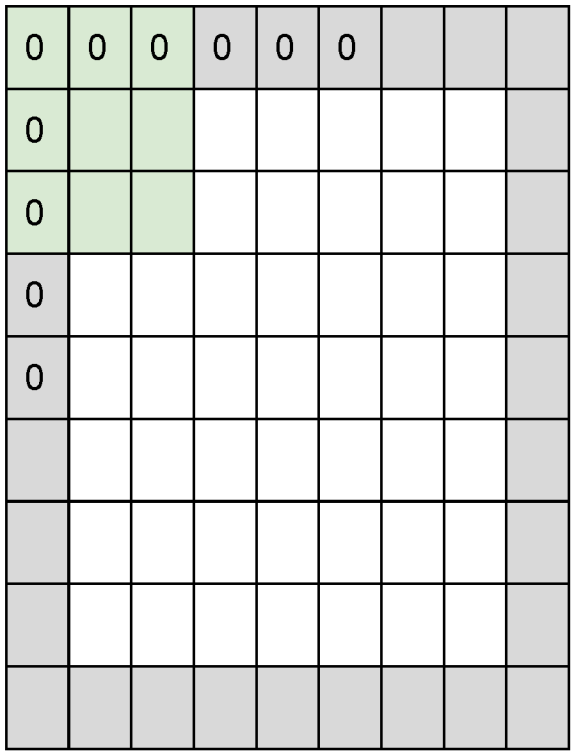
doesn't fit!
cannot apply 3x3 filter on
7x7 input with stride 3.



Output size:
(N - F) / stride + 1

e.g. N = 7, F = 3:
stride 1 => (7 - 3)/1 + 1 = 5
stride 2 => (7 - 3)/2 + 1 = 3
stride 3 => (7 - 3)/3 + 1 = 2.33 :\

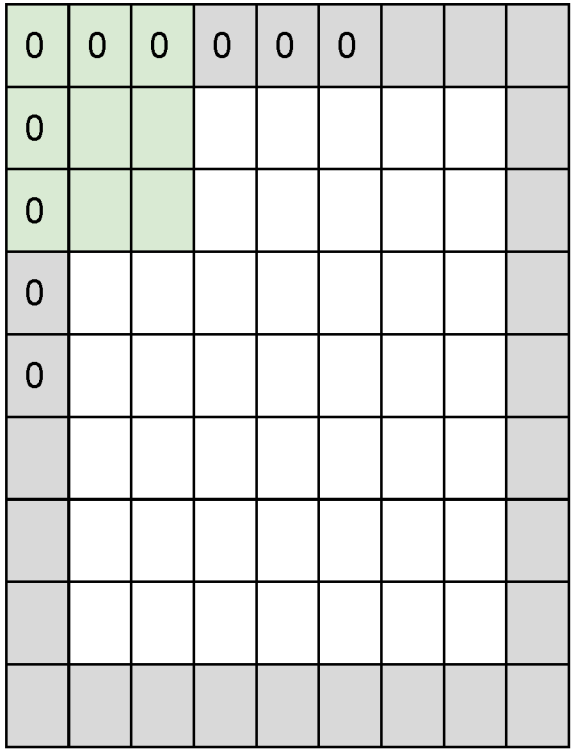
In practice: Common to zero pad the border



e.g. input 7x7
3x3 filter, applied with **stride 1**
pad with 1 pixel border => what is the output?

(recall:)
(N - F) / stride + 1

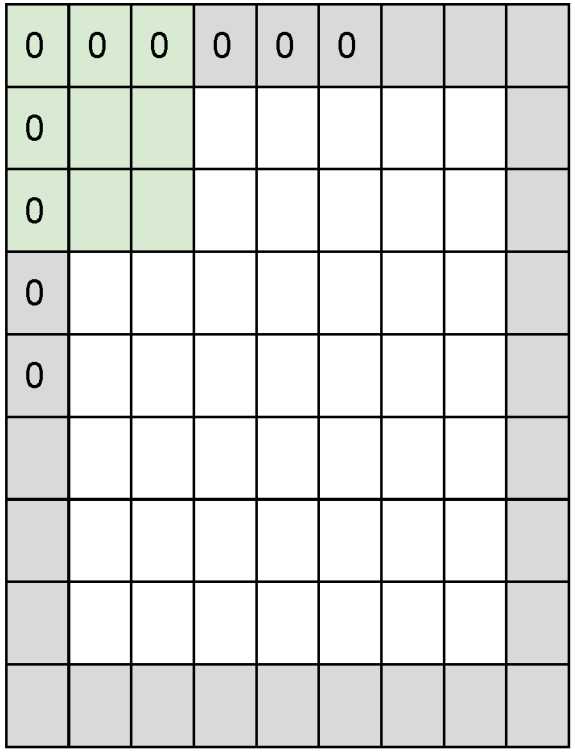
In practice: Common to zero pad the border



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

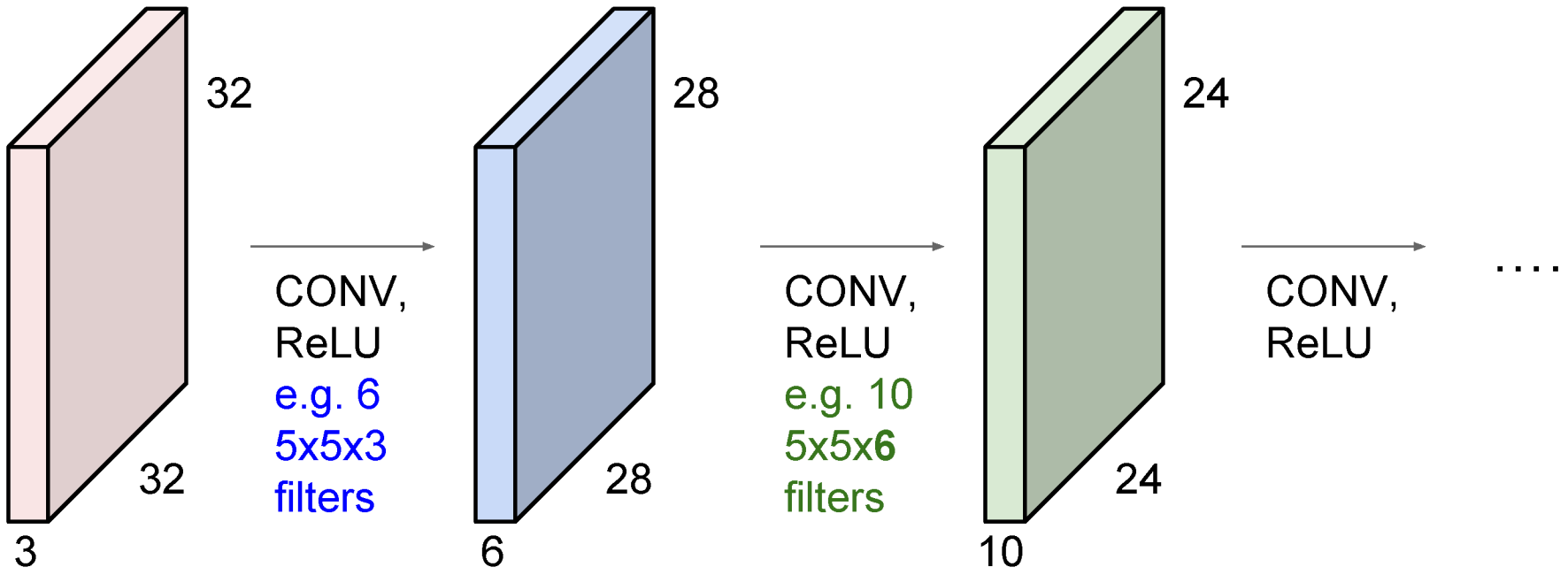


e.g. input 7x7
3x3 filter, applied with **stride 1**
pad with 1 pixel border => what is the output?

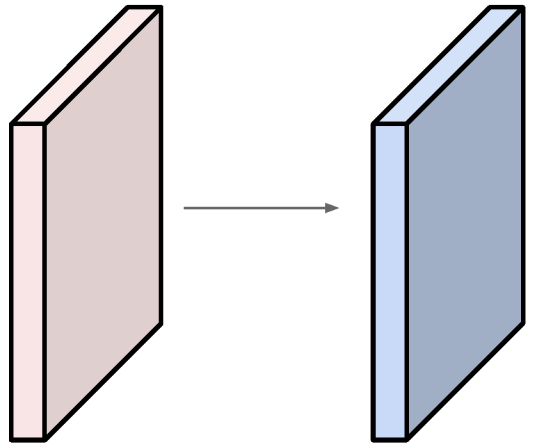
7x7 output!
in general, common to see CONV layers with stride 1, filters of size FxF, and zero-padding with (F-1)/2. (will preserve size spatially)
e.g. F = 3 => zero pad with 1
F = 5 => zero pad with 2
F = 7 => zero pad with 3

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.



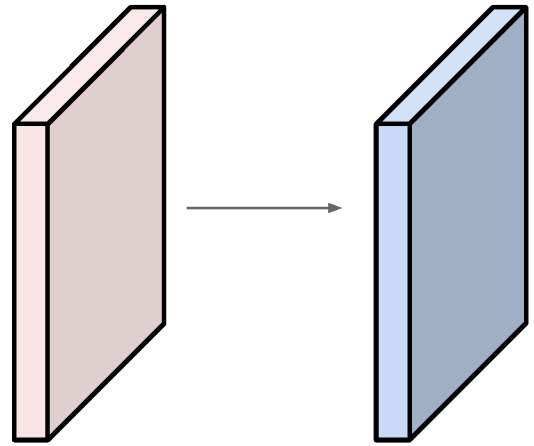
Examples time:



Input volume: **32x32x3**
10 5x5 filters with stride 1, pad 2

Output volume size: ?

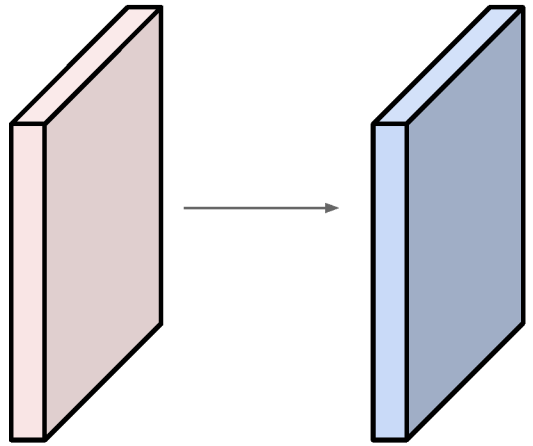
Examples time:



Input volume: **32x32x3**
10 5x5 filters with stride 1, pad 2

Output volume size:
(32+2*2-5)/1+1 = 32 spatially, so
32x32x10

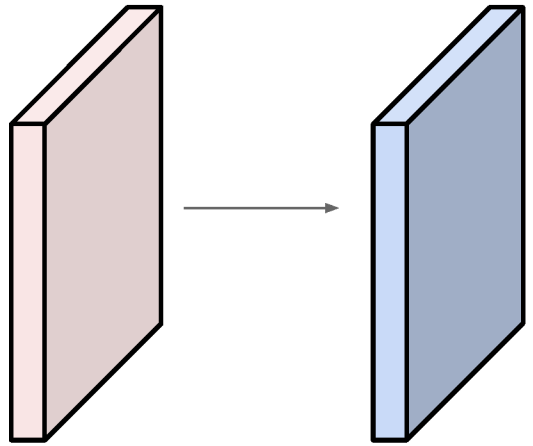
Examples time:



Input volume: **32x32x3**
10 5x5 filters with stride 1, pad 2

Number of parameters in this layer?

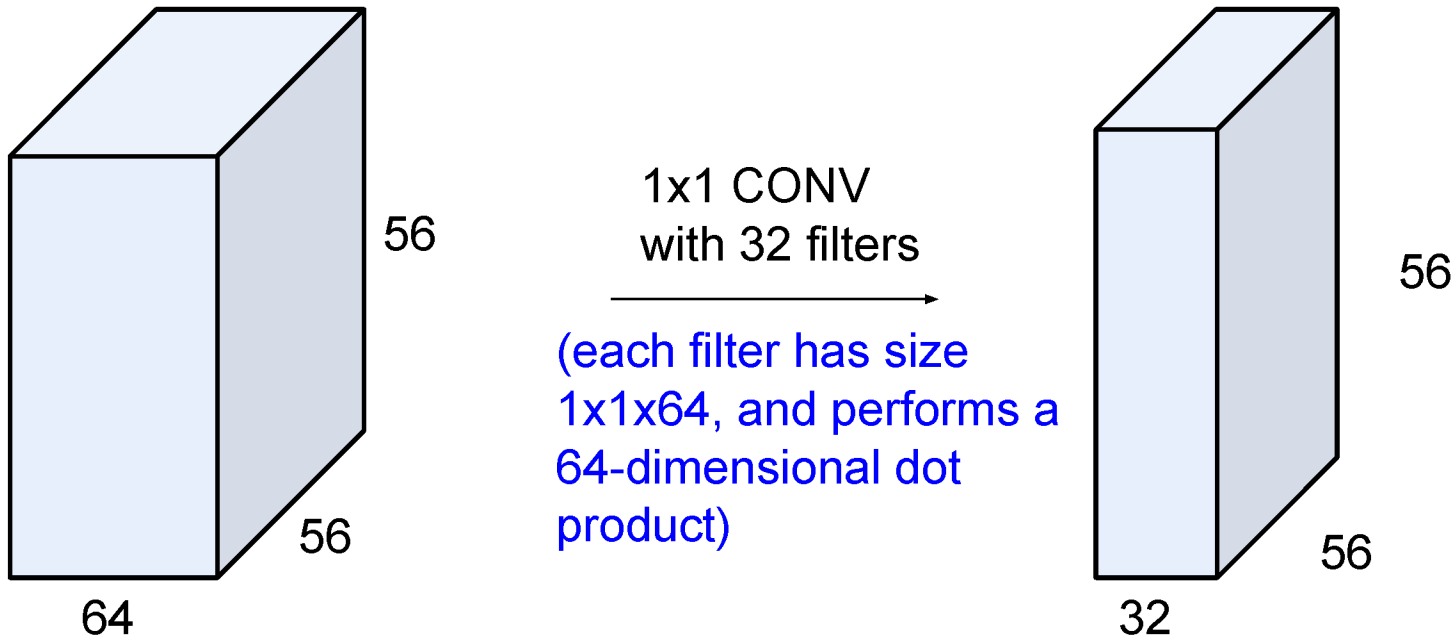
Examples time:



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)
=> 76*10 = **760**

(btw, 1x1 convolution layers make perfect sense)

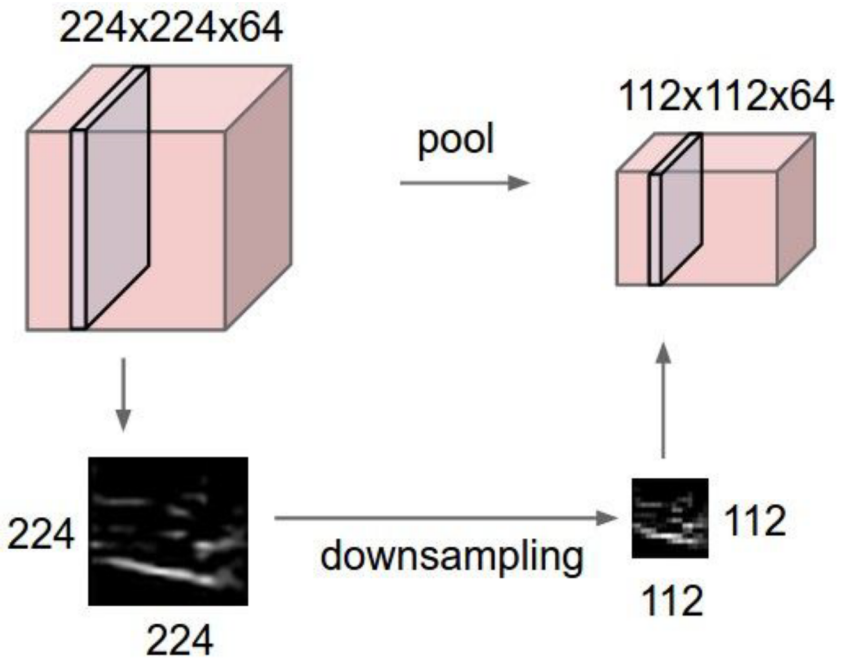


Convolutional layer—properties

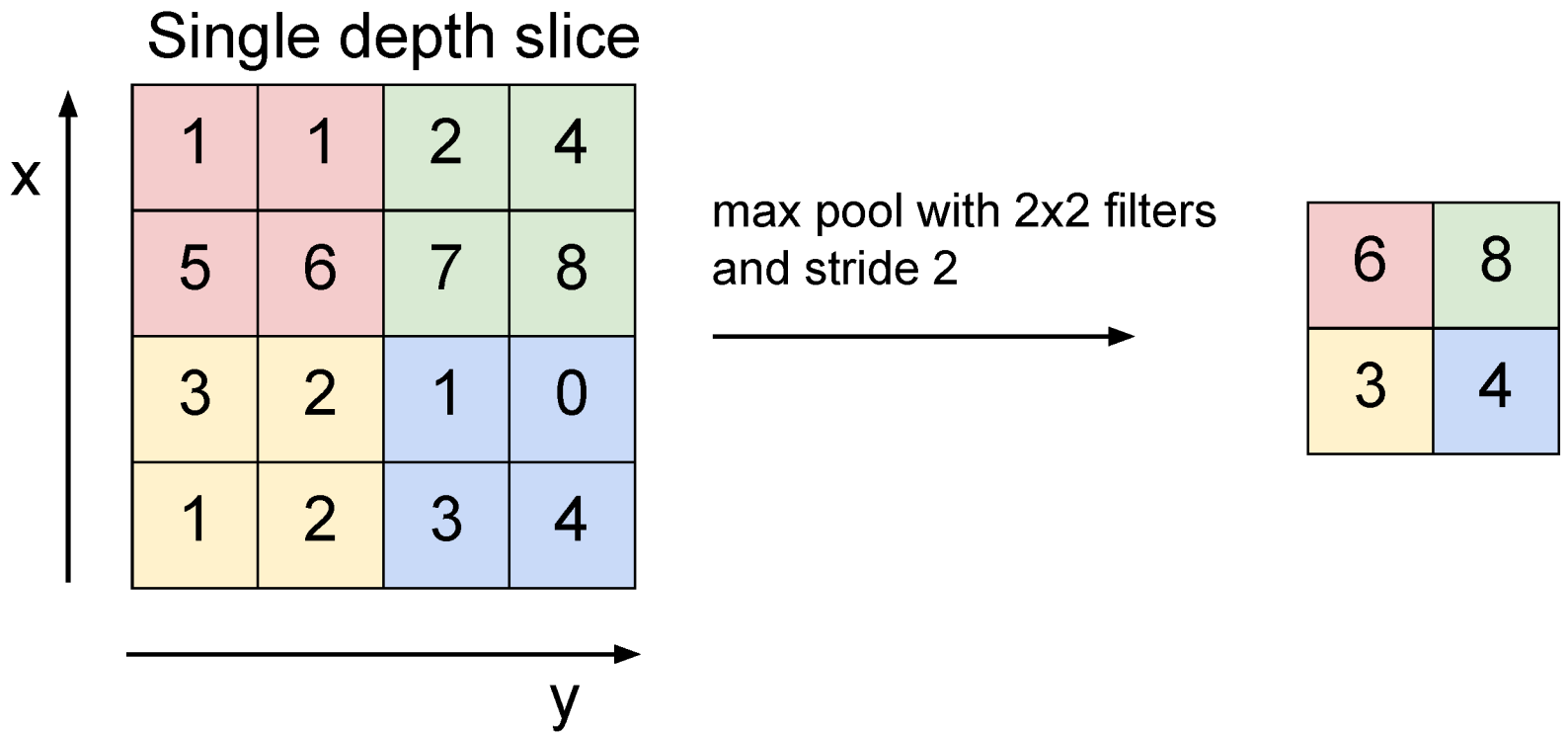
- Small number of parameters to learn compared to a fully connected layer
- Preserves spatial structure—output of a convolutional layer is shaped like an image
- **Translation equivariant**: passing a translated image through a convolutional layer is (almost) equivalent to translating the convolution output (but be careful of image boundaries)

Pooling layer

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

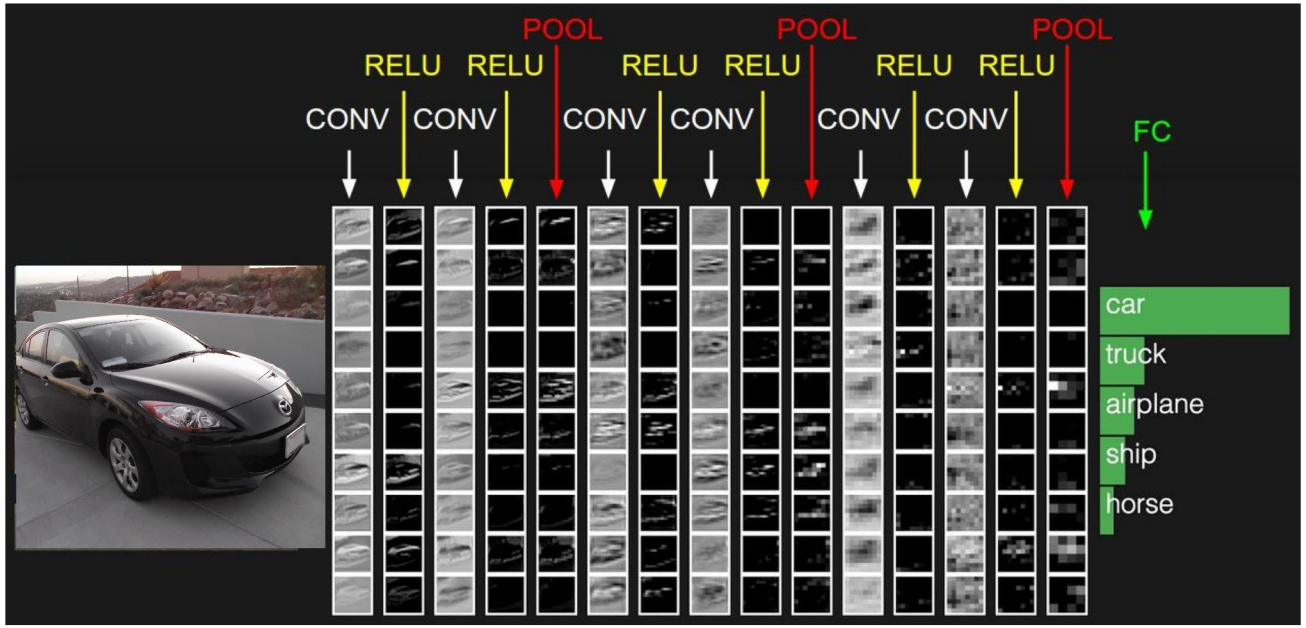


MAX POOLING


Single depth slice
x
y
1 1 2 4
5 6 7 8
3 2 1 0
1 2 3 4
max pool with 2x2 filters
and stride 2
6 8
3 4

Fully Connected Layer (FC layer)

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



[ConvNetJS demo: training on CIFAR-10]

ConvNetJS CIFAR-10 demo

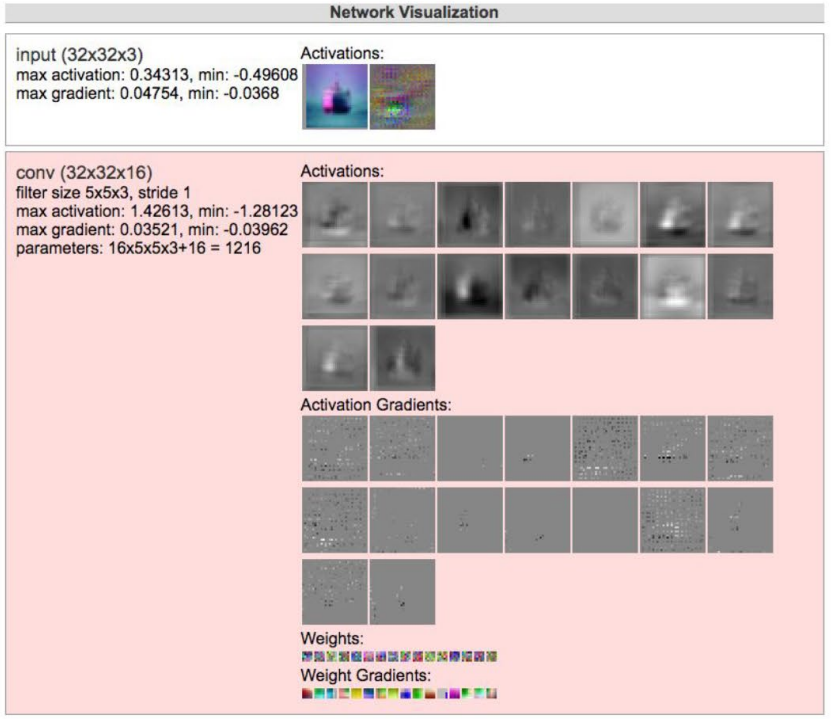
Description

This demo trains a Convolutional Neural Network on the CIFAR-10 dataset in your browser, with nothing but Javascript. The state of the art on this dataset is about 90% accuracy and human performance is at about 94% (not perfect as the dataset can be a bit ambiguous). I used this python script to parse the original files (python version) into batches of images that can be easily loaded into page DOM with img tags.

This dataset is more difficult and it takes longer to train a network. Data augmentation includes random flipping and random image shifts by up to 2px horizontally and verically.

By default, in this demo we're using Adadelta which is one of per-parameter adaptive step size methods, so we don't have to worry about changing learning rates or momentum over time. However, I still included the text fields for changing these if you'd like to play around with SGD+Momentum trainer.

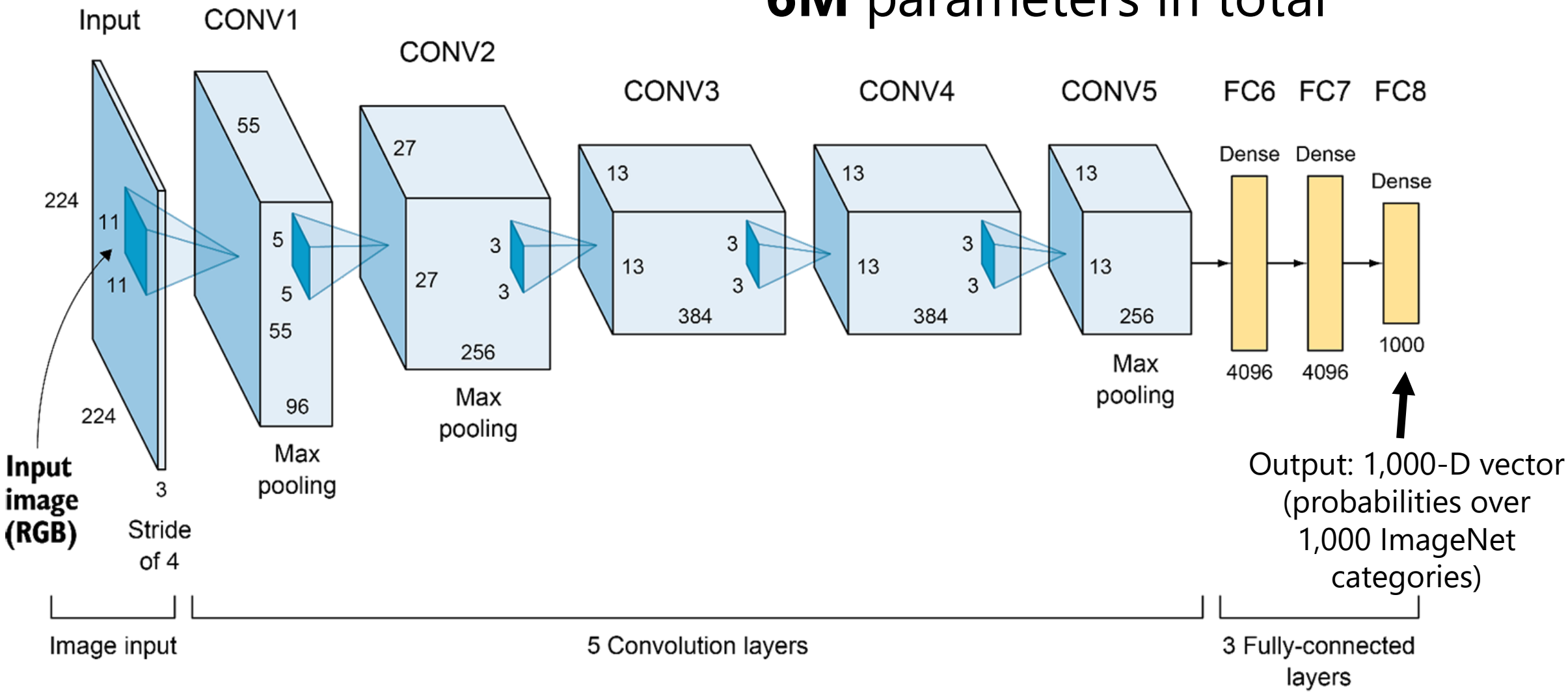
Report questions/bugs/suggestions to @karpathy.



https://cs.stanford.edu/people/karpathy/convnetjs/demo/cifar10.html

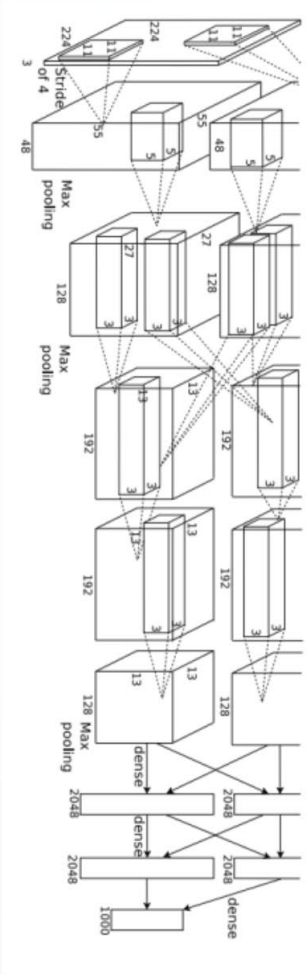
AlexNet (2012)

6M parameters in total



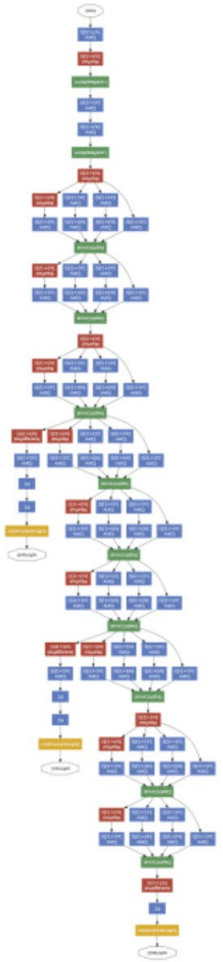
Elgendy, *Deep Learning for Vision Systems*, https://livebook.manning.com/book/grokking-deep-learning-for-computer-vision/chapter-5/v-3/

“AlexNet”



[Krizhevsky et al. NIPS 2012]

“GoogLeNet”

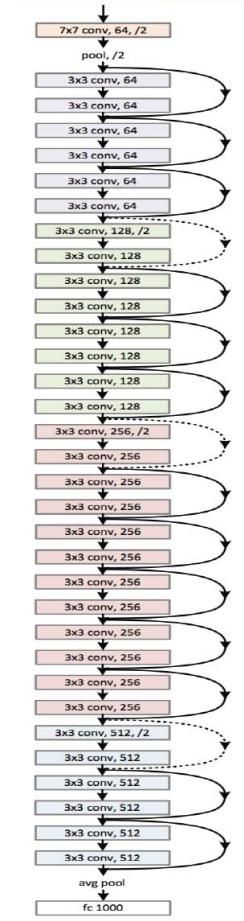


[Szegedy et al. CVPR 2015]

“VGG Net”

[Simonyan & Zisserman, ICLR 2015]

“ResNet”



[He et al. CVPR 2016]

Big picture

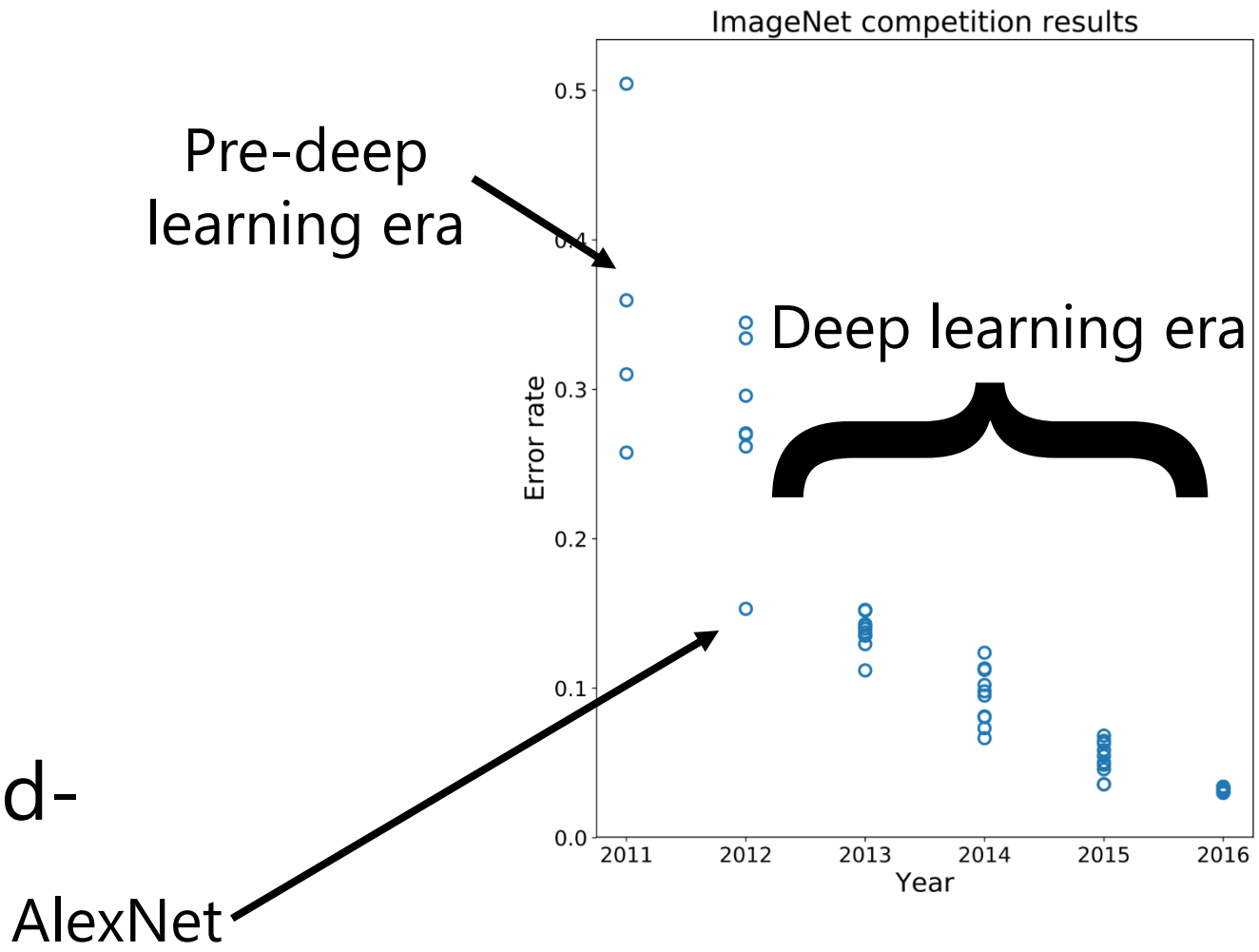
- A convolutional neural network can be thought of as a function from images to class scores
  - With millions of adjustable weights…
  - … leading to a very non-linear mapping from images to features / class scores.
  - We will set these weights based on classification accuracy on training data…
  - … and hopefully our network will generalize to new images at test time

Data is key—enter ImageNet

- ImageNet (and the ImageNet Large-Scale Visual Recognition Challege, aka **ILSVRC**) has been key to training deep learning methods
  - J. Deng, W. Dong, R. Socher, L.-J. Li, K. Li and L. Fei-Fei, **ImageNet: A Large-Scale Hierarchical Image Database.** *CVPR*, 2009.
- **ILSVRC**: 1,000 object categories, each with ~700-1300 training images. Test set has 100 images per categories (100,000 total).
- Standard ILSVRC error metric: top-5 error
  - if the correct answer for a given test image is in the top 5 categories, your answer is judged to be correct

Performance improvements on ILSVRC

- ImageNet Large-Scale Visual Recognition Challenge
- Held from 2011-2017
- 1000 categories, 1000 training images per category
- Test performance on held-out test set of images



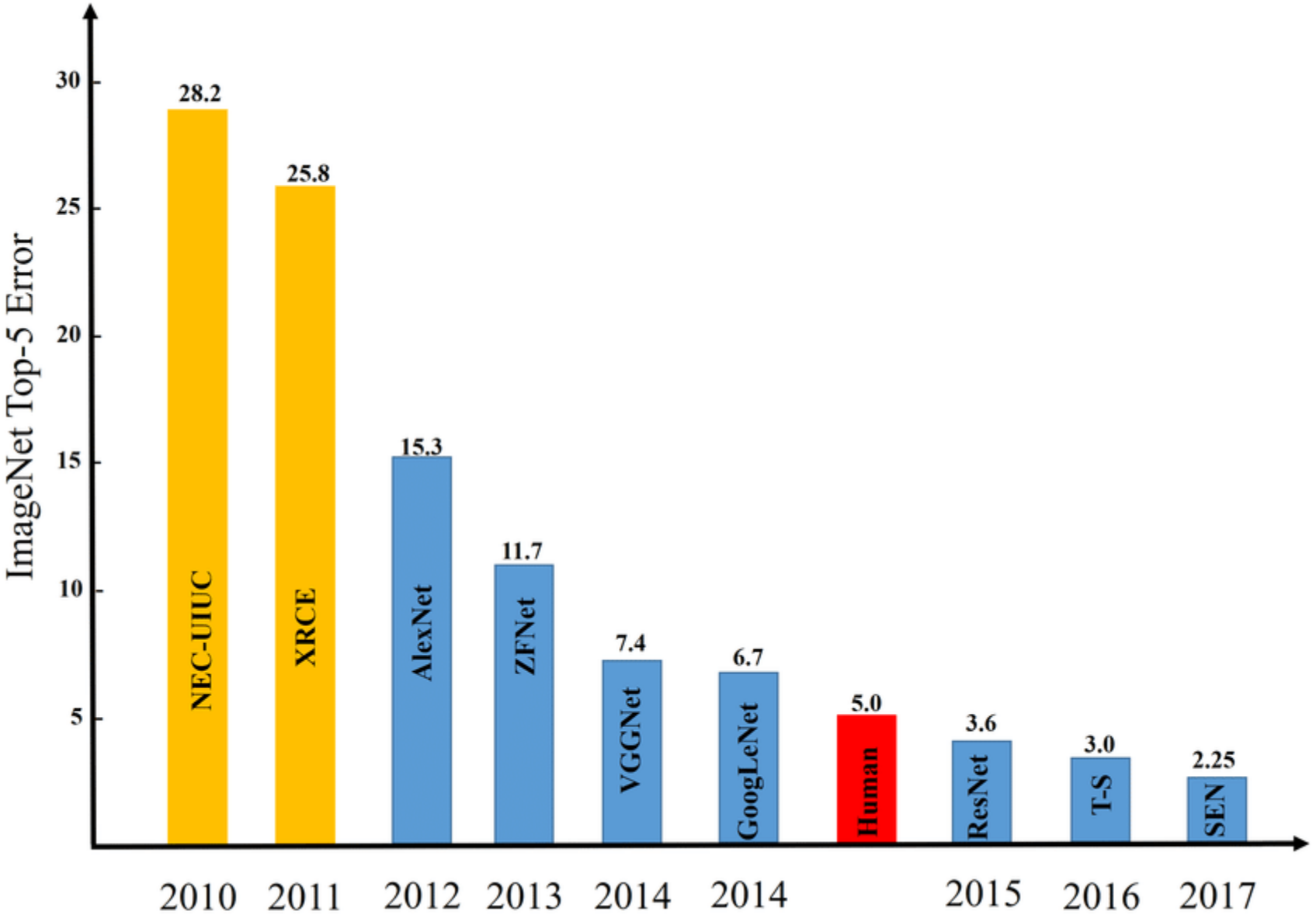


Image credit: Zaid Alyafeai, Lahouari Ghouti