

10707

Deep Learning: Spring 2020

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Machine Learning Department

Lecture 4:
Convolutional
architectures

Used Resources

Disclaimer: Some material in this lecture was borrowed from:

Hugo Larochelle's class on Neural Networks:

<https://sites.google.com/site/deeplearningsummerschool2016/>

Rob Fergus' CIFAR tutorial on ConvNets:

http://mlss.tuebingen.mpg.de/2015/slides/fergus/Fergus_1.pdf

Marc'Aurelio Ranzato's CVPR 2014 tutorial on Convolutional Nets

<https://sites.google.com/site/lsvrtutorialcvpr14/home/deeplearning>

Neural networks for vision

Prototypical task in vision is **object recognition**: given an input image, identify what kind of object it contains.



Are feedforward networks the right architecture for this?

Desiderata for networks for vision

- 🌀 Inputs are very **high-dimensional**: 150×150 pixels = 22500 inputs, or 3×22500 if RGB pixels instead of grayscale.
- 🌀 Should leverage the **spatial locality** (in the pixel sense) of data
- 🌀 Build in invariance to natural variations: **translation, illumination, etc.**

Convolutional architectures are designed for this:

- 🌀 **Local connectivity** (reflects spatial locality and decreases # params)
- 🌀 **Parameter sharing** (further decreases # params)
- 🌀 **Convolution**
- 🌀 **Pooling / subsampling hidden units**

Local Connectivity

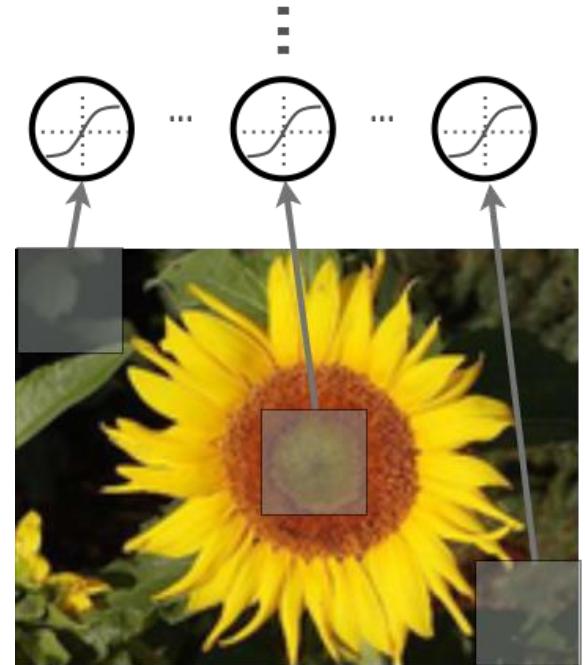
Use local connectivity of hidden units

- Each hidden unit is connected only to a **sub-region (patch)** of the input image.

It is connected to all channels: 1 if grayscale, 3 (R, G, B) if color image

Why this is a good idea:

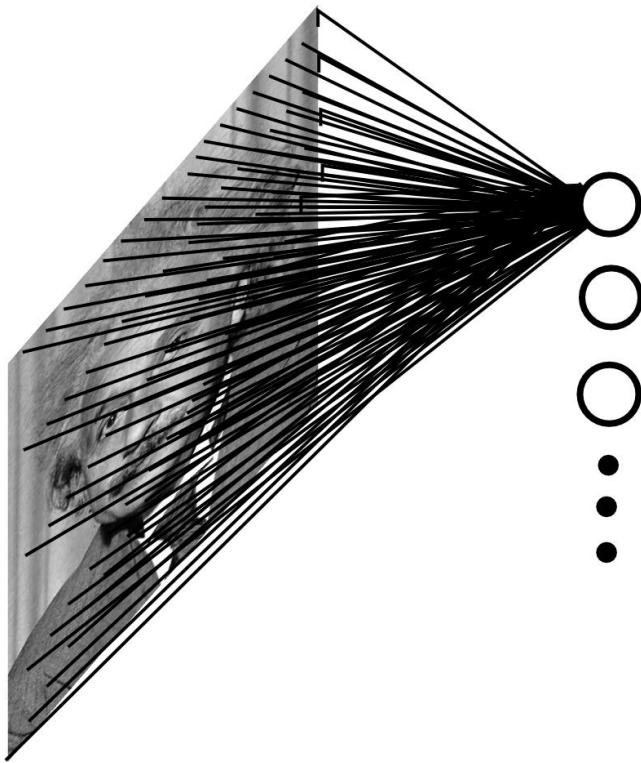
- Fully connected layer has **a lot of parameters** to fit, which requires a lot of training data
- Image data isn't arbitrary: neighboring pixels are "meaningfully related" – e.g. if a node is to be a "dog nose" detector – need to look at small patch of pixels.



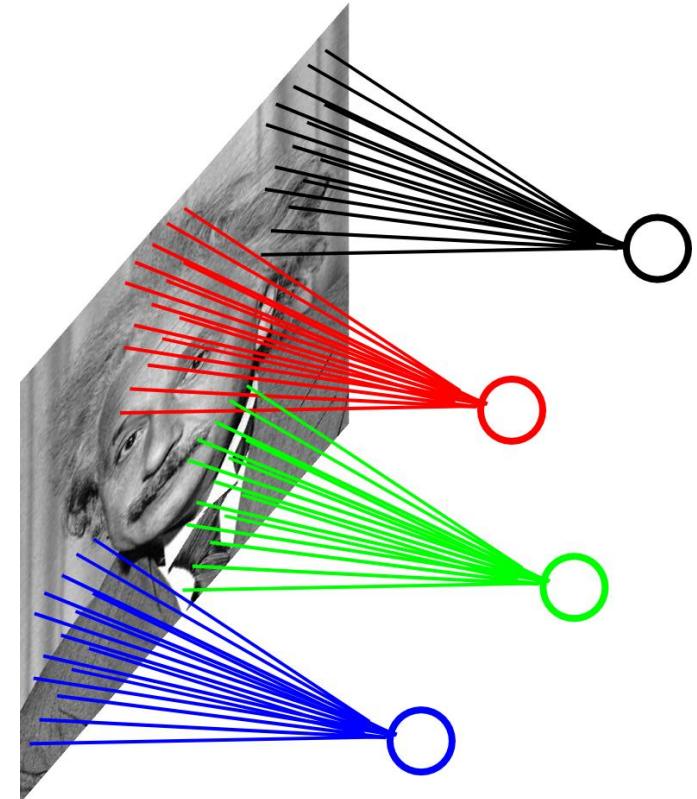
$$r \boxed{} = \text{receptive field}$$

Decrease in # of parameters

Fully connected: 200x200 image,
40K hidden units, **~2B parameters!**

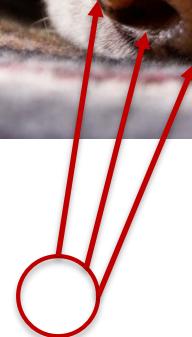


Convolutional: 200x200 image, 40K
hidden units, window size 10x10,
~4M parameters!

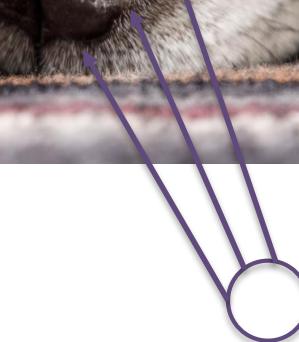


Parameter Sharing

Prior approach makes weights sensitive to translations: e.g.



Might learn weights for
nose detector here

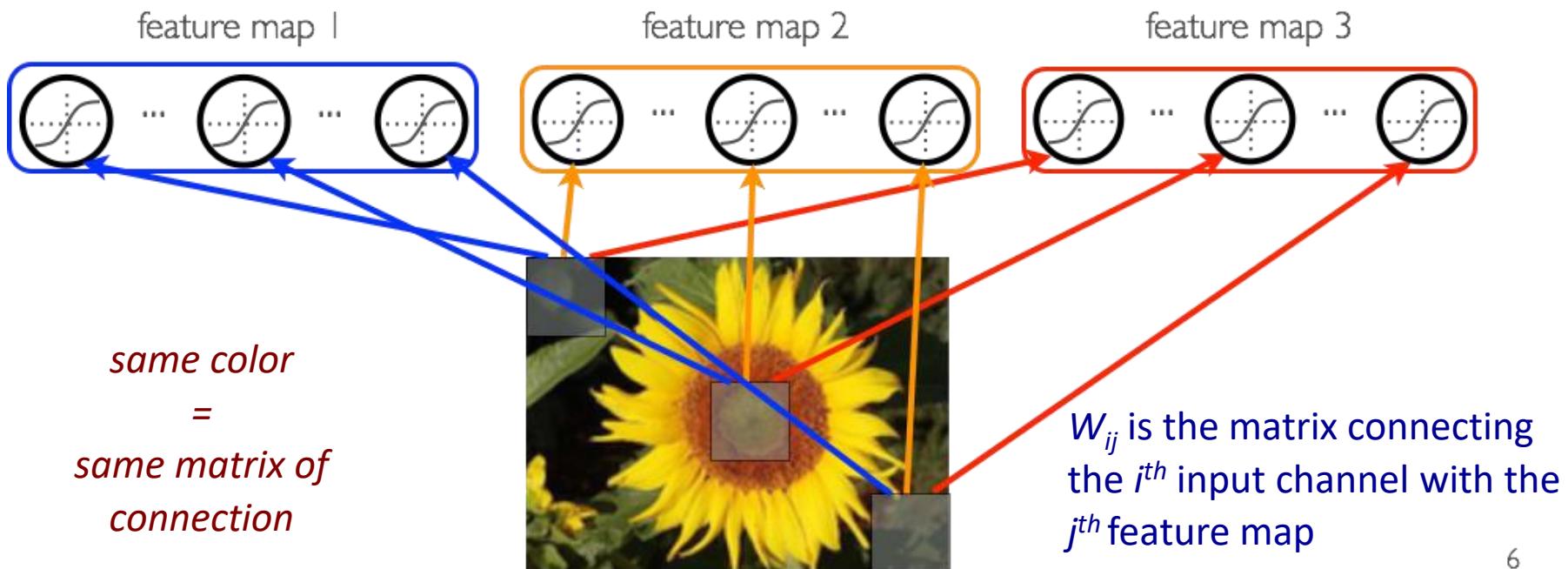


But not learn weights
for a nose detector here

Parameter Sharing

Share matrix of parameters across some units

- Units that are organized into the “**feature map**” share parameters
- Hidden units within a feature map cover different positions in the image



Desiderata for networks for vision

Our goal is to design neural networks that are specifically adapted for such problems

- ✿ Must deal with very high-dimensional inputs: 150×150 pixels = 22500 inputs, or 3×22500 if RGB pixels
- ✿ Can exploit the 2D topology of pixels (or 3D for video data)
- ✿ Can build in invariance to certain variations: translation, illumination, etc.

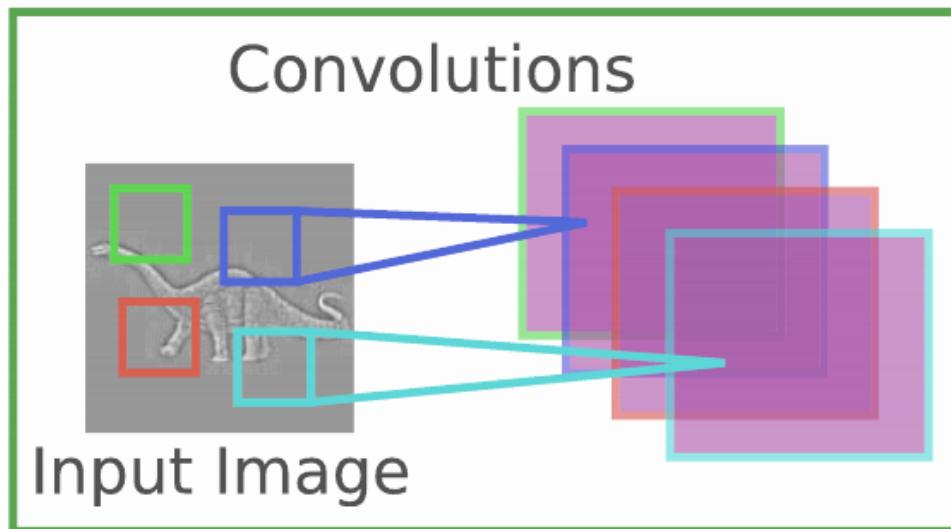
Convolutional networks leverage these ideas

- ✿ Local connectivity
- ✿ Parameter sharing
- ✿ Convolution
- ✿ Pooling / subsampling hidden units

Discrete Convolution

Each feature map forms a **2D grid of features**

Can be computed with a **discrete convolution** ($*$) of a kernel matrix k_{ij}



Jarret et al. 2009

$$y_j = g_j \tanh\left(\sum_i k_{ij} * x_i\right)$$

- x_i is the i^{th} channel of input
- k_{ij} is the convolution kernel
- g_j is a learned scaling factor
- y_j is the hidden layer

Can add bias

Discrete Convolution

$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example:

$$\begin{matrix} 0 & 80 & 40 \\ 20 & 40 & 0 \\ 0 & 0 & 40 \end{matrix} \quad x \quad * \quad \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \end{matrix} \quad k \quad =$$

Discrete Convolution

$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example:

$$\begin{matrix} & & & \\ & & & \\ & & & \\ & & & \\ \begin{matrix} 1 & 0,5 \\ 0,25 & 0 \end{matrix} & \begin{matrix} 80 & 40 \\ 40 & 0 \end{matrix} & \begin{matrix} 0 & 0 \\ 0 & 40 \end{matrix} & \end{matrix} \quad * \quad \begin{matrix} \tilde{k} = k & \text{with rows and columns flipped} \\ \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \end{matrix} & \end{matrix} = \begin{matrix} & & \\ & & \\ & & \\ & & \\ k & & \end{matrix}$$

Discrete Convolution

$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example: $1 \times 0 + 0.5 \times 80 + 0.25 \times 20 + 0 \times 40 = 45$

The diagram shows the convolution operation between two matrices, x and k . The input matrix x is a 3x3 grid with values: top row [1, 0.5, 80], middle row [0.25, 0, 40], bottom row [0, 0, 40]. The kernel matrix k is a 2x2 grid with values: top row [0, 0.25], bottom row [0.5, 1]. The result of the convolution is a single value 45.

$$\begin{matrix} 1 & 0,5 & 80 \\ 0,25 & 0 & 40 \\ 0 & 0 & 40 \end{matrix} \quad * \quad \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \end{matrix} = 45$$

x k

Discrete Convolution

$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example: $1 \times 80 + 0.5 \times 40 + 0.25 \times 40 + 0 \times 0 = 110$

The diagram illustrates the discrete convolution operation between an input tensor x and a kernel k . The input x is a 3x3 matrix with values [1, 0.5, 40; 0.25, 0, 0; 0, 0, 40]. The kernel k is a 2x2 matrix with values [0, 0.25; 0.5, 1]. The result of the convolution is a scalar value of 110.

$$\begin{matrix} 1 & 0,5 & 40 \\ 0,25 & 0 & 0 \\ 0 & 0 & 40 \end{matrix} \quad * \quad \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \end{matrix} \quad = \quad \begin{matrix} 45 & 110 \end{matrix}$$

x k

Discrete Convolution

$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example: $1 \times 20 + 0.5 \times 40 + 0.25 \times 0 + 0 \times 0 = 40$

The diagram illustrates the discrete convolution operation between an input matrix x and a kernel matrix k . The input matrix x is a 3x3 grid with values [0, 80, 40; 80, 40, 0; 40, 0, 40]. The kernel matrix k is a 2x2 grid with values [0, 0.25; 0.5, 1]. The result of the convolution is a 2x2 output matrix with values [45, 110; 40, 0]. The operation is shown as $x * k = \text{result}$.

$$\begin{matrix} 0 & 80 & 40 \\ 80 & 40 & 0 \\ 40 & 0 & 40 \end{matrix} \quad * \quad \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \end{matrix} \quad = \quad \begin{matrix} 45 & 110 \\ 40 & 0 \end{matrix}$$

x k

Discrete Convolution

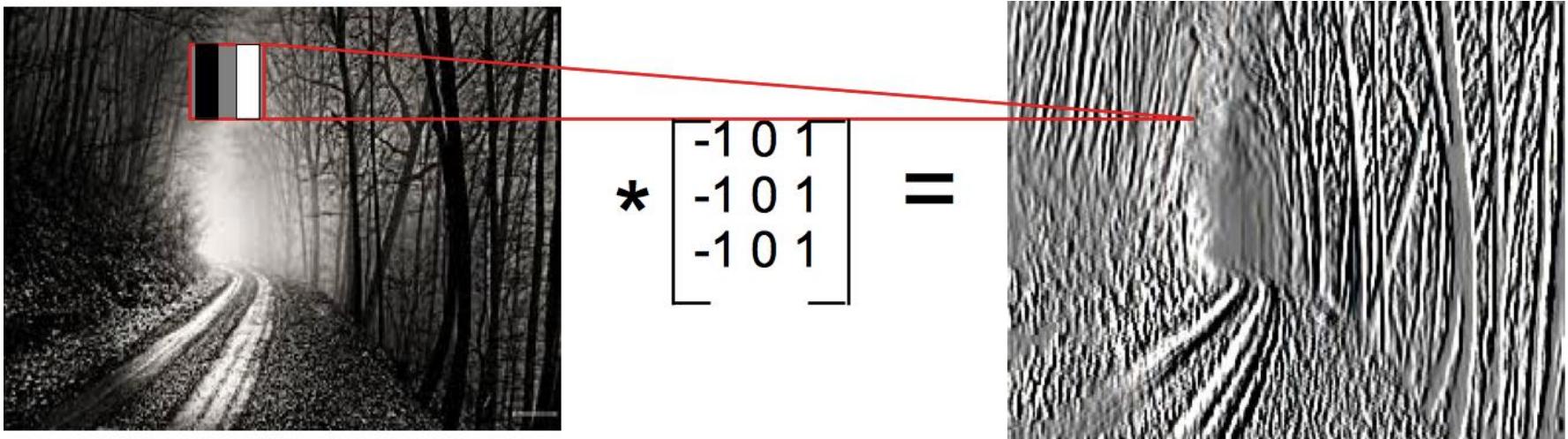
$$(x * k)_{ij} = \sum_{pq} x_{i+p, j+q} k_{r-p, r-q}$$

Example: $1 \times 40 + 0.5 \times 0 + 0.25 \times 0 + 0 \times 40 = 40$

The diagram illustrates the computation of a discrete convolution. On the left, a 3x3 input image x is shown with values: top row [0, 80, 40], middle row [20, 40, 0], bottom row [0, 0, 0]. A 2x2 kernel k is applied to it. The kernel k has values: top-left [0, 0.25], top-right [0.5, 1], bottom-left [0.25, 0], bottom-right [0, 0]. The result of the convolution is a 2x2 output image with values: top-left [45, 110], bottom-left [40, 40]. The multiplication and summation steps are indicated by the asterisk (*) and equals sign (=) between the input and output.

$$\begin{matrix} 0 & 80 & 40 \\ 20 & 40 & 0 \\ 0 & 0 & 0 \end{matrix} * \begin{matrix} 0 & 0,25 \\ 0,5 & 1 \\ 0,25 & 0 \\ 0 & 0 \end{matrix} = \begin{matrix} 45 & 110 \\ 40 & 40 \end{matrix}$$

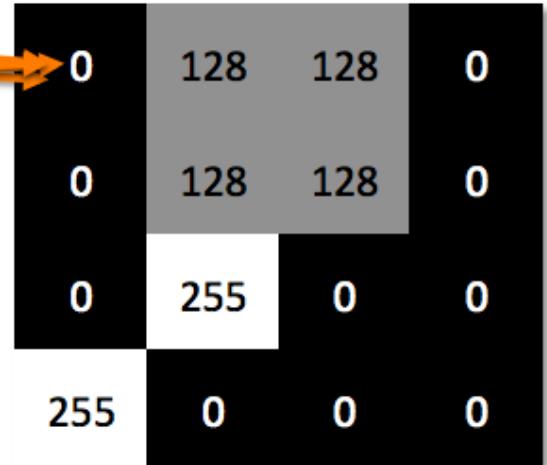
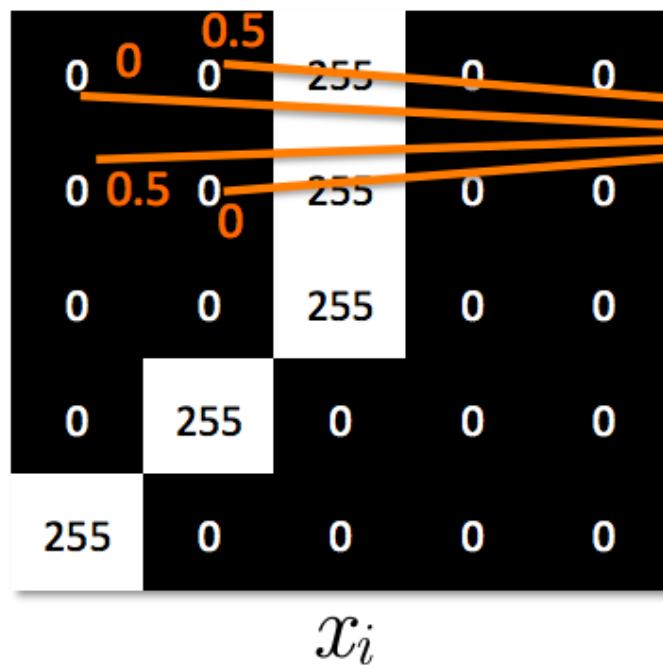
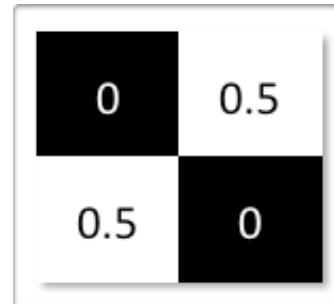
Example of a convolution



Adding non-linearity

With a non-linearity, we get a detector of a feature at any position in the image:

$$x * k_{ij},$$

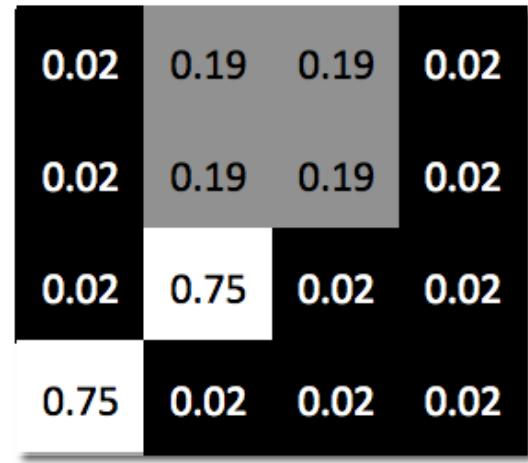
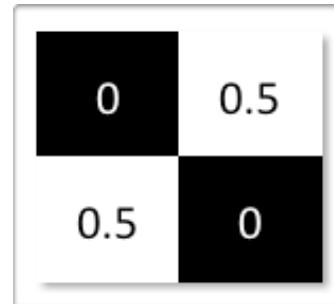


$$x_i * k_{ij}$$

Adding non-linearity

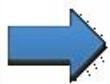
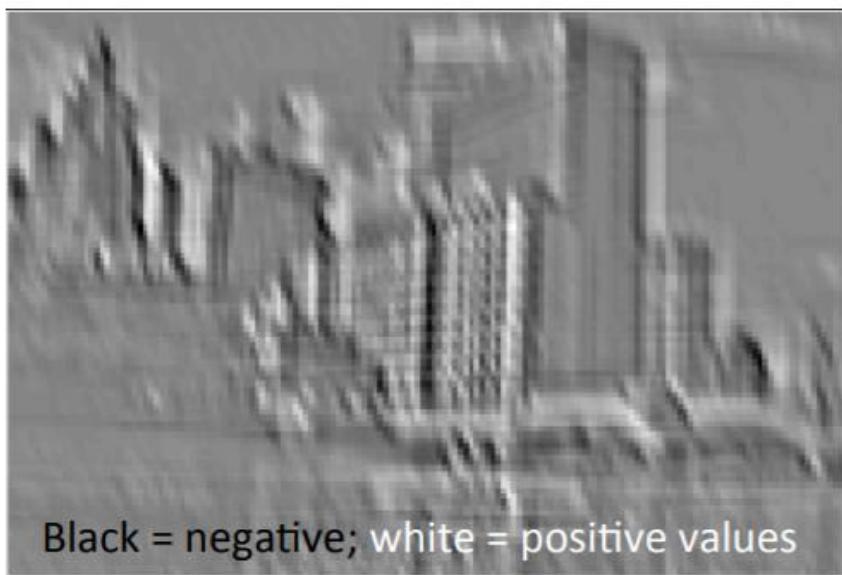
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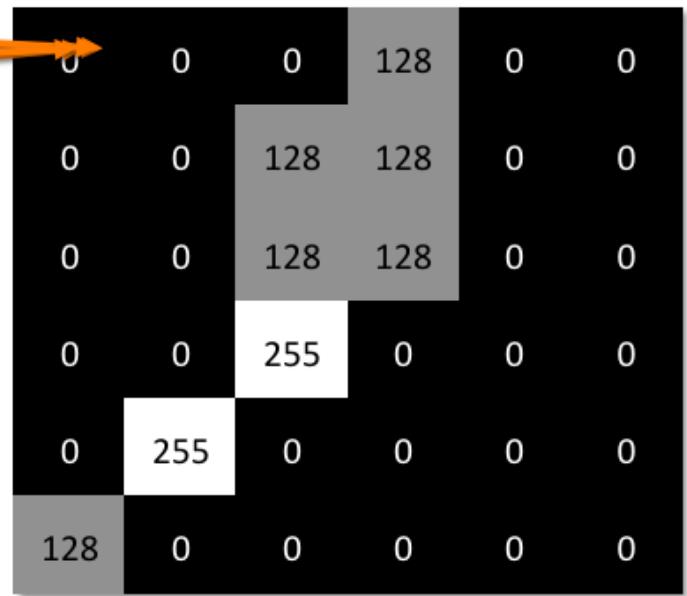
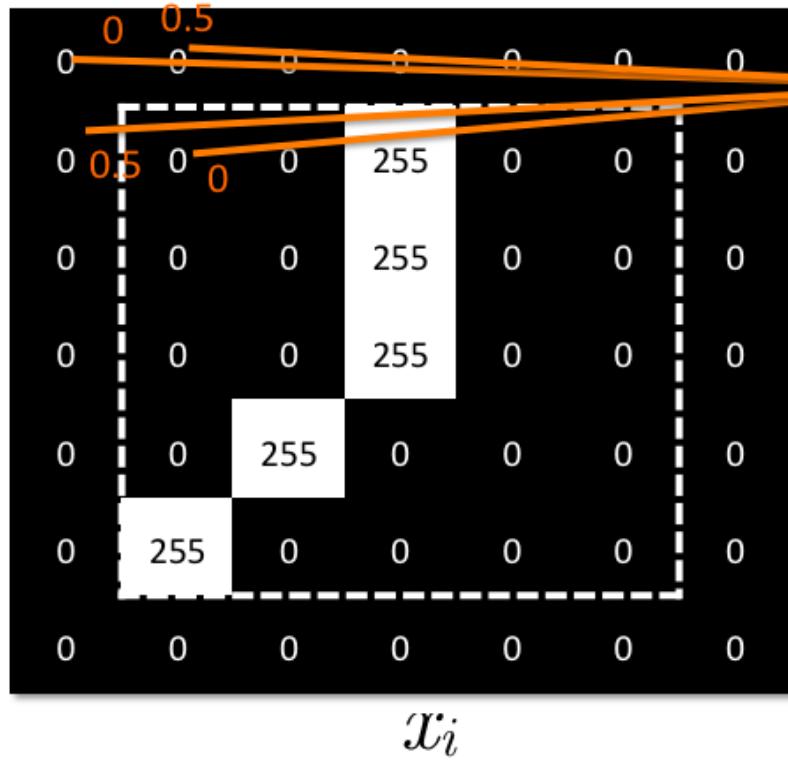
$$\text{sigm}(0.02 \ x_i * k_{ij} - 4)$$

Example of ReLU non-linearity



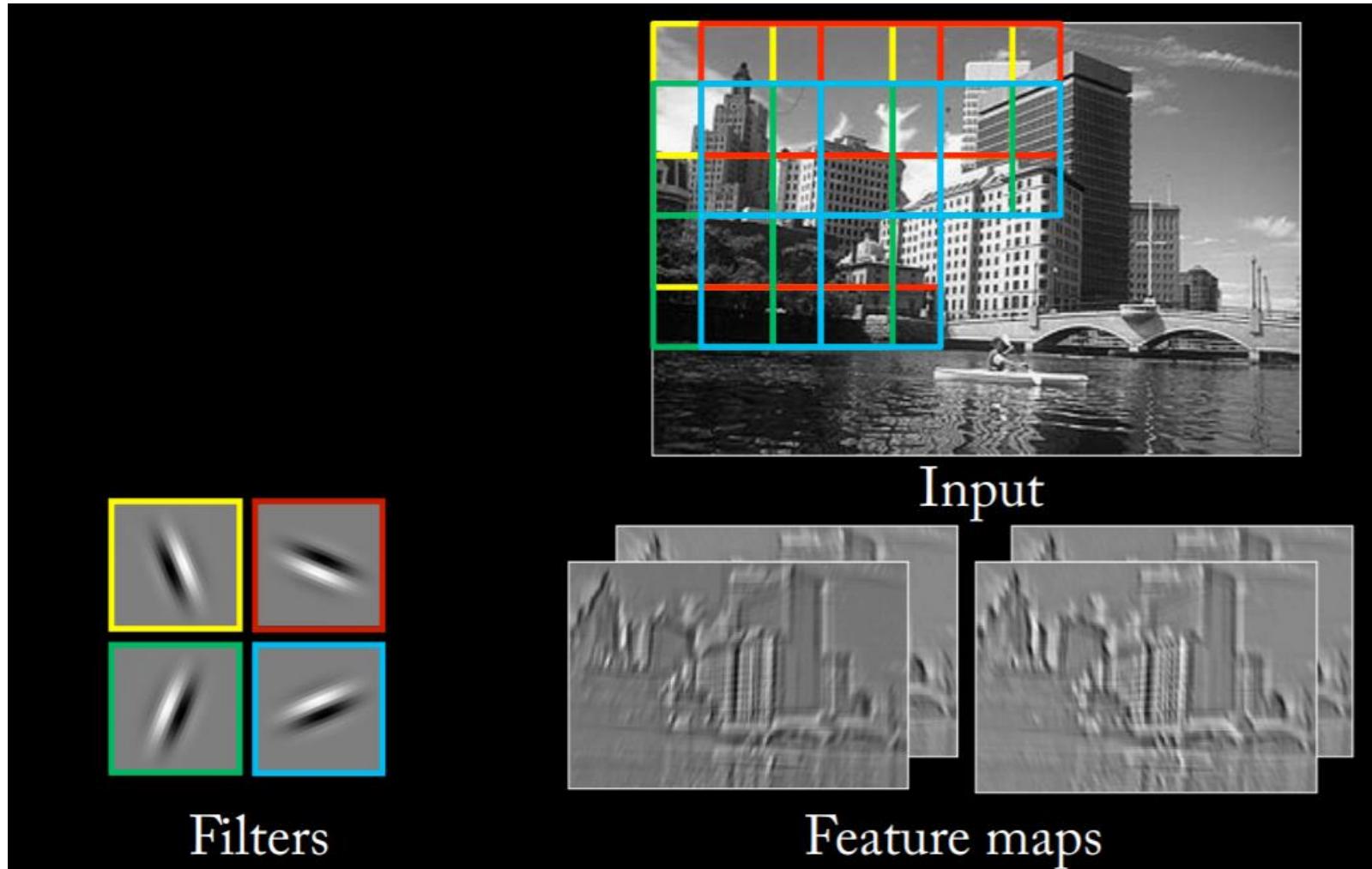
Padding

Can use “zero padding” to allow going over the borders



$$x_i * k_{ij}$$

The picture so far



From Rob Fergus tutorial (http://mlss.tuebingen.mpg.de/2015/slides/fergus/Fergus_1.pdf)

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- ✿ Must deal with very high-dimensional inputs: 150×150 pixels = 22500 inputs, or 3×22500 if RGB pixels
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- ✿ Can build in invariance to certain variations: translation, illumination, etc.

Convolutional networks leverage these ideas

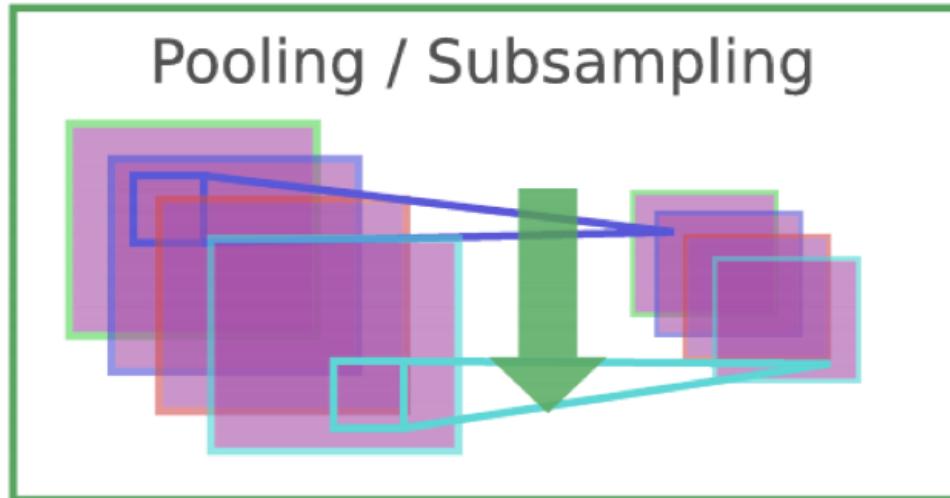
- ✿ Local connectivity
- ✿ Parameter sharing
- ✿ Convolution
- ✿ Pooling / subsampling hidden units

Pooling

Pool hidden units in same neighborhood

Pooling is performed in non-overlapping neighborhoods (subsampling)

$$y_{ijk} = \max_{p,q} x_{i,j+p,k+q}$$



- x_i is the i^{th} channel of input
- $x_{i,j,k}$ is value of the i^{th} feature map at position j,k
- p is vertical index in local neighborhood
- q is horizontal index in local neighborhood
- y_{ijk} is pooled / subsampled layer

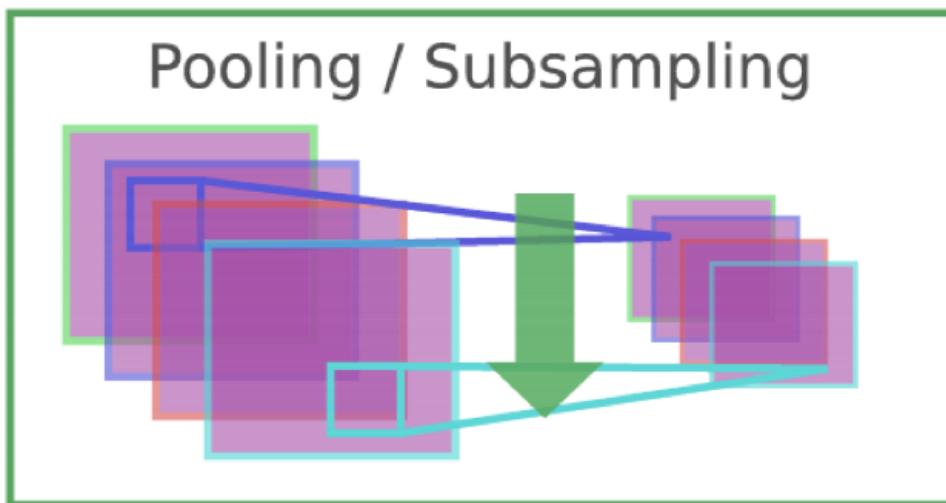
Jarret et al. 2009

Pooling

Pool hidden units in same neighborhood

An alternative to “max” pooling is “average” pooling

$$y_{ijk} = \frac{1}{m^2} \sum_{p,q} x_{i,j+p,k+q}$$

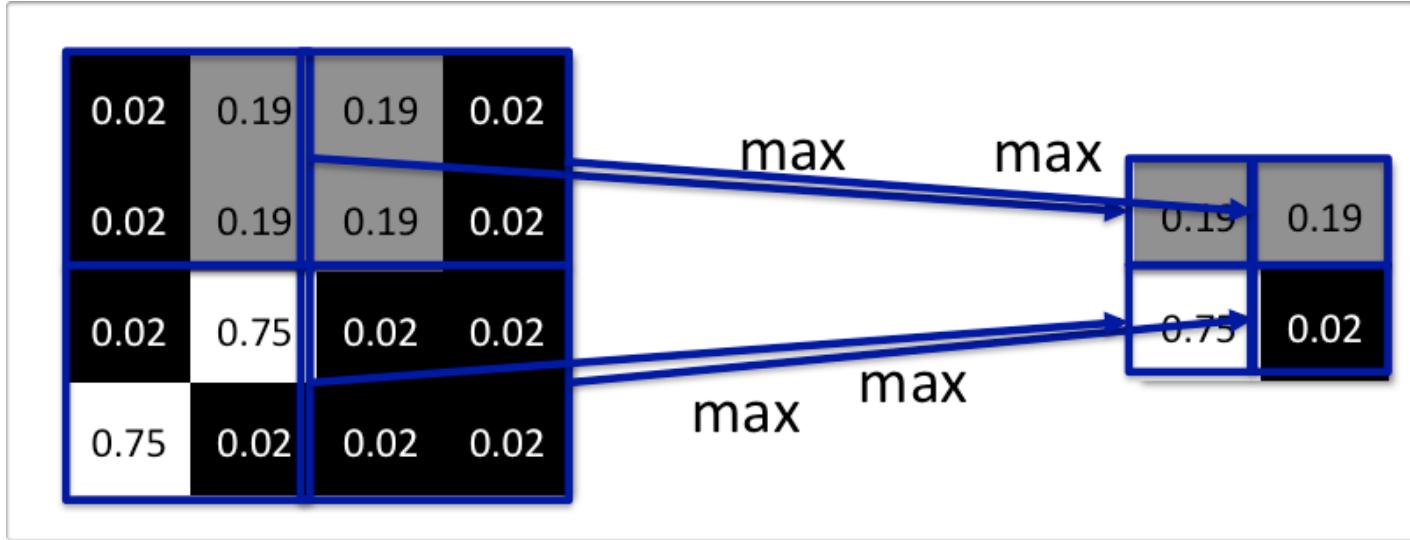


Jarret et al. 2009

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- y_{ijk} is pooled / subsampled layer
- m is the neighborhood height/width

Example: Pooling

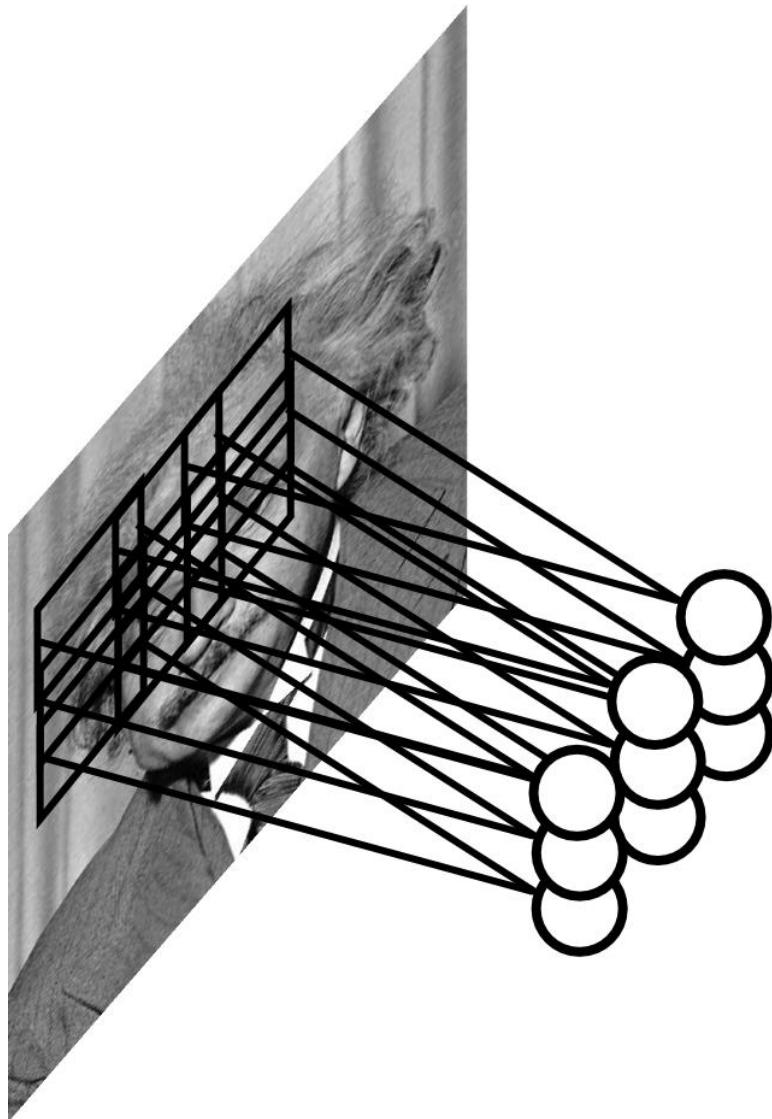
Illustration of pooling/subsampling operation



Why pooling?

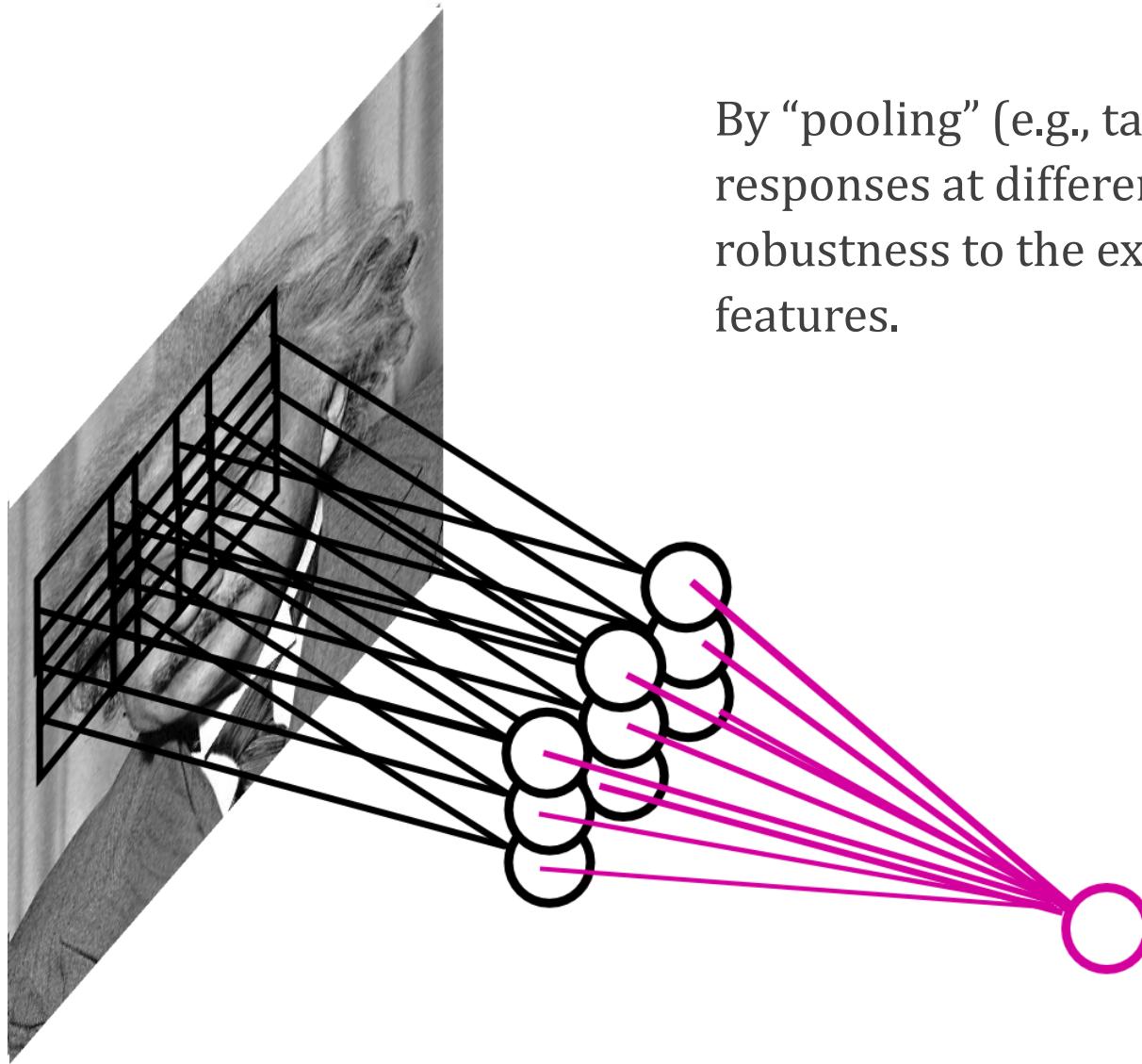
- 🌀 Introduces invariance to local translations
- 🌀 Reduces the number of hidden units in hidden layer

Example: Pooling



Can we make the detection robust to the exact location of the eye?

Example: Pooling

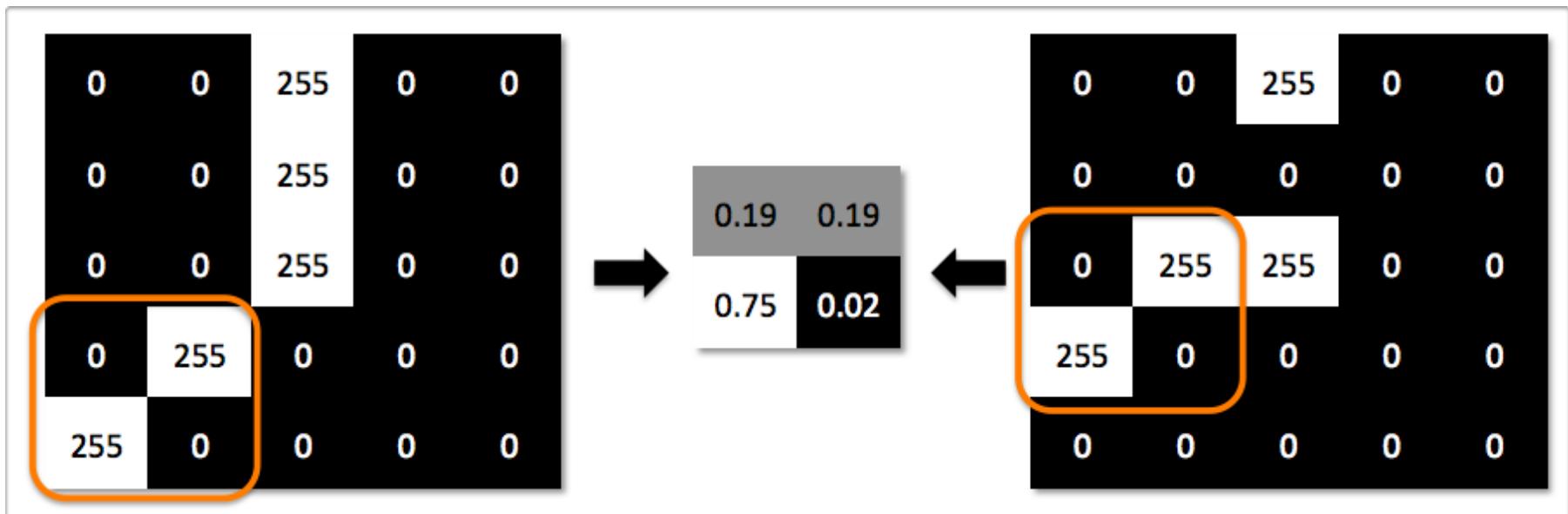


By “pooling” (e.g., taking max) filter responses at different locations we gain robustness to the exact spatial location of features.

Translation Invariance

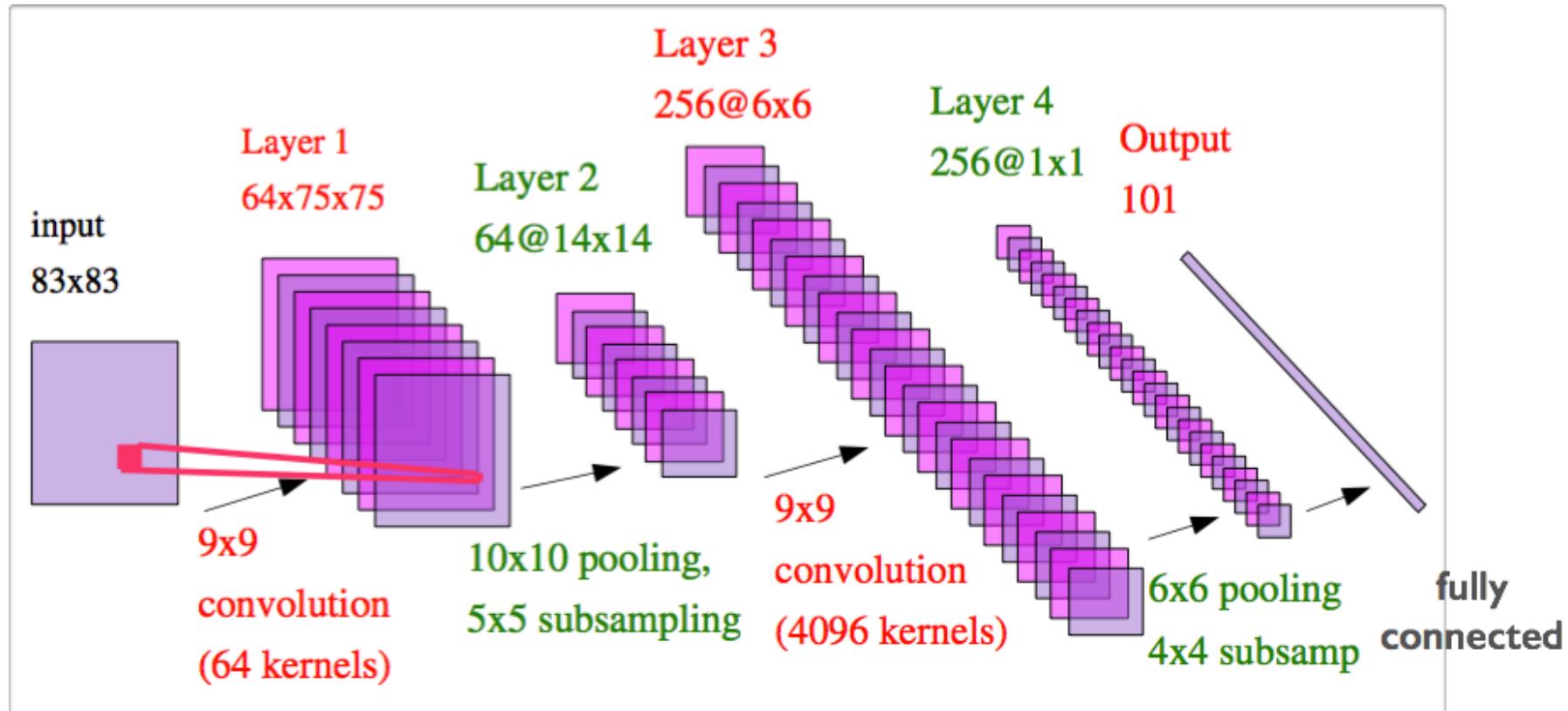
Illustration of local translation invariance

Both images result in the same feature map after pooling/subsampling



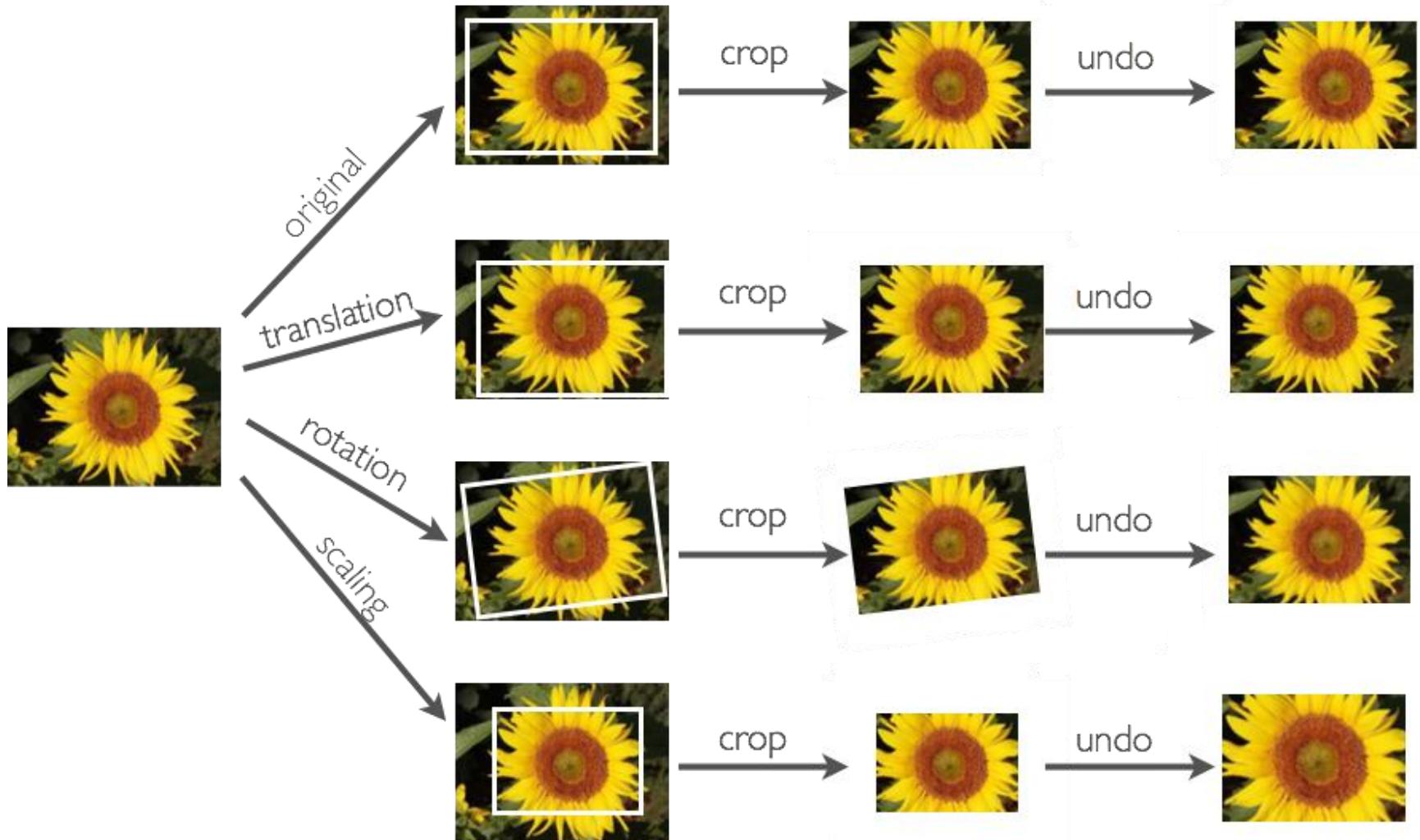
Convolutional Network

Convolutional neural network alternates between convolutional and pooling layers



From Yann LeCun's slides

Generating Additional Examples

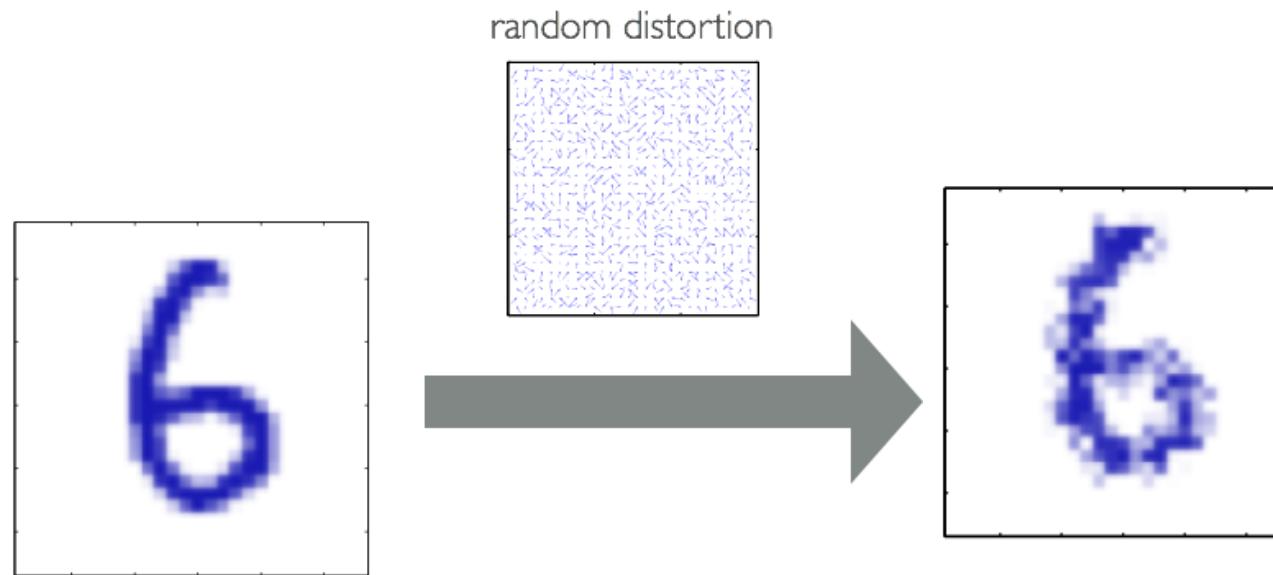


Elastic Distortions

Can add “**elastic**” deformations (useful in character recognition)

We can do this by applying a “**distortion field**” to the image

A distortion field specifies where to displace each pixel value



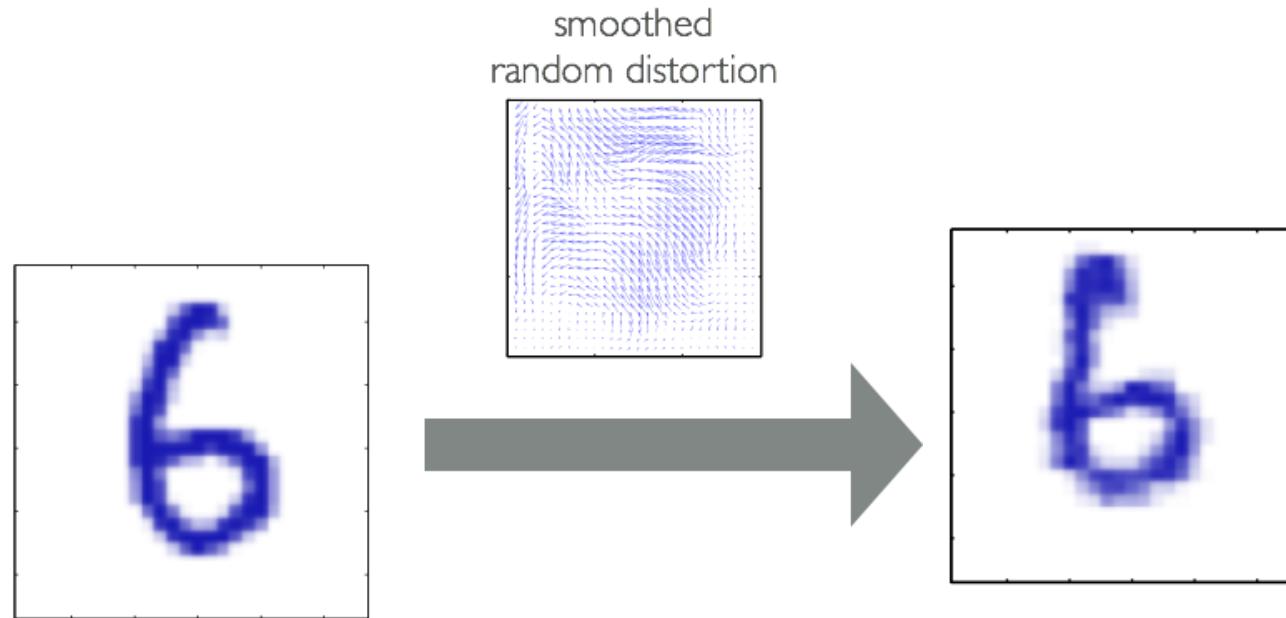
Bishop's book

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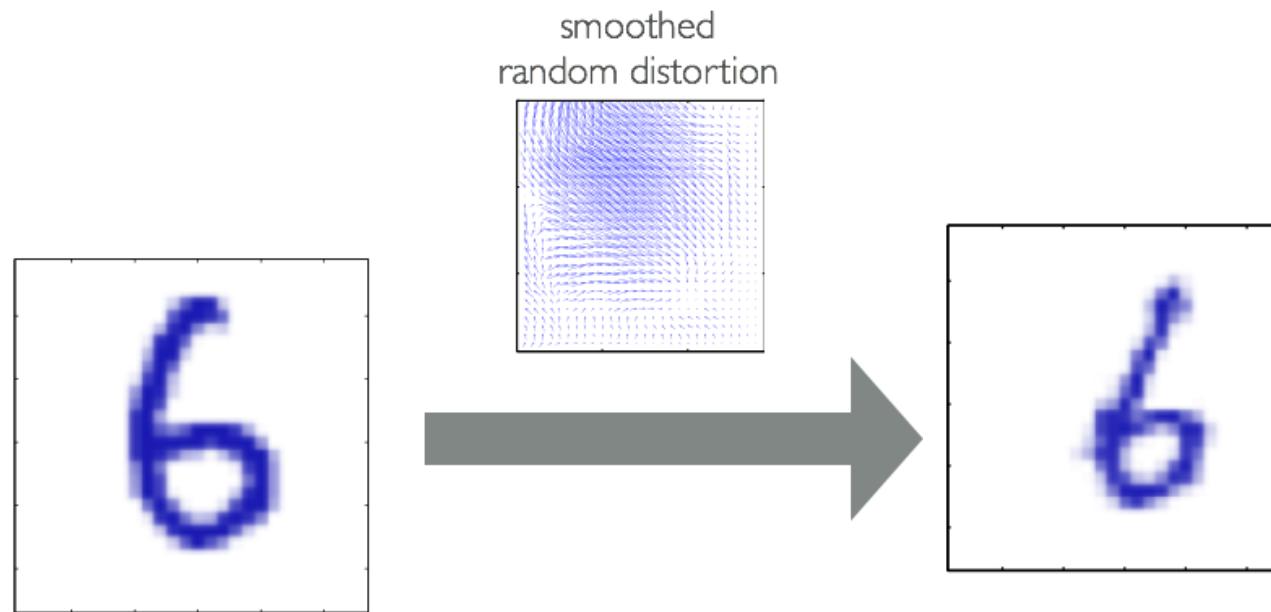
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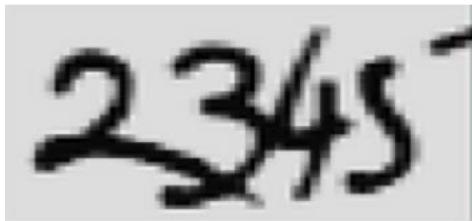
A distortion field specifies where to displace each pixel value



Bishop's book

Conv Nets: Examples

Optical Character Recognition, House Number and Traffic Sign classification



Ciresan et al. "MCDNN for image classification" CVPR 2012

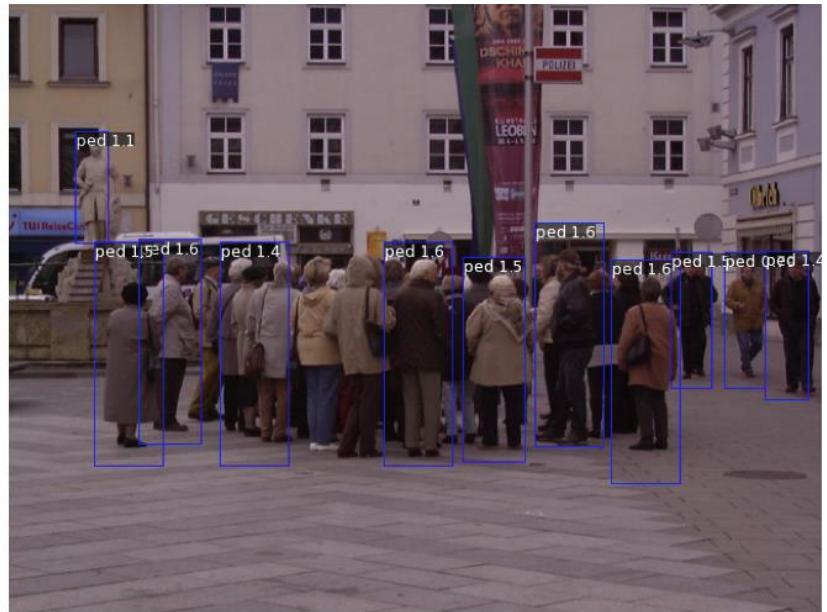
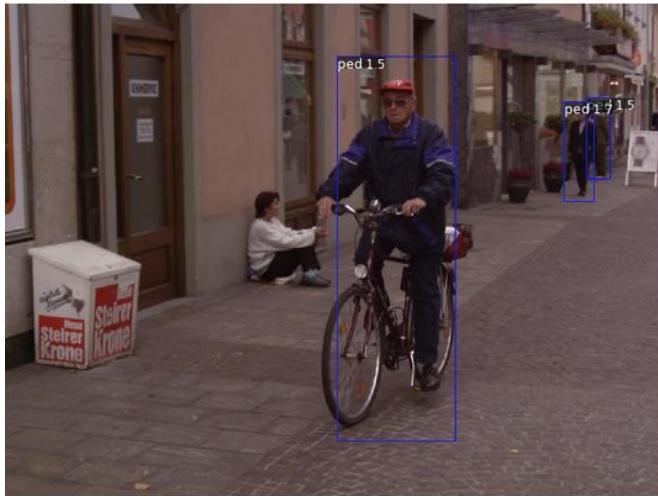
Wan et al. "Regularization of neural networks using dropconnect" ICML 2013

Goodfellow et al. "Multi-digit number recognition from StreetView..." ICLR 2014

Jaderberg et al. "Synthetic data and ANN for natural scene text recognition" arXiv 2014

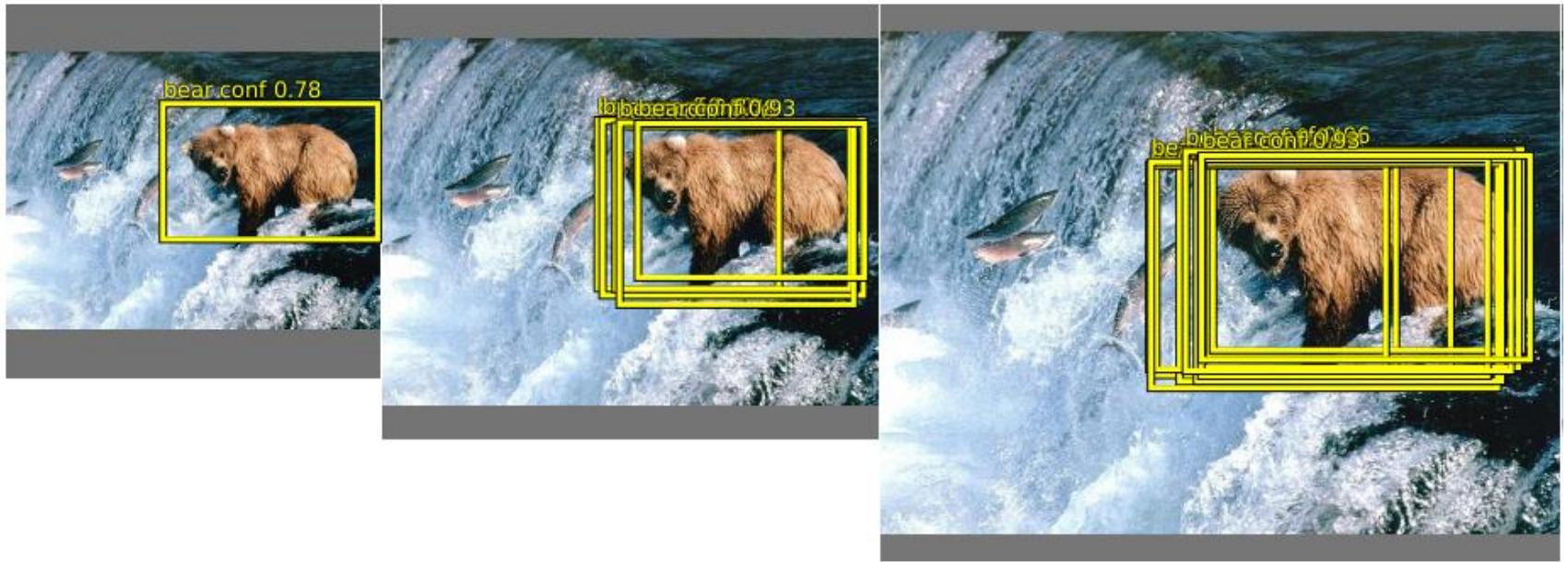
Conv Nets: Examples

Pedestrian detection



Conv Nets: Examples

Object Detection



Sermanet et al. “OverFeat: Integrated recognition, localization” arxiv 2013

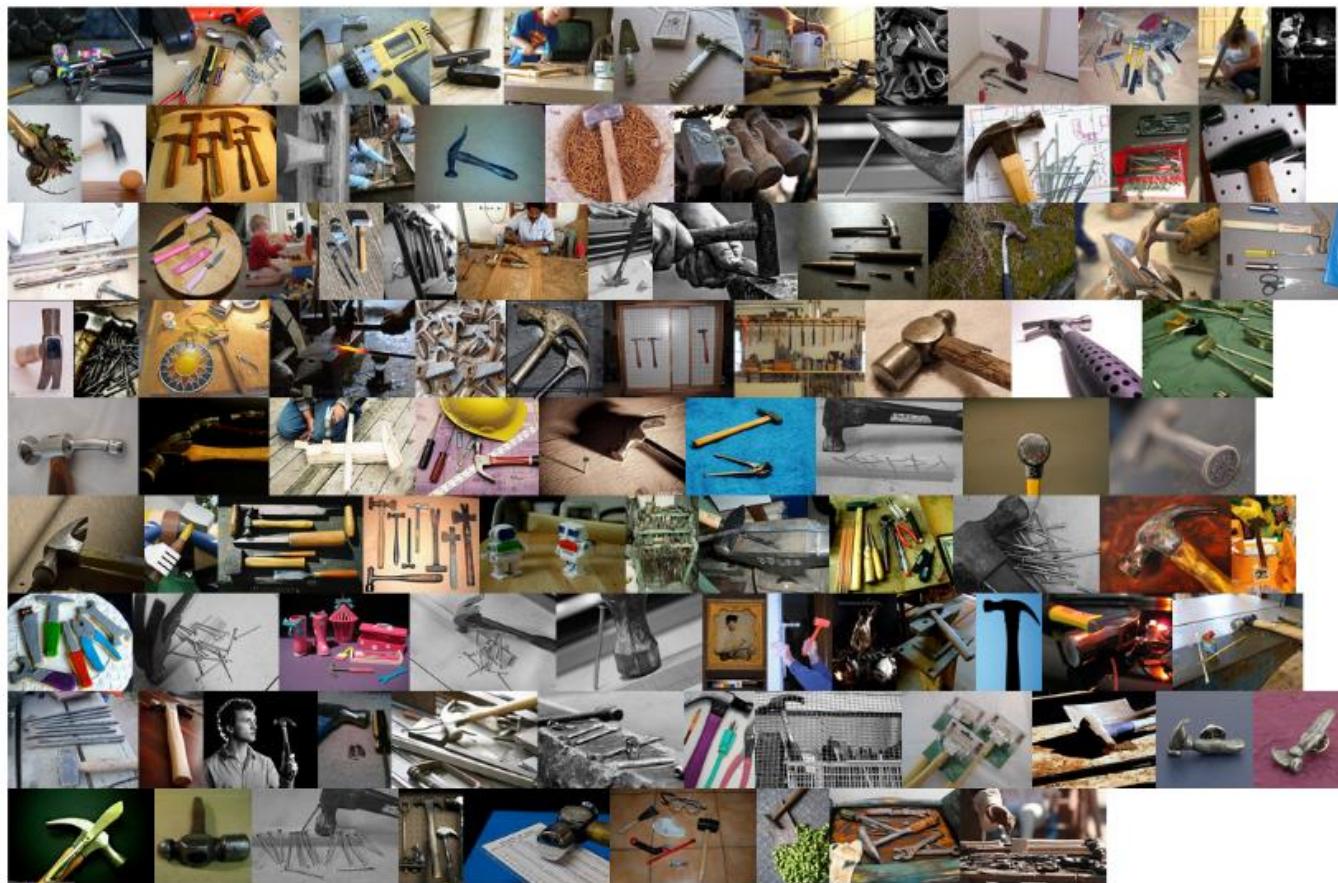
Girshick et al. “Rich feature hierarchies for accurate object detection” arxiv 2013

Szegedy et al. “DNN for object detection” NIPS 2013

ImageNet Dataset

~14 million images, 20k classes

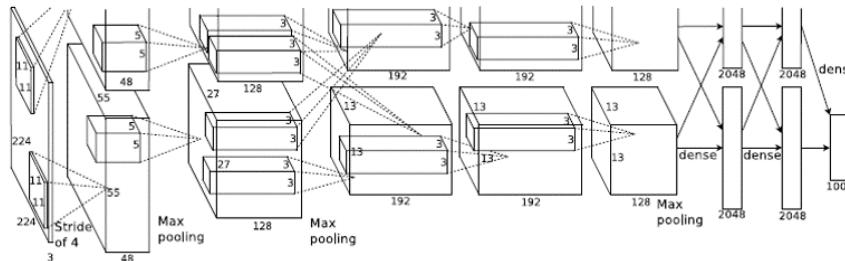
Examples of “Hammer”



Important Breakthroughs

Deep Convolutional Nets for Vision (Supervised)

Krizhevsky, A., Sutskever, I. and Hinton, G. E., ImageNet Classification with Deep Convolutional Neural Networks, NIPS, 2012.



~14 million images, 20k classes



Architecture

How can we select the “right” architecture:

Manual tuning of features is now replaced with the manual tuning of architectures

- 🌀 Depth
- 🌀 Width
- 🌀 Parameter count

How to Choose Architecture

Many **hyper-parameters**:

Number of layers, number of feature maps

🌀 Cross Validation

🌀 Grid Search (need lots of GPUs)

🌀 Smarter Strategies

Random search [*Bergstra & Bengio JMLR 2012*]

Bayesian Optimization

Famous architectures

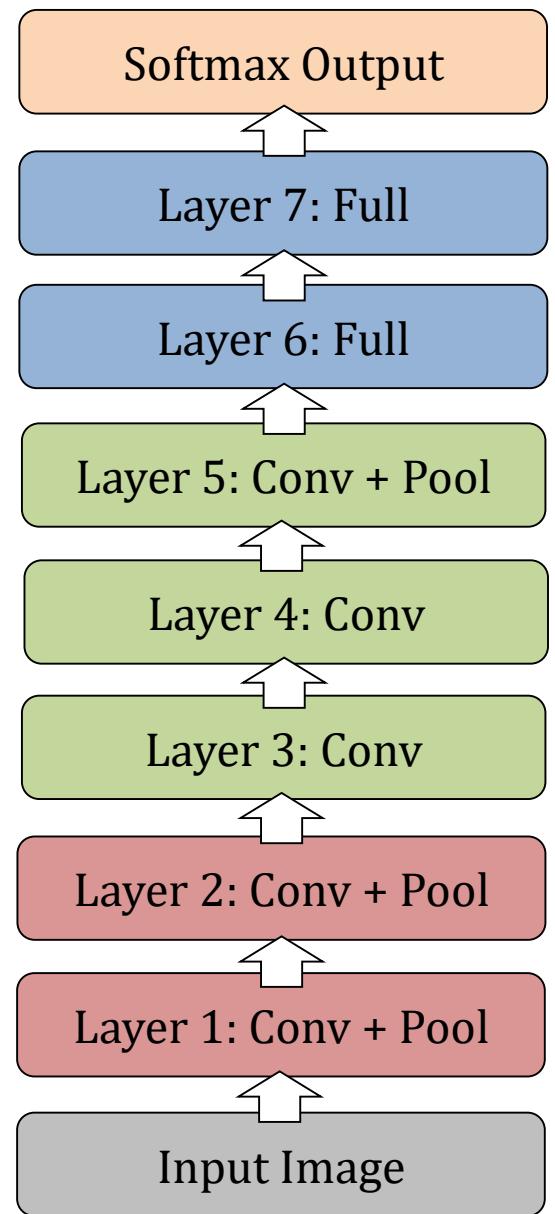
AlexNet

8 layers total, ~60 million parameters

Trained on Imagenet
dataset [Deng et al. CVPR'09]

18.2% top-5 error

[From Rob Fergus' CIFAR 2016 tutorial]

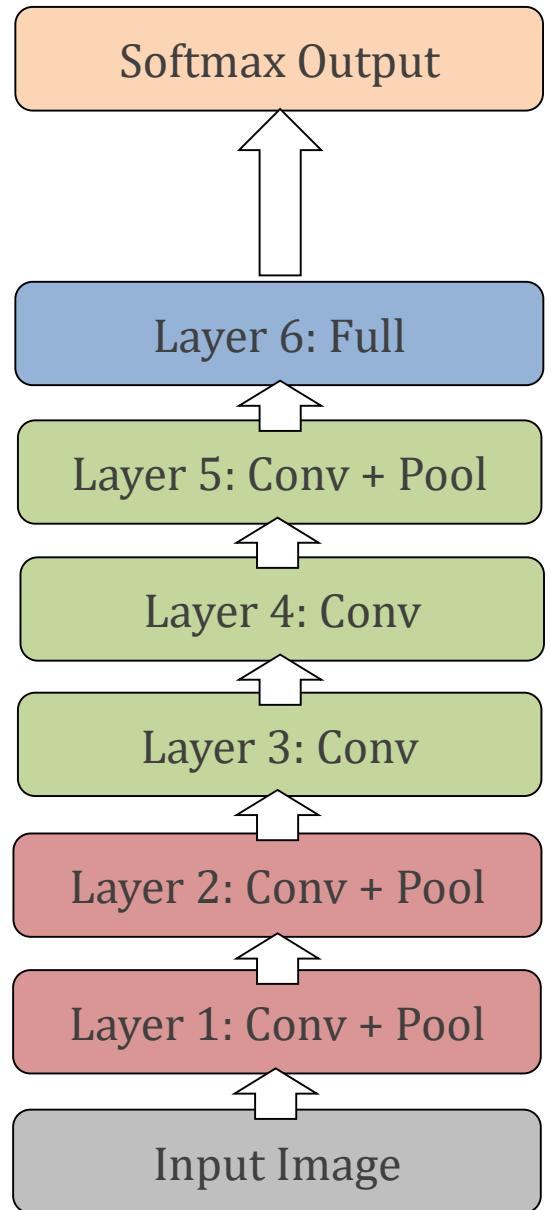


AlexNet: ablation study

Remove top fully connected layer 7

Drop ~16 million parameters

Only 1.1% drop in performance!



[From Rob Fergus' CIFAR 2016 tutorial]

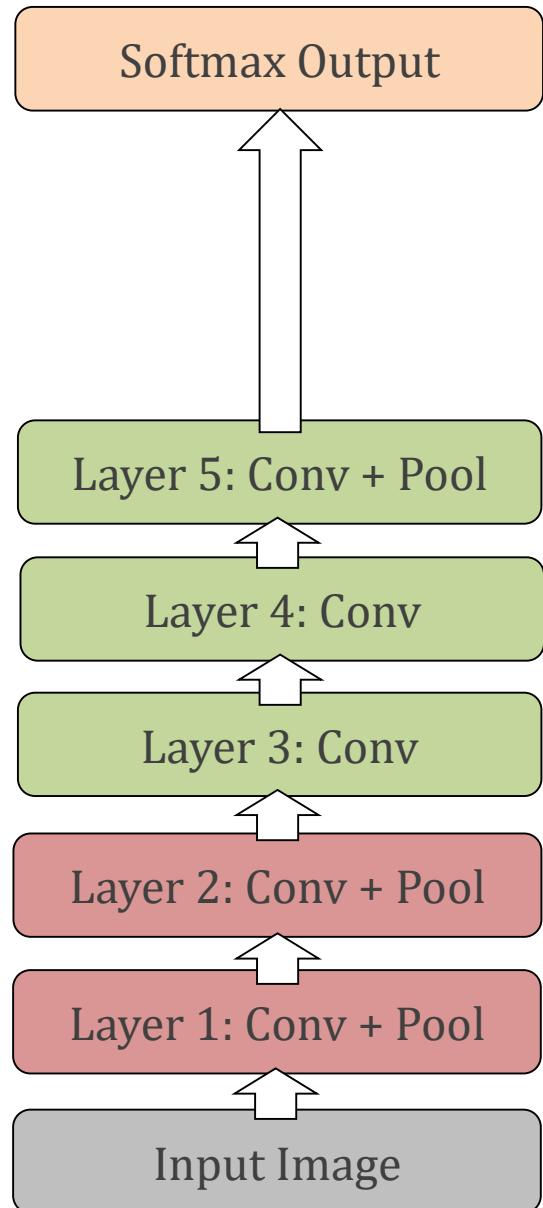
AlexNet: ablation study

Remove both fully connected layers 6,7

Drop ~50 million parameters

5.7% drop in performance!

Softmax Output



[From Rob Fergus' CIFAR 2016 tutorial]

AlexNet: ablation study

Remove upper feature extractor layers
(Layers 3 & 4)

Drop ~1 million parameters

3% drop in performance.

Softmax Output

Layer 7: Full

Layer 6: Full

Layer 5: Conv + Pool

Layer 2: Conv + Pool

Layer 1: Conv + Pool

Input Image

AlexNet: ablation study

Let us remove upper feature extractor layers and fully connected:

- Layers 3,4, 6 and 7

33.5% drop in performance!

Depth of the network is the key.

Softmax Output

Layer 5: Conv + Pool

Layer 2: Conv + Pool

Layer 1: Conv + Pool

Input Image

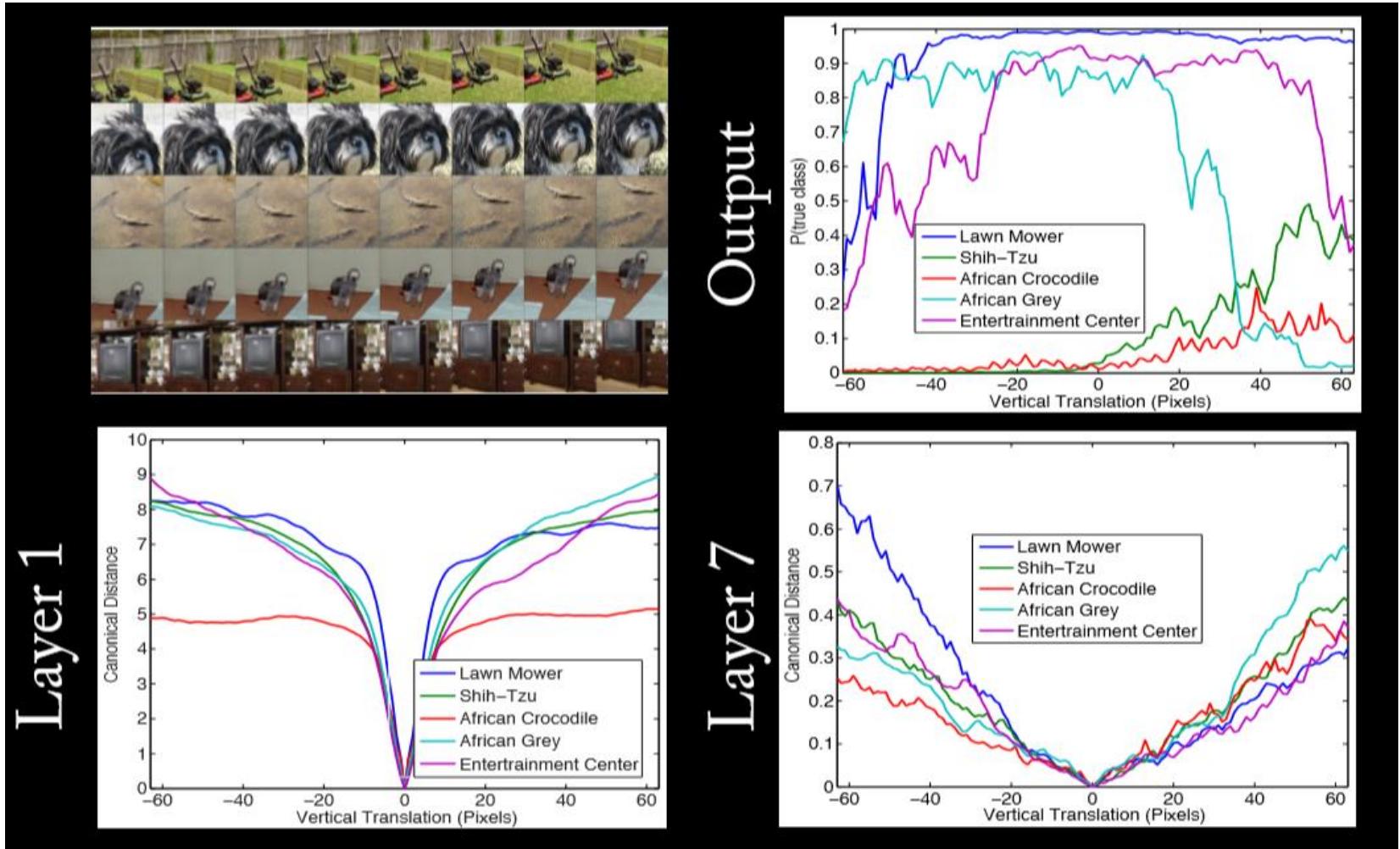
AlexNet: intermediate features

Plug features from each layer into linear SVM or soft-max

	Cal-101 (30/class)	Cal-256 (60/class)
SVM (1)	44.8 ± 0.7	24.6 ± 0.4
SVM (2)	66.2 ± 0.5	39.6 ± 0.3
SVM (3)	72.3 ± 0.4	46.0 ± 0.3
SVM (4)	76.6 ± 0.4	51.3 ± 0.1
SVM (5)	86.2 ± 0.8	65.6 ± 0.3
SVM (7)	85.5 ± 0.4	71.7 ± 0.2
Softmax (5)	82.9 ± 0.4	65.7 ± 0.5
Softmax (7)	85.4 ± 0.4	72.6 ± 0.1

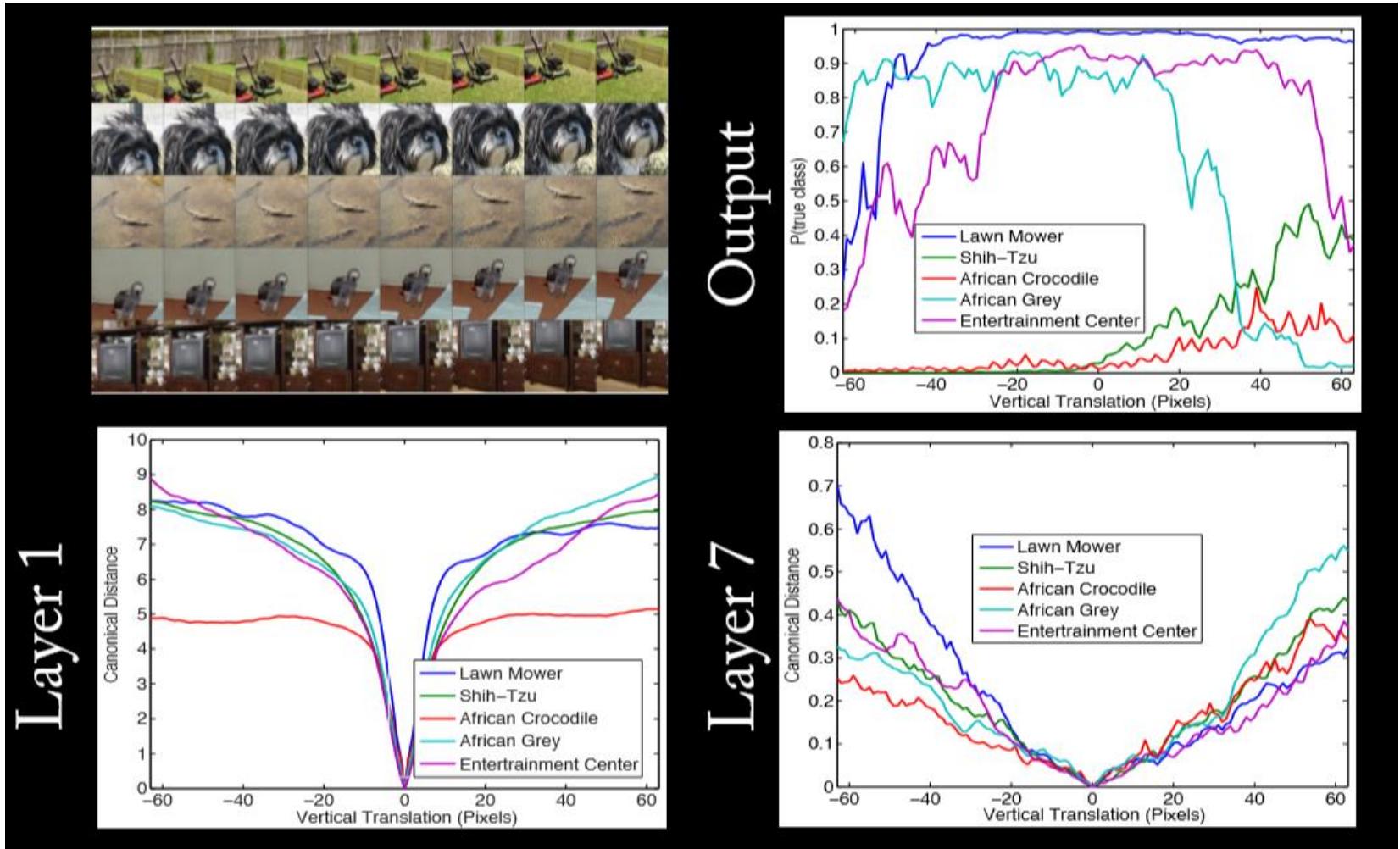
[From Rob Fergus' CIFAR 2016 tutorial]

AlexNet: translation invariance



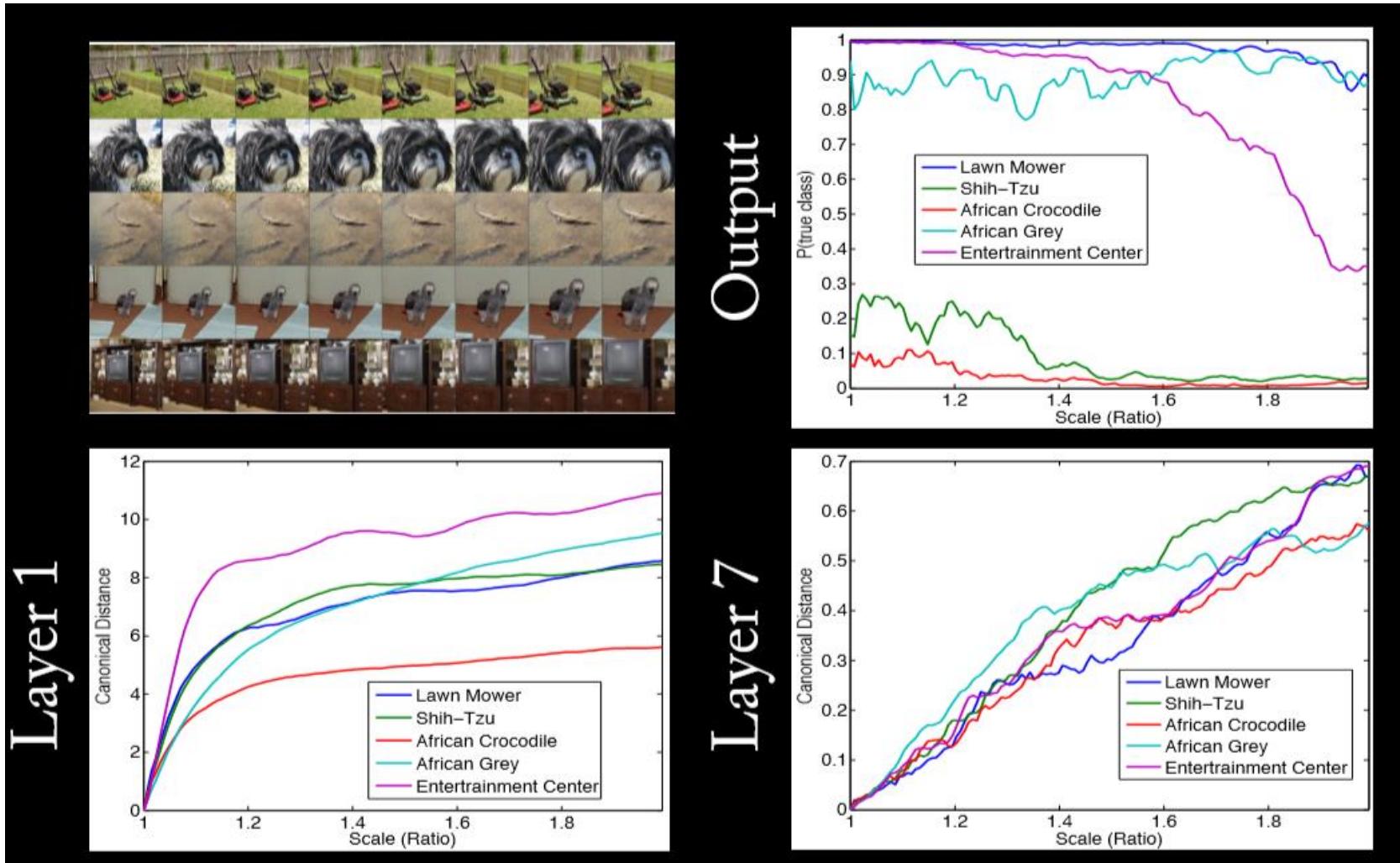
[From Rob Fergus' CIFAR 2016 tutorial]

AlexNet: translation invariance



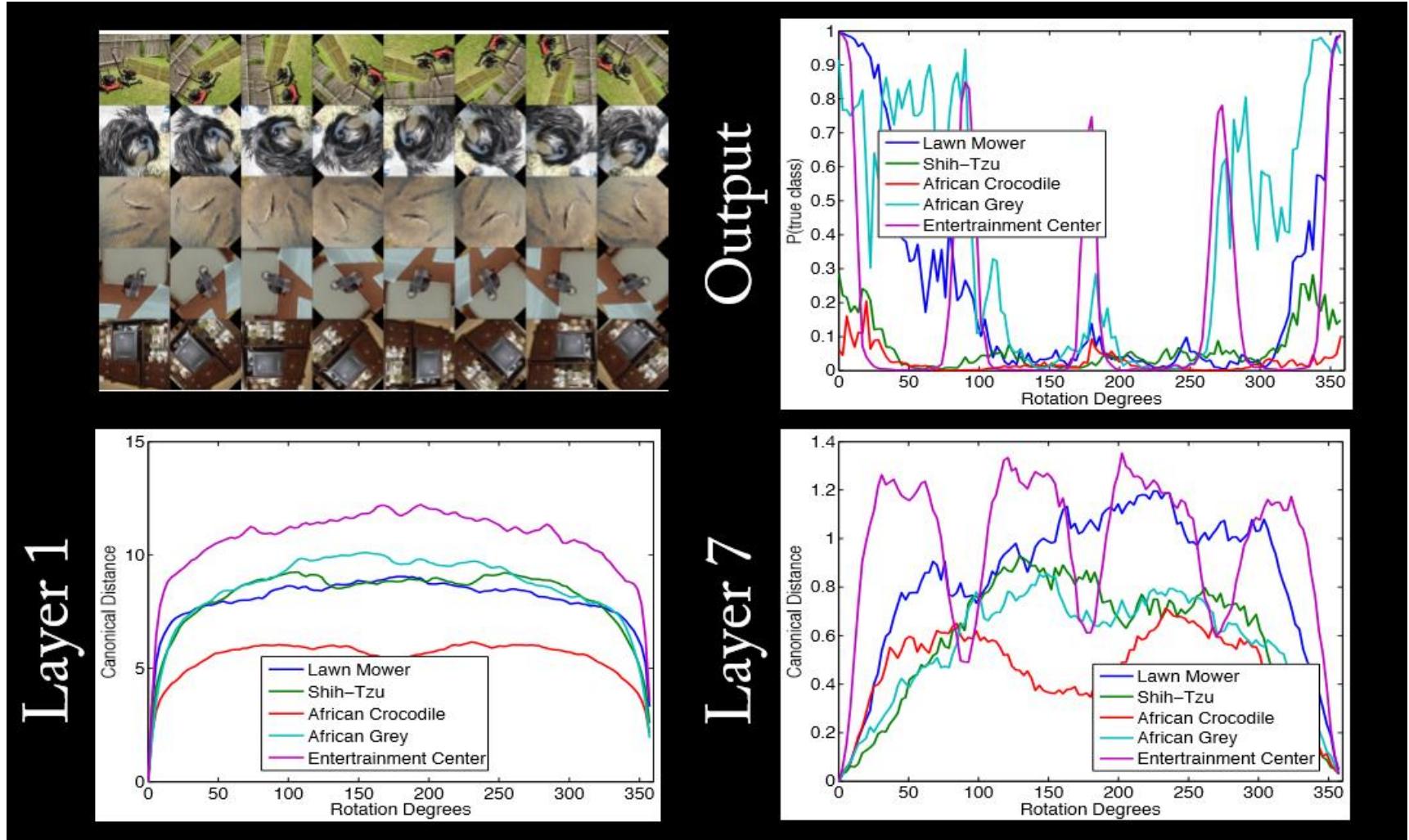
[From Rob Fergus' CIFAR 2016 tutorial]

AlexNet: scaling invariance



[From Rob Fergus' CIFAR 2016 tutorial]

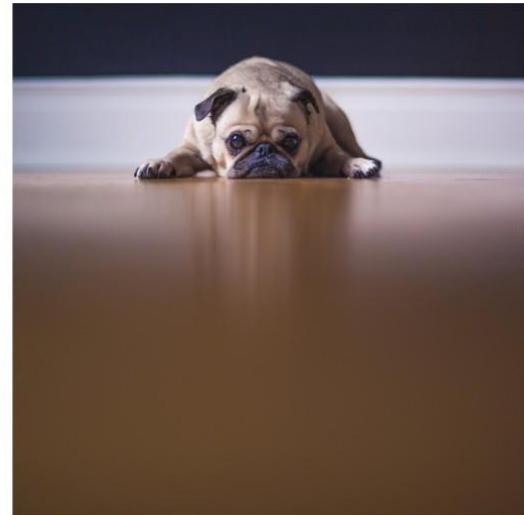
AlexNet: rotation invariance



[From Rob Fergus' CIFAR 2016 tutorial]

GoogLeNet

Issue: multiscale nature of images

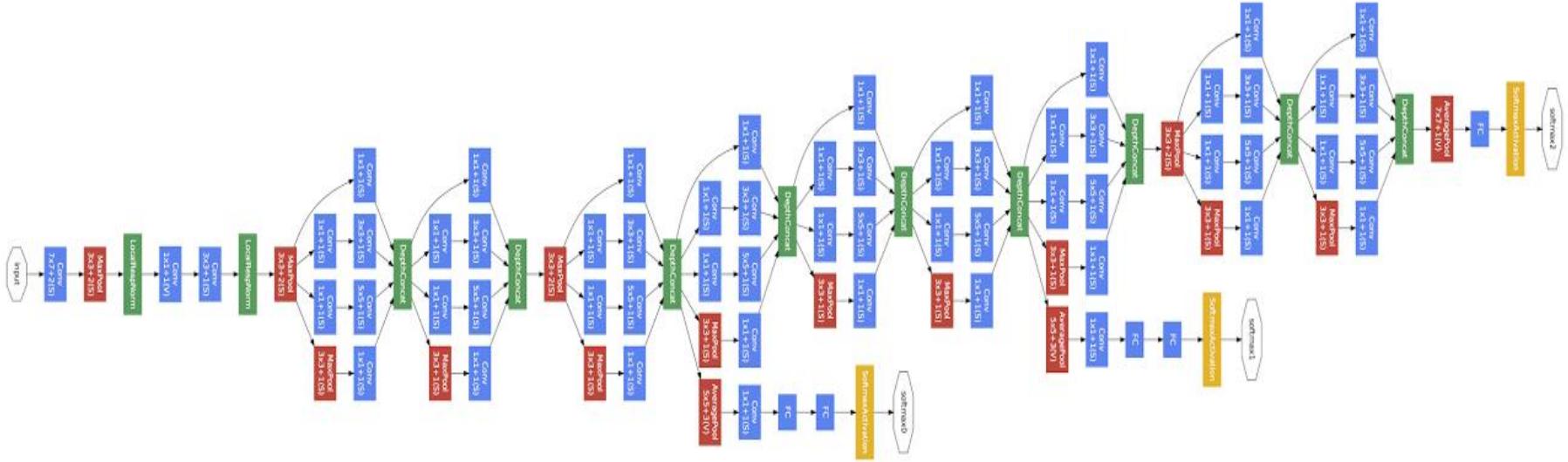


<https://towardsdatascience.com/a-simple-guide-to-the-versions-of-the-inception-network-7fc52b863202>

Larger kernel good for global features, and *smaller kernel* for local features.

Idea: have multiple different-size kernels at any given level.

GoogLeNet

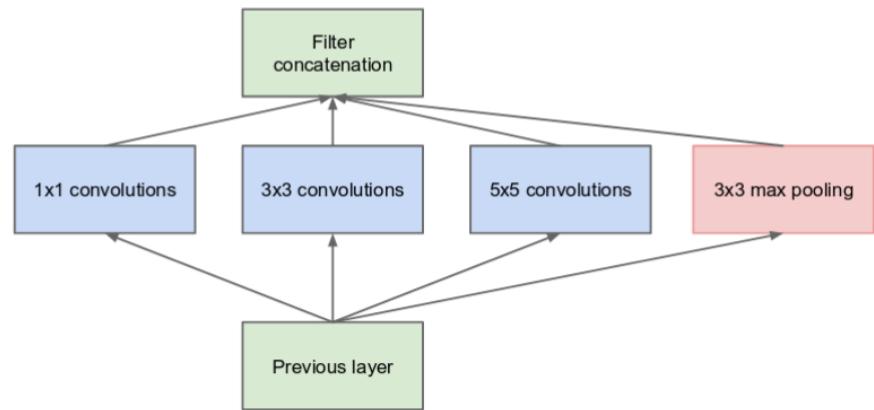
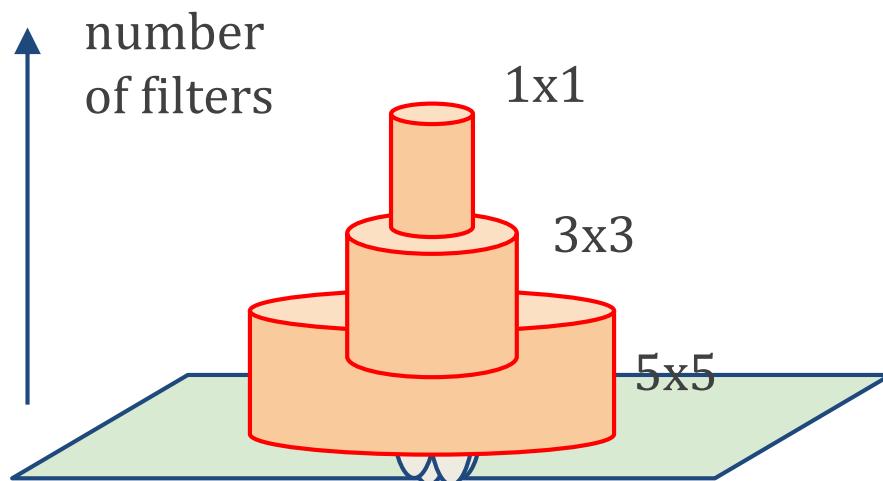


24-layer model that uses so-called **inception module**.

GoogLeNet

GoogLeNet inception module:

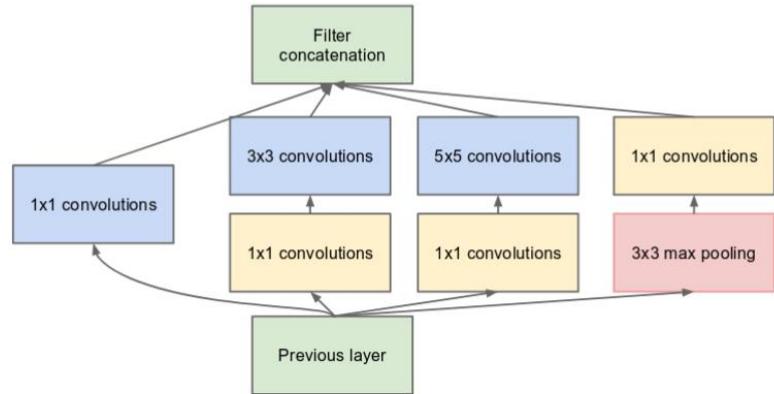
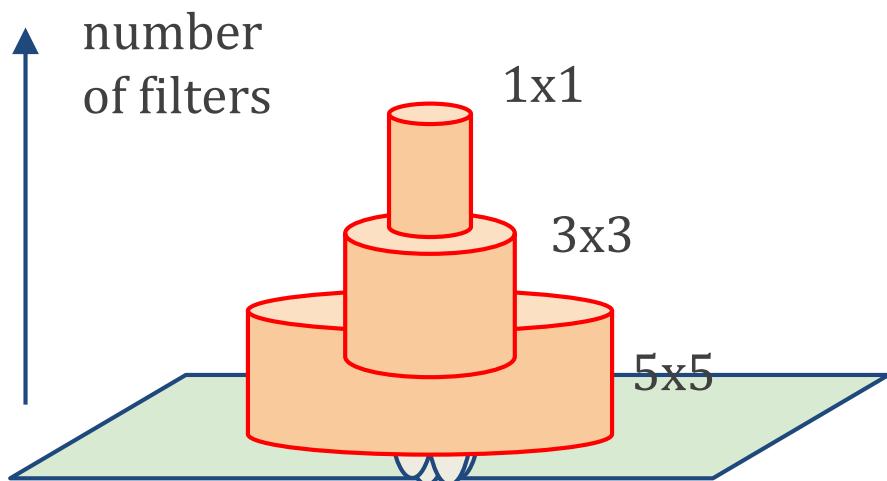
- Multiple filter scales at each layer



GoogLeNet

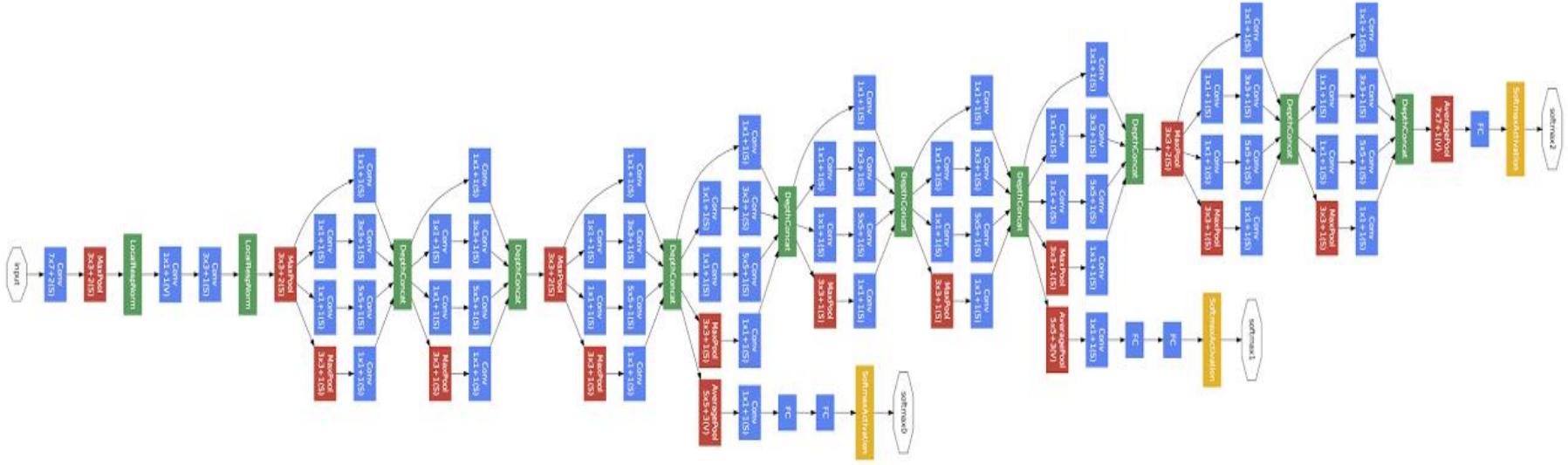
GoogLeNet inception module:

- ⌚ Multiple filter scales at each layer
- ⌚ Dimensionality reduction to keep computational requirements down



(b) Inception module with dimension reductions

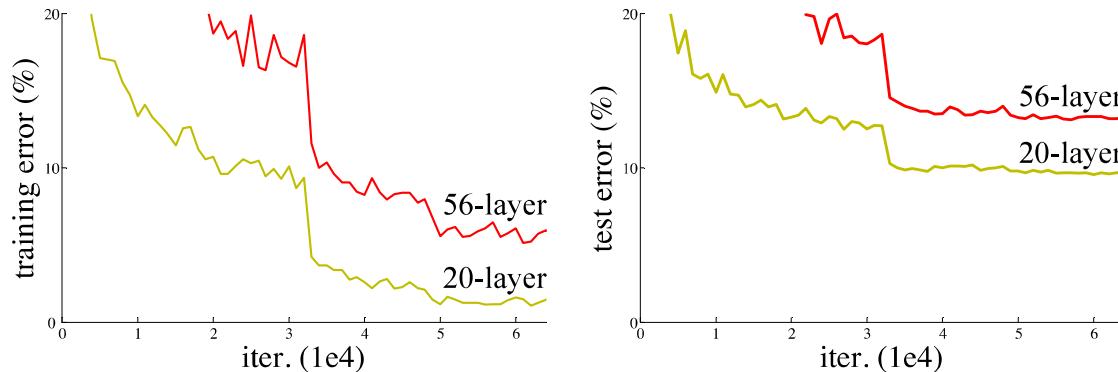
GoogLeNet



- 🌀 Width of inception modules ranges from 256 filters (in early modules) to 1024 in top inception modules.
- 🌀 Can remove fully connected layers on top completely
- 🌀 Number of parameters is reduced to 5 million
- 🌀 6.7% top-5 validation error on Imagnet

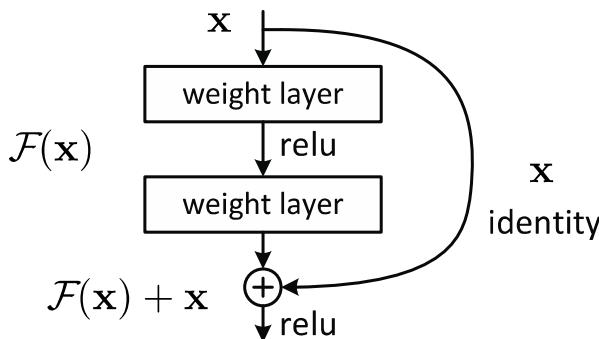
Residual Networks

Really, really deep convnets do not train well, E.g. CIFAR10:



Reason: gradients involve multiplications of a # of matrices proportional to depth.

Vanishing/exploding gradients: gradients get very small/very large.

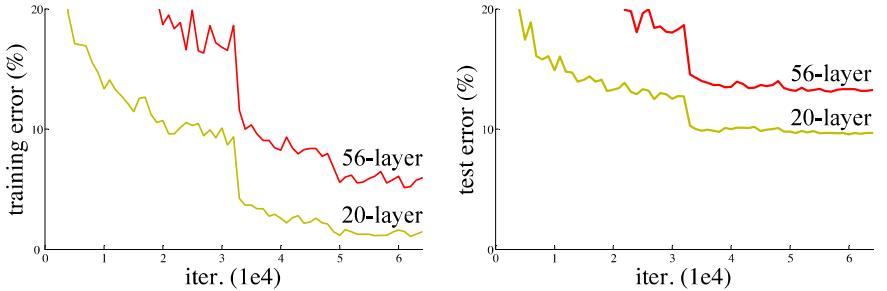


Key idea: introduce “identity shortcut” connection, skipping one or more layers.

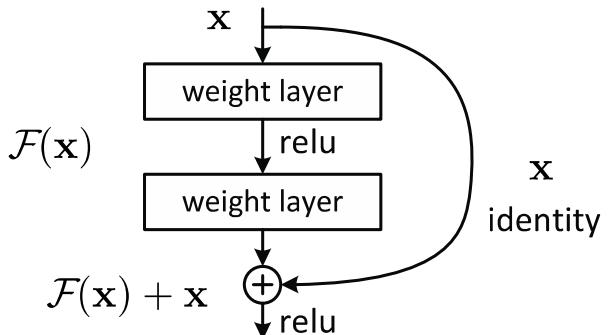
Intuition: network can easily simulate shallower network (at initialization, F is not too far from 0 map), so performance should not degrade by going deeper.

Residual Networks

Really, really deep convnets do not train well,
E.g. CIFAR10:



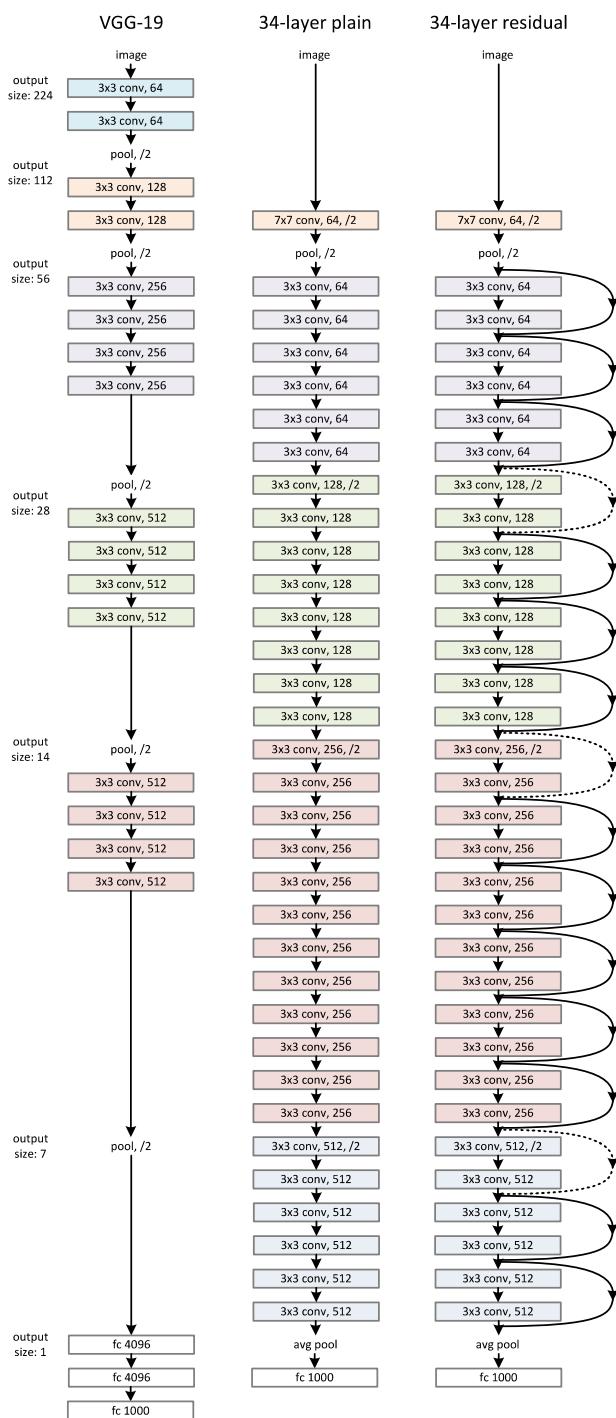
Key idea: introduce “identity shortcut”



method	top-1 err.	top-5 err.
VGG [41] (ILSVRC'14)	-	8.43 [†]
GoogLeNet [44] (ILSVRC'14)	-	7.89
VGG [41] (v5)	24.4	7.1
PReLU-net [13]	21.59	5.71
BN-inception [16]	21.99	5.81
ResNet-34 B	21.84	5.71
ResNet-34 C	21.53	5.60
ResNet-50	20.74	5.25
ResNet-101	19.87	4.60
ResNet-152	19.38	4.49

Table 4. Error rates (%) of **single-model** results on the ImageNet validation set (except \dagger reported on the test set).

With ensembling, 3.57% top-5
test error on ImageNet



Dense Convolutional Networks

Information in ResNets is only carried implicitly, through addition.

Idea: explicitly forward output of layer to ***all*** future layers (by **concatenation**).

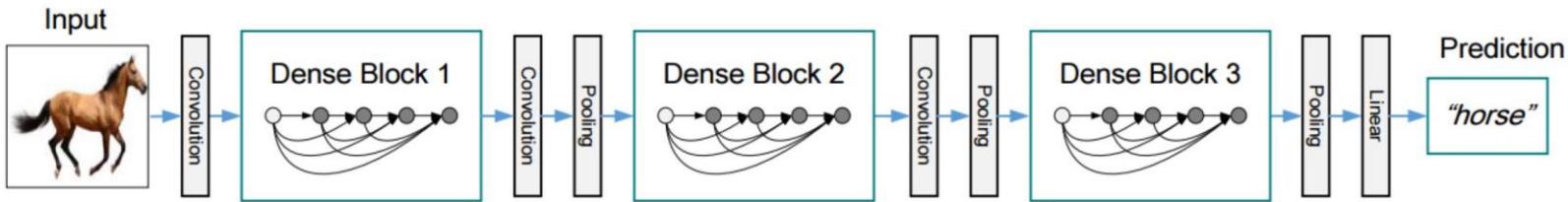
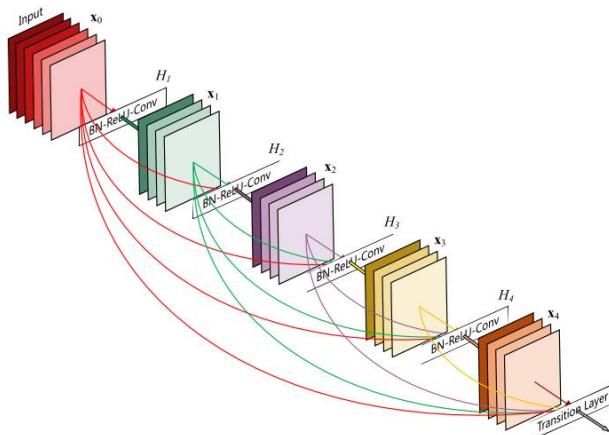


Figure 2. A deep DenseNet with three dense blocks. The layers between two adjacent blocks are referred to as transition layers and change feature map sizes via convolution and pooling.

Intuition: helps vanishing gradients; encourage reuse features (& hence reduce parameter count);



Layers	Output Size	DenseNet-121($k = 32$)	DenseNet-169($k = 32$)	DenseNet-201($k = 32$)	DenseNet-161($k = 48$)
Convolution	112×112				7×7 conv, stride 2
Pooling	56×56				3×3 max pool, stride 2
Dense Block (1)	56×56	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 6$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 6$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 6$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 6$
Transition Layer (1)	56×56 28×28				1×1 conv 2×2 average pool, stride 2
Dense Block (2)	28×28	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 12$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 12$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 12$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 12$
Transition Layer (2)	28×28 14×14				1×1 conv 2×2 average pool, stride 2
Dense Block (3)	14×14	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 24$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 32$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 48$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 36$
Transition Layer (3)	14×14 7×7				1×1 conv 2×2 average pool, stride 2
Dense Block (4)	7×7	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 16$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 32$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 32$	$\begin{bmatrix} 1 \times 1 \text{ conv} \\ 3 \times 3 \text{ conv} \end{bmatrix} \times 24$
Classification Layer	1×1				7×7 global average pool 1000D fully-connected, softmax

Full architecture for Imagenet

Debugging hints

- ⟳ Check gradients numerically by finite differences
- ⟳ Visualize features (feature maps need to be uncorrelated) and have high variance

samples



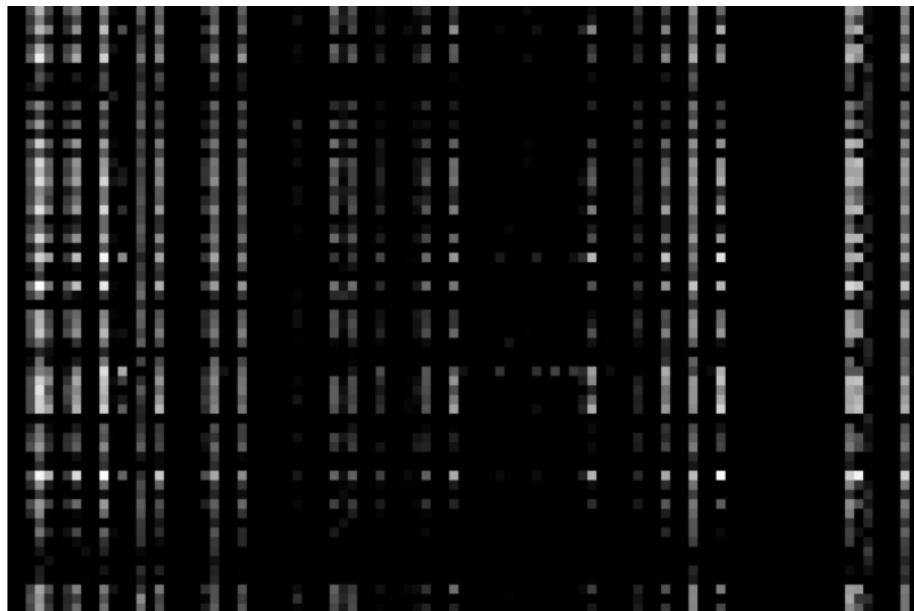
hidden unit

Good training: hidden units
are sparse across samples

Debugging hints

- ⟳ Check gradients numerically by finite differences
- ⟳ Visualize features (feature maps need to be uncorrelated) and have high variance

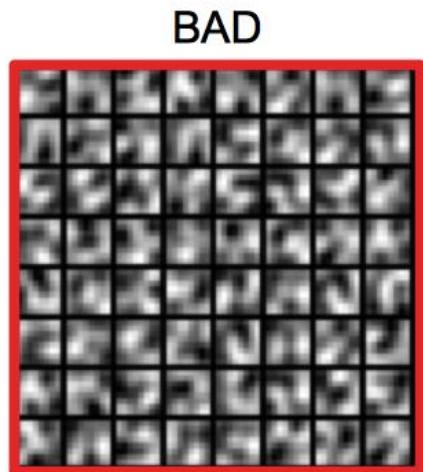
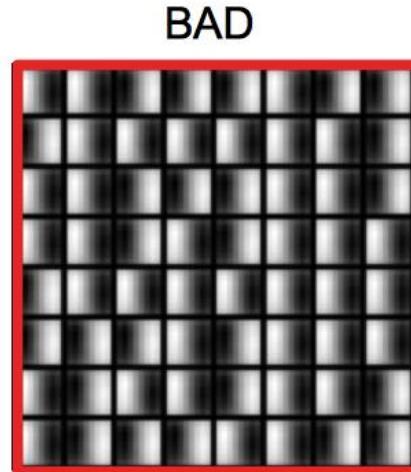
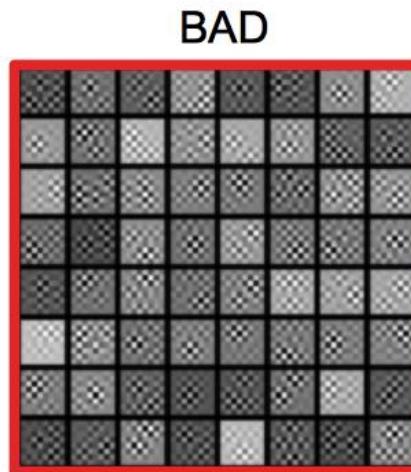
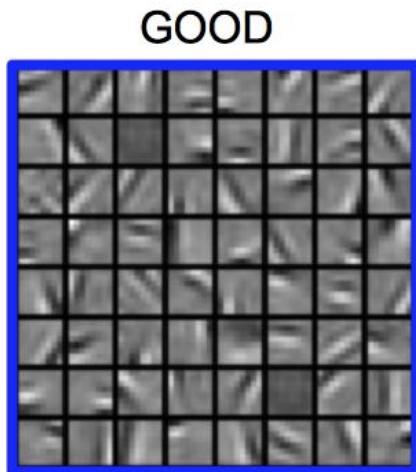
samples



Bad training: many hidden units ignore the input and/or exhibit strong correlations

Debugging hints

- 🌀 Check gradients numerically by finite differences
- 🌀 Visualize features (feature maps need to be uncorrelated) and have high variance
- 🌀 Visualize parameters: learned features should exhibit structure and should be uncorrelated and are uncorrelated



[From Marc'Aurelio Ranzato, CVPR 2014 tutorial]

Debugging hints

- 🌀 Check gradients numerically by finite differences
- 🌀 Visualize features (feature maps need to be uncorrelated) and have high variance
- 🌀 Visualize parameters: learned features should exhibit structure and should be uncorrelated and are uncorrelated
- 🌀 Measure error on both training and validation set
- 🌀 Test on a small subset of the data and check the error → 0.

When it does not work

Training diverges:

- 🌀 Learning rate may be too large → decrease learning rate
- 🌀 Backprop is buggy → numerical gradient checking

Parameters collapse / loss is minimized but accuracy is low

- 🌀 Check loss function: is it appropriate for the task you want to solve?
- 🌀 Does it have degenerate solutions?

Network is underperforming

- 🌀 Compute flops and nr. params. → if too small, make net larger
- 🌀 Visualize hidden units/params → fix optimization

Network is too slow

- 🌀 GPU, distrib. framework, make net smaller