

Deep Convolutional Networks

Aarti Singh

Machine Learning 10-315

Feb 21, 2022

Slides Courtesy: Barnabas Poczos, Ruslan Salakhutdinov, Joshua Bengio,
Geoffrey Hinton, Yann LeCun, Pat Virtue

Convolutional Neural Networks



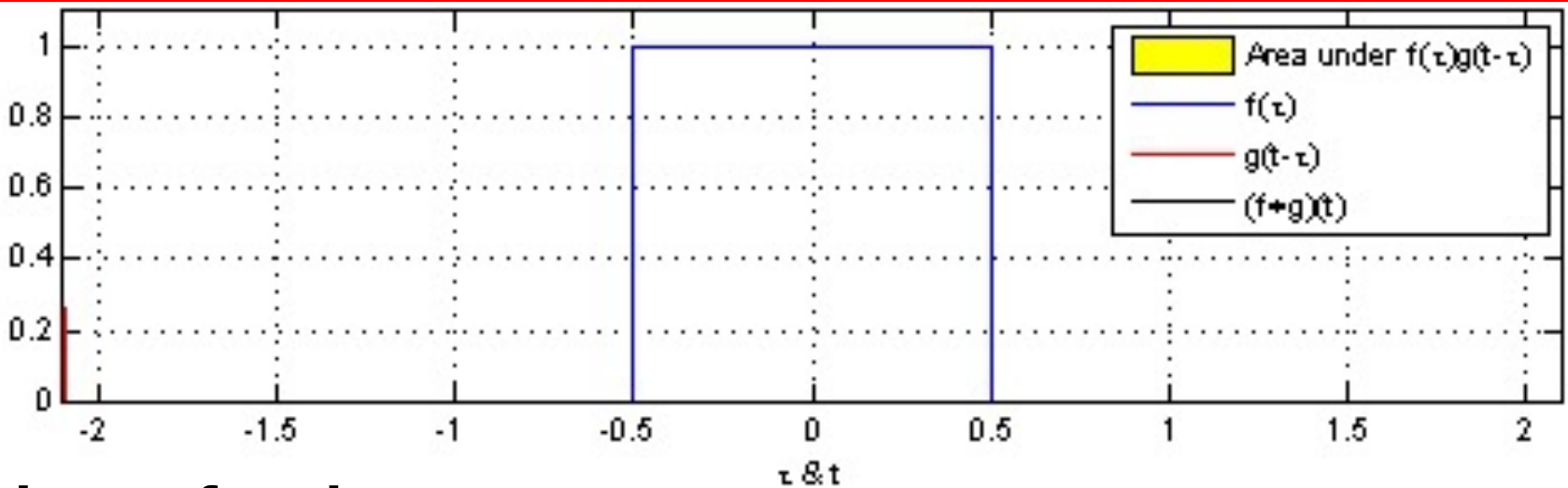
Compared to standard feedforward neural networks with similarly-sized layers,

- CNNs have much fewer connections and shared parameters
- and so they are easier to train,
- while their performance is likely to be only slightly worse, particularly for images as inputs.

LeNet 5

Y. LeCun, L. Bottou, Y. Bengio and P. Haffner: **Gradient-Based Learning Applied to Document Recognition**, *Proceedings of the IEEE*, 86(11):2278-2324, November 1998

Convolution operator



Continuous functions:

$$(f * g)(t) = \int_{-\infty}^{\infty} \underbrace{f(\tau)} \underbrace{g(t - \tau)} d\tau = \int_{-\infty}^{\infty} f(t - \tau) g(\tau) d\tau.$$

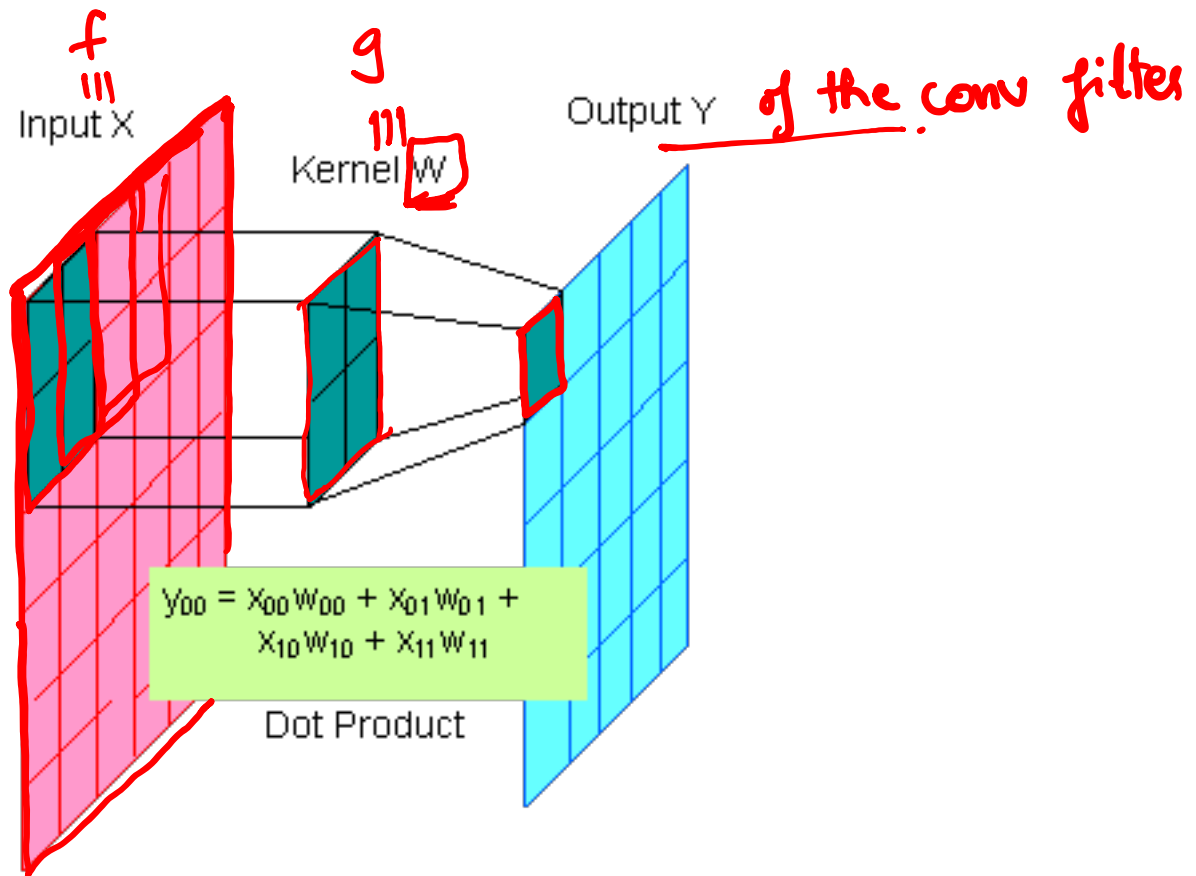
Discrete functions:

$$(f * g)[n] = \sum_{m=-\infty}^{\infty} f[m] g[n - m] = \sum_{m=-\infty}^{\infty} f[n - m] g[m]$$

If discrete g has support on $\{-M, \dots, M\}$:

$$(f * g)[n] = \sum_{m=-M}^M f[n - m] g[m]$$

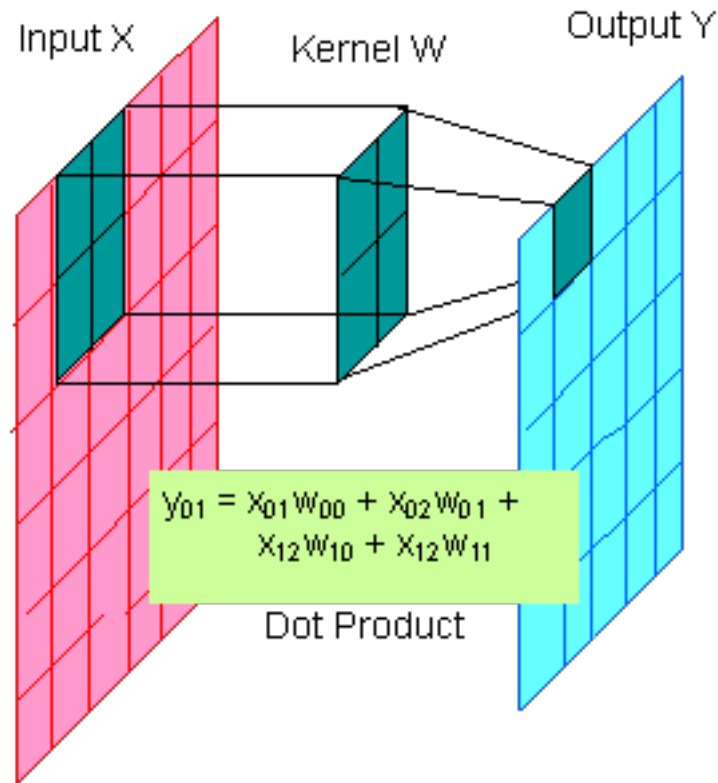
2-Dimensional Convolution filter



kernel
= filter
= weight matrix

shift of filter = stride

2-Dimensional Convolution filter



2-Dimensional Convolution filter

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

<https://graphics.stanford.edu/courses/cs178/applets/convolution.html>

Original



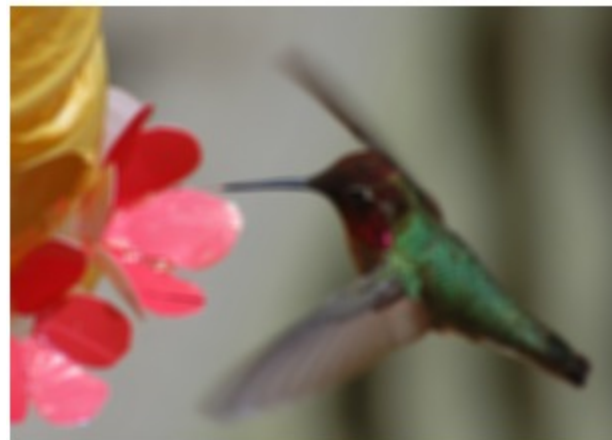
Filter (=kernel)

✓

0.00	0.00	0.00	0.00	0.00
0.00	0.00	-2.00	0.00	0.00
0.00	2.00	8.00	-2.00	0.00
0.00	0.00	-2.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00

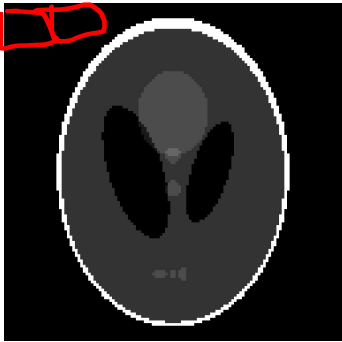
✓

0.04	0.04	0.04	0.04	0.04
0.04	0.04	0.04	0.04	0.04
0.04	0.04	0.04	0.04	0.04
0.04	0.04	0.04	0.04	0.04
0.04	0.04	0.04	0.04	0.04



Poll: Which filter goes with which output image?

Input



K1

-1	0	1
-2	0	2
-1	0	1

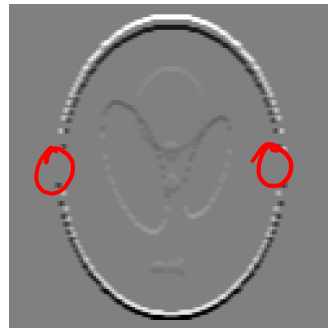
K2

-1	-2	-1
0	0	0
1	2	1

K3

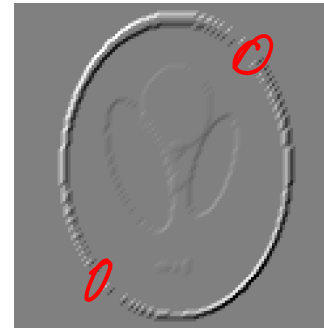
0	0	-1	0
0	-2	0	1
-1	0	2	0
0	1	0	0

Im1



✓

Im2



✓

Im3



✓

Poll: Which filter goes with which output image?

Input



K1

-1	0	1
-2	0	2
-1	0	1

K2

-1	-2	-1
0	0	0
1	2	1

K3

0	0	-1	0
0	-2	0	1
-1	0	2	0
0	1	0	0

Im1



Im2

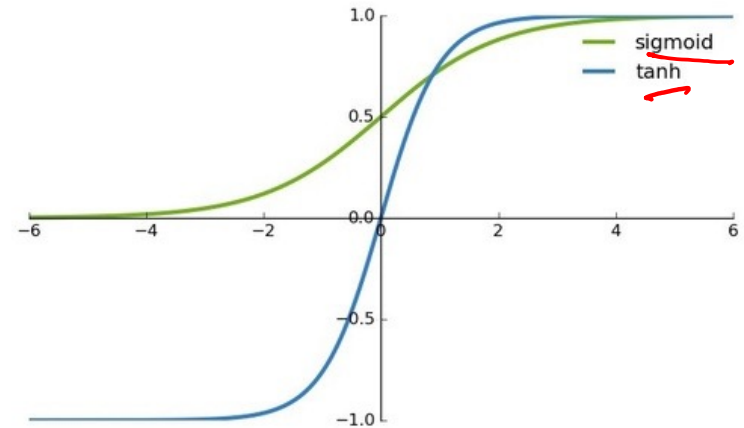
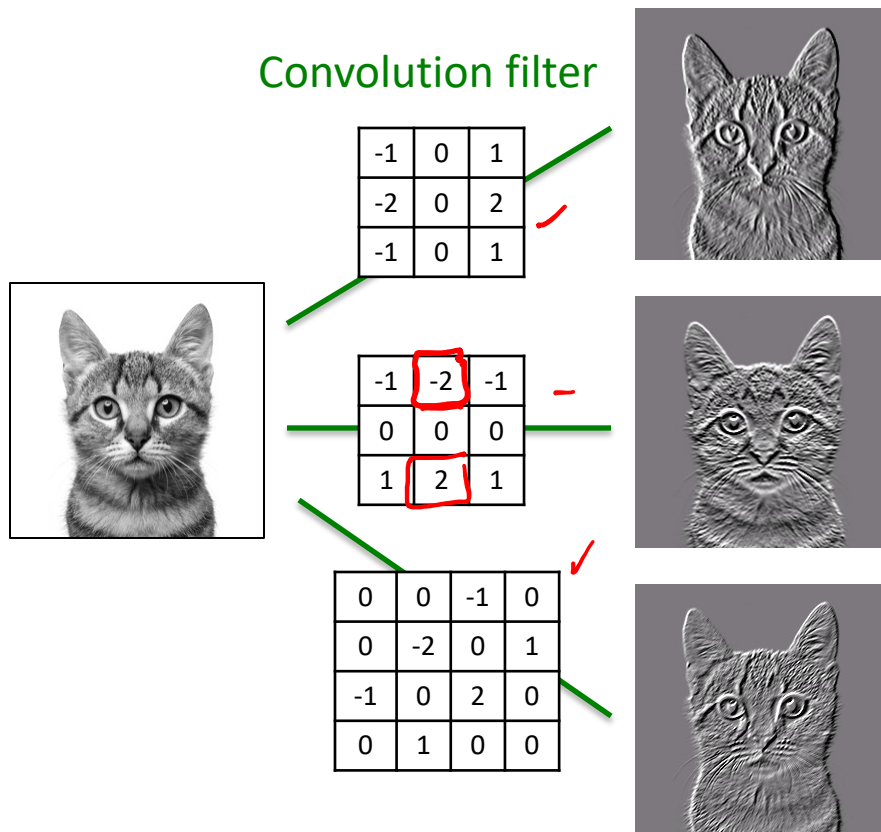


Im3



Convolutional Neural Networks

[Convolution filter + Nonlinear activation] + Pooling

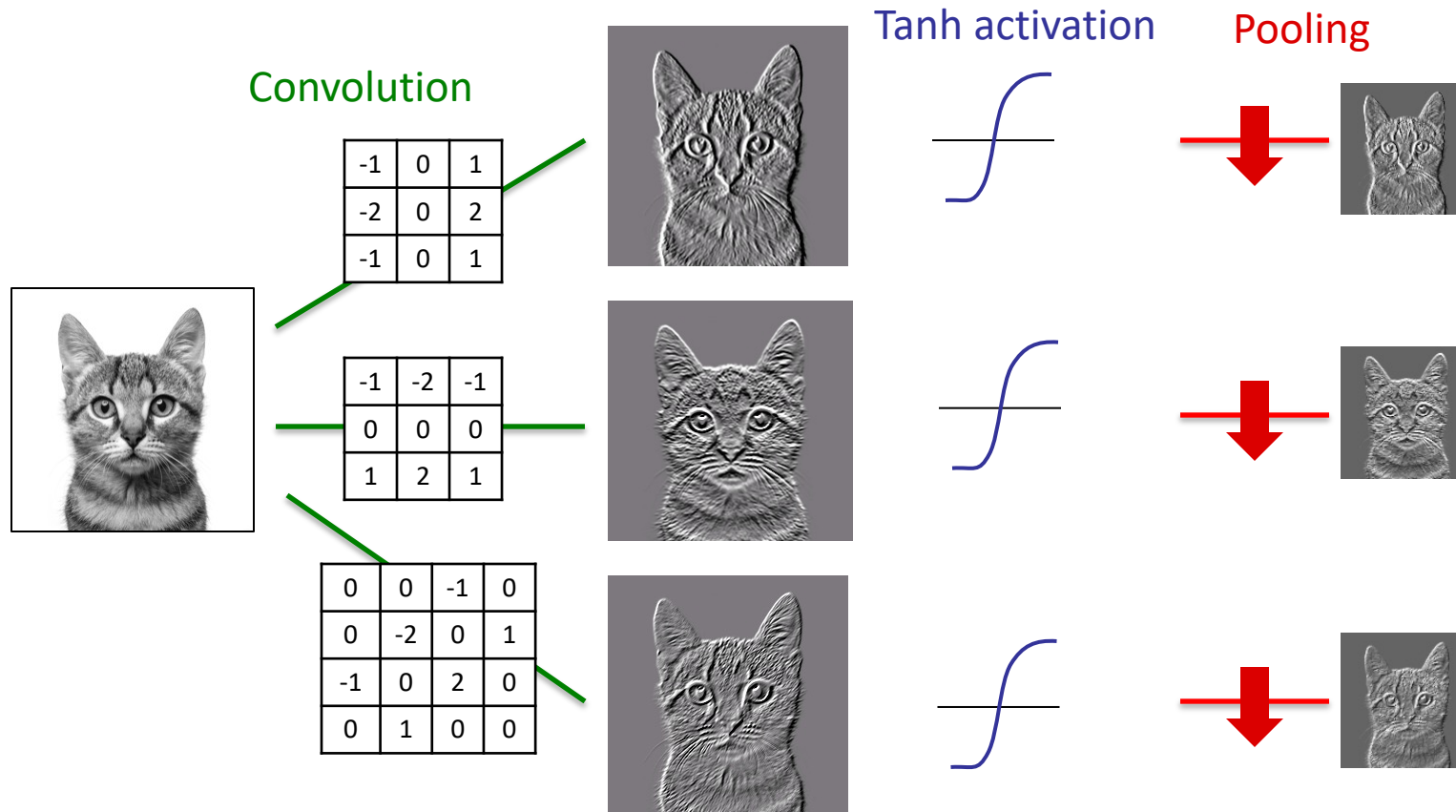


LeNet – tanh activation

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

Convolutional Neural Networks

[Convolution filter + Nonlinear activation] + Pooling



Pooling = Down-sampling

Reduce size to reduce number of parameters

Average pooling: convolution with stride = filter size

0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0	0

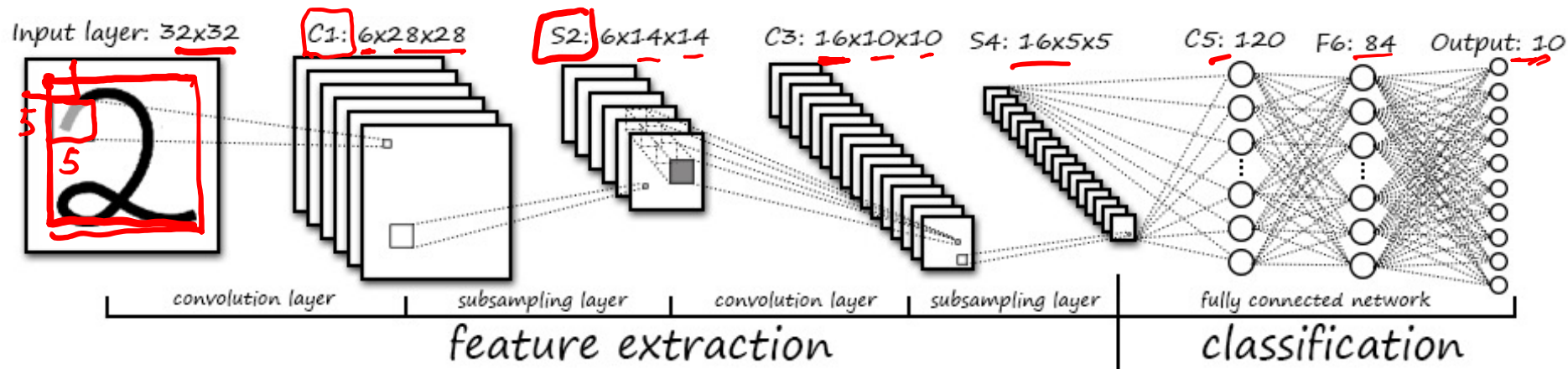


.25	.25
.25	.25

Convolutional Neural Networks

Lenet5 – Lecun, et al, 1998

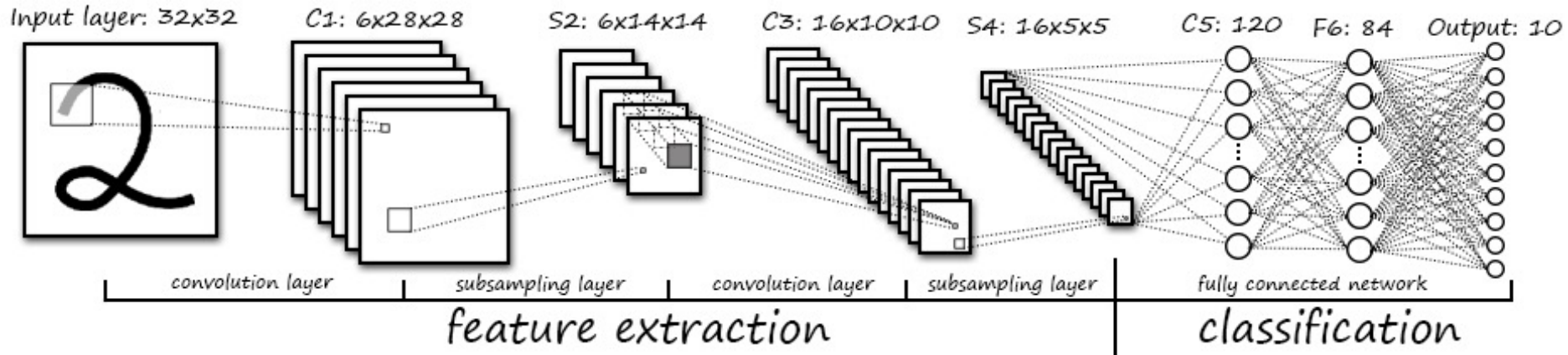
- Convnets for digit recognition



LeNet 5

Y. LeCun, L. Bottou, Y. Bengio and P. Haffner: **Gradient-Based Learning Applied to Document Recognition**, *Proceedings of the IEEE*, 86(11):2278-2324, November **1998**

LeNet 5, LeCun 1998



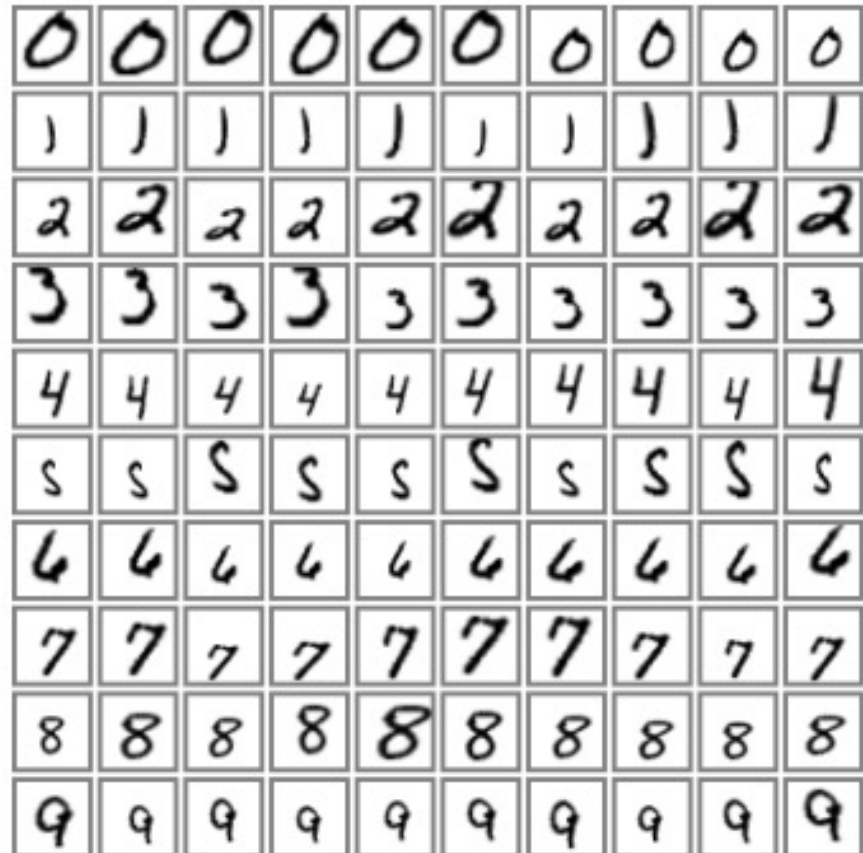
- **Input:** 32x32 pixel image. Largest character is 20x20
(All important info should be in the center of the receptive fields of the highest level feature detectors)
- **Cx:** Convolutional layer (C1, C3, C5) tanh nonlinear units
- **Sx:** Subsample layer (S2, S4) average pooling
- **Fx:** Fully connected layer (F6) logistic/sigmoid units
- Black and White pixel values are normalized:
E.g. White = -0.1, Black = 1.175 (Mean of pixels = 0, Std of pixels = 1)

MINIST Dataset



60,000 original dataset

Test error: 0.95%



540,000 artificial distortions

+ 60,000 original

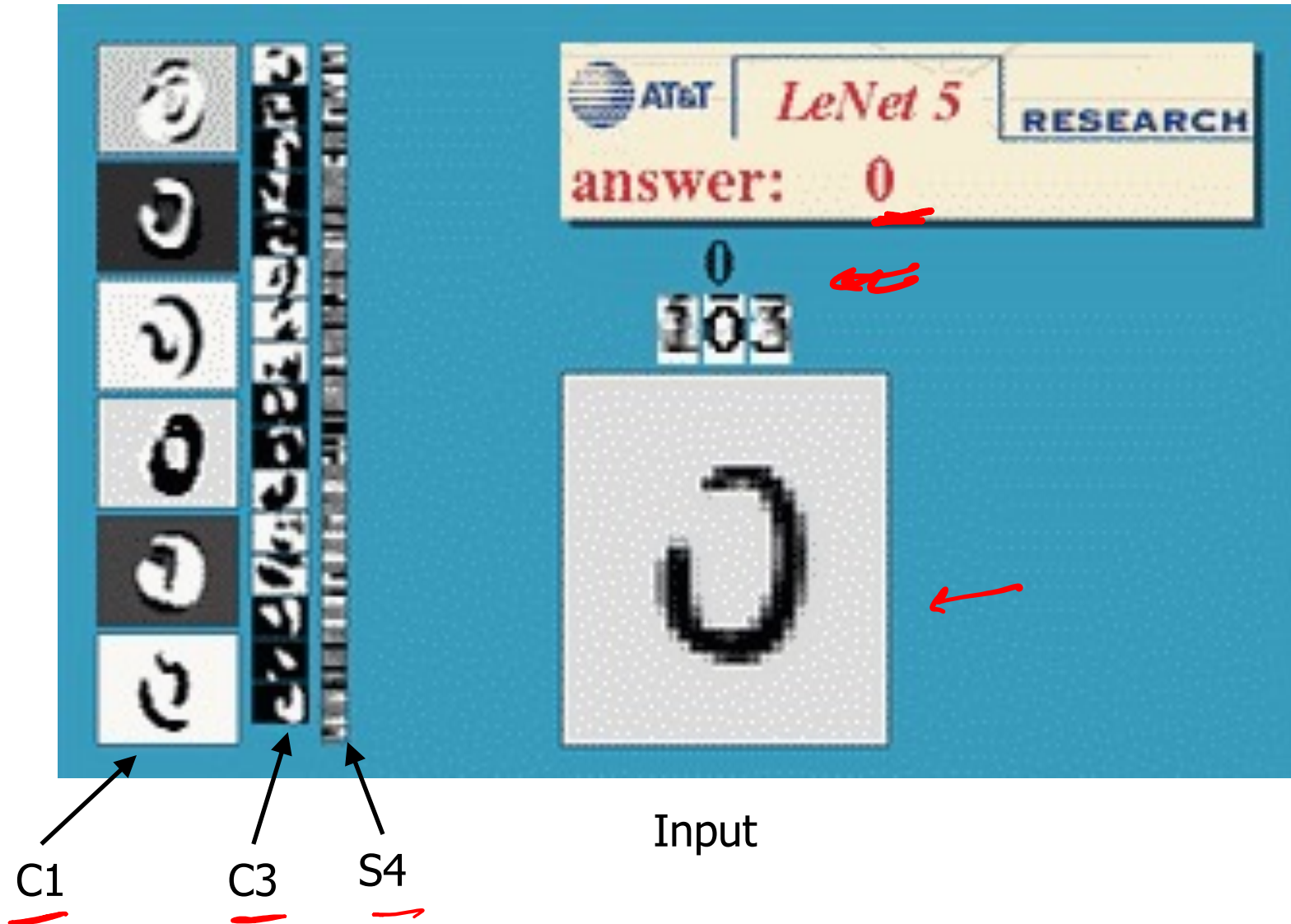
Test error: 0.8%

Misclassified examples

True label -> Predicted label

 4->6	 3->5	 8->2	 2->1	 5->3	 4->8	 2->8	 3->5	 6->5	 7->3
 9->4	 8->0	 7->8	 5->3	 8->7	 0->6	 3->7	 2->7	 8->3	 9->4
 8->2	 5->3	 4->8	 3->9	 6->0	 9->8	 4->9	 6->1	 9->4	 9->1
 9->4	 2->0	 6->1	 3->5	 3->2	 9->5	 6->0	 6->0	 6->0	 6->8
 4->6	 7->3	 9->4	 4->6	 2->7	 9->7	 4->3	 9->4	 9->4	 9->4
 8->7	 4->2	 8->4	 3->5	 8->4	 6->5	 8->5	 3->8	 3->8	 9->8
 1->5	 9->8	 6->3	 0->2	 6->5	 9->5	 0->7	 1->6	 4->9	 2->1
 2->8	 8->5	 4->9	 7->2	 7->2	 6->5	 9->7	 6->1	 5->6	 5->0
 4->9	 2->8								

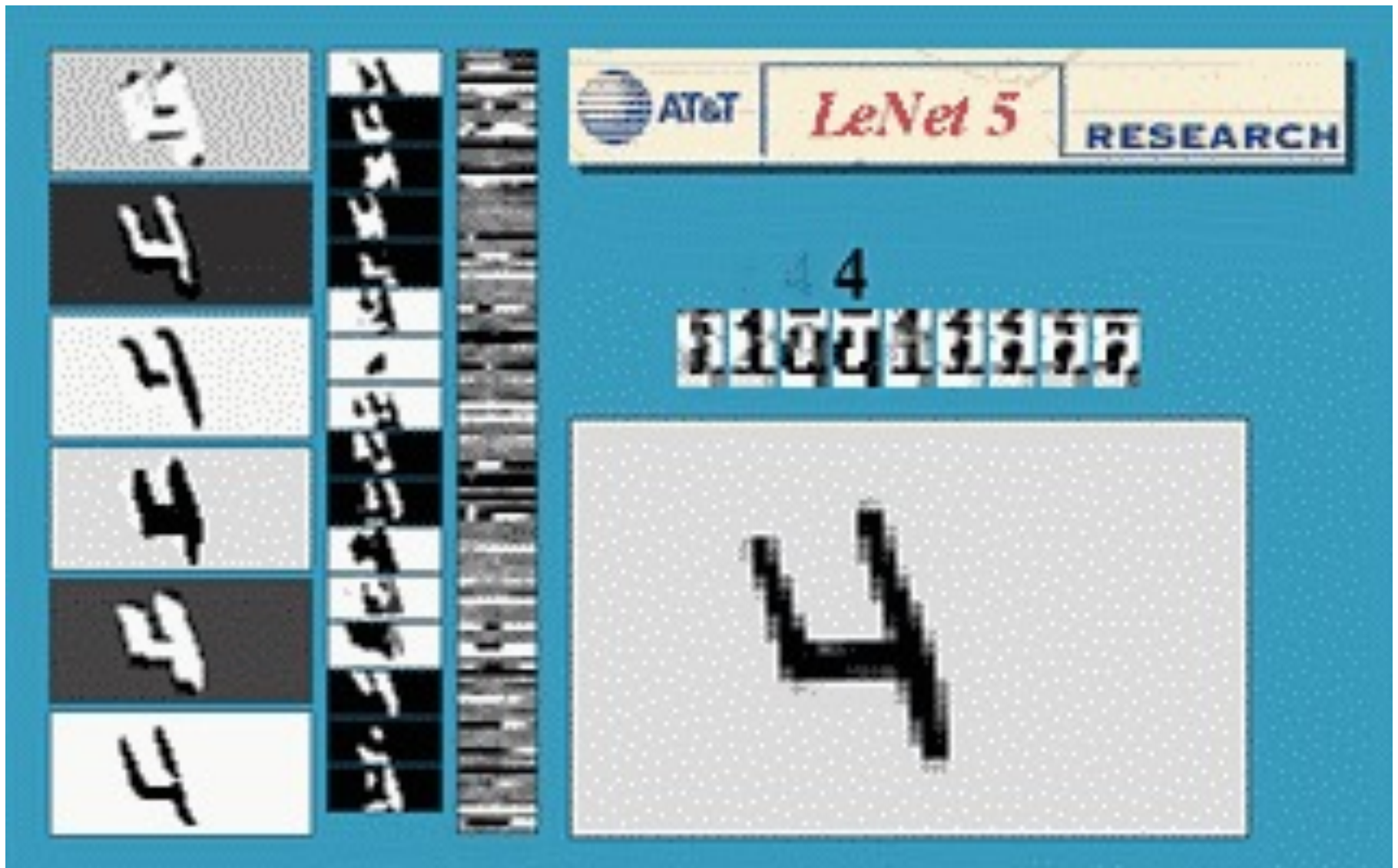
LeNet 5 in Action



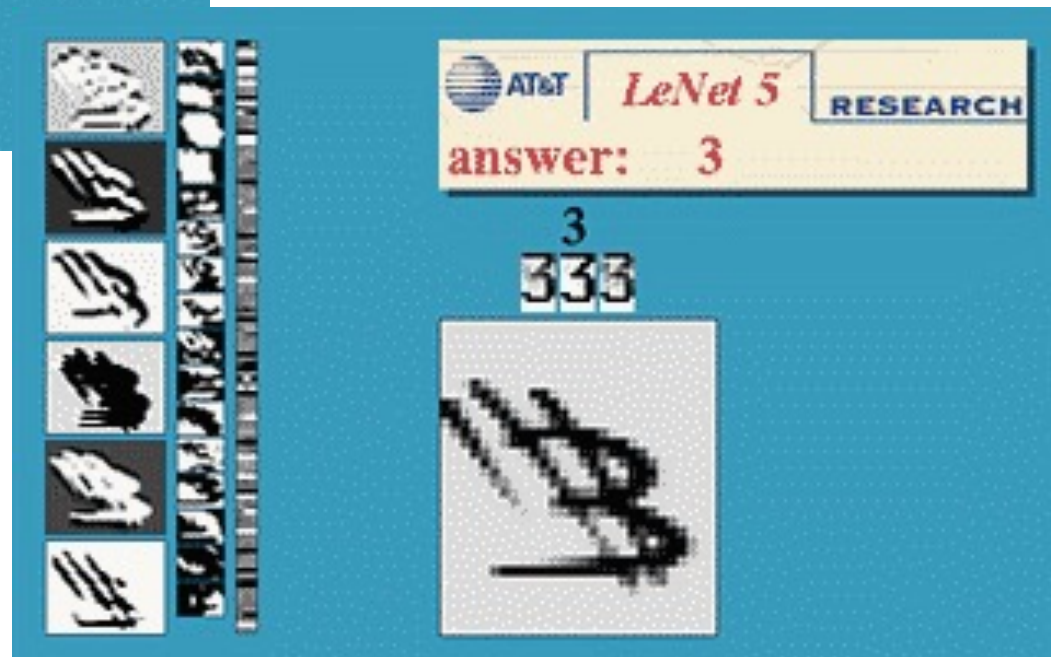
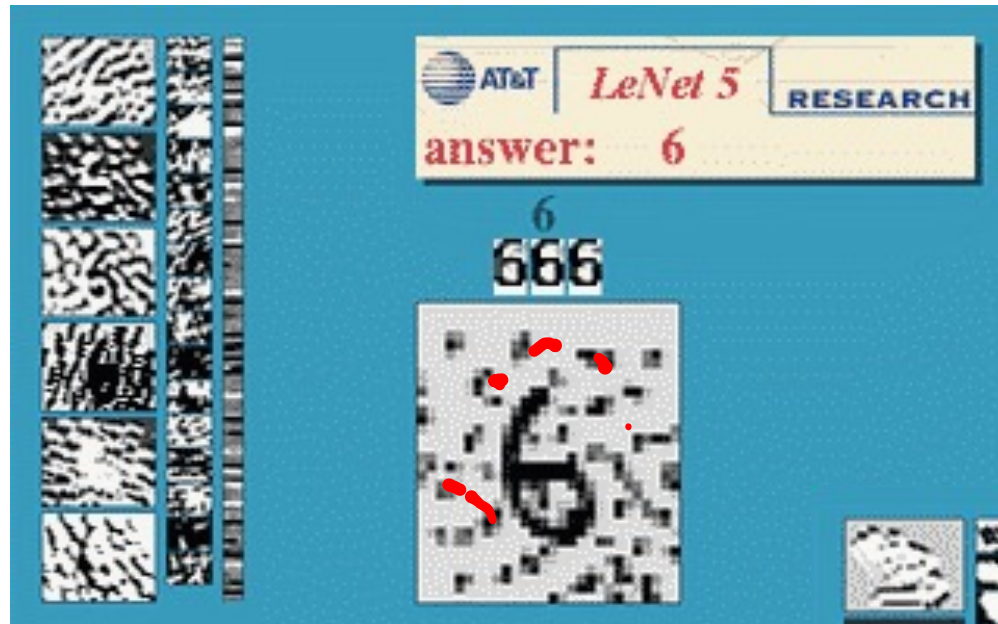
LeNet 5, Shift invariance



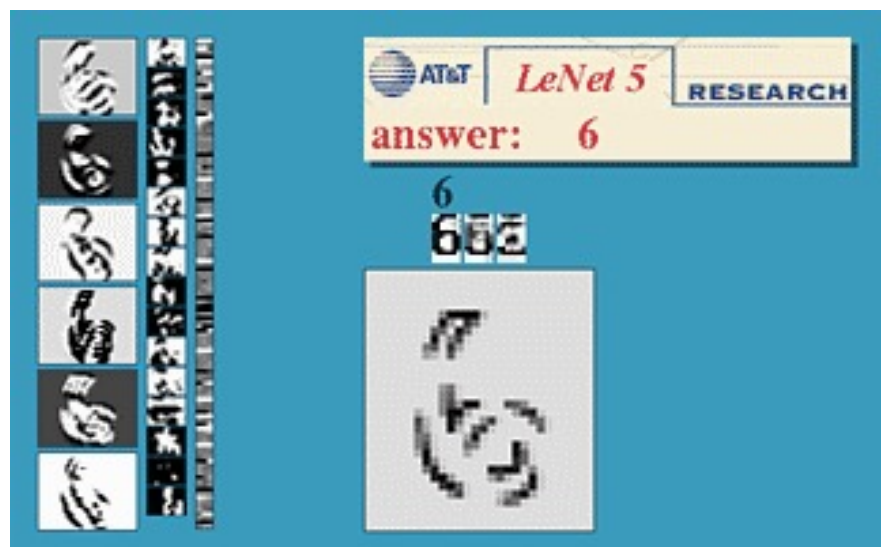
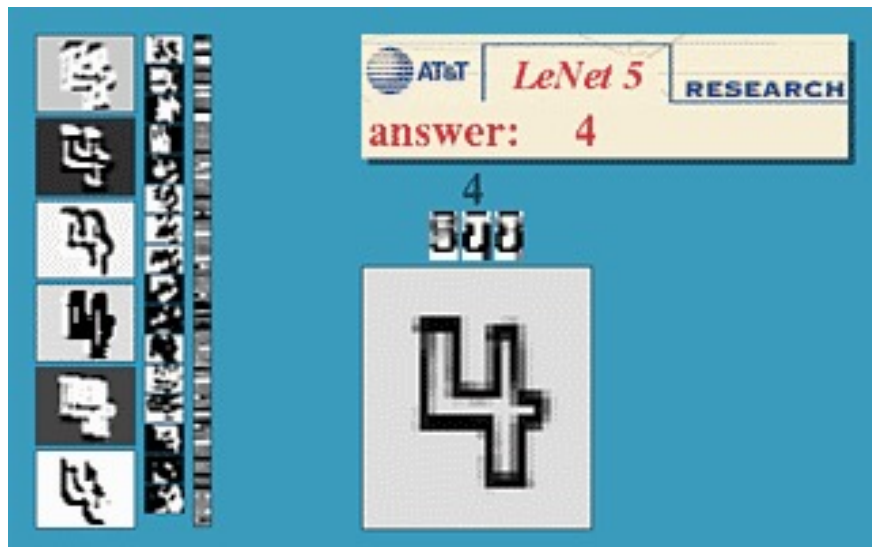
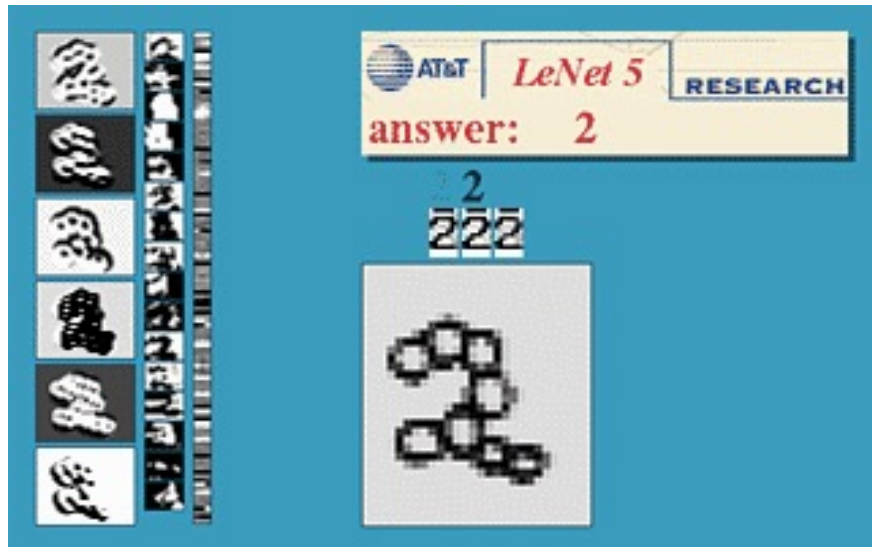
LeNet 5, Rotation invariance



LeNet 5, Noise resistance



LeNet 5, Unusual Patterns



ImageNet Classification with Deep Convolutional Neural Networks

Alex Krizhevsky, Ilya Sutskever, Geoffrey Hinton,
Advances in Neural Information Processing Systems 2012

Alex Net

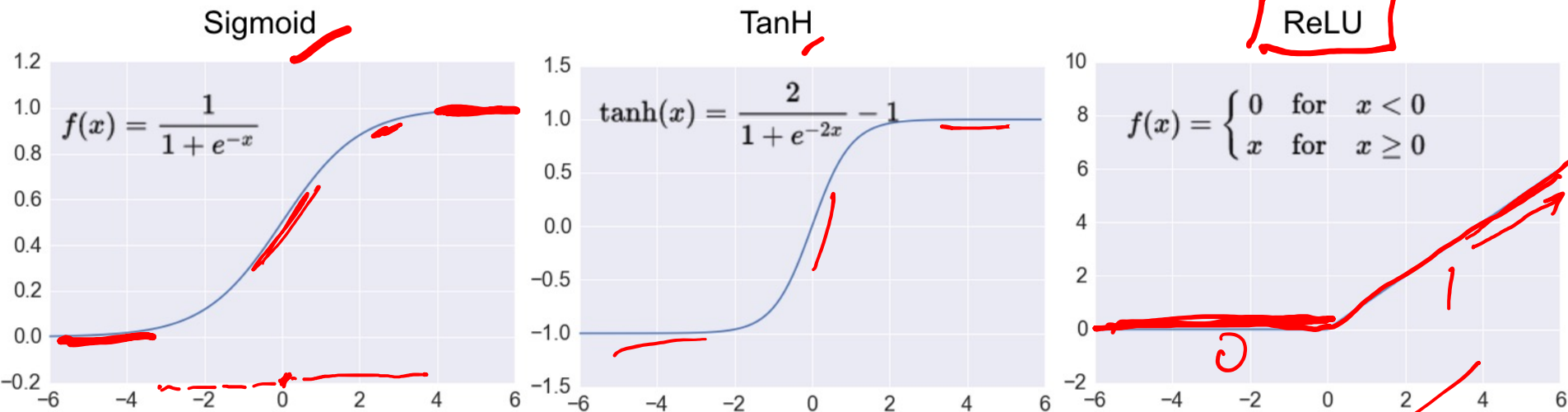
The Architecture

Typical nonlinearities: $f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$

$$f(x) = (1 + e^{-x})^{-1} \quad (\text{logistic function})$$

Here, **Rectified Linear Units (ReLU)** are used: $f(x) = \max(0, x)$

Non-saturating / Gradients don't vanish – faster training



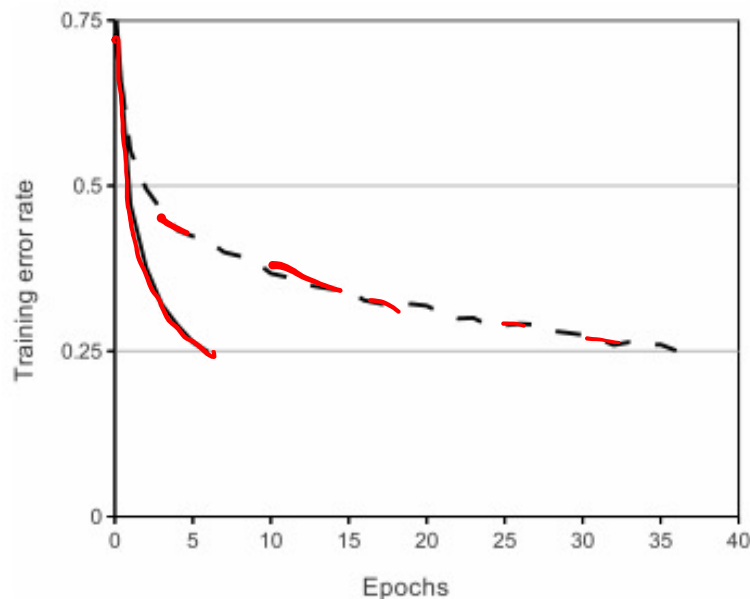
The Architecture

Typical nonlinearities: $f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$

$f(x) = (1 + e^{-x})^{-1}$ (logistic function)

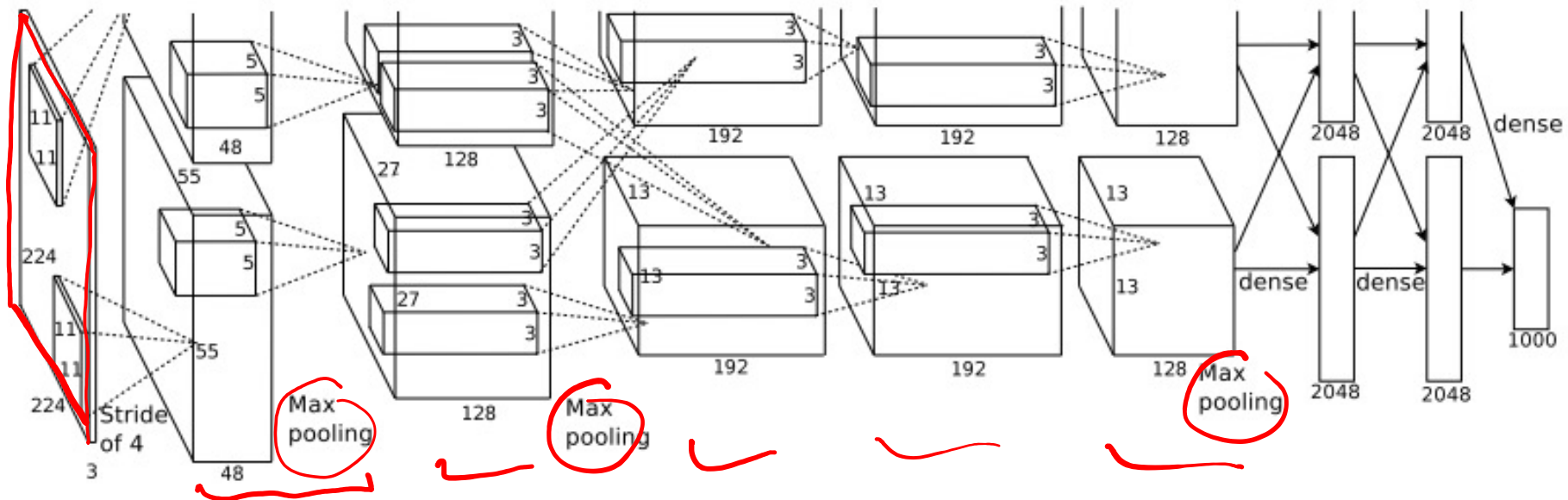
Here, **Rectified Linear Units (ReLU)** are used: $f(x) = \max(0, x)$

Non-saturating / Gradients don't vanish – faster training



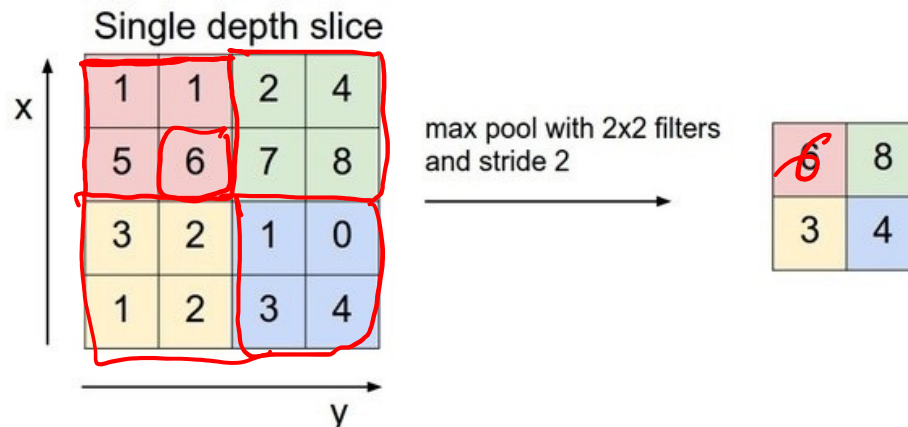
A four-layer convolutional neural network with ReLUs (solid line) reaches a 25% training error rate on CIFAR-10 six times faster than an equivalent network with tanh neurons (dashed line)

The Architecture

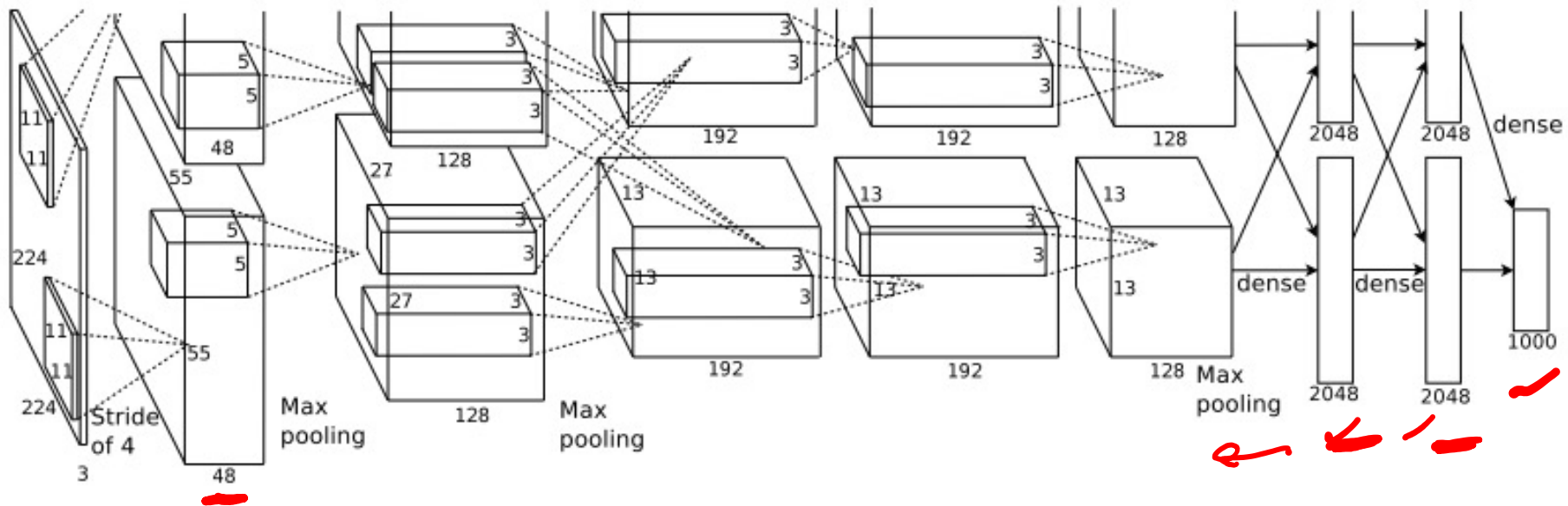


5 convolution layers (ReLU)

3 overlapping max pooling – nonlinear downsampling (max value of regions)



The Architecture



5 convolution layers (ReLU)

3 overlapping max pooling – nonlinear downsampling (max value of regions)

2 fully connected layers

output softmax

Training

- Trained with stochastic gradient descent
- on two NVIDIA GTX 580 3GB GPUs
- for about a week
- ❑ 650,000 neurons
- ❑ 60,000,000 parameters
- ❑ 630,000,000 connections
- ❑ 5 convolutional layer with Rectified Linear Units (ReLUs), 3 overlapping max pooling, 2 fully connected layer ✓
- ❑ Final feature layer: 4096-dimensional
- ❑ Prevent overfitting – data augmentation, dropout trick ←
- ❑ Randomly extracted 224x224 patches for more data

Preventing overfitting

1) **Data augmentation:** The easiest and most common method to reduce overfitting on image data is to artificially enlarge the dataset using label-preserving transformations:

- image translation
- horizontal reflections
- changing RGB intensities

2) **Dropout:** set the output of each hidden neuron to zero w.p. 0.5.

- So every time an input is presented, the neural network samples a different architecture, but all these architectures share weights.
- This technique reduces complex co-adaptations of neurons, since a neuron cannot rely on the presence of particular other neurons.
- forced to learn more robust features that are useful in conjunction with many different random subsets of the other neurons.

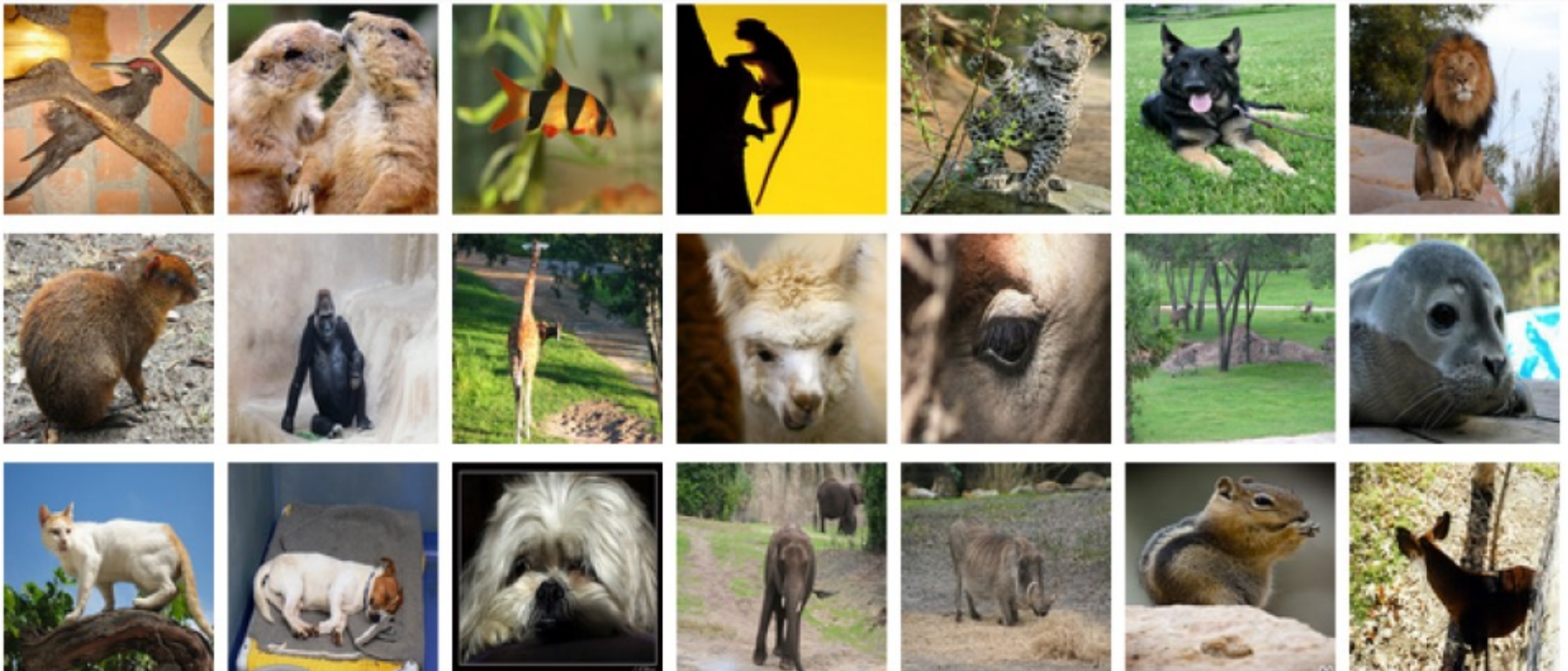
ImageNet

- ❑ 15M images ←
- ❑ 22K categories ←
- ❑ Images collected from Web
- ❑ Human labelers (Amazon's Mechanical Turk crowd-sourcing)
- ❑ ImageNet Large Scale Visual Recognition Challenge (ILSVRC-2010)
 - 1K categories
 - 1.2M training images (~1000 per category) }
 - 50,000 validation images }
 - 150,000 testing images }
- ❑ RGB images
- ❑ Variable-resolution, but this architecture scales them to 256x256 size

ImageNet

Classification goals:

- ❑ Make 1 guess about the label (Top-1 error)
- ❑ make 5 guesses about the label (Top-5 error) ✓



Results



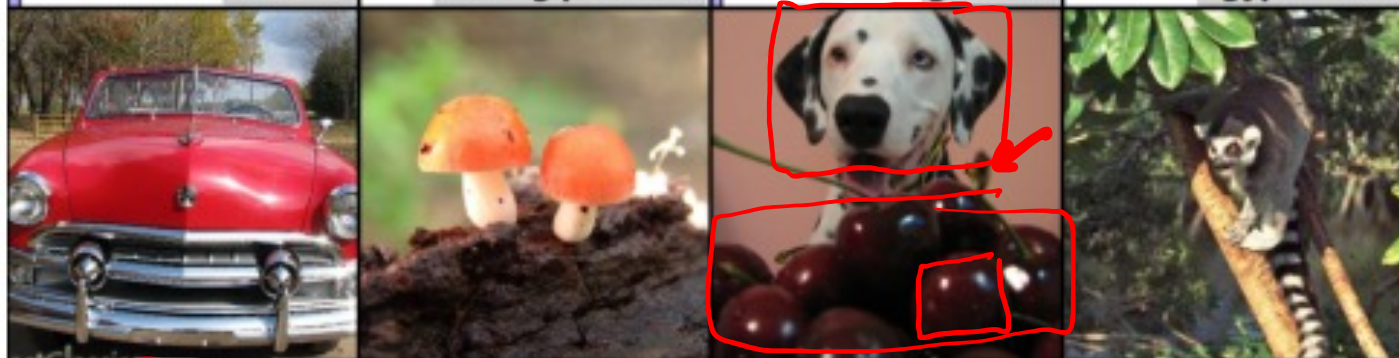
mite

container ship

motor scooter

leopard

mite	container ship	motor scooter	leopard
black widow	lifeboat	go-kart	jaguar
cockroach	amphibian	moped	cheetah
tick	fireboat	bumper car	snow leopard
starfish	drilling platform	golfcart	Egyptian cat



grille

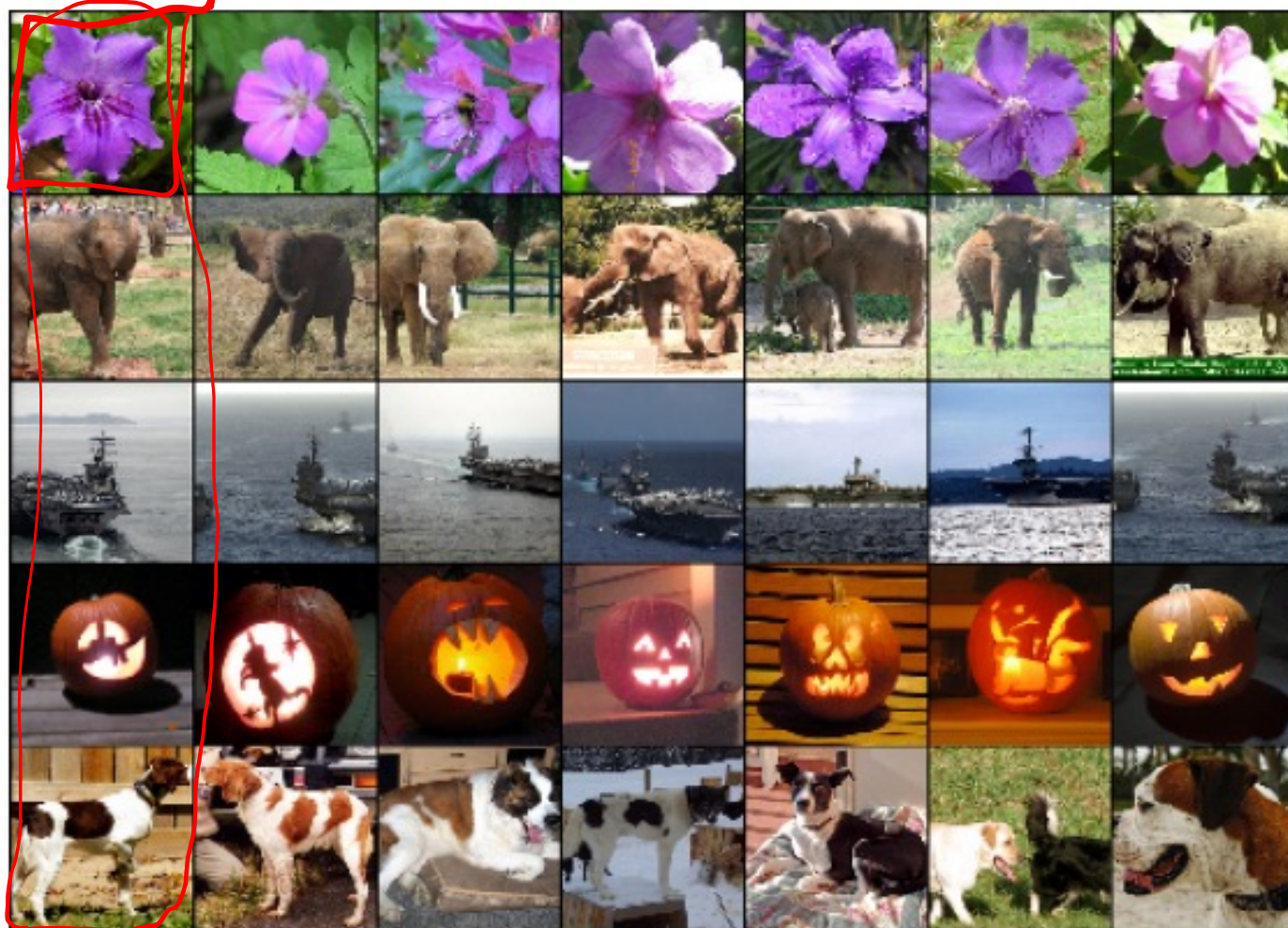
mushroom

cherry

Madagascar cat

convertible	agaric	dalmatian	squirrel monkey
grille	mushroom	grape	spider monkey
pickup	jelly fungus	elderberry	titl
beach wagon	gill fungus	ffordshire bullterrier	indri
fire engine	dead-man's-fingers	currant	howler monkey

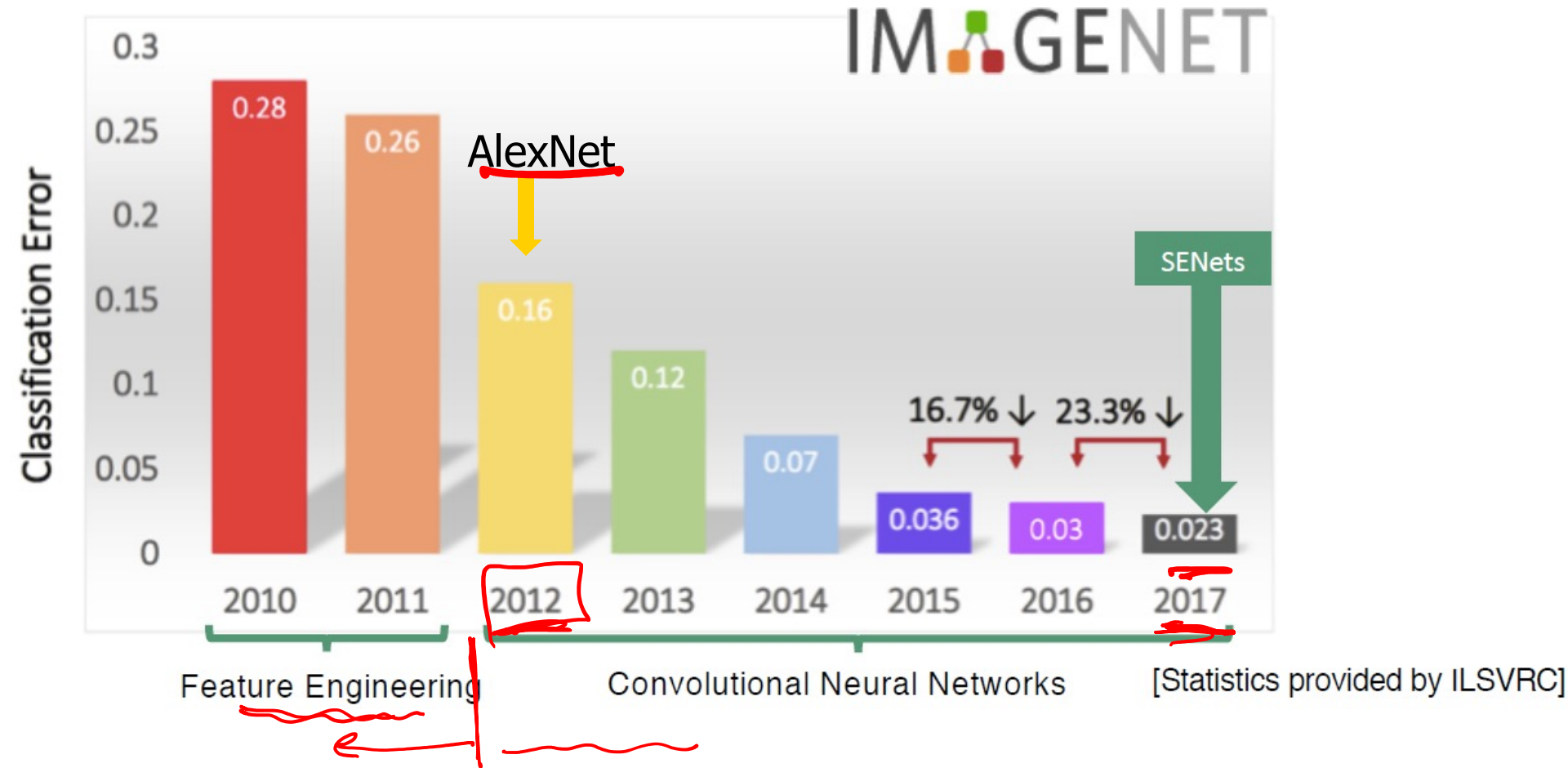
Results: Image similarity



Test column

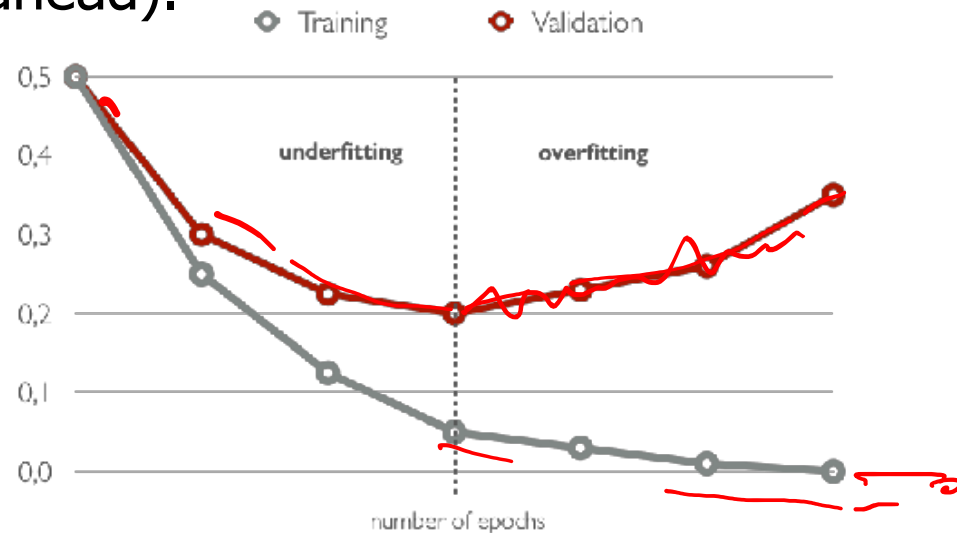
six training images that produce feature vectors in the last hidden layer with the smallest Euclidean distance from the feature vector for the test image.

Results



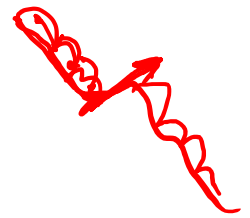
Tips and tricks for preventing overfitting

- **Dropout**
- **Data augmentation**
- **Early stopping:** stop training when validation set error increases (with some look ahead).



- **Neural Architecture search:** tune number of layers and neurons per layer using grid search or clever optimization

Other optimization tips and tricks



- **Initialization:** cannot initialize to same value, all units in a hidden layer will behave same; randomly initialize to small value
- **Momentum:** use exponentially weighted sum of previous gradients

$$\bar{\nabla}_{\theta}^{(t)} = \nabla_{\theta} l(\mathbf{f}(\mathbf{x}^{(t)}), y^{(t)}) + \beta \bar{\nabla}_{\theta}^{(t-1)}$$

θ - Weights
of Network

can get pass plateaus more quickly, by “gaining momentum”

- **Adaptive learning rates:** one learning rate per weight

e.g. RMSProp uses exponentially weighted average of squared gradients

$$\gamma^{(t)} = \beta \gamma^{(t-1)} + (1 - \beta) \left(\nabla_{\theta} l(\mathbf{f}(\mathbf{x}^{(t)}), y^{(t)}) \right)^2 \quad \bar{\nabla}_{\theta}^{(t)} = \frac{\nabla_{\theta} l(\mathbf{f}(\mathbf{x}^{(t)}), y^{(t)})}{\sqrt{\gamma^{(t)} + \epsilon}}$$

Adam combines RMSProp with momentum

Tips and Tricks for training deep NNs

- First hypothesis (underfitting): better optimize
 - Increase the capacity of the neural network
 - Check initialization
 - Check gradients (saturating units and vanishing gradients)
 - Tune learning rate
- Second hypothesis (overfitting): use better regularization
 - Dropout
 - Data augmentation
 - Early stopping
 - Architecture search
- For many large-scale practical problems, you will need to use both: better optimization and better regularization!