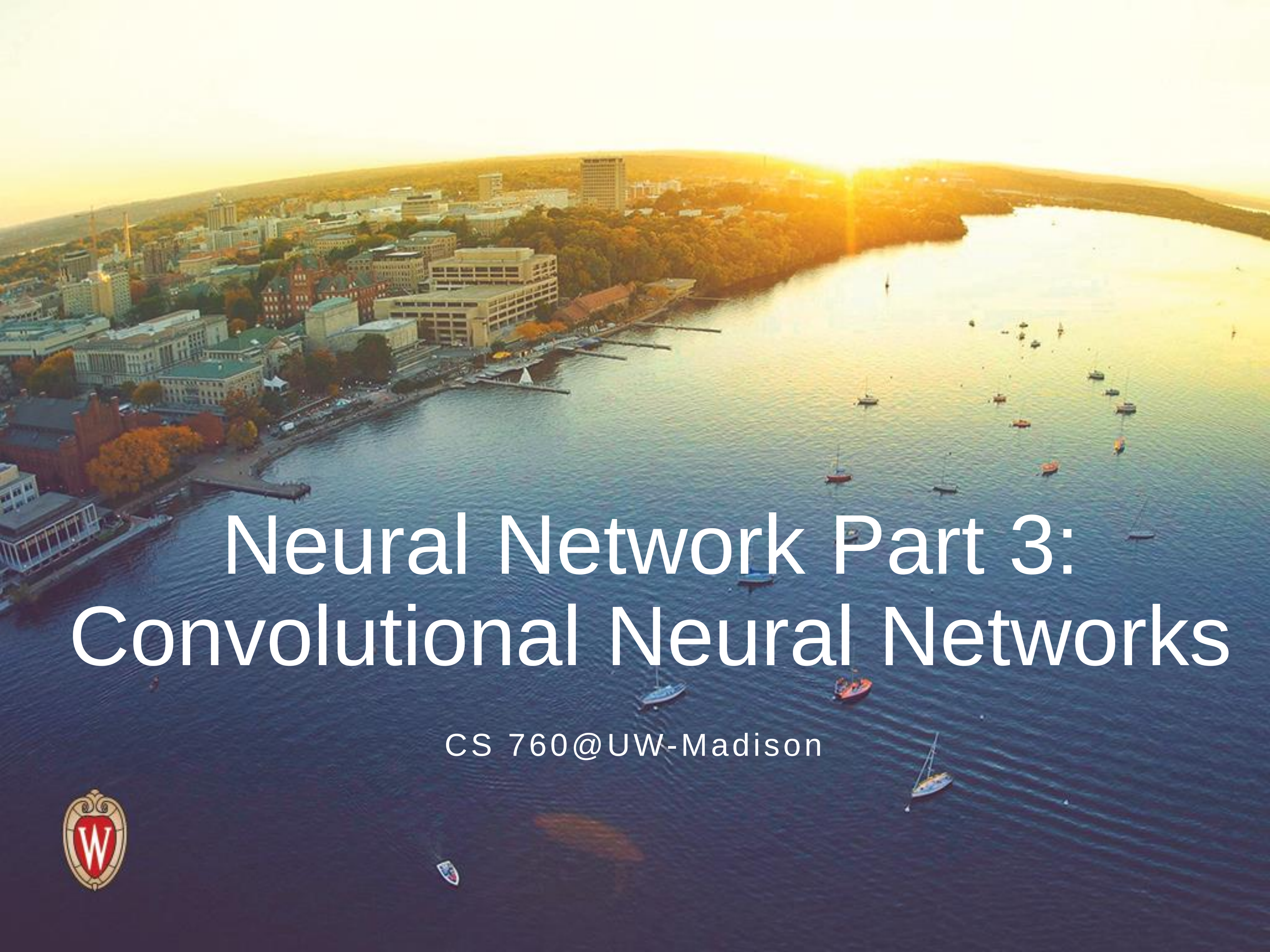


Neural Network Part 3: Convolutional Neural Networks

CS 760@UW-Madison

Goals for the lecture

you should understand the following concepts

- convolutional neural networks (CNN)
- convolution and its advantage
- pooling and its advantage

Convolutional neural networks

- Strong empirical application performance

- Convolutional networks: neural networks that use convolution in place of general matrix multiplication in at least one of their layers

$$h = \sigma(W^T x + b)$$

for a specific kind of weight matrix W

Convolution

Convolution: math formula

- Given functions $u(t)$ and $w(t)$, their convolution is a function $s(t)$

$$s(t) = \int u(a)w(t-a)da$$

- Written as

$$s = (u * w) \quad \text{or} \quad s(t) = (u * w)(t)$$

Convolution: discrete version

- Given array u_t and w_t, their convolution is a function s_t

$$s_t = \sum_{a=-\infty}^{+\infty} u_a w_{t-a}$$

- Written as

$$s = (u * w) \quad \text{or} \quad s_t = (u * w)_t$$

- When u_t or w_t is not defined, assumed to be 0

Illustration 1

w = [z, y, x]
u = [a, b, c, d, e, f]

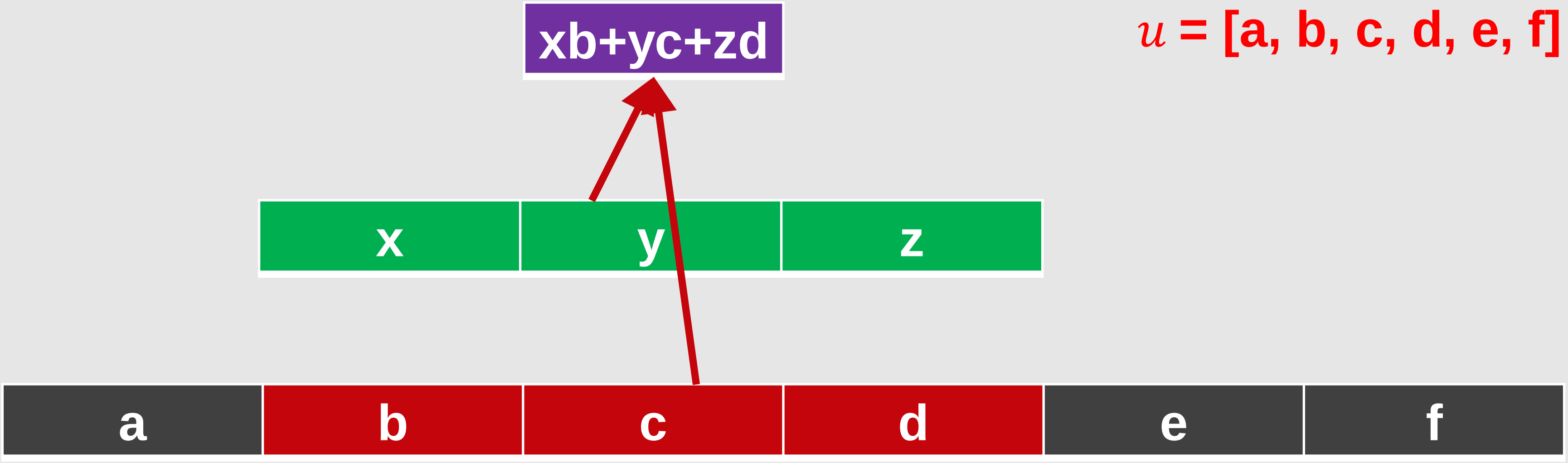


Illustration 1

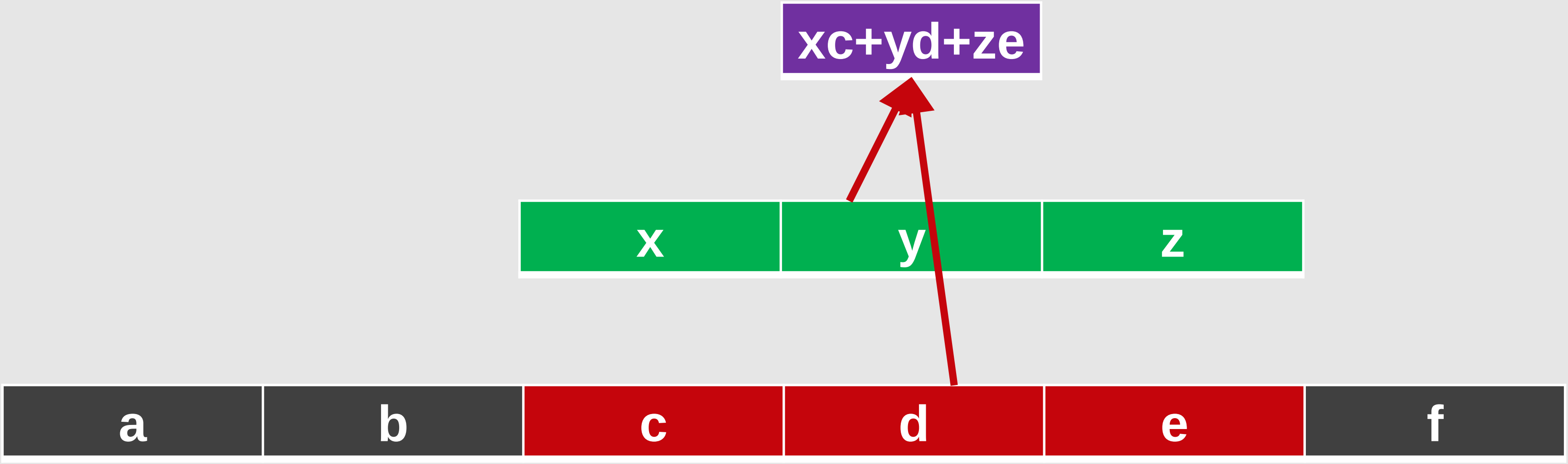


Illustration 1

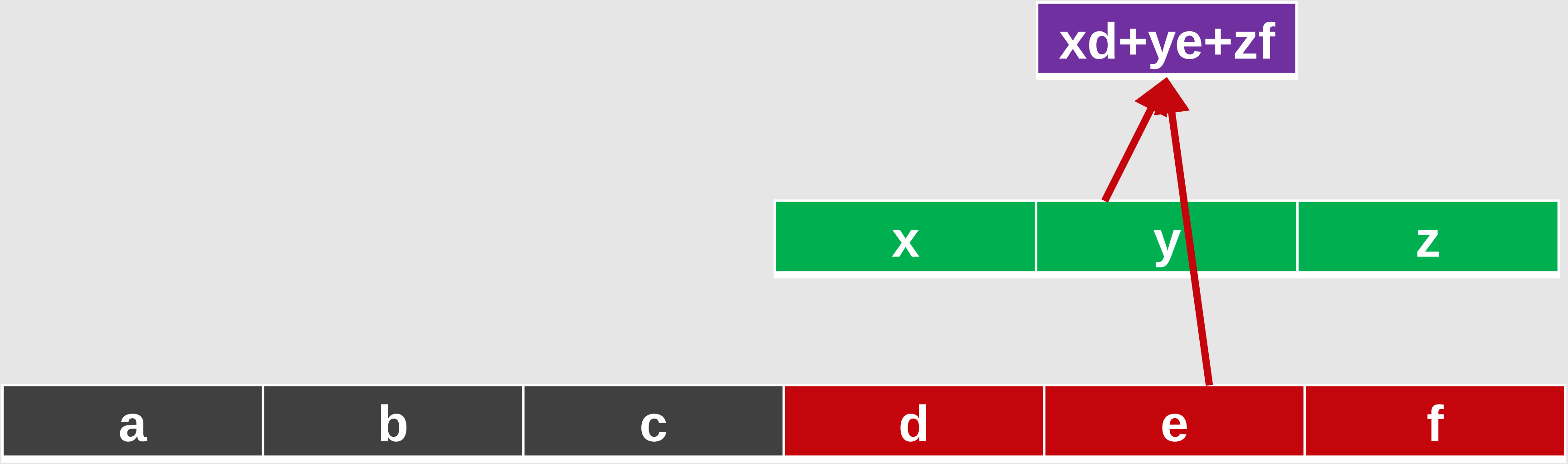


Illustration 1: boundary case

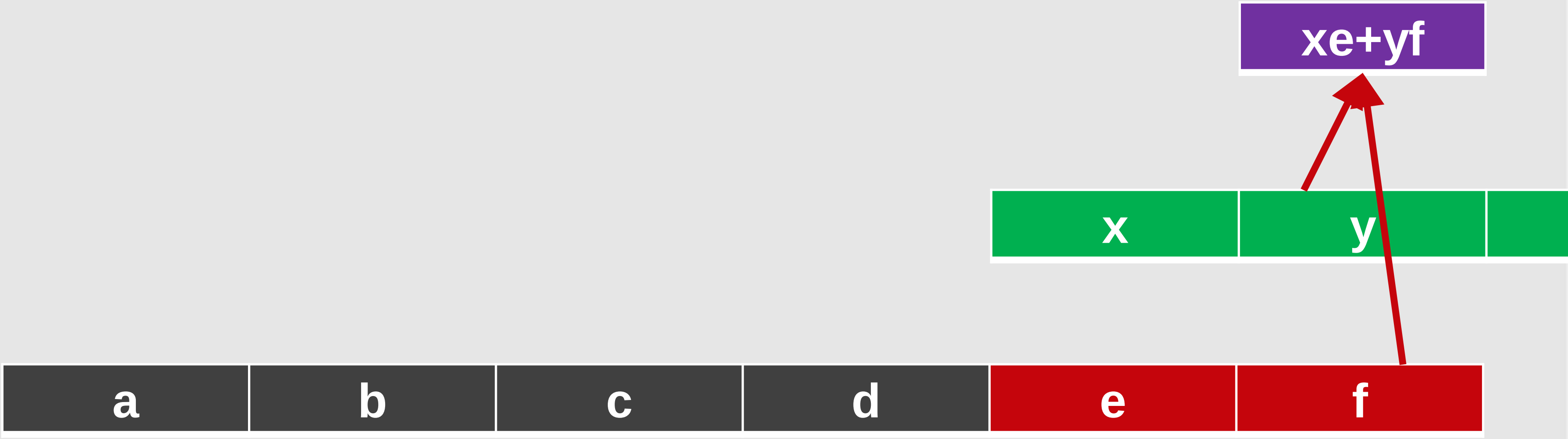


Illustration 1 as matrix multiplication

$$\begin{bmatrix} y & z & & & & \\ x & y & z & & & \\ & x & y & z & & \\ & & x & y & z & \\ & & & x & y & z \\ & & & & x & y \end{bmatrix} \quad \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix}$$

Illustration 2: two dimensional case

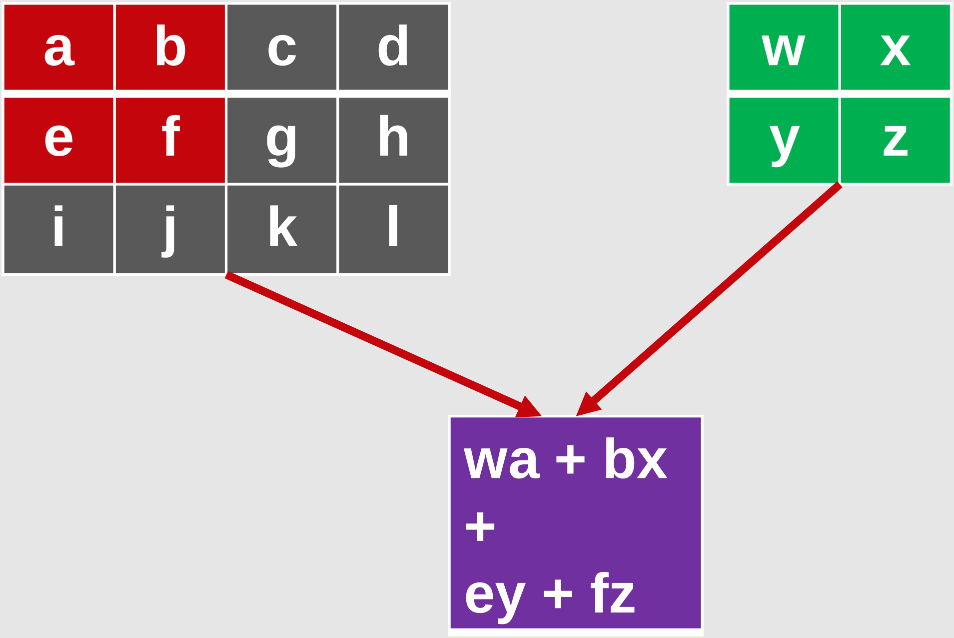


Illustration 2

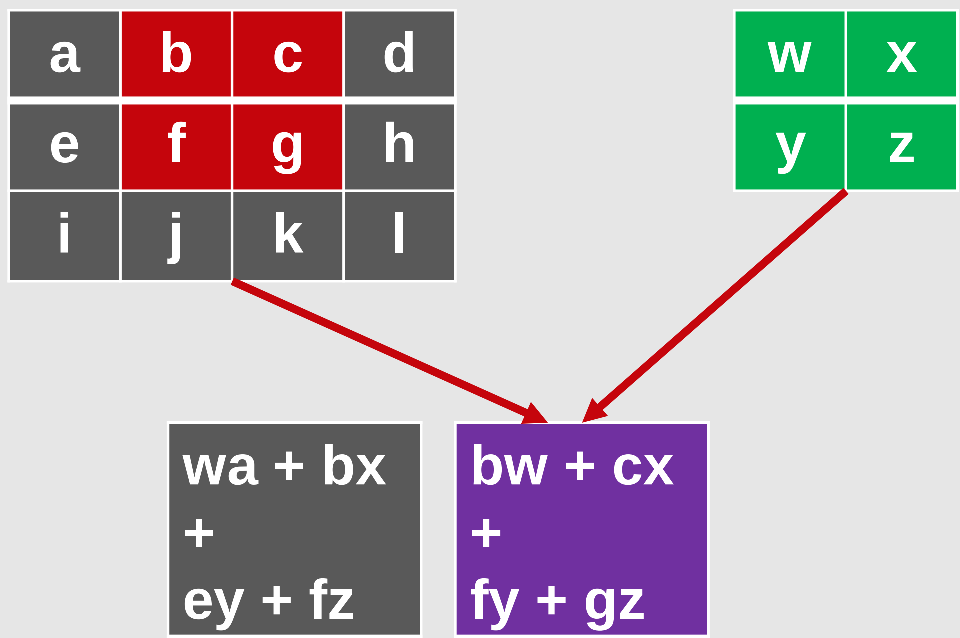


Illustration 2

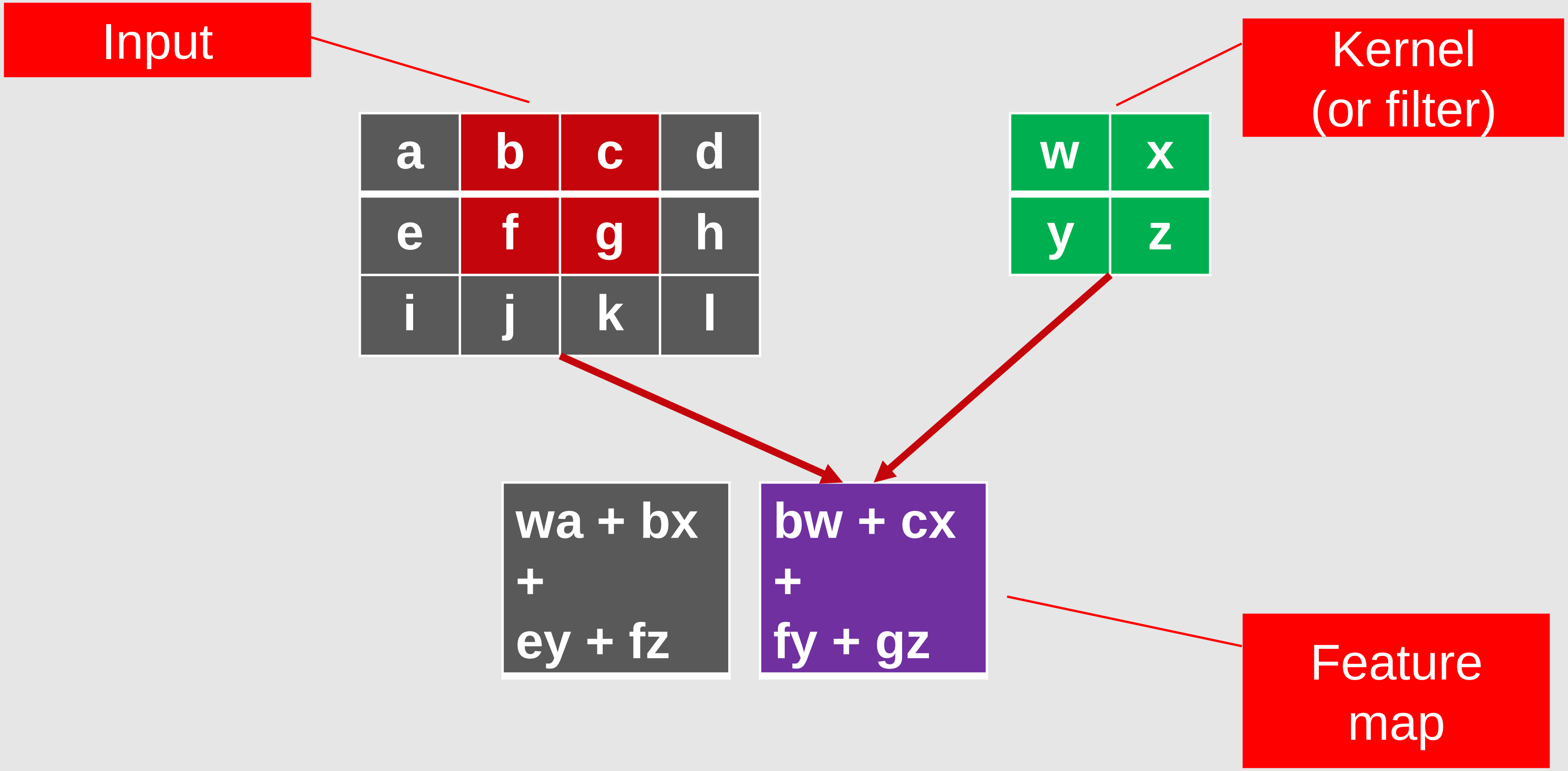
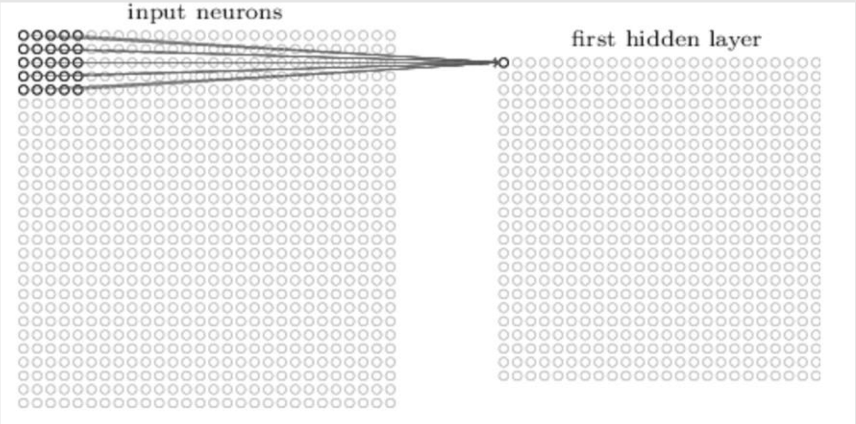
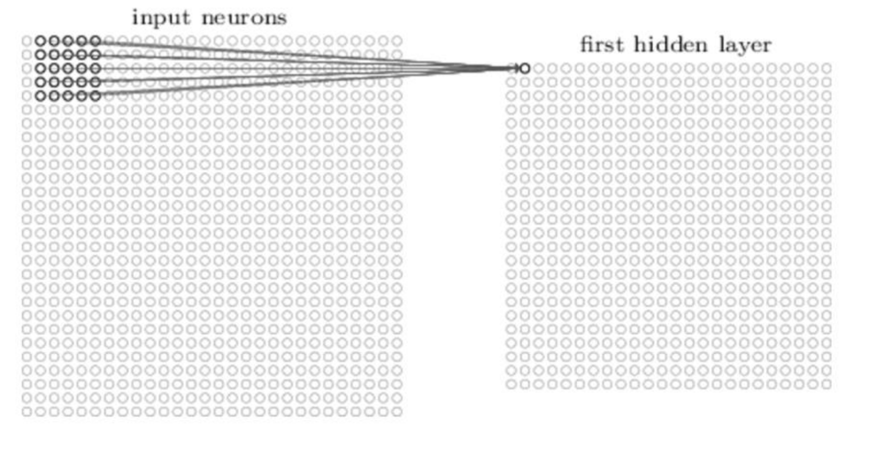


Illustration 2

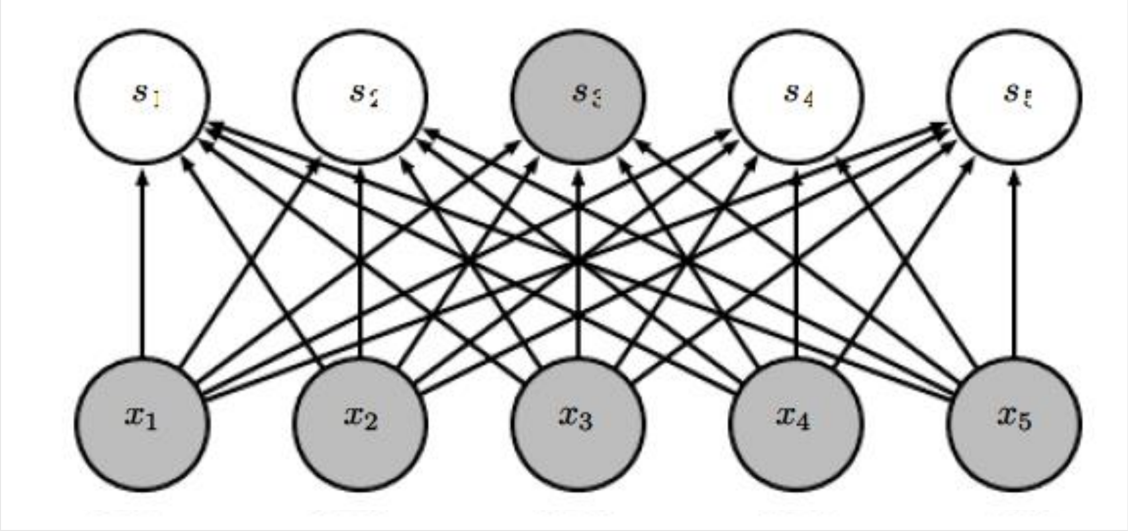
- All the units used the same set of weights (kernel)
- The units detect the same “feature” but at different locations





Advantage: sparse interaction

Fully connected layer, $m \times n$ edges



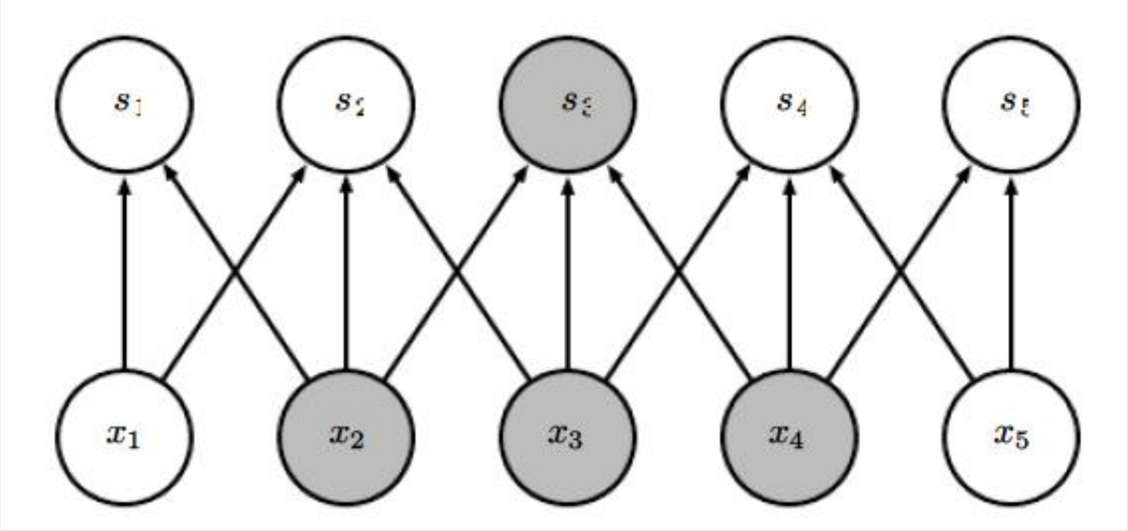
m output nodes

n input nodes

Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Advantage: sparse interaction

Convolutional layer, $\leq m \times k$ edges



m output nodes

k kernel size

n input nodes

Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Advantage: sparse interaction

Multiple convolutional layers: larger receptive field

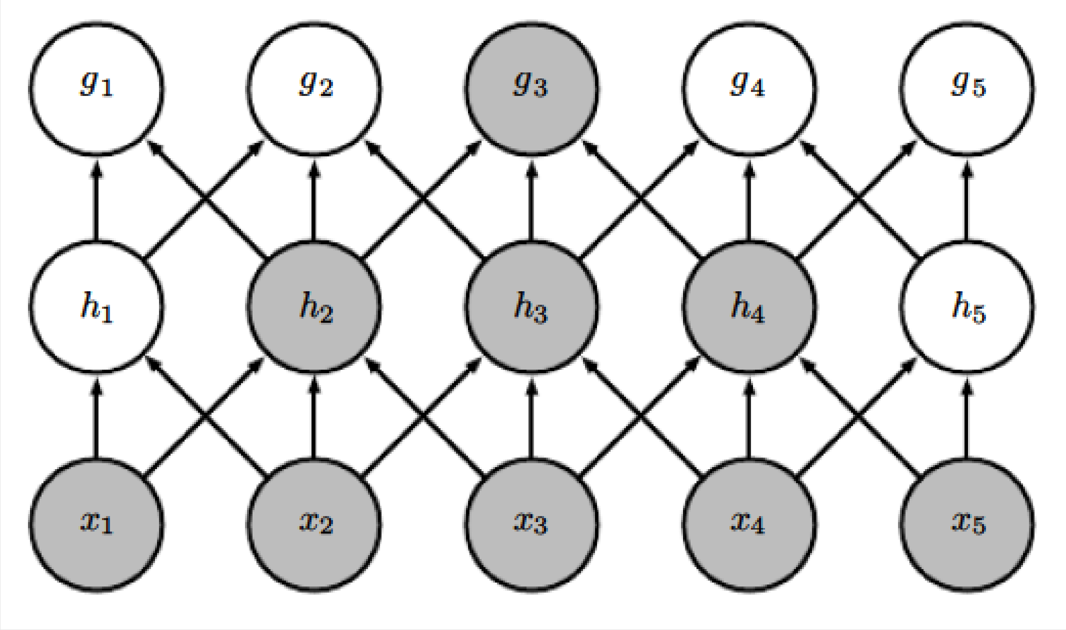
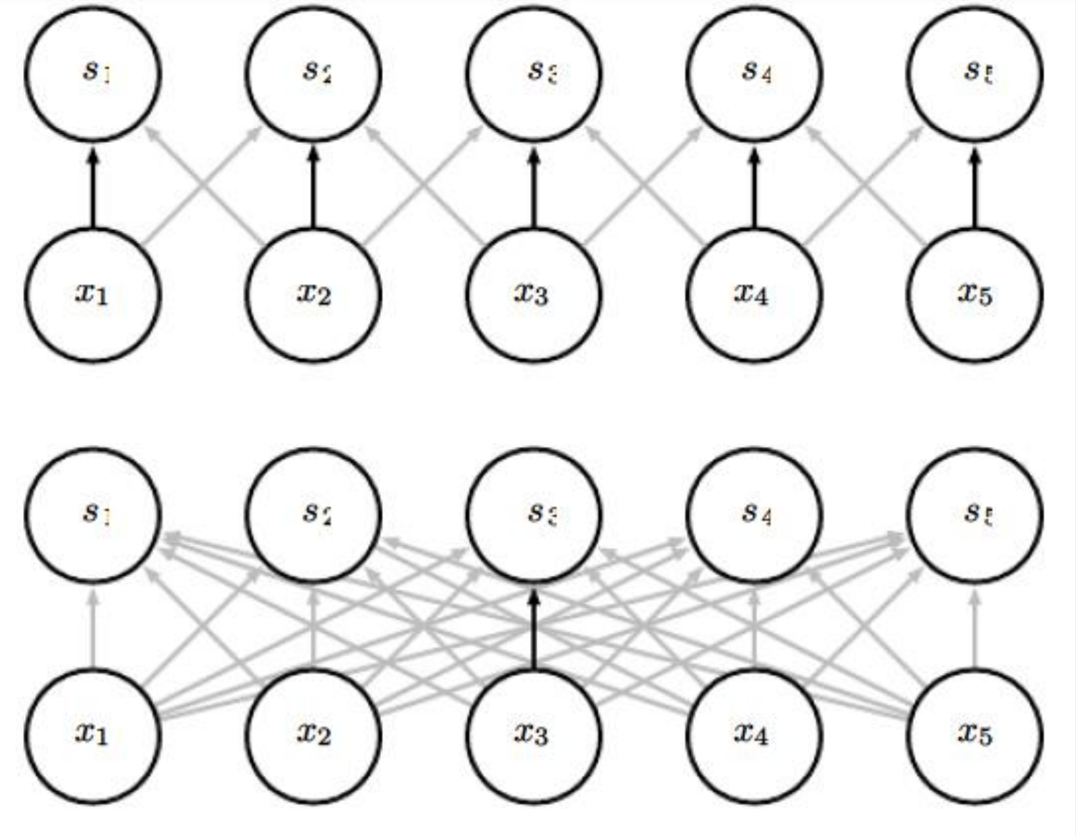


Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Advantage: parameter sharing/weight tying



The same kernel are used repeatedly. E.g., the black edge is the same weight in the kernel.

Figure from *Deep Learning*, by Goodfellow, Bengio, and Courville

Advantage: equivariant representations

- Equivariant: transforming the input = transforming the output

- Example: input is an image, transformation is shifting
- Convolution(shift(input)) = shift(Convolution(input))

- Useful when care only about the existence of a pattern, rather than the location

Pooling

Terminology

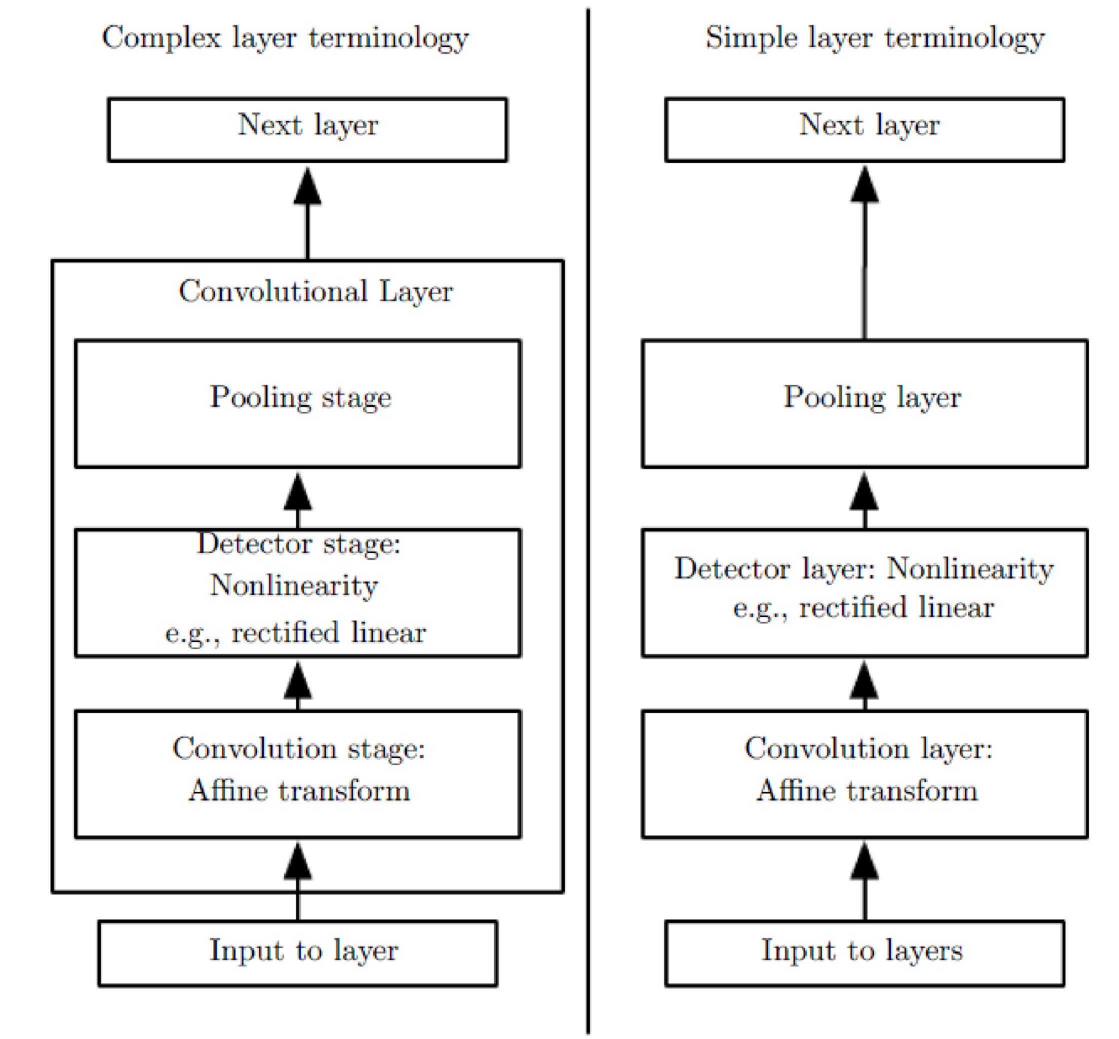


Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Pooling

- Summarizing the input (i.e., output the max of the input)

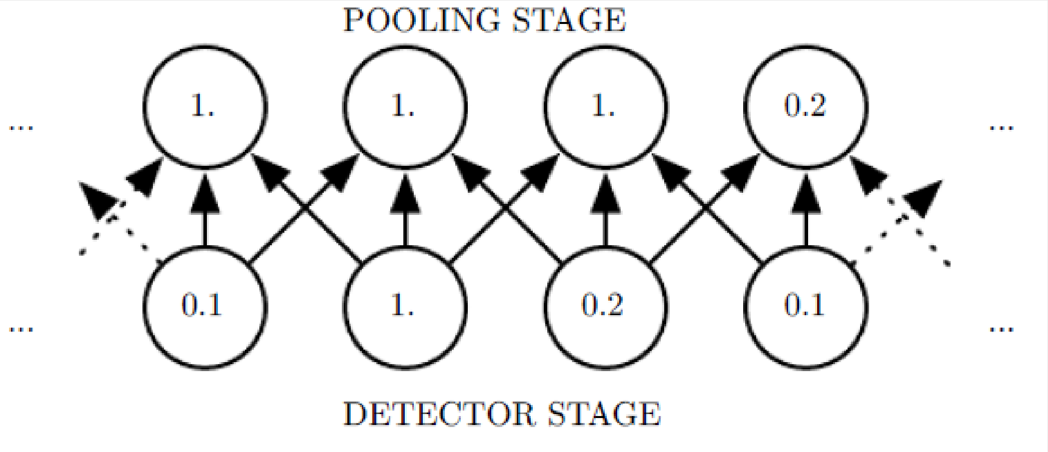
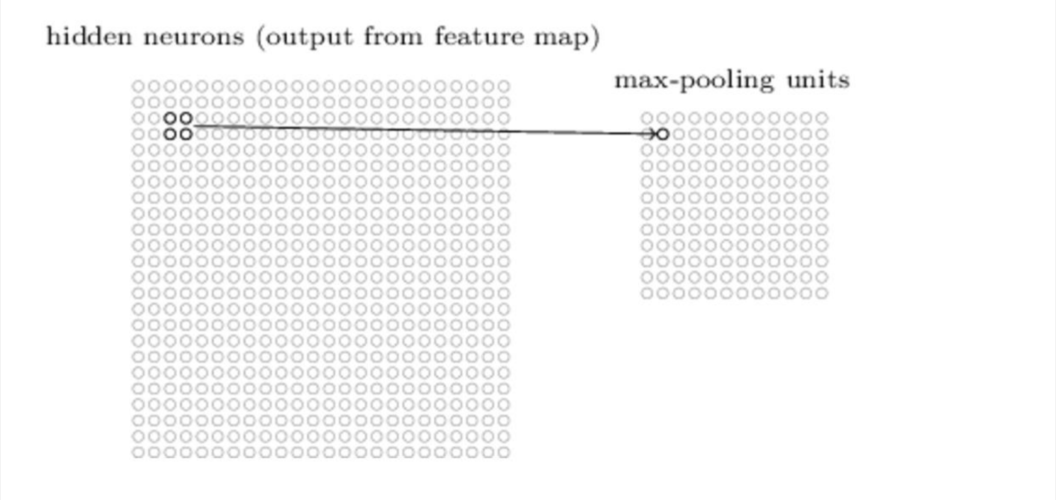


Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Illustration

- Each unit in a pooling layer outputs a max, or similar function, of a subset of the units in the previous layer



[Figure from neuralnetworksanddeeplearning.com]

Advantage

Induce invariance

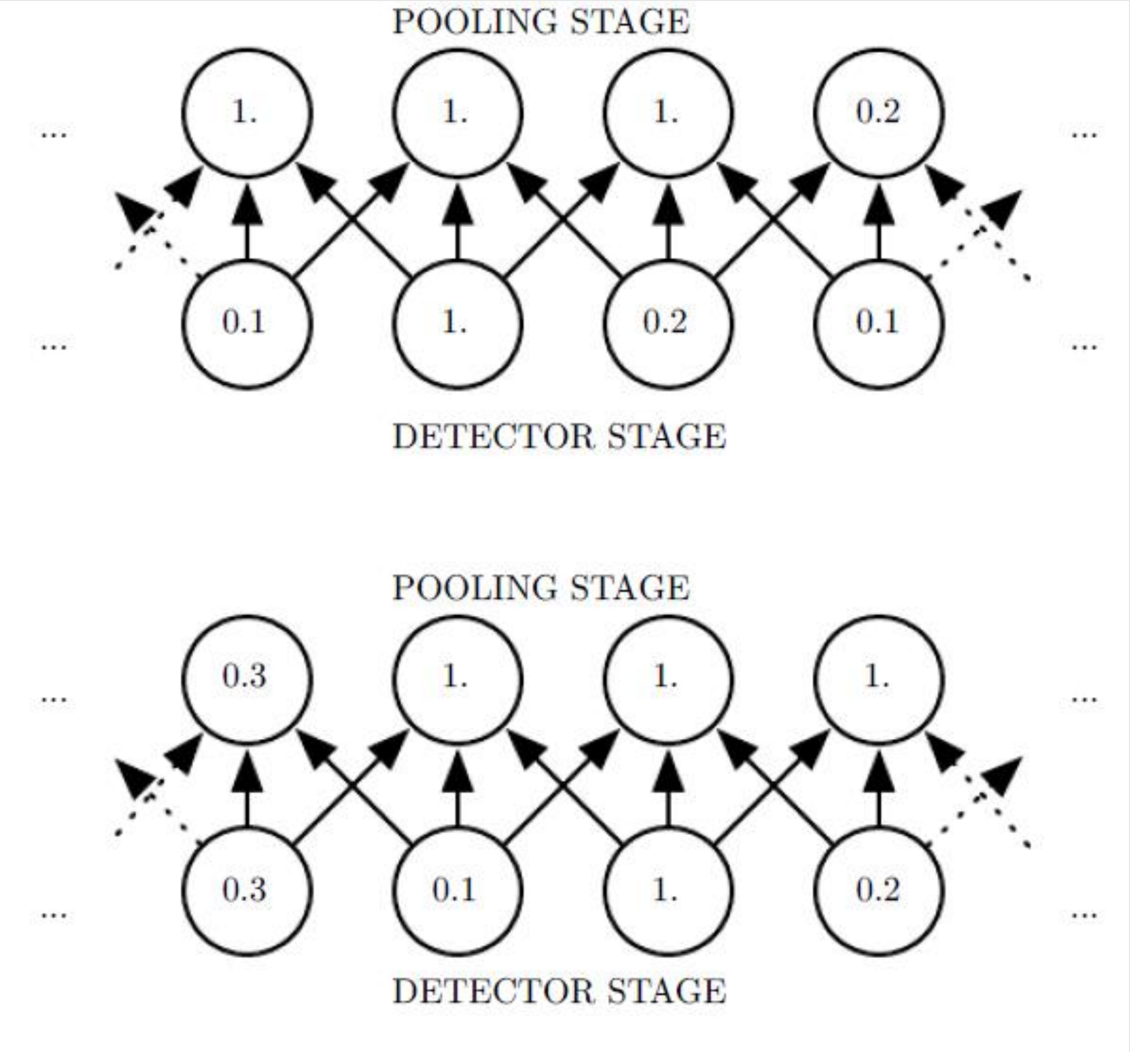


Figure from *Deep Learning,* by Goodfellow, Bengio, and Courville

Motivation from neuroscience

- David Hubel and Torsten Wiesel studied early visual system in human brain (V1 or primary visual cortex), and won Nobel prize for this

- V1 properties
  - 2D spatial arrangement
  - Simple cells: inspire convolution layers
  - Complex cells: inspire pooling layers

Example: LeNet

LeNet-5

- Proposed in *"Gradient-based learning applied to document recognition"* , *by Yann LeCun, Leon Bottou, Yoshua Bengio and Patrick Haffner, in Proceedings of the IEEE, 1998*

- Apply convolution on 2D images (MNIST) and use backpropagation

- Structure: 2 convolutional layers (with pooling) + 3 fully connected layers
  - Input size: 32x32x1
  - Convolution kernel size: 5x5
  - Pooling: 2x2

LeNet-5

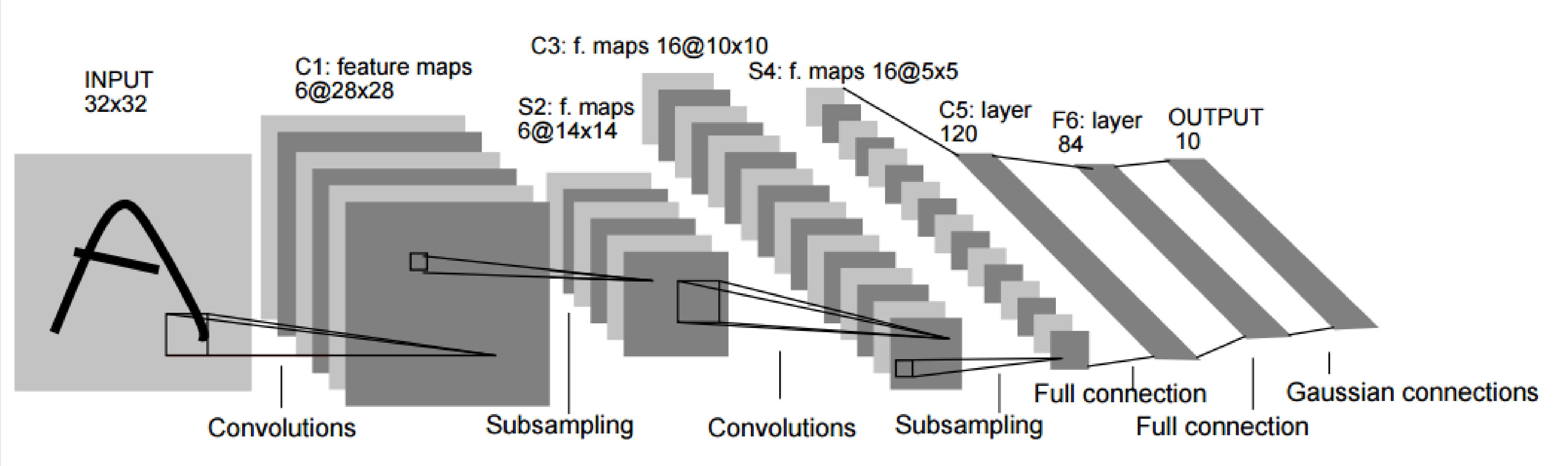


Figure from *Gradient-based learning applied to document recognition, by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

LeNet-5

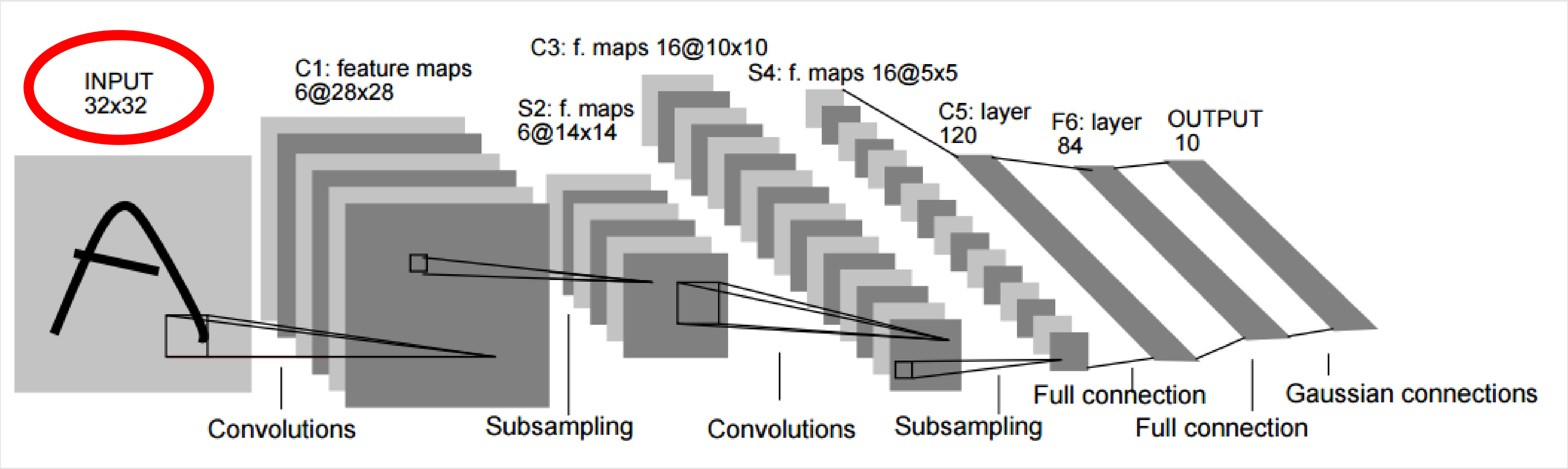
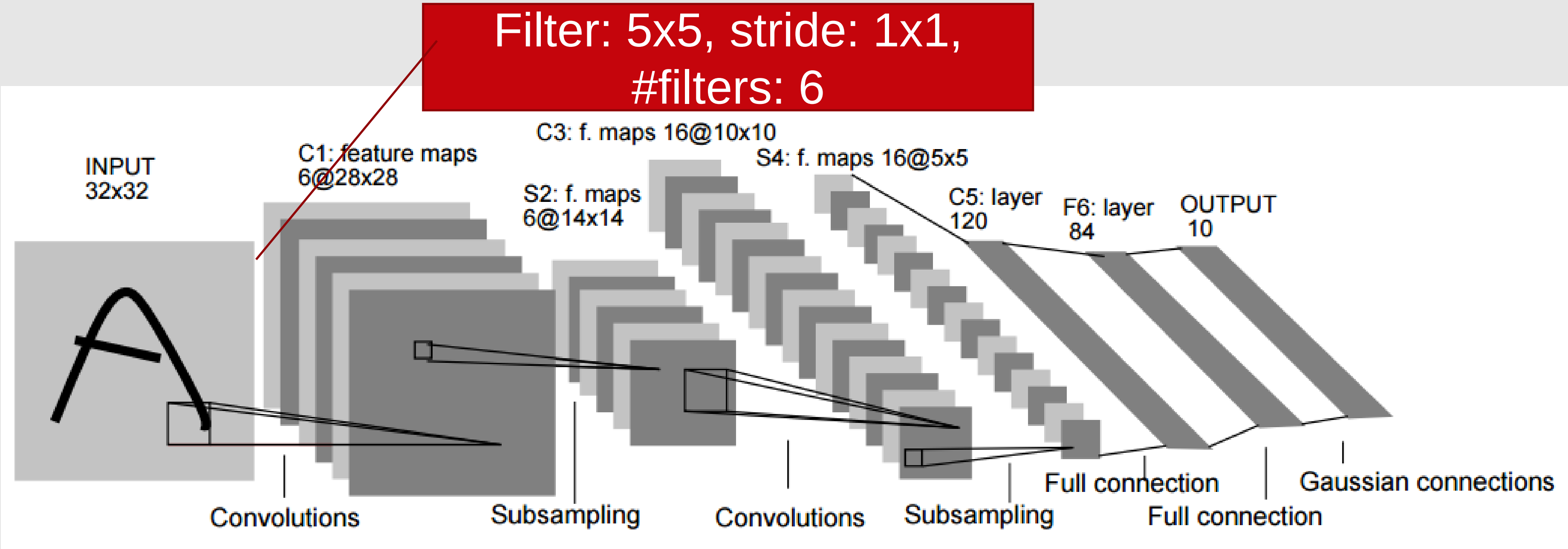


Figure from *Gradient-based learning applied to document recognition, by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

LeNet-5



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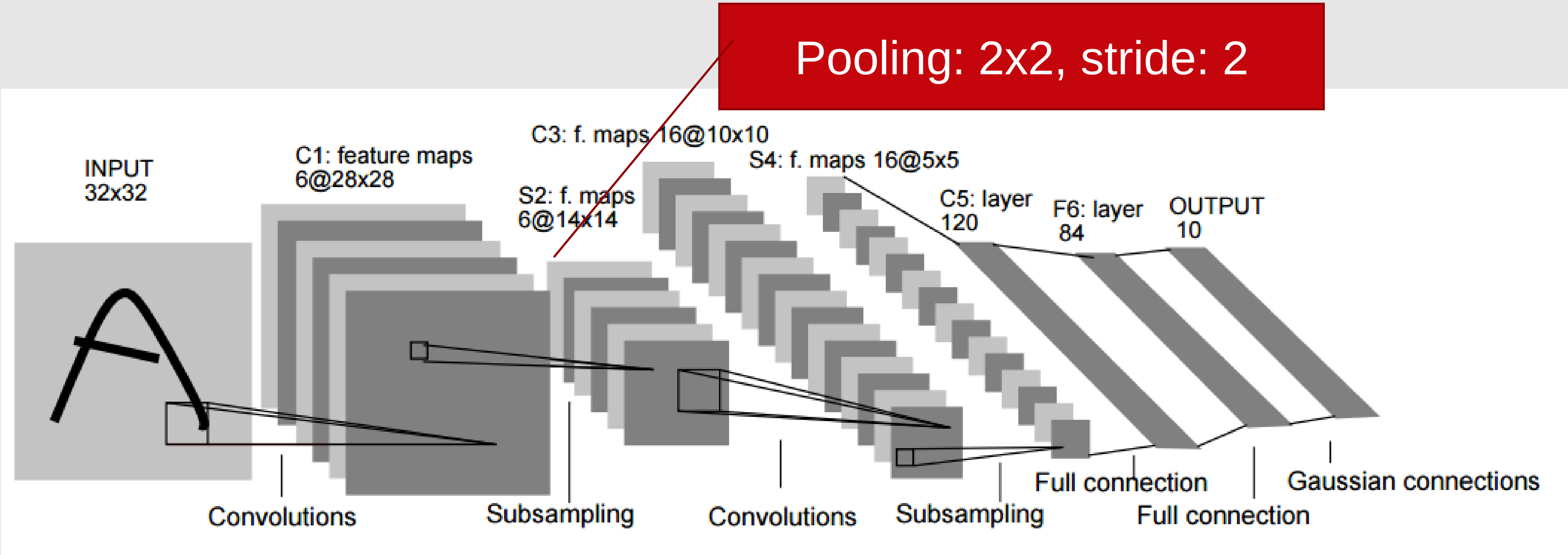
LeNet-5



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LeNet-5

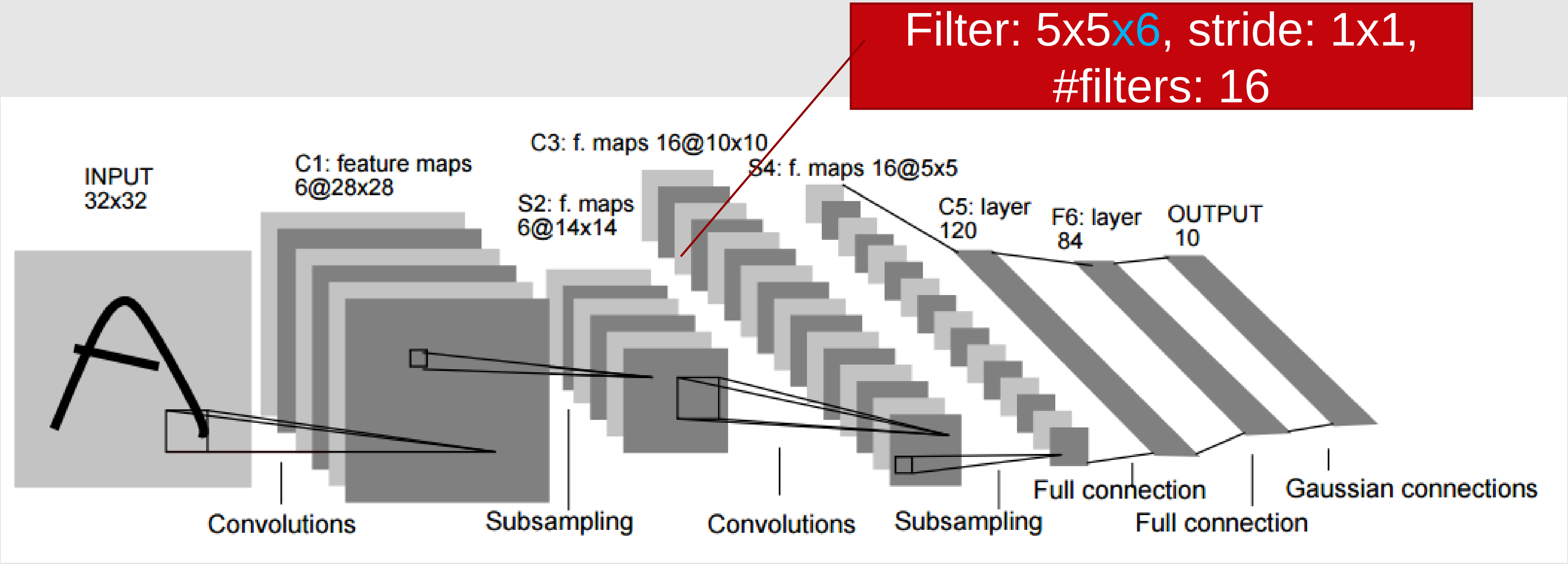


Figure from *Gradient-based learning applied to document recognition, by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

LeNet-5

Pooling: 2x2, stride: 2

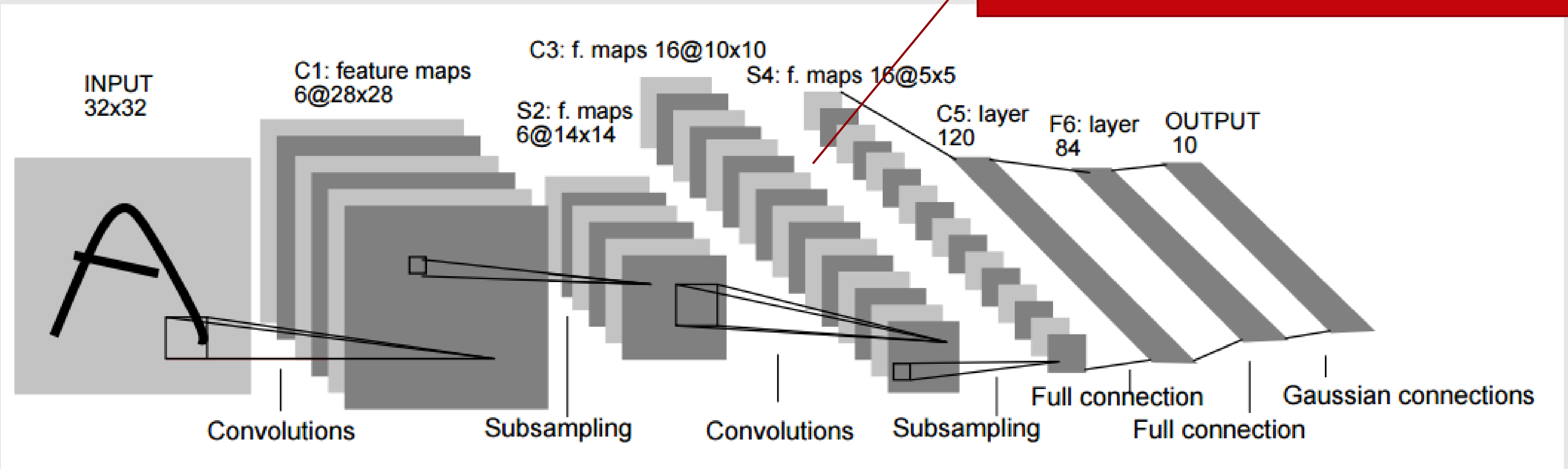


Figure from *Gradient-based learning applied to document recognition, by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

LeNet-5

Weight matrix: 400x120

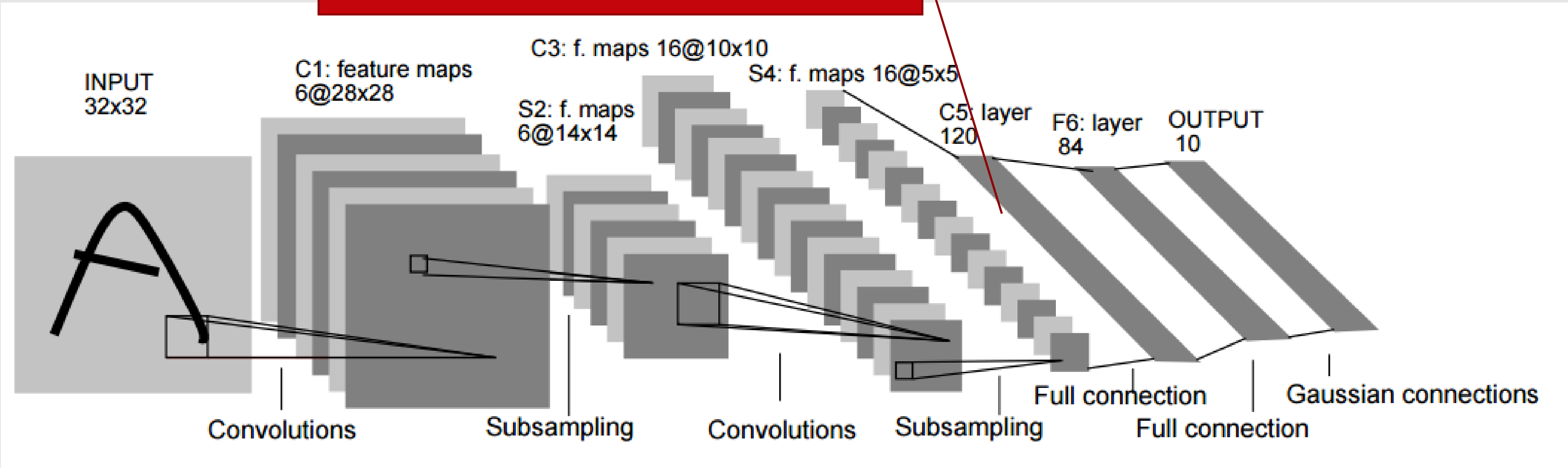


Figure from *Gradient-based learning applied to document recognition, by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

LeNet-5

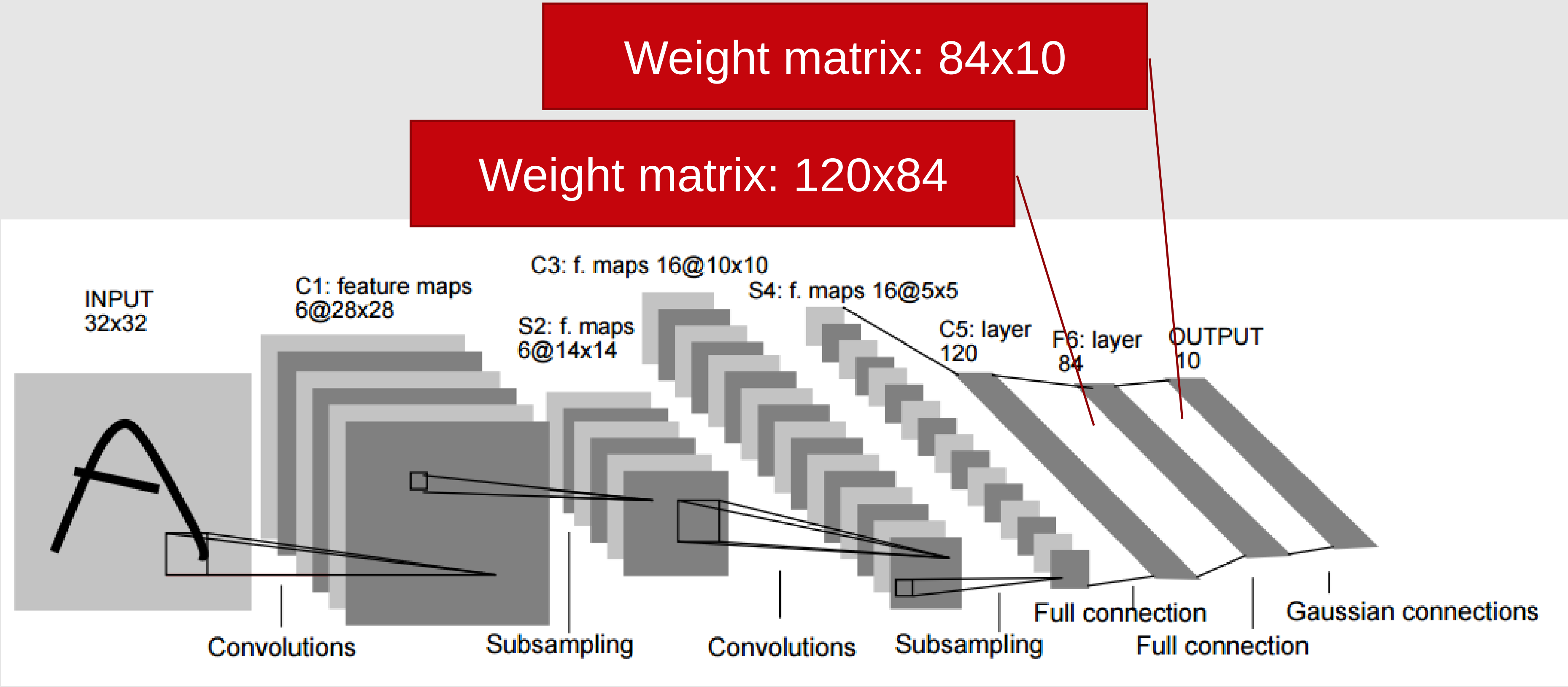


Figure from *Gradient-based learning applied to document recognition*, *by Y. LeCun, L. Bottou, Y. Bengio and P. Haffner*

Example: ResNet

ResNet

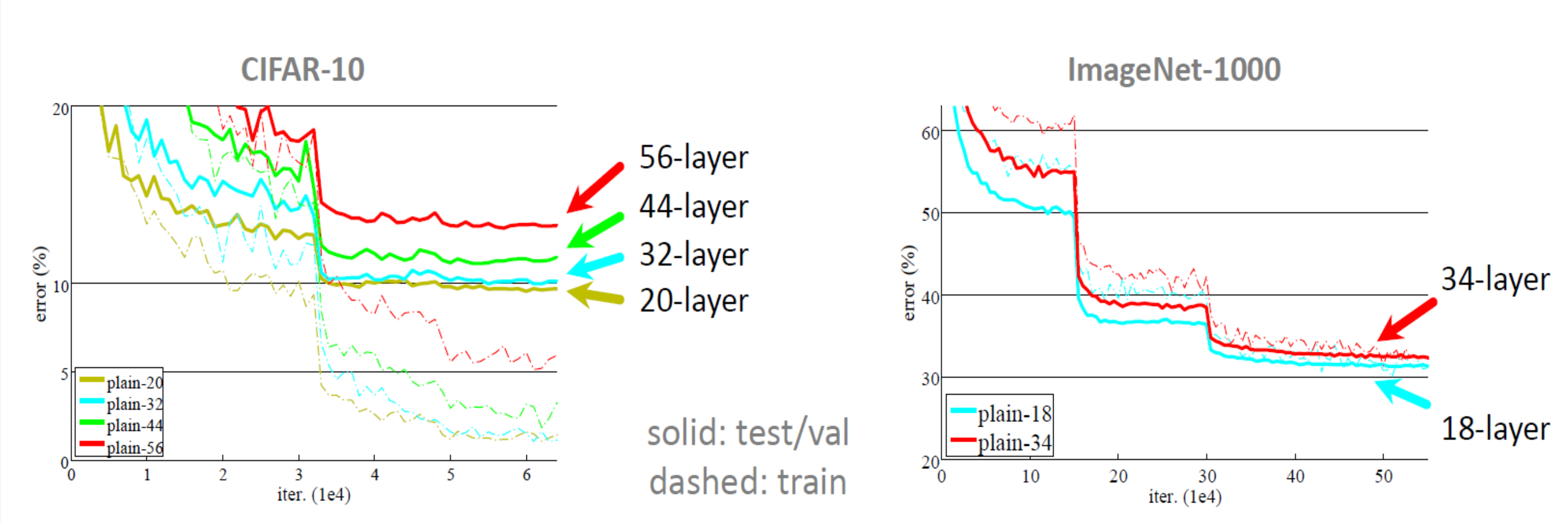
- Proposed in “Deep residual learning for image recognition” by *He, Kaiming, Xiangyu Zhang, Shaoqing Ren, and Jian Sun*. In *Proceedings of the IEEE conference on computer vision and pattern recognition*,. 2016.

- Apply very deep networks with repeated residue blocks

- Structure: simply stacking residue blocks

Plain Network

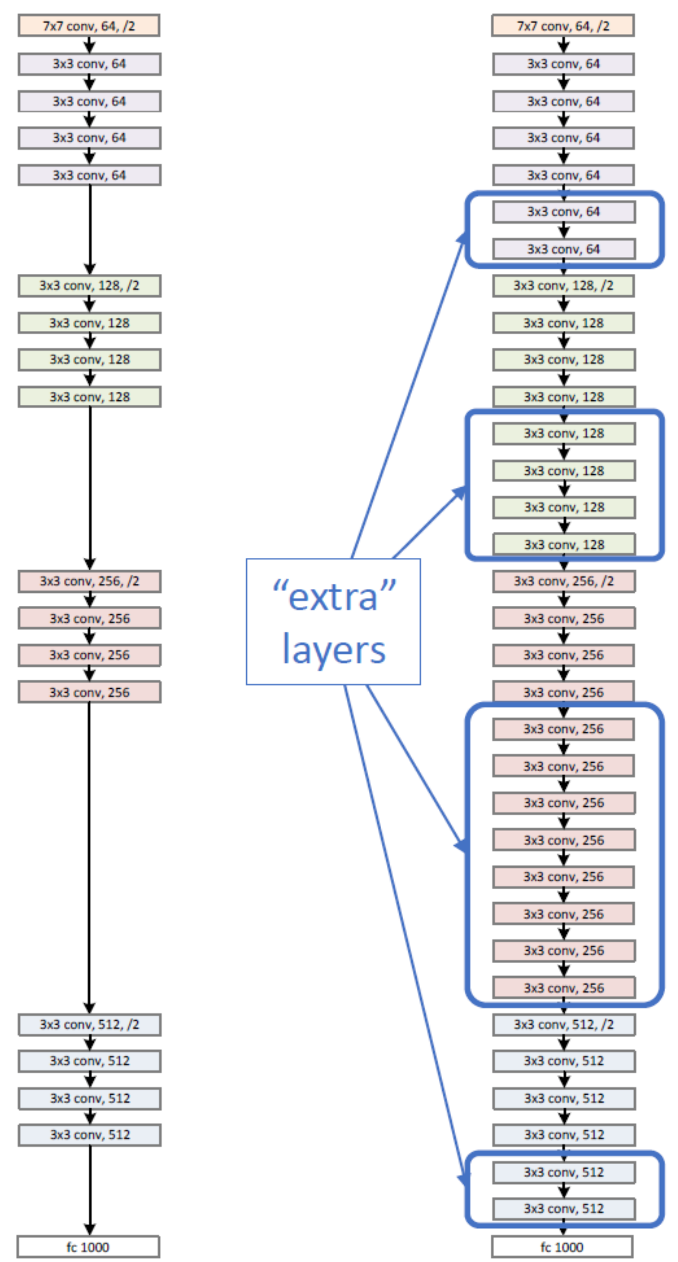
- “Overly deep” plain nets have higher training error
- A general phenomenon, observed in many datasets



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. arXiv 2015.

Residual Network

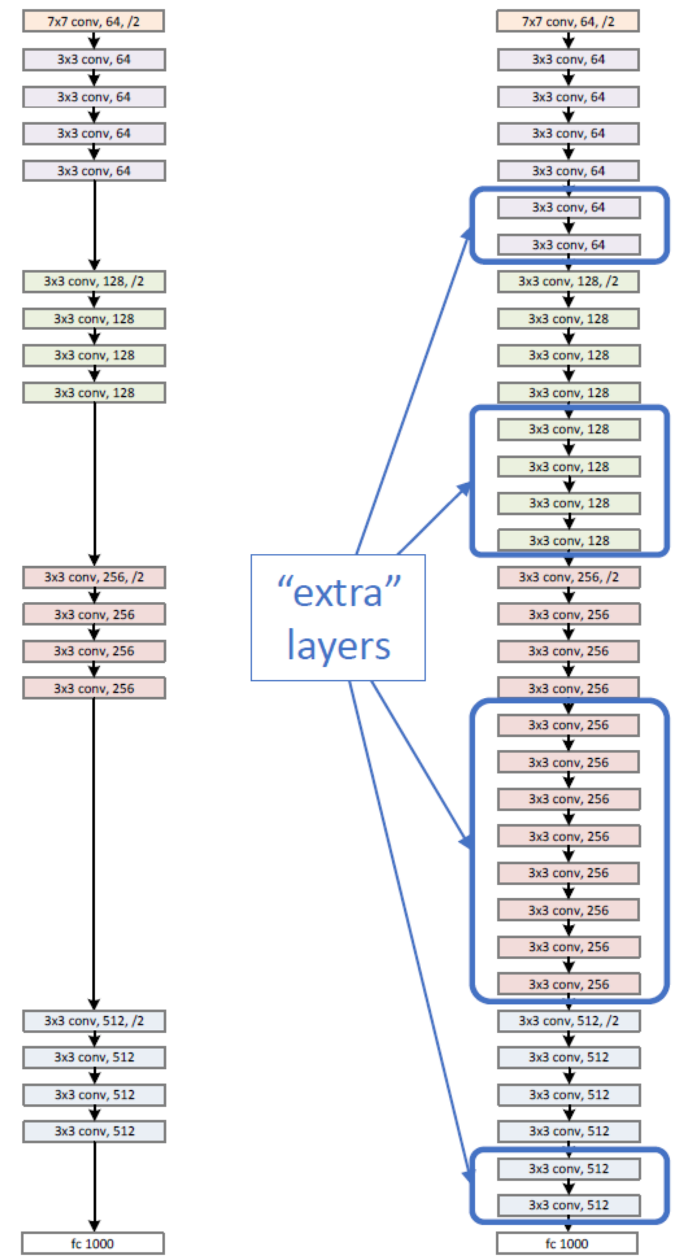
- Naïve solution
  - If extra layers are an identity mapping, then a training errors does not increase



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun.
"Deep Residual Learning for Image Recognition". arXiv 2015.

Residual Network

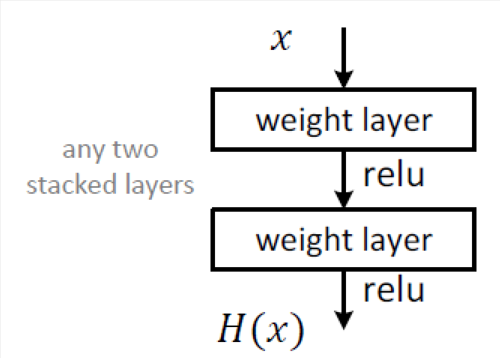
- Deeper networks also maintain the tendency of results
  - Features in same level will be almost same
  - An amount of changes is fixed
  - Adding layers makes smaller differences
  - Optimal mappings are closer to an identity



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.

Residual Network

- Plain block
  - Difficult to make identity mapping because of multiple non-linear layers

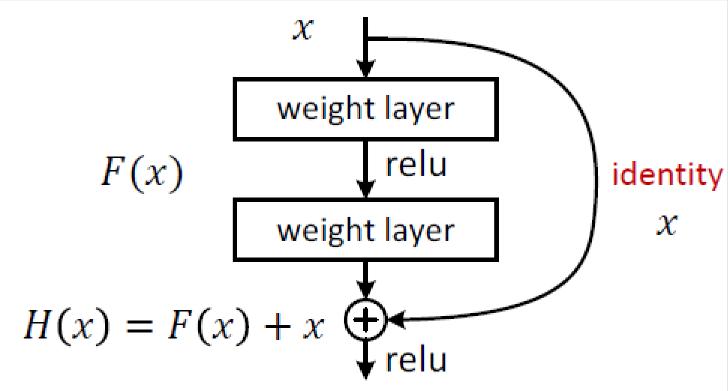


Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun.
“Deep Residual Learning for Image Recognition”. arXiv 2015.

Residual Network

- Residual block
  - If identity were optimal, easy to set weights as 0
  - If optimal mapping is closer to identity, easier to find small fluctuations

-> Appropriate for treating perturbation as keeping a base information

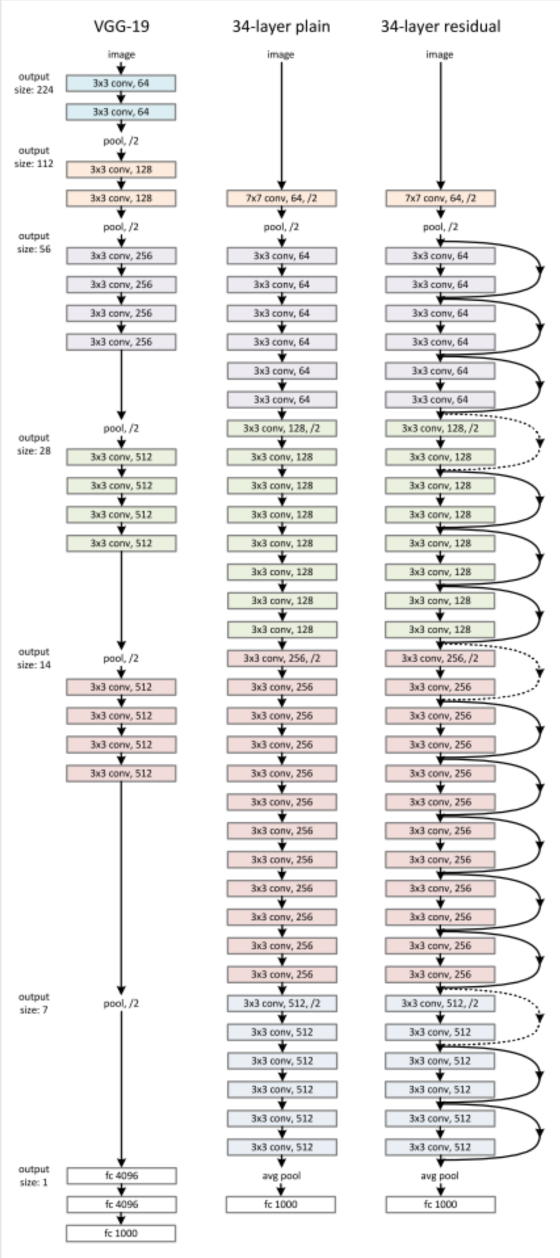


Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.

Network Design

- Basic design (VGG-style)
  - All 3x3 conv (almost)
  - Spatial size/2 => #filters x2
  - Batch normalization
  - Simple design, just deep

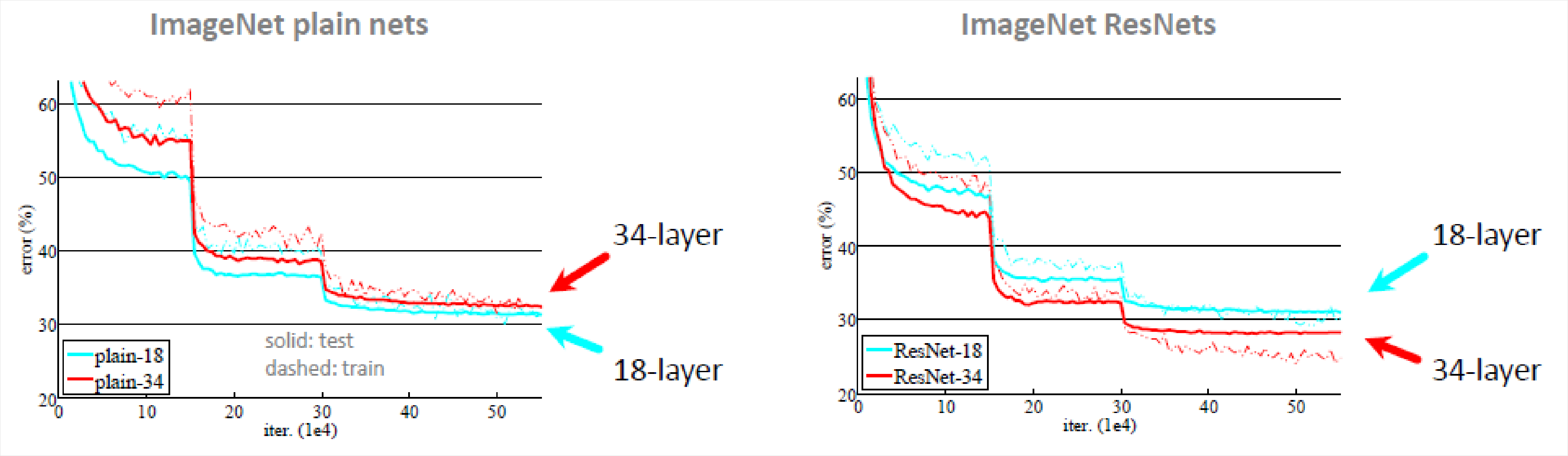
- Other remarks
  - No max pooling (almost)
  - No hidden fc
  - No dropout



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.

Results

- Deep Resnets can be trained without difficulties
- Deeper ResNets have lower training error, and also lower test error



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. arXiv 2015.

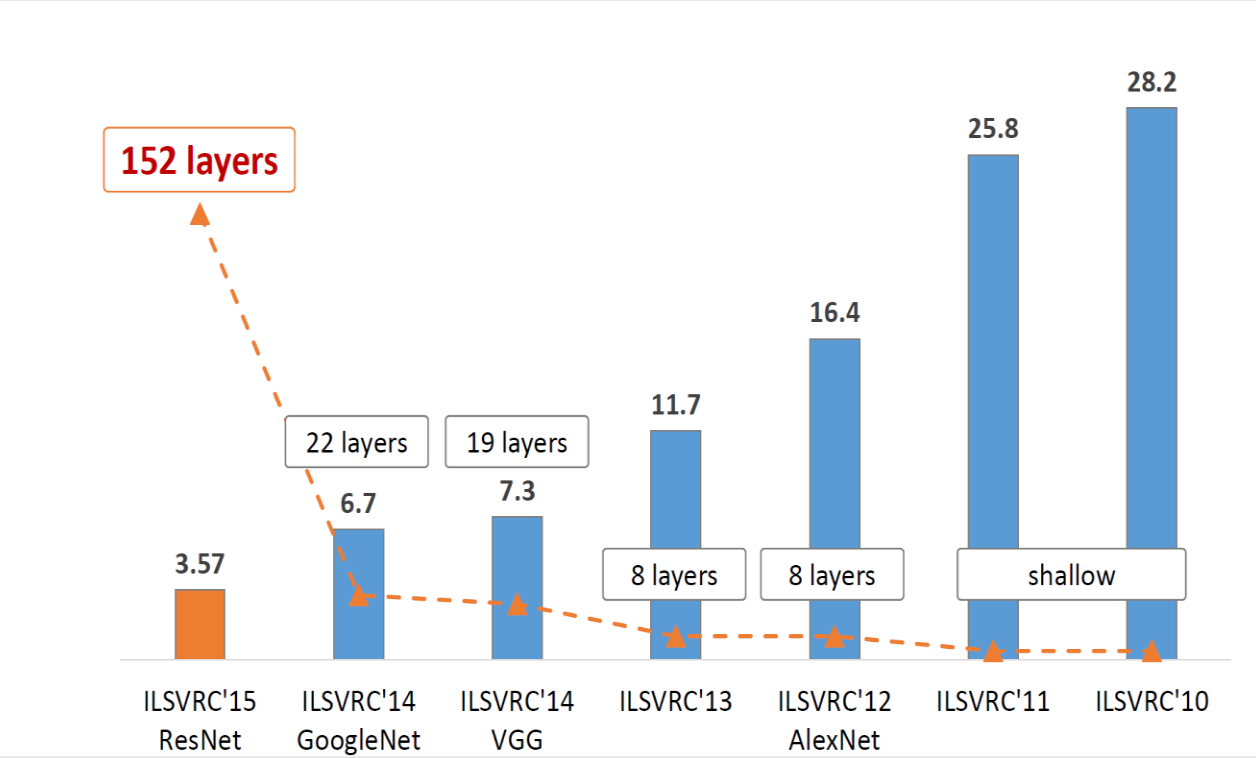
Results

- 1st places in all five main tracks in "ILSVRC & COCO 2015 Competitions"
  - ImageNet Classification
  - ImageNet Detection
  - ImageNet Localization
  - COCO Detection
  - COCO Segmentation

Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. "Deep Residual Learning for Image Recognition". arXiv 2015.

Quantitative Results

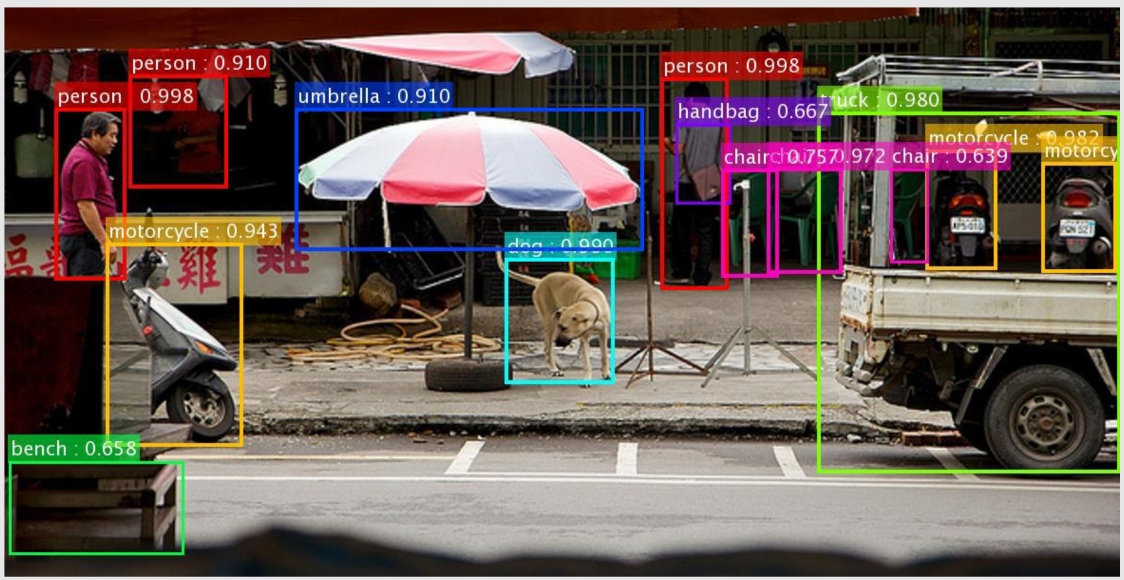
- ImageNet Classification



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. arXiv 2015.

Qualitative Result

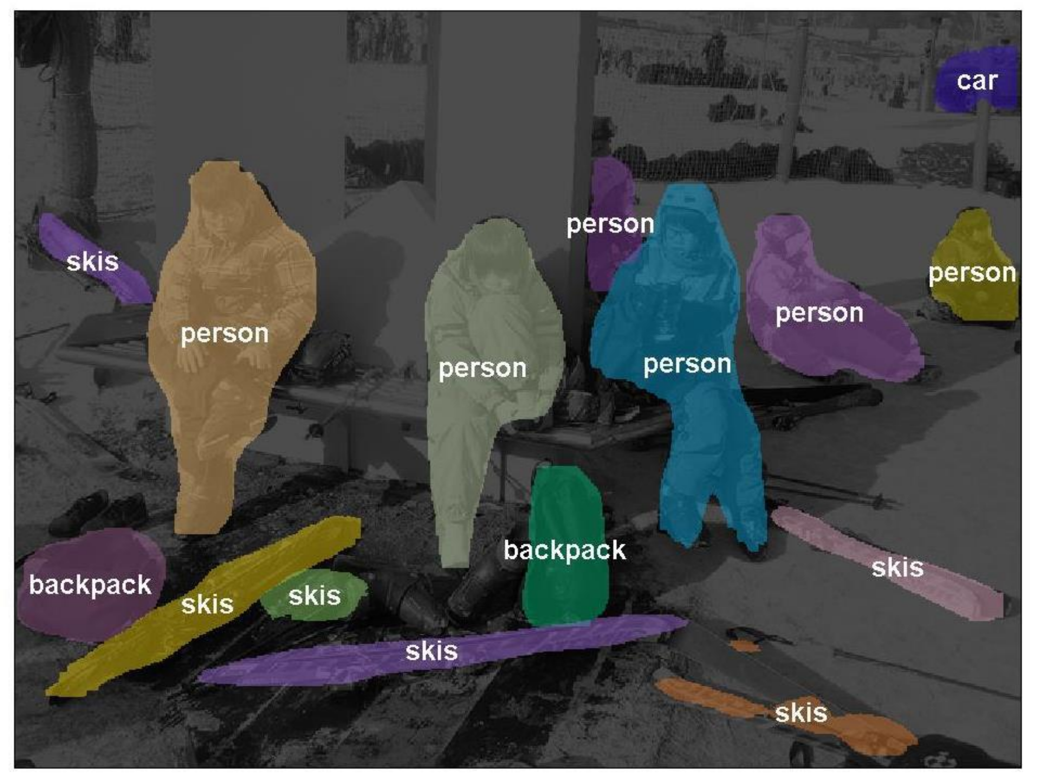
- Object detection
  - Faster R-CNN + ResNet



Kaiming He, Xiangyu Zhang, Shaoqing Ren, & Jian Sun. “Deep Residual Learning for Image Recognition”. arXiv 2015.
Jifeng Dai, Kaiming He, & Jian Sun. “Instance-aware Semantic Segmentation via Multi-task Network Cascades”. arXiv 2015.

Qualitative Results

- Instance Segmentation



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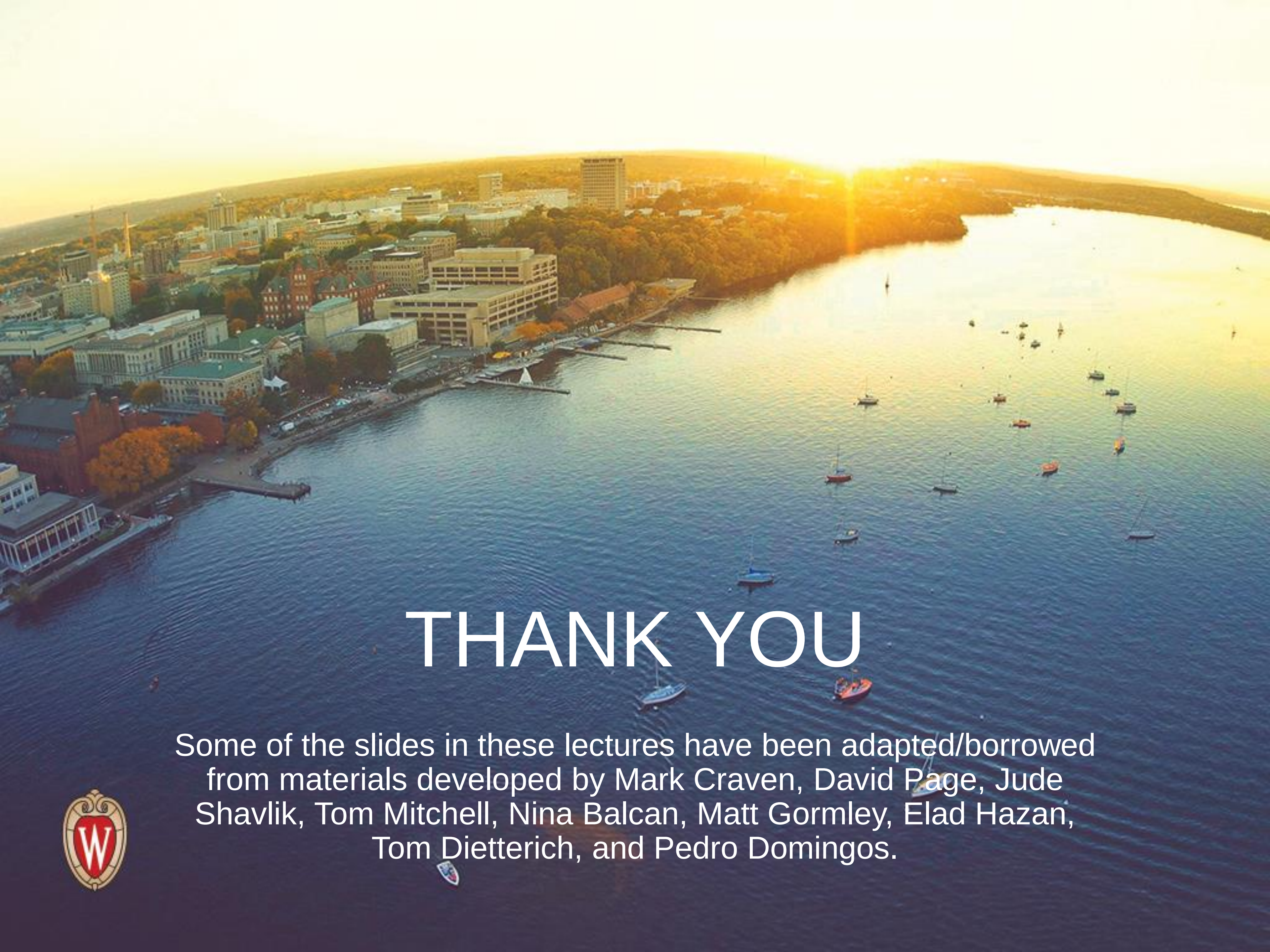

THANK YOU

Some of the slides in these lectures have been adapted/borrowed from materials developed by Mark Craven, David Page, Jude Shavlik, Tom Mitchell, Nina Balcan, Matt Gormley, Elad Hazan, Tom Dietterich, and Pedro Domingos.