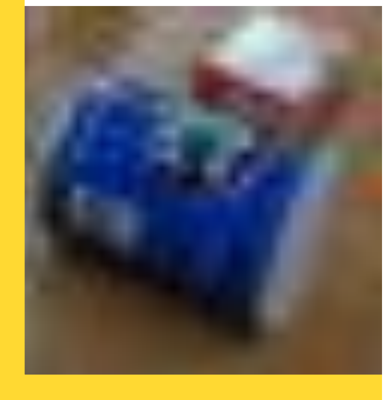
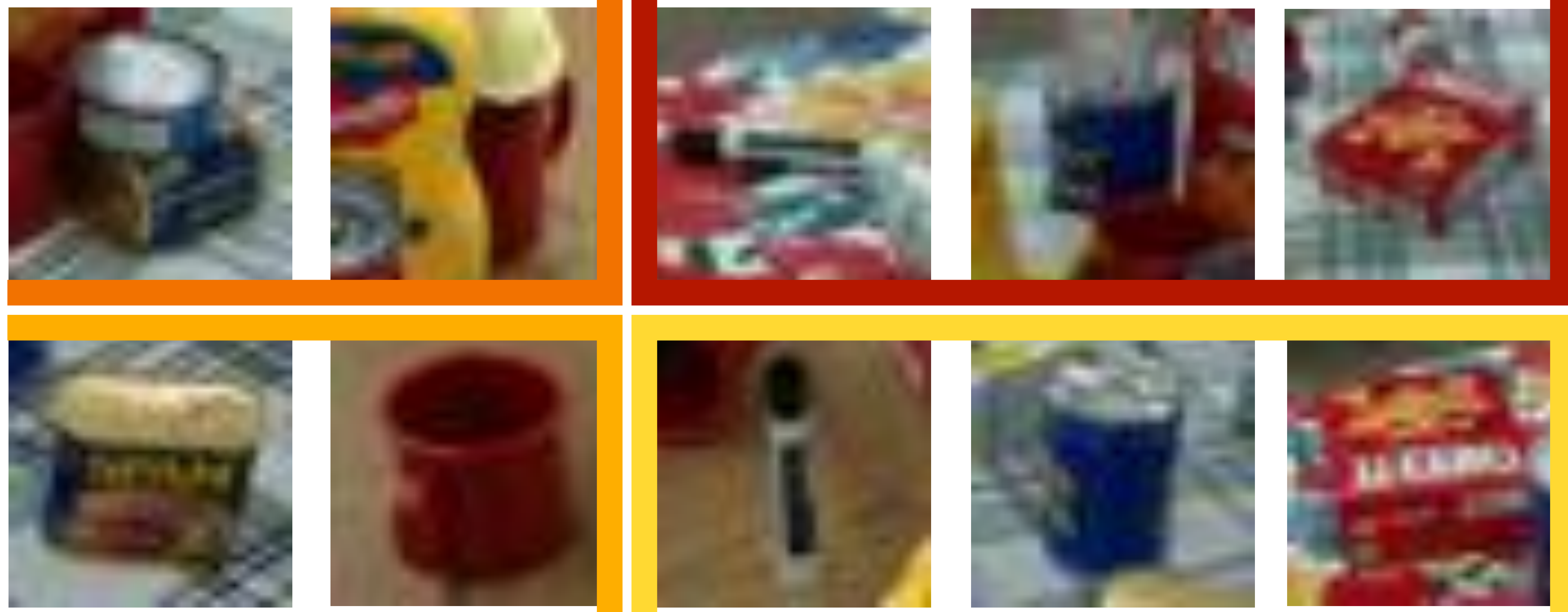


DeepRob

Lecture 7
Convolutional Neural Networks
University of Minnesota

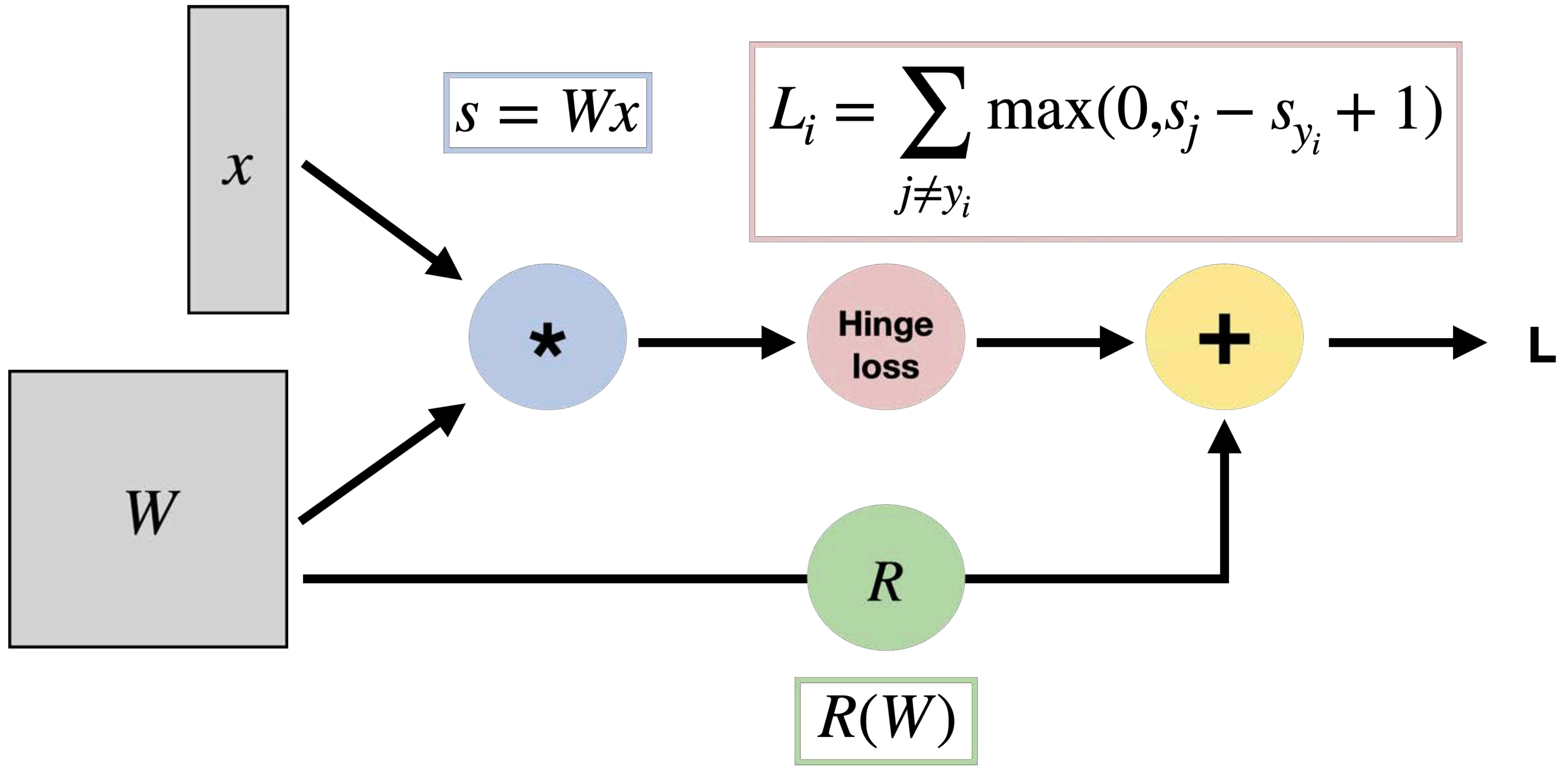


Project 1—Reminder

- Instructions and code available on the website
  - Here: https://rpm-lab.github.io/CSCI5980-F24-DeepRob/projects/project1/
- Uses Python, PyTorch and Google Colab
- Implement KNN, linear SVM, and linear softmax classifiers
- **Autograder is available!**
- **Due Monday, Sept 30th 11:59 PM CT**

Recap from Previous Lecture

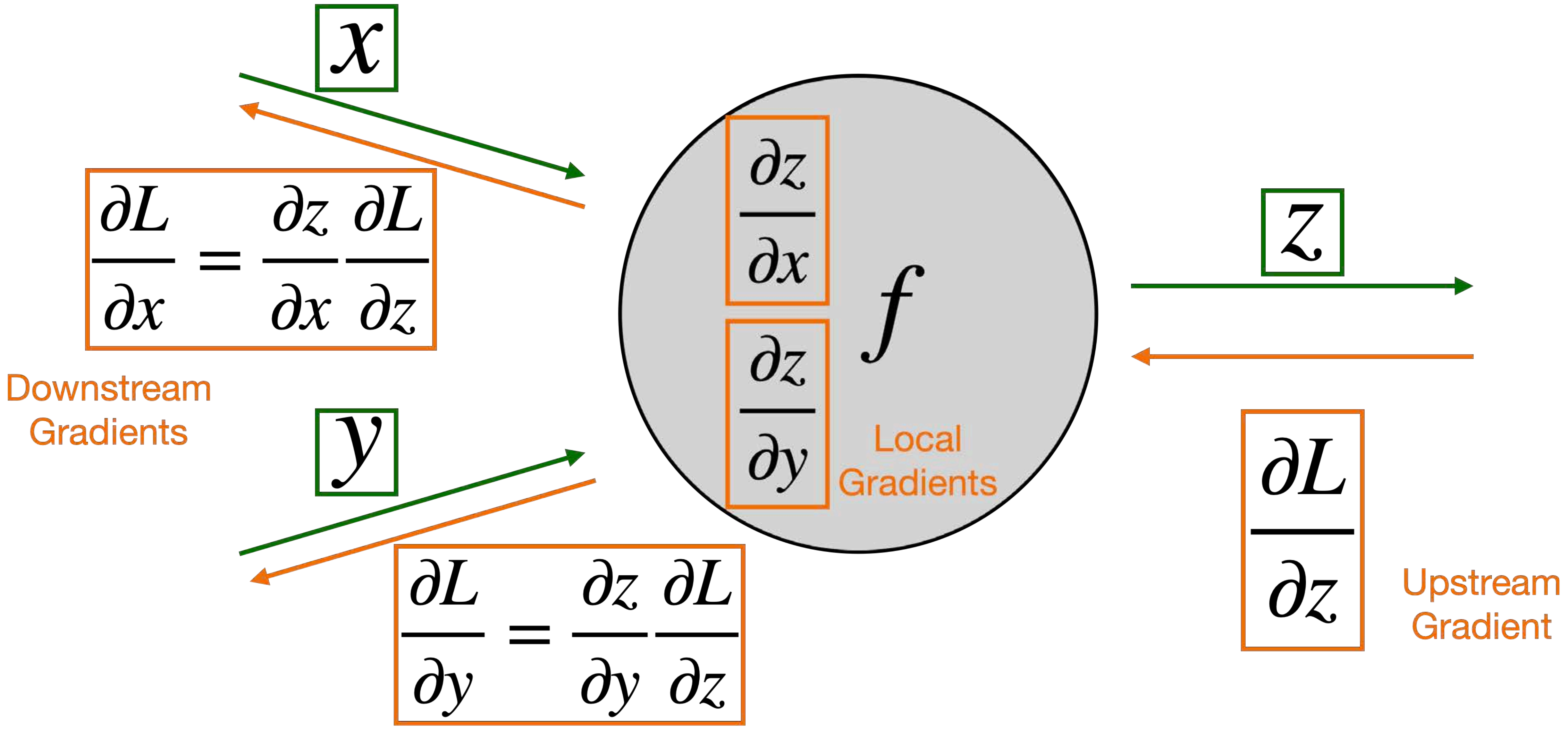
Represent complex expressions as **computational graphs**



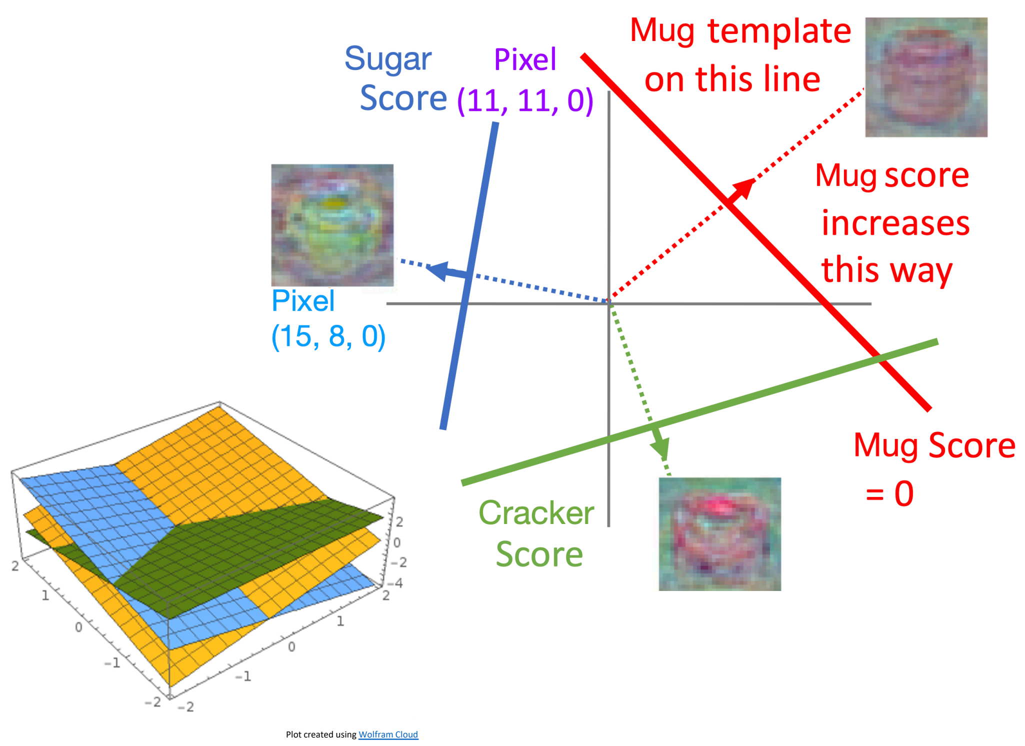
1. Forward pass: Compute outputs

2. Backward pass: Compute gradients

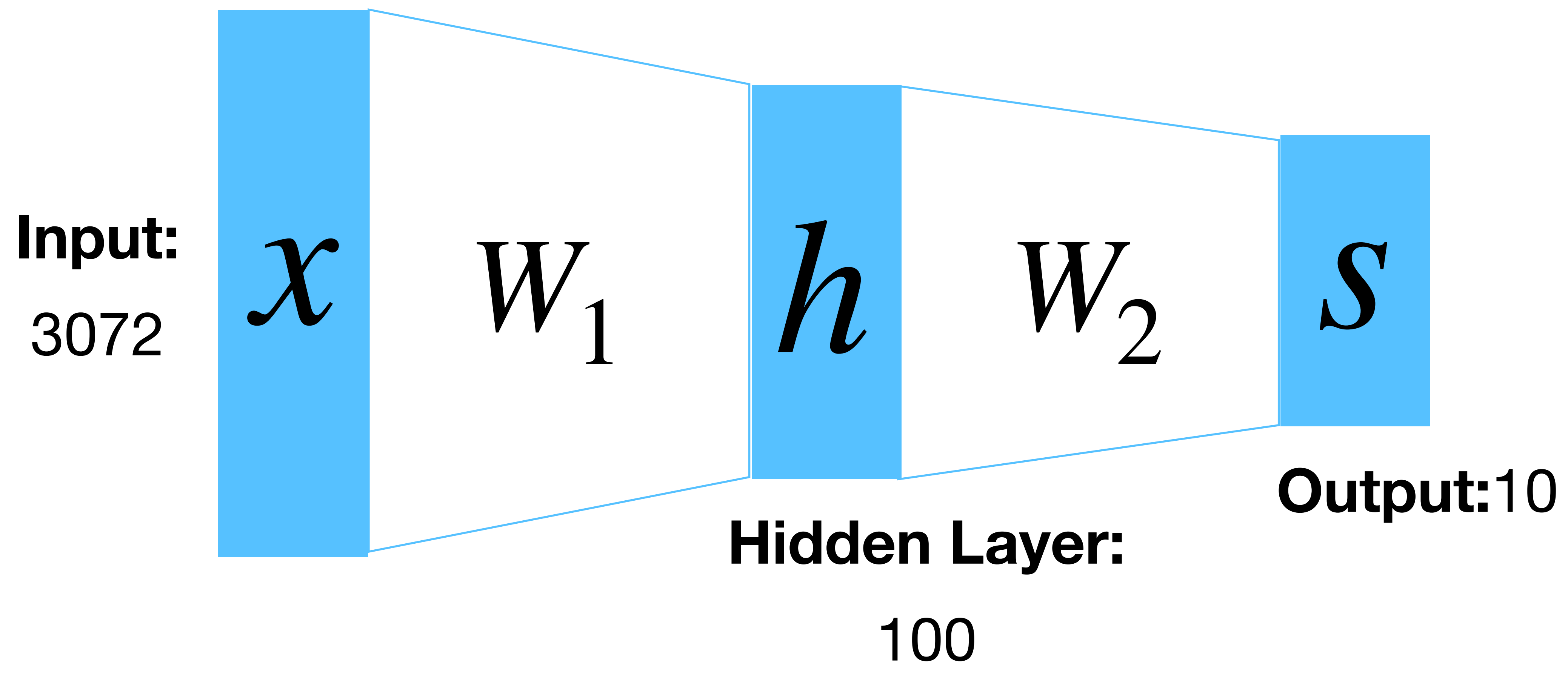
During the backward pass, each node in the graph receives **upstream gradients** and multiplies them by **local gradients** to compute **downstream gradients**



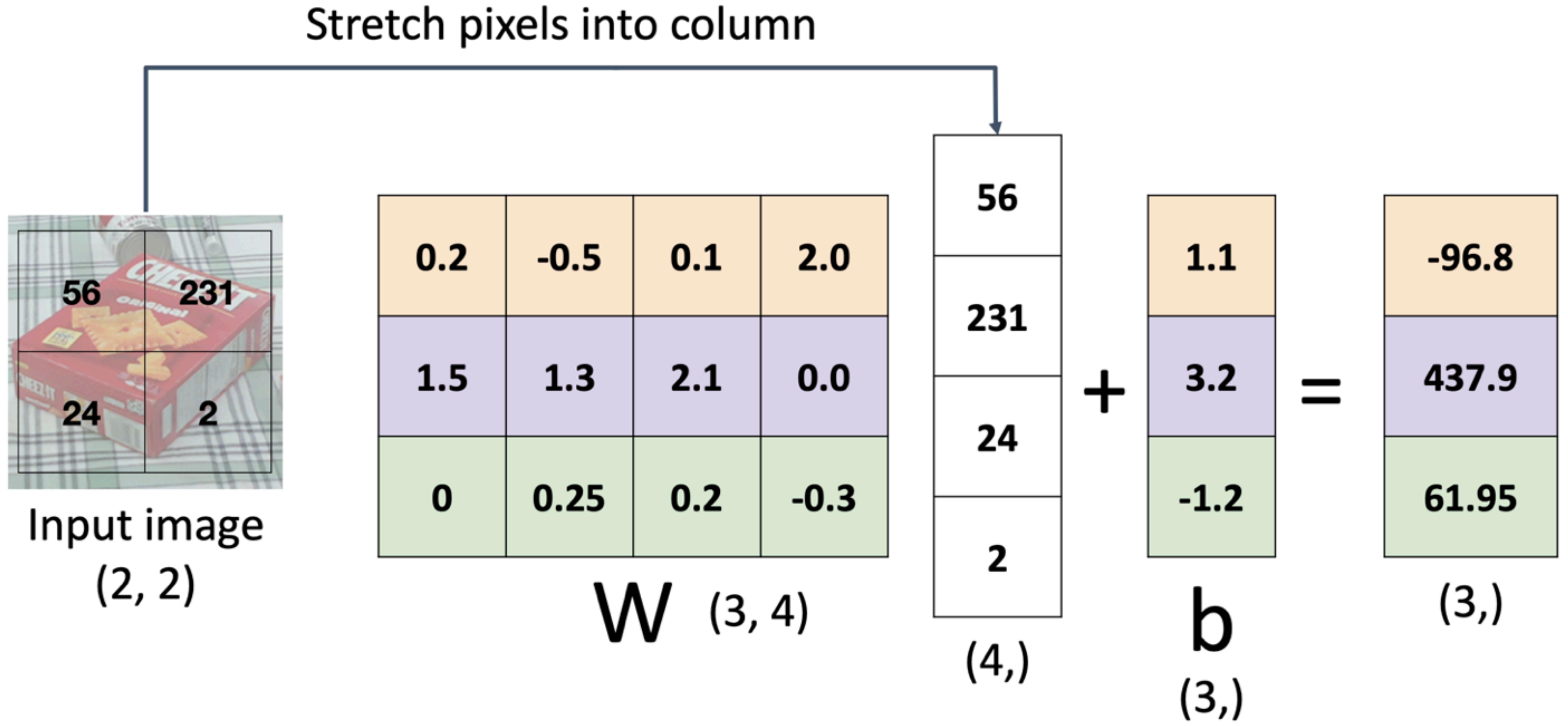
Recap from Previous Lecture



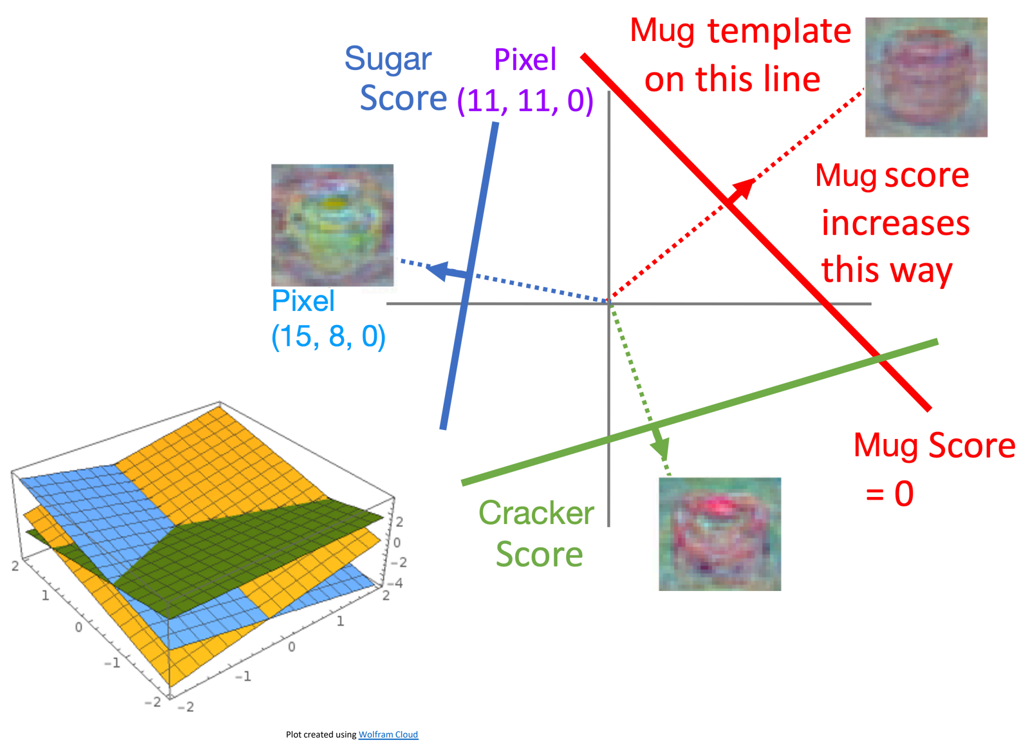
$$f(x) = W_2 \max(0, W_1 x + b_1) + b_2$$



Problem: So far our classifiers don't respect the spatial structure of images!



Recap from Previous Lecture



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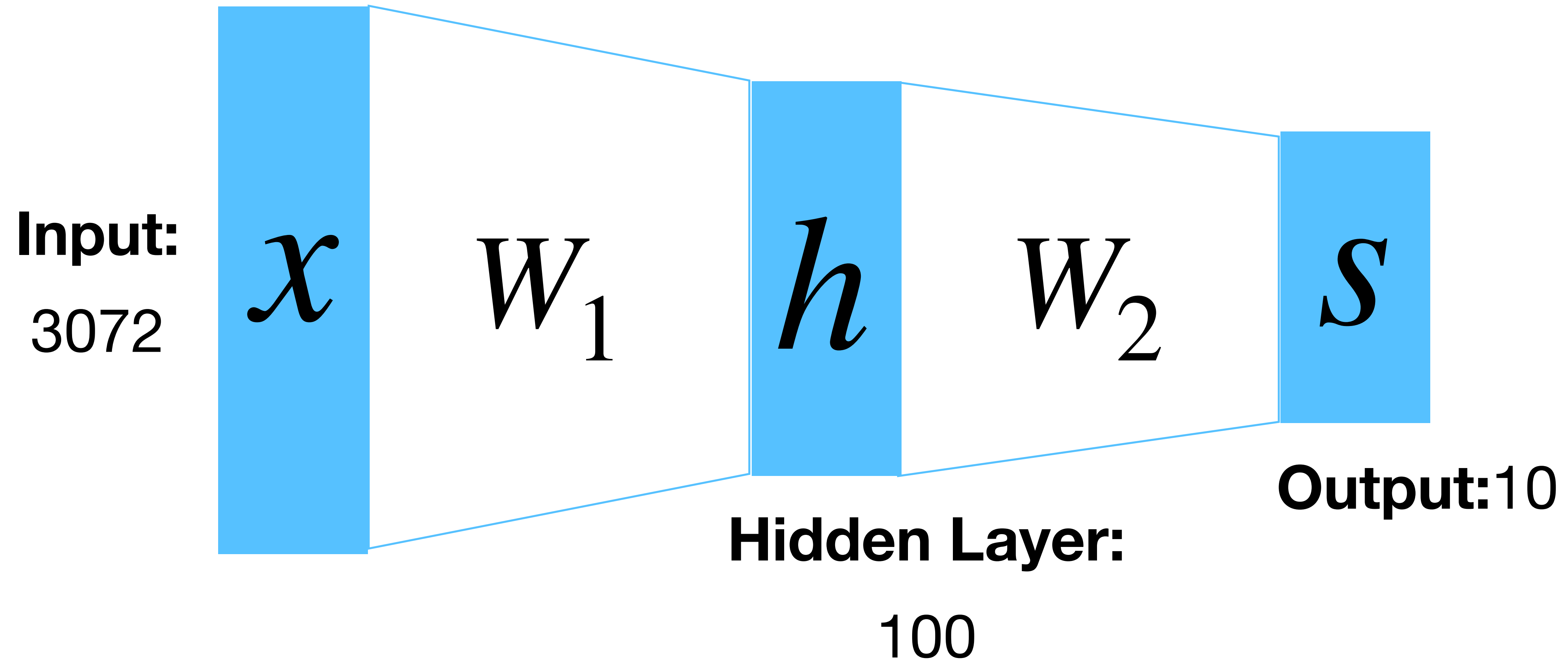
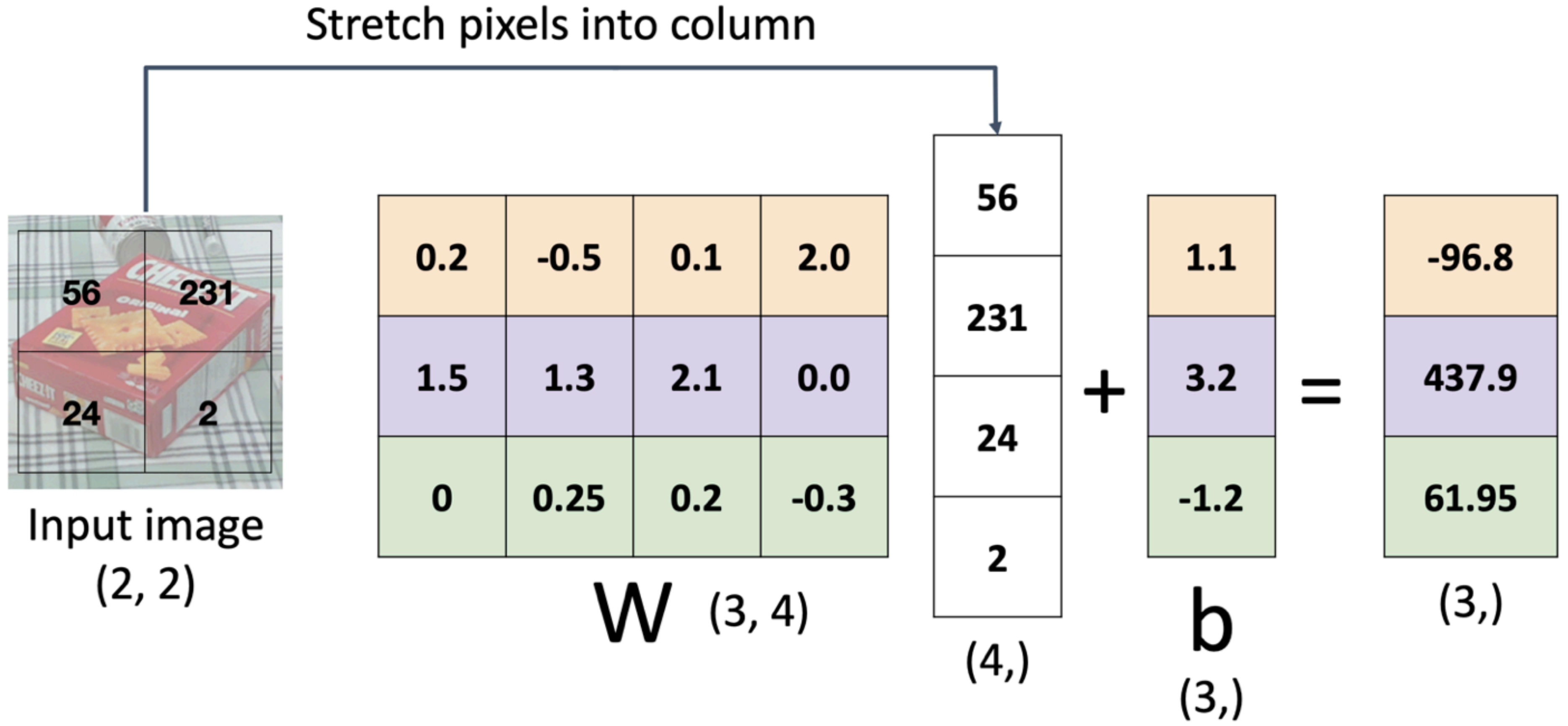


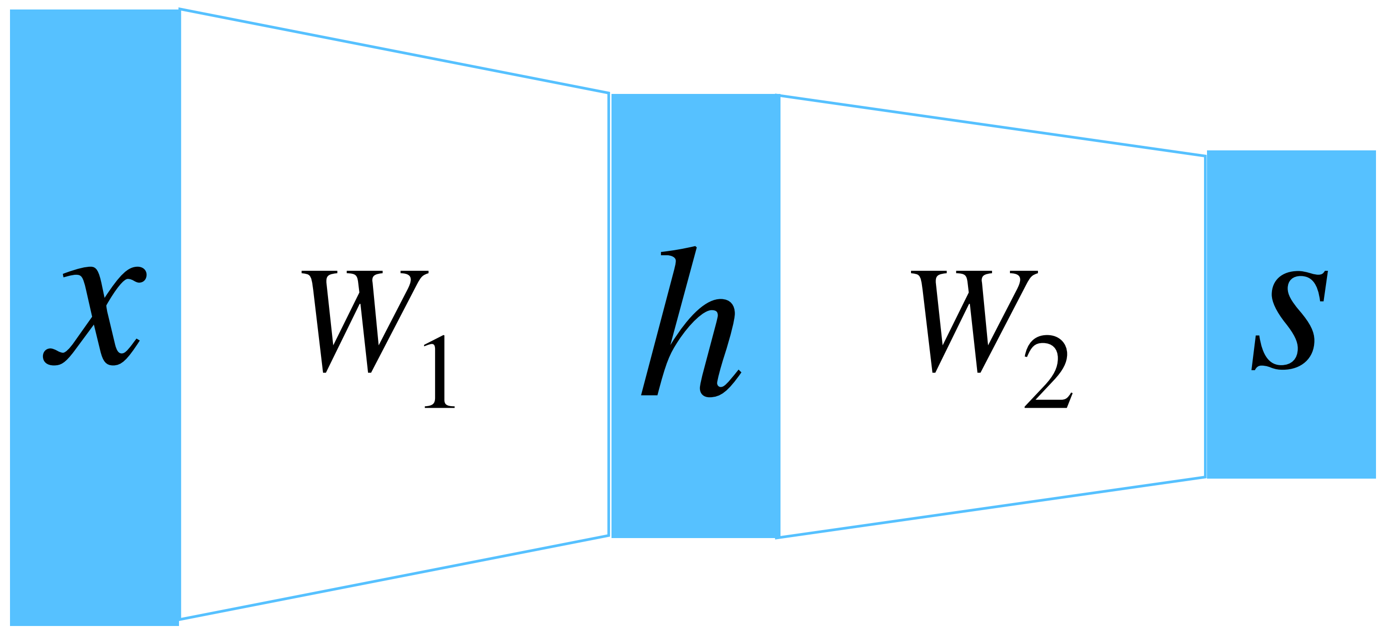
Problem: So far our classifiers don't respect the spatial structure of images!

Solution: Define new computational nodes that operate on images!

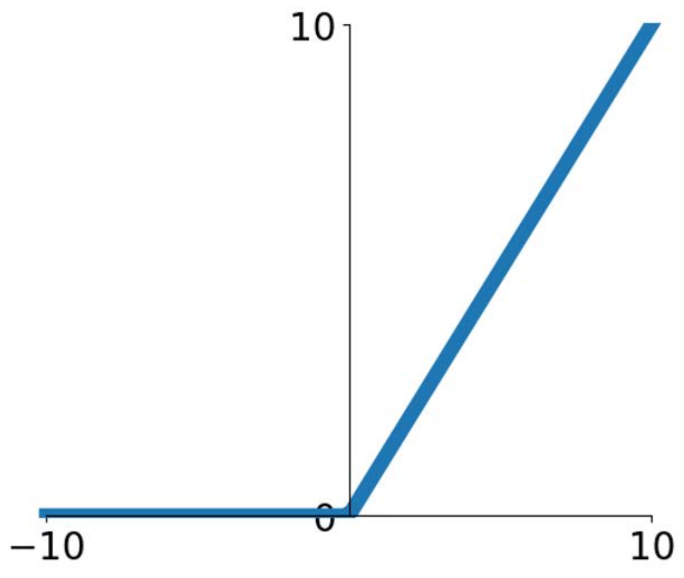


Components of Fully-Connected Networks

Fully-Connected Layers

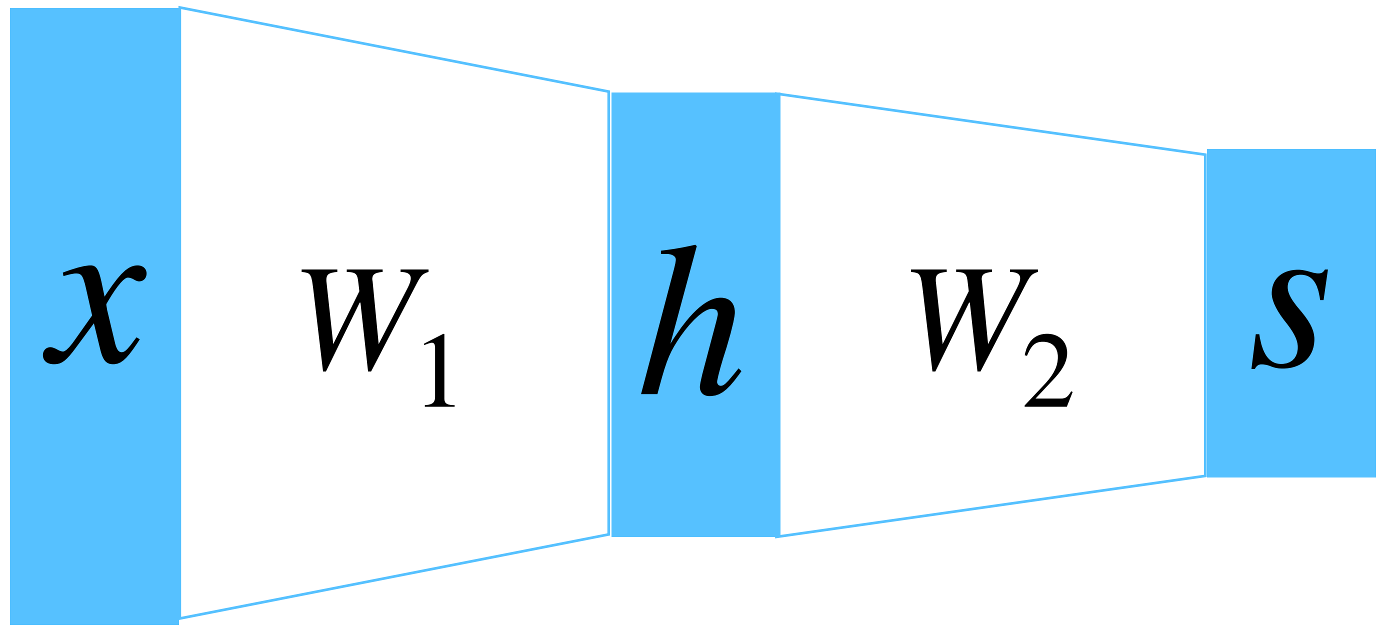


Activation Functions

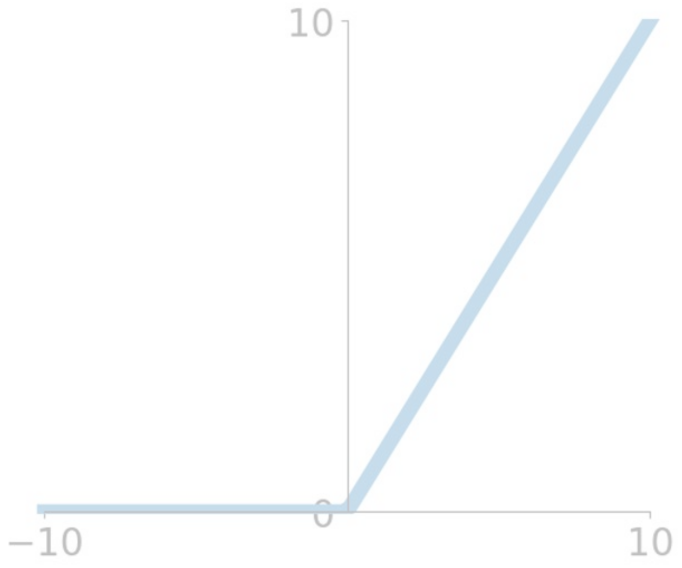


Components of Convolutional Neural Networks

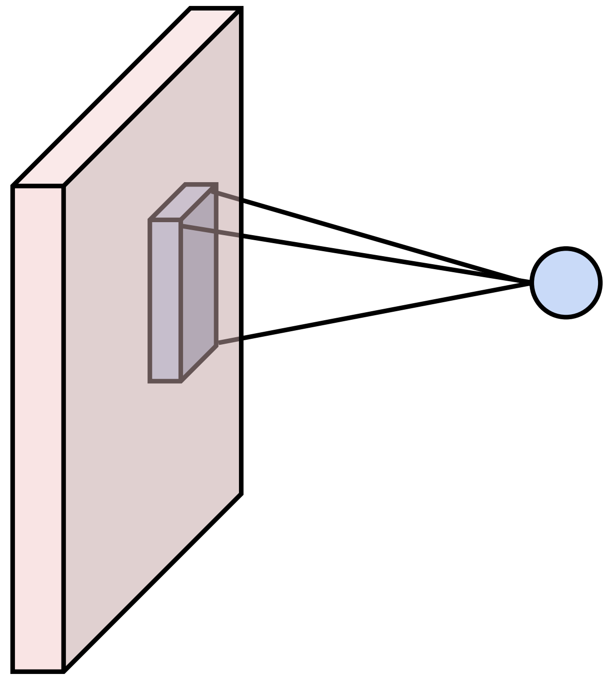
Fully-Connected Layers



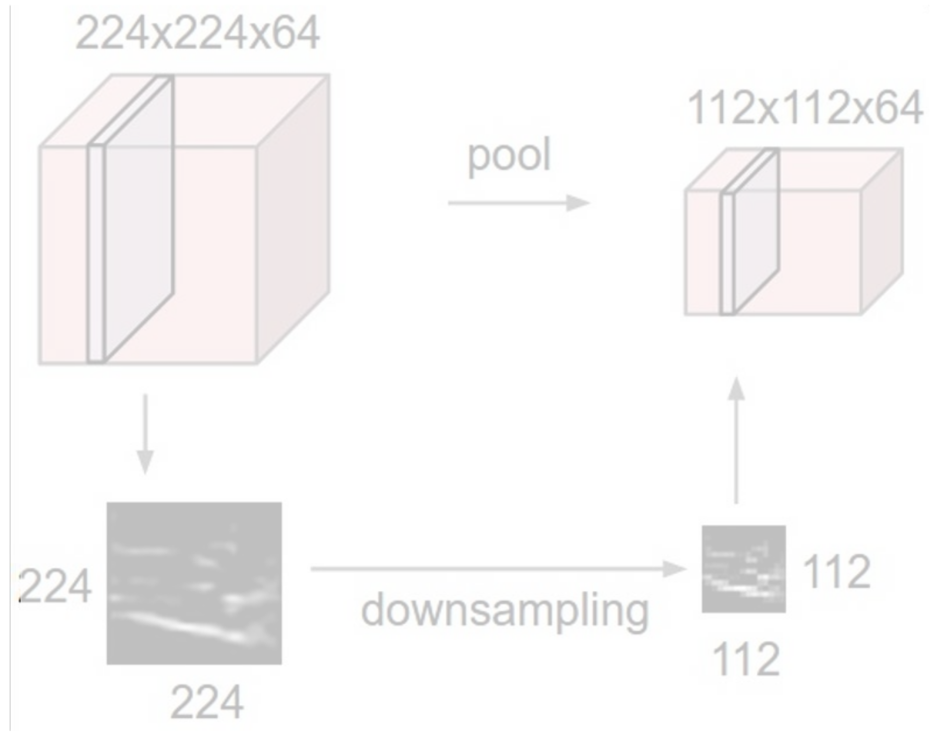
Activation Functions



Convolution Layers



Pooling Layers

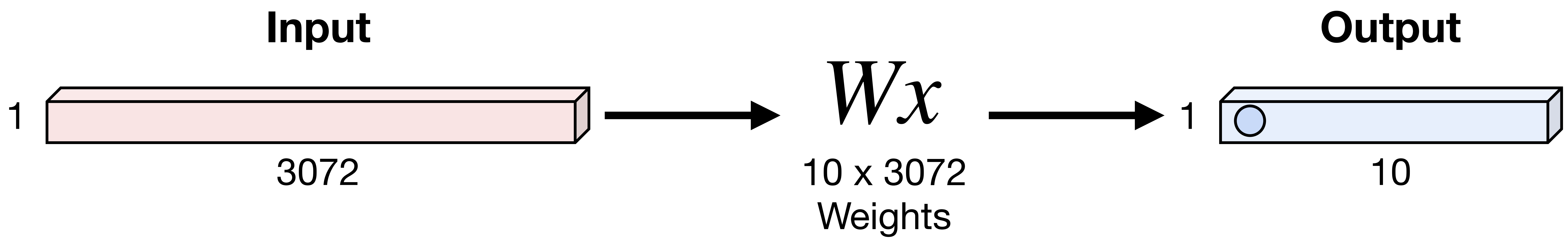


Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Fully-Connected Layer

3x32x32 image → stretch to 3072x1



Fully-Connected Layer

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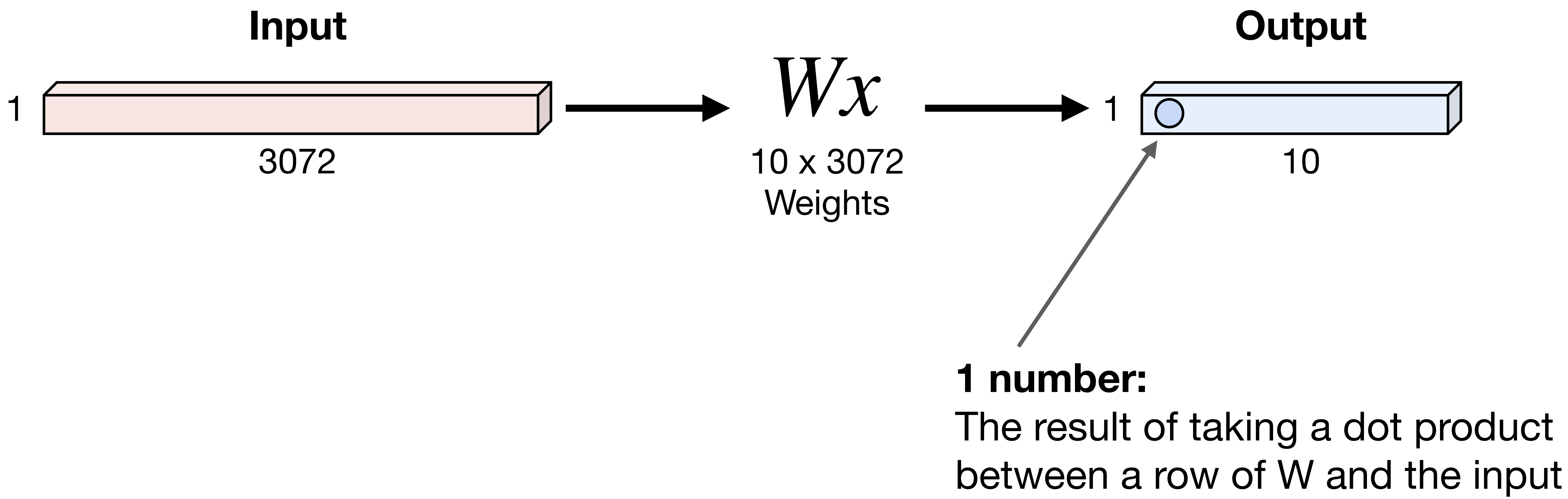
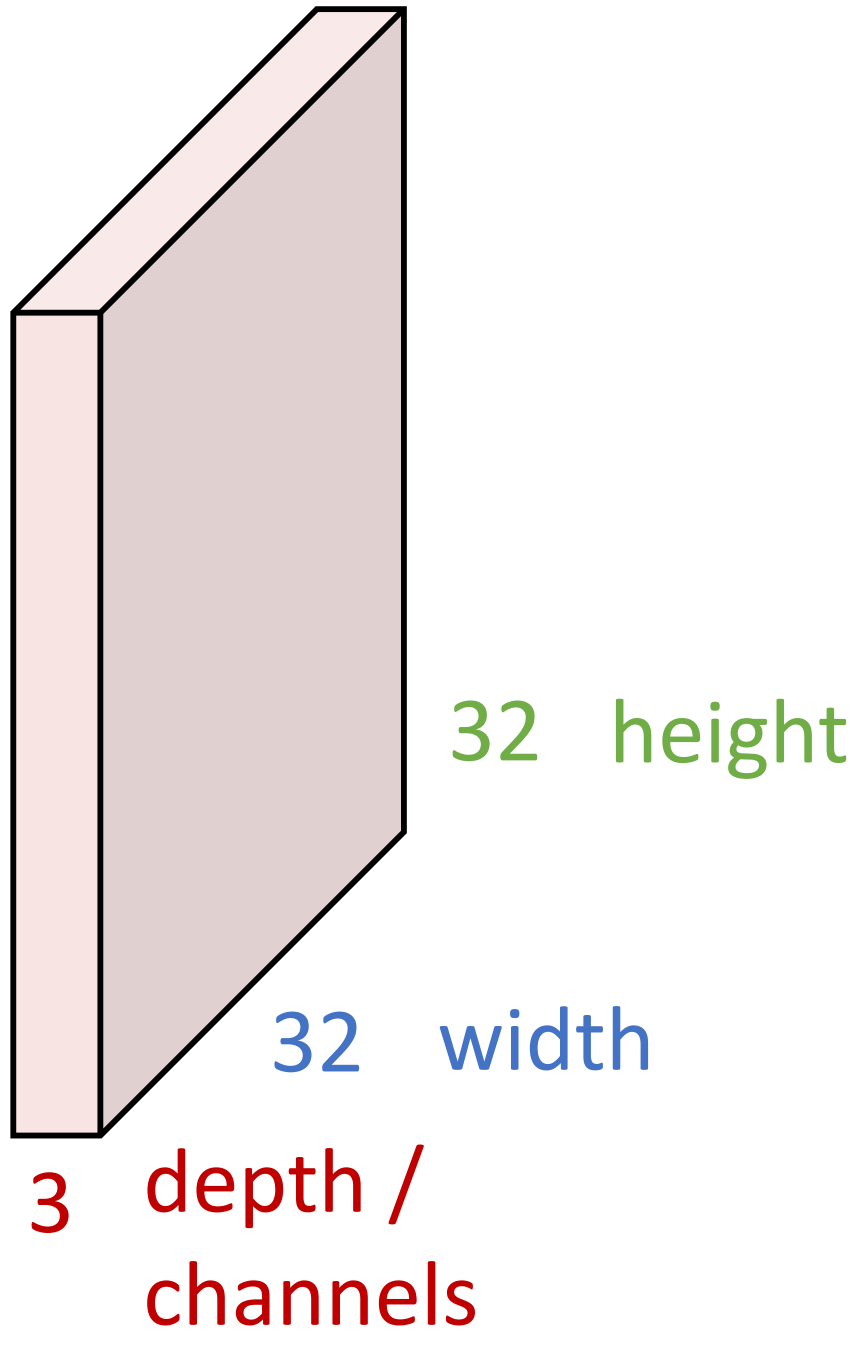
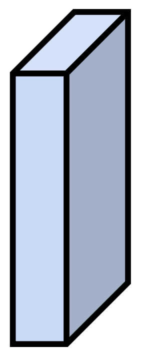


Convolution Layer

3x32x32 image: preserve spatial structure

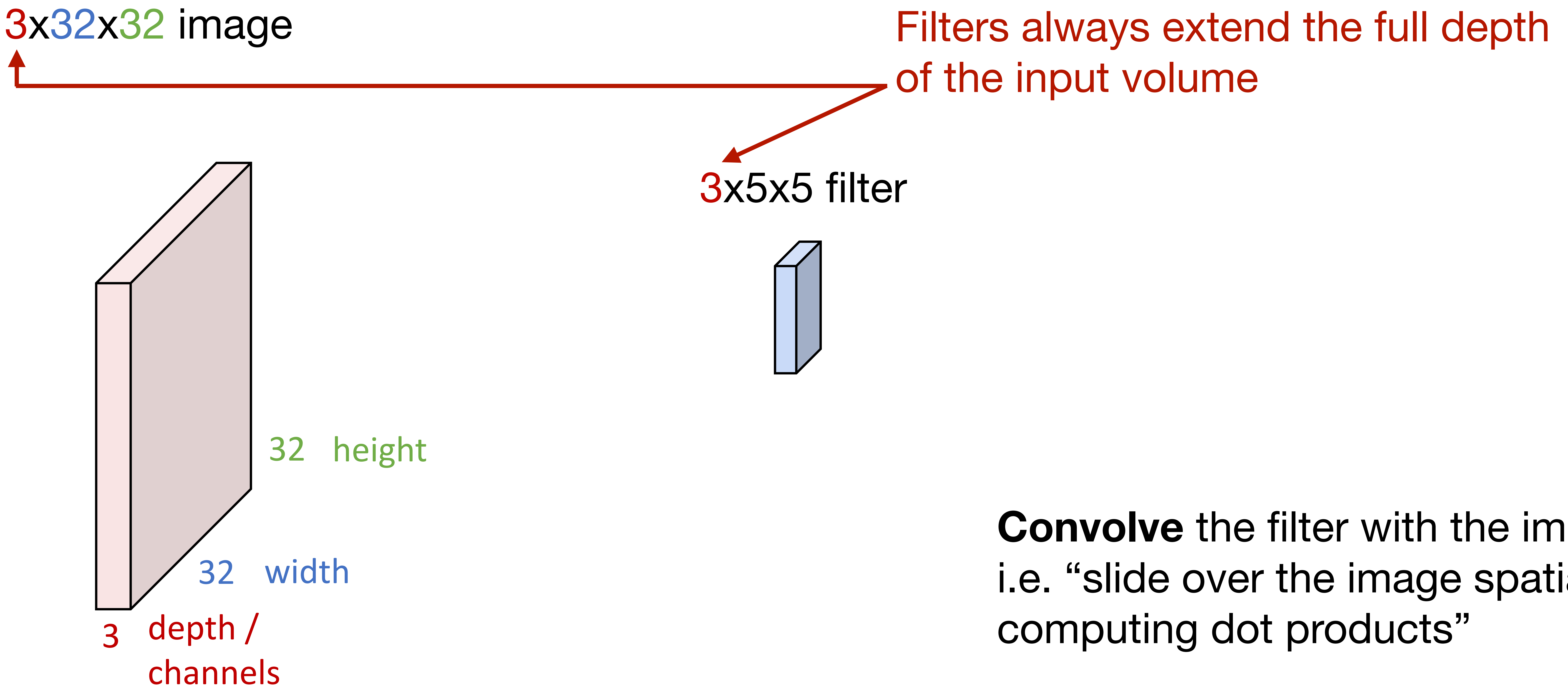


3x5x5 filter



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

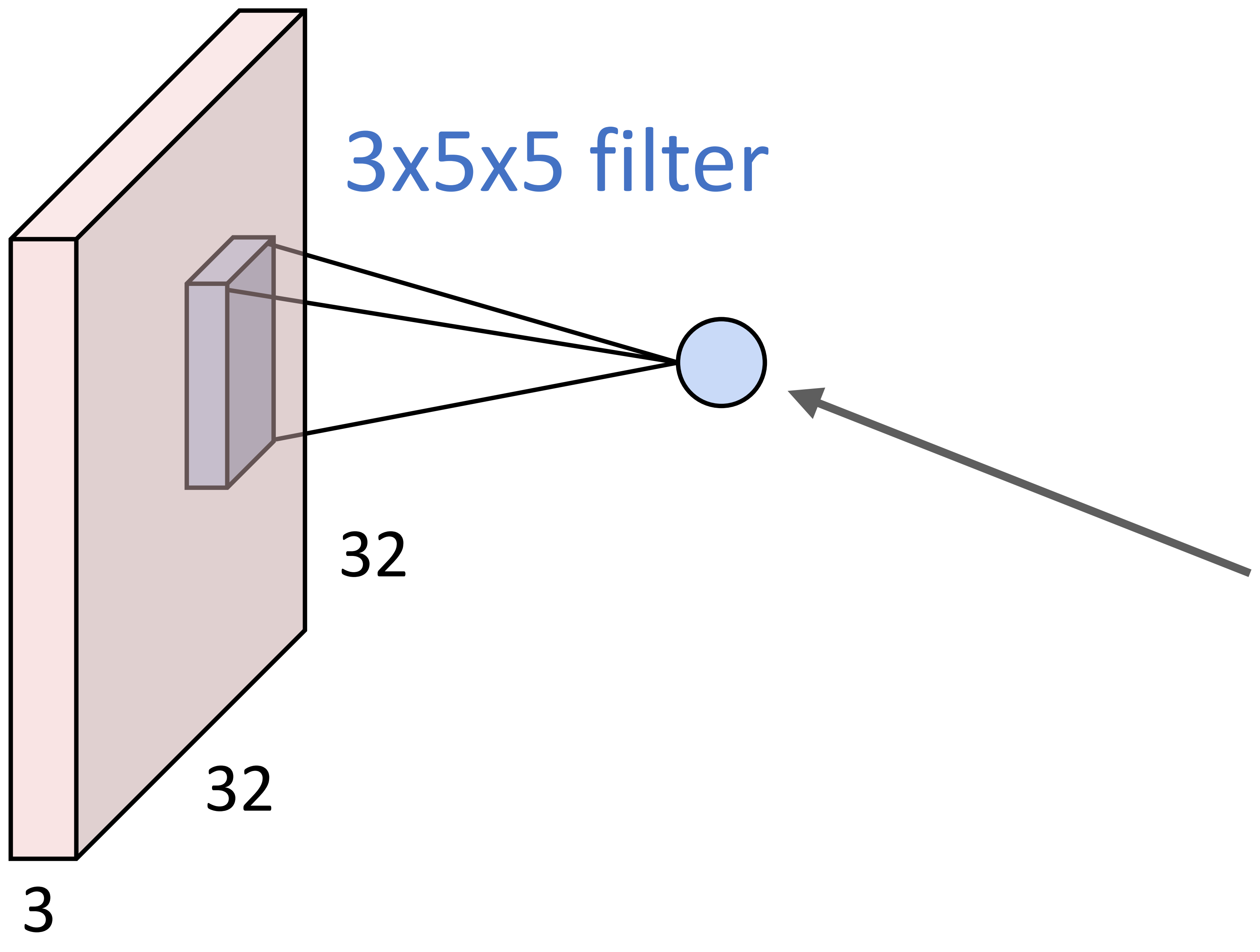
Convolution Layer



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

Convolution Layer

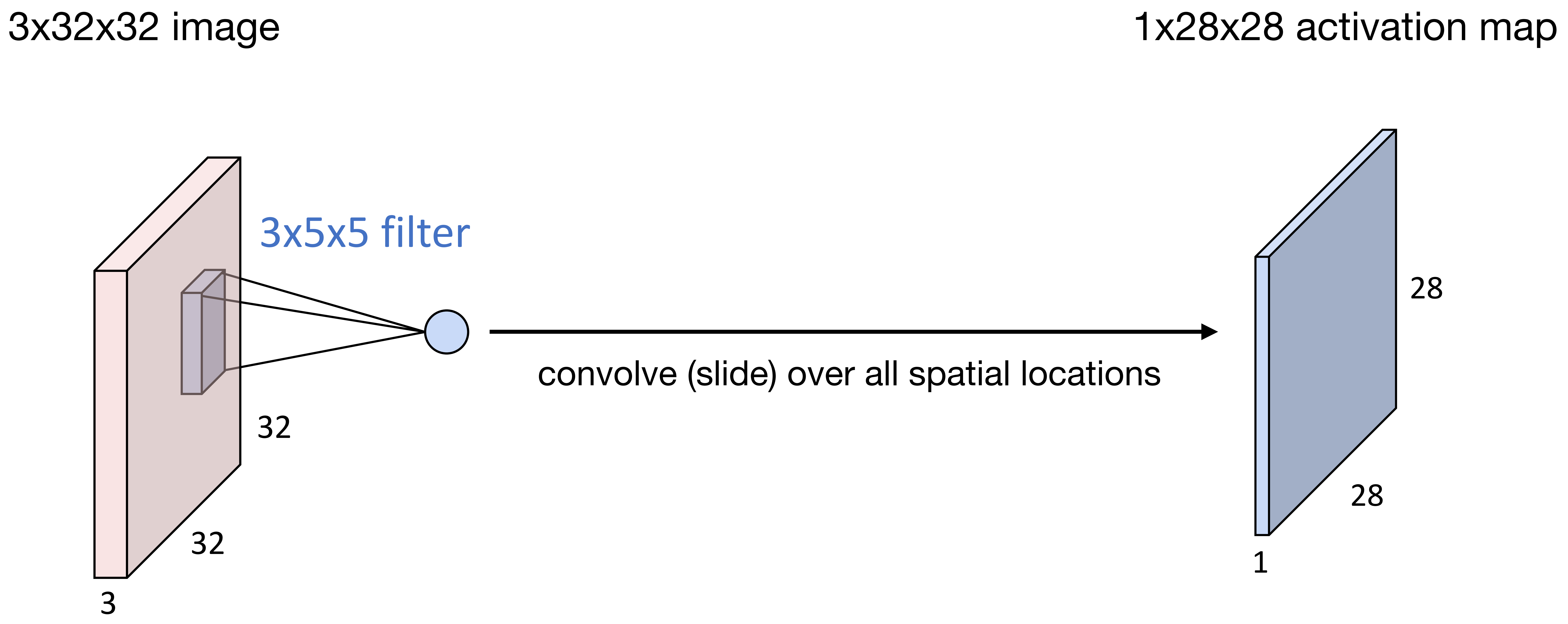
3x32x32 image



1 number:
The result of taking a dot product between the filter and a small 3x5x5 portion of the image (i.e. 3*5*5=75-dimensional dot product + bias)

$$w^T x + b$$

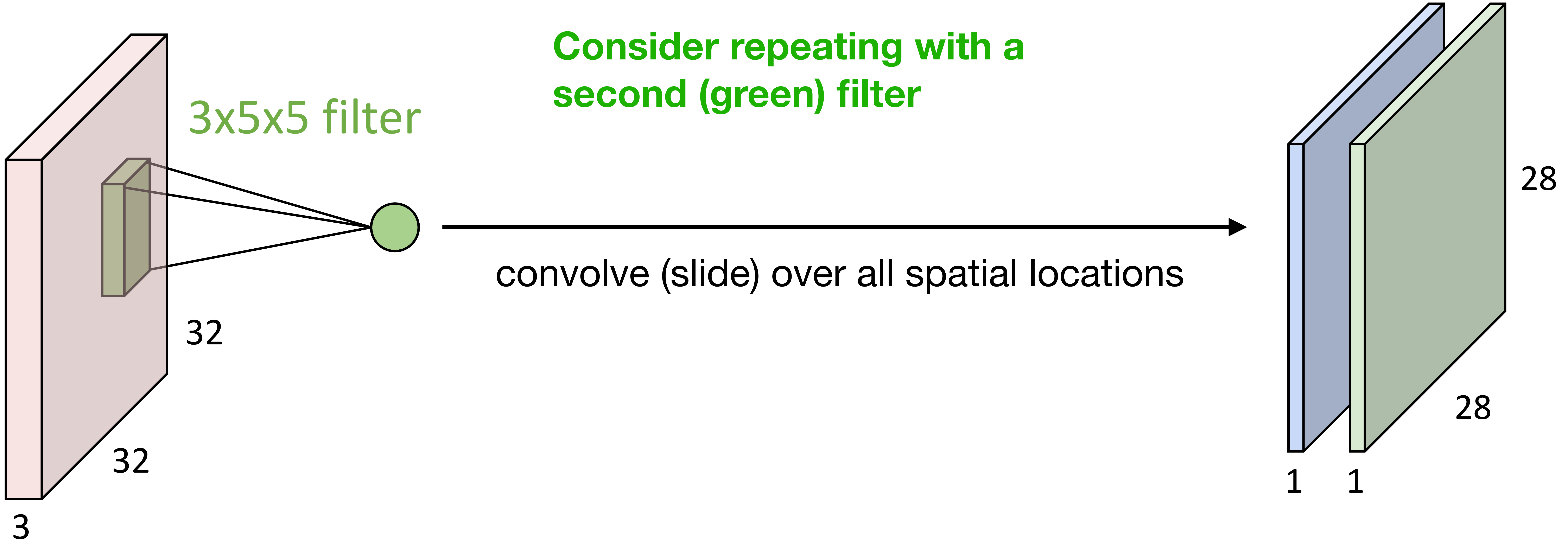
Convolution Layer



Convolution Layer

3x32x32 image

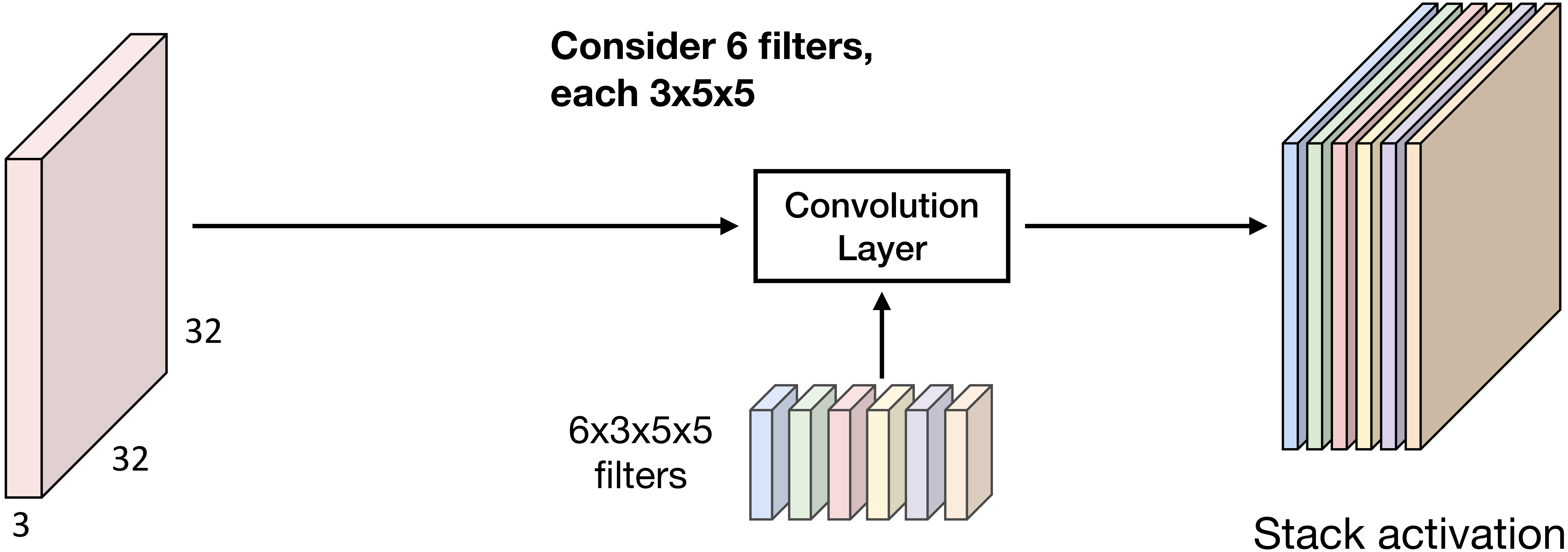
two 1x28x28 activation map



Convolution Layer

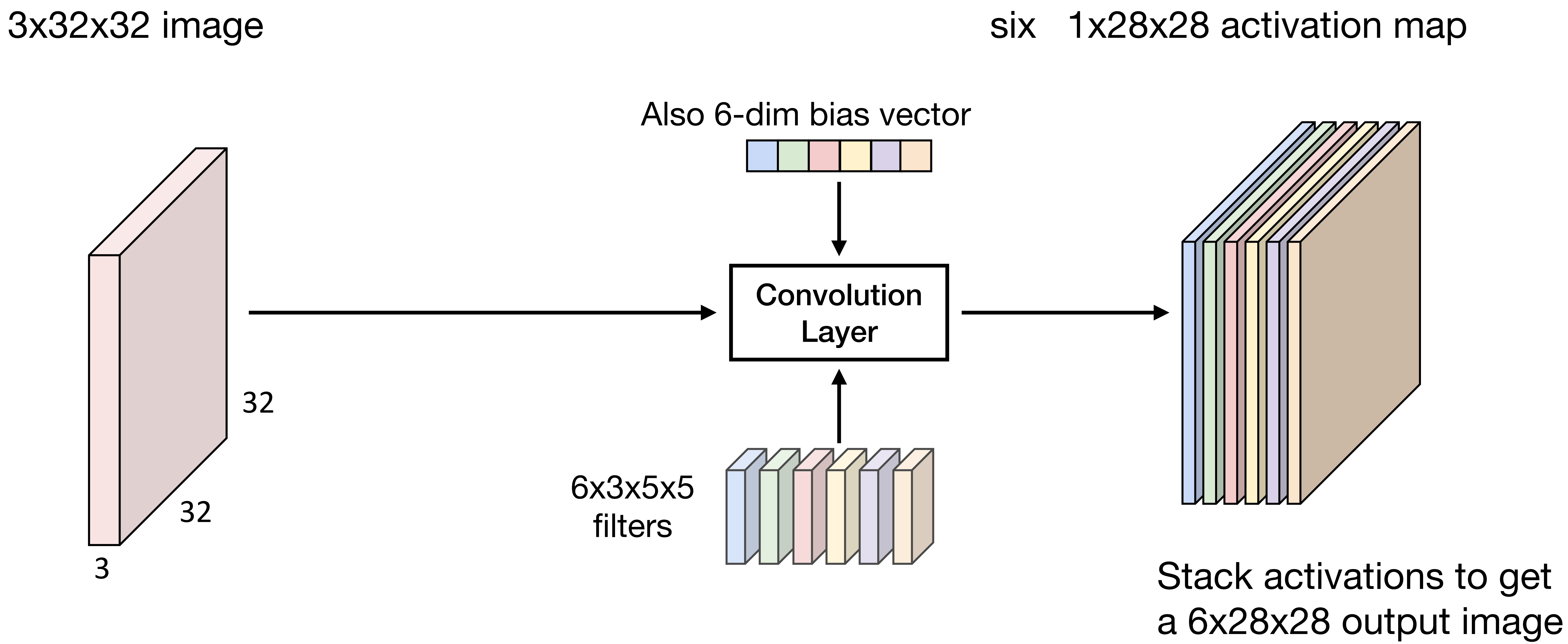
3x32x32 image

six 1x28x28 activation map



Stack activations to get a 6x28x28 output image

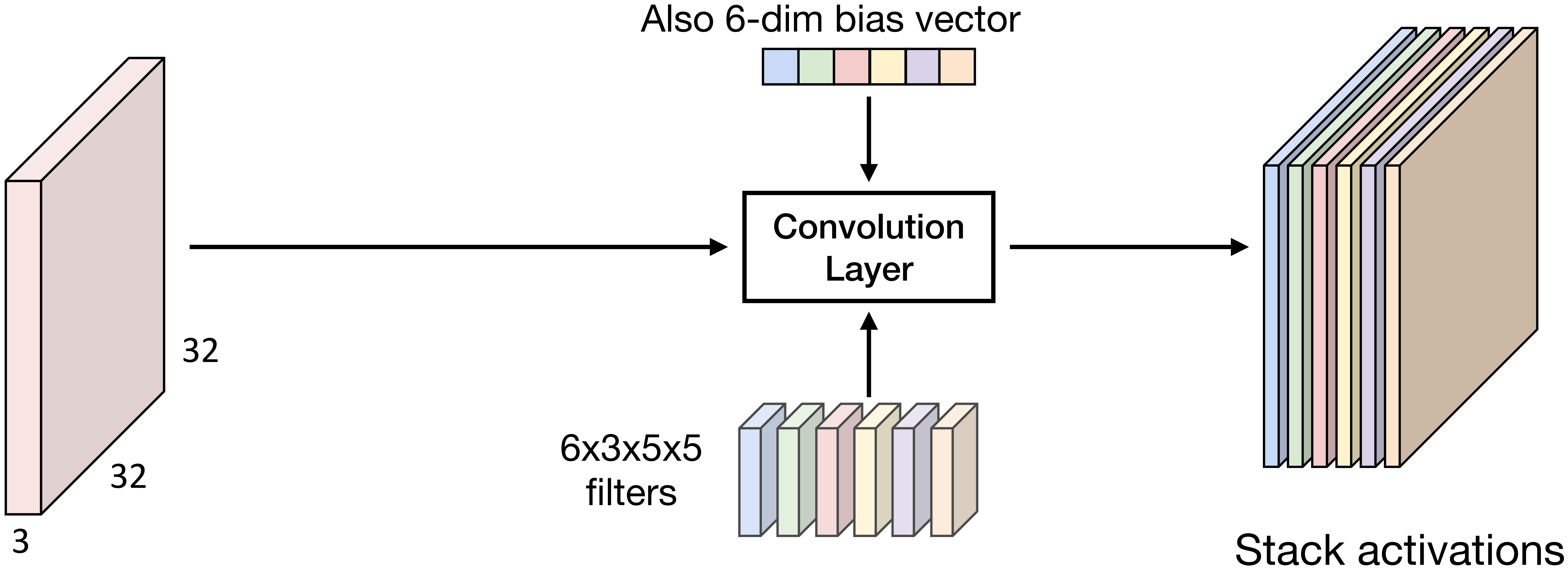
Convolution Layer



Convolution Layer

3x32x32 image

28x28 grid, at each point a 6-dim vector



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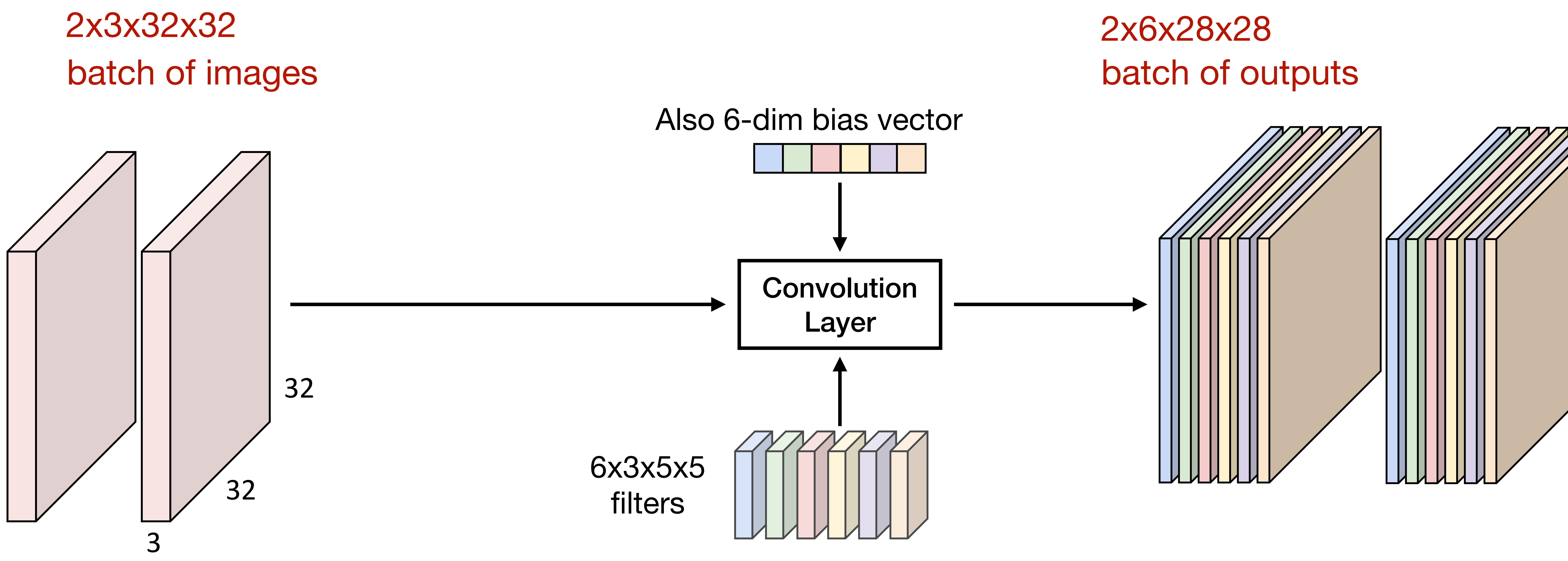
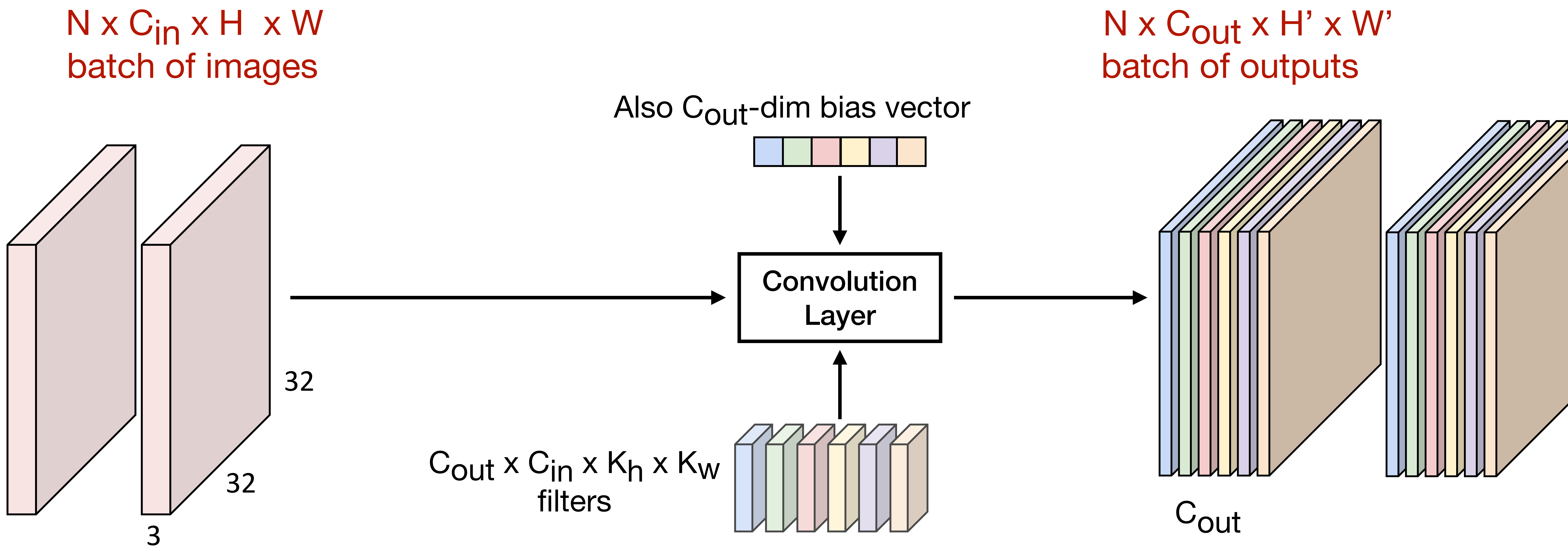
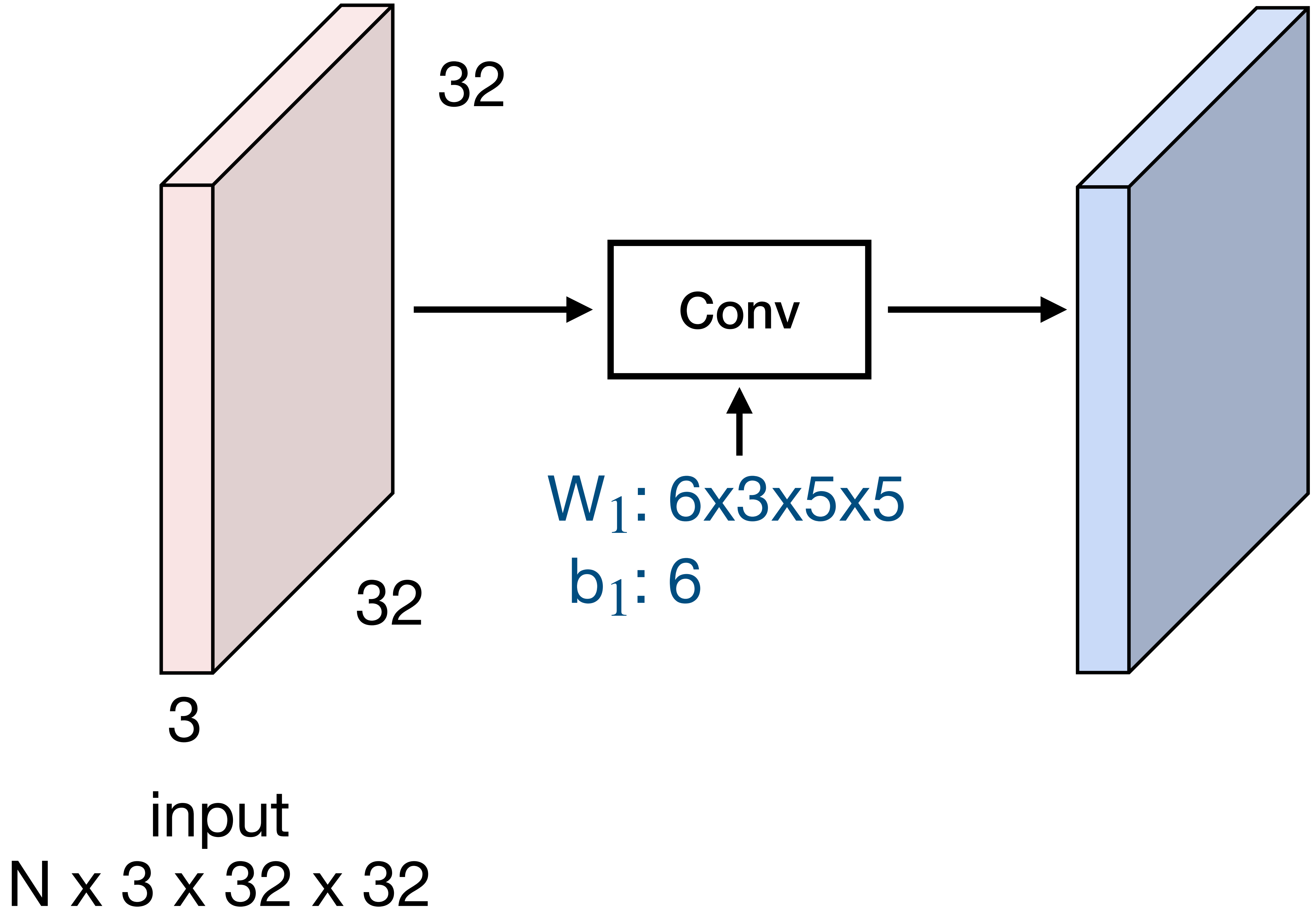


Convolution Layer



Stacking Convolutions



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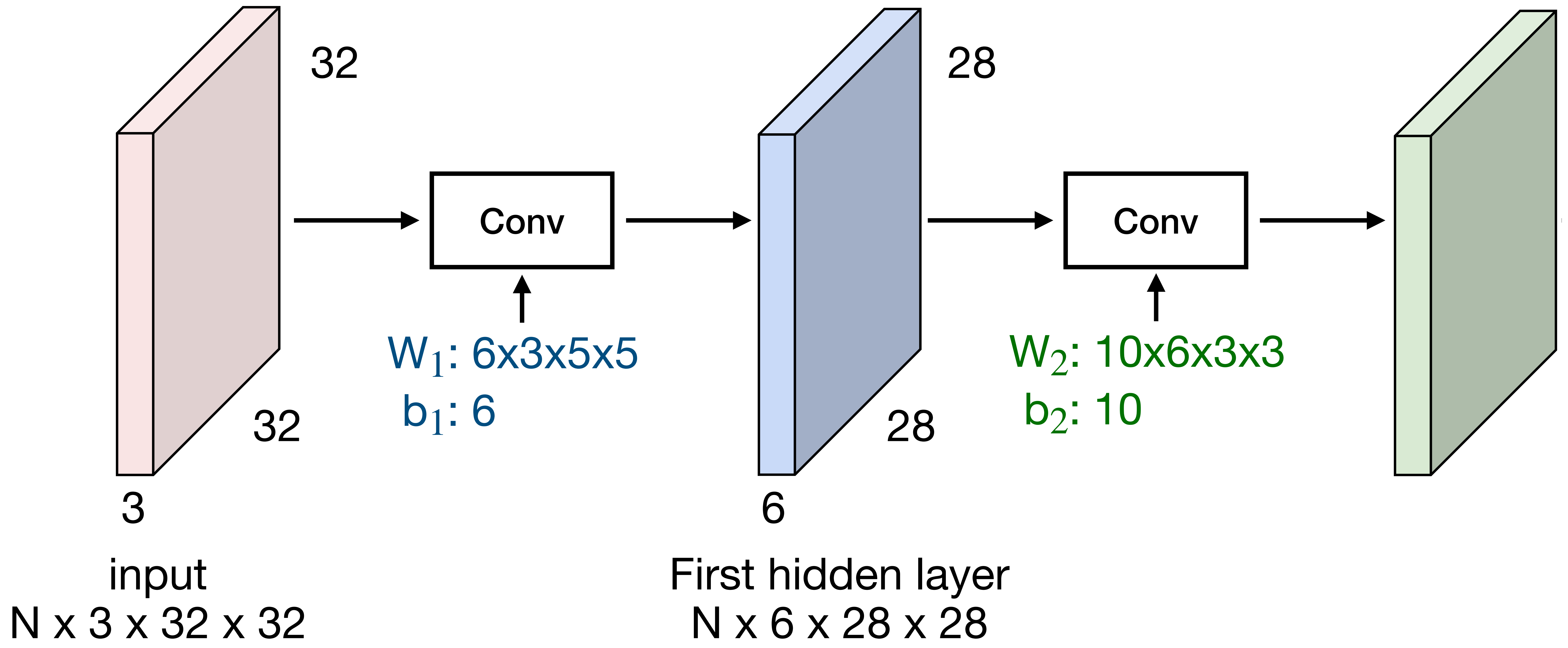

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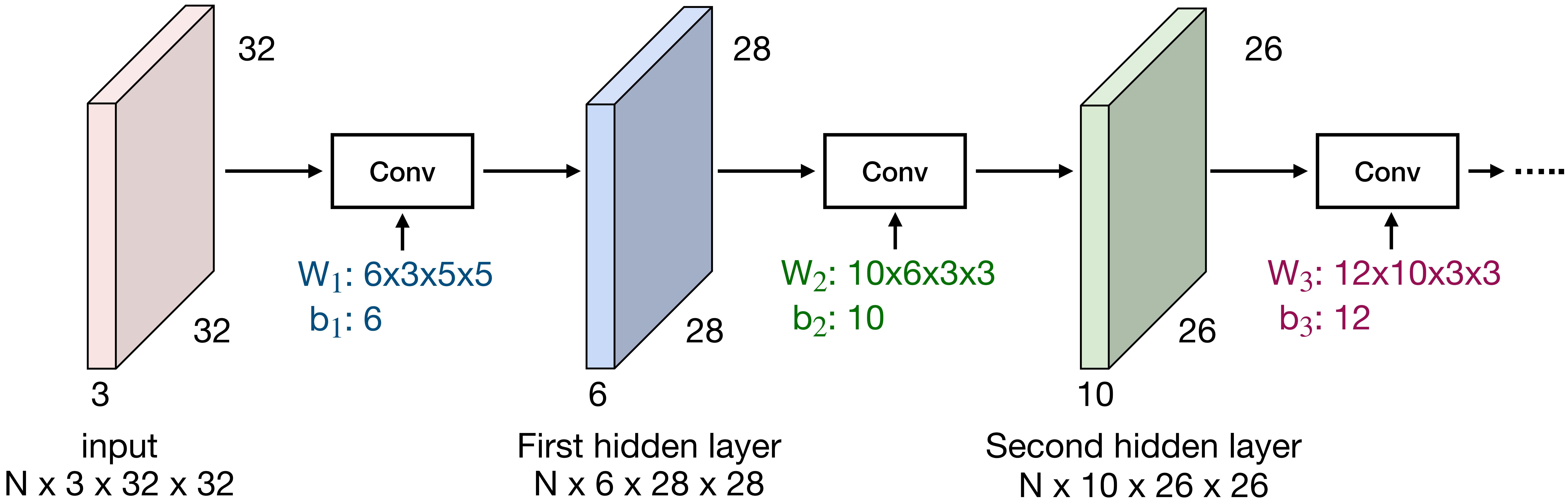
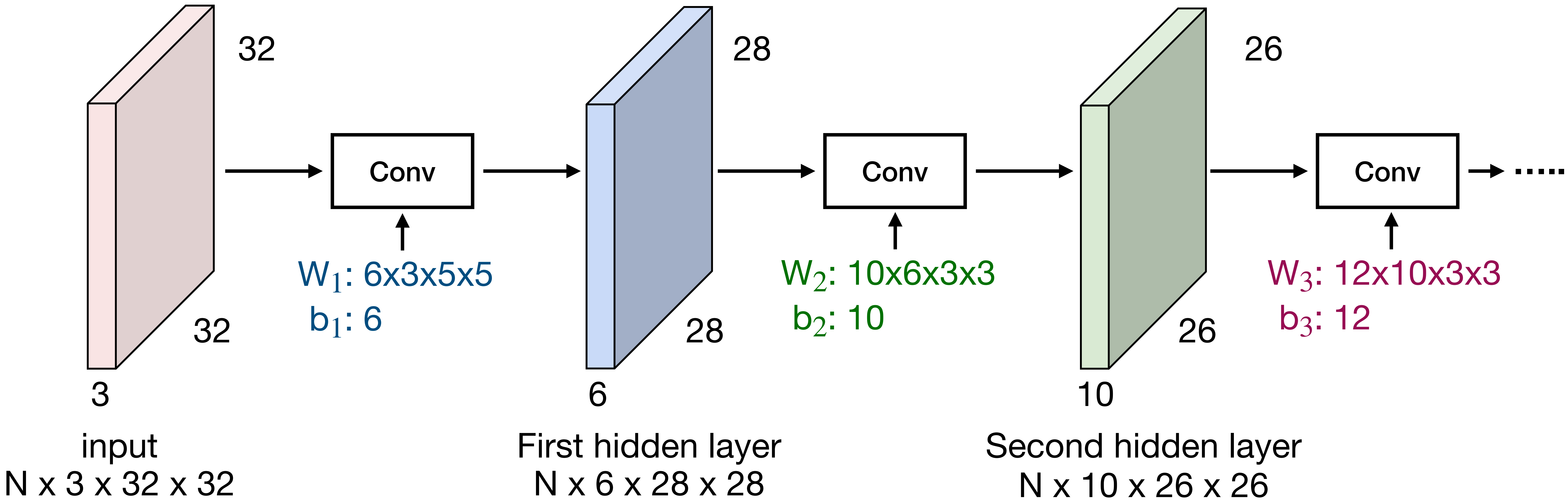


Stacking Convolutions

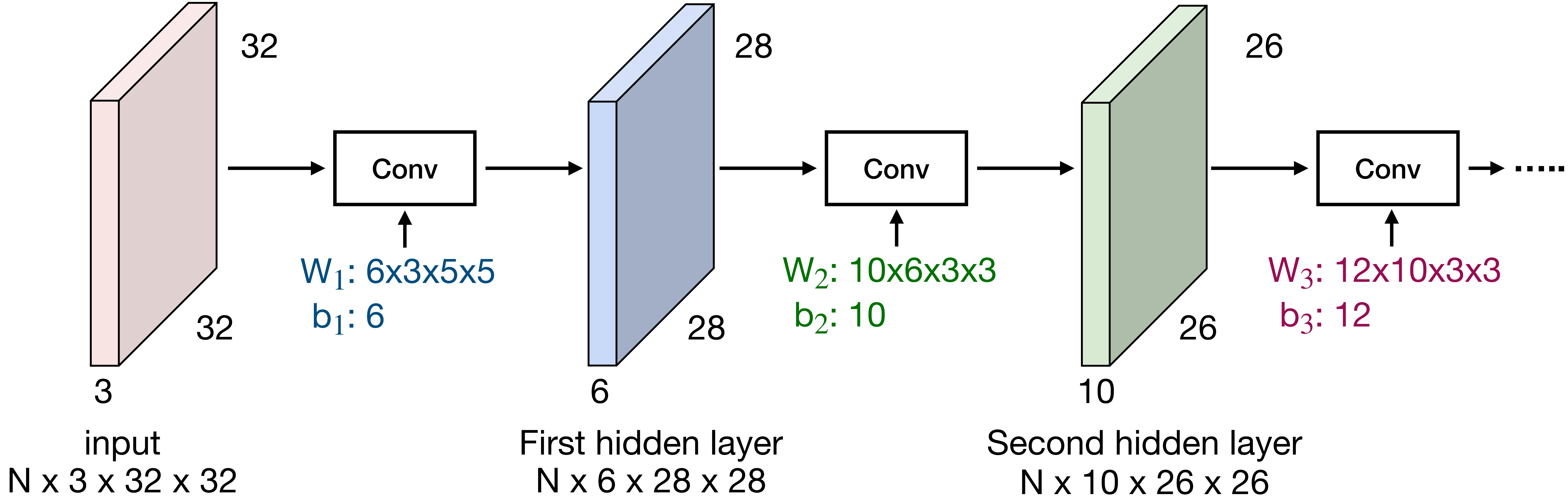
Q: What happens if we stack two convolution layers?



Stacking Convolutions

Q: What happens if we stack two convolution layers?

(Recall $y=W_2W_1x$ is a linear classifier)

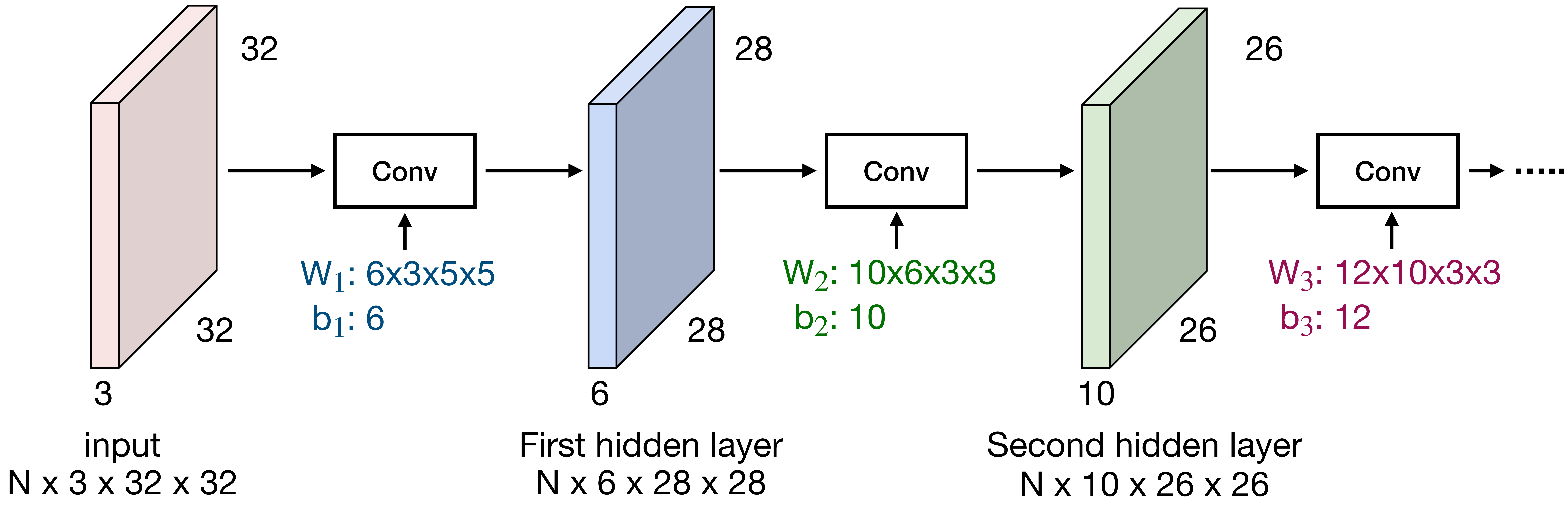


Stacking Convolutions

Q: What happens if we stack two convolution layers?

(Recall $y=W_2W_1x$ is a linear classifier)

A: We get another convolution!



Stacking Convolutions

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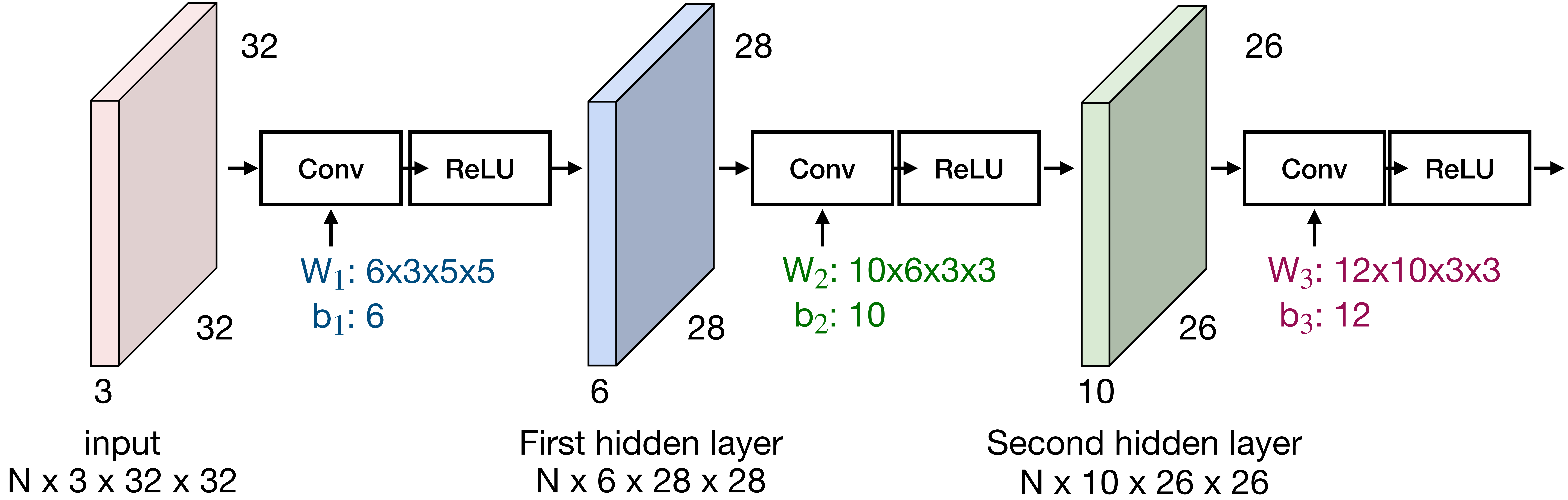
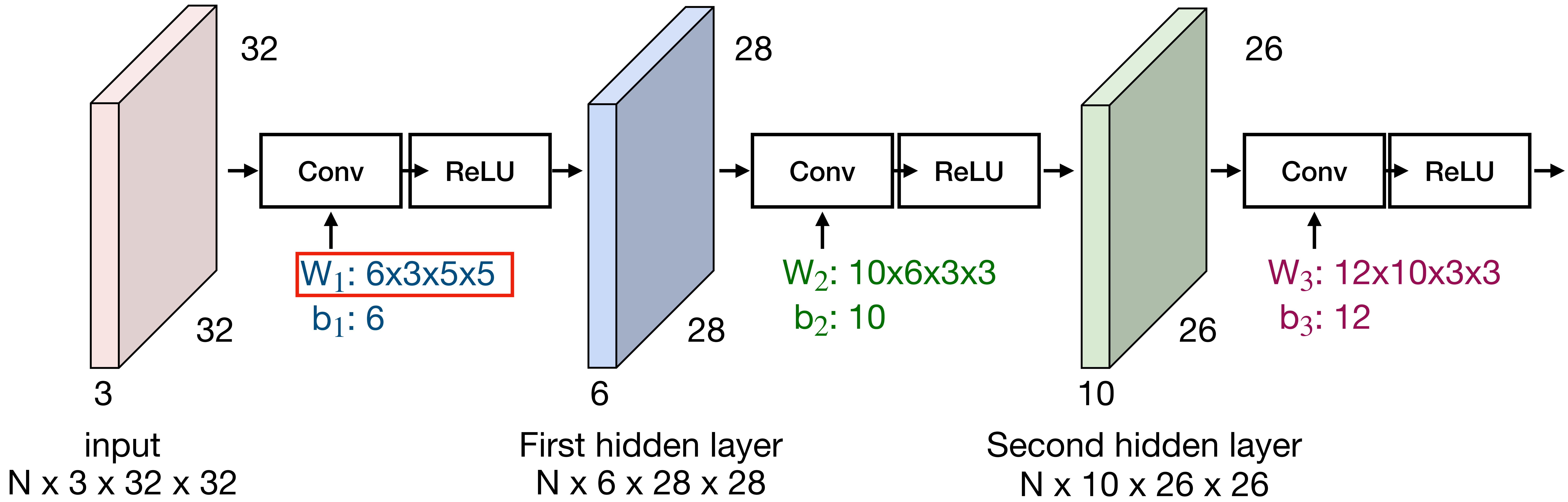
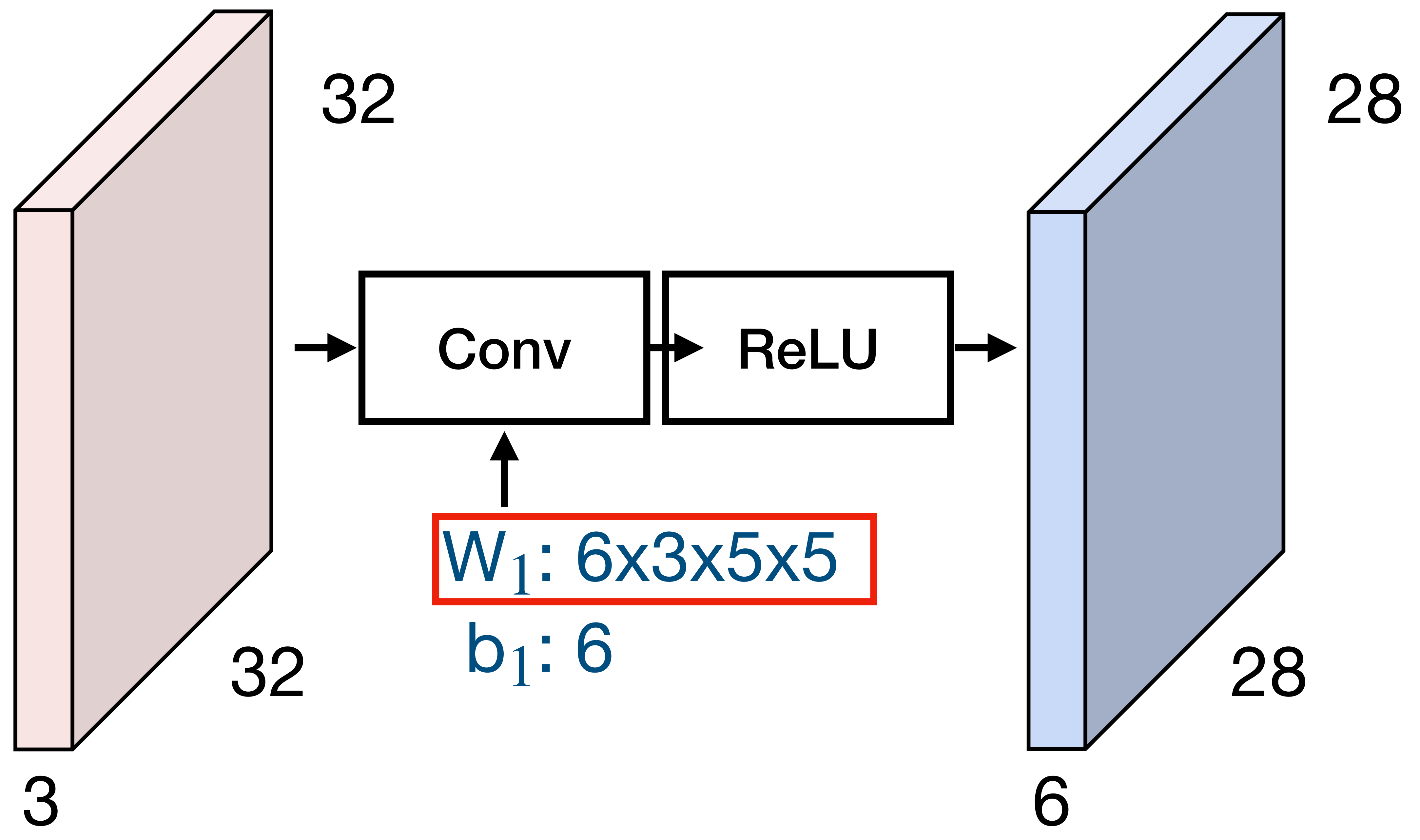


What do convolutional filters learn?



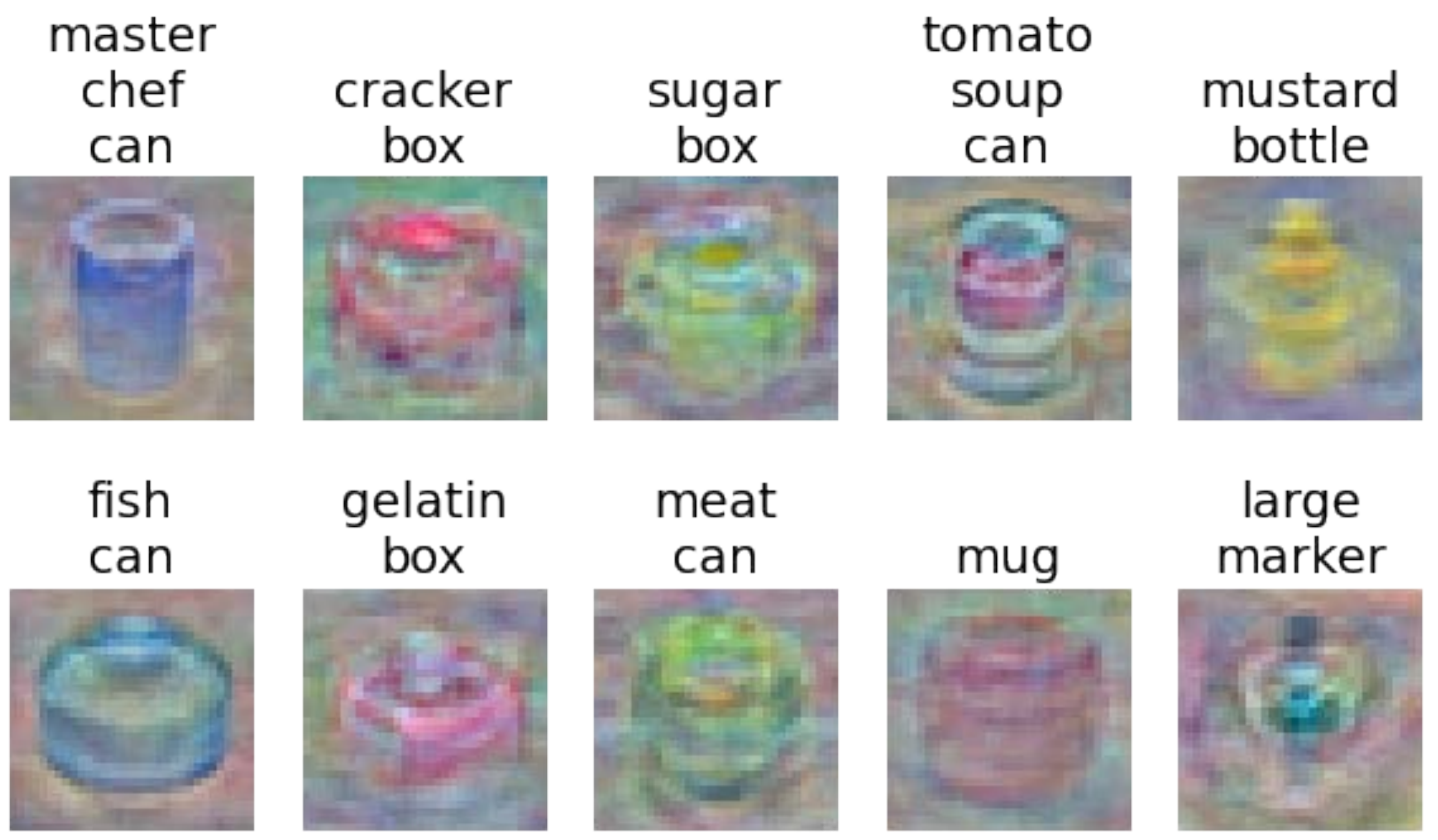
What do convolutional filters learn?



input
N x 3 x 32 x 32

First hidden layer
N x 6 x 28 x 28

Linear classifier: One template per class



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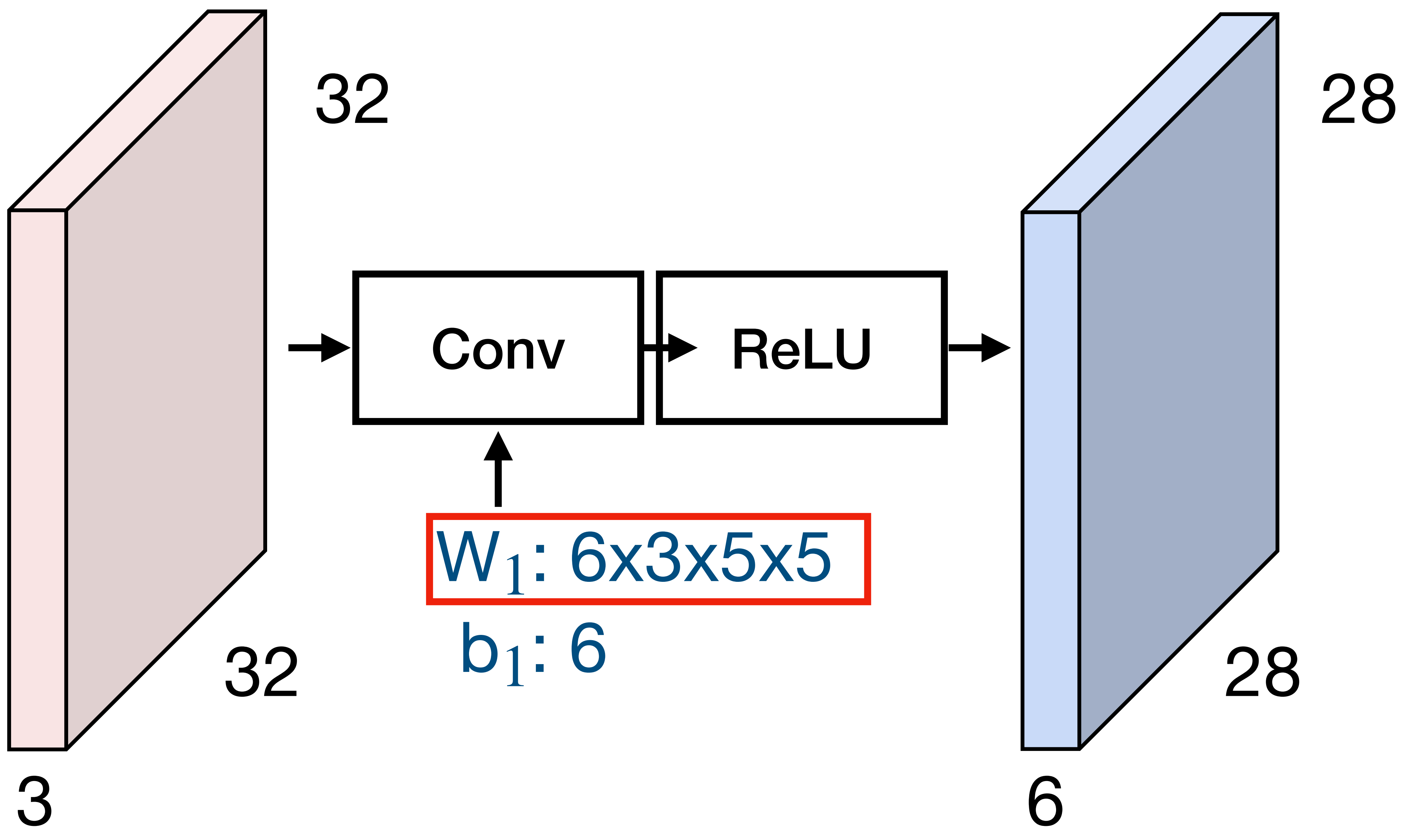
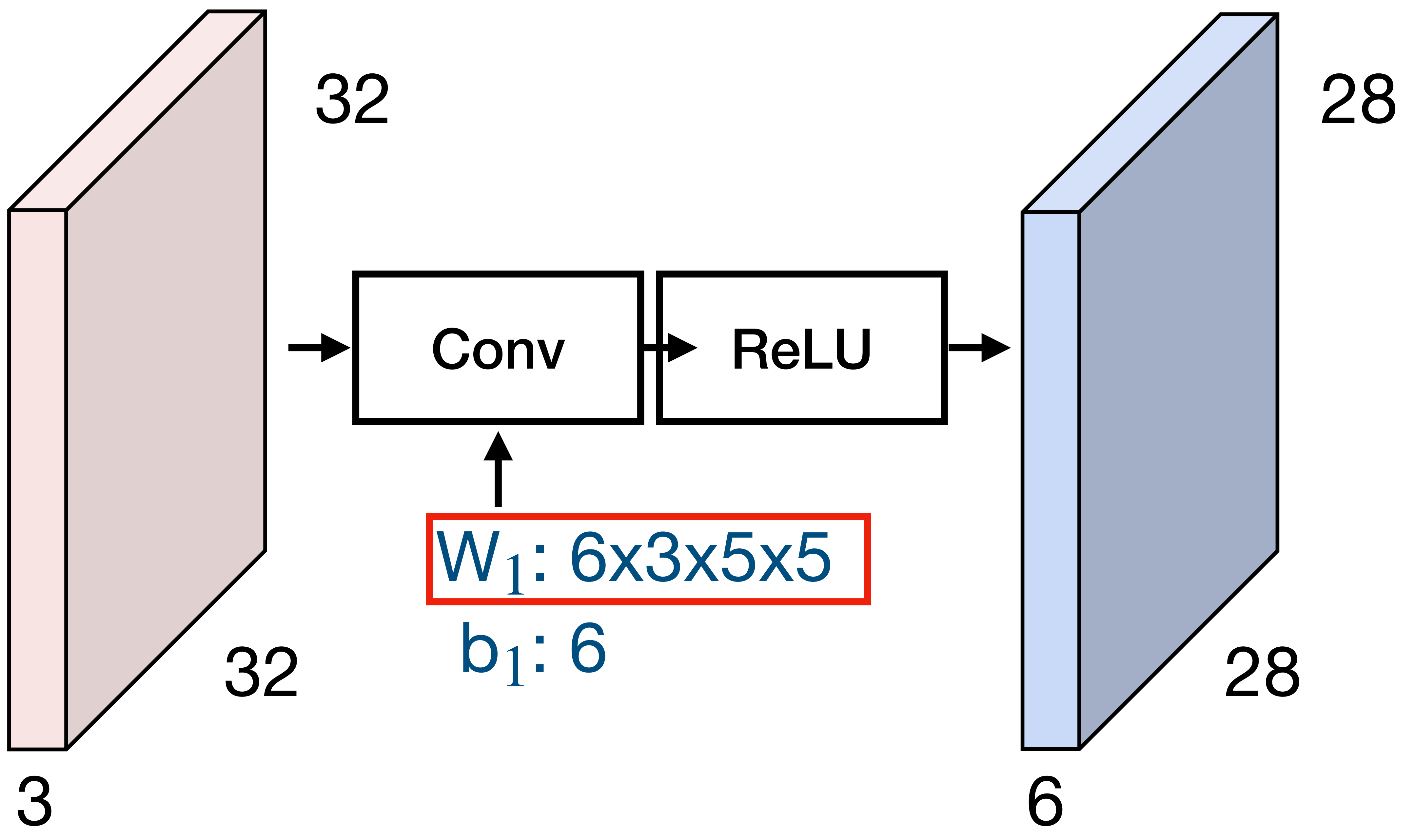


input
N x 3 x 32 x 32

First hidden layer
N x 6 x 28 x 28

MLP: Bank of whole-image templates

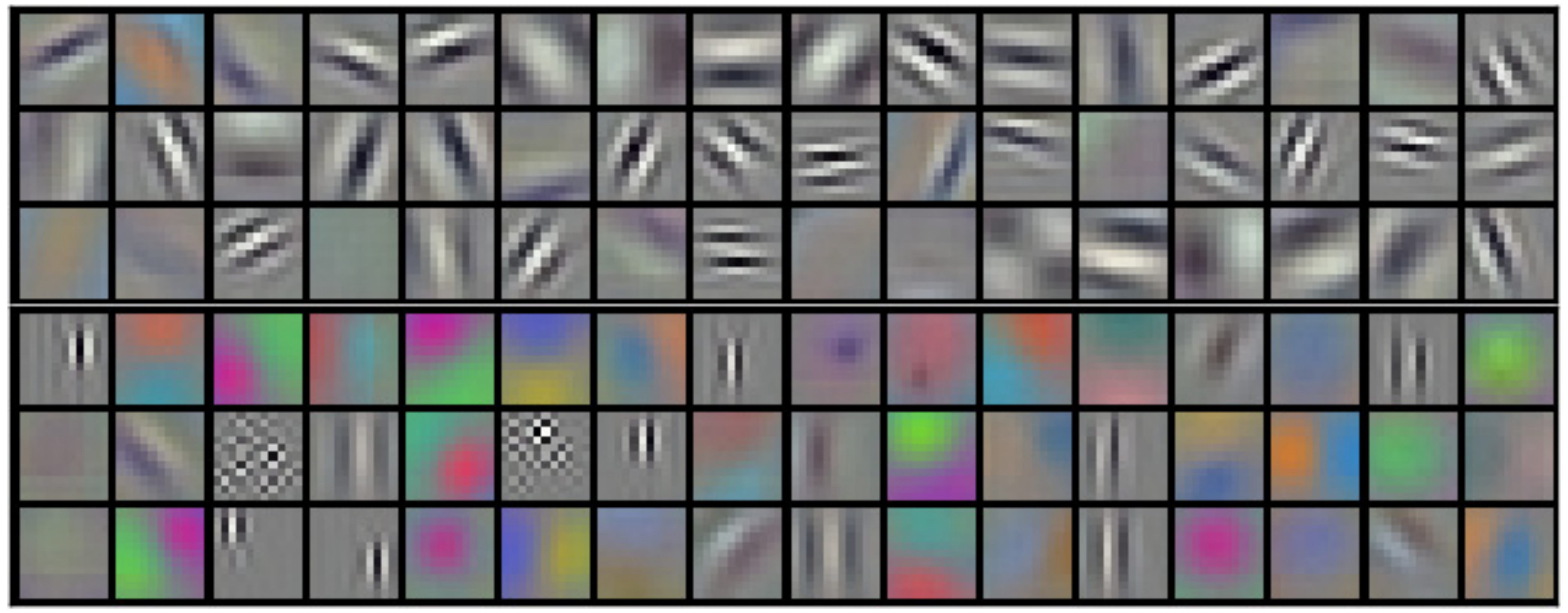
What do convolutional filters learn?



input
N x 3 x 32 x 32

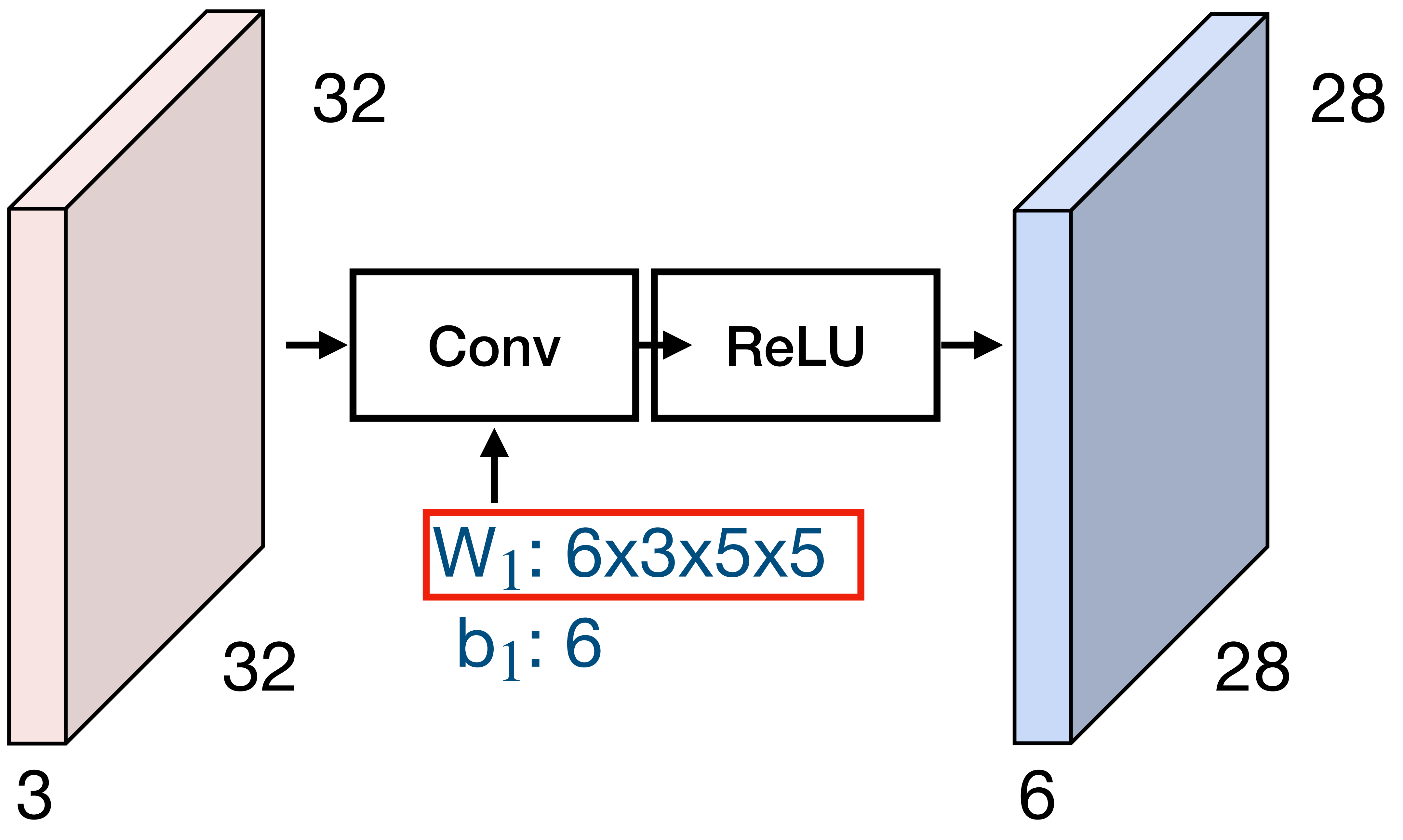
First hidden layer
N x 6 x 28 x 28

First-layer conv filters: local image templates (often learns oriented edges, opposing colors)



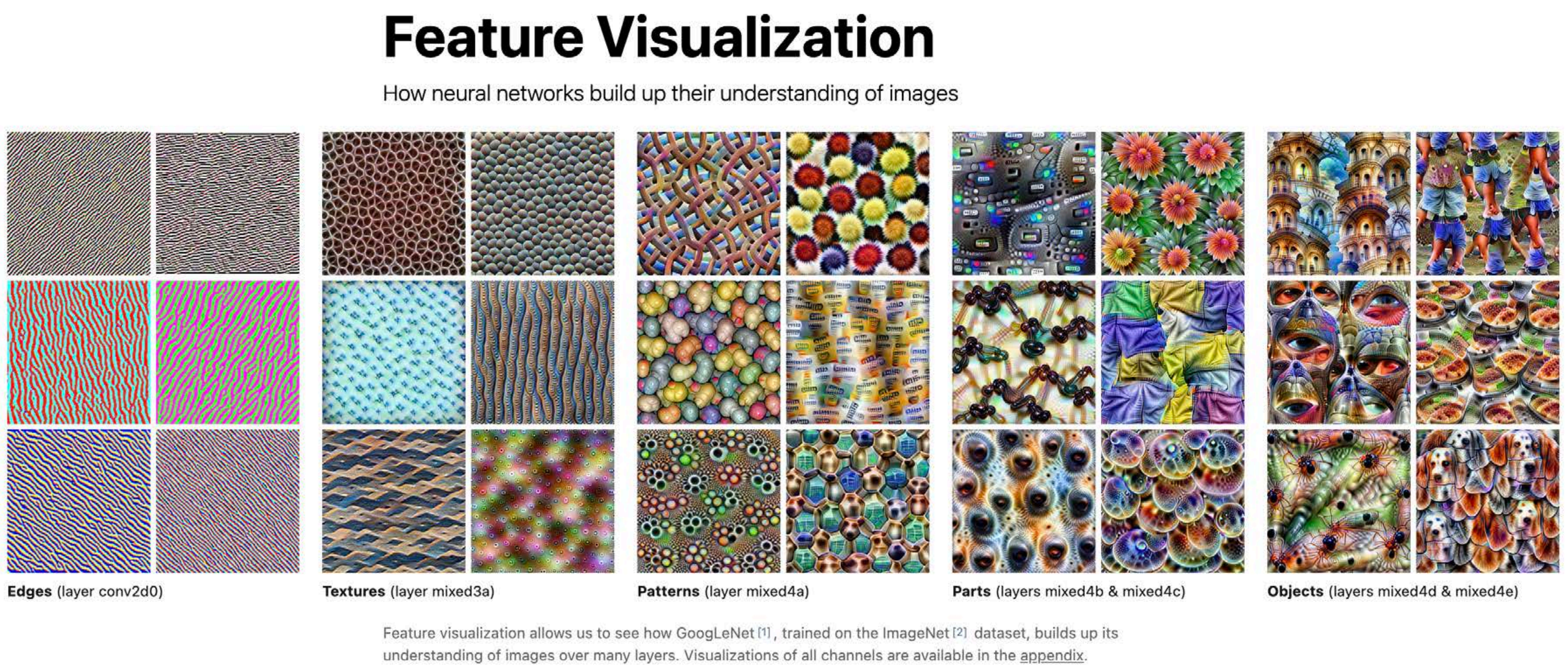
AlexNet: 96 filters, each 3x11x11

What do convolutional filters learn?



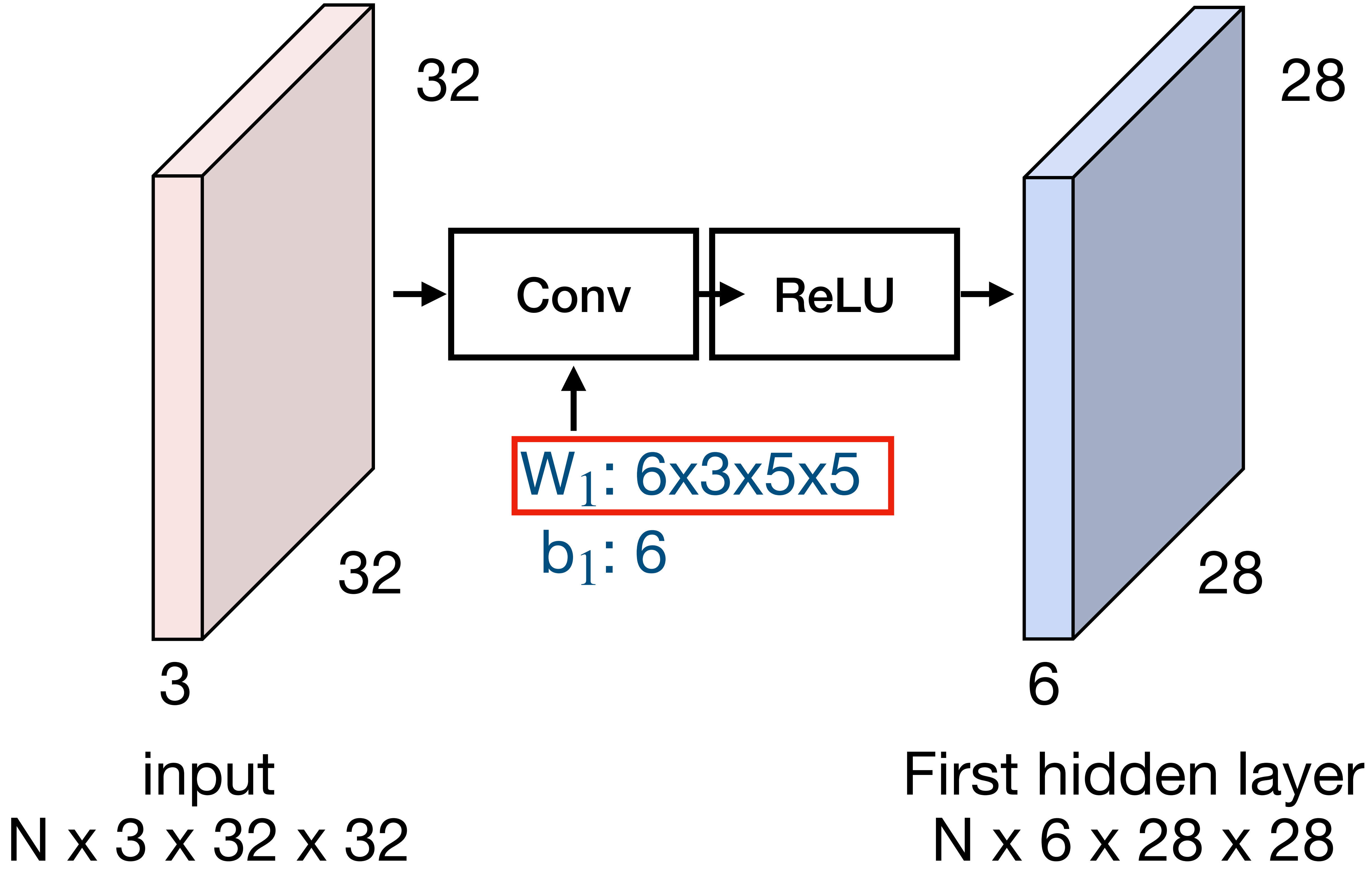
input
N x 3 x 32 x 32

First hidden layer
N x 6 x 28 x 28



Olah, et al., "Feature Visualization", Distill, 2017.

A closer look at spatial dimensions



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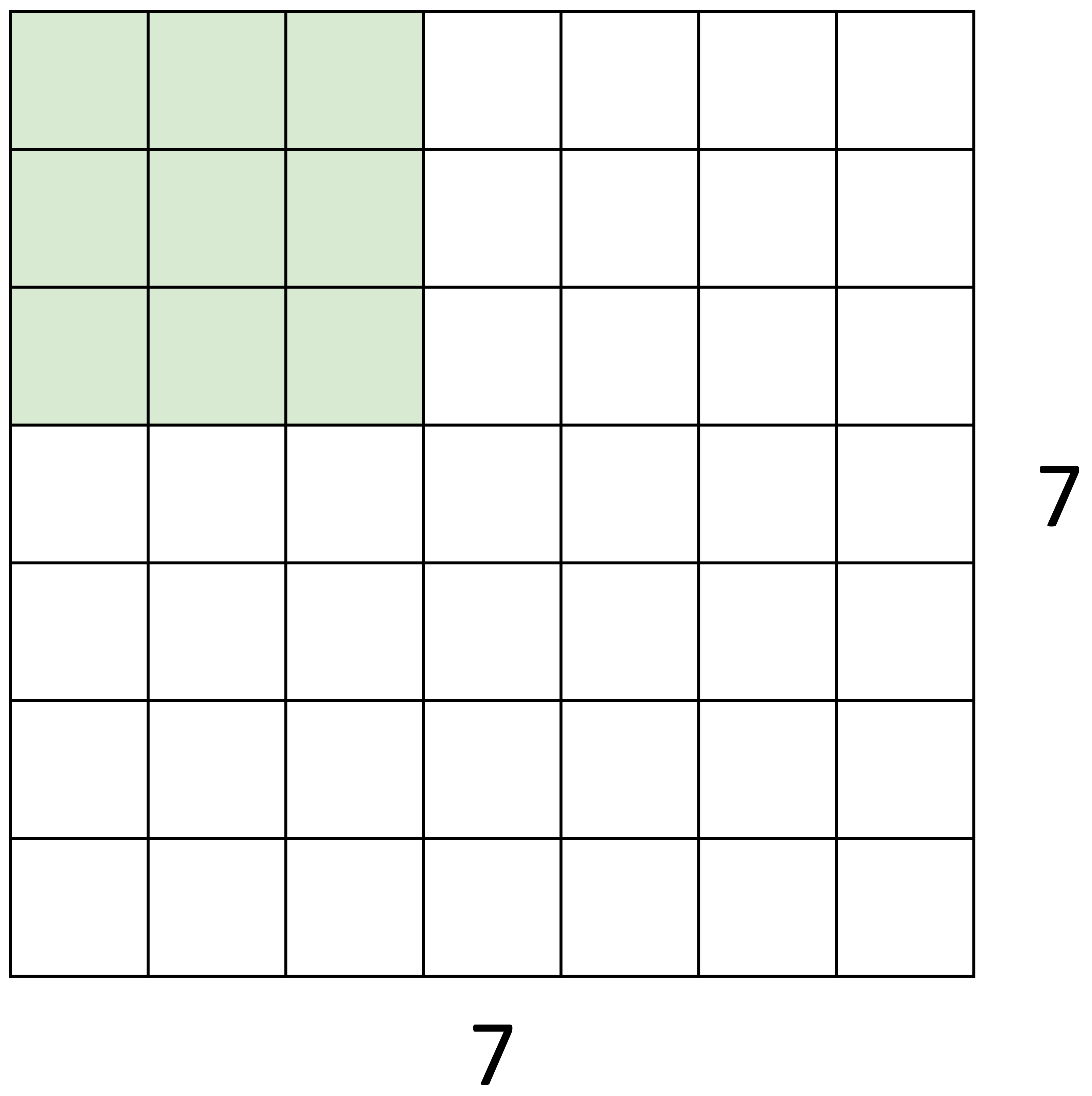
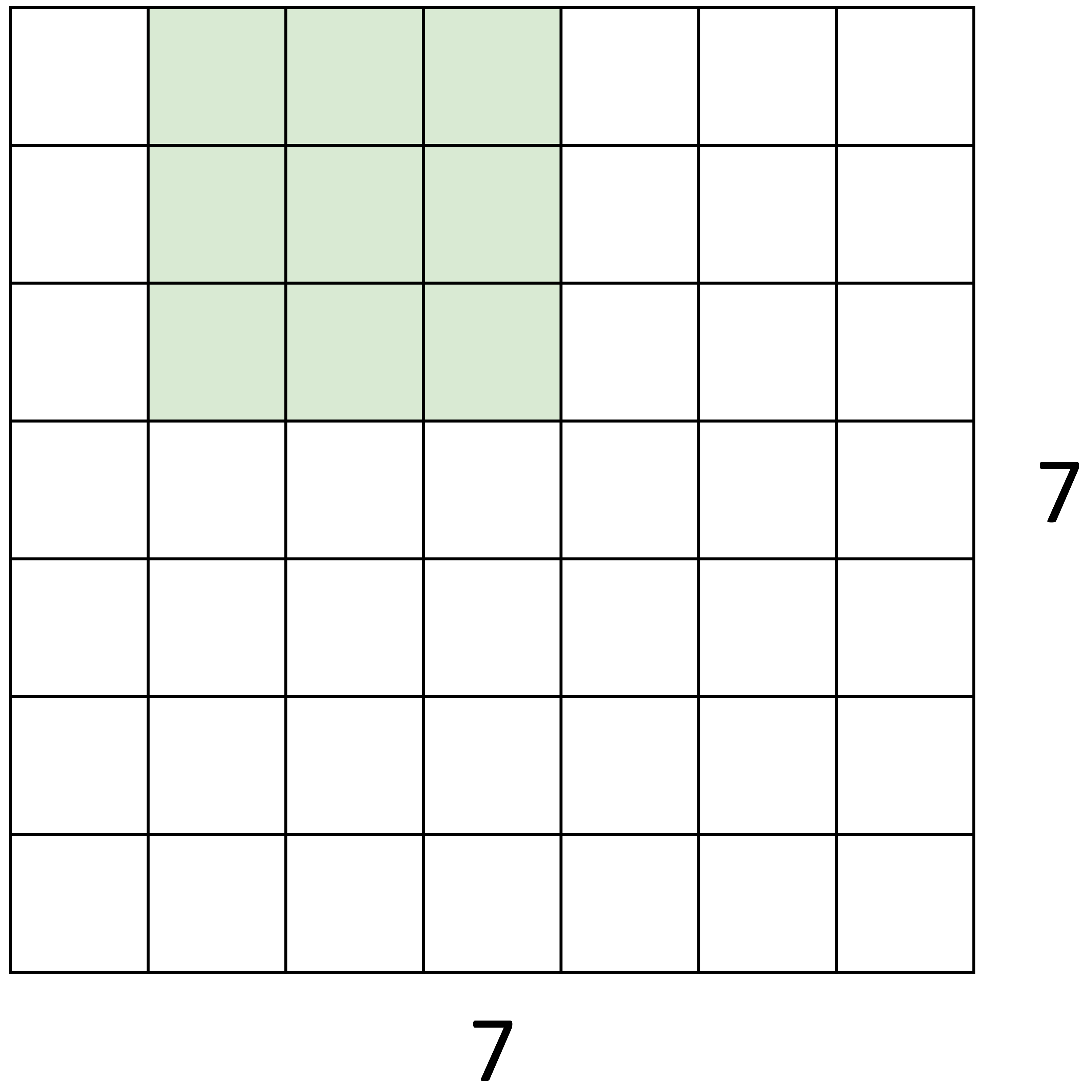


Input: 7x7

Filter: 3x3

A closer look at spatial dimensions



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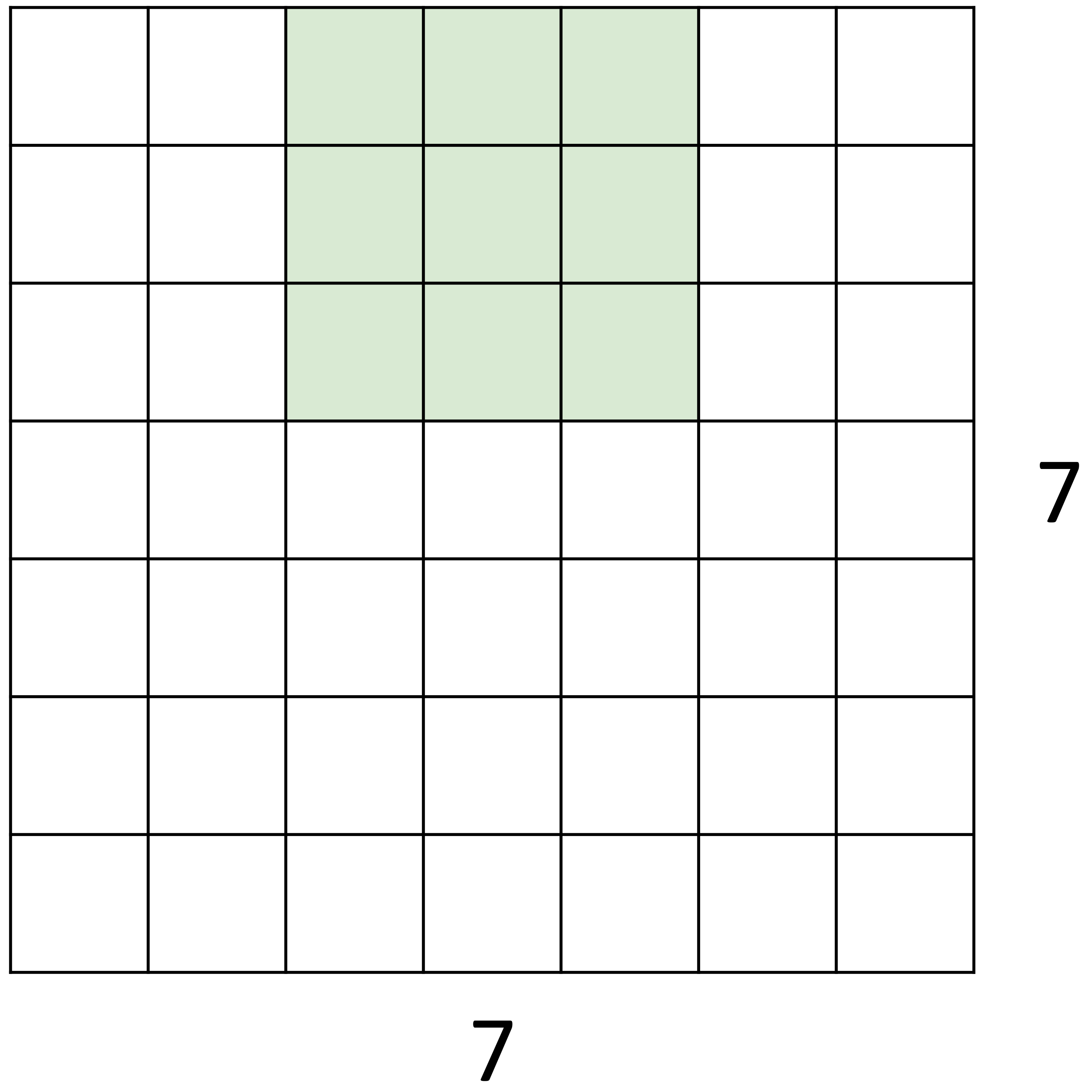
A closer look at spatial dimensions



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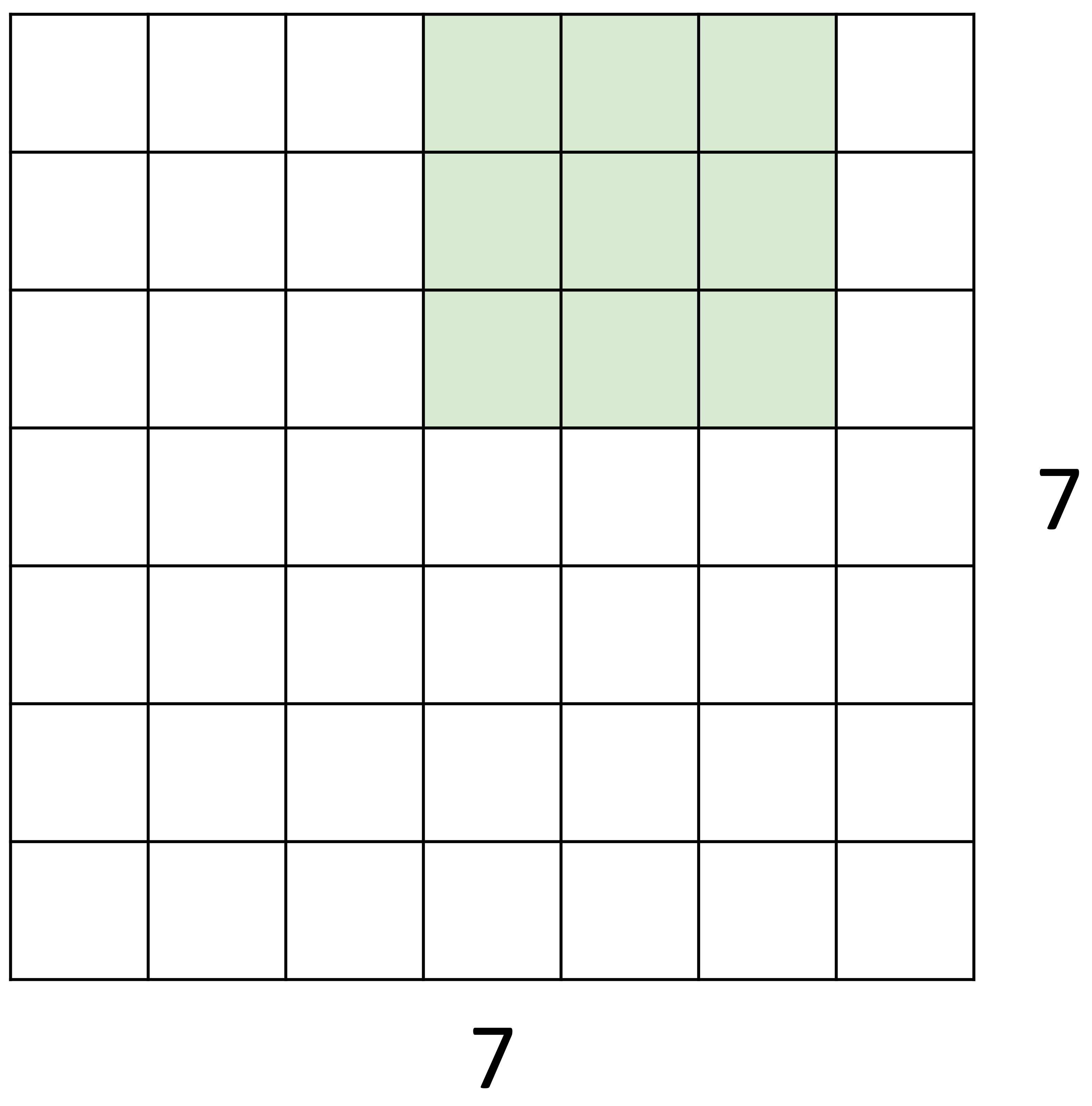
A closer look at spatial dimensions



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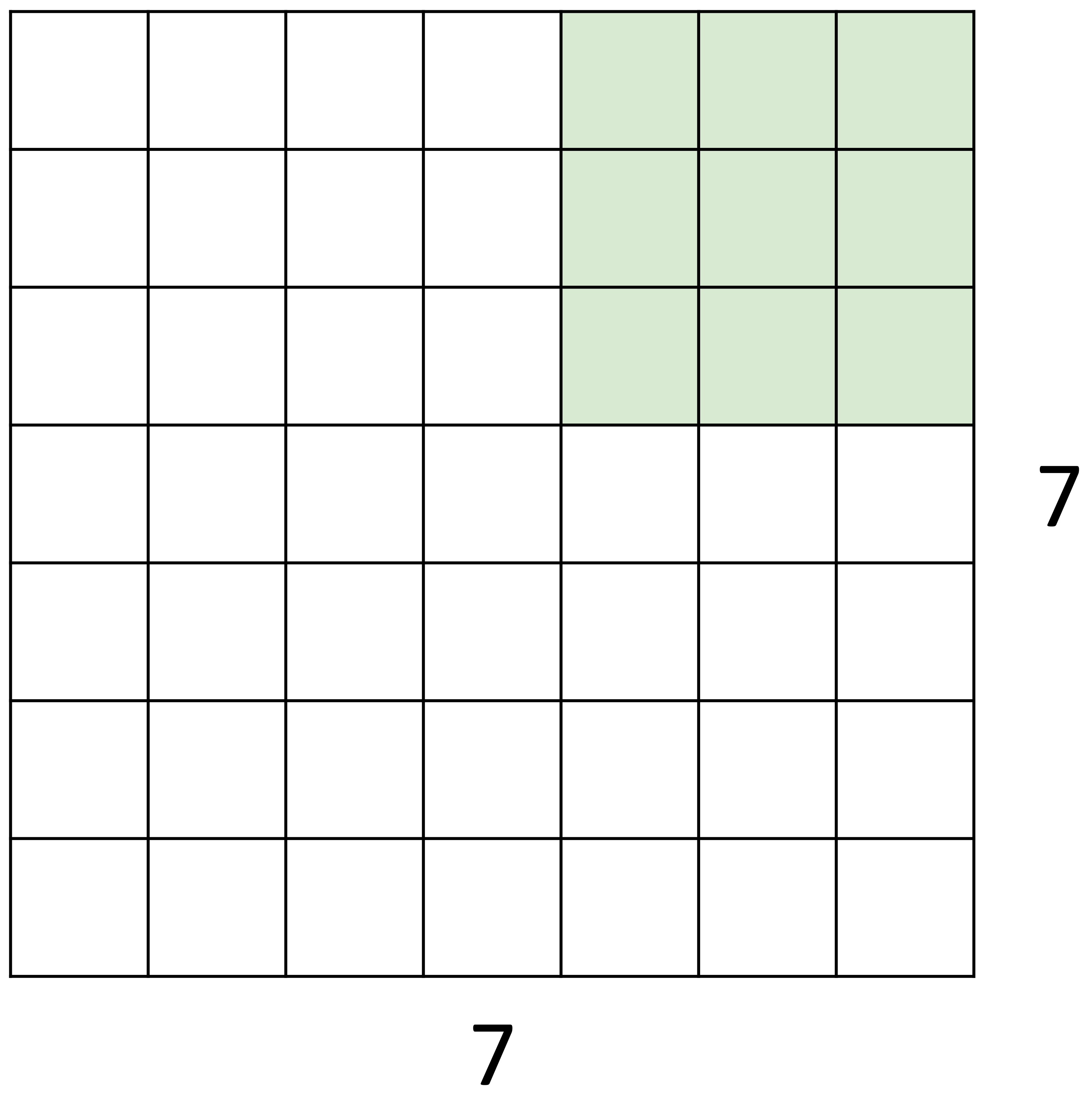
Filter: 3x3

A closer look at spatial dimensions

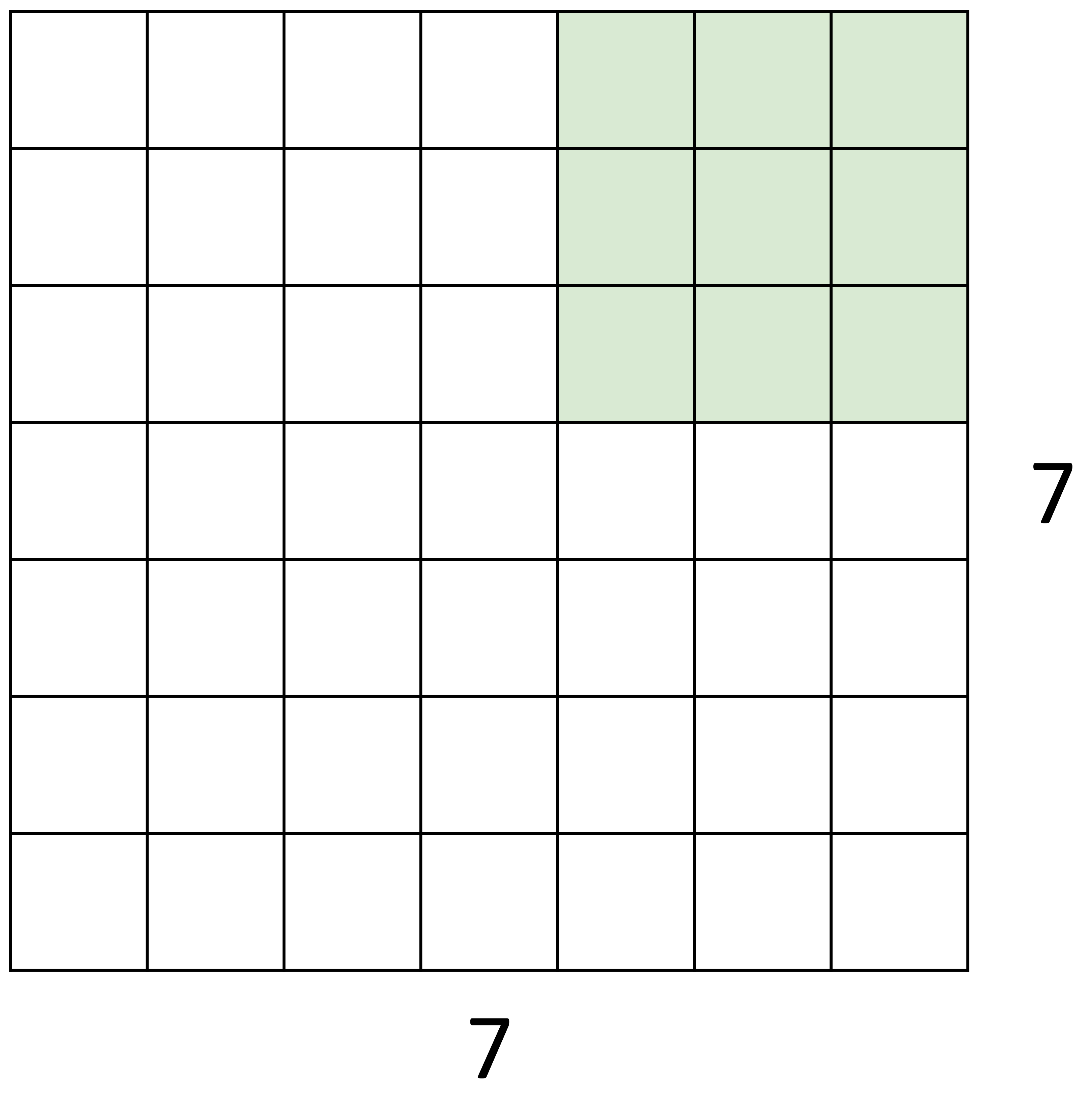


Input: 7x7

Filter: 3x3

Output: 5x5

A closer look at spatial dimensions



Input: 7x7

Filter: 3x3

Output: 5x5

In general:

Input: W

Filter: K

Output: W – K + 1

Problem: Feature maps “shrink” with each layer!

A closer look at spatial dimensions

0	0	0	0	0	0	0	0	0
0								0
0								0
0								0
0								0
0								0
0								0
0								0
0	0	0	0	0	0	0	0	0

Input: 7x7
Filter: 3x3
Output: 5x5

In general:
Input: W
Filter: K
Output: W – K + 1

Problem: Feature maps "shrink" with each layer!

Solution: **padding**
Add zeros around the input

A closer look at spatial dimensions

0	0	0	0	0	0	0	0	0
0								0
0								0
0								0
0								0
0								0
0								0
0								0
0	0	0	0	0	0	0	0	0

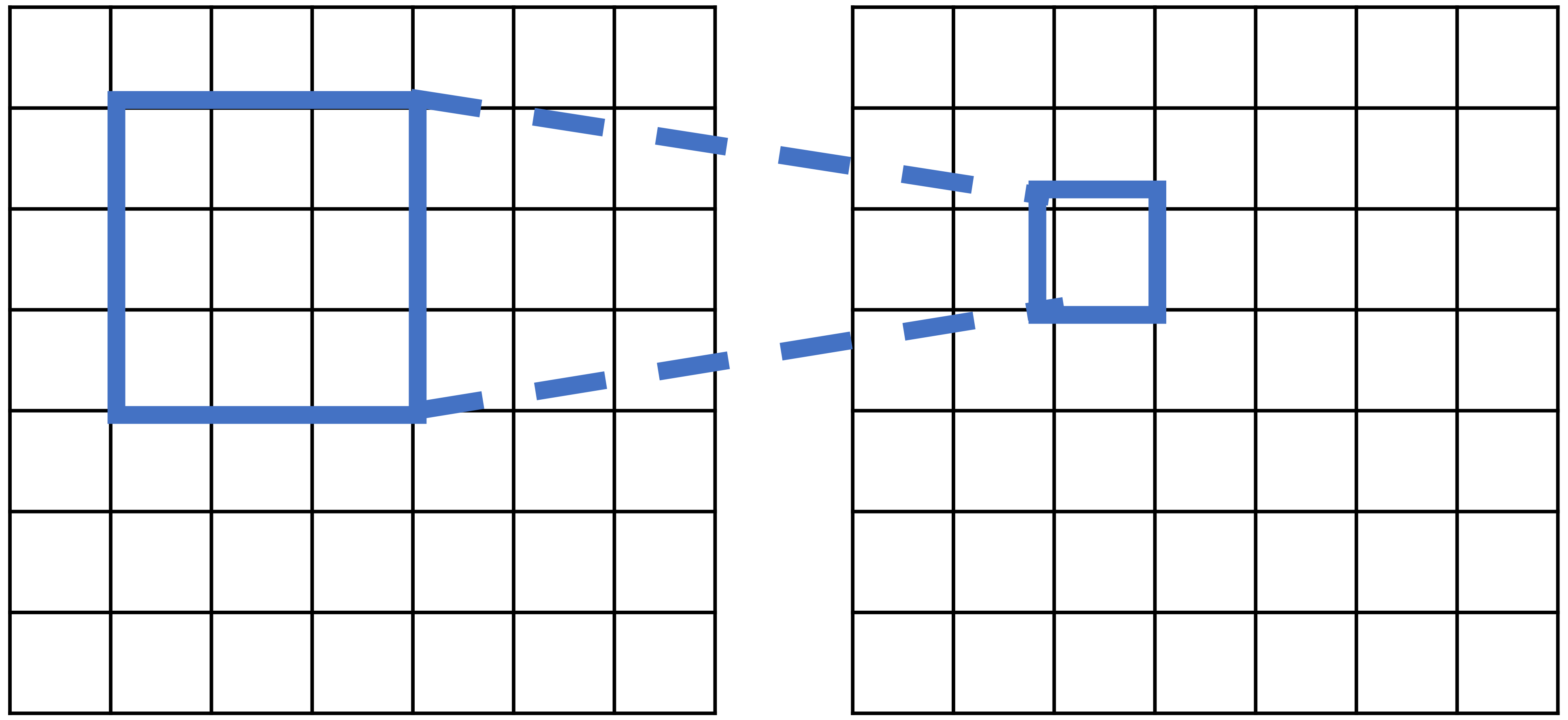
Input: 7x7
Filter: 3x3
Output: 5x5

In general:
Input: W
Filter: K
Padding: P
Output: W – K + 1 + 2P

Very common:
Set P = (K – 1) / 2 to make output have same size as input!

Receptive Fields

For convolution with kernel size K, each element in the output depends on a K x K **receptive field** in the input



Input

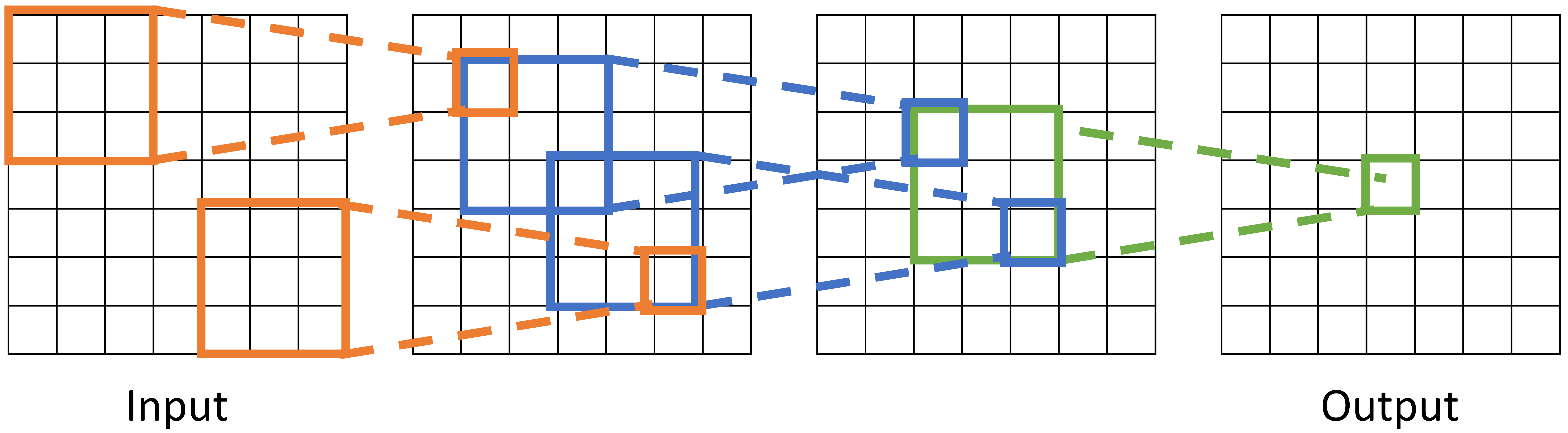
Output

Formally, it is the region in the input space that a particular CNN's feature is affected by.

Informally, it is the part of a tensor that after convolution results in a feature.

Receptive Fields

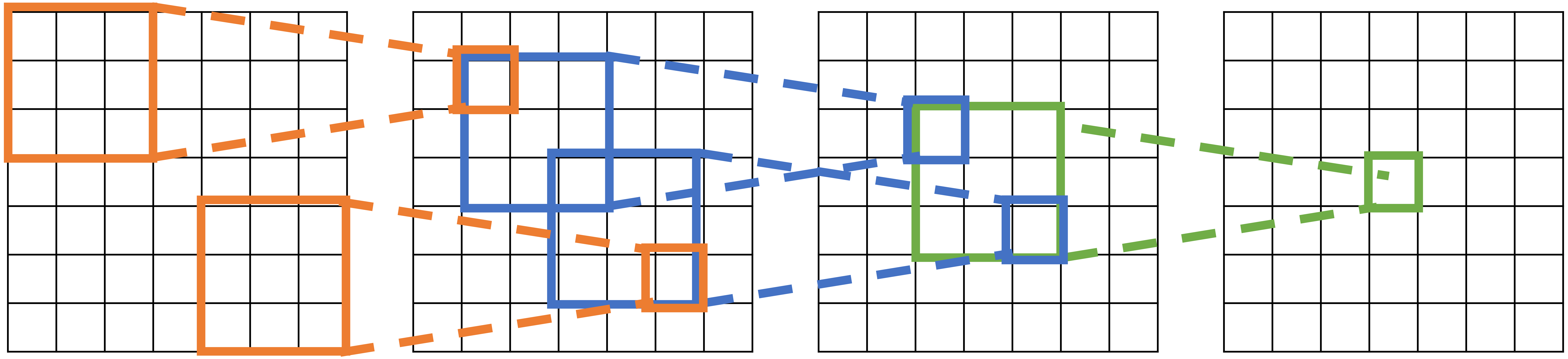
Each successive convolution adds K – 1 to the receptive field size
With L layers the receptive field size is 1 + L * (K – 1)



Be careful – ”receptive field in the input” vs “receptive field in the previous layer”
Hopefully clear from context!

Receptive Fields

Each successive convolution adds K – 1 to the receptive field size
With L layers the receptive field size is 1 + L * (K – 1)



Input

Output

Problem: For large images we need many layers for each output to “see” the whole image image

Receptive Fields

Each successive convolution adds K – 1 to the receptive field size
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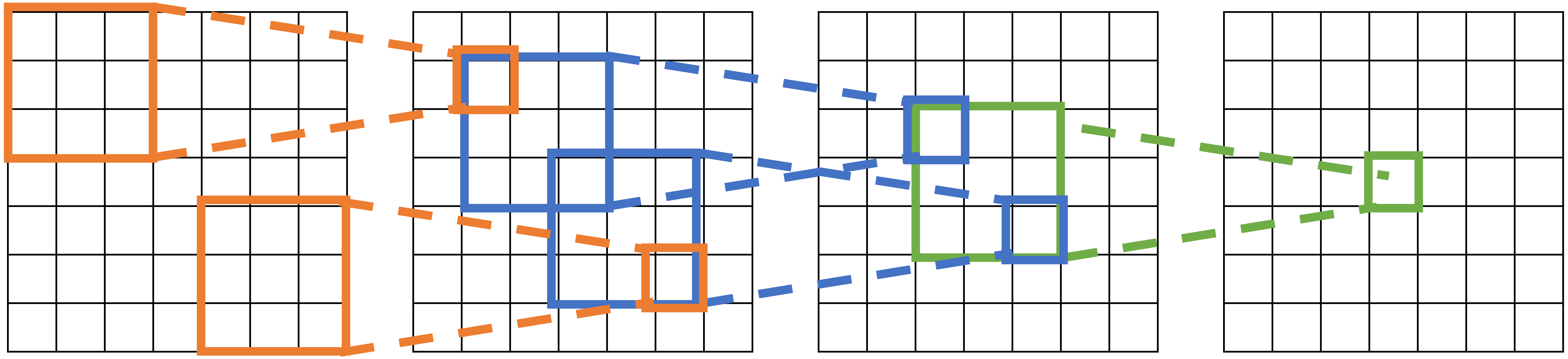


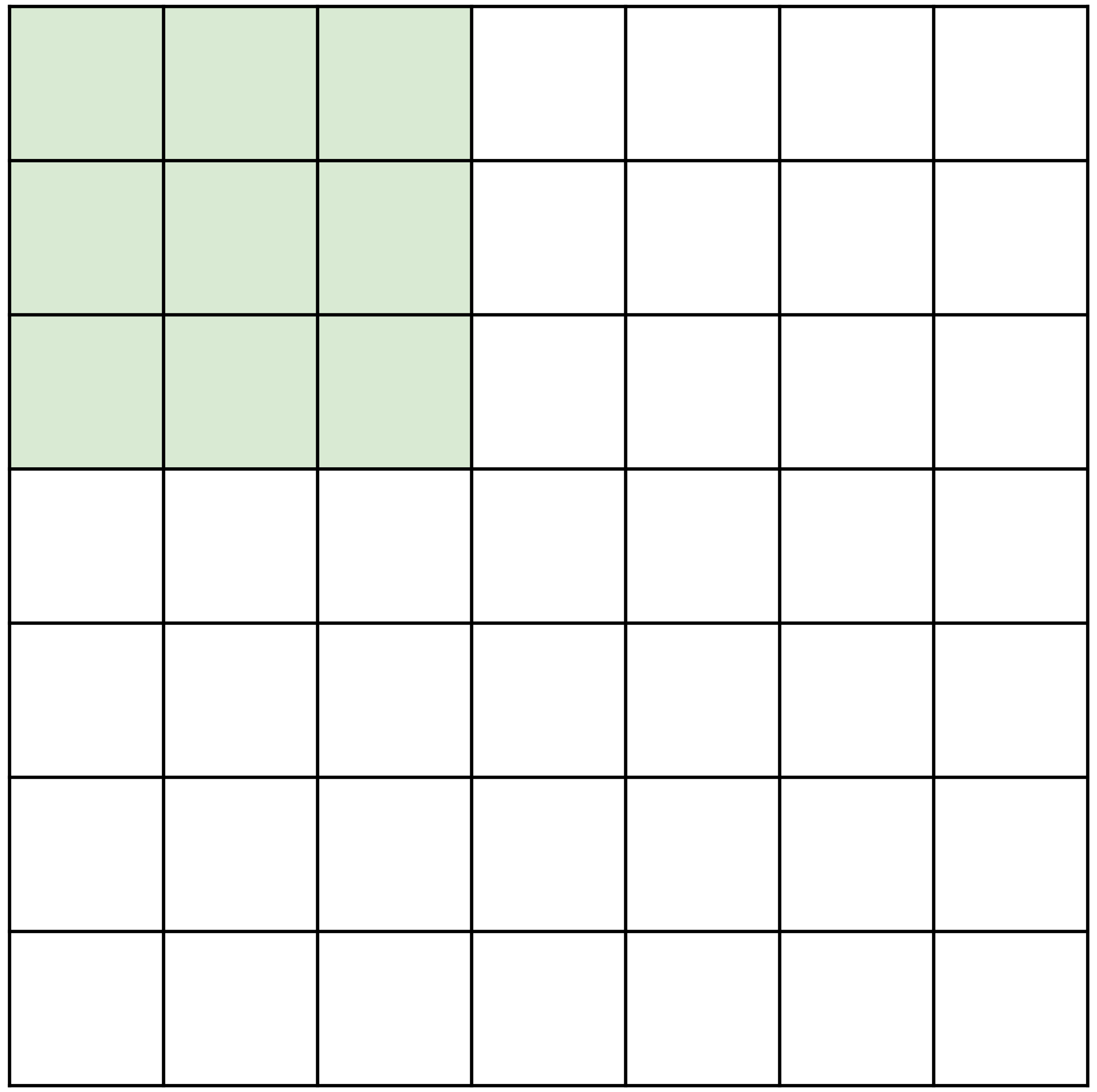
Input

Output

Problem: For large images we need many layers for each output to "see" the whole image image

Solution: Downsample inside the network

Strided Convolution

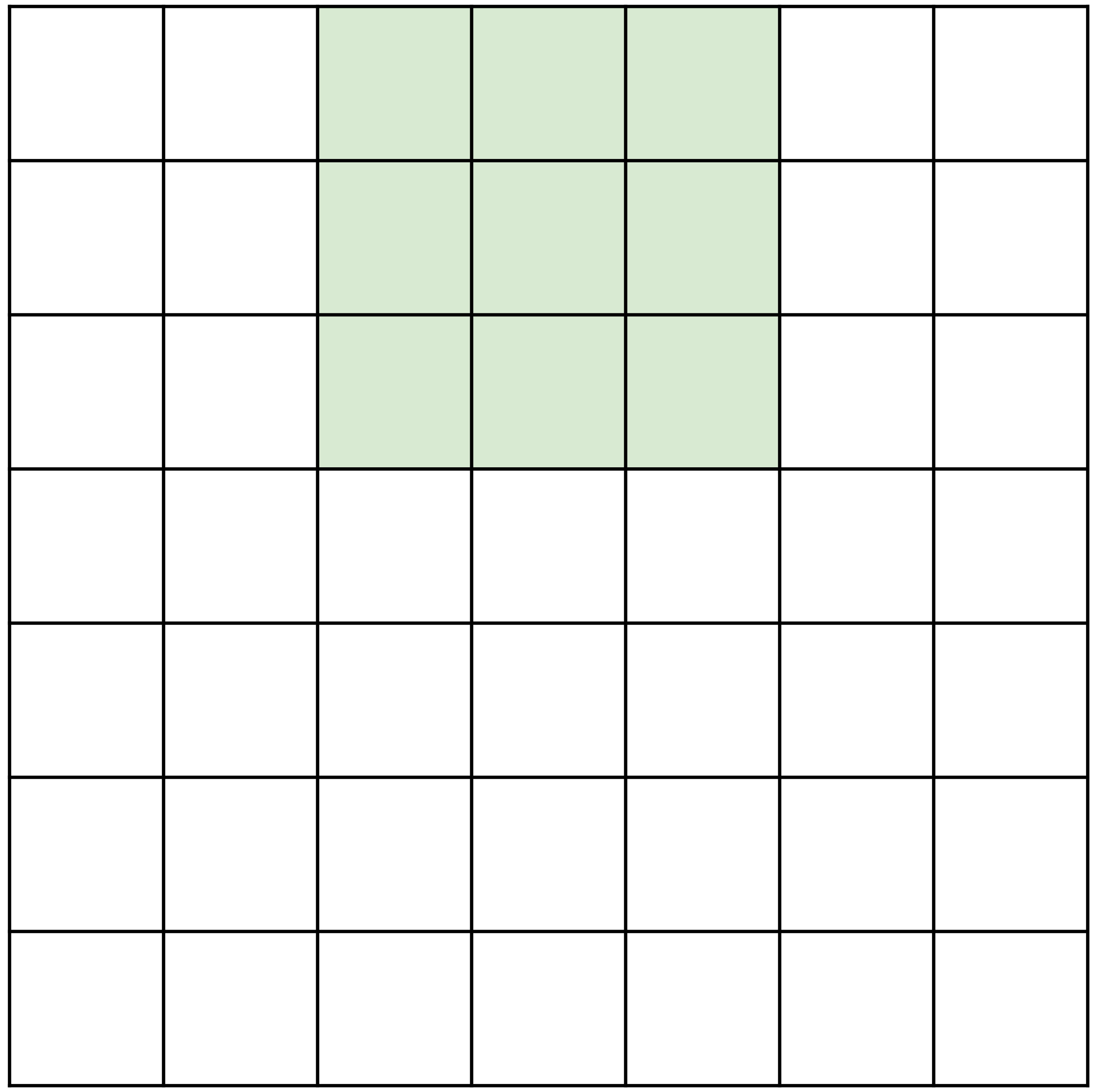


Input: 7x7

Filter: 3x3

Stride: 2

Strided Convolution

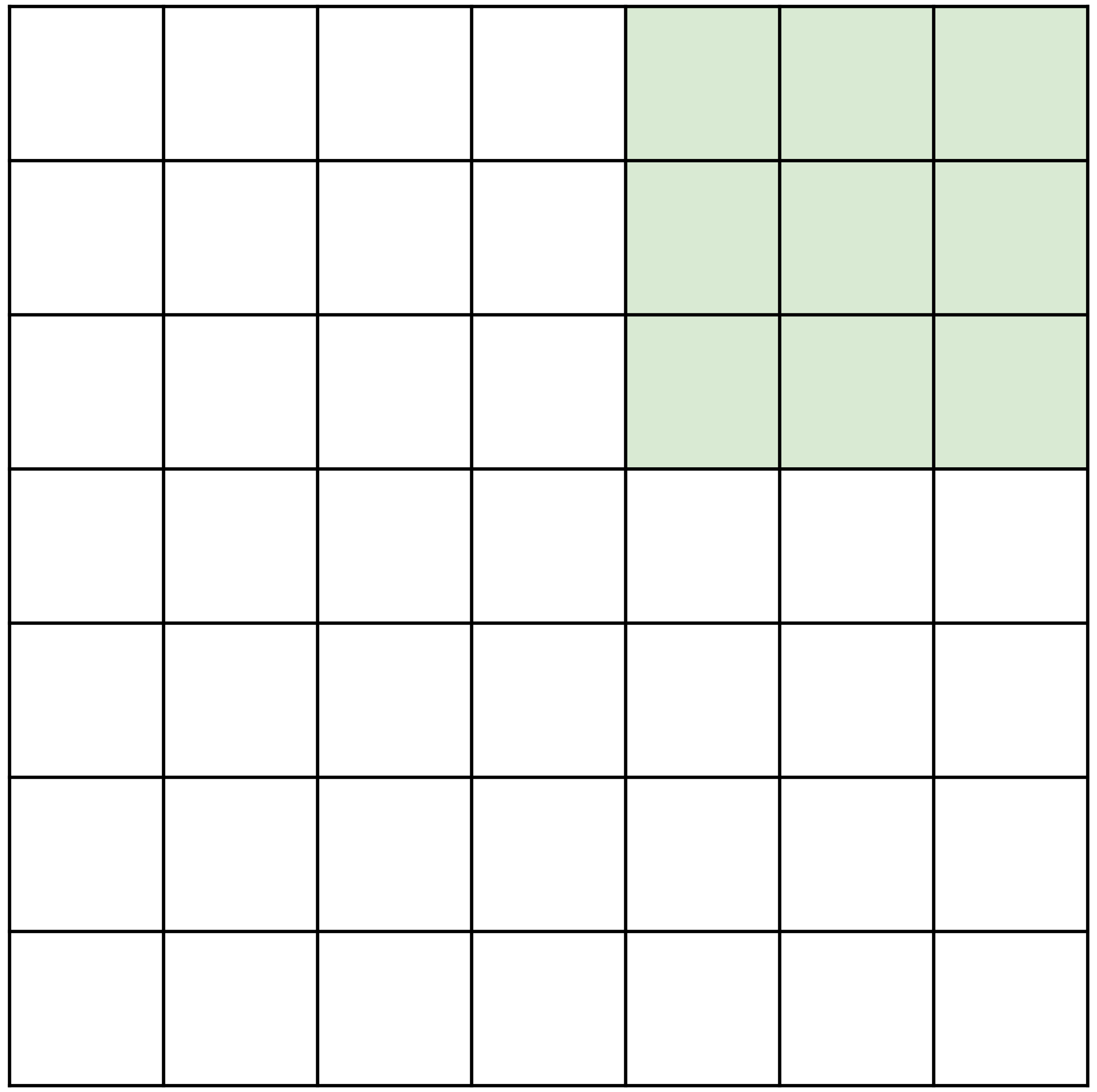


Input: 7x7

Filter: 3x3

Stride: 2

Strided Convolution



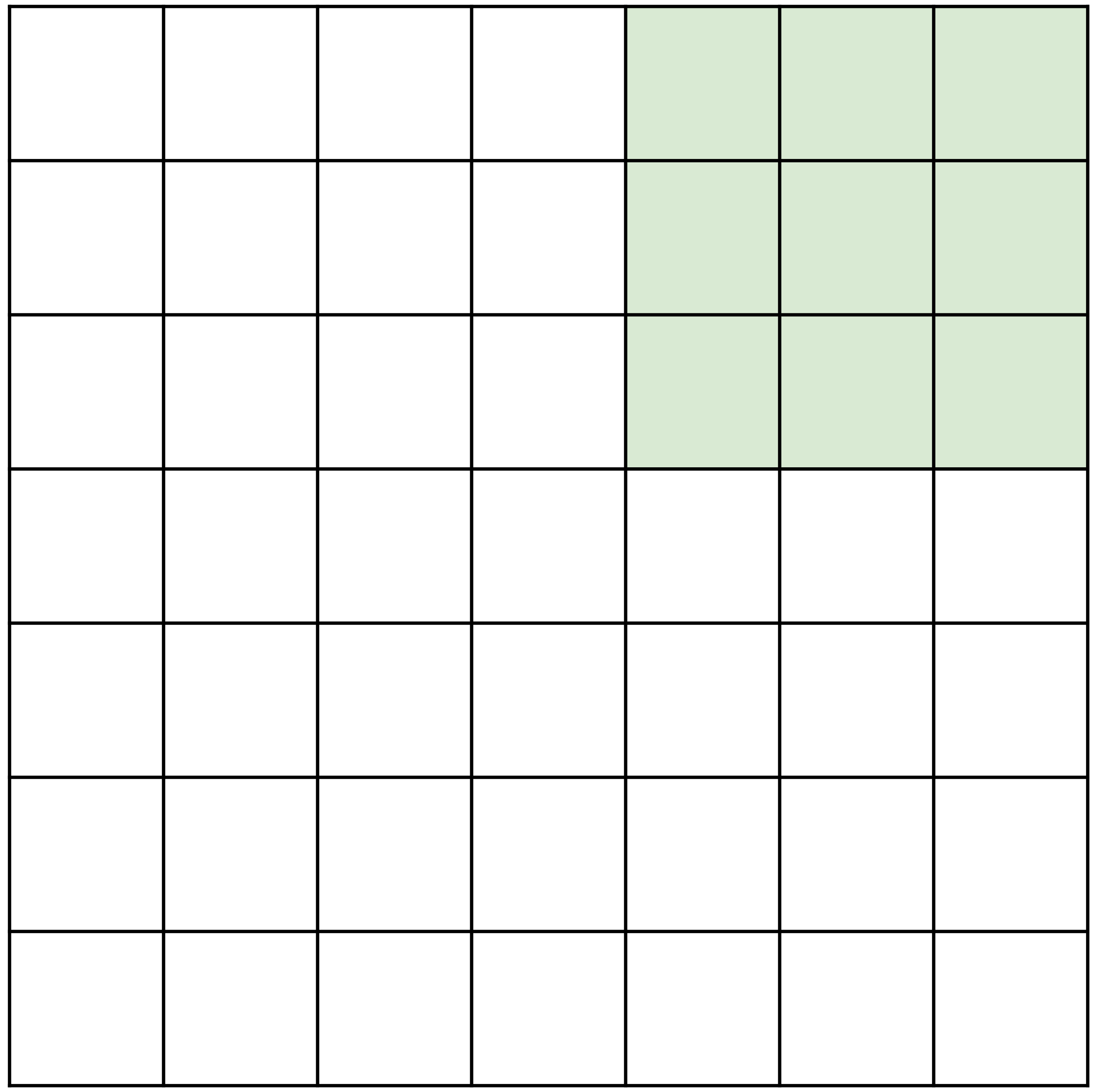
Input: 7x7

Filter: 3x3

Stride: 2

Output: 3x3

Strided Convolution



Input: 7x7

Filter: 3x3

Stride: 2

Output: 3x3

In general:

Input: W

Filter: K

Padding: P

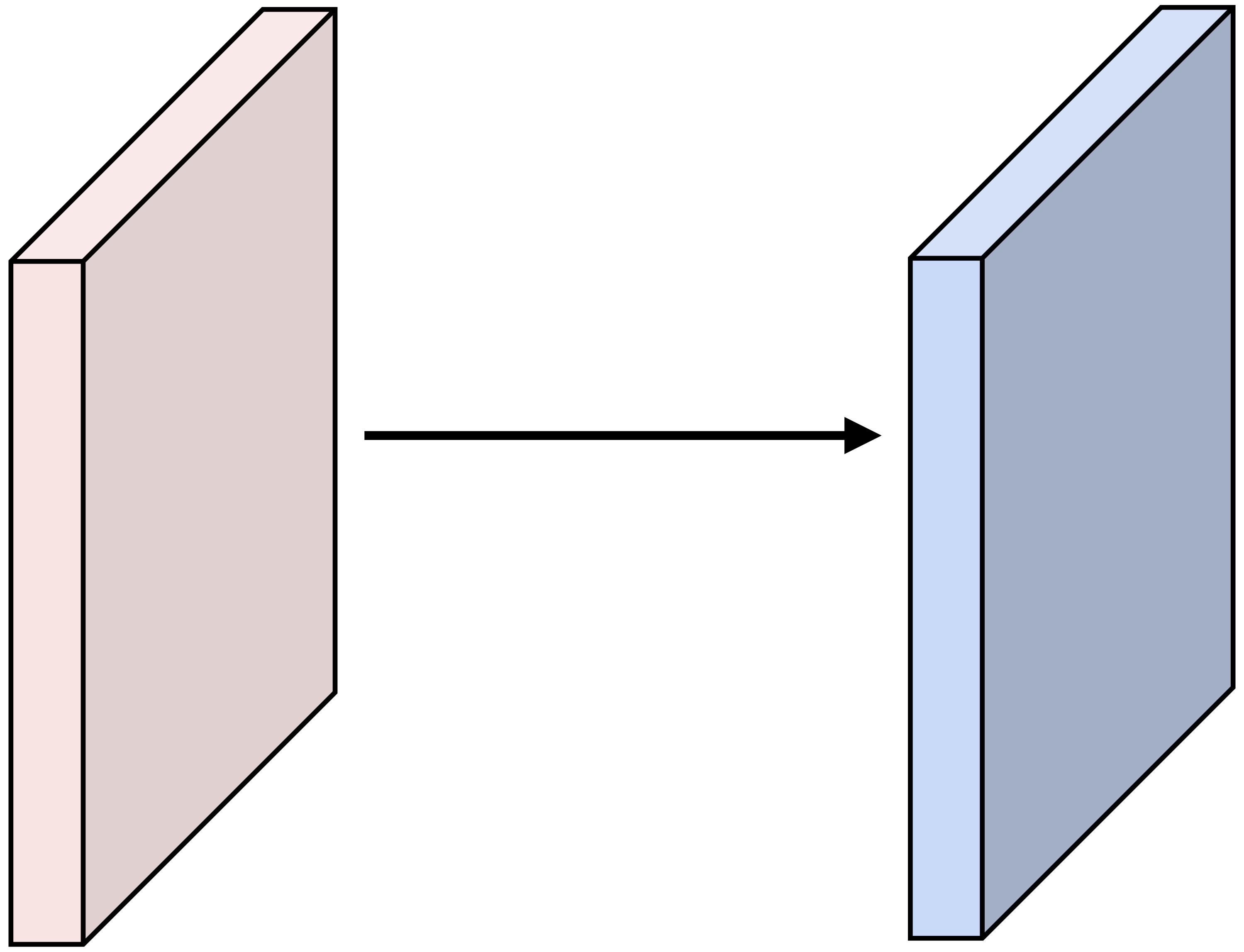
Stride: S

Output: (W – K + 2P) / S + 1

Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

Q: What is the output volume size?



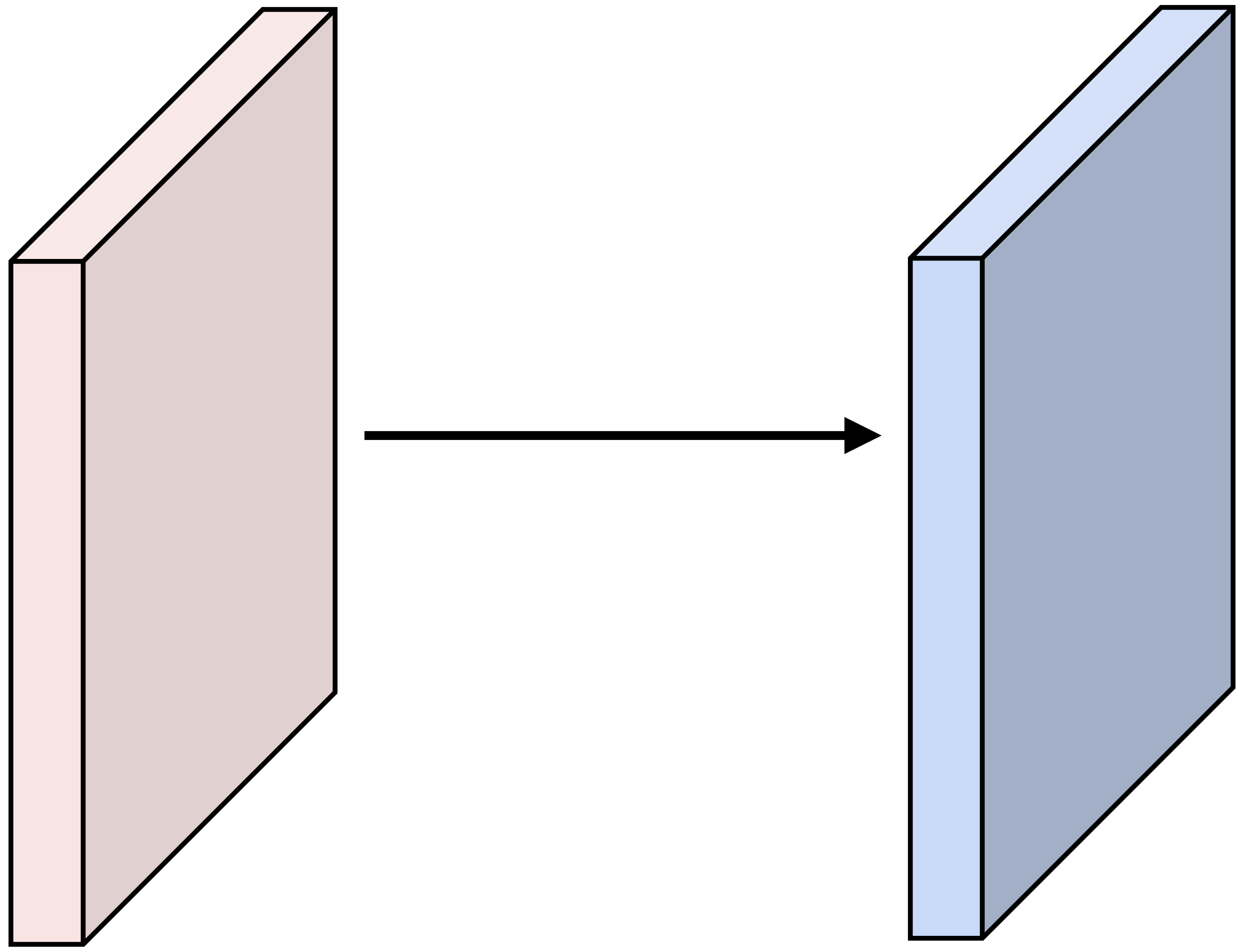
Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

Q: What is the output volume size?

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

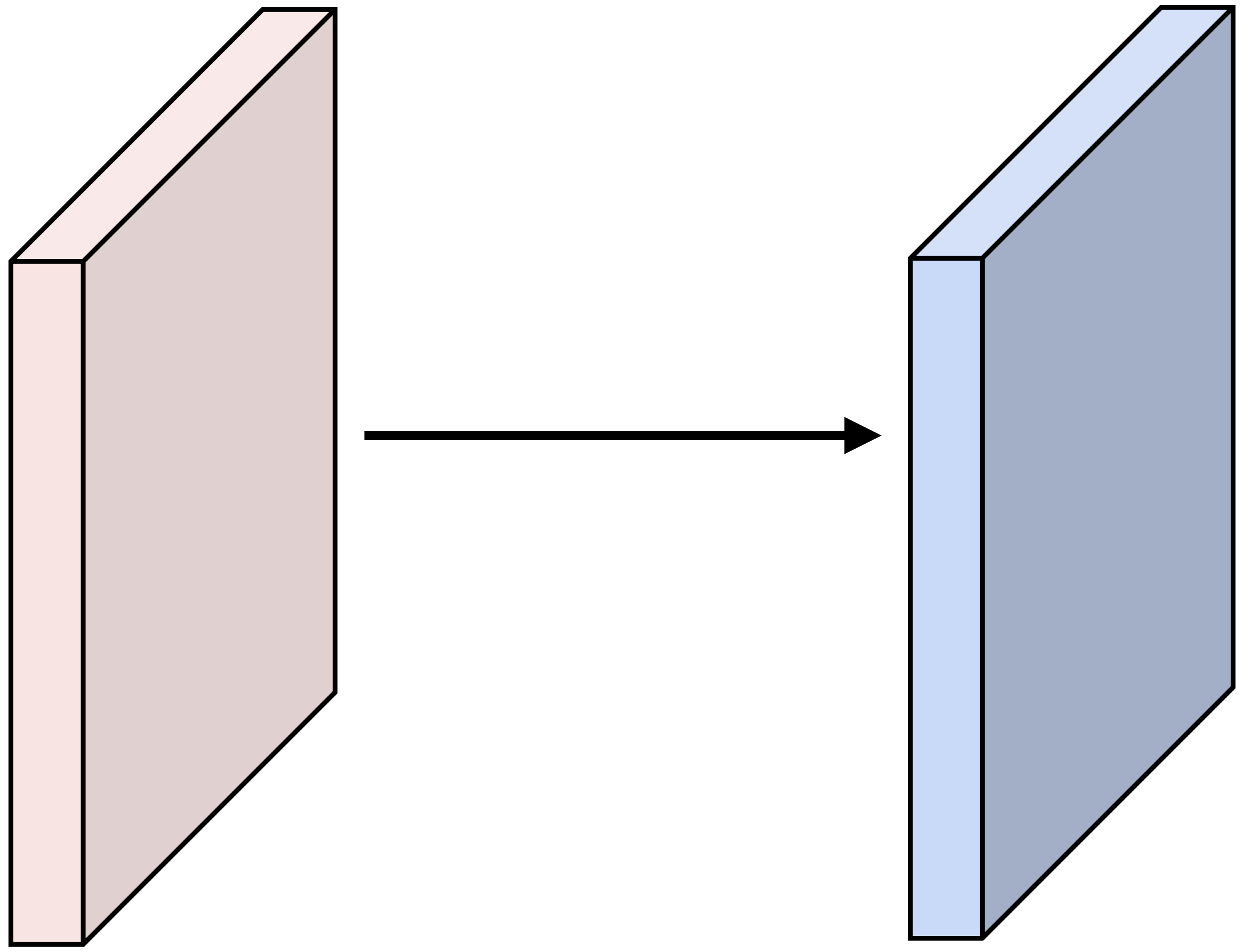
So, 10 x 32 x 32 output



Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

Output volume size: 10 x 32 x 32
Q: What is the number of learnable parameters?



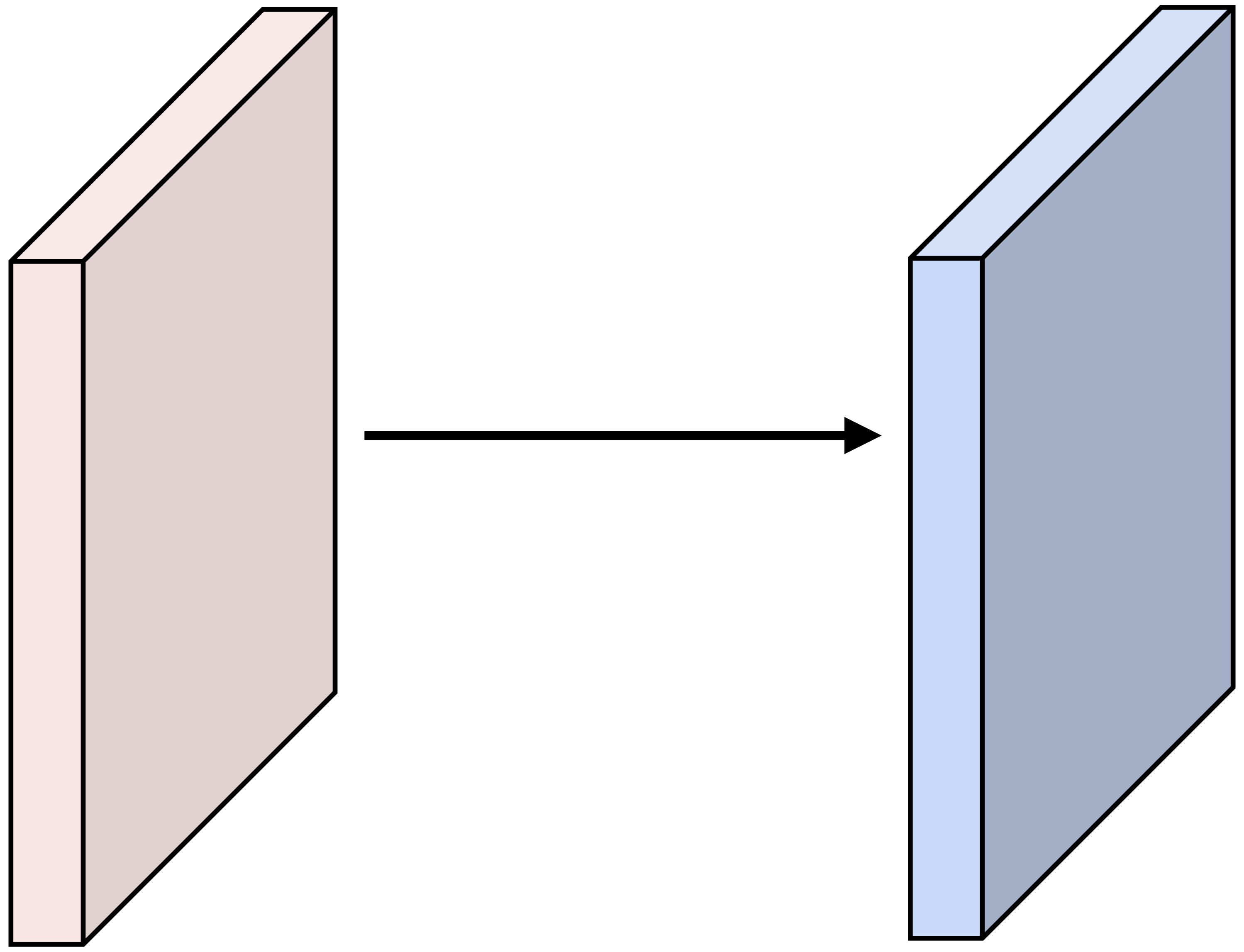
Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

Output volume size: 10 x 32 x 32
Q: What is the number of learnable parameters?

Parmeters per filter: (3*5*5) + 1 = 76

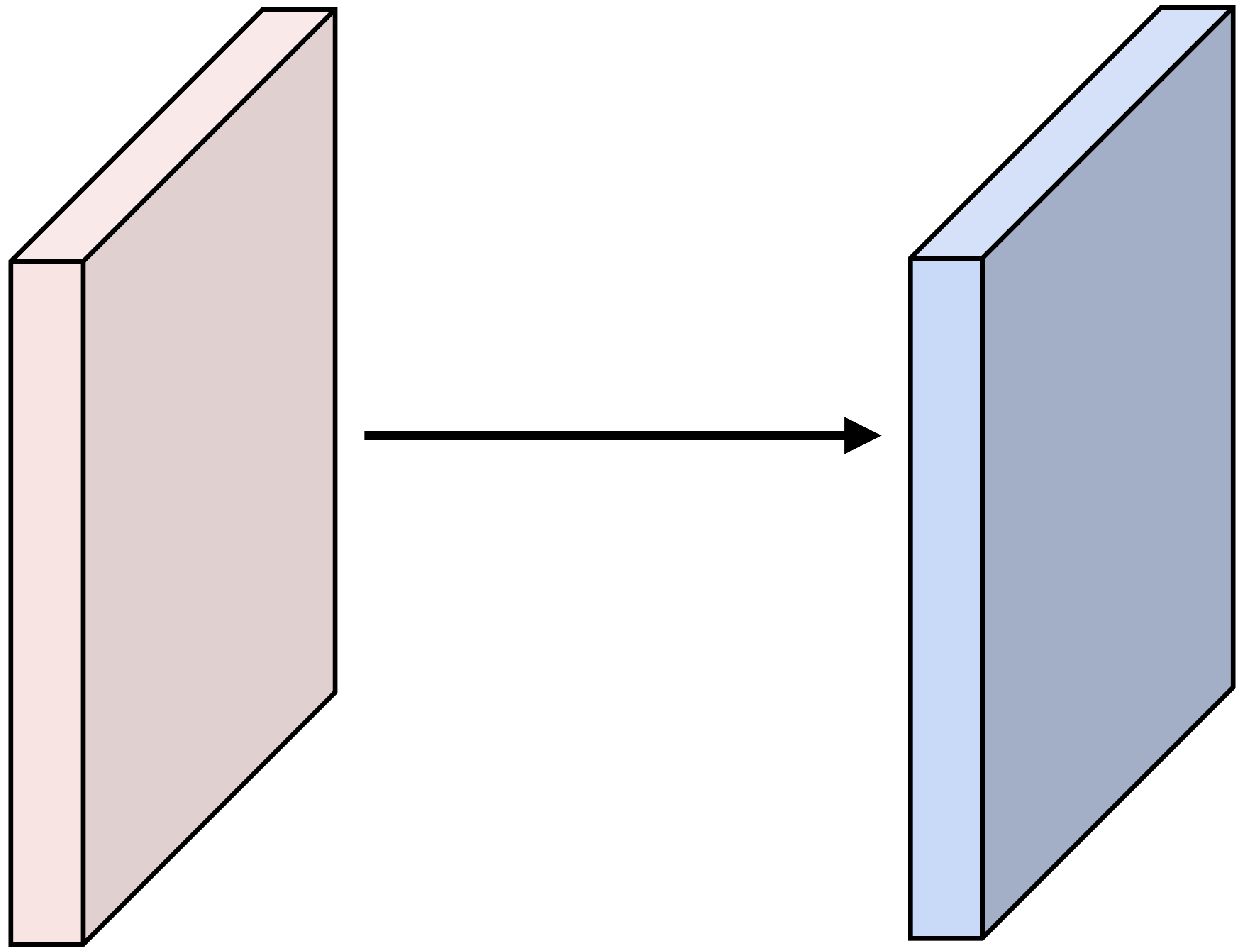
10 filters, so total is 10*76 = 760



Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

Output volume size: 10 x 32 x 32
Number of learnable parameters: 760
Q: What is the number of multiply-add operations?



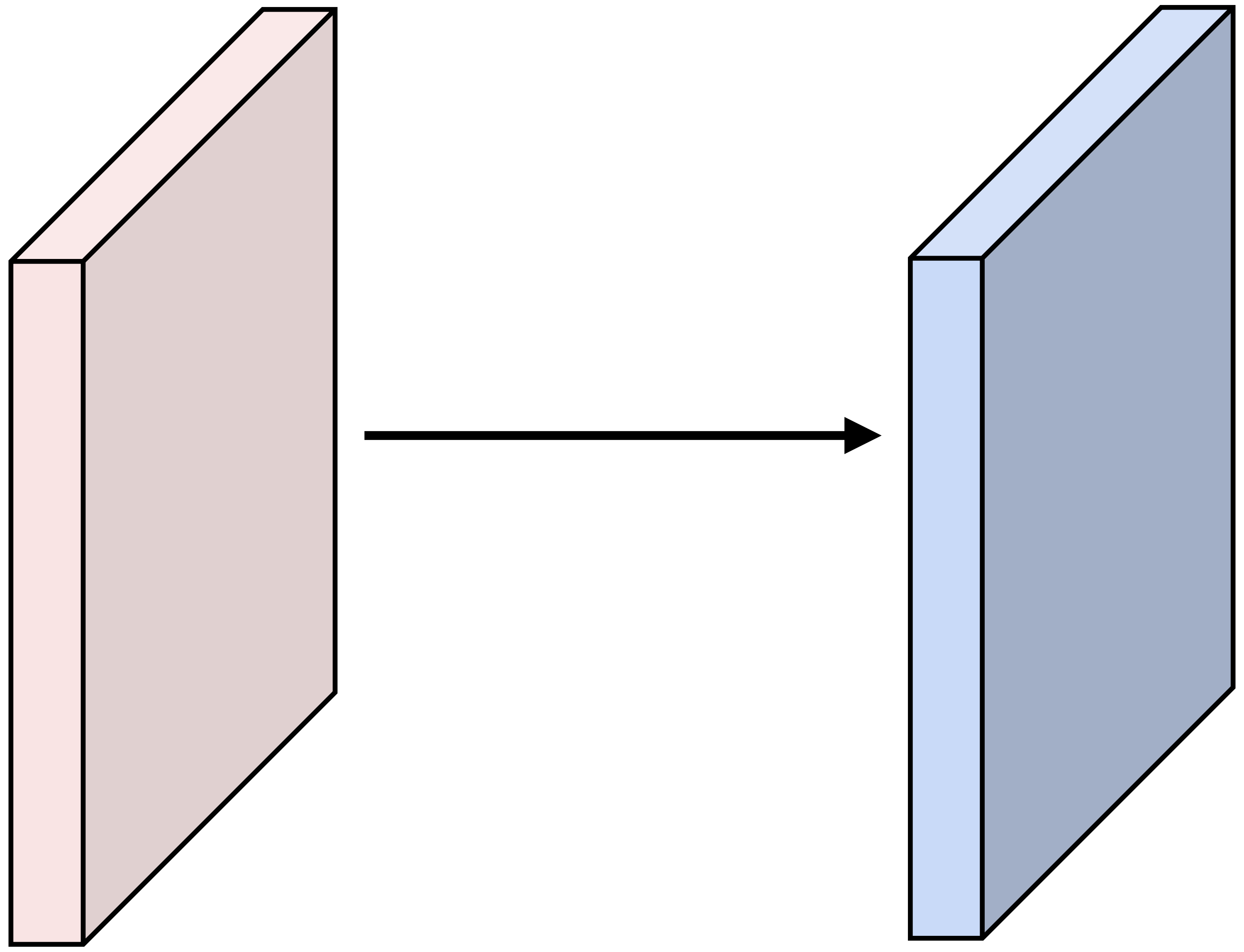
Convolution Example

Input volume: 3 x 32 x 32
10 5x5 filters with stride 1, pad 2

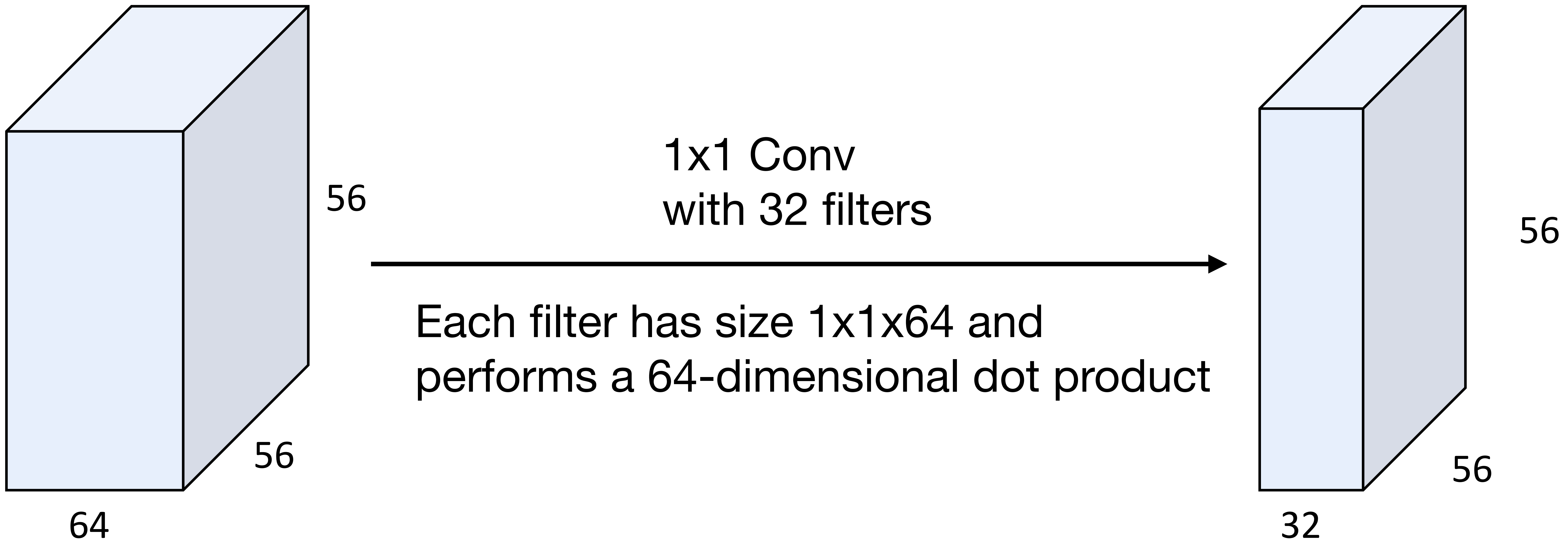
Output volume size: 10 x 32 x 32
Number of learnable parameters: 760
Q: What is the number of multiply-add operations?

10*32*32=10,240 outputs, each from inner product

of two 3x5x5 tensors, so total = 75 * 10,240 = **768,000**

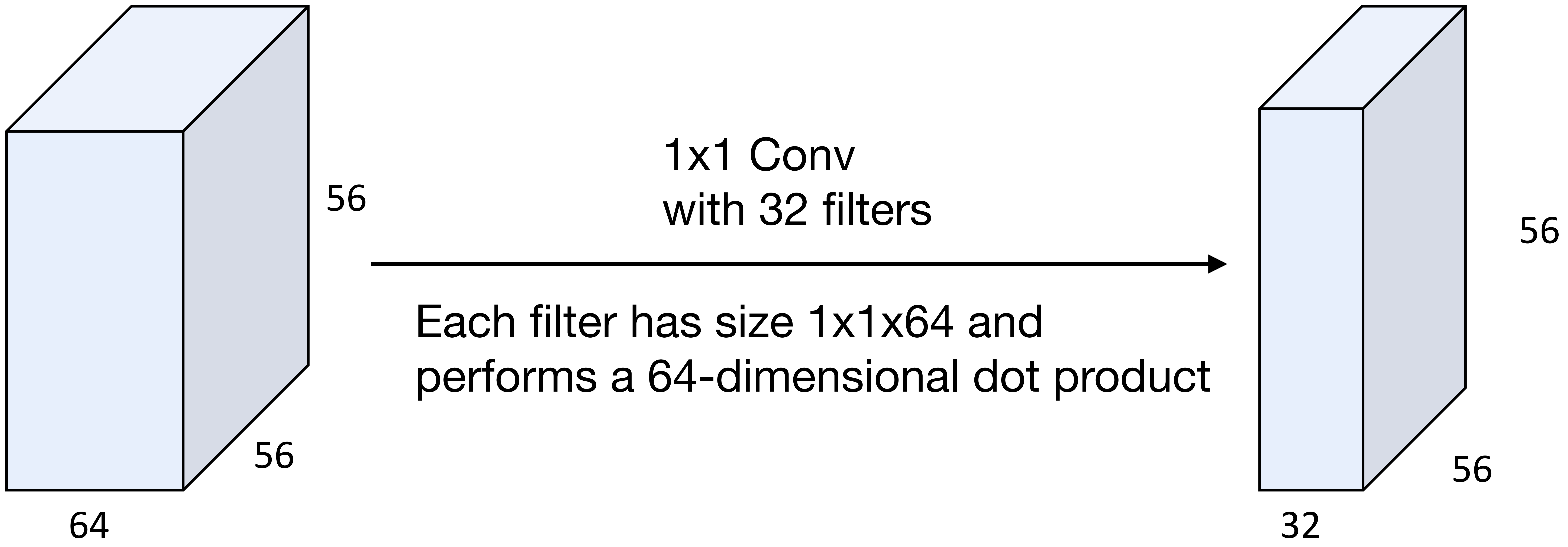


Example: 1x1 Convolution



Lin et al., “Network in Network”, ICLR 2014

Example: 1x1 Convolution



Each filter has size 1x1x64 and performs a 64-dimensional dot product

Stacking 1x1 conv layers gives MLP operating on each input position

Lin et al., “Network in Network”, ICLR 2014

Convolution Summary

Input: C_{in} x H x W

Hyperparameters:

- **Kernel size**: K_H x K_W
- **Number filters**: C_{out}
- **Padding**: P
- **Stride**: S

Weight matrix: C_{out} x C_{in} x K_H x K_W
giving C_{out} filters of size C_{in} x K_H x K_W

Bias vector: C_{out}

Output size: C_{out} x H' x W' where:

- $H' = (H - K + 2P) / S + 1$
- $W' = (W - K + 2P) / S + 1$

Convolution Summary

Input: C_{in} x H x W

Hyperparameters:

- **Kernel size**: K_H x K_W
- **Number filters**: C_{out}
- **Padding**: P
- **Stride**: S

Weight matrix: C_{out} x C_{in} x K_H x K_W
giving C_{out} filters of size C_{in} x K_H x K_W

Bias vector: C_{out}

Output size: C_{out} x H' x W' where:

- H' = (H – K + 2P) / S + 1
- W' = (W – K + 2P) / S + 1

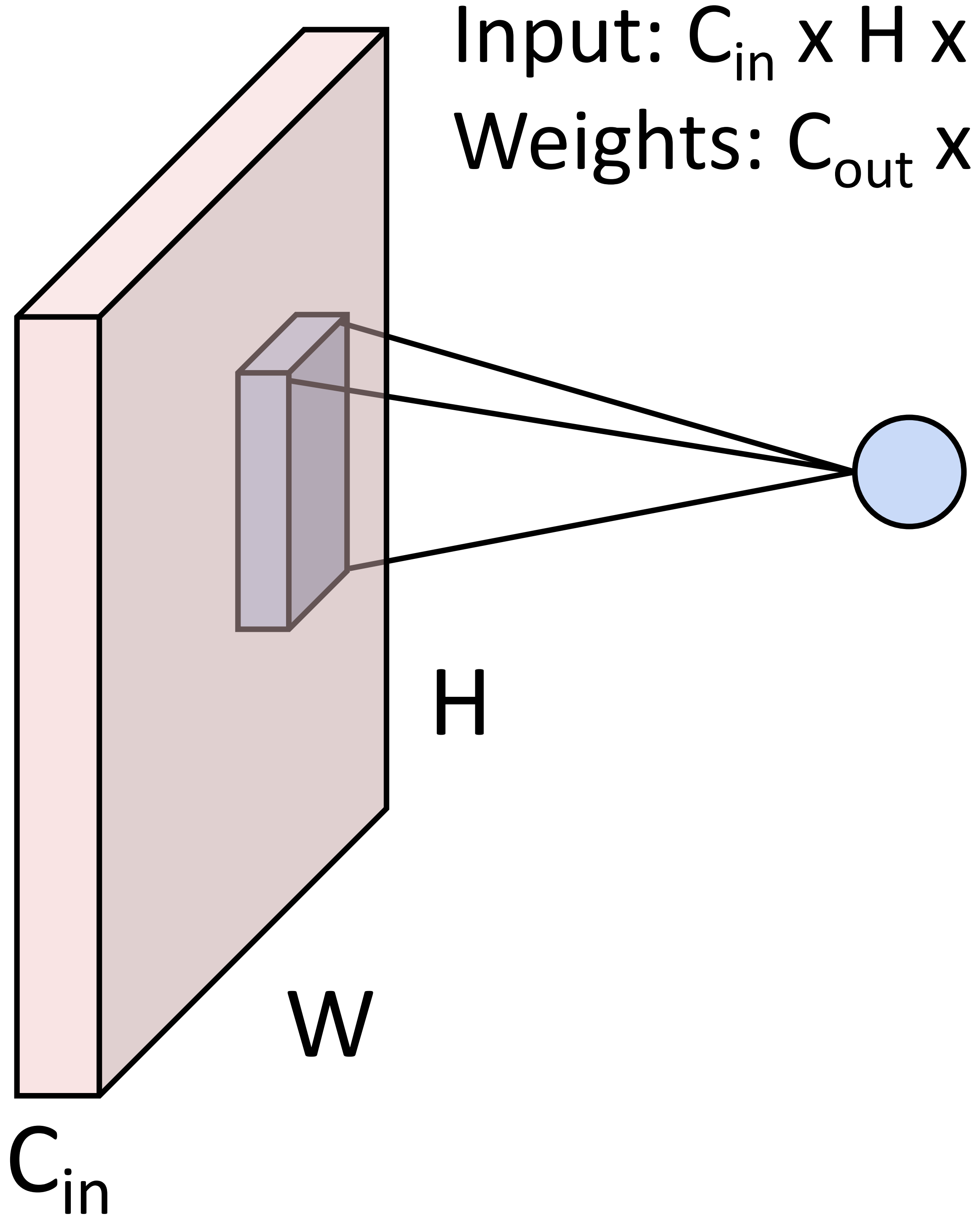
Common settings:
$K_H = K_W$ (Small square filters)
P = (K – 1) / 2 ("Same" padding)
C_{in}, C_{out} = 32, 64, 128, 256 (powers of 2)
K = 3, P = 1, S = 1 (3x3 conv)
K = 5, P = 2, S = 1 (5x5 conv)
K = 1, P = 0, S = 1 (1x1 conv)
K = 3, P = 1, S = 2 (Downsample by 2)

Other types of convolution

So far: 2D Convolution

Input: C_{in} x H x W

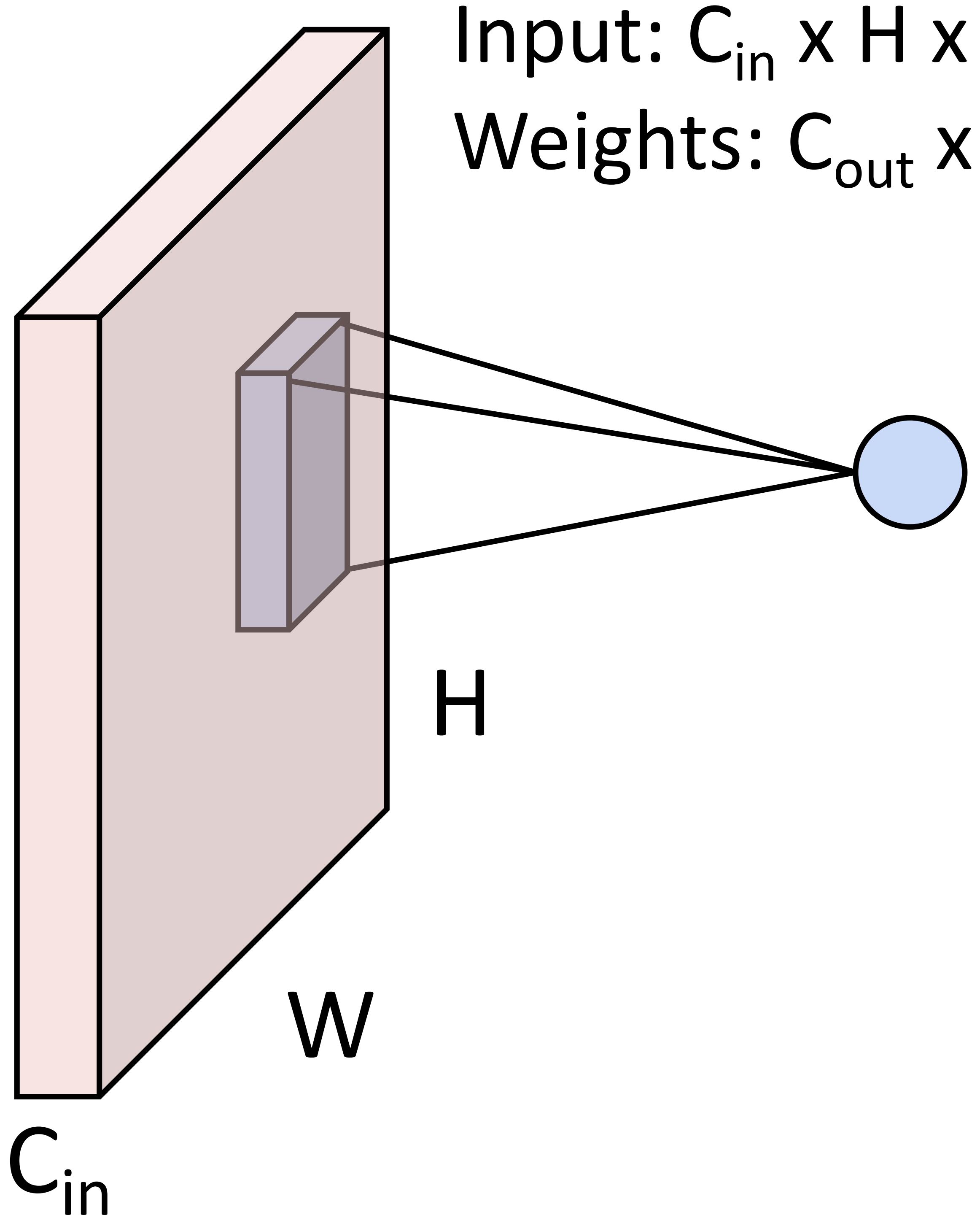
Weights: C_{out} x C_{in} x K x K



Other types of convolution

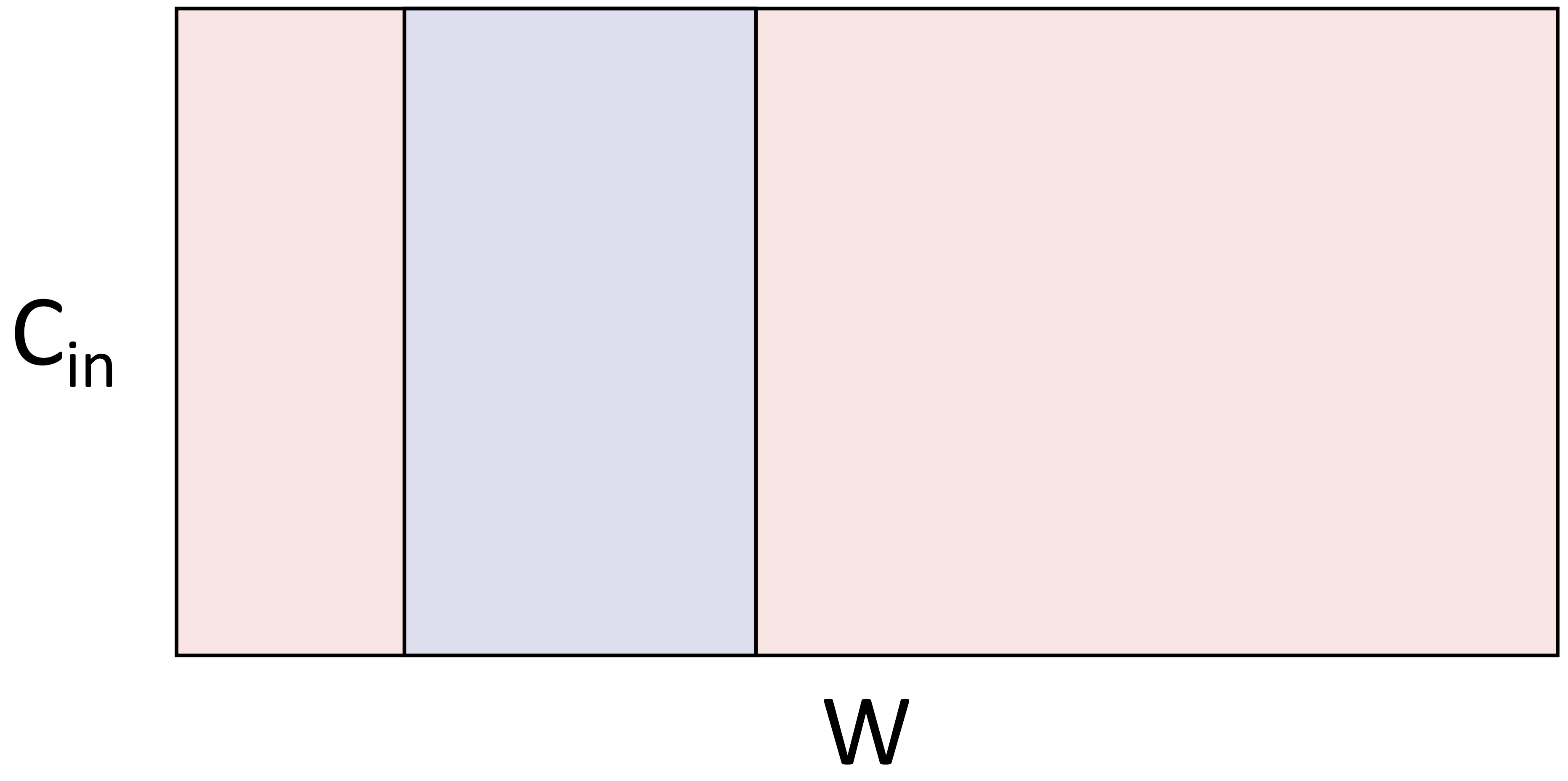
So far: 2D Convolution

Input: C_{in} x H x W
Weights: C_{out} x C_{in} x K x K



1D Convolution

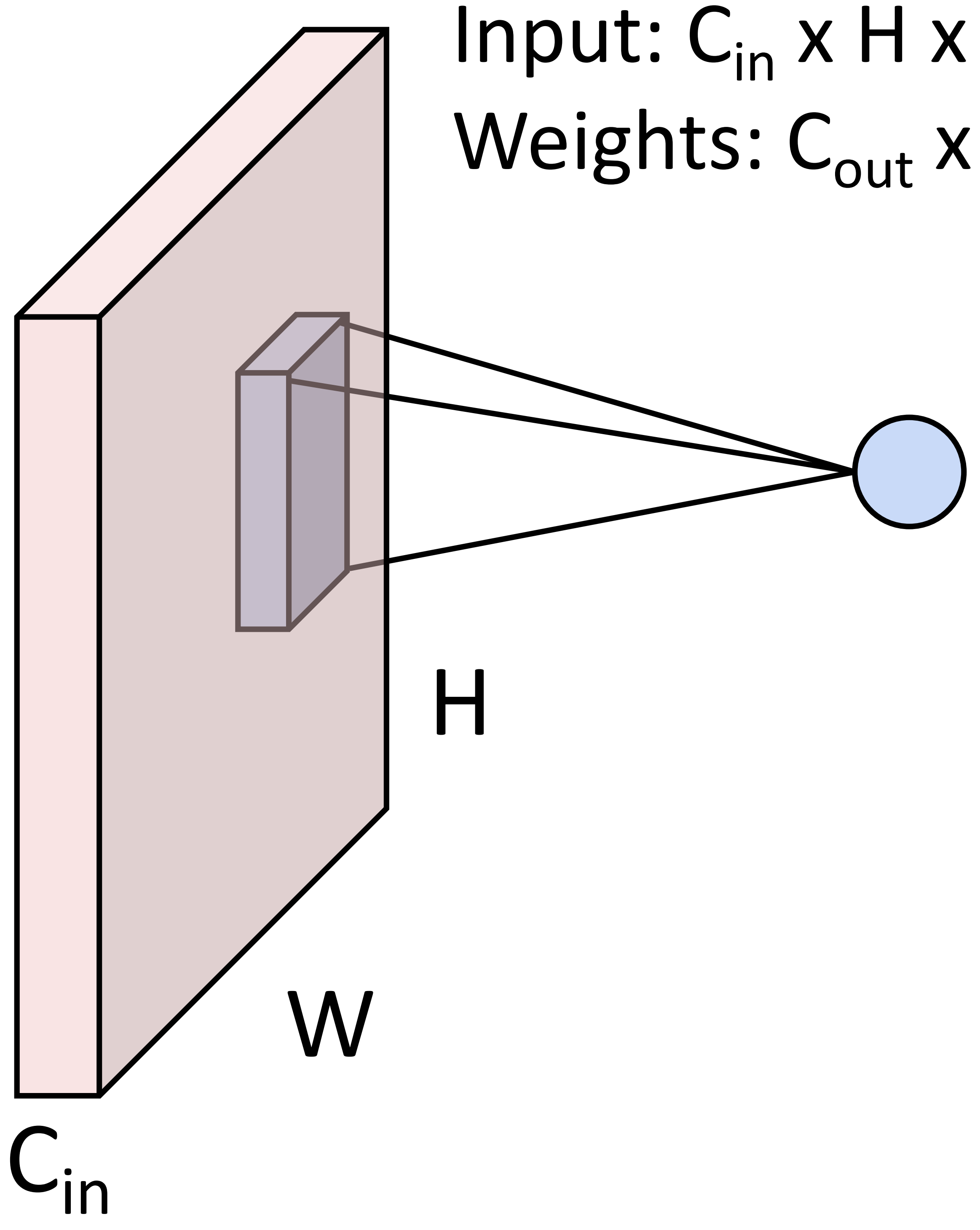
Input: C_{in} x W
Weights: C_{out} x C_{in} x K



Other types of convolution

So far: 2D Convolution

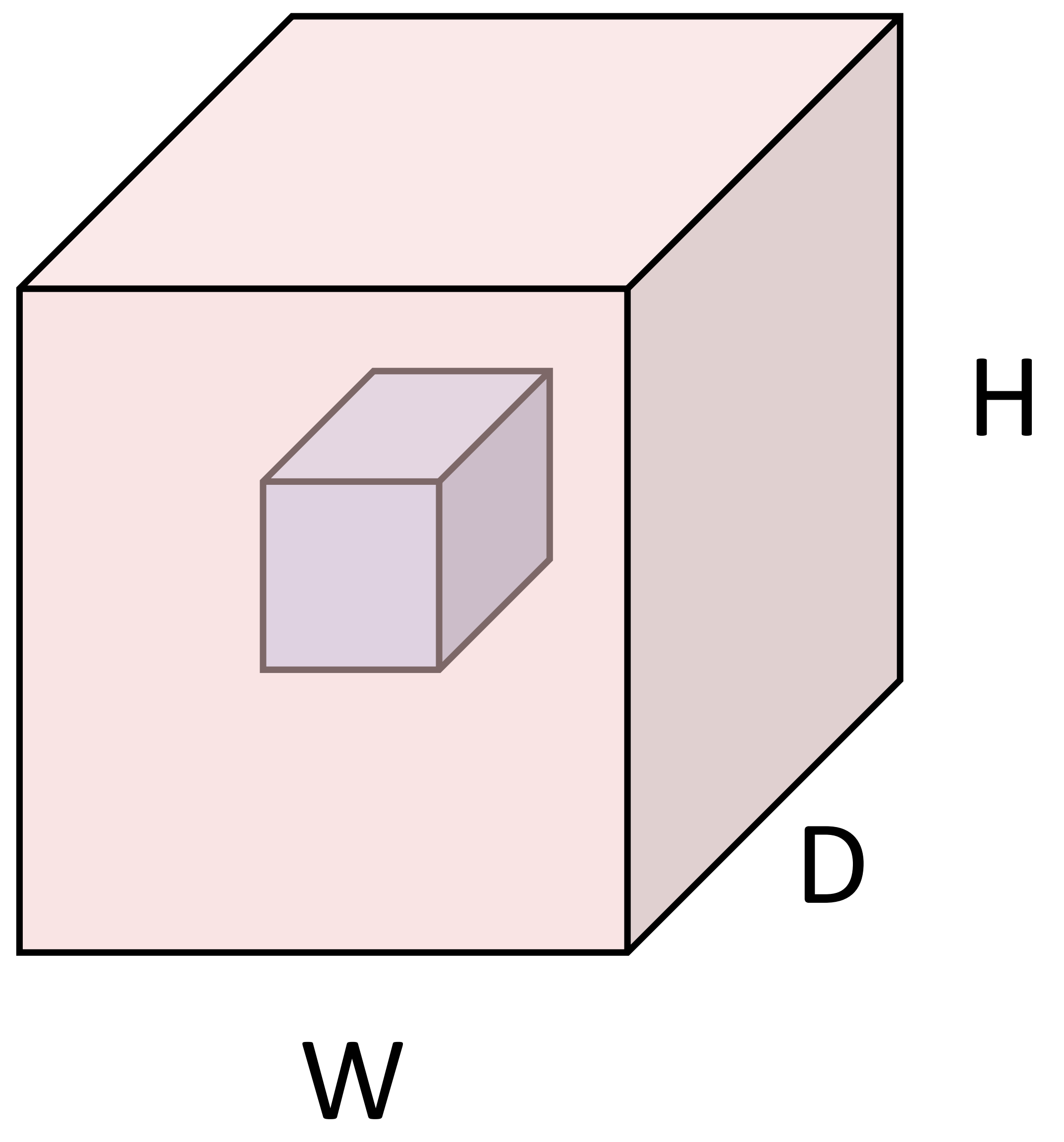
Input: C_{in} x H x W
Weights: C_{out} x C_{in} x K x K



3D Convolution

Input: C_{in} x H x W x D
Weights: C_{out} x C_{in} x K x K x K

C_{in}-dim vector at each point in the volume



PyTorch Convolution Layer

Conv2d

CLASS `torch.nn.Conv2d(in_channels, out_channels, kernel_size, stride=1, padding=0, dilation=1, groups=1, bias=True, padding_mode='zeros')` [SOURCE]

Applies a 2D convolution over an input signal composed of several input planes.

In the simplest case, the output value of the layer with input size (N, C_{in}, H, W) and output $(N, C_{\text{out}}, H_{\text{out}}, W_{\text{out}})$ can be precisely described as:

$$\text{out}(N_i, C_{\text{out}_j}) = \text{bias}(C_{\text{out}_j}) + \sum_{k=0}^{C_{\text{in}}-1} \text{weight}(C_{\text{out}_j}, k) \star \text{input}(N_i, k)$$

PyTorch Convolution Layer

Conv2d

CLASS `torch.nn.Conv2d(in_channels, out_channels, kernel_size, stride=1, padding=0, dilation=1, groups=1, bias=True, padding_mode='zeros')` [SOURCE]

Conv1d

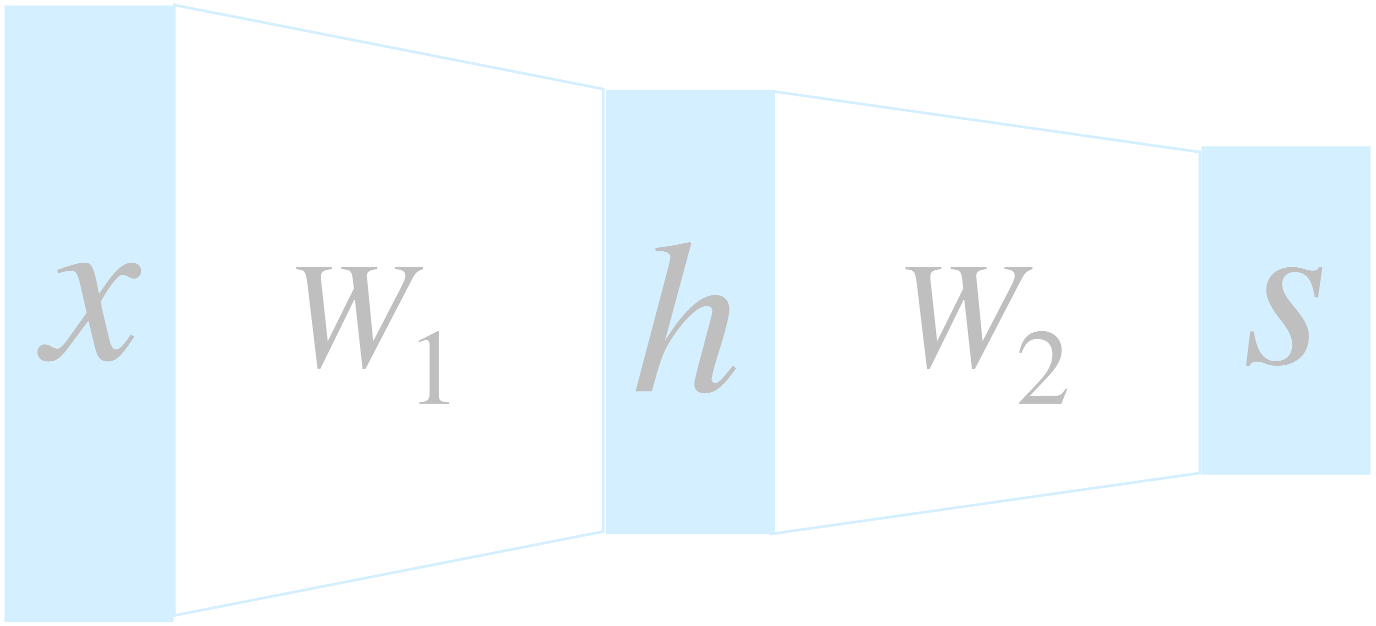
CLASS `torch.nn.Conv1d(in_channels, out_channels, kernel_size, stride=1, padding=0, dilation=1, groups=1, bias=True, padding_mode='zeros')` [SOURCE]

Conv3d

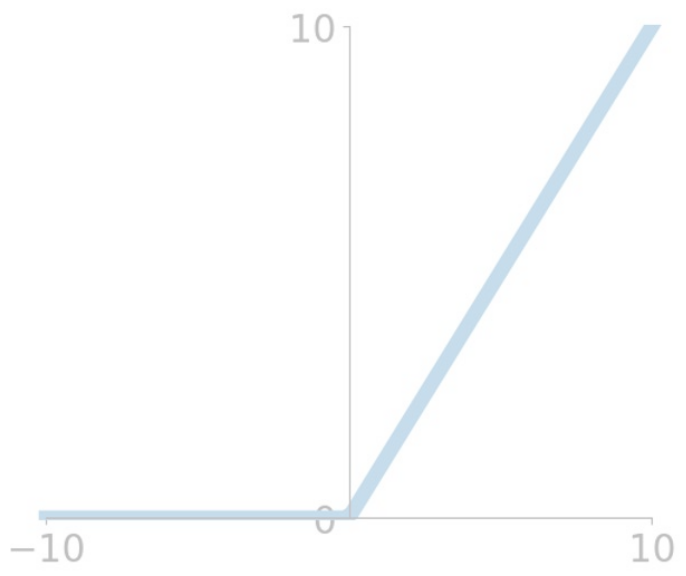
CLASS `torch.nn.Conv3d(in_channels, out_channels, kernel_size, stride=1, padding=0, dilation=1, groups=1, bias=True, padding_mode='zeros')` [SOURCE]

Components of Convolutional Neural Networks

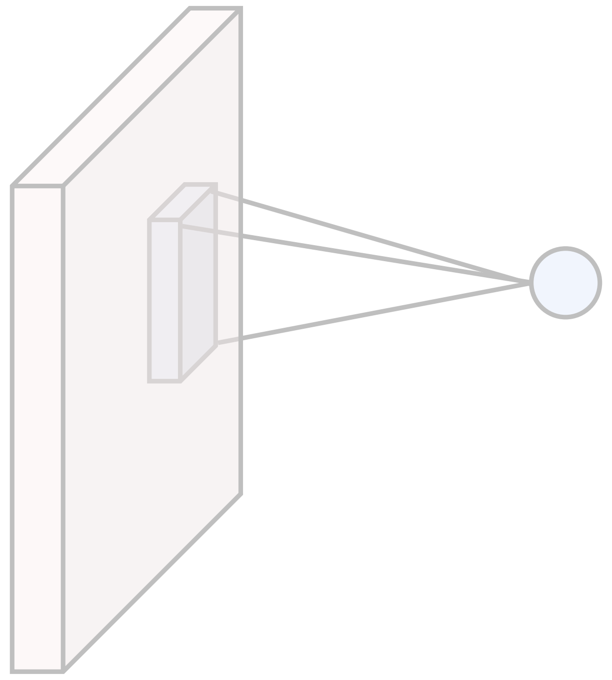
Fully-Connected Layers



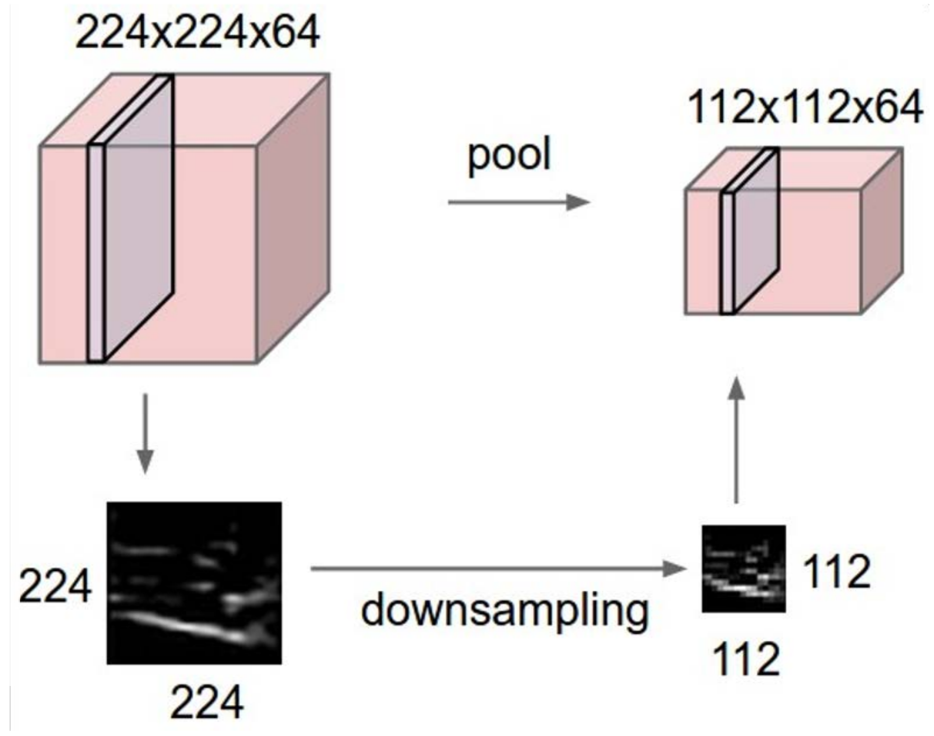
Activation Functions



Convolution Layers



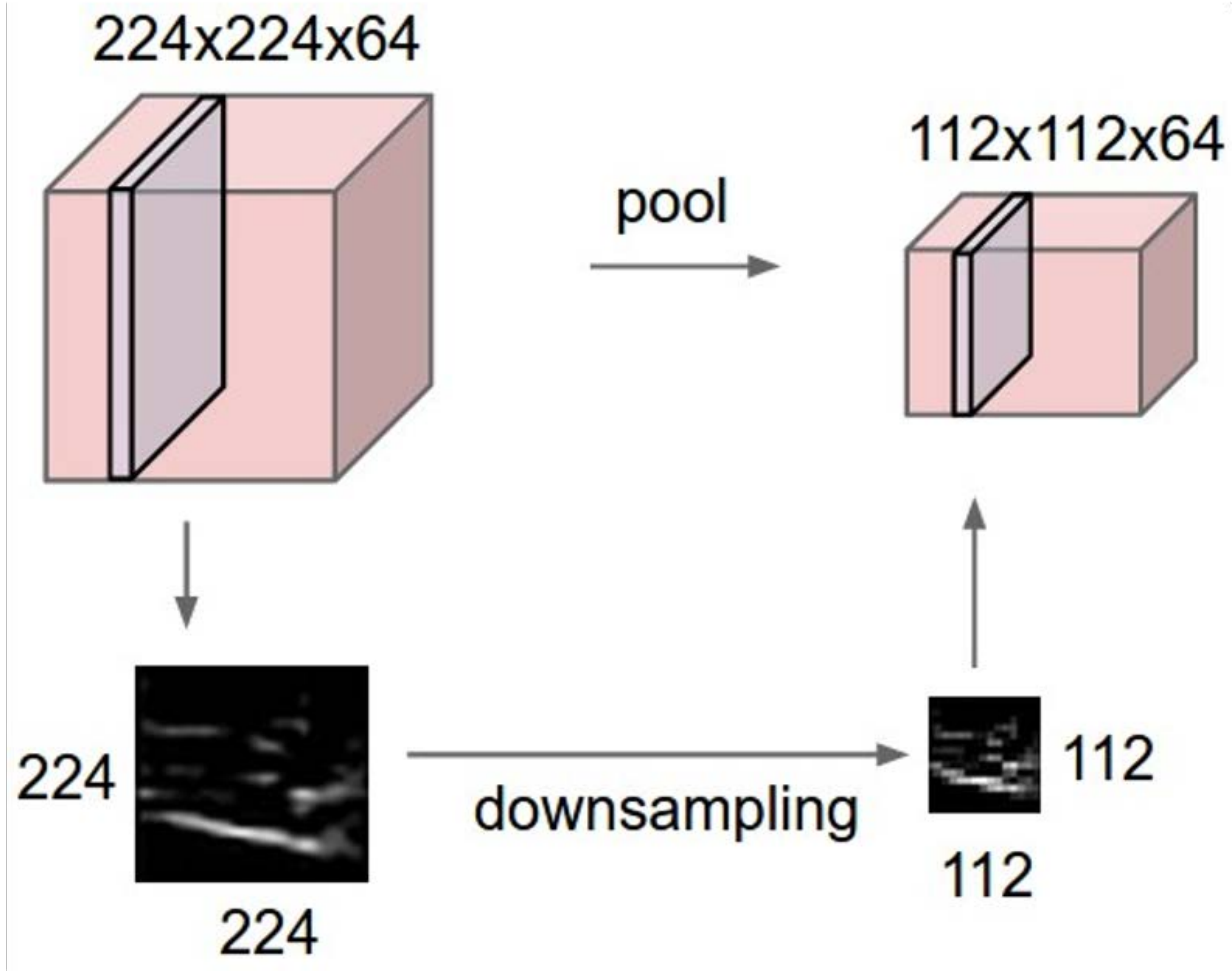
Pooling Layers



Normalization

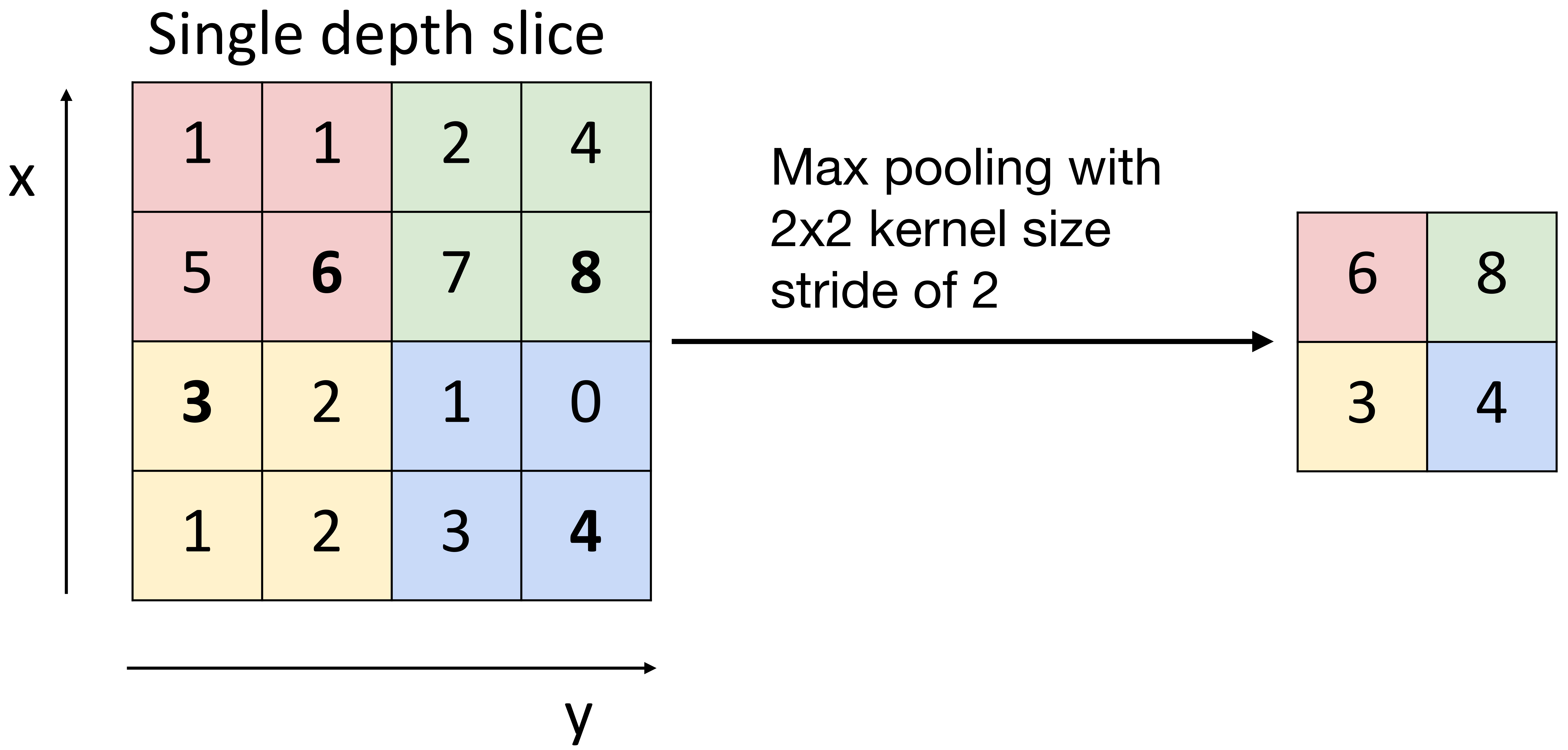
$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Pooling Layers: Another way to downsample

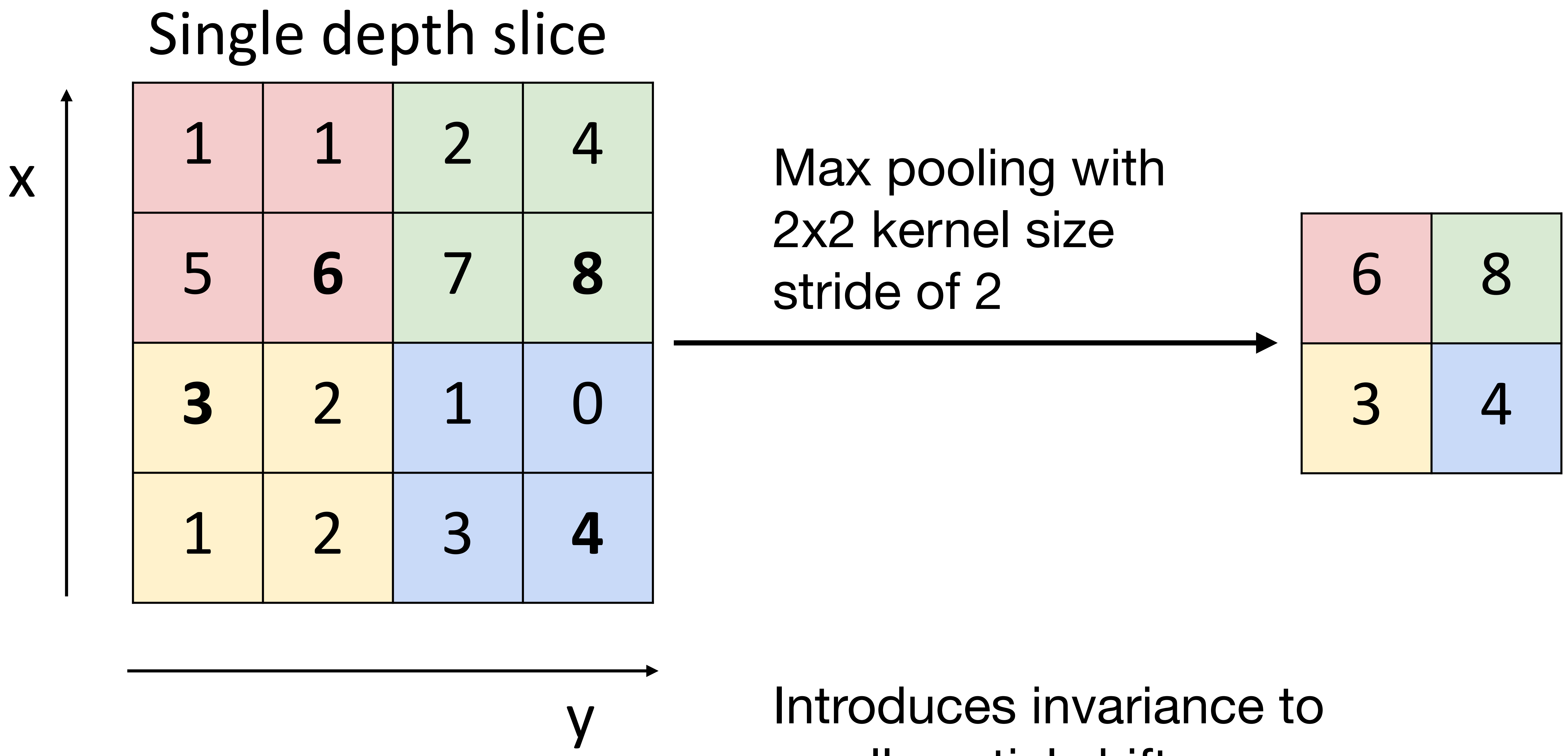


Hyperparameters:
Kernel size
Stride
Pooling function

Max Pooling


Single depth slice
x
y
1 1 2 4
5 6 7 8
3 2 1 0
1 2 3 4
Max pooling with
2x2 kernel size
stride of 2
6 8
3 4

Max Pooling



Introduces invariance to small spatial shifts

No learnable parameters!

Pooling Summary

Input: C x H x W

Hyperparameters:

- Kernel size: K
- Stride: S
- Pooling function (max, avg)

Output: C x H’ x W’ where

- H’ = (H – K) / S + 1
- W’ = (W – K) / S + 1

Learnable parameters: None!

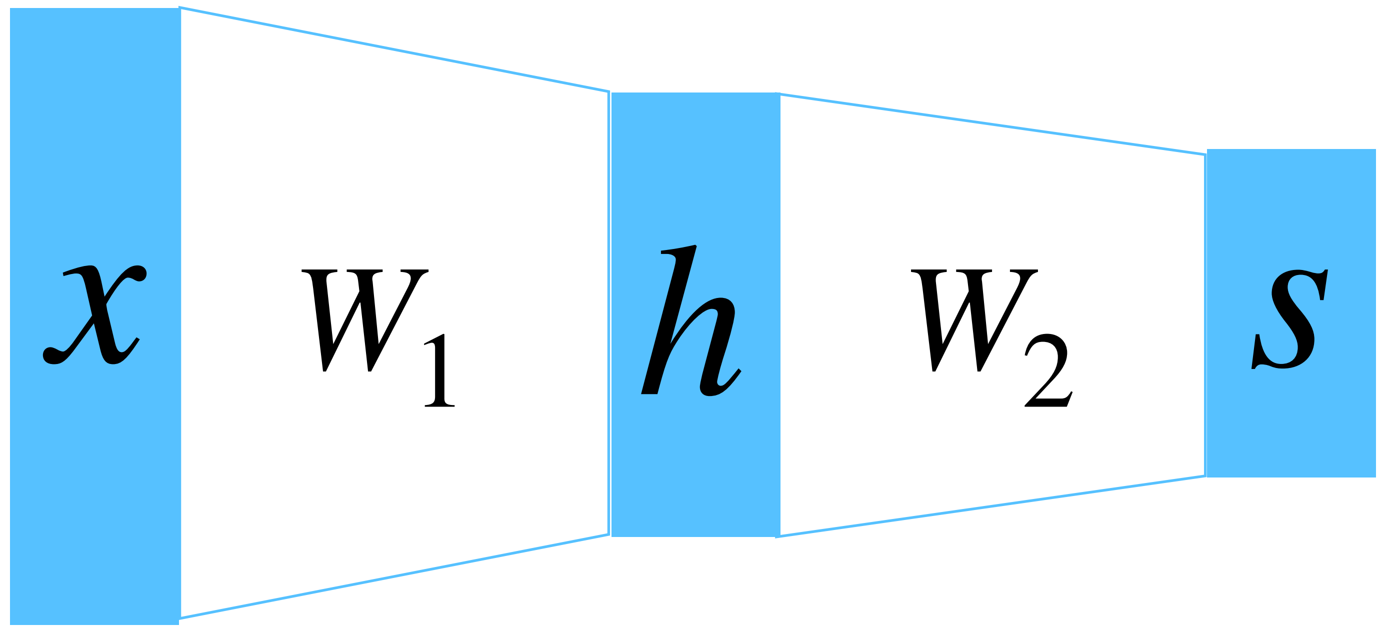
Common settings:

max, K = 2, S = 2

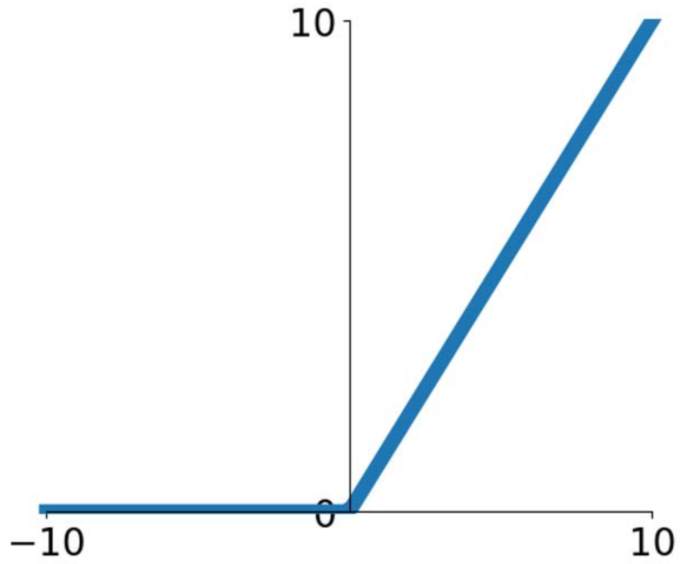
max, K = 3, S = 2 (AlexNet)

Components of Convolutional Neural Networks

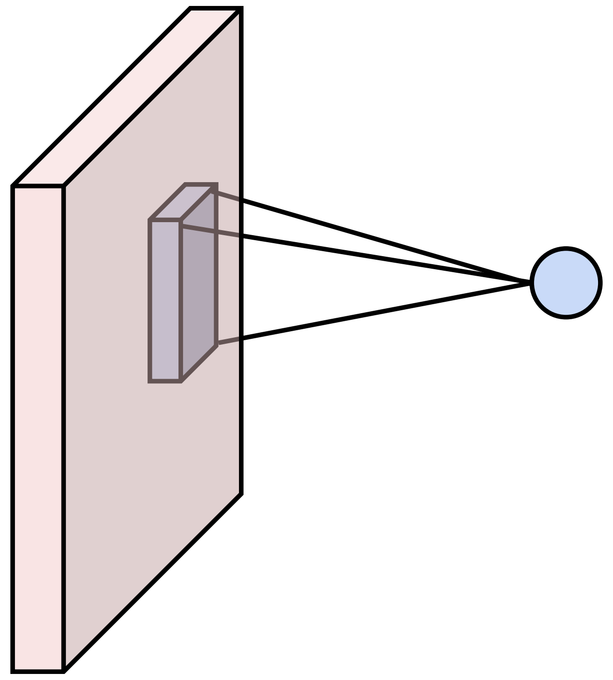
Fully-Connected Layers



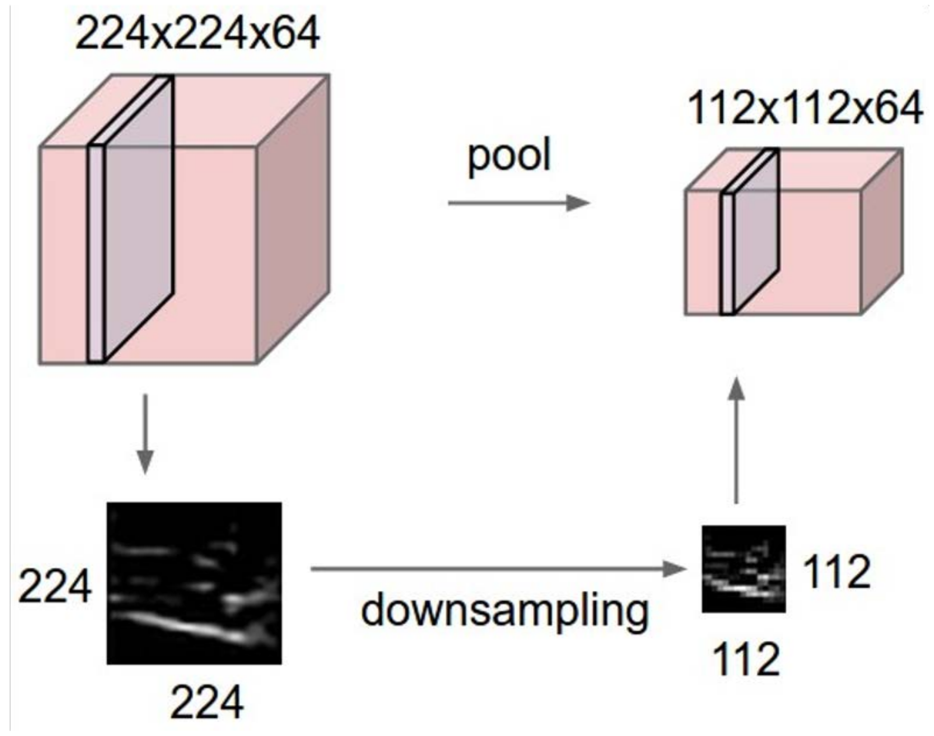
Activation Functions



Convolution Layers



Pooling Layers



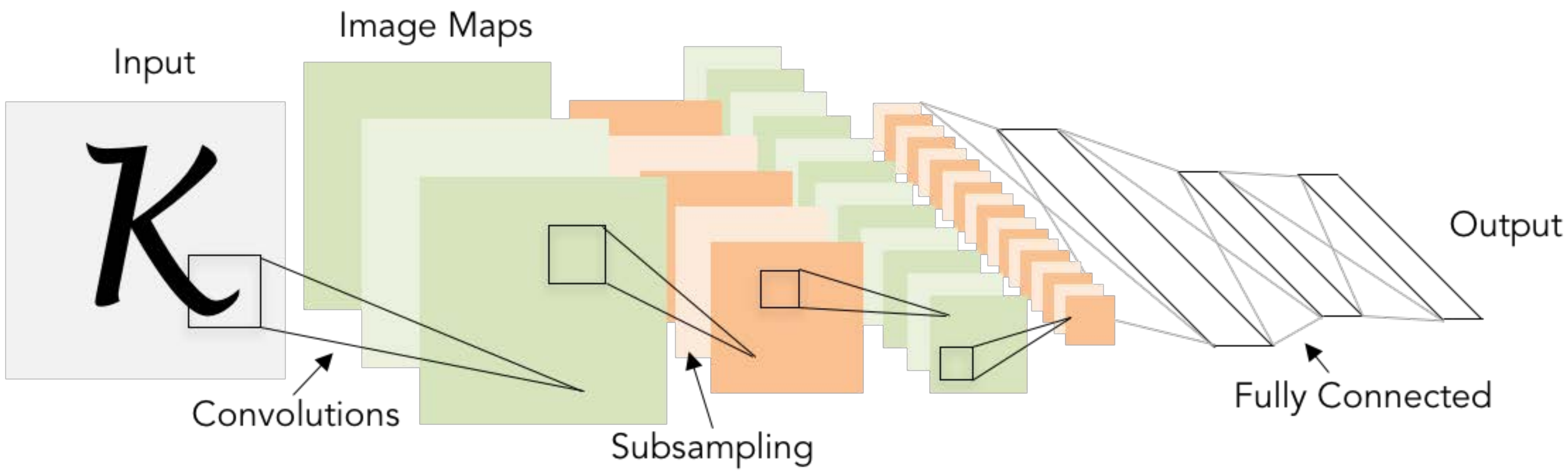
Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Convolutional Neural Networks

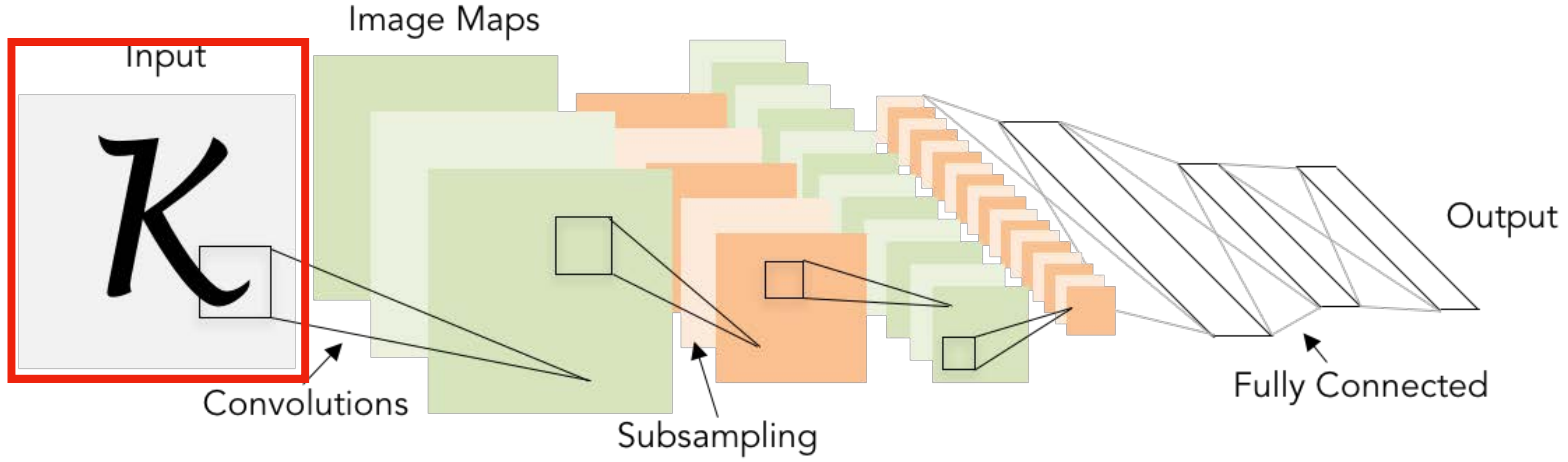
Classic architecture: [Conv, ReLU, Pool] x N, flatten, [FC, ReLU] x N, FC

Example: LeNet-5



Example: LeNet-5

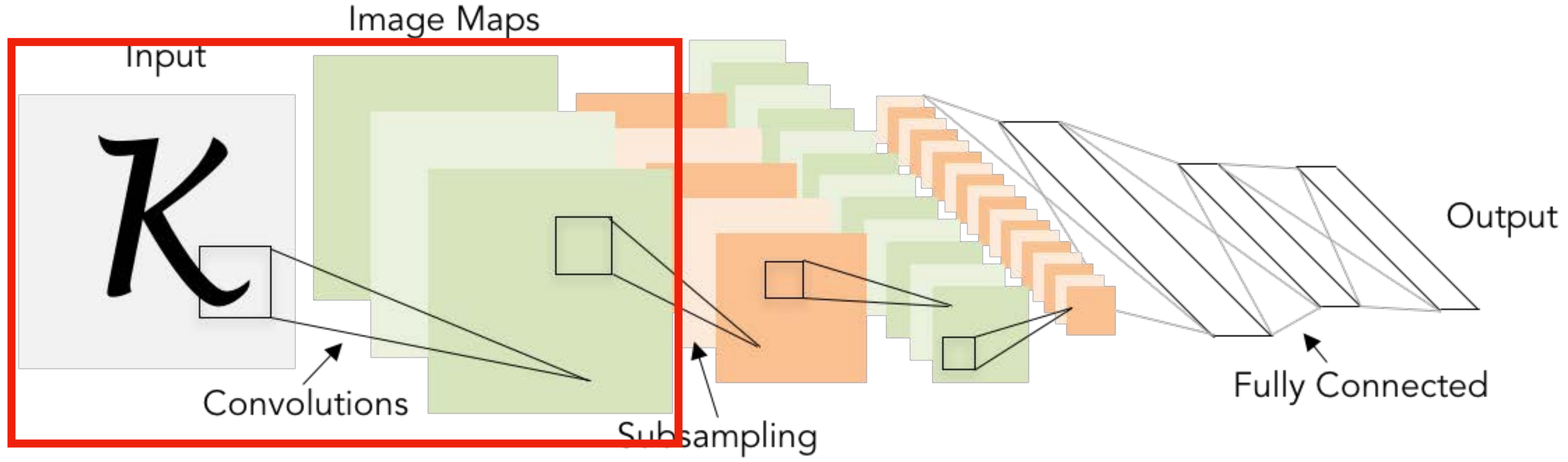
Layer	Output Size	Weight Size
Input	1 x 28 x 28	



Lecun et al., "Gradient-based learning applied to document recognition", 1998

Example: LeNet-5

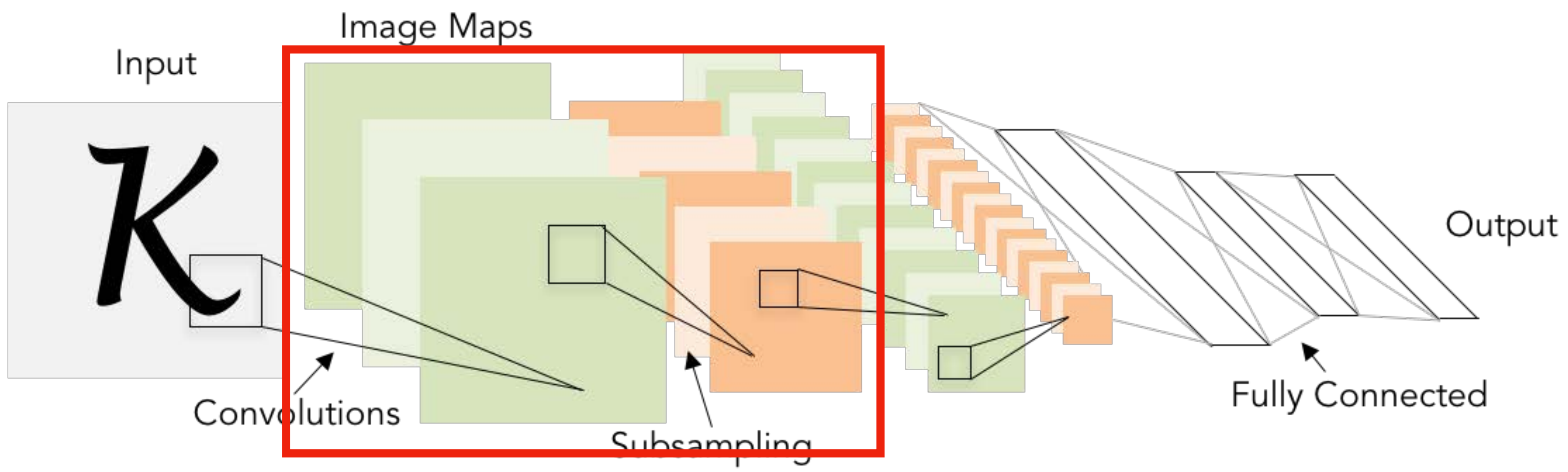
Layer	Output Size	Weight Size
Input	1 x 28 x 28	
Conv (C_{out}=20, K=5, P=2, S=1)	20 x 28 x 28	20 x 1 x 5 x 5
ReLU	20 x 28 x 28	



Lecun et al., "Gradient-based learning applied to document recognition", 1998

Example: LeNet-5

Layer	Output Size	Weight Size
Input	1 x 28 x 28	
Conv (C_{out}=20, K=5, P=2, S=1)	20 x 28 x 28	20 x 1 x 5 x 5
ReLU	20 x 28 x 28	
MaxPool(K=2, S=2)	20 x 14 x 14	



Lecun et al., "Gradient-based learning applied to document recognition", 1998

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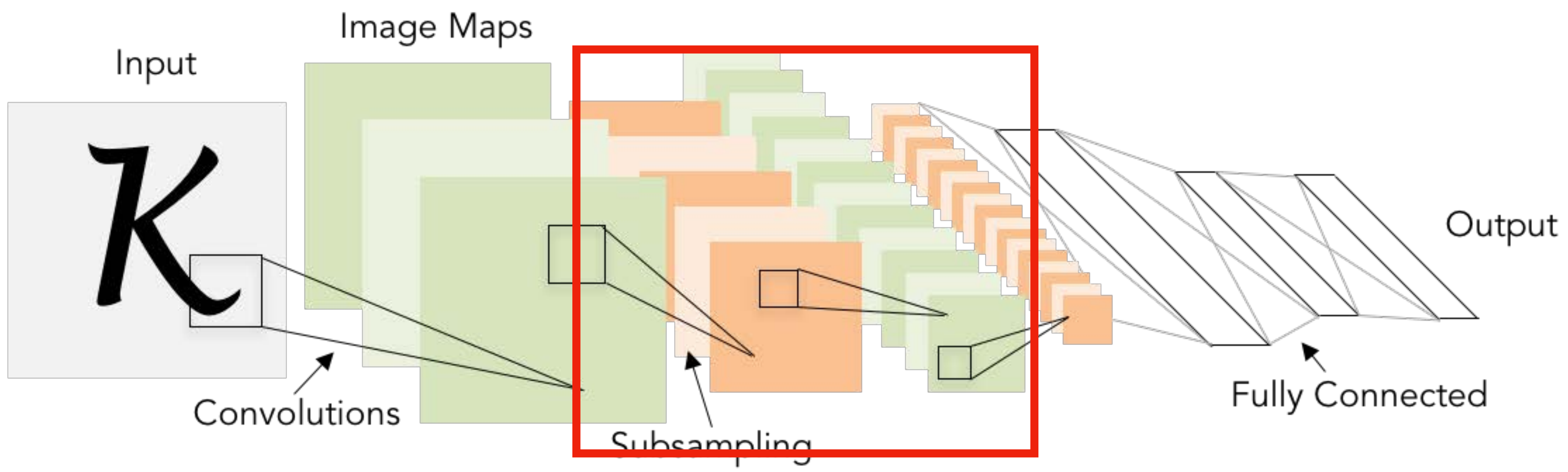
Conv (C_{out}=20, K=5, P=2, S=1)	20 x 28 x 28	20 x 1 x 5 x 5
ReLU	20 x 28 x 28	
MaxPool(K=2, S=2)	20 x 14 x 14	
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	



Lecun et al., "Gradient-based learning applied to document recognition", 1998

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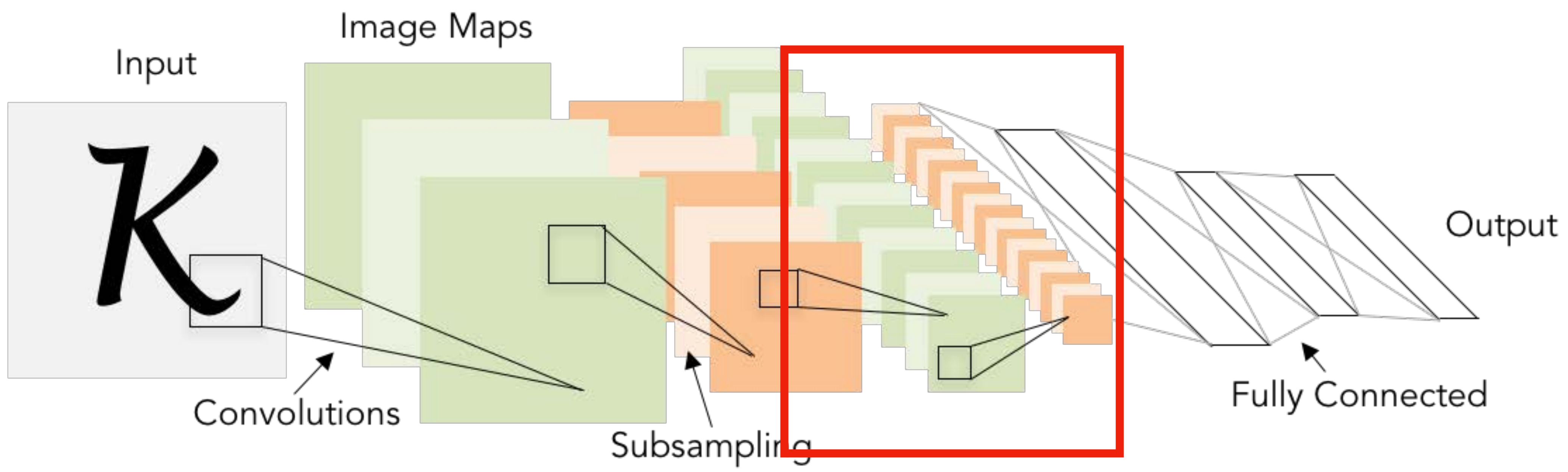
MaxPool(K=2, S=2)	20 x 14 x 14	
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	



Lecun et al., "Gradient-based learning applied to document recognition", 1998

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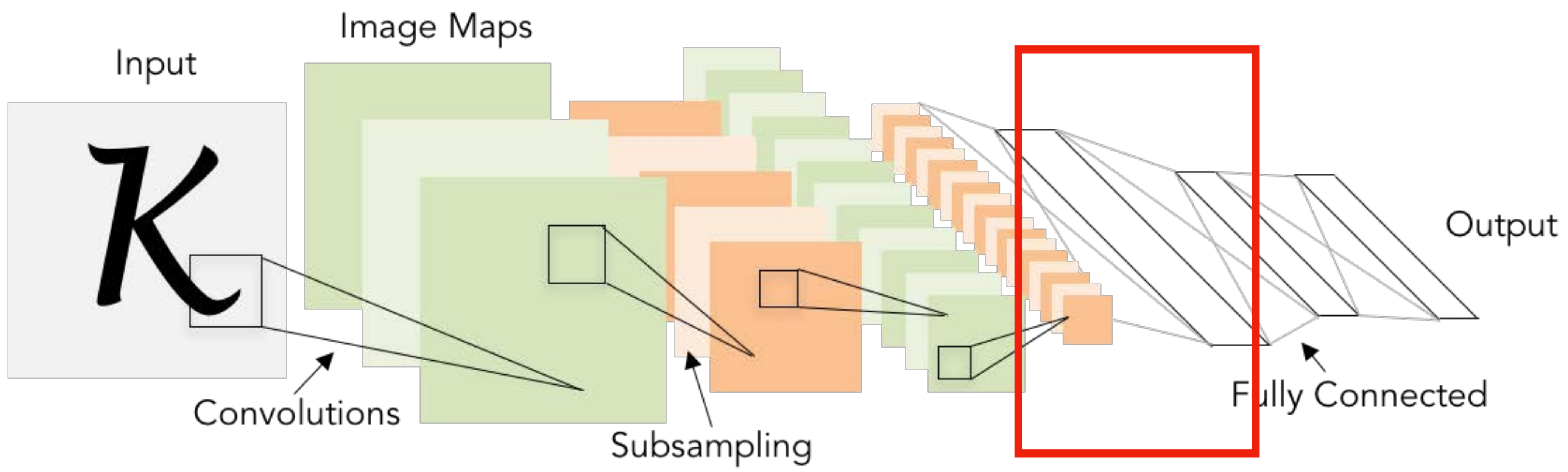
MaxPool(K=2, S=2)	20 x 14 x 14	
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	
Flatten	2450	



Lecun et al., “Gradient-based learning applied to document recognition”, 1998

Example: LeNet-5

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Input	1 x 28 x 28	
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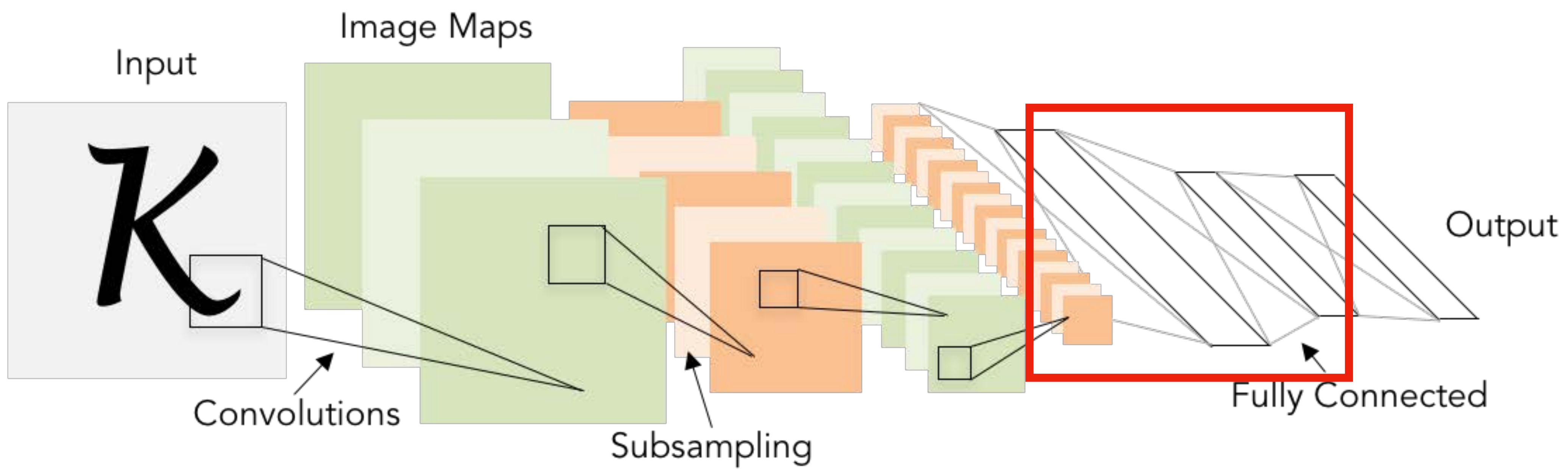
ReLU	20 x 28 x 28	
MaxPool(K=2, S=2)	20 x 14 x 14	
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	
Flatten	2450	
Linear (2450 -> 500)	500	2450 x 500
ReLU	500	



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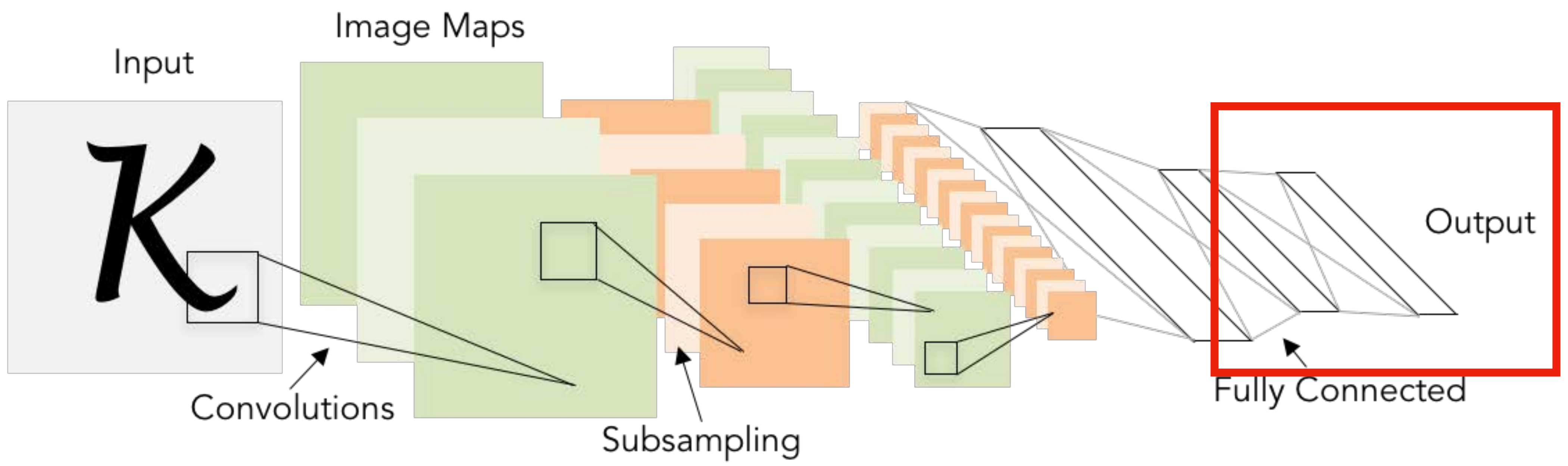
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	
Flatten	2450	
Linear (2450 -> 500)	500	2450 x 500
ReLU	500	
Linear (500 -> 10)	10	500 x 10



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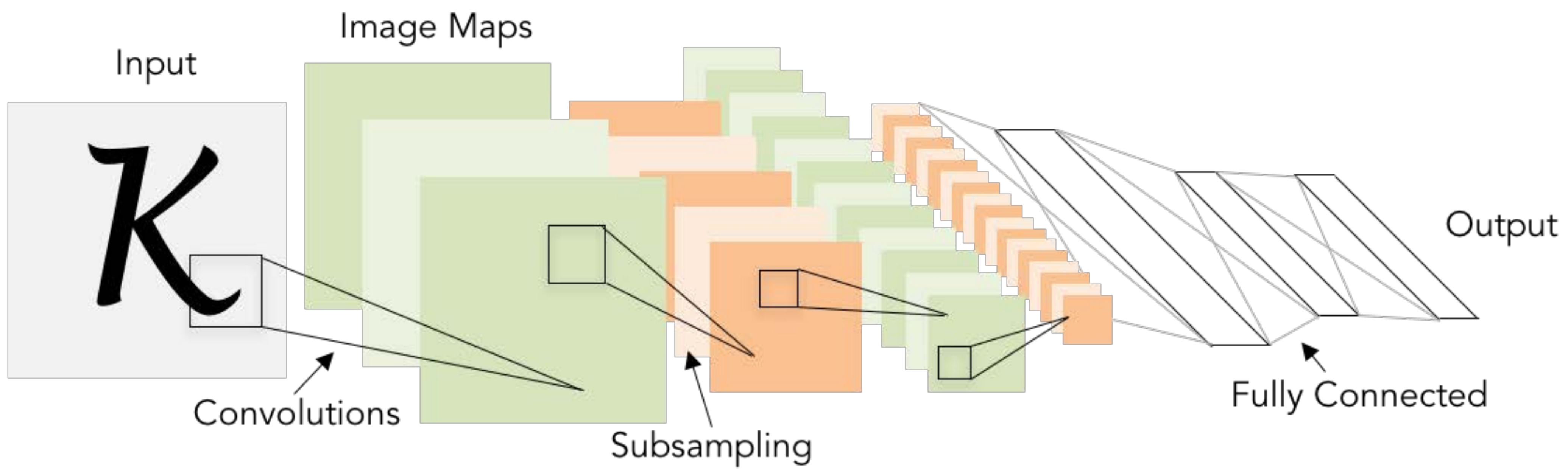
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	
Flatten	2450	
Linear (2450 -> 500)	500	2450 x 500
ReLU	500	
Linear (500 -> 10)	10	500 x 10



As we progress through the network:

Spatial size **decreases**
(using pooling or striped convolution)

Number of channels **increases**
(total “volume” is preserved!)

Lecun et al., “Gradient-based learning applied to document recognition”, 1998

Example: LeNet-5

Layer	Output Size	Weight Size
Input	1 x 28 x 28	
Conv (C_{out}=20, K=5, P=2, S=1)	20 x 28 x 28	20 x 1 x 5 x 5
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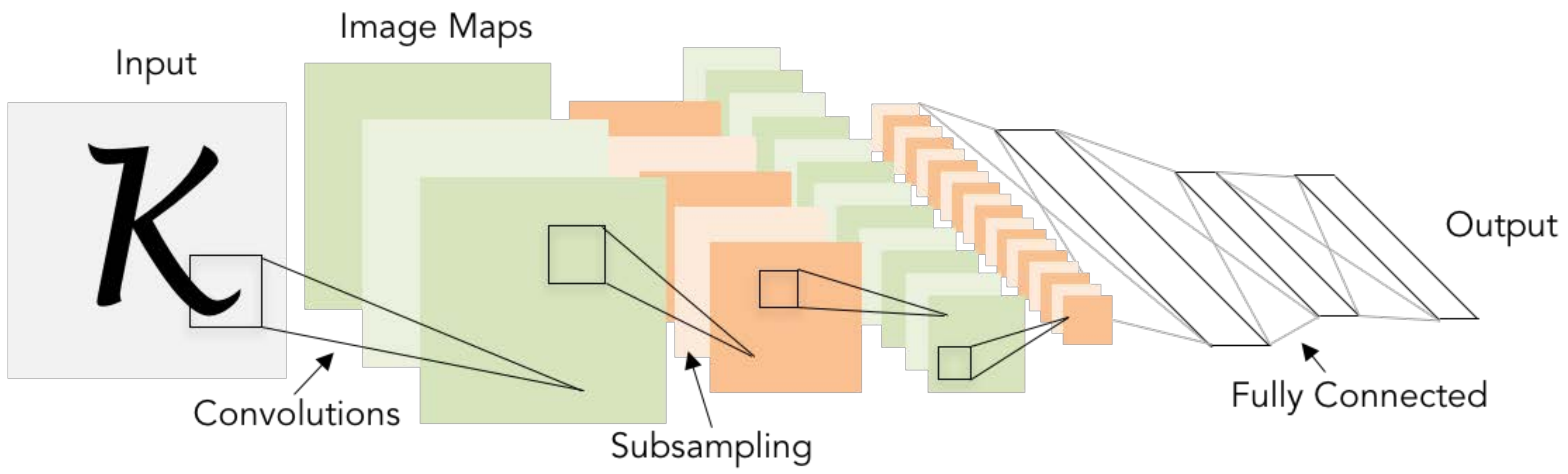
Conv (C_{out}=50, K=5, P=2, S=1)	50 x 14 x 14	50 x 20 x 5 x 5
ReLU	50 x 14 x 14	
MaxPool(K=2, S=2)	50 x 7 x 7	
Flatten	2450	
Linear (2450 -> 500)	500	2450 x 500
ReLU	500	
Linear (500 -> 10)	10	500 x 10



As we progress through the network:

Spatial size **decreases**
(using pooling or striped convolution)

Number of channels **increases**
(total “volume” is preserved!)

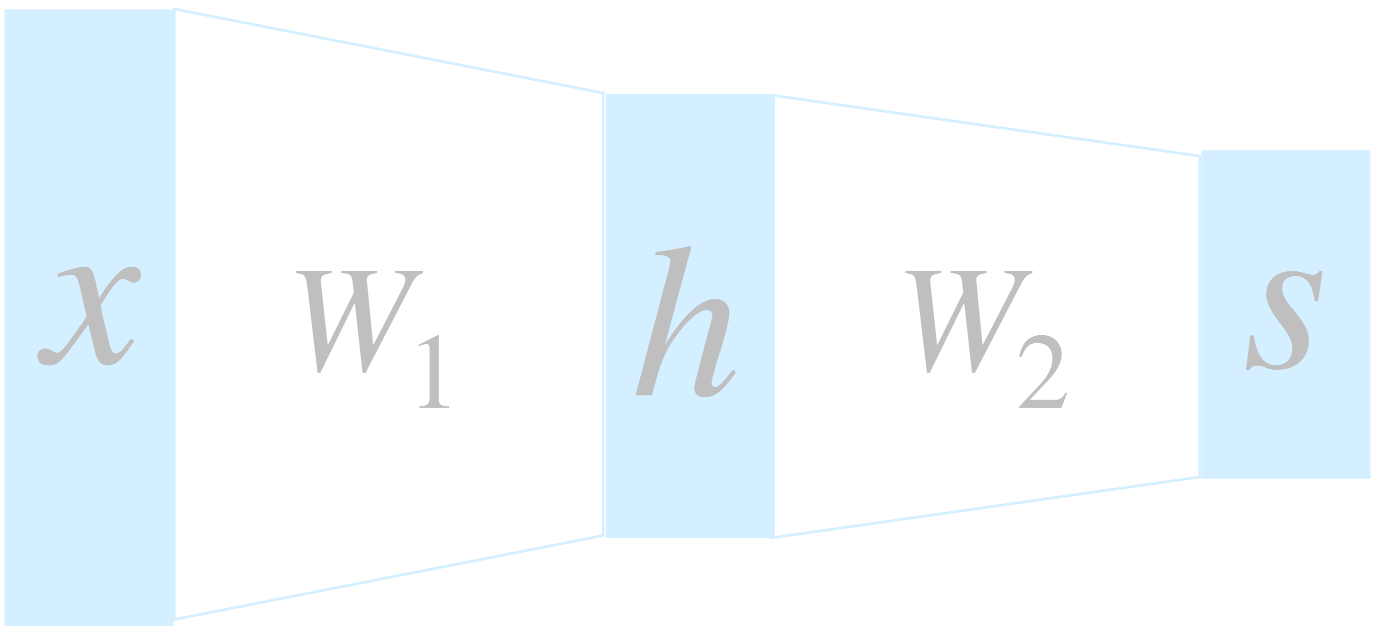
Some modern architectures
break this trend—stay tuned!

Lecun et al., “Gradient-based learning applied to document recognition”, 1998

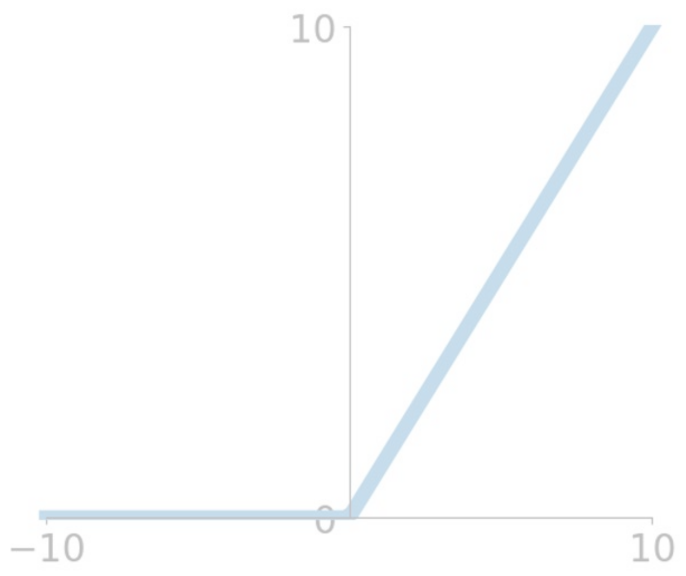
Problem: Deep Networks very hard to train

Components of Convolutional Neural Networks

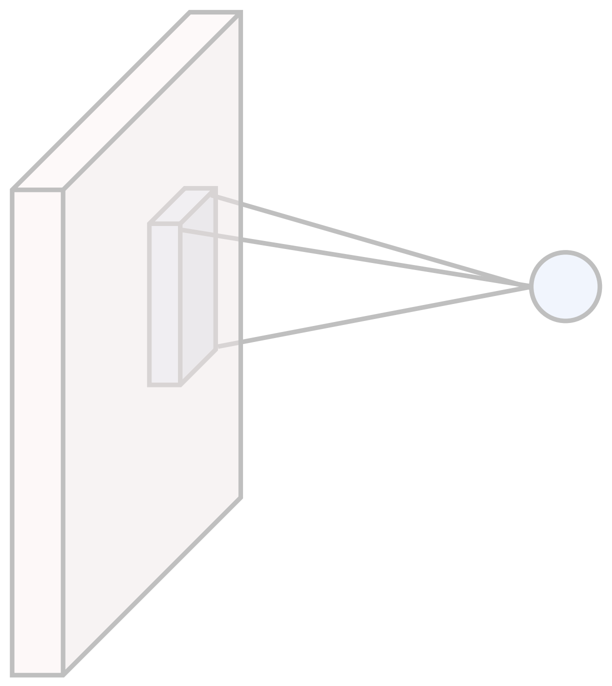
Fully-Connected Layers



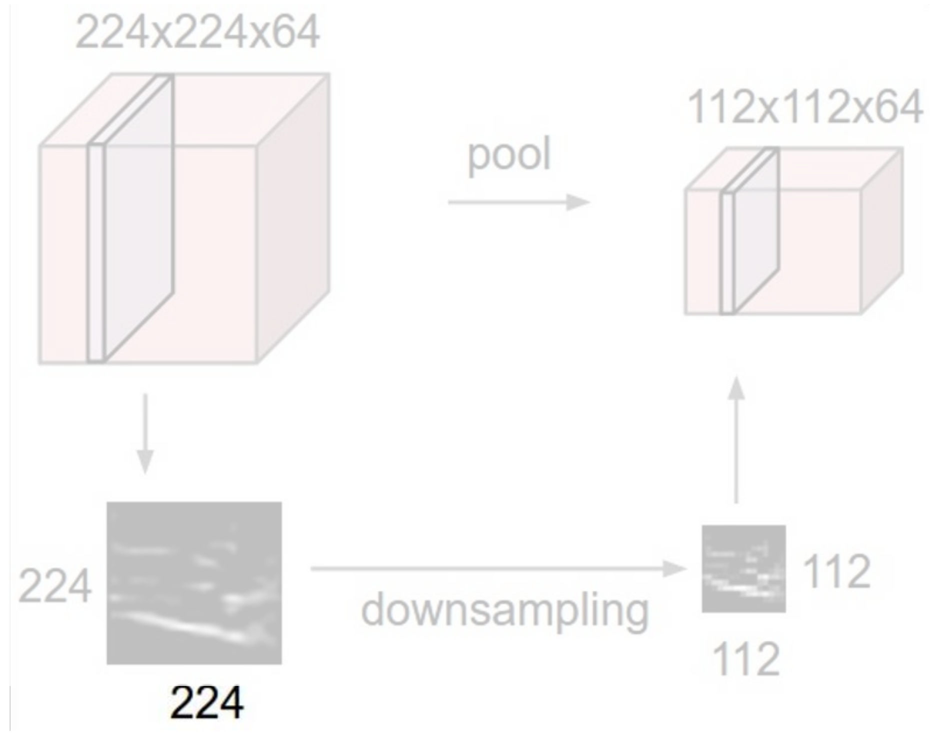
Activation Functions



Convolution Layers



Pooling Layers



Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

Batch Normalization

Idea: "Normalize" the outputs of a layer so they have zero mean and unit variance

Why? Helps reduce "internal covariate shift", improves optimization results

We can normalize a batch of activations using:

$$\hat{x} = \frac{x - E[x]}{\sqrt{Var[x]}}$$

Ioffe and Szegedy, "Batch normalization: Accelerating deep network training by reducing internal covariate shift", ICML 2015

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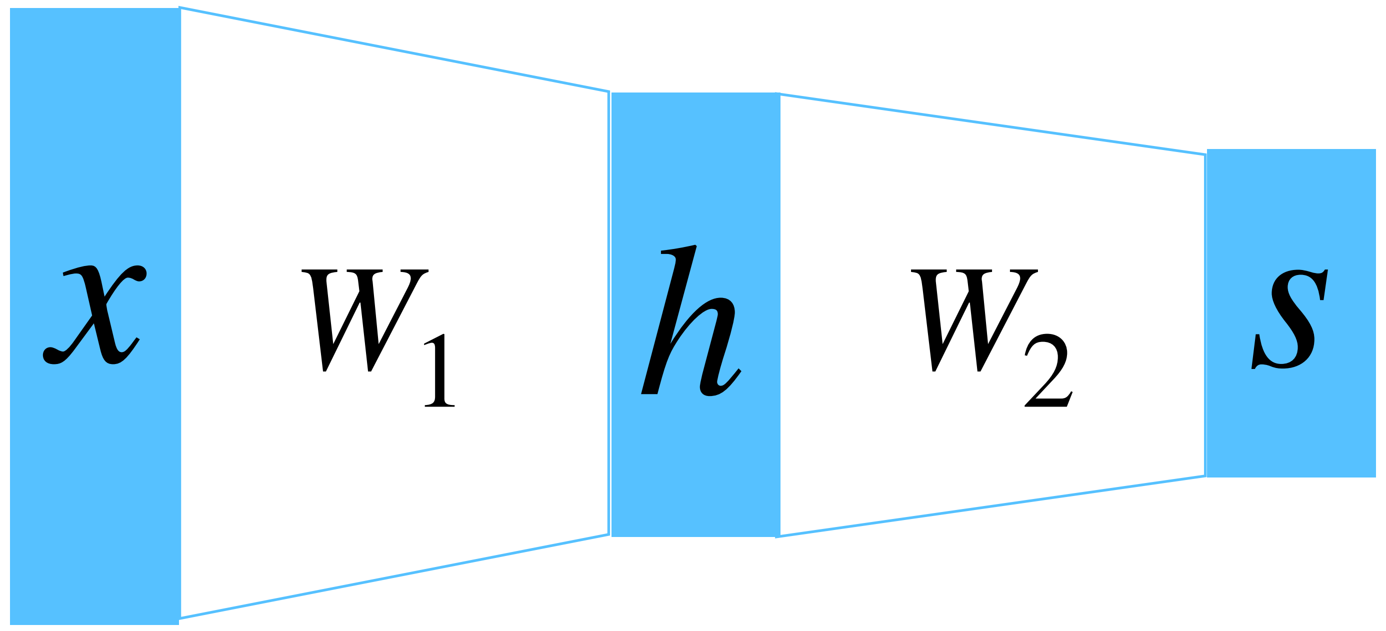
This is a **differentiable function**, so we can use it as an operator in our networks and backdrop through it!

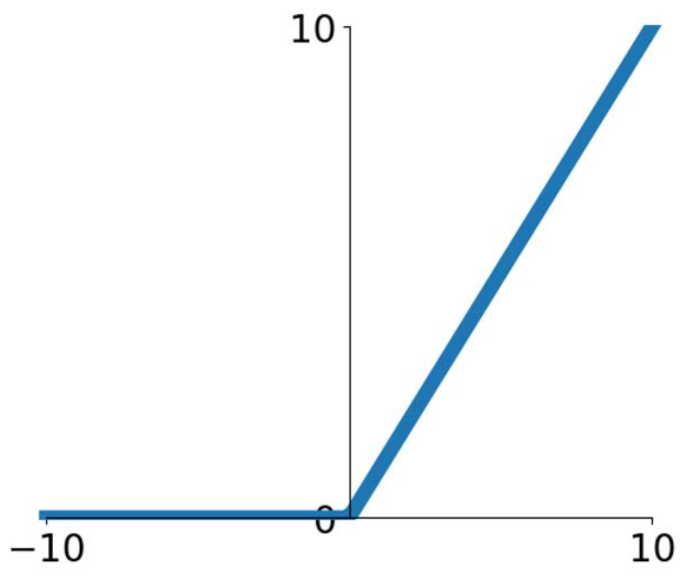
Ioffe and Szegedy, "Batch normalization: Accelerating deep network training by reducing internal covariate shift", ICML 2015

Summary: Components of Convolutional Network

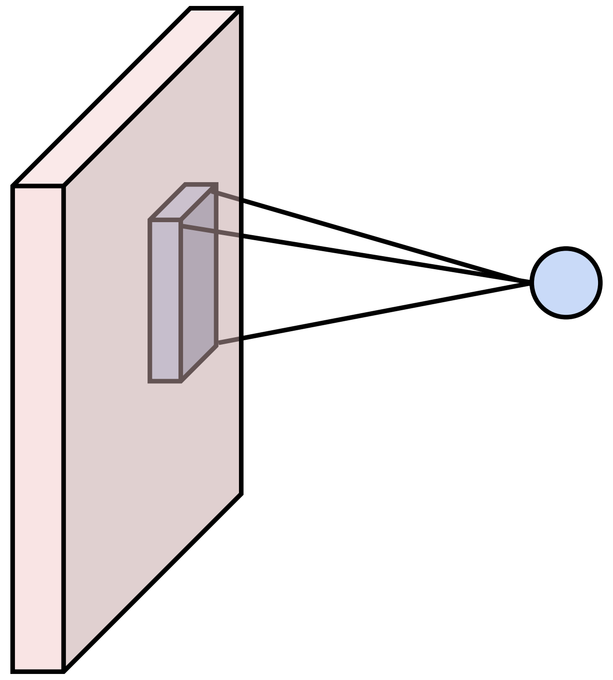
Fully-Connected Layers



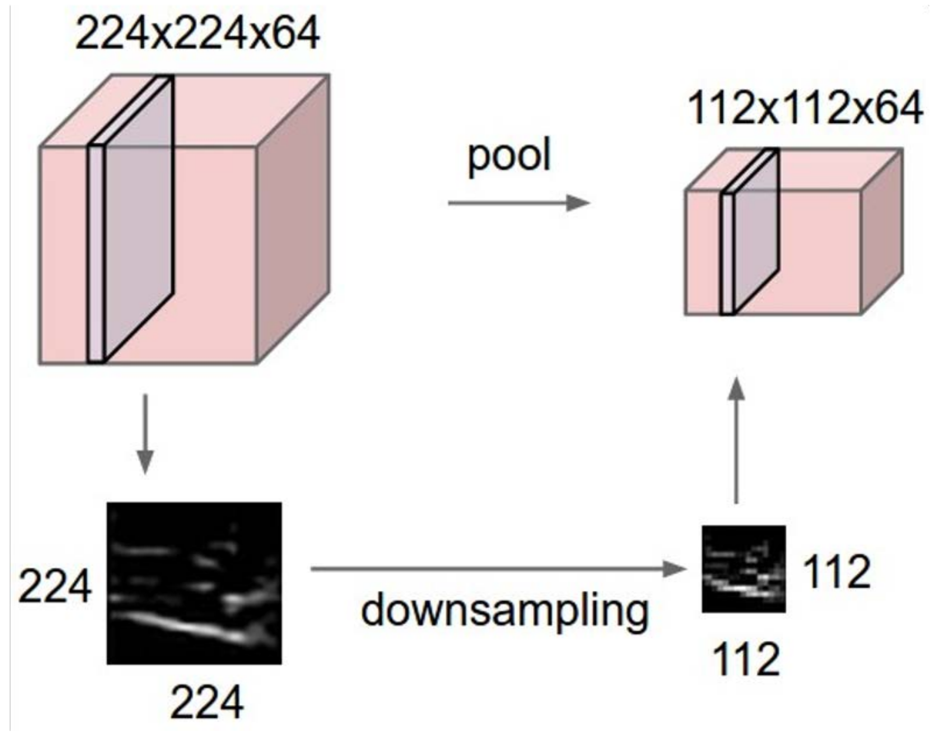
Activation Functions



Convolution Layers



Pooling Layers

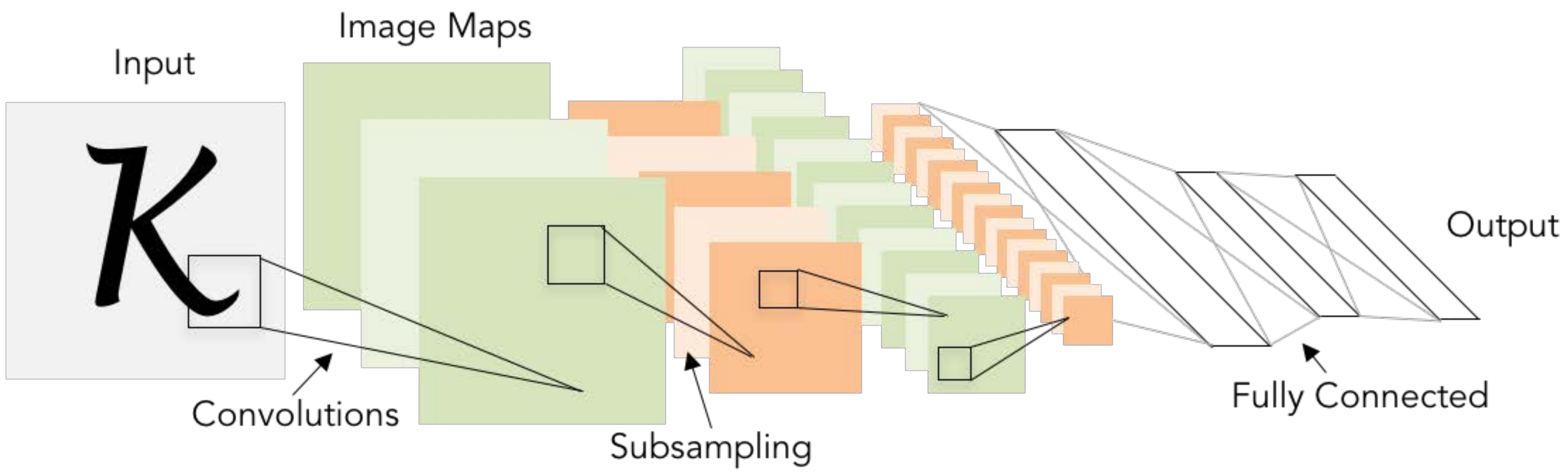


Normalization

$$\hat{x}_{i,j} = \frac{x_{i,j} - \mu_j}{\sqrt{\sigma_j^2 + \varepsilon}}$$

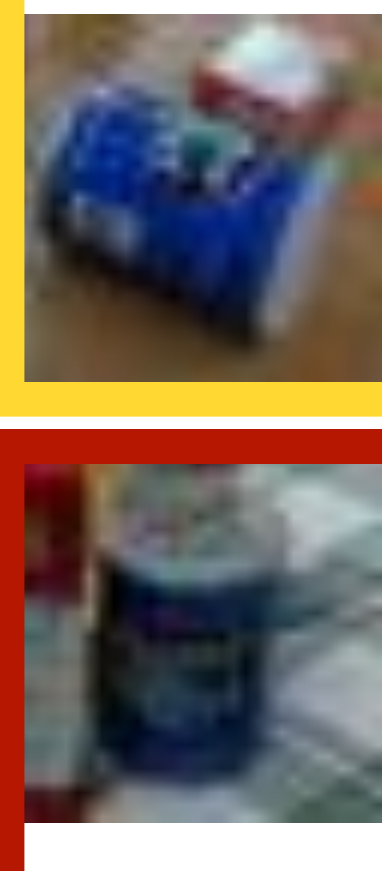
Summary: Components of Convolutional Network

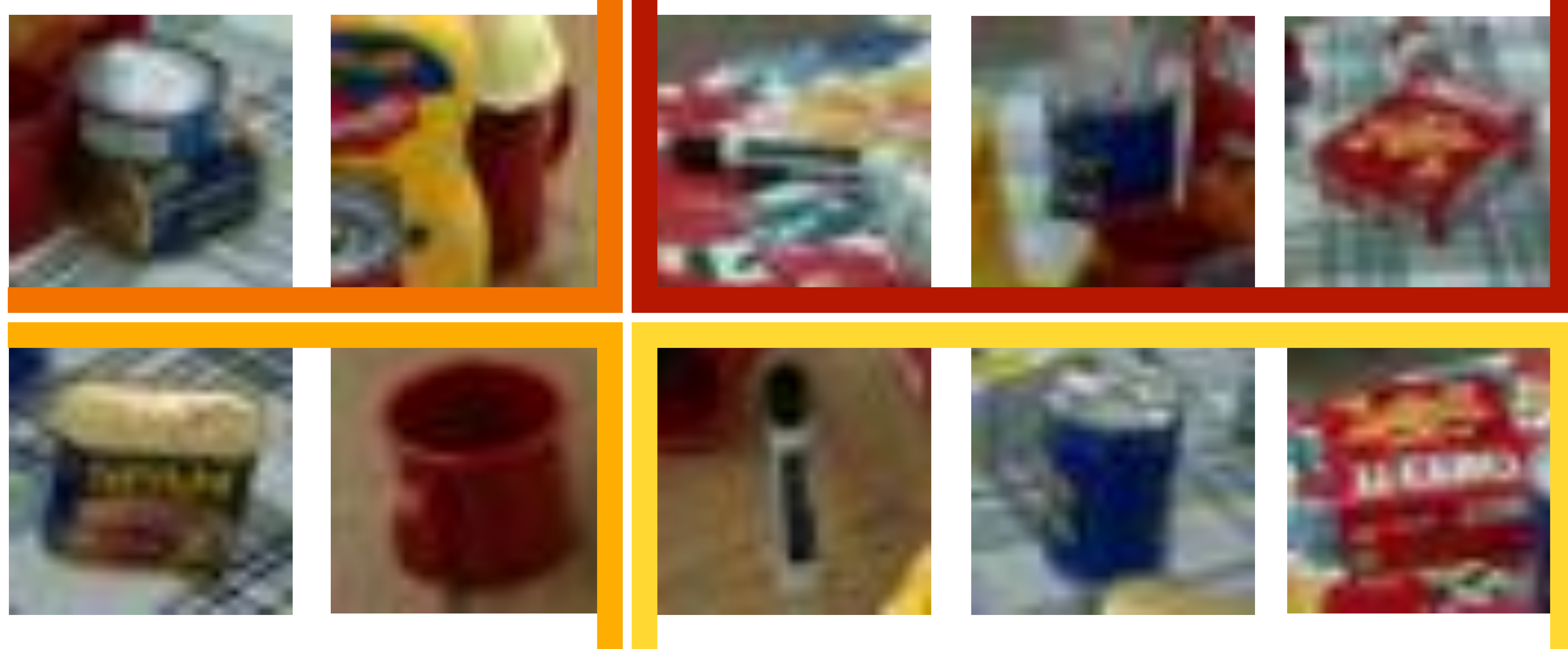
Problem: What is the right way to combine all these components?



Next time: CNN Architectures

DeepRob





Lecture 7
Convolutional Neural Networks
University of Minnesota