

Deep Neural Networks

Convolutional Networks II

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Fall 2025

Attendance: @681

Story so far

- Pattern classification tasks such as “does this picture contain a cat”, or “does this recording include HELLO” are best performed by scanning for the target pattern
- Scanning an input with a network and combining the outcomes is equivalent to scanning with individual neurons hierarchically
 - First level neurons scan the input
 - Higher-level neurons scan the “maps” formed by lower-level neurons
 - A final “decision” unit or subnetwork makes the final decision
- Deformations in the input can be handled by “pooling”
- For 2-D (or higher-dimensional) scans, the structure is called a convolutional network
- For 1-D scan along time, it is called a Time-delay neural network



A little history



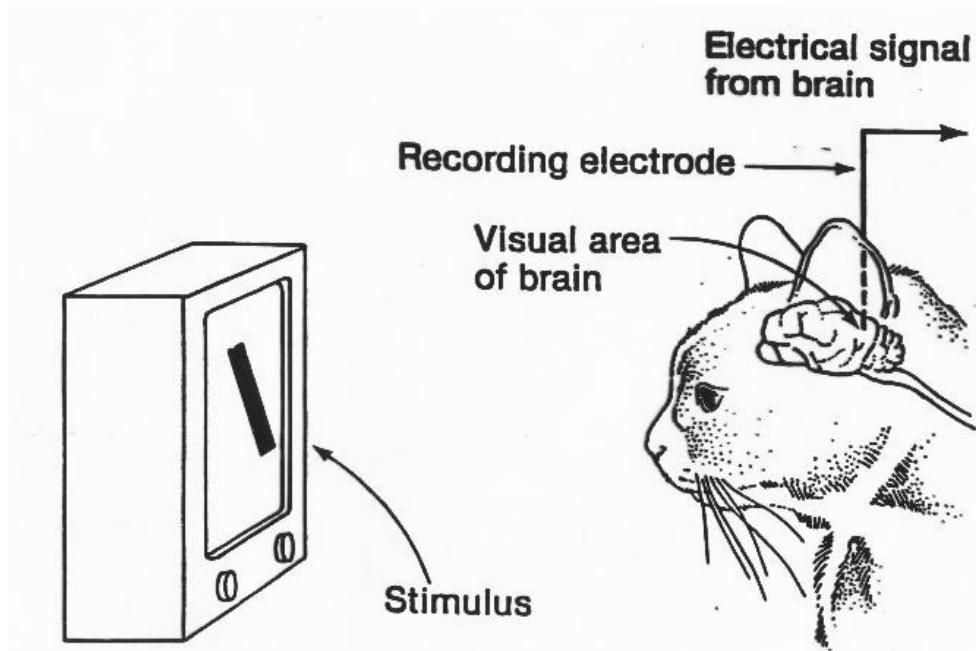
- How do animals see?
 - What is the neural process from eye to recognition?
- Early research:
 - largely based on behavioral studies
 - Study behavioral judgment in response to visual stimulation
 - Visual illusions
 - and gestalt
 - Brain has innate tendency to organize disconnected bits into whole objects
 - But no real understanding of how the brain processed images

Hubel and Wiesel 1959



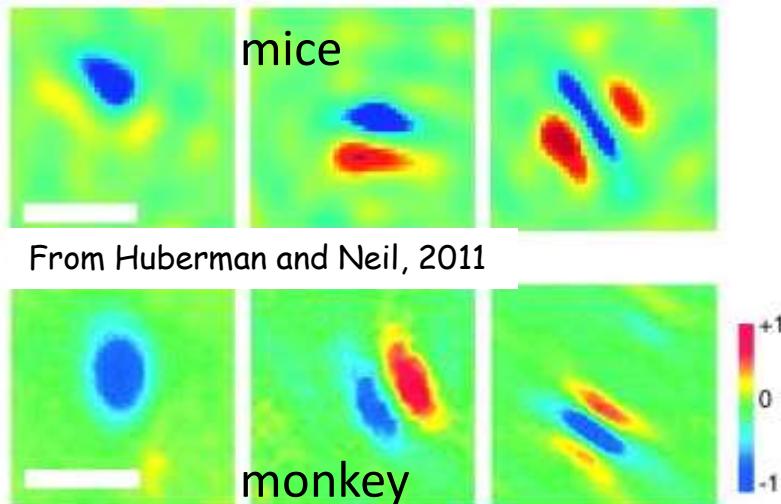
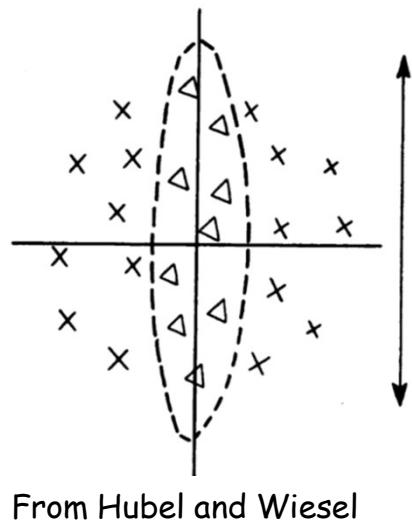
- First study on neural correlates of vision.
 - “Receptive Fields in Cat Striate Cortex”
 - “Striate Cortex”: Approximately equal to the V1 visual cortex
 - “Striate” – defined by structure, “V1” – functional definition
- 24 cats, anaesthetized, immobilized, on artificial respirators
 - Anaesthetized with truth serum
 - Electrodes into brain
 - Do not report if cats survived experiment, but claim brain tissue was studied

Hubel and Wiesel 1959



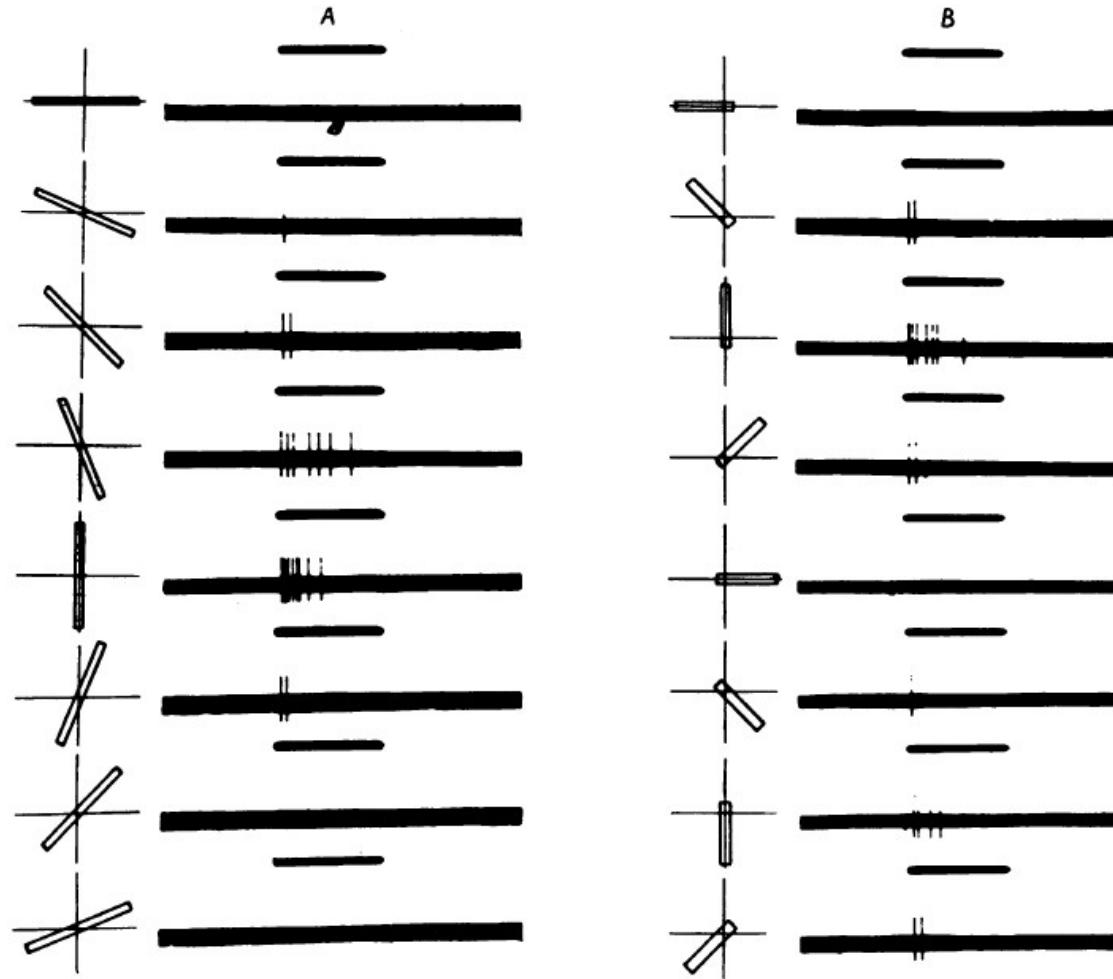
- Light of different wavelengths incident on the retina through fully open (slitted) Iris
 - Defines *immediate* (20ms) response of retinal cells
- Beamed light of different patterns into the eyes and measured neural responses in striate cortex

Hubel and Wiesel 1959



- Restricted retinal areas which on illumination influenced the firing of single cortical units were called **receptive fields**.
 - These fields were usually subdivided into excitatory and inhibitory regions.
- Findings:
 - A light stimulus covering the whole receptive field, or diffuse illumination of the whole retina, was ineffective in driving most units, as excitatory regions cancelled inhibitory regions
 - Light must fall on excitatory regions and NOT fall on inhibitory regions, resulting in clear patterns
 - A spot of light gave greater response for some directions of movement than others.
 - Can be used to determine the receptive field
 - Receptive fields could be oriented in a vertical, horizontal or oblique manner.
 - Based on the arrangement of excitatory and inhibitory regions within receptive fields.

Hubel and Wiesel 59

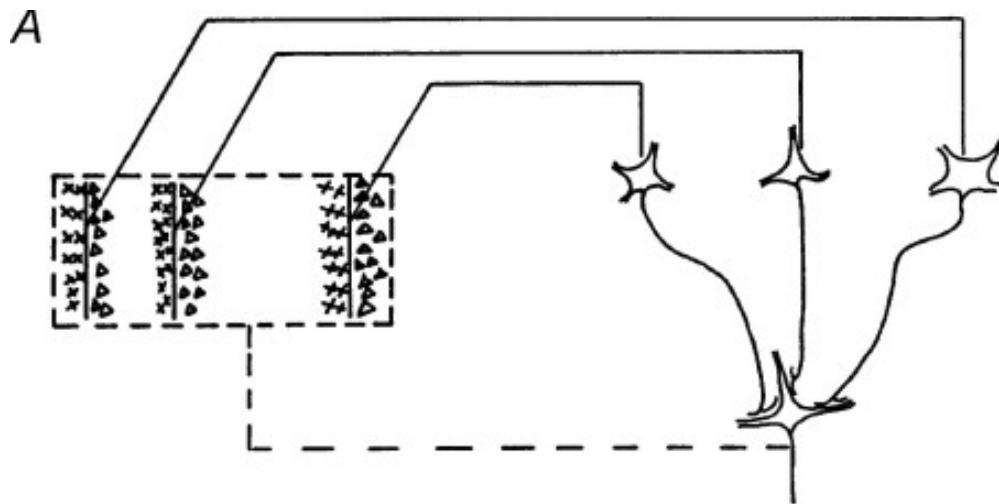


- Response as orientation of input light rotates
 - Note spikes – this neuron is sensitive to vertical bands

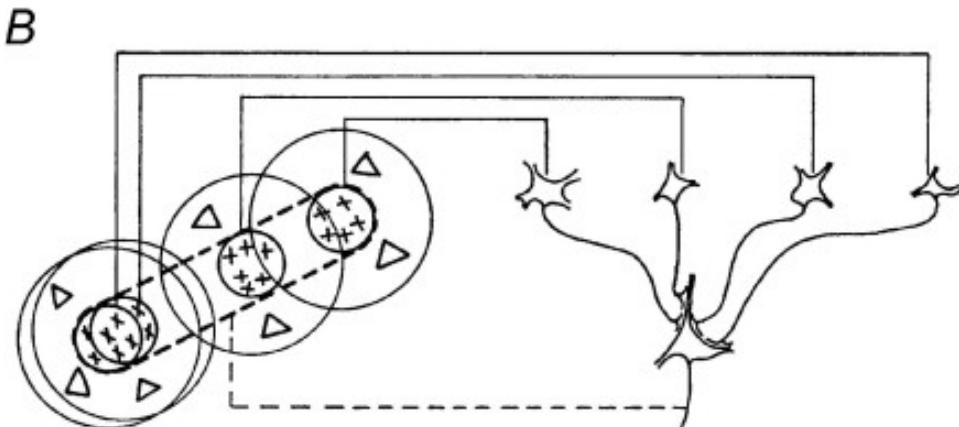
Hubel and Wiesel

- Oriented slits of light were the most effective stimuli for activating striate cortex neurons
- The orientation selectivity resulted from *the previous level of input* because lower-level neurons responding to a slit also responded to patterns of spots if they were aligned with the same orientation as the slit.
- In a later paper (**Hubel & Wiesel, 1962**), they showed that within the striate cortex, two levels of processing could be identified
 - Between neurons referred to as *simple S-cells* and *complex C-cells*.
 - Both types responded to oriented slits of light, but complex cells were not “confused” by spots of light while simple cells could be confused

Hubel and Wiesel model



Composition of complex receptive fields from simple cells. The C-cell responds to the largest output from a bank of S-cells to achieve oriented response that is robust to distortion



Transform from circular retinal receptive fields to elongated fields for simple cells. The simple cells are susceptible to fuzziness and noise

Hubel and Wiesel

- Complex C-cells build from similarly oriented simple cells
 - They “fine-tune” the response of the simple cell
- Show complex buildup – building *more complex patterns* by composing early neural responses
 - Successive transformation through Simple-Complex combination layers
- Demonstrated more and more complex responses in later papers
 - Later experiments were on waking macaque monkeys
 - Too horrible to recall



Adding insult to injury..

- “However, this model cannot accommodate the color, spatial frequency and many other features to which neurons are tuned. The exact organization of all these cortical columns within V1 remains a hot topic of current research.”

Poll 1 (@682)

- According to Hubel and Wiesel which type of cells found patterns in the input and which cells “cleaned” up these patterns?
 - S cells find patterns and C cells clean them up
 - C cells find patterns and S cells clean them up

Poll 1

- According to Hubel and Wiesel which type of cells found patterns in the input and which cells “cleaned” up these patterns?
 - **S cells find patterns and C cells clean them up**
 - C cells find patterns and S cells clean them up

Forward to 1980

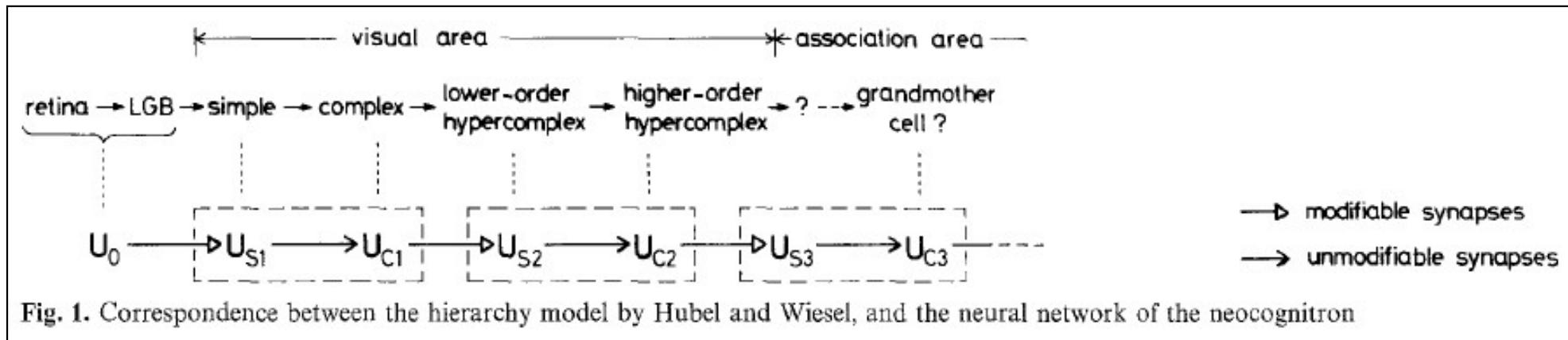
- Kunihiko Fukushima
- Recognized deficiencies in the Hubel-Wiesel model
- One of the chief problems: Position invariance of input
 - Your grandmother cell fires even if your grandmother moves to a different location in your field of vision



Kunihiko Fukushima

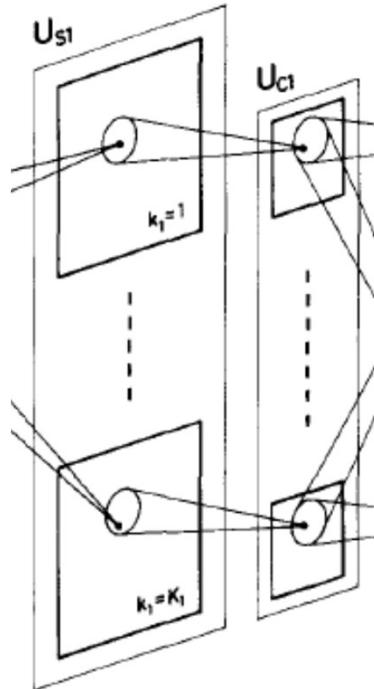
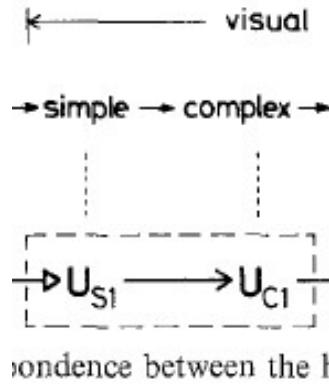
NeoCognitron

Figures from Fukushima, '80



- Visual system consists of a hierarchy of modules, each comprising a layer of “S-cells” followed by a layer of “C-cells”
 - U_{Sl} is the l^{th} layer of S cells, U_{Cl} is the l^{th} layer of C cells
- S-cells **respond** to the signal in the previous layer
- C-cells **confirm** the S-cells’ response
- Only S-cells are “plastic” (i.e. learnable), C-cells are fixed in their response

NeoCognitron



Each cell in a plane "looks" at a slightly shifted region of the **input** than the adjacent cells in the plane.
... "through" the previous layer planes

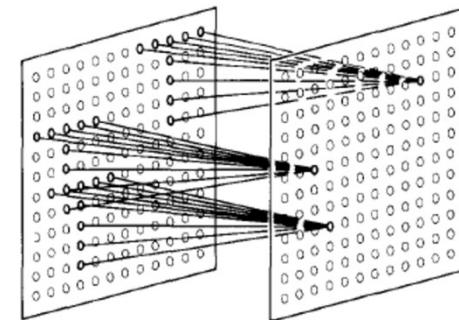
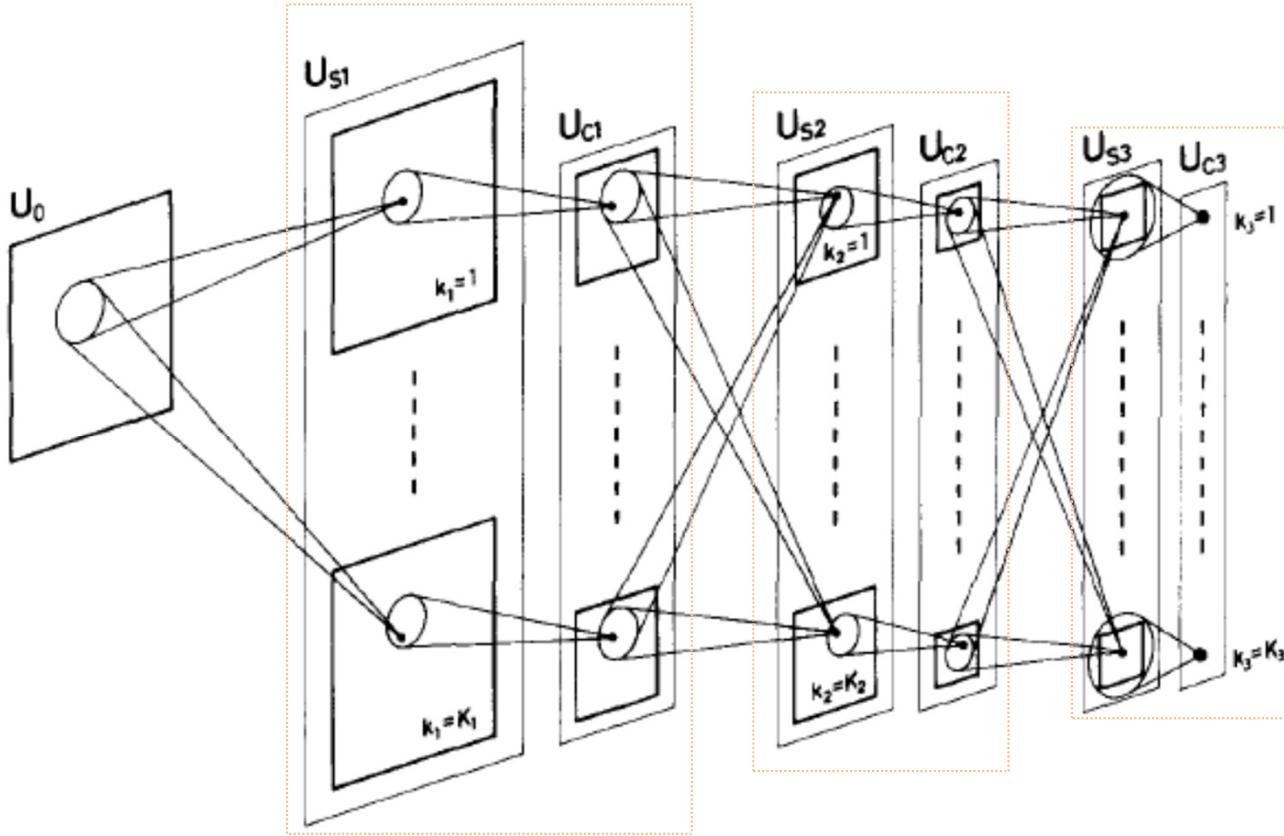


Fig. 3. Illustration showing the input interconnections to the cells within a single cell-plane

- Each simple-complex module includes a layer of S-cells and a layer of C-cells
- S-cells are organized in rectangular groups called S-planes.
 - All the cells within an S-plane have identical learned responses
- C-cells too are organized into rectangular groups called C-planes
 - One C-plane per S-plane
 - All C-cells have identical fixed response
- In Fukushima's original work, each C and S cell "looks" at an elliptical region in the previous plane

NeoCognitron



- The complete network
- U_0 is the retina
- In each subsequent module, the planes of the S layers detect plane-specific patterns in the previous layer (C layer or retina)
- The planes of the C layers “refine” the response of the corresponding planes of the S layers

Neocognitron

- S cells: RELU like activation

$$u_{Sl}(k_l, \mathbf{n}) = r_l \cdot \varphi \left[\frac{1 + \sum_{k_{l-1}=1}^{K_{l-1}} \sum_{\mathbf{v} \in S_l} a_l(k_{l-1}, \mathbf{v}, k_l) \cdot u_{Cl-1}(k_{l-1}, \mathbf{n} + \mathbf{v})}{1 + \frac{2r_l}{1+r_l} \cdot b_l(k_l) \cdot v_{Cl-1}(\mathbf{n})} - 1 \right]$$

- φ is a RELU

- C cells: Also RELU like, but with an inhibitory bias
 - Fires if weighted combination of S cells fires strongly enough

$$u_{Cl}(k_l, \mathbf{n}) = \psi \left[\frac{1 + \sum_{\mathbf{v} \in D_l} d_l(\mathbf{v}) \cdot u_{Sl}(k_l, \mathbf{n} + \mathbf{v})}{1 + v_{Sl}(\mathbf{n})} - 1 \right]$$

$$\psi[x] = \varphi[x/(\alpha + x)]$$

—

Neocognitron

- S cells: RELU like activation

$$u_{Sl}(k_l, \mathbf{n}) = r_l \cdot \varphi \left[\frac{1 + \sum_{k_{l-1}=1}^{K_{l-1}} \sum_{\mathbf{v} \in S_l} a_l(k_{l-1}, \mathbf{v}, k_l) \cdot u_{Cl-1}(k_{l-1}, \mathbf{n} + \mathbf{v})}{1 + \frac{2r_l}{1+r_l} \cdot b_l(k_l) \cdot v_{Cl-1}(\mathbf{n})} - 1 \right]$$

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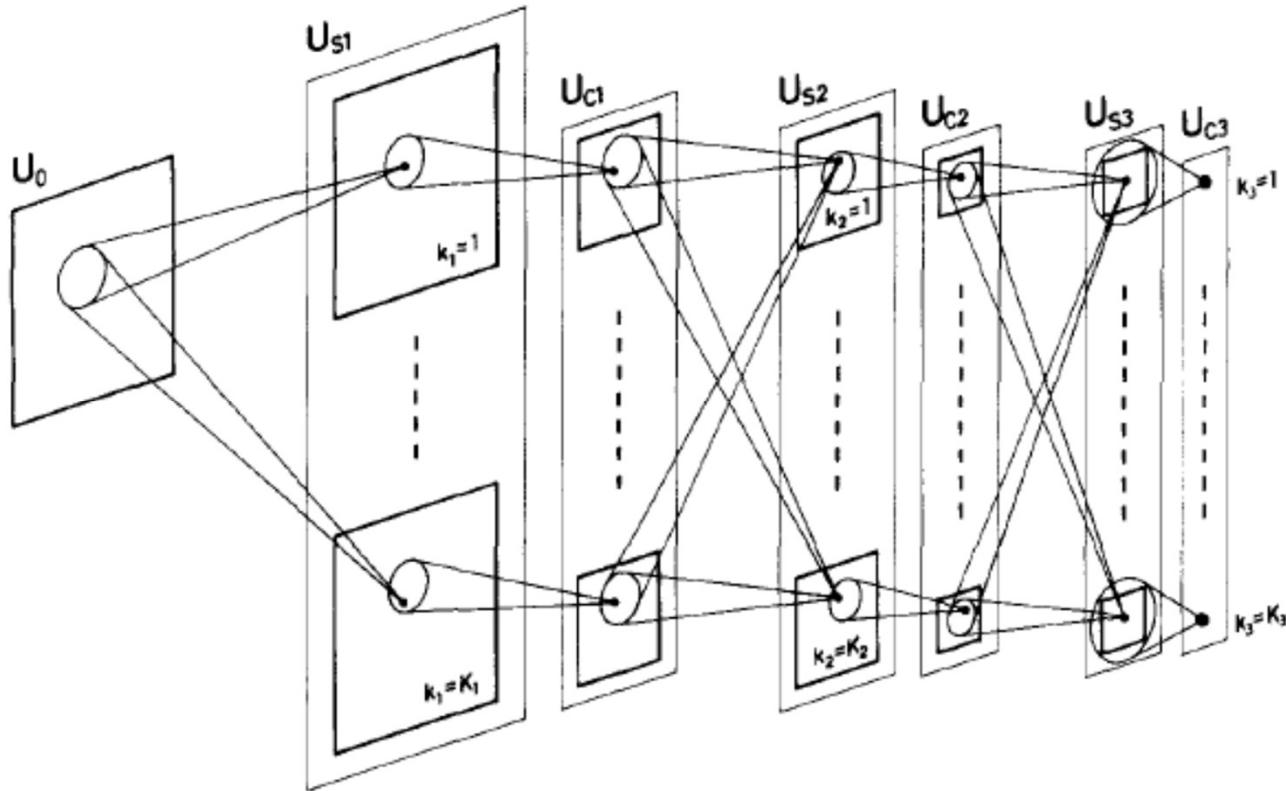
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$$\psi[x] = \varphi[x/(\alpha + x)]$$

Could simply replace these
strange functions with a
RELU and a max

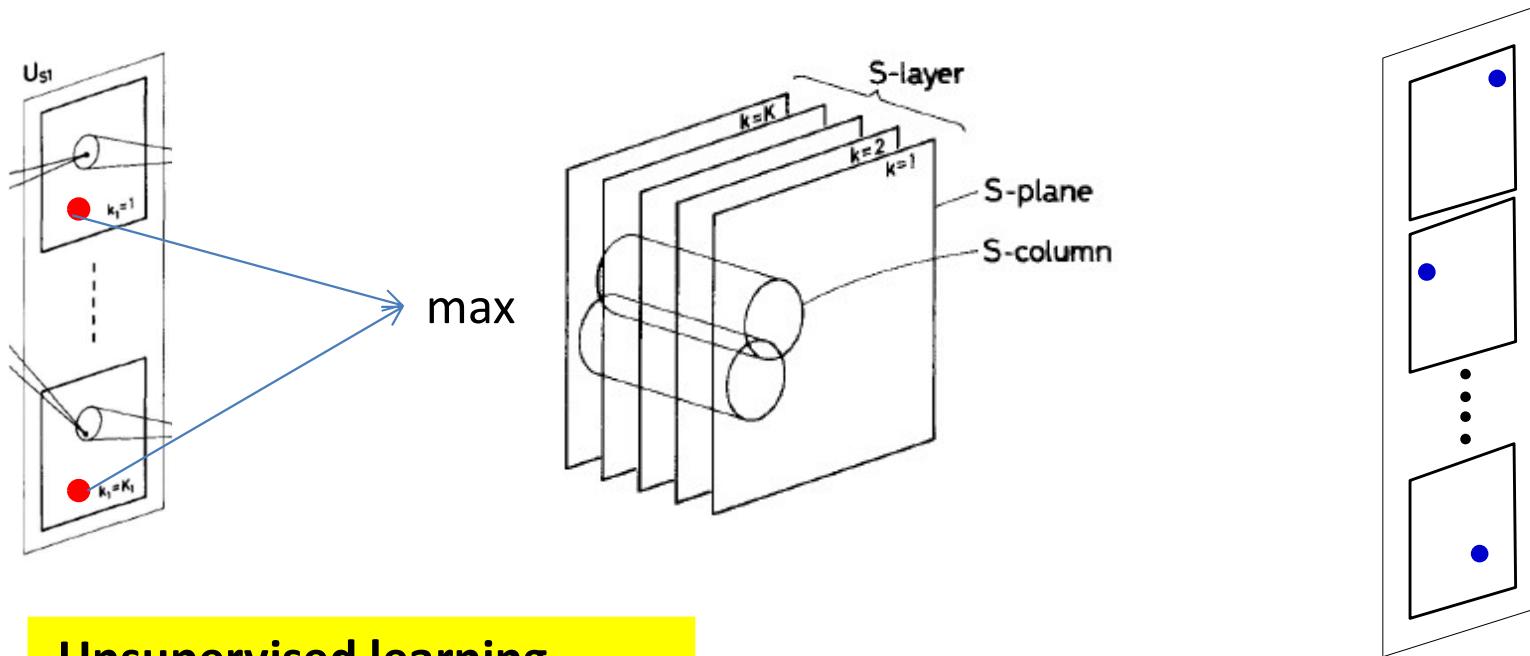
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NeoCognitron



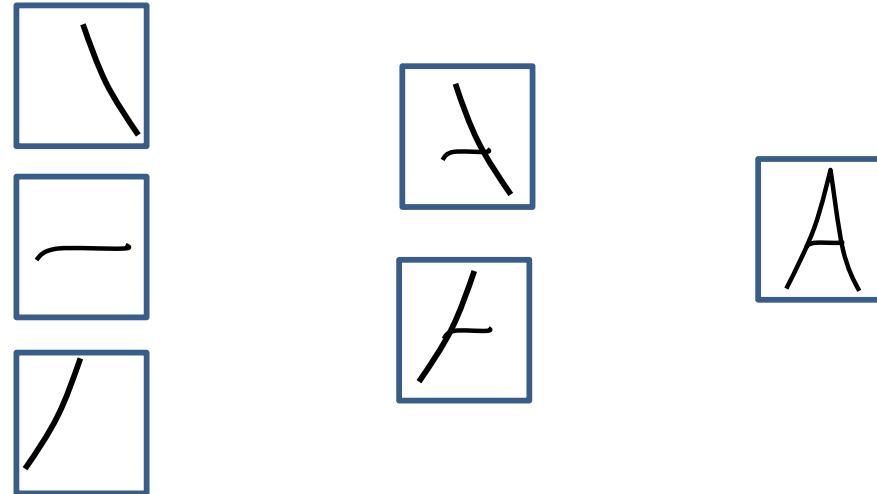
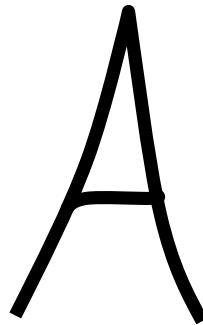
- The deeper the layer, the larger the receptive field of each neuron
 - Cell planes get smaller with layer number
 - Number of planes increases
 - i.e the number of complex pattern detectors increases with layer

Learning in the neocognitron



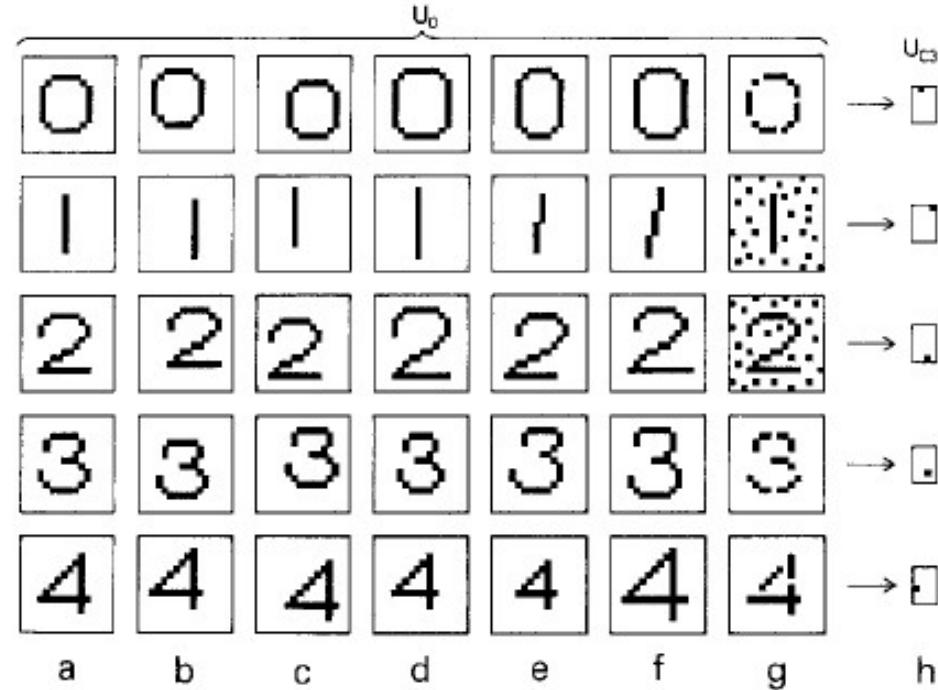
- **Unsupervised learning**
- Randomly initialize S cells, perform Hebbian learning updates in response to input
 - update = product of input and output : $\Delta w_{ij} = x_i y_j$
- Within any layer, at any position, only the maximum S from all the layers is selected for update
 - Also viewed as max-valued cell from each *S column*
 - Ensures only one of the planes picks up any feature
 - If multiple max selections are on the same plane, only the largest is chosen
 - But across all positions, multiple planes will be selected
- Updates are distributed across all cells within the plane

Learning in the neocognitron



- Ensures different planes learn different features
 - E.g. Given many examples of the character “A” the different cell planes in the S-C layers may learn the patterns shown
 - Given other characters, other planes will learn their components
 - Going up the layers goes from local to global receptor fields
- Winner-take-all strategy makes it robust to distortion
- Unsupervised: Effectively clustering

Neocognitron – finale



- Fukushima showed it successfully learns to cluster semantic visual concepts
 - E.g. number or characters, even in noise

Poll 2 (@683, @684)

Fukushima's model is an unsupervised CNN, true or false

- True
- False

Supervision can be added to Fukushima's model, true or false

- True
- False

Poll 2

Fukushima's model is an unsupervised CNN, true or false

- **True**
- False

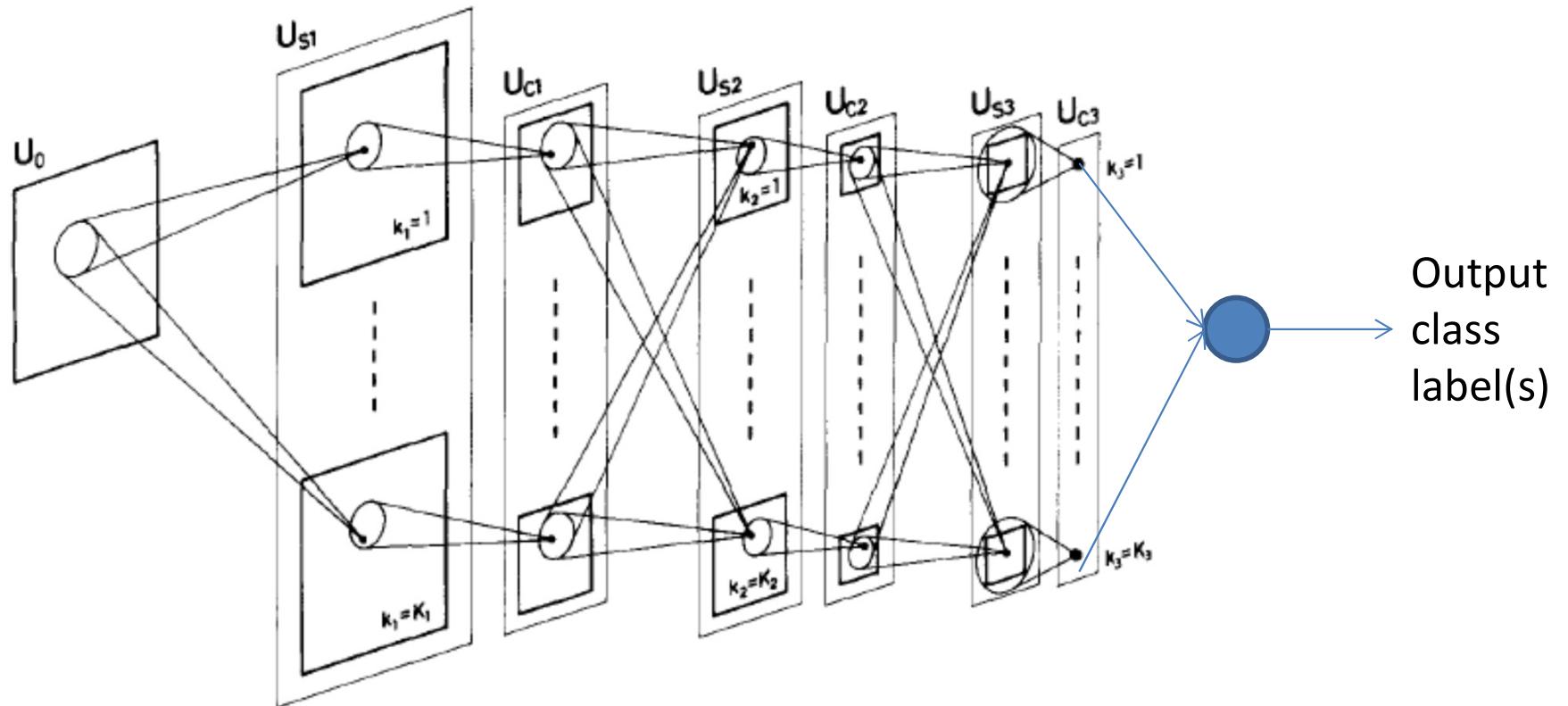
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- **True**
- False

Adding Supervision

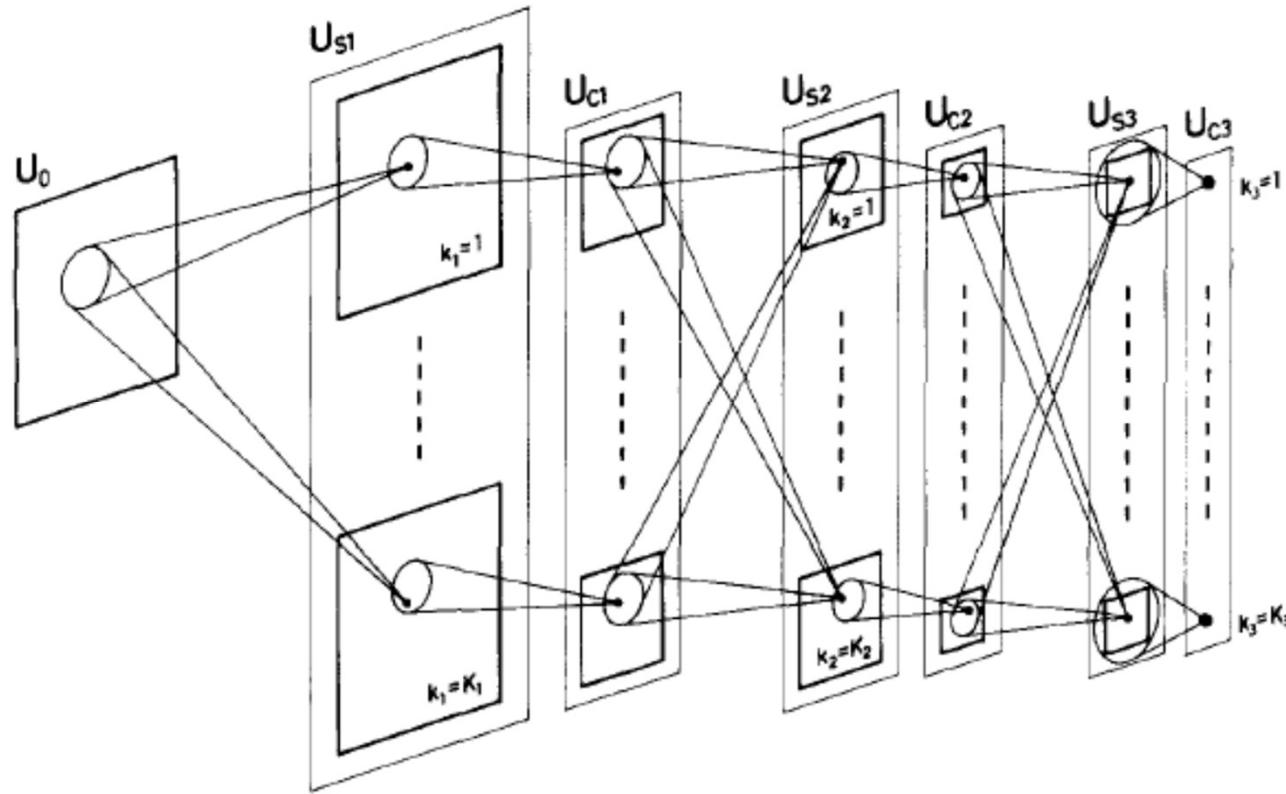
- The neocognitron is fully unsupervised
 - Semantic labels are automatically learned
- Can we add external supervision?
- Various proposals:
 - Temporal correlation: Homma, Atlas, Marks, '88
 - TDNN: Lang, Waibel et. al., 1989, '90
- Convolutional neural networks: LeCun

Supervising the neocognitron



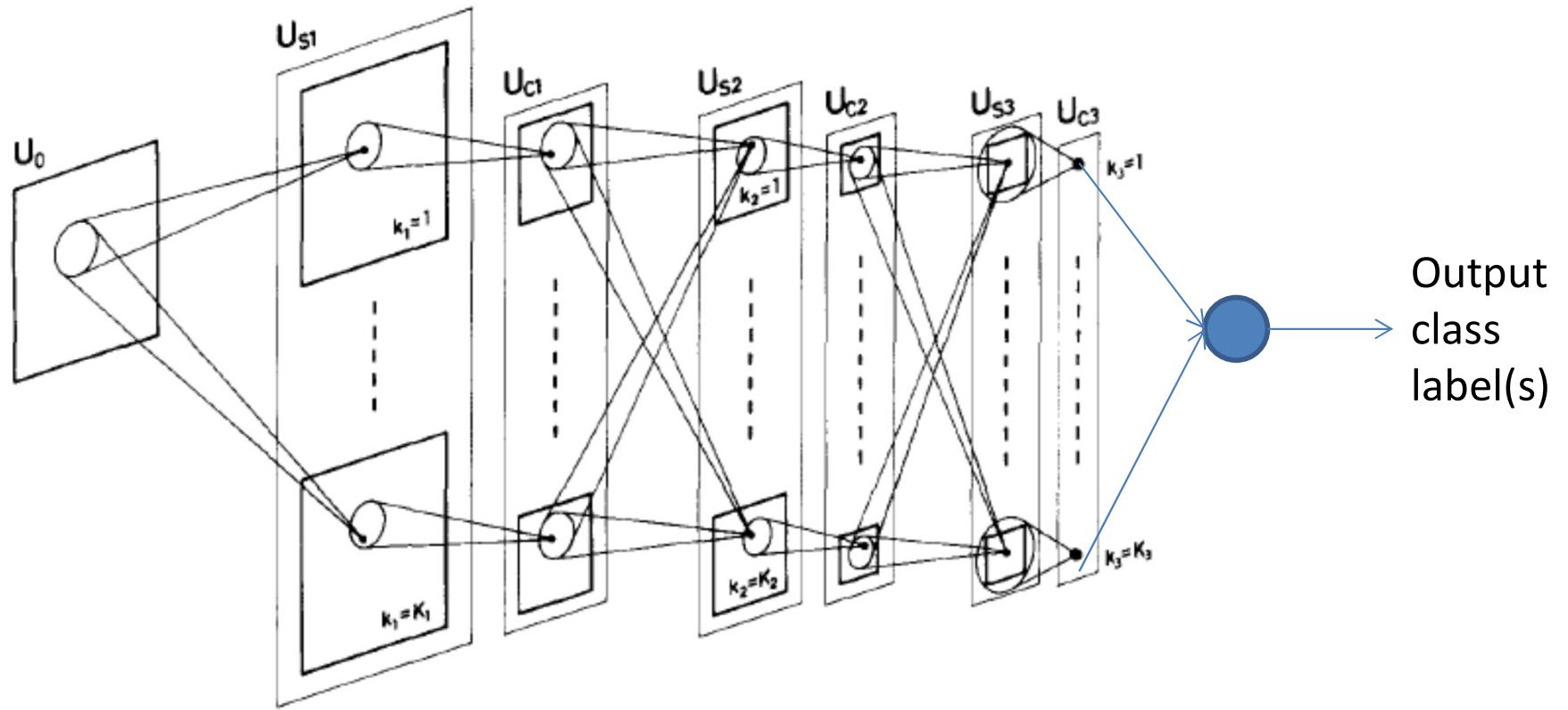
- Add an extra decision layer after the final C layer
 - Produces a class-label output
- We now have a fully feed forward MLP with shared parameters
 - All the S-cells within an S-plane have the same weights
- Simple backpropagation can now train the S-cell weights in every plane of every layer
 - C-cells are not updated

Scanning vs. multiple filters



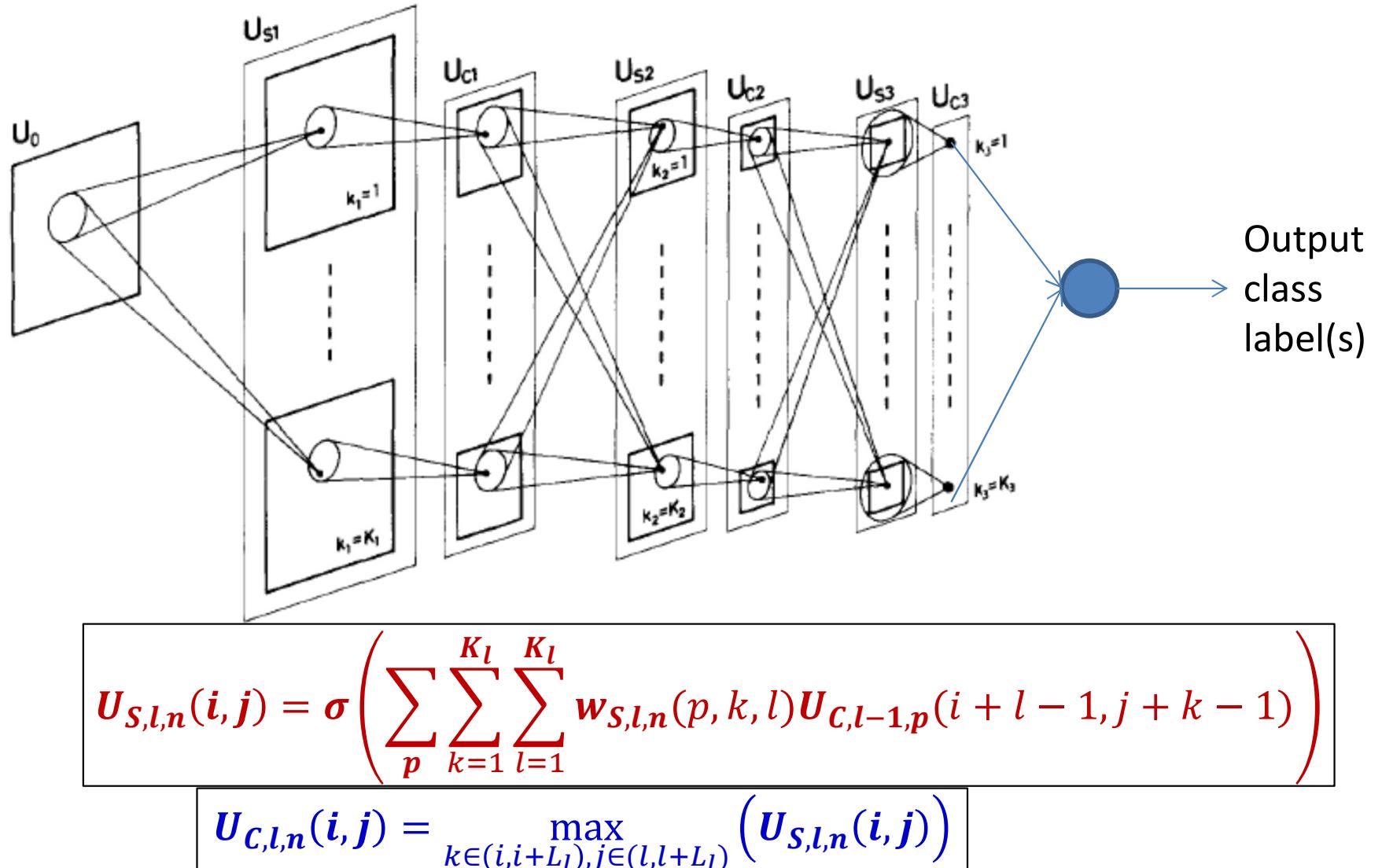
- **Note:** The original Neocognitron actually uses many identical copies of a neuron in each S and C plane
 - Mathematically identical to “scanning” with a single copy

Supervising the neocognitron



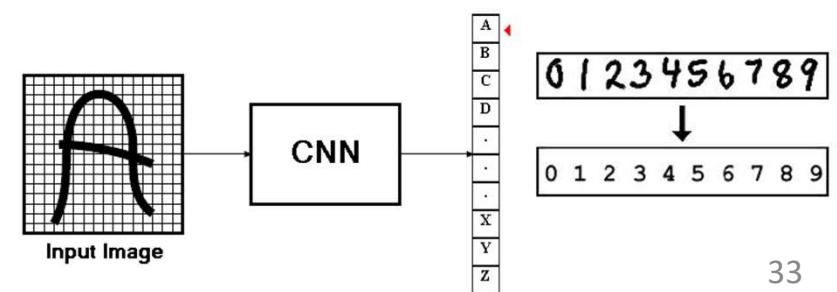
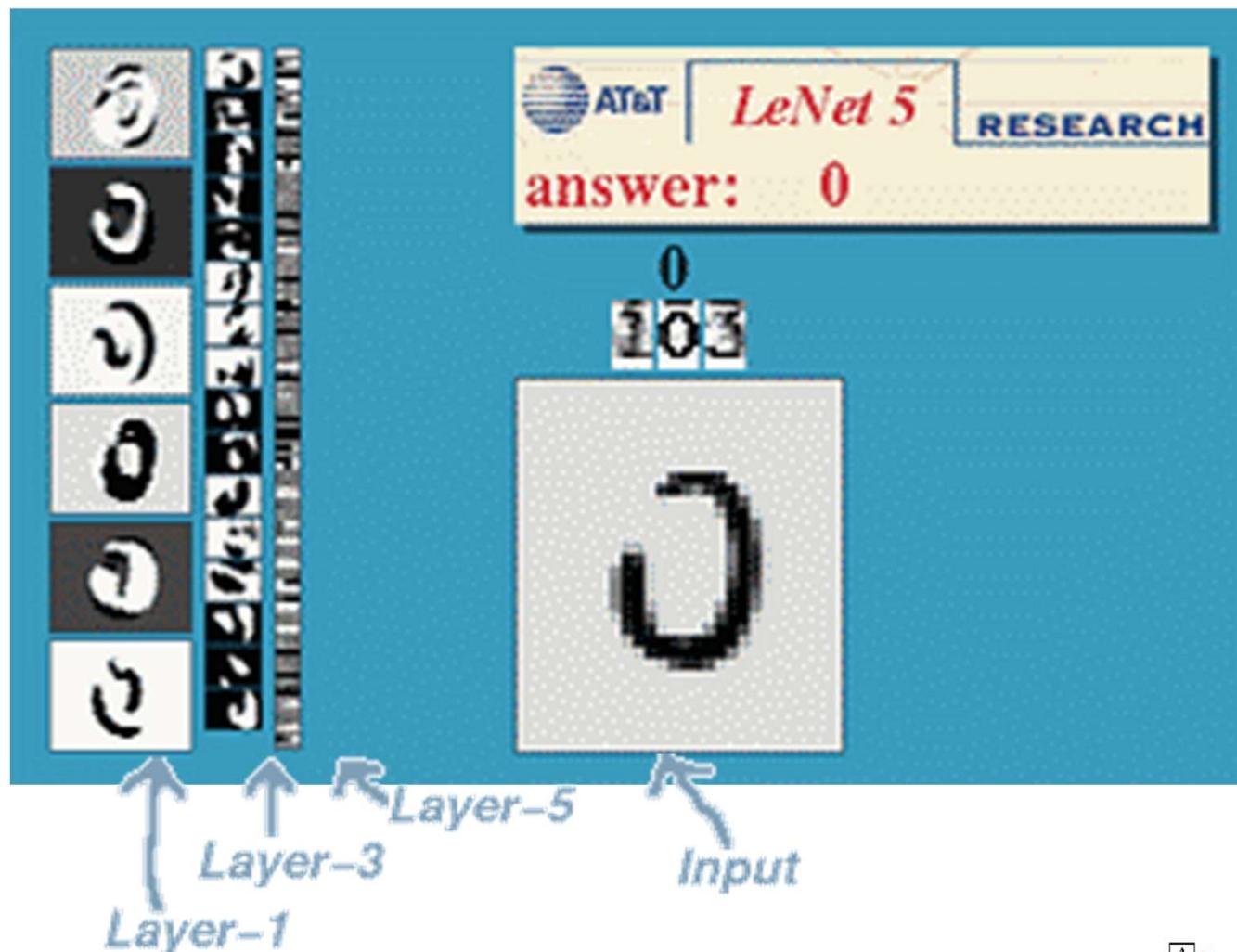
- The Math
 - Assuming *square* receptive fields, rather than elliptical ones
 - Receptive field of S cells in lth layer is $K_l \times K_l$
 - Receptive field of C cells in lth layer is $L_l \times L_l$
 - C cells “stride” by more than one pixel, resulting in a shrinking, or “downsampling” of the maps

Supervising the neocognitron



- This is, identical to “scanning” (convolving) with a single neuron/filter (what LeNet actually did)

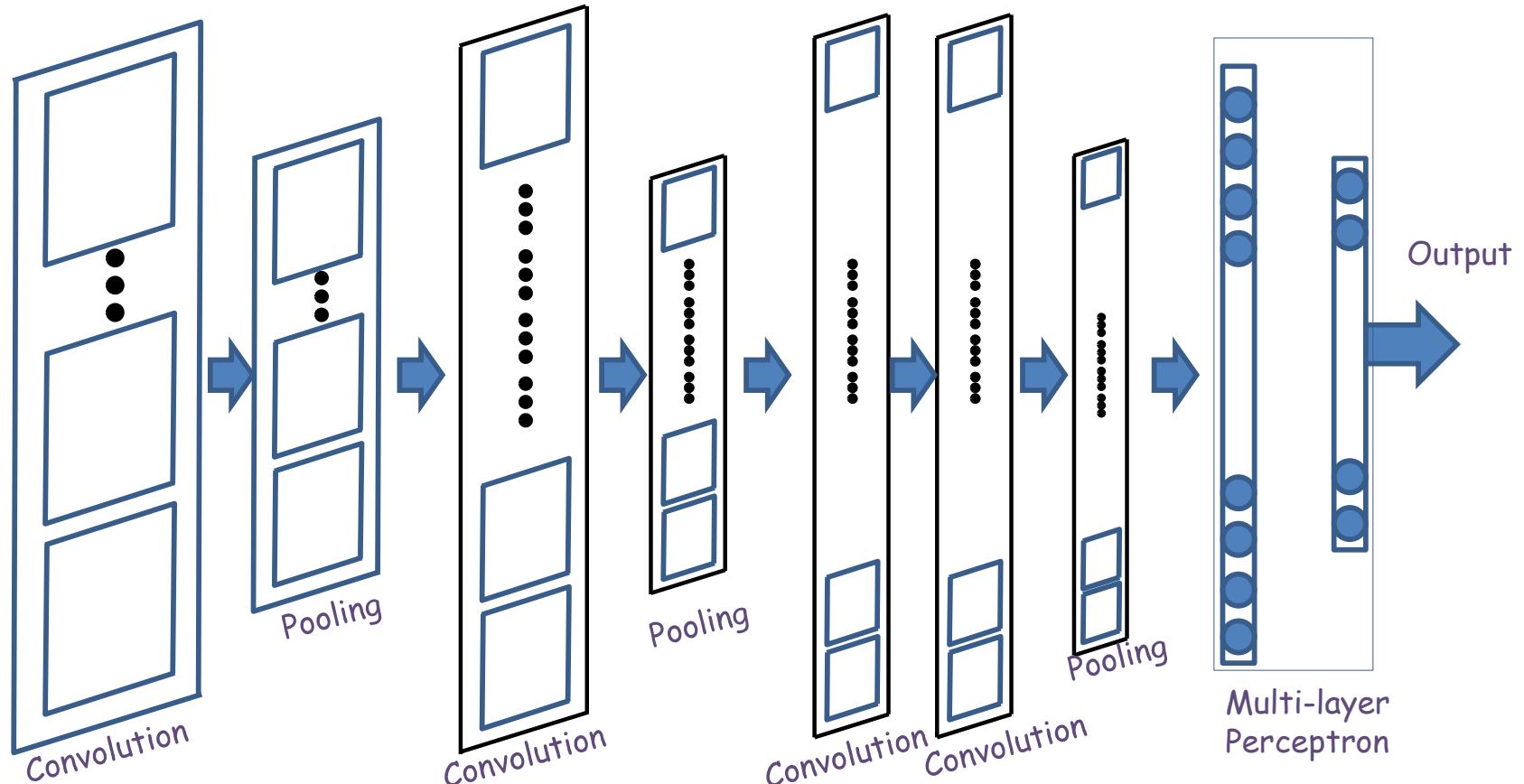
Convolutional Neural Networks



Story so far

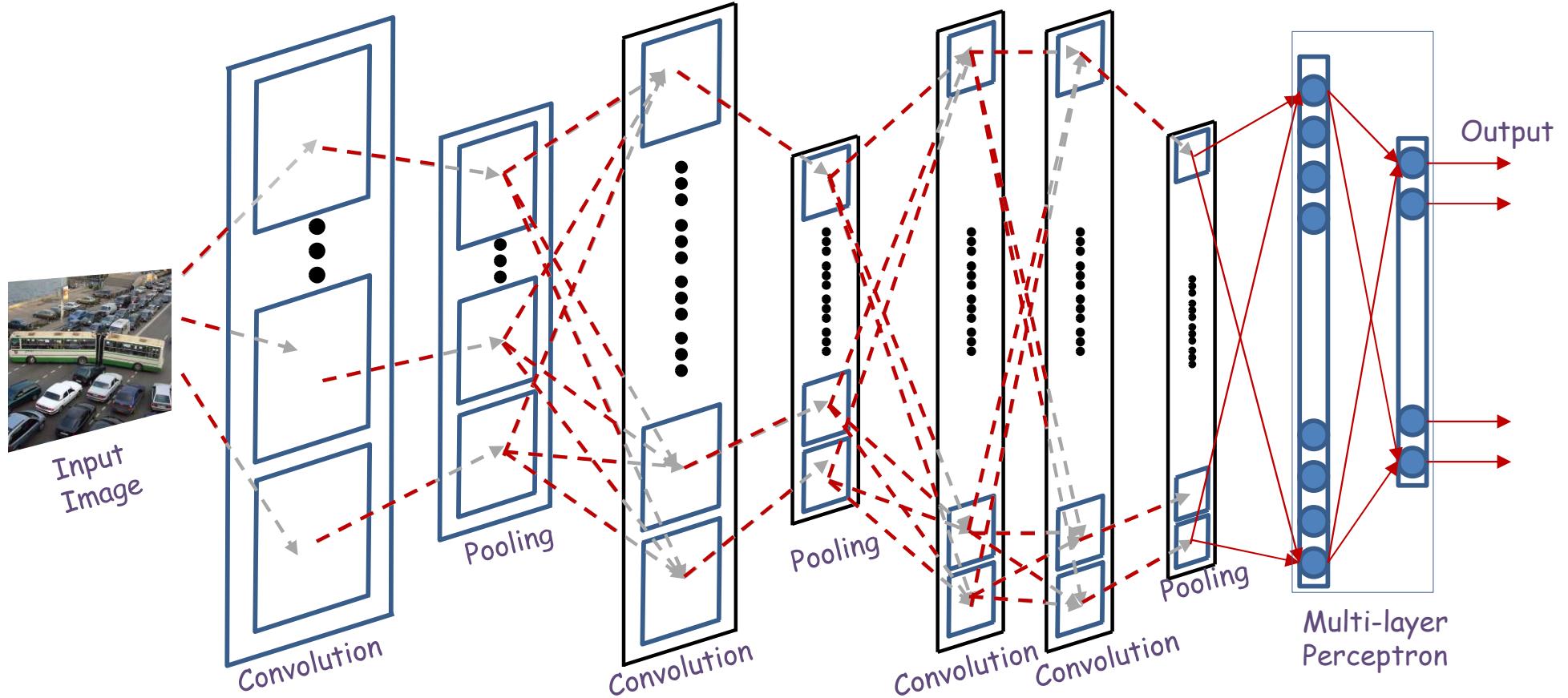
- The mammalian visual cortex contains of S cells, which capture oriented visual patterns and C cells which perform a “majority” vote over groups of S cells for robustness to noise and positional jitter
- The neocognitron emulates this behavior with planar banks of S and C cells with identical response, to enable shift invariance
 - Only S cells are learned
 - C cells perform the equivalent of a max over groups of S cells for robustness
 - Unsupervised learning results in learning useful patterns
- LeCun’s LeNet added external supervision to the neocognitron
 - S planes of cells with identical response are modelled by a scan (convolution) over image planes by a single neuron
 - C planes are emulated by cells that perform a max over groups of S cells
 - Reducing the size of the S planes
 - Giving us a “Convolutional Neural Network”

The general architecture of a convolutional neural network



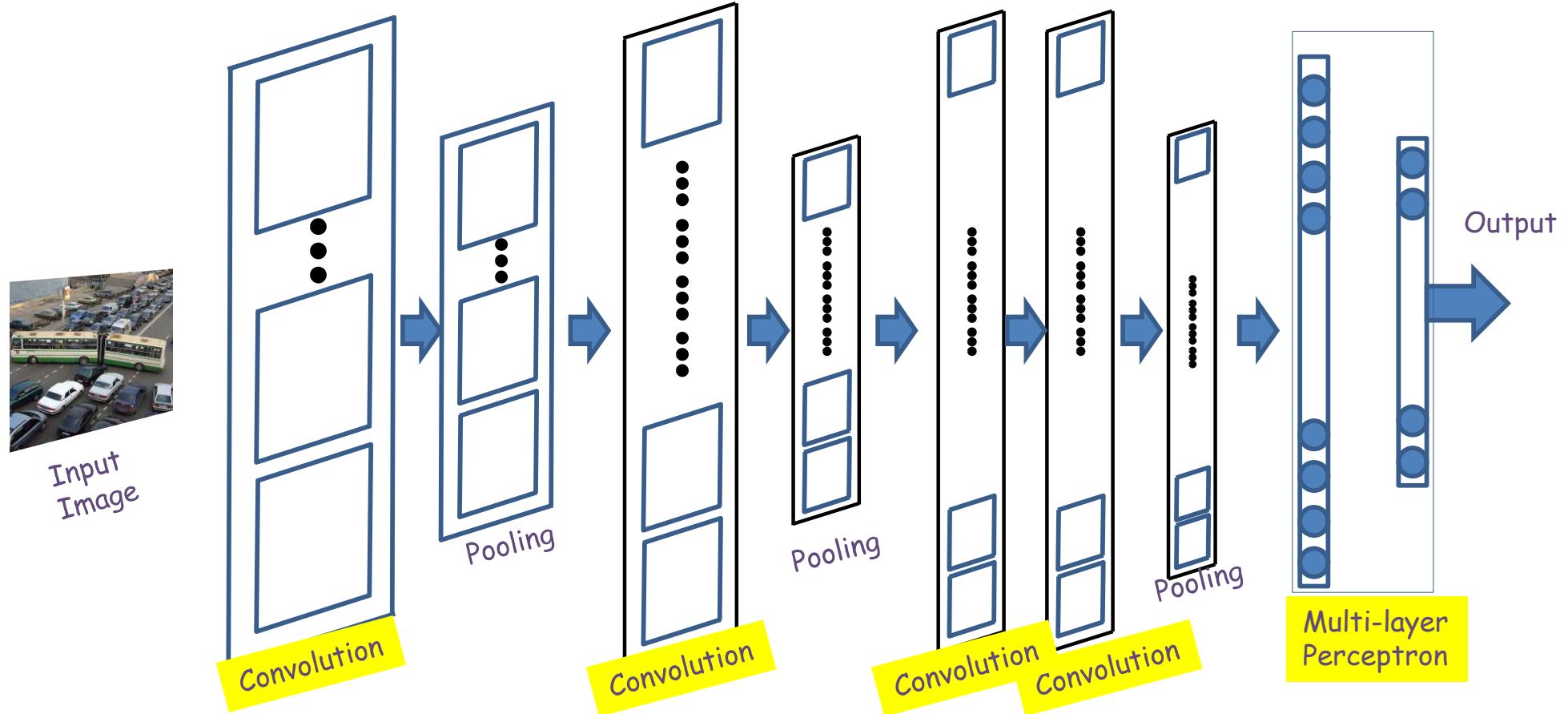
- A convolutional neural network comprises “convolutional” and “pooling” layers
 - Convolutional layers comprise neurons that scan their input for patterns
 - Correspond to S planes
 - Pooling layers perform max operations on groups of outputs from the convolutional layers
 - Correspond to C planes
 - The two may occur in any sequence, but typically they alternate
- Followed by an MLP with one or more layers

The general architecture of a convolutional neural network



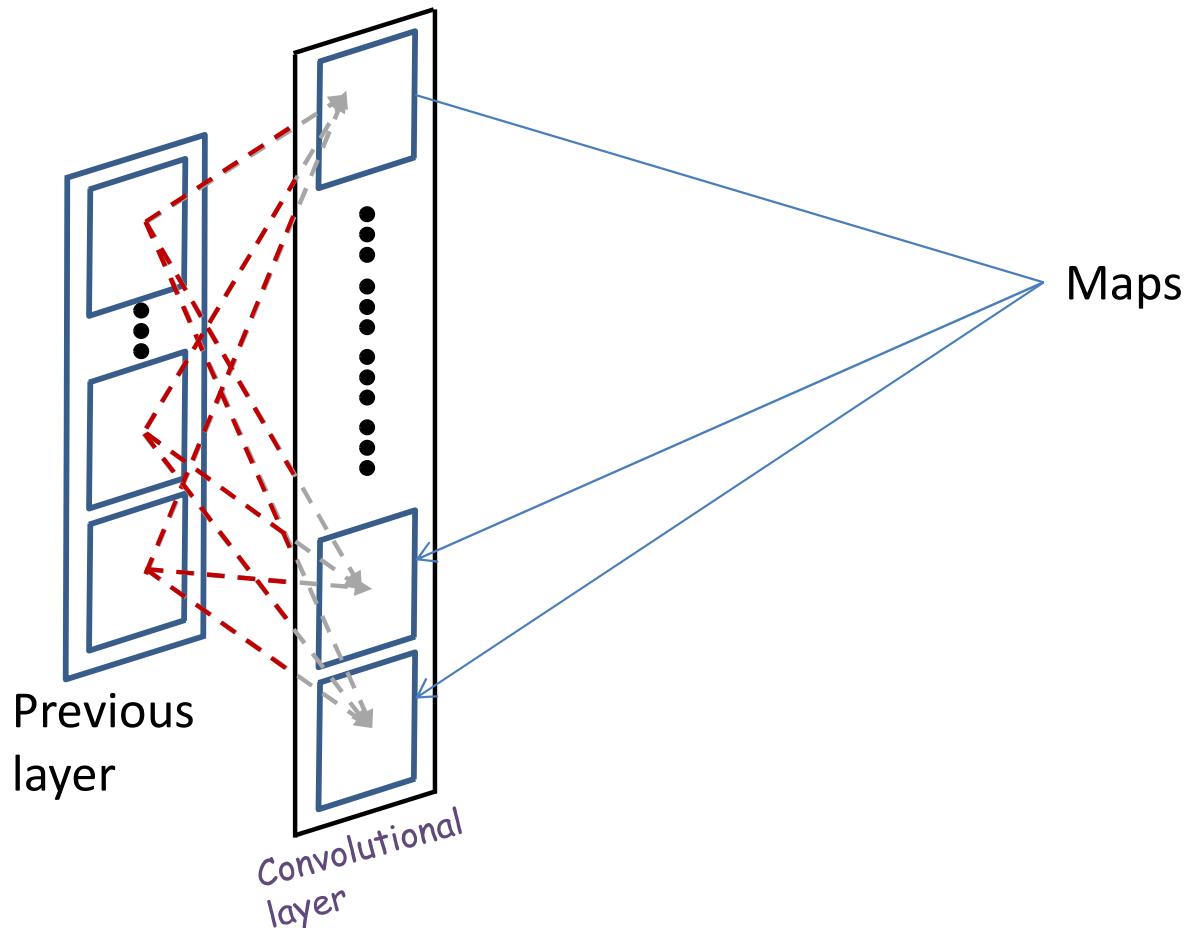
- A convolutional neural network comprises of “pooling” and “downsampling” layers
 - The two may occur in any sequence, but typically they alternate
- Followed by an MLP with one or more layers

The general architecture of a convolutional neural network



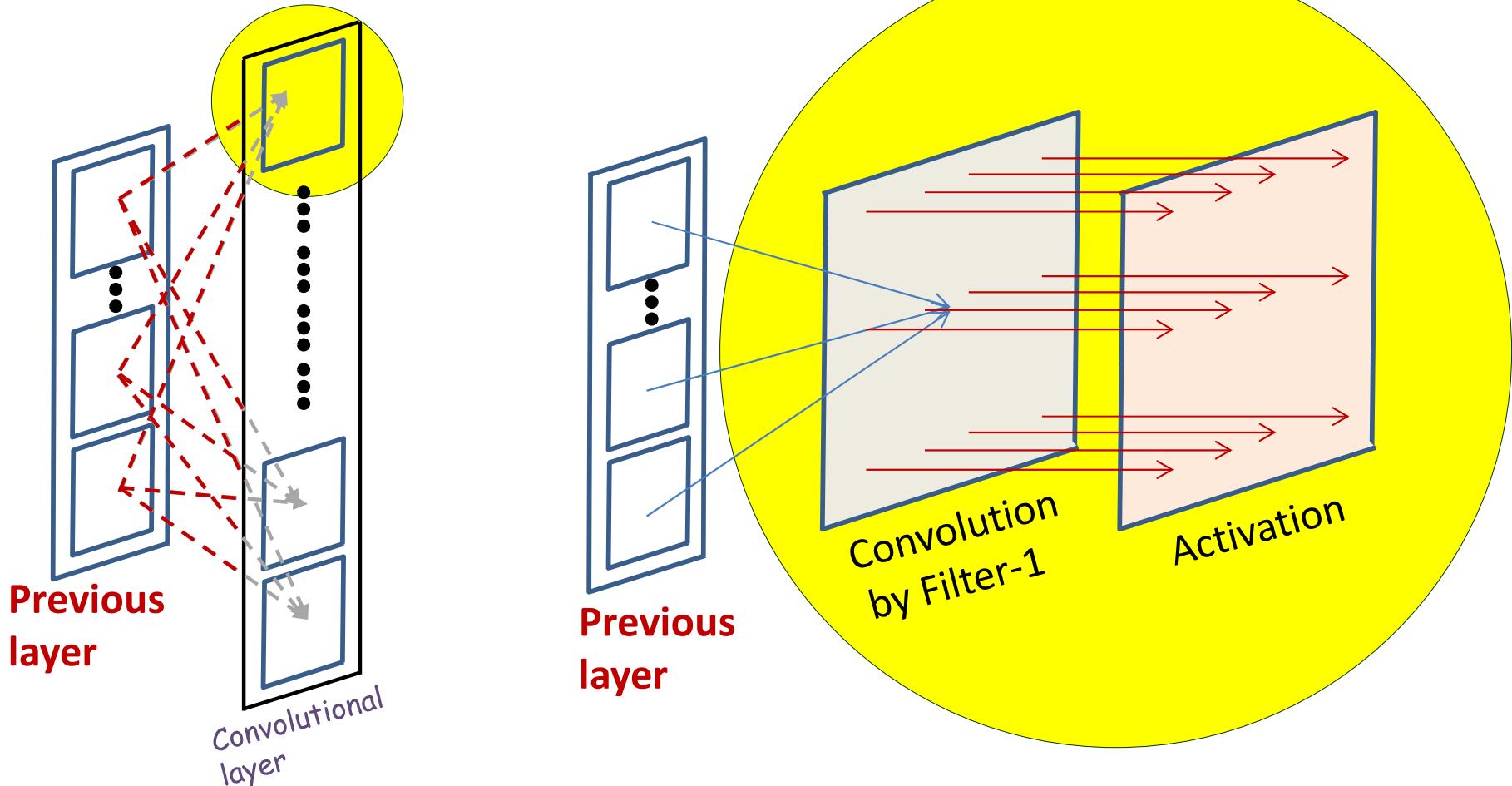
- **Convolutional layers and the MLP are *learnable***
 - Their parameters must be learned from training data for the target classification task
- Pooling layers are fixed and generally not learnable

A convolutional layer



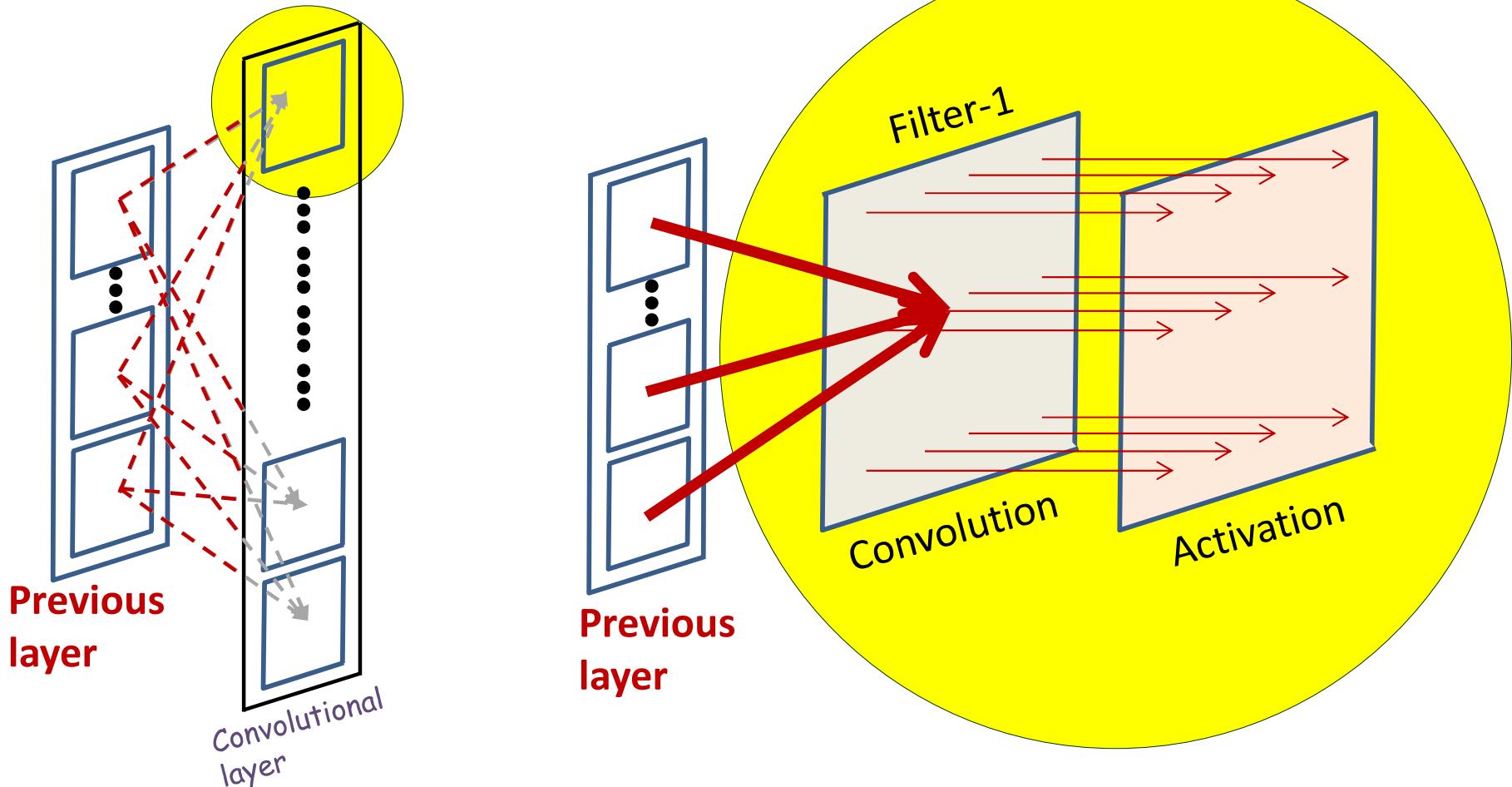
- A convolutional layer comprises of a series of “maps”
 - Corresponding the “S-planes” in the Neocognitron
 - Variously called feature maps or activation maps

A convolutional layer



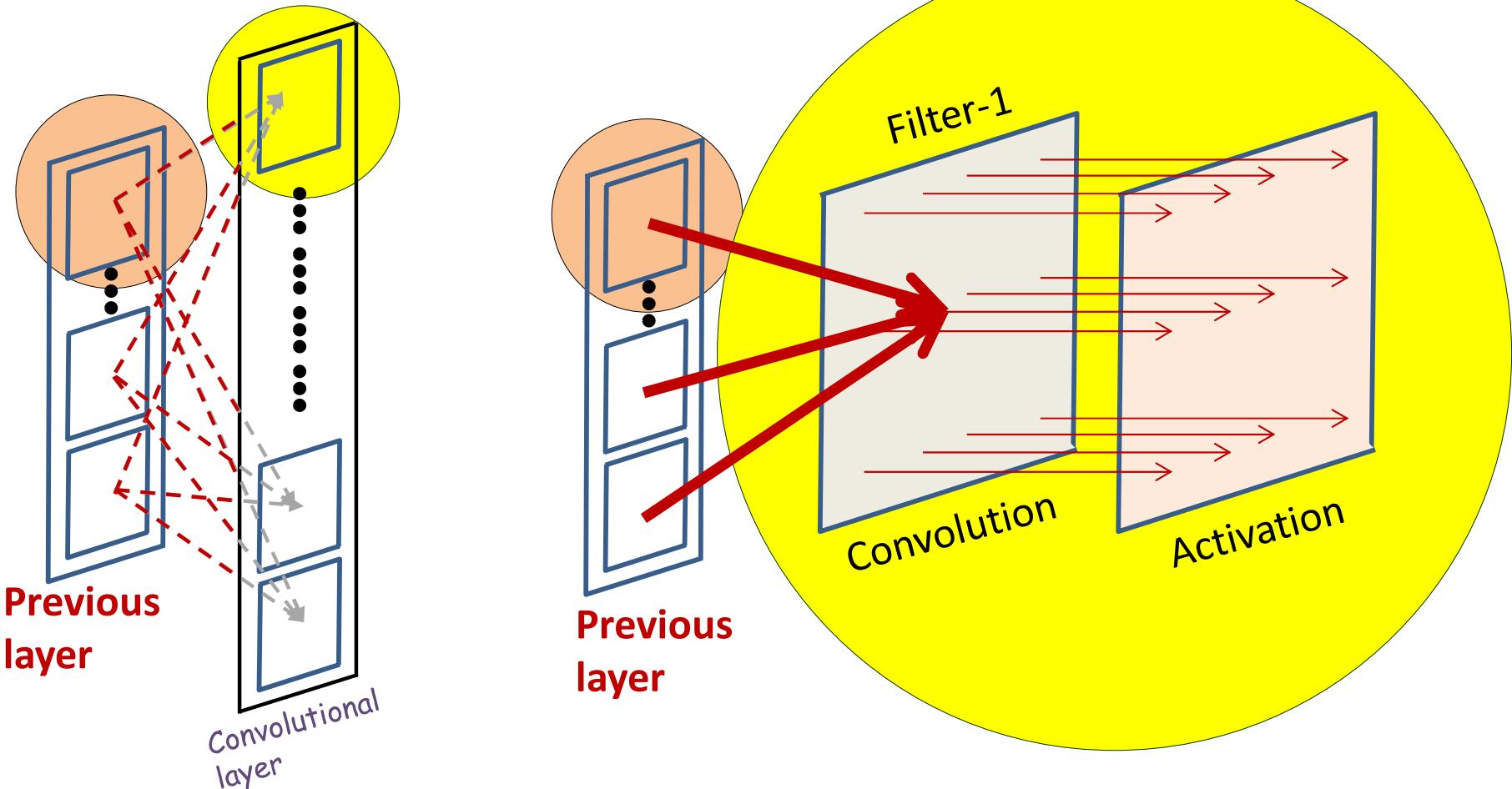
- Each activation map has two components
 - An *affine* map, obtained by *convolution* over maps in the previous layer
 - Each affine map has, associated with it, a **learnable filter**
 - An *activation* that operates pointwise on the output of the convolution

A convolutional layer: affine map



- All the maps in the previous layer contribute to each convolution

A convolutional layer: affine map



- All the maps in the previous layer contribute to each convolution
 - Consider the contribution of a *single* map

What is a convolution

Example 5x5 image with binary pixels

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

Example 3x3 filter

1	0	1
0	1	0
1	0	1

bias

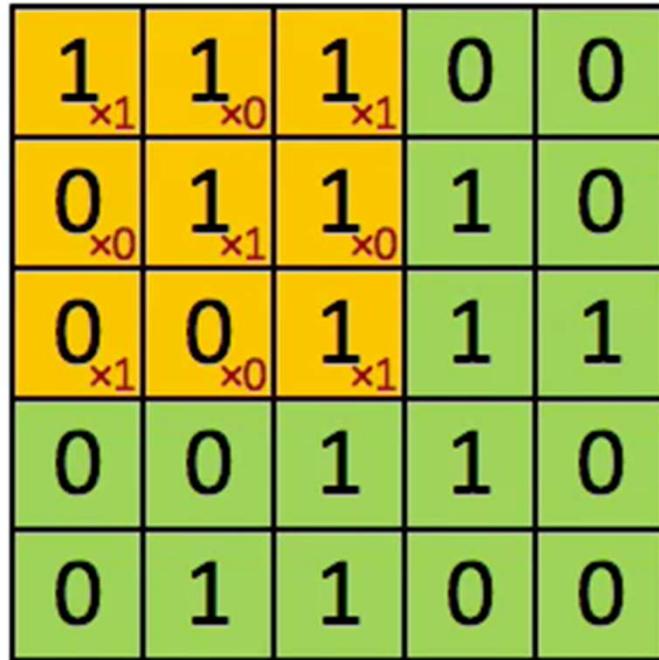
0

- Scanning an image with a “filter”
 - Note: a filter is really just a perceptron, with weights and a bias

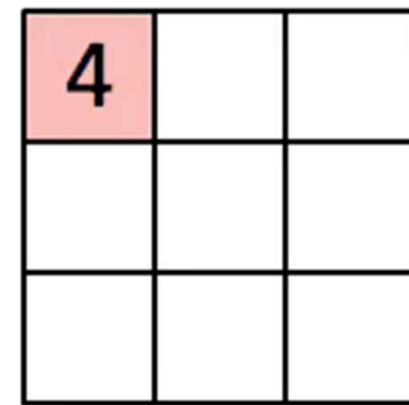
What is a convolution

0
bias
Filter

1	0	1
0	1	0
1	0	1



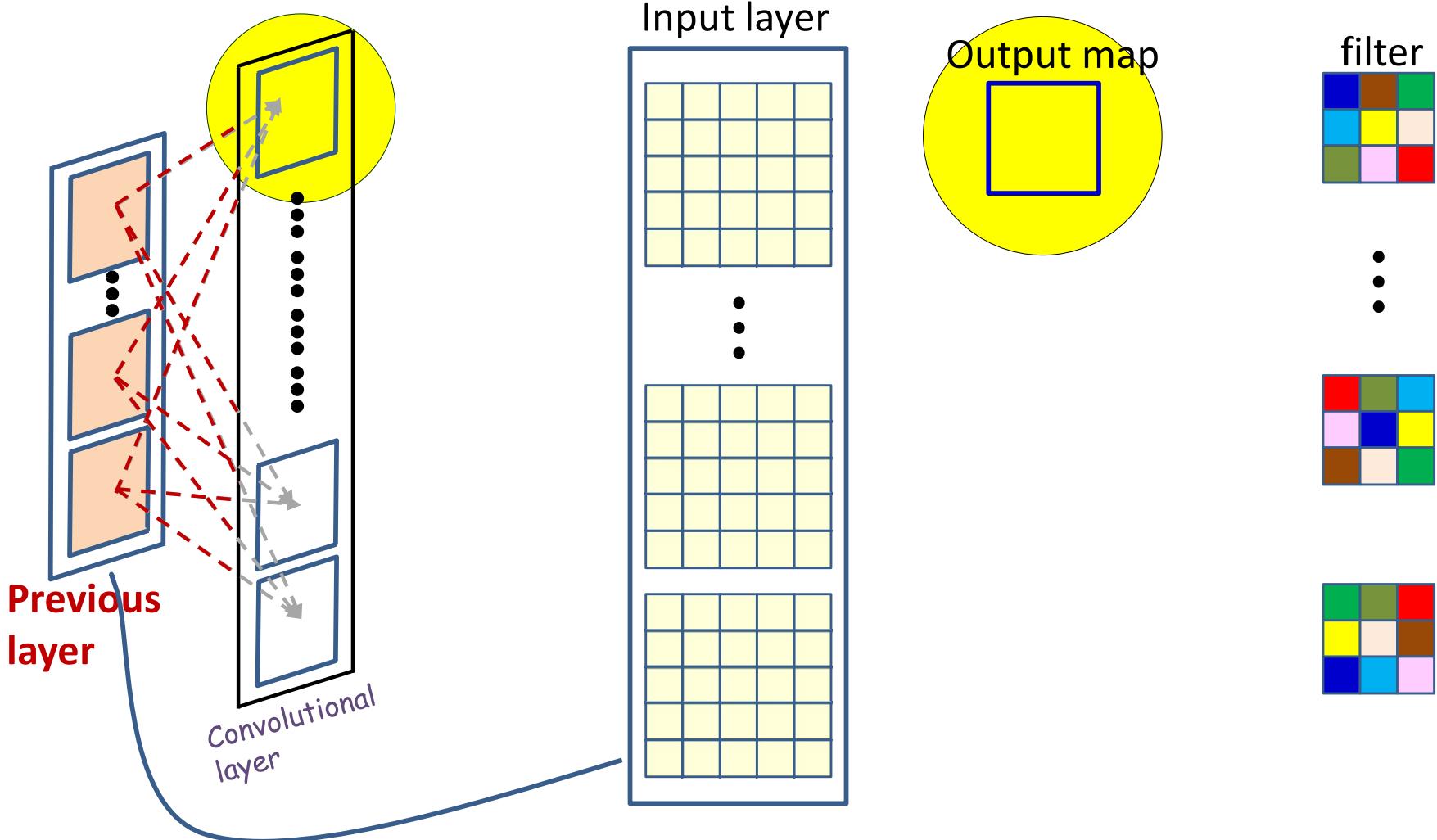
Input Map



Convolved Feature

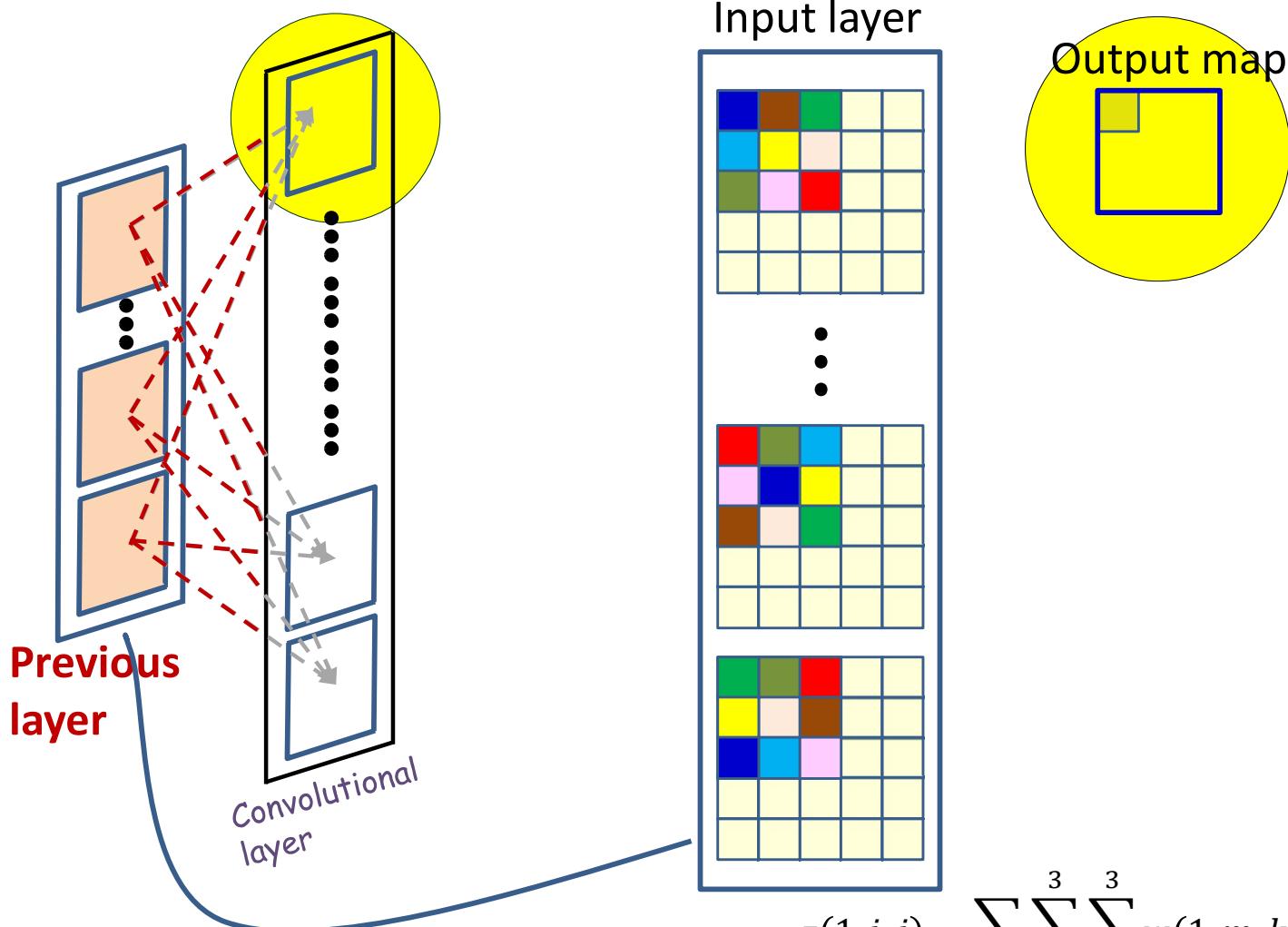
- Scanning an image with a “filter”
 - At each location, the “filter and the underlying map values are multiplied component wise, and the products are added along with the bias

What really happens



- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as
size of the filter x no. of maps in previous layer

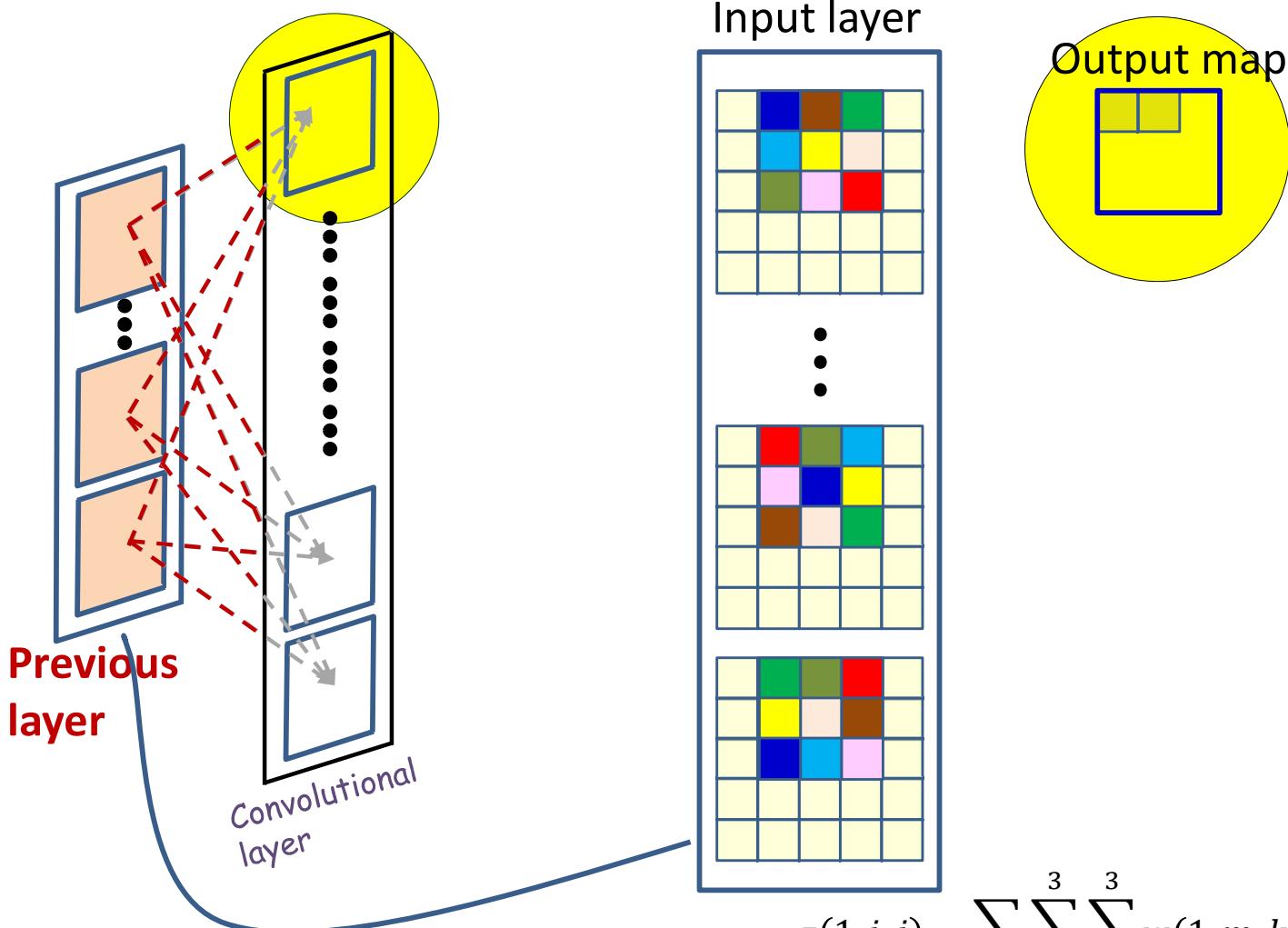
What really happens



$$z(1, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(1, m, k, l) I(m, i + l - 1, j + k - 1) + b$$

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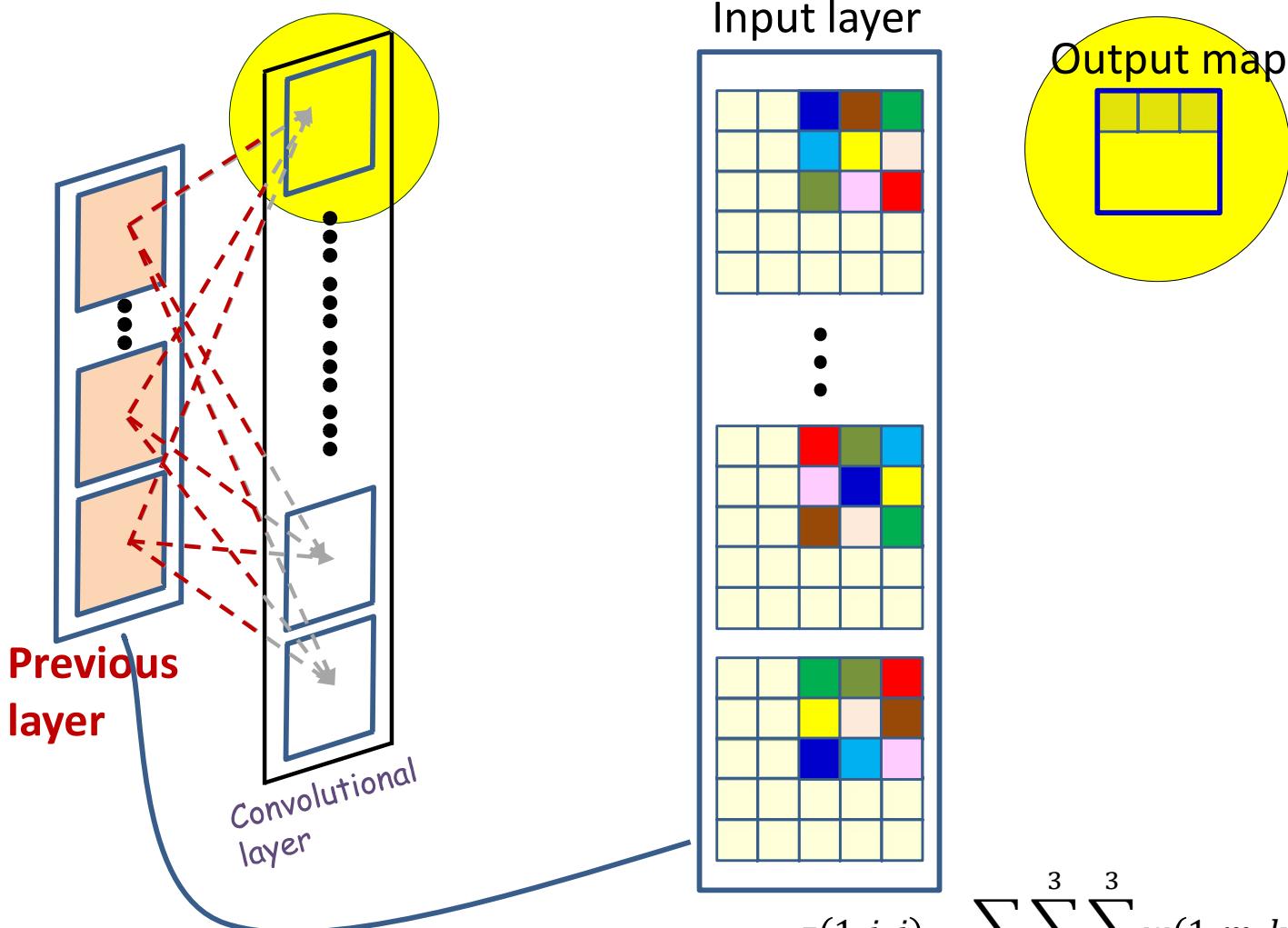
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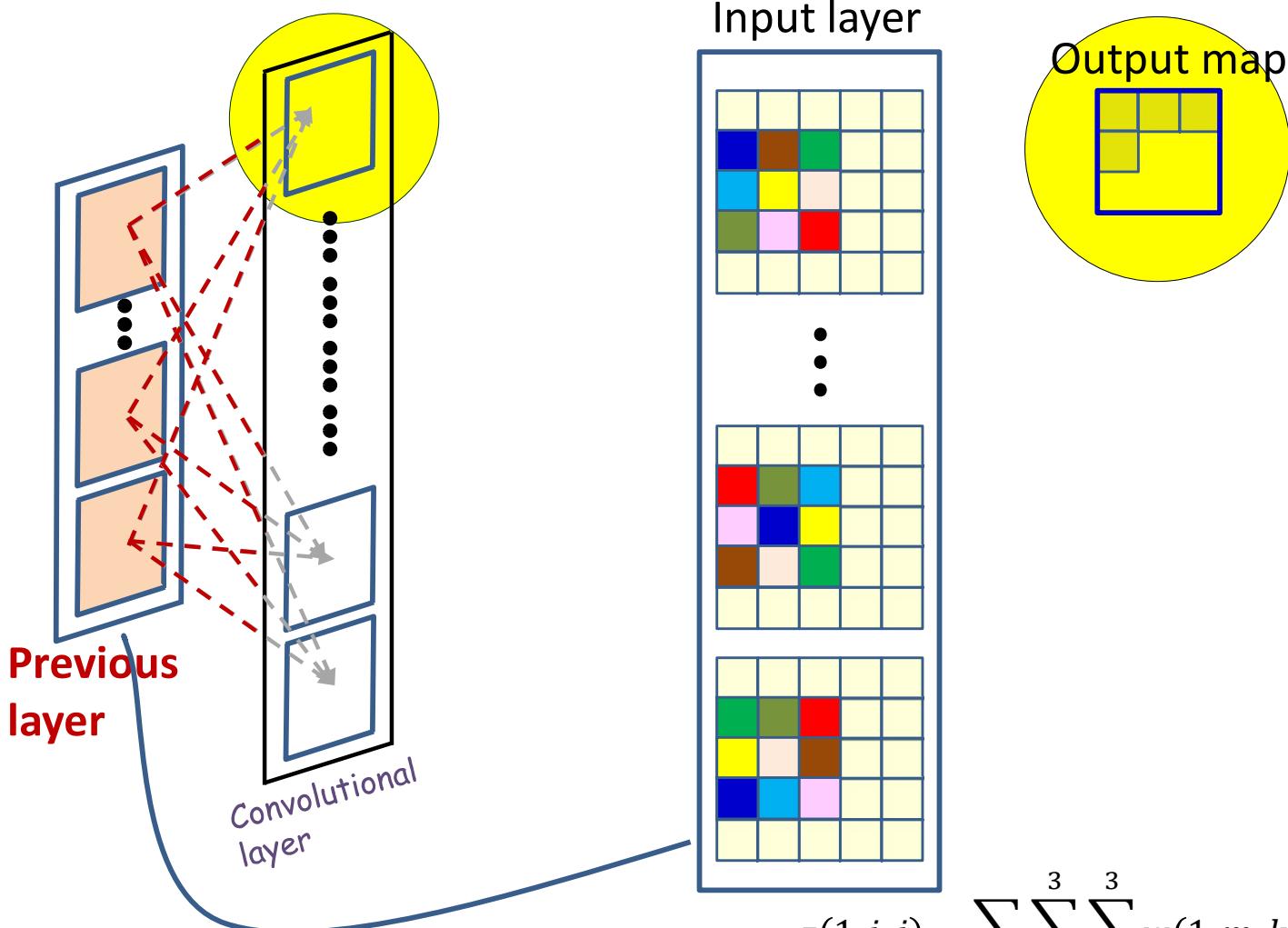
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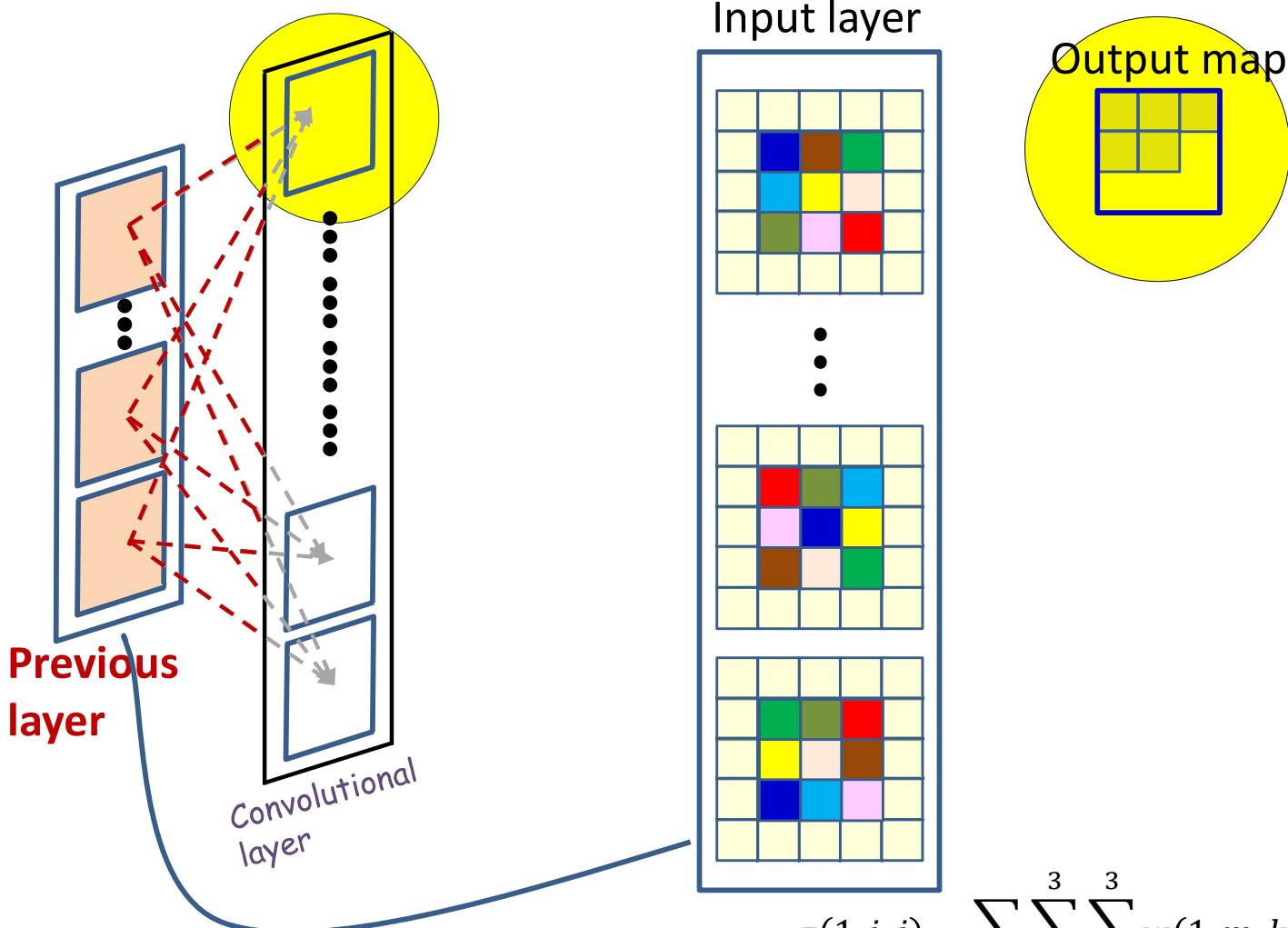
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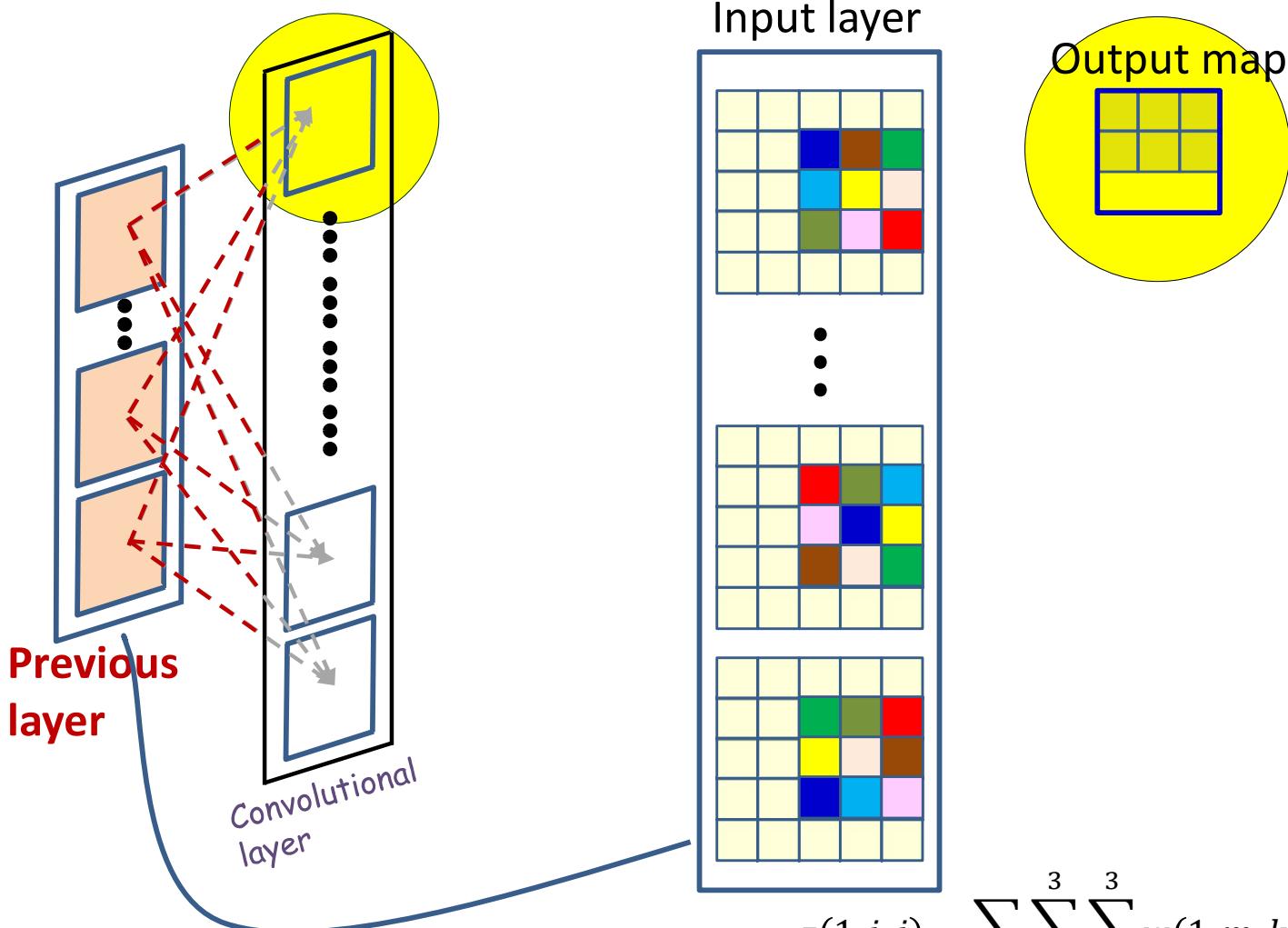
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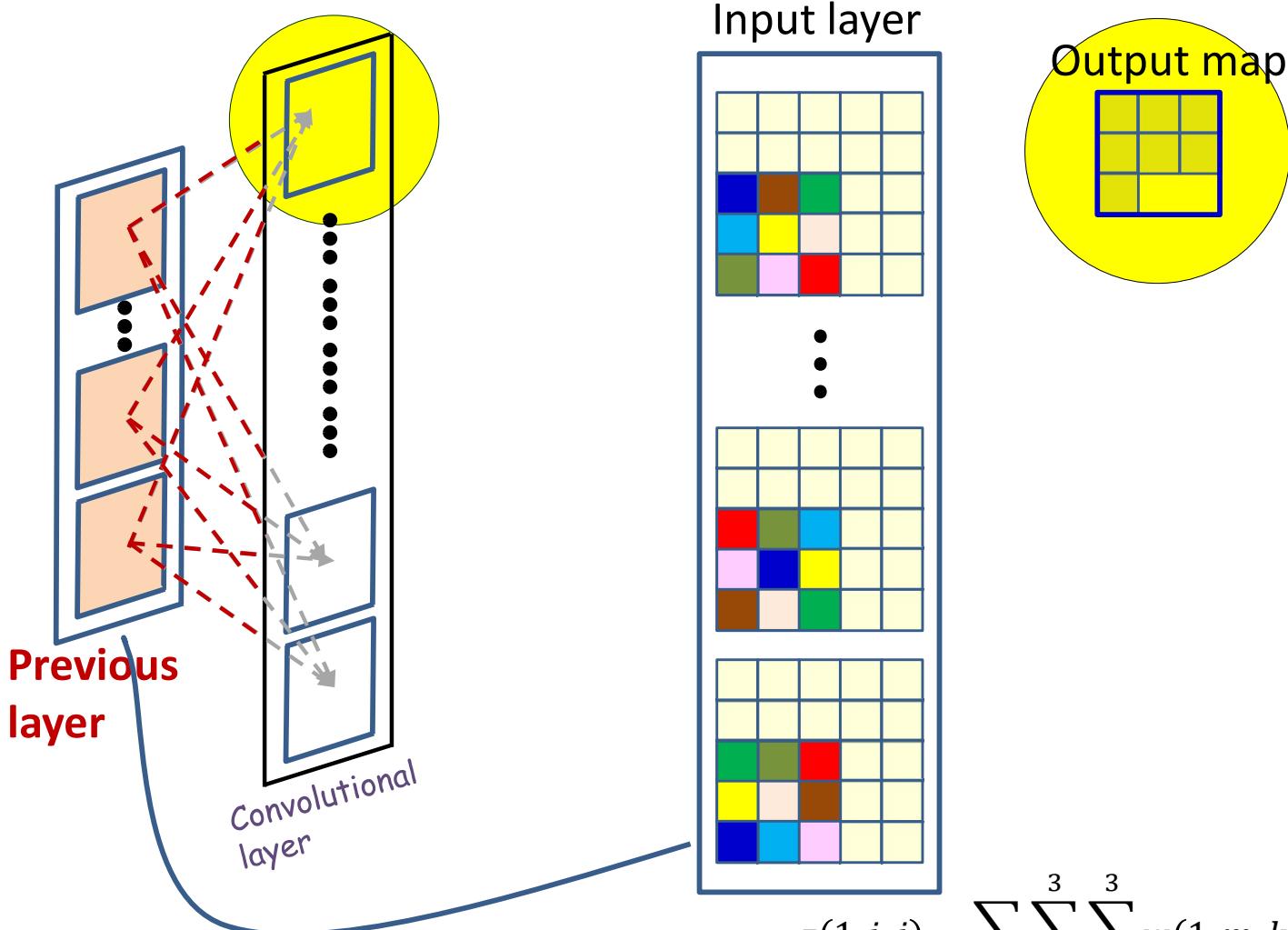
What really happens



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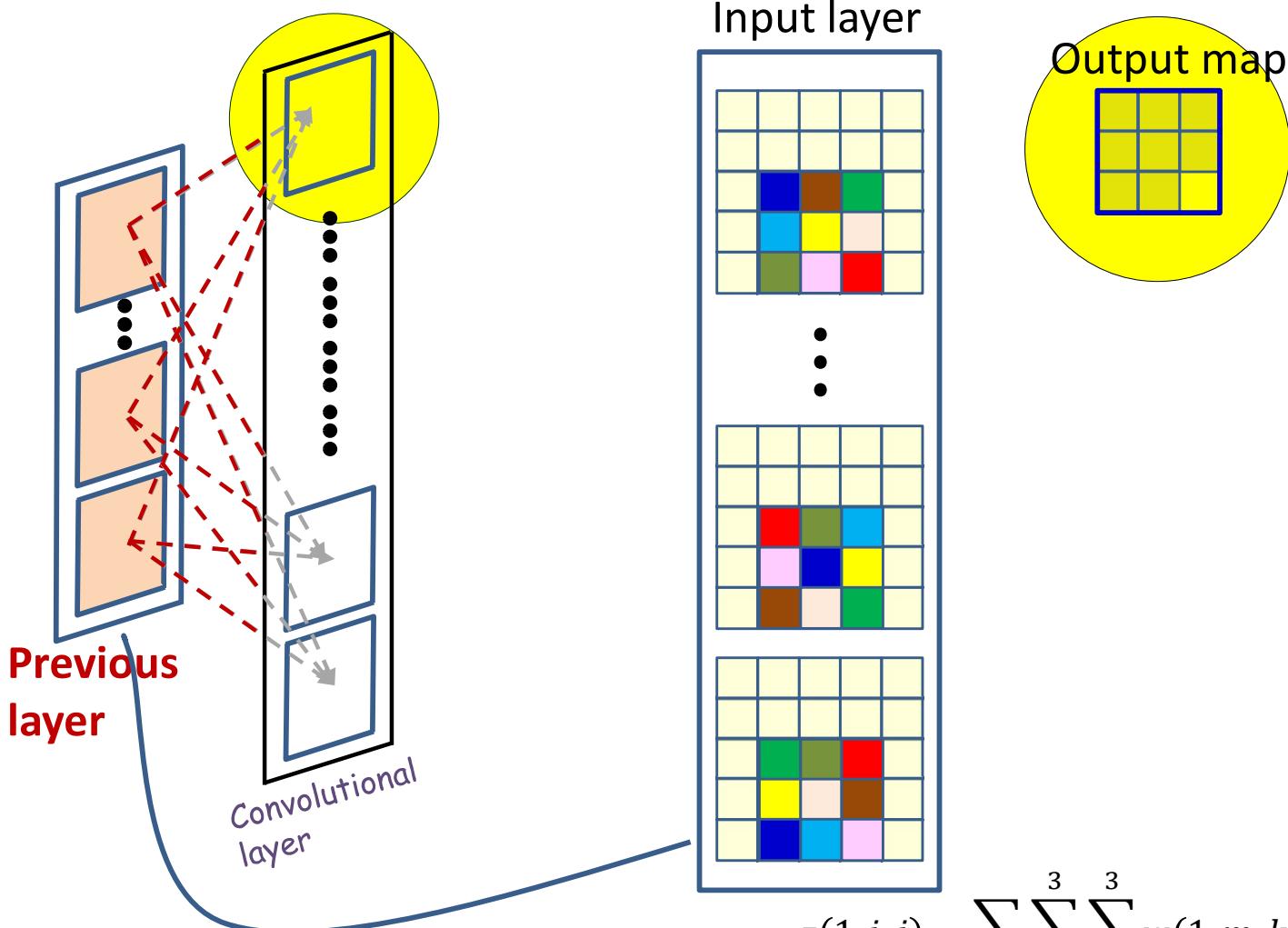
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size of the filter x no. of maps in previous layer

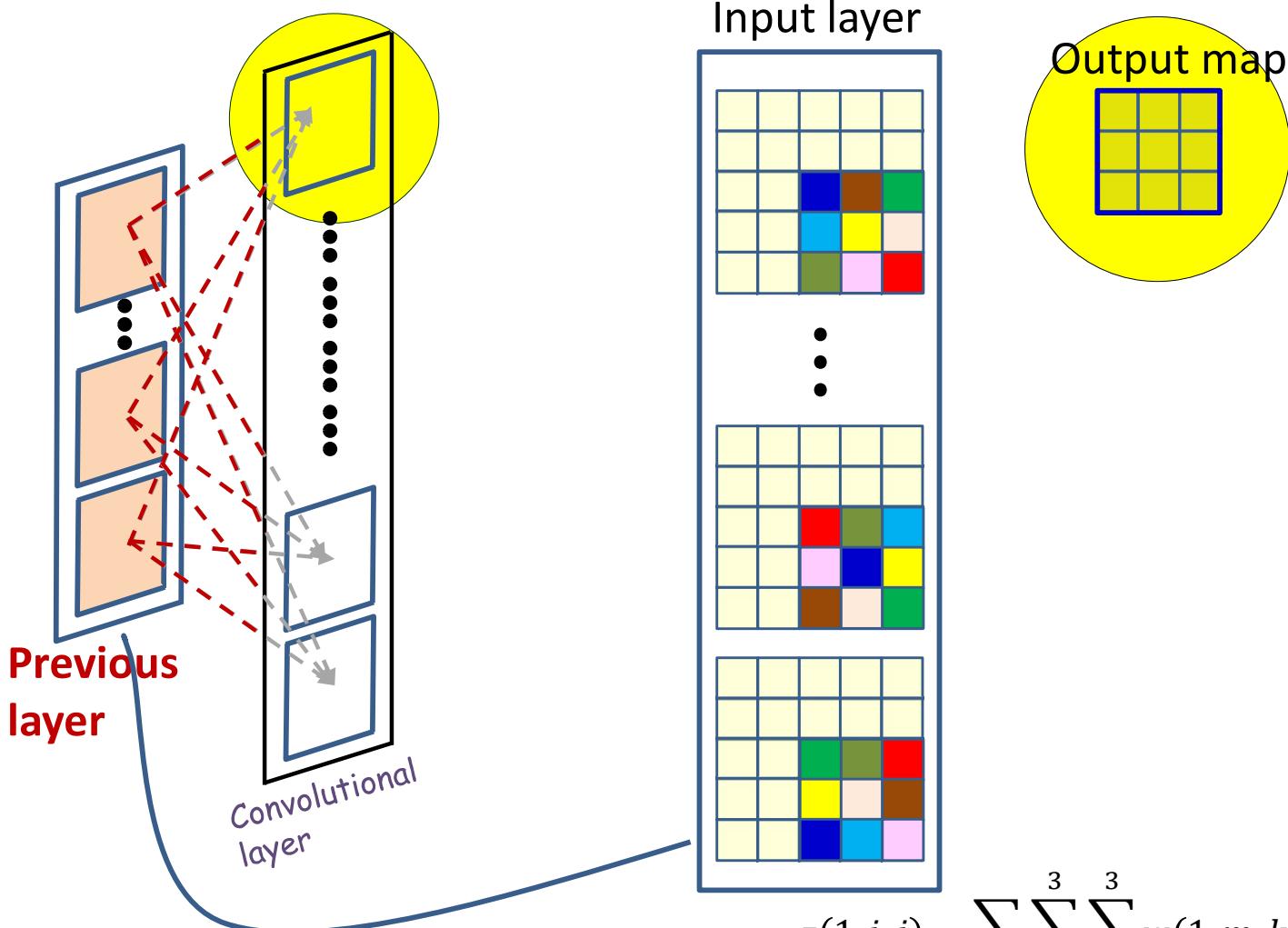
What really happens



$$z(1, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(1, m, k, l) I(m, i + l - 1, j + k - 1) + b$$

- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as
size of the filter x no. of maps in previous layer

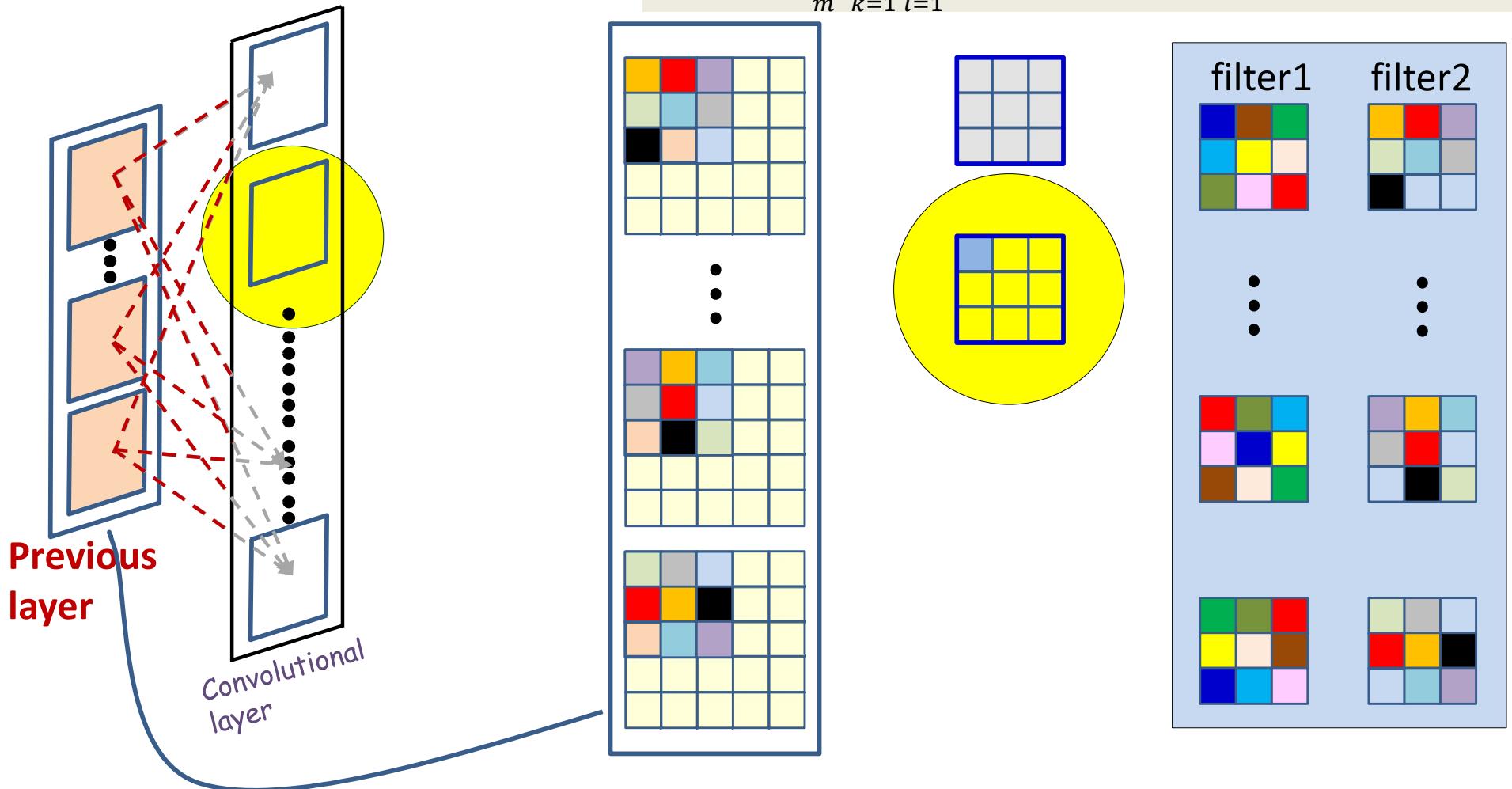
What really happens



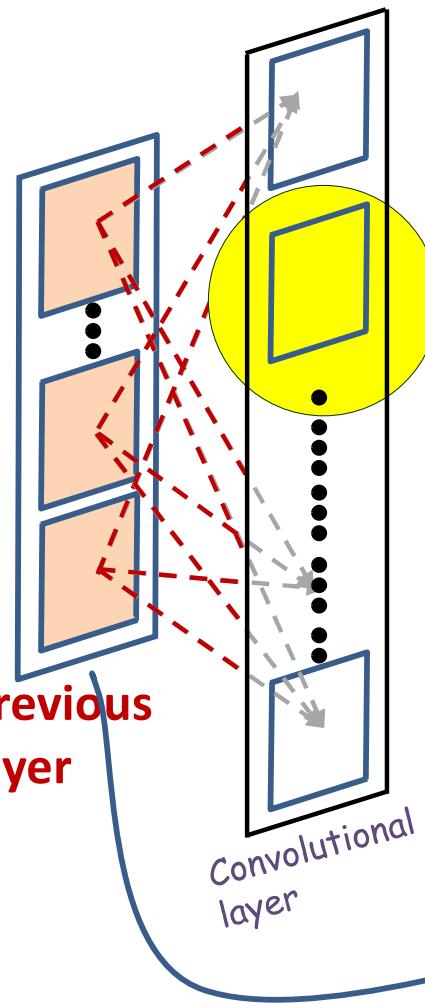
$$z(1, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(1, m, k, l) I(m, i + l - 1, j + k - 1) + b$$

- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as *size of the filter x no. of maps in previous layer*

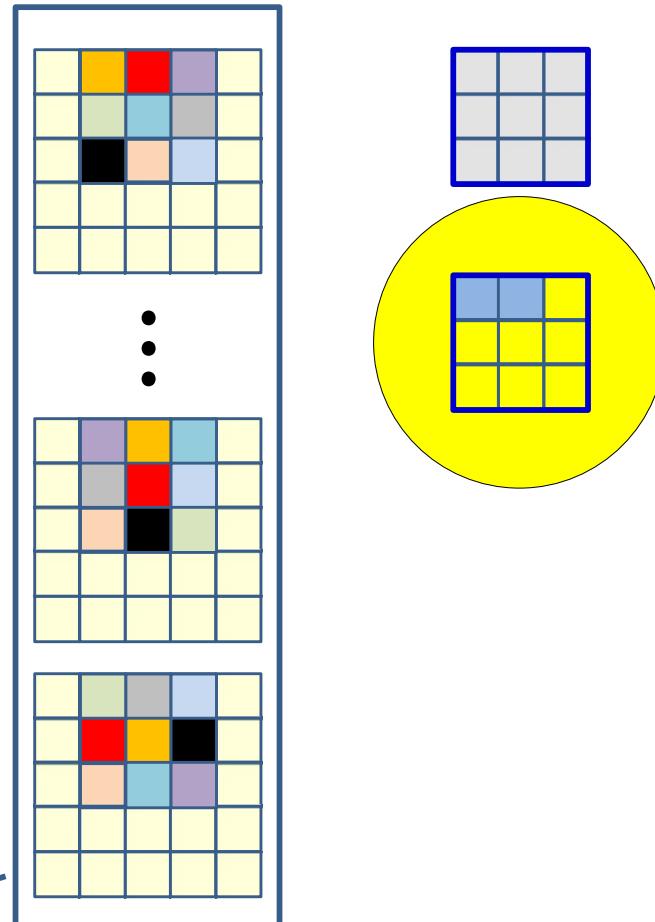
$$z(2, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(2, m, k, l) I(m, i + l - 1, j + k - 1) + b(2)$$



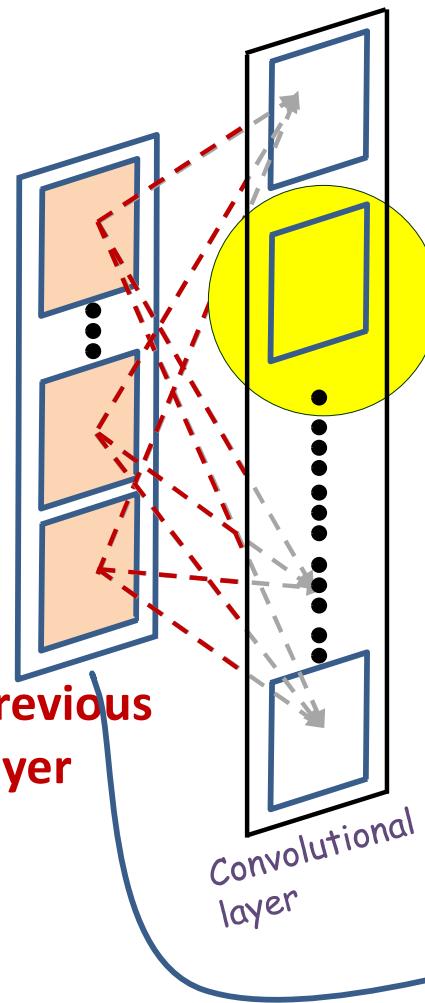
- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as *size of the filter x no. of maps in previous layer*



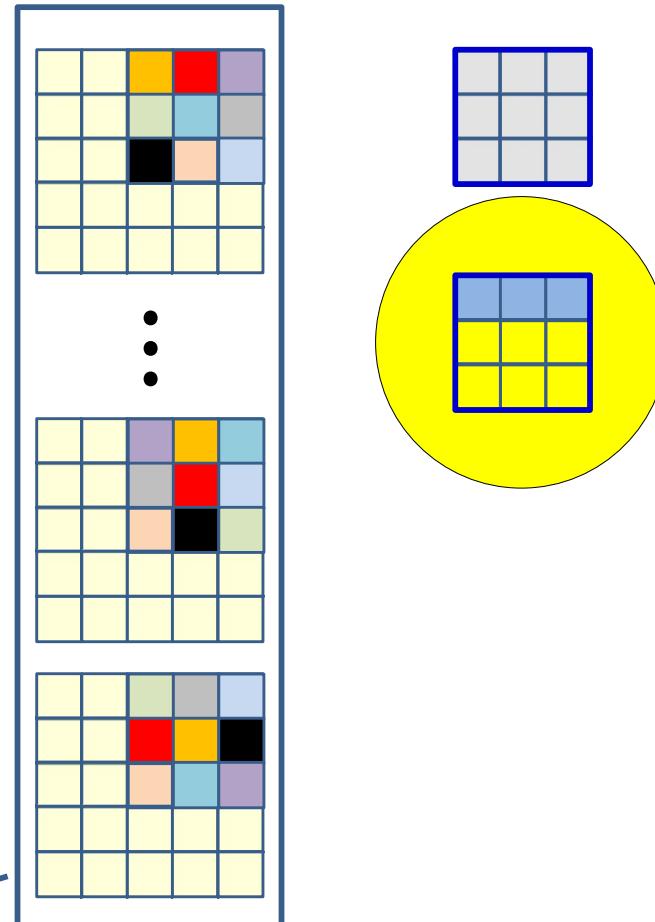
$$z(2, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(2, m, k, l) I(m, i + l - 1, j + k - 1) + b(2)$$



- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as
size of the filter x no. of maps in previous layer

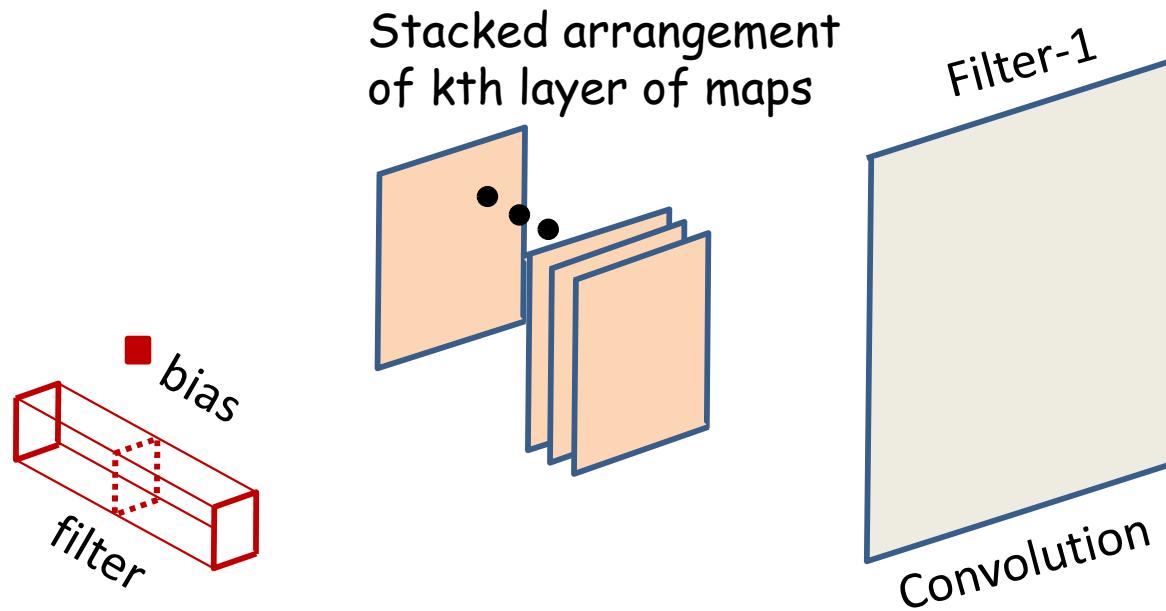


$$z(2, i, j) = \sum_m \sum_{k=1}^3 \sum_{l=1}^3 w(2, m, k, l) I(m, i + l - 1, j + k - 1) + b(2)$$



- Each output is computed from multiple maps simultaneously
- There are as many weights (for each output map) as
size of the filter x no. of maps in previous layer

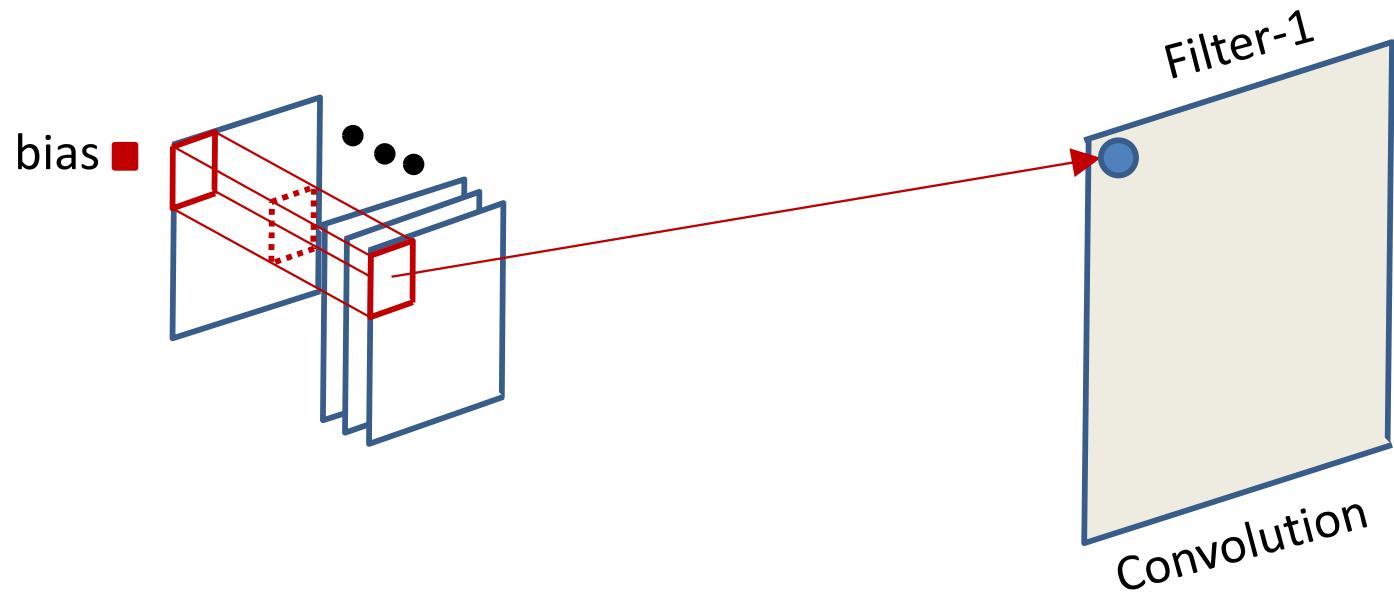
A different view



Filter applied to kth layer of maps
(convulsive component plus bias)

- ..A *stacked* arrangement of planes
- We can view the joint processing of the various maps as processing the stack using a three-dimensional filter

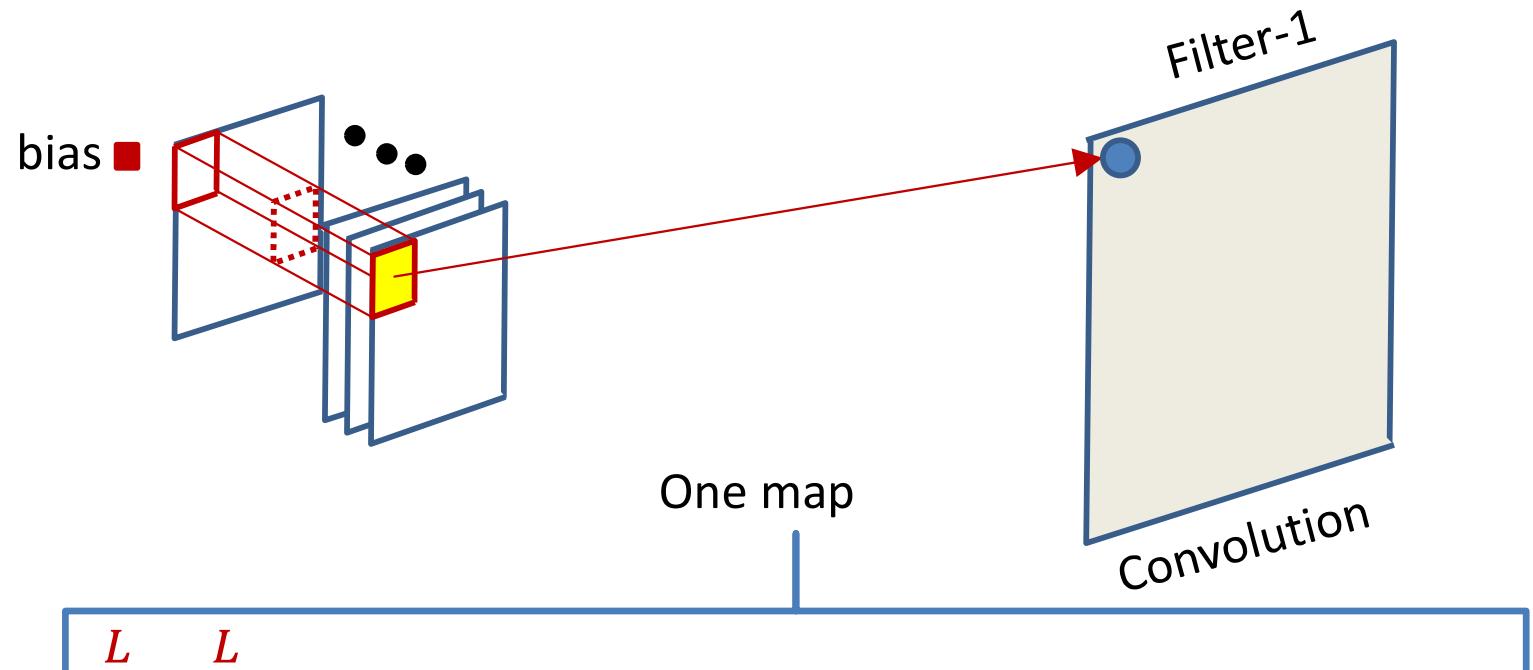
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

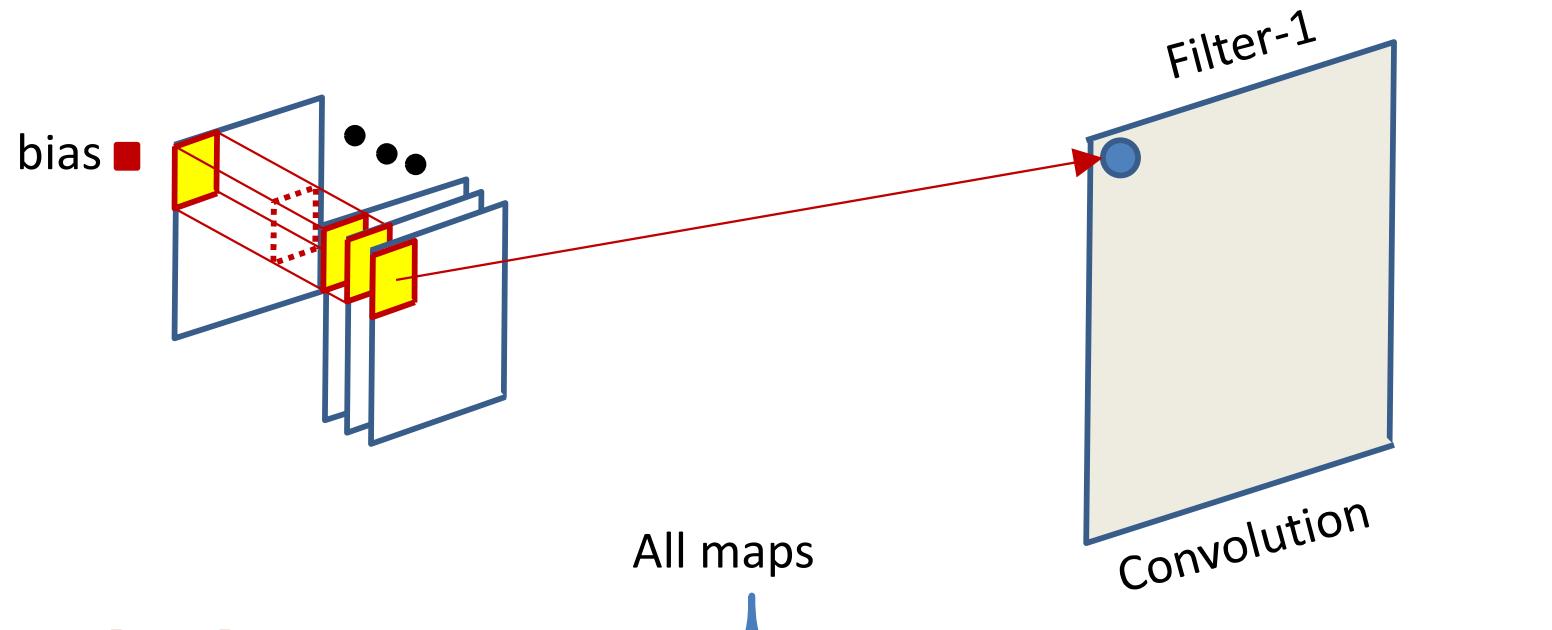
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

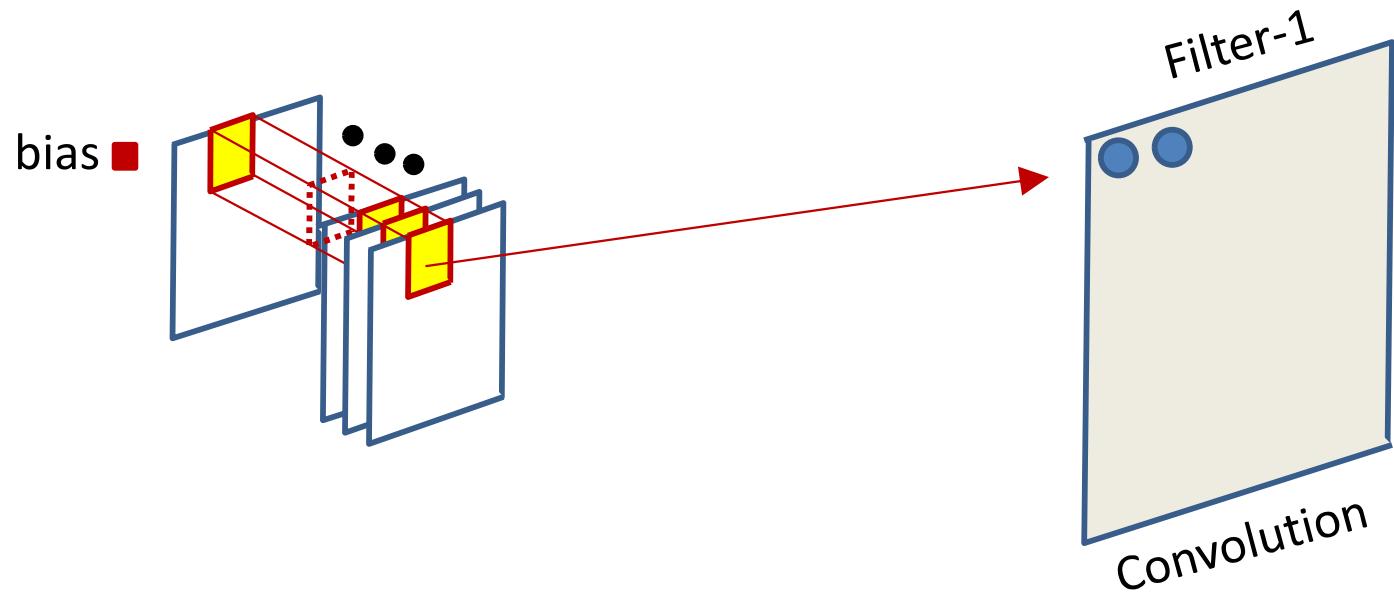
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

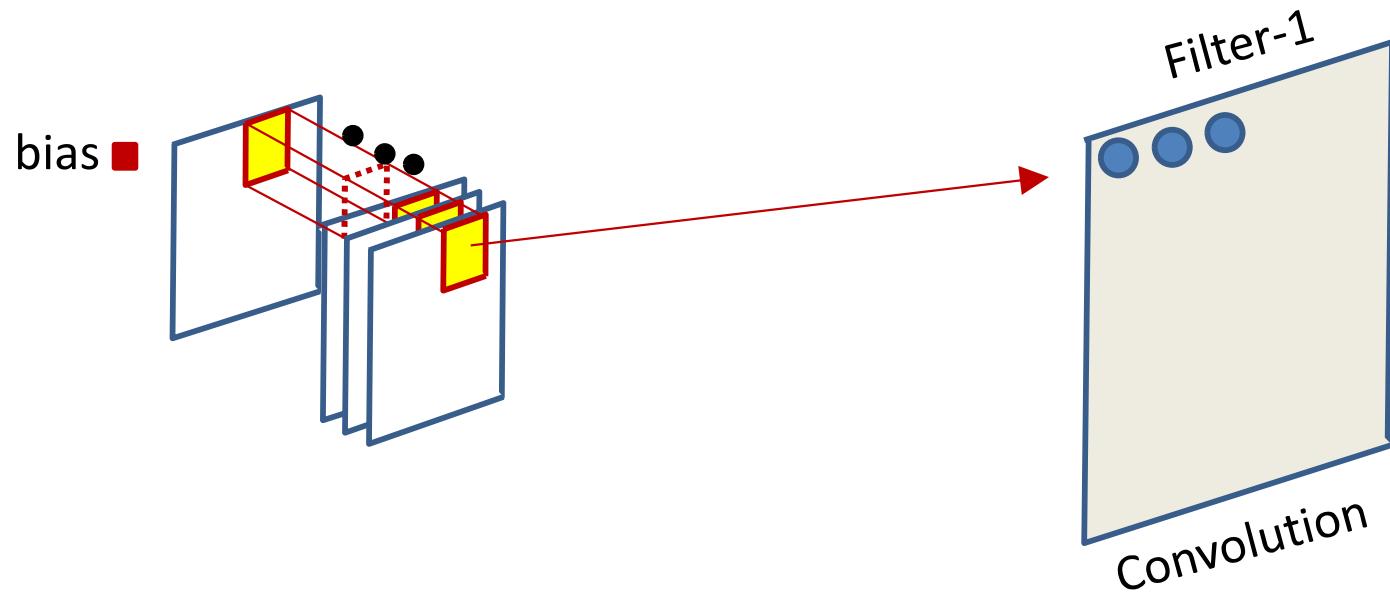
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

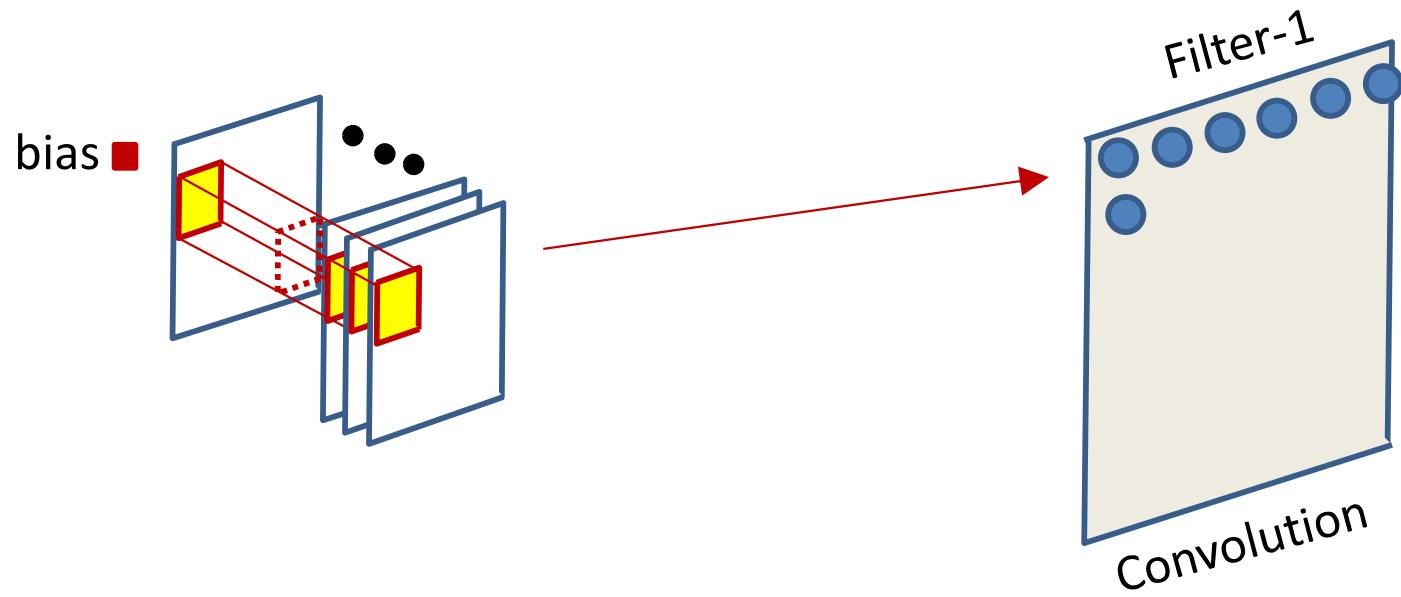
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

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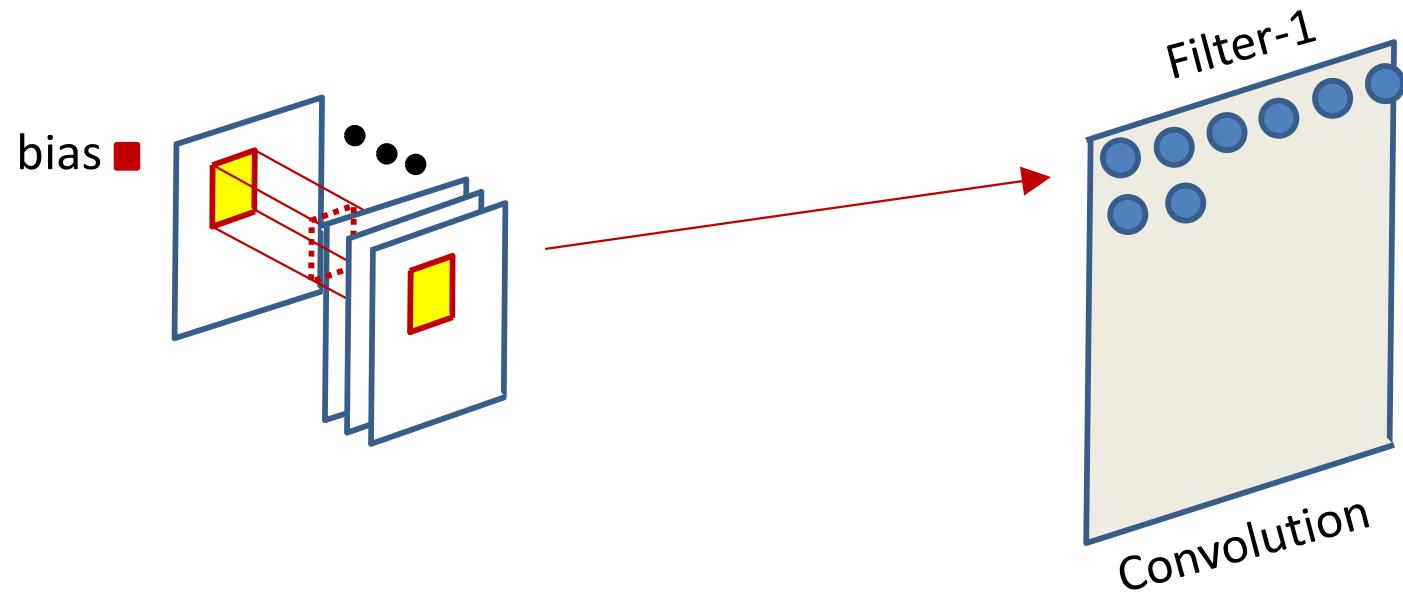
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

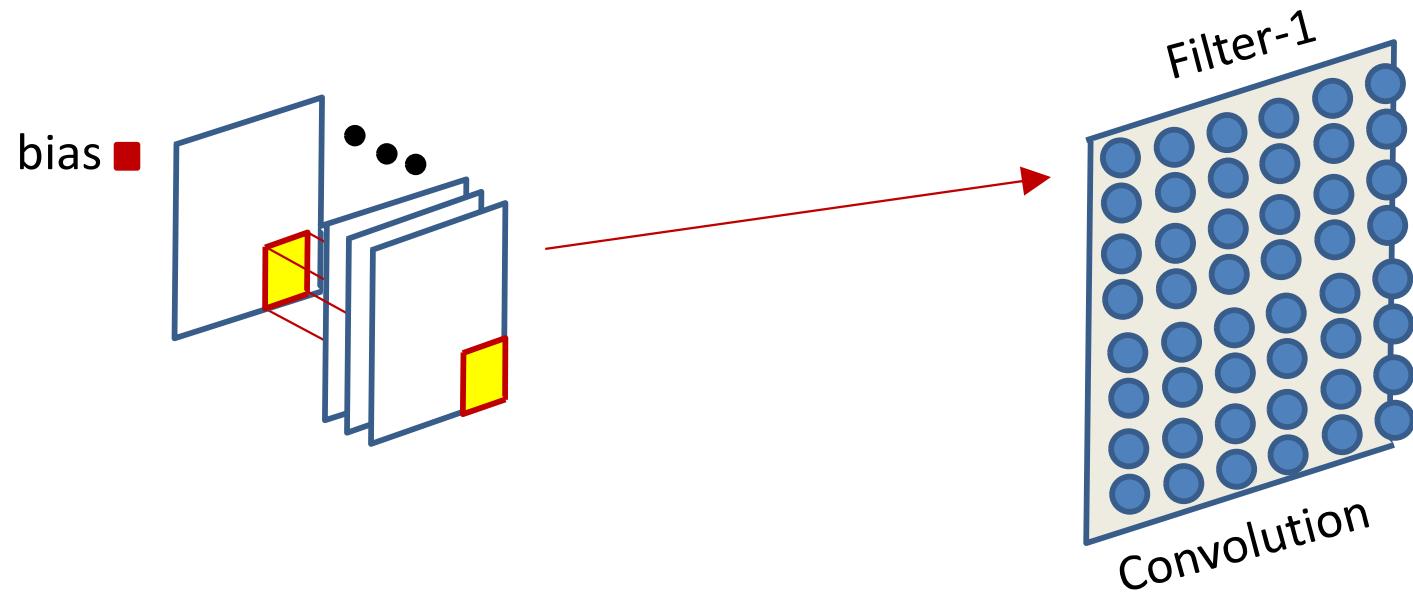
The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

The “cube” view of input maps



$$z(s, i, j) = \sum_p \sum_{k=1}^L \sum_{l=1}^L w(s, p, k, l) Y(p, i + l - 1, j + k - 1) + b(s)$$

- The computation of the convolutional map at any location *sums* the convolutional outputs *at all planes*

CNN: Vector notation to compute a single output map

The weight $W(l, j)$ is now a 3D $D_{l-1} \times K_l \times K_l$ tensor (assuming square receptive fields)

The product in blue is a tensor inner product with a scalar output

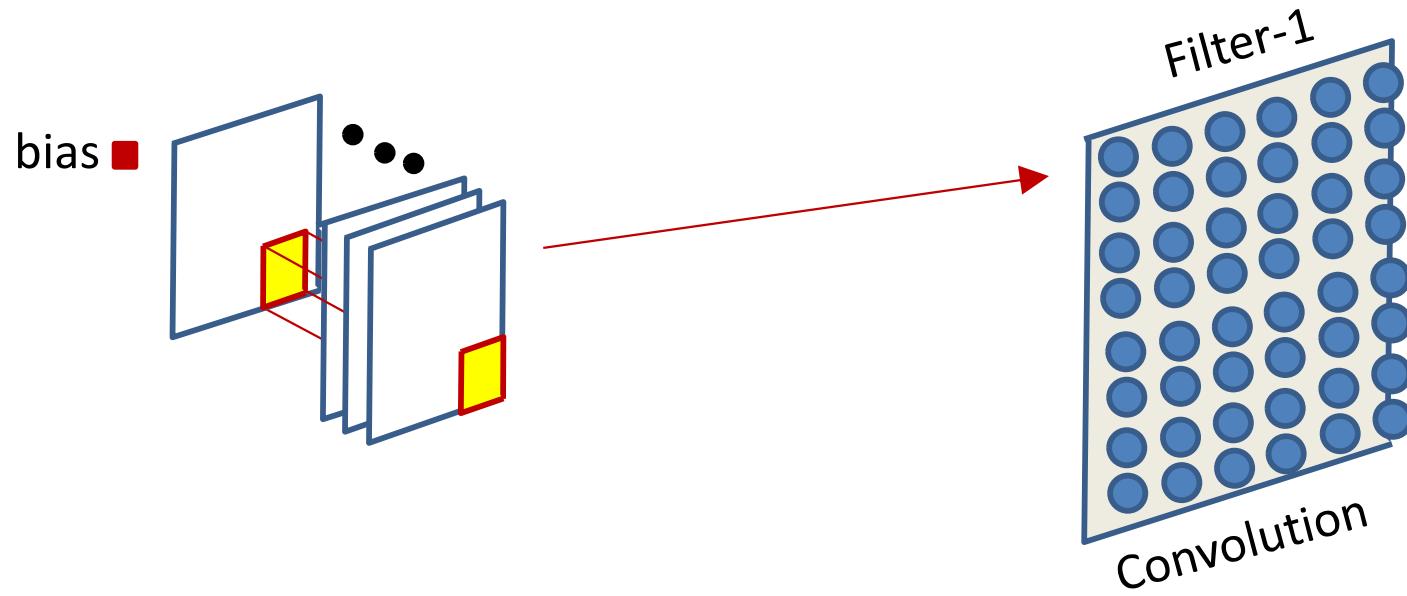
$\mathbf{Y}(0) = \text{Image}$

for $l = 1:L$ # layers operate on vector at (x, y)

```
for  $x = 1:W_{l-1}-K_l+1$ 
    for  $y = 1:H_{l-1}-K_l+1$ 
        for  $j = 1:D_l$ 
            segment =  $\mathbf{Y}(l-1, :, x:x+K_l-1, y:y+K_l-1)$  #3D tensor
             $\mathbf{z}(l, j, x, y) = W(l, j) \cdot \text{segment}$  #tensor inner prod.
             $\mathbf{Y}(l, j, x, y) = \text{activation}(\mathbf{z}(l, j, x, y))$ 
```

$\mathbf{Y} = \text{softmax}(\{\mathbf{Y}(L, :, :, :)\})$

Engineering consideration: The size of the result of the convolution



- The size of the output of the convolution operation depends on implementation factors
 - The size of the input, the size of the filter
- And may not be identical to the size of the input
 - Let's take a brief look at this for completeness sake

The size of the convolution

0
bias
Filter

1	0	1
0	1	0
1	0	1

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

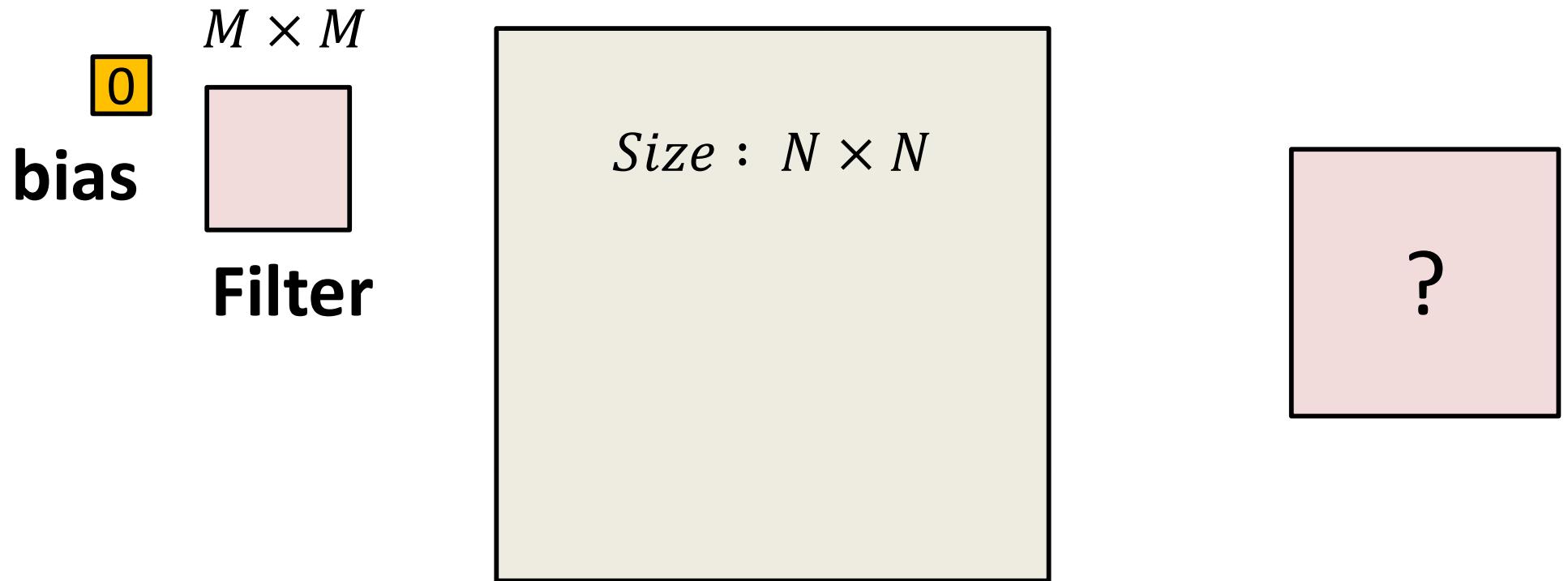
Input Map

4		

Convolved Feature

- Image size: 5x5
- Filter: 3x3
- Output size = ?

The size of the convolution

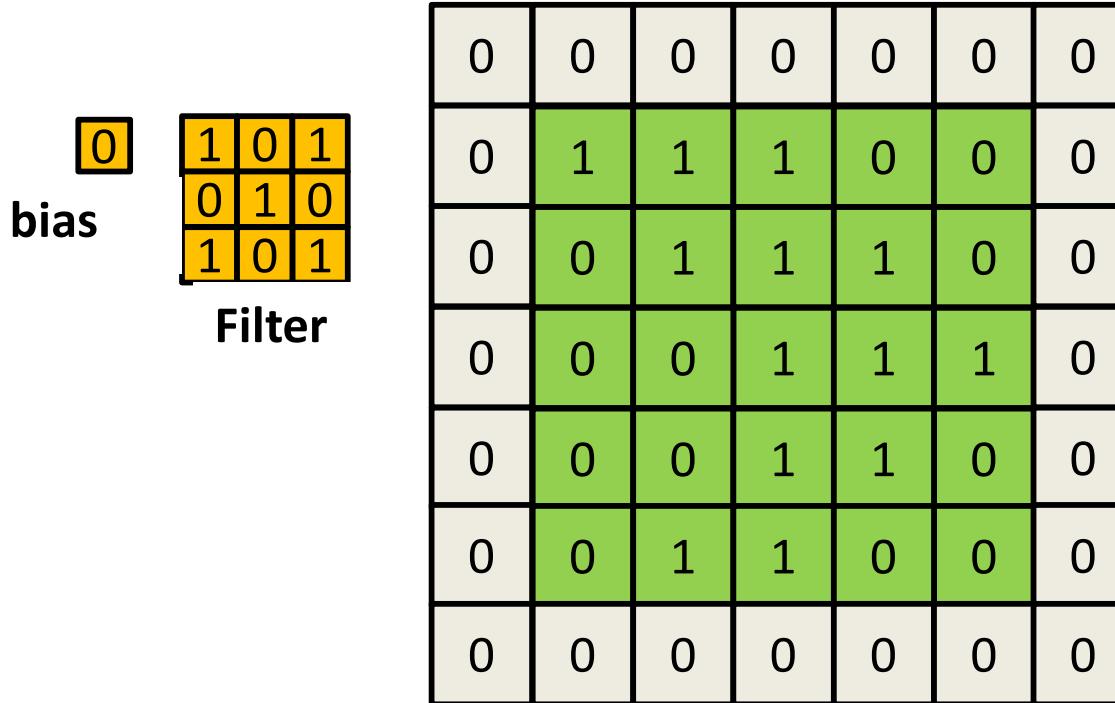


- Image size: $N \times N$
- Filter: $M \times M$
- Output size = $(N-M)+1$ on each side

Convolution Size

- Simple convolution size pattern:
 - Image size: $N \times N$
 - Filter: $M \times M$
 - **Output size (each side)** = $(N - M) + 1$
 - Assuming you're not allowed to go beyond the edge of the input
- Results in a reduction in the output size
 - Sometimes not considered acceptable

Solution

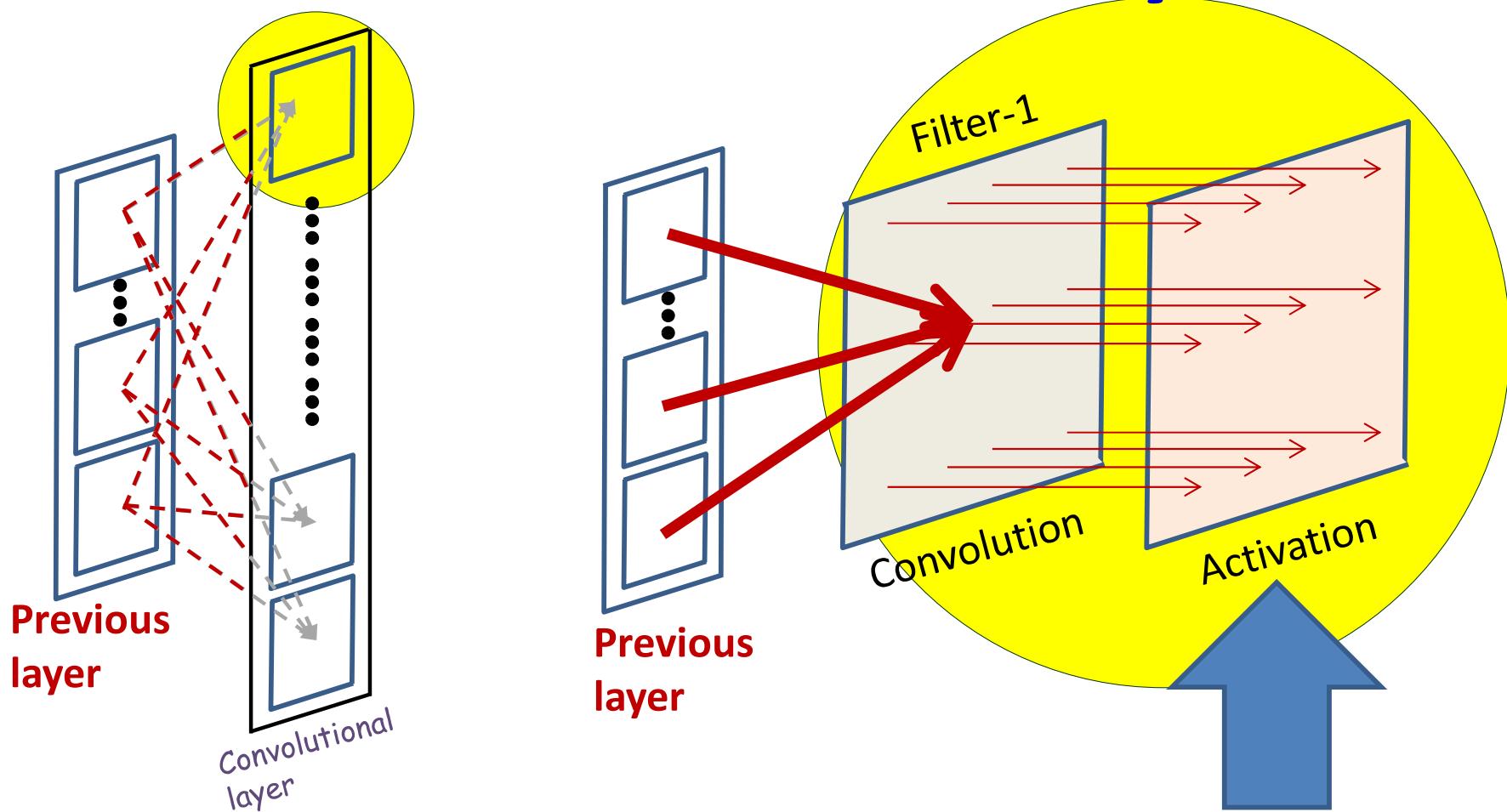


- Zero-pad the input
 - Pad the input image/map all around
 - Pad as symmetrically as possible, such that..
 - **The result of the convolution is the same size as the original image**

Zero padding

- For an L width filter:
 - Odd L : Pad on both left and right with $(L - 1)/2$ columns of zeros
 - Even L : Pad one side with $L/2$ columns of zeros, and the other with $\frac{L}{2} - 1$ columns of zeros
 - The resulting image is width $N + L - 1$
 - The result of the convolution is width N
- The top/bottom zero padding follows the same rules to maintain map height after convolution

A convolutional layer



- The convolution operation results in an affine map
- An *Activation* is finally applied to every entry in the map

Convolutional neural net: Vector notation

The weight $W(l, j)$ is now a 4D $D_l \times D_{l-1} \times K_l \times K_l$ tensor (assuming square receptive fields)

The product in blue is a tensor inner product with a scalar output

$\mathbf{Y}(0) = \text{Image}$

for $l = 1:L$ # layers operate on vector at (x, y)

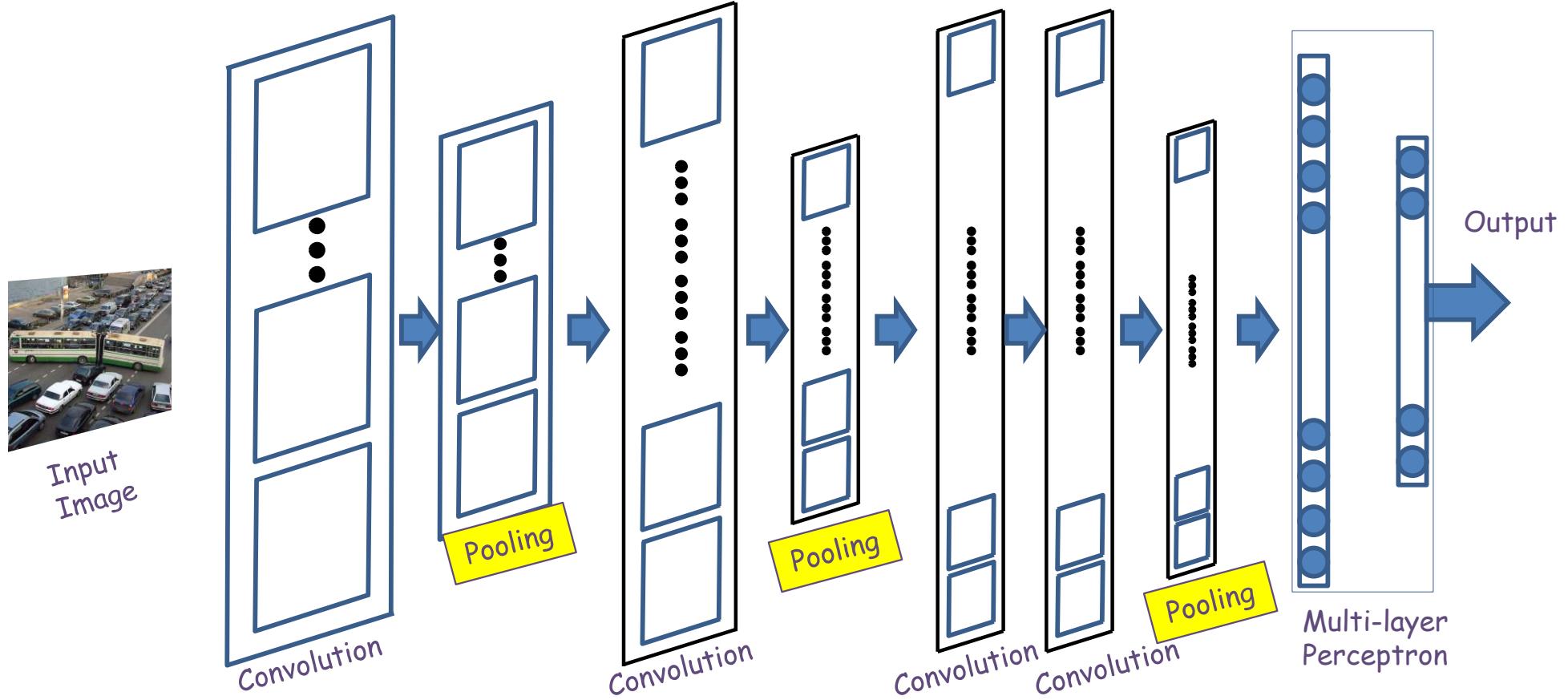
```
for x = 1:W_{l-1}-K_l+1
    for y = 1:H_{l-1}-K_l+1
        segment = Y(l-1, :, x:x+K_l-1, y:y+K_l-1) #3D tensor
        z(l, :, x, y) = W(l).segment #tensor inner prod.
        Y(l, :, x, y) = activation(z(l, :, x, y))
```

$\mathbf{Y} = \text{softmax}(\{\mathbf{Y}(L, :, :, :)\})$

Convolution Summary

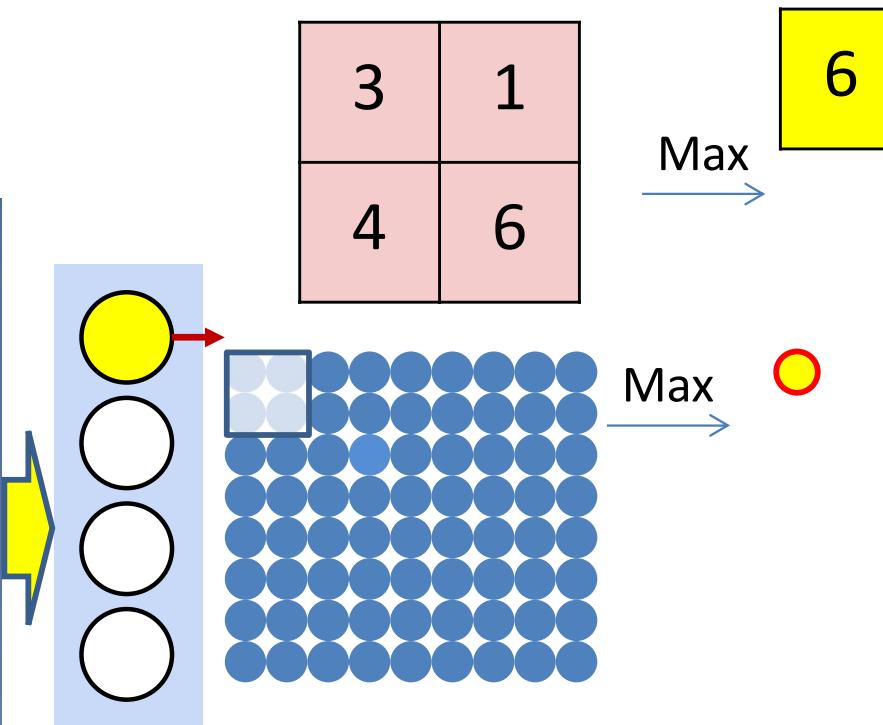
- Convolutional layers “scan” the input using a bank of “filters”
 - A “filter” is just a neuron in a scanning layer
- Each filter jointly scans the maps in the previous layer to produce an output “map”
 - As many output maps as *filters* (one output map per filter)
 - Regardless of the number of input maps
- We may have to pad the edges of the input maps to ensure that the output maps are the same size as input maps
 - If not, convolution loses rows/columns at the edges of the scan

The other component: Pooling



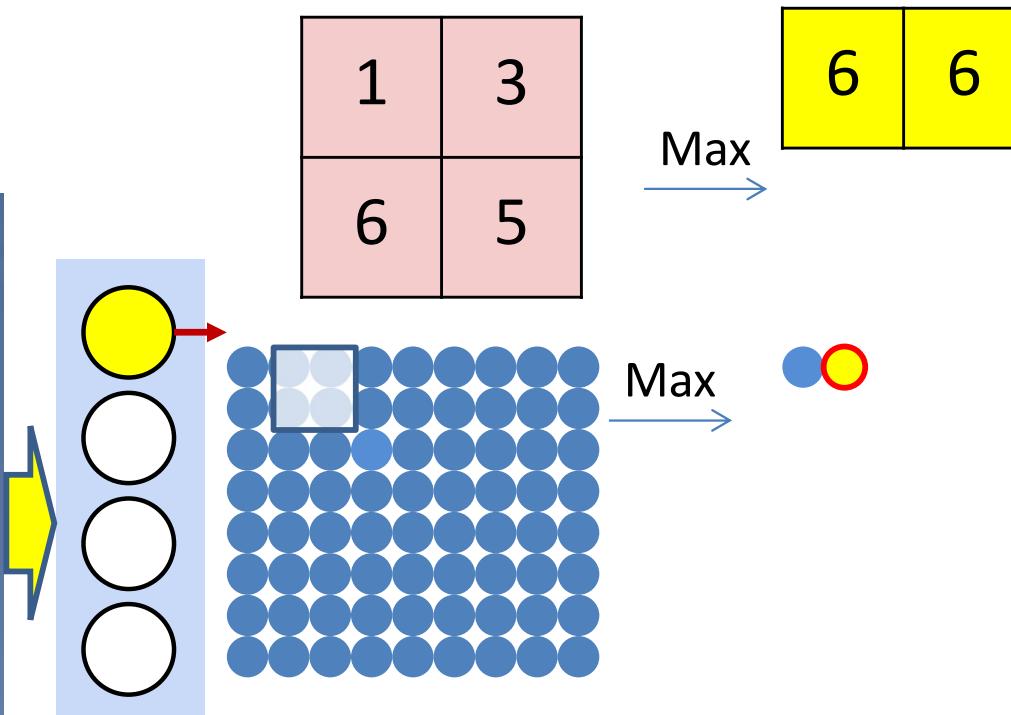
- Convolution (and activation) layers are followed intermittently by “pooling” layers
 - Typically (but not always) “max” pooling
 - Often, they alternate with convolution, though this is not necessary

Max pooling



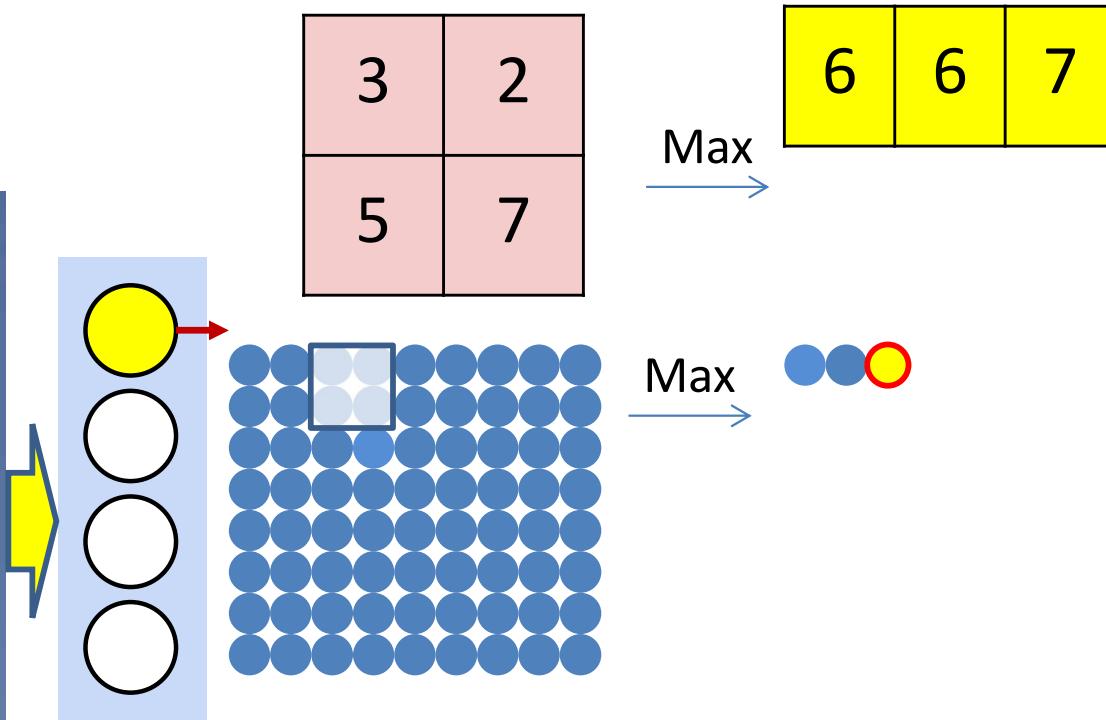
- Max pooling selects the largest from a pool of elements
- Pooling is performed by “scanning” the input

Recall: Max pooling



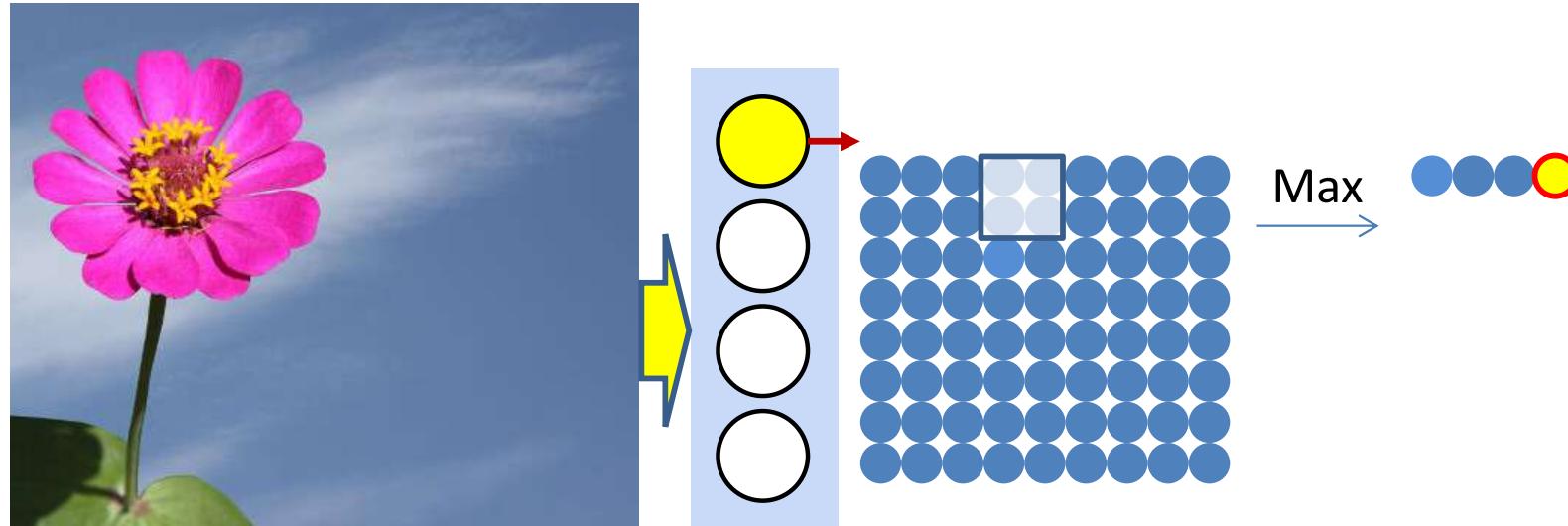
- Max pooling selects the largest from a pool of elements
- Pooling is performed by “scanning” the input

Recall: Max pooling



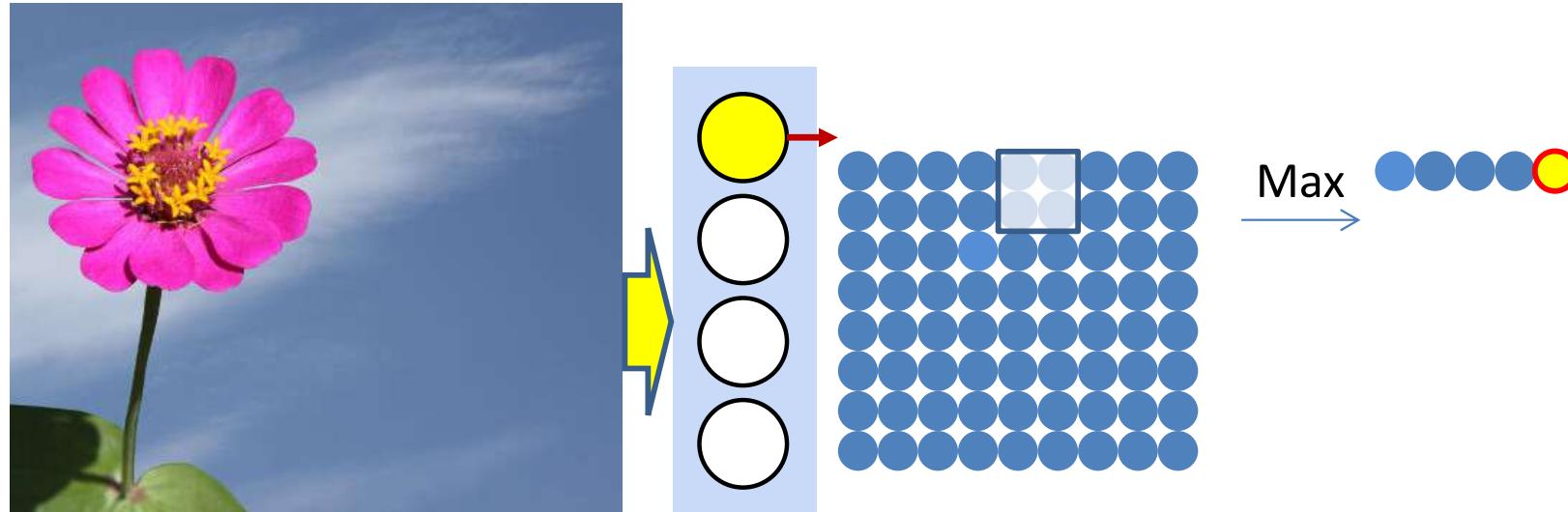
- Max pooling selects the largest from a pool of elements
- Pooling is performed by “scanning” the input

Recall: Max pooling



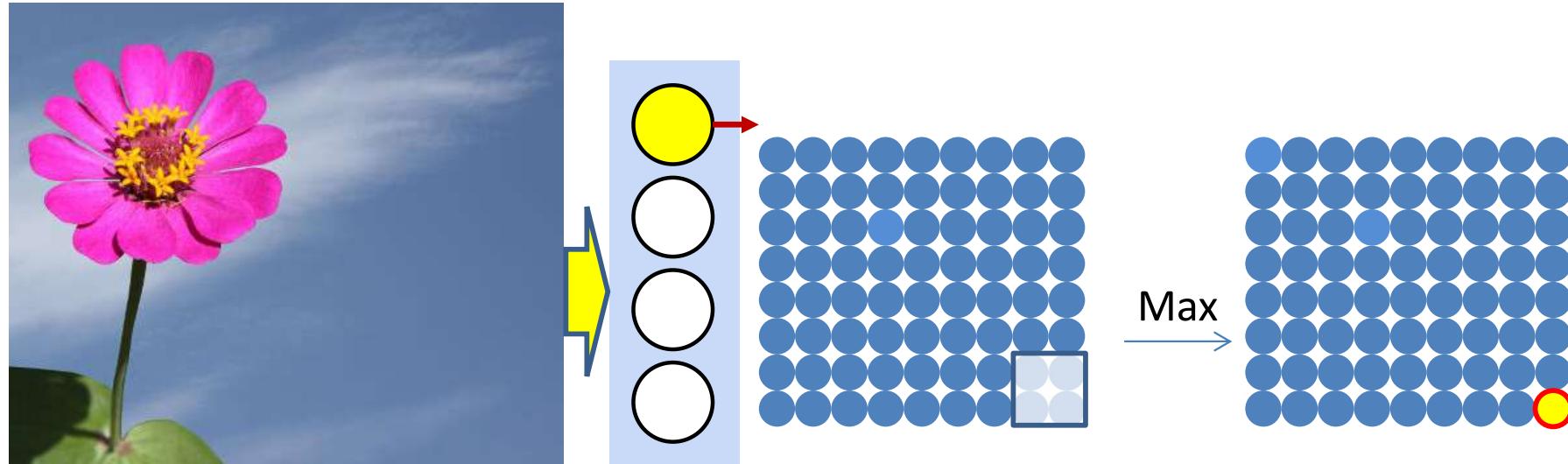
- Max pooling selects the largest from a pool of elements
- Pooling is performed by “scanning” the input

Recall: Max pooling



- Max pooling selects the largest from a pool of elements
- Pooling is performed by “scanning” the input

Recall: Max pooling



- Max pooling scans with a stride of 1 confer jitter-robustness
 - Typically performed with a stride > 1 , whereupon it also results in “downsampling”
 - We return to downsampling shortly

Max Pooling layer at layer l

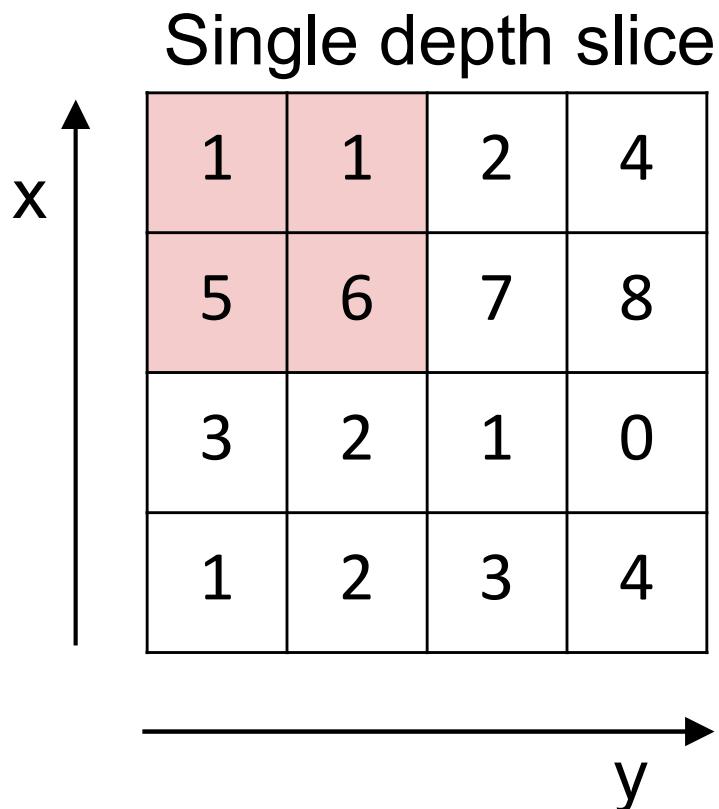
- a) Performed separately for every map (j).
*) Not combining multiple maps within a single max operation.
- b) Keeping track of location of max

Max pooling

```
for j = 1:Dl
    for x = 1:Wl-1-Kl+1
        for y = 1:Hl-1-Kl+1
            pidx(l,j,x,y) = maxidx(Y(l-1,j,x:x+Kl-1,y:y+Kl-1))
            Y(l,j,x,y) = Y(l-1,j,pidx(l,j,x,y))
```



Alternative to Max pooling: Mean Pooling



Mean pool with 2x2 filters

3.25		

- Compute the mean of the pool, instead of the max

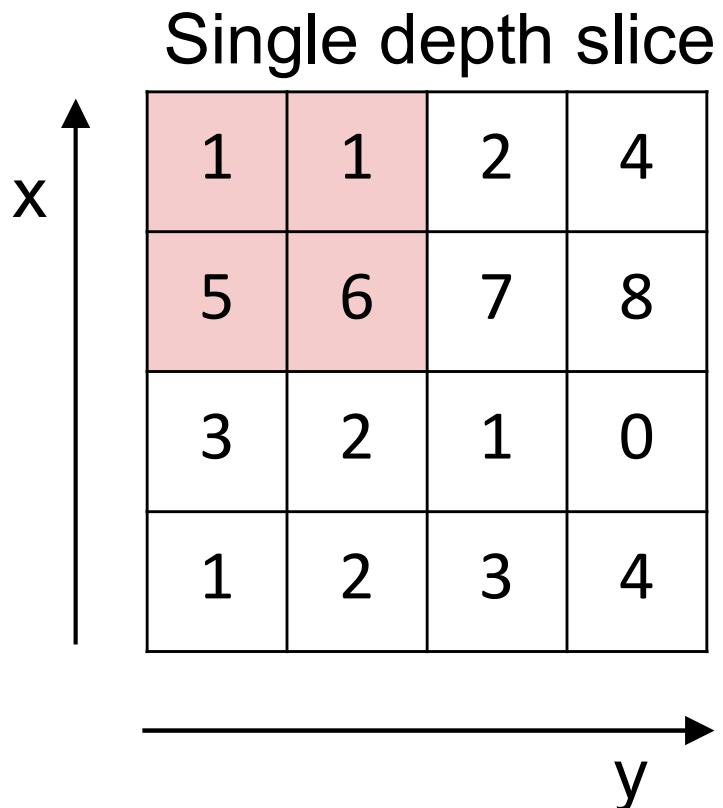
Mean Pooling layer at layer l

Performed separately for every map (j).

Mean pooling

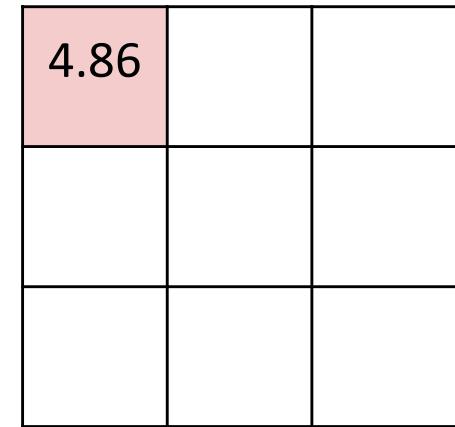
```
for j = 1:Dl
    for x = 1:Wl-1-Kl+1
        for y = 1:Hl-1-Kl+1
            Y(l,j,x,y) = mean(Y(l-1,j,x:x+Kl-1, y:y+Kl-1))
```

Alternative to Max pooling: *p*-norm



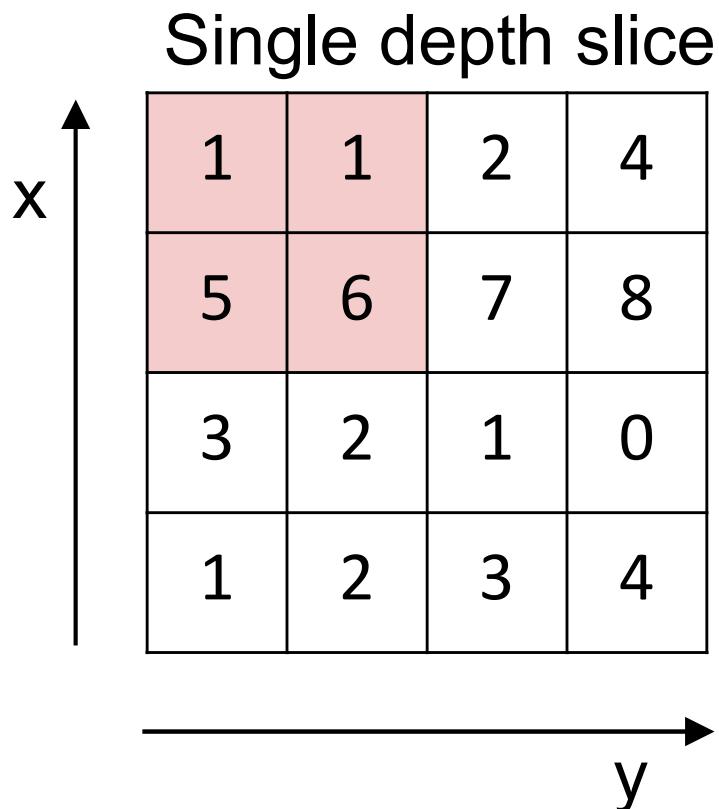
P-norm with 2x2 filters
and $p = 5$

$$y = \sqrt[p]{\frac{1}{K^2} \sum_{i,j} x_{ij}^p}$$

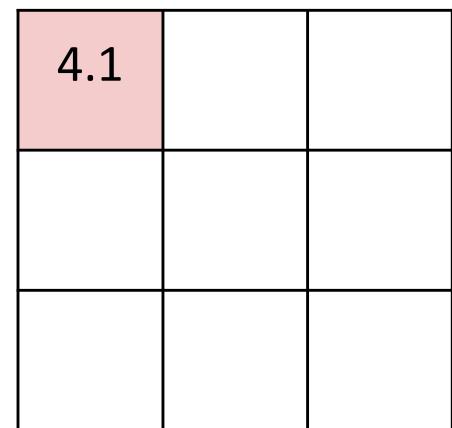
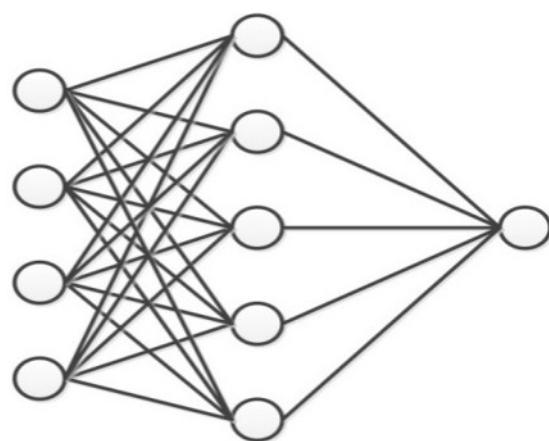


- Compute a p-norm of the pool

Other options



Network applies to each
2x2 block n this example



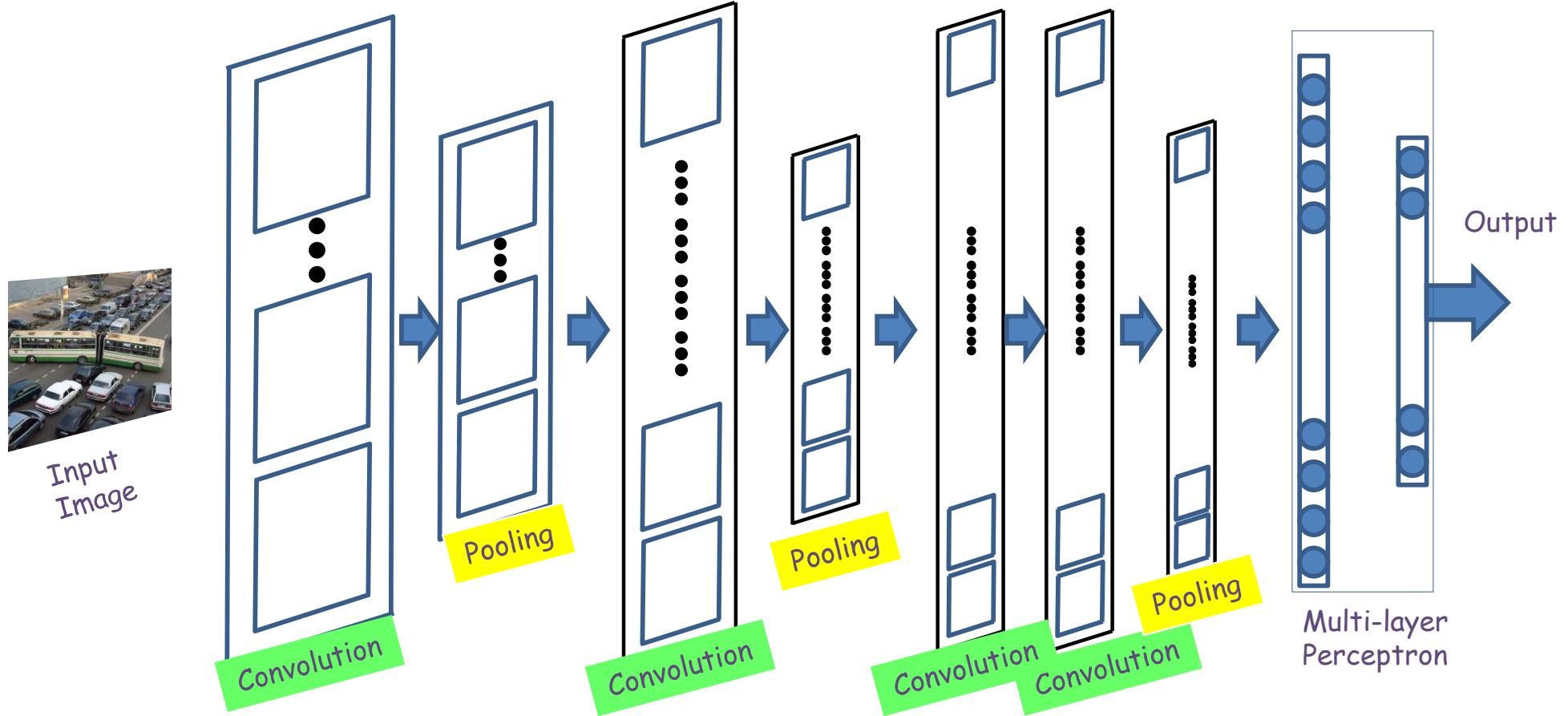
Network in network

- The pooling may even be a *learned* filter
 - The *same* network is applied on each block
 - (Again, a shared parameter network)

Pooling Summary

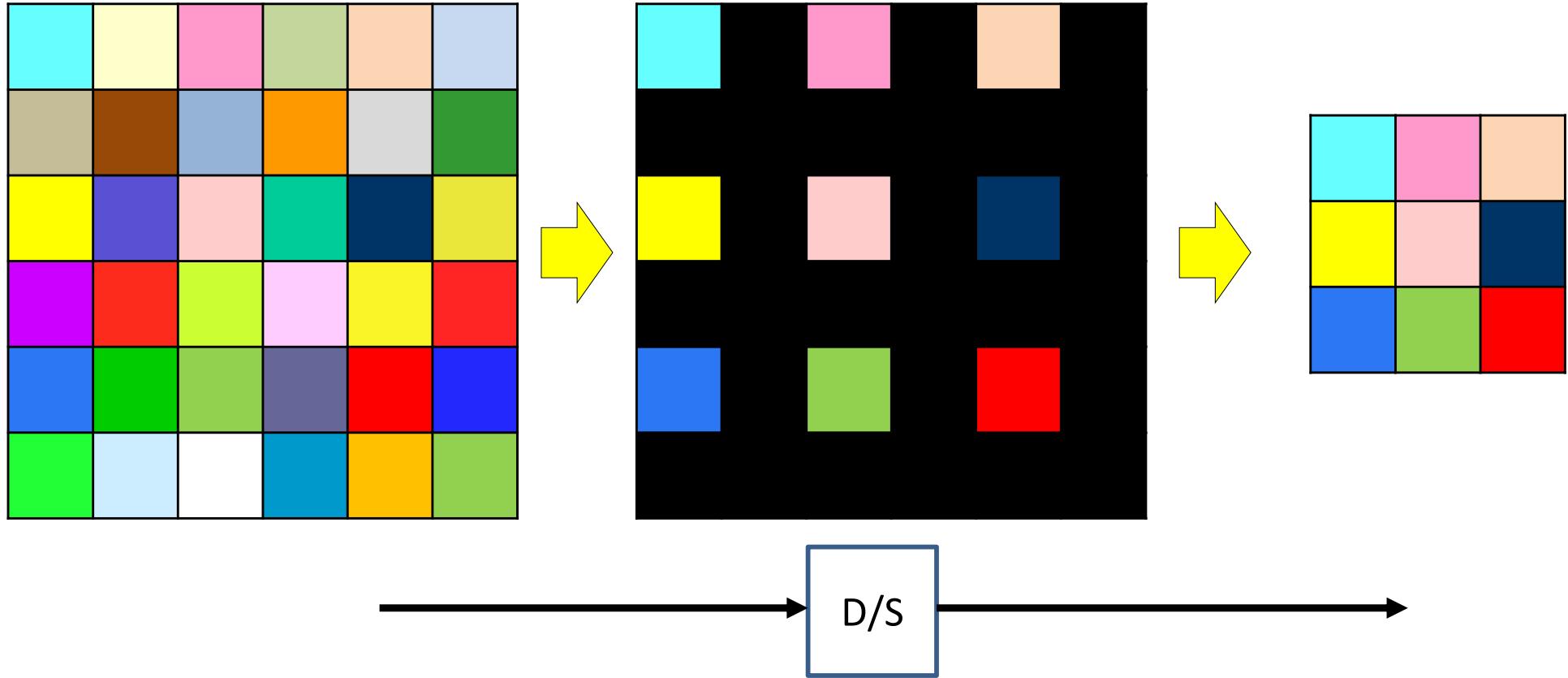
- Pooling layers “scan” the input using a “pooling” operation
 - E.g. selecting the max from a $K \times K$ block of input
- Each “pooling filter” scans an *individual* maps in the previous layer to produce an output “pooled map”
 - As many output maps as input maps
- For pooling we do not generally pad the edges
 - The zeros may result in bogus pooled values, e.g. when all inputs are –ve and we apply max pooling

The types of layers considered so far



- So far we have only considered layers where the output size is approximately equal to input size
- There are two other operations that *change* the size of the output

The Downsampling Layer

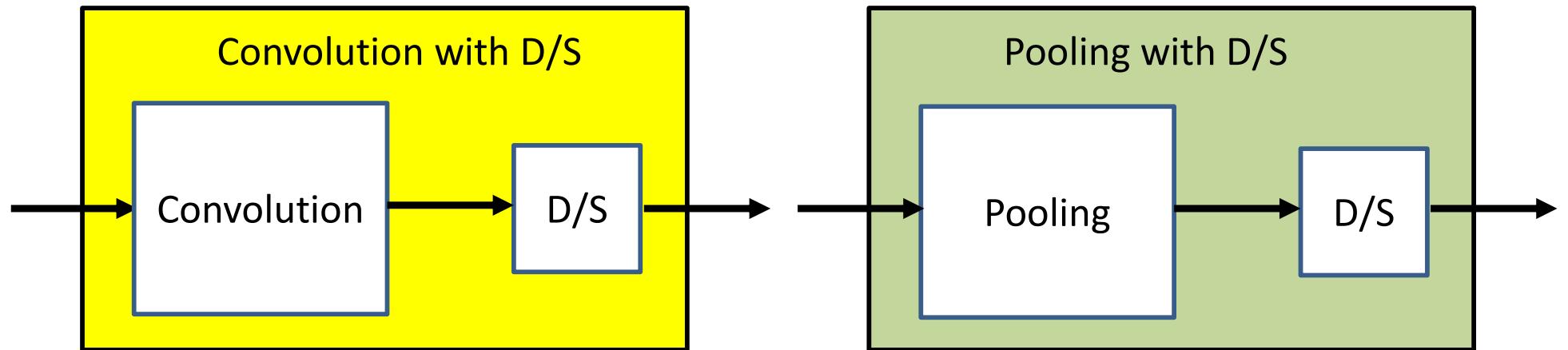


- A *downsampling* layer simply “drops” $S - 1$ of S rows and columns for every map in the layer
 - Effectively reducing the size of the map by factor S in every direction

Downsampling Pseudocode

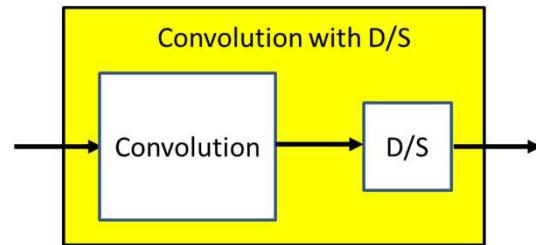
```
m = 1
for i = 1:S:W
    n = 1
    for j = 1:S:H
        y(m, n) = x(i, j)
        n++
    end
    m++
end
```

Downsampling in practice



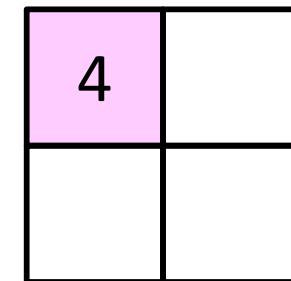
- In practice, the downsampling is combined with the layers just before it
 - Which could be convolutional or pooling layers

Downsampling after Convolution



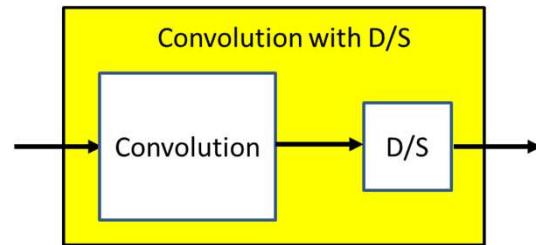
bias
Filter

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



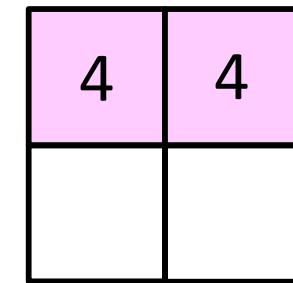
- A downsampling layer can be combined with a convolutional layer into a single convolutional layer with convolution stride S

Downsampling after Convolution



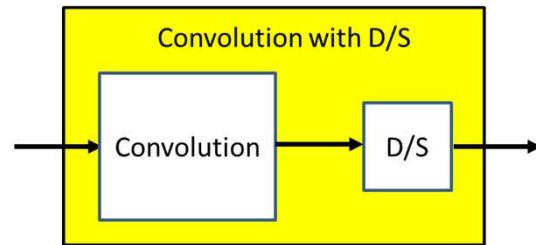
bias
Filter

1	1	1 _{x1}	0 _{x0}	0 _{x1}
0	1	1 _{x0}	1 _{x1}	0 _{x0}
0	0	1 _{x1}	1 _{x0}	1 _{x1}
0	0	1	1	0
0	1	1	0	0



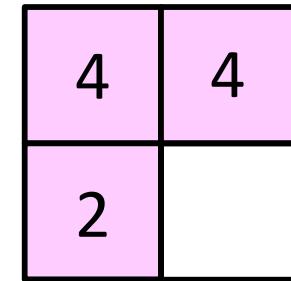
- A downsampling layer can be combined with a convolutional layer into a single convolutional layer with convolution stride S

Downsampling after Convolution



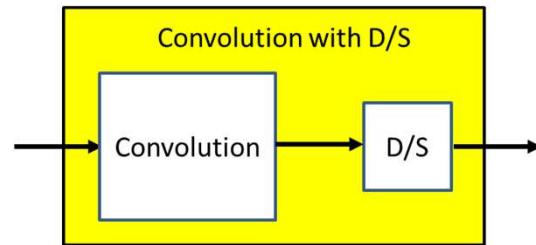
bias 0 $\begin{matrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{matrix}$
Filter

1	1	1	0	0
0	1	1	1	0
0 _{x1}	0 _{x0}	1 _{x1}	1	1
0 _{x0}	0 _{x1}	1 _{x0}	1	0
0 _{x1}	1 _{x0}	1 _{x1}	0	0



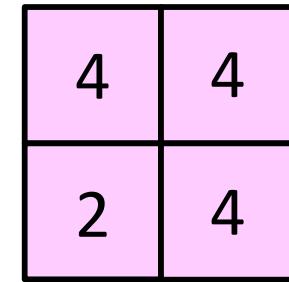
- A downsampling layer can be combined with a convolutional layer into a single convolutional layer with convolution stride S

Downsampling after Convolution



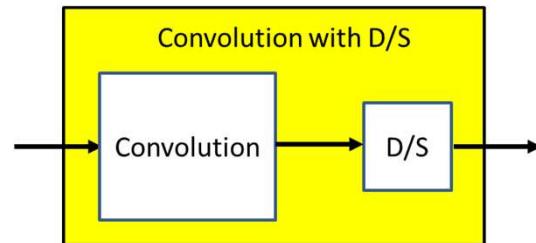
bias 0 $\begin{matrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{matrix}$
Filter

1	1	1	0	0
0	1	1	1	0
0	0	1 _{x1}	1 _{x0}	1 _{x1}
0	0	1 _{x0}	1 _{x1}	0 _{x0}
0	1	1 _{x1}	0 _{x0}	0 _{x1}



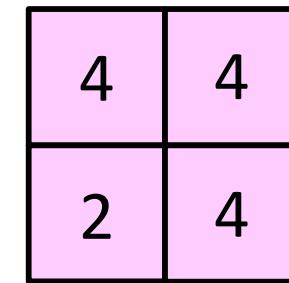
- A downsampling layer can be combined with a convolutional layer into a single convolutional layer with convolution stride S

Downsampling after Convolution



bias 0 $\begin{matrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{matrix}$
Filter

1	1	1	0	0
0	1	1	1	0
0	0	1 _{x1}	1 _{x0}	1 _{x1}
0	0	1 _{x0}	1 _{x1}	0 _{x0}
0	1	1 _{x1}	0 _{x0}	0 _{x1}



For an input of size $N \times N$ and filters of size $M \times M$ and stride S , the output size will be $\left\lfloor \frac{N-M}{S} \right\rfloor + 1$ on every side

Convolution with downsampling

The weight $W(l, j)$ is now a 4D $D_l \times D_{l-1} \times K_l \times K_l$ tensor

The product in blue is a tensor inner product with a scalar output

$\mathbf{Y}(0) = \text{Image}$

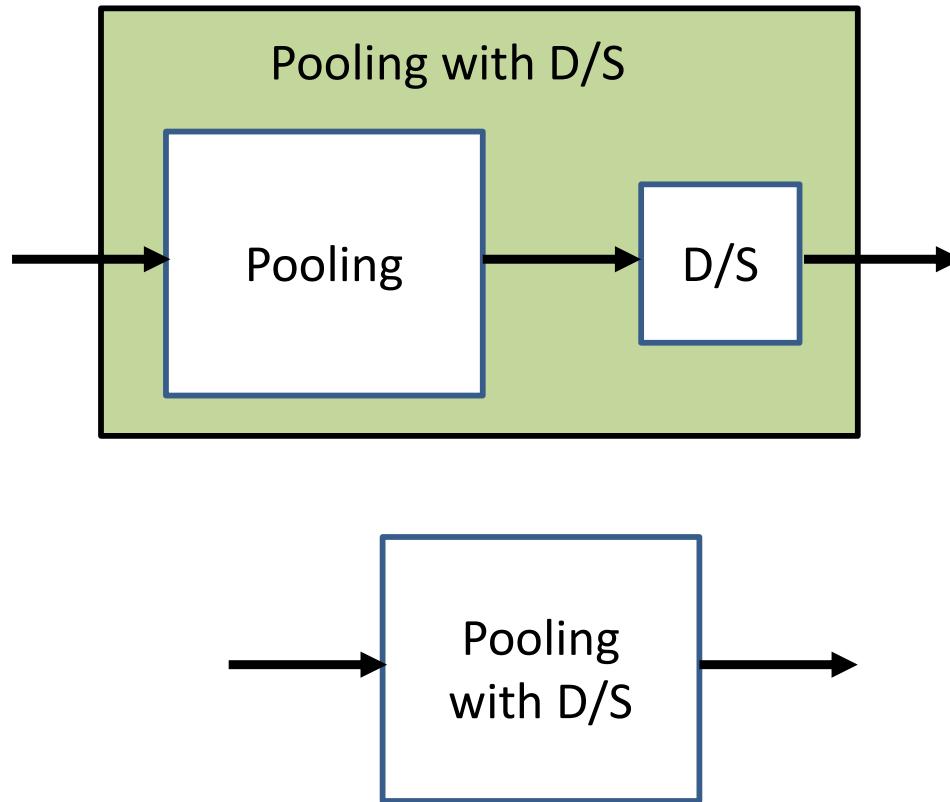
for $l = 1:L$ # layers operate on vector at (x, y)

```
m = 1
for x = 1:S:Wl-1-Kl+1
    n = 1
    for y = 1:S:Hl-1-Kl+1
        segment = Y(l-1, :, x:x+Kl-1, y:y+Kl-1) #3D tensor
        z(l, :, m, n) = W(l).segment #tensor inner prod.
        Y(l, :, m, n) = activation(z(l, :, m, n))
        n++
    m++
```

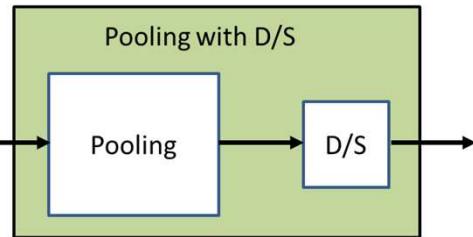
Downsampled indices

$\mathbf{Y} = \text{softmax}(\{\mathbf{Y}(L, :, :, :)\})$

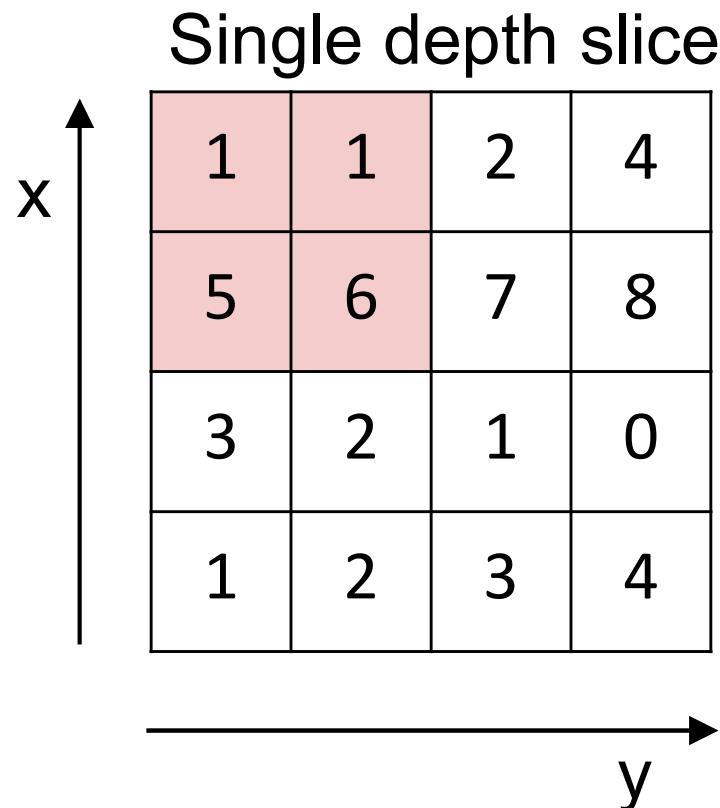
Downsampling and Pooling



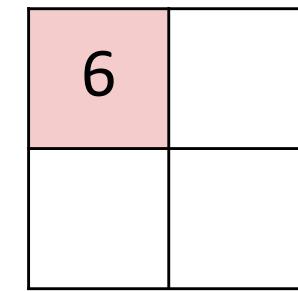
- Downsampling after a pooling layer can be merged with it to obtain pooling with stride S



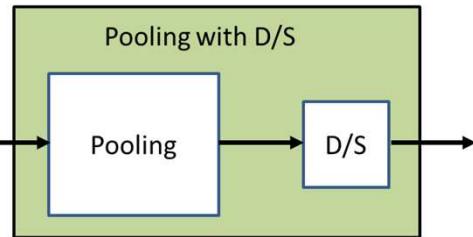
Max Pooling



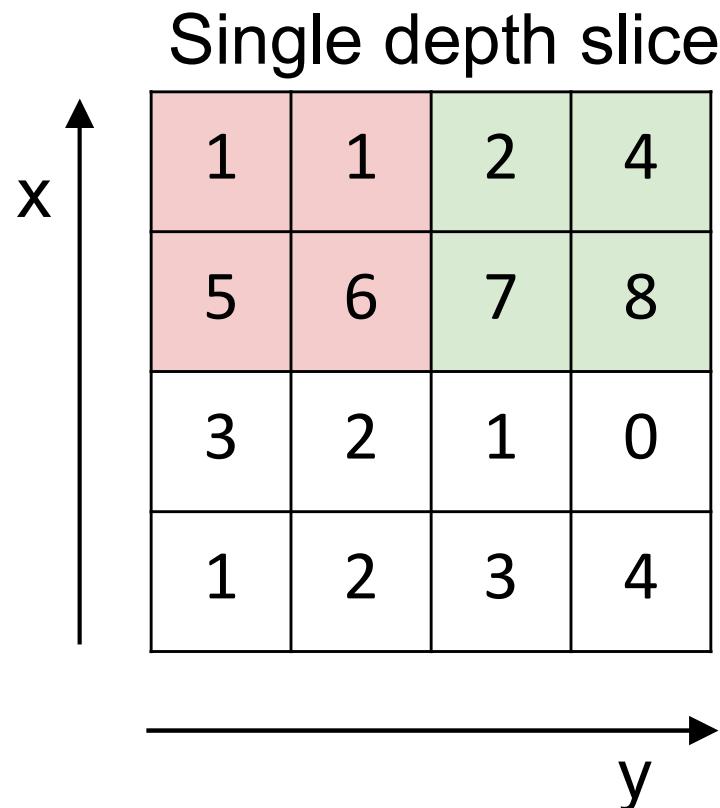
max pool with 2x2 filters
and stride 2



- Find the max in each block and stride by 2



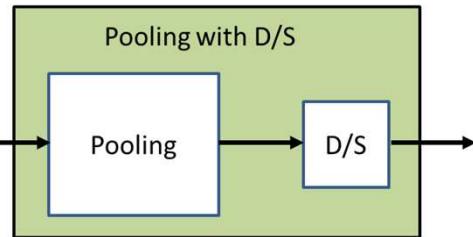
Max Pooling



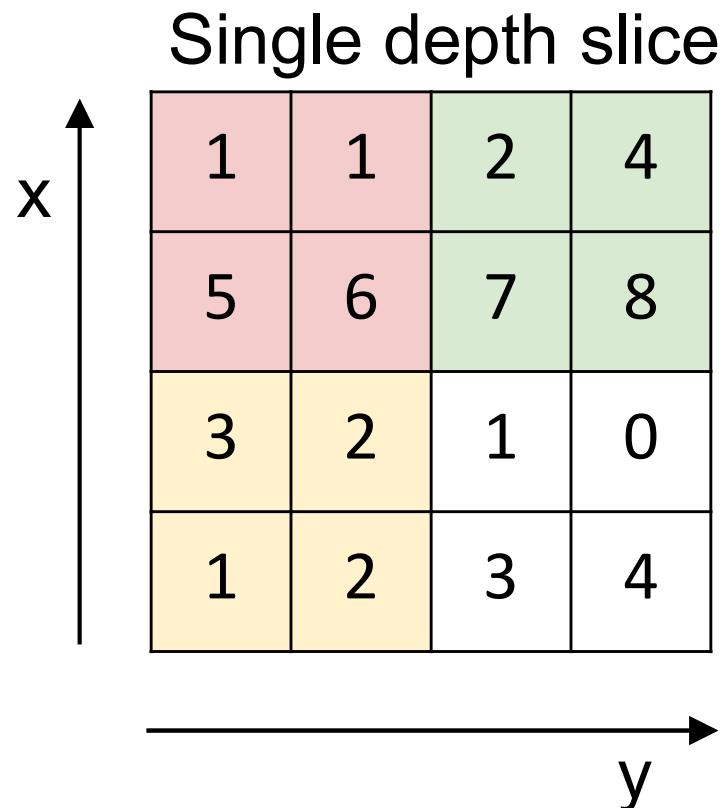
max pool with 2x2 filters
and stride 2

A smaller 2x2 grid representing the output of the max pooling operation. It contains the maximum values from the 2x2 blocks of the input: the top-left cell contains 6 (from the block [5,6]), and the top-right cell contains 8 (from the block [7,8]). The bottom cells are empty.

- Find the max in each block and stride by 2



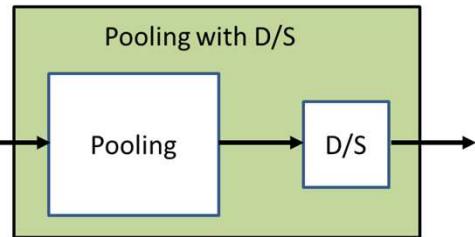
Max Pooling



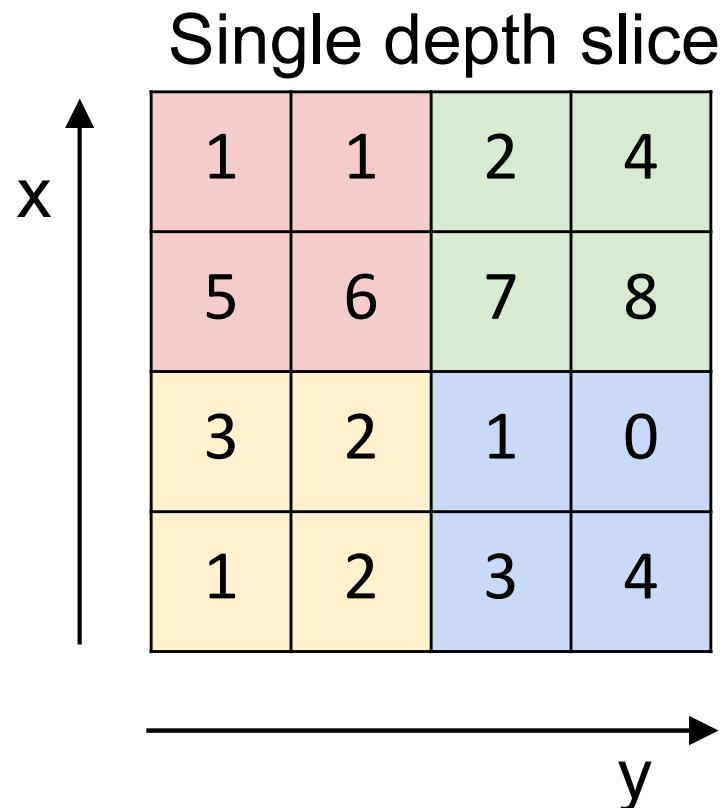
max pool with 2x2 filters
and stride 2

6	8
3	

- Find the max in each block and stride by 2



Max Pooling



max pool with 2x2 filters
and stride 2

6	8
3	4

- Find the max in each block and stride by 2

Max Pooling layer at layer l

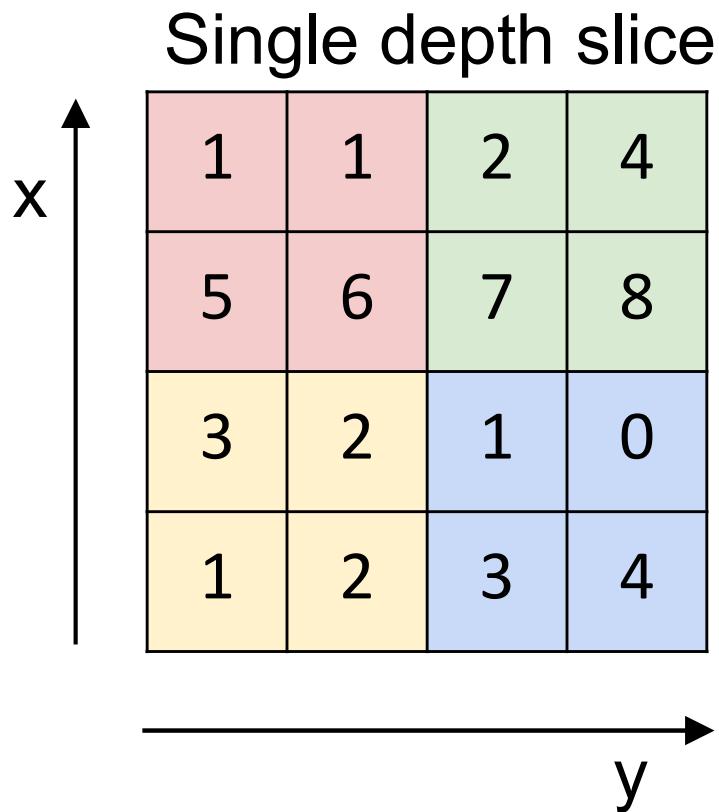
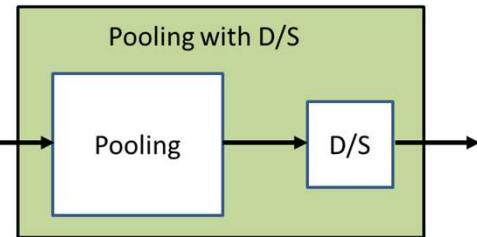
- a) Performed separately for every map (j).
*) Not combining multiple maps within a single max operation.
- b) Keeping track of location of max

Max pooling

```
for j = 1:Dl
    m = 1
    for x = 1:stride(l):Wl-1-Kl+1
        n = 1
        for y = 1:stride(l):Hl-1-Kl+1
            pidx(l,j,m,n) = maxidx(Y(l-1,j,x:x+Kl-1,y:y+Kl-1))
            Y(l,j,m,n) = Y(l-1,j,pidx(l,j,m,n))
            n = n+1
        m = m+1
```



Mean Pooling



Mean pool with 2x2 filters and stride 2

The output tensor is a 2x2 matrix resulting from the mean pooling operation. The values are calculated as follows:

3.25	5.25
2	2

- Compute the mean of the pool, instead of the max

Mean Pooling layer at layer l

Performed separately for every map (j).

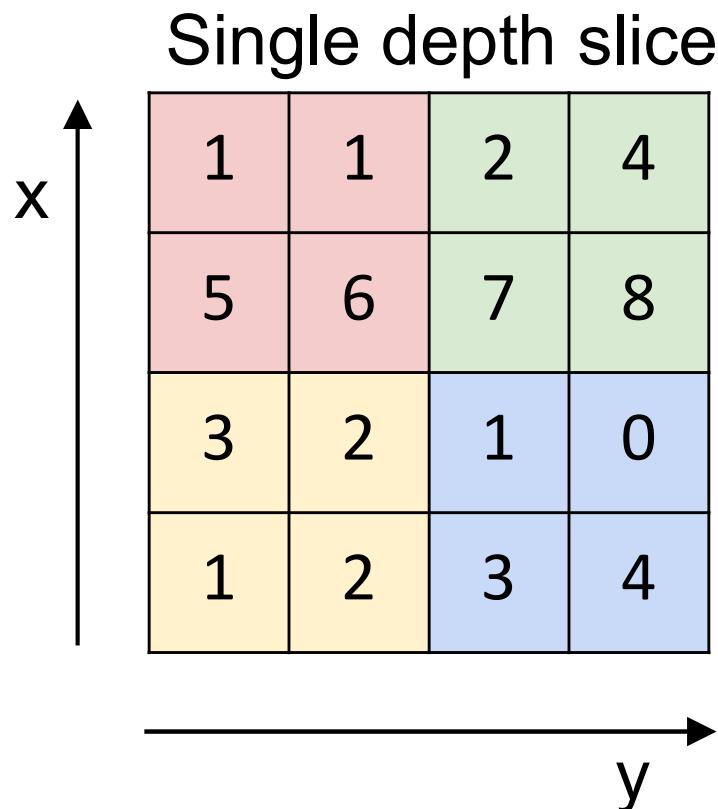
*) Not combining multiple maps within a single operation.

Mean pooling

```
for j = 1:Dl
    m = 1
    for x = 1:stride(l):Wl-1-Kl+1
        n = 1
        for y = 1:stride(l):Hl-1-Kl+1
            Y(l,j,m,n) = mean(Y(l-1,j,x:x+Kl-1,y:y+Kl-1))
            n = n+1
        m = m+1
```



Downsampling: Size of output

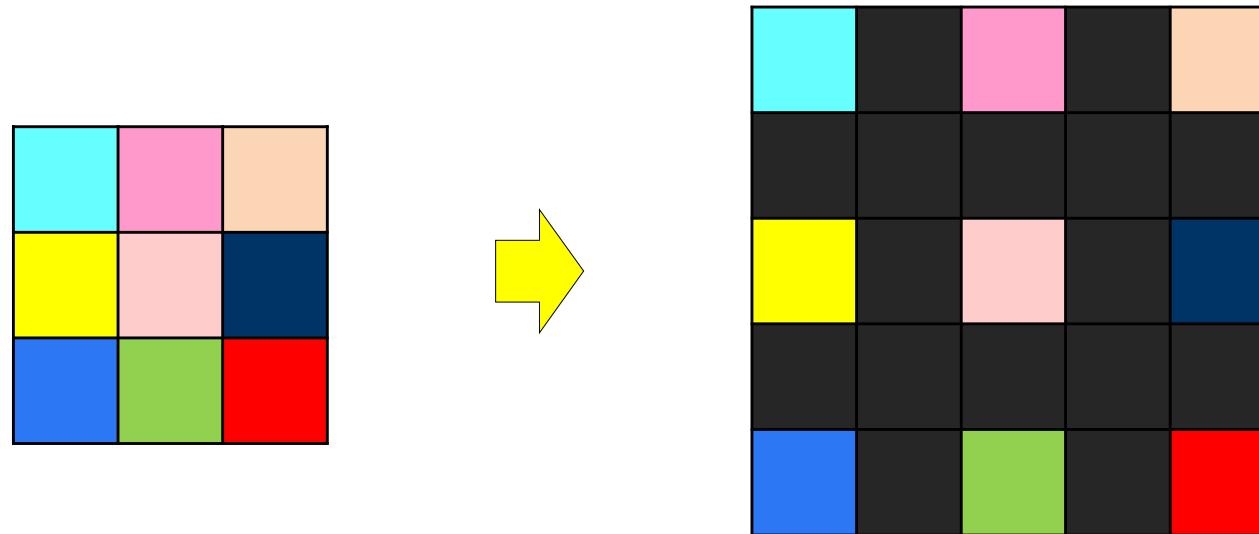


pool with 2×2 filters and
stride 2

6	8
3	4

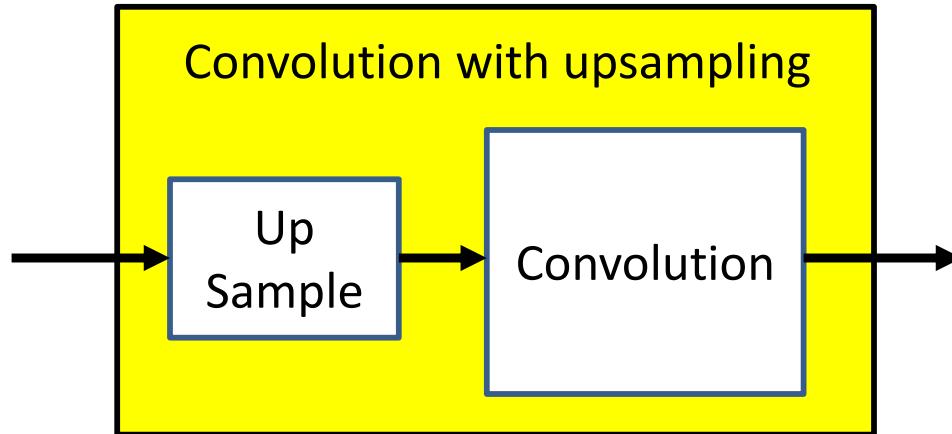
- An $N \times N$ picture compressed by a $P \times P$ pooling filter with stride D results in an output map of side $\lceil (N - P)/D \rceil + 1$
 - Typically do not zero pad

The Upsampling Layer



- A *upsampling* (or dilation) layer simply introduces $S - 1$ rows and columns for every map in the layer
 - Effectively *increasing* the size of the map by factor S in every direction
- Used explicitly to increase the map size by a uniform factor

The Upsampling Layer



- A *upsampling* layer is generally followed by a Convolutional layer
 - It is not useful to follow it by a pooling layer
 - It is also not useful as the *final* layer of a CNN

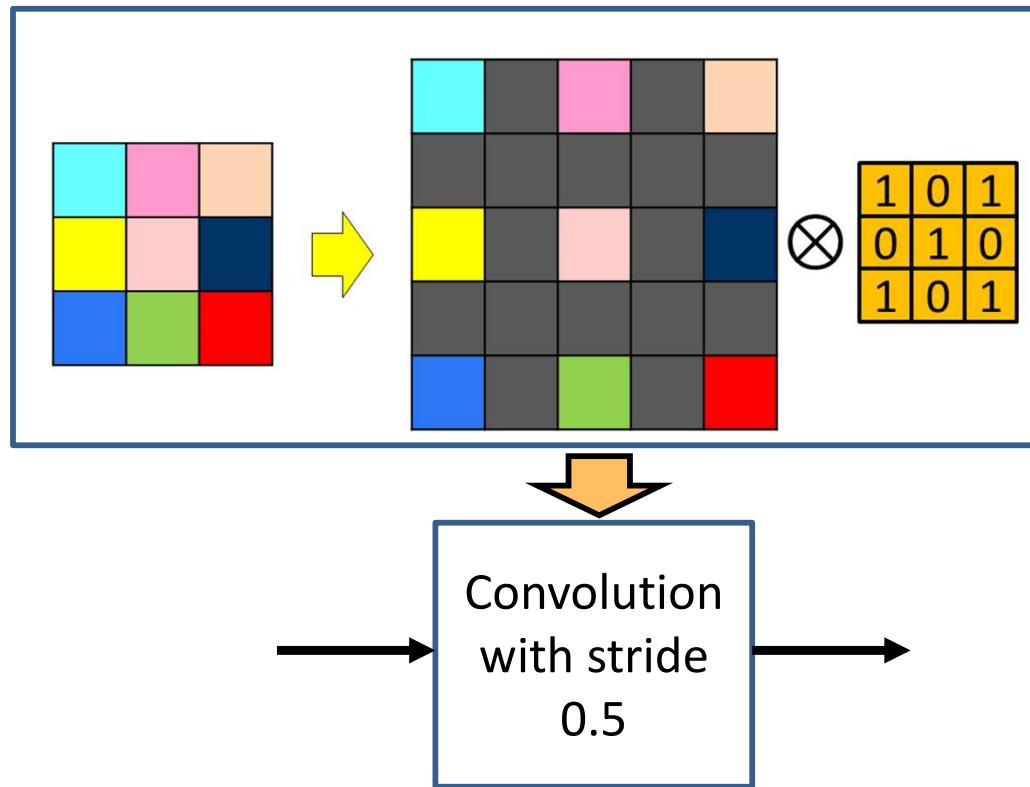
Upsampling

X is a 3D $D_1 \times W \times H$ tensor

Assuming D_1 , W and H are also passed in

```
function dilate(X)
    Xup = zeros(D1, (W-1)S+1, (H-1)S+1)
    for i = 1:W
        for j = 1:H
            Xup(:, (i-1)S+1, (j-1)S+1) = X(:, i, j)
    return Xup
```

The Upsampling Layer



- Upsampling layers followed by a convolutional layer are also often viewed as convolving with a fractional stride
 - Upsampling by factor S is the same as striding by factor $1/S$

Resampling Summary

- Map sizes can be changed by downsampling or upsampling
 - Downsampling: Drop $S-1$ of S rows and columns
 - Upsampling: Insert $S-1$ zeros between every two rows / columns
- Downsampling typically *follows* convolution or pooling
 - Reduces the size of the maps
- Upsampling occurs *before* convolution
 - Increases the size of the map
 - Does not generally occur before pooling layers

Story so far

- The convolutional neural network is a supervised version of a computational model of mammalian vision
- It includes
 - Convolutional layers comprising learned filters that scan the outputs of the previous layer
 - “Pooling” layers that vote over groups of outputs from the convolutional layer
- Convolution can change the size of the output. This may be controlled via zero padding.
- Pooling layers may perform max, p-norms, or be learned
- Resampling layers increase or decrease the size of the map
 - Downsampling can be merged with the preceding operation, by simply scanning with a stride > 1
 - Upsampling must occur before convolution operations

Poll 3 (@685, @686)

Mark all that are true of upsampling layers

- Upsampling by S introduces S-1 zeroes between adjacent rows and columns
- Upsampling layers are generally followed by pooling layers
- Upsampling layers are generally followed by convolutional layers
- Upsampling layers can be combined with the convolutional or pooling layers before them into a single operation with fractional stride

Mark all that are true of downsampling layers

- Downsampling by S replaces every Sth row and column with zeros
- Downsampling by S deletes S-1 consecutive rows/columns and retains only every Sth row/column
- Downsampling layers are usually merged with the convolution or pooling layers after them, which are then modified to convolution or pooling with a stride
- Downsampling layers are usually merged with the convolution or pooling layers before them, which are then modified to convolution or pooling with a stride

Poll 3

Mark all that are true of upsampling layers

- **Upsampling by S introduces S-1 zeroes between adjacent rows and columns**
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- **Upsampling layers are generally followed by convolutional layers**
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Mark all that are true of downsampling layers

- Downsampling by S replaces every Sth row and column with zeros
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- Downsampling layers are usually merged with the convolution or pooling layers after them, which are then modified to convolution or pooling with a stride
- **Downsampling layers are usually merged with the convolution or pooling layers before them, which are then modified to convolution or pooling with a stride**

Setting everything together

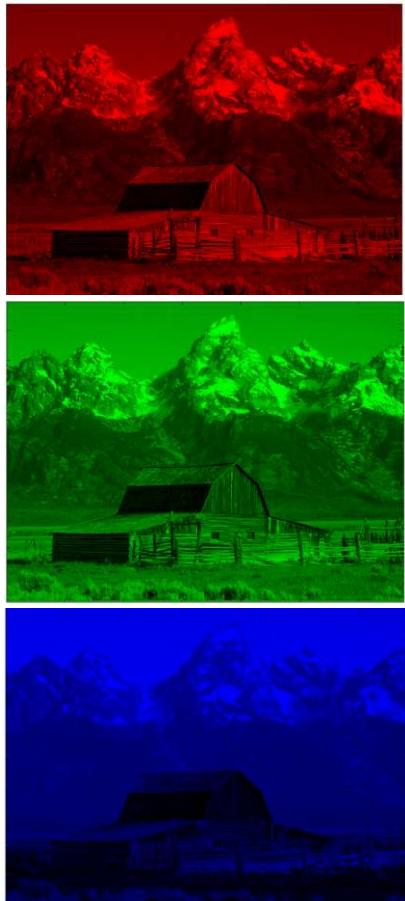
- Typical image classification task
 - Assuming maxpooling..

Convolutional Neural Networks



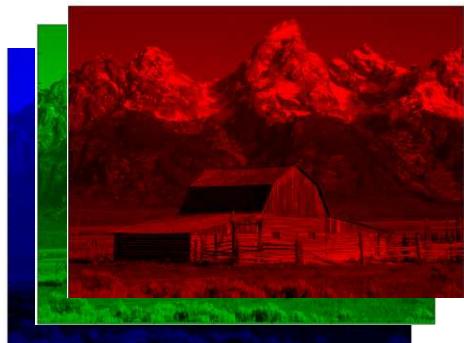
- Input: 1 or 3 images
 - Grey scale or color
 - Will assume color to be generic

Convolutional Neural Networks



- Input: 3 pictures

Convolutional Neural Networks

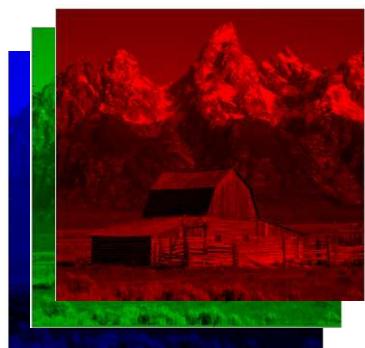


- Input: 3 pictures

Preprocessing

- Large images are a problem
 - Too large
 - Compute and memory intensive to process
- Sometimes scaled to smaller sizes, e.g. 128x128 or even 32x32
 - Based on how much will fit on your GPU
 - Typically cropped to *square* images
 - Filters are also typically square

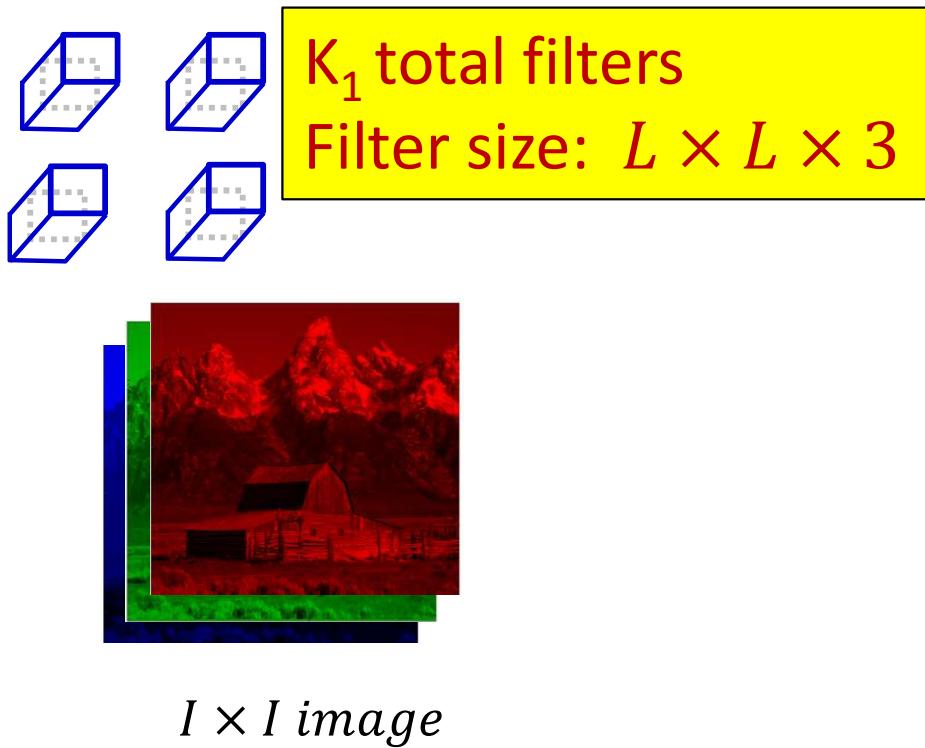
Convolutional Neural Networks



$I \times I$ image

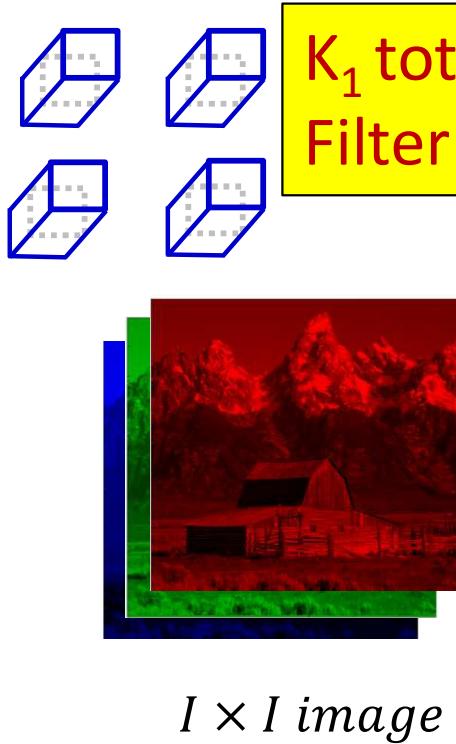
- Input: 3 pictures

Convolutional Neural Networks



- Input is convolved with a set of K₁ filters
 - Typically K₁ is a power of 2, e.g. 2, 4, 8, 16, 32,..
 - Filters are typically 5x5, 3x3, or even 1x1

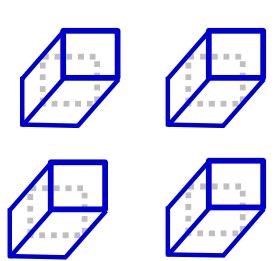
Convolutional Neural Networks



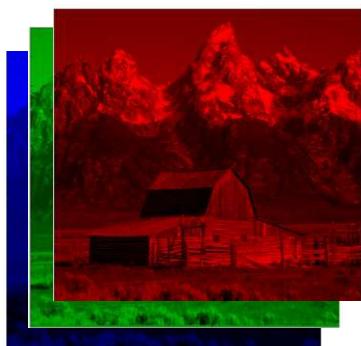
Small enough to capture fine features
(particularly important for scaled-down images)

- Input is convolved with a set of K₁ filters
 - Typically K₁ is a power of 2, e.g. 2, 4, 8, 16, 32,..
 - Filters are typically 5x5, 3x3, or even 1x1

Convolutional Neural Networks



K_1 total filters
Filter size: $L \times L \times 3$

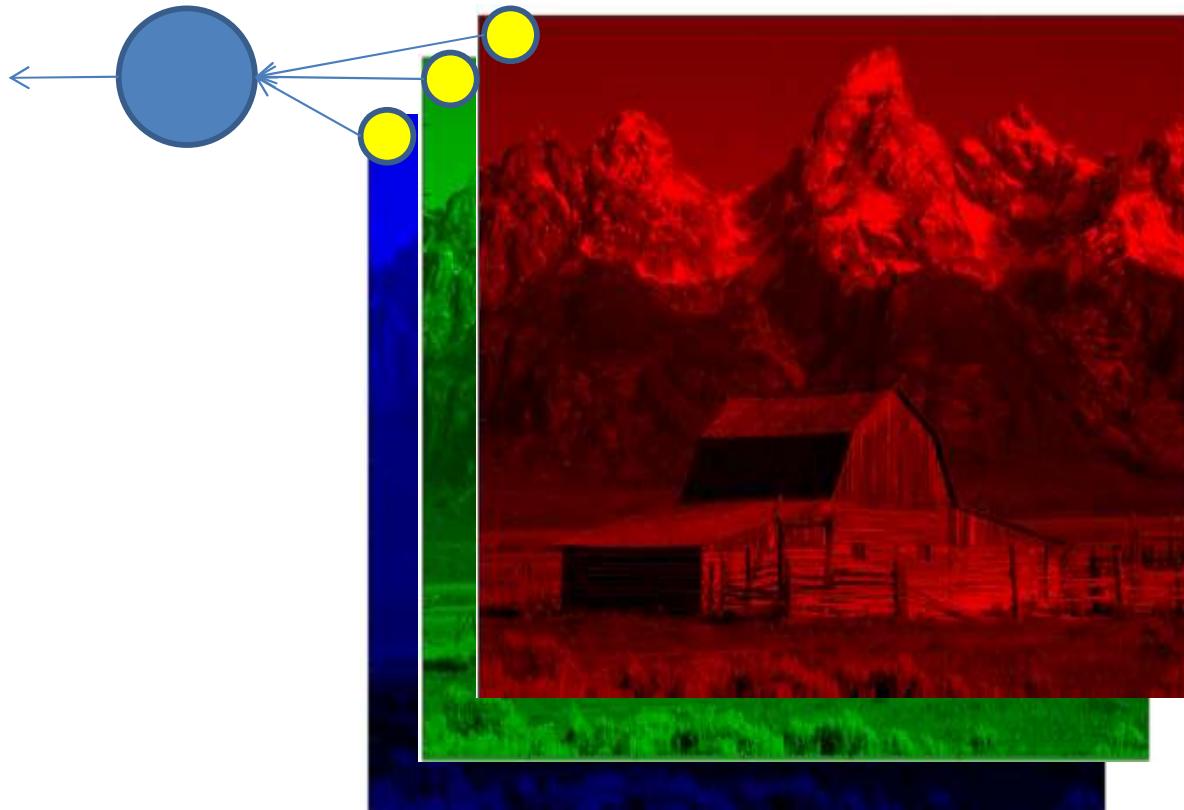


Small enough to capture fine features
(particularly important for scaled-down images)

What on earth is this?

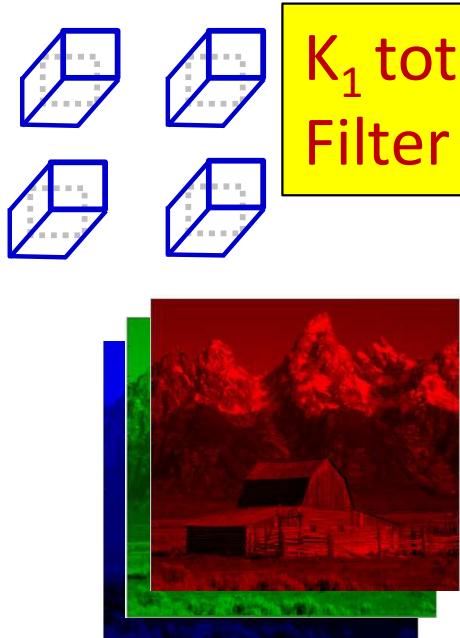
- Input is convolved with a set of K_1 filters
 - Typically K_1 is a power of 2, e.g. 2, 4, 8, 16, 32,..
 - Filters are typically 5x5, 3x3, or even 1x1

The 1x1 filter



- A 1x1 filter is simply a perceptron that operates over the *depth* of the stack of maps, but has no spatial extent
 - Takes one pixel from each of the maps (at a given location) as input
 - A *non-distributed* layer of the scanning MLP

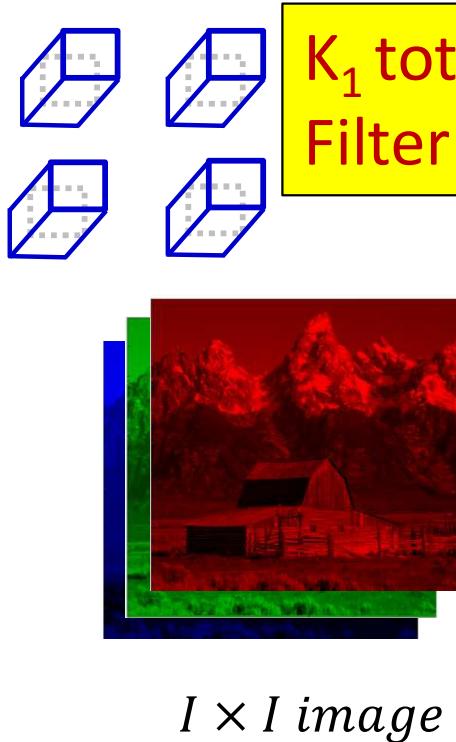
Convolutional Neural Networks



$I \times I$ image

- Input is convolved with a set of K₁ filters
 - Typically K₁ is a power of 2, e.g. 2, 4, 8, 16, 32,..
 - **Better notation:** Filters are typically 5x5(x3), 3x3(x3), or even 1x1(x3)

Convolutional Neural Networks



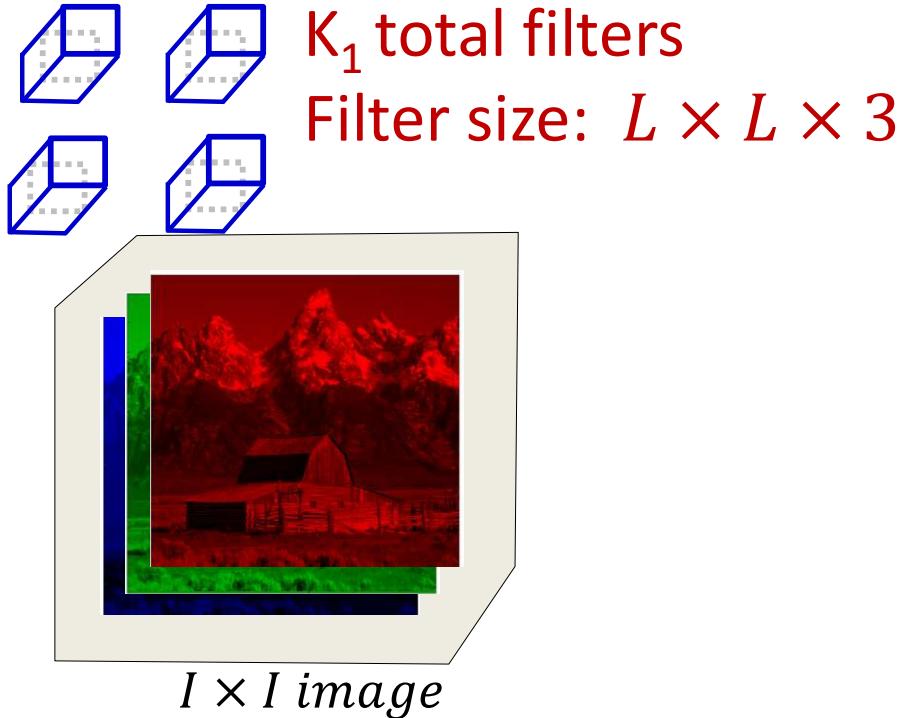
Parameters to choose: K_1, L and S

1. Number of filters K_1
2. Size of filters $L \times L \times 3 + bias$
3. Stride of convolution S

Total number of parameters: $K_1(3L^2 + 1)$

- Input is convolved with a set of K_1 filters
 - Typically K_1 is a power of 2, e.g. 2, 4, 8, 16, 32,..
 - **Better notation:** Filters are typically 5x5(x3), 3x3(x3), or even 1x1(x3)
 - **Typical stride:** 1 or 2

Convolutional Neural Networks

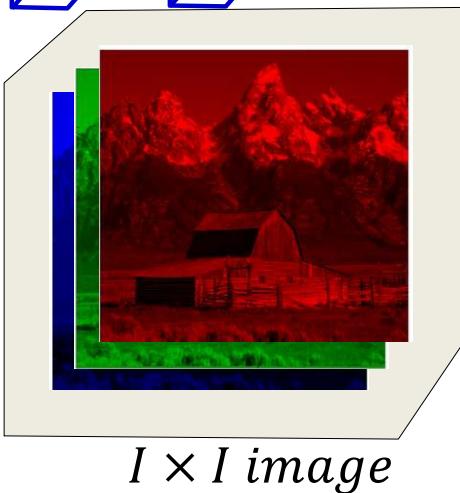
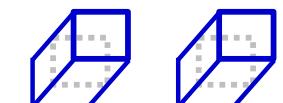


- The input may be zero-padded according to the size of the chosen filters

Convolutional Neural Networks

K_1 filters of size:

$$L \times L \times 3$$



$$I \times I$$

$$Y_1^{(1)}$$

$$Y_2^{(1)}$$

⋮

$$Y_{K_1}^{(1)}$$

The layer includes a convolution operation followed by an activation (typically RELU)

$$z_m^{(1)}(i, j) = \sum_{c \in \{R, G, B\}} \sum_{k=1}^L \sum_{l=1}^L w_m^{(1)}(c, k, l) I_c(i + k, j + l) + b_m^{(1)}$$

$$Y_m^{(1)}(i, j) = f(z_m^{(1)}(i, j))$$

- **First convolutional layer:** Several convolutional filters
 - Filters are “3-D” (third dimension is color)
 - Convolution followed typically by a RELU activation
- Each filter creates a single 2-D output map

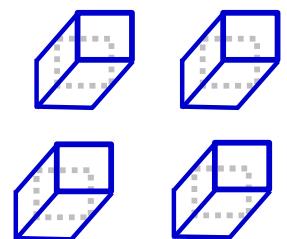
Learnable parameters in the first convolutional layer

- The first convolutional layer comprises K_1 filters, each of size $L \times L \times 3$
 - Spatial span: $L \times L$
 - Depth : 3 (3 colors)
- This represents a total of $K_1(3L^2 + 1)$ parameters
 - “+ 1” because each filter also has a bias
- All of these parameters must be learned

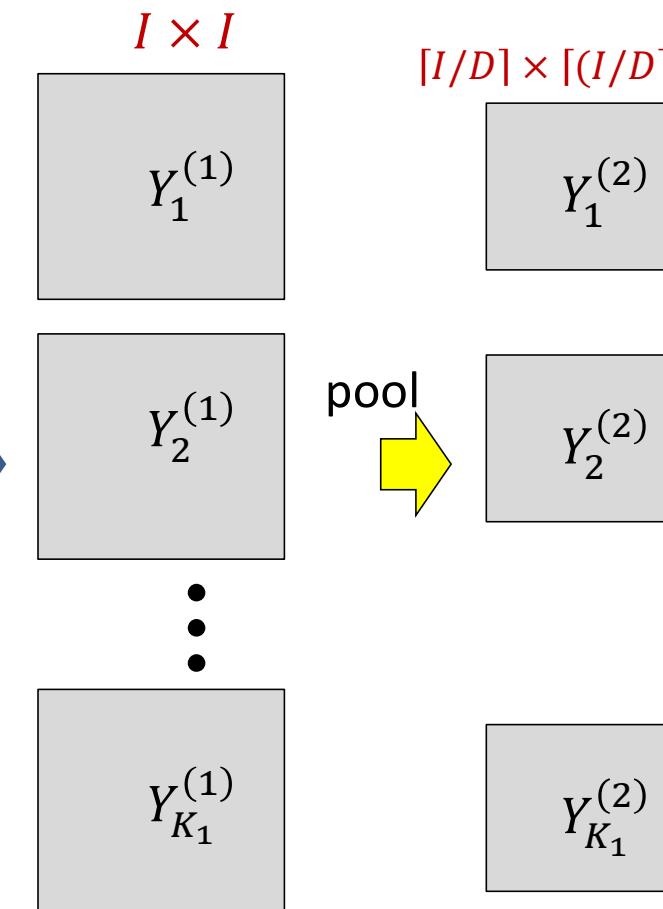
Convolutional Neural Networks

Filter size:

$$L \times L \times 3$$



$I \times I$ image



The layer pools $P \times P$ blocks of $Y_m^{(1)}$ into a single value. It employs a stride D between adjacent blocks.

$$X_{win}(i) = [(i - 1)D + 1, (i - 1)D + P]$$

$$Y_{win}(j) = [(j - 1)D + 1, (j - 1)D + P]$$

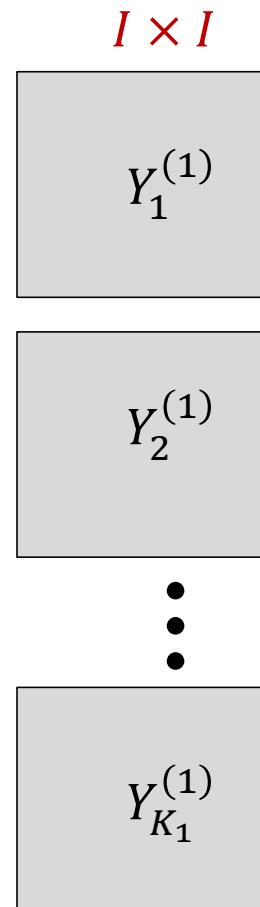
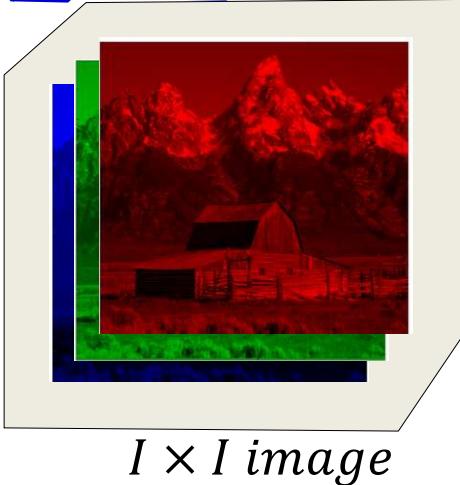
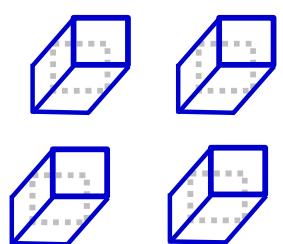
$$Y_m^{(2)}(i, j) = \max_{\substack{k \in X_{win}(i), \\ l \in Y_{win}(j)}} Y_m^{(1)}(k, l)$$

- **First pooling/downsampling layer:** From each $P \times P$ block of each map, pool down to a single value
 - For max pooling, during training keep track of which position had the highest value

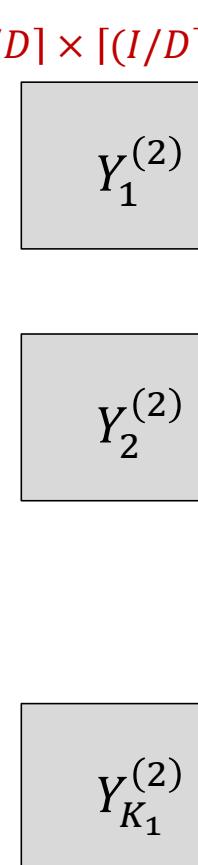
Convolutional Neural Networks

Filter size:

$$L \times L \times 3$$



pool



$$X_{win}(i) = [(i - 1)D + 1, (i - 1)D + P]$$

$$Y_{win}(j) = [(j - 1)D + 1, (j - 1)D + P]$$

$$Y_m^{(2)}(i, j) = \max_{\substack{k \in X_{win}(i), \\ l \in Y_{win}(j)}} Y_m^{(1)}(k, l)$$

Parameters to choose:
Size of pooling block P
Pooling stride D

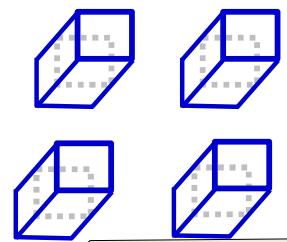
Choices: Max pooling or
mean pooling?

- **First pooling/downsampling layer:** From each $P \times P$ block of each map, pool down to a single value
 - For max pooling, during training keep track of which position had the highest value

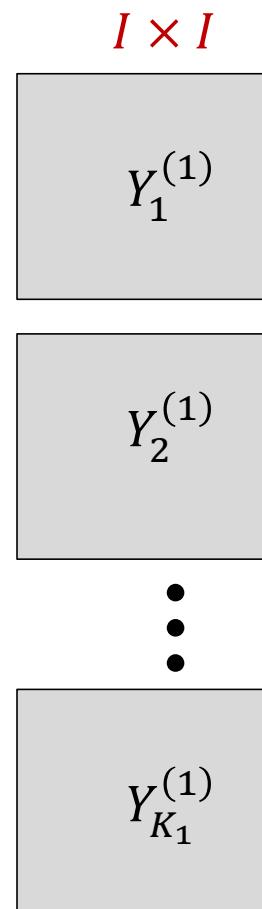
Convolutional Neural Networks

Filter size:

$$L \times L \times 3$$

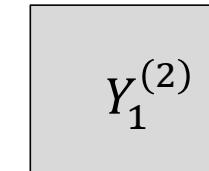


$I \times I$ image



pool

$$[I/D] \times [I/D]$$



$$X_{win}(i) = [(i-1)D + 1, (i-1)D + P]$$

$$Y_{win}(j) = [(j-1)D + 1, (j-1)D + P]$$

$$P_m^{(2)}(i, j) = \underset{k \in X_{win}(i), l \in Y_{win}(j)}{\operatorname{argmax}} Y_m^{(1)}(k, l)$$

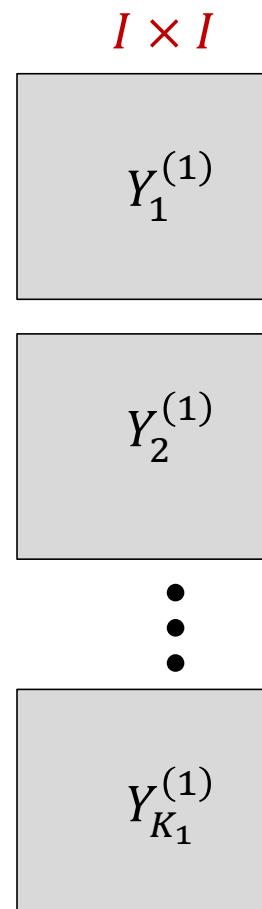
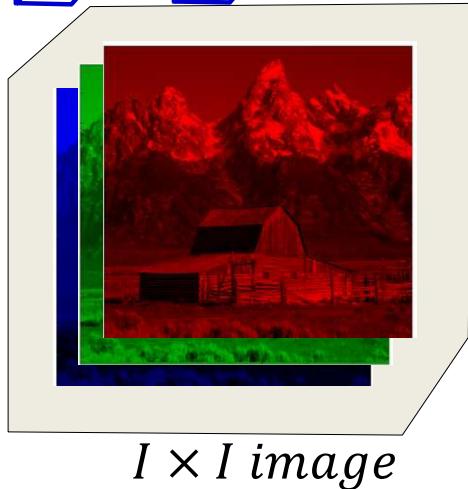
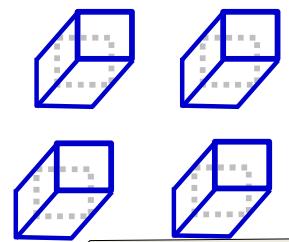
$$Y_m^{(2)}(i, j) = Y_m^{(1)}(P_m^{(2)}(i, j))$$

- **First pooling/downsampling layer:** From each $P \times P$ block of each map, *pool* down to a single value
 - **For max pooling, during training keep track of which position had the highest value**

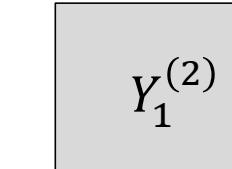
Convolutional Neural Networks

Filter size:

$$L \times L \times 3$$



$$[I/D] \times [I/D]$$



pool

$$X_{win}(i) = [(i - 1)D + 1, (i - 1)D + P]$$

$$Y_{win}(j) = [(j - 1)D + 1, (j - 1)D + P]$$

$$P_m^{(2)}(i, j) = \underset{k \in X_{win}(i), l \in Y_{win}(j)}{\operatorname{argmax}} Y_m^{(1)}(k, l)$$

$$Y_m^{(2)}(i, j) = Y_m^{(1)}(P_m^{(2)}(i, j))$$

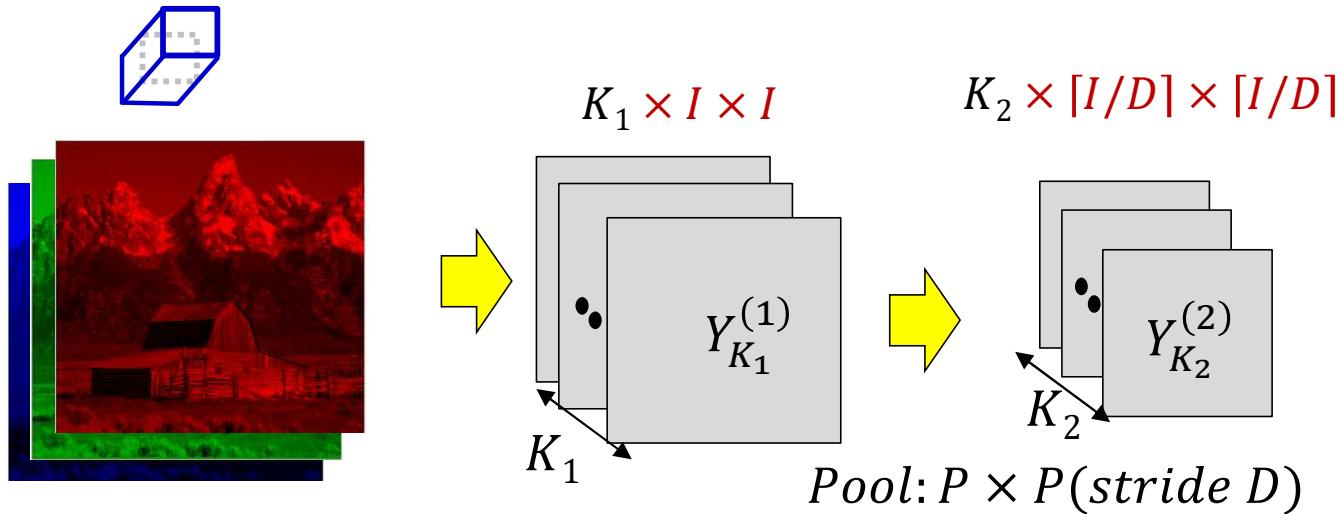
$K_2 = K_1$. Just using the new index K_2 for notational uniformity.
Pooling layers do not change the number of maps because pooling is performed individually on each of the maps in the previous layer.

- **First pooling/downsampling layer:** From each map, pool down to a single value
 - For max pooling, during training keep track of which position had the highest value

Convolutional Neural Networks

$W_m: 3 \times L \times L$

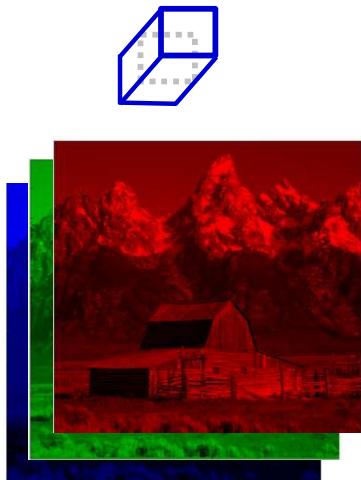
$m = 1 \dots K_1$



- **First pooling layer:** Drawing it differently for convenience

Convolutional Neural Networks

$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$

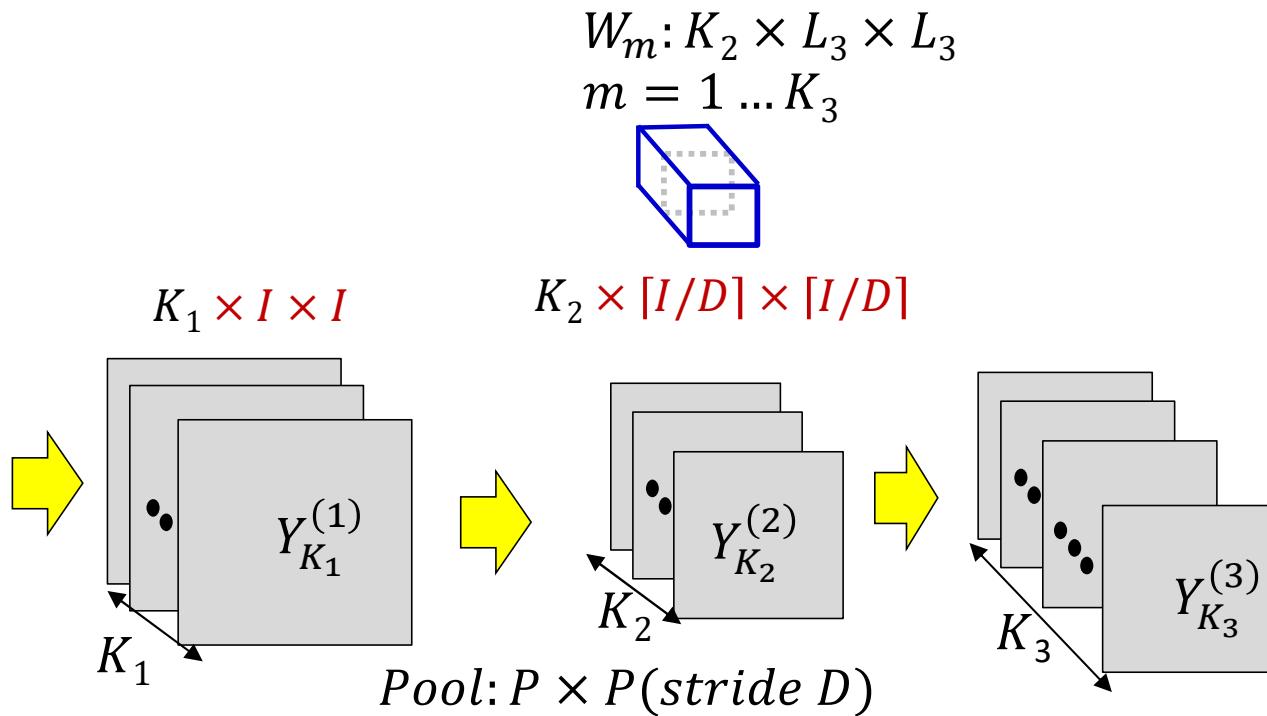
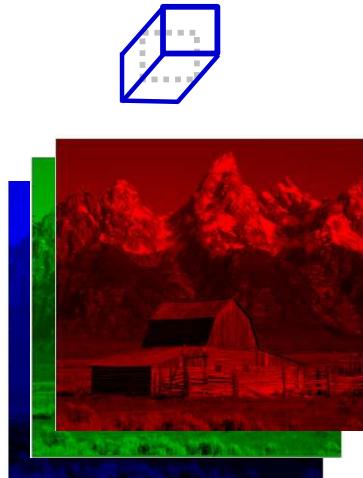


Jargon: Filters are often called "Kernels"
The outputs of individual filters are called "channels"
The number of filters (K_1, K_2 , etc) is the number of channels

- **First pooling layer:** Drawing it differently for convenience

Convolutional Neural Networks

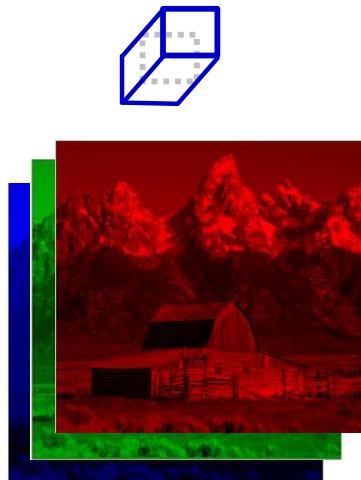
$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$



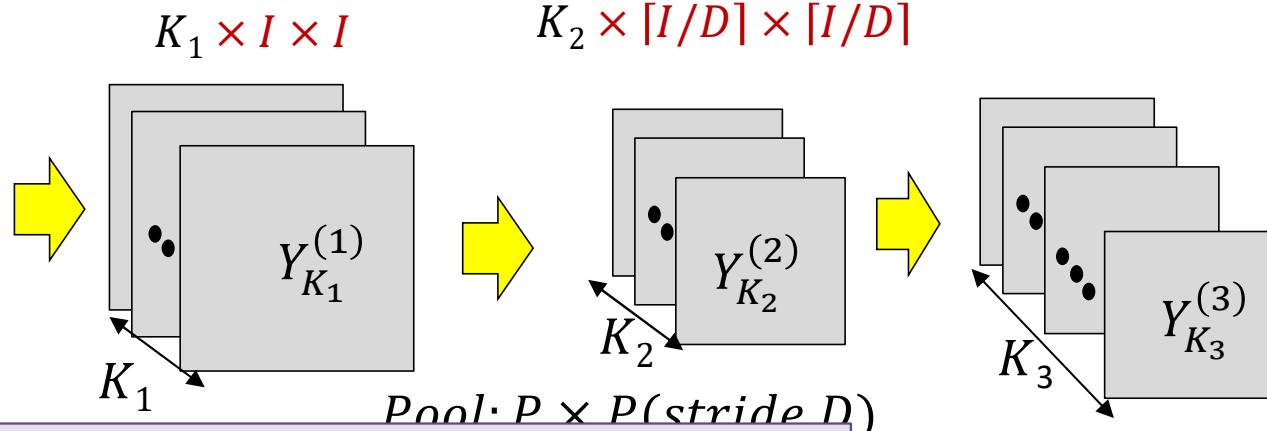
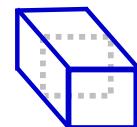
- **Second convolutional layer:** K_3 3-D filters resulting in K_3 2-D maps
 - Alternately, a kernel with K_3 output channels

Convolutional Neural Networks

$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$



$$W_m: K_2 \times L_3 \times L_3 \\ m = 1 \dots K_3$$



Parameters to choose: K_3 , L_3 and S_3

1. Number of filters K_3
2. Size of filters $L_3 \times L_3 \times K_2 + bias$
3. Stride of convolution S_3

$\frac{(n)}{m}$

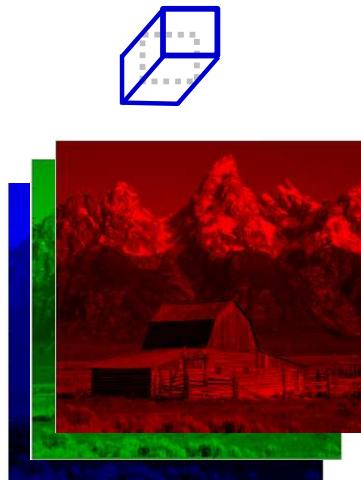
Total number of parameters: $K_3(K_2L_3^2 + 1)$

All these parameters must be learned

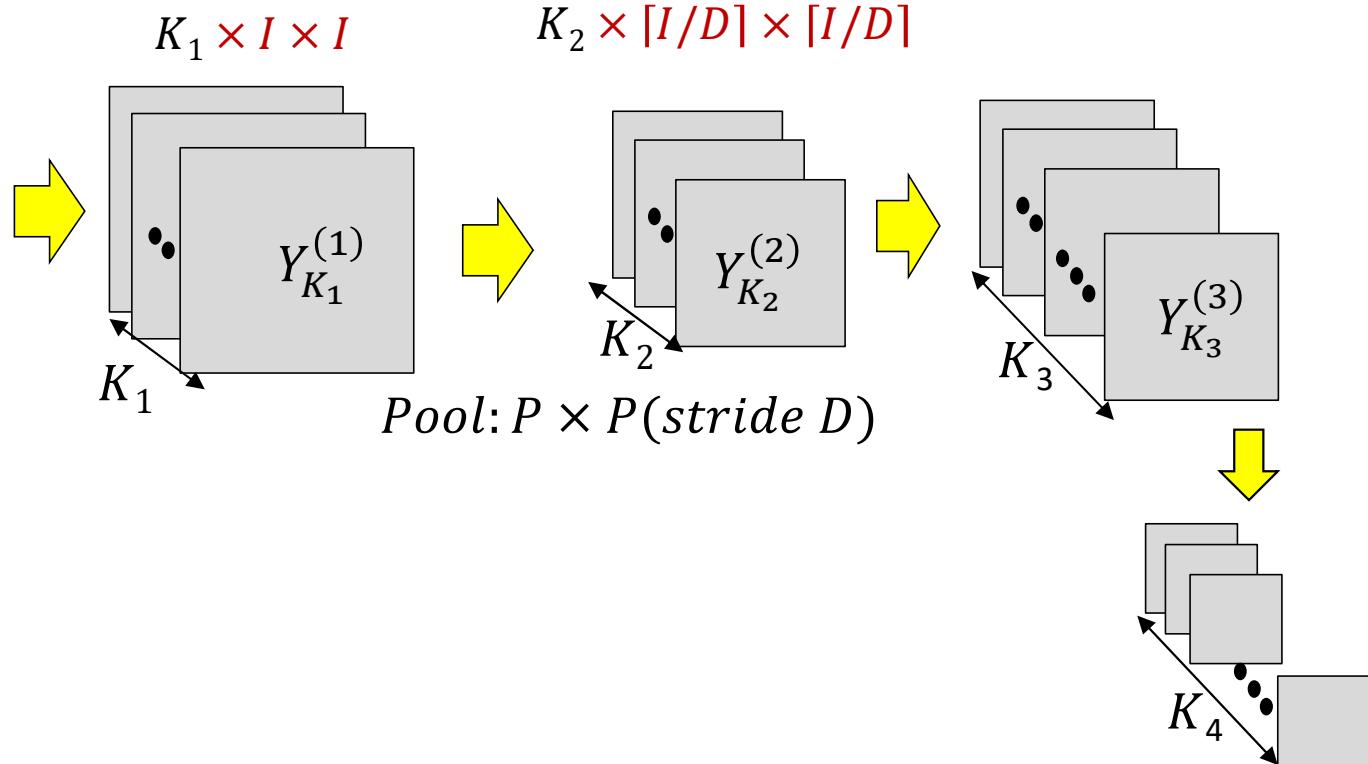
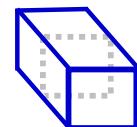
...ing in K_3 2-D maps

Convolutional Neural Networks

$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$



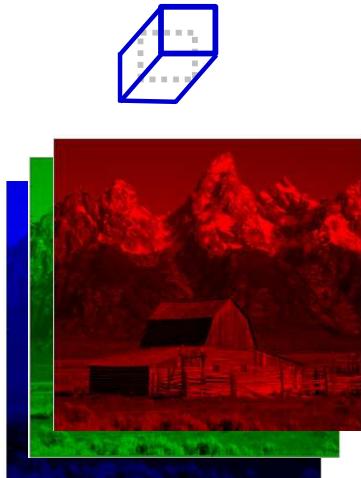
$$W_m: K_2 \times L_3 \times L_3 \\ m = 1 \dots K_3$$



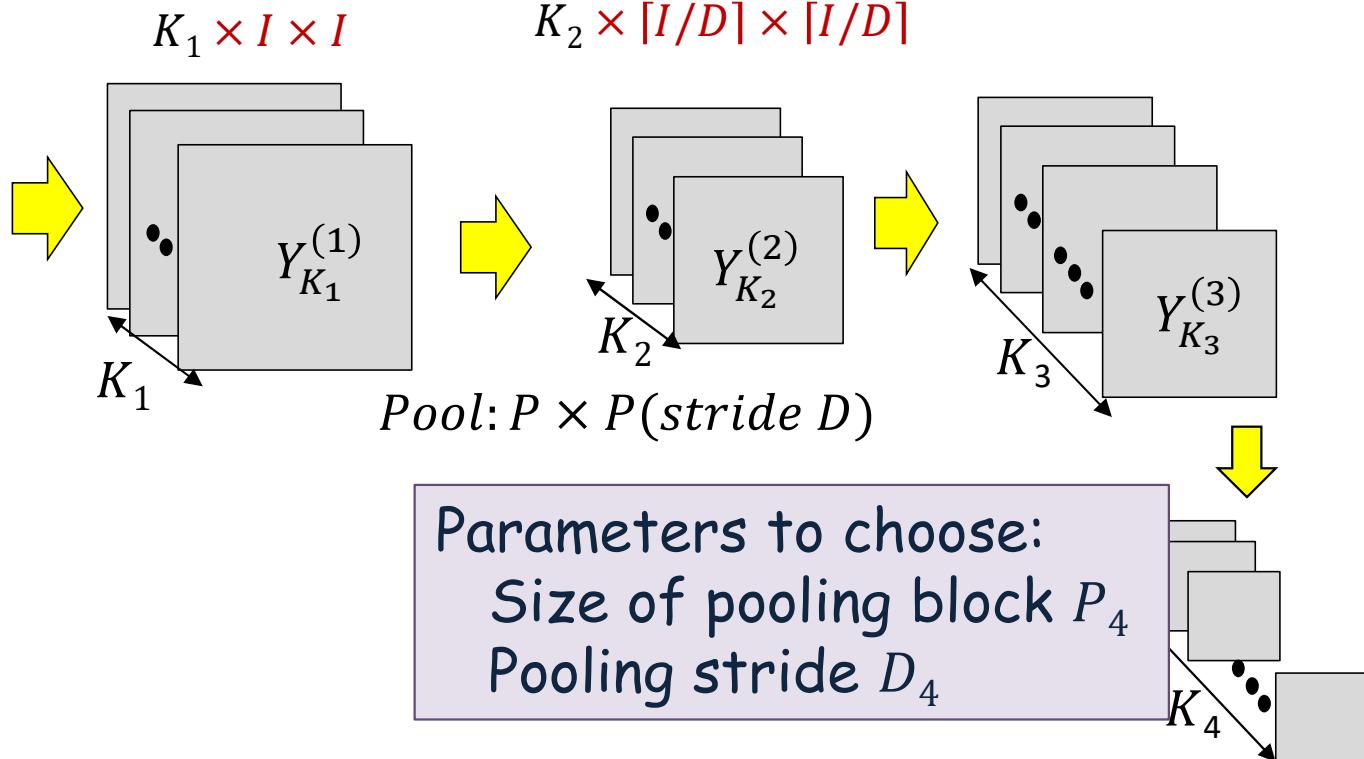
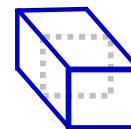
- **Second pooling layer:** K_2 Pooling operations: outcome K_2 reduced 2D maps

Convolutional Neural Networks

$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$



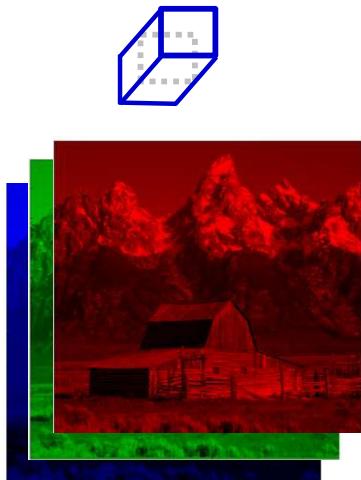
$$W_m: K_2 \times L_3 \times L_3 \\ m = 1 \dots K_3$$



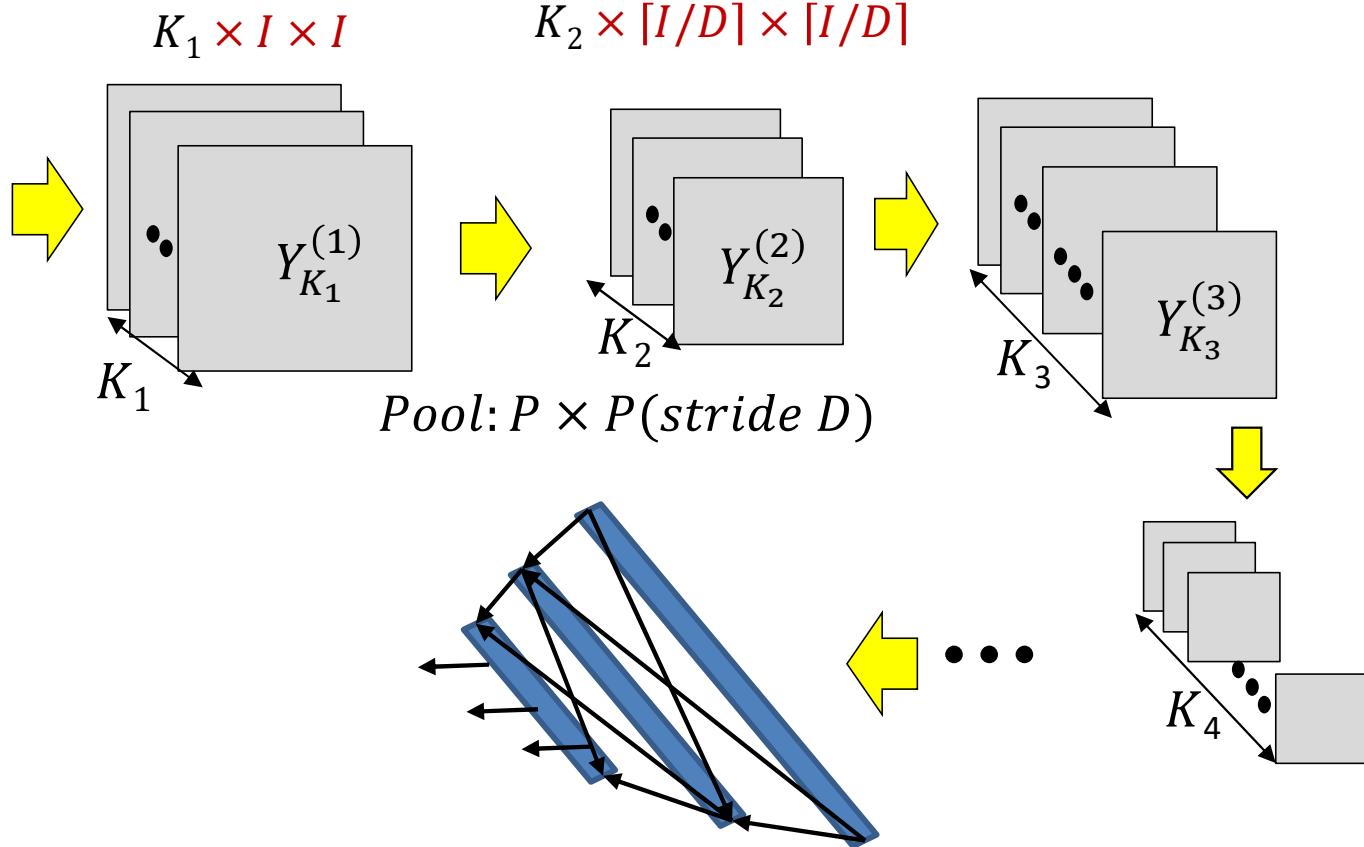
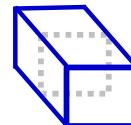
- **Second pooling layer:** K_2 Pooling operations: outcome K_2 reduced 2D maps

Convolutional Neural Networks

$$W_m: 3 \times L \times L \\ m = 1 \dots K_1$$



$$W_m: K_2 \times L_3 \times L_3 \\ m = 1 \dots K_3$$



- This continues for several layers until the final convolved output is fed to a softmax
 - Or a full MLP

The Size of the Layers

- Each convolution layer with stride 1 typically maintains the size of the image
 - With appropriate zero padding
 - If performed *without* zero padding it will decrease the size of the input
- Each convolution layer will generally *increase* the **number** of maps from the previous layer
 - Increasing layers reduces the amount of information lost by subsequent downsampling
- Each pooling layer with stride D *decreases* the **size** of the maps by a factor of D
- Filters within a layer must all be the same size, but sizes may vary with layer
 - Similarly for pooling, D may vary with layer
- In general the number of convolutional filters increases with layers

Parameters to choose (design choices)

- Number of convolutional and downsampling layers
 - And arrangement (order in which they follow one another)
- For each convolution layer:
 - Number of filters K_i
 - Spatial extent of filter $L_i \times L_i$
 - The “depth” of the filter is fixed by the number of filters in the previous layer K_{i-1}
 - The stride S_i
- For each downsampling/pooling layer:
 - Spatial extent of filter $P_i \times P_i$
 - The stride D_i
- For the final MLP:
 - Number of layers, and number of neurons in each layer

Poll 4 (@687)

What is the relationship between the number of channels in the output of a convolutional layer and the number of neurons in the corresponding layer of a scanning MLP

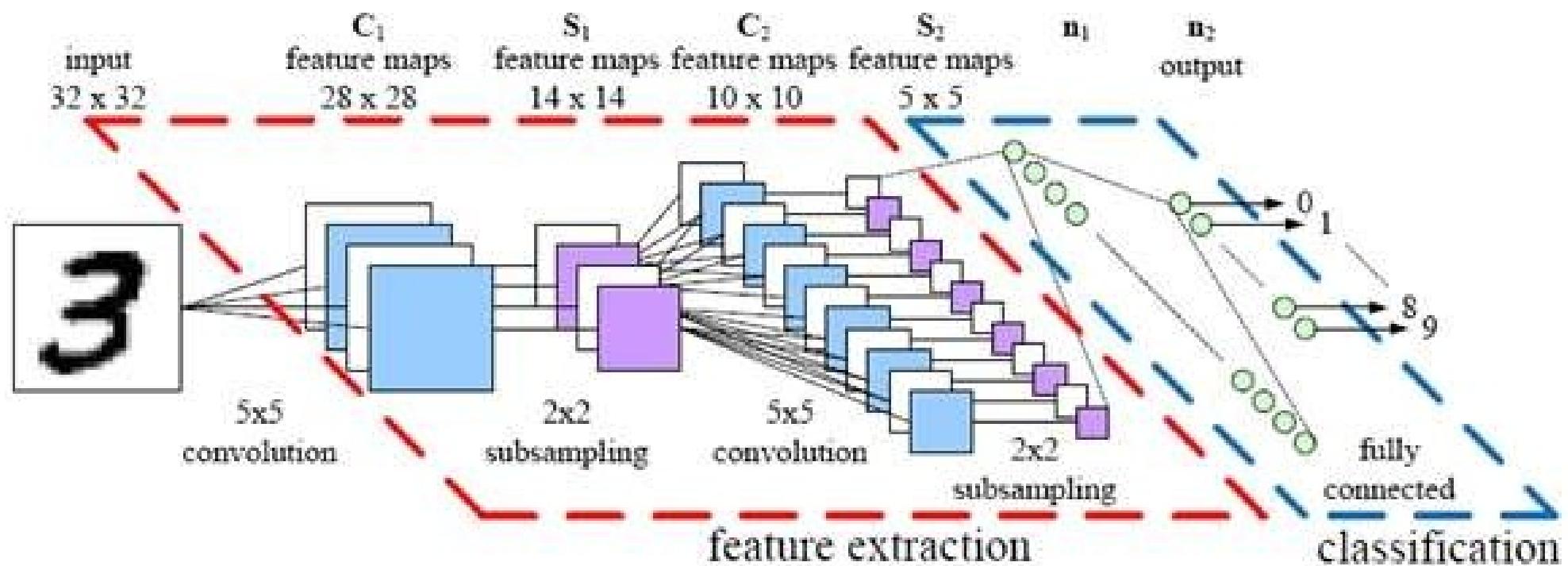
- They are the same
- The two are not related.

Poll 4

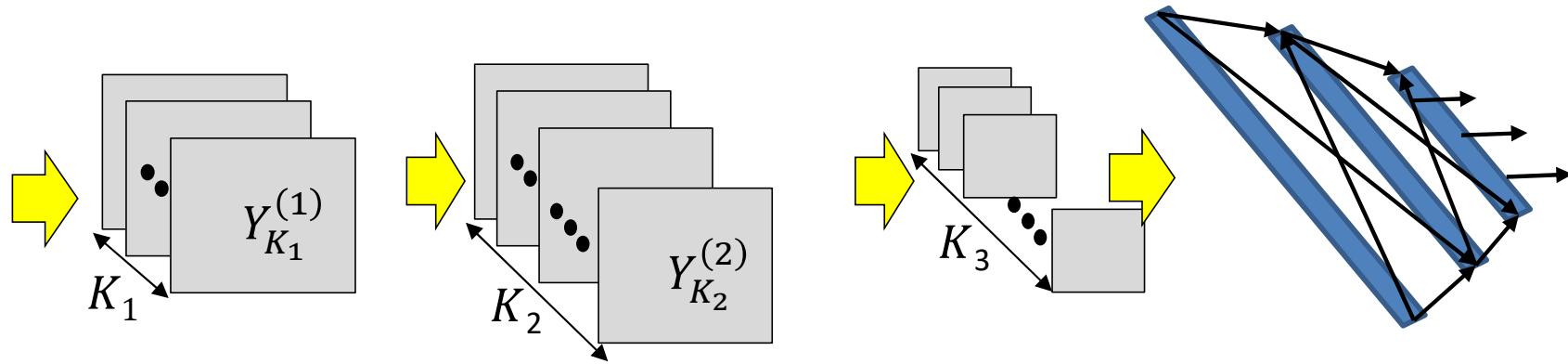
What is the relationship between the number of channels in the output of a convolutional layer and the number of neurons in the corresponding layer of a scanning MLP

- **They are the same**
- The two are not related.

Digit classification



Training



- Training is as in the case of the regular MLP
 - The *only* difference is in the *structure* of the network
- **Training examples of (Image, class) are provided**
- Define a divergence between the desired output and true output of the network in response to any input
- **Network parameters are trained through variants of gradient descent**
- **Gradients are computed through backpropagation**
- **Details in the next class**

Story so far

- The convolutional neural network is a supervised version of a computational model of mammalian vision
- It includes
 - Convolutional layers comprising learned filters that scan the outputs of the previous layer for shift-invariant pattern recognition
 - Pooling layers that operate over groups of outputs from the convolutional layer to improve robustness to jitter
- The parameters of the network can be learned through regular back propagation
 - Continued in next lecture..