Semantic Segmentation

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Last Class

- Finetuning with CNN
- The developments and insights of CNN architectures

This Class

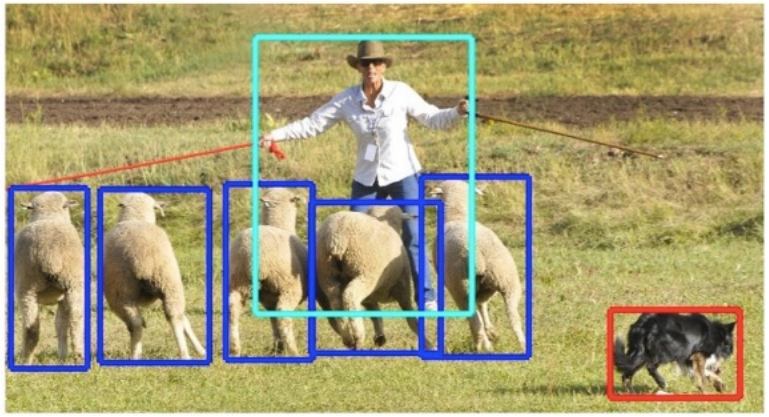
- Naïve FCN model for Image Segmentation
- Transpose Convolution
- Skip Connection, Hypercolumn

Slides partially from: http://cs231n.stanford.edu/ https://slazebni.cs.illinois.edu/fall20/

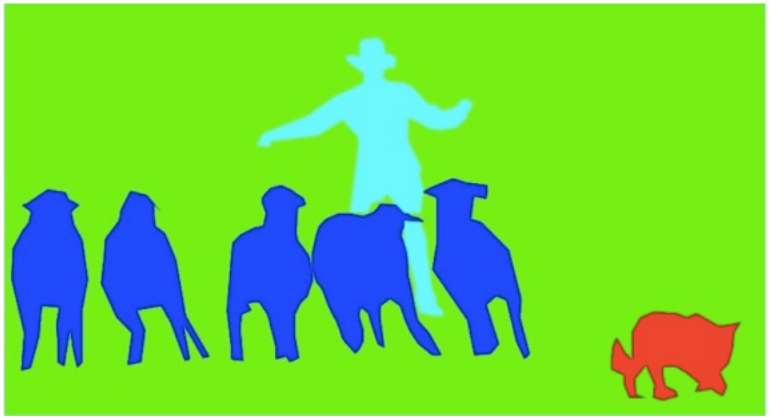
Segmentation Problem and FCN

The problem

image classification



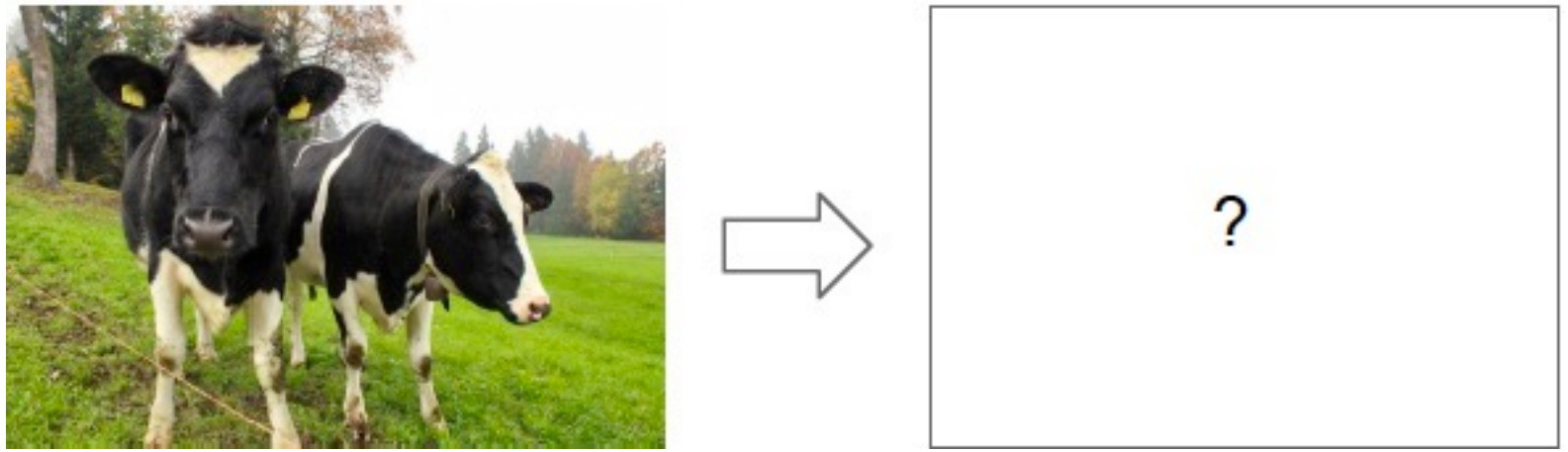
object detection



semantic segmentation

instance segmentation

The problem

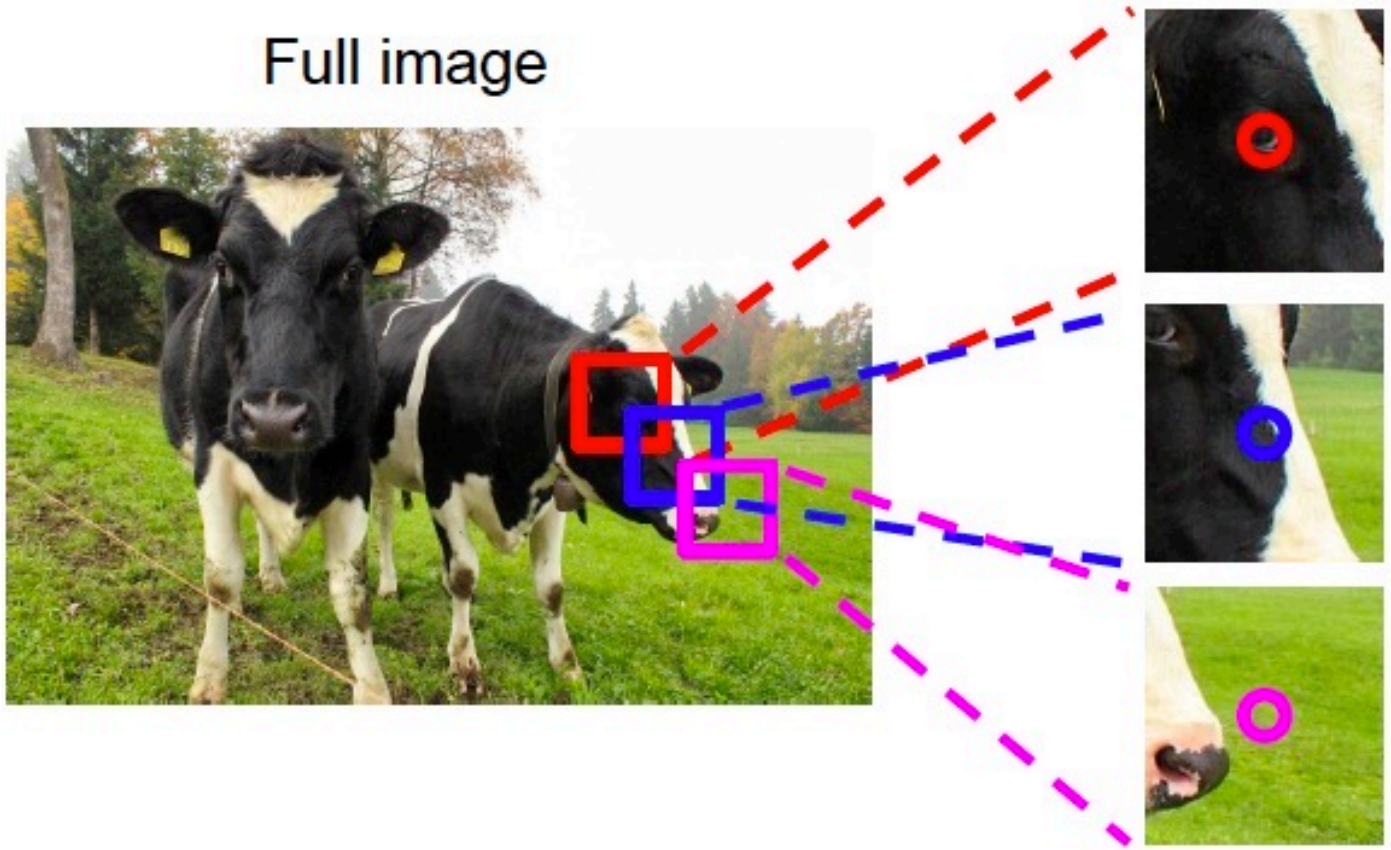


Semantic Segmentation

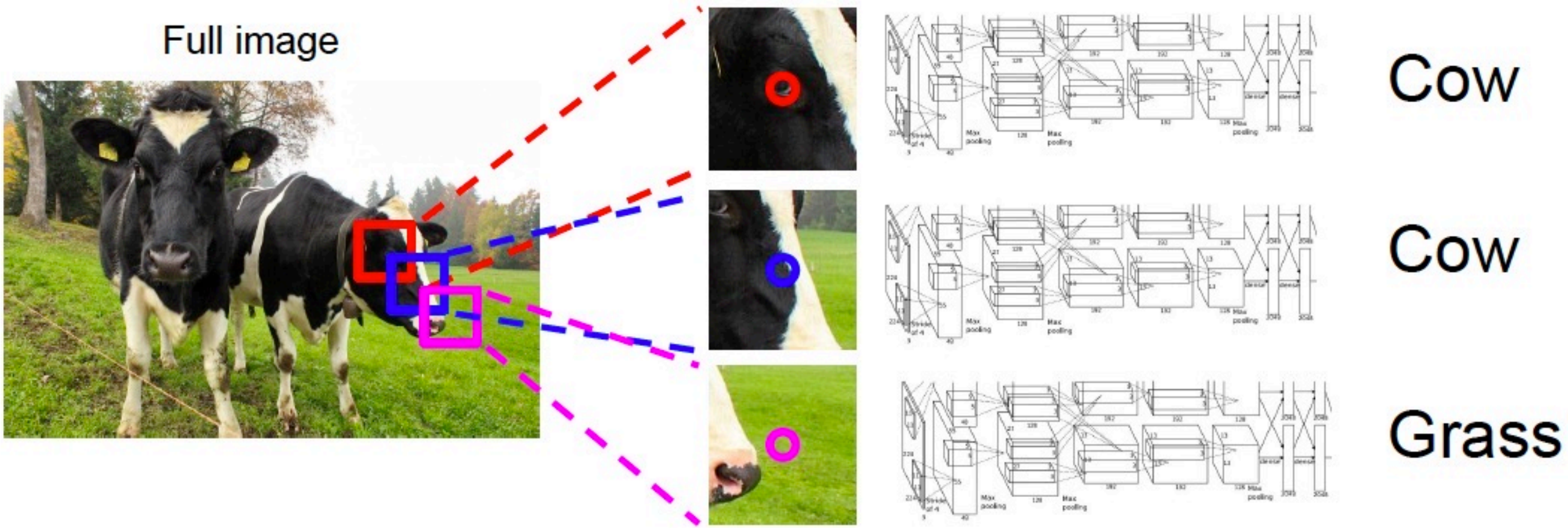
Simply staring one pixel is impossible to do the classification

Let’s put in some context!

Semantic Segmentation



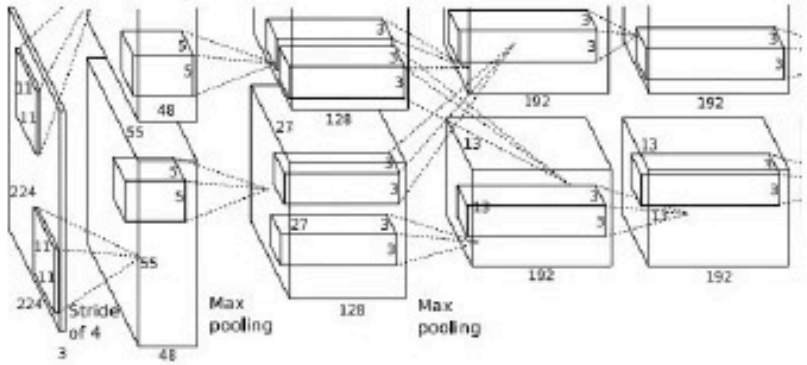
Semantic Segmentation



Time Consuming!

Can we process the whole image at one time?

Full image



AlexNet input:
227 x 277 x 3

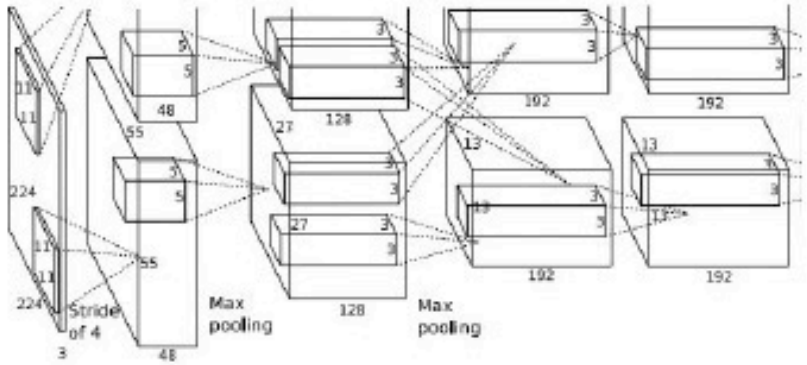
AlexNet Conv5:
13 x 13 x 128

Output ?
13 x 13 x 21

Output is too small!

Can we process the whole image at one time?

Full image



AlexNet input:
227 x 277 x 3

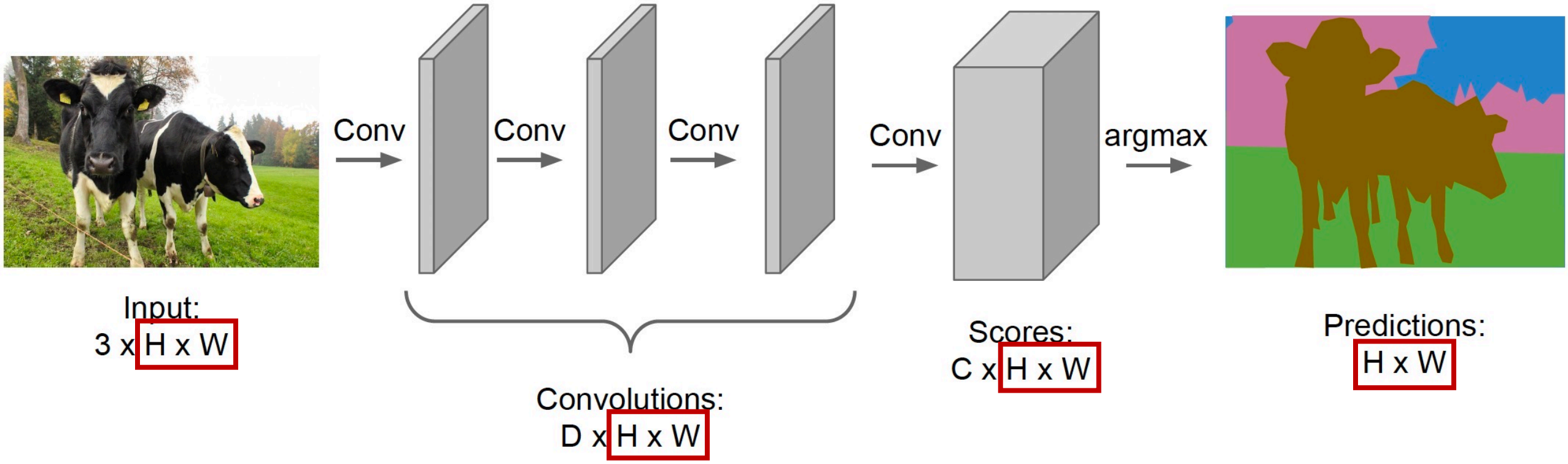
AlexNet Conv5:
13 x 13 x 128

FC + reshape

Output ?
227 x 227 x 21

Huge number of Parameters for FC: 13 x 13 x 128 x 227 x 227 x 21

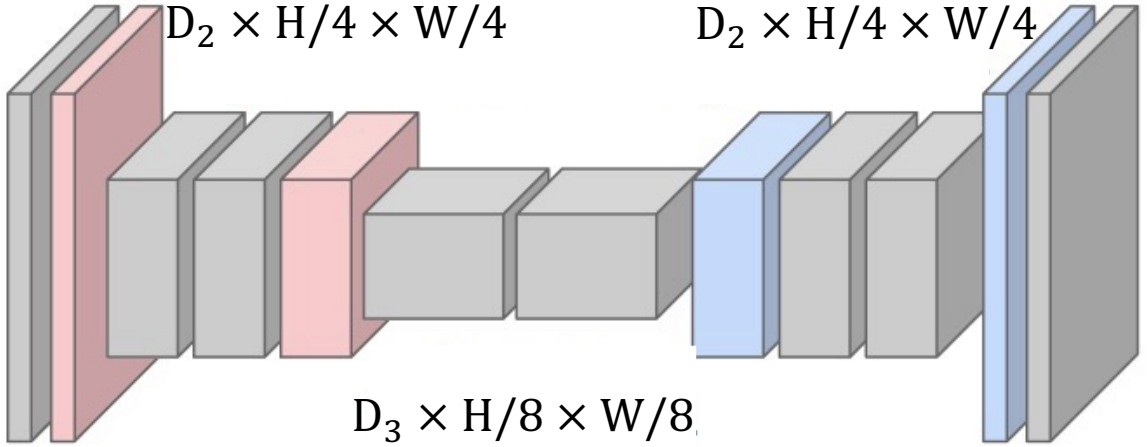
Fully Convolutional Network



Convolution at original image resolution has high computation cost.

Fully Convolutional Network

Input:
3 x H x W



Transpose Convolution

High-res:
D_1 x H/2 x W/2

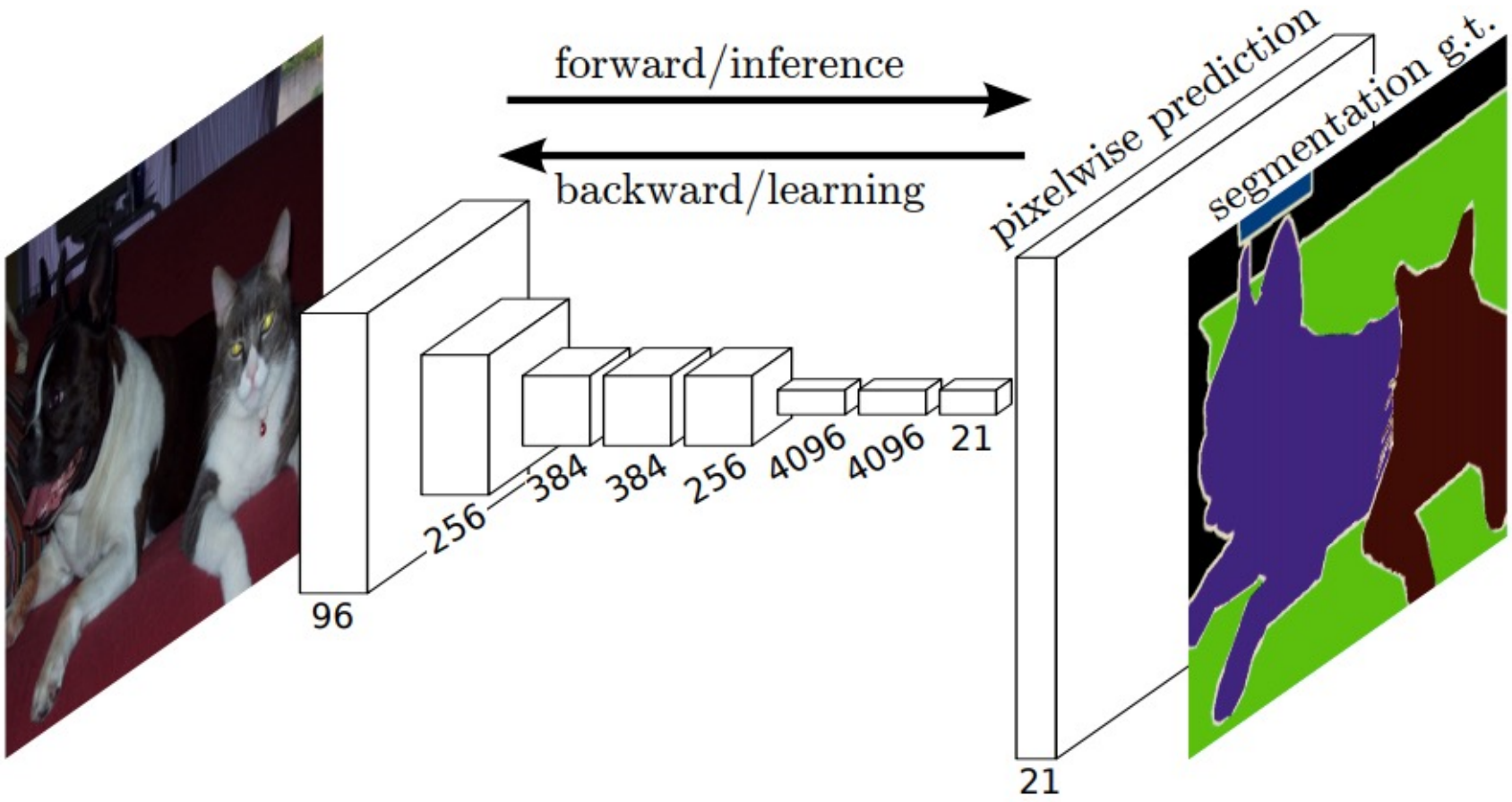
High-res:
D_1 x H/2 x W/2

Predictions:
H x W

Make the feature map small increases the receptive field

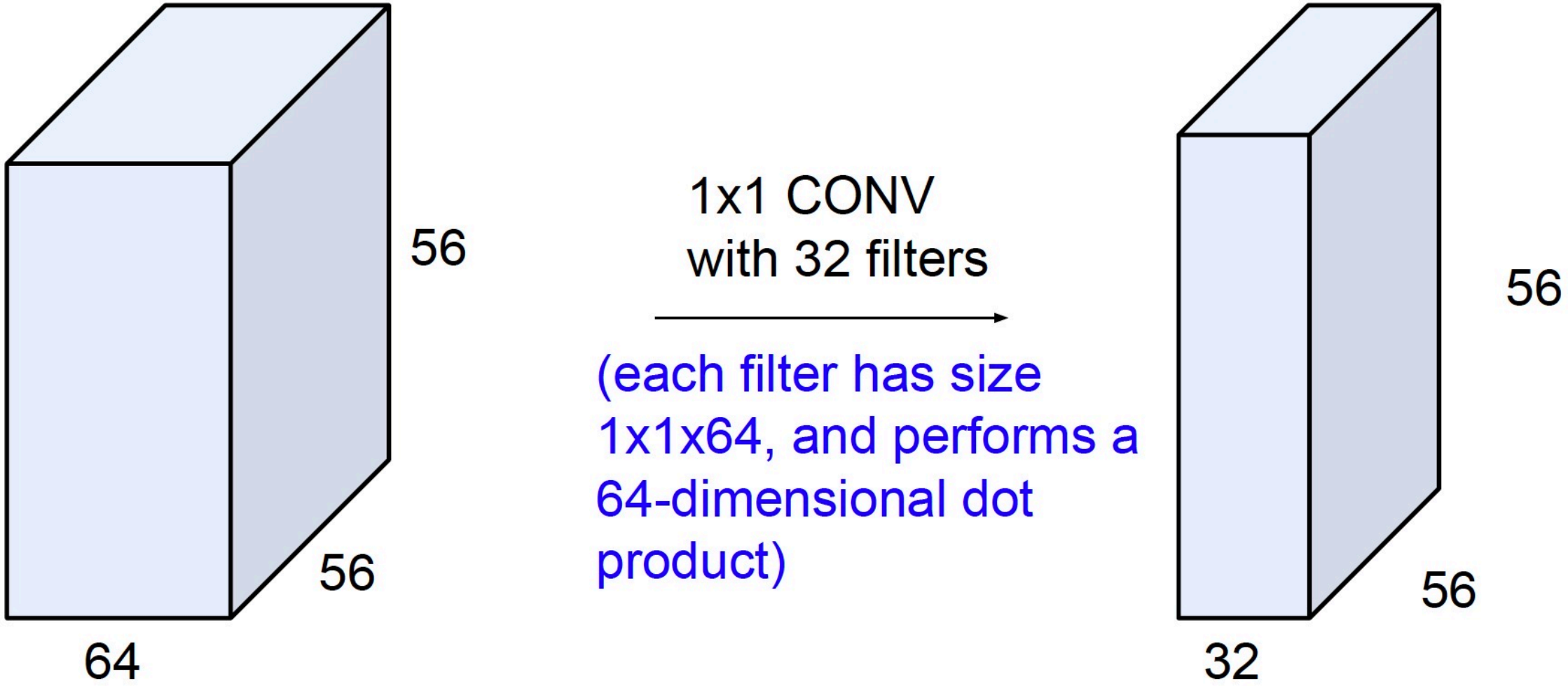
Make the feature map larger again increases the resolution

The FCN paper

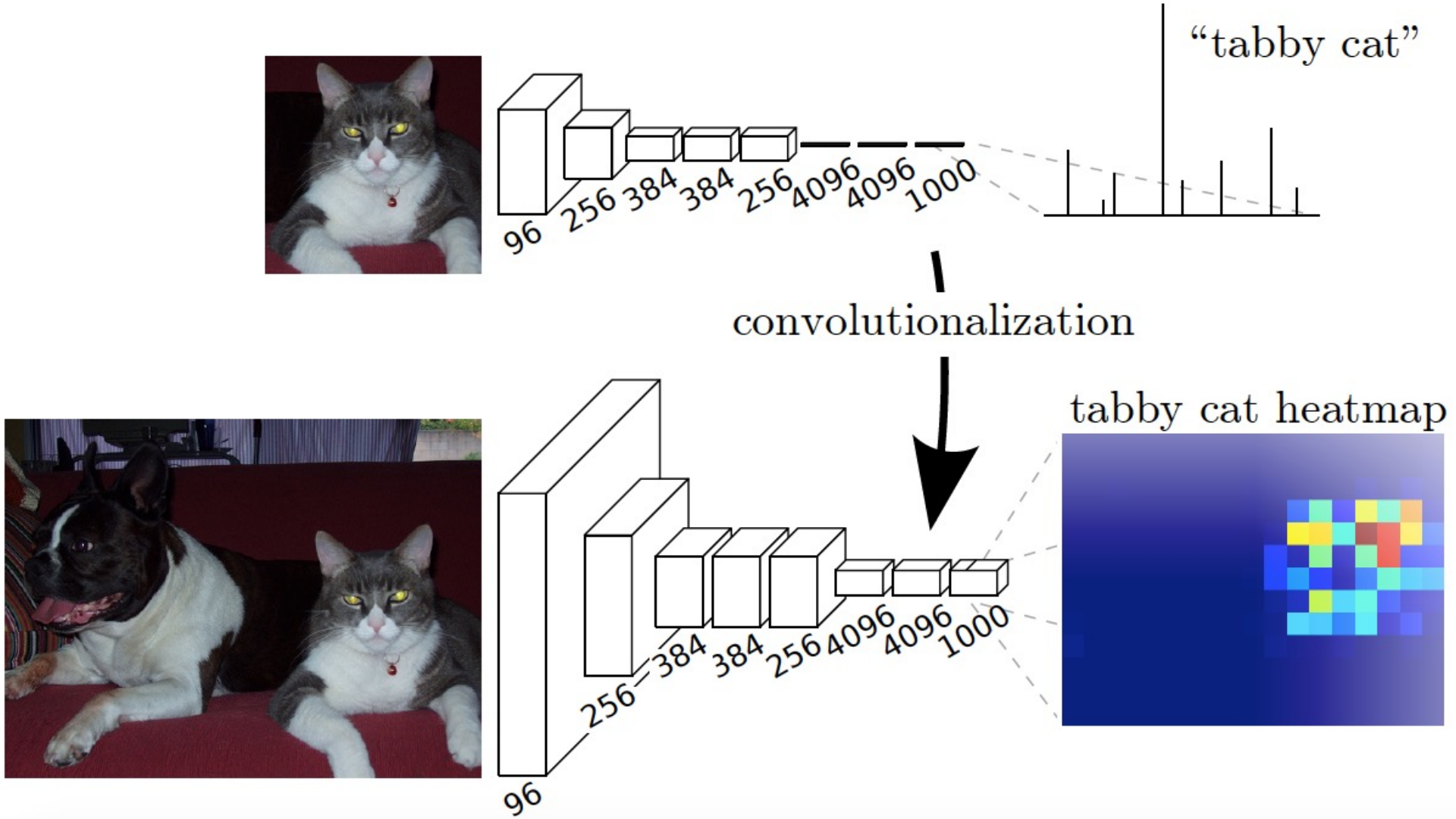


Long et al. 2015

1 x 1 convolutions



The FCN paper



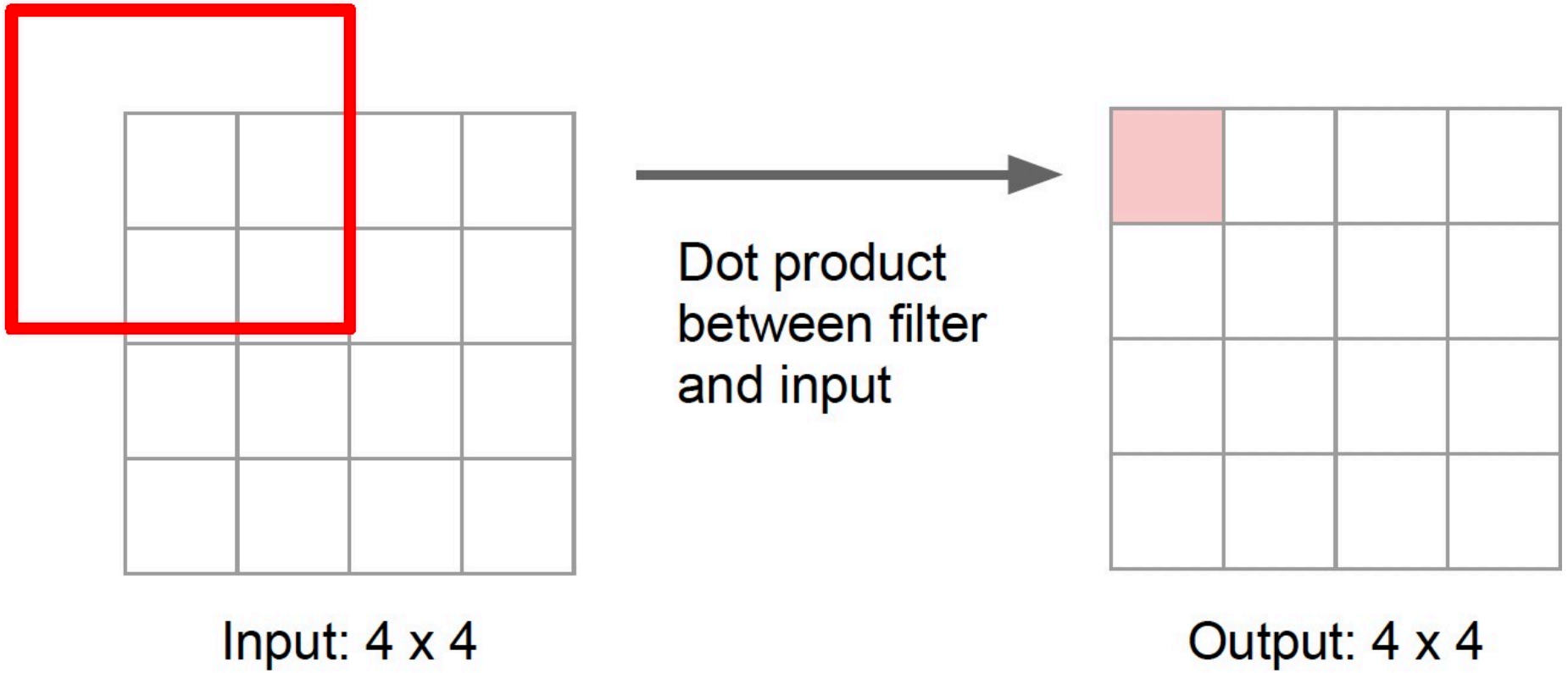
The upsamling

- Upsampling Layer
- Deconvolution Layer
- Transpose Convolution Layer

Transpose Convolution

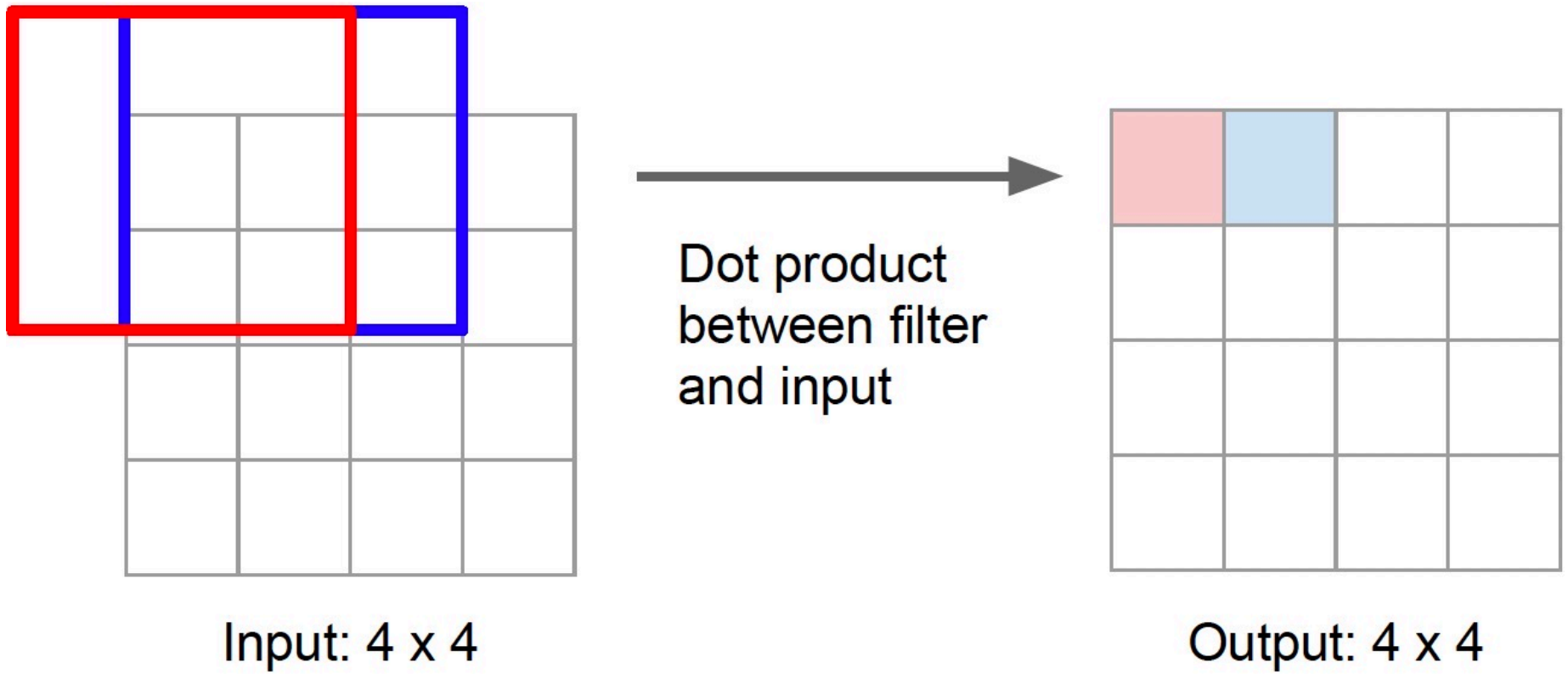
Recall Convolution

3 X 3 convolution with stride 1 and padding 1



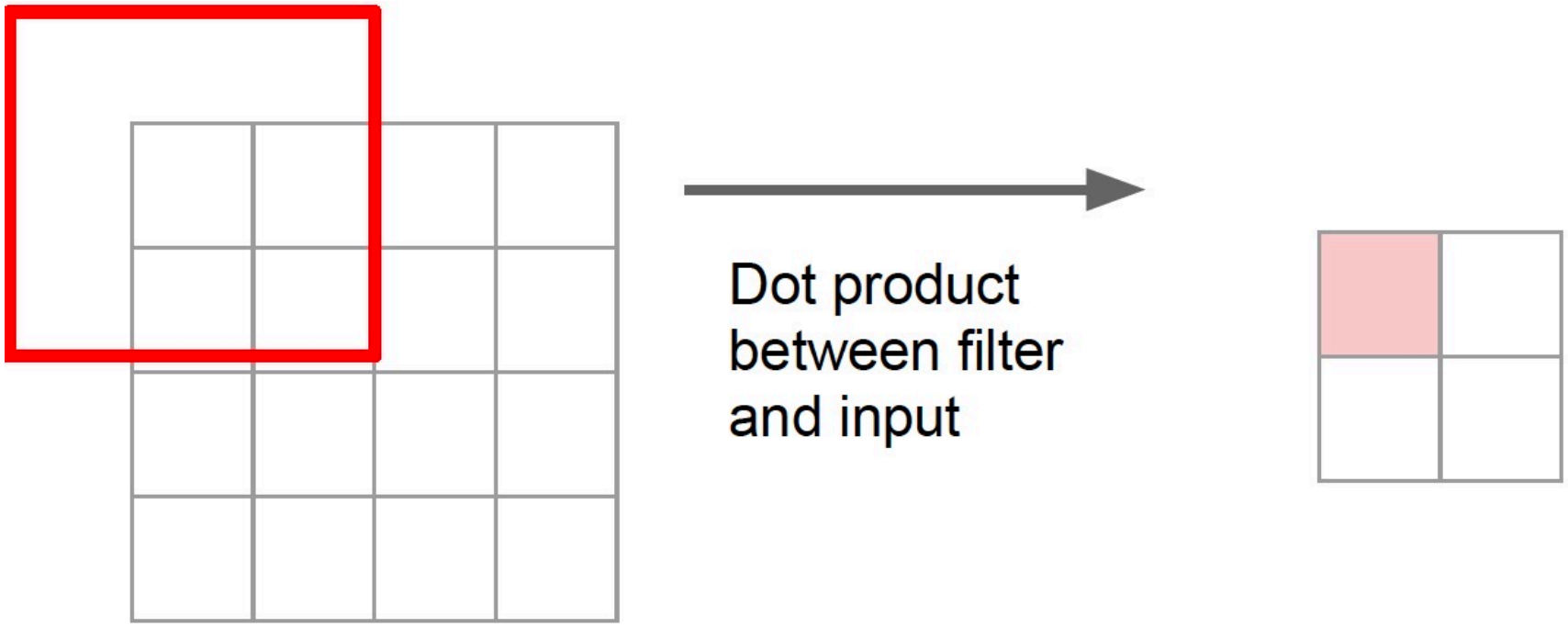
Recall Convolution

3 X 3 convolution with stride 1 and padding 1



Recall Convolution

3 X 3 convolution with stride 2 and padding 1

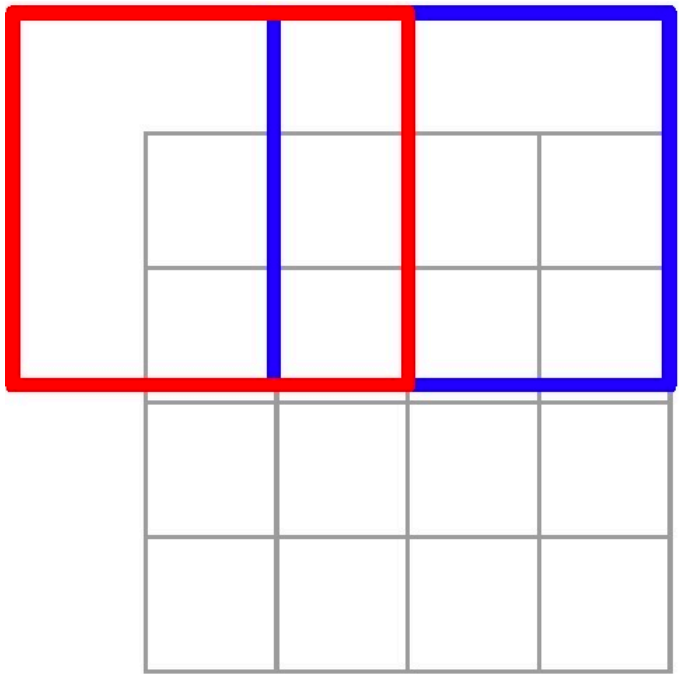


Input: 4 x 4

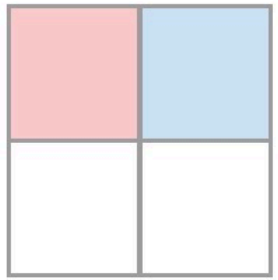
Output: 2 x 2

Recall Convolution

3 X 3 convolution with stride 2 and padding 1



Dot product between filter and input

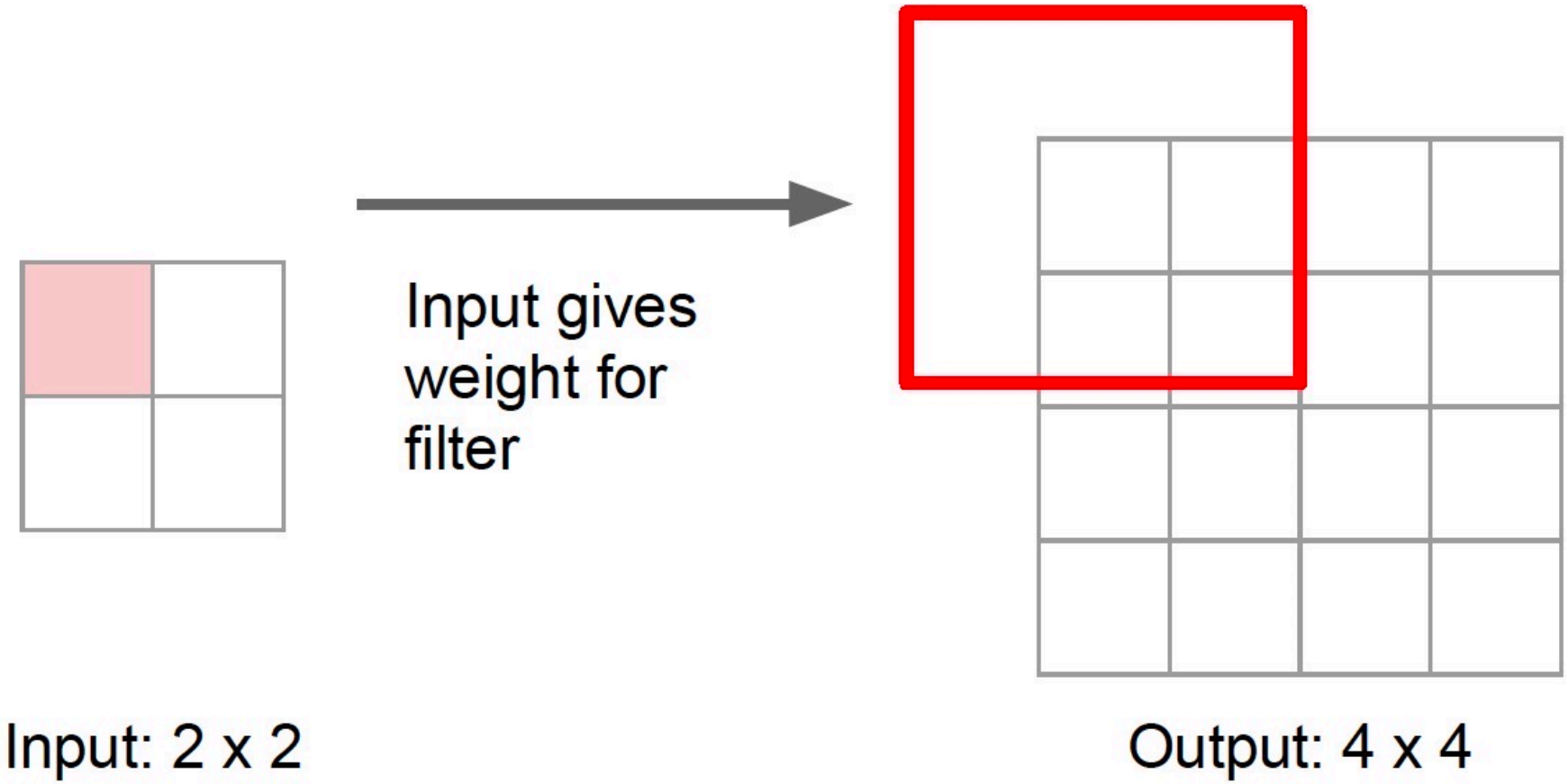


Input: 4 x 4

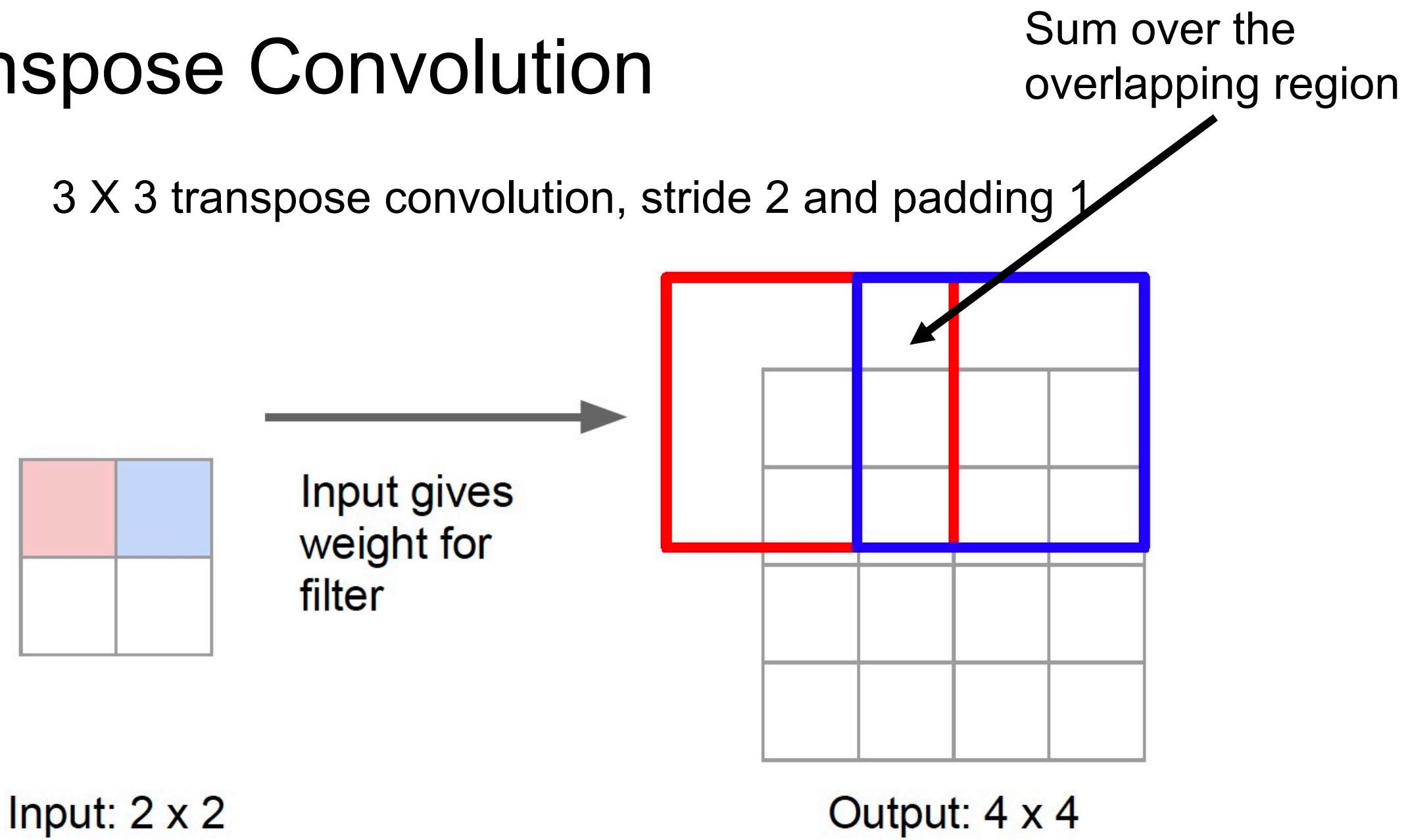
Output: 2 x 2

Transpose Convolution

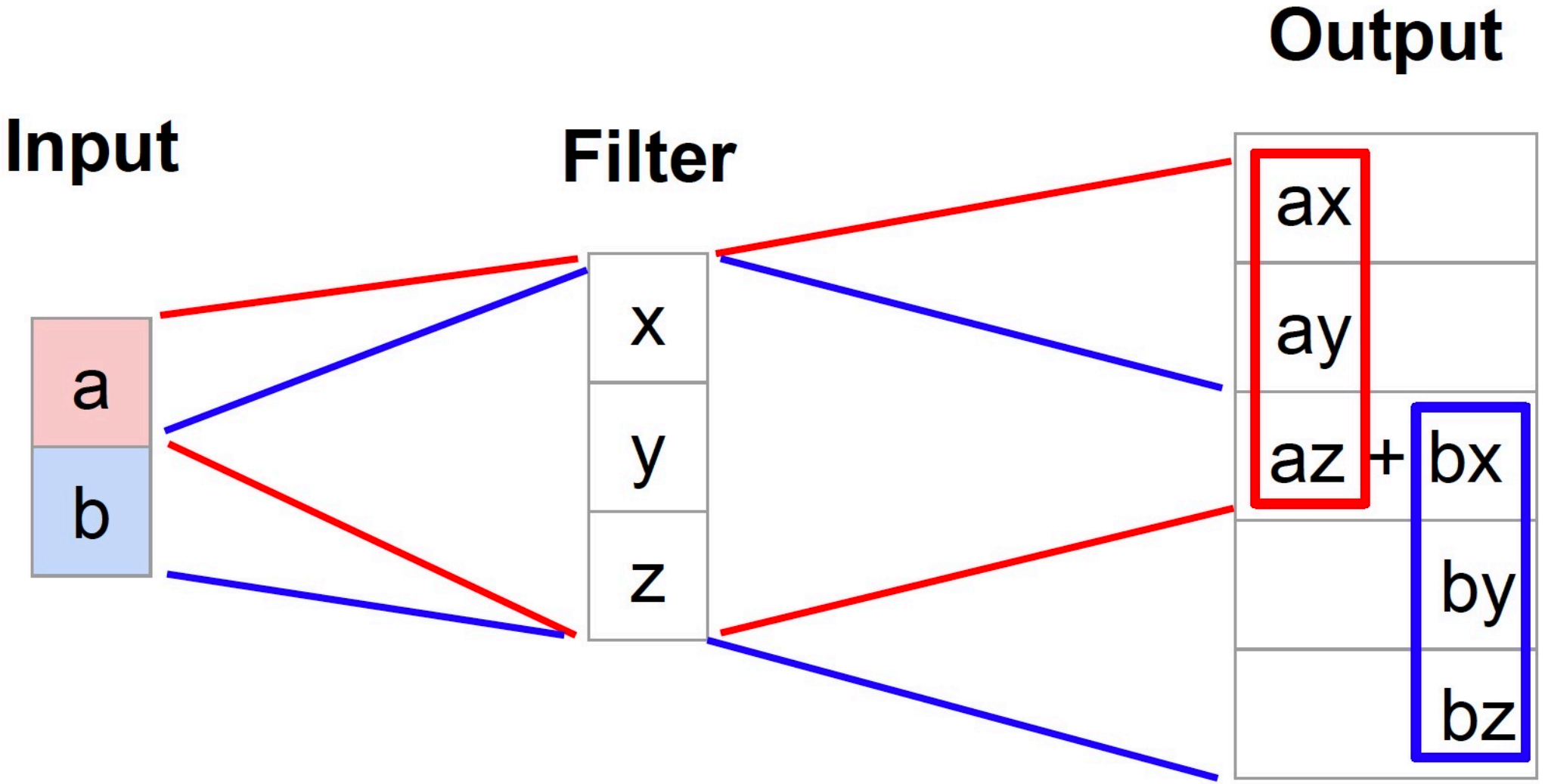
3 X 3 transpose convolution, stride 2 and padding 1



Transpose Convolution



1D Transpose Convolution Example



2D Convolution

Regular convolution (stride 1, pad 0)

$$\begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix} * \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}$$

Matrix-vector form:

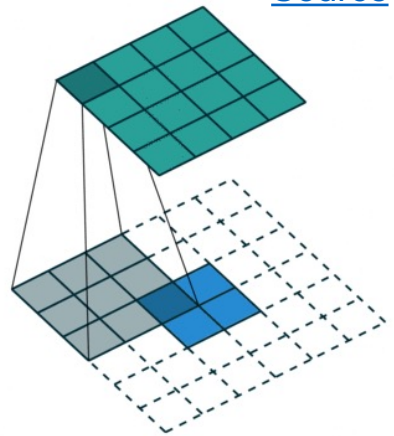
$$\begin{pmatrix} w_{11} & w_{12} & w_{13} & 0 & w_{21} & w_{22} & w_{23} & 0 & w_{31} & w_{32} & w_{33} & 0 & 0 & 0 & 0 & 0 \\ 0 & w_{11} & w_{12} & w_{13} & 0 & w_{21} & w_{22} & w_{23} & 0 & w_{31} & w_{32} & w_{33} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{11} & w_{12} & w_{13} & 0 & w_{21} & w_{22} & w_{23} & 0 & w_{31} & w_{32} & w_{33} & 0 \\ 0 & 0 & 0 & 0 & 0 & w_{11} & w_{12} & w_{13} & 0 & w_{21} & w_{22} & w_{23} & 0 & w_{31} & w_{32} & w_{33} \end{pmatrix} \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ \vdots \\ x_{44} \end{pmatrix} = \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix}$$

4x4 input, 2x2 output

Transpose Convolution

$$\begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} *^T \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix}$$

Source



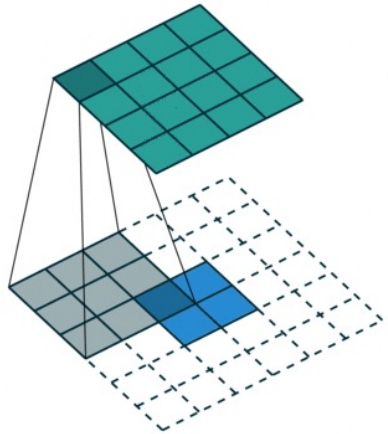
$$\begin{pmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{pmatrix} \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix} = \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{pmatrix}$$

2x2 input, 4x4 output

Not an inverse of the original convolution operation, simply reverses dimension change!

Transp Convolution

$$\begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} *^{T} \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix}$$



$$\begin{bmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{bmatrix} \begin{bmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{bmatrix} = \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{bmatrix}$$

$$x_{11} = w_{11} z_{11}$$

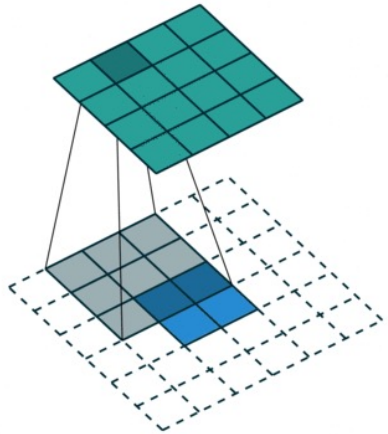
Transpose convolution

$$\begin{matrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{matrix}$$

$$\begin{matrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{matrix}$$

$$*^T \quad \begin{matrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{matrix} \quad =$$

$$\begin{matrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{matrix}$$



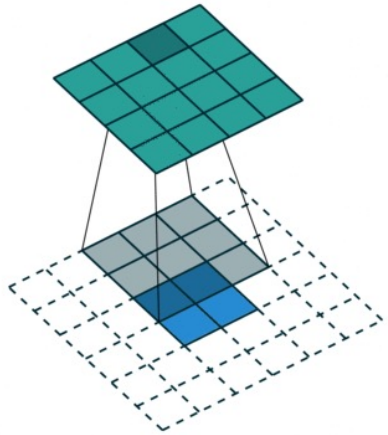
$$\begin{pmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{pmatrix} \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix} = \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{pmatrix}$$

Convolve input with *flipped* filter

$$x_{12} = w_{12}z_{11} + w_{11}z_{12}$$

Transpose convolution

$$\begin{bmatrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{bmatrix} \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} *^{T} \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix}$$



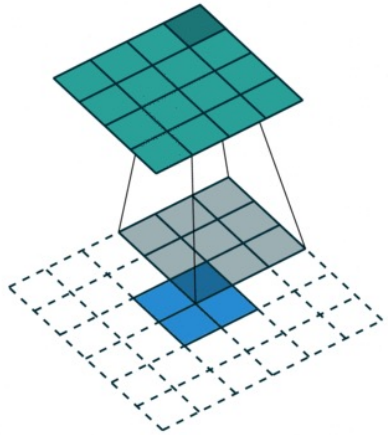
Convolve input with *flipped* filter

$$\begin{pmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{pmatrix} \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix} = \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{pmatrix}$$

$$x_{13} = w_{13}z_{11} + w_{12}z_{12}$$

Transpose convolution

$$\begin{bmatrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{bmatrix} \quad \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \quad *^T \quad \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix}$$



Convolve input with *flipped* filter

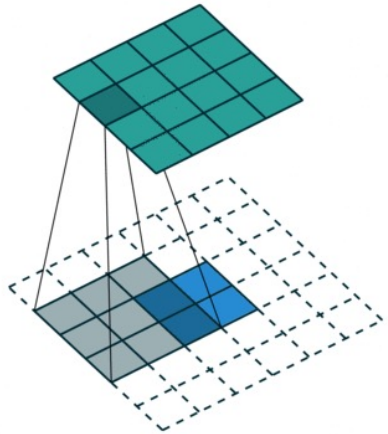
$$\begin{bmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{bmatrix} \begin{bmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{bmatrix} = \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{bmatrix}$$

$$x_{14} = w_{13} z_{12}$$

Transpose Convolution

$$\begin{matrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{matrix}$$

$$\begin{matrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{matrix} \quad *^T \quad \begin{matrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{matrix} \quad = \quad \begin{matrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{matrix}$$



Convolve input with *flipped* filter

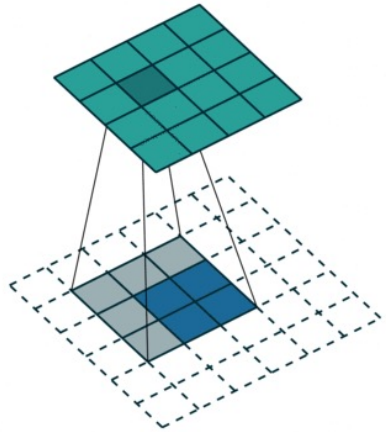
$$\begin{pmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{pmatrix} \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix} = \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{pmatrix}$$

$$x_{21} = w_{21}z_{11} + w_{11}z_{21}$$

Transpose convolution

$$\begin{matrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{matrix}$$

$$\begin{matrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{matrix} \quad *^T \quad \begin{matrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{matrix} \quad = \quad \begin{matrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{matrix}$$



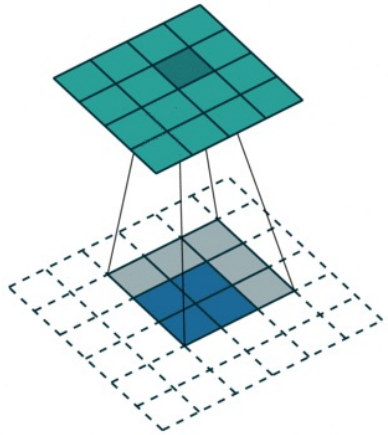
Convolve input with *flipped* filter

$$\begin{pmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{pmatrix} \begin{pmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{pmatrix} = \begin{pmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{pmatrix}$$

$$x_{22} = w_{22}z_{11} + w_{21}z_{12} + w_{12}z_{21} + w_{11}z_{22}$$

Transpose convolution

$$\begin{bmatrix} w_{33} & w_{32} & w_{31} \\ w_{23} & w_{22} & w_{21} \\ w_{13} & w_{12} & w_{11} \end{bmatrix} \quad \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \quad *^T \quad \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ x_{41} & x_{42} & x_{43} & x_{44} \end{bmatrix}$$

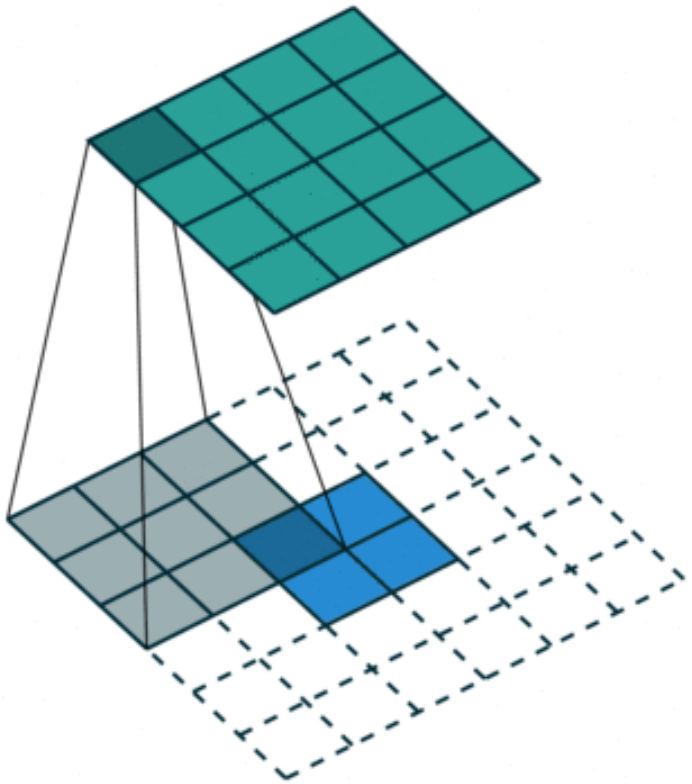


Convolve input with *flipped* filter

$$\begin{bmatrix} w_{11} & 0 & 0 & 0 \\ w_{12} & w_{11} & 0 & 0 \\ w_{13} & w_{12} & 0 & 0 \\ 0 & w_{13} & 0 & 0 \\ w_{21} & 0 & w_{11} & 0 \\ w_{22} & w_{21} & w_{12} & w_{11} \\ w_{23} & w_{22} & w_{13} & w_{12} \\ 0 & w_{23} & 0 & w_{13} \\ w_{31} & 0 & w_{21} & 0 \\ w_{32} & w_{31} & w_{22} & w_{21} \\ w_{33} & w_{32} & w_{23} & w_{22} \\ 0 & w_{33} & 0 & w_{23} \\ 0 & 0 & w_{31} & 0 \\ 0 & 0 & w_{32} & w_{31} \\ 0 & 0 & w_{33} & w_{32} \\ 0 & 0 & 0 & w_{33} \end{bmatrix} \begin{bmatrix} z_{11} \\ z_{12} \\ z_{21} \\ z_{22} \end{bmatrix} = \begin{bmatrix} x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{21} \\ x_{22} \\ x_{23} \\ x_{24} \\ x_{31} \\ x_{32} \\ x_{33} \\ x_{34} \\ x_{41} \\ x_{42} \\ x_{43} \\ x_{44} \end{bmatrix}$$

$$x_{23} = w_{23}z_{11} + w_{22}z_{12} + w_{13}z_{21} + w_{12}z_{22}$$

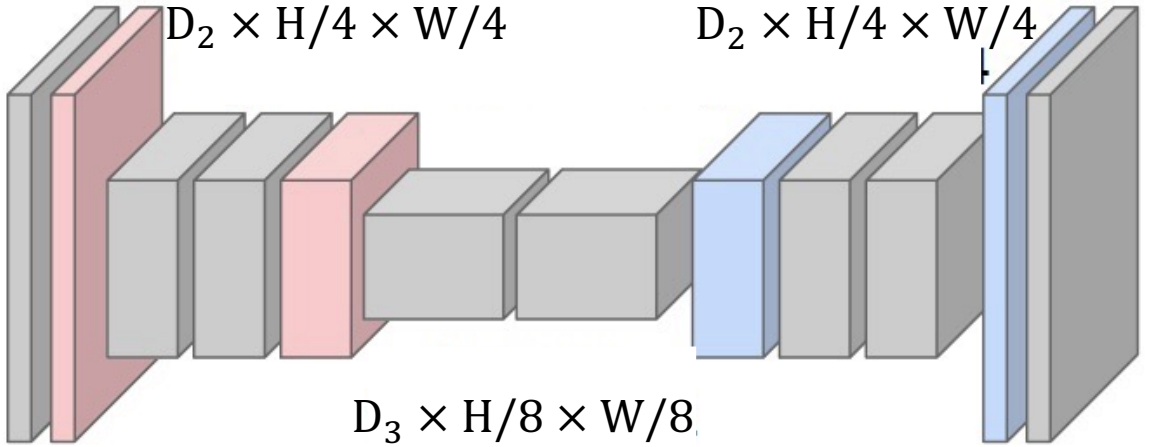
Transpose Convolution



output

input

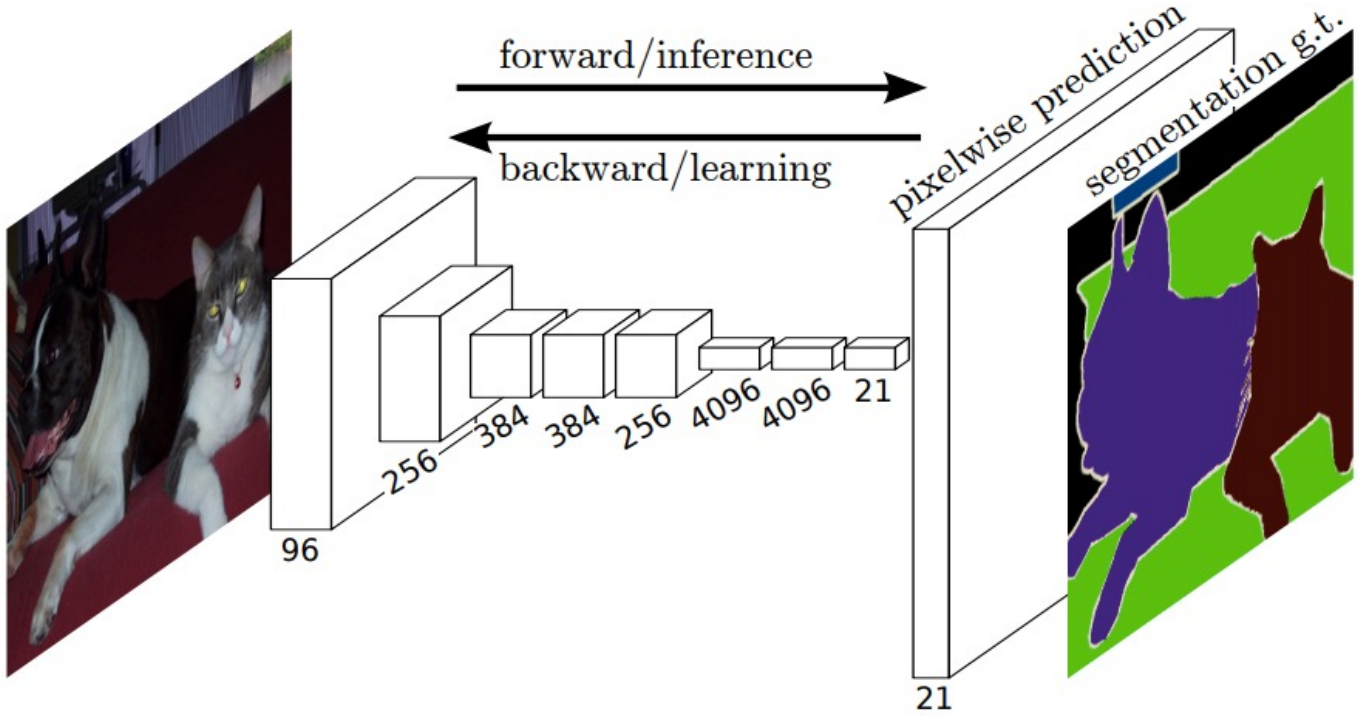
Input:
3 x H x W



High-res:
D_1 x H/2 x W/2

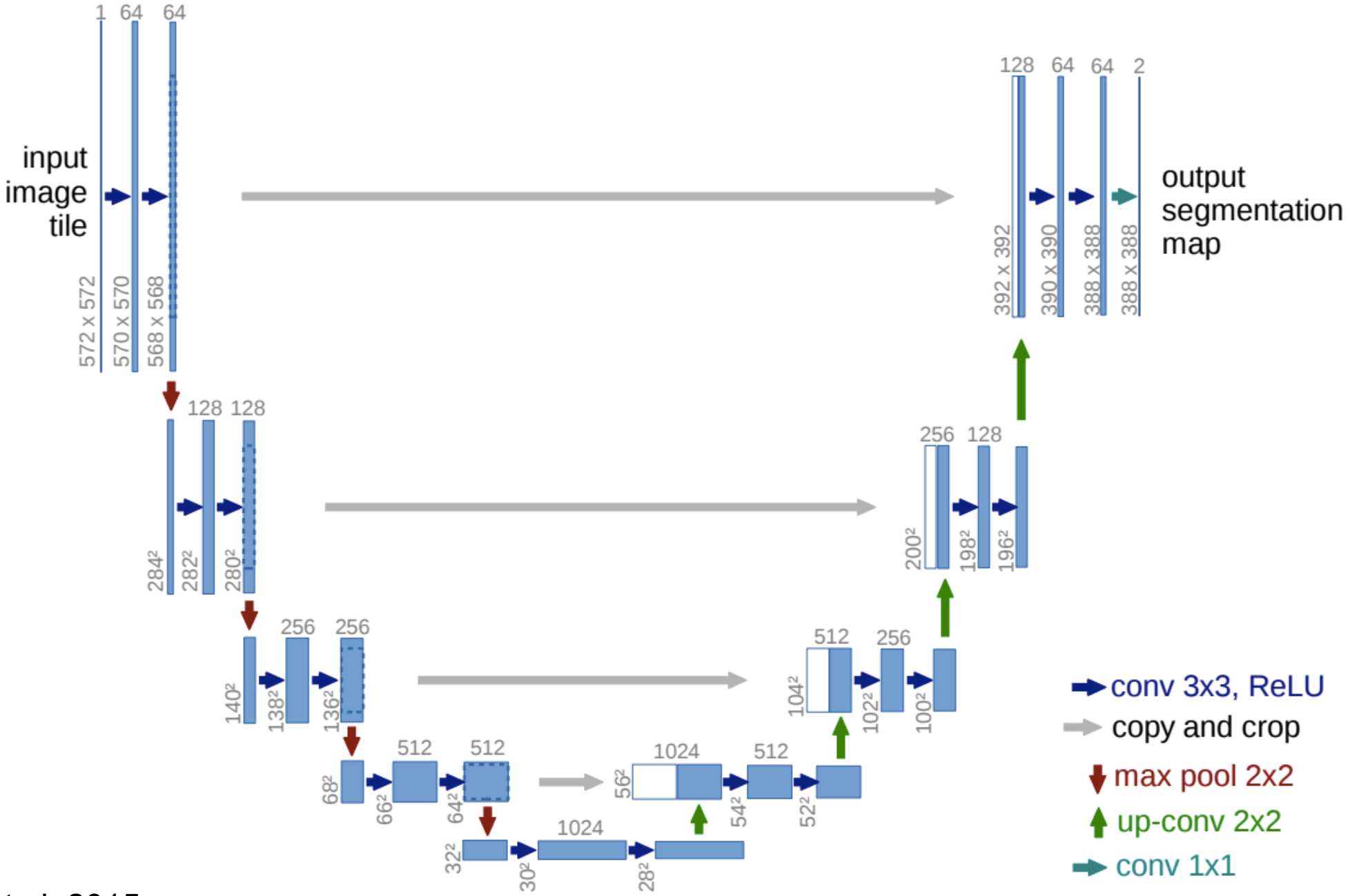
High-res:
D_1 x H/2 x W/2

Predictions:
H x W



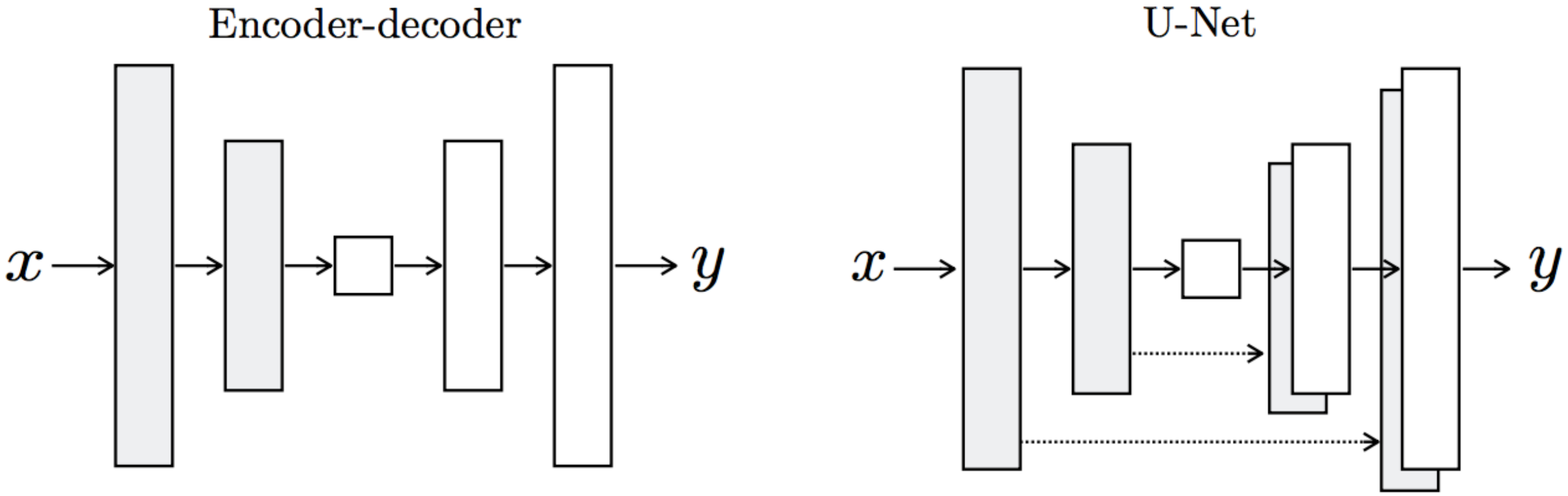
Advanced Techniques in Segmentation

U-Net



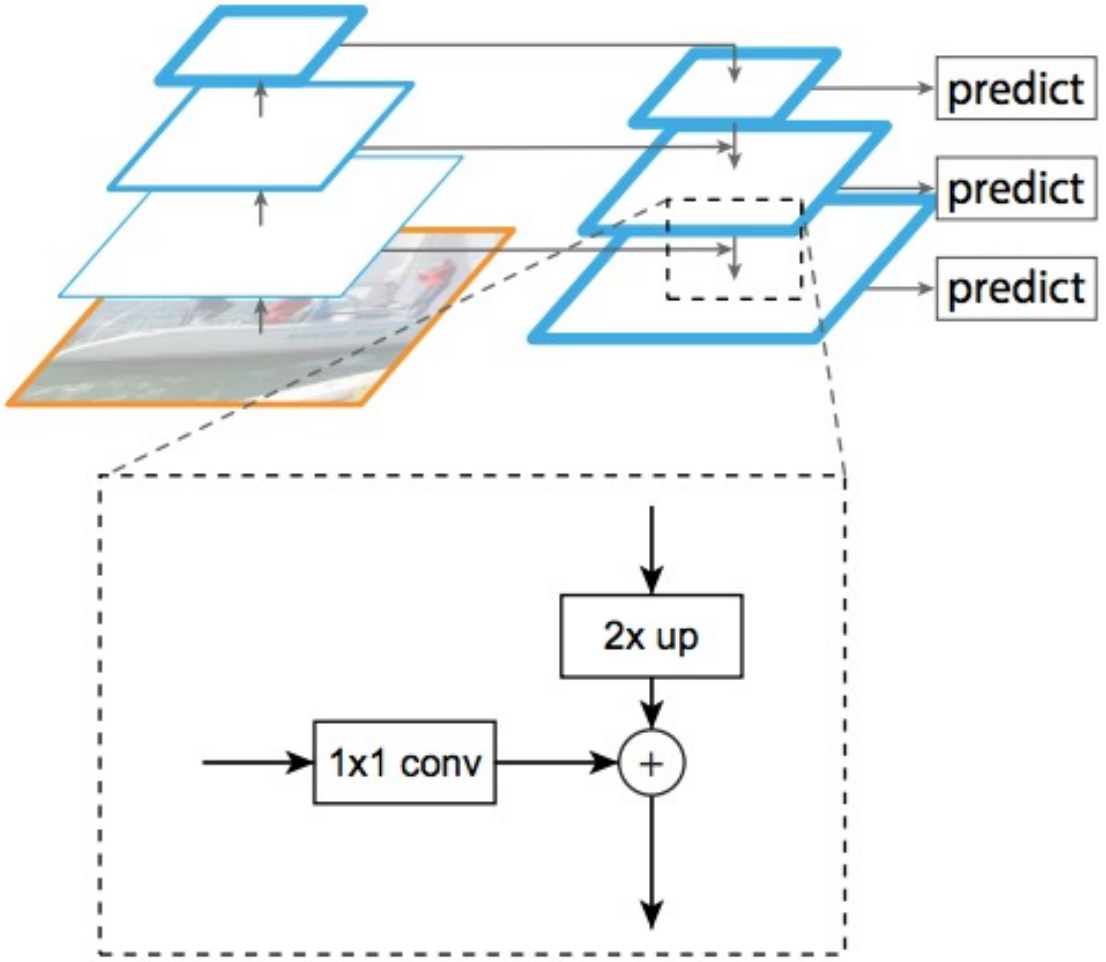
Ronneberger et al. 2015

U-Net



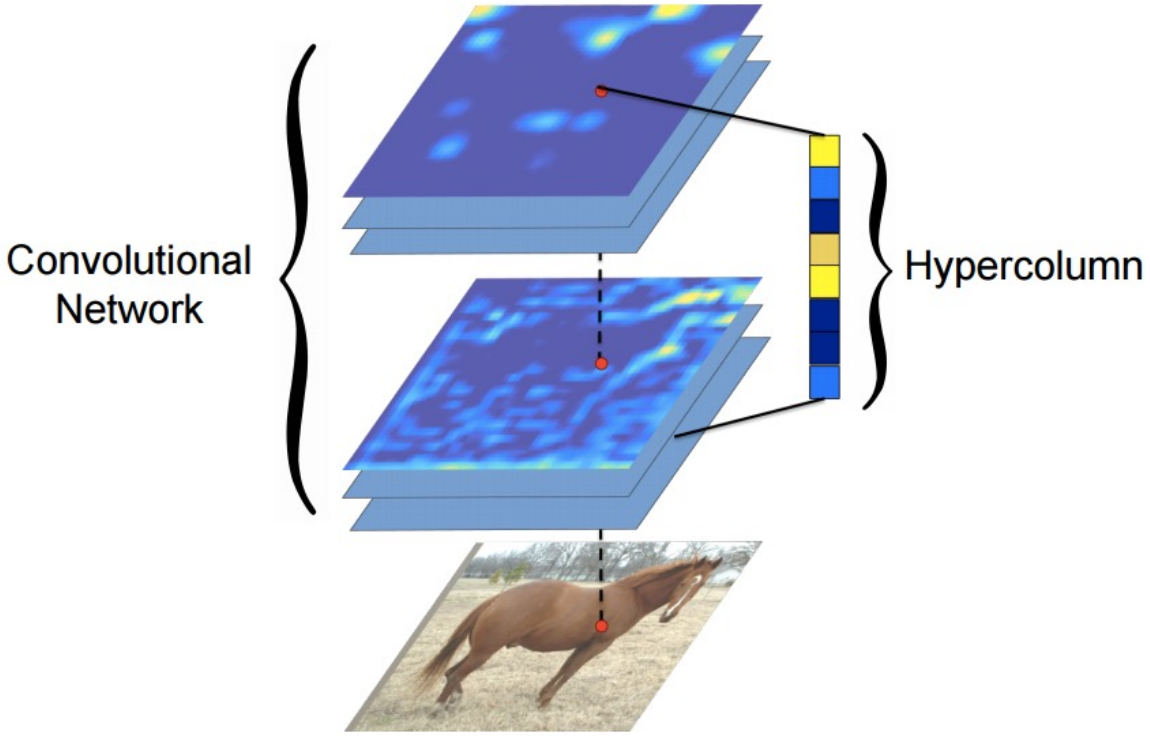
https://phillipi.github.io/pix2pix/

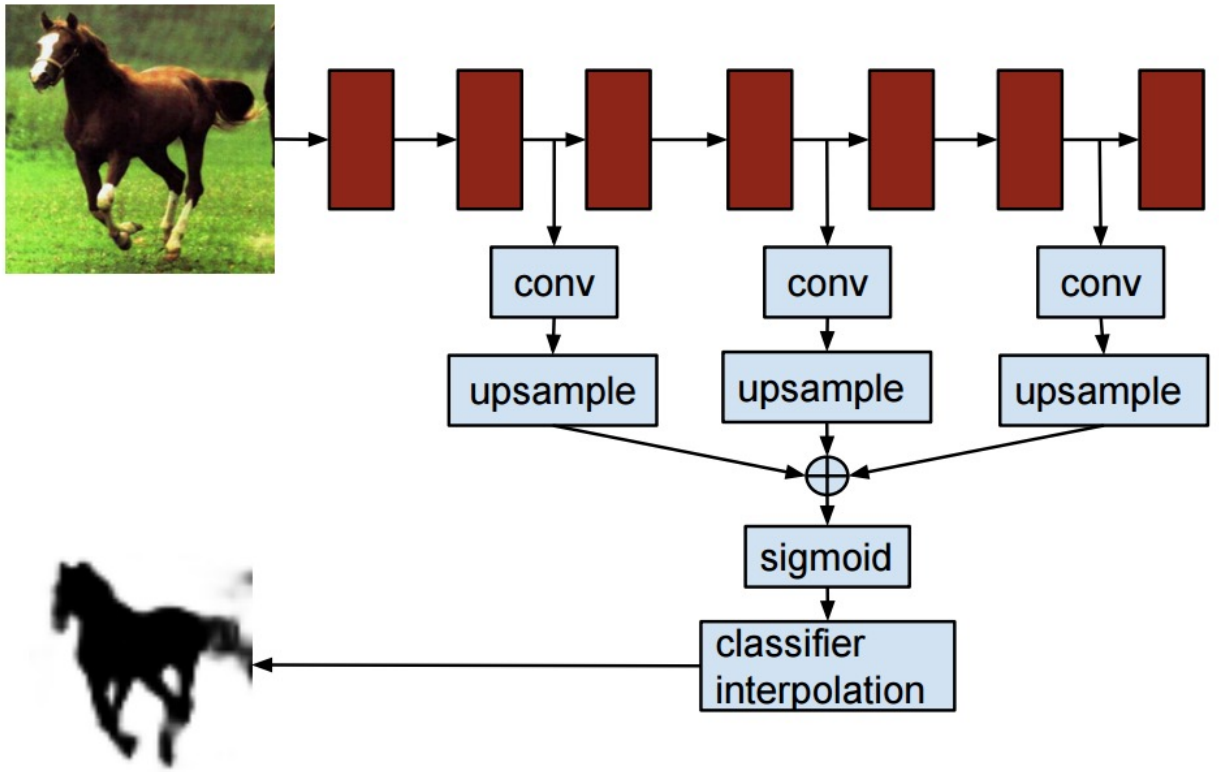
U-Net and FPN



Lin et al. 2017

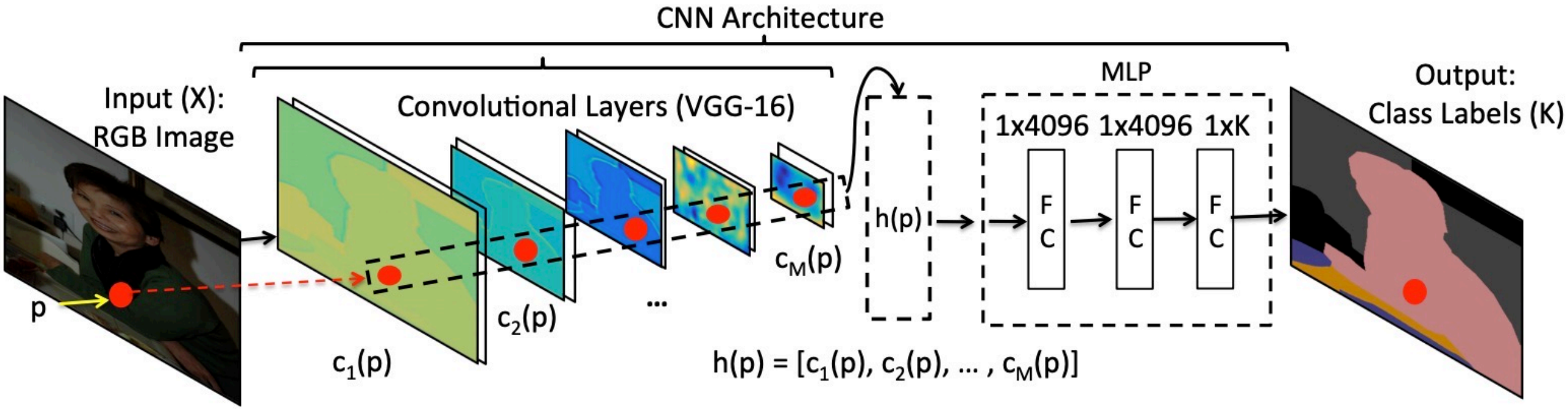
Hypercolumn and Skip Connection





Hariharan et al. 2015

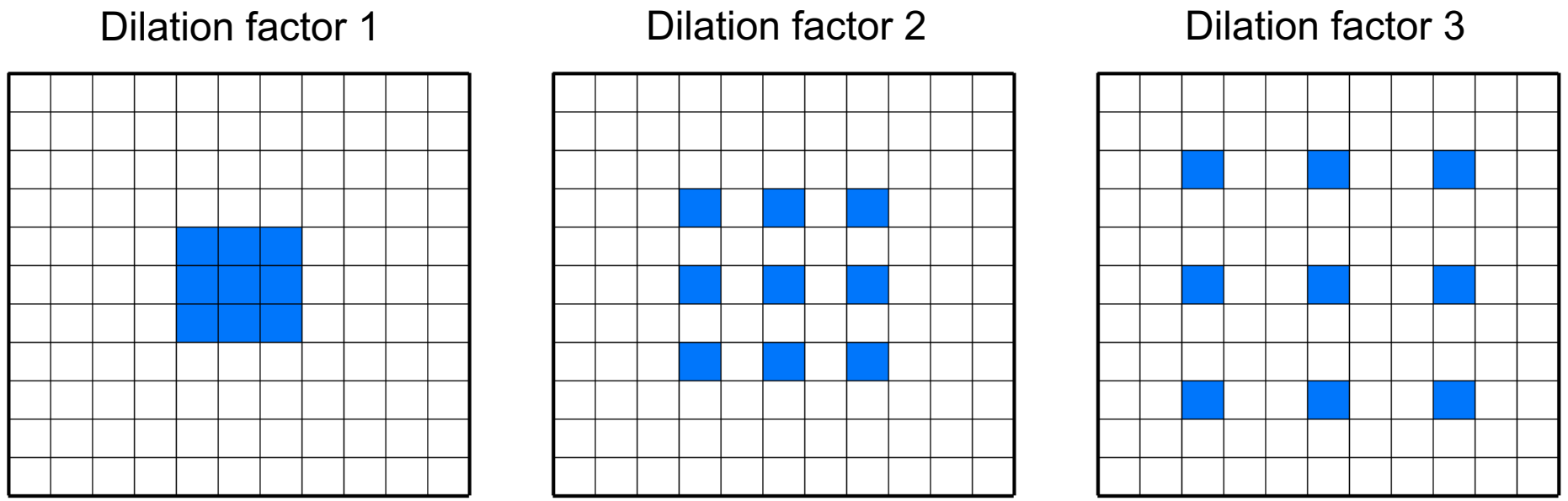
Hypercolumn and Skip Connection



Bansal et al. 2017

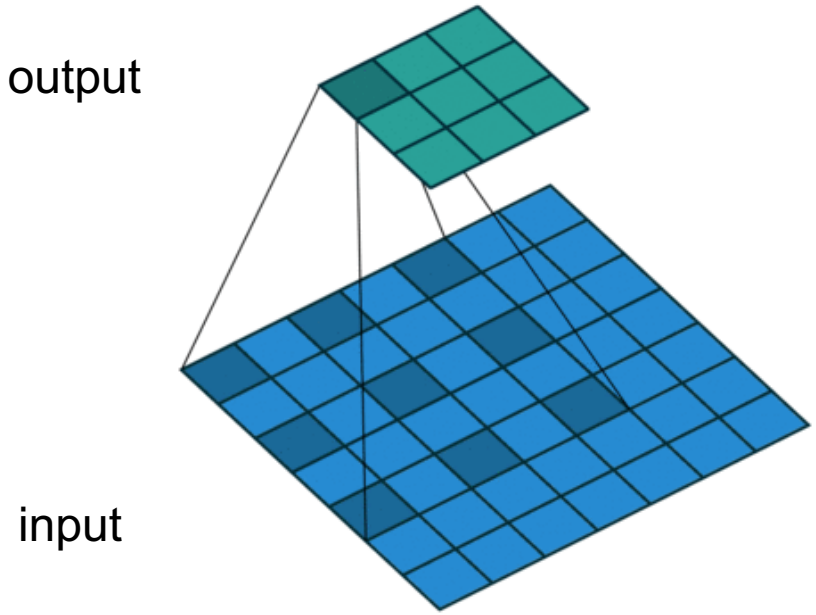
Dilated convolutions

- Idea: instead of reducing spatial resolution of feature maps, use a large sparse filter

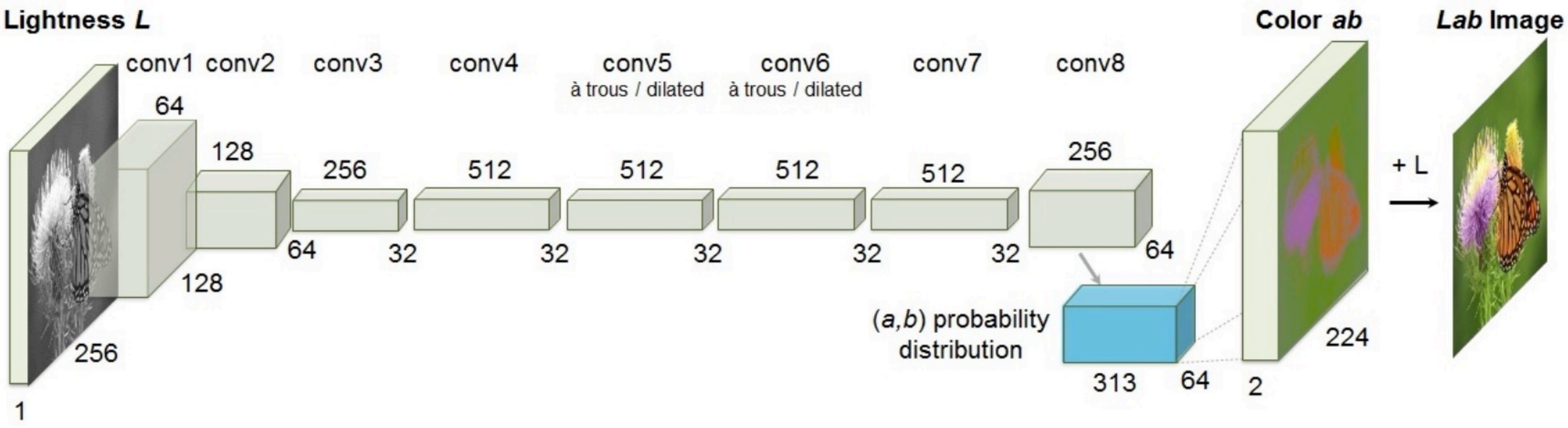


Dilated convolutions

- Increase the receptive field



Dilated convolutions



Zhang et al. 2016

This Class

- Naïve FCN model for Image Segmentation
- Transpose Convolution
- Advanced Techniques in Segmentation

Next Class

Visualizing Deep Networks