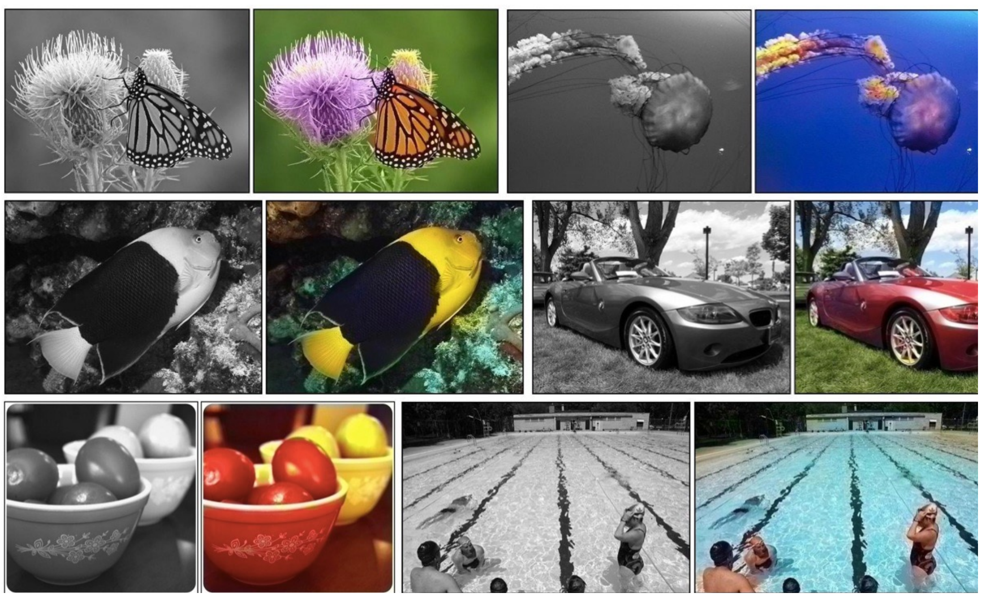
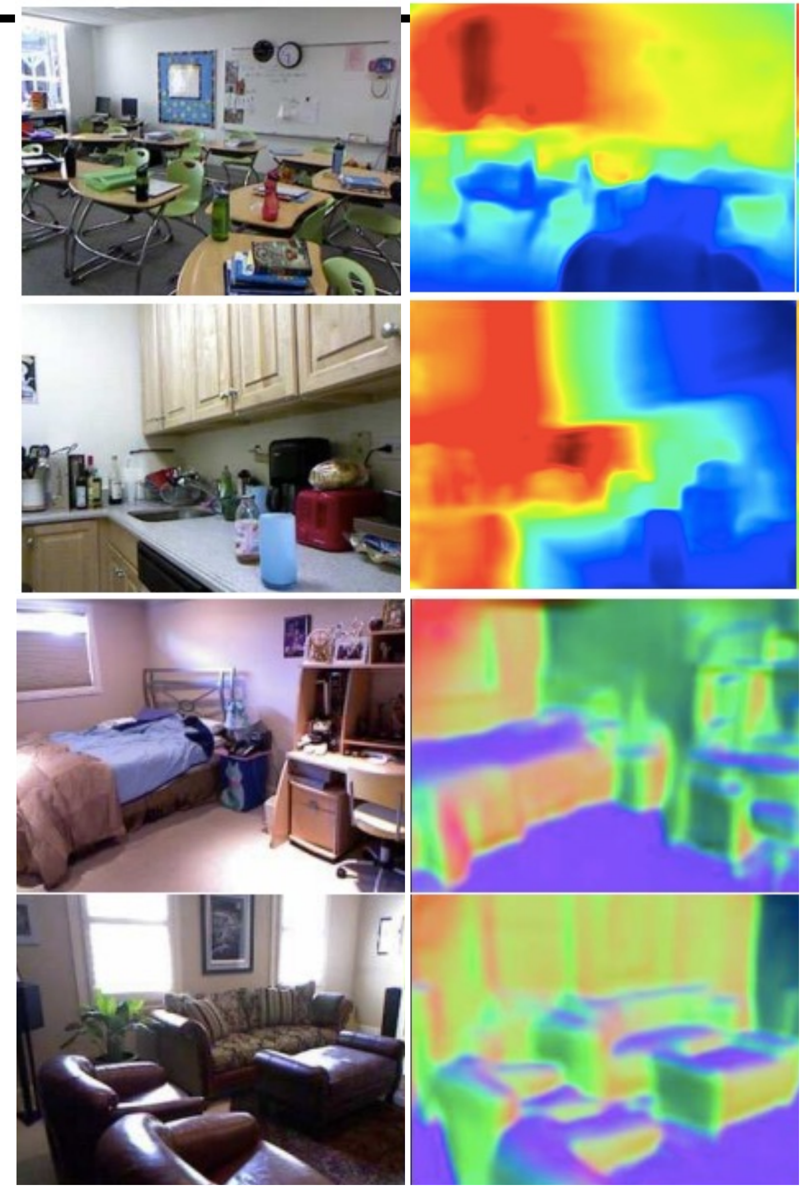
Pixel Prediction Tasks

Semantic segmentation



Colorization



Depth / Surface Normal Estimation

Many Slides from L. Lazebnik.

Outline

- Semantic segmentation
  - Metrics
  - Architectures
    - "Convolutionalization"
    - Dilated convolutions
    - Hyper-columns / skip-connections
    - Learned up-sampling architectures
- Other dense prediction problems

Semantic Segmentation: Metrics

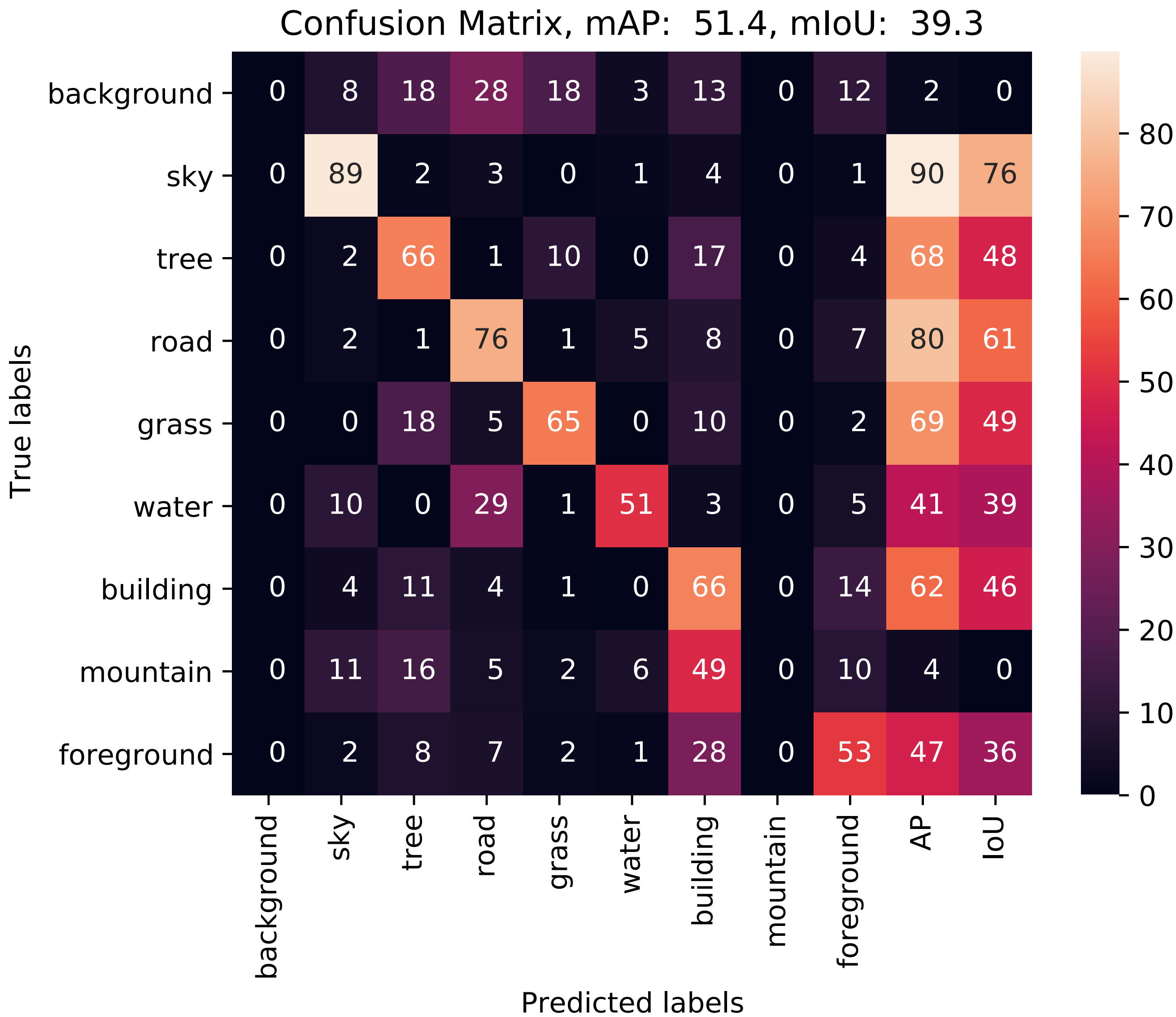
Image

Ground Truth

Prediction

- Pixel Classification Accuracy
- Intersection over Union
- Average Precision

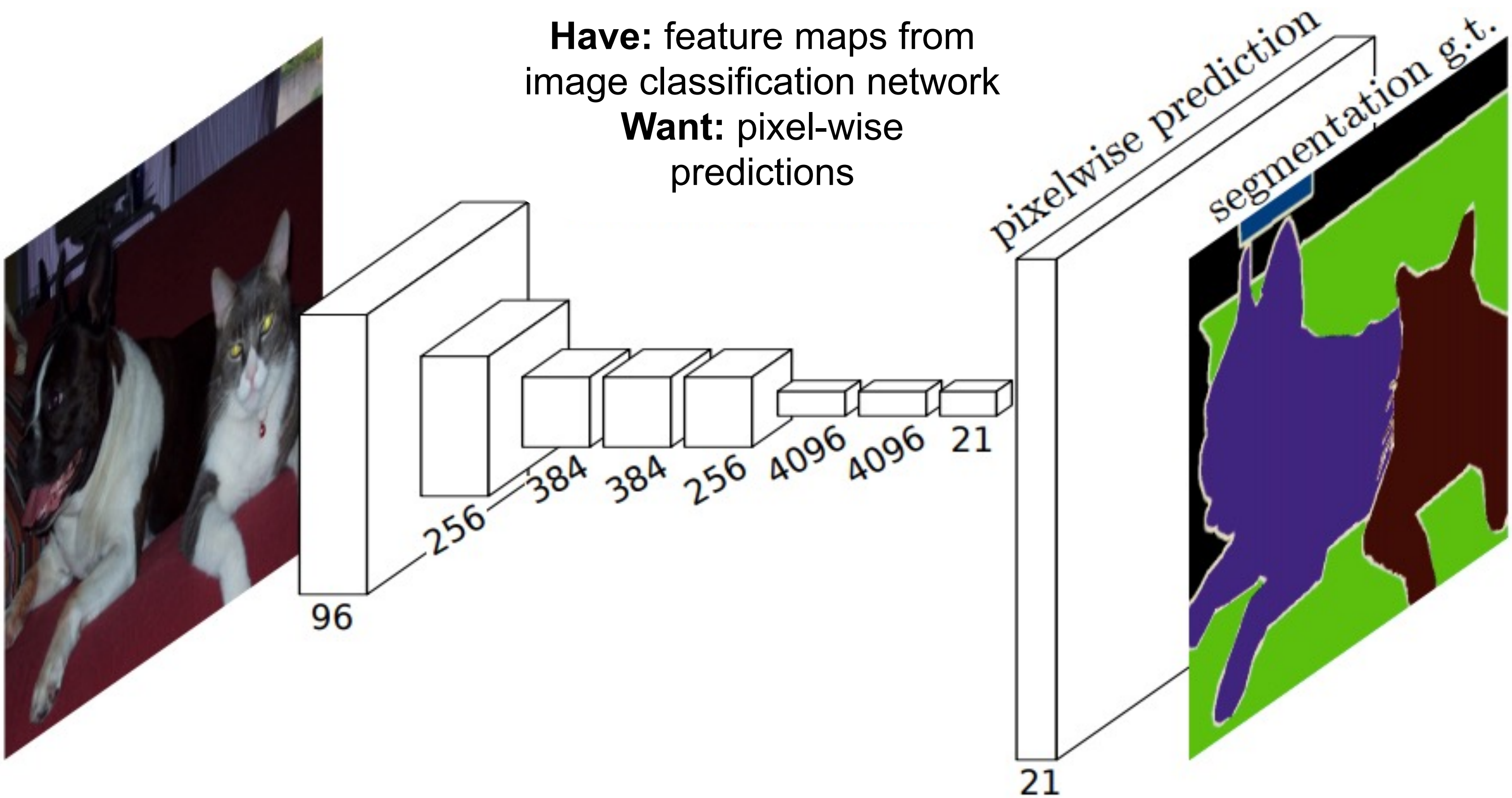
Semantic Segmentation: Metrics



Semantic Segmentation

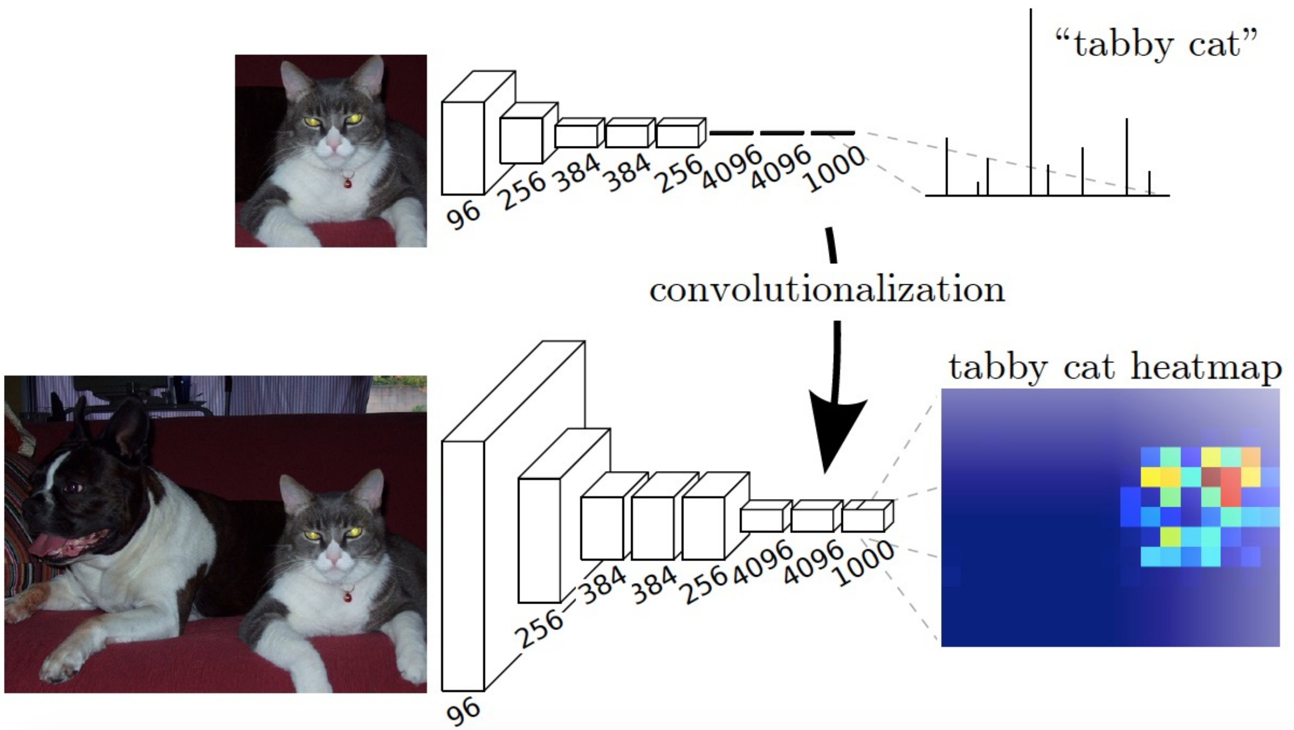
- Do dense prediction as a post-process on top of an image classification CNN

Have: feature maps from image classification network
Want: pixel-wise predictions



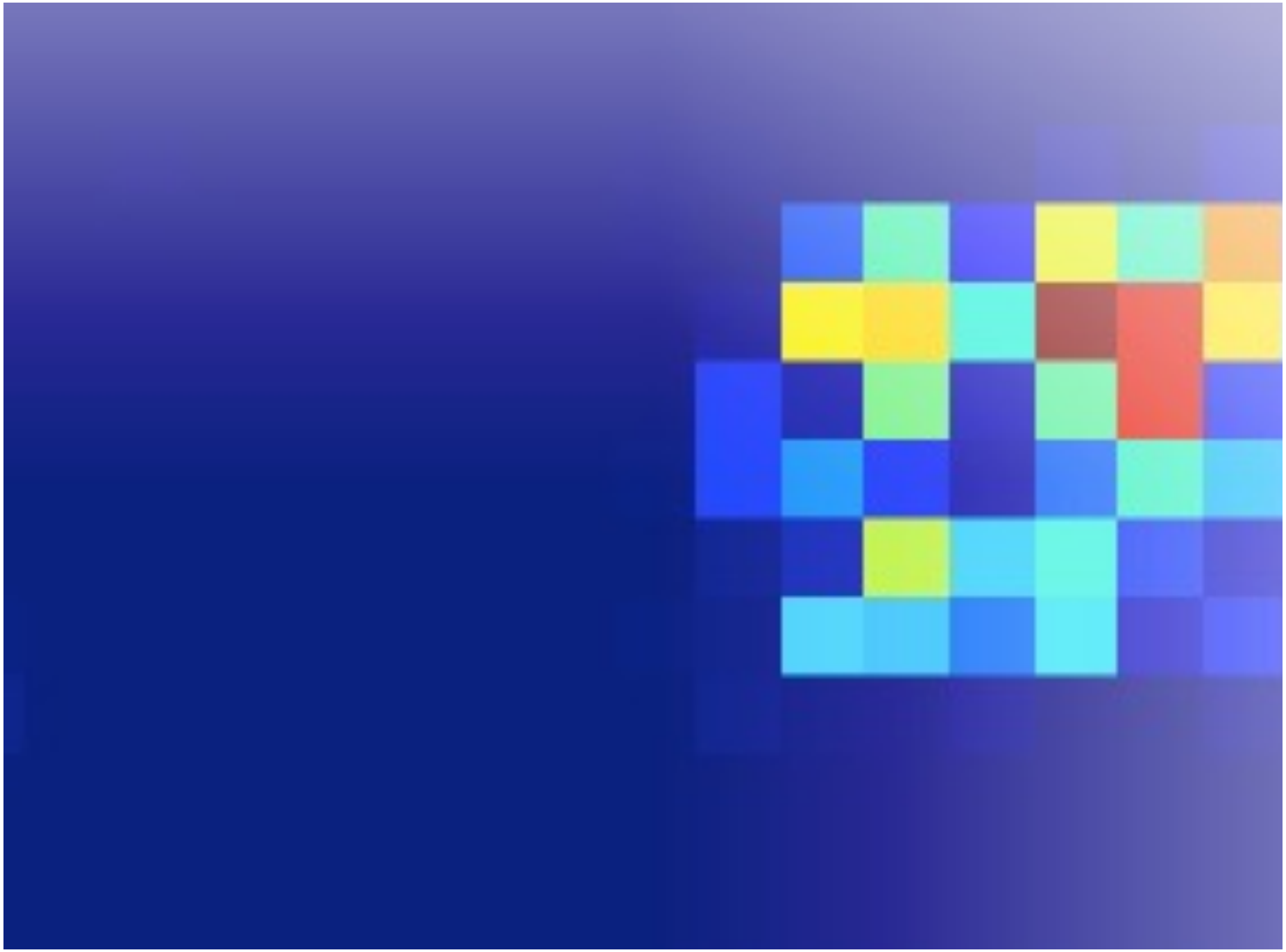
Convolutionalization

- Design a network with only convolutional layers, make predictions for all pixels at once



J. Long, E. Shelhamer, and T. Darrell, [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

Sparse, Low-resolution Output

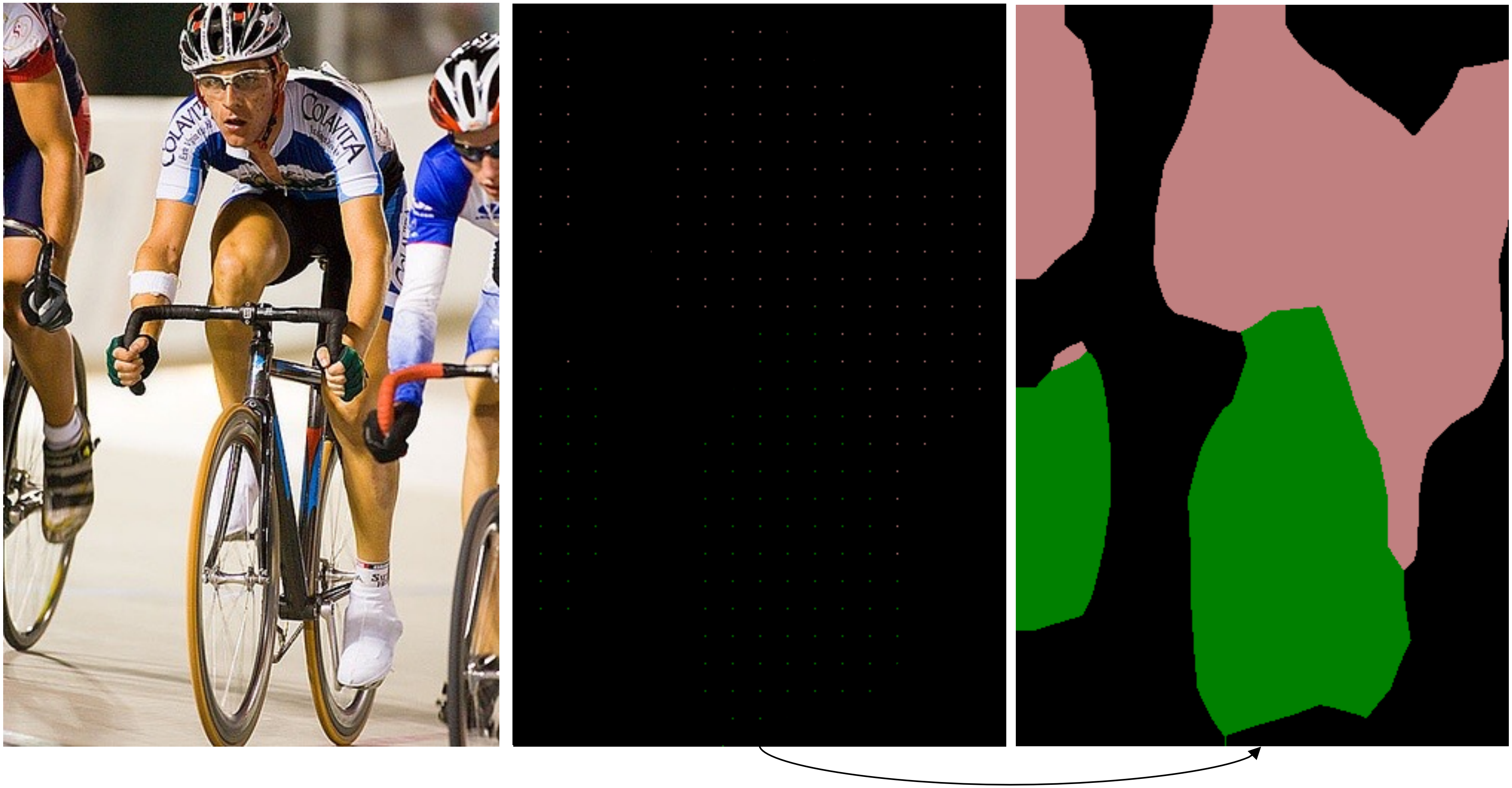


J. Long, E. Shelhamer, and T. Darrell, [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

Aside: Receptive Field, Stride

- Receptive Field: Pixels in the image that are "connected" to a given unit.
- Stride: Shift in receptive field between consecutive units in a convolutional feature map.
- See: https://distill.pub/2019/computing-receptive-fields/

Sparse, Low-resolution Output

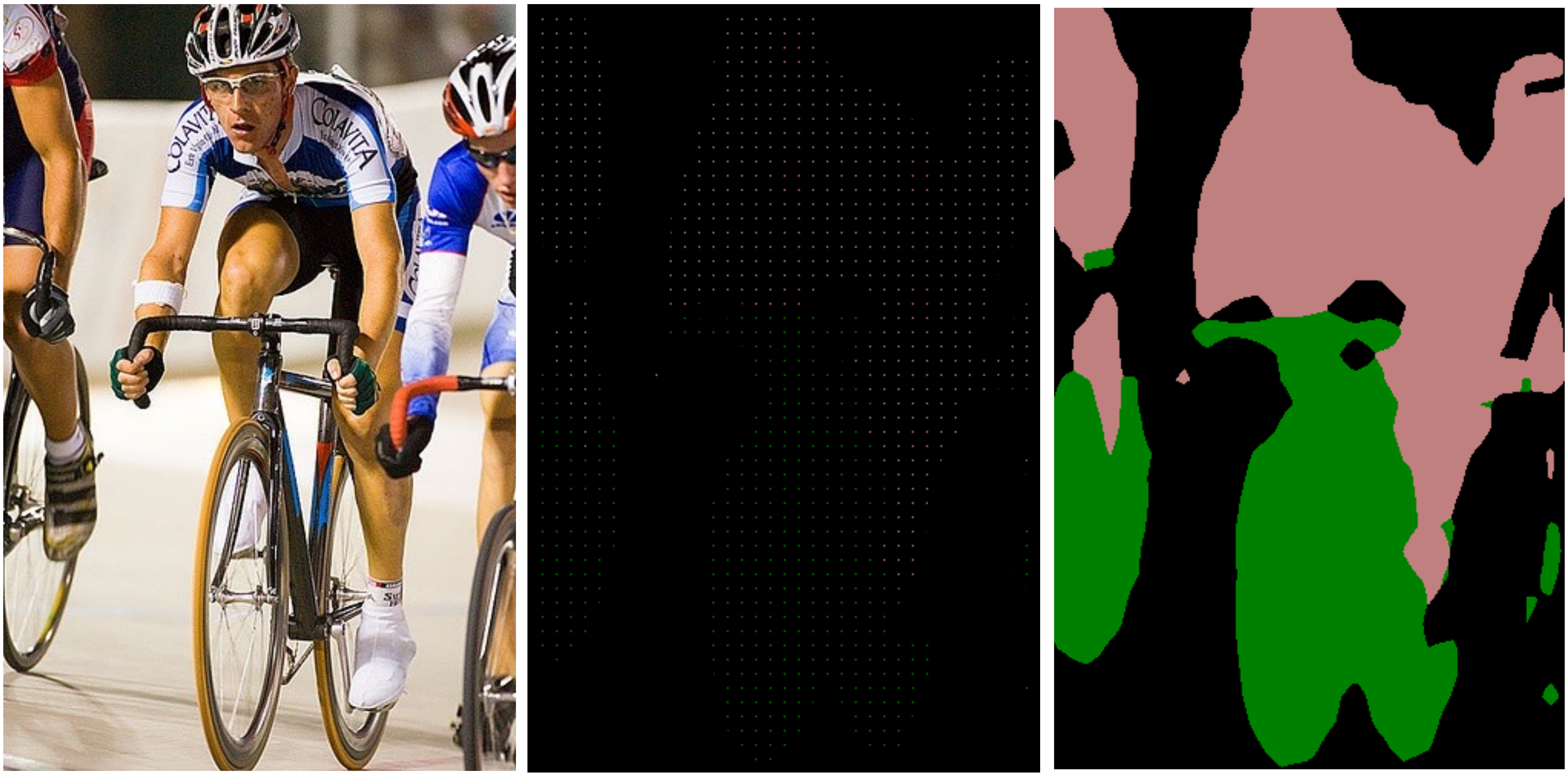


Bilinear Up sampling: Differentiable,
train through up-sampling.

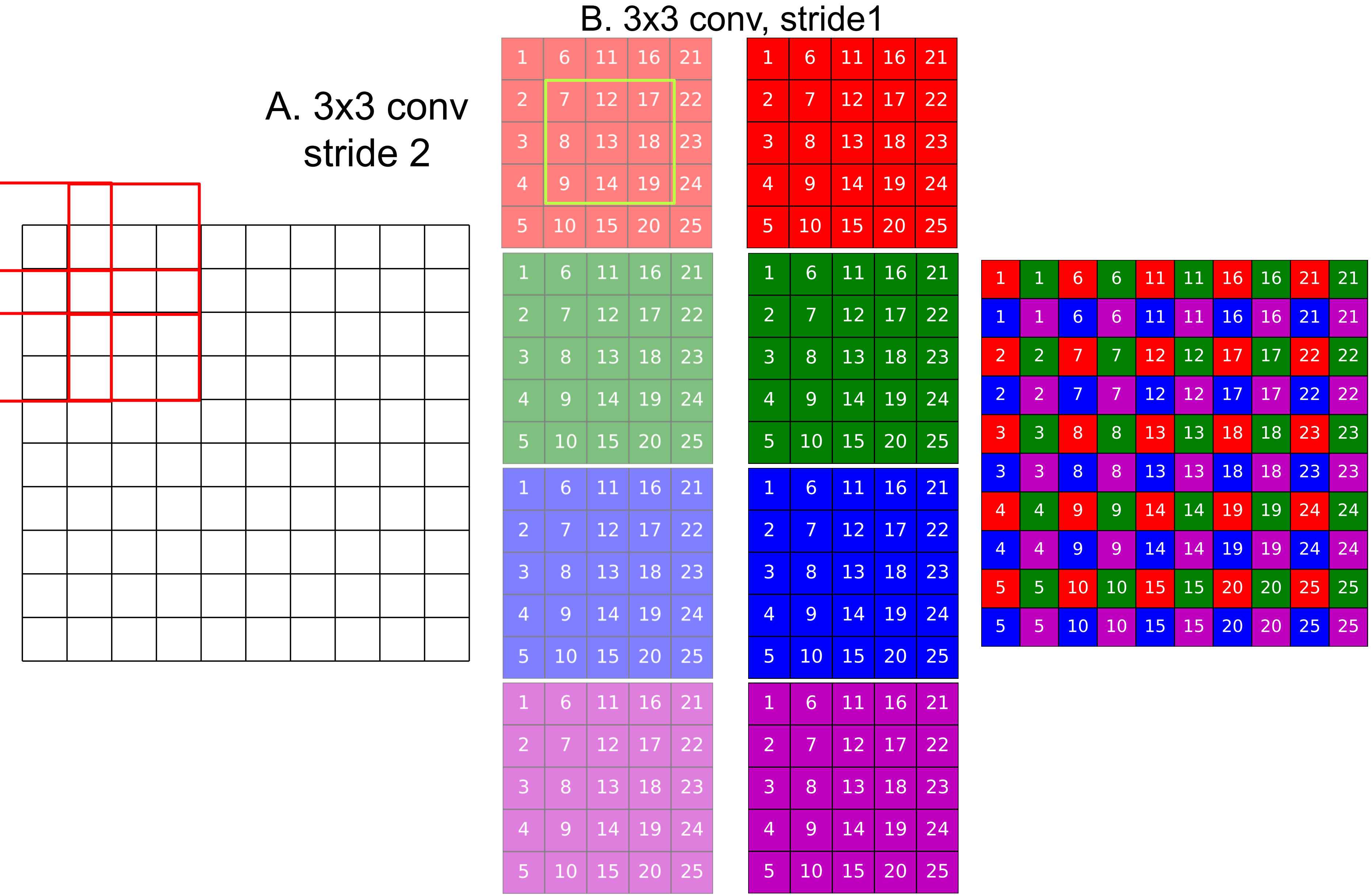
J. Long, et al., [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

Fix 1: Shift and Stitch

- Shift the image, and re-run CNN to get denser output.



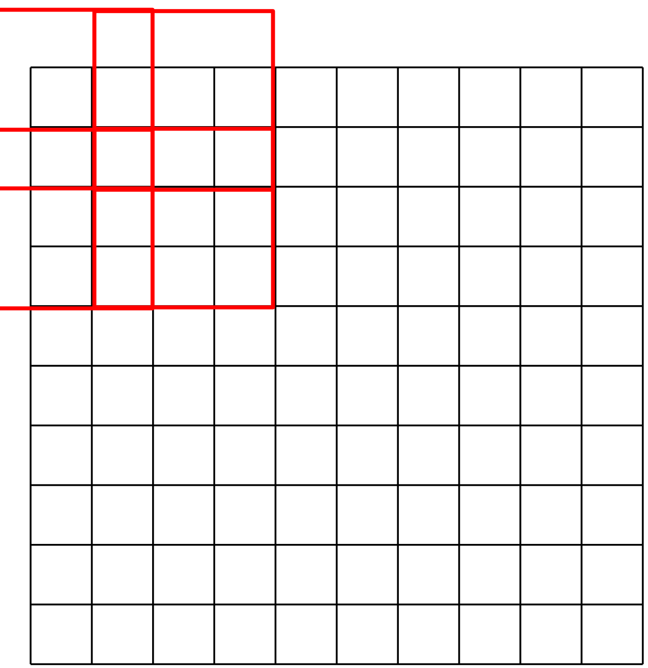
Fix 1: A trous Conv., Dilated Conv.

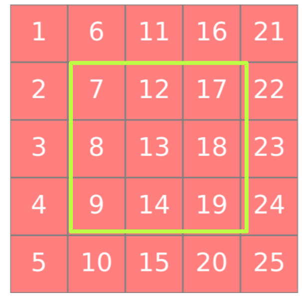


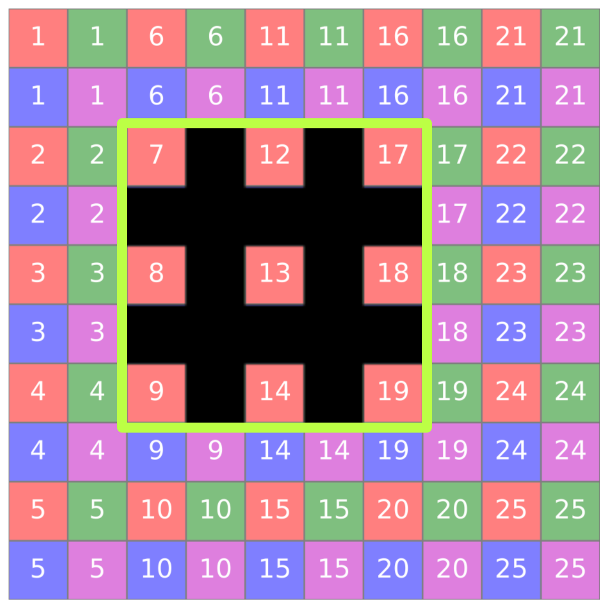
Fix 1: A trous Conv., Dilated Conv.

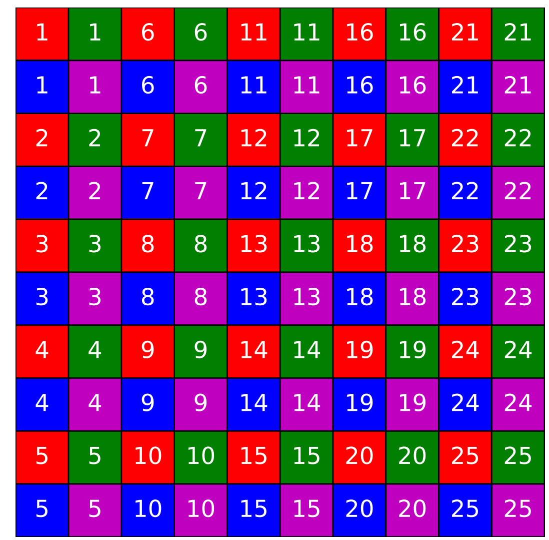
B. 3x3 conv, stride1,
dilation 2

A. 3x3 conv
stride **1**

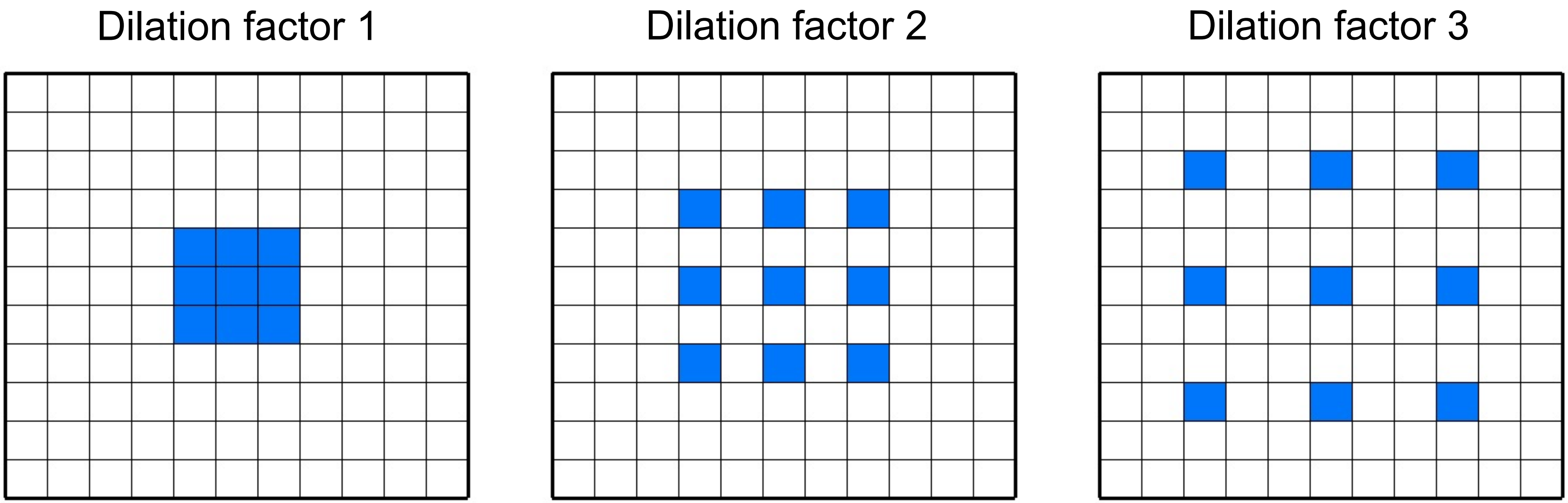








Fix 1: A trous Conv., Dilated Conv.



[Image source](#)

Fix 1: A trous Conv., Dilated Conv.

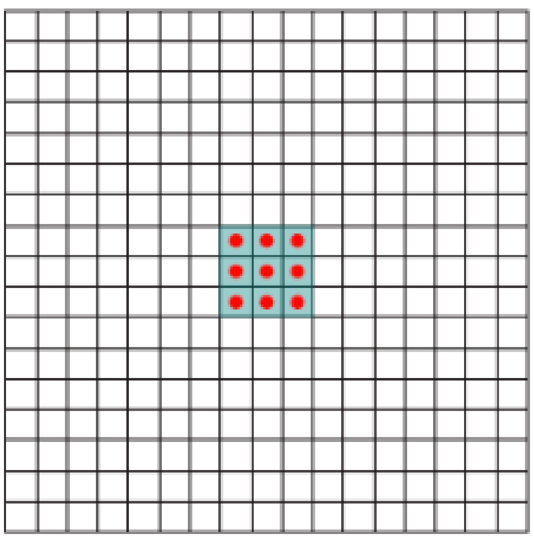
- Use in FCN to remove downsampling: change stride of max pooling layer from 2 to 1, dilate subsequent convolutions by factor of 2 (possibly without re-training any parameters)
- Instead of reducing spatial resolution of feature maps, use a large sparse filter

L. Chen, G. Papandreou, I. Kokkinos, K. Murphy, A. Yuille, [DeepLab: Semantic Image Segmentation with Deep Convolutional Nets, Atrous Convolution, and Fully Connected CRFs](), PAMI 2017

Fix 1: A trous Conv., Dilated Conv.

- Can increase receptive field size exponentially with a linear growth in the number of parameters

Feature map 1 (F1) produced from F0 by 1-dilated convolution



Receptive field: 3x3

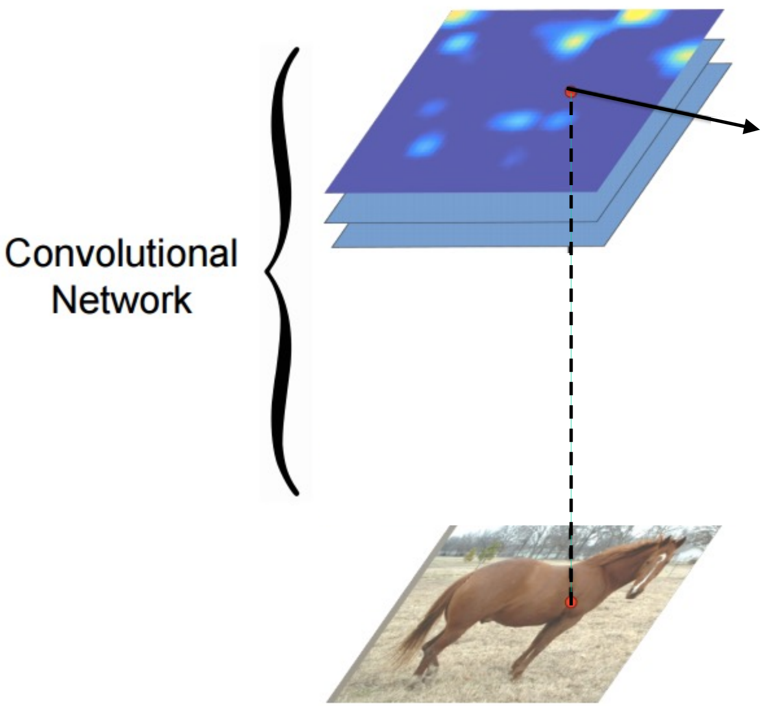
Receptive field: 7x7

Receptive field: 15x15

F. Yu and V. Koltun, [Multi-scale context aggregation by dilated convolutions](), ICLR 2016

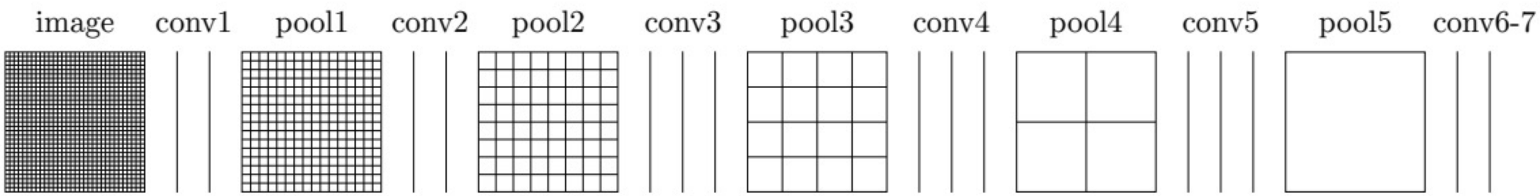
Fix 2: Hyper-columns/Skip Connections

- Even though with dilation we can predict each pixel, fine-grained information needs to be propagated through the network.
- Idea: Additionally use features from within the network.



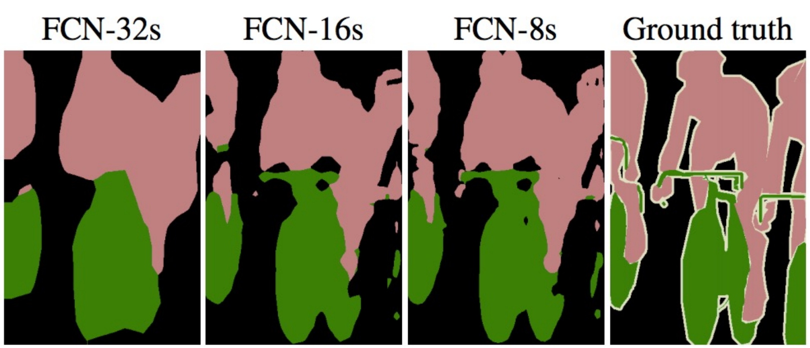
B. Hariharan, P. Arbelaez, R. Girshick, and J. Malik, Hypercolumns for Object Segmentation and Fine-grained Localization, CVPR 2015
J. Long, et al., Fully Convolutional Networks for Semantic Segmentation, CVPR 2015

Fix 2: Hyper-columns/Skip Connections



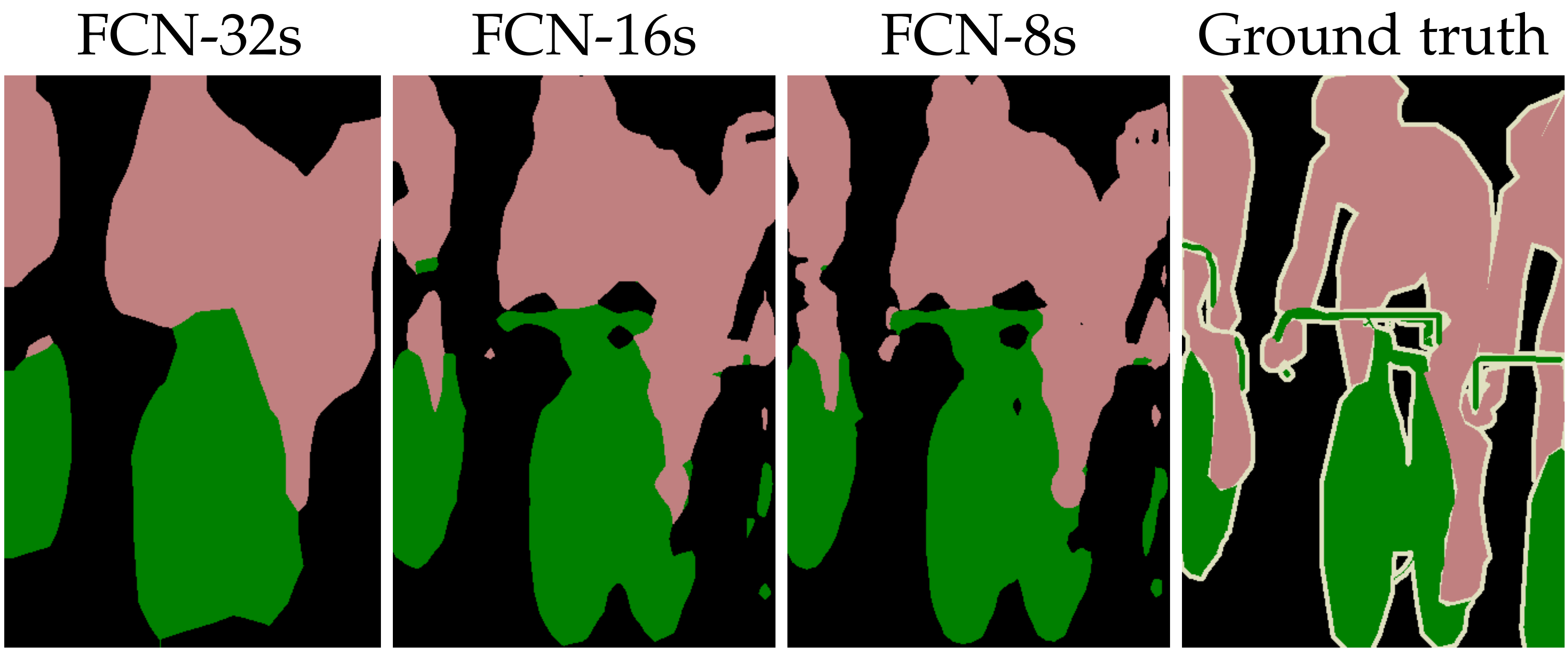
- Predictions by 1x1 conv layers, bilinear upsampling

- Predictions by 1x1 conv layers, learned 2x upsampling, fusion by summing



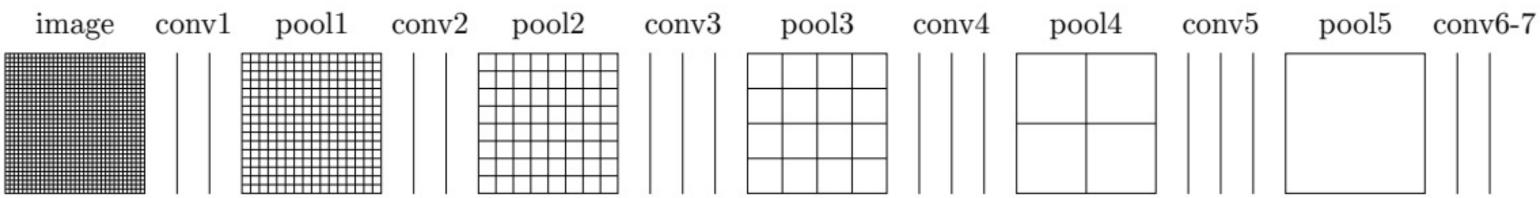
J. Long, E. Shelhamer, and T. Darrell, [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

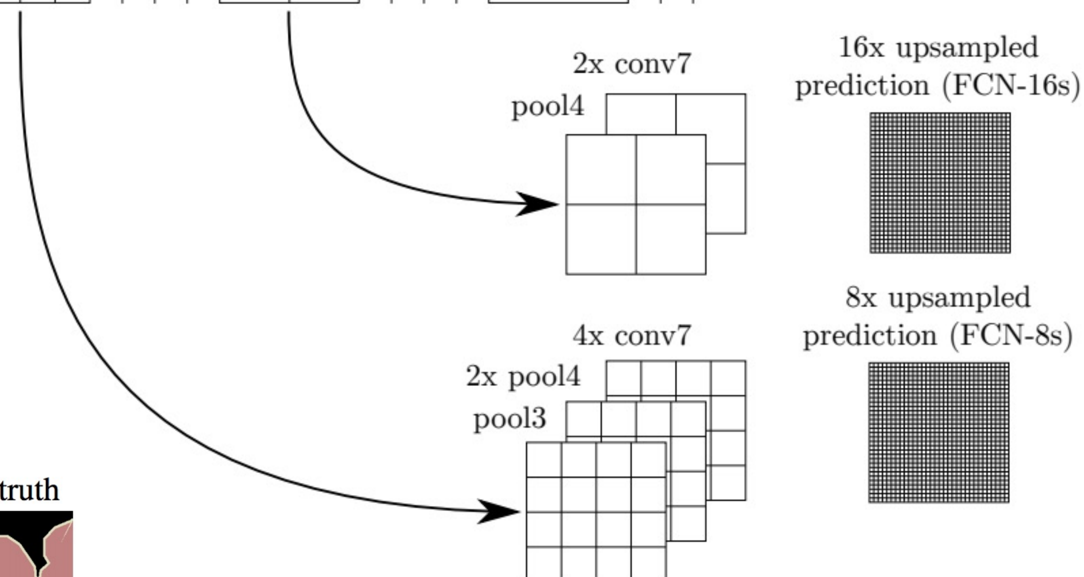
Fix 2: Hyper-columns/Skip Connections



J. Long, et al., [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

Fix 2b: Learned Upsampling





- Predictions by 1x1 conv layers, bilinear upsampling

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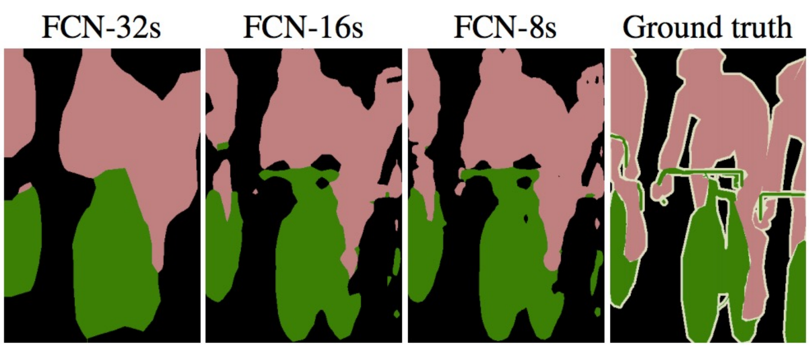
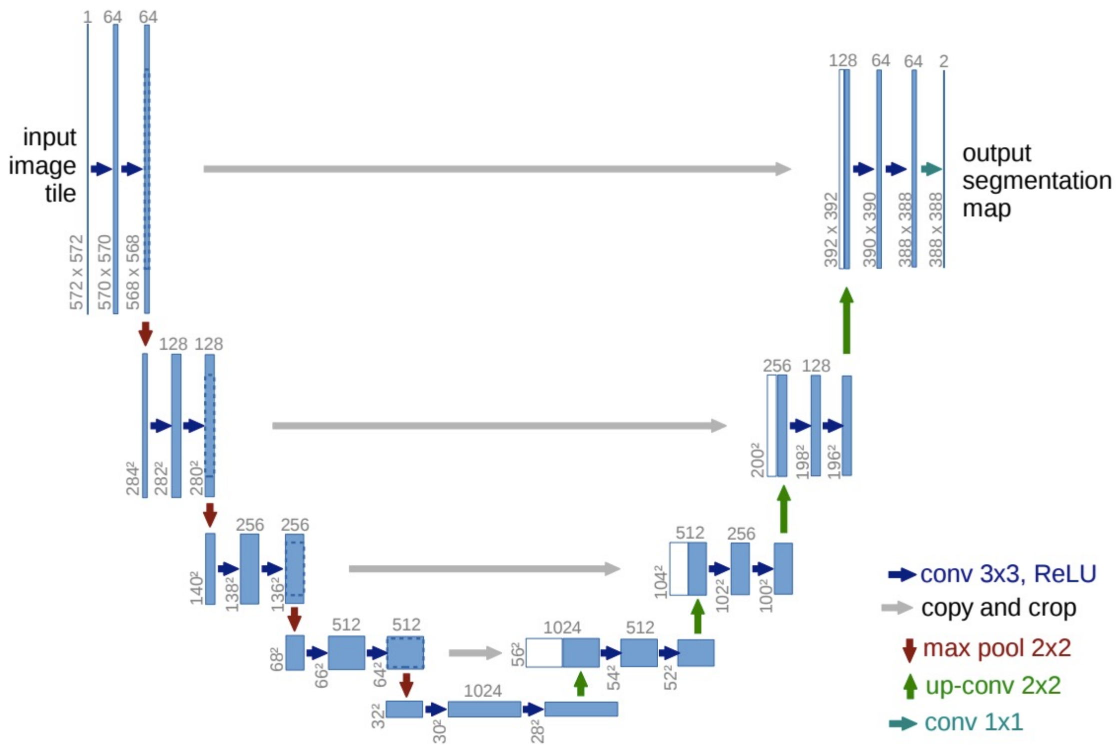


J. Long, E. Shelhamer, and T. Darrell, [Fully Convolutional Networks for Semantic Segmentation](), CVPR 2015

U-Net

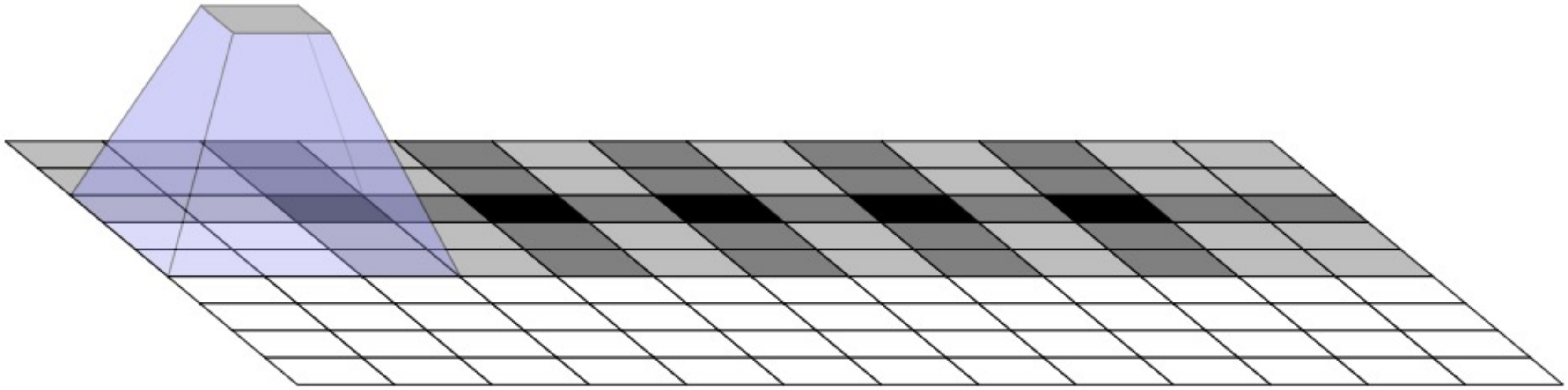
- Like FCN, fuse upsampled higher-level feature maps with higher-res, lower-level feature maps
- Unlike FCN, fuse by concatenation, predict at the end



O. Ronneberger, P. Fischer, T. Brox [U-Net: Convolutional Networks for Biomedical Image Segmentation](), MICCAI 2015

Up-convolution

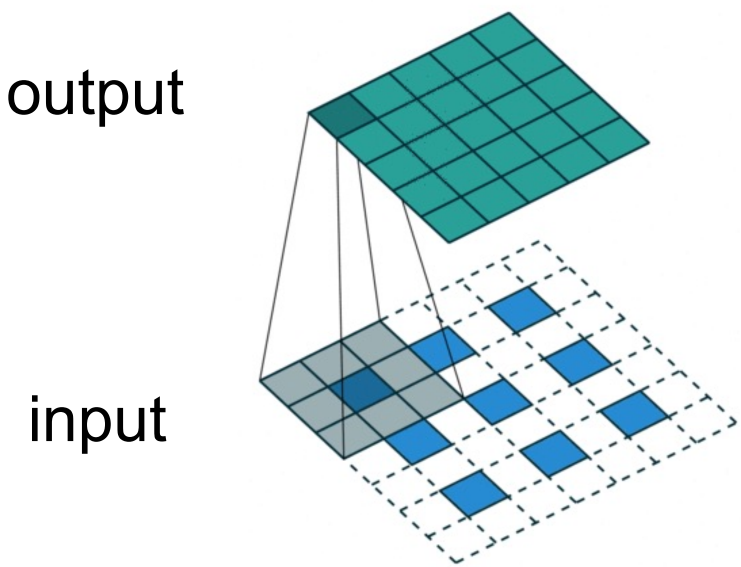
- "Paint" in the output feature map with the learned filter
  - Multiply input value by filter, place result in the output, sum overlapping values



Animation: https://distill.pub/2016/deconv-checkerboard/

Up-convolution: Alternate view

- 2D case: for stride 2, dilate the input by inserting rows and columns of zeros between adjacent entries, convolve with flipped filter
- Sometimes called convolution with *fractional input stride* 1/2



Q: What 3x3 filter would correspond to bilinear upsampling?

$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$
$\frac{1}{2}$	1	$\frac{1}{2}$
$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$

V. Dumoulin and F. Visin, [A guide to convolution arithmetic for deep learning](), arXiv 2018

Summary of upsampling architectures

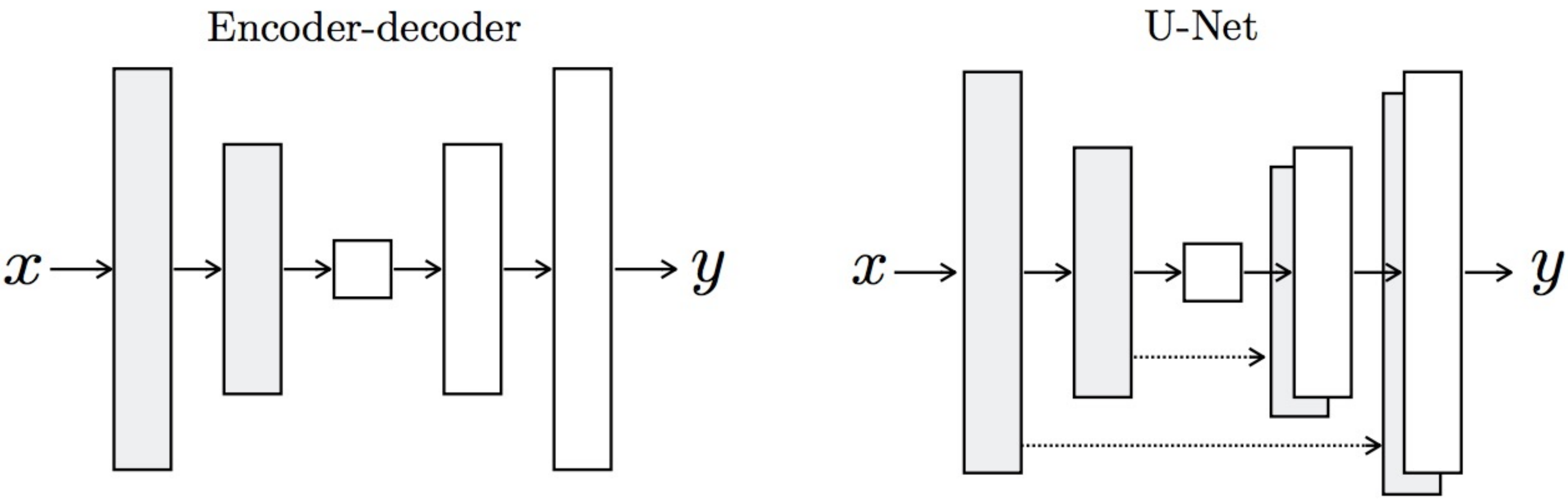
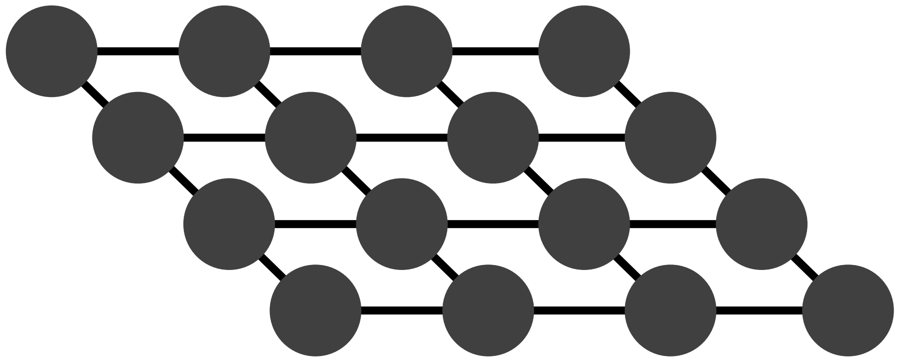


Figure source

Fix 3: Use local edge information (CRFs)



$$P(\mathbf{y}|\mathbf{x}) = \frac{1}{Z} e^{-E(\mathbf{y},\mathbf{x})}$$

$$\mathbf{y}^* = \arg\max_{\mathbf{y}} P(\mathbf{y}|\mathbf{x})$$

$$= \arg\min_{\mathbf{y}} E(\mathbf{y},\mathbf{x})$$

$$E(\mathbf{y},\mathbf{x}) = \sum_i E_{data}(y_i,\mathbf{x}) + \sum_{i,j\in\mathcal{N}} E_{smooth}(y_i,y_j,\mathbf{x})$$

Source: B. Hariharan

Fix 3: Use local edge information (CRFs)

Idea: take convolutional network prediction and sharpen using classic techniques

Conditional Random Field

$$\mathbf{y}^* = \arg\min_{\mathbf{y}} \sum_i E_{data}(y_i, \mathbf{x}) + \sum_{i,j \in \mathcal{N}} E_{smooth}(y_i, y_j, \mathbf{x})$$

$$E_{smooth}(y_i, y_j, \mathbf{x}) = \underbrace{\mu(y_i, y_j)}_{\text{Label compatibility}} \underbrace{w_{ij}(\mathbf{x})}_{\text{Pixel similarity}}$$

Label compatibility **Pixel similarity**

Source: B. Hariharan

Fix 3: Use local edge information (CRFs)

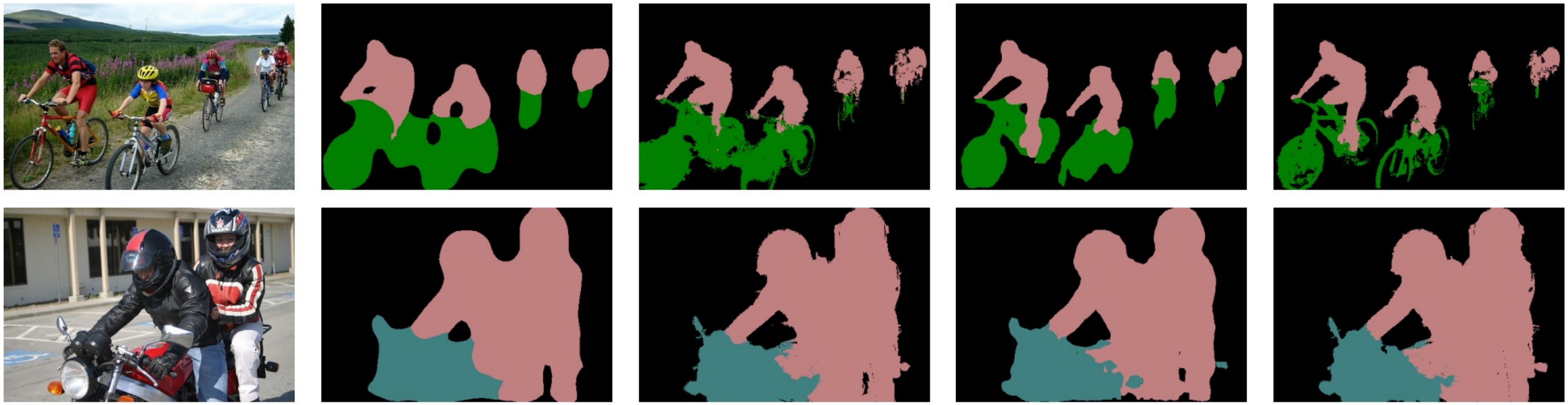
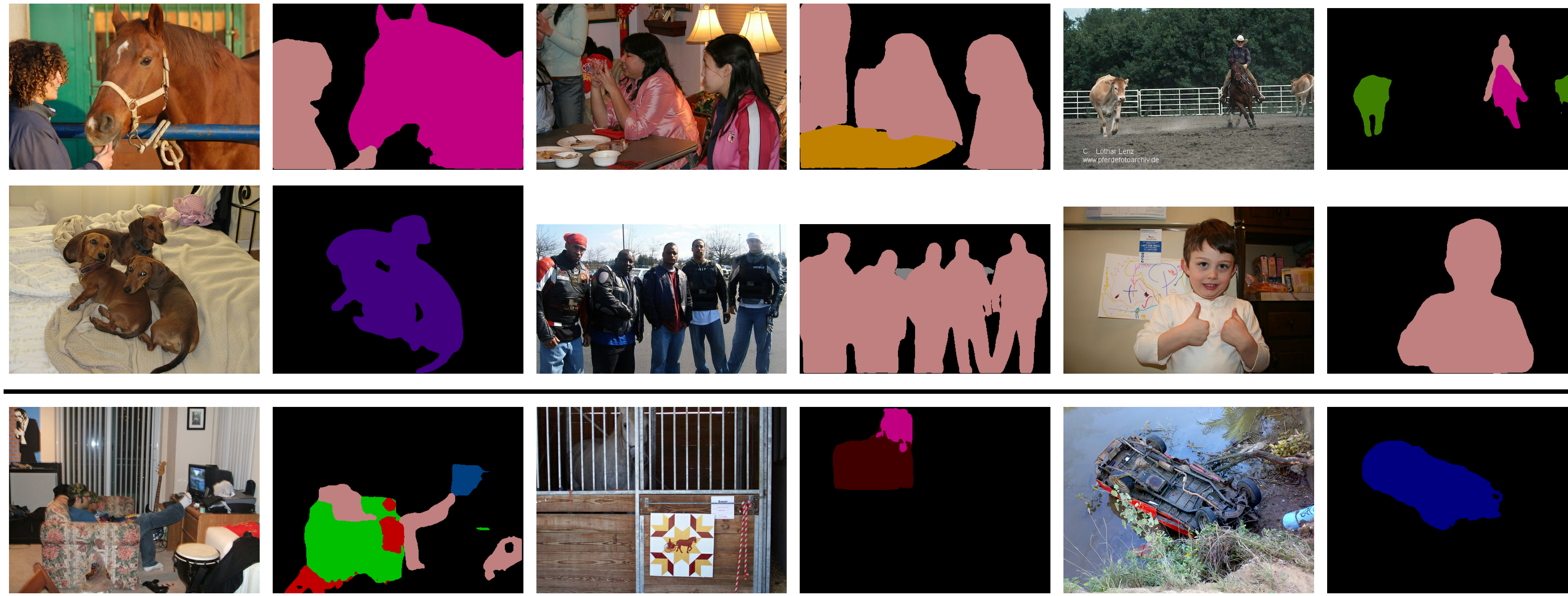


Image VGG-16 Bef. VGG-16 Aft. ResNet Bef. ResNet Aft.

Source: B. Hariharan

Semantic Segmentation Results



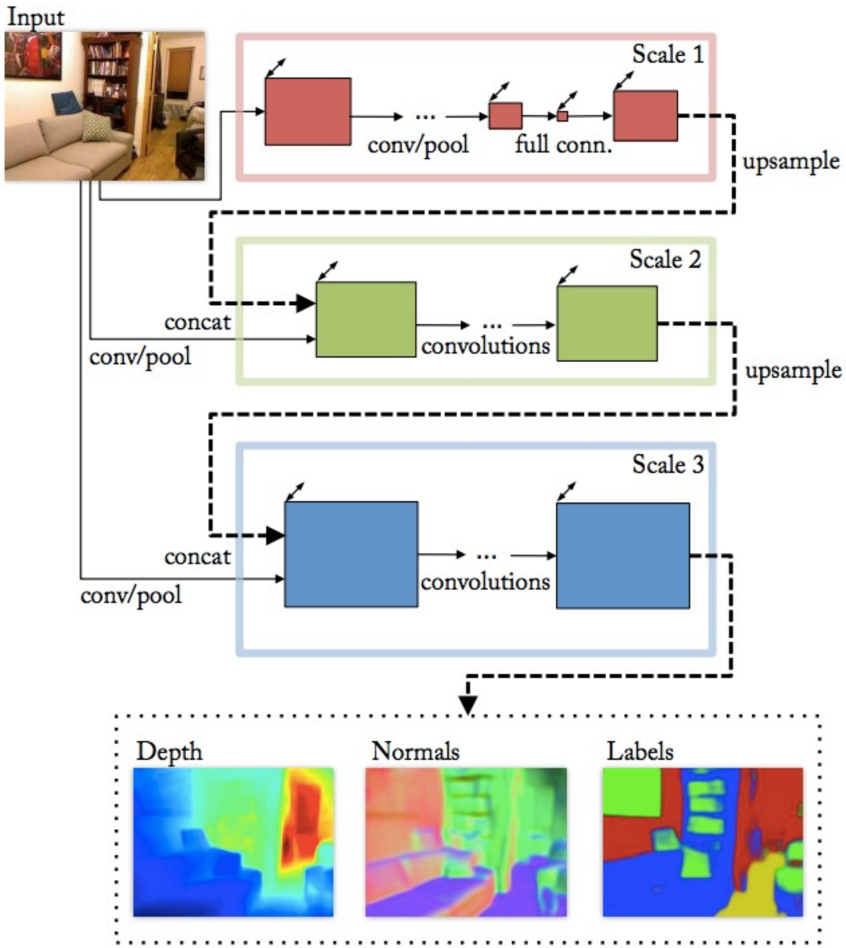
Method	mIOU
Deep Layer Cascade (LC) [82]	82.7
TuSimple [77]	83.1
Large_Kernel_Matters [60]	83.6
Multipath-RefineNet [58]	84.2
ResNet-38_MS_COCO [83]	84.9
PSPNet [24]	85.4
IDW-CNN [84]	86.3
CASIA_IVA_SDN [63]	86.6
DIS [85]	86.8
DeepLabv3 [23]	85.7
DeepLabv3-JFT [23]	86.9
DeepLabv3+ (Xception)	87.8
DeepLabv3+ (Xception-JFT)	89.0

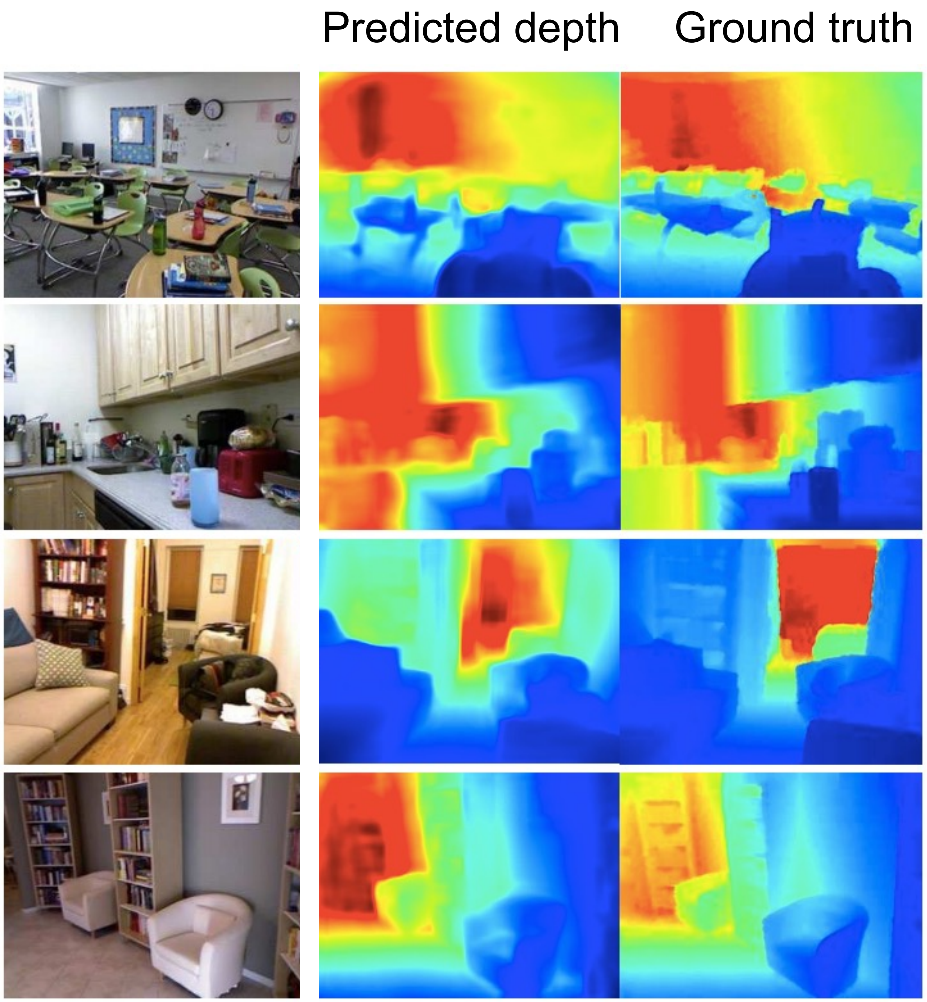
Liang-Chieh Chen, Yukun Zhu, George Papandreou, Florian Schroff, Hartwig Adam, [DeepLabv3+: Encoder-Decoder with Atrous Separable Convolution](), ECCV 2018

Other dense prediction tasks

- Depth estimation
- Surface normal estimation
- Colorization
- ….

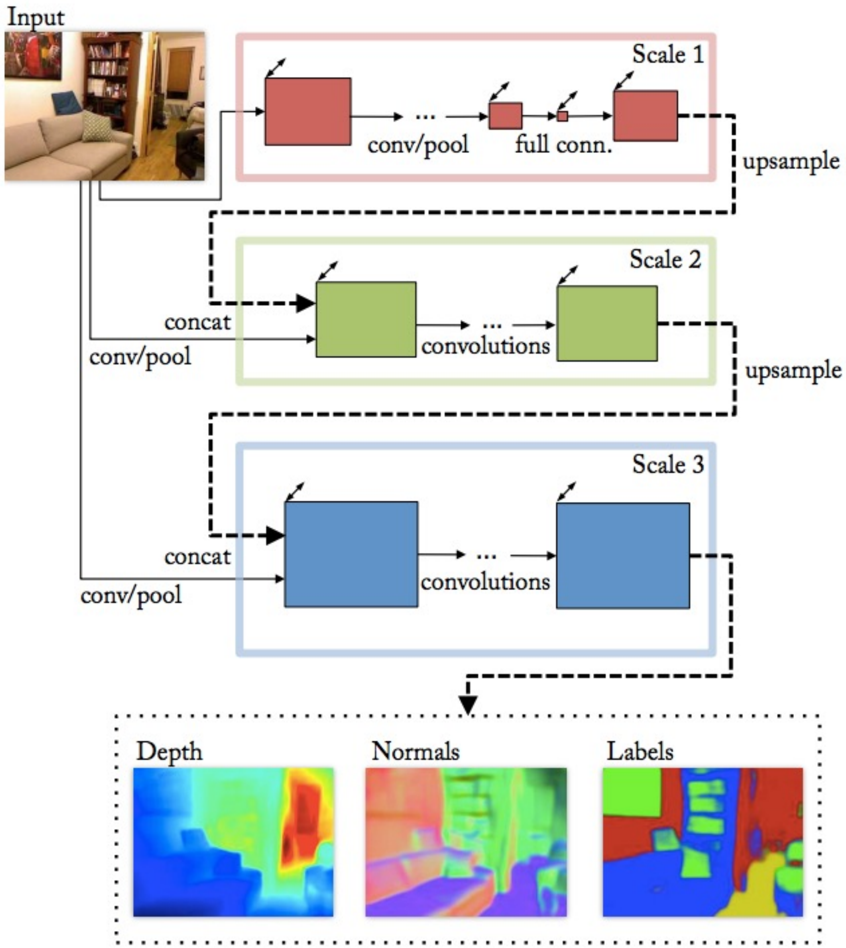
Depth and normal estimation





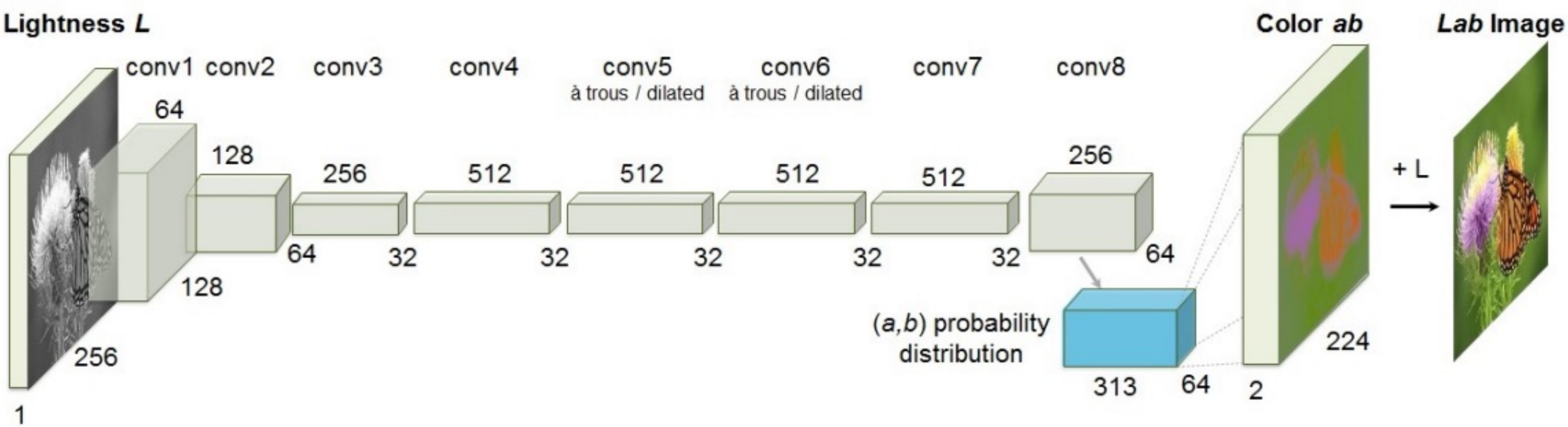
D. Eigen and R. Fergus, [Predicting Depth, Surface Normals and Semantic Labels with a Common Multi-Scale Convolutional Architecture](), ICCV 2015

Depth and normal estimation



D. Eigen and R. Fergus, [Predicting Depth, Surface Normals and Semantic Labels with a Common Multi-Scale Convolutional Architecture](), ICCV 2015

Colorization



R. Zhang, P. Isola, and A. Efros, [Colorful Image Colorization](), ECCV 2016