Deep Learning for Images: Convolutional Neural Networks

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Review: Neural networks as feature learners

Input x

Classifier 1:
Is front clear?

Classifier 2:
Is left clear?

Classifier 3:
Is right clear?

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

Classifier 4:
Where to go?

Output y
Turn left

Learn to classify based on features
(same as linear model)

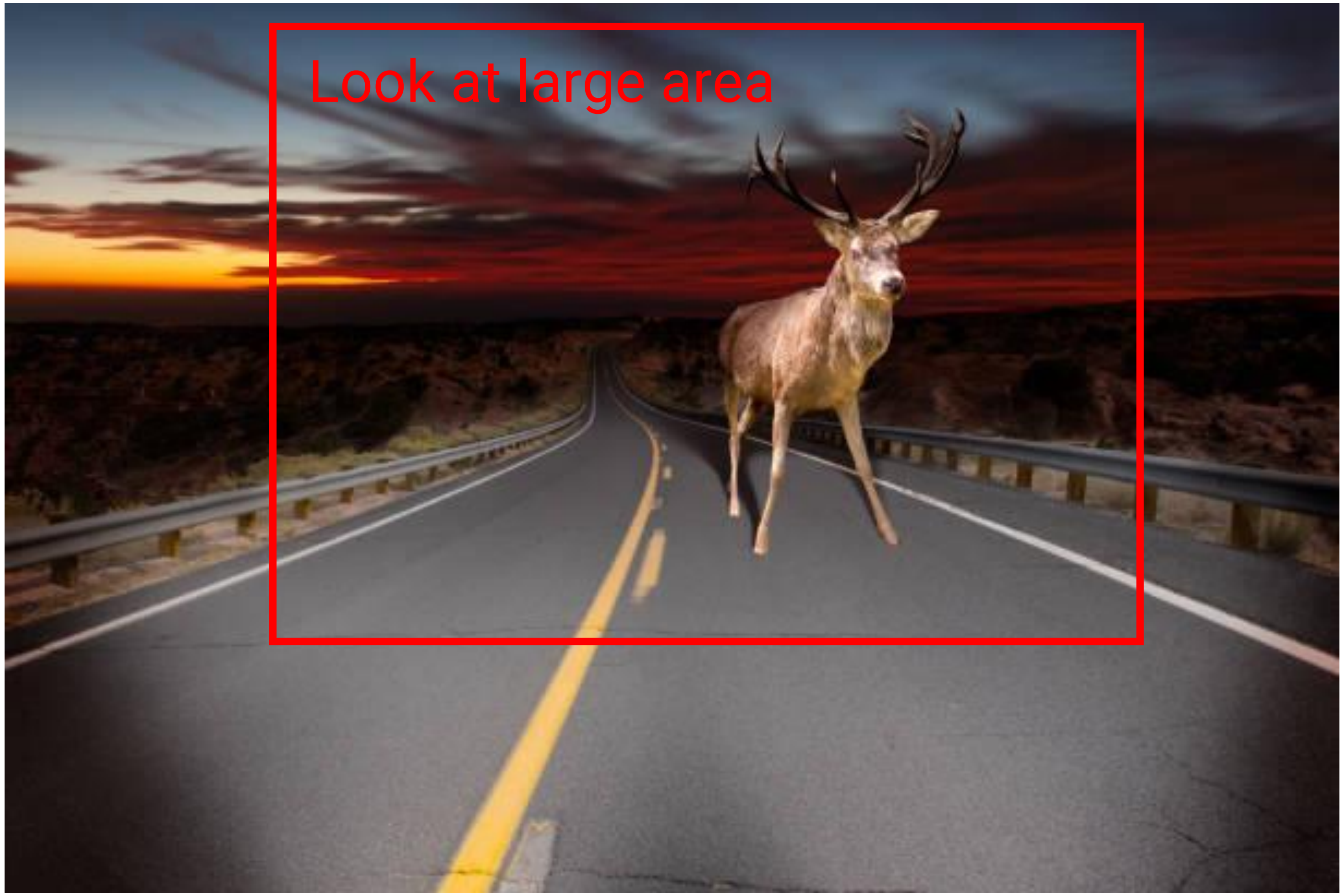
Learn a classifier whose output is a good feature
We don't tell the model what classifier to learn
Model must learn that "is front clear" is a useful concept

A hierarchy of features

- Turn left?

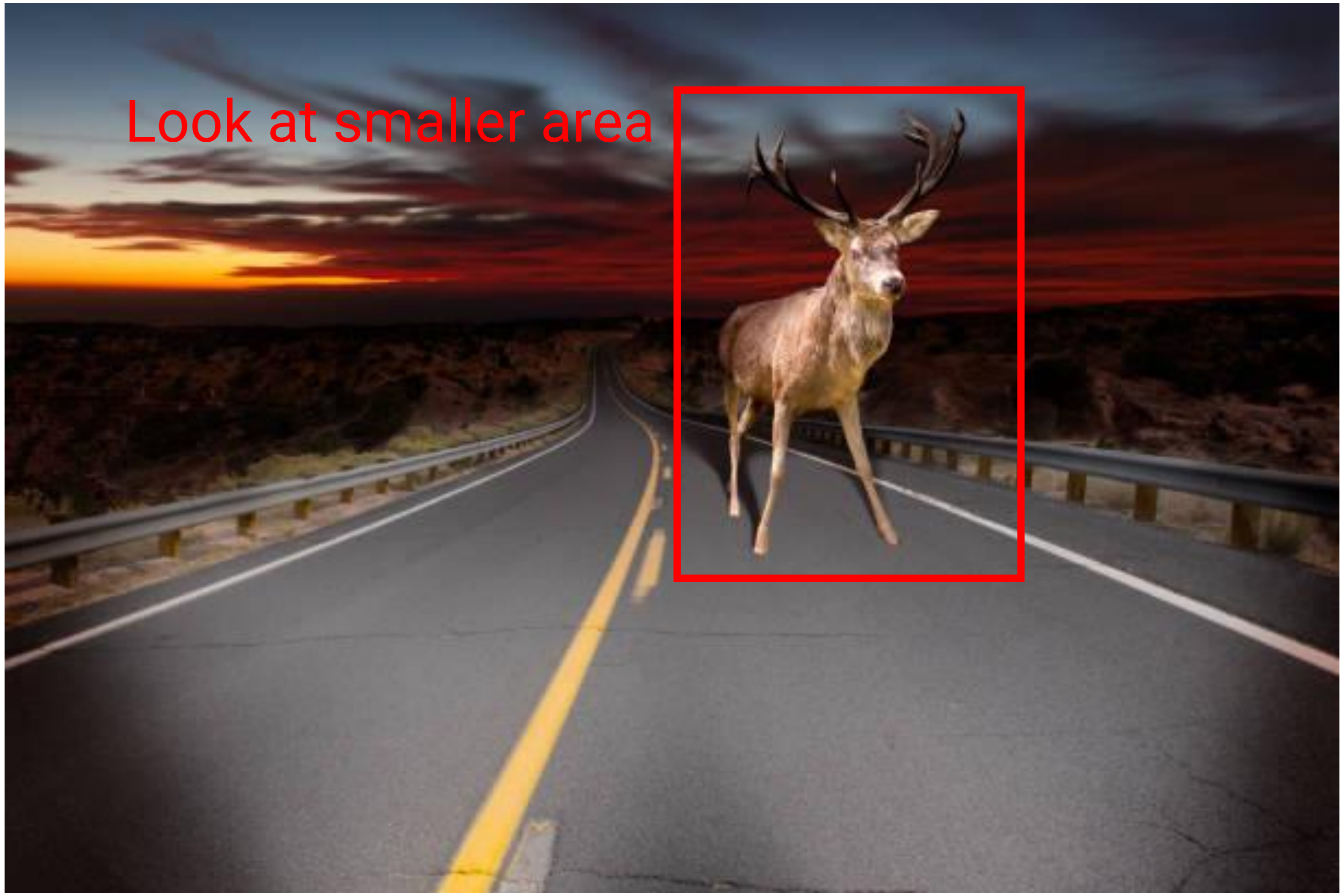
A hierarchy of features

- Turn left?
- **Front is clear?**



A hierarchy of features

- Turn left?
- Front is clear?
- **Is object a moose?**



A hierarchy of features

- Turn left?
- Front is clear?
- Is object a moose?
- **Is this a head?**

A hierarchy of features

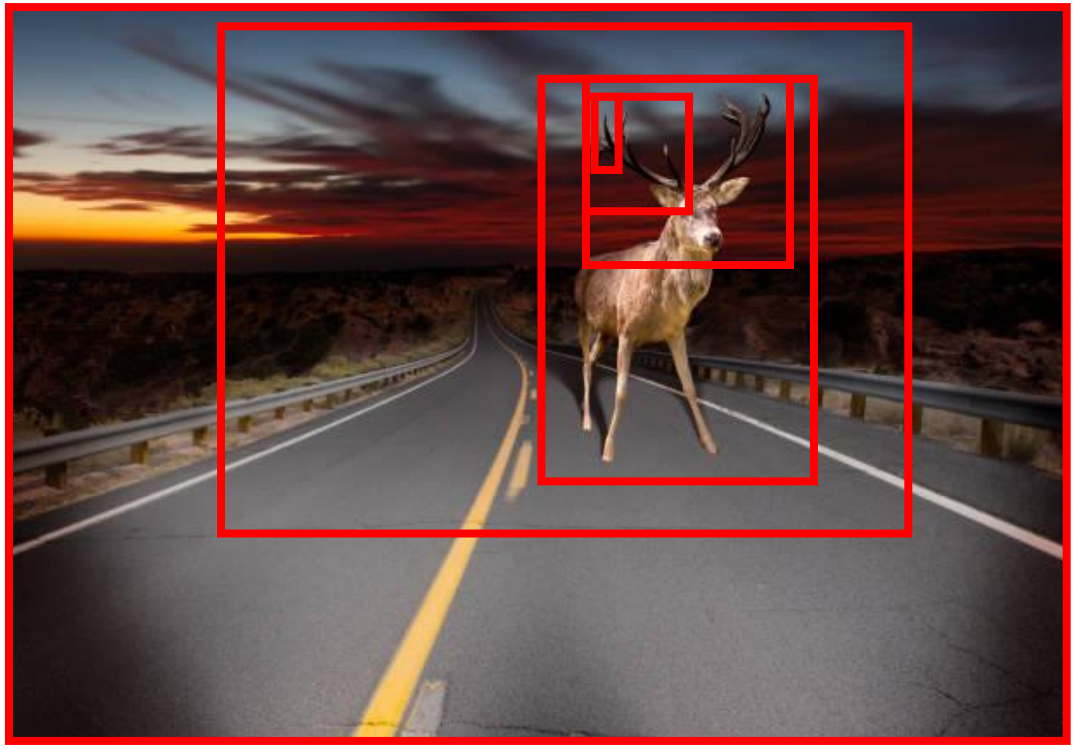
- Turn left?
- Front is clear?
- Is object a moose?
- Is this a head?
- **Is this an antler?**

A hierarchy of features

- Turn left?
- Front is clear?
- Is object a moose?
- Is this a head?
- Is this an antler?
- **Is this a line?**

Learning features hierarchically

- Today: **Process images by learning features hierarchically**
- Start with most basic features on smallest patches (e.g., a line)
- Based on those, identify more complex features (e.g., a moose)

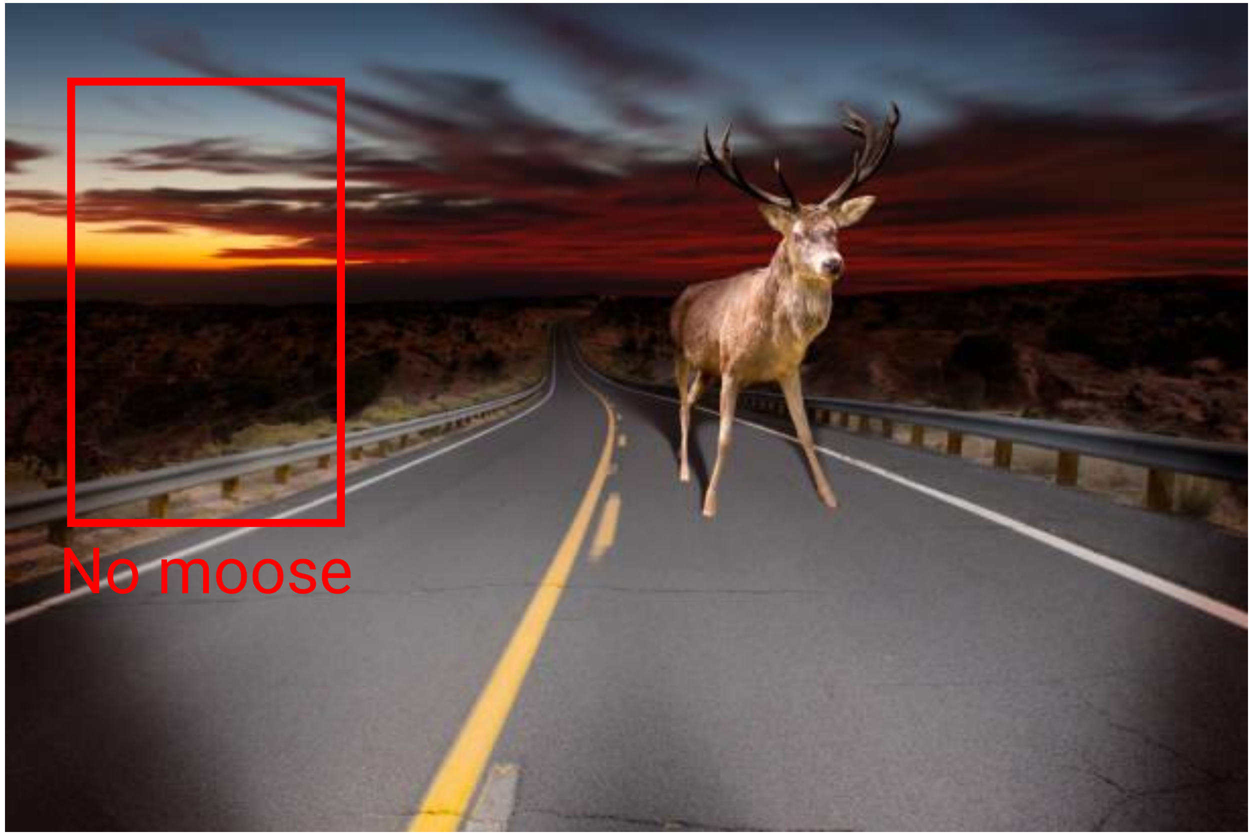


Outline

- Extracting features with convolutions
- Convolutional neural networks
- Computer vision tasks

A moose detector

- Suppose you have a classifier that can tell if a region has a moose
- How to use it to create a useful feature vector?
- Slide it over each region and check if there's a moose there!



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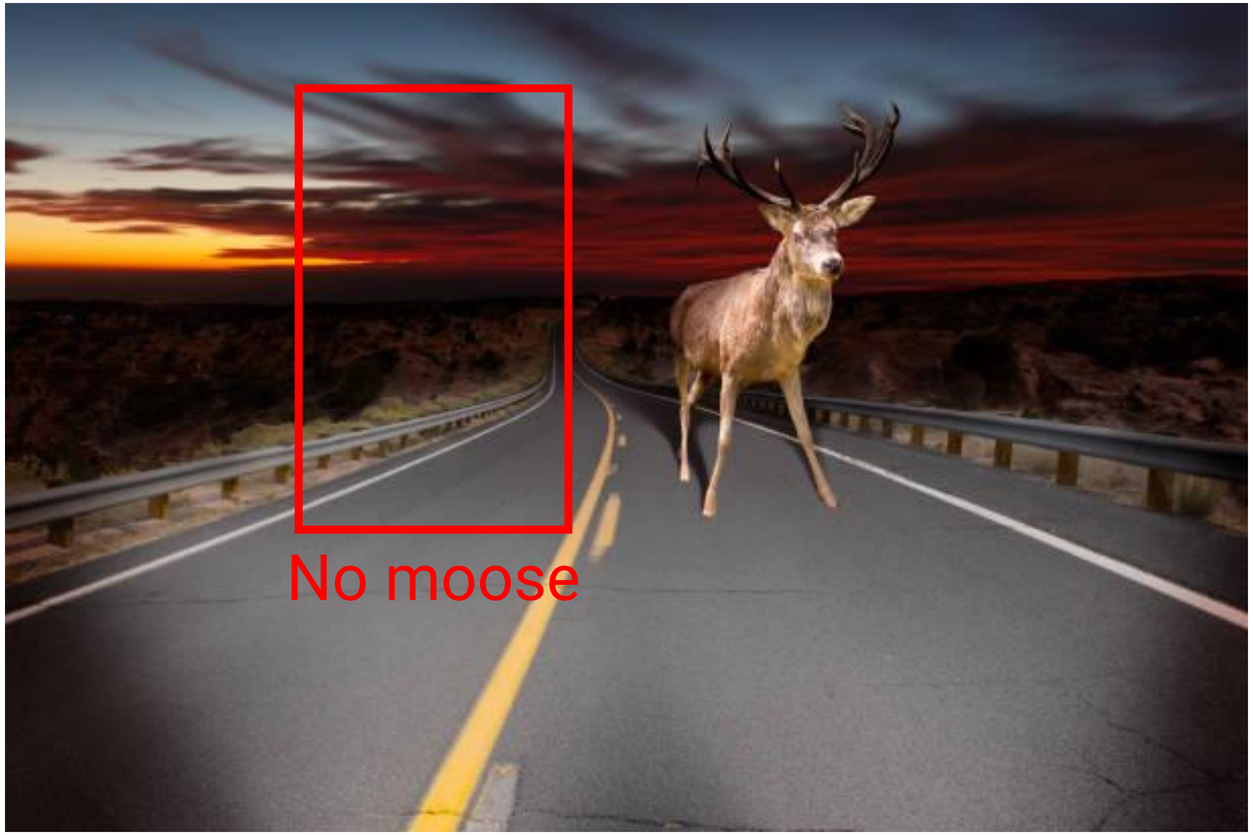

A moose detector

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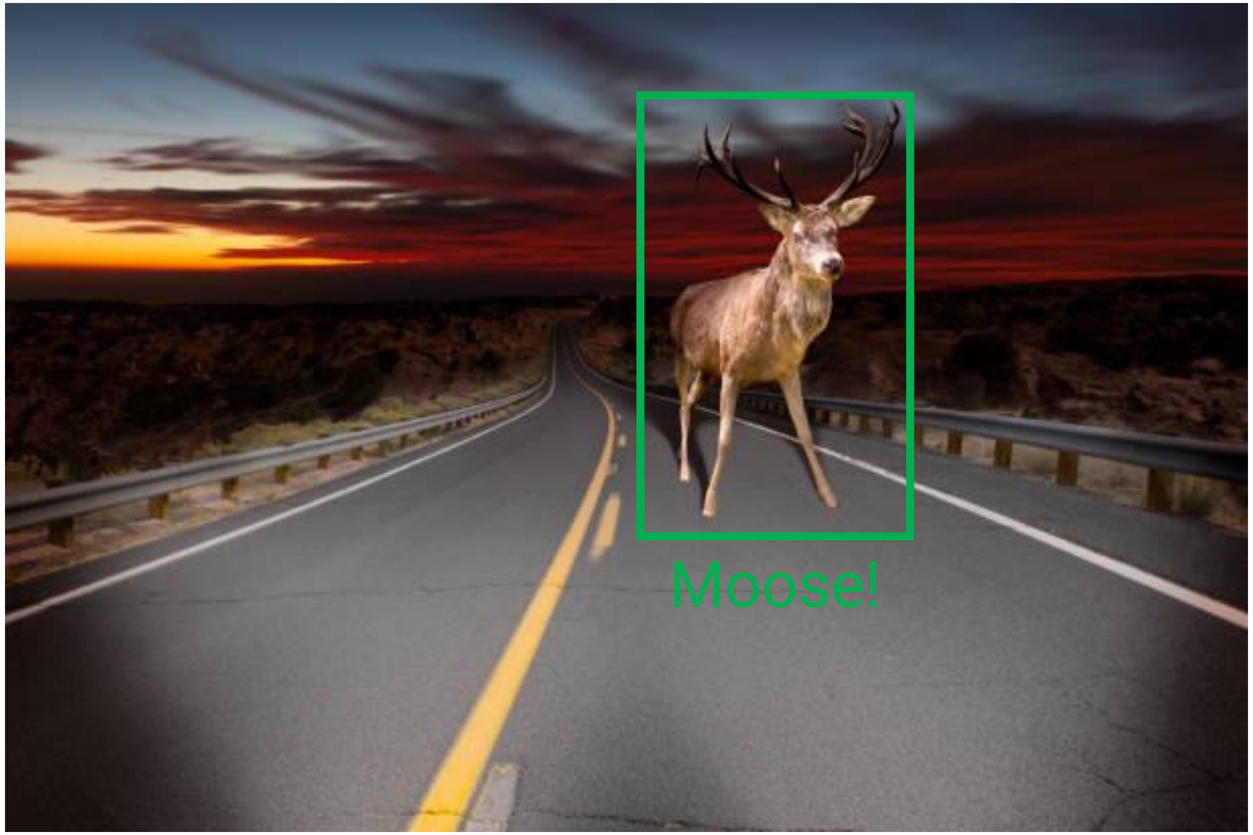
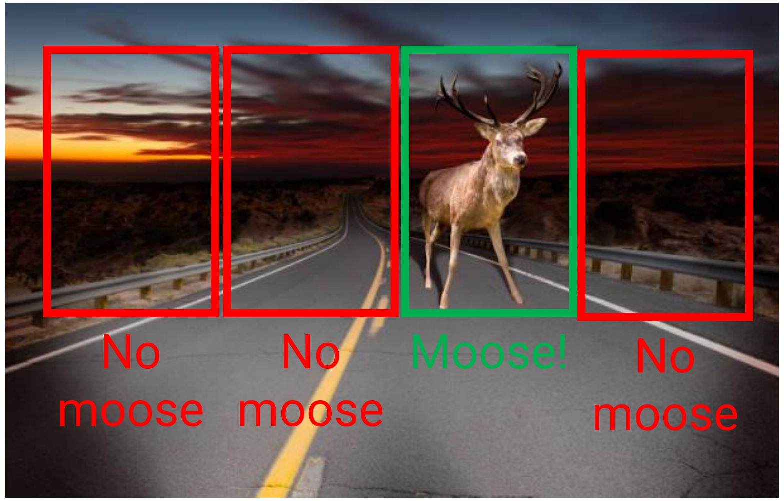


A moose detector

- Suppose you have a classifier that can tell if a region has a moose
- How to use it to create a useful feature vector?
- Slide it over each region and check if there's a moose there!
- We just did a convolution!



Learned features

$$\begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ \dots \end{pmatrix}$$

Moose in far left?
Moose in center left?
Moose in center right?
Moose in far right?

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve
$\longrightarrow$
Dot product kernel & each image patch

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve →
Dot product kernel & each image patch

3			

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve →
Dot product kernel & each image patch

3	-1		

Output
3x4 matrix

An edge detector

Let’s start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve →
Dot product kernel & each image patch

3	-1	0	

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve →
Dot product kernel & each image patch

3	-1	0	0

Output
3x4 matrix

An edge detector

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-1	2	-1
-1	2	-1
-1	2	-1

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3x3 matrix

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

Input image
5x6 matrix

Convolve →

Dot product kernel & each image patch

3	-1	0	0
5			

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve $\longrightarrow$

Dot product kernel & each image patch

3	-1	0	0
5	-2		

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
-1	2	-1
-1	2	-1

(Convolutional) Kernel
3x3 matrix

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

Input image
5x6 matrix

Convolve

Dot product kernel & each image patch

3	-1	0	0
5	-2	0	

Output
3x4 matrix

An edge detector

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-1	2	-1
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3x3 matrix

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

Input image
5x6 matrix

Convolve →

Dot product kernel & each image patch

3	-1	0	0
5	-2	0	0

Output
3x4 matrix

An edge detector

Let's start a little less ambitiously…can we detect a vertical line?

-1	2	-1
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3x3 matrix

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

Input image
5x6 matrix

Convolve

Dot product kernel & each image patch

3	-1	0	0
5	-2	0	0
3	-1	0	0

Output
3x4 matrix

"is there vertical edge in top left?"

"is there vertical edge in bottom right?"

Each extracted feature looks for the same thing in different location

Convolutions

-1	2	-1
-1	2	-1
-1	2	-1

Kernel
(K=3)

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

Input
(5 x 6)

input[1:4,2:5]

3	-1	0	0
5	-2	0	0
3	-1	0	0

Output
(5-3+1 x 6-3+1)
=(3 x 4)

(1, 2)-th
element

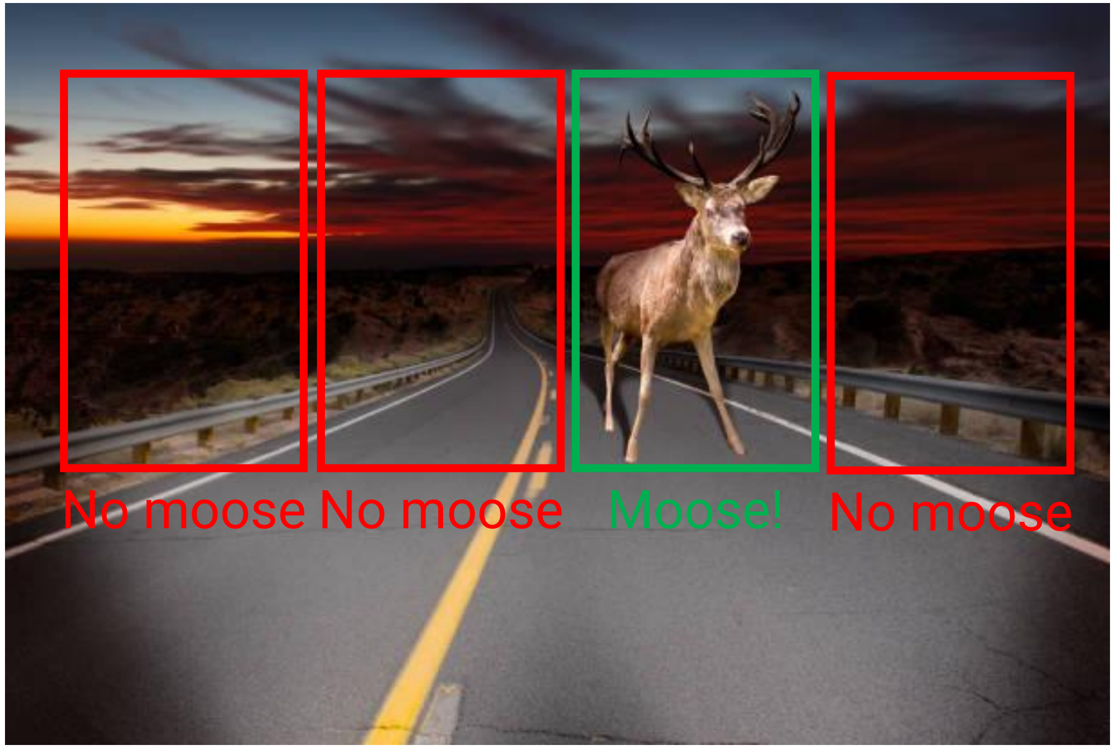
- Convolution is an operation that takes in two matrices:
  - Kernel: K x K matrix (e.g., K=3)
  - Input: W x H matrix
- Output: (W-K+1) x (H-K+1) matrix
  - ij-th element of output is dot product of kernel & input[i:i+K,j:j+K]
  - (I'm 0-indexing in these slides)
- Convolutional Layer: Kernel is our weight/parameter, use convolution to extract features
- Note: Convolution is a **linear** operation!

Motivation #1: Local Receptive Fields

- Motivation #1: Each neuron should only look at a small patch of input
- Why? Local textures/shapes are useful
- First understand local patterns, build up to global understanding

Motivation #2: Weight Sharing

- Motivation #2: In each local receptive field, the same types of features are useful
  - Basic: Detecting edges
  - More advanced: Detecting moose
- So, **share the same kernel** (i.e. weights) for all image patches
- Convolutions encode **translation equivariance**
  - If your image gets shifted, convolution outputs just get shifted too



Convolutional vs. Fully Connected Layers

-1	2	-1
-1	2	-1
-1	2	-1

Kernel
(size 9)

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

Input
(size 30)

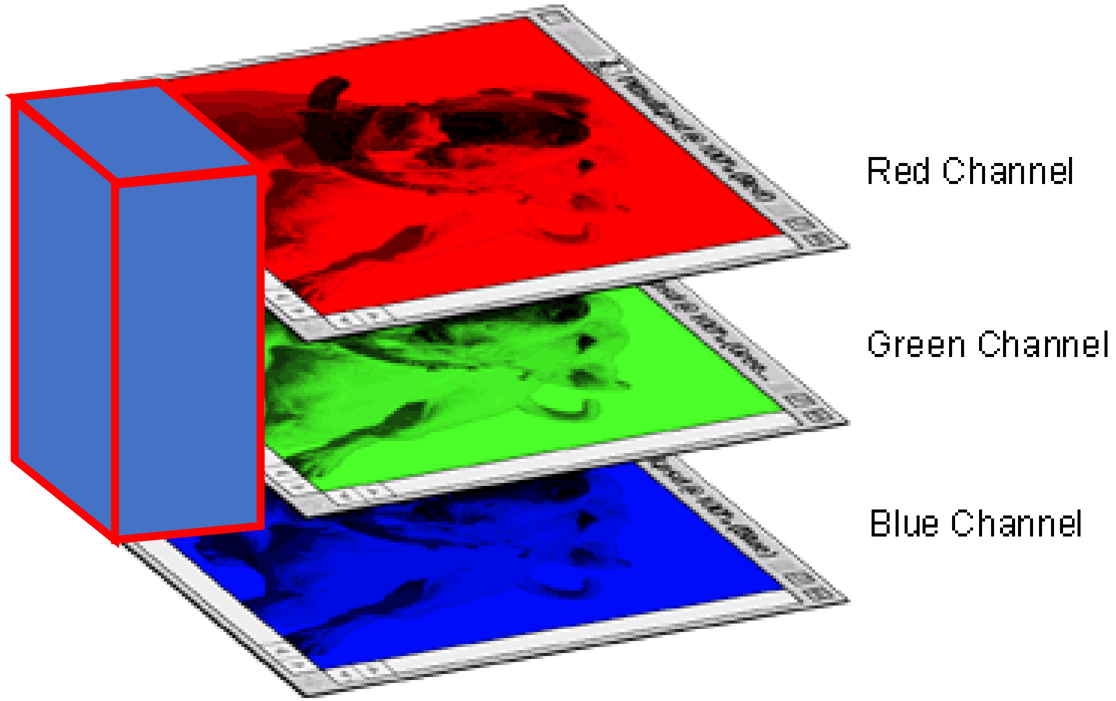
3	-1	0	0
5	-2	0	0
3	-1	0	0

Output
(size 12)

- Let's count parameters needed
  - Convolutional layer with K=3
    - Kernel = 3 x 3 = 9 parameters
    - Add a bias term = **10 parameters**
  - Fully connected layer with 30-dim input, 12-dim output needs
    - W: 30 * 12 = 360 parameters
    - b: 12 parameters
    - Total: **372 parameters**
- Fewer parameters = need less data to learn useful features
- FC would have to learn to detect the same feature (e.g., an edge) over and over again at different locations

Multiple Input Channels

- Input may have multiple input channels
  - Color image has 3 “channels” for red/green/blue
  - Input is actually 3 x W x H
  - Solution: Kernel must be of size C_{in} x K x K
    - Where C_{in} is number of input channels



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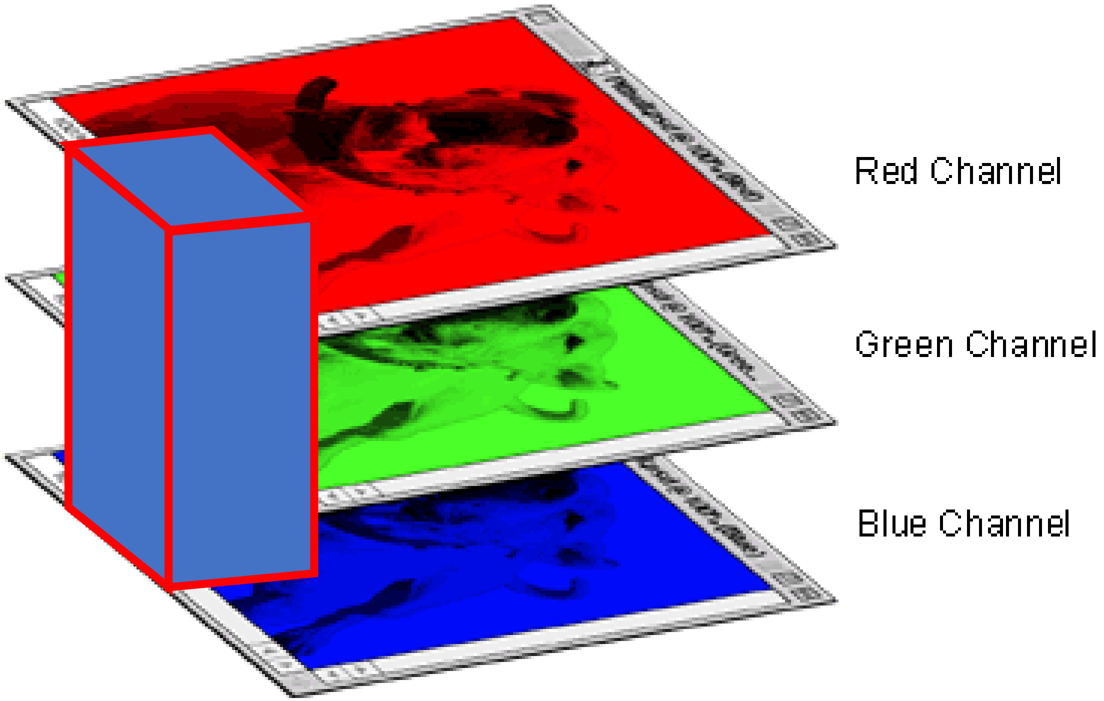

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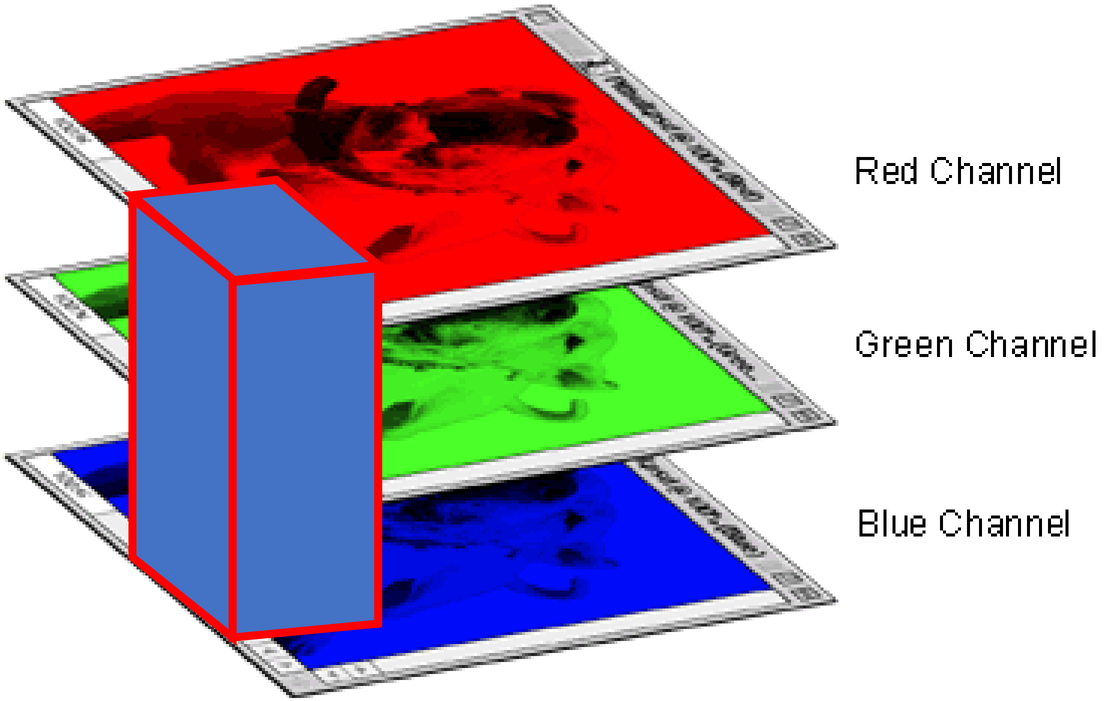


Multiple Output Channels

- What if you want more than one kernel?
  - Can have multiple kernels, each to detect a different thing
  - One for vertical lines, one for horizontal lines, etc.
  - So the total size of kernel tensor is C_{out} x C_{in} x K x K

-1	2	-1
-1	2	-1
-1	2	-1

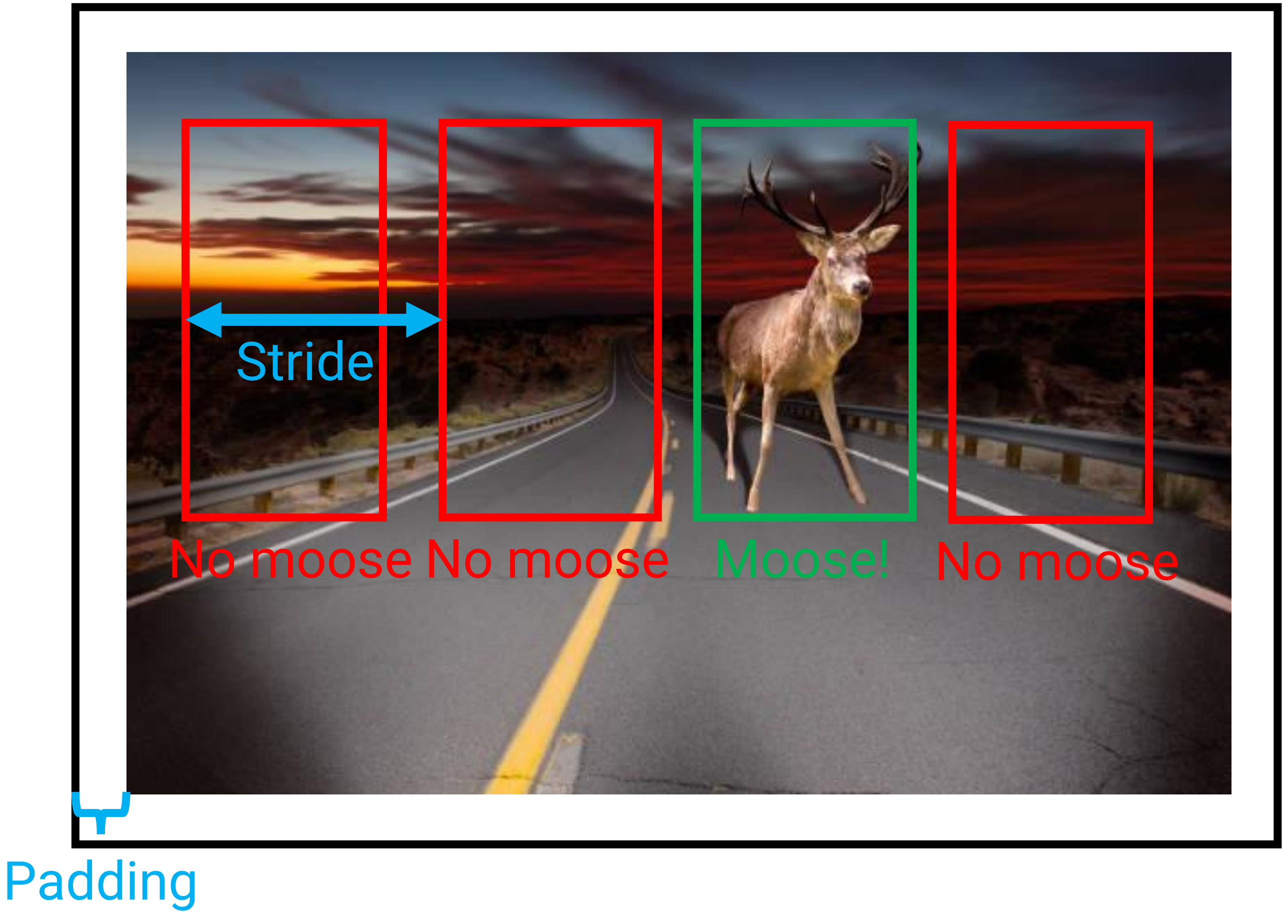
Kernel[0,0,:,:]

-1	-1	-1
2	2	2
-1	-1	-1

Kernel[1,0,:,:]

Stride and Padding

- Stride: As you slide across image, how big of a step do you take?
  - Default: stride=1 pixel
  - Can choose larger stride to reduce dimensionality
- Padding: Can pad the edges of images with 0's
  - For K=3 and no padding, width/height shrink by 2 each time
  - Adding width-1 padding on each side prevents this
  - For K=5, pad by 2, etc.
  - Default: No padding



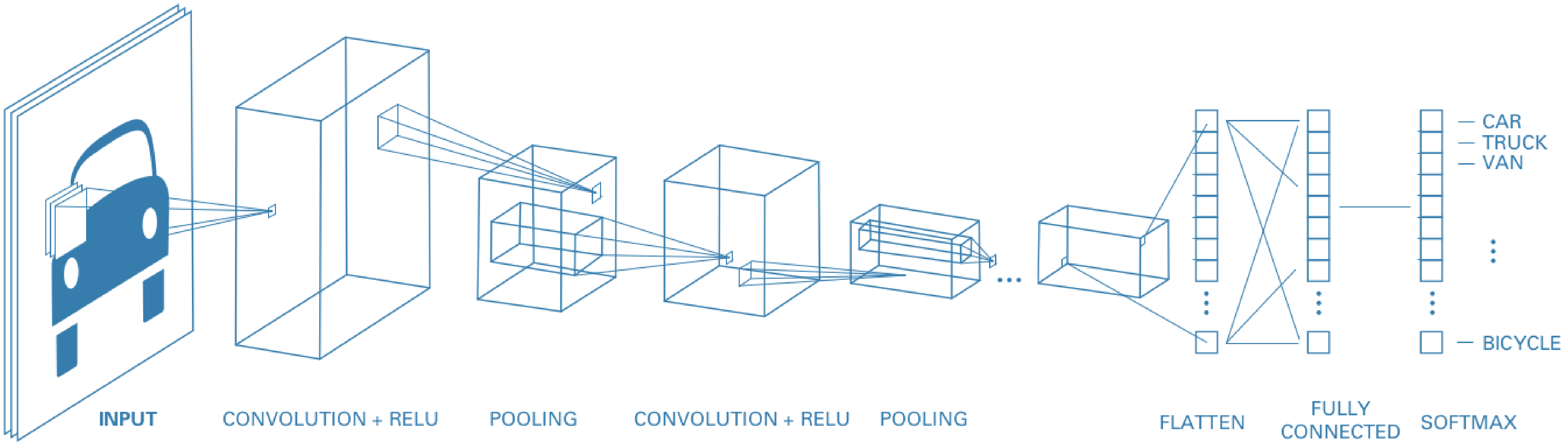
Announcements

- HW1 grades out
  - Please review the solutions posted on blackboard
- HW2 due next Thursday, February 29
- Section tomorrow: Scikit-learn tutorial
  - Useful for final project, has implementations for many machine learning methods

Outline

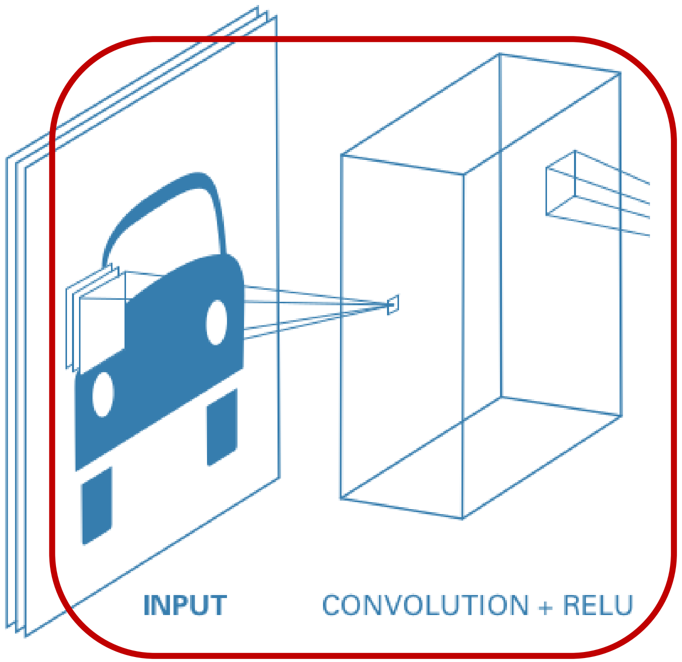
- Extracting features with convolutions
- Convolutional neural networks
- Computer vision tasks

Convolutional Neural Networks (CNNs)



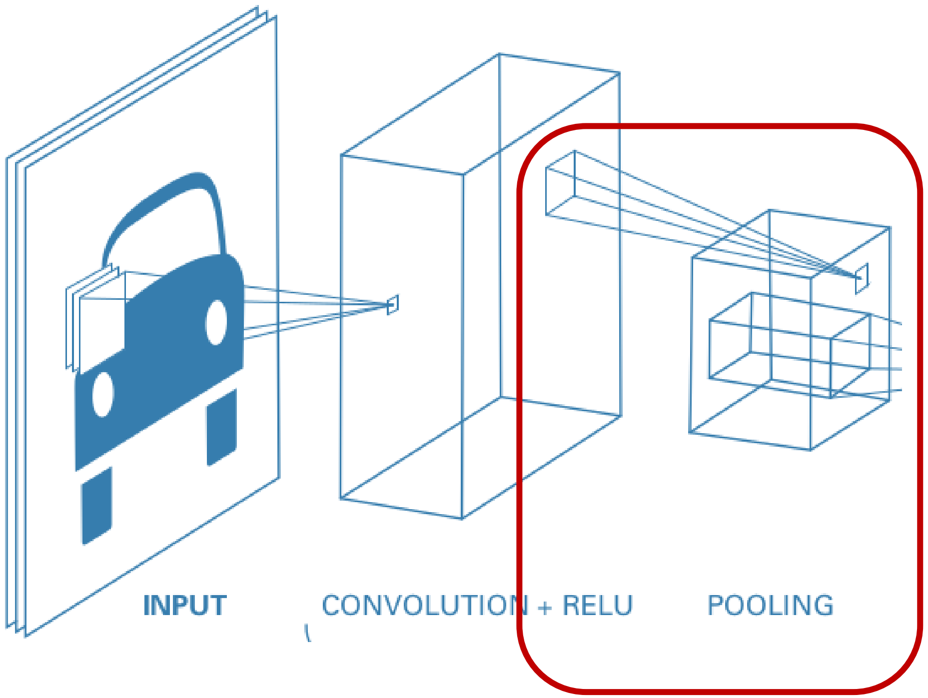
- How to incorporate convolutions into a full model?
- Basic idea: Use convolutions at beginning, then fully connected layer at end

Convolutional Layers



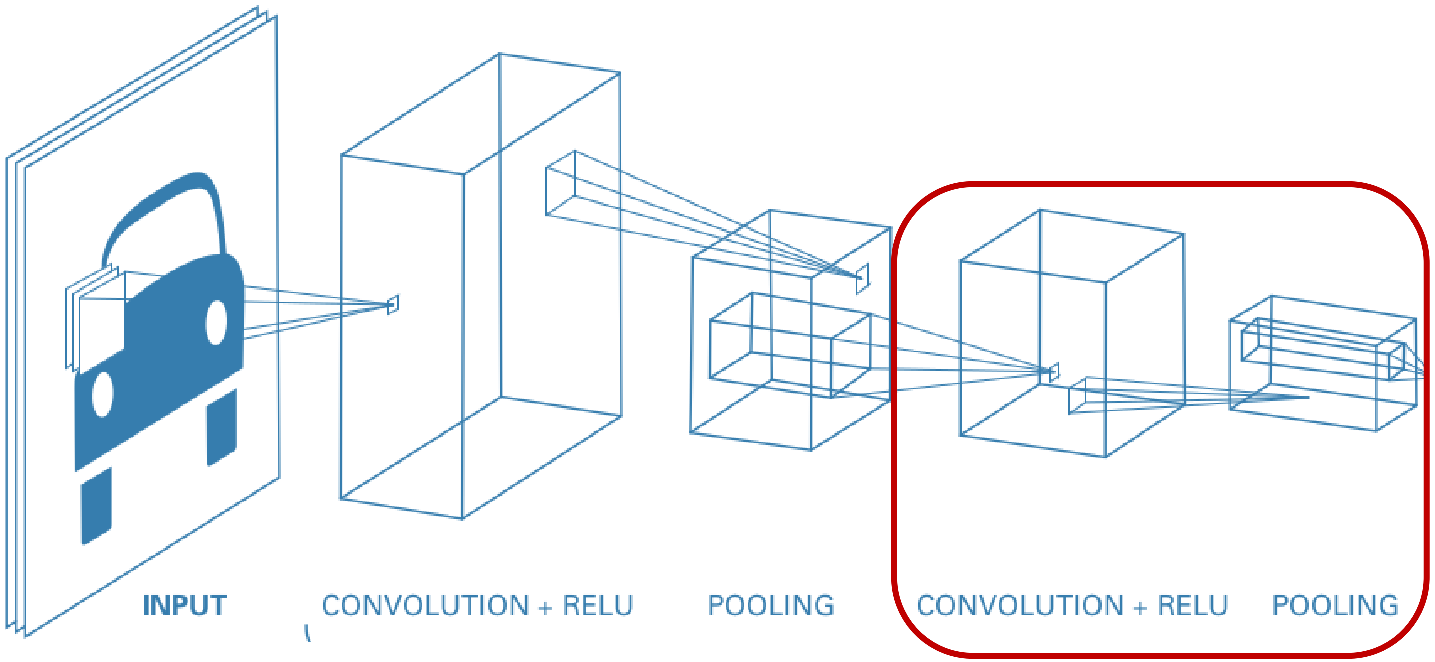
- First step: Convolutional Layer + ReLU
- Analogous to Linear layer + ReLU
  - Convolutional layer is just a special type of linear layer with local receptive fields & weight sharing!
  - So we again want to apply a non-linearity after the linear operation
- ReLU is standard for CNNs

Pooling



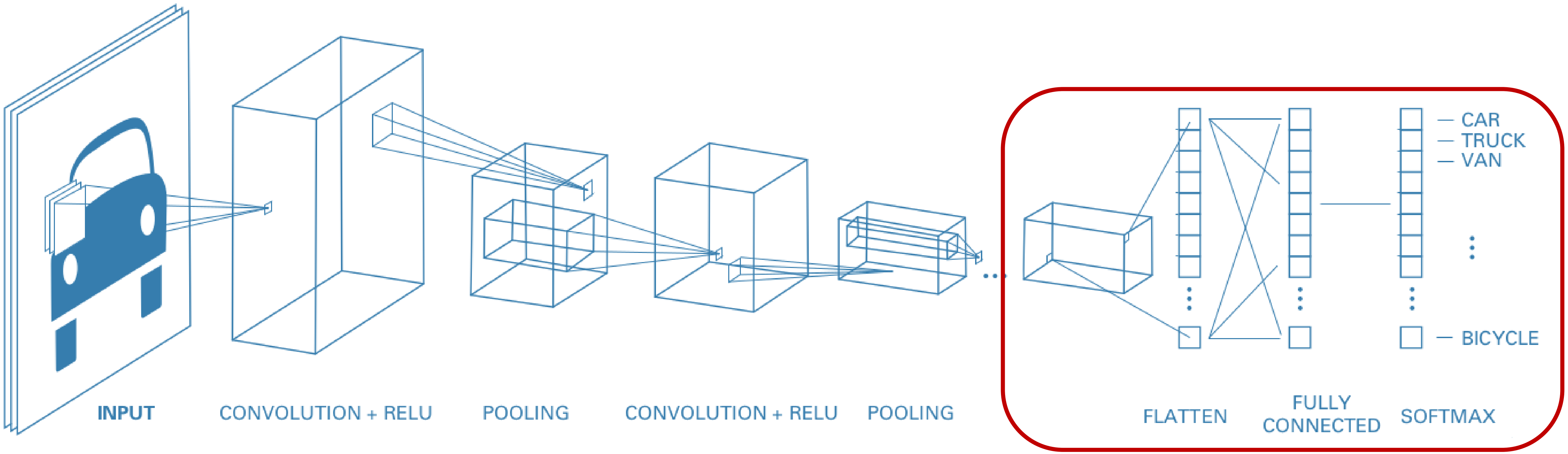
- Goal: Make receptive field bigger as we process the image
  - Early: Look for edges (small patch)
  - Later: Look for moose (larger patch)
- How do we do this? Pooling!
- Effectively we reduce resolution of input by a factor of P (often P=2)
  - Average pool: Average in each 2x2 patch
  - Max pool: Max in each 2x2 patch

More Conv + ReLU + Pool



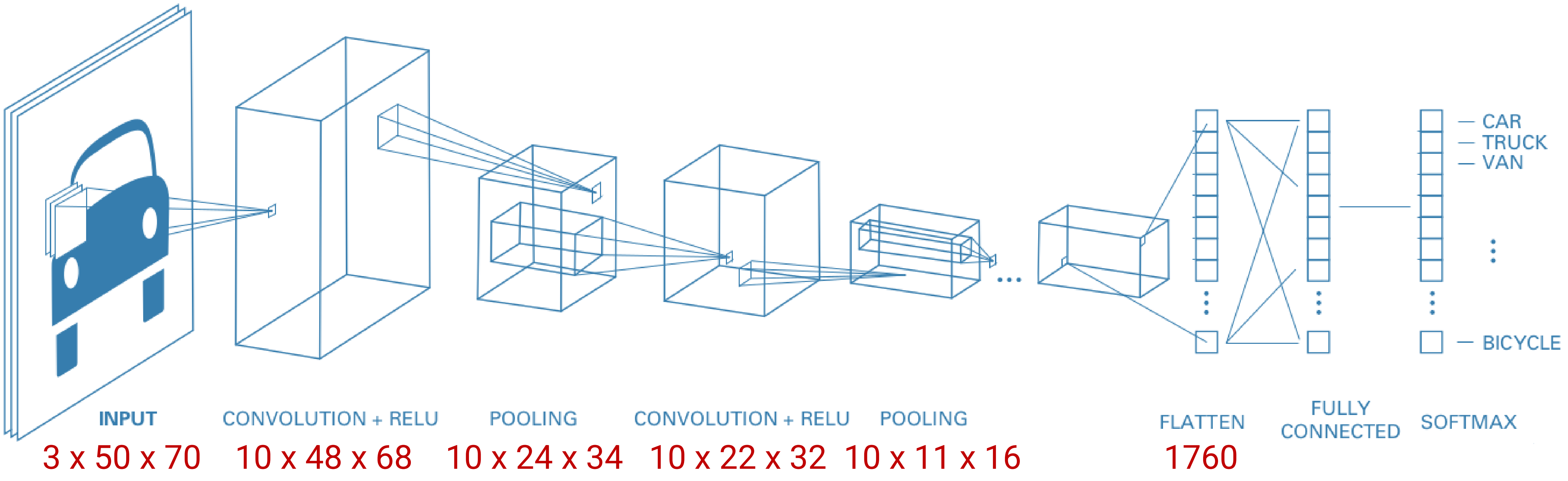
- Can stack multiple Conv + ReLU + pool blocks
- Similar to increasing number of hidden layers in MLP
- Deeper layers convolutional layers have larger effective receptive field
  - Can learn higher-level concepts

Fully connected layers



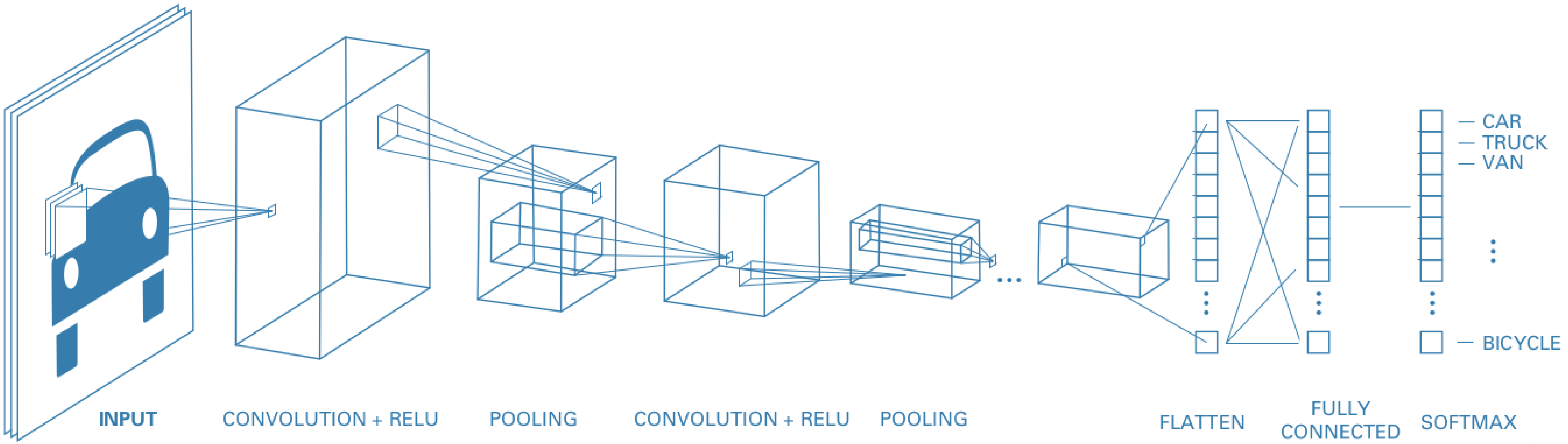
- At the very end, we want fully global processing
- Fully connected layers are good at this!
- First flatten from [channels x width x height] to a flat vector
- Then do a MLP (e.g., 2-layer neural network) on top

Keeping the dimensions straight



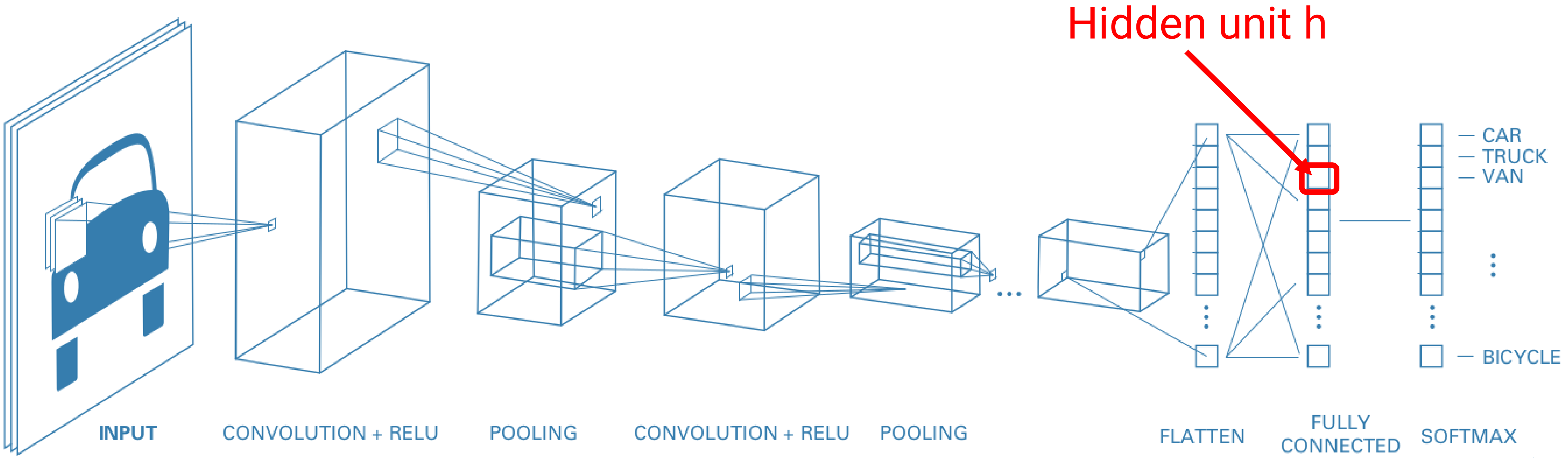
- Suppose convolution kernels are 3x3, 10 output channels, pooling is 2x2, no padding, stride=1
  - Each convolution operation loses 3-1=2 in width and height
- In code, also a "batch" dimension because we process all examples in batch together

How does backprop learn features?



- Every convolution & fully connected layer has (many) parameters
  - Convolutional: Kernel with #outChannels x (#inChannels x K x K + 1) params
  - Fully connected: #outDimensions x (#inDimensions + 1) params
- These all have to get learned by backprop + gradient descent on the loss

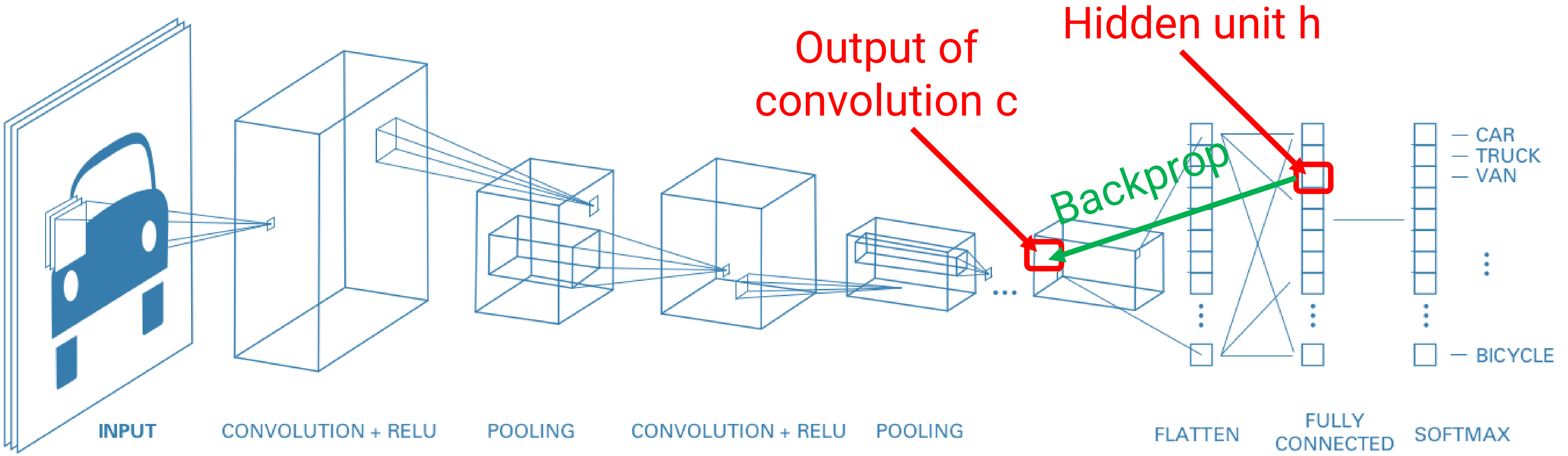
How does backprop learn features?



- Training example $(x^{(1)}, y^{(1)})$: $\partial(\text{Loss})/\partial(h) > 0$
  - Means that making h **smaller** leads to lower loss
- Training example $(x^{(2)}, y^{(2)})$: $\partial(\text{Loss})/\partial(h) < 0$
  - Means that making h **larger** leads to lower loss

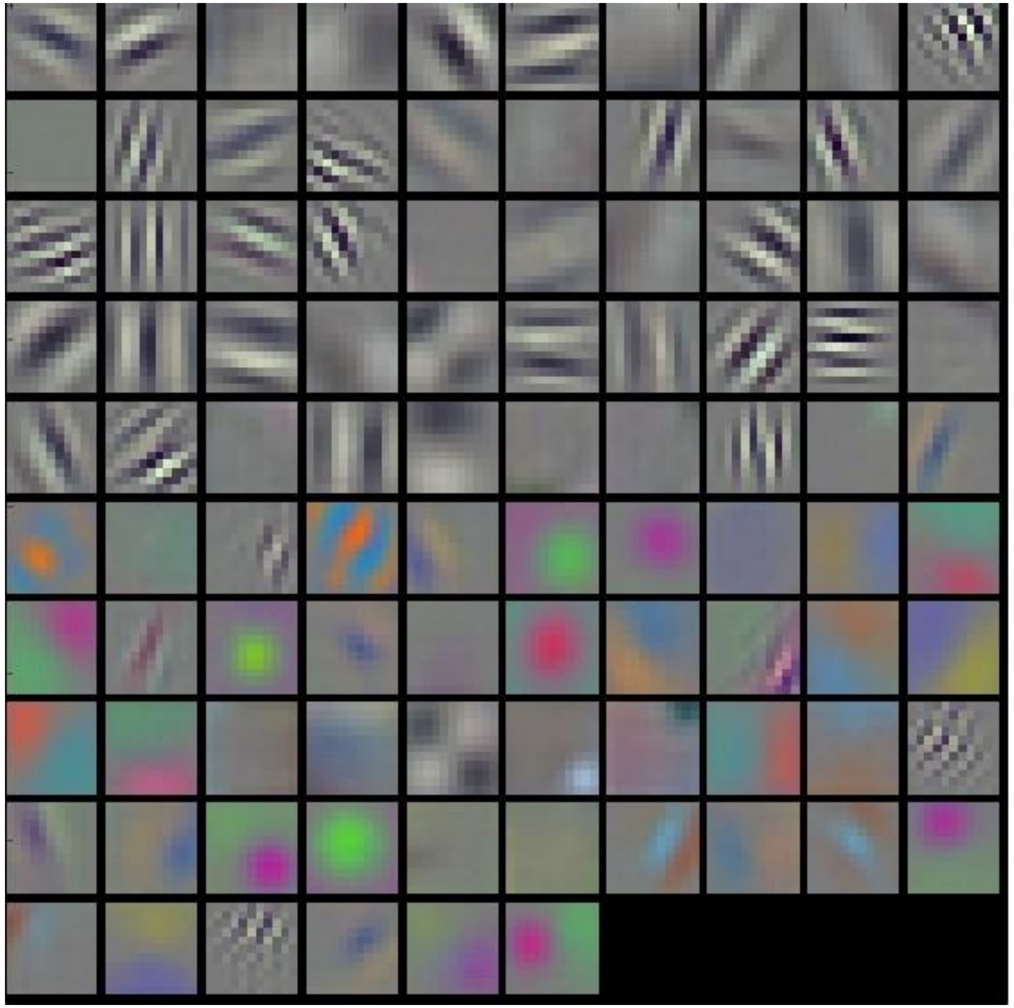
- h is output of "classifier"
- Gradient tunes classifier parameters to make output larger on some examples, smaller on others

How does backprop learn features?



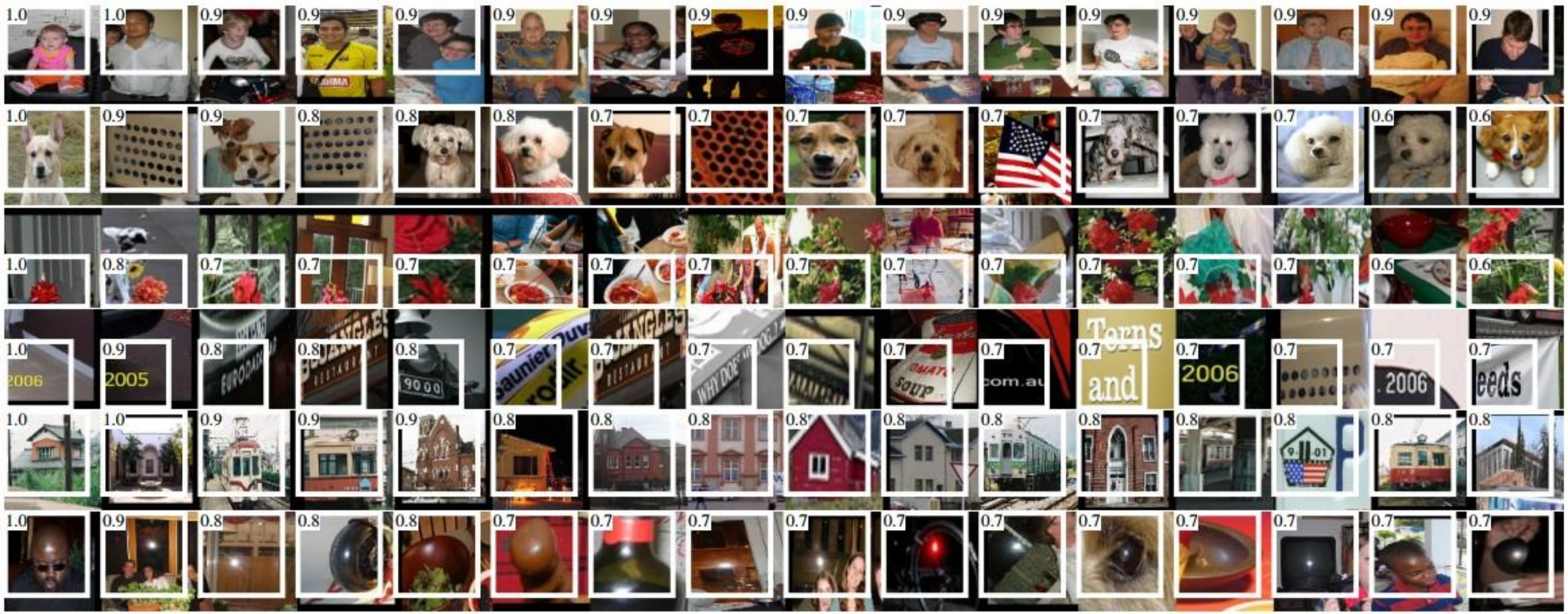
- Backpropagation: Does making c bigger change h in good or bad way?
- Sum up these considerations over all hidden units that depend on c
- Train convolutional kernel parameters so that value of c leads to [values of h's that lead to good outputs]
- And so on for earlier layers…

What features do CNNs learn?



- Kernels of AlexNet first layer
  - Each one is 3 (for RGB) x 11 x 11
- What is learned?
  - Edge detectors in different directions and widths
  - Patches of various colors

What features do CNNs learn?



Faces

Dogs (eyes?)

Red ornaments/ flowers

Text (years?)

Houses

Lens flare?

Each Row: Images that activate a different neuron in 5th POOL layer of AlexNet

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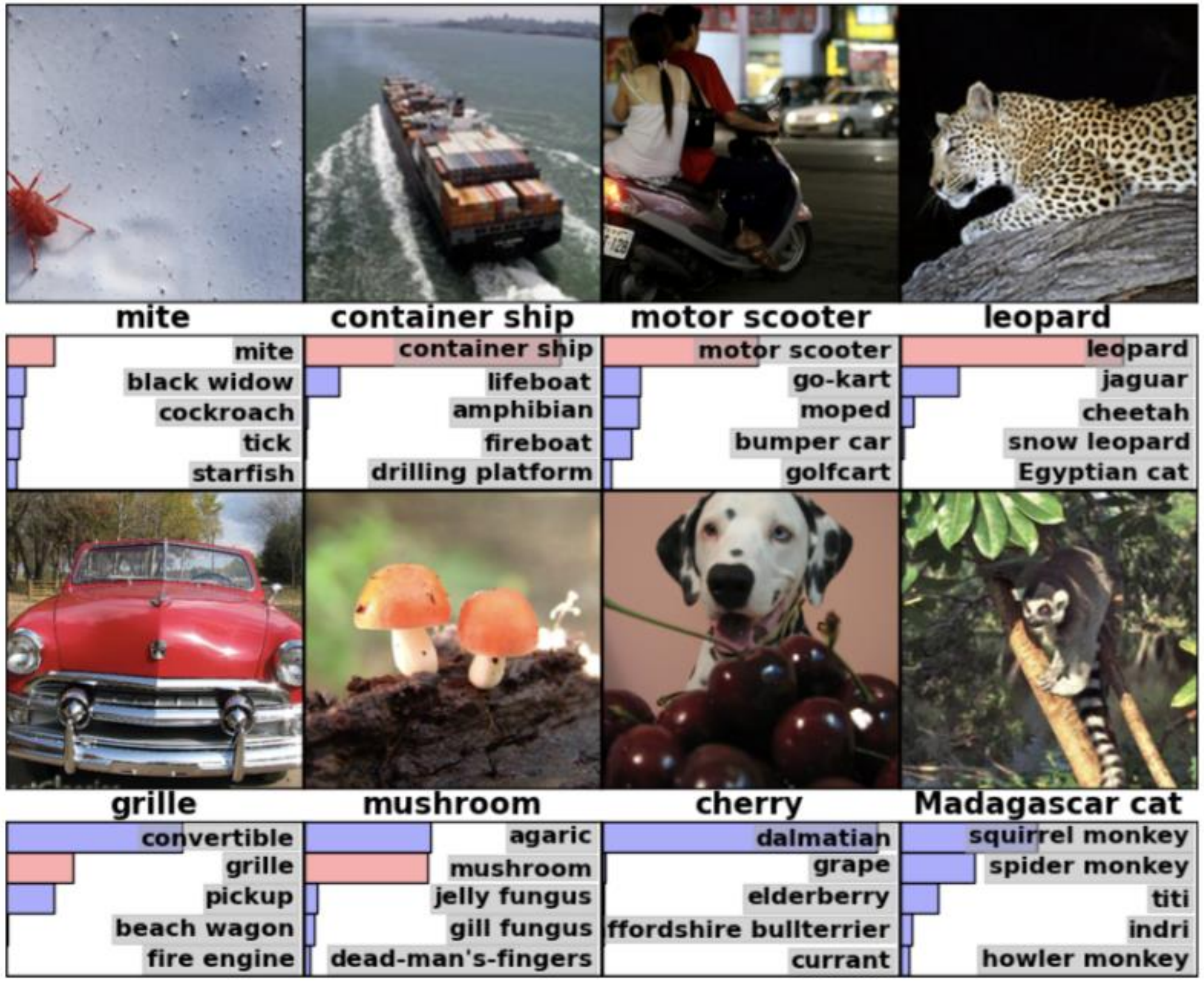
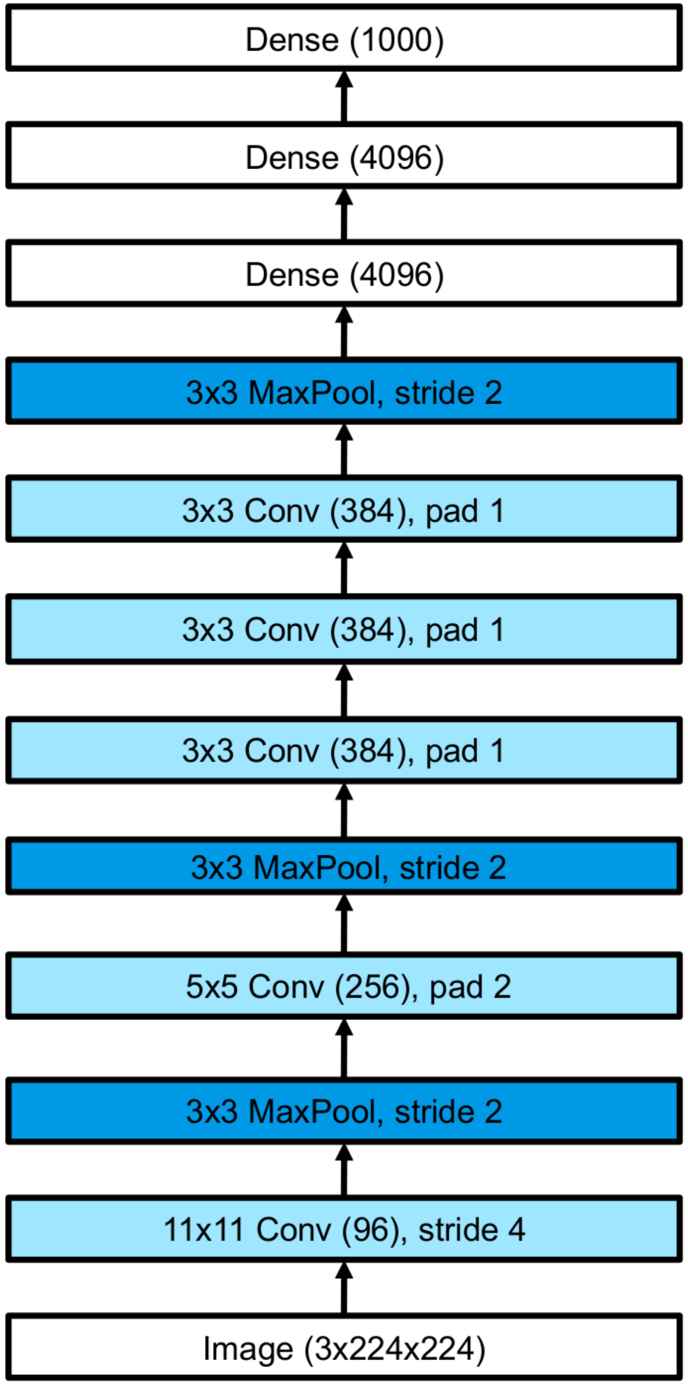
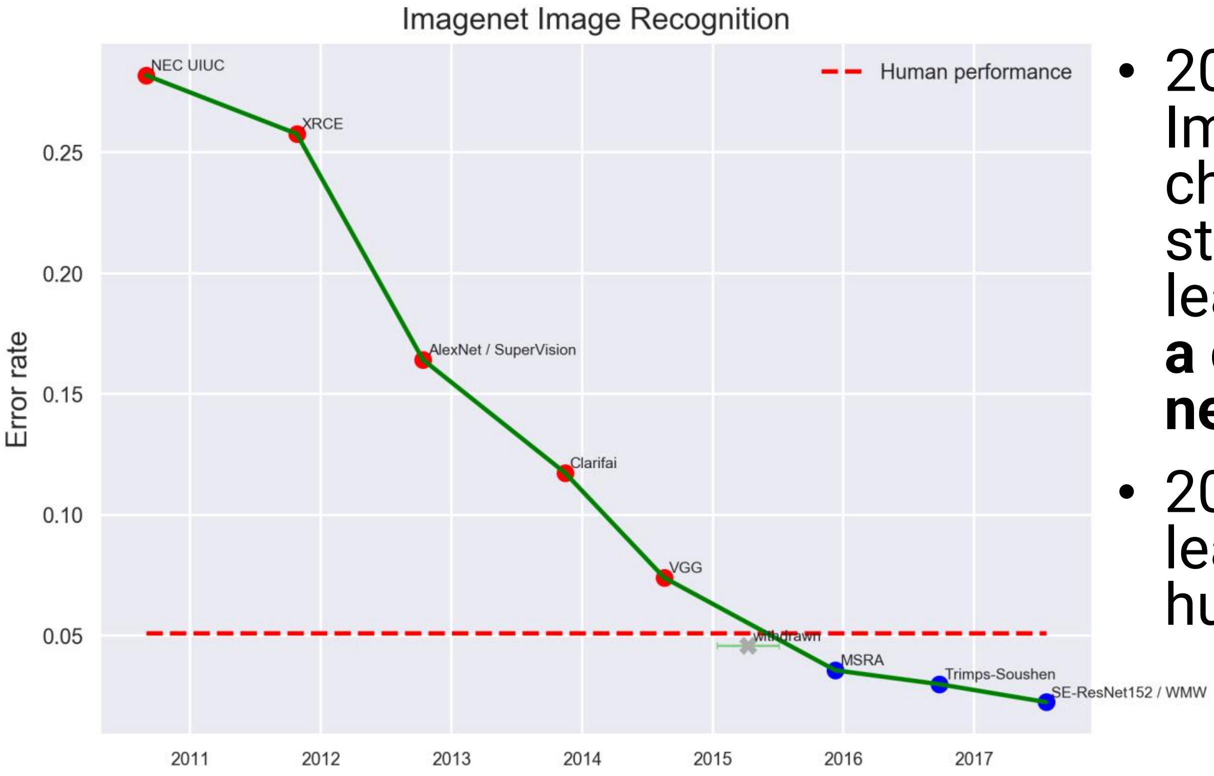
Image Classification



- ImageNet dataset: 14 million images, 1000 labels
- **CNNs do very well at these tasks!**



Progress on ImageNet



- 2012: AlexNet wins ImageNet challenge, marks start of deep learning era **(and is a convolutional neural network)**
- 2016: Machine learning surpasses human accuracy

Source: https://www.eff.org/files/AI-progress-metrics.html

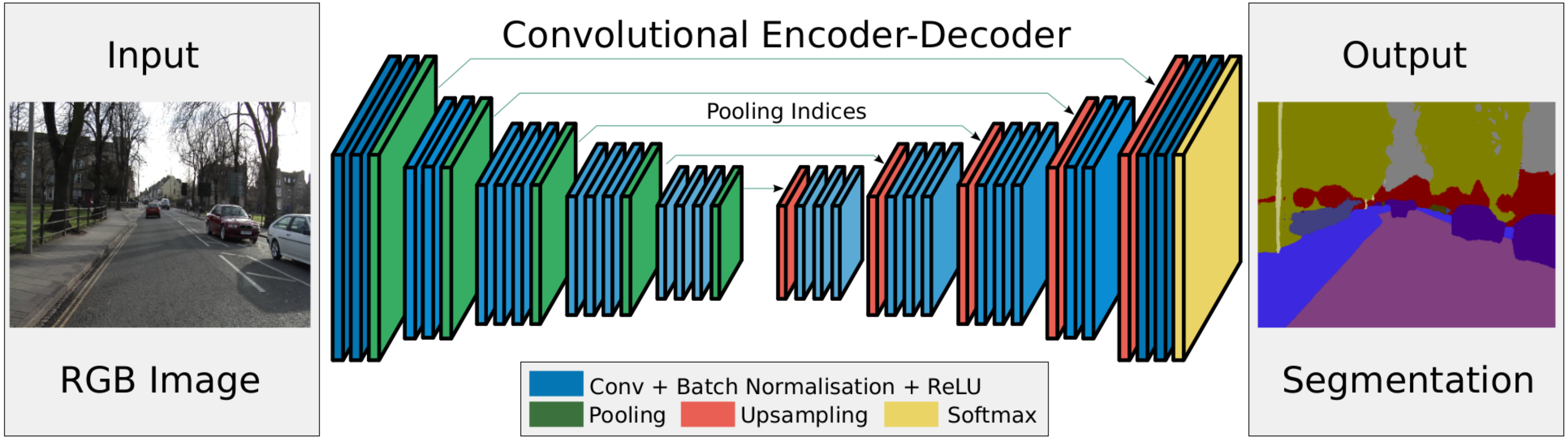
Object Detection

- Task: Identify objects, provide bounding boxes, and label them
- One strategy: Propose candidate bounding boxes, then classify each box (possibly as nothing)

Semantic Segmentation

- Task: Predict a class label for each pixel

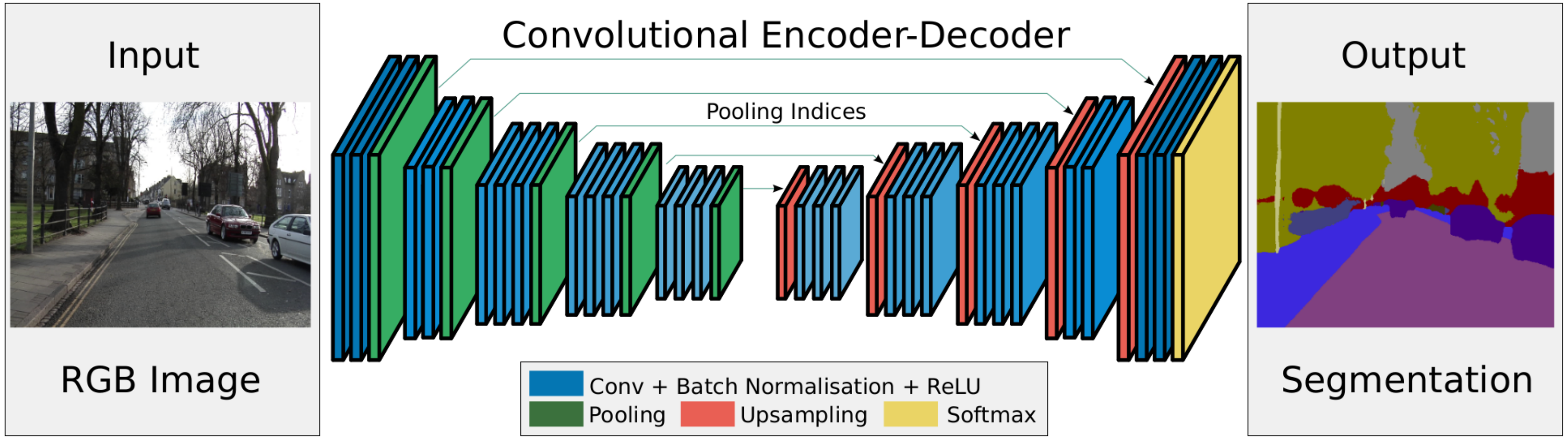
Semantic Segmentation



- One strategy: Encoder-Decoder ("U-net")
  - First do conv + ReLU + pooling as before
  - Then do upsampling + conv + ReLU to generate an output of original size

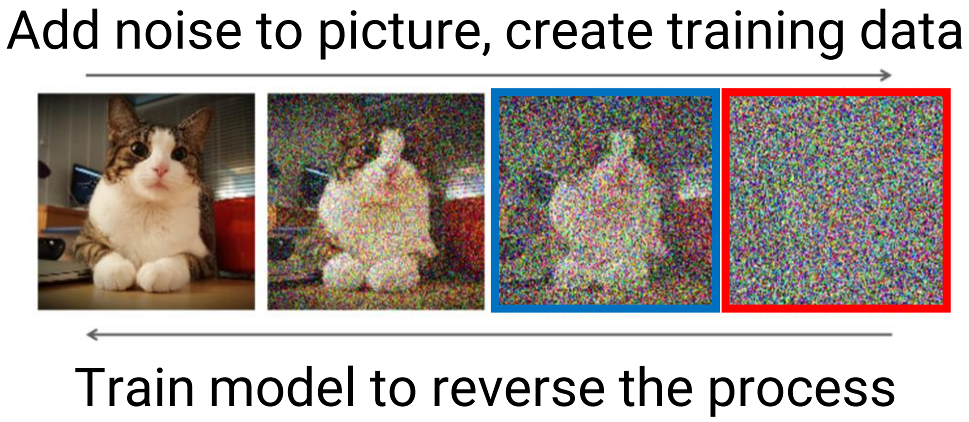
Image Generation

- Segmentation: "generates" a 2-D grid of predictions
  - This is almost like generating an image
- Can we use CNNs to generate new images?



Diffusion Models

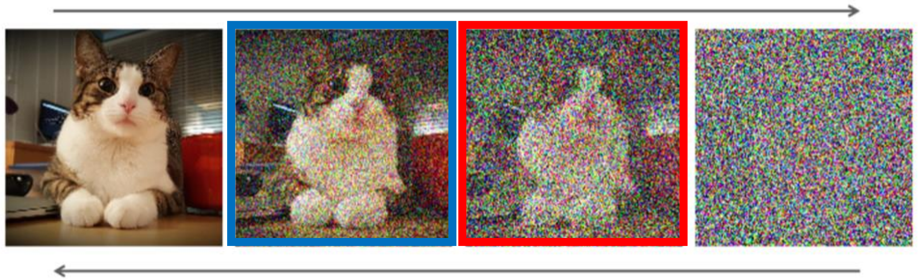
- Training: Add noise to good images, train neural network to undo the noise
  - **Input**: Noisy image
  - **Output**: Less noisy image
  - Architecture: Can also use U-Net
  - Objective: Per-pixel regression loss



Diffusion Models

- Training: Add noise to good images, train neural network to undo the noise
    - **Input**: Noisy image
    - **Output**: Less noisy image
    - Architecture: Can also use U-Net
    - Objective: Per-pixel regression loss

Add noise to picture, create training data



Train model to reverse the process

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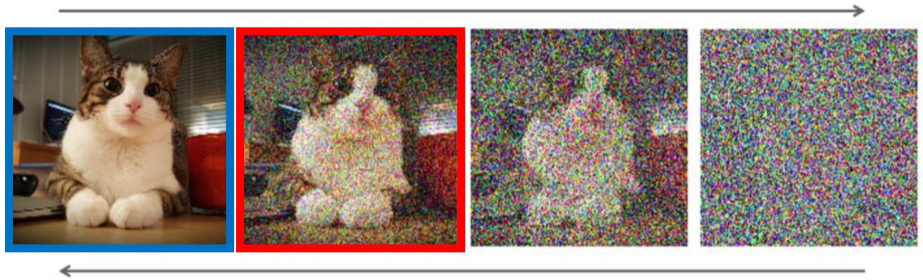
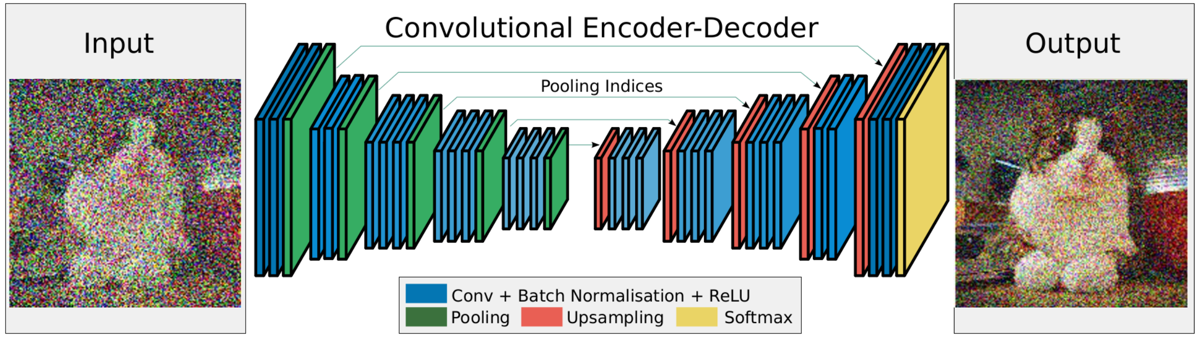


Train model to reverse the process



Noisy Image

Less Noisy Image

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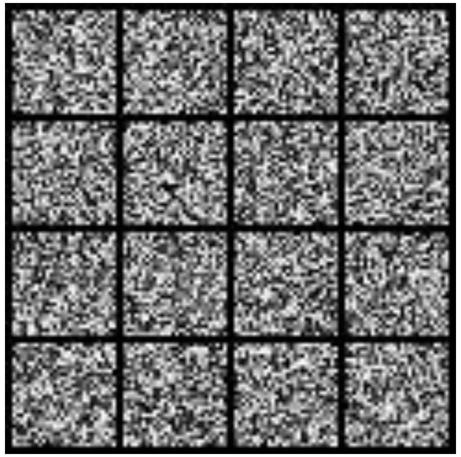
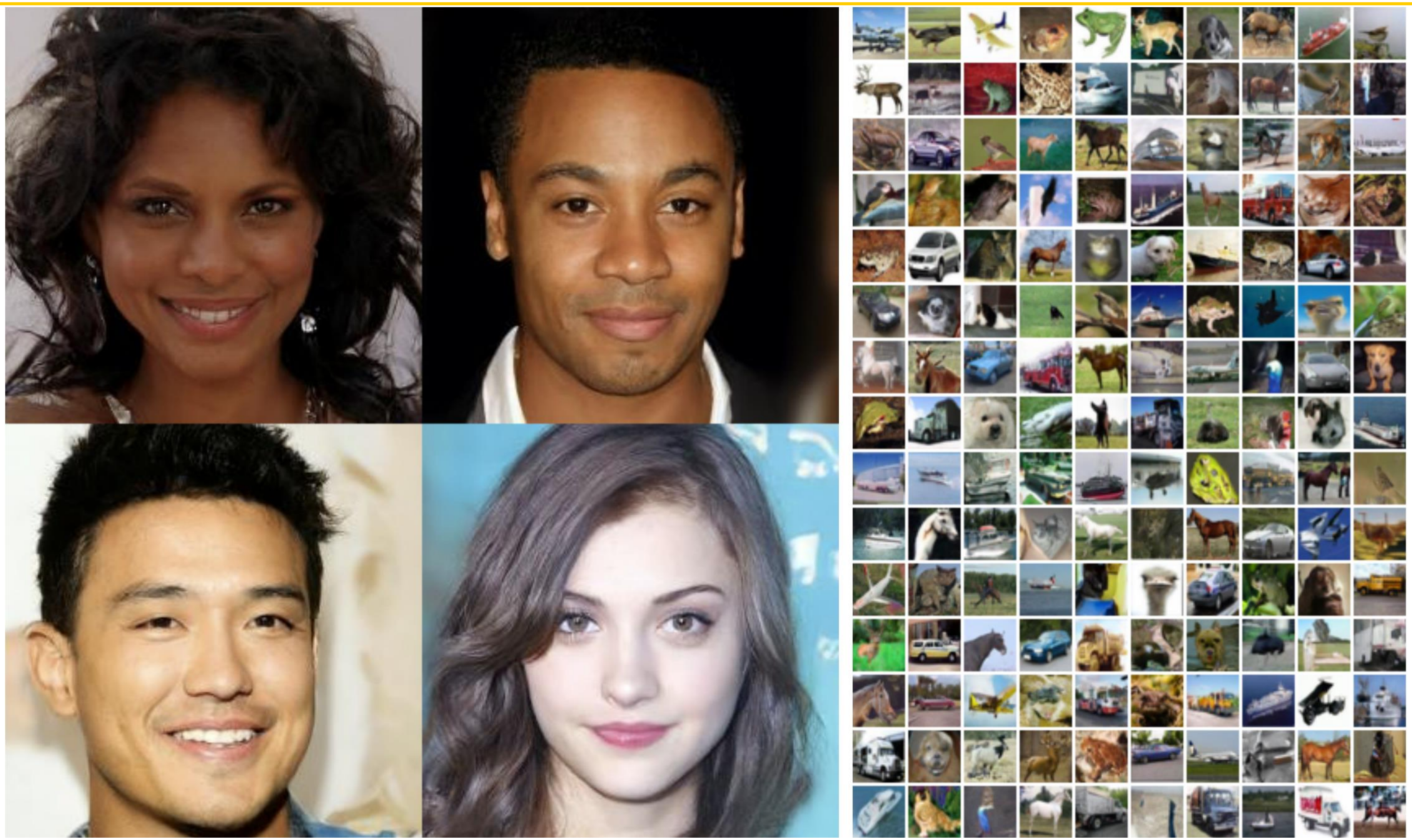
- Test-time: Start from pure noise, apply the neural network many times to create an image!
- How to input a caption? More on this later…

Test time: Model converts noise to images over many iterations



Diffusion Model Generated Images



Denoising Diffusion Probabilistic Models. Jonathan Ho, Ajay Jain, and Pieter Abbeel. NeurIPS 2020.

Conclusion

- Convolution: Restricted linear operation parameterized by a small kernel
- Convolutional layers extract useful features for images
  - Motivation #1: Local Receptive Fields
  - Motivation #2: Weight Sharing
- Standard CNN architecture
  - Start: Convolutional layer + ReLU + Max Pooling
  - End: Fully connected layer

-1	2	-1
-1	2	-1
-1	2	-1

Kernel
(K=3)

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

Input

3	-1	0	0
5	-2	0	0
3	-1	0	0

Output