6.874, 6.802, 20.390, 20.490, HST.506
Computational Systems Biology
Deep Learning in the Life Sciences

Lecture 3: Convolutional Neural Networks

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Slides credit: 6.S191, Dana Erlich, Param Vir Singh, David Gifford, Alexander Amini, Ava Soleimany

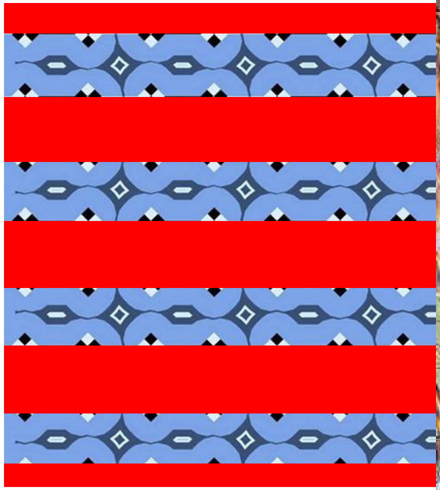
Today: Convolutional Neural Networks (CNNs)

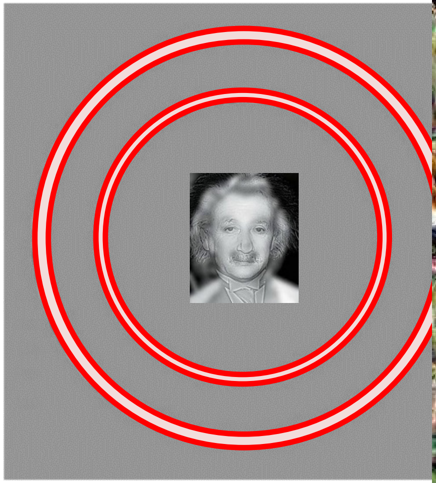
1. **Scene understanding and object recognition for machines (and humans)**
   - Scene/object recognition challenge. Illusions reveal primitives, conflicting info
   - Human neurons/circuits. Visual cortex layers==abstraction. General cognition
2. **Classical machine vision foundations: features, scenes, filters, convolution**
   - Spatial structure primitives: edge detectors & other filters, feature recognition
   - Convolution: basics, padding, stride, object recognition, architectures
3. **CNN foundations: LeNet, *de novo* feature learning, parameter sharing**
   - Key ideas: ***learn*** features, hierarchy, re-use parameters, back-prop filter learning
   - CNN formalization: representations(Conv+ReLU+Pool)*N layers + Fully-connected
4. **Modern CNN architectures: millions of parameters, dozens of layers**
   - Feature invariance is hard: apply perturbations, learn for each variation
   - ImageNet progression of best performers
   - AlexNet: First top performer CNN, 60M parameters (from 60k in LeNet-5), ReLU
   - VGGNet: simpler but deeper (8→19 layers), 140M parameters, ensembles
   - GoogleNet: new primitive=inception module, 5M params, no FC, efficiency
   - ResNet: 152 layers, vanishing gradients ➔ fit residuals to enable learning
5. **Countless applications: General architecture, enormous power**
   - Semantic segmentation, facial detection/recognition, self-driving, image colorization, optimizing pictures/scenes, up-scaling, medicine, biology, genomics

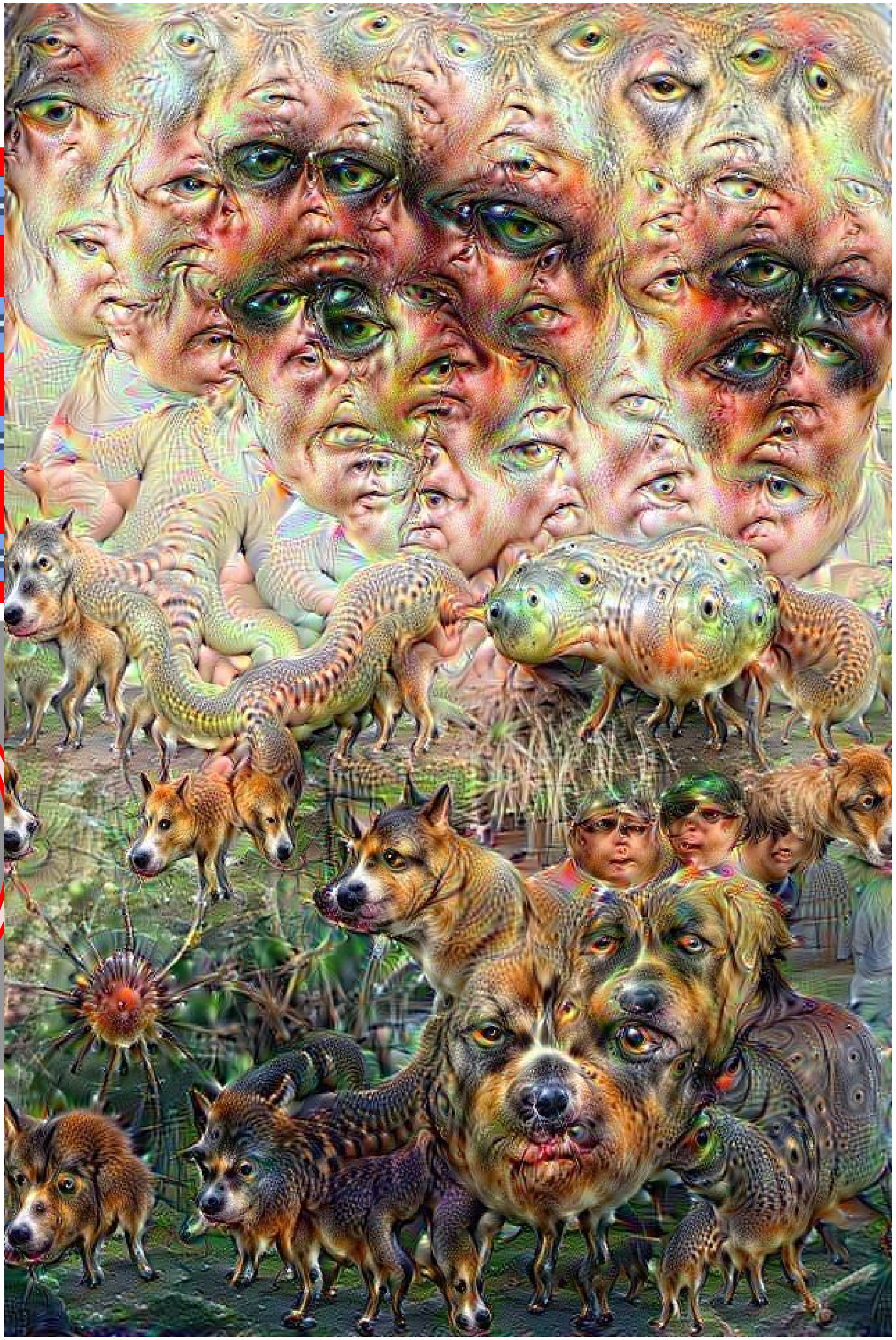
1a. What do you see, and how?
Can we teach machines to see?

What do *you* see?

How do you see?



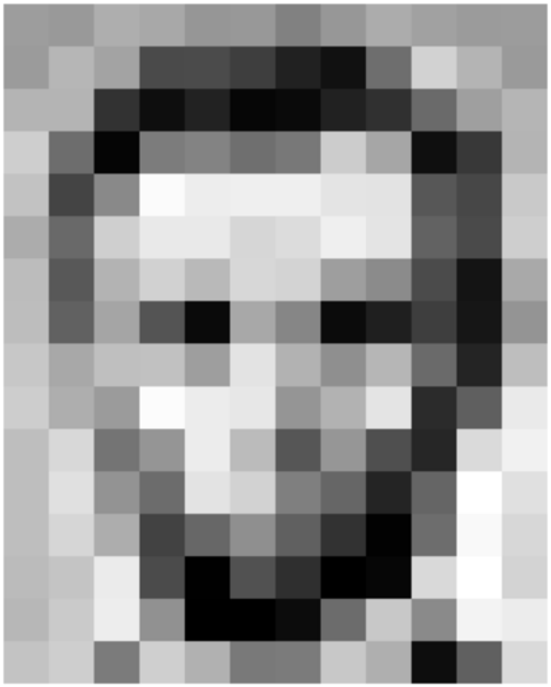




How can we help computers see?

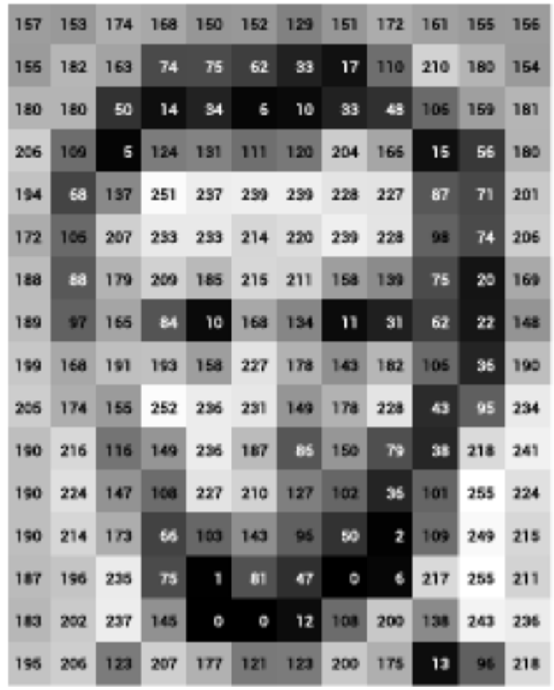
What computers ‘see’: Images as Numbers

What you see



Input Image

What you both see



Input Image + values

What the computer "sees"

157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

Levin *Image Processing & Computer Vision*

Pixel intensity values
(“pix-el”=picture-element)

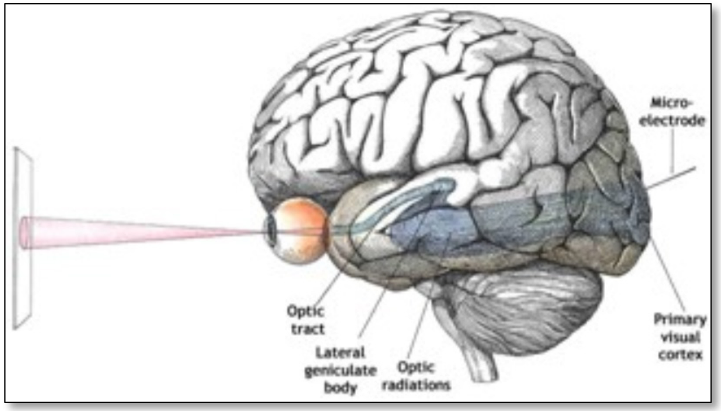
An image is just a matrix of numbers [0,255]. i.e., 1080x1080x3 for an RGB image.
Question: is this Lincoln? Washington? Jefferson? Obama?
How can the computer answer this question?

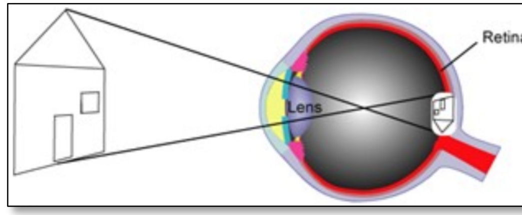
Can I just do classification on the 1,166400-long image vector directly?

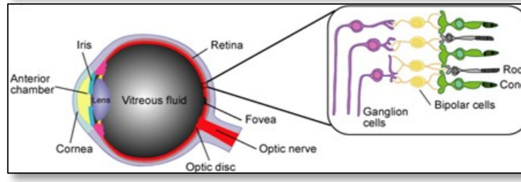
No. Instead: exploit image spatial structure. Learn patches. Build them up

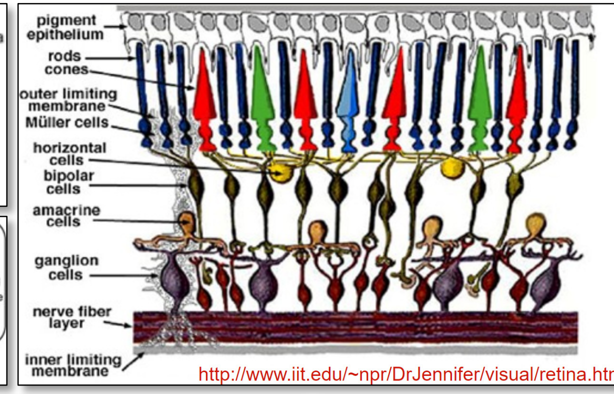
1b. Classical machine vision roots in study of human/animal brains

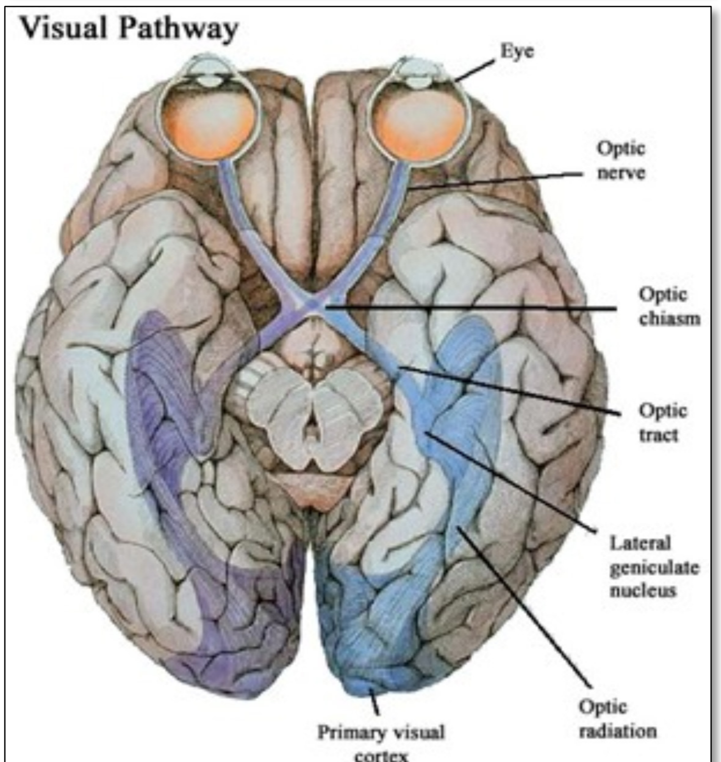
Inspiration: human/animal visual cortex

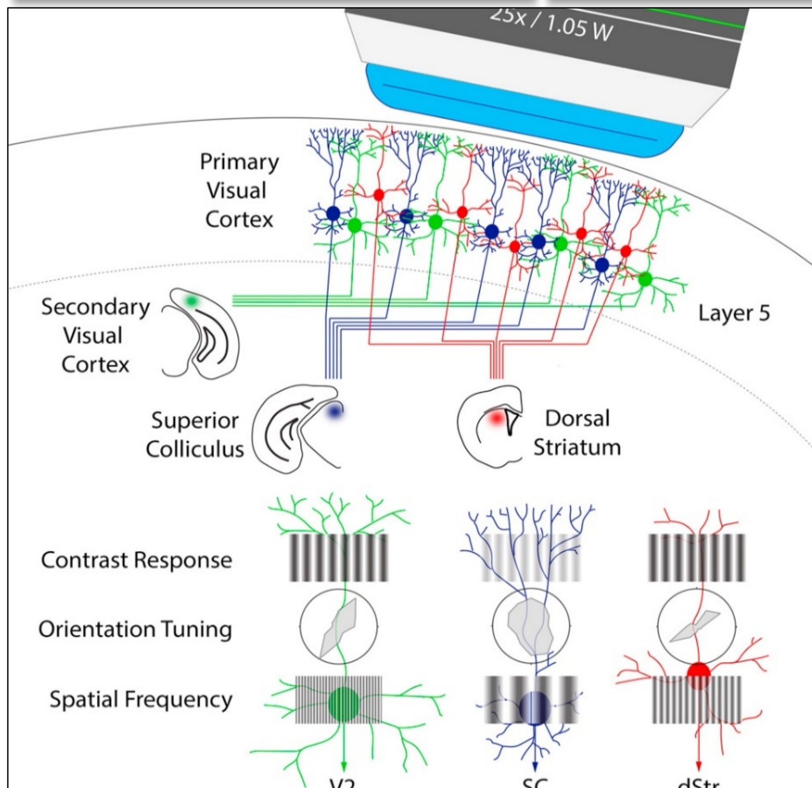


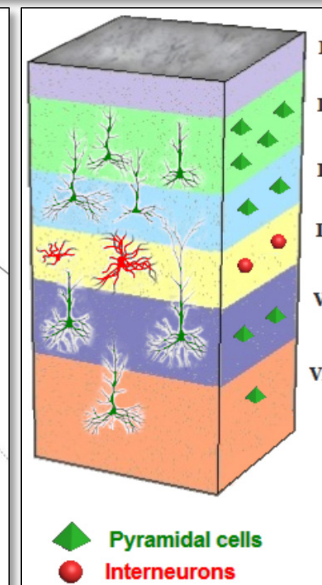






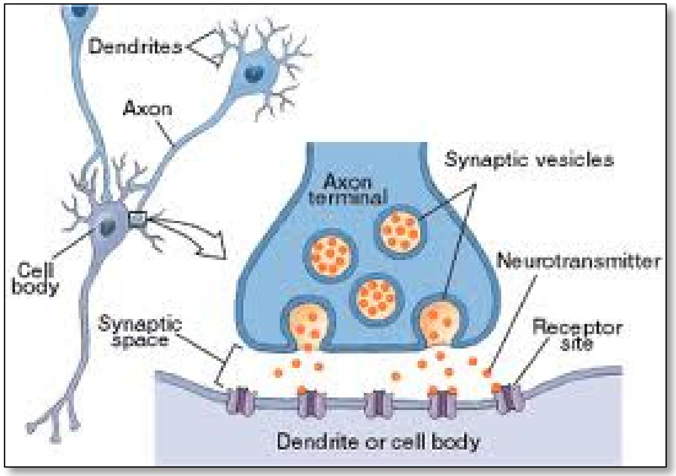


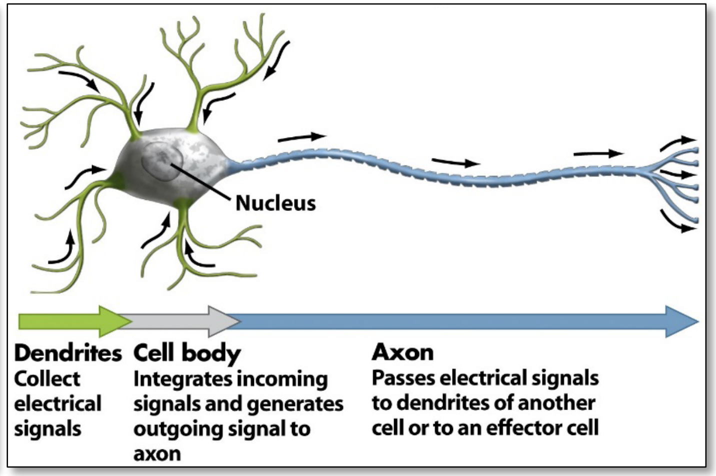


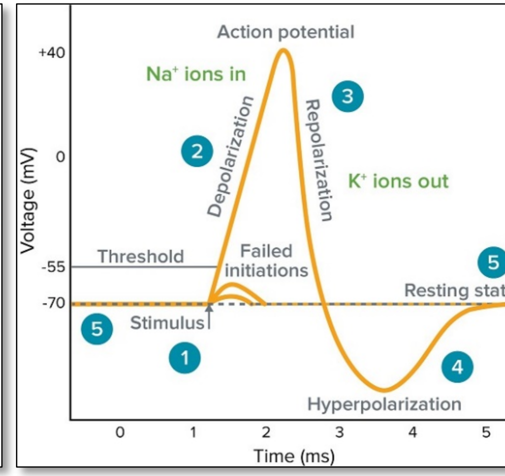


- **Layers of neurons: pixels, edges, shapes, primitives, scenes**
- **E.g. Layer 4 responds to bands w/ given slant, contrasting edges**

Primitives: Neurons & action potentials



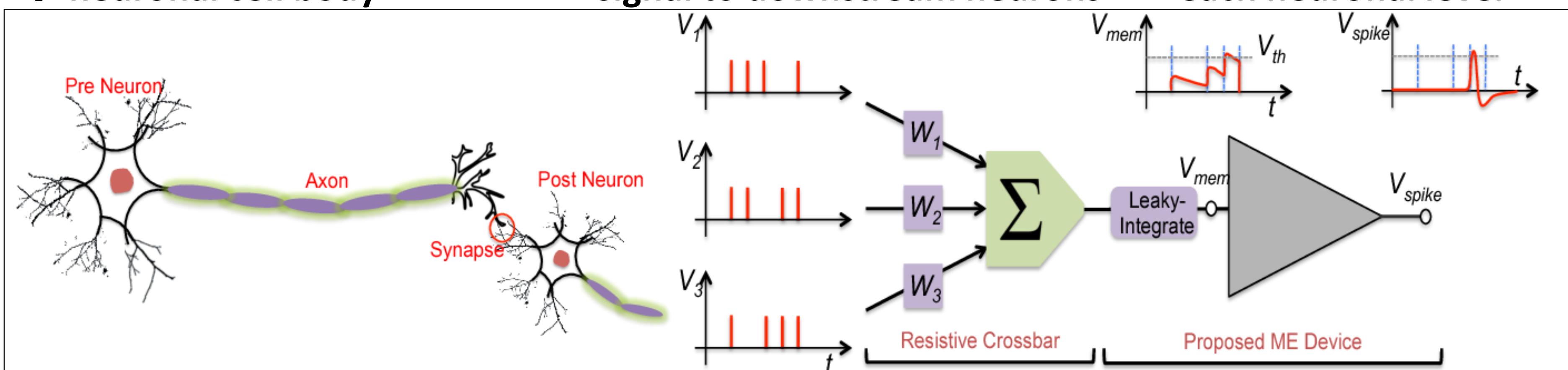




- Chemical accumulation across dendritic connections
- Pre-synaptic axon
  → post-synaptic dendrite
  → neuronal cell body

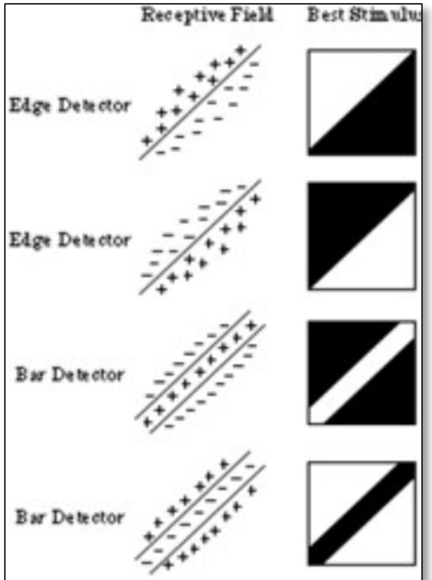
- Each neuron receives multiple signals from its many dendrites
- When threshold crossed, it fires
- Its axon then sends outgoing signal to downstream neurons

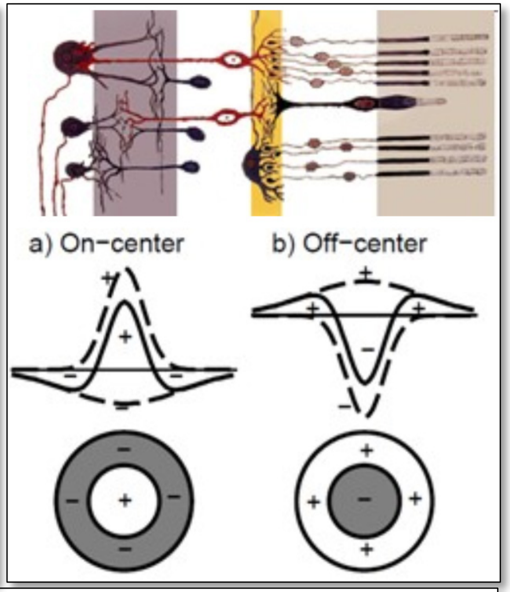
- Weak stimuli ignored
- Sufficiently strong cross activation threshold
- Non-linearity within each neuronal level

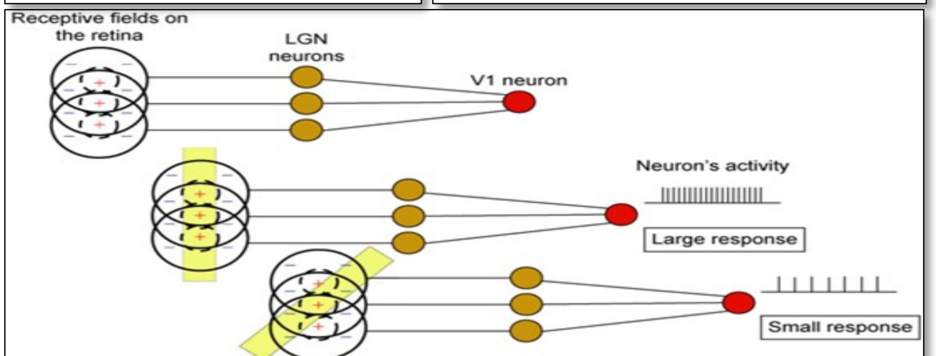


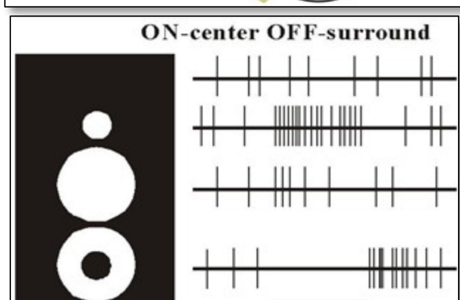
- Neurons connected into circuits (neural networks): emergent properties, learning, memory
- Simple primitives arranged in simple, repetitive, and extremely large networks
- 86 billion neurons, each connects to 10k neurons, 1 quadrillion (10^{12}) connections

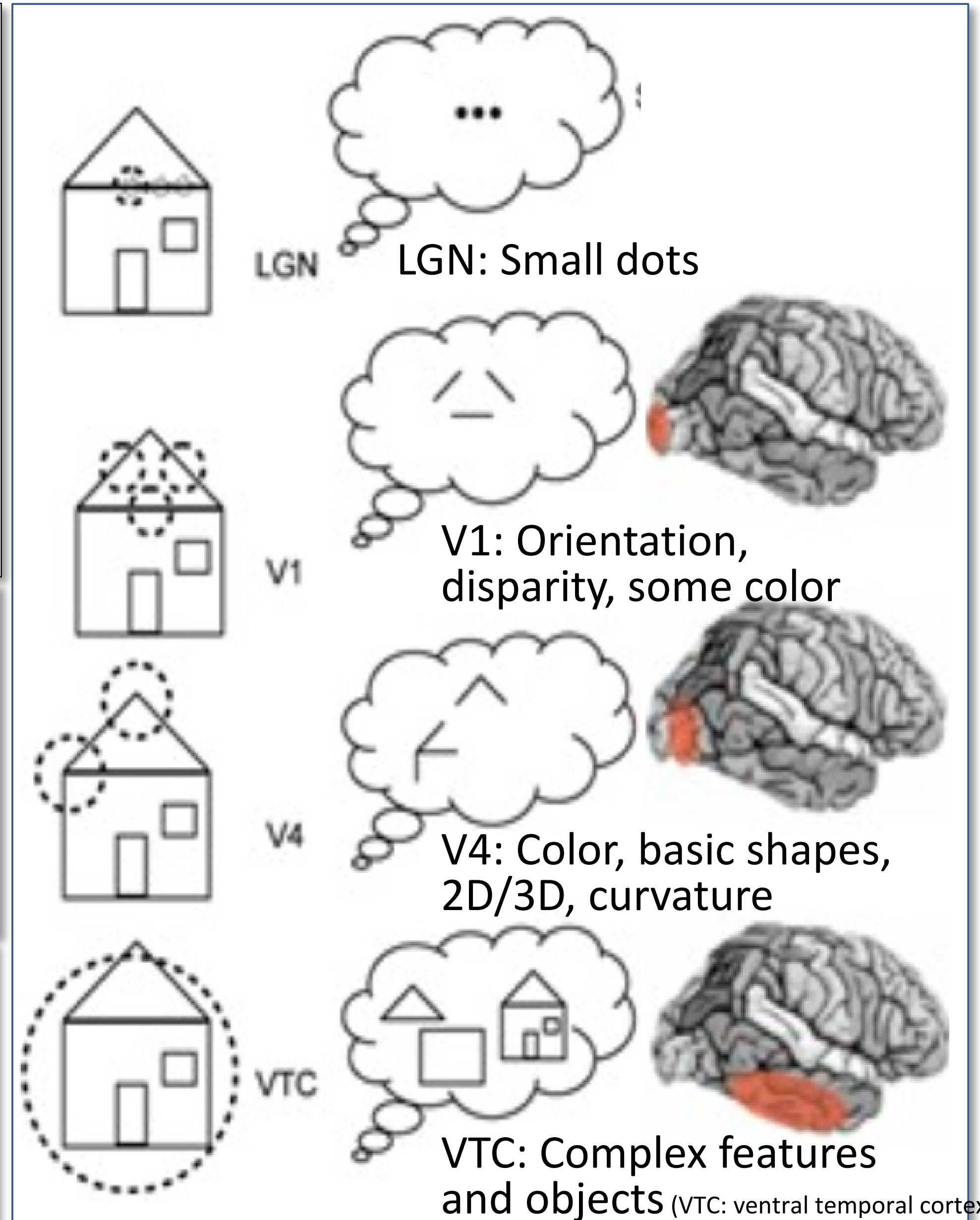
Abstraction layers: edges, bars, dir., shapes, objects, scenes





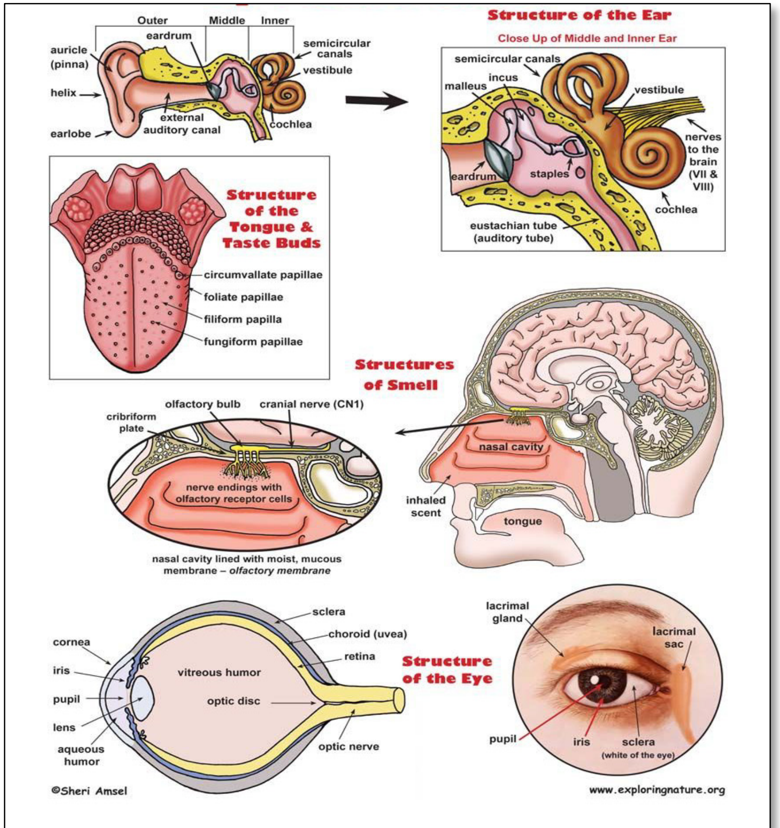




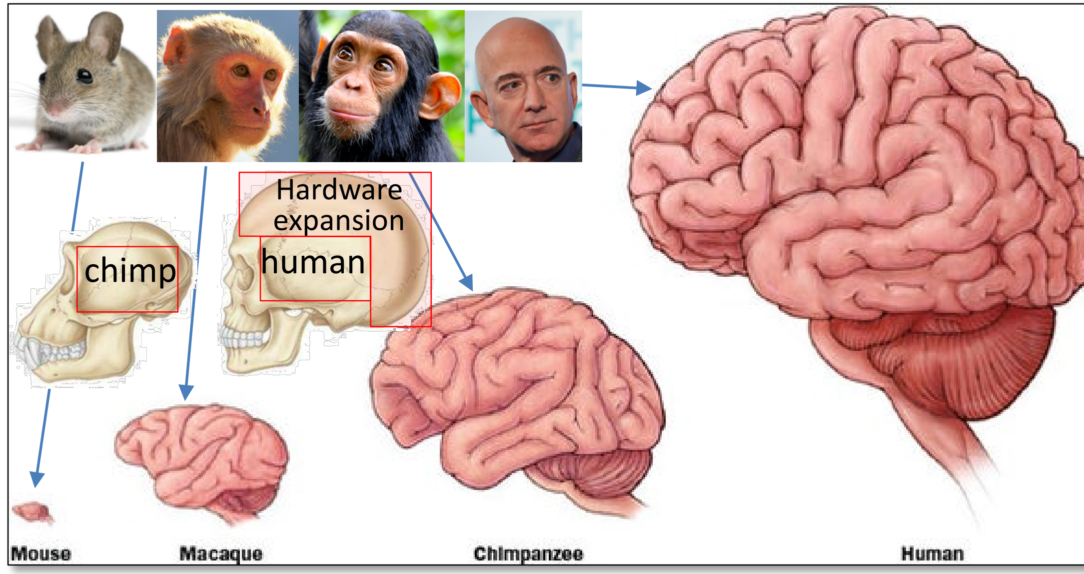


- **Primitives of visual concepts encoded in neuronal connection in early cortical layers**
- **Abstraction layers ⇔ visual cortex layers**
- **Complex concepts from simple parts, hierarchy**

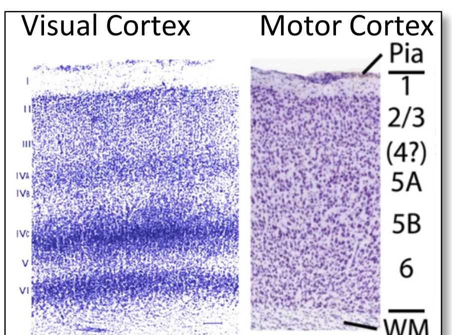
General "learning machine", reused widely



- Hearing, taste, smell, sight, touch all re-use similar learning architecture



- Massive recent expanse of human brain has re-used a relatively simple but general learning architecture



- Interchangeable circuitry
- Auditory cortex learns to 'see' if sent visual signals
- Injury area tasks shift to uninjured areas

- Not fully-general learning, but well-adapted to our world
- Humans co-opted this circuitry to many new applications
- Modern tasks accessible to any homo sapiens (<70k years)
- ML primitives not too different from animals: more to come?

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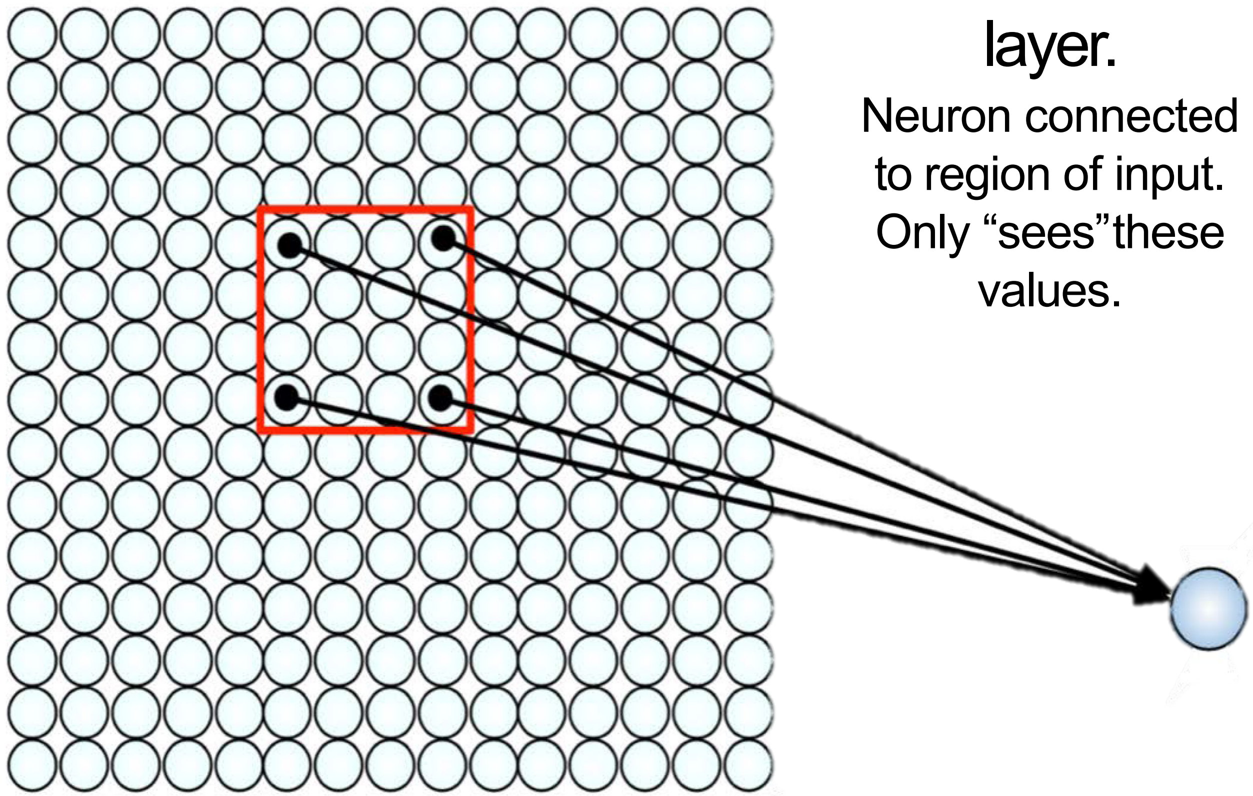
2a. Spatial structure for image recognition

Using Spatial Structure

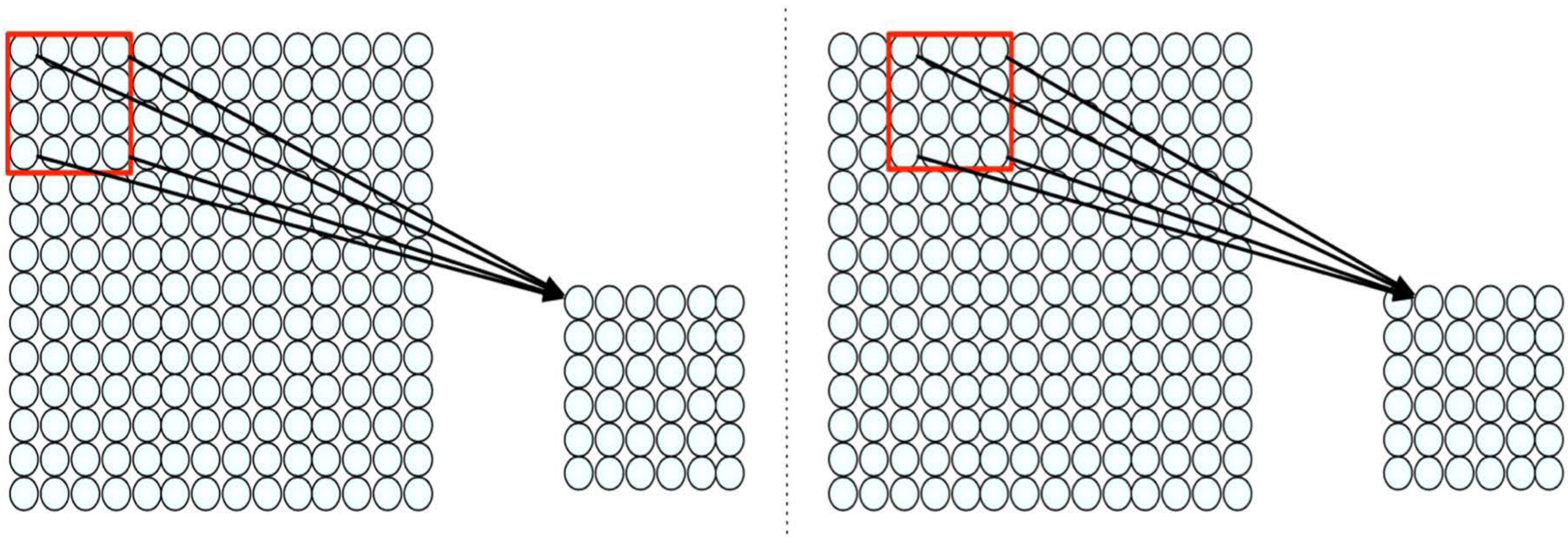
Input: 2D image.
Array of pixel values

Idea: connect patches of input to neurons in hidden layer.

Neuron connected to region of input. Only “sees”these values.

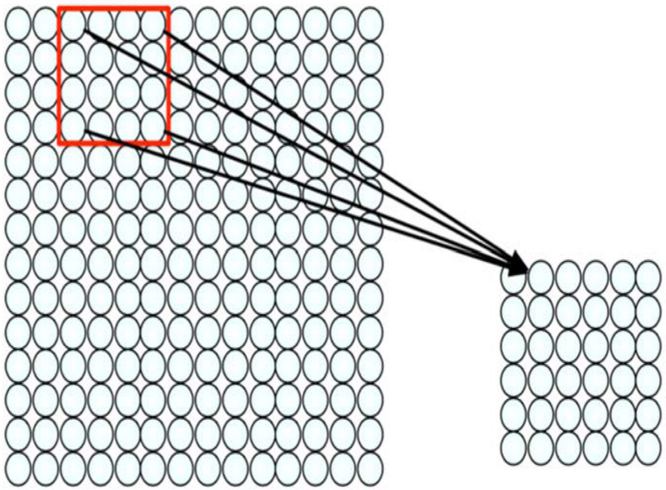


Using Spatial Structure



Connect patch in input layer to a single neuron in subsequent layer.
Use a sliding window to define connections.
How can we **weight** *the patch to detect particular features?*

Feature Extraction with Convolution



- Filter of size 4x4 : 16 different weights
- Apply this same filter to 4x4 patches in input
- Shift by 2 pixels for next patch

This "patchy" operation is **convolution**

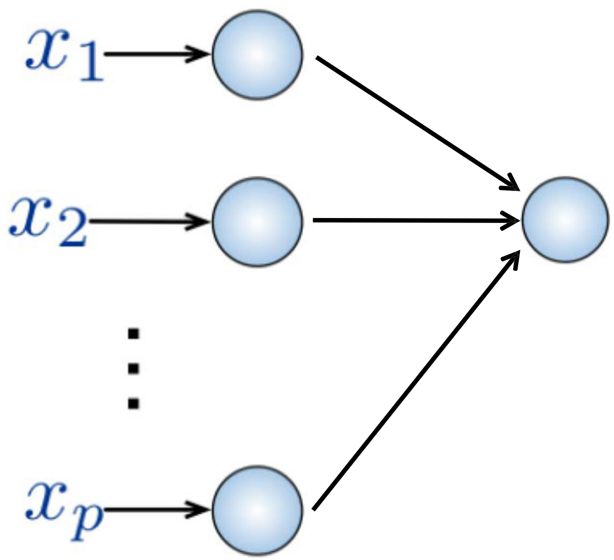
1) Apply a set of weights – a filter – to extract **local features**

2) Use **multiple filters** to extract different features

3) Spatially share parameters of each filter

Fully Connected Neural Network

Input:
- 2D image
- Vector of pixel values



Fully Connected:
- Each neuron in hidden layer connected to all neurons in input layer
- No spatial information
- Many, many parameters

Key idea: Use **spatial structure** in input to inform architecture of the network

High Level Feature Detection

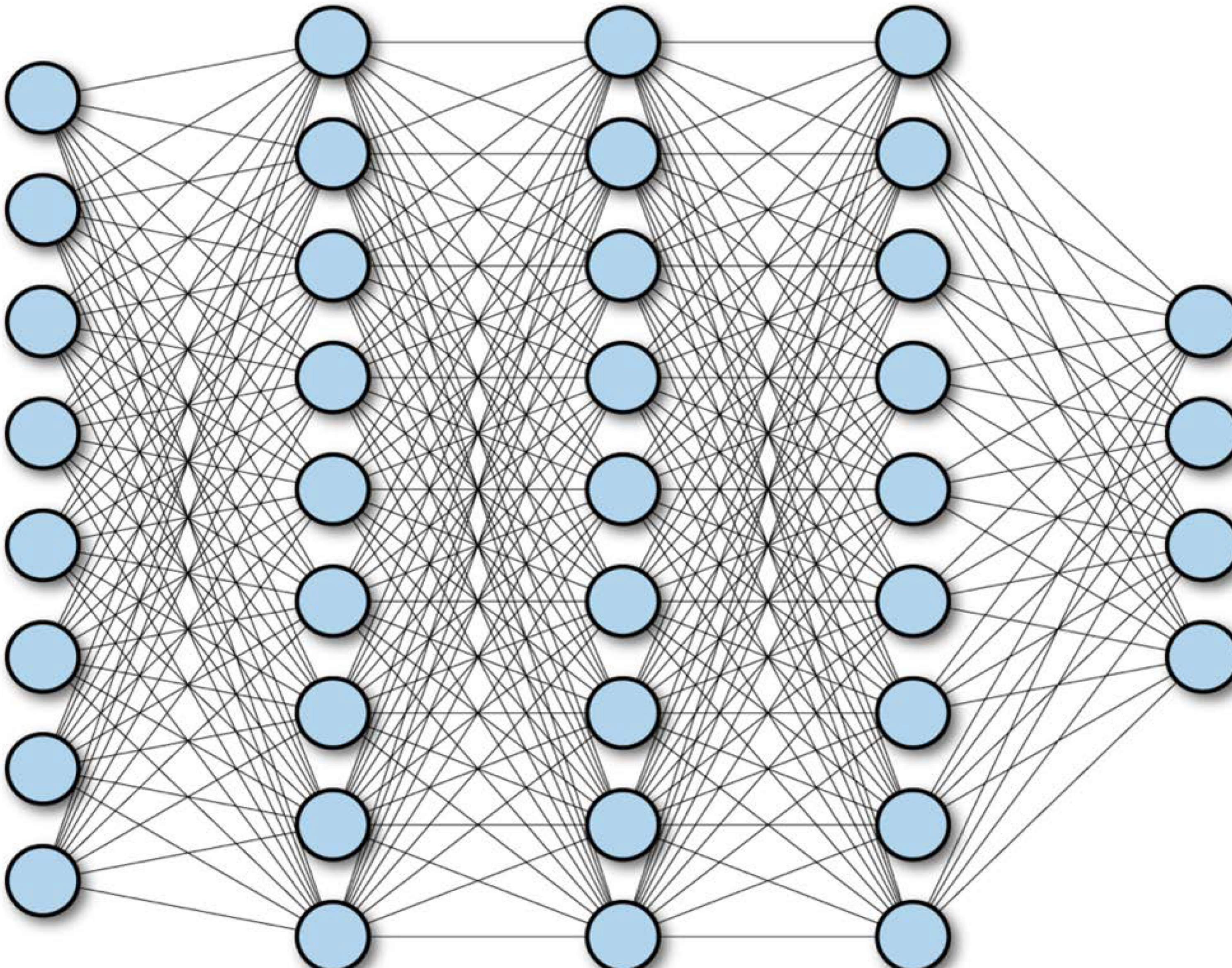
Let's identify key features in each image category

Nose, Eyes, Mouth

Wheels, License Plate, Headlights

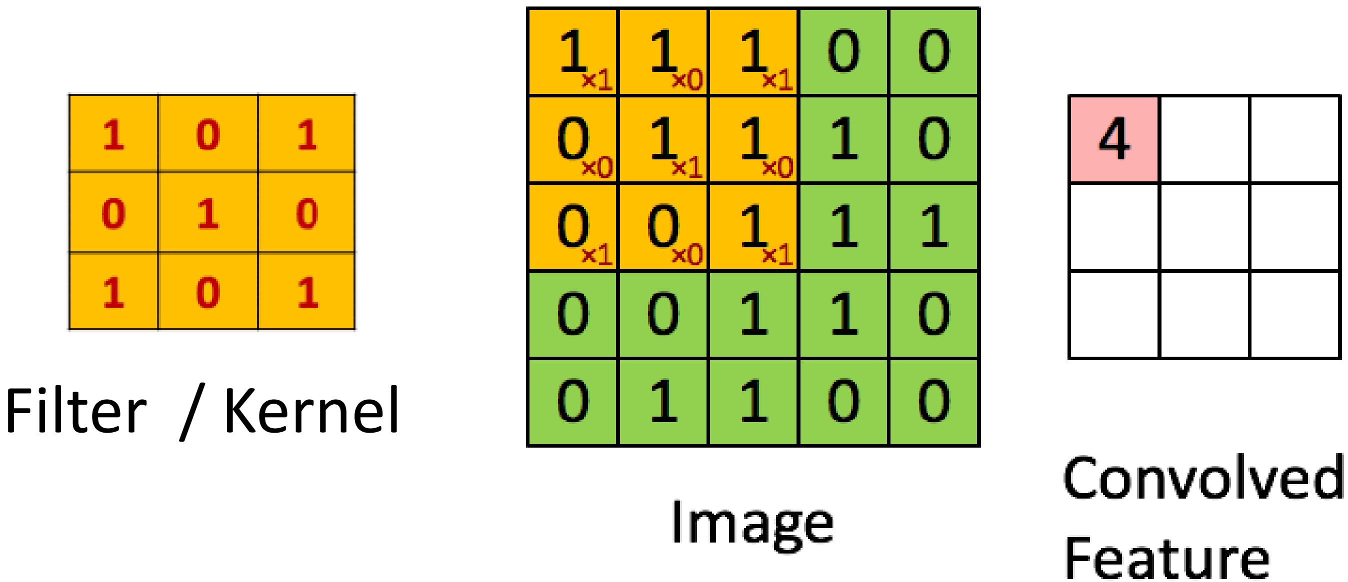
Door, Windows, Steps

Fully Connected Neural Network



2b. Convolutions and filters

Convolution operation is element wise multiply and add

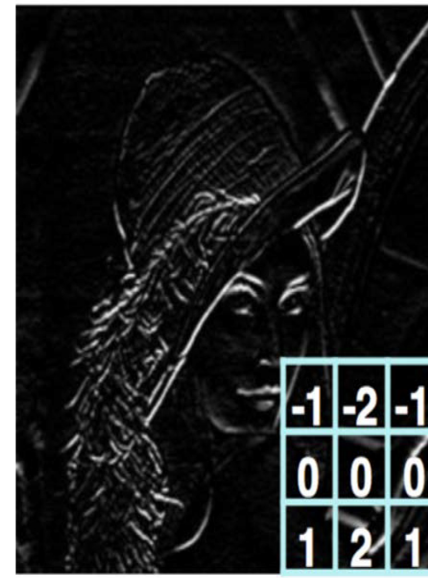


Producing Feature Maps

Original

Sharpen

Edge Detect



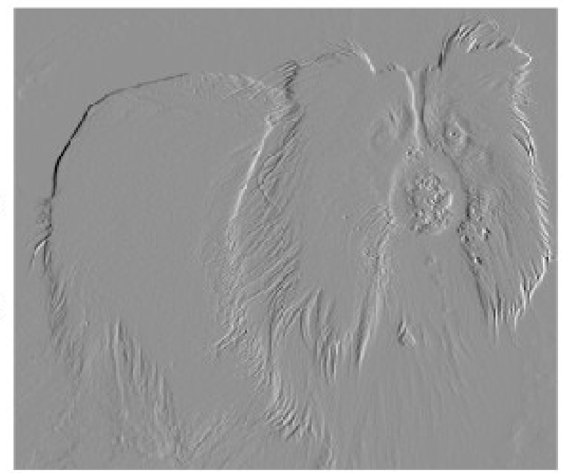
"Strong" Edge Detect

A simple pattern: Edges
How can we detect edges with a kernel?

Input

1	-1

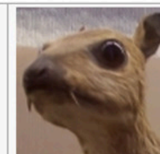
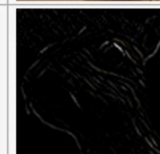
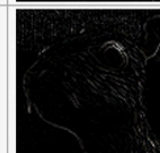
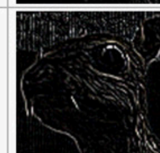
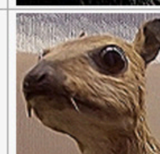
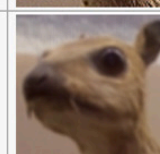
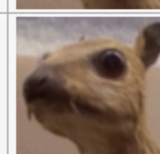
Filter



Output

(Goodfellow 2016)

Simple Kernels / Filters

Operation	Filter	Convolved Image
Identity	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	
Edge detection	$\begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}$	
	$\begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}$	
	$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$	
Sharpen	$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$	
Box blur (normalized)	$\frac{1}{9}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$	
Gaussian blur (approximation)	$\frac{1}{16}\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$	

X or X?

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	-1	-1	-1
-1	-1	1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	-1	-1	1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

$$\stackrel{?}{=}$$

-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	1	-1	-1
-1	1	-1	-1	-1	1	-1	-1	-1
-1	-1	1	1	-1	1	-1	-1	-1
-1	-1	-1	-1	1	-1	-1	-1	-1
-1	-1	-1	1	-1	1	1	-1	-1
-1	-1	-1	1	-1	-1	-1	1	-1
-1	-1	1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1	-1	-1

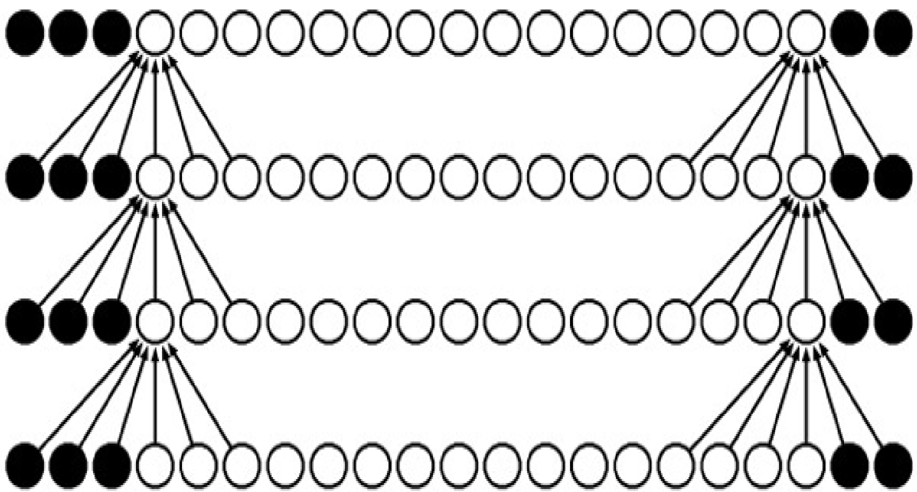
Image is represented as matrix of pixel values… and computers are literal!
We want to be able to classify an X as an X even if it's shifted, shrunk, rotated, deformed.

Rohrer *How do CNNs work?*

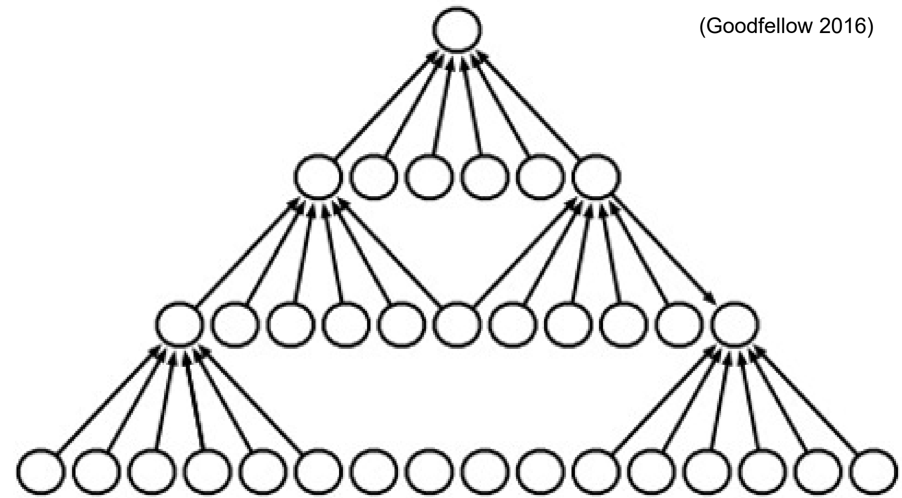
There are three approaches to edge cases in convolution

$$S(i,j) = (I * K)(i,j) = \sum_m \sum_n I(i+m, j+n) K(m,n).$$

Zero Padding Controls Output Size



(Goodfellow 2016)



- **Same convolution**: zero pad input so output is same size as input dimensions
- **Valid-only convolution**: output only when entire kernel contained in input (shrinks output)
- **Full convolution**: zero pad input so output is produced whenever an output value contains at least one input value (expands output)

$$S(i,j) = (I * K)(i,j) = \sum_m \sum_n I(i+m, j+n) K(m,n)$$

```
x = tf.nn.conv2d(x, W, strides=[1,strides,strides,1],padding='SAME')
```

Output Input Kernel Batch H W Input channel

- TF convolution operator takes stride and zero fill option as parameters
- Stride is distance between kernel applications in each dimension
- Padding can be SAME or VALID

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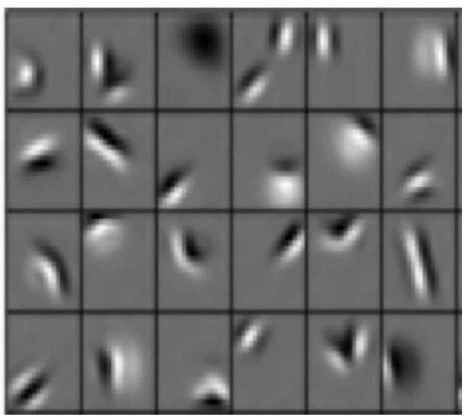
3a. Learning Visual Features *de novo*

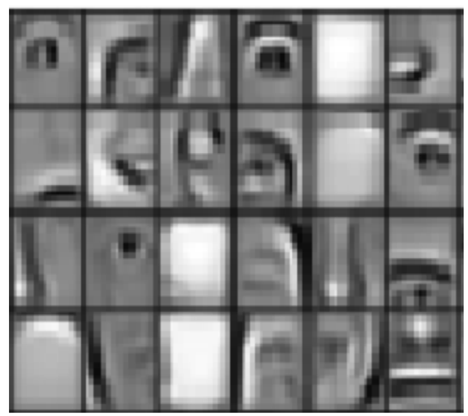
Key idea:
learn hierarchy of features
directly from the data
(rather than hand-engineering them)

Low level features



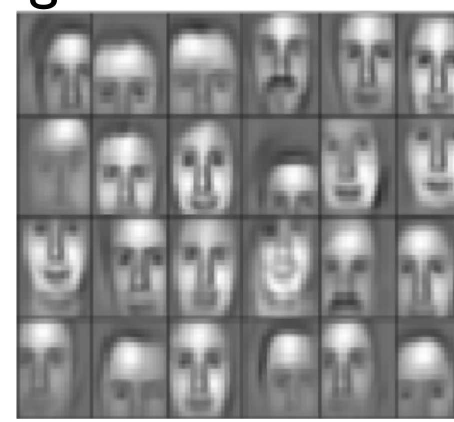
Edges, dark spots

Mid level features



Eyes, ears,nose

High level features



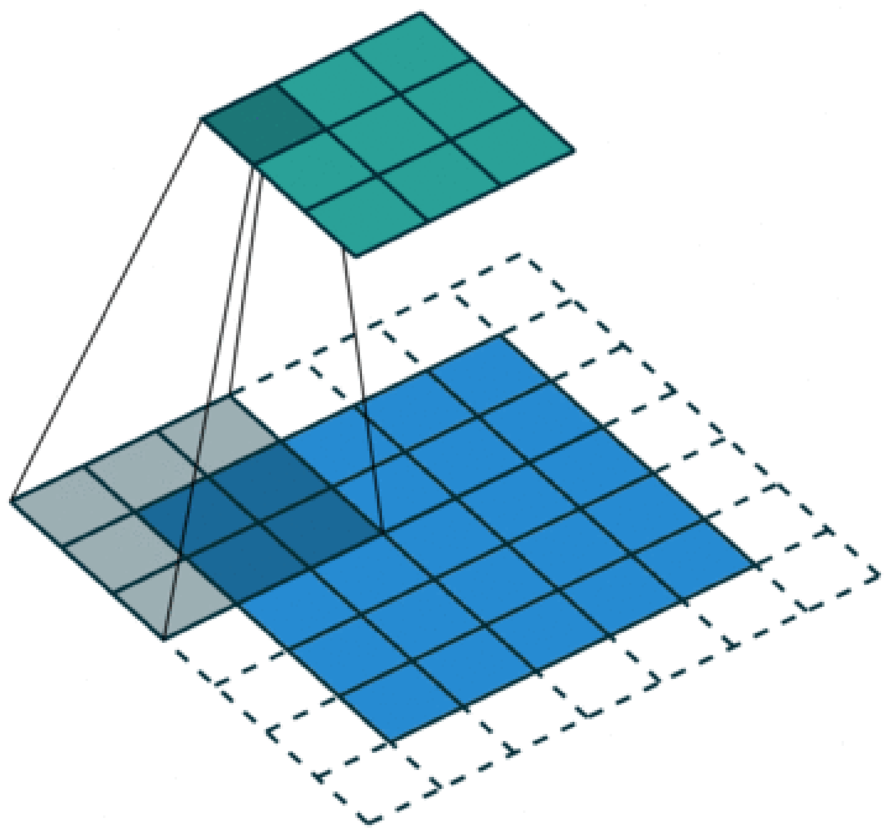
Facial structure

Lee+ *ICML* 2009

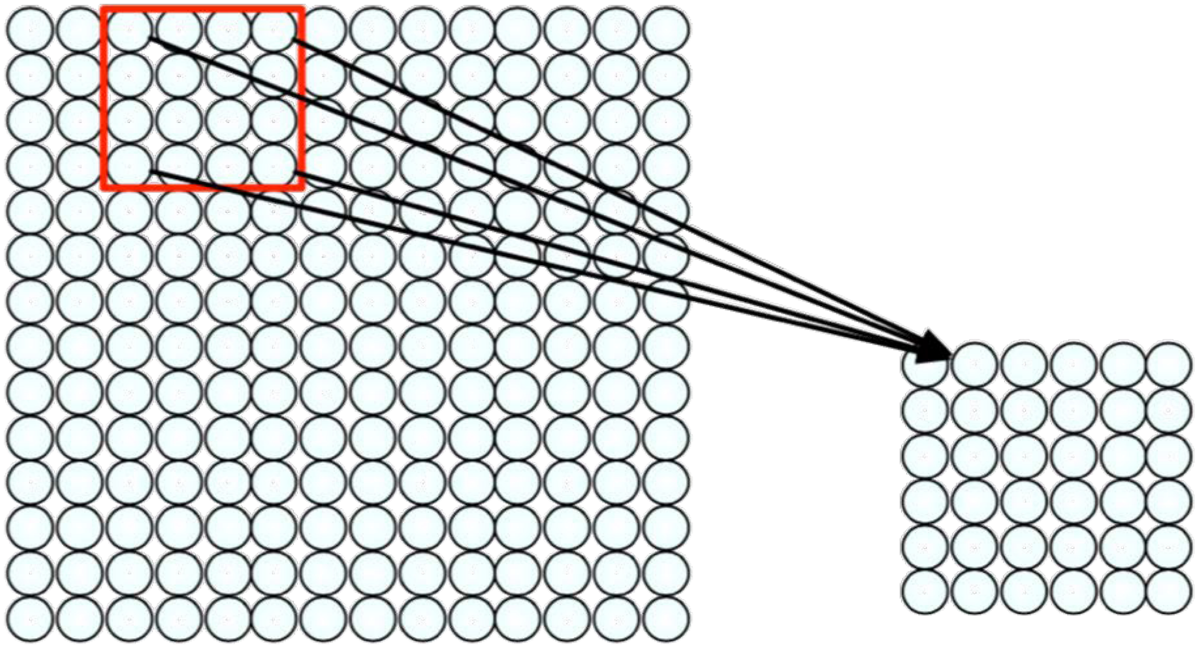
Key idea: re-use parameters

Convolution shares parameters

Example 3x3 convolution on a 5x5 image



Feature Extraction with Convolution



1) Apply a set of weights – a filter – to extract **local features**

2) Use **multiple filters** to extract different features

3) Spatially share parameters of each filter

LeNet-5

- *Gradient Based Learning Applied To Document Recognition - Y. Lecun, L. Bottou, Y. Bengio, P. Haffner; 1998*
- Helped establish how we use CNNs today
- Replaced manual feature extraction

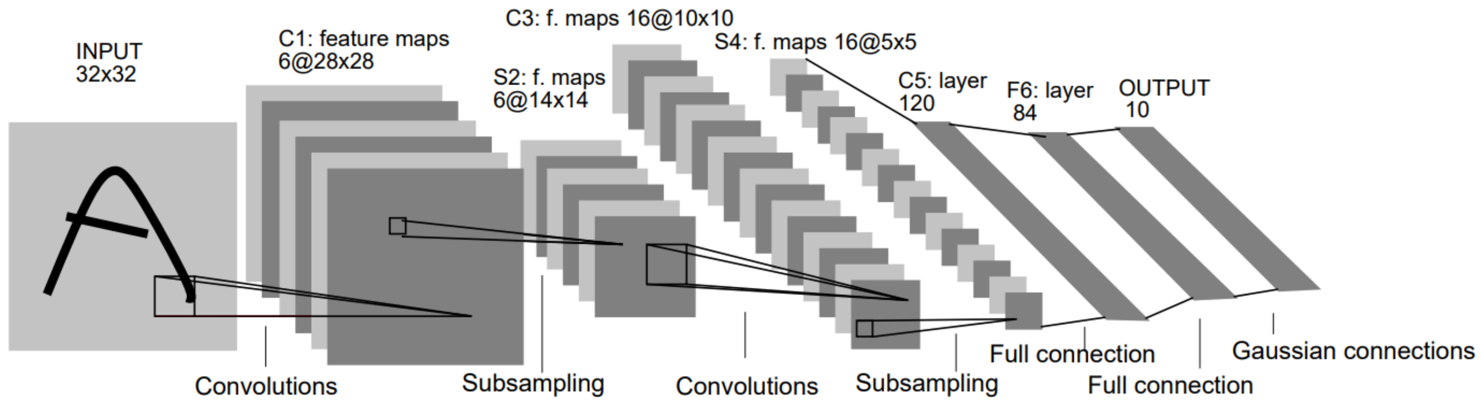
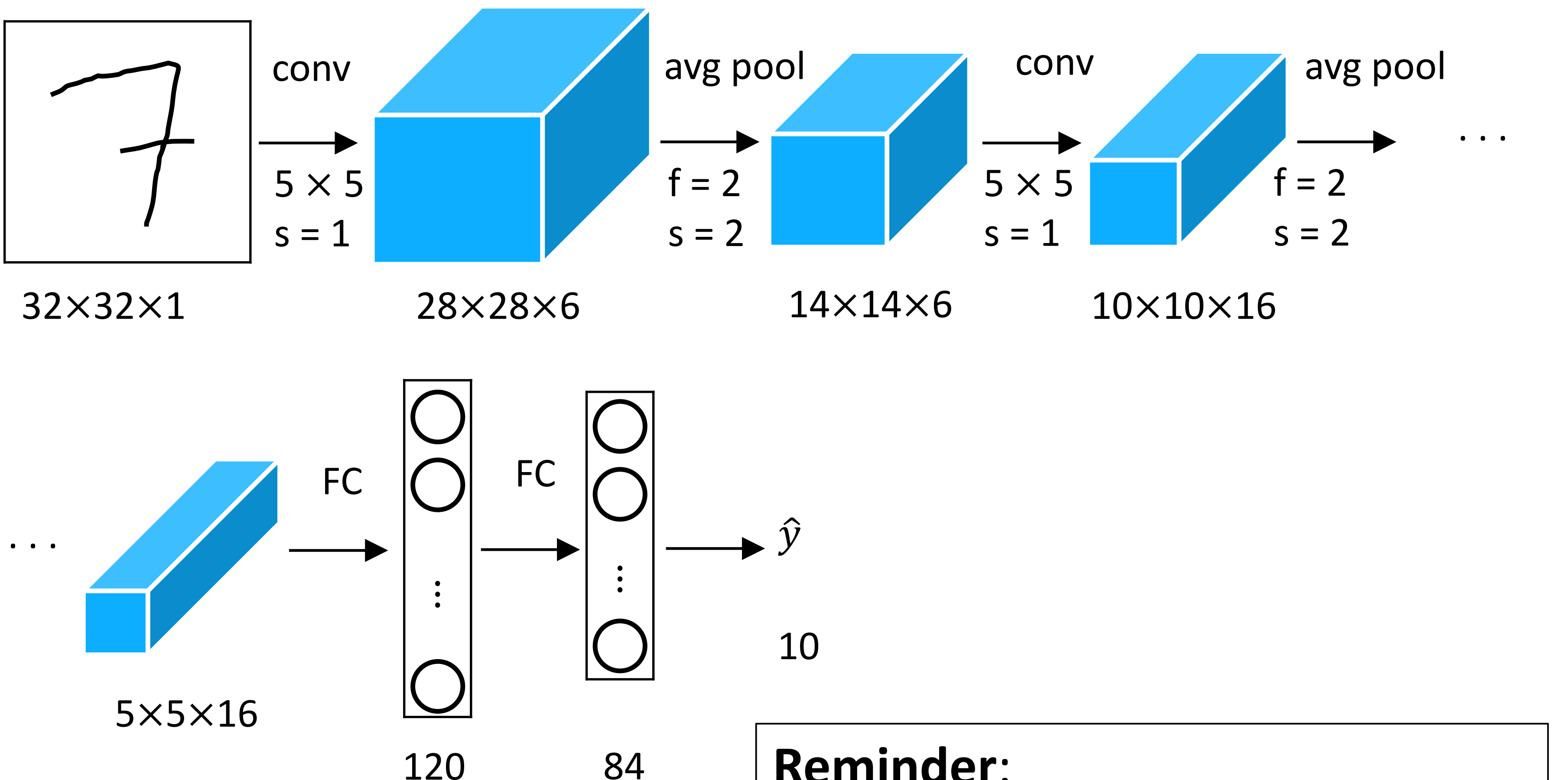


Fig. 2. Architecture of LeNet-5, a Convolutional Neural Network, here for digits recognition. Each plane is a feature map, i.e. a set of units whose weights are constrained to be identical.

[**LeCun et al.**, **1998**]

LeNet-5



Reminder:
Output size = (N+2P-F)/stride + 1

[**LeCun et al.**, **1998**]

This slide is taken from Andrew Ng

LeNet-5

- Only 60K parameters
- As we go deeper in the network: $N_H \downarrow,\ N_W\downarrow,\ N_C \uparrow$
- General structure:
  conv->pool->conv->pool->FC->FC->output

- Different filters look at different channels
- Sigmoid and Tanh nonlinearity

[**LeCun et al**., **1998**]

Backpropagation of convolution

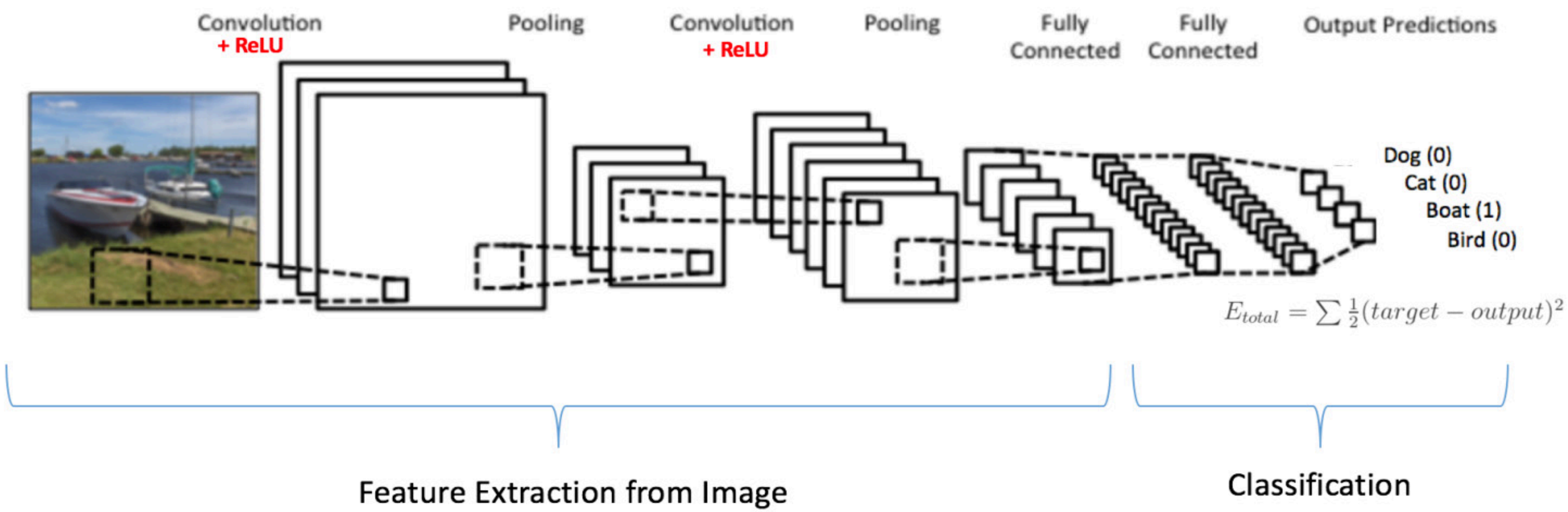
$$\begin{bmatrix} O_{11} & O_{12} \\ O_{21} & O_{22} \end{bmatrix} = \textbf{Convolution}\left(\begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}, \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} \right)$$

$$\begin{bmatrix} \partial E/\partial F_{11} & \partial E/\partial F_{12} \\ \partial E/\partial F_{21} & \partial E/\partial F_{22} \end{bmatrix} = \textbf{Convolution}\left(\begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}, \begin{bmatrix} \partial E/\partial O_{11} & \partial E/\partial O_{12} \\ \partial E/\partial O_{21} & \partial E/\partial O_{22} \end{bmatrix} \right)$$

Slide taken from Forward And Backpropagation in Convolutional Neural Network. - Medium

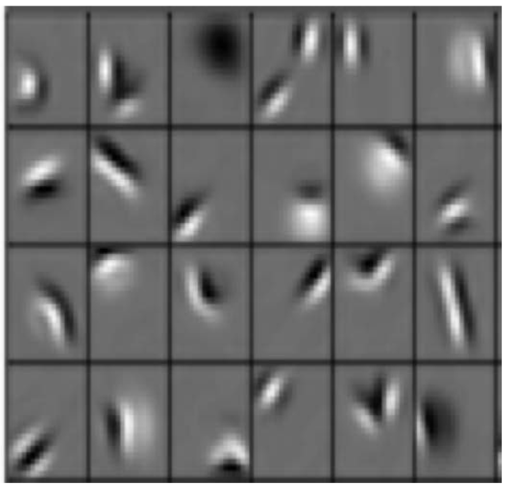
3b. Convolutional Neural Networks (CNNs)

An image classification CNN



Representation Learning in Deep CNNs

Low level features



Edges, dark spots

Conv Layer 1

Mid level features

Eyes, ears,nose

Conv Layer 2

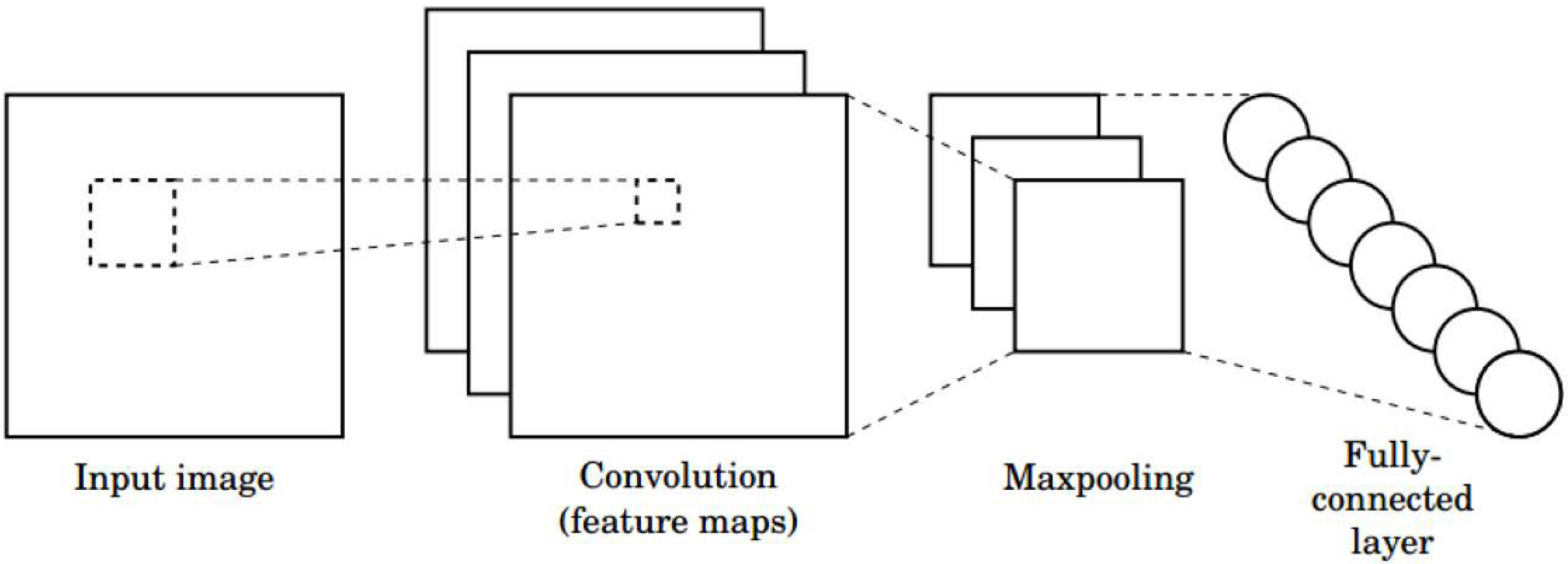
High level features

Facial structure

Conv Layer 3

Lee+ *ICML* 2009

CNNs for Classification



1. **Convolution**: Apply filters to generate feature maps.
2. **Non-linearity**: Often ReLU.
3. **Pooling**: Downsampling operation on each feature map.

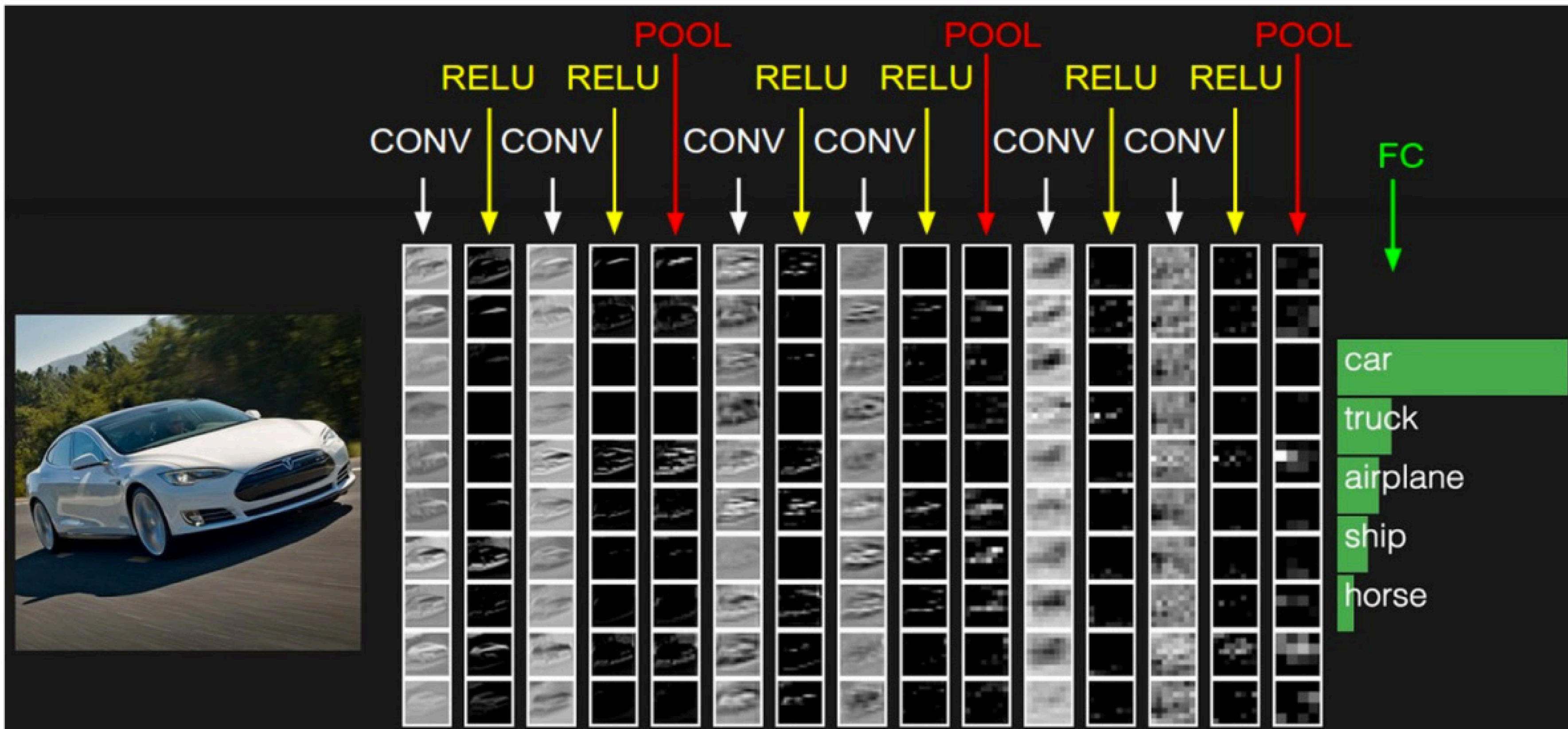
Train model with image data.
Learn weights of filters in convolutional layers.

```
tf.keras.layers.Conv2D
```

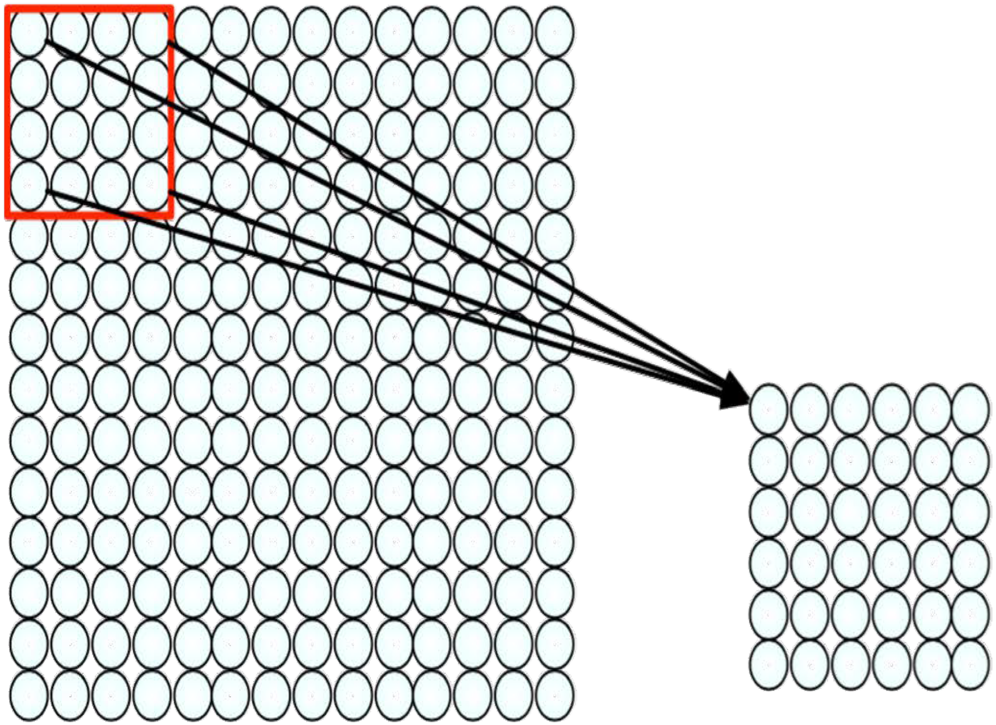
```
tf.keras.activations.*
```

```
tf.keras.layers.MaxPool2D
```

Example – Six convolutional layers



Convolutional Layers: Local Connectivity



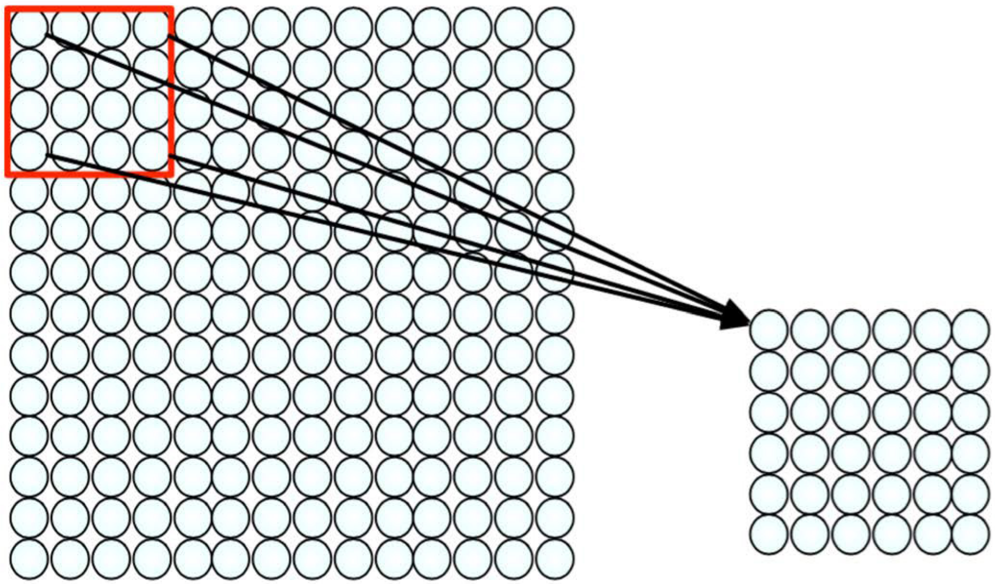
`tf.keras.layers.Conv2D`

For a neuron in hidden layer:

- Take inputs from patch
- Compute weighted sum
- Apply bias

Convolutional Layers: Local Connectivity

`tf.keras.layers.Conv2D`



For a neuron in hidden layer:
- Take inputs from patch
- Compute weighted sum
- Apply bias

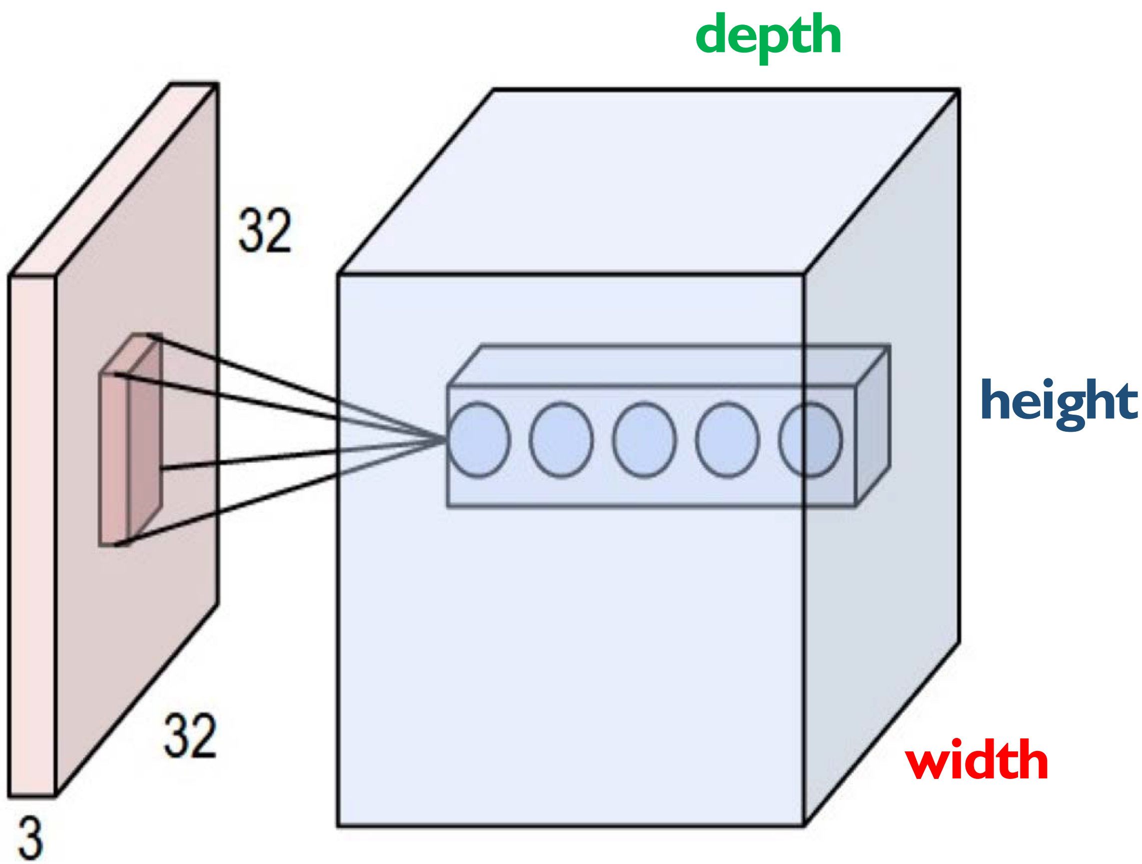
4x4 filter: matrix of weights w_{ij}

$$\sum_{i=1}^{4}\sum_{j=1}^{4} w_{ij}\, x_{i+p,j+q} + b$$

for neuron (p,q) in hidden layer

1) applying a window of weights
2) computing linear combinations
3) activating with non-linear function

CNNs: Spatial Arrangement of Output Volume



Layer Dimensions:

$$h \times w \times d$$

where h and w are spatial dimensions d (depth) = number of filters

Stride:

Filter step size

Receptive Field:

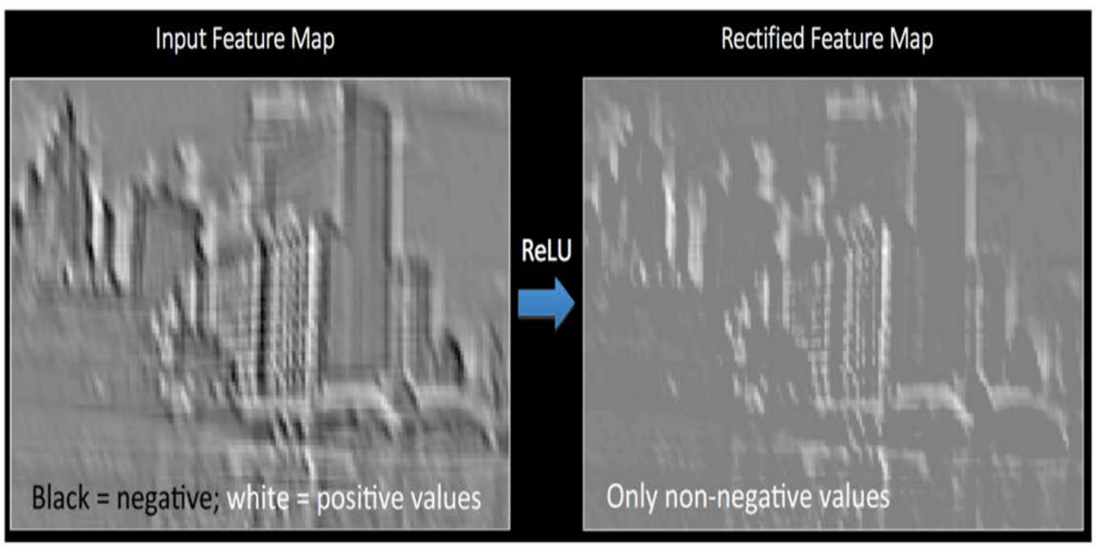
Locations in input image that a node is path connected to

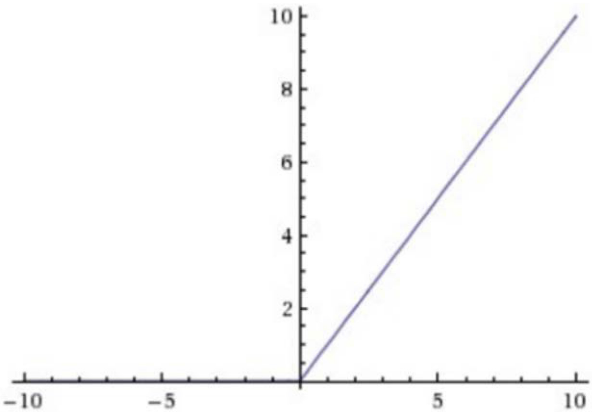
```
tf.keras.layers.Conv2D( filters=d, kernel_size=(h,w), strides=s )
```

Introducing Non-Linearity

- Apply after every convolution operation (i.e., after convolutional layers)
- ReLU: pixel-by-pixel operation that replaces all negative values by zero.
- **Non-linear operation**

Rectified Linear Unit (ReLU)

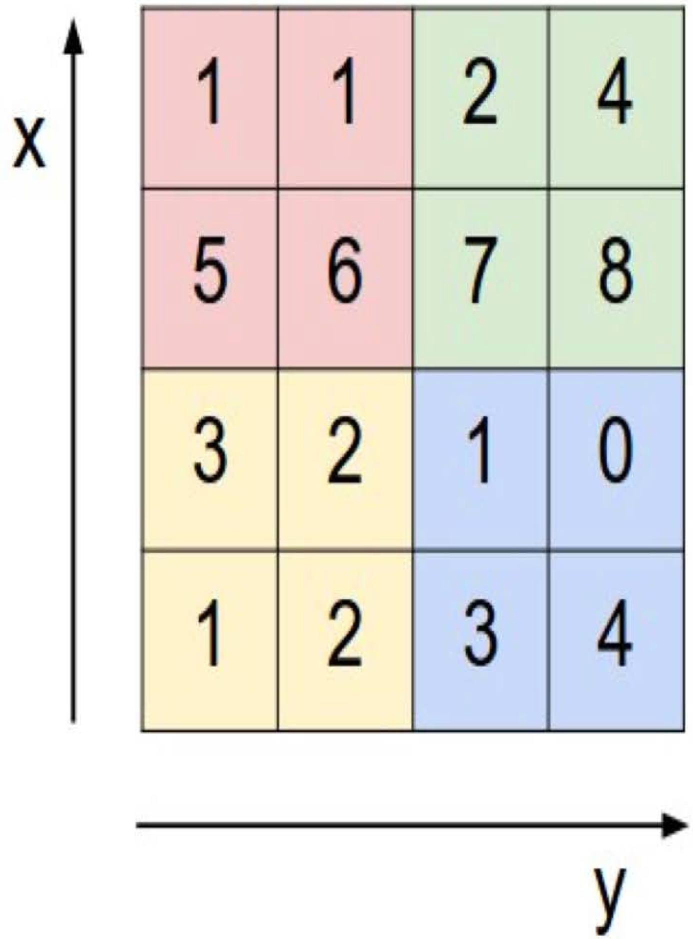




$$g(z) = \max(0, z)$$

```
tf.keras.layers.ReLU
```

Pooling



max pool with 2x2 filters
and stride 2

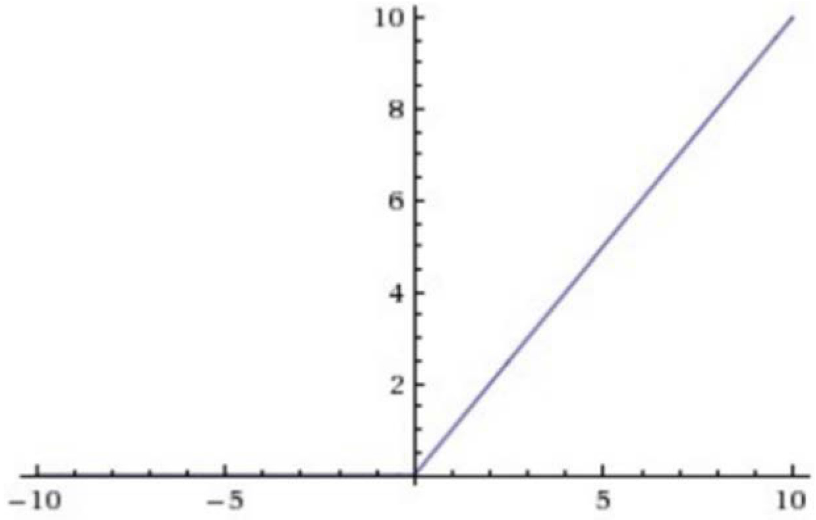
```
tf.keras.layers.Max
    Pool2D(
    pool_size=(2,2),
)   strides=2
```

1) Reduced dimensionality
2) Spatial invariance

Max Pooling, average pooling

The REctified Linear Unit (RELU) is a common non-linear **detector** stage after convolution

```
x = tf.nn.conv2d(x, W, strides=[1, strides, strides, 1], padding='SAME')
x = tf.nn.bias_add(x, b)
x= tf.nn.relu(x)
```



f(x) = max(0, x)

When will we backpropagate through this?

Once it “dies” what happens to it?

Pooling reduces dimensionality by giving up spatial location

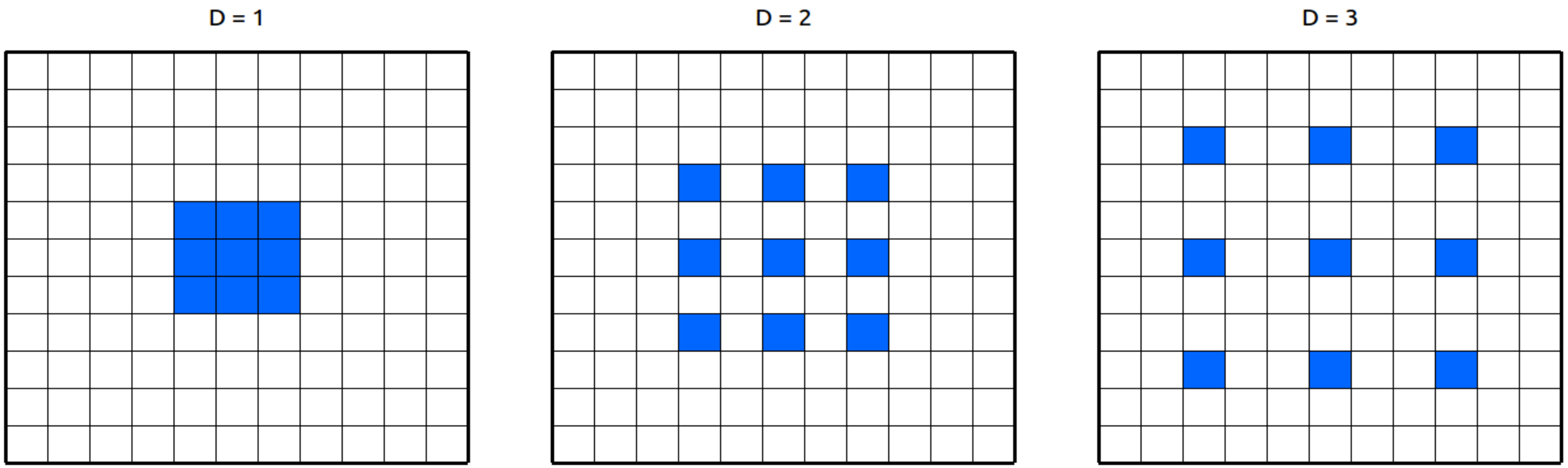
- **max pooling** reports the maximum output within a defined neighborhood
- Padding can be SAME or VALID

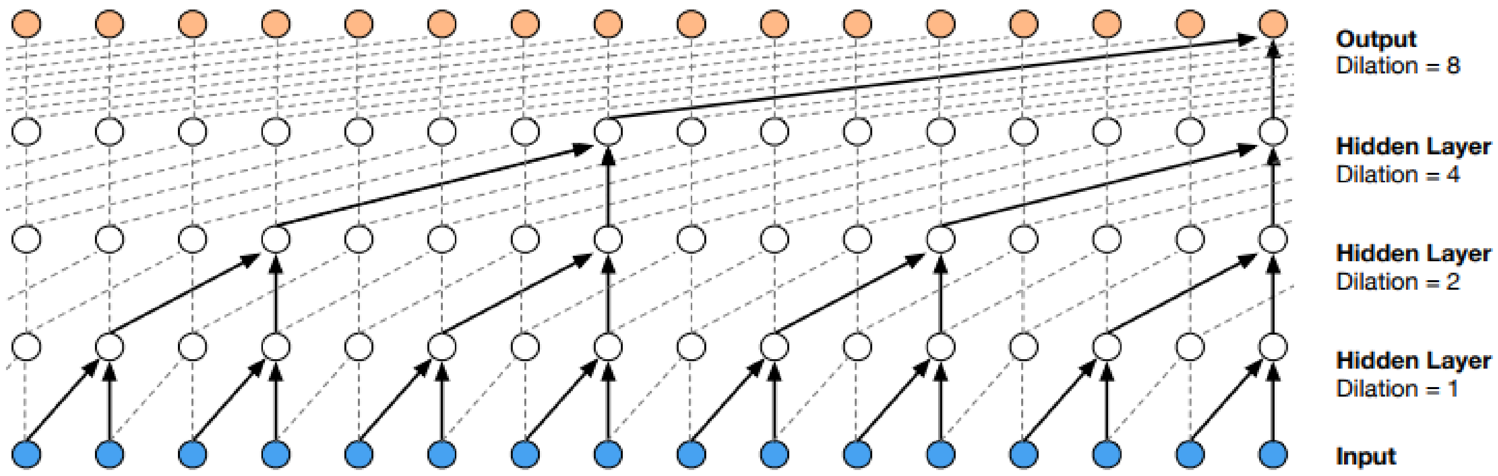
```
x = tf.nn.max_pool(x, ksize=[1, k, k, 1], strides=[1, k, k, 1], padding='SAME')
```

Output Input Pooling Neighborhood Batch H W Input channel

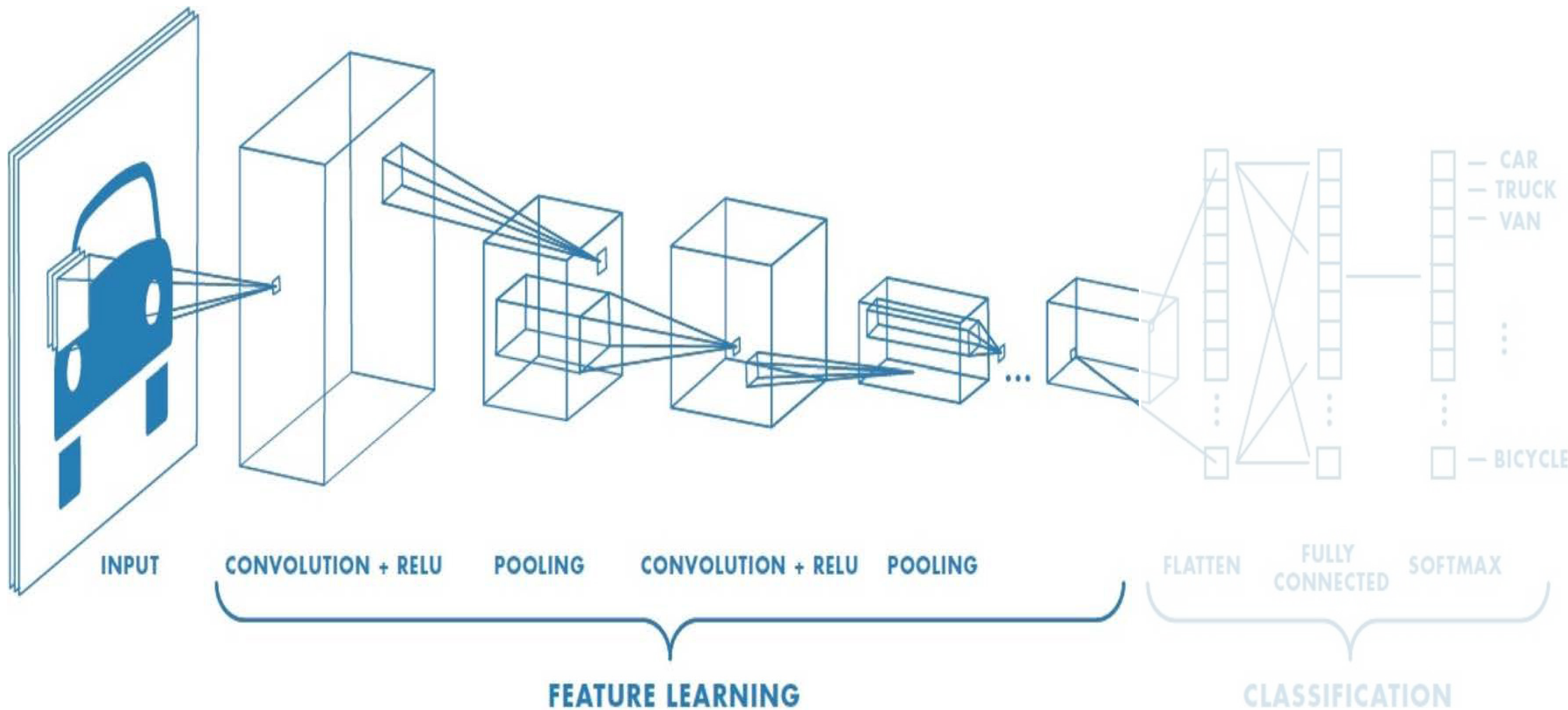
[batch, height, width, channels]

Dilated Convolution



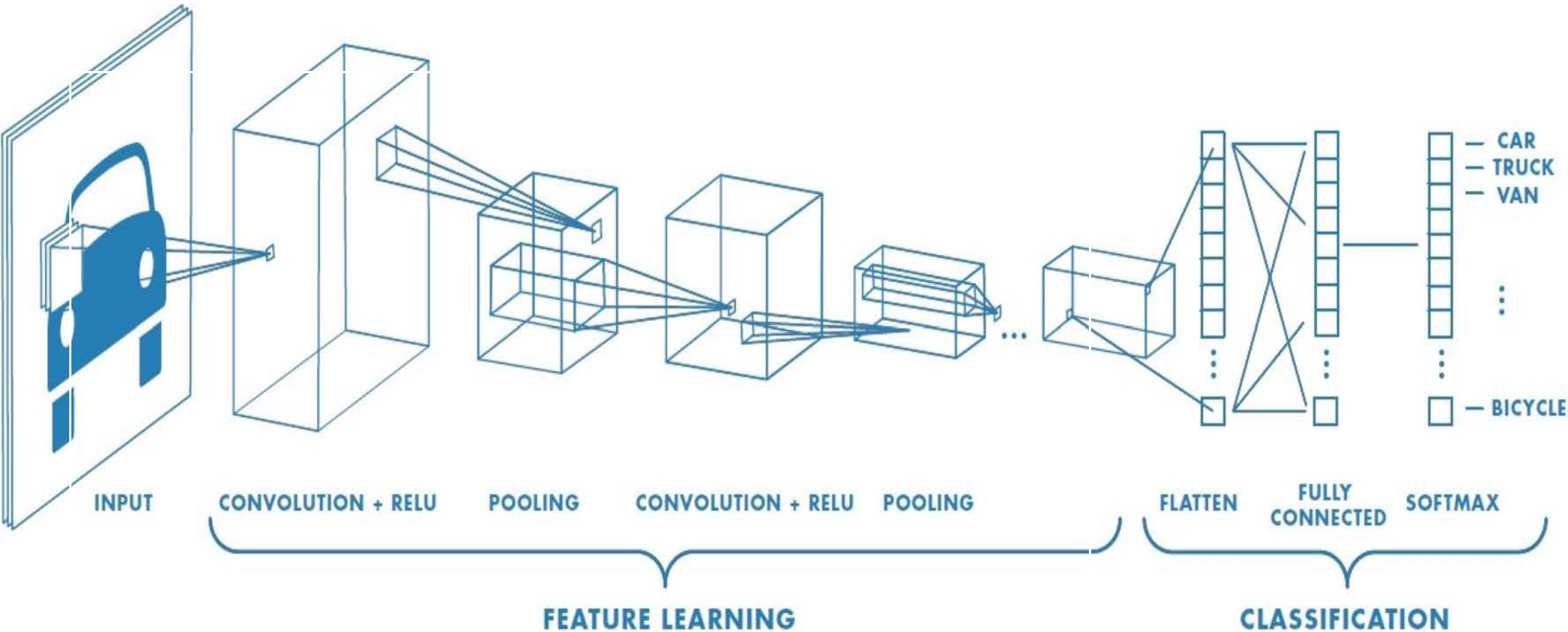


CNNs for Classification: Feature Learning



1. Learn features in input image through **convolution**
2. Introduce **non-linearity** through activation function (real-world data is non-linear!)
3. Reduce dimensionality and preserve spatial invariance with **pooling**

CNNs for Classification: Class Probabilities



$$\text{softmax}(y_i) = \frac{e^{y_i}}{\sum_j e^{y_j}}$$

- CONV and POOL layers output high-level features of input
- Fully connected layer uses these features for classifying input image
- Express output as **probability** of image belonging to a particular class

Putting it all together

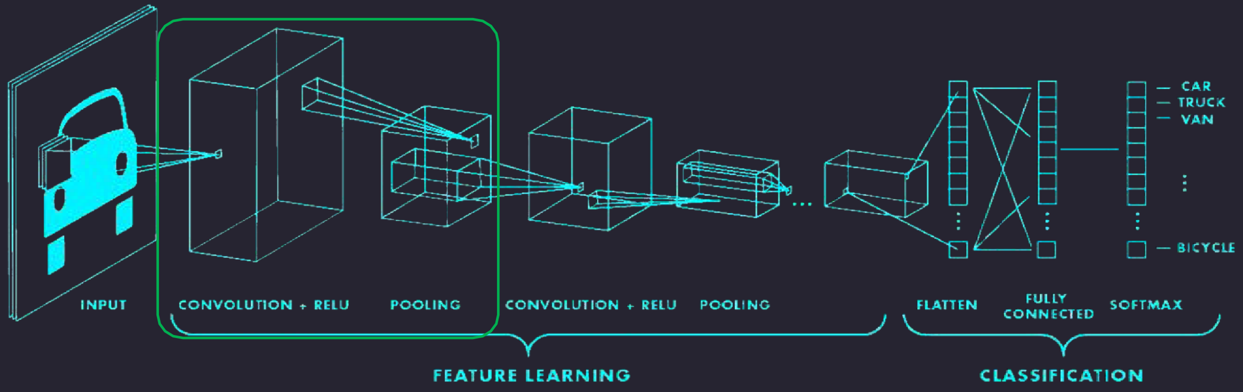
```python
import tensorflow as tf

def generate_model():
    model = tf.keras.Sequential([
        # first convolutional layer
        tf.keras.layers.Conv2D(32, filter_size=3, activation='relu’),
        tf.keras.layers.MaxPool2D(pool_size=2, strides=2),

        # second convolutional layer
        tf.keras.layers.Conv2D(64, filter_size=3, activation='relu’),
        tf.keras.layers.MaxPool2D(pool_size=2, strides=2),

      # fully connected classifier
      tf.keras.layers.Flatten(),
      tf.keras.layers.Dense(1024, activation='relu’),
      tf.keras.layers.Dense(10, activation=‘softmax’)
      # 10 outputs

  ])
  return model
```



Today: Convolutional Neural Networks (CNNs)

1. **Scene understanding and object recognition for machines (and humans)**
   - Scene/object recognition challenge. Illusions reveal primitives, conflicting info
   - Human neurons/circuits. Visual cortex layers==abstraction. General cognition
2. **Classical machine vision foundations: features, scenes, filters, convolution**
   - Spatial structure primitives: edge detectors & other filters, feature recognition
   - Convolution: basics, padding, stride, object recognition, architectures
3. **CNN foundations: LeNet, *de novo* feature learning, parameter sharing**
   - Key ideas: ***learn*** features, hierarchy, re-use parameters, back-prop filter learning
   - CNN formalization: representations(Conv+ReLU+Pool)*N layers + Fully-connected
4. **Modern CNN architectures: millions of parameters, dozens of layers**
   - Feature invariance is hard: apply perturbations, learn for each variation
   - ImageNet progression of best performers
   - AlexNet: First top performer CNN, 60M parameters (from 60k in LeNet-5), ReLU
   - VGGNet: simpler but deeper (8→19 layers), 140M parameters, ensembles
   - GoogleNet: new primitive=inception module, 5M params, no FC, efficiency
   - ResNet: 152 layers, vanishing gradients → fit residuals to enable learning
5. **Countless applications: General architecture, enormous power**
   - Semantic segmentation, facial detection/recognition, self-driving, image colorization, optimizing pictures/scenes, up-scaling, medicine, biology, genomics

4a. Real-world feature invariance is hard

How can computers recognize objects?

How can computers recognize objects?

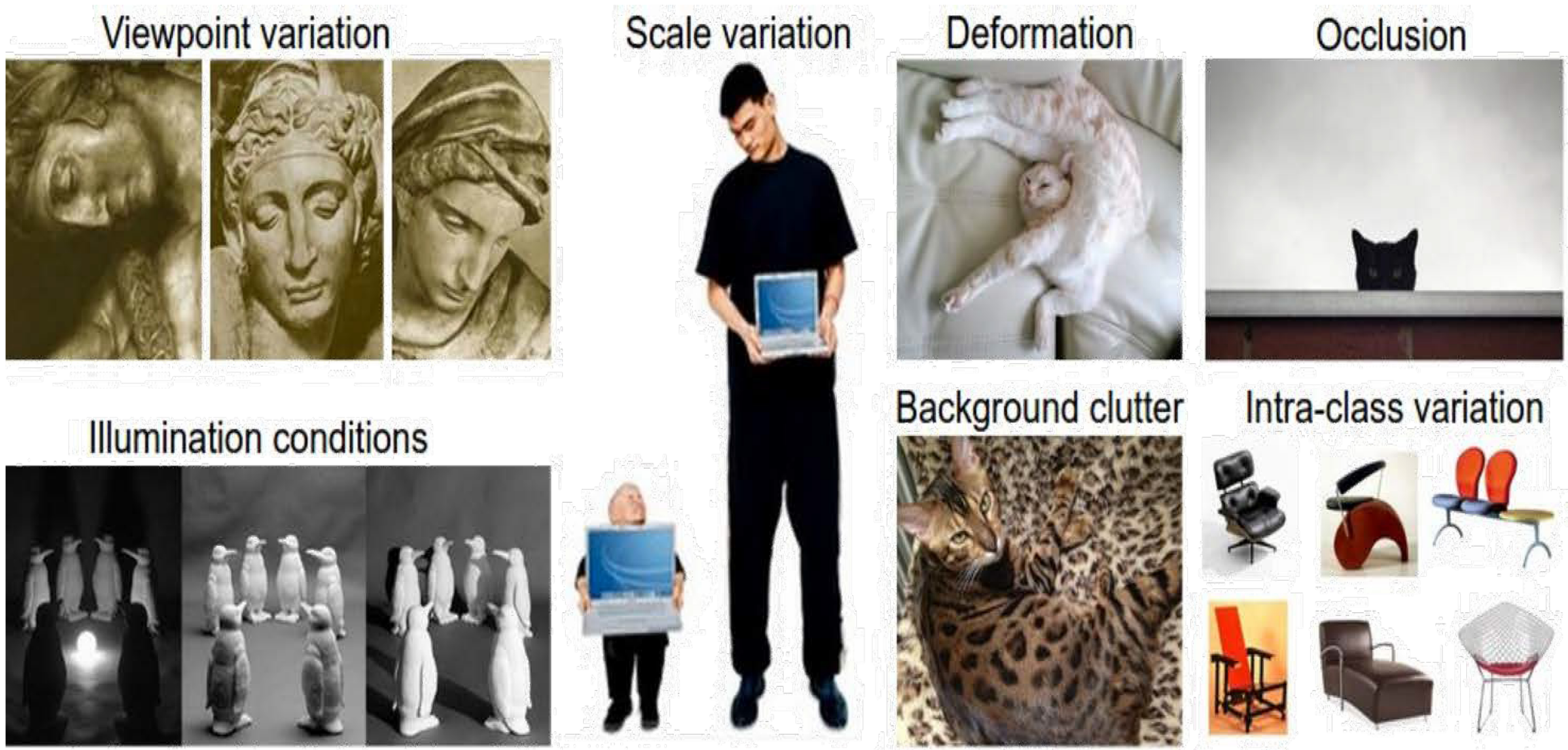
Challenge:

- Objects can be anywhere in the scene, in any orientation, rotation, color hue, etc.
- How can we overcome this challenge?

Answer:

- Learn a ton of features (millions) from the bottom up
- Learn the convolutional filters, rather than pre-computing them

Feature invariance to perturbation is hard



Next-generation models explode # of parameters

LeNet-5

- *Gradient Based Learning Applied To Document Recognition - Y. Lecun, L. Bottou, Y. Bengio, P. Haffner; 1998*
- Helped establish how we use CNNs today
- Replaced manual feature extraction

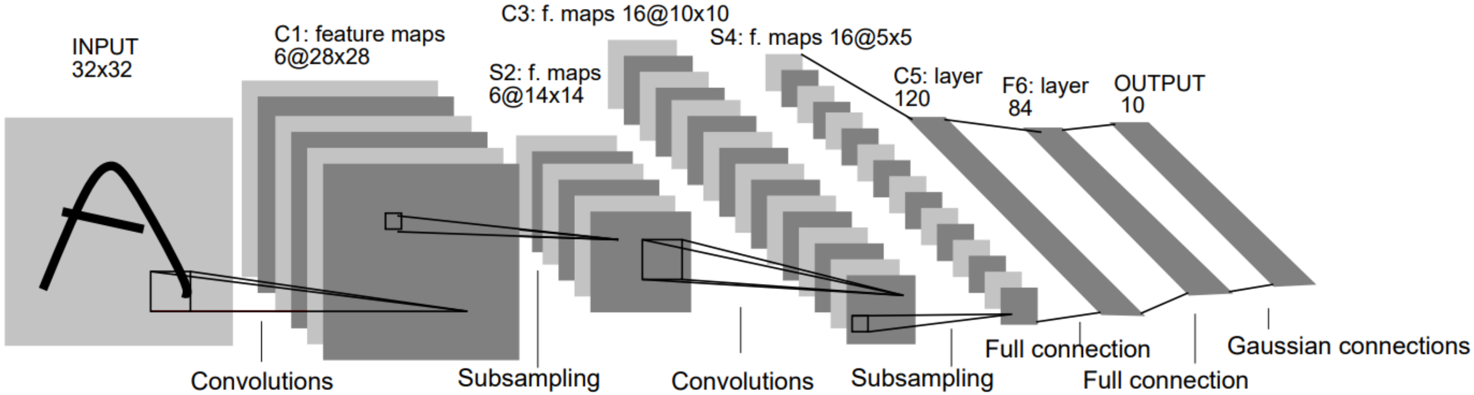
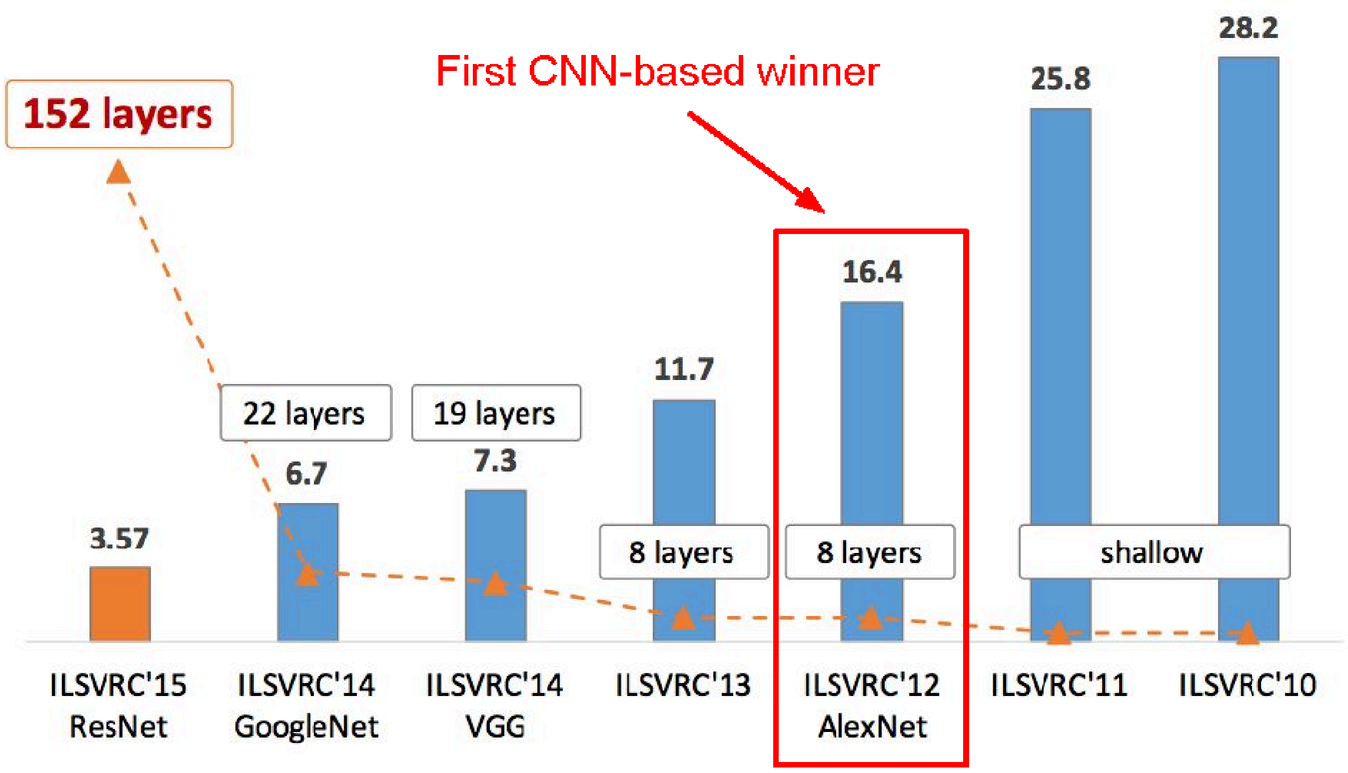


Fig. 2. Architecture of LeNet-5, a Convolutional Neural Network, here for digits recognition. Each plane is a feature map, i.e. a set of units whose weights are constrained to be identical.

[**LeCun et al.**, **1998**]

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

AlexNet

- *ImageNet Classification with Deep Convolutional Neural Networks - Alex Krizhevsky, Ilya Sutskever, Geoffrey E. Hinton; 2012*
- Facilitated by GPUs, highly optimized convolution implementation and large datasets (ImageNet)
- One of the largest CNNs to date
- Has 60 Million parameter compared to 60k parameter of LeNet-5

[**Krizhevsky et al.**, **2012**]

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

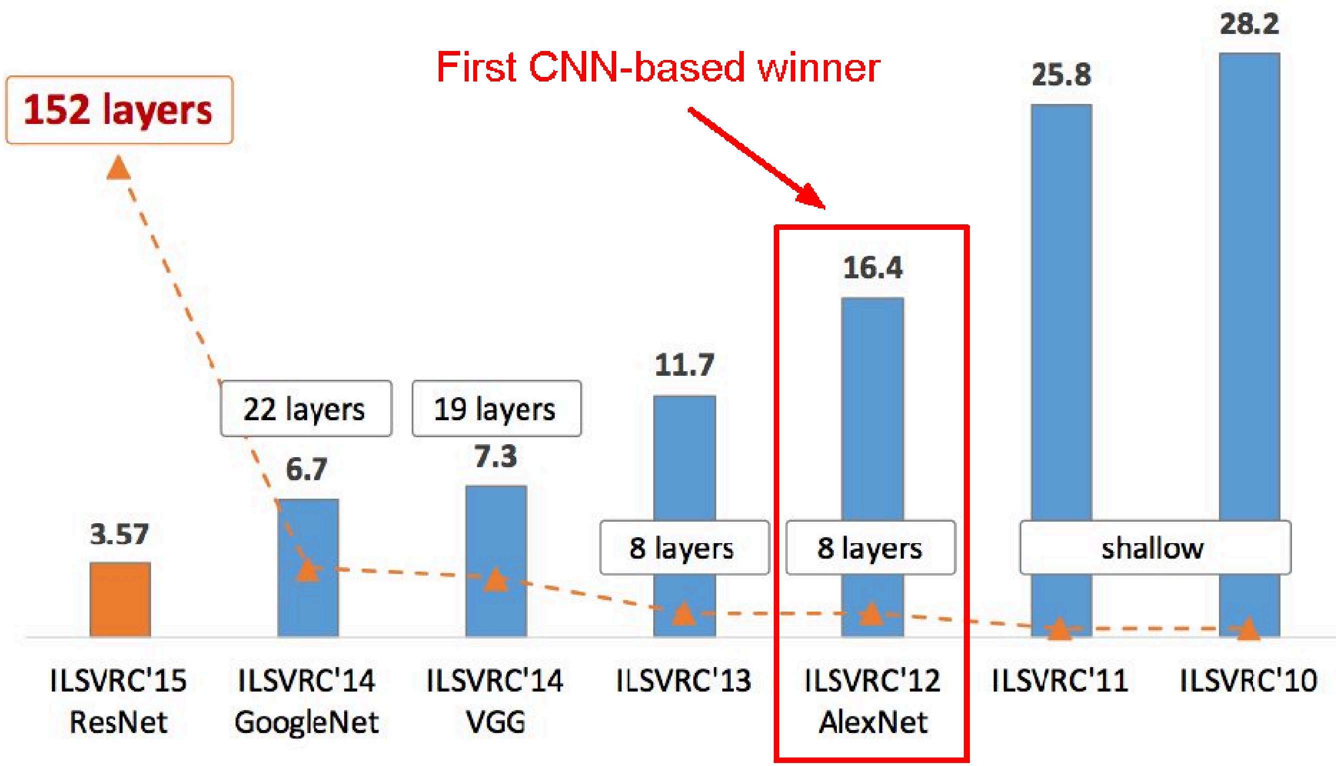
- The annual “Olympics” of computer vision.

- Teams from across the world compete to see who has the best computer vision model for tasks such as classification, localization, detection, and more.

- **2012** marked **the first year where a CNN was used** to achieve a top 5 test error rate of 15.3%.

- The next best entry achieved an error of 26.2%.

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

AlexNet

Architecture
CONV1
MAX POOL1
NORM1
CONV2
MAX POOL2
NORM2
CONV3
CONV4
CONV5
Max POOL3
FC6
FC7
FC8

- Input: 227x227x3 images (224x224 before padding)
- First layer: 96 11x11 filters applied at stride 4
- **Output volume size?**

(N-F)/s+1 = (227-11)/4+1 = 55 -> [55x55x96]

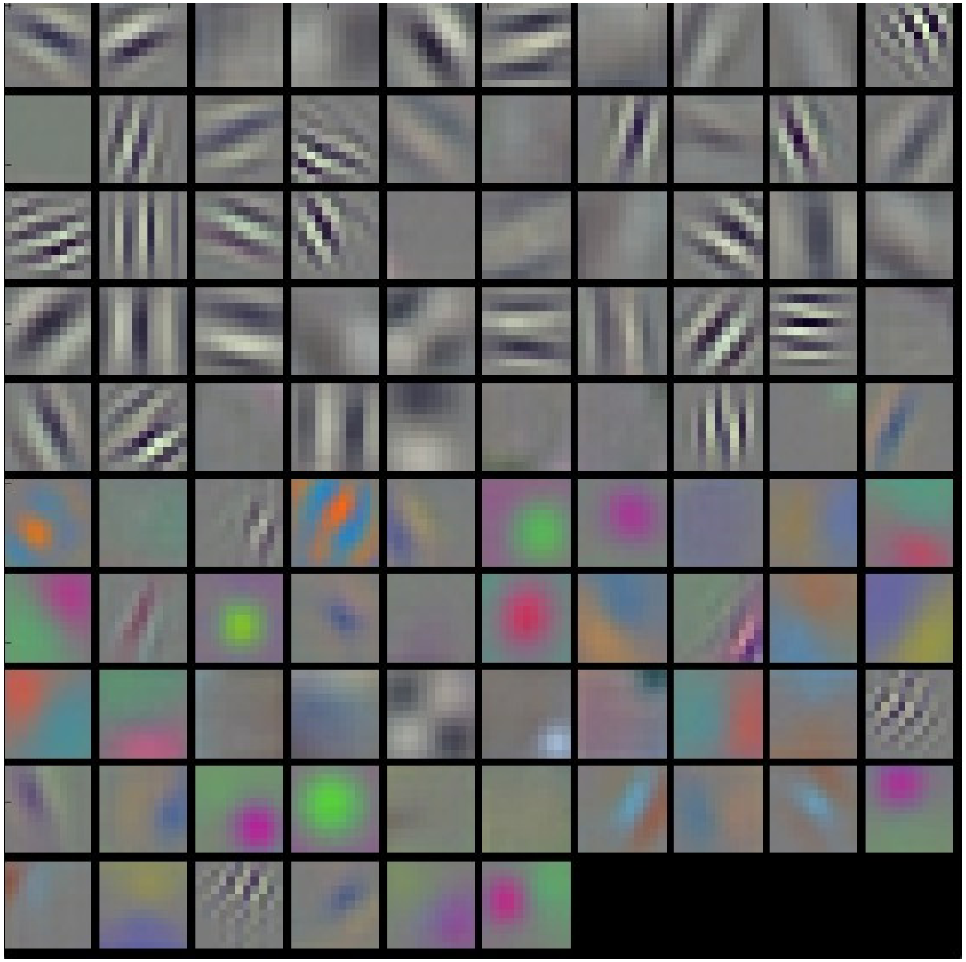
- **Number of parameters in this layer?**

(11*11*3)*96 = 35K

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[Krizhevsky et al., 2012]

AlexNet



[Krizhevsky et al., 2012]

Architecture

CONV1
MAX POOL1
NORM1
CONV2
MAX POOL2
NORM2
CONV3
CONV4
CONV5
Max POOL3
FC6
FC7
FC8

AlexNet

- Input: 227x227x3 images (224x224 before padding)
- After CONV1: 55x55x96
- Second layer: 3x3 filters applied at stride 2

- **Output volume size?**

  (N-F)/s+1 = (55-3)/2+1 = 27 -> [27x27x96]

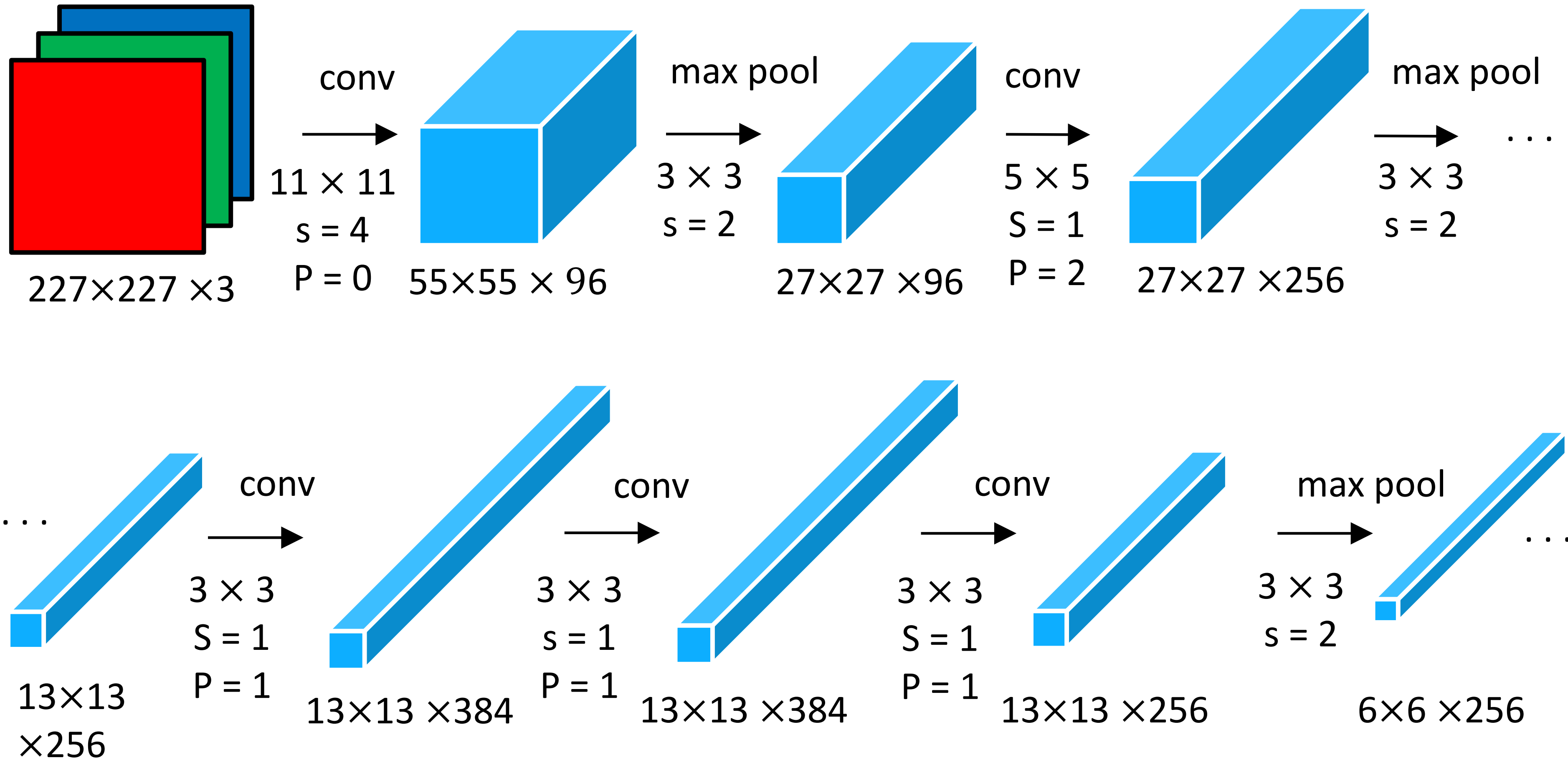
- **Number of parameters in this layer?**

  0!

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[Krizhevsky et al., 2012]

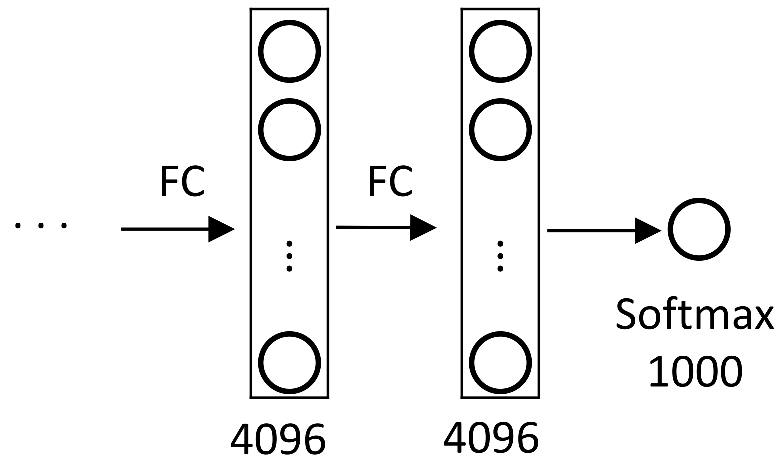
AlexNet



This slide is taken from Andrew Ng

[Krizhevsky et al., 2012]

AlexNet



This slide is taken from Andrew Ng

[**Krizhevsky et al.**, **2012**]

AlexNet

Details/Retrospectives:

- first use of ReLU
- used Norm layers (not common anymore)
- heavy data augmentation
- dropout 0.5
- batch size 128
- 7 CNN ensemble

[**Krizhevsky et al**., **2012**]

AlexNet

- Trained on GTX 580 GPU with only 3 GB of memory.

- Network spread across 2 GPUs, half the neurons (feature maps) on each GPU.

- CONV1, CONV2, CONV4, CONV5:
  Connections only with feature maps on same GPU.
- CONV3, FC6, FC7, FC8:
  Connections with all feature maps in preceding layer, communication across GPUs.

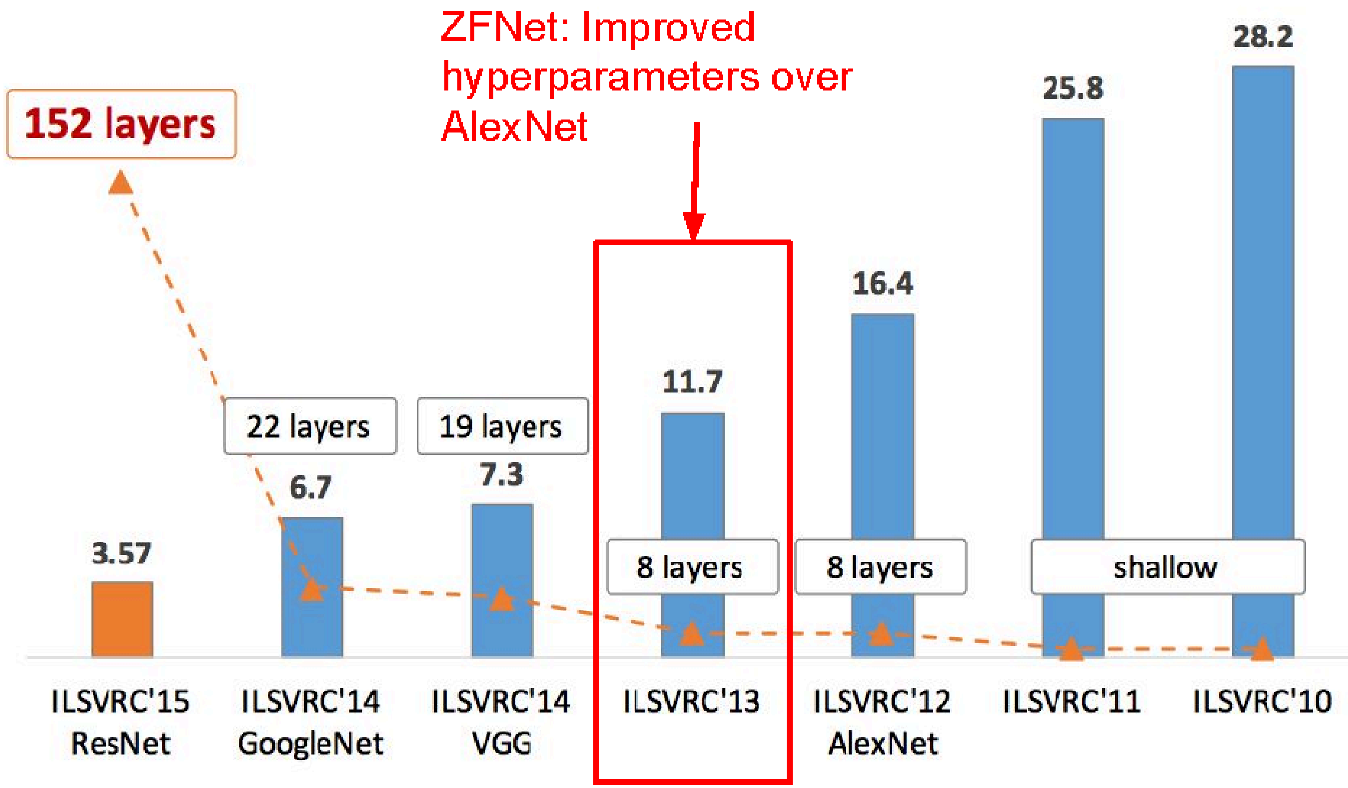
[**Krizhevsky et al.**, **2012**]

AlexNet

AlexNet was the coming out party for CNNs in the computer vision community. This was **the first time a model performed so well on a historically difficult ImageNet dataset**. This paper illustrated the benefits of CNNs and backed them up with record breaking performance in the competition.

[**Krizhevsky et al**., **2012**]

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



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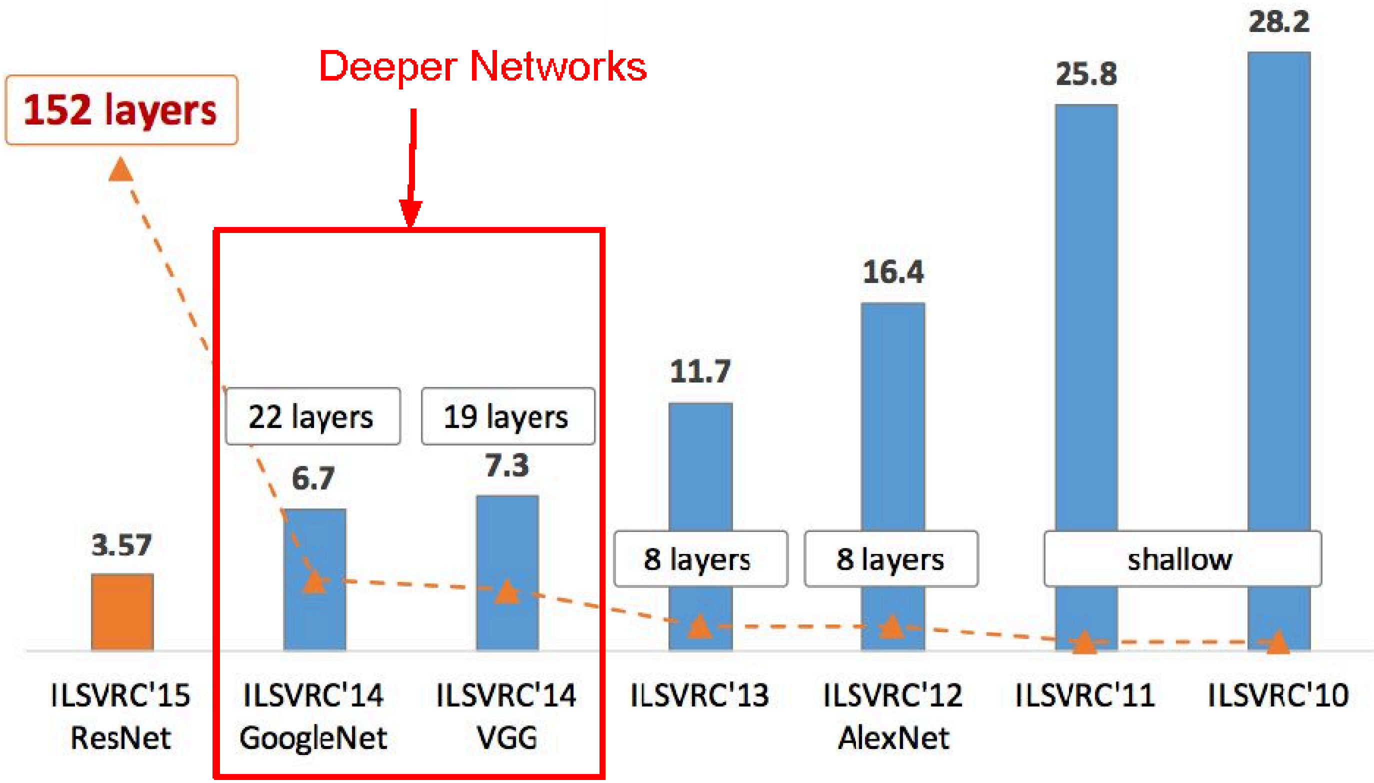
ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

VGGNet

- *Very Deep Convolutional Networks For Large Scale Image Recognition - Karen Simonyan and Andrew Zisserman; 2015*
- The runner-up at the ILSVRC 2014 competition
- Significantly deeper than AlexNet
- 140 million parameters

[Simonyan and Zisserman, 2014]

Input
3x3 conv, 64
3x3 conv, 64
Pool 1/2
3x3 conv, 128
3x3 conv, 128
Pool 1/2
3x3 conv, 256
3x3 conv, 256
Pool 1/2
3x3 conv, 512
3x3 conv, 512
3x3 conv, 512
Pool 1/2
3x3 conv, 512
3x3 conv, 512
3x3 conv, 512
Pool 1/2
FC 4096
FC 4096
FC 1000
Softmax

VGGNet

- **Smaller filters**
  Only 3x3 CONV filters, stride 1, pad 1
  and 2x2 MAX POOL , stride 2

- **Deeper network**
  AlexNet: 8 layers
  VGGNet: 16 - 19 layers

- ZFNet: 11.7% top 5 error in ILSVRC’13
- VGGNet: 7.3% top 5 error in ILSVRC’14

[Simonyan and Zisserman, 2014]

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

VGGNet

- **Why use smaller filters? (3x3 conv)**

Stack of three 3x3 conv (stride 1) layers has the same effective receptive field as one 7x7 conv layer.

- **What is the effective receptive field of three 3x3 conv (stride 1) layers?**

  7x7

But deeper, more non-linearities

And fewer parameters: $3 * (3^2C^2)$ vs. 7^2C^2 for C channels per layer

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[Simonyan and Zisserman, 2014]

Input
3x3 conv, 64
3x3 conv, 64
Pool
3x3 conv, 128
3x3 conv, 128
Pool
3x3 conv, 256
3x3 conv, 256
3x3 conv, 256
Pool
3x3 conv, 512
3x3 conv, 512
3x3 conv, 512
Pool
3x3 conv, 512
3x3 conv, 512
3x3 conv, 512
Pool
FC 4096
FC 4096
FC 1000
Softmax

VGGNet

VGG16:

TOTAL memory: 24M * 4 bytes ~= 96MB / image

TOTAL params: 138M parameters

[Simonyan and Zisserman, 2014]

Input	memory: 224*224*3=150K	params: 0
3x3 conv, 64	memory: 224*224*64=3.2M	params: (3*3*3)*64 = 1,728
3x3 conv, 64	memory: 224*224*64=3.2M	params: (3*3*64)*64 = 36,864
Pool	memory: 112*112*64=800K	params: 0
3x3 conv, 128	memory: 112*112*128=1.6M	params: (3*3*64)*128 = 73,728
3x3 conv, 128	memory: 112*112*128=1.6M	params: (3*3*128)*128 = 147,456
Pool	memory: 56*56*128=400K	params: 0
3x3 conv, 256	memory: 56*56*256=800K	params: (3*3*128)*256 = 294,912
3x3 conv, 256	memory: 56*56*256=800K	params: (3*3*256)*256 = 589,824
3x3 conv, 256	memory: 56*56*256=800K	params: (3*3*256)*256 = 589,824
Pool	memory: 28*28*256=200K	params: 0
3x3 conv, 512	memory: 28*28*512=400K	params: (3*3*256)*512 = 1,179,648
3x3 conv, 512	memory: 28*28*512=400K	params: (3*3*512)*512 = 2,359,296
3x3 conv, 512	memory: 28*28*512=400K	params: (3*3*512)*512 = 2,359,296
Pool	memory: 14*14*512=100K	params: 0
3x3 conv, 512	memory: 14*14*512=100K	params: (3*3*512)*512 = 2,359,296
3x3 conv, 512	memory: 14*14*512=100K	params: (3*3*512)*512 = 2,359,296
3x3 conv, 512	memory: 14*14*512=100K	params: (3*3*512)*512 = 2,359,296
Pool	memory: 7*7*512=25K	params: 0
FC 4096	memory: 4096	params: 7*7*512*4096 = 102,760,448
FC 4096	memory: 4096	params: 4096*4096 = 16,777,216
FC 1000	memory: 1000	params: 4096*1000 = 4,096,000

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[Simonyan and Zisserman, 2014]

VGGNet

Details/Retrospectives :

- ILSVRC’14 2nd in classification, 1st in localization
- Similar training procedure as AlexNet
- No Local Response Normalisation (LRN)
- Use VGG16 or VGG19 (VGG19 only slightly better, more memory)
- Use ensembles for best results
- FC7 features generalize well to other tasks
- Trained on 4 Nvidia Titan Black GPUs for **two to three weeks**.

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[Simonyan and Zisserman, 2014]

VGGNet

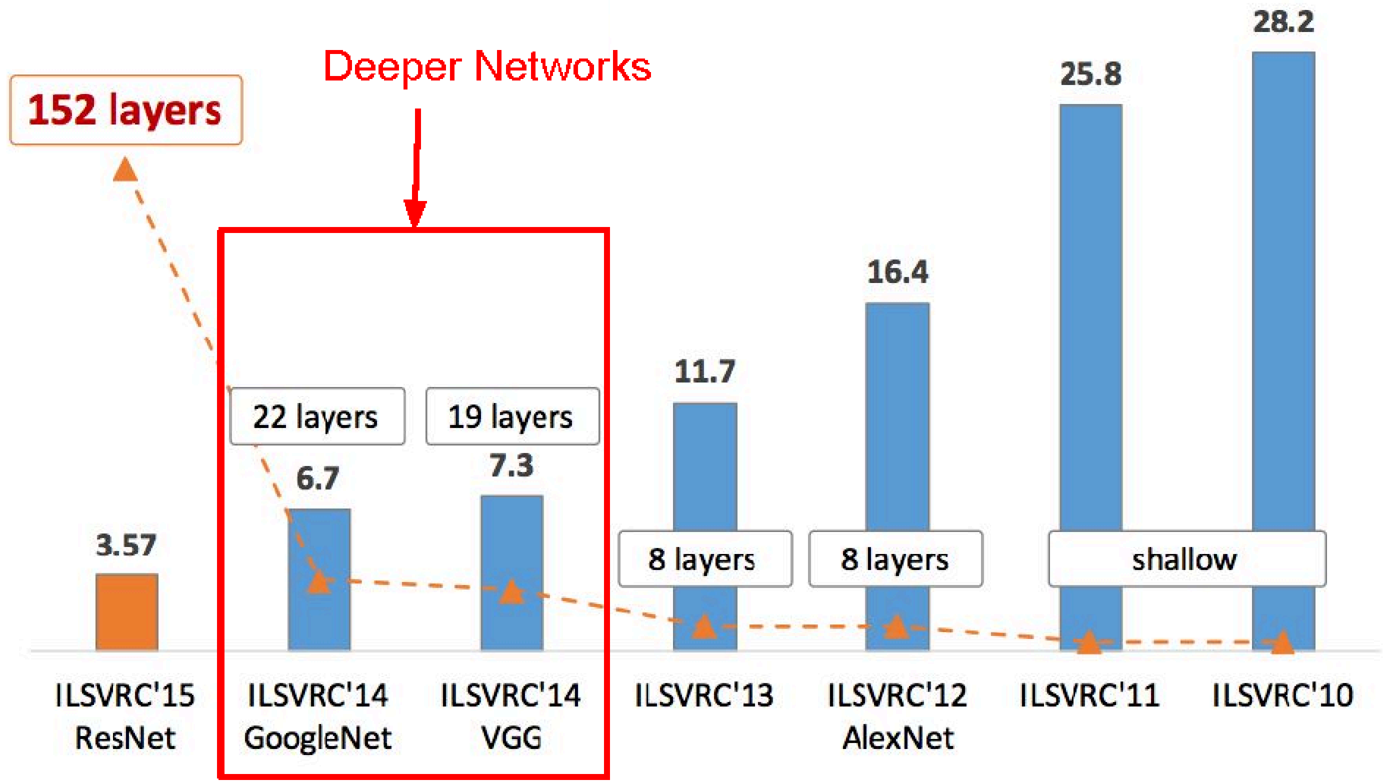
VGG Net reinforced the notion that **convolutional neural networks have to have a deep network of layers in order for this hierarchical representation of visual data to work**.

Keep it deep.

Keep it simple.

[Simonyan and Zisserman, 2014]

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

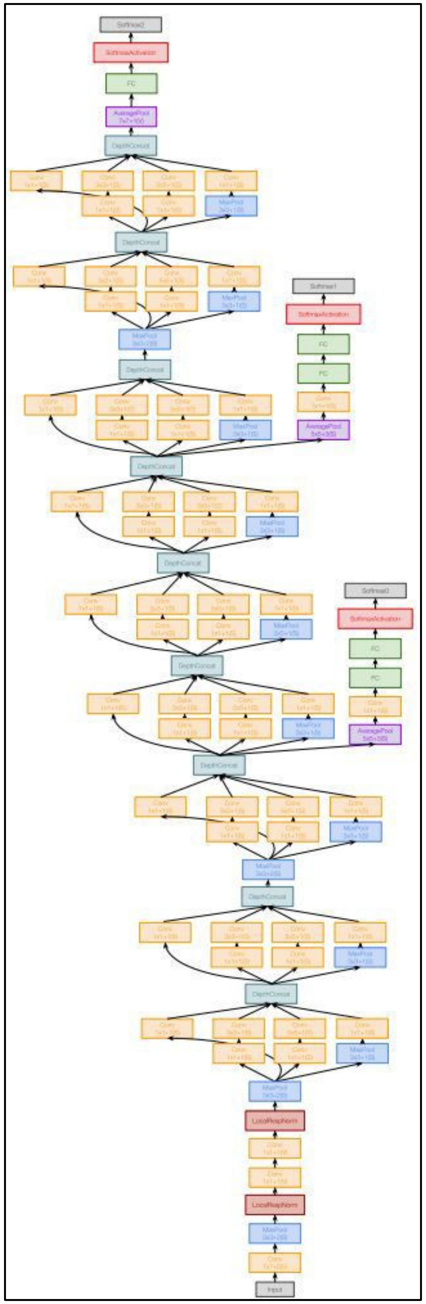


Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

GoogleNet

- *Going Deeper with Convolutions - Christian Szegedy et al.; 2015*
- ILSVRC 2014 competition winner
- Also significantly deeper than AlexNet
- x12 less parameters than AlexNet
- Focused on computational efficiency

[Szegedy et al., 2014]



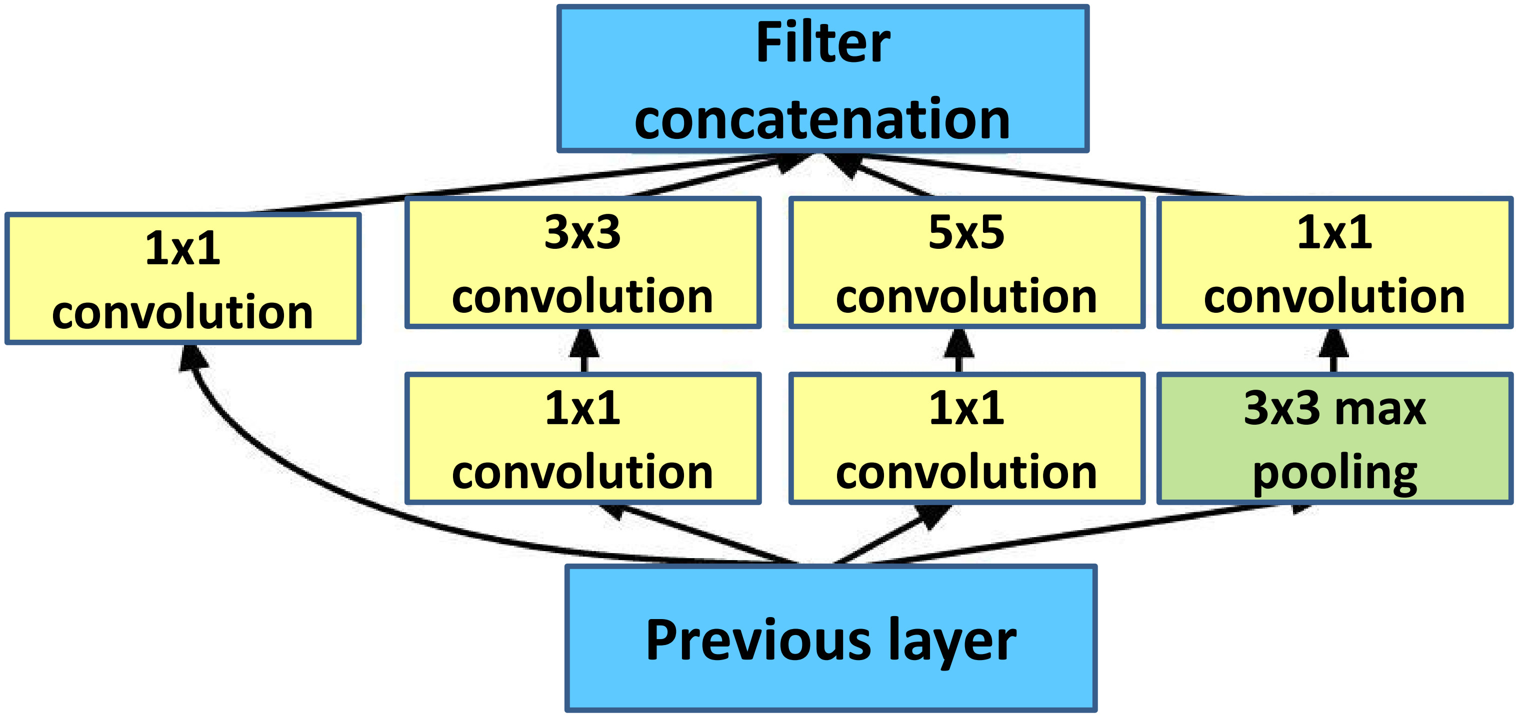
GoogleNet

- 22 layers
- Efficient **“Inception” module** - strayed from the general approach of simply stacking conv and pooling layers on top of each other in a sequential structure
- No FC layers
- Only 5 million parameters!
- ILSVRC’14 classification winner (6.7% top 5 error)

[Szegedy et al., 2014]

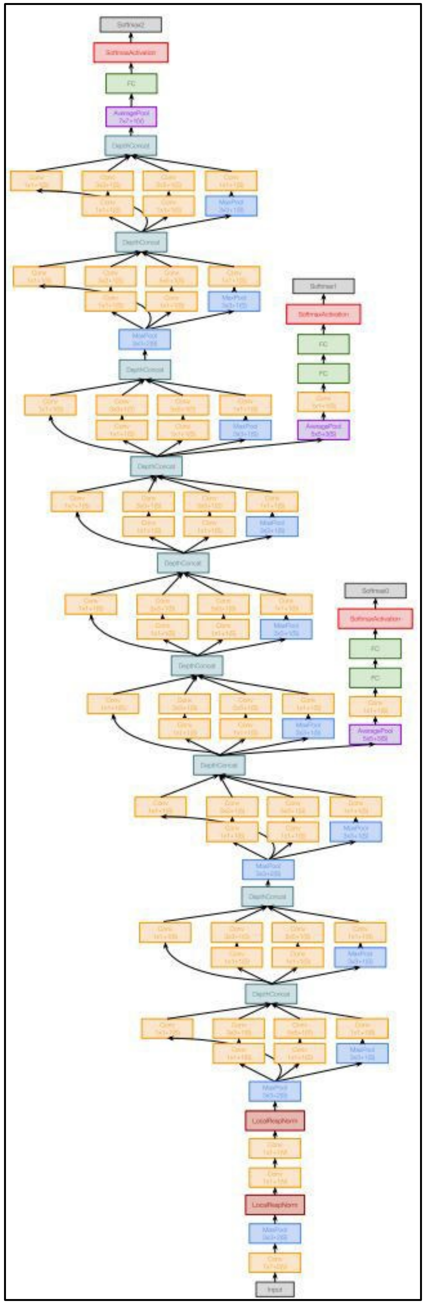
GoogleNet

“**Inception module”:** design a good local network topology (network within a network) and then stack these modules on top of each other



[Szegedy et al., 2014]

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.



GoogleNet

Details/Retrospectives :

- Deeper networks, with computational efficiency
- 22 layers
- Efficient "Inception" module
- No FC layers
- 12x less params than AlexNet
- ILSVRC'14 classification winner (6.7% top 5 error)

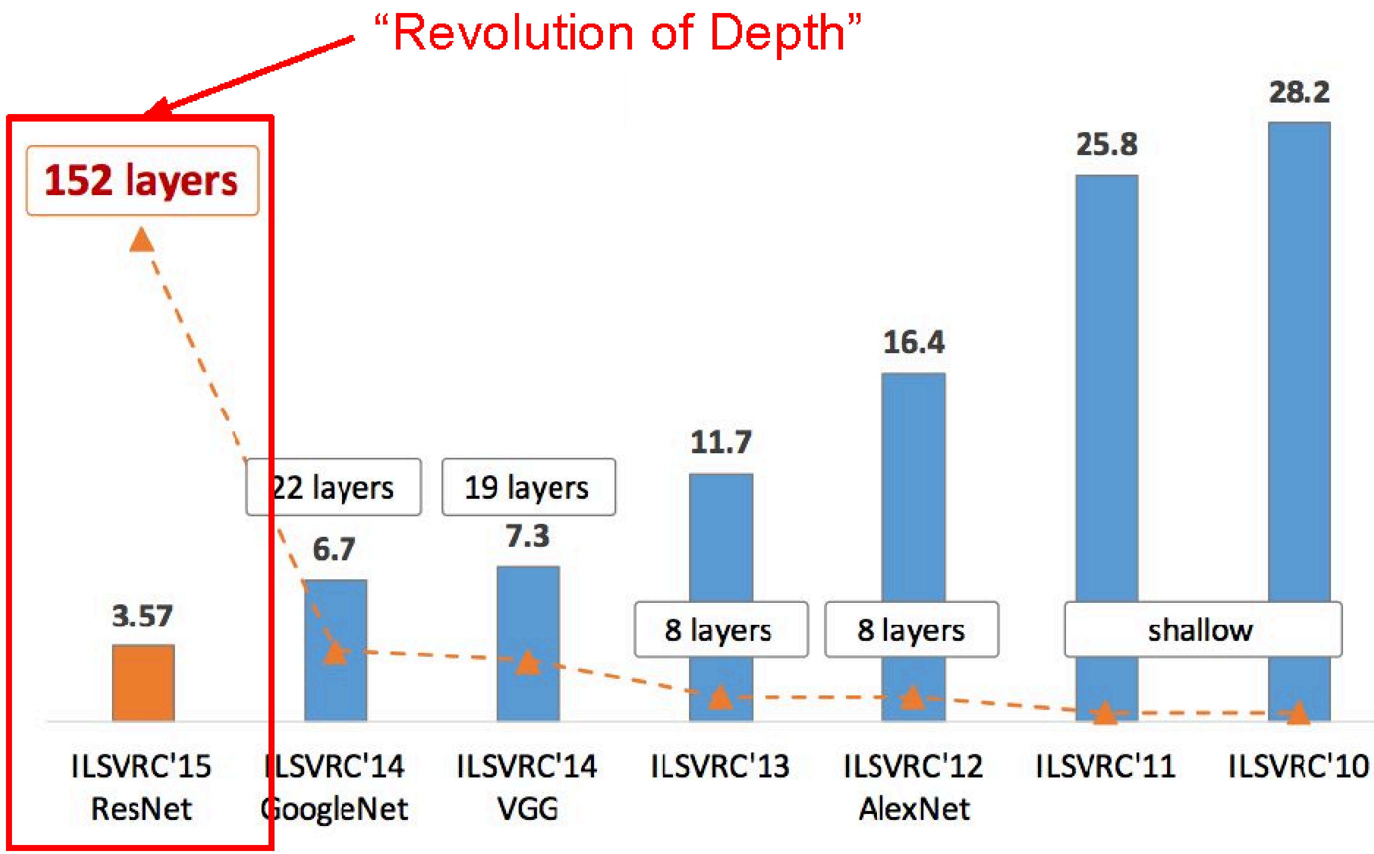
[Szegedy et al., 2014]

GoogleNet

Introduced the idea that CNN layers **didn't always have to be stacked up sequentially**. Coming up with the Inception module, the authors showed that a creative structuring of layers can lead to improved performance and **computationally efficiency**.

[Szegedy et al., 2014]

ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners

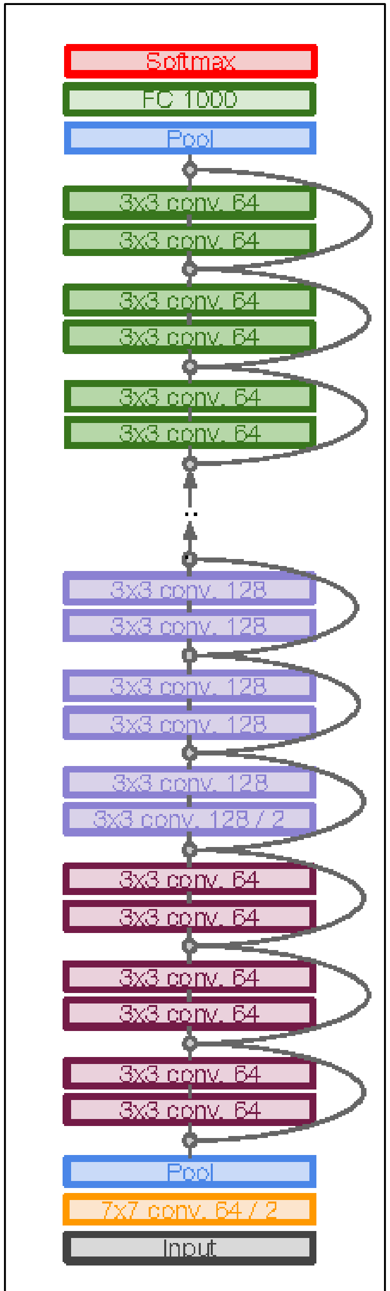


Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

ResNet

- *Deep Residual Learning for Image Recognition - Kaiming He, Xiangyu Zhang, Shaoqing Ren, Jian Sun; 2015*
- Extremely deep network – 152 layers
- Deeper neural networks are more difficult to train.
- Deep networks suffer from vanishing and exploding gradients.
- Present a residual learning framework to ease the training of networks that are substantially deeper than those used previously.

[He et al., 2015]



ResNet

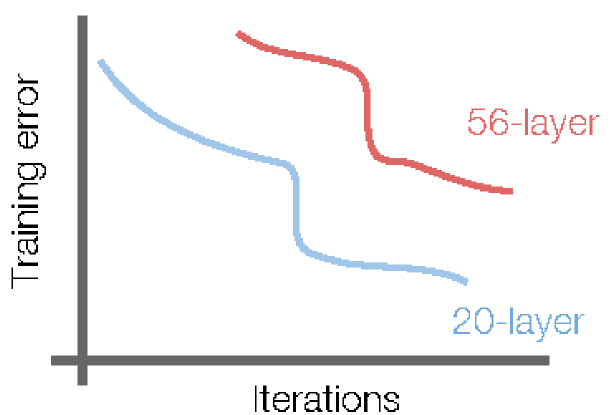
- ILSVRC'15 classification winner (3.57% top 5 error, humans generally hover around a 5-10% error rate)
  Swept all classification and detection competitions in ILSVRC'15 and COCO'15!

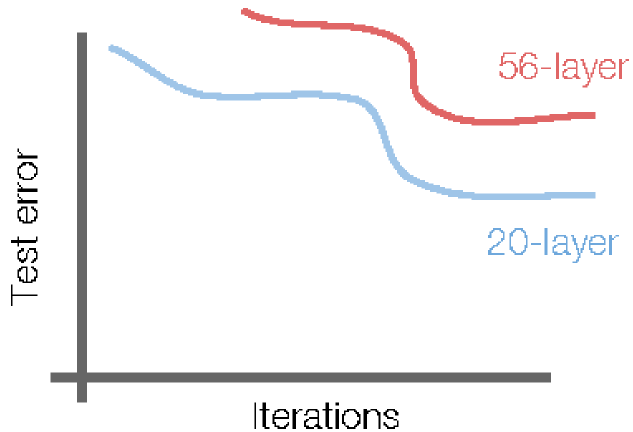
[He et al., 2015]

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

ResNet

- What happens when we continue stacking deeper layers on a convolutional neural network?





- 56-layer model performs worse on both training and test error

-> The deeper model performs worse (not caused by overfitting)!

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[He et al., 2015]

ResNet

- **Hypothesis**: The problem is an optimization problem. Very deep networks are harder to optimize.
- **Solution**: Use network layers to fit residual mapping instead of directly trying to fit a desired underlying mapping.

- We will use **skip connections** allowing us to take the activation from one layer and feed it into another layer, much deeper into the network.
- Use layers to fit residual $F(x) = H(x) - x$ instead of $H(x)$ directly

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

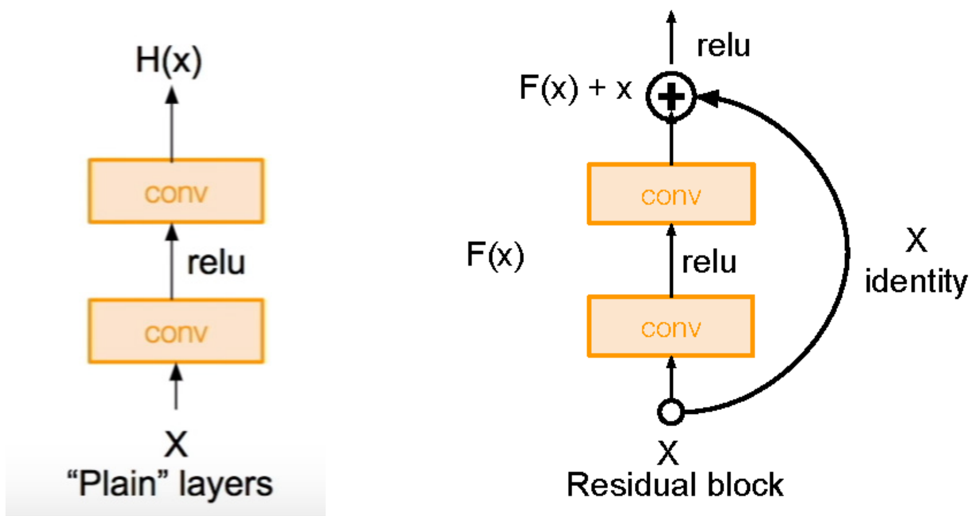
[He et al., 2015]

ResNet

Residual Block

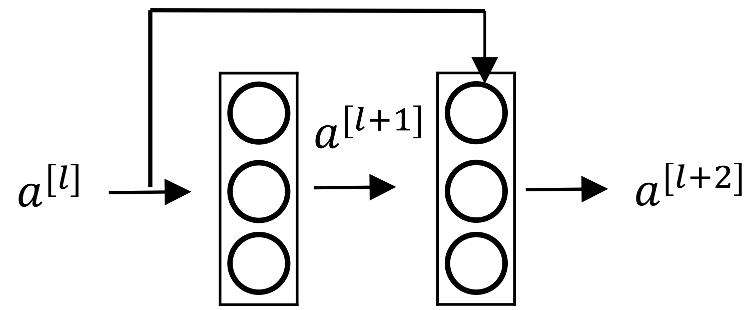
Input x goes through conv-relu-conv series and gives us F(x). That result is then added to the original input x. Let's call that H(x) = F(x) + x.

In traditional CNNs, H(x) would just be equal to F(x). So, instead of just computing that transformation (straight from x to F(x)), we're computing the term that we have to *add*, F(x), to the input, x.



[He et al., 2015]

ResNet



Short cut/ skip connection

$a^{[l]}$ → **Linear** → **ReLU** → **Linear** → **ReLU** → $a^{[l+2]}$

$a^{[l+1]}$

$$\mathbf{z^{[l+1]} = W^{[l+1]}\, a^{[l]} + b^{[l+1]}}$$

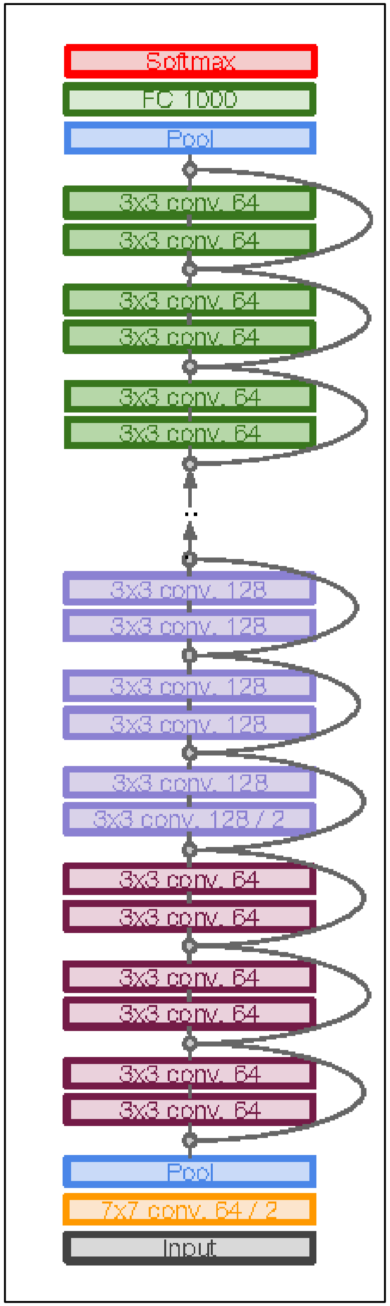
$$\mathbf{z^{[l+2]} = W^{[l+2]} a^{[l+1]} + b^{[l+2]}}$$

$$\mathbf{a^{[l+1]} = g(z^{[l+1]})}$$

$$\mathbf{a^{[l+2]} = g(z^{[l+2]})}$$

$$\mathbf{a^{[l+2]} = g\left(z^{[l+2]} + a^{[l]}\right) = g(W^{[l+2]} a^{[l+1]} + b^{[l+2]} + a^{[l]})}$$

[He et al., 2015]



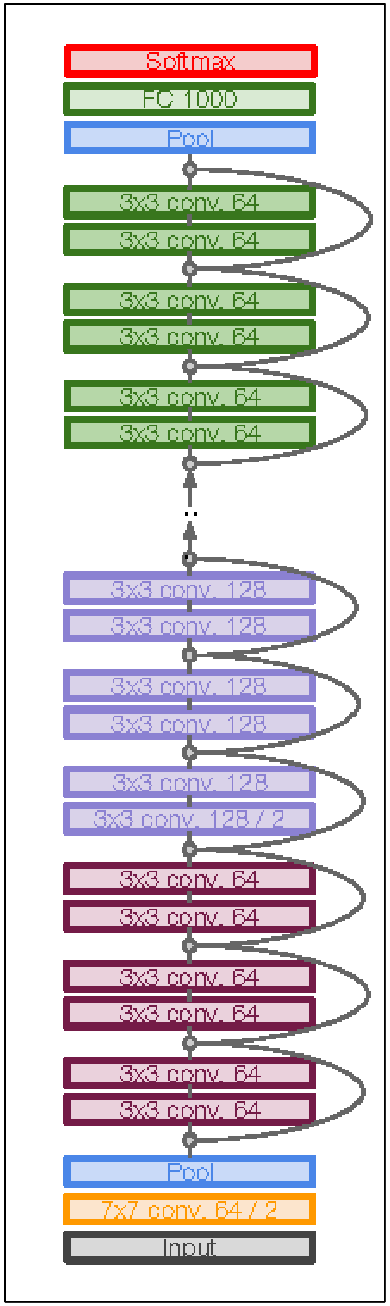
ResNet

Full ResNet architecture:

- Stack residual blocks
- Every residual block has two 3x3 conv layers
- Periodically, double # of filters and downsample spatially using stride 2 (in each dimension)
- Additional conv layer at the beginning
- No FC layers at the end (only FC 1000 to output classes)

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[He et al., 2015]



ResNet

- Total depths of 34, 50, 101, or 152 layers for ImageNet
- For deeper networks (ResNet-50+), use “bottleneck” layer to improve efficiency (similar to GoogLeNet)

Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

[He et al., 2015]

ResNet

Experimental Results:

- Able to train very deep networks without degrading
- Deeper networks now achieve lower training errors as expected

[He et al., 2015]

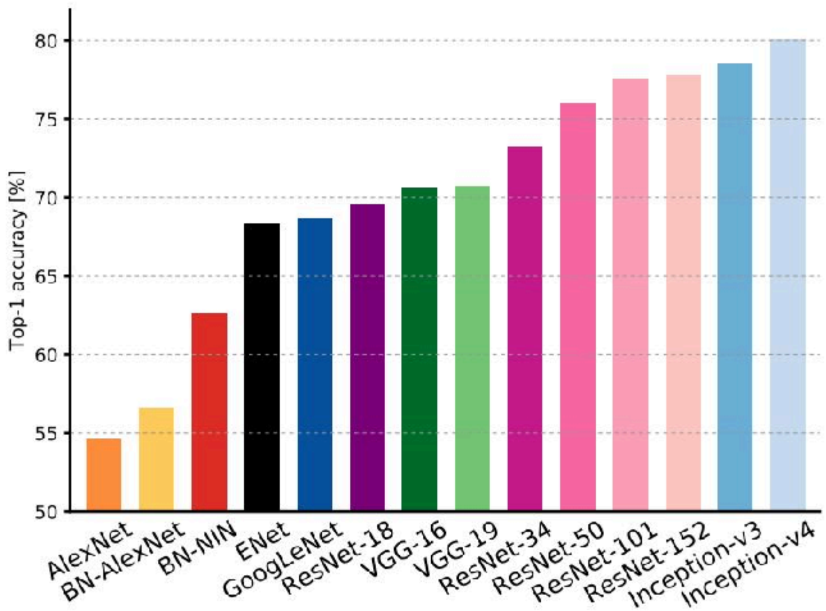
ResNet

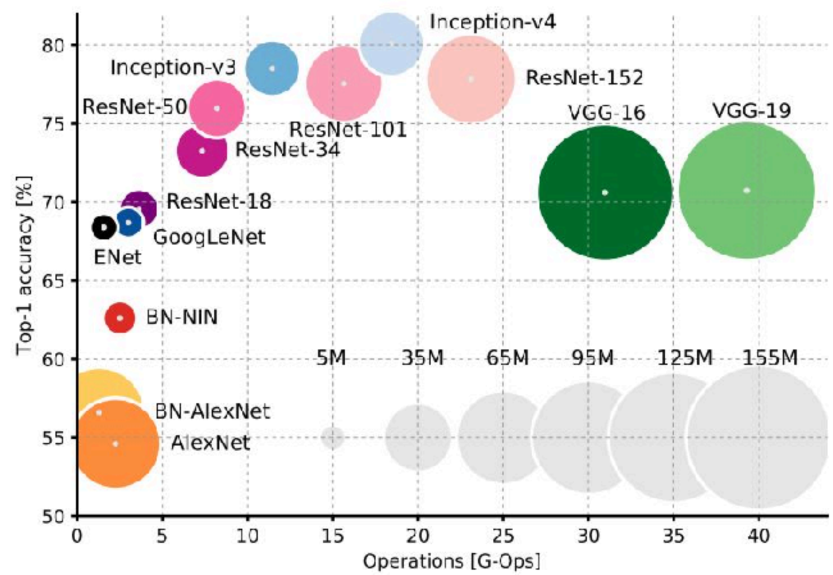
The **best** CNN architecture that we currently have and is a great innovation for the idea of residual learning.

Even better than human performance!

[He et al., 2015]

Accuracy comparison





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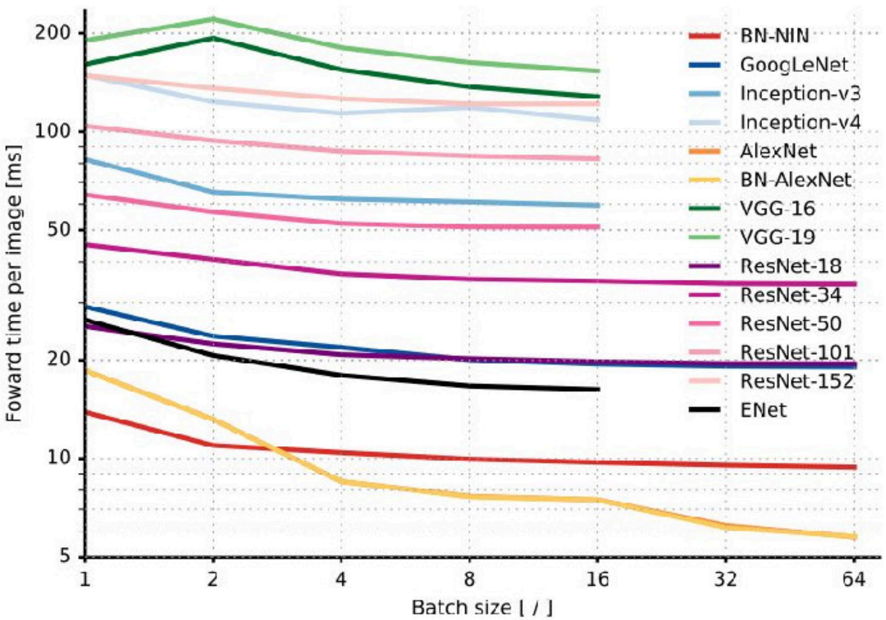
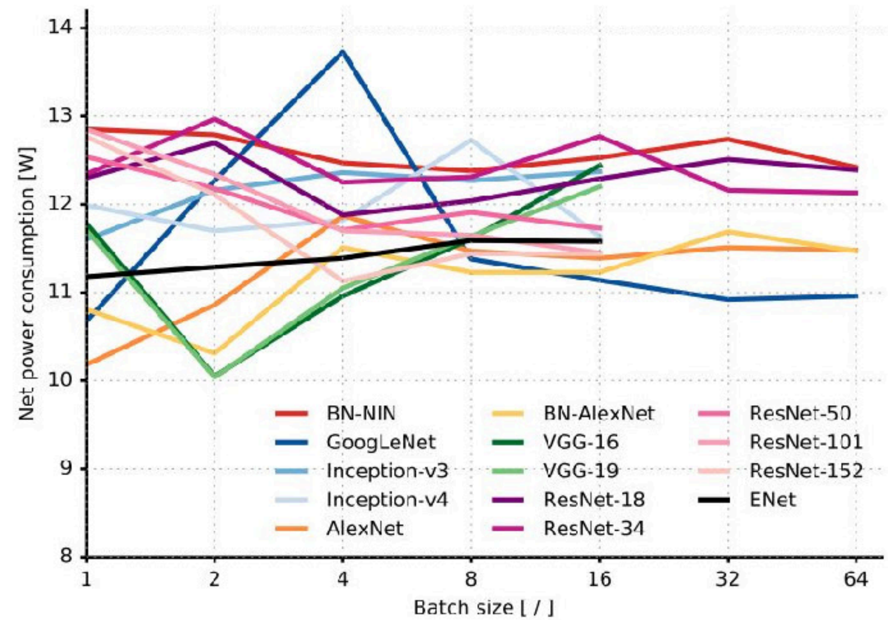
Forward pass time and power consumption





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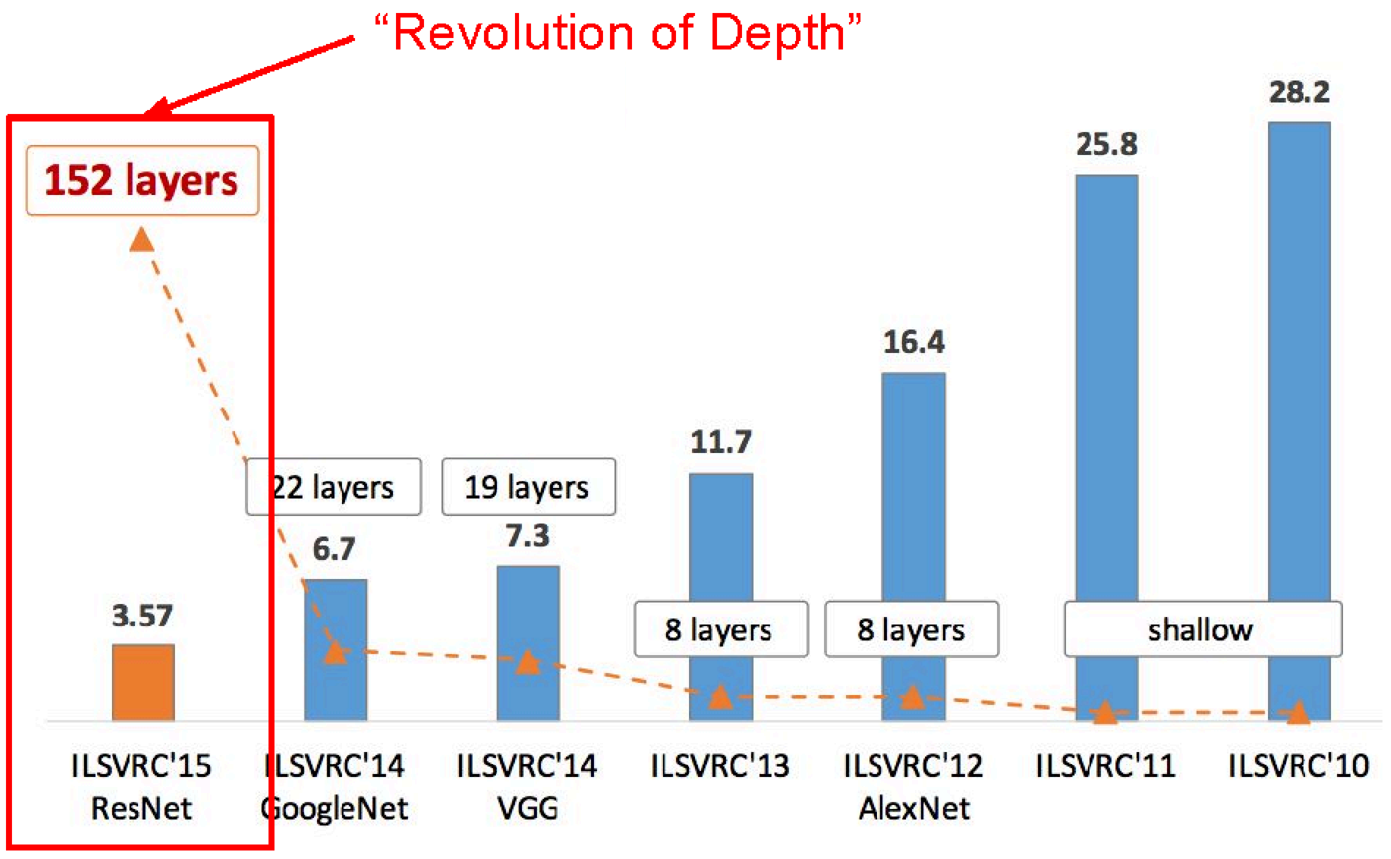
ImageNet Large Scale Visual Recognition Challenge (ILSVRC) winners



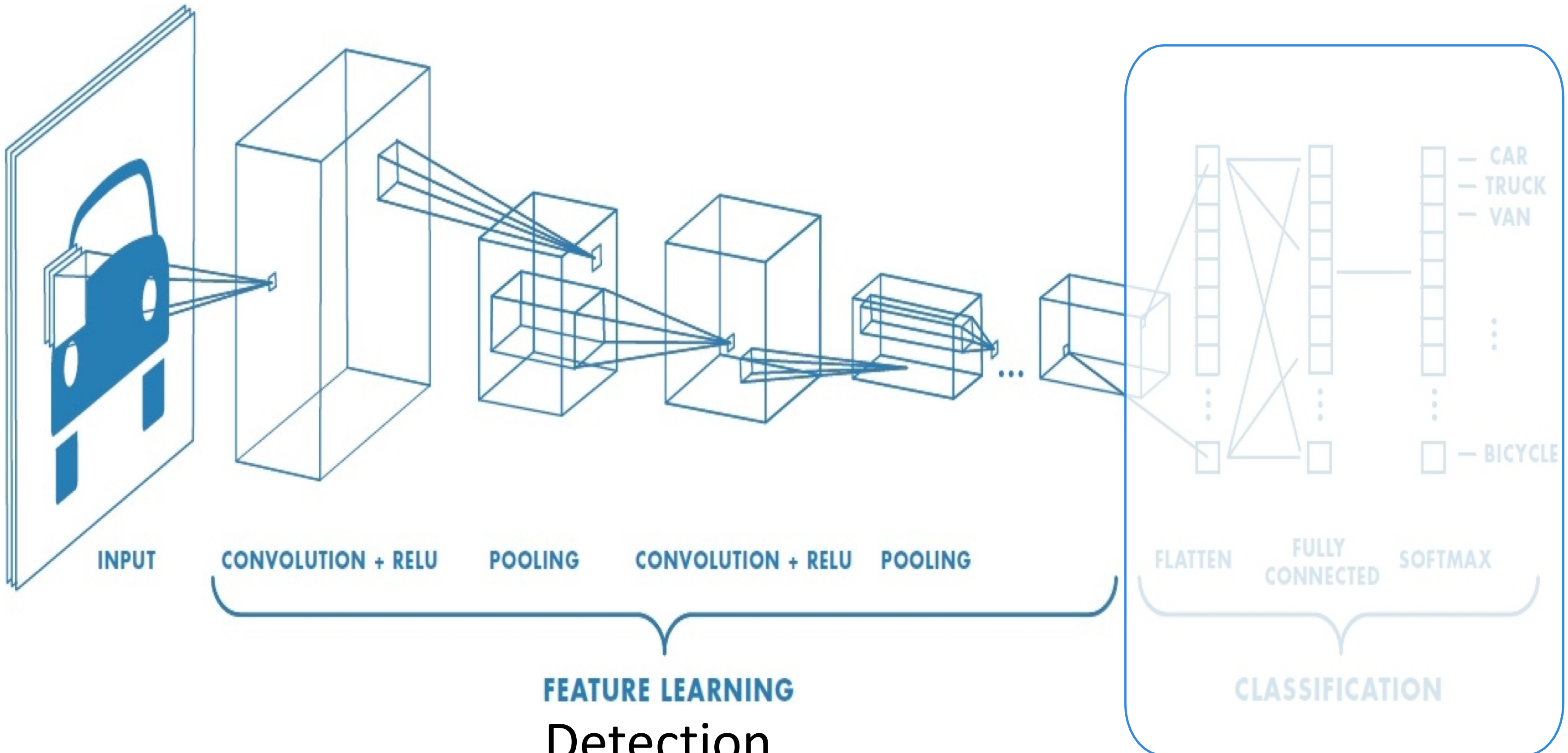
Slide taken from Fei-Fei & Justin Johnson & Serena Yeung. Lecture 9.

Today: Convolutional Neural Networks (CNNs)

1. **Scene understanding and object recognition for machines (and humans)**
   - Scene/object recognition challenge. Illusions reveal primitives, conflicting info
   - Human neurons/circuits. Visual cortex layers==abstraction. General cognition
2. **Classical machine vision foundations: features, scenes, filters, convolution**
   - Spatial structure primitives: edge detectors & other filters, feature recognition
   - Convolution: basics, padding, stride, object recognition, architectures
3. **CNN foundations: LeNet, *de novo* feature learning, parameter sharing**
   - Key ideas: ***learn*** features, hierarchy, re-use parameters, back-prop filter learning
   - CNN formalization: representations(Conv+ReLU+Pool)*N layers + Fully-connected
4. **Modern CNN architectures: millions of parameters, dozens of layers**
   - Feature invariance is hard: apply perturbations, learn for each variation
   - ImageNet progression of best performers
   - AlexNet: First top performer CNN, 60M parameters (from 60k in LeNet-5), ReLU
   - VGGNet: simpler but deeper (8→19 layers), 140M parameters, ensembles
   - GoogleNet: new primitive=inception module, 5M params, no FC, efficiency
   - ResNet: 152 layers, vanishing gradients ➔ fit residuals to enable learning
5. **Countless applications: General architecture, enormous power**
   - Semantic segmentation, facial detection/recognition, self-driving, image colorization, optimizing pictures/scenes, up-scaling, medicine, biology, genomics

Countless applications

An Architecture for Many Applications



Detection

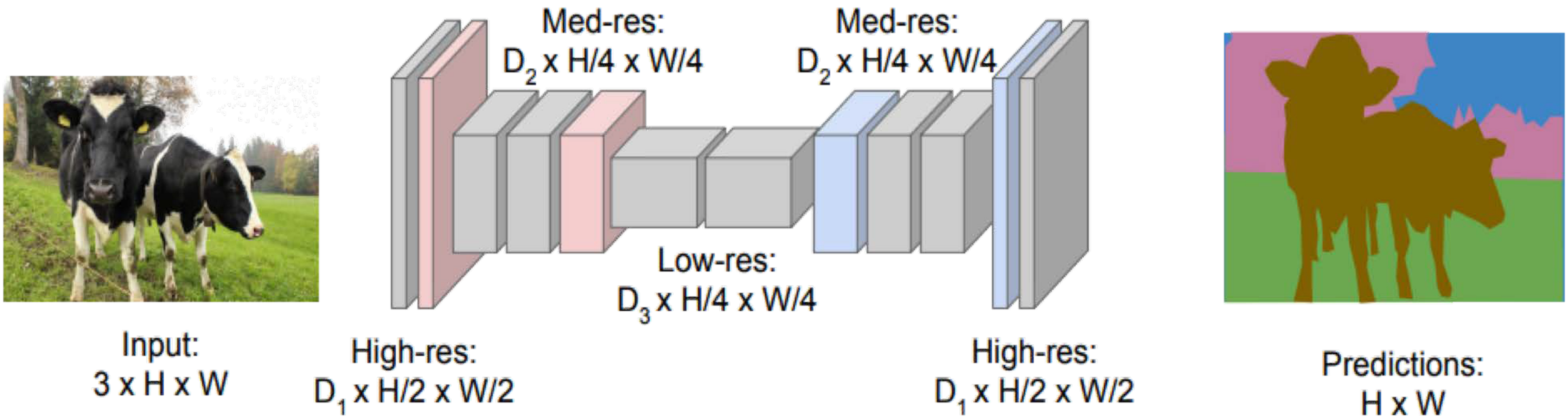
Semantic segmentation

End-to-end robotic control

Semantic Segmentation: Fully Convolutional Networks

FCN: Fully Convolutional Network.

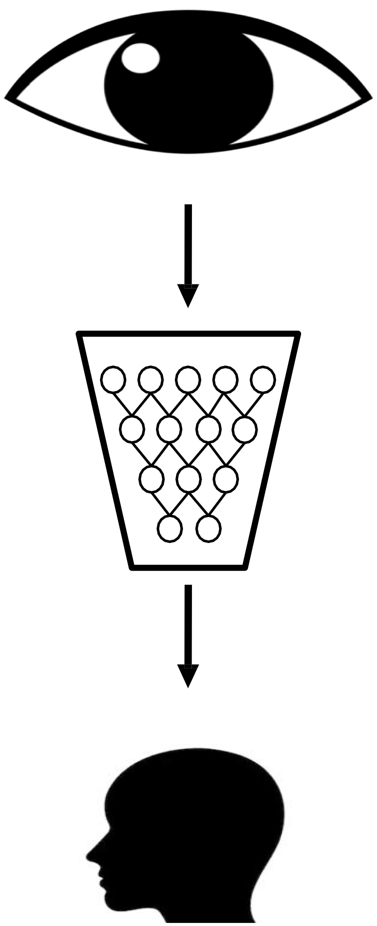
Network designed with all convolutional layers, with **downsampling** and **upsampling** operations

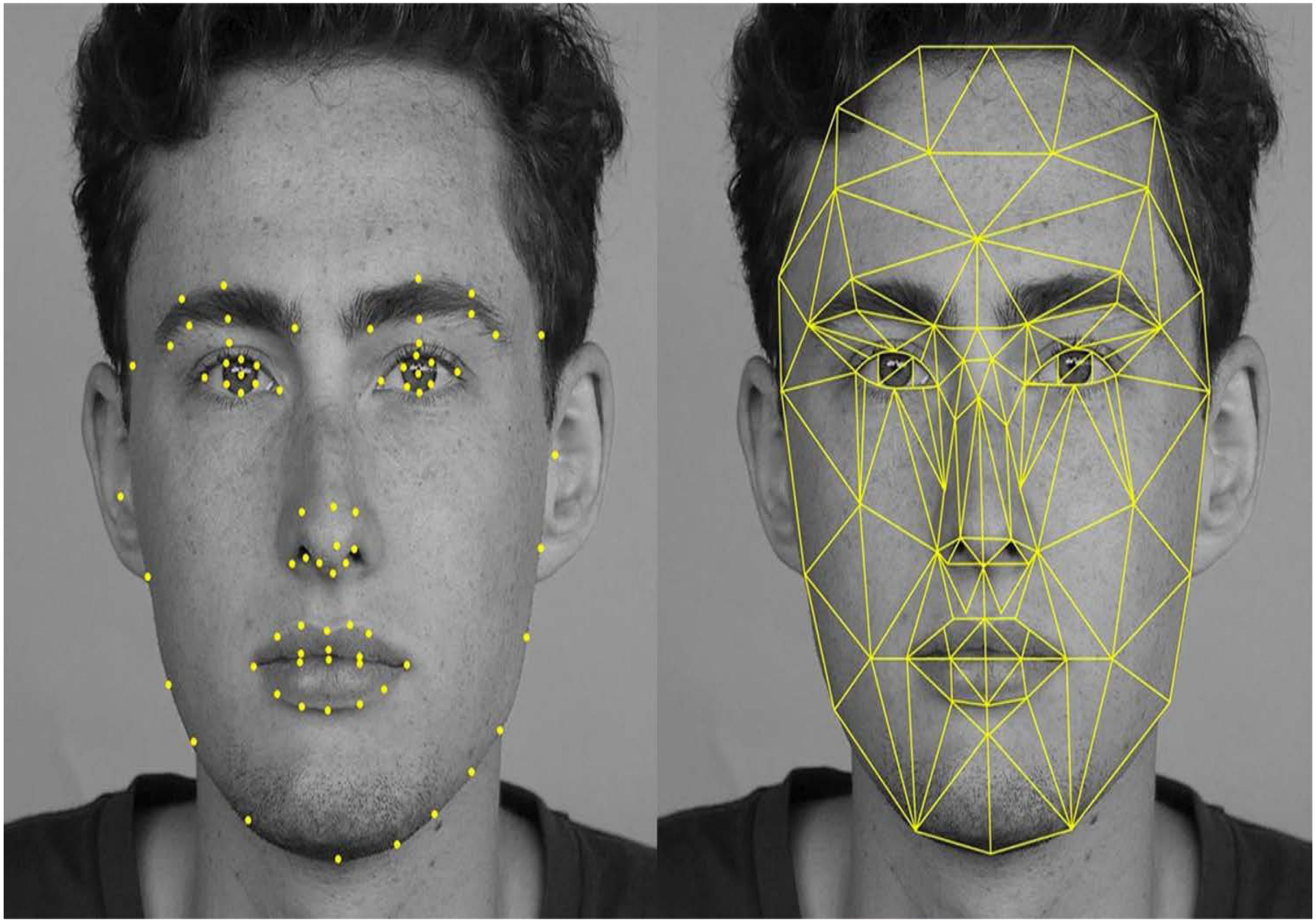



```
tf.keras.layers.Conv2DTranspose
```

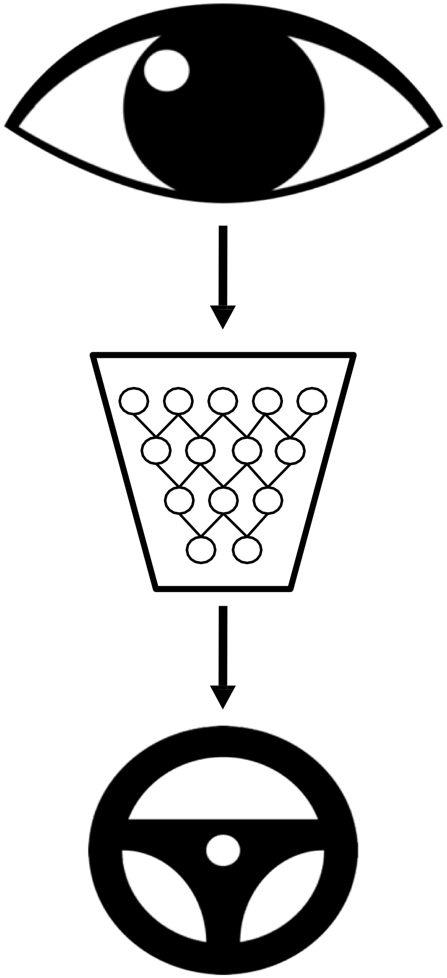
Long+ *CVPR* 2015

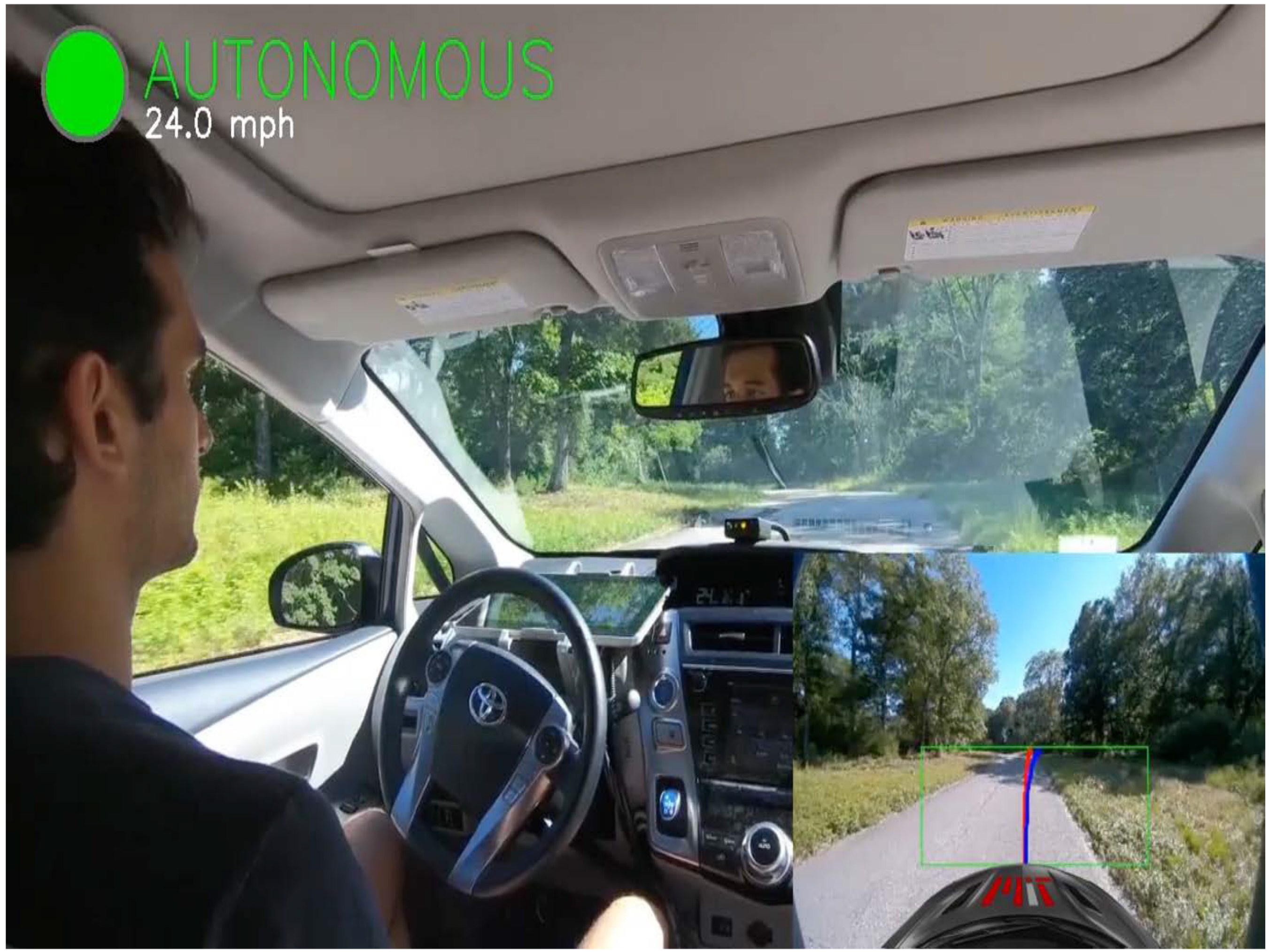
Facial Detection & Recognition





Self-Driving Cars



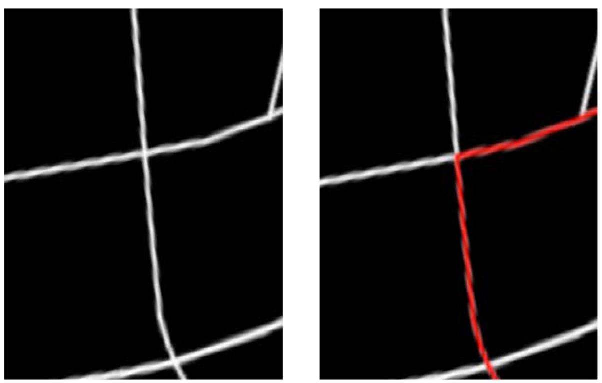


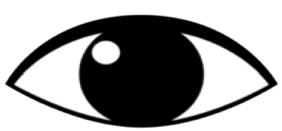
Amini+ *ICRA* 2019.

Self-Driving Cars: Navigation from Visual Perception

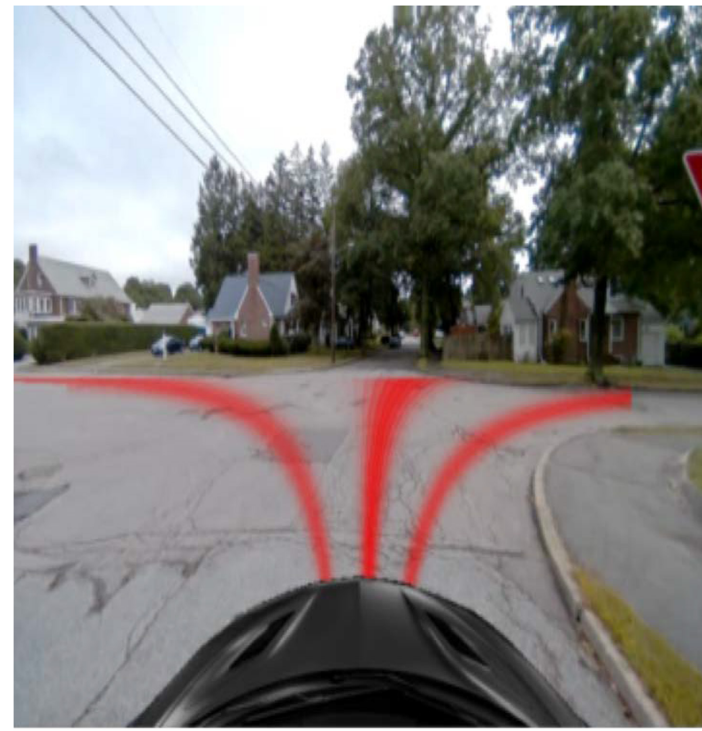
Raw Perception
I
(ex. camera)

Coarse Maps
M
(ex. GPS)



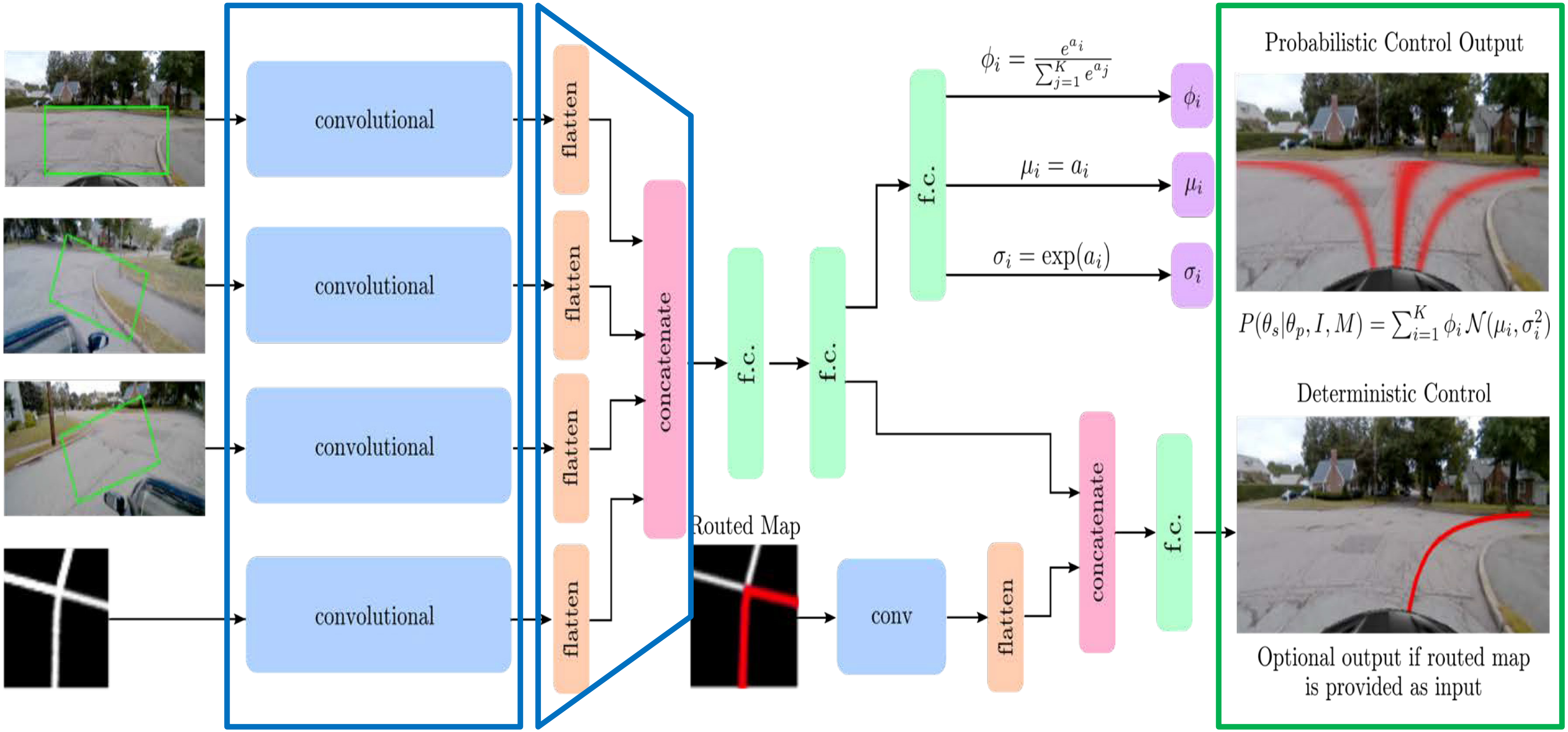


Possible Control Commands



Amini+ *ICRA* 2019

End-to-End Framework for Autonomous Navigation

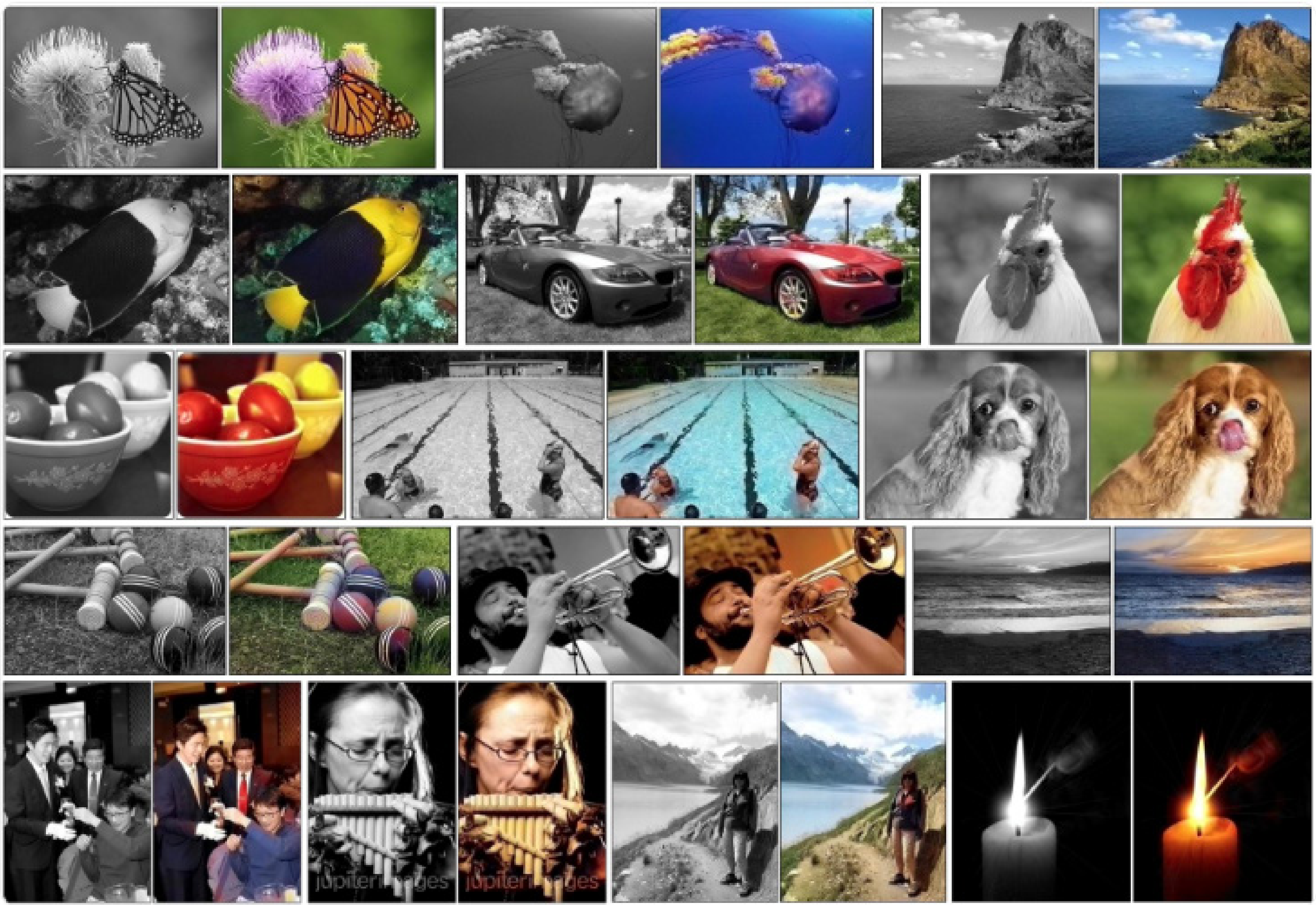


Amini+ *ICRA* 2019

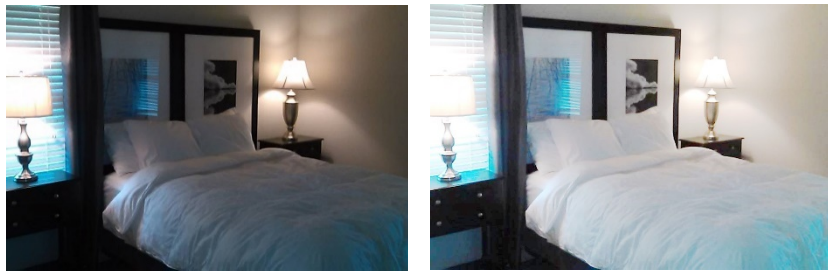
Entire model trained end-to-end

without any human labelling or annotations

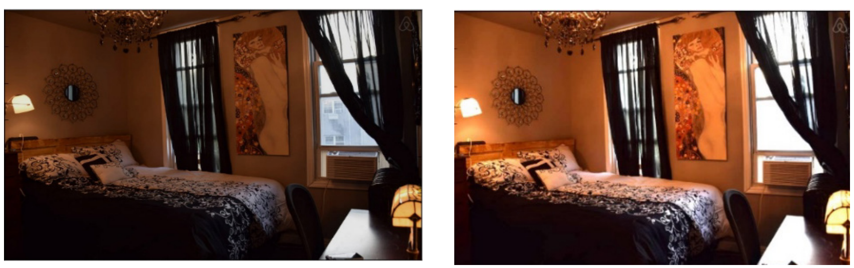
Automatic Colorization of Black and White Images



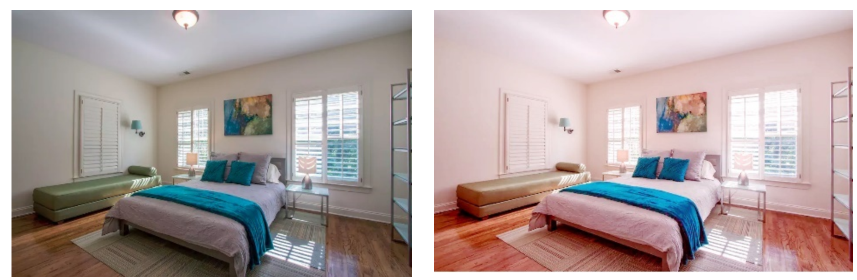
Optimizing Images



Post Processing Feature Optimization
(Color Curves and Details)

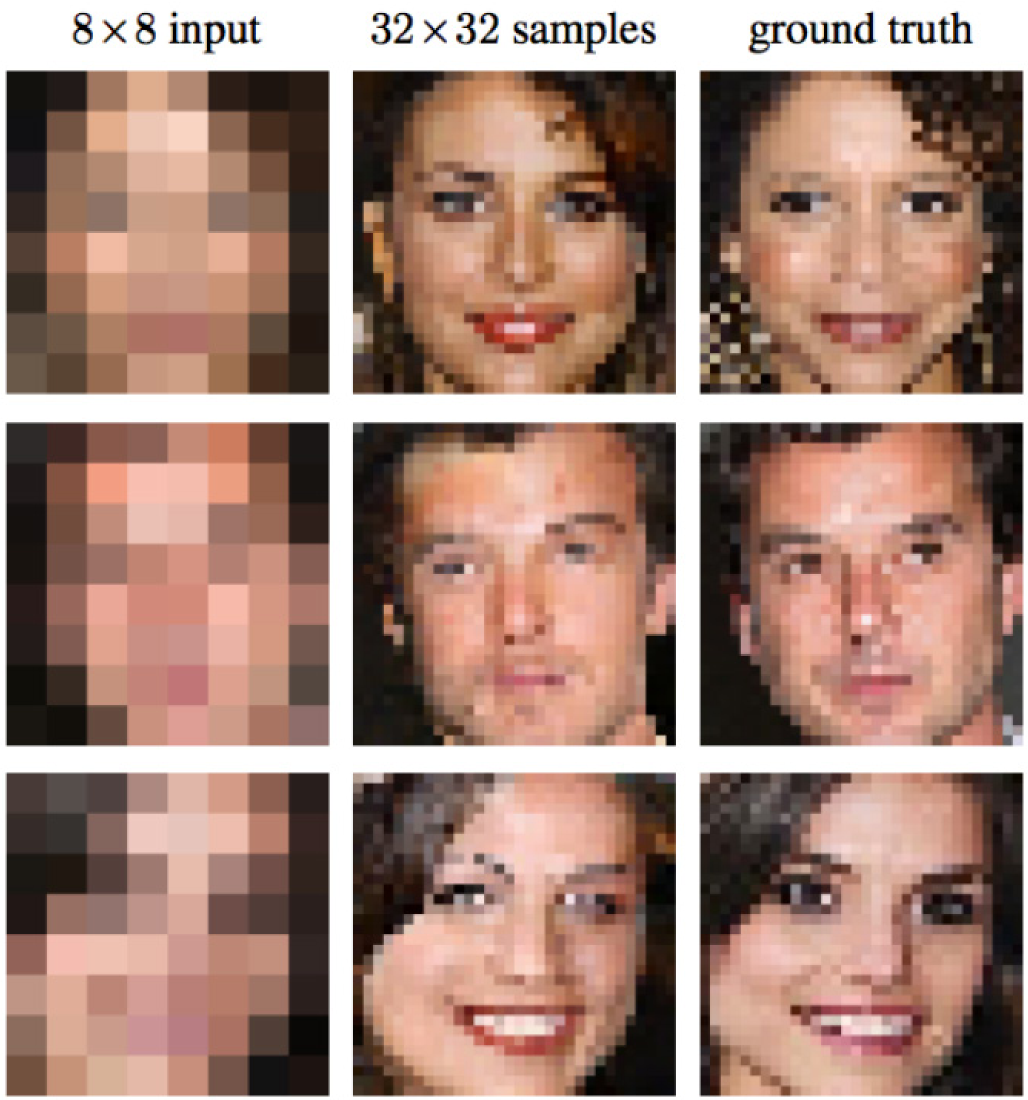


Post Processing Feature Optimization
(Illumination)



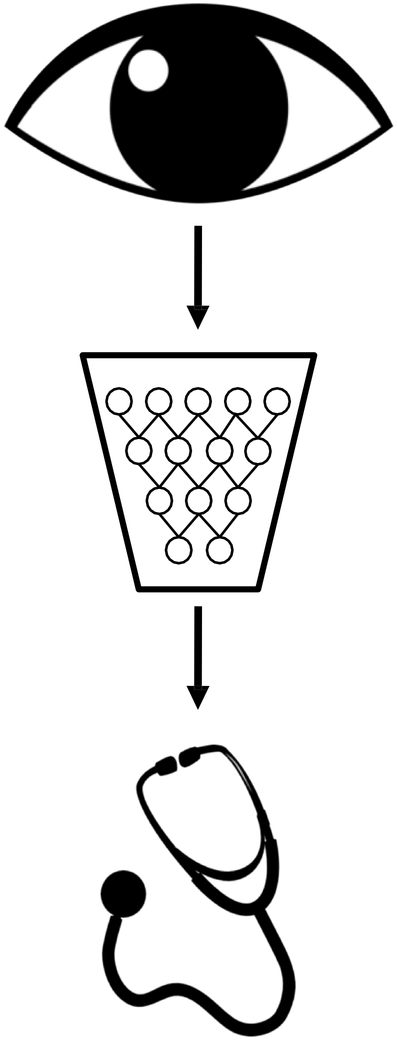
Post Processing Feature Optimization
(Color Tone: Warmness)

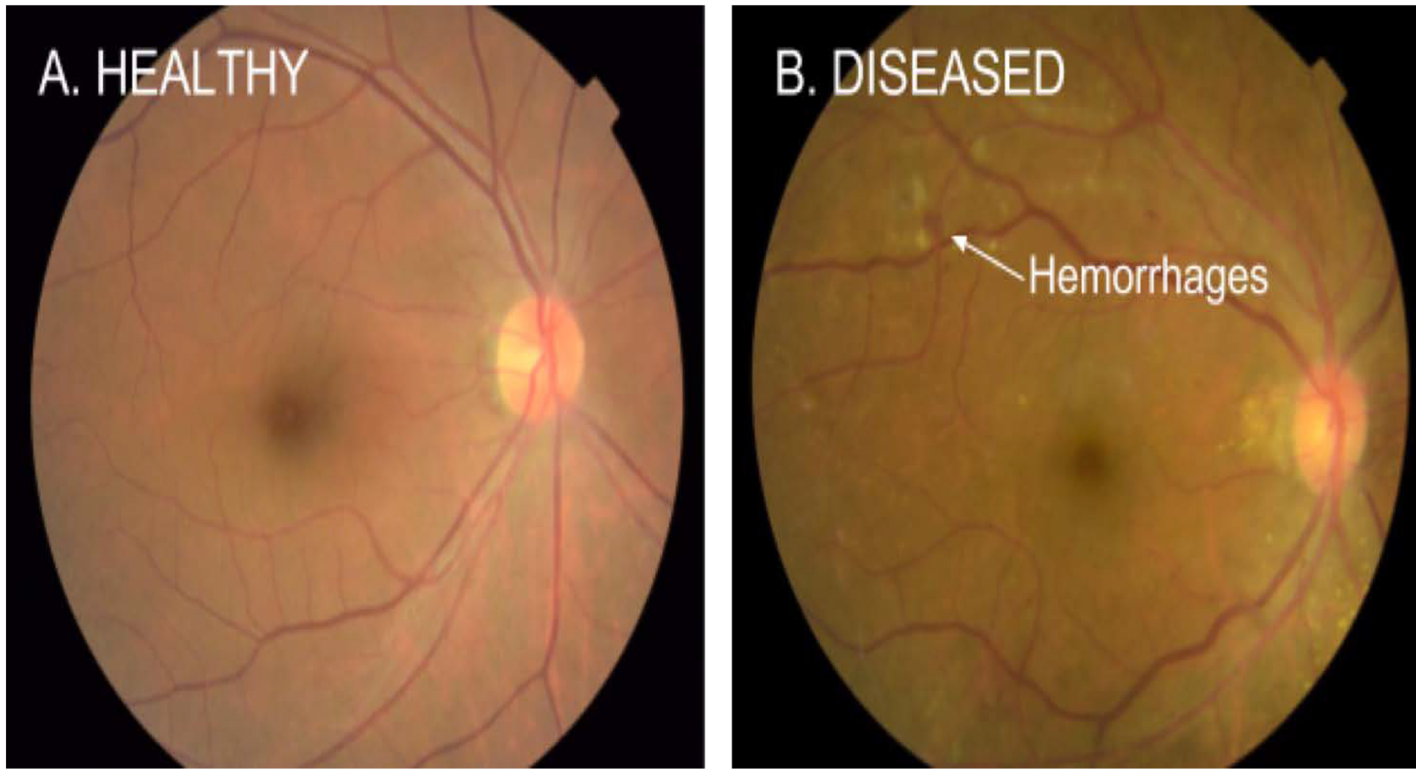
Up-scaling low-resolution images



8x8 pixel photos were inputted into a Deep Learning network which tried to guess what the original face looked like. As you can see it was fairly close (the correct answer is under "ground truth").

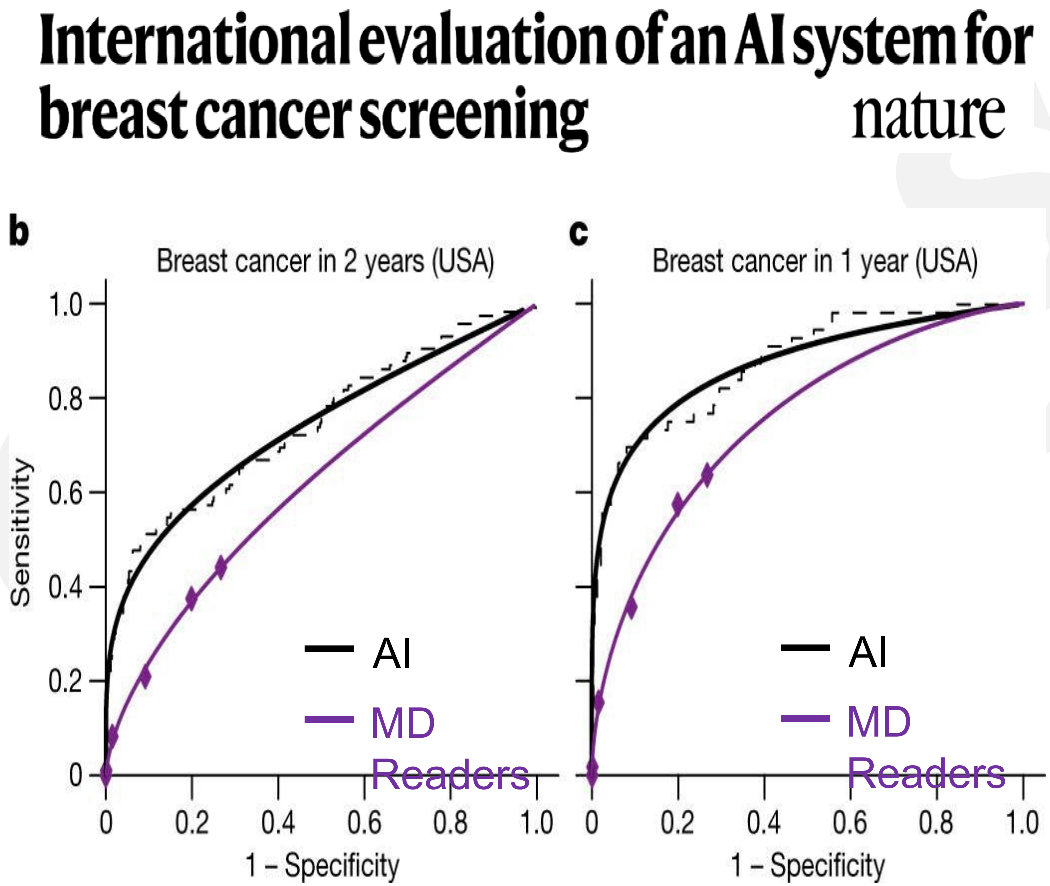
Medicine, Biology, Healthcare



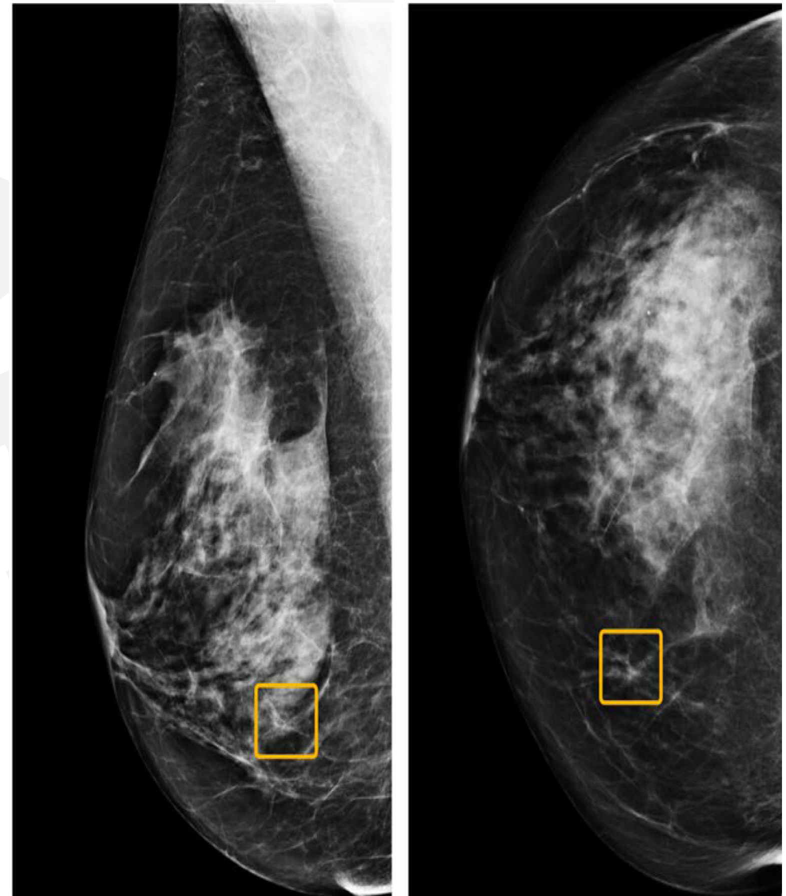


Gulshan+ *JAMA* 2016.

Breast Cancer Screening



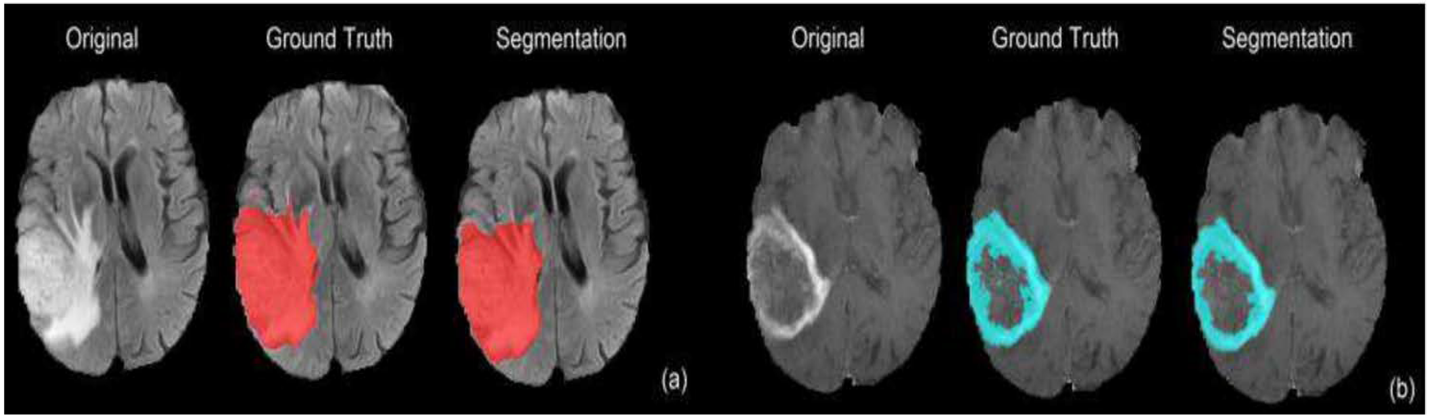
CNN-based system outperformed expert radiologists at detecting breast cancer from mammograms



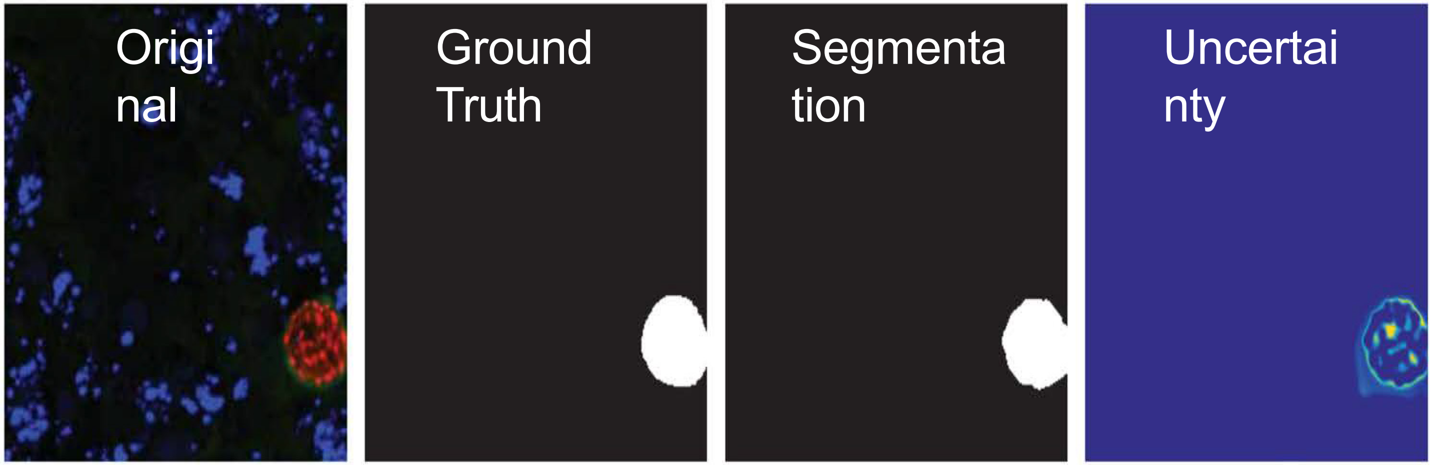
Breast cancer case missed by radiologist but detected by AI

Semantic Segmentation: Biomedical Image Analysis

Brain Tumors
Dong+ *MIUA*
2017.

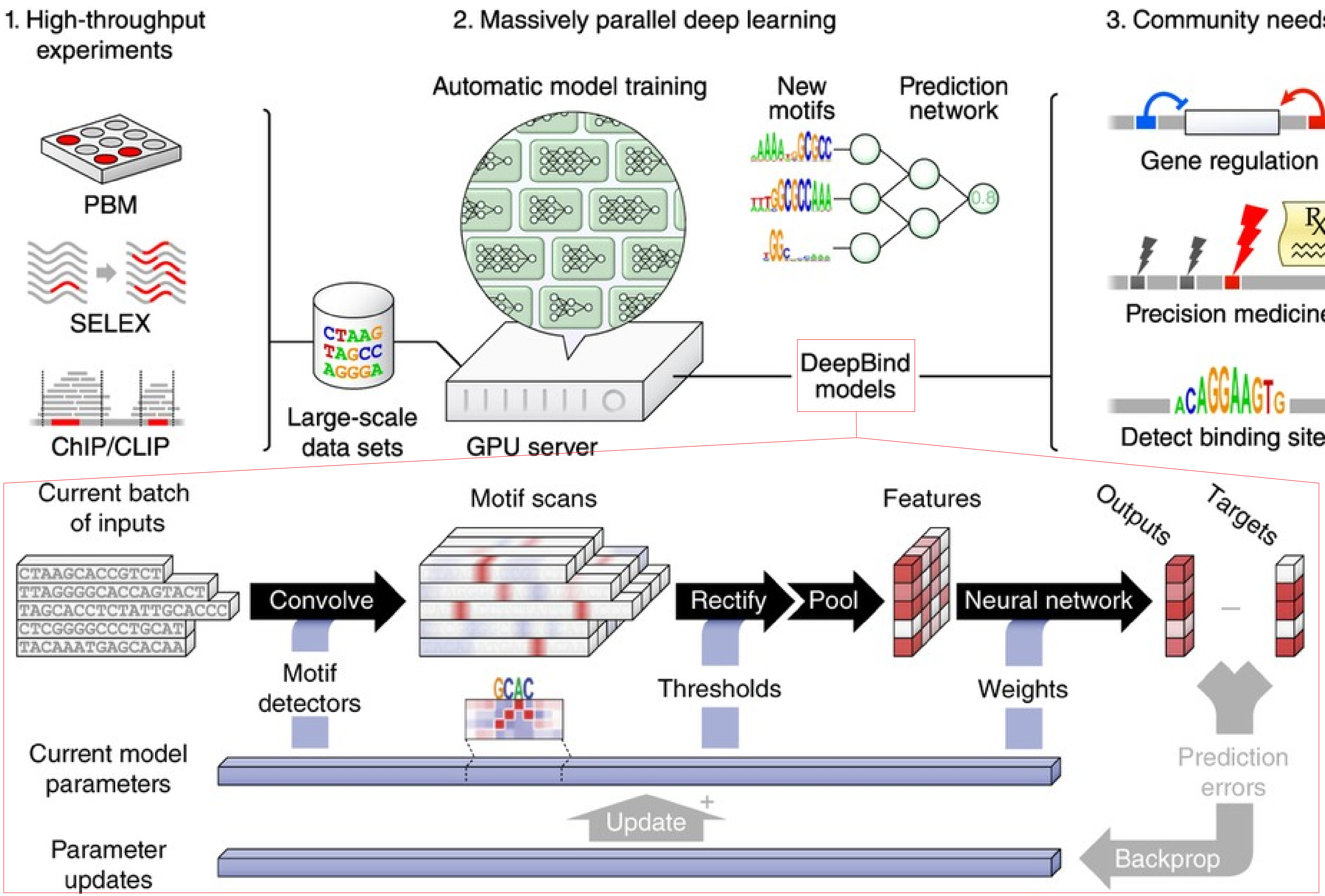


Malaria Infection
Soleimany+ *arXiv*
2019.



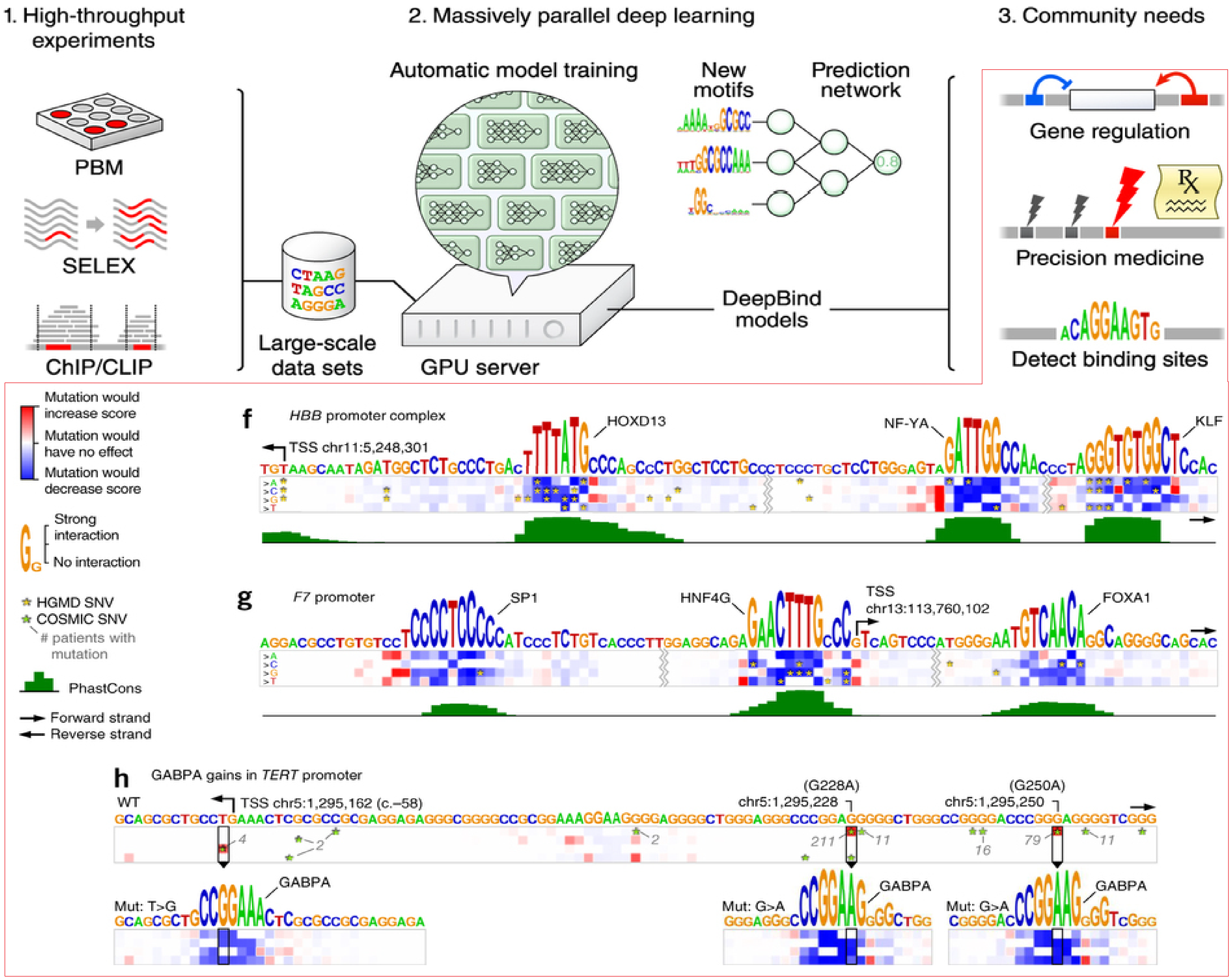
Dong+ *MIUA* 2017; Soleimany+ *arXiv* 2019

DeepBind



[Alipanahi et al., 2015]

Predicting disease mutations



[Alipanahi et al., 2015]

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Deep Learning for Computer Vision: Summary

Foundations

- Why computer vision?
- Representing images
- Convolutions for feature extraction

CNNs

- CNN architecture
- Application to classification
- ImageNet

Applications

- Segmentation, image captioning, control
- Security, medicine, robotics