ECE 6775
High-Level Digital Design Automation
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Introduction to Neural Networks

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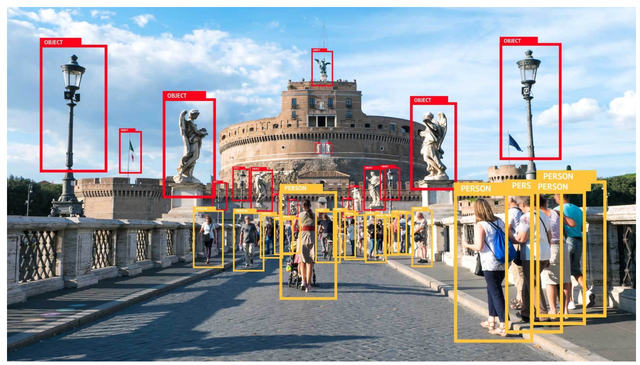
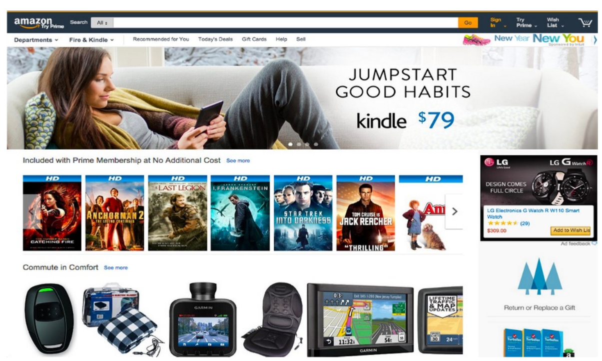
CSL

Rise of Deep Neural Networks (DNNs)

- DNNs have revolutionized information technology
  - computer vision, e-commerce, finance, game AI, healthcare, machine transcription & translation, robots, web search, and many more (to come)



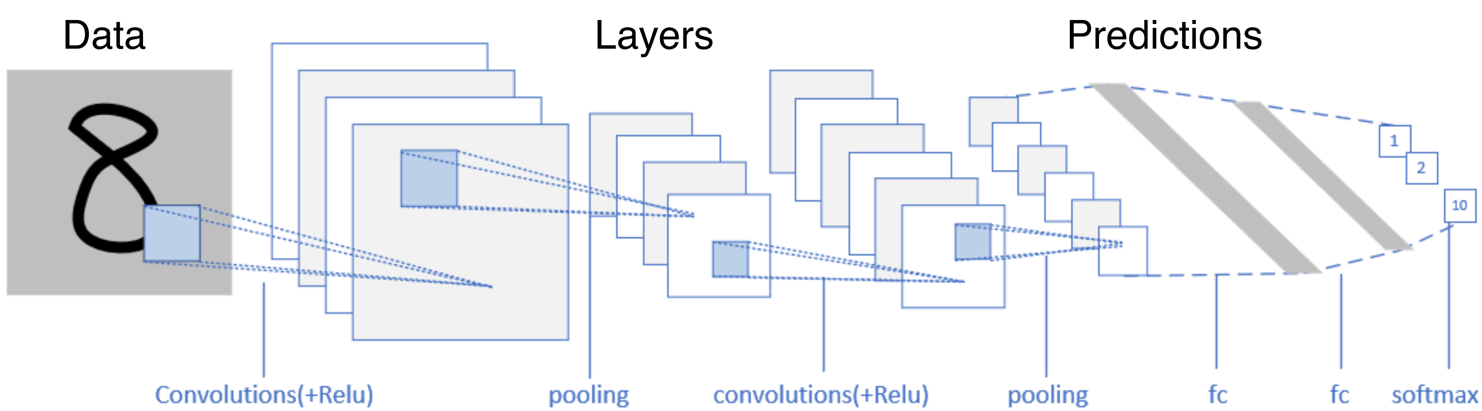


A Brief History

- **1940's – 1950's:** First artificial neural networks proposed based on biological structures in the human visual cortex
- **1980's – 2000's:** Neural networks (NNs) considered inferior to other simpler algorithms (e.g., SVM)
- **Mid 2000's**: NN research considered "dead", machine learning conferences outright reject most NN papers
- **2010 – 2012**: DNNs begin winning large-scale image and document classification contests
- **2012 – Now**: DNNs prove themselves in many industrial applications (web search, translation, image analysis)

Neural Network (NN) in a Nutshell

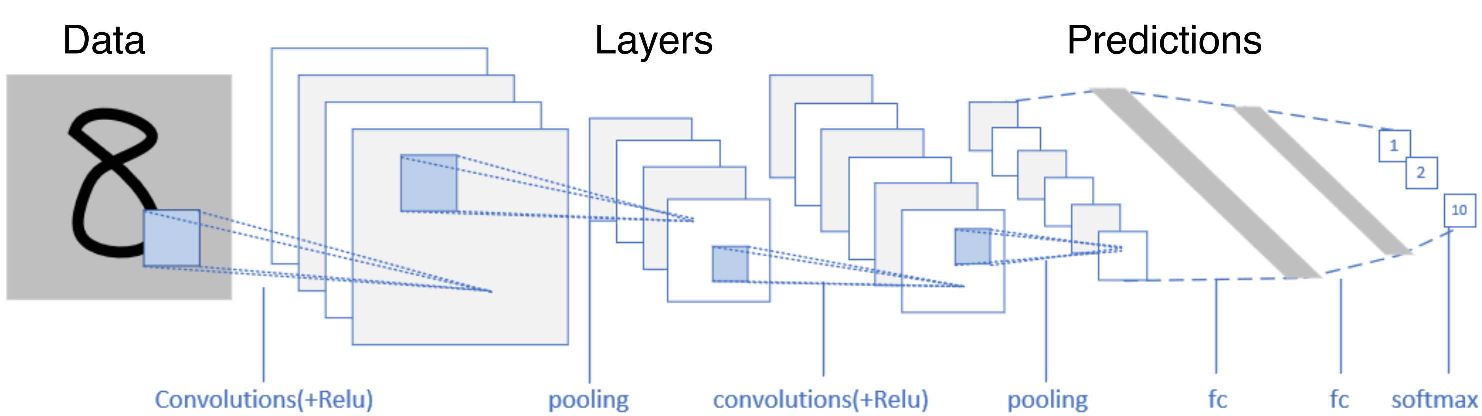
- Depends on a large volume of data & mostly supervised
- **Learns a function** that encodes a hierarchy of abstract *features*
  - Consists of a stack of connected *layers*, such as convolutional, pooling, full connected, attention



NN Training and Inference

- **Training** refers to the process of building an NN model to accomplish a specific AI task by “learning” from a predetermined dataset

- **Inference** refers to the use of a trained NN model to make a prediction (or decision) on unseen data



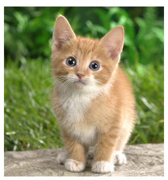
Part 1

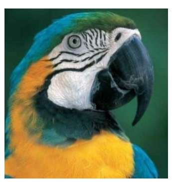
CLASSIFICATION WITH THE PERCEPTRON

Classification Problems

- We'll discuss neural networks for solving **supervised classification problems**

Inputs | **Labels**

 → Cat

 → Bird

 → Human

Training Set

- Given a training set consisting of labeled inputs
- Learn a function which maps inputs to labels
- This function is used to predict the labels of new inputs

Inputs | **Predictions**

 → ???

Predict New Data

Artificial Neuron

- The simplest possible neural network contains only one "neuron", which is described by the following equation:

$$y = \sigma\left(\sum_{i=1}^{n} w_i x_i + b\right)$$

w_i = weights
b = bias
σ = activation function

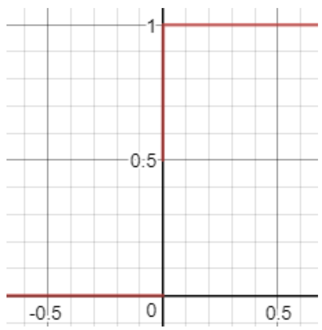
- When σ is the unit step (or sign) function, we have a **perceptron** *
  - Invented in 1957 by Frank Rosenblatt

* Perceptron is often used as a synonym for artificial neuron, where σ could be any activation function

Activation Function

- The activation function σ is non-linear

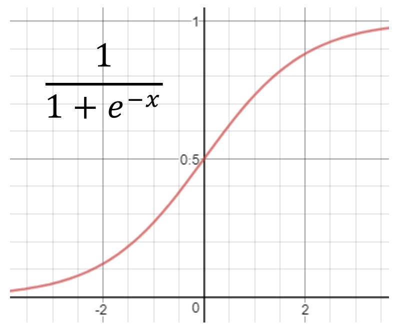
Unit Step



Hard Yes/No decision

Used in the initial perceptrons

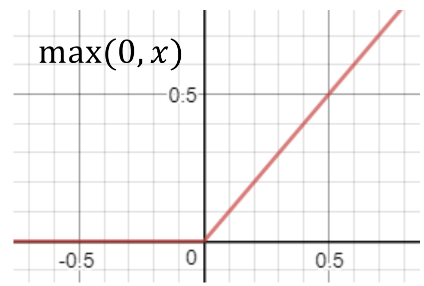
Sigmoid



Soft probability

Used in early neural nets

ReLU

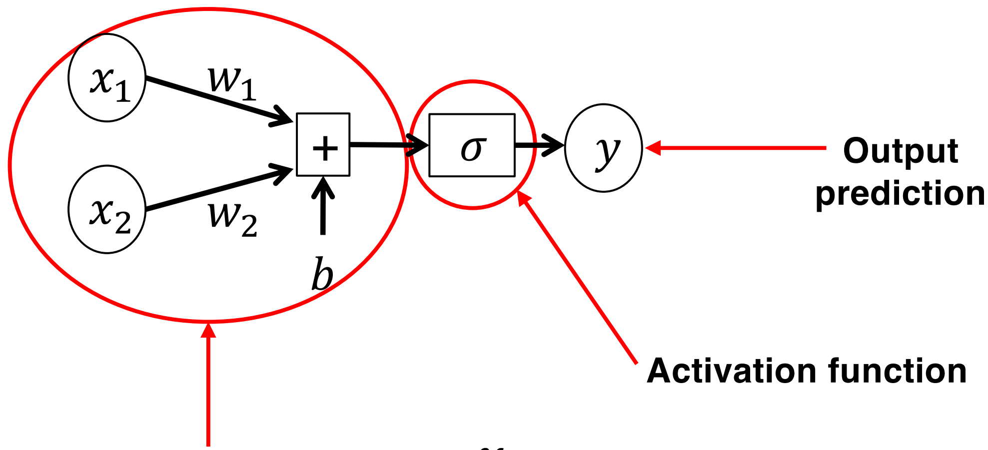


Makes deep networks easier to train

Used in modern deep nets

Breaking Down the "Neuron"

A 2-input, 1-output neuron

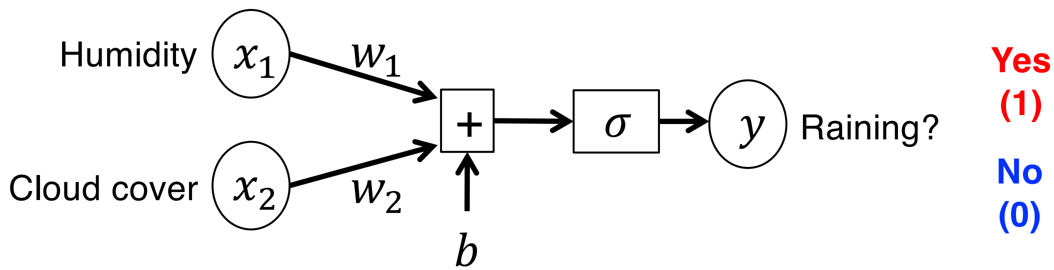


Linear function of $\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

$$\boldsymbol{w}^{\boldsymbol{T}}\boldsymbol{x} + b$$

Breaking Down the "Neuron"

A 2-input, 1-output neuron



A real-life analogue

A Real-life Classification Problem

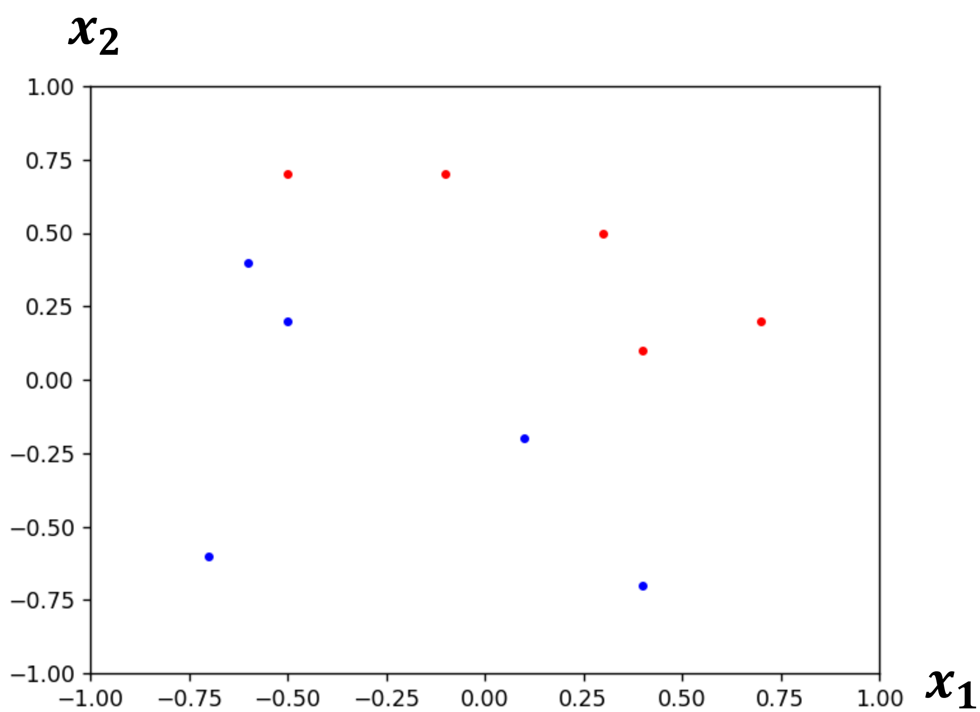
- **Inputs**: Pairs of numbers (x_1, x_2)
- **Labels**: 0 or 1 (binary decision problem)

- Real-life analogue:
  - Label = Raining or Not Raining
  - x_1 = Relative humidity
  - x_2 = Cloud coverage

x_1	x_2	Label
-0.7	-0.6	0
-0.6	0.4	0
-0.5	0.7	1
-0.5	-0.2	0
-0.1	0.7	1
0.1	-0.2	0
0.3	0.5	1
0.4	0.1	1
0.4	-0.7	0
0.7	0.2	1

Training set

Visualizing the Data

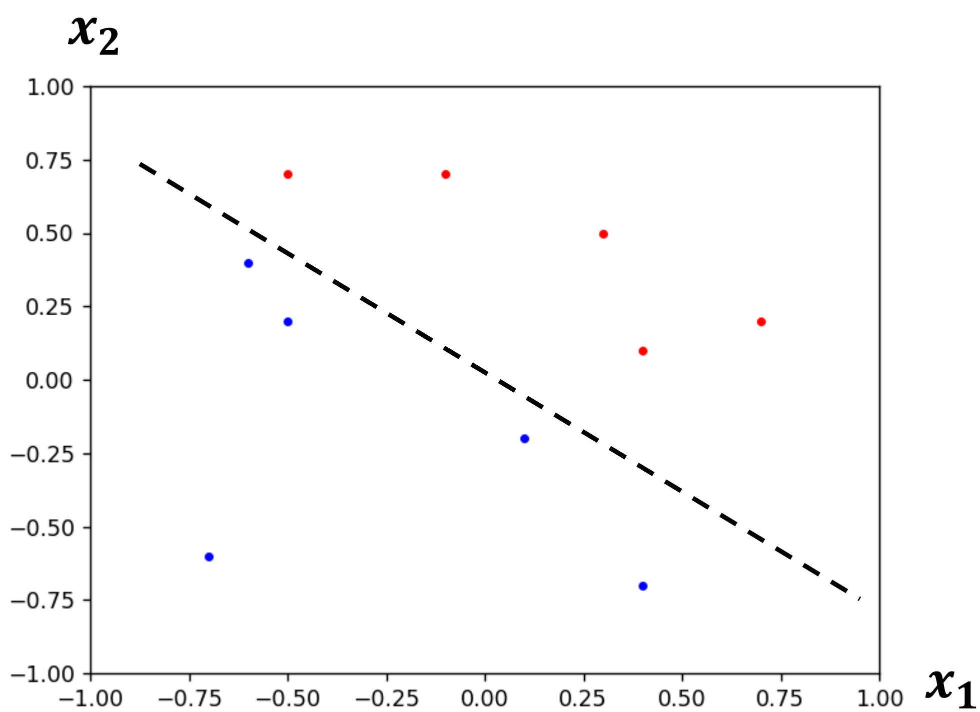


Plot of the data points

x_1	x_2	Label
-0.7	-0.6	0
-0.6	0.4	0
-0.5	0.7	1
-0.5	-0.2	0
-0.1	0.7	1
0.1	-0.2	0
0.3	0.5	1
0.4	0.1	1
0.4	-0.7	0
0.7	0.2	1

Training set

Decision Boundary



In this case, the data points can be classified with a **linear decision boundary** produced by a perceptron

x_1	x_2	Label
-0.7	-0.6	0
-0.6	0.4	0
-0.5	0.7	1
-0.5	-0.2	0
-0.1	0.7	1
0.1	-0.2	0
0.3	0.5	1
0.4	0.1	1
0.4	-0.7	0
0.7	0.2	1

Training set

Finding the Parameters

- The right parameters (weights and bias) will create any linear decision boundary we want

- **Training** = process of finding the parameters to solve our classification problem
  - Basic idea: iteratively modify the parameters to reduce the **training loss**
  - **Training loss**: measure of difference between predictions and labels on the training set

Gradient Descent

- **Loss function**
  - Measure of difference between predictions and true labels

$$L = \sum_{i=0}^{N} (y^{(i)} - t^{(i)})^2$$

Sum over training samples

$y^{(i)}$ = Prediction
$t^{(i)}$ = True label

- **Gradient Descent**:

$$w_{k+1} = w_k - \eta \frac{\partial L}{\partial w_k}$$

Gradient = direction of steepest descent in L

k = training step
η = learning rate or step size

Training a Neural Network

- At each step k:
  1. Classify each sample to get each $y^{(i)}$
  2. Compute the **loss** L
  3. Compute the **gradient** $\frac{\partial L}{\partial w_k}$
  4. Update the parameters using **gradient descent**

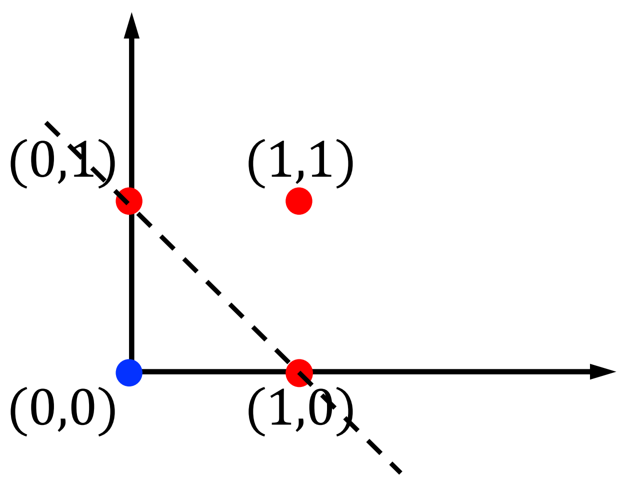
$$w_{k+1} = w_k - \eta \frac{\partial L}{\partial w_k}$$

Demo

- Perceptron training demo
  - No bias (bias = 0)
  - No test set (training samples only)

Another Example

x_2	x_1	OR		
0	0	0	$w_1x_1 + w_2x_2 + b < 0$	$\Rightarrow b < 0$
0	1	1	$w_1x_1 + w_2x_2 + b \geq 0$	$\Rightarrow w_1 \geq -b$
1	0	1	$w_1x_1 + w_2x_2 + b \geq 0$	$\Rightarrow w_2 \geq -b$
1	1	1	$w_1x_1 + w_2x_2 + b < 0$	$\Rightarrow w_1 + w_2 \geq -b$

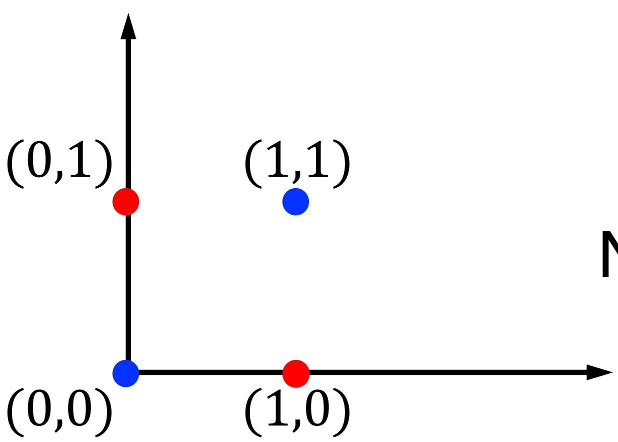


One solution:

$w_1 = 1;\ w_2 = 1;\ b = -1$

Yet Another Example (The XOR Problem)

x_2	x_1	XOR		
0	0	0	$w_1x_1 + w_2x_2 + b < 0$	$\Rightarrow$ $b < 0$
0	1	1	$w_1x_1 + w_2x_2 + b \geq 0$	$\Rightarrow$ $w_1 \geq -b$
1	0	1	$w_1x_1 + w_2x_2 + b \geq 0$	$\Rightarrow$ $w_2 \geq -b$
1	1	0	$w_1x_1 + w_2x_2 + b < 0$	$\Rightarrow$ $w_1 + w_2 < -b$



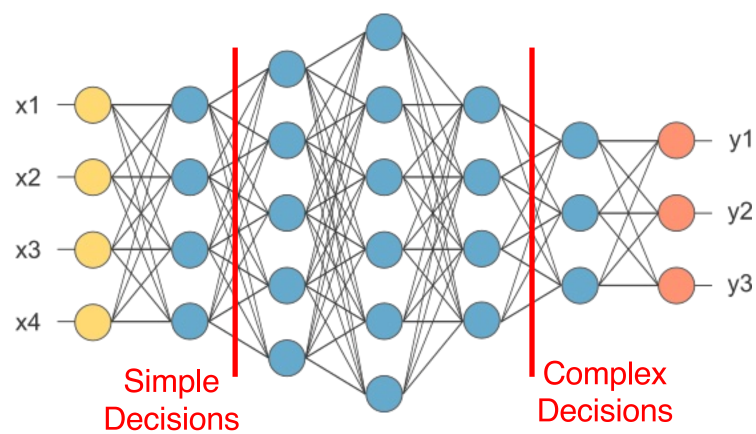
Not linearly separable

Part 2

DEEP NEURAL NETWORKS

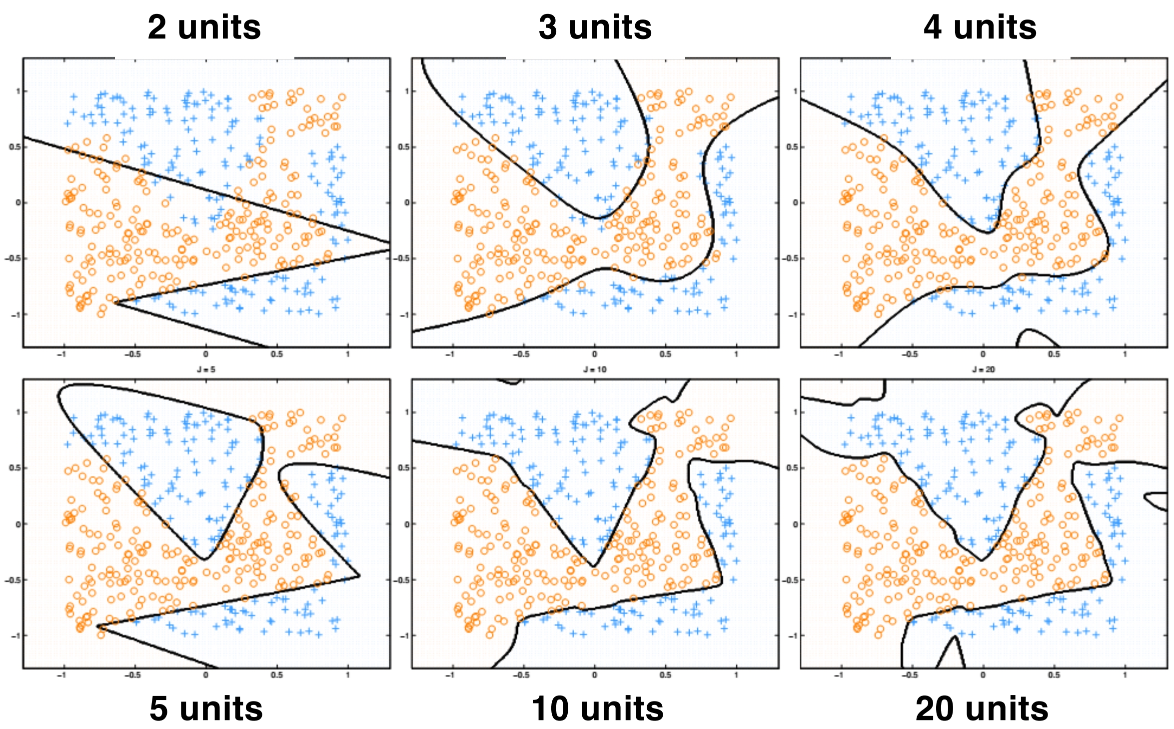
Combining Neurons

- A single neuron can only make a simple decision
- Feeding neurons into each other allows a neural network to learn **complex decision boundaries**



Source: http://www.opennn.net/

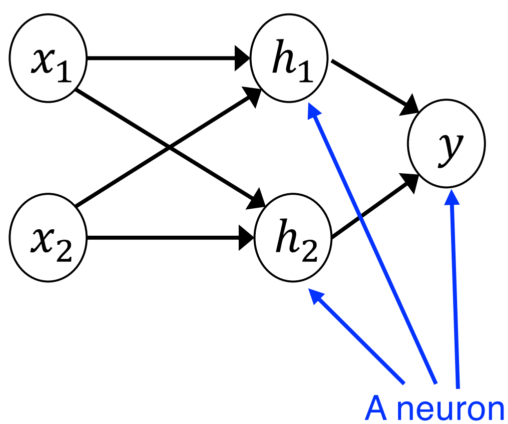
Complex Decision Boundaries



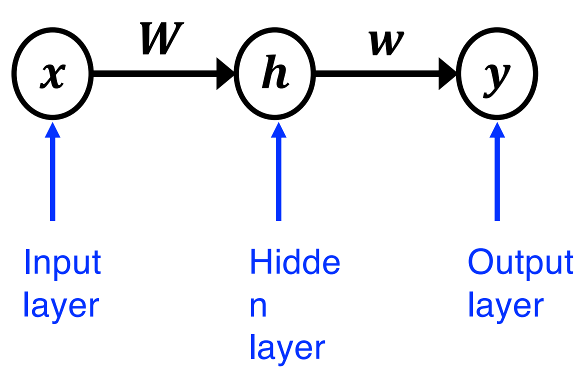
Source: https://www.carl-olsson.com/fall-semester-2013/

Multi-Layer Perceptron (MLP)

- MLP is a fully connected class of feedforward artificial neural network (ANN)
  - An MLP model consists of multiple **layers** of neurons
  - Often referred to as "vanilla" ANNs, especially with a single hidden layer



A vectorized (tensorized) view of MLP



Deep Neural Network (DNN)

- MLPs are neural networks with at least three layers, while DNNs typically have even more (hidden) layers

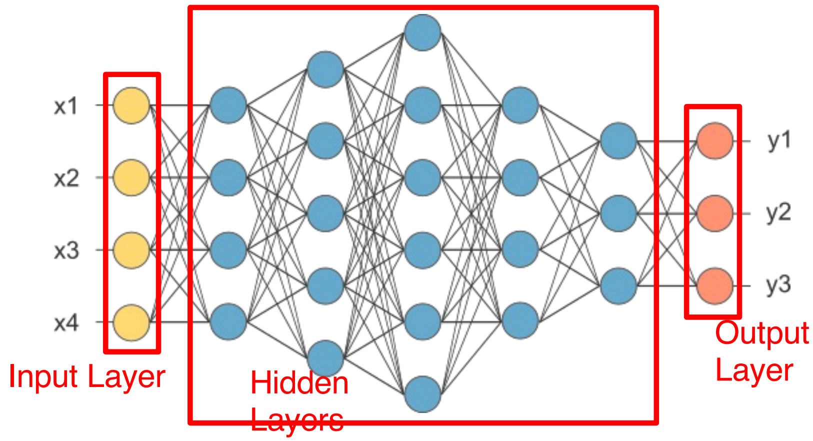


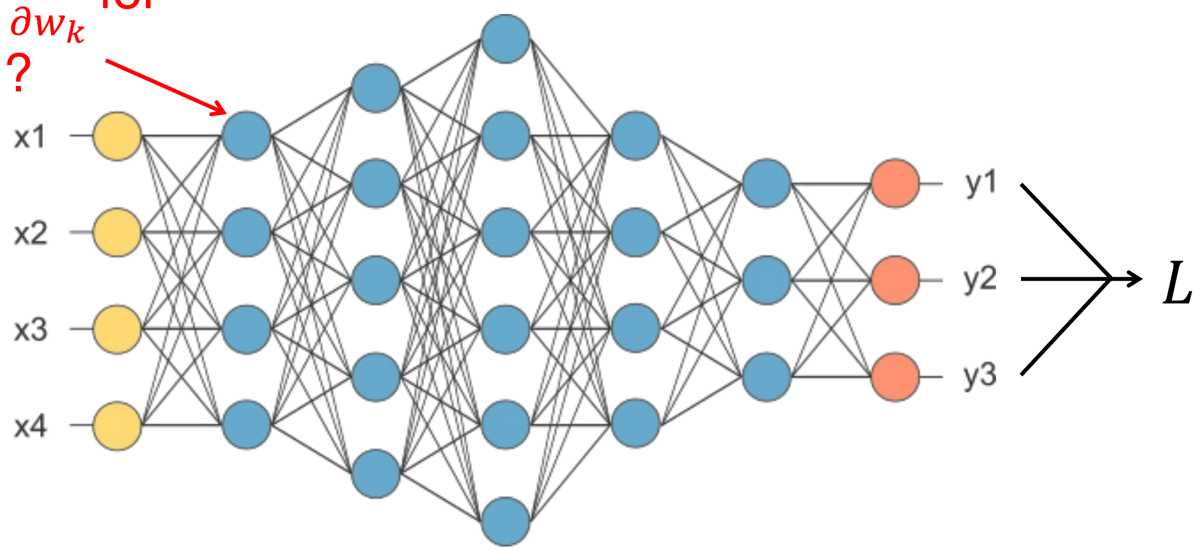
Image credit: http://www.opennn.net/

Learning a Deep Neural Network

- **Gradient Descent**:

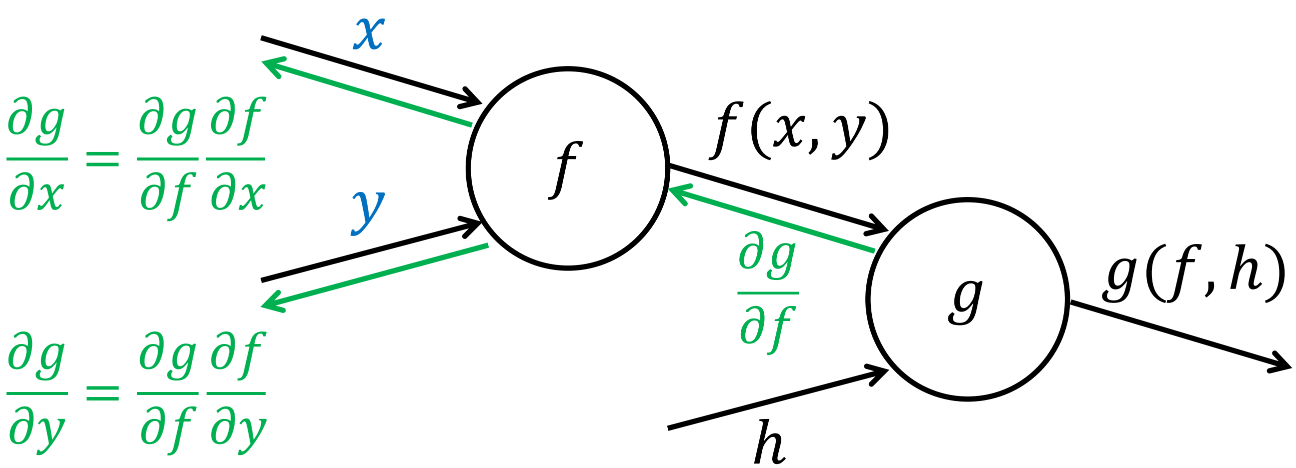
$$w_{k+1} = w_k - \eta \frac{\partial L}{\partial w_k}$$

How to get $\frac{\partial L}{\partial w_k}$ for this neuron?



Backpropagation

- **Backpropagation:** use the chain rule from calculus to propagate the gradients backwards through the network



Stochastic Gradient Descent

- Remember **Gradient Descent?**

$$w_{k+1} = w_k - \eta \frac{\partial L}{\partial w_k}$$

- L must be computed over the entire training set, which can be millions of samples!

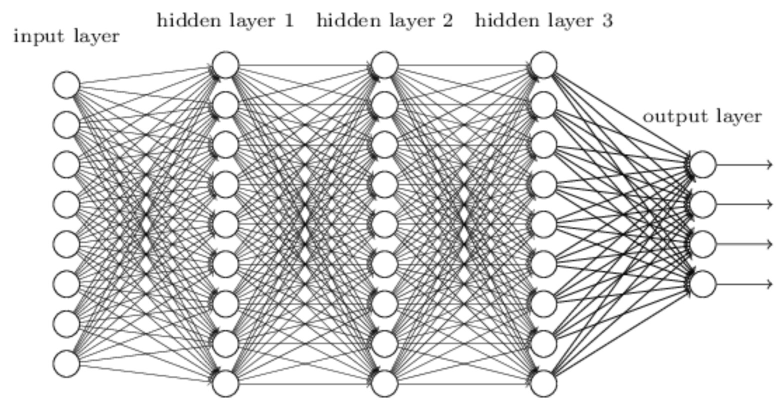
- **Stochastic Gradient Descent:**
  - At each set, only compute L for a **minibatch** (a few samples randomly taken from the training set)
  - SGD is faster and **more accurate** than GD for DNNs!

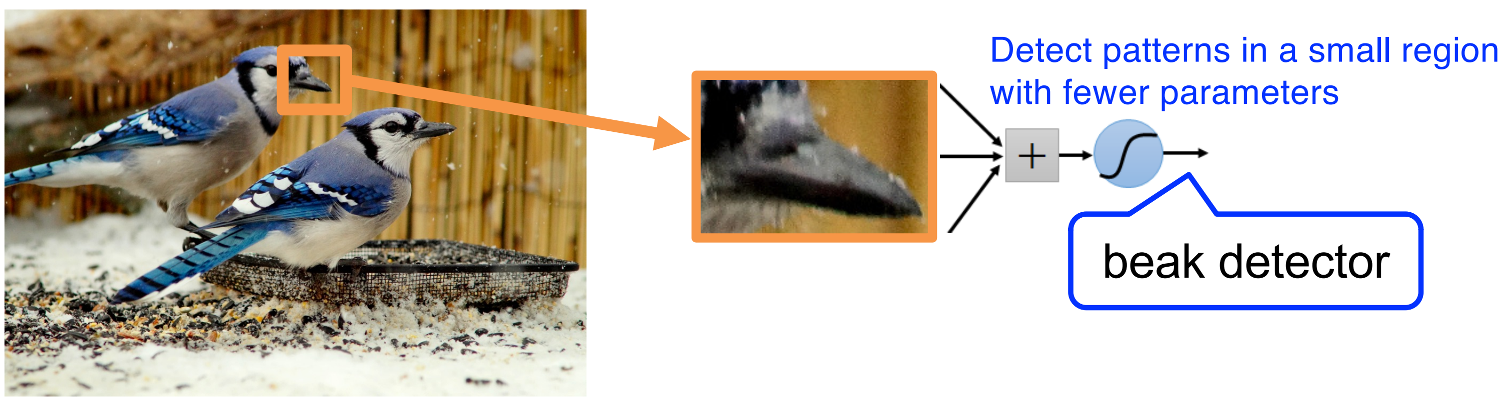
Part 3

CONVOLUTIONAL NEURAL NETWORKS

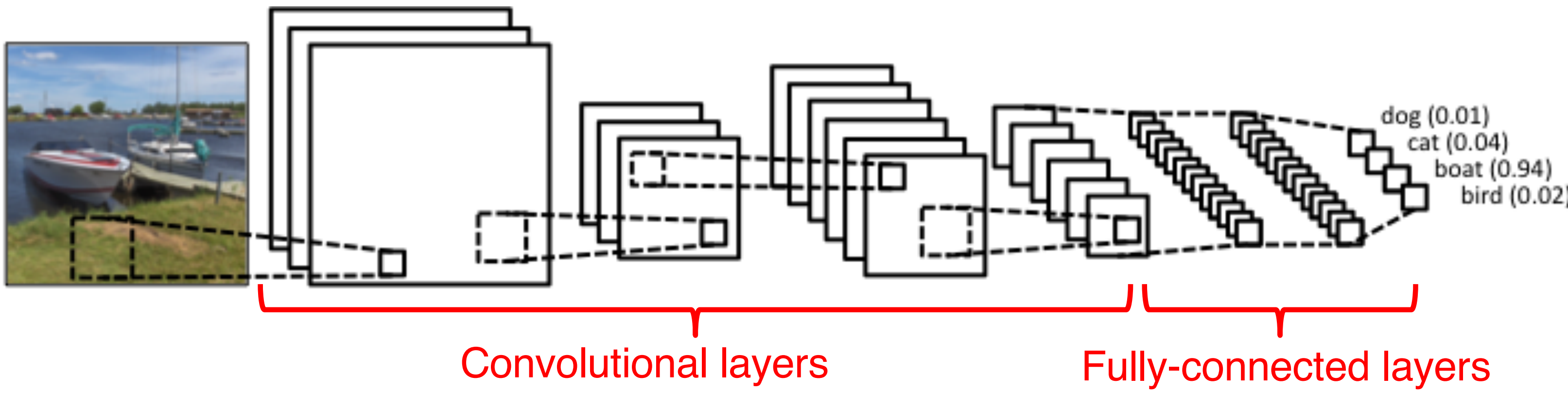
Neural Networks for Images

- So far, we've seen neural networks built from **fully-connected layers**
- Do we really need all the edges for learning an image?
  - Important patterns are typically much smaller than the whole image
  - Images are also shift-invariant (e.g., a bird is a bird even when shifted)





Convolutional Neural Network (CNN)

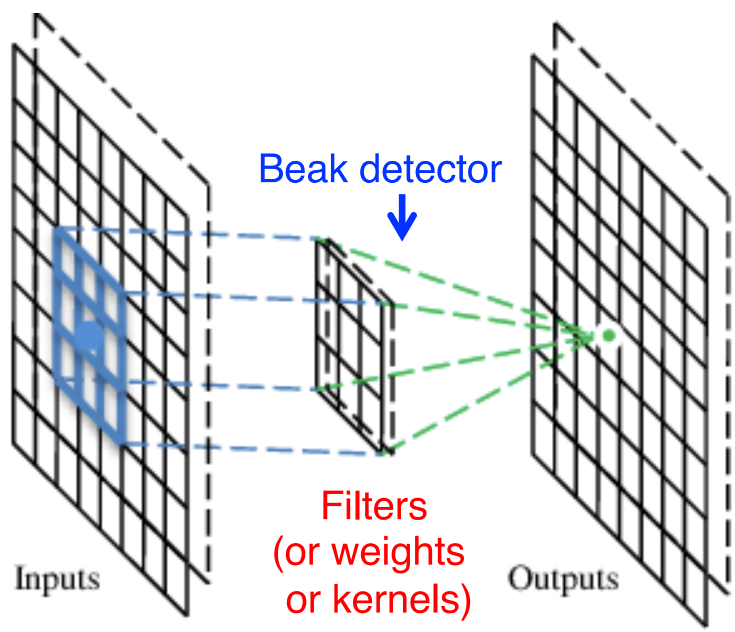


- **Front**: convolutional layers learn visual features
- Feature maps get downsampled through the network
- **Back**: fully-connected layers perform classification using the visual features

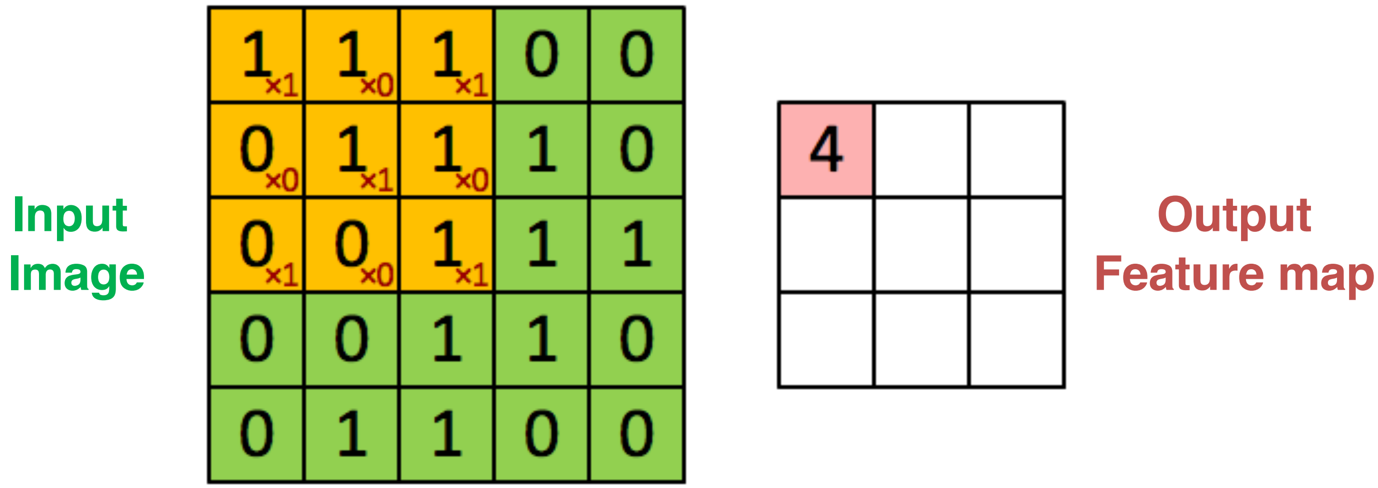
Image credit: http://www.wildml.com/2015/11/understanding-convolutional-neural-networks-for-nlp/

A Convolutional (conv) Layer

- A CNN stacks multiple conv layers (and some other layers)
- A conv layer has a set of learnable filters that perform convolution operation



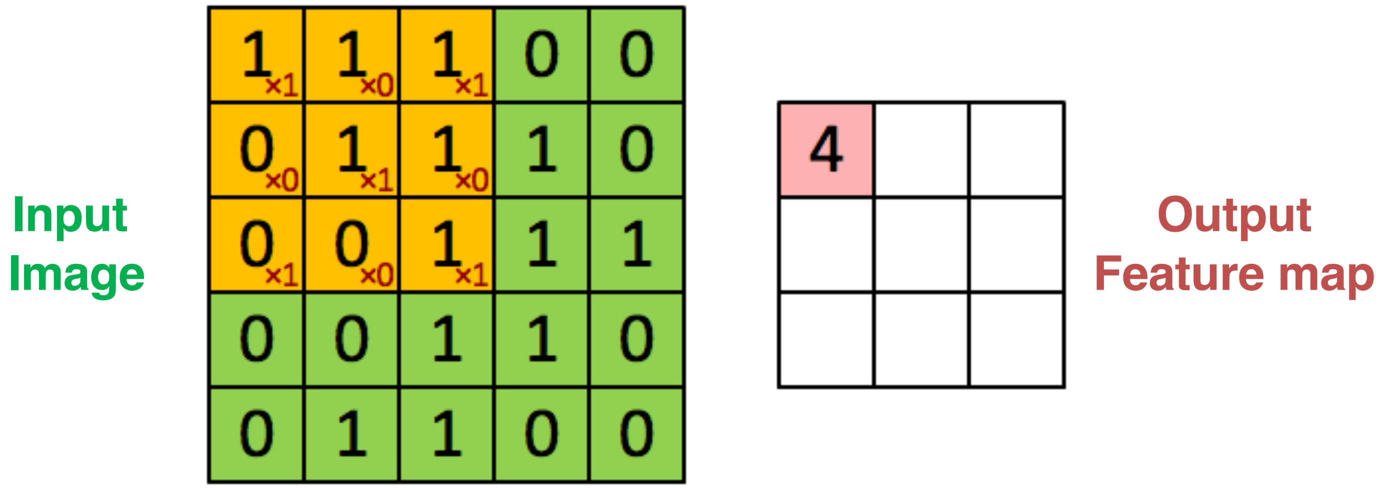
The Convolutional Filter



- Each neuron learns a **weight filter** and **convolves** the filter over the image
- Each neuron outputs a 2D **feature map** (basically an image of features)

Image credit: http://deeplearning.stanford.edu/wiki/index.php/Feature_extraction_using_convolution

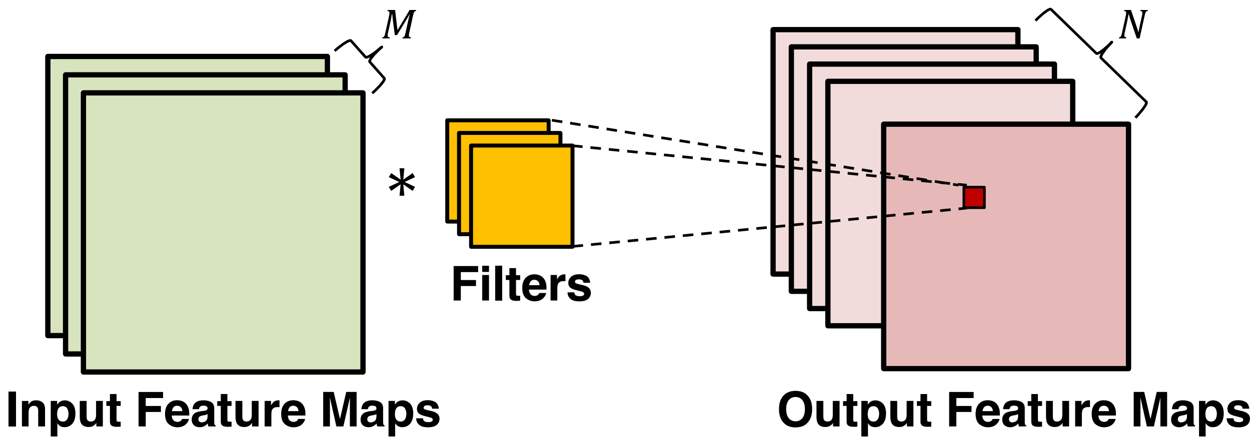
The Convolutional Filter



- Each point in the feature map encodes both a decision and its spatial location
- **Detects the pattern anywhere in the image!**

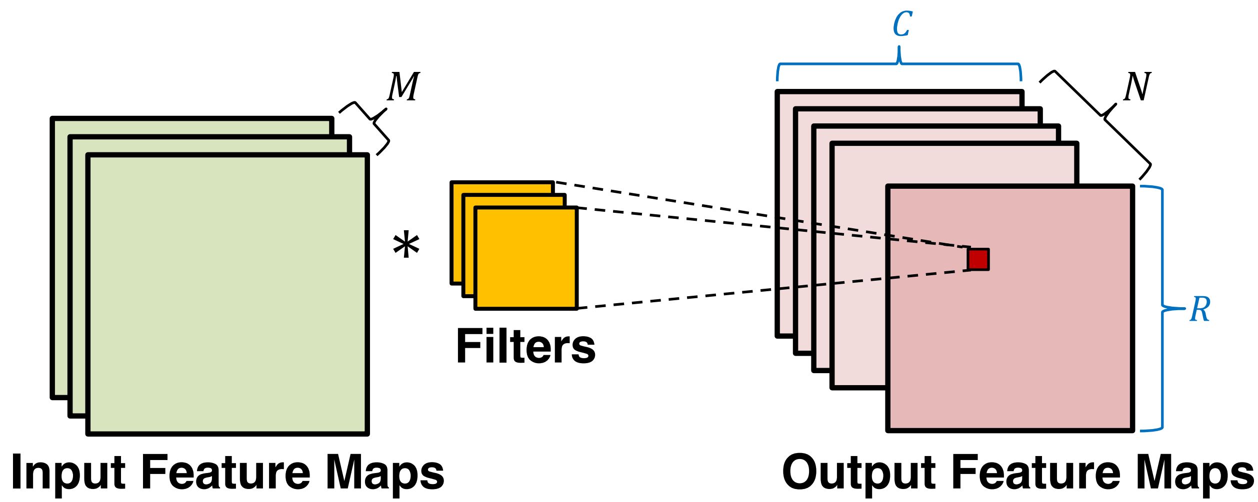
Image credit: http://deeplearning.stanford.edu/wiki/index.php/Feature_extraction_using_convolution

The Convolutional Layer: A Closer Look



- M input and N output feature maps
- Each output map uses M filters, 1 per input map
- $M \times N$ total filters

The Convolutional Layer: A Closer Look




```
for(row=0; row<R; row++) {
   for(col=0; col<C; col++) {
      for(to=0; to<N; to++) {
         for(ti=0; ti<M; ti++) {
            for(i=0; i<K; i++) {
               for(j=0; j<K; j++) {
                  output_fm[to][row][col] +=
                           weights[to][ti][i][j]*input_fm[ti][S*row+i][S*col+j];
}}}}}}
```

Huge amount of parallelism!

Learning Complex Features with CNNs

- Deep CNNs combine simple features into complex patterns
  - Early conv layers = edges, textures, ridges
  - Later conv layers = eyes, noses, mouths

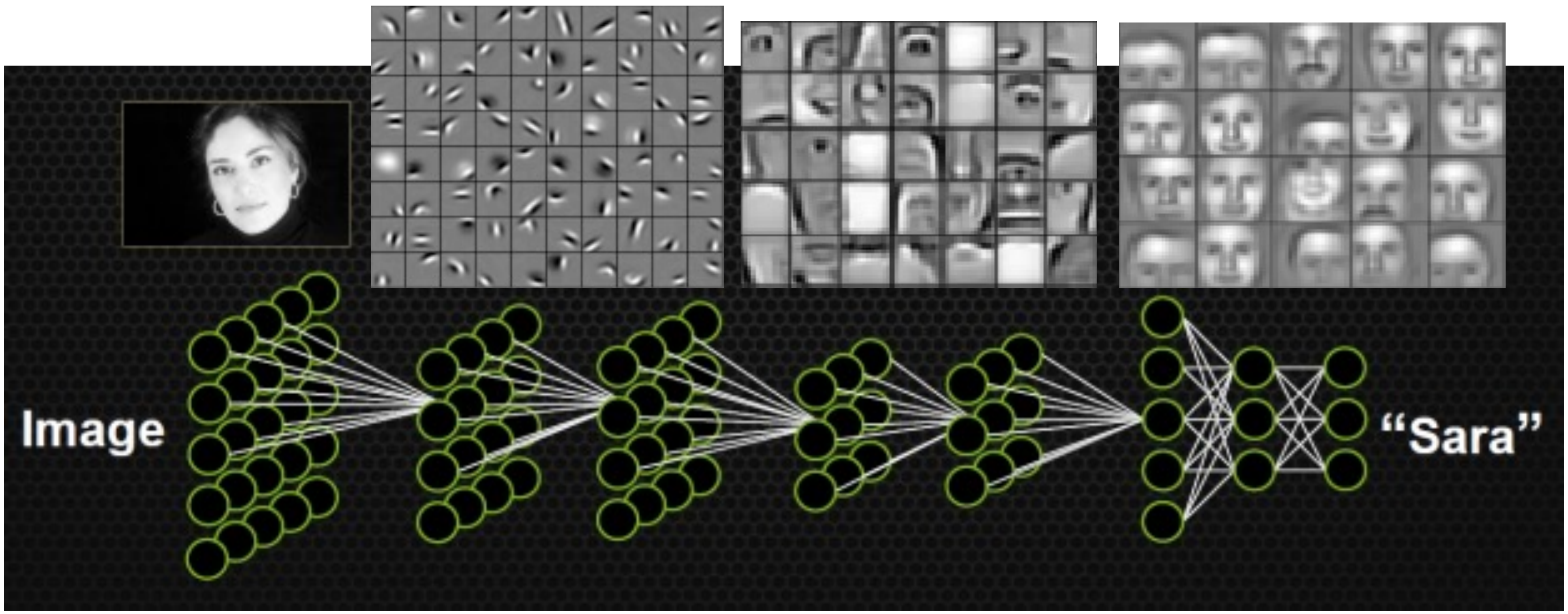


Image credit: https://devblogs.nvidia.com/parallelforall/accelerate-machine-learning-cudnn-deep-neural-network-library/; H. Lee, R. Grosse, R. Ranganath, and A. Y. Ng, "Unsupervised Learning of Hierarchical Representations with Convolutional Deep Belief Networks", CACM Oct 2011

Acknowledgements

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  - CS898 by Prof. Ming Li (University of Waterloo)
  - System for AI Education Resource by Microsoft Research