

Deep Learning Specialization

Declan Lim

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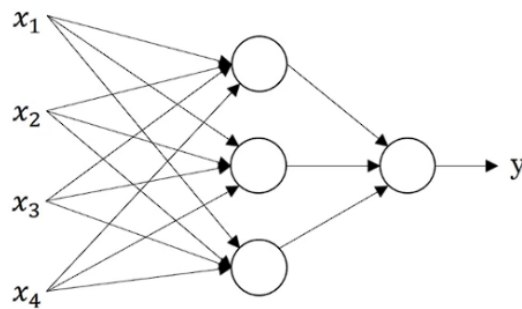
1 Neural Networks and Deep Learning

1.1 Introduction to Deep Learning

- Takes input x to a “neuron” and gives some output y



- Simple neural network has a single input, neuron and output
- x : size of the house
- y : price of the house
- Hypothesis (blue line) is a ReLU (Rectified Linear Unit)
- More complex neural networks can be formed by “stacking” neurons



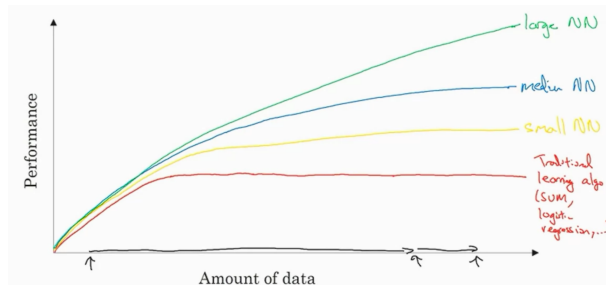
- Every input layer feature is interconnected with every hidden layer feature
 - The neural network will decide what the intermediate features will be
- Most useful in supervised learning settings

1.1.1 Supervised Learning

- Aims to learn a function to map an input x to an output y
 - Real estate: predicting house prices from the house features
 - Online advertising: showing ads based on probability of user clicking on ad
 - Photo tagging: tagging images based on objects in the image
 - Speech recognition: generating a text transcript from audio
 - Machine translation: translating from one language to another
 - Autonomous driving: returning the positions of other cars from images and radar info
- Different types of neural network used for different tasks
 - Standard neural network: real estate and online advertising
 - Convolutional neural network (CNN): image data
 - Recurrent neural network (RNN): audio and language data (sequenced data)
 - Hybrid neural network: Autonomous driving (more complex input)



- Supervised learning can be applied to structured and unstructured data
 - Structured data has features with well defined meanings
 - Unstructured data has more abstract features (images, audio, text)
- Deep learning has only recently started to become more widespread
 - Given large amounts of data and a large NN, deep learning will outperform more traditional learning algorithms
 - For small amounts of data, any performance of the algorithm depends on specific implementation
- “Scale drives deep learning progress”
 - Both the scale of the data and the NN
- Recent algorithmic innovations with increase scale of computation



- Idea to switch from sigmoid activation function to ReLu function increased NN performance
- Ends of sigmoid function have close to 0 gradient so and therefore result in small changes in θ
- ReLu function has gradient of 1 for positive values
- Neural network process is iterative
 - Increasing speed at which a NN can be trained allows different ideas to be tried

1.2 Neural Network Basics

1.2.1 Logistic Regression as a Neural Network

- Logistic regression used for binary classification
- For a colour image, of 64×64 pixels, will have total 12288 input features
 - Image is stored as 3 separate matrices for each colour channel
 - All pixel intensities should be unrolled into a single feature vector

$$n = 12288$$

$$x \in \mathbb{R}^{12288}$$

- For a matrix X of shape (a, b, c, d) , want a matrix `X_flatten` of shape $(b * c * d, 1)$

```
X_flatten = X.reshape(X.shape[0], -1).T
```

Notation

$$\{(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \dots, (x^{(m)}, y^{(m)})\}$$

- (x, y) : single training example
 - $x \in \mathbb{R}^{n_x}$ (n_x = number of features)
 - $y \in \{0, 1\}$

- $(x^{(i)}, y^{(i)})$: i^{th} training example
- $m = m_{train}$
- $m_{test} = \#$ of test examples
- $X = \begin{bmatrix} | & | & & | \\ x^{(1)} & x^{(2)} & \dots & x^{(m)} \\ | & | & & | \end{bmatrix}$
 - $X \in \mathbb{R}^{n_x \times m}$
- $Y = [y^{(1)} \ y^{(2)} \ \dots \ y^{(m)}]$
 - $Y \in \mathbb{R}^{1 \times m}$

Logistic Regression

- Given x , want $\hat{y} = P(y = 1|x)$
 - Since \hat{y} is a probability, want $0 \leq \hat{y} \leq 1$
- Parameters: $w \in \mathbb{R}^{n_x}, b \in \mathbb{R}$
- Output: $\hat{y} = \sigma(w^T x + b)$



$$\sigma(z) = \frac{1}{1 + e^{-z}}$$

$$z = w^T x + b$$

- Aim is to learn parameters w and b such that \hat{y} is a good estimate of the probability
- Previous convention had θ vector with an additional θ_0 parameter
 - Keeping θ_0 (b) separate from the rest of the parameters is easier to implement

Cost Function

- Given $\{(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \dots, (x^{(m)}, y^{(m)})\}$, want $\hat{y}^{(i)} \approx y^{(i)}$
- Squared error function not used for logistic regression loss function

- Optimization problem becomes non convex and will have local optima

$$\mathcal{L}(\hat{y}, y) = -(y \log(\hat{y}) + (1 - y) \log(1 - \hat{y}))$$

- If $y = 1$:
 - $\mathcal{L}(\hat{y}, y) = -\log(\hat{y})$
 - Want large $\log(\hat{y}) \therefore$ want large \hat{y}
 - \hat{y} has a max of 1 \therefore want $\hat{y} = 1$
- If $y = 0$:
 - $\mathcal{L}(\hat{y}, y) = -\log(1 - \hat{y})$
 - Want large $\log(1 - \hat{y}) \therefore$ want small \hat{y}
 - \hat{y} has a min of 0 \therefore want $\hat{y} = 0$

- Cost function:

$$\begin{aligned} J(w, b) &= \frac{1}{m} \sum_{i=1}^m \mathcal{L}(\hat{y}^{(i)}, y^{(i)}) \\ &= -\frac{1}{m} \sum_{i=1}^m [y^{(i)} \log(\hat{y}^{(i)}) + (1 - y^{(i)}) \log(1 - \hat{y}^{(i)})] \end{aligned}$$

- Average loss function over all training examples

Gradient Descent

- Want to find values of w and b that minimize the cost function $J(w, b)$
 - For logistic regression, w and b usually initialized to 0
- One iteration of gradient descent will take a step in the direction of steepest descent

```
Repeat {
  w := w -  $\alpha \frac{\partial J(w, b)}{\partial w}$ 
  b := b -  $\alpha \frac{\partial J(w, b)}{\partial b}$ 
}
```

- Using the computation graph:

$$\frac{\partial \mathcal{L}(a, y)}{\partial a} = -\frac{y}{a} + \frac{1 - y}{1 - a}$$



$$\begin{aligned}
 \frac{\partial \mathcal{L}(a, y)}{\partial z} &= \frac{\partial \mathcal{L}}{\partial a} \times \frac{\partial a}{\partial z} \\
 &= \left(-\frac{y}{a} + \frac{1-y}{1-a}\right) \times a(1-a) \\
 &= a - y
 \end{aligned}$$

$$\frac{\partial \mathcal{L}}{\partial w_1} = x_1 \times \frac{\partial \mathcal{L}}{\partial z}$$

$$\frac{\partial \mathcal{L}}{\partial w_2} = x_2 \times \frac{\partial \mathcal{L}}{\partial z}$$

$$\frac{\partial \mathcal{L}}{\partial b} = \frac{\partial \mathcal{L}}{\partial z}$$

- Partial derivative over all training examples calculated by taking the average $\mathbf{dw1}$

$$\frac{\partial}{\partial w_1} J(w, b) = \frac{1}{m} \sum_{i=1}^m \frac{\partial}{\partial w_1} \mathcal{L}(a^{(i)}, y^{(i)})$$

Initialize $J = 0$, $\mathbf{dw1} = 0$, $\mathbf{dw2} = 0$, $\mathbf{db} = 0$

For $i = 1$ to m :

$$\mathbf{z}^{(i)} = \mathbf{w}^T \mathbf{x}^{(i)} + \mathbf{b}$$

$$\mathbf{a}^{(i)} = \sigma(\mathbf{z}^{(i)})$$

$$J += -[y^{(i)} \log(a^{(i)}) + (1-y^{(i)}) \log(1-a^{(i)})]$$

$$d\mathbf{z}^{(i)} = \mathbf{a}^{(i)} - \mathbf{y}^{(i)}$$

$$d\mathbf{w1} += \mathbf{x}_1^{(i)} d\mathbf{z}^{(i)}$$

$$d\mathbf{w2} += \mathbf{x}_2^{(i)} d\mathbf{z}^{(i)}$$

$$d\mathbf{b} += d\mathbf{z}^{(i)}$$

$J /= m$

$d\mathbf{w1} /= m$

$d\mathbf{w2} /= m$

$d\mathbf{b} /= m$

$$\mathbf{w1} := \mathbf{w1} - \alpha d\mathbf{w1}$$

$$\mathbf{w2} := \mathbf{w2} - \alpha d\mathbf{w2}$$

$$\mathbf{b} := \mathbf{b} - \alpha d\mathbf{b}$$

- Above implementation requires **for** loop over all features for all training examples
 - Vectorization can be used to remove explicit **for** loops
 - Vectorization required for deep learning to be efficient

1.2.2 Vectorisation in Python

- Deep learning performs best on large data sets
 - Code must be able to run quickly to be effective on large data sets

$$z = w^T x + b$$

$$w \in \mathbb{R}^{n_x} \quad x \in \mathbb{R}^{n_x}$$

- Non vectorized implementation:

```
z = 0
for i in range(n_x):
    z += w[i] * x[i]
z += b
```

- GPUs and CPUs both have parallelization instructions (SIMD: Single Instruction Multiple Data)
 - If built in functions are used, **numpy** will use parallelism to perform computations faster
- For logistic regression, need to calculate z and a values for each training example

$$z^{(i)} = w^T x^{(i)} + b$$

$$a^{(i)} = \sigma(z^{(i)})$$

$$X = \begin{bmatrix} | & | & \dots & | \\ x^{(1)} & x^{(2)} & \dots & x^{(m)} \\ | & | & & | \end{bmatrix}$$

$$w \in \mathbb{R}^{n_x} \quad X \in \mathbb{R}^{n_x \times m}$$

$$\begin{aligned} [z^{(1)} \quad z^{(2)} \quad \dots \quad z^{(m)}] &= w^T X + [b \quad b \quad \dots \quad b] \\ &= [w^T x^{(1)} + b \quad w^T x^{(2)} + b \quad \dots \quad w^T x^{(m)} + b] \end{aligned}$$

- In Python:


```
Z = np.dot(w.T, X) + b
```

- Python will broadcast the value **b** so it can be added to the matrix
- Vectorized implementation of sigmoid function can be used on **Z** to calculate **A**

$$A = [a^{(1)} \quad a^{(2)} \quad \dots \quad a^{(m)}]$$

$$dz^{(i)} = a^{(i)} - y^{(i)}$$

$$dz = A - Y$$

$$db = \frac{1}{m} \sum_{i=1}^m dz^{(i)}$$

$$dw = \frac{1}{m} X(dz)^T$$

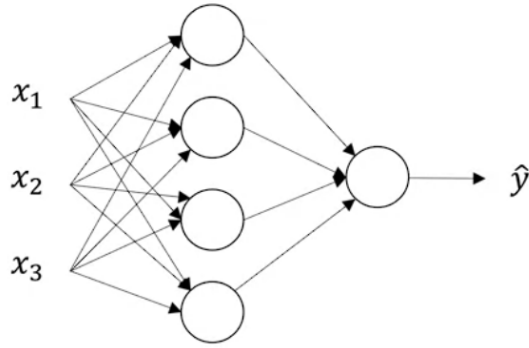
```
Z = np.dot(w.T,X) + b
A = sigmoid(Z)
dz = A - Y
dw = 1/m * np.dot(X, dz.T)
db = 1/m * np.sum(dz)

# Gradient descent update
w = w - alpha * dw
b = b - alpha * db
```

- for loop is required to run multiple iterations of gradient descent

1.3 Shallow Neural Networks

- A neural network will have stacked logistic regression units in each layer
 - Logistic regression output from one layer will be fed to another layer



- Input layer of the neural network contains the feature x_1, x_2, x_3
 - $a^{[0]} = X$
- Intermediate layers in the network are hidden layers
 - Hidden layers do not have “true” values in the training set
- Final layer in the network is the output layer
 - Generates the predicted value \hat{y}
- Above diagram is a 2 layer NN
 - Input layer is layer 0
- Each layer will have parameters w and b associated with them
- Each node in the NN will perform logistic regression with its inputs

$$z_i^{[l]} = w_i^{[l]T} x + b_i^{[l]} \rightarrow a_i^{[l]} = \sigma(z_i^{[l]})$$

$$W^{[1]} = \begin{bmatrix} - & w_1^{[1]T} & - \\ - & w_2^{[1]T} & - \\ - & w_3^{[1]T} & - \\ - & w_4^{[1]T} & - \end{bmatrix}$$

$$a^{[0]} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$b^{[1]} = \begin{bmatrix} b_1^{[1]} \\ b_2^{[1]} \\ b_3^{[1]} \\ b_4^{[1]} \end{bmatrix}$$

$$\begin{aligned}
z^{[1]} &= \begin{bmatrix} z_1^{[1]} \\ z_2^{[1]} \\ z_3^{[1]} \\ z_4^{[1]} \end{bmatrix} \\
&= \begin{bmatrix} w_1^{[1]T} a^{[0]} + b_1^{[1]} \\ w_2^{[1]T} a^{[0]} + b_1^{[1]} \\ w_3^{[1]T} a^{[0]} + b_1^{[1]} \\ w_4^{[1]T} a^{[0]} + b_1^{[1]} \end{bmatrix} \\
&= w^{[1]} a^{[0]} + b^{[1]}
\end{aligned}$$

$$\begin{aligned}
a^{[1]} &= \begin{bmatrix} a_1^{[1]} \\ a_2^{[1]} \\ a_3^{[1]} \\ a_4^{[1]} \end{bmatrix} \\
&= \sigma(z^{[1]})
\end{aligned}$$

$$z^{[2]} = W^{[2]} a^{[1]} + b^{[2]} \rightarrow a^{[2]} = \sigma(z^{[2]})$$

- Vectorized method should be able to work on all training examples at one time
 - Vector for each training example can be stacked horizontally in a matrix
 - Vertical dimension will be the number of units in a layer (n_x for the input layer)

$$X = \begin{bmatrix} \begin{matrix} | \\ x^{(1)} \\ | \end{matrix} & \begin{matrix} | \\ x^{(2)} \\ | \end{matrix} & \begin{matrix} | \\ x^{(m)} \\ | \end{matrix} \end{bmatrix}$$

$$Z^{[1]} = \begin{bmatrix} \begin{matrix} | \\ z^{1} \\ | \end{matrix} & \begin{matrix} | \\ z^{[1](2)} \\ | \end{matrix} & \dots & \begin{matrix} | \\ z^{[1](m)} \\ | \end{matrix} \end{bmatrix}$$

$$A^{[1]} = \begin{bmatrix} \begin{matrix} | \\ a^{1} \\ | \end{matrix} & \begin{matrix} | \\ a^{[1](2)} \\ | \end{matrix} & \dots & \begin{matrix} | \\ a^{[1](m)} \\ | \end{matrix} \end{bmatrix}$$

$$Z^{[1]} = W^{[1]} X + b^{[1]}$$

$$A^{[1]} = \sigma(Z^{[1]})$$

$$Z^{[2]} = W^{[2]} A^{[1]} + b^{[2]}$$

$$A^{[2]} = \sigma(Z^{[2]})$$

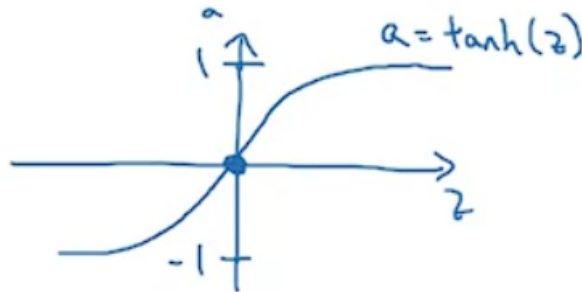
1.3.1 Activation Functions

- After z values are calculated, activation function must be run to get the activation value a

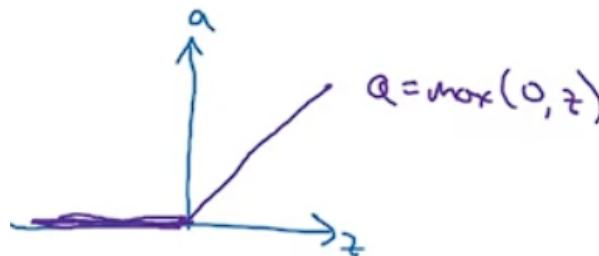
$$a_{sigmoid} = \frac{1}{1 + e^{-z}}$$

- Alternatively $a^{[1]} = g(z^{[1]})$ where g is a non linear function
- tanh function almost always performs better than the sigmoid function
 - Equivalent to a transformed version of the sigmoid function
 - tanh function is odd and is “centered” around the origin
 - The mean of the data will be closer to 0 and will help with learning in the next layer

$$a_{tanh} = \frac{e^z - e^{-z}}{e^z + e^{-z}}$$



- For binary classification, the final output layer can use the sigmoid function
 - Want the value of \hat{y} to be between 0 and 1
- For both the sigmoid and tanh functions, when z is large, the gradient is very small
 - Results in a slower gradient descent
- ReLU function has a gradient of 1 when z is positive



- Gradient is 0 when z is negative
- For majority of the ReLU function, gradient is very different from 0
 - Will typically allow NN to learn much faster than sigmoid or tanh function
- ReLU function should be used as the default activation function
- The leaky ReLU function has a slight positive gradient when z is negative

$$a_{leakyReLU} = \max(0.01z, z)$$



- For a NN to compute more complex functions, activation function must be non linear
 - If a linear activation function is used, final output of the NN can only be a linear function
 - Multiple linear activation neurons with a sigmoid as the output neuron is equivalent to standard logistic regression
- Linear activation function can be used in the output layer if output is a real number
- Derivative of the activation function must be calculated for backpropagation
 - Sigmoid function

$$g(z) = \frac{1}{1 + e^{-z}}$$

$$\begin{aligned} \frac{d}{dz}g(z) &= \frac{1}{1 + e^{-z}} \left(1 - \frac{1}{1 + e^{-z}} \right) \\ &= g(z)(1 - g(z)) \end{aligned}$$

- tanh function

$$\begin{aligned} g(z) &= \tanh(z) \\ &= \frac{e^z - e^{-z}}{e^z + e^{-z}} \end{aligned}$$

$$\begin{aligned}\frac{d}{dz}g(z) &= 1 - \left(\frac{e^z - e^{-z}}{e^z + e^{-z}}\right)^2 \\ &= 1 - g(z)^2\end{aligned}$$

– ReLU function

$$\begin{aligned}g(z) &= \max(0, z) \\ \frac{d}{dz}g(z) &= \begin{cases} 0 & \text{if } z < 0 \\ 1 & \text{if } z \geq 0 \end{cases}\end{aligned}$$

– Leaky ReLU function

$$\begin{aligned}g(z) &= \max(0.01z, z) \\ \frac{d}{dz}g(z) &= \begin{cases} 0.01 & \text{if } z < 0 \\ 1 & \text{if } z \geq 0 \end{cases}\end{aligned}$$

1.3.2 Gradient Descent for Neural Networks

- For a single hidden layer NN, parameters are: $w^{[1]}, b^{[1]}, w^{[2]}, b^{[2]}$
 - $w^{[1]} \in \mathbb{R}^{n_1 \times n_0}$
 - $b^{[1]} \in \mathbb{R}^{n_1 \times 1}$
 - $w^{[2]} \in \mathbb{R}^{n_2 \times n_1}$
 - $b^{[2]} \in \mathbb{R}^{n_2 \times 1}$
- Cost function: $J(w^{[1]}, b^{[1]}, w^{[2]}, b^{[2]}) = \frac{1}{m} \sum_{i=1}^n \mathcal{L}(\hat{y}, y)$
- For one iteration of gradient descent:

$$w^{[1]} := w^{[1]} - \alpha dw^{[1]}, \quad b^{[1]} := b^{[1]} - \alpha db^{[1]}$$

$$w^{[2]} := w^{[2]} - \alpha dw^{[2]}, \quad b^{[2]} := b^{[2]} - \alpha db^{[2]}$$

– Gradient descent step will take place after backpropagation calculates the derivatives

- Forward propagation:

$$Z^{[1]} = W^{[1]}X + b^{[1]}$$

$$A^{[1]} = g^{[1]}(Z^{[1]})$$

$$Z^{[2]} = W^{[2]}A^{[1]} + b^{[2]}$$

$$A^{[2]} = g^{[2]}(Z^{[2]})$$

- Backpropagation:

$$\begin{aligned}
 dz^{[2]} &= A^{[2]} - Y \\
 dw^{[2]} &= \frac{1}{m} dz^{[2]} A^{[1]T} \\
 db^{[2]} &= \frac{1}{m} \text{np.sum}(dz^{[2]}, \text{axis} = 1, \text{keepdims} = \text{True}) \\
 dz^{[1]} &= w^{[2]T} dz^{[2]} \times g^{[1]'}(z^{[1]}) \\
 dw^{[1]} &= \frac{1}{m} dz^{[1]} X^T \\
 db^{[1]} &= \frac{1}{m} \text{np.sum}(dz^{[1]}, \text{axis} = 1, \text{keepdims} = \text{True})
 \end{aligned}$$

1.3.3 Random Initialization

- Weights must be initialized randomly for a NN
 - Weights can be initialized to 0 for logistic regression
 - The bias terms b can be initialized
- If weights are initialized to 0, all neurons in a layer will compute the same hypothesis

```

W1 = np.random.randn((2,2)) * 0.01
b1 = np.zeros((2,1))

```

- Weights should be initialized to small random values
 - If weight is too large, activation value $z^{[1]}$ will be large
 - If sigmoid or tanh function is used, derivative will be very small and learning will be very slow
- Different constant for `np.random.randn` should be used for deeper neural networks

1.4 Deep Neural Networks

- Logistic regression is equivalent to a 1-layer NN
- Deep NN have more hidden layers
 - Number of hidden layers in the network can be a parameter for the ML problem



- Above network has 4 layers, $L = 4$
- $n^{[l]}$ = number of units in layer l
- $a^{[l]}$ = activations in layer l
- The inputs x are the activations of the first layer, $x = a^{[0]}$
 - Prediction \hat{y} will be the activations of the last layer, $\hat{y} = a^{[L]}$
- Forward propagation for a deep NN will follow the same pattern for all layers

$$z^{[l]} = w^{[l]}a^{[l-1]} + b^{[l]}$$

$$a^{[l]} = g^{[l]}(z^{[l]})$$

- For a vectorized implementation

$$Z^{[l]} = W^{[l]}A^{[l-1]} + b^{[l]}$$

$$A^{[l]} = g^{[l]}(z^{[l]})$$

- Explicit for loop will be used to loop over the layers in the network
- b will still be a column vector but will apply correctly due to broadcasting
- When working with W and A matrices, A will be for the previous layer so the dimensions will fit
- When debugging NN, can look at dimensions of all the matrices
- For a non vectorized implementation:
 - $W^{[l]} : (n^{[l]}, n^{[l-1]})$
 - $b^{[l]} : (n^{[l]}, 1)$
 - Dimensions of dw and db should be the same as the dimensions of W and b
 - $a^{[l]}, z^{[l]} : (n^{[l]}, 1)$
- For a vectorized implementation, z vectors and a vectors will be stacked horizontally for all training examples

- $Z^{[l]}, A^{[l]} : (n^{[l]}, m)$
- Deep NN tend to work better as each layer can compute increasingly complex functions
 - Face recognition: edge detection \rightarrow individual features \rightarrow large parts of the face
 - Audio: low level waveforms \rightarrow phonemes \rightarrow words \rightarrow sentences
- Functions that can be computed with a “small” deep neural network require exponentially more hidden units in a shallower network
- For each forward propagation step, the value of $z^{[l]}$ should be cached for backpropagation
 - Values of $w^{[l]}$ and $b^{[l]}$ can also be stored in the cache so they can be accessed for backpropagation



- All forward propagation steps will be carried out until the hypothesis, \hat{y} is found
 - Using cached values, all backpropagation steps will be carried out until $dz^{[1]}$
 - Parameters $W^{[l]}$ and $b^{[l]}$ can be updated accordingly

$$W^{[l]} := W^{[l]} - \alpha dw^{[l]}$$

$$b^{[l]} := b^{[l]} - \alpha db^{[l]}$$

- Backpropagation will also follow a pattern for all layers in the NN
 - $dz^{[l]} = da^{[l]} * g^{[l]'}(z^{[l]})$
 - $dW^{[l]} = dz^{[l]} a^{[l-1]T}$

- $db^{[l]} = dz^{[l]}$
- $da^{[l-1]} = W^{[l]T} dz^{[l]}$
- For a vectorized implementation:
 - $dZ^{[l]} = dA^{[l]} * g^{[l]'}(Z^{[l]})$
 - $dW^{[l]} = \frac{1}{m} dZ^{[l]} A^{[l-1]T}$
 - $db^{[l]} = \frac{1}{m} \text{np.sum}(dZ^{[l]}, \text{axis}=1, \text{keepdims}=\text{True})$
 - $dA^{[l-1]} = W^{[l]T} dZ^{[l]}$

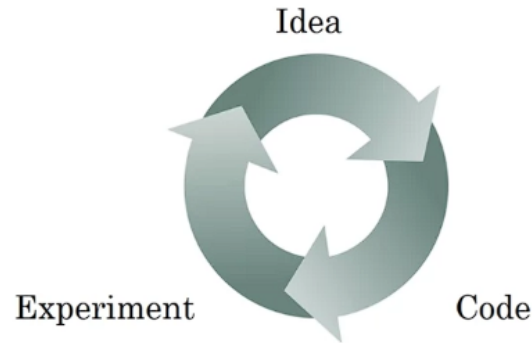
1.4.1 Parameters vs Hyperparameters

- Parameters of the NN are the W and b matrices
- NN also has a number of associated hyperparameters:
 - Learning rate α
 - Number of iterations z'
 - Number of layers in the network
 - Number of hidden units
 - Choice of activation function
- Hyperparameters will control the values of W and b
- Deep learning has many more hyperparameters than earlier eras of machine learning
 - Applying deep learning becomes an empirical process
- Intuitions about hyperparameters may be different across different applications

2 Improving Deep Neural Networks: Hyperparameter Tuning, Regularization and Optimization

2.1 Practical Aspects of Deep Learning

- Applying ML is a highly iterative process
 - Very hard to choose “correct” values for hyperparameters



- Deep learning used in many different areas
 - NLP
 - Computer vision
 - Speech analysis
 - Structured data
 - * Advertisement
 - * Search engines
 - * Computer security
 - * Logistics
- Intuitions from one subject area often don't transfer to another application
- Success of deep learning can depend on speed of iteration
 - Choice of split of the data can influence speed of iteration
- Whole dataset should be split into training, development and test set
 - Dev set should be used rate performance of different models
 - Final model should be evaluated on the test set
 - Split will allow better evaluation of bias and variance of the model
- Previous eras of ML had a 60/20/20 split between dataset

- For the big data era, a smaller percentage of data is given to the dev and test sets
 - For 1,000,000 examples, can allocate just 10,000 examples each to dev and test set
 - 10,000 examples is enough to run the algorithm and get a good idea about the algorithm performance
- Recent trends also show mismatched training and test set distributions
 - For images, training set may have very high quality images while test set may have lower quality
 - Dev and test set should come from the same distribution
- Dataset might be split to not include a test set
 - Dev set can be used to get to a “good” model
 - Since data is fit to the dev set, there is no unbiased estimate of performance
 - When data doesn’t include a test set, dev set is usually referred to as “test” set
 - Resulting model may overfit to the dev set

2.1.1 Bias and Variance

- In the deep learning era, there tends to be less of a discussion about the bias/variance trade off
- In 2 dimensions, data can be plotted to look for high bias or variance
 - High bias classifiers underfit the data
 - High variance classifiers overfit the data
- For higher dimensions, training set error and dev set error can be used
 - High variance classifier has low training error and high dev set error
 - High bias classifier has high training error and high dev set error
 - Classifier with high bias and high variance will have high training error and even higher dev set error
- Above ideas only work with the assumption that the optimal error is 0%
 - Training and dev set must also come from the same distribution

2.1.2 Basic Recipe for Machine Learning

- Train initial algorithm and reduce bias of algorithm to an “acceptable value”
 - Use a larger network
 - Train algorithm for longer

- Reduce variance of the algorithm by getting more data
 - Add regularization terms to the cost function
- Bias and variance can also be reduced by using a more appropriate NN architecture
- In the big data era, bias and variance can be reduced without affecting each other
 - Training a bigger network typically reduce the bias
 - Getting more training data will typically reduce the variance
- Using regularization will have a bias variance trade off

2.1.3 Regularization

- Adding regularization will usually help in reducing variance and prevent overfitting
 - Regularization will only affect how the weights change during backpropagation
 - For forward propagation, regularization has no effect
- For logistic regression:

$$J(w, b) = \frac{1}{m} \sum_{i=1}^m \mathcal{L}(\hat{y}^{(i)}, y^{(i)}) + \frac{\lambda}{2m} \|w\|_2^2$$

$$\begin{aligned} \|w\|_2^2 &= \sum_{j=1}^{n_x} w_j^2 \\ &= w^T w \end{aligned}$$

- Above method is L_2 regularization after the L_2 norm (Euclidean norm) of w
 - b values can also be regularized but will have a much smaller effect than w
- L_1 regularization adds the term:

$$\frac{\lambda}{m} \sum_{i=1}^{n_x} |w| = \frac{\lambda}{m} \|w\|_1$$

- Using L_1 regularization will result in w being sparse
 - Can be seen to compressing the model
- L_2 regularization is more common for deep learning
- Regularization parameter λ will be set using the cross validation set
 - `lambda` is a reserved keyword in Python

- For a neural network:

$$J(w^{[1]}, b^{[1]}, \dots, w^{[L]}, b^{[L]}) = \frac{1}{m} \sum_{i=1}^m \mathcal{L}(\hat{y}^{(i)}, y^{(i)}) + \frac{\lambda}{2m} \sum_{l=1}^L ||w^{[l]}||^2$$

$$||w^{[L]}||^2 = \sum_{i=1}^{n^{[L]}} \sum_{j=1}^{n^{[L-1]}} (w_{i,j}^{[L]})^2$$

– $||W^{[L]}||_F^2$ known as the Frobenius norm of the matrix

- Since new term added to cost function, $\frac{\partial J}{\partial W^{[l]}}$ will be different

$$dW^{[l]} = \dots + \frac{\lambda}{m} W^{[l]}$$

$$W^{[l]} = W^{[l]} - \frac{\alpha \lambda}{m} W^{[l]} - \alpha(\dots)$$

– Also known as weight decay as value of W will decrease on every iteration

$$W^{[l]} - \frac{\alpha \lambda}{m} W^{[l]} = \left(1 - \frac{\alpha \lambda}{m}\right) W^{[l]}$$

– Value of $\left(1 - \frac{\alpha \lambda}{m}\right)$ will be slightly less than 1

- Adding regularization term will penalize the weight matrix from being too large
 - As the value of λ is increased, the weights in w will get closer to 0
 - Each hidden unit will have a smaller effect and the resulting NN will be simpler
- When using the tanh function, penalizing w will make $z^{[l]}$ smaller
 - For a small $z^{[l]}$, tanh function is roughly linear
 - If all hidden units in the network are roughly linear, the result of the NN will also be roughly linear

Dropout Regularization

- Each layer in the NN has a probability of eliminating a node
 - When a node is eliminated, all outgoing links from the node are also deleted
 - Each example will be trained on a smaller network so will have less chance of overfitting
- For each different training example, the NN is reset and randomly eliminates nodes again
- Inverted dropout:

```
d3 = np.random.rand(a3.shape[0], a3.shape[1]) < keep_prob
a3 = np.multiply(a3, d3)
a3 /= keep_prob
```

- For **keep_prob** = 0.8 each node has a 0.2 chance of being removed
- Activation values should be scaled by **keep_prob** so the expected value of z can stay constant
- On each pass through the training set, a different set of units should be zeroed out
- At test time, dropout should not be used as it will create noise in the predictions
- A single hidden unit cannot rely on a specific feature as it may not be used on each iteration
 - Weights for the unit will be spread out between the units
 - Has the same effect as shrinking the weights like L2 regularization
 - The equivalent L2 penalty on different weights depends on the size of the activations being used for the weight
- **keep_prob** can be varied between the layers
 - Larger layers may be more prone to overfitting and can have a larger **keep_prob**
 - For small layers with a very small chance of overfitting, **keep_prob** can be set to 1
- Many dropout implementations started with computer vision
 - Input size for computer vision is extremely large
- Cost function is not well defined when dropout is used
 - Can set **keep_prob** to 1 and check for monotonically decreasing J
 - When J is decreasing, then can reduce the value of **keep_prob** to use dropout

Other Regularization Methods

- Getting more training data will almost always help overfitting
 - May not be possible to get more training data or very expensive
- Data augmentation will create new examples and can help reduce overfitting
- For an image dataset:
 - Flipping the image horizontally

- Randomly cropping and distorting the image
- Magnitude of image transformation depends on classifier
 - For a cat dataset, image should not be flipped vertically
 - For OCR, distortions and rotations can be slightly more extreme



- Early stopping can be used to prevent overfitting from happening
 - If the NN is overfitting the data, the dev set error will initially decrease before increasing
 - Training of the NN can be stopped when the dev set error is lowest and the data has not been overfit
- Using early stopping links the task of optimizing J and not overfitting the data
 - Early stopping will prevent the cost function from being optimized
- L2 regularization is a better method to prevent overfitting
 - Requires a choice for the value of λ and is much more computationally expensive

2.1.4 Setting up the Optimization Problem

- Normalization can be used to speed up the training of a NN
 - Subtract the mean:

$$\mu = \frac{1}{m} \sum_{i=1}^m x^{(i)}$$

$$x := x - \mu$$

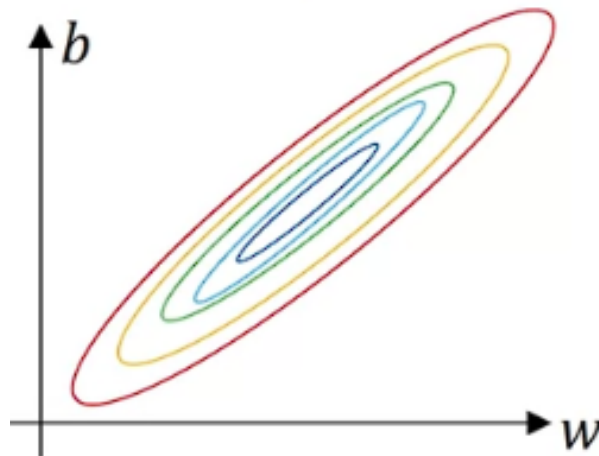
- Normalize the variance:

$$\sigma^2 = \frac{1}{m} \sum_{i=1}^m x^{(i)} * x^{(i)}$$

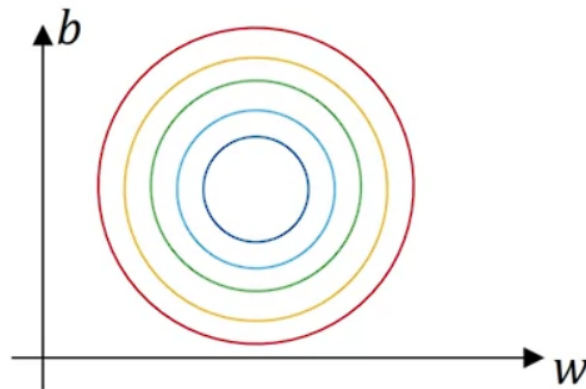
$$x /= \sigma$$

- When normalizing a training set, test set and training set should be processed together

- All the data must go through the same transformation
- For data that is not normalized, the cost function will be very elongated
 - The gradient will be quite shallow and will take longer to converge
 - Algorithm will require a smaller learning rate



- On average, normalized data will have a cost function that is more symmetric
 - Gradient descent will converge faster and can use a larger learning rate



Vanishing/Exploding Gradients

- For very deep neural networks, the derivatives can get exponentially big or small
- If the weights of a NN are all the same, the prediction \hat{y} will x to the L th power
 - For $W^{[l]} > I$ the gradient will explode
 - For $W^{[l]} < I$ the gradient will vanish

- Some modern applications use 152 layer NN
 - Require careful initialization of the weights to ensure correct training
- For a single neuron:
 - The output \hat{y} will be the sum of all $w_i x_i$

$$z = w_1 x_1 + w_2 x_2 + \dots + w_n x_n$$

- For a large n , want a smaller w_i
- Want $\text{Var}(w_i) = \frac{1}{n}$

$$W^{[l]} = \text{np.random.randn(shape)} * \text{np.sqrt}\left(\frac{1}{n^{[l-1]}}\right)$$

- Variance of Gaussian random variable can be set by multiplying by sqrt tem
- For ReLU activation function, the variance should be set to $\frac{2}{n}$
 - tanh activation uses Xavier initialization $\frac{1}{n^{[l-1]}}$
 - Yoshua Bengio multiplied random variable by $\sqrt{\frac{2}{n^{[l-1]} + n^{[l]}}}$
- Initialization of weights aims to set weight matrices close to 1
 - Helps to prevent \hat{y} from vanishing or exploding too quickly
- Variance parameter can be tuned as another hyperparameter

Gradient Checking

- Can be used to ensure implementation of backpropagation is correct
- Requires numerical approximations of gradients
 - For a function f at a point θ , gradient can be approximated by looking at $\theta + \epsilon$ and $\theta - \epsilon$
 - Approximation is closer when double sided estimate is used
- If g is the derivative of f :

$$g(\theta) \approx \frac{f(\theta + \epsilon) - f(\theta - \epsilon)}{2\epsilon}$$

- Using the 2 sided difference will give a much better estimate but is more computationally expensive

- The derivative of a function at a point is the limit of the numerical approximation

$$f'(\theta) = \lim_{\epsilon \rightarrow 0} \frac{f(\theta + \epsilon) - f(\theta - \epsilon)}{2\epsilon}$$

- For a non 0 value of ϵ , the error of the approximation is $O(\epsilon^2)$
- For the single sided numerical approximation, the error is $O(\epsilon)$
- To perform gradient checking on a NN:
 1. Reshape $W^{[1]}, b^{[1]}, \dots, W^{[L]}, b^{[L]}$ into a single vector θ
 2. Reshape $dW^{[1]}, db^{[1]}, \dots, dW^{[L]}, db^{[L]}$ into a single vector $d\theta$
 3. For every i in θ , calculate:

$$d\theta_{approx}[i] = \frac{J(\theta_1, \theta_2, \dots, \theta_i + \epsilon) - J(\theta_1, \theta_2, \dots, \theta_i - \epsilon)}{2\epsilon}$$

4. Check if $d\theta_{approx}$ and $d\theta$ are reasonably close to each other

For $\epsilon = 10^{-7}$:

$$\frac{\|d\theta_{approx} - d\theta\|_2}{\|d\theta_{approx}\|_2 + \|d\theta\|_2} \approx 10^{-7}$$

- Grad check should be only be used when debugging
 - Calculating $d\theta_{approx}$ is very computationally expensive
- If regularization is used, correct cost function must be used to calculate the gradient
- If dropout is used, J is not well defined and cannot use grad check
 - Cost function J that is optimized by dropout is defined by summing over all subsets of nodes that could be eliminated on each iteration
 - Can implement grad check with a `keep_prob` of 1 before turning on dropout
- Implementation of gradient descent may be correct when W and b are close to 0
 - Can run grad check just after random initialization
 - After training the network for a number of iterations, can run grad check again

2.2 Optimization Algorithms

2.2.1 Mini Batch Gradient Descent

- For gradient descent, vectorization will allow computation over all m training examples
 - If m is very large, then vectorization will still be very slow
- Gradient descent requires the whole training set to be processed for a single step of gradient descent

- Data from training set can be split into mini batches

$$X^{\{1\}} = [x^{(1)}, x^{(2)}, \dots, x^{(1000)}]$$

$$Y^{\{1\}} = [y^{(1)}, y^{(2)}, \dots, y^{(1000)}]$$

- Mini batch gradient descent looks at one mini batch on each iteration of gradient descent
- For each mini batch in the training set:

- Run forward propagation on $X^{\{t\}}$

$$Z^{[1]} = W^{[1]}X^{\{t\}} + b^{[1]}$$

$$A^{[1]} = g^{[1]}(Z^{[1]})$$

...

$$A^{[l]} = g^{[l]}(Z^{[l]})$$

- Compute cost: $J^{\{t\}} = \frac{1}{1000} \sum_{i=1}^l \mathcal{L}(\hat{y}^{(i)}, y^{(i)}) + \frac{\lambda}{2 \times 1000} \sum_l \|W^{[l]}\|_F^2$
- Use backpropagation to calculate gradients wrt $J^{\{t\}}$
- Update weights

$$W^{[l]} := W^{[l]} - \alpha dW^{[l]}$$

$$b^{[l]} := b^{[l]} - \alpha db^{[l]}$$

- A single pass through the training set is known as an epoch
- Algorithm can continue to run for multiple passes through the training set until an optimal solution is found
- For batch gradient descent, the cost should decrease on each iteration
 - If the cost doesn't decrease per iteration, then the algorithm has a bug
- For mini batch gradient descent, the cost will trend downwards but will be more noisy
 - Algorithm is being trained on a different batch of results on each iteration
- When running mini batch gradient descent, must choose the size of the mini batch
 - For mini batch size = m : Batch gradient descent
 - For mini batch size = 1: Stochastic gradient descent
- For stochastic gradient descent, each example may be good or bad for gradient descent
 - On average the cost function will be minimized for gradient descent
 - Path taken by gradient descent will be very noisy

- Stochastic gradient descent will never converge and just oscillate around the minimum
- Choice of mini batch size should be between 1 and m
 - Batch gradient descent will take very long for a single iteration
 - Stochastic gradient descent will lose all the speed from vectorization
- For a small training set ($m \leq 2000$), can just use gradient descent
- Otherwise can try a mini batch size from 64-512
 - Code may run faster if the mini batch size is a power of 2
- A single mini batch should be able to fit in the whole CPU/GPU memory

Advanced Optimization Algorithms

- Some advanced algorithms require the use of exponentially weighted averages
- Moving averages can be calculated for data such as daily temperature

$$V_0 = 0$$

$$V_t = \beta V_{t-1} + (1 - \beta)\theta_t$$

- V_t is the approximated average temperature over the last $\frac{1}{1-\beta}$ days
- If β is larger then the average will adapt slower to changes in the data
- Exponentially weighted average can be found by summing the daily temperature with an exponentially decaying function
- If $\beta = 0.9$:

$$V_{100} = 0.1\theta_{100} + (0.1)(0.9)\theta_{99} + (0.1)(0.9)^2\theta_{98} + (0.1)(0.9)^3\theta_{97} + \dots$$

- When calculating the exponentially weighted average, the same variable v should be used and overwritten each time
 - Implementation will be much more efficient than calculating average manually from the past 10 values
- For large values of β , initial average will be much lower than they should be

$$\frac{V_t}{1 - \beta^t}$$

- Bias correction can be used to ensure initial values are correct estimations of the averages
 - As t becomes larger, denominator becomes closer to 1

Momentum

- Gradient descent with momentum uses an exponentially weighted average of the gradients to update the weights
 - Almost always performs better than standard gradient descent
- $$V_{dW} = \beta V_{dW} + (1 - \beta)dW$$
- $$V_{db} = \beta V_{db} + (1 - \beta)db$$
- $$W = W - \alpha V_{dW}$$
- $$b = b - \alpha V_{db}$$
- Taking the average of the gradients will slow down any unnecessary oscillations in the algorithm
 - Algorithm may oscillate at first but will start to take more direct steps to the minimum
 - $\beta = 0.9$ is a common choice for most applications of momentum

RMSprop

- RMSprop takes the weighted average of the squares of the derivatives
 - Derivatives will get divided by the RMS before the weights are updated
- $$S_{dW} = \beta_2 S_{dW} + (1 - \beta_2)dW^2$$
- $$S_{db} = \beta_2 S_{db} + (1 - \beta_2)db^2$$
- $$W = W - \alpha \frac{dW}{\sqrt{S_{dW}}}$$
- $$b = b - \alpha \frac{db}{\sqrt{S_{db}}}$$
- Updates in the direction of oscillation will be divided by a large number
 - Will allow the learning rate to be larger and therefore allows faster training
 - In practice, very small value ϵ is added to the denominator for more numerical stability

Adam Optimization Algorithm

- Adam optimization shown to work well for a range of deep learning architectures
 - Merges Momentum and RMSprop to one algorithm
 - “Adam” stands for adaptive moment estimation
- On iteration t :
 - Compute dW, db using the current mini batch

$$\begin{aligned}
V_{dw} &= \beta_1 V_{dw} + (1 - \beta_1) dW, & V_{db} &= \beta_1 V_{db} + (1 - \beta_1) db \\
S_{dw} &= \beta_2 S_{dw} + (1 - \beta_2) dW^2, & S_{db} &= \beta_2 S_{db} + (1 - \beta_2) db^2 \\
V_{dw}^C &= \frac{V_{dw}}{1 - \beta_1^t}, & V_{db}^C &= \frac{V_{db}}{1 - \beta_1^t} \\
S_{dw}^C &= \frac{S_{dw}}{1 - \beta_2^t}, & S_{db}^C &= \frac{S_{db}}{1 - \beta_2^t} \\
W &:= W - \alpha \frac{V_{dw}^C}{\sqrt{S_{dw}^C + \epsilon}} \\
b &:= b - \alpha \frac{V_{db}^C}{\sqrt{S_{db}^C + \epsilon}}
\end{aligned}$$

- Must choose many hyperparameters to run Adam optimization
 - α : needs to be tuned to the specific NN
 - β_1 : 0.9 (default)
 - β_2 : 0.999 (default)
 - ϵ : 10^{-8} (default)

Learning Rate Decay

- For mini batch gradient descent, the algorithm will oscillate around the minimum point
- If the learning rate is reduced over time, then the oscillations will become smaller
 - During the initial steps of learning, algorithm can afford to take large steps
 - As the algorithm starts to converge, smaller steps are preferred

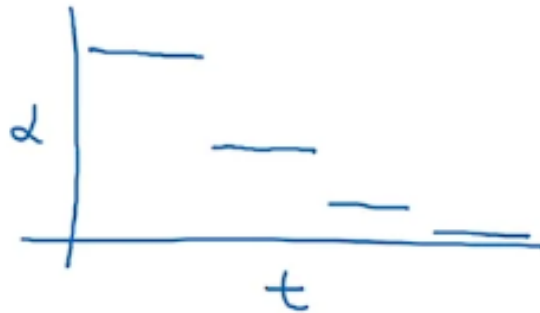
$$\alpha = \frac{1}{1 + \text{decay rate} \times \text{epoch num}} \alpha_0$$

- Other formulas can be used to decay the learning rate

- Exponential decay

$$\alpha = 0.95^{\text{epoch num}} \alpha_0$$

- Discrete staircase



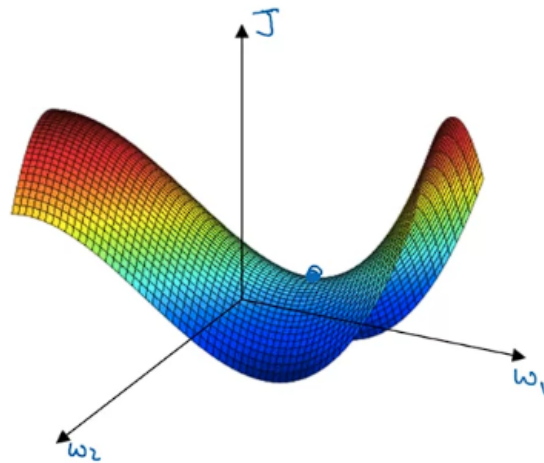
- Square root of epoch number

$$\alpha = \frac{k}{\sqrt{\text{epoch num}}} \alpha_0$$

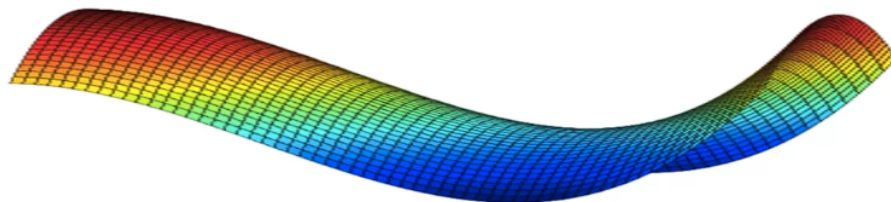
- Manual decay can be used for larger models that take a longer time to train

Local Optima

- Initial ideas believed that a cost function with many points of 0 gradient would have many local optima
 - When training a NN, most points with 0 gradient are saddle points



- For a point with 0 gradient, Each direction can either be a convex or concave function
 - For a local optima, must have a convex function in all directions
 - In a high dimensional space, chance of all directions being convex functions is very small
- Intuitions about lower dimensional spaces may not transfer to high dimensional spaces
- Plateaus are areas where the gradient is near to 0 for a large area



- Will take a very long time to move down off the plateau

- Learning will be slow but unlikely to get stuck in a local optima
- Optimization algorithms like Adam can help to speed up the training

2.3 Hyperparameter Tuning, Batch Normalization and Programming Frameworks

2.3.1 Hyperparameter Tuning

- Deep neural networks have many hyperparameters associated with the actual network and the training implementation
 - Numbers of layers and hidden units
 - Learning rate or method for learning rate decay
 - Hyperparameters for momentum or Adam optimization
 - Mini batch size
- Most important hyperparameter is the learning rate
 - Secondary importance can be given to momentum (β), number of hidden units and the mini batch size
 - Number of layers and learning rate decay can be tuned last
 - Parameters for Adam optimization usually don't need to be tuned
- In practice, random values for the hyperparameters should be sampled and tested
 - If values are arranged in a grid, fewer distinct values can be tested
 - Choosing random values for the hyperparameters gives a higher chance of finding an optimum value for important hyperparameters
- Can use coarse to fine sampling scheme to find optimum values
 - Sample initial values and find which values work the best
 - “Zoom in” to the area and take more samples in the smaller region
- For some hyperparameters (number of layers / hidden units), can sample over a reasonable range
- Some hyperparameters may not have an even distribution (Learning rate between 0.0001 and 1)
 - Can use a log scale to ensure the numbers are better distributed

```
r = -4 * np.random.rand
learning_rate = 10 ** r
```

- Can look for a range $10^a \dots 10^b$ and take a random sample $r \in [a, b]$
- For exponentially weighted averages, β will be around 0.9-0.999
 - Equivalent to averaging over the last 10 days or last 1000 days
 - Can sample values for $1 - \beta$ for $r \in [-3, -1]$
- For exponentially weighted averages, the sensitivity of the results is very high when β is close to 1
 - A change from 0.999 to 0.9995 will change the average from 1000 to 2000 examples
- Intuitions about the hyperparameters won't always transfer across applications
 - Ideas found in one application can still be applied to other applications
- Hyperparameters can become stale over time with changing data or hardware
 - Hyperparameters should be reevaluated every few months to ensure values are optimal
- Depending on resources, can babysit a single model or train models in parallel
 - For a single model, hyperparameters can be tweaked over time depending on training performance
 - If resources allow, can train the same model with many different hyperparameters and choose the best model

2.3.2 Batch Normalization

- Inputs to a NN can be normalized to speed up learning

$$X = \frac{X - \mu}{\sigma}$$

- Batch normalization normalizes the input values $Z^{[l]}$ to each layer
 - Can instead normalize the values $A^{[l]}$ after the activation function
- Given intermediate values $z^{(1)}, \dots, z^{(m)}$:

$$\mu = \frac{1}{m} \sum_i z^{(i)}$$

$$\sigma^2 = \frac{1}{m} \sum_i (z^{(i)} - \mu)^2$$

$$z_{norm}^{(i)} = \frac{z^{(i)} - \mu}{\sqrt{\sigma^2 + \epsilon}}$$

$$\tilde{z}^{(i)} = \gamma z_{norm}^{(i)} + \beta$$

- γ and β are learnable parameters of the model
 - Allows the mean and variance of \tilde{z} to be set to any value

- If $\gamma = \sqrt{\sigma^2 + \epsilon}$, $\beta = \mu$, then $\tilde{z}^{(i)} = z^{(i)}$
 - May not want mean 0 and standard deviation 1 for the activation function
 - NN will have new parameters $\beta^{[1]}, \gamma^{[1]}, \dots, \beta^{[L]}, \gamma^{[L]}$
 - Will be updated like normal parameters
- $$\beta^{[l]} = \beta^{[l]} - \alpha d\beta^{[l]}$$
- $$\gamma^{[l]} = \gamma^{[l]} - \alpha d\gamma^{[l]}$$
- Batch normalization is typically applied to mini batch gradient descent
 - Mean and variance will be calculated from the mini batch being used
 - When using batch normalization, normalization step removes the need for $b^{[l]}$ parameters
 - When subtracting the mean from the z values, the constant will get cancelled out
 - Mean of the \tilde{Z} values will be decided by the $\beta^{[l]}$ parameters
 - Batch normalization will make weights deeper in a network more robust to changes earlier in the network
 - Data can have a covariate shift where the distribution changes after a generalization
 - Function mapping from X to Y can be the same but model may need to be retrained
 - Batch normalization will reduce the amount of movement of the distribution of the hidden values
 - Even if there is a covariate shift in the data, batch norm will make the z values have the same mean and variance
 - The individual layers in the network will be more independent of each other
 - Batch norm will also add a slight regularization effect
 - Each mini batch is scaled by the mean/variance of the specific mini batch
 - Normalizing with the mean/variance of the individual mini batch will add noise to the activations
 - Similar to dropout where the algorithm will not rely on any single hidden unit
 - Noise added to the z values is very small so dropout can be used as well
 - If a larger mini batch size is used, noise is reduced and will have a smaller regularization effect
 - At test time, data will typically be processed one example at a time

- Cannot calculate the mean/variance of a single example
- Mean/variance can be estimated using exponentially weighted averages across the mini batches

2.3.3 Multi Class Classification

- Logistic regression can be generalized to apply to multiple classes

C = number of classes

- Output layer for the NN will have C units
 - Each unit will be the probability of each class
 - Sum of all numbers in the vector must be 1
- Softmax layer used in the output layer to output vector of probabilities
 - $Z^{[L]}$ values are calculated as normal: $Z^{[L]} = W^{[L]}a^{[L-1]} + b^{[L]}$
 - Use the softmax activation function

$$t = e^{(Z^{[L]})}$$

$$a^{[L]} = \frac{t}{\sum_{i=1}^C t_i}$$

- Softmax activation function has a vector for its input and output
 - Other activation functions had a single value for input and output
- Largest input to softmax function will result in the largest output
 - “Hard max” function would return 1 for the largest input and 0 for the other inputs
- If $C = 2$, softmax reduces to logistic regression
- Softmax classifier cannot be trained as a normal NN

$$\mathcal{L}(\hat{y}, y) = - \sum_{j=1}^C y_j \log \hat{y}_j$$

- Loss function will only be active for the ground truth class in the training set

$$J(W^{[1]}, b^{[1]}, \dots) = \frac{1}{m} \sum_{i=1}^m \mathcal{L}(\hat{y}^{(i)}, y^{(i)})$$

$$dz^{[L]} = \hat{y} - y$$

2.3.4 Deep Learning Frameworks

- For larger NNs, using a framework can save a lot of time
- Can look at the community behind the frameworks and the strengths
 - Ease of programming (development and deployment)
 - Running speed
 - Truly open (open source with good governance)
 - Application of NN

Tensorflow

- Assume a simple cost function:

$$J(w) = w^2 + 10w + 25$$

```
import numpy as np
import tensorflow as tf

w = tf.Variable(0, dtype=tf.float32)
optimizer = tf.keras.optimizers.Adam(0.1)

def train_step():
    with tf.GradientTape() as tape():
        cost = w ** 2 - 10 * w + 25
        trainable_variables = [w]
        grads = tape.gradient(cost, trainable_variables)
        optimizer.apply_gradients(zip(grads, trainable_variables))

for i in range(1000):
    train_step()
```

- No need to compute backpropagation steps with tensorflow
- More complex tensorflow program will have cost as a function of variables

```
w = tf.Variable(0, dtype=tf.float32)
x = np.array([1.0, -10.0, 25.0], dtype=np.float32)
optimizer = tf.keras.optmizers.Adam(0.1)
```

```
def training(x, w, optimizer):  
    def cost_fn():  
        return x[0] * w ** 2 + x[1] * w + x[2]  
  
    for i in range(1000):  
        optimizer.minimize(cost_fn, [w])  
  
    return w
```

- Tensorflow will create a computation graph from the defined cost function
 - From the computation graph, tensorflow will compute the backpropagation steps

3 Structuring Machine Learning Projects

3.1 ML Strategy

3.1.1 Setting up a ML Project

- A machine learning project may have many ideas that can improve performance
 - Collect more data
 - Use a more diverse training set
 - Train the algorithm over a longer period of time
 - Use a different optimization algorithm (Adam instead of gradient descent)
 - Use a bigger/smaller network
 - Add dropout or L_2 regularization
 - Change the network architecture (activation functions or hidden units)
- Some methods may not be useful for the specific scenario
- ML strategy is changing with deep learning
 - Deep learning algorithms have different options when compared with previous generations
- Orthogonalization is where specific functions can be split up into different areas
- For a supervised learning system to perform well, system requires a chain of assumptions
 - Performance of algorithm on the training set must pass some threshold (\approx human-level performance)
 - Algorithm must be fit well to the dev set
 - Algorithm must be fit well to the test set
 - Algorithm must perform well in the real world
- Each step has specific “knobs” to tune to improve performance in the specific area
 - Training set: bigger network, Adam optimization
 - Dev set: regularization, bigger training set
 - Test set: bigger dev set
 - Real world: change dev set or cost function
- Early stopping can be used but is less orthogonalized
 - Worsens the performance on the training set

- Improves the performance on the dev set
- Single number evaluation metric can be used to test effectiveness of a model
- F1 score combines precision and recall into a single metric
 - Precision is the percentage of positively classified examples that are actually positive
 - Recall is the percentage of positive examples that are correctly classified
 - F1 score takes the harmonic mean of precision and recall

$$F_1 = \frac{2}{\frac{1}{P} + \frac{1}{R}}$$

- Having a well defined test set and single number evaluation metric will speed up iteration
- Scenario may have more than one type of metric that is relevant
 - Classification algorithm may value accuracy as well as running time
 - May not make sense to use a numerical function of some metrics
- Accuracy would be a optimizing metric and running time would be the satisficing metric
 - Goal can be to maximize accuracy subject to running time $\leq 100\text{ms}$
- For N different metrics:
 - 1 should be optimizing
 - $N - 1$ should be satisficing
- Dev set and test set should come from the same distribution
 - If different distributions are used, algorithm may perform on the dev set but not on the test set
 - Dev set and test set must have the same target
- Dev set should be used to evaluate the performance of different models
 - Setting up a dev set and an evaluation metric allows teams to iterate quickly

“Choose a dev set and test set to reflect data you expect to get in the future and consider important to do well on”

- Previous eras of machine learning had a 60%, 20%, 20%
- Modern eras of machine learning have much larger datasets
 - For 1000000 examples, can assign 1% each to dev and test set

- Larger amount of data in the training set will help algorithm

“Set your test set to be big enough to give high confidence in the overall performance of your system”

- Some applications may only use a train and dev set
 - Specific scenario may not require high confidence in the overall performance of the algorithm
 - Must be careful to not overfit the dev set too much
- Evaluation metric may not give a full representation of the specific scenario
 - Cat classifier with very low error may allow some pornographic images through the algorithm
 - Algorithm with slightly higher error but no pornographic images would be preferred
- Evaluation metric should be changed if it doesn’t correctly rank the algorithm’s performance
 - Standard error function treats all images equally
 - Weight can be added to the error function to weight unwanted images higher
 - Requires labelling of unwanted images in dev and test set
- Task of changing evaluation metric is separate from changing cost function to achieve good performance
- Metric and/or dev/test set should be changed if performance on the application is not linked

3.1.2 Comparing to Human Level Performance

- With advances in deep learning, ML algorithms have much better performance
 - More feasible for algorithms to be competitive with human level performers
- Workflow of designing and building a ML system is more efficient when trying to learn something that humans can do
- For many ML projects, initial learning will be very fast as algorithm approaches human level performance
 - Rate of learning decreases after algorithm surpasses human level performance
 - Algorithm will approach Bayes optimal error
- Bayes optimal error is the best theoretical function for mapping from X to Y
 - For many tasks, human level performance is not very far from Bayes optimal error

- Once human level performance is surpassed, there may not be many areas to improve in
- If algorithm has lower than human level performance:
 - Get labelled data from humans
 - Gain insight from manual error analysis
 - Better analysis of bias/variance
- If human level performance is much lower than the training and dev set error, can focus on the bias of the algorithm
- If human level performance is close to the training error, can focus on the variance of the algorithm
- Human level performance can be used as an estimate for Bayes error
 - Difference between the Bayes error and training error is the avoidable bias
 - Difference between the training and dev set error can measure the variance
- For specialized tasks, different parties may have different errors for human classification
 - For medical image classification, a team of experienced doctors will have much lower error than an average human
 - Bayes error must be less than or equal to the lowest human error
 - Lowest human error can be used as estimate for Bayes error
- For publishing a paper or deploying a system, human error definition may be different
- When algorithm is very close to human level performance, can be hard to see if bias or variance should be trained
- With deep learning, algorithms in some areas can surpass human level performance
 - Online advertising
 - Product recommendations
 - Logistics
 - Loan approvals
- Above areas are not natural perception problems and come from structured data
 - Currently more challenging for computers to surpass humans in natural perception tasks
- ML has also surpassed humans in some natural perception tasks
 - Speech recognition
 - Some image recognition

- Medical tasks
- For supervised learning, must assume that the training set can be fit well (low avoidable bias)
 - The training set performance must also generalize well to the dev/test set (low variance)
- For high bias:
 - Train a bigger model
 - Train for longer or use a better optimization algorithm (momentum, RMSprop, Adam)
 - Change the NN architecture or find better hyperparameters
- For high variance:
 - Use more data
 - Use regularization (L_2 , dropout, data augmentation)
 - Change the NN architecture or find better hyperparameters

3.1.3 Error Analysis

- Misclassified examples can be manually examined to look for any patterns
 - Finding patterns can give an upper bound of any increase in performance
- Different ideas for error analysis can be evaluated in parallel with a table
 - For each image, can fill in a checkbox for any patterns
 - Percentage of total for each pattern will give an idea of how to best improve performance
- Manual analysis may show new patterns in the errors
- Some errors may be incorrectly labelled examples in the dev/test set
 - Deep learning algorithms are quite robust to random errors in the training set
 - Algorithms are fairly susceptible to systematic errors in the training set
- Incorrectly labelled examples can be recorded in the error analysis table
 - Percentage of error caused by incorrect labels can be calculated to see if fixing labels is a worthwhile task
- Any processes should be applied to the dev and test set at the same time to ensure they come from the same distribution
 - Training set may end up coming from a different distribution than the dev/test set

- Can also look at examples that the algorithm got right to see if got any errors
- For a new ML system, priority should be to build initial system then iterate
 - Set up a dev/test set and evaluation metric
 - Build initial system quickly
 - Use bias/variance and error analysis to prioritize next steps
- Error analysis will give idea for next steps

3.1.4 Mismatched Training and Dev/Test Sets

- Deep learning algorithms perform best with a lot of training data
 - Many teams are putting as much data as possible into training sets
 - Extra data added to the training set will give a different distribution to the training set data
- Other sources of data may have more examples but can come from a slightly different distribution
- Data can be pooled together and randomly split into training, dev and test set
 - All data will come from the same distribution
 - Much of the dev set will come from the additional distribution of images rather than the original distribution
 - Algorithm will optimize to the wrong distribution of images
- Training set can be set to include all images from the additional distribution
 - Examples from the original distribution will be split between the dev and test set
 - Dev and test set will have the correct distribution of images
 - Training set will have a different distribution
- Estimate of bias and variance changes when training set has a different distribution to dev and test set
 - Comparatively high dev set error might mean dev set has more challenging images than training set
 - Data from the dev set will be new to the algorithm and will have a different distribution to the training data
- Portion of the training set can be set as the training-dev set
 - Should not be used for training but will have the same distribution as the training set
- For error analysis, can look at the training set, training-dev set and dev set

- Large difference between the training error and training-dev error indicates a variance problem
- Large difference between the training-dev error and dev error indicates a data mismatch problem
- Large difference between training error and human error indicates high bias problem
- Difference between the dev error and test error indicates degree of overfitting to the dev set
- For each distribution of data, can look at:
 - Human level error
 - Error on examples trained on
 - Error on examples not trained on
- For data mismatch:
 - Use manual data analysis to try understand the difference between training and dev sets
 - Can try to make the training set more similar to the dev set (collect more examples or use artificial data synthesis)
- For some applications, algorithm may overfit during artificial data synthesis
 - For speech recognition, same recording of noise may be added to many examples
 - As much as possible, should aim to get a large range of examples with data synthesis

3.1.5 Learning From Multiple Tasks

- For some applications, NN trained for one task can be applied to another task
 - NN trained for cat recognition can be retrained for radiology diagnosis
- After initial NN is trained, output layer should be deleted
 - Weights for the output layer should be randomly initialized
 - Dataset can be switched to new application and NN retrained
- If the new dataset is small, can just retrain the last layer of the NN
 - If there is a lot of data, all layers in the NN can be retrained
 - Pre-training is the training of the NN for the original application
- Learning basic feature of images from a large dataset can help performance of algorithm

- Transfer learning works best when there is comparatively more data for the initial training
 - Initial training will not be useful if there is more data in the fine-tuning dataset
 - Both tasks must have the same input type
 - Low level features should be helpful for learning B
- For multi task learning, a single NN will try to learn multiple things at a time
 - Each task will ideally help the other tasks
- For self driving vehicles, many objects need to be identified from input data
 - Pedestrians
 - Cars
 - Different types of signs
 - Traffic lights
- Output from NN will be a vector for each object

$$\frac{1}{m} \sum_{i=1}^m \sum_{j=1}^4 \mathcal{L}(\hat{y}_j^{(i)}, y_j^{(i)})$$

- Output from NN can have all objects in the same image
- Softmax regression had only one output label for each image
- NN trained to minimize above cost function is using multi task learning
 - Separate NN could have been trained for each object
 - Basic image features for all NN can be shared
- Multi task learning can also be done if the dataset is incomplete
 - Dataset may have missing values for some objects
 - When calculating the cost, missing values can be ignored in the sum
- Multi task learning should have tasks that benefit from having shared lower level features
 - Amount of data for each task tends to be similar
 - Must be able to train a big enough NN to do well on all tasks
- Transfer learning tends to be more common than multi task learning
 - Multi task learning more common in computer vision

3.1.6 End to End Deep Learning

- End to end deep learning takes multiple stages of processing and combines it into a single NN
 - For sound recognition:
 - Individual features of the sound (MFCC)
 - Recognizing phonemes
 - Recognizing words
 - Final transcript
 - End to end deep learning requires a lot more data than the standard pipeline
 - A medium sized dataset can use a mixture of end to end learning and the standard pipeline
 - For an identity detection algorithm using a camera, algorithm will first detect the person's face
 - Algorithm will then crop the image to the face and use the image to identify the person
 - Algorithm will compare new image to all existing images of recognized people
 - For each individual step, there is a lot of data for each step
 - Will be a lot harder to find data for both concurrent steps
 - End to end deep learning used for machine translation
 - Estimating a child's age from an x-ray more suited to different tasks
 - Much easier to identify bones from x-ray before estimating age
 - Possible to use end to end method with a lot of data
 - End to end deep learning requires less hand-designing of components
 - Hand-designing components may be constricting the data
 - End to end deep learning requires a large amount of data
 - Hand-designed components could be useful when there is comparatively little data
- “Do you have sufficient data to learn a function of the complexity needed to map x to y ”

4 Convolutional Neural Networks

4.1 Foundations of Convolutional Neural Networks

- Computer vision has benefitted greatly from deep learning
 - Many current applications of computer vision were not possible a few years ago
 - Some ideas in deep learning also transferable across disciplines
- Computer vision can be split into many subareas:
 - Image classification
 - Object detection
 - Neural style transfer
- For computer vision applications, input from an image can be very large
 - 64×64 color image has 12288 features
 - 1000×1000 color image (1 megapixel) has 3000000 features
- For a 1000×1000 image with 100 hidden units in the first layer, $W^{[1]}$ will have 3 billion parameters
 - Computational requirements will be very large
 - Also hard to get enough data to prevent the NN from overfitting
- For an object detection problem, can start by detecting vertical and horizontal edges in the image
 - Using a grayscale image, a filter can be convolved with the image
 - Each pixel in the filter takes an element wise product and sum over the whole filter
- 6×6 grayscale image convolved with a 3×3 gives a 4×4 image

$$\begin{bmatrix} 1 & 0 & -1 \\ 1 & 0 & -1 \\ 1 & 0 & -1 \end{bmatrix}$$

- Above filter used for vertical edge detection
- Filter represents area in image that has a light section on the left section and dark on the right section
- Filter will have better performance on larger images

$$\begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix}$$

- Above filter used for horizontal edge detection
- Using the same filter, dark to light and light to dark edges will look different
 - Absolute value can be taken if type of edge detected is not needed
- Different numbers may be used for the edge detection filter
 - Sobel filter

$$\begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}$$
 - Scharr filter

$$\begin{bmatrix} 3 & 0 & -3 \\ 10 & 0 & -10 \\ 3 & 0 & -3 \end{bmatrix}$$
- Numbers in the filter can be learned with backpropagation
 - Can define what type of edge the filter should learn

4.1.1 Padding and Strides

- For a $n \times n$ image with a $f \times f$ filter, dimensions of the result will be $n - f + 1$
 - Dimensions of the image will shrink with every convolution
 - With the standard convolution operation, corner pixel is only used once
 - Pixels in the center of the image will get used many more times
- Image can be padded with a 1×1 border
 - Original image size will be preserved with convolution operation
 - 0s are typically used for padding
- Dimensions of the new image will be $n + 2p - f + 1$
- Valid convolution has no padding on the input
- Same convolution uses padding such that the output is the same size as the input
 - For same convolution, need $p = \frac{f-1}{2}$
- Size of filter is usually an odd number
 - For an even number, asymmetrical padding is needed for same convolution
 - Odd filter will always have a central pixel to the filter
- Strided convolutions change the size of the step taken by the filter
 - Standard convolution uses a stride of 1

- For an $n \times n$ image with an $f \times f$ filter, size of resultant image is:

$$\left\lfloor \frac{n + 2p - f}{s} + 1 \right\rfloor$$

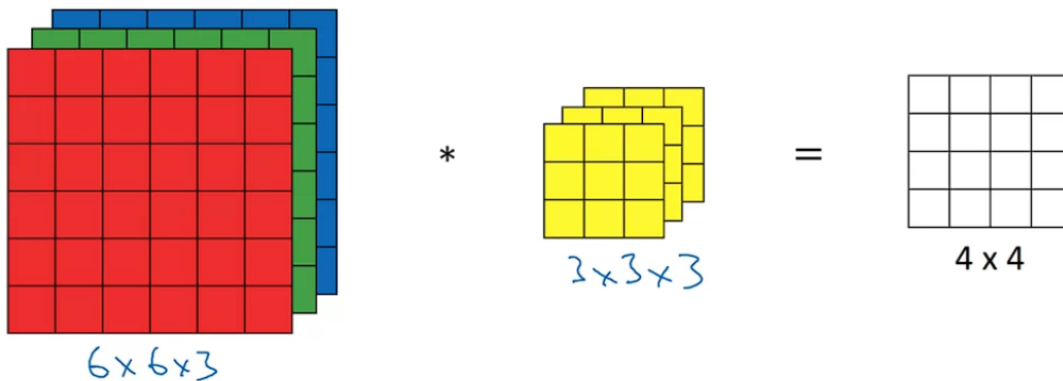
- For a non standard stride length, the filter must be completely within the image for the computation
- Convolution in mathematical literature flips the filter across the horizontal and diagonal before operation

$$\begin{bmatrix} 3 & 4 & 5 \\ 1 & 0 & 2 \\ -1 & 9 & 7 \end{bmatrix} \rightarrow \begin{bmatrix} 7 & 9 & -1 \\ 2 & 0 & 1 \\ 5 & 4 & 3 \end{bmatrix}$$

- Convolution operation in deep learning literature known as cross-correlation
- Flipping the filter in convolution gives associativity to the operation

$$(A * B) * C = A * (B * C)$$

- Associativity not required for NN so flipping of filter can be omitted
- For a 3 channel RGB image, filter will also have 3 channels
- Output from the RGB convolution will be a single image



- For RGB image, convolutions in each layer are applied then summed together for each pixel
 - Filter can be set to detect edges in specific colors or all edges
- To detect all edges, vertical filter and horizontal filter can be used
 - Outputs from both filters can be stacked over each other
- Single layer in a convolutional NN will add a bias term and non-linearity to each output
 - Same bias term will be added to all pixels in the image

- If using 10 $3 \times 3 \times 3$ filters, total parameters will be 280
 - Number of parameters is independent of the size of the input
 - Makes CNN less prone to overfitting than standard NN
- For a convolution layer l :
 - $f^{[l]}$ = filter size
 - $p^{[l]}$ = padding
 - $s^{[l]}$ = stride
 - Input: $n_H^{[l-1]} \times n_W^{[l-1]} \times n_C^{[l-1]}$
 - Output: $n_H^{[l]} \times n_W^{[l]} \times n_C^{[l]}$

$$n_H^{[l]} = \left\lfloor \frac{n_H^{[l-1]} + 2p^{[l]} - f^{[l]}}{s^{[l]}} + 1 \right\rfloor$$

- Filter: $f^{[l]} \times f^{[l]} \times n_C^{[l-1]}$
 - Activations: $a^{[l]} \rightarrow n_H^{[l]} \times n_W^{[l]} \times n_C^{[l]}$

$$A^{[l]} \rightarrow m \times n_H^{[l]} \times n_W^{[l]} \times n_C^{[l]}$$
 - Weights: $f^{[l]} \times f^{[l]} \times n_C^{[l-1]} \times n_C^{[l]}$
 - Bias: $n_C^{[l]}$
- Each layer in a CNN can have different sizes for padding, filters and stride length
 - A lot of the work for CNNs is choosing the hyperparameters for each layer in the network
- Final output from the CNN can be unrolled and fed to a logistic regression unit to make a prediction
- In a CNN, will have convolution layers, pooling layers and fully connected layers
- Pooling layers reduce the size of the representation and can make detected features more robust
 - Max pooling splits the input into sections and takes the maximum value from each section
 - Max pooling will have a filter size and stride length
 - Max pooling will “preserve” any standout features
- For a 3D input to max pooling, output will have the same 3rd dimension
 - Computation will be applied to each channel separately

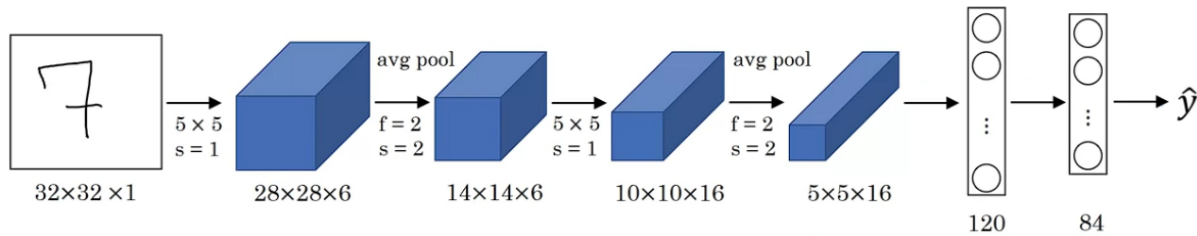
- Average pooling takes the average from each filter
 - Not as commonly used as max pooling
- Padding size of 0 usually used for pooling layers
- A fully connected layer is the same as a layer in a standard neural network
 - FC layer will have W and b parameters
 - Will reduce the dimension of the output of the NN
- Further in the CNN, the height and width of the input will gradually decrease
 - As n_W and n_H decrease, the depth of the input will typically increase
- Typical CNN will have one or more conv layers followed by a pool layer
 - CNN will usually finish with some fully connected layers then a softmax layer
- Conv layers help the network with sparsity of connections
 - Using a $32 \times 32 \times 3$ input image, 6 filters ($f = 5$) will give around 14m parameters
 - Conv layer will have 456 parameters for same calculation
 - In every layer, each output value is depends on only a small number of inputs
- Conv layers use parameter sharing
 - A feature detector (filter) that is useful in one part of an image will likely be useful in another part of the image
- Conv layers and FC layers all have associated parameters
 - Cost function can be defined over the parameters
 - Gradient descent or other optimization algorithm can be used to train the network and reduce J

4.2 Deep Convolutional Models: Case Studies

- Intuition about own deep learning problem can be gained by looking at existing research
 - NN architecture and other ideas may be transferrable to other problems
 - Ideas may also be transferrable to other areas of machine learning

4.2.1 LeNet-5

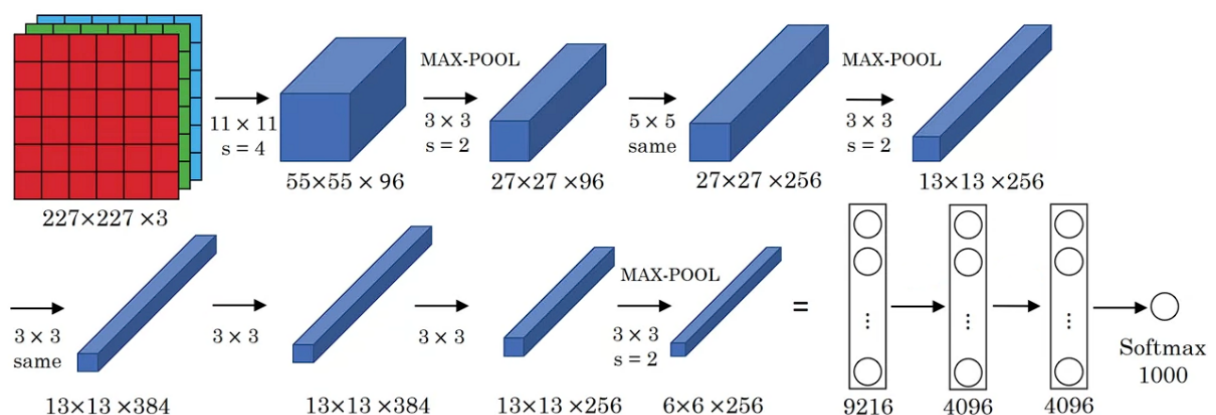
- Goal of LeNet-5 was to recognize handwritten digits
- NN was trained on grayscale images ($32 \times 32 \times 1$)
- Output from the NN had 10 possible values



- Modern implementation would use a softmax layer
- When the NN was implemented, no padding was used
- LeNet-5 was “small” compared to other networks
 - Whole NN had 60K parameters
 - Modern NN can have 10m to 100m parameters
- Deeper in the network, n_H and n_W decrease and n_C increase
- Network starts with conv and pool layers, followed by FC layers then output
- Modern computers have the capacity for each filter to have the same number of channels as its input
 - LeNet-5 had a method of making different filters looking at different inputs
- LeNet-5 used sigmoid or tanh activation functions
 - Non linearity was also added after the pooling layers

4.2.2 AlexNet

- Input was a 227×227 color image

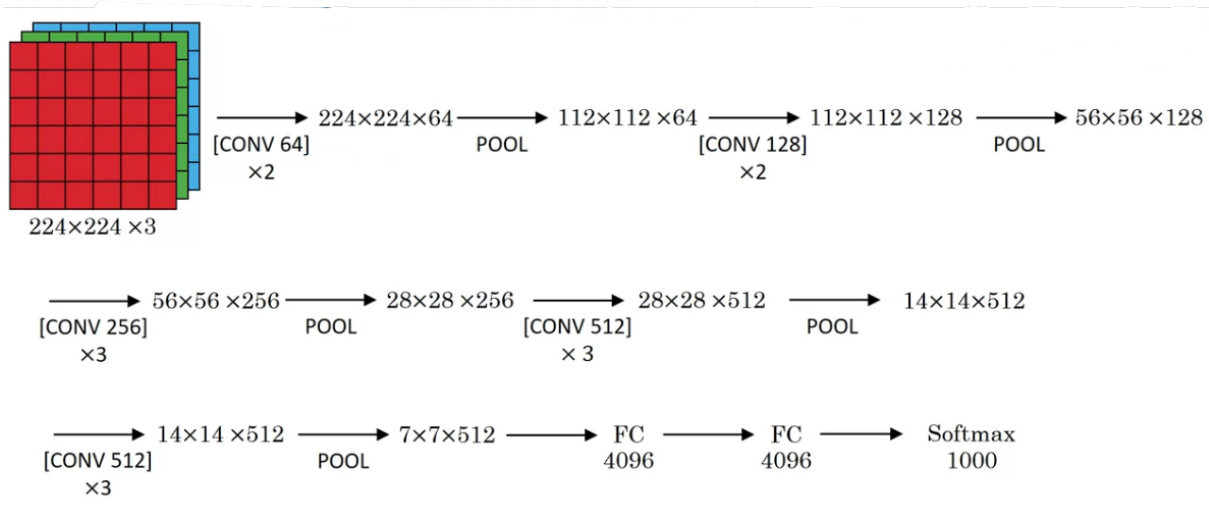


- Similar structure to LeNet-5 but much larger
 - Contains around 60m parameters

- Used ReLU activation functions
- Training of AlexNet was split across multiple GPUs
- AlexNet used a Local Response Normalization layer
 - After some layers, the outputs would be normalized across all the channels
 - Not used very often as research showed layer is not very helpful

4.2.3 VGG-16

- Uses a much simpler network compared to AlexNet
 - Conv layers: 3×3 filter, $s = 1$, same padding
 - Max pool layers: 2×2 filter, $s = 2$
- NN has 16 layers with weights
 - NN has around 138m weights



- NN is much more uniform when compared with other architectures

4.2.4 ResNets

- Very deep networks are hard to train due to vanishing and exploding gradients
- Skip connections use activations from one layer in another layer deeper in the NN
- ResNets created by using a residual block
 - In between $a^{[l]}$ and $a^{[l+2]}$, the activations $a^{[l]}$ will go through two sets of linear and non linear functions
 - $a^{[l]}$ can be added later in the network before the second non-linearity

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

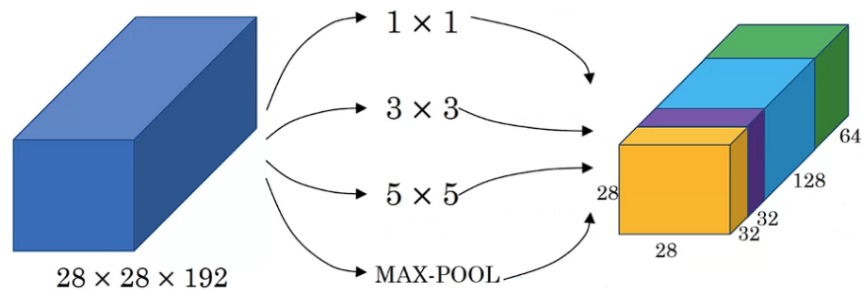
- Residual blocks can be stacked together to form a deep network
 - Residual blocks allow deeper NN to be trained
- For “plain” NN, increasing the number of layers will initially decrease the training error
 - When the number of layers is very large, the NN is hard to train and the training error increases
 - With ResNets, the training error shouldn’t increase with the number of layers
- Residual blocks can quite easily learn the identity function
 - Using the ReLU activation, $a^{[l+2]} = g(W^{[l+2]}a^{[l+1]} + b^{[l+2]} + a^{[l]})$
 - With regularization, W and b will be close to 0
 - $\therefore a^{[l+2]} \approx g(a^{[l]})$
 - Since ReLU activation is used, $a^{[l+2]} \approx a^{[l]}$
- If adding residual blocks is similar to using the identity function, the performance of the network will not be affected
 - Residual blocks can also learn parameters that are better than the identity function
- For ResNets, it is assumed that $z^{[l+2]}$ and $a^{[l]}$ have the same dimensions
 - Same convolutions tend to be used for ResNets
 - If same convolution is not used, $a^{[l]}$ is multiplied by a matrix W_s to create the correct dimension
 - W_s can have parameters that can be learnt or can be a fixed matrix that adds zero padding

4.2.5 Networks in Networks

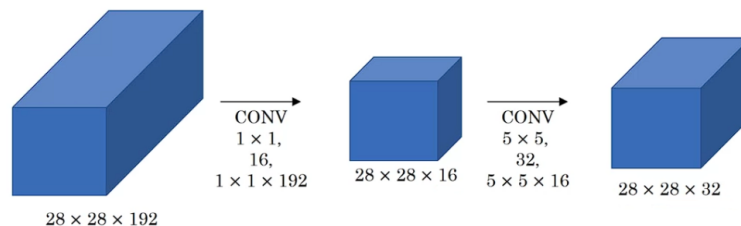
- For a single $1 \times 1 \times 1$ filter, pixels in the image will get multiplied by the filter value
 - If the filter has a depth of more than 1, the filter will take the element wise product of all numbers in the slice
 - Very similar to a neuron taking all the numbers in a slice as input
- Having a 1×1 convolution on an input is the same as having a fully connected NN in each position
- Using 1×1 convolutions known as network in network
- 1×1 convolutions can be used to shrink the depth of an input
 - Pooling layers used to shrink the height and width of the volume

4.2.6 Inception Network

- For CNNs, must choose the size of the filters and order of layers
 - Inception network works with multiple choices of filters and layers at the same time
- Outputs from all possible choices are stacked on top of each other



- Same padding used for conv layers so outputs have the same dimension
- Same padding and $s = 1$ must also be used for max pooling layer
- Output from the layer will be a $28 \times 28 \times 256$ volume
- For the 5×5 filter section of the layer, 120,422,400 calculations are needed
 - Single layer of an inception network can be very computationally expensive
 - 1×1 convolutions can be used to reduce the computational cost by a factor of 10
- 1×1 convolutions can be used in a bottleneck layer to shrink the input



- With the bottleneck layer, only 12,443,648 calculations are needed
- For an inception module, 1×1 convolution should be used before any filters that have larger dimensions
 - For pooling layers, 1×1 convolutions should be used to shrink the number of channels
- Inception network created from multiple inception modules

4.2.7 MobileNet

- MobileNet networks can be built and deployed in low compute environments
 - Can be used for mobile and embedded vision applications due to low computational cost at deployment

- For a normal convolution:

$$\text{Computational cost} = \# \text{ filter params} \times \# \text{ filter positions} \times \# \text{ of filters}$$

- A depthwise separable convolution separates process into depthwise and pointwise convolution
- Depthwise convolution uses n_C filters of $f \times f$
 - Separate filter used for each channel
 - Output of depthwise convolution will be $n_{out} \times n_{out} \times n_C$
- Pointwise convolution uses filters of size $1 \times 1 \times n_C$
 - n_C' filters used to get the correct dimensions in the output volume
- Computational cost of depthwise and pointwise convolutions will be less than the computational cost for a normal convolution
 - In general, the ratio of computational costs is $\frac{1}{n_C'} + \frac{1}{f^2}$
- MobileNet will use a depthwise separable convolution for all convolutions in the network
 - Original MobileNet V1 network had 13 depthwise separable convolutions
 - Last layers of the network were pooling, FC and softmax layers
- MobileNet V2 used residual connections across each layer
 - Convolution also added an expansion layer before the depthwise convolution
 - MobileNet V2 had 17 convolution (bottleneck) blocks with pooling, FC and softmax layers
- Expansion layer similar to the pointwise convolution (projection) but increases the depth of the volume
 - The expansion increases the size of the representation to allow the NN to learn a richer function
 - The projection reduces the depth of the volume to reduce the amount of memory required for the output

4.2.8 EfficientNet

- Specific application can benefit from being scaled to the hardware specifications
- To scale a NN:
 - Higher resolution image
 - Change the depth of the network
 - Change the width of the layers
- r, d, w can be scaled according to available resources
 - Rate of scaling for each variable may not be the same

4.2.9 Practical Advice for CNNs

- A lot of details about CNNs are hard to replicate in practice
 - Open source implementation of code can often be found online
 - Reimplementing the whole algorithm from scratch can help in terms of understanding
- Specific architecture may also take a very long time to train on own device
 - Transfer learning can be used from pre trained networks
- When using a pre trained network, softmax layer can be replaced to suit new application
 - Parameters in the rest of the network can be ignored and softmax output layer can be trained
 - If only the last layer is being trained, the activations input to the softmax layer can be saved separately to prevent extra computation
- If the training set is very big, more layers from the end of the network can be trained
 - Weights from original network can be used for initialization
 - Layers can also be completely removed and trained again from the start
 - Whole network can be retrained if there is enough data
- Most computer vision tasks can benefit from data augmentation
- Mirroring and random cropping are commonly used for data augmentation
 - Mirroring images works well for most applications
 - Random cropping works well as long as the crop is a reasonable subset of the image
- Other methods can be used but can be less effective

- Rotation
- Shearing
- Local warping
- Color shifting can be used in almost all computer vision applications
 - Can help to eliminate any biases caused by specific lighting
 - In practice, color shifting will be more structured (PCA color augmentation)
- When training, a specific CPU thread will be used to apply distortions
 - The data will be processed by the thread then passed to the CPU/GPU for training
 - CPU thread for distortion and CPU for training can run in parallel
- Some applications of deep learning have comparatively more data than other applications
 - Speech recognition has a lot of available labelled data
 - Image recognition has a lot of data but not “enough” for applications
 - Object detection had relatively little labelled data
- Applications with comparatively more data can use simpler algorithms
 - Applications with comparatively less data require more hand engineering of features
- Historically, computer vision relies more on hand engineered features
 - Network architectures are also hand engineered for computer vision
- Researchers also want to do well on benchmarks and win ML competitions
 - Some researchers will use ideas that will specifically help the benchmark
 - Same ideas would not be used in a standard application
- Ensembling can give a slight increase to the performance of an algorithm
 - Several networks are trained independently and the outputs are averaged
 - 3-15 networks can be used but will greatly slow down the running time
- Multi-crop at test time is more computationally expensive and much slower
 - The trained classifier is run on multiple versions of test images and results are averaged
 - 10-crop applies same network to 10 separate crops of the image

4.3 Object Detection

- Image classification identifies whether an object is contained within an image
 - Classification with localization will identify the location of the object on the image
 - Detection will search and locate multiple objects in an image
- For classification with localization, output of the NN will typically include a softmax output
 - Output layer must also be modified to output the coordinates for the bounding box (b_x, b_y, b_w, b_h)
- For a 4 class localization problem:

$$y = \begin{bmatrix} P_c \\ b_x \\ b_y \\ b_h \\ b_w \\ c_1 \\ c_2 \\ c_3 \end{bmatrix}$$

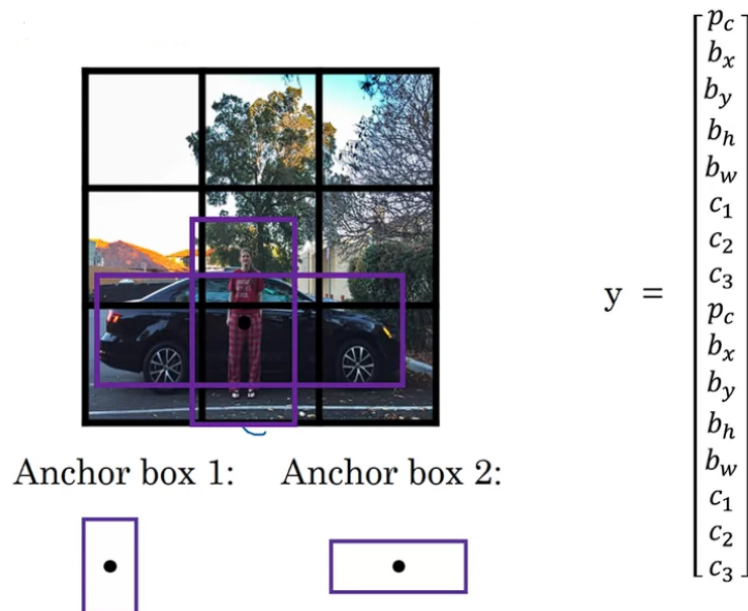
- P_c : 1 if an object has been identified
- b_x, b_y, b_h, b_w : coordinates for the bounding box
- c_1, c_2, c_3 : class labels for 3 positive classes

$$\mathcal{L}(\hat{y}, y) = \begin{cases} (\hat{y}_1 - y_1)^2 + (\hat{y}_2 - y_2)^2 + \dots + (\hat{y}_8 - y_8)^2, & \text{if } y_1=1 \\ (\hat{y}_1 - y_1)^2, & \text{if } y_1=0 \end{cases}$$

- In practice, feature loss for softmax output or logistic regression loss is used
- NNs can be trained to output coordinates for landmarks in the image
 - Training set must be labelled with all the landmarks on the image
- Landmark detection can be used for AR filters or to track emotions and poses
- Object detection with CNNs can be done with a sliding windows detection algorithm
 - Training set should contain closely cropped images of wanted object
 - CNN can be trained to output label for closely cropped image
 - Trained CNN passed to the sliding windows classifier
- For sliding windows classifier, specific window size is chosen and overlayed on the image
 - Section of image in the window passed to the trained CNN
 - Window “slides” across the whole image

- After initial pass of image is made, a larger window size is used
- Sliding windows detection is very computationally expensive
 - A coarser stride can be used to reduce computational load
 - Larger stride length can damage the algorithm performance
 - Initial classifiers used, simpler classifiers with hand engineered features
- Convolutional implementation of the sliding windows detection is more computationally feasible
- FC layers can be transformed into convolutional layers
 - For a input of $5 \times 5 \times 16$ to a FC layer, a 5×5 filter can be used
 - 400 filters must be used for output to have the correct dimension
 - Softmax output can be seen as a $1 \times 1 \times n_{Cout}$ volume
- Once the initial CNN is trained, the network can be run on the whole image
 - Output from the image will be a volume that represents all the possible inputs to the CNN
 - Only requires forward propagation to be run once as computation is shared
- Using convolutional implementation, bounding boxes still may not be very accurate
 - Discrete steps may not match up exactly with the object
 - Object may be more rectangular in the image
- YOLO algorithm will increase the accuracy of the bounding boxes
 - Image is split into grid and object classifier run on each cell
 - Any located objects assigned to the cell containing the midpoint
 - Using above output and a 3×3 grid, target output will be $3 \times 3 \times 8$
 - CNN should be chosen so that output is also $3 \times 3 \times 8$
- Trained network will give precise bounding boxes for each cell
 - Each cell cannot have more than a single object
 - For a fine grid, the chances of having more than one object in each cell is low
 - Algorithm is fast enough for real time object detection
- When specifying the coordinates for the bounding box, b_x and b_y should be relative to their cell
 - b_h and b_w should be a fraction of the cell dimensions
 - b_h and b_w can be larger than 1

- Intersection over union can be used to evaluate an object detection algorithm
 - Calculates the quotient of the intersection and union for the ground truth and predicted bounding box
 - May CV tasks judge the answer as correct if $\text{IoU} \geq 0.5$
- Non-max suppression ensures the algorithm only detects each object once
 - With the YOLO algorithm, more than one box may think it has the center of the object
- Algorithm starts by discarding rectangles with $p_c \leq 0.6$
 - Rectangle with the largest p_c is chosen as prediction
 - Any other boxes with $\text{IoU} \geq 0.5$ can be discarded
- Non-max suppression should be carried out on each of the output classes
- Anchor boxes can be used to allow cells to detect multiple objects
 - Shapes for anchor boxes can be defined for possible objects in the image
 - Output vector y will have a vector for each anchor box
 - Each object is assigned to the grid cell that contains the midpoint and anchor box that has the highest IoU

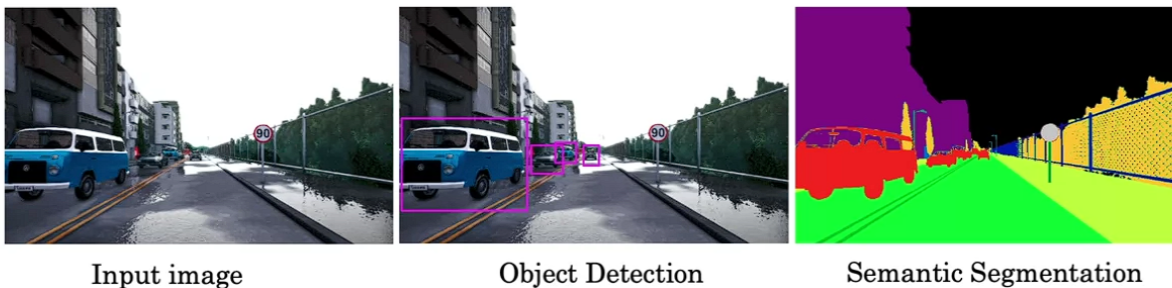


- If there are more objects than anchor boxes, alternative case should be implemented in the algorithm
- Anchor boxes allow the algorithm to better specialize to certain objects

- K means algorithm can be used to group together object shapes that get detected
- To train YOLO algorithm, all images in the training set must be properly labelled
 - For each image, the output y will be a volume with the vector y for each cell
 - For each class, non-max suppression used to generate final predictions
- Convolutional object classifiers will get run on all parts of the image
 - Some areas of the image clearly do not have any object in them
 - R-CNN will use a segmentation algorithm to propose regions that likely have objects in them
 - All proposed regions run through the object classifier
- R-CNN still a relatively slow algorithm
 - Fast R-CNN uses a convolutional implementation to classify the proposed regions
 - Faster R-CNN uses a CNN to propose the regions

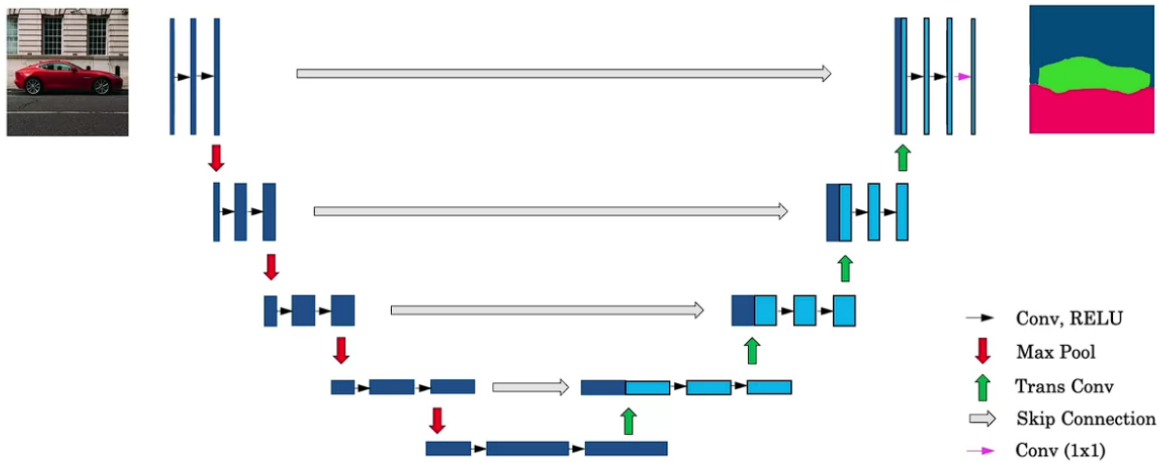
4.3.1 U-Nets

- Semantic segmentation aims to identify an outline of any identified objects



- Used by some self driving car teams to detect drivable roads
- Used by medical teams to help with reading scans
- Segmentation done with a U-Net
- U-Net has to generate a matrix of labels for each image to segment each pixel
 - First few layers of standard CNN can be reused
 - Last few layers of the CNN must make the output the same size as the input
 - Transpose convolution must be used to increase the height and width of each layer
- Regular convolution will place filter on top of the input
 - Transpose convolution will put the filter on top of the output

- For each value in the input, filter gets multiplied by the input and overlayed on the output
 - Numbers for each filter get added to the output values
 - Values in the padding can be ignored
- For the U-Net architecture, skip connections can be used to improve performance
 - When the dimensions of the layers decrease in the CNN, spatial information is lost



- Conv and ReLU layers will increase number of channels in the image
 - Height and width will remain unchanged
- Max pool layers will decrease the height and width of the image
 - Number of channels will remain constant
- After transpose convolutions are used, corresponding conv layer will use a skip connection
- Last layer will be a 1×1 convolution
- Dimension of last layer will be $h \times w \times n_{classes}$

4.4 Special Applications of CNNs

4.4.1 Face Recognition

- Face recognition can be paired with liveness detection to distinguish real faces from images
- Face verification takes an input image and an ID
 - Output will state if the input image is the same as the ID

- Face recognition will take an input image and compare it to K different people
 - Output will give the ID of any recognized person
- Face verification system may have a very low 1% error rate
 - If the system is used for face recognition with a database of 100 people, error will be very high
- Majority of face recognition systems must be able to recognize a person from a single example (one-shot learning problem)
 - Deep learning problems don't tend to work well with a single example
- Standard CNN with softmax output won't be able to learn well
 - If another person is added to the database, the whole CNN must be retrained
- Face recognition functions will learn a similarity function to output the degree of difference between images
 - If $d(\text{img1}, \text{img2}) \leq \tau$ the images are the "same"
- Similarity function will be run on all images in the database
- Siamese network can be used to create the similarity function
 - Standard CNN ends with a feature vector being fed to a softmax unit
 - Final layer of the CNN can be seen as an encoding of the input image $x^{(1)}$
 - Siamese network runs the same CNN network on two inputs and compares the output

- Difference between the images can be calculated as the norm between the 2 vectors:

$$d(x^{(1)}, x^{(2)}) = \|f(x^{(1)}) - f(x^{(2)})\|^2$$

- Parameters of the CNN define the encoding $f(x^{(i)})$
 - If $x^{(i)}$ and $x^{(j)}$ are the same person, $\|f(x^{(i)}) - f(x^{(j)})\|^2$ should be small
 - If $x^{(i)}$ and $x^{(j)}$ are different people, $\|f(x^{(i)}) - f(x^{(j)})\|^2$ should be large
- Parameters of the CNN can be learnt by using gradient descent on the triplet loss function
 - Triplet loss will look at an anchor image, positive image and negative image
 - Want $d(A, P) \leq d(A, N)$

- Loss function can have a trivial solution where all encodings get output to 0

$$\|f(A) - f(P)\|^2 - \|f(A) - f(N)\|^2 + \alpha \leq 0$$

- Adding constant α prevents the trivial solution from being learnt

$$\mathcal{L}(A, P, N) = \max(\|f(A) - f(P)\|^2 - \|f(A) - f(N)\|^2 + \alpha, 0)$$

$$J = \sum_{i=1}^m \mathcal{L}(A^{(i)}, P^{(i)}, N^{(i)})$$

- Training the system requires sets of anchor, positive and negative images
- During training, if A, P, N are chosen randomly, loss function is easily satisfied
 - Ideally, chosen triplets should be “hard” to train on ($d(A, P) \approx d(A, N)$)
- Large scale face recognition systems can be trained on datasets with 10,000,000+ images
- Face recognition can also be seen as a binary classification problem
 - Outputs from the siamese networks can be fed to a logistic regression unit
 - Training set will require pairs of images

$$\hat{y} = \sigma \left(\sum_{k=1}^{128} w_k |f(x^{(i)})_k - f(x^{(j)})_k| + b \right)$$

- Different formula can be used to combine both outputs
 - Chi Squared similarity

$$\frac{(f(x^{(i)})_k - f(x^{(j)})_k)^2}{f(x^{(i)})_k + f(x^{(j)})_k}$$

- With Siamese networks, values can be precomputed for stored images

4.4.2 Neural Style Transfer

- Neural style transfer allows existing content to be generated in a different style
- To visualize the learning of a CNN, can manually look for image patches that maximize the unit’s activation
 - First layers of the network will detect simple patterns or colors
 - Deeper layers will detect more complex patterns and will start to detect certain objects
- Cost function can be defined to see how “good” an image is

$$J(G) = \alpha J_{content}(C, G) + \beta J_{style}(S, G)$$

- The new image G will be first initialized randomly
 - Use gradient descent to minimize $J(G)$
 - Gradient descent will change the pixel values of the image

- A layer l will be chosen to compute the content cost
 - If the layer l is too shallow, the pixel values are forced to be very close to the content image
 - If the layer l is too deep, the content may be too dissimilar
- Using a pre trained CNN, activations of the images on layer l can be calculated
 - If $a^{[l](c)}$ and $a^{[l](G)}$ are similar, both images have similar content

$$J_{content}(C, G) = \frac{1}{2} ||a^{[l](C)} - a^{[l](G)}||^2$$

- The style of a layer can be calculated as the correlation between activations across different channels
 - All pixels can be compared with the corresponding pixel in a different channel
 - A single pixel will have a specific pattern that results in high activation
 - Correlation between the layers show which patterns tend to occur together
- Style matrix can be defined:
 - Let $a_{i,j,k}^{[l]}$ be the activation of layer l at (i, j, k)
 - $G^{[l]}$ is a $n_c^{[l]} \times n_c^{[l]}$ matrix

$$G_{k \ k'}^{[l](G)} = \sum_{i=1}^{n_H^{[l]}} \sum_{j=1}^{n_W^{[l]}} a_{i,j,k}^{[l](G)} a_{i,j,k'}^{[l](G)}$$

- G is calculated for all values of k and k' for the style image and generated image
- Style cost function is then the difference between the style matrices

$$\begin{aligned} J_{style}^{[l]}(S, G) &= ||G^{[l](S)} - G^{[l](G)}||_F^2 \\ &= \frac{1}{\left(2n_H^{[l]}n_W^{[l]}n_C^{[l]}\right)^2} \sum_k \sum_{k'} \left(G_{k \ k'}^{[l](S)} - G_{k \ k'}^{[l](G)}\right)^2 \end{aligned}$$

- Constant comes from original authors of the paper
- Constant will be superseded by the constant in the overall style transfer cost function
- Performance is increased when the style cost function is taken from multiple layers

$$J_{style}(S, G) = \sum_l \lambda^{[l]} J_{style}^{[l]}(S, G)$$

- Using all layers of the CNN allows all levels of features to be used

- Convolutions can also be applied to 1D data
 - ECG data can be convolved with a 1D filter
 - CT scans can be convolved with a 3D filter