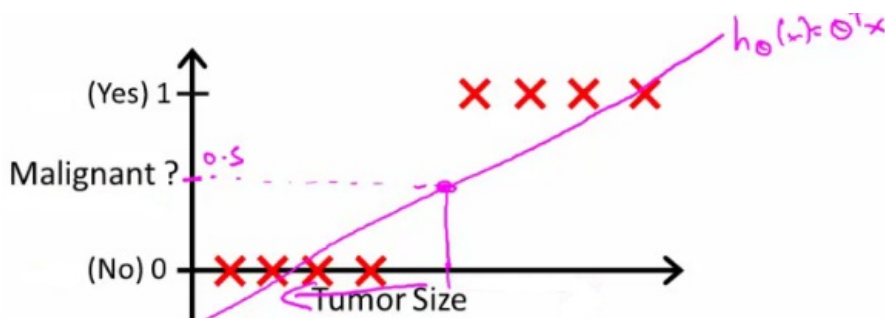


06: Logistic Regression

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Classification

- Where y is a discrete value
 - Develop the logistic regression algorithm to determine what class a new input should fall into
- Classification problems
 - Email -> spam/not spam?
 - Online transactions -> fraudulent?
 - Tumor -> Malignant/benign
- Variable in these problems is Y
 - Y is either 0 or 1
 - 0 = negative class (absence of something)
 - 1 = positive class (presence of something)
- Start with **binary class problems**
 - Later look at multiclass classification problem, although this is just an extension of binary classification
- How do we develop a classification algorithm?
 - Tumour size vs malignancy (0 or 1)
 - We *could* use linear regression
 - Then threshold the classifier output (i.e. anything over some value is yes, else no)
 - In our example below linear regression with thresholding seems to work



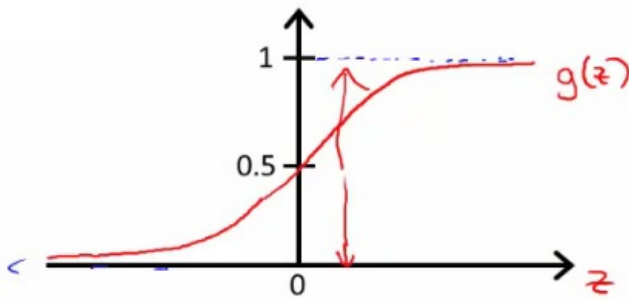
- We can see above this does a reasonable job of stratifying the data points into one of two classes
 - But what if we had a single Yes with a very small tumour
 - This would lead to classifying all the existing yeses as nos
- Another issues with linear regression
 - We know Y is 0 or 1
 - Hypothesis can give values large than 1 or less than 0
- So, logistic regression generates a value where is always either 0 or 1
 - Logistic regression is a **classification algorithm** - don't be confused

Hypothesis representation

- What function is used to represent our hypothesis in classification
- We want our classifier to output values between 0 and 1
 - When using linear regression we did $h_{\theta}(x) = (\theta^T x)$
 - For classification hypothesis representation we do $h_{\theta}(x) = g((\theta^T x))$
 - Where we define $g(z)$
 - z is a real number
 - $g(z) = 1/(1 + e^{-z})$
 - This is the **sigmoid function**, or the **logistic function**
 - If we combine these equations we can write out the hypothesis as

$$h_{\theta}(x) = \frac{1}{1 + e^{-\theta^T x}}$$

- What does the sigmoid function look like
- Crosses 0.5 at the origin, then flattens out]
 - Asymptotes at 0 and 1



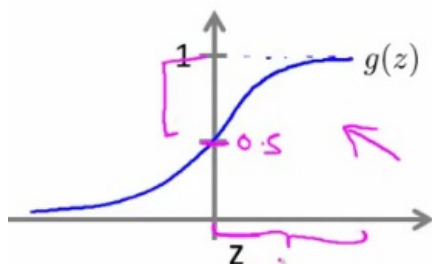
- Given this we need to fit θ to our data

Interpreting hypothesis output

- When our hypothesis ($h_{\theta}(x)$) outputs a number, we treat that value as the estimated probability that $y=1$ on input x
 - Example
 - If X is a feature vector with $x_0 = 1$ (as always) and $x_1 = \text{tumourSize}$
 - $h_{\theta}(x) = 0.7$
 - Tells a patient they have a 70% chance of a tumor being malignant
 - We can write this using the following notation
 - $h_{\theta}(x) = P(y=1|x; \theta)$
 - What does this mean?
 - Probability that $y=1$, given x , parameterized by θ
- Since this is a binary classification task we know $y = 0$ or 1
 - So the following must be true
 - $P(y=1|x; \theta) + P(y=0|x; \theta) = 1$
 - $P(y=0|x; \theta) = 1 - P(y=1|x; \theta)$

Decision boundary

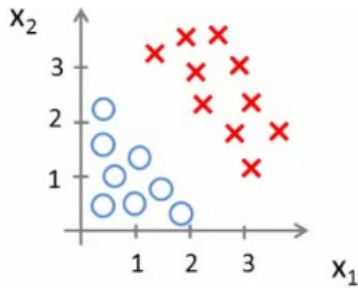
- Gives a better sense of what the hypothesis function is computing
- Better understand of what the hypothesis function looks like
 - One way of using the sigmoid function is;
 - When the probability of y being 1 is greater than 0.5 then we can predict $y = 1$
 - Else we predict $y = 0$
 - When is it exactly that $h_{\theta}(x)$ is greater than 0.5?
 - Look at sigmoid function
 - $g(z)$ is greater than or equal to 0.5 when z is greater than or equal to 0



- So if z is positive, $g(z)$ is greater than 0.5
 - $z = (\theta^T x)$
 - So when
 - $\theta^T x \geq 0$
 - Then $h_{\theta} \geq 0.5$
- So what we've shown is that the hypothesis predicts $y = 1$ when $\theta^T x \geq 0$
 - The corollary of that when $\theta^T x \leq 0$ then the hypothesis predicts $y = 0$
 - Let's use this to better understand how the hypothesis makes its predictions

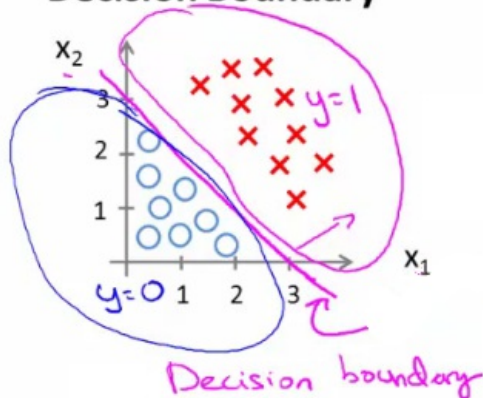
Decision boundary

- $h_{\theta}(x) = g(\theta_0 + \theta_1 x_1 + \theta_2 x_2)$



- So, for example
 - $\theta_0 = -3$
 - $\theta_1 = 1$
 - $\theta_2 = 1$
- So our parameter vector is a column vector with the above values
 - So, θ^T is a row vector $[-3, 1, 1]$
- What does this mean?
 - The z here becomes $\theta^T x$
 - We predict "y = 1" if
 - $-3x_0 + 1x_1 + 1x_2 \geq 0$
 - $-3 + x_1 + x_2 \geq 0$
- We can also re-write this as
 - If $(x_1 + x_2 \geq 3)$ then we predict $y = 1$
 - If we plot
 - $x_1 + x_2 = 3$ we graphically plot our **decision boundary**

Decision Boundary

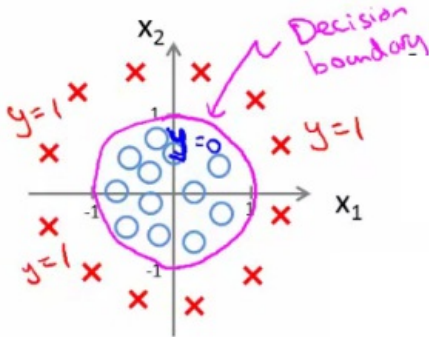


- Means we have these two regions on the graph
 - Blue = false
 - Magenta = true
 - Line = decision boundary
 - Concretely, the straight line is the set of points where $h_\theta(x) = 0.5$ exactly
 - The decision boundary is a property of the hypothesis
 - Means we can create the boundary with the hypothesis and parameters without any data
 - Later, we use the data to determine the parameter values
 - i.e. $y = 1$ if
 - $5 - x_1 > 0$
 - $5 > x_1$

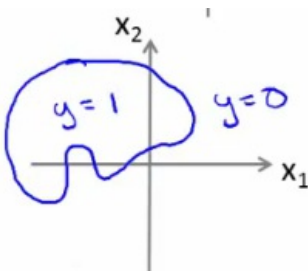
Non-linear decision boundaries

- Get logistic regression to fit a complex non-linear data set
 - Like polynomial regress add higher order terms
 - So say we have
 - $h_\theta(x) = g(\theta_0 + \theta_1 x_1 + \theta_3 x_1^2 + \theta_4 x_2^2)$
 - We take the transpose of the θ vector times the input vector

- Say θ^T was $[-1, 0, 0, 1, 1]$ then we say;
- Predict that " $y = 1$ " if
 - $-1 + x_1^2 + x_2^2 \geq 0$
 - or
 - $x_1^2 + x_2^2 \geq 1$
- If we plot $x_1^2 + x_2^2 = 1$
 - This gives us a circle with a radius of 1 around 0



- Mean we can build more complex decision boundaries by fitting complex parameters to this (relatively) simple hypothesis
- More complex decision boundaries?
 - By using higher order polynomial terms, we can get even more complex decision boundaries



Cost function for logistic regression

- Fit θ parameters
- Define the optimization object for the cost function we use the fit the parameters
 - Training set of m training examples
 - Each example has is $n+1$ length column vector

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

m examples $x \in \begin{bmatrix} x_0 \\ x_1 \\ \dots \\ x_n \end{bmatrix} \quad x_0 = 1, y \in \{0, 1\}$

$$h_{\theta}(x) = \frac{1}{1 + e^{-\theta^T x}}$$

- This is the situation
 - Set of m training examples
 - Each example is a feature vector which is $n+1$ dimensional
 - $x_0 = 1$
 - $y \in \{0, 1\}$
 - Hypothesis is based on parameters (θ)
 - Given the training set how to we chose/fit θ ?

- Linear regression uses the following function to determine θ

$$J(\theta) = \frac{1}{m} \sum_{i=1}^m \frac{1}{2} (h_{\theta}(x^{(i)}) - y^{(i)})^2$$

- Instead of writing the squared error term, we can write
 - If we define "cost()" as;
 - $\text{cost}(h_{\theta}(x^i), y) = 1/2(h_{\theta}(x^i) - y^i)^2$
 - Which evaluates to the cost for an individual example using the same measure as used in linear regression

- We can **redefine $J(\theta)$** as

$$J(\theta) = \frac{1}{m} \sum_{i=1}^m \text{Cost}(h_{\theta}(x^{(i)}), y^{(i)})$$

- Which, appropriately, is the sum of all the individual costs over the training data (i.e. the same as linear regression)
- To further simplify it we can get rid of the superscripts
 - So

$$J(\theta) = \frac{1}{m} \sum_{i=1}^m \text{Cost}(h_{\theta}(x), y)$$

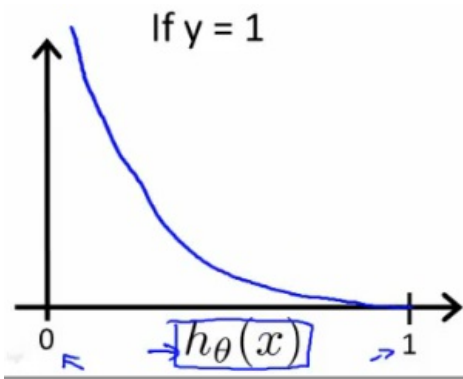
- What does this actually mean?
 - This is the cost you want the learning algorithm to pay if the outcome is $h_{\theta}(x)$ and the actual outcome is y
 - If we use this function for logistic regression this is a **non-convex function** for parameter optimization
 - Could work....
- What do we mean by non convex?
 - We have some function - $J(\theta)$ - for determining the parameters
 - Our hypothesis function has a non-linearity (sigmoid function of $h_{\theta}(x)$)
 - This is a complicated non-linear function
 - If you take $h_{\theta}(x)$ and plug it into the $\text{Cost}()$ function, and then plug the $\text{Cost}()$ function into $J(\theta)$ and plot $J(\theta)$ we find many local optimum -> *non convex function*
 - Why is this a problem
 - Lots of local minima mean gradient descent may not find the global optimum - may get stuck in a local minimum
 - We would like a convex function so if you run gradient descent you converge to a global minimum

A convex logistic regression cost function

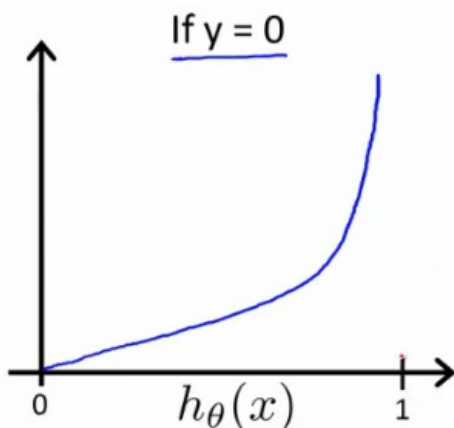
- To get around this we need a different, convex $\text{Cost}()$ function which means we can apply gradient descent

$$\text{Cost}(h_{\theta}(x), y) = \begin{cases} -\log(h_{\theta}(x)) & \text{if } y = 1 \\ -\log(1 - h_{\theta}(x)) & \text{if } y = 0 \end{cases}$$

- This is our logistic regression cost function**
 - This is the penalty the algorithm pays
 - Plot the function
- Plot $y = 1$
 - So $h_{\theta}(x)$ evaluates as $-\log(h_{\theta}(x))$



- So when we're right, cost function is 0
 - Else it slowly increases cost function as we become "more" wrong
 - X axis is what we predict
 - Y axis is the cost associated with that prediction
- This cost functions has some interesting properties
 - If $y = 1$ and $h_{\theta}(x) = 1$
 - If hypothesis predicts exactly 1 and thats exactly correct then that corresponds to 0 (exactly, not nearly 0)
 - As $h_{\theta}(x)$ goes to 0
 - Cost goes to infinity
 - This captures the intuition that if $h_{\theta}(x) = 0$ (predict $P(y=1|x; \theta) = 0$) but $y = 1$ this will penalize the learning algorithm with a massive cost
- What about if $y = 0$
- then cost is evaluated as $-\log(1 - h_{\theta}(x))$
 - Just get inverse of the other function



- Now it goes to plus infinity as $h_{\theta}(x)$ goes to 1
- With our particular cost functions $J(\theta)$ is going to be convex and avoid local minimum

Simplified cost function and gradient descent

- Define a simpler way to write the cost function and apply gradient descent to the logistic regression
 - By the end should be able to implement a fully functional logistic regression function
- Logistic regression cost function is as follows

$$\rightarrow J(\theta) = \frac{1}{m} \sum_{i=1}^m \text{Cost}(h_{\theta}(x^{(i)}), y^{(i)})$$

$$\text{Cost}(h_{\theta}(x), y) = \begin{cases} -\log(h_{\theta}(x)) & \text{if } y = 1 \\ -\log(1 - h_{\theta}(x)) & \text{if } y = 0 \end{cases}$$

Note: $y = 0$ or 1 always

- This is the cost for a single example
 - For binary classification problems y is always 0 or 1
 - Because of this, we can have a simpler way to write the cost function
 - Rather than writing cost function on two lines/two cases
 - Can compress them into one equation - more efficient
 - Can write cost function is
 - **$\text{cost}(h_{\theta}(x), y) = -y \log(h_{\theta}(x)) - (1-y) \log(1 - h_{\theta}(x))$**
 - This equation is a more compact of the two cases above
 - We know that there are only two possible cases
 - $y = 1$
 - Then our equation simplifies to
 - $-\log(h_{\theta}(x)) - (0) \log(1 - h_{\theta}(x))$
 - $-\log(h_{\theta}(x))$
 - Which is what we had before when $y = 1$
 - $y = 0$
 - Then our equation simplifies to
 - $-(0) \log(h_{\theta}(x)) - (1) \log(1 - h_{\theta}(x))$
 - $= -\log(1 - h_{\theta}(x))$
 - Which is what we had before when $y = 0$
 - Clever!
- So, in summary, our cost function for the θ parameters can be defined as

$$J(\theta) = -\frac{1}{m} \left[\sum_{i=1}^m y^{(i)} \log h_{\theta}(x^{(i)}) + (1 - y^{(i)}) \log (1 - h_{\theta}(x^{(i)})) \right]$$

- Why do we chose this function when other cost functions exist?
 - This cost function can be derived from statistics using the principle of **maximum likelihood estimation**
 - Note this does mean there's an underlying Gaussian assumption relating to the distribution of features
 - Also has the nice property that it's convex
- To fit parameters θ :
 - Find parameters θ which minimize $J(\theta)$
 - This means we have a set of parameters to use in our model for future predictions
- Then, if we're given some new example with set of features x , we can take the θ which we generated, and output our prediction using

$$h_{\theta}(x) = \frac{1}{1 + e^{-\theta^T x}}$$

- This result is
 - $p(y=1 | x ; \theta)$
 - Probability $y = 1$, given x , parameterized by θ

How to minimize the logistic regression cost function

- Now we need to figure out how to minimize $J(\theta)$
 - Use gradient descent as before
 - Repeatedly update each parameter using a learning rate

Repeat {

$$\theta_j := \theta_j - \alpha \sum_{i=1}^m (h_{\theta}(x^{(i)}) - y^{(i)}) x_j^{(i)}$$

(simultaneously update all θ_j)

}

- If you had n features, you would have an $n+1$ column vector for θ
- This equation is the same as the linear regression rule
 - The only difference is that our definition for the hypothesis has changed
- Previously, we spoke about how to monitor gradient descent to check it's working
 - Can do the same thing here for logistic regression
- When implementing logistic regression with gradient descent, we have to update all the θ values (θ_0 to θ_n)

simultaneously

- Could use a for loop
- Better would be a vectorized implementation
- Feature scaling for gradient descent for logistic regression also applies here

Advanced optimization

- Previously we looked at gradient descent for minimizing the cost function
- Here look at advanced concepts for minimizing the cost function for logistic regression
 - Good for large machine learning problems (e.g. huge feature set)
- *What is gradient descent actually doing?*
 - We have some cost function $J(\theta)$, and we want to minimize it
 - We need to write code which can take θ as input and compute the following
 - $J(\theta)$
 - Partial derivative of $J(\theta)$ with respect to j (where $j=0$ to $j = n$)

$$J(\theta)$$
$$\frac{\partial}{\partial \theta_j} J(\theta) \quad (\text{for } j = 0, 1, \dots, n)$$

- Given code that can do these two things
 - Gradient descent repeatedly does the following update

$$\text{Repeat } \{ \theta_j := \theta_j - \alpha \frac{\partial}{\partial \theta_j} J(\theta) \}$$

- So update each j in θ sequentially
- So, we must;
 - Supply code to compute $J(\theta)$ and the derivatives
 - Then plug these values into gradient descent
- Alternatively, instead of gradient descent to minimize the cost function we could use
 - **Conjugate gradient**
 - **BFGS** (Broyden-Fletcher-Goldfarb-Shanno)
 - **L-BFGS** (Limited memory - BFGS)
- These are more optimized algorithms which take that same input and minimize the cost function
- These are very complicated algorithms
- Some properties
 - **Advantages**
 - No need to manually pick alpha (learning rate)
 - Have a clever inner loop (line search algorithm) which tries a bunch of alpha values and picks a good one
 - Often faster than gradient descent
 - Do more than just pick a good learning rate
 - Can be used successfully without understanding their complexity
 - **Disadvantages**
 - Could make debugging more difficult
 - Should not be implemented themselves
 - Different libraries may use different implementations - may hit performance

Using advanced cost minimization algorithms

- How to use algorithms
 - Say we have the following example

Example:

$$\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

$$J(\theta) = (\theta_1 - 5)^2 + (\theta_2 - 5)^2$$

$$\frac{\partial}{\partial \theta_1} J(\theta) = 2(\theta_1 - 5)$$

$$\frac{\partial}{\partial \theta_2} J(\theta) = 2(\theta_2 - 5)$$

- Example above
 - θ_1 and θ_2 (two parameters)
 - Cost function here is $J(\theta) = (\theta_1 - 5)^2 + (\theta_2 - 5)^2$
 - The derivatives of the $J(\theta)$ with respect to either θ_1 and θ_2 turns out to be the $2(\theta_i - 5)$
- First we need to define our cost function, which should have the following signature

function [jval, gradient] = costFunction(THETA)

- Input for the cost function is **THETA**, which is a vector of the θ parameters
- Two return values from **costFunction** are
 - **jval**
 - How we compute the cost function θ (the underived cost function)
 - In this case $= (\theta_1 - 5)^2 + (\theta_2 - 5)^2$
 - **gradient**
 - 2 by 1 vector
 - 2 elements are the two partial derivative terms
 - i.e. this is an n-dimensional vector
 - Each indexed value gives the partial derivatives for the partial derivative of $J(\theta)$ with respect to θ_i
 - Where i is the index position in the **gradient** vector
- With the cost function implemented, we can call the advanced algorithm using

options= optimset('GradObj', 'on', 'MaxIter', '100'); % define the options data structure

initialTheta= zeros(2,1); # set the initial dimensions for theta % initialize the theta values

[optTheta, funtionVal, exitFlag]= fminunc(@costFunction, initialTheta, options); % run the algorithm

- Here
 - **options** is a data structure giving options for the algorithm
 - **fminunc**
 - function minimize the cost function (find **minimum** of **un**constrained multivariable function)
 - **@costFunction** is a pointer to the costFunction function to be used
- For the octave implementation
 - **initialTheta** must be a matrix of at least two dimensions
- How do we apply this to logistic regression?
 - Here we have a vector

$$\text{theta} = \begin{bmatrix} \theta_0 \\ \theta_1 \\ \vdots \\ \theta_n \end{bmatrix}$$

```
function [jVal, gradient] = costFunction(theta)
```

```
    jVal = [code to compute  $J(\theta)$ ];
```

```
    gradient(1) = [code to compute  $\frac{\partial}{\partial \theta_0} J(\theta)$ ];
```

```
    gradient(2) = [code to compute  $\frac{\partial}{\partial \theta_1} J(\theta)$ ];
```

```
    ⋮
```

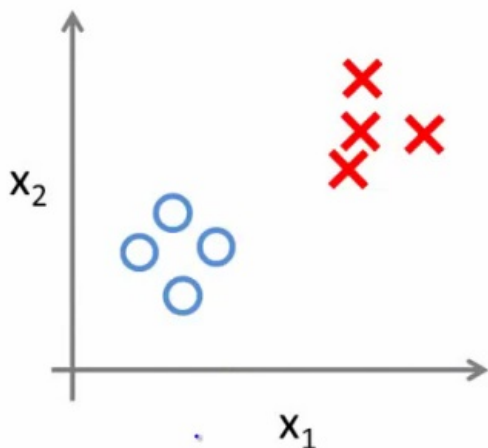
```
    gradient(n+1) = [code to compute  $\frac{\partial}{\partial \theta_n} J(\theta)$  1];
```

- Here
 - theta is a n+1 dimensional column vector
 - Octave indexes from 1, not 0
- Write a cost function which captures the cost function for logistic regression

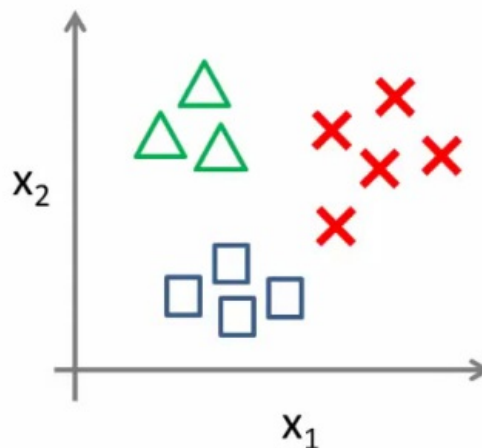
Multiclass classification problems

- Getting logistic regression for multiclass classification using **one vs. all**
- Multiclass - more than yes or no (1 or 0)
 - Classification with multiple classes for assignment

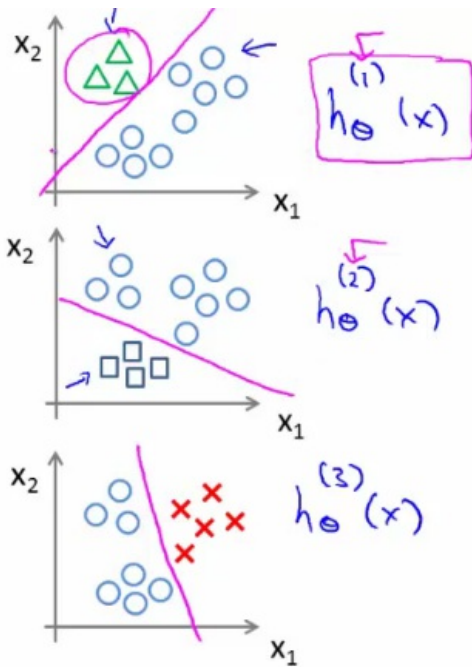
Binary classification:



Multi-class classification:



- Given a dataset with three classes, how do we get a learning algorithm to work?
 - Use one vs. all classification make binary classification work for multiclass classification
- **One vs. all classification**
 - Split the training set into three separate binary classification problems
 - i.e. create a new fake training set
 - Triangle (1) vs crosses and squares (0) $h_0^1(x)$
 - $P(y=1 | x_1; \theta)$
 - Crosses (1) vs triangle and square (0) $h_0^2(x)$
 - $P(y=1 | x_2; \theta)$
 - Square (1) vs crosses and square (0) $h_0^3(x)$
 - $P(y=1 | x_3; \theta)$



- **Overall**

- Train a logistic regression classifier $h_{\theta}^{(i)}(x)$ for each class i to predict the probability that $y = i$
- On a new input, x to make a prediction, pick the class i that maximizes the probability that $h_{\theta}^{(i)}(x) = 1$