Introduction to Support Vector Machines

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Outline

- Purpose and Intuition
- Separating Hyperplanes and the Maximal Margin Classifier
- Support Vector Classifiers
- Support Vector Machines with 2 classes

Purpose and Intuition

- Classification technique used for separating observations into one of two classes
  - This can be extended to K > 2 classes using One-vs-One or One-vs-All classification
- Construct a decision boundary that divides the predictor space into two halves

Hyperplanes - Definition

- **Definition:**
  - A **hyperplane** of a p-dimensional space is a flat subset with dimension p-1
  - For a 2-dimensional space, a **hyperplane** will just be a line; in 3 dimensions we have a 2-dimensional plane
- More formally:
  - Let $\beta \neq 0$ be a vector in $\mathbb{R}^n$ and let $a \in \mathbb{R}$
  - A **hyperplane** H is then defined as the set:

$$H = \{x \in \mathbb{R}^n \mid \beta \cdot x = a\}$$

Hyperplanes - Definition

- A hyperplane in $\mathbb{R}^2$ can be described with the following equation:

$$\beta_0 + \beta_1 X_1 + \beta_2 X_2 = 0$$

- We say that two sets D and E in $\mathbb{R}^2$ are **separated** by the hyperplane H if we have

$$\beta_0 + \beta_1 X_1 + \beta_2 X_2 \geq 0 \;\; \forall \;\; d \in D \beta_0 + \beta_1 X_1 + \beta_2 X_2 \leq 0 \;\; \forall \;\; e \in E$$

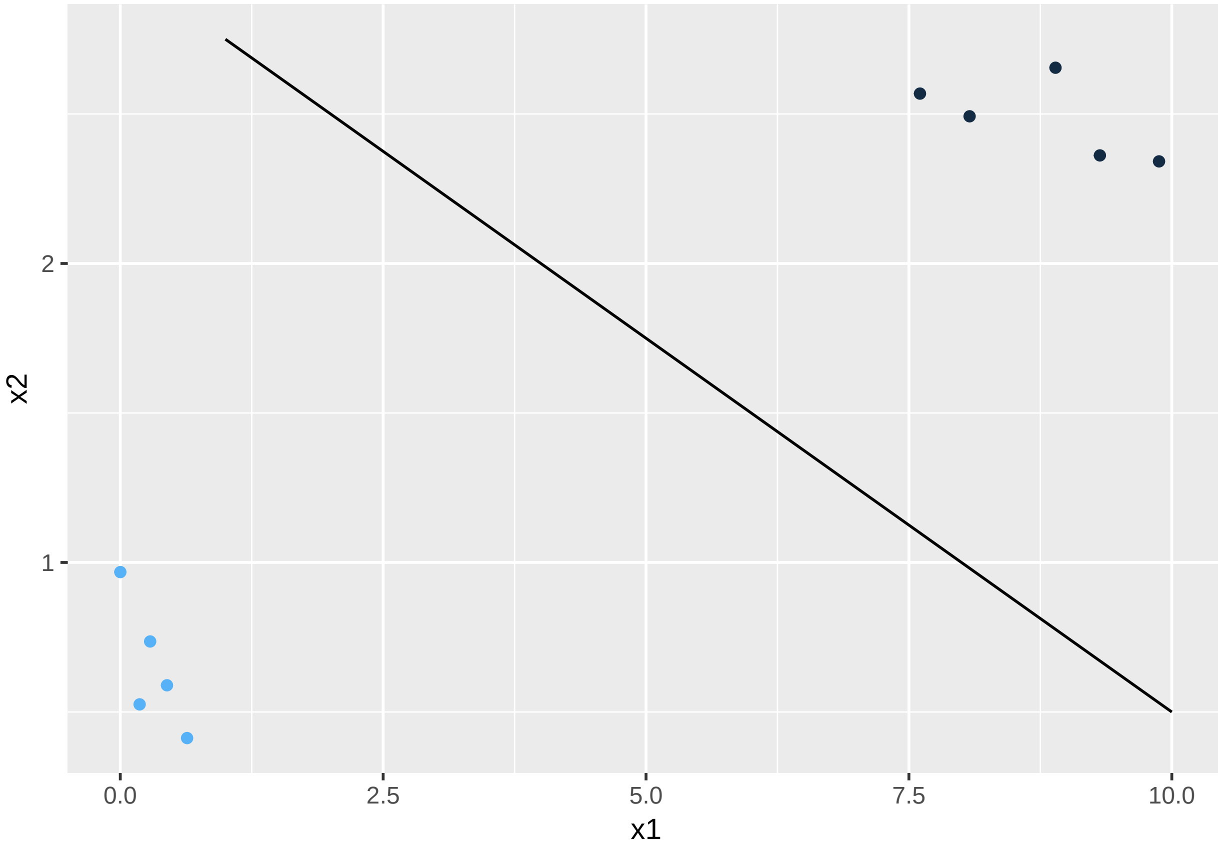
Hyperplanes - Separation

$$\beta_0 + \beta_1 X_1 + \beta_2 X_2 < 0 \quad [1] \beta_0 + \beta_1 X_1 + \beta_2 X_2 = 0 \quad [2] \beta_0 + \beta_1 X_1 + \beta_2 X_2 > 0 \quad [3]$$

- When we have an observation $x = (x_1, x_2)$ that satisfies the first or third equation, we can get an idea of what side of the hyperplane it lies on
- If we have [2] then x is simply a point on the hyperplane

Hyperplanes - Example

- The hyperplane $-3 + \frac{1}{4}X_1 + X_2 = 0$. The set of points (x_1, x_2) for which this equation is greater than 0 are colored black, where those less than 0 are colored blue



The Maximal Margin Classifier

- Usually if we can define one hyperplane that separates our data, we can define many
- An intuitive choice for the *best* hyperplane is the one that is furthest from our training observations
  - Think of it as being the boundary that creates the most distance between the two groups

The Maximal Margin Classifier

- For each hyperplane, we can find the distance to the closest observation
  - This is known as the **margin**
  - The points that are closest to each side of the hyperplane are called **support vectors**
- Hence, the **maximal margin classifier** will be the hyperplane for which the margin is the largest

The Maximal Margin Classifier

- Can lead to overfitting in high-dimensional cases
- Usually unrealistic to assume that data is linearly separable

- Even if it is, the margin might be small and sensitive to new observations

- Need to come up with less rigid solution to the classification problem

Support Vector Classifiers

- Support Vector Classifiers loosen the requirement that all training observations lie on the correct side of a separating hyperplane
- We allow some observations to be misclassified for two reasons:
  - Allow our model to be more robust to individual observations (overfitting)
  - "Widen" our margin to allow for better classification on testing sets
- For these reasons Support Vector Classifiers are also known as *Soft Margin Classifiers*

Support Vector Classifiers - Setup

- $i = 1, ..., n$ observations in the training set
- $j = 1, ..., p$ predictors
- $y_i \in \{-1, 1\}$ classes
- Our hyperplane will be defined as:

$$\beta_0 + \beta_1 X_1 + ... + \beta_p X_p = 0$$

Support Vector Classifiers - Setup

- A support vector classifier can then be described as the solution to the optimization problem:

$$\begin{array}{lrl} \max\limits_{\beta,\epsilon} & M & \\ \text{s.t.} & \sum_{j=1}^{p} \beta_j^2 = 1, & \\ & y_i(\beta_0 + \beta_1 x_{i1} + ... + \beta_p x_{ip}) \geq & M(1-\epsilon_i) \\ & \epsilon_i \geq 0, \forall i \in 1, ..., n & \\ & \sum_{i=1}^{n} \epsilon_i \leq C & \end{array}$$

Support Vector Classifiers - Setup

- M is the **margin** and is a positive number
- $\sum_{j=1}^{p} \beta_j^2 = 1$ constrains the size of each β_j
- $y_i(\beta_0 + \beta_1 x_{i1} + ... + \beta_p x_{ip}) \geq M(1-\epsilon_i)$ ensures that each observation will fall on the correct side of the hyperplane, except for maybe a couple
  - Note that a hyperplane $a_o + a_1 x_1 + a_2 x_2 = 0$ is still a hyperplane when it is multiplied by a scalar $y(a_0 + a_1 x_1 + a_2 x_2) = 0$
  - Also recall that y_i is either 1 or -1; y_i will give us an indication of which side of the hyperplane the observation is (above or below)

Support Vector Classifiers - Setup

- Think of all the ϵ_i as individual tolerances to violations of the hyperplane
  - When $\epsilon_i < 1$, the observation will be within the margin (but still classified correctly)

  - In the case of $\epsilon_i > 1$, our observation will be misclassified
  - $\epsilon_i = 0$ implies that the observation is at least M distance away from the margin

Support Vector Classifiers - Setup

- In total, we choose to only allow C amount of error
- $C = 0$ implies that there is no tolerance at all, which is equivalent to the maximal margin classifier problem
- Larger and larger values of C increase the margin, allowing for less accuracy but lower variance
- C can be tuned using cross-validation

Support Vector Classifiers - Example

```r
# Set up toy data to work with
set.seed(1)
dat <- tibble(
  x1 = rnorm(500),
  x2 = rnorm(500),
  y = factor(c(rep('A',250), (rep('B',250))))       # Y is a factor
)

# Add a little of separability between the classes
dat$x1[dat$y == "A"] <-  dat$x1[dat$y == "A"] + 4
```

Support Vector Classifiers - Example

Support Vector Classifiers - Example

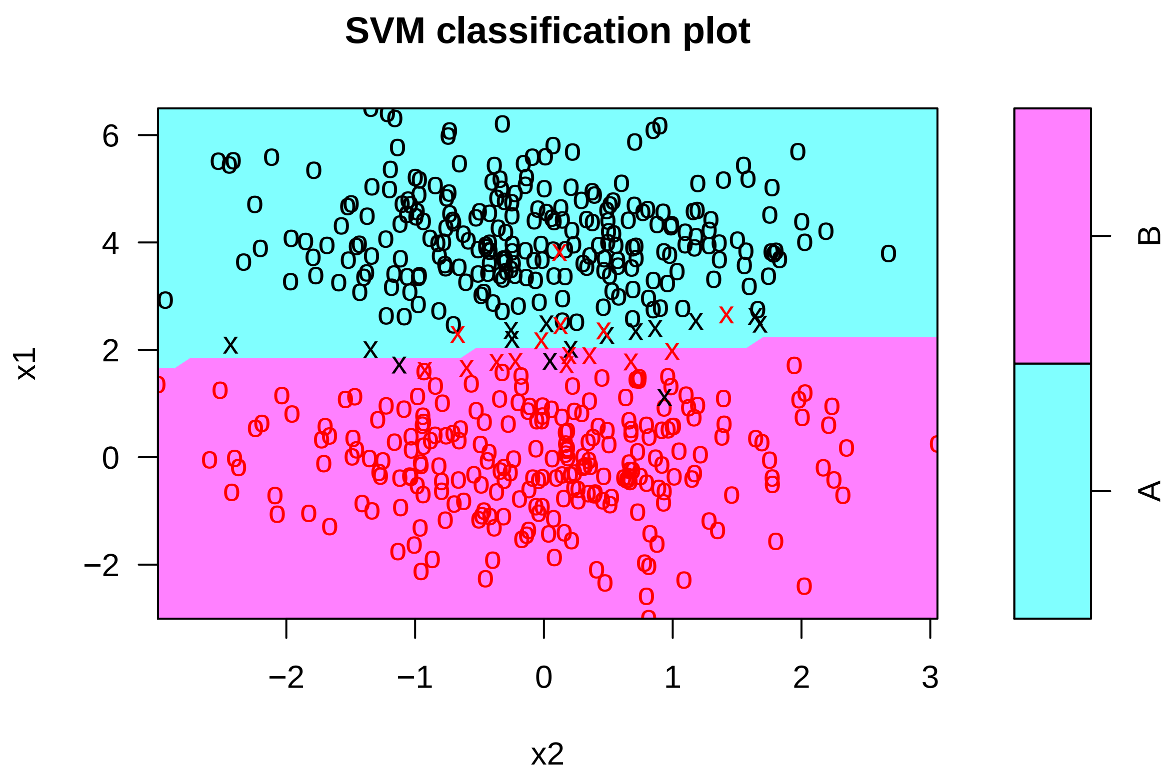
```
library("e1071")
svc <- svm(y ~ ., data = dat, kernel = 'linear',
           cost = 10, scale = FALSE)
```

Support Vector Classifiers - Example

```
##
## Call:
## svm(formula = y ~ ., data = dat, kernel = "linear", cost = 10,
##     scale = FALSE)
##
##
## Parameters:
##    SVM-Type:  C-classification
##  SVM-Kernel:  linear
##        cost:  10
##       gamma:  0.5
##
## Number of Support Vectors:  30
```

```
##
##  ( 15 15 )
##
##
## Number of Classes:  2
##
## Levels:
##  A B
```

Support Vector Classifiers - Example



Support Vector Classifiers - Tuning

- How do we decide on a value for our cost parameter C?
- `e1071::tune()` allows us to specify a range of values that it will test using 10-fold cross-validation

```
svc_cv <-  tune(svm,y ~., data = dat, kernel = 'linear',
                ranges = list(
                  cost = c(.001, .01, .1, 1, 5, 10, 100)))
```

Support Vector Classifiers - Tuning

- Extract the best performing model by grabbing the `best.model` component of `svc_cv`

```r
best_model <-  svc_cv$best.model
best_model
```

```
##
## Call:
## best.tune(method = svm, train.x = y ~ ., data = dat, ranges = list(cost = c(0.001,
##     0.01, 0.1, 1, 5, 10, 100)), kernel = "linear")
##
##
## Parameters:
##    SVM-Type:  C-classification
##  SVM-Kernel:  linear
##        cost:  0.01
##       gamma:  0.5
##
## Number of Support Vectors:  232
```

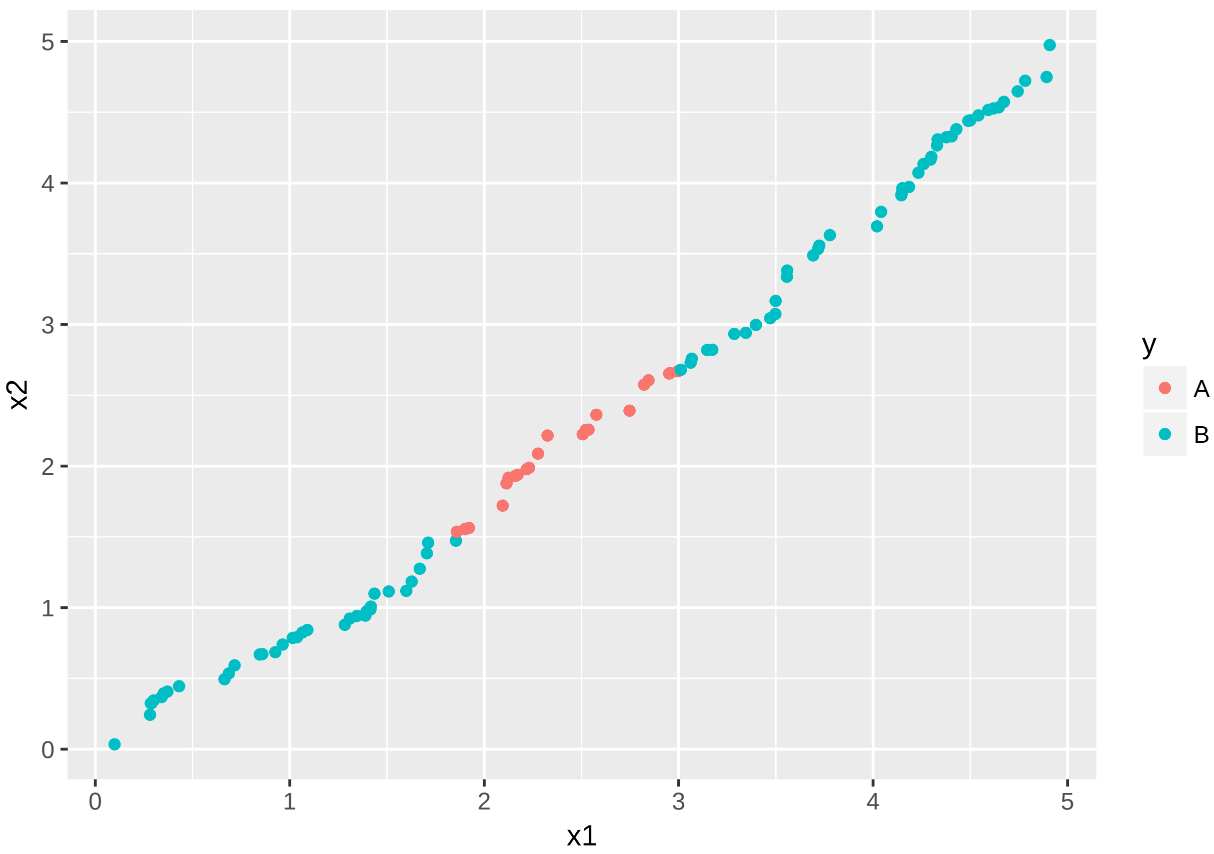
Support Vector Classifiers - Prediction

```r
predictions <- predict(best_model, test)
table(predictions, truth = test$y)
```

```
##            truth
## predictions   A   B
##           A 243   5
##           B   7 245
```

Non-linear Boundaries

What happens when we can't separate our data with a linear boundary?



Non-linear Boundaries

- Enlarge our feature space using functions of the predictors
    - $X \mapsto \phi(X)$
- Before we fit the SVC with p predictors:

$$X_1, X_2, ..., X_p$$

- We could have fit the SVC with any amount of predictors to allow our boundary to deal with the non-linearity:

$$X_1, X_2, ..., X_p, X_1^2, X_2^2, ..., X_p^2$$

Non-linear Boundaries - Example

Groups **A** and **B** can't be separated with one boundary, but what if put this line into a 2-dimensional space?

Non-linear Boundaries - Computation

- The optimization problem described earlier is computed using the *inner products* of the support vectors
    - *inner products* can be thought as a measure of similarity between two observations
    - The inner product between two points x_1, x_2 is denoted $\langle x_1, x_2 \rangle$

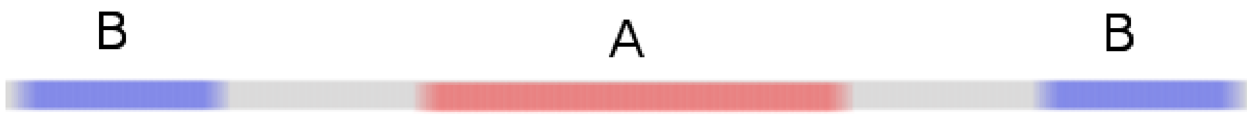


Figure 1:

Non-linear Boundaries - Computation

- Transforming our feature space $X \mapsto \phi(X)$ could potentially make the computation much more difficult
  - instead of $\langle x_1, x_2 \rangle$ we have $\langle \phi(x_1), \phi(x_2) \rangle$
  - could be super time consuming depending on ϕ
- We can simplify this computation by knowing the **kernel function**

Non-linear Boundaries - Kernels

- **Kernels** generalize inner products by allowing us to use different metrics of similarity
- SVCs have linear kernels
- A **kernel function** is usually written:
$$K(x_1, x_2)$$
- **Support Vector Machines** transform the feature space using kernels

Support Vector Machines - Kernels

- A **support vector machine** is a combination of a support vector classifier with a non-linear kernel
- There are 3 very popular kernels:

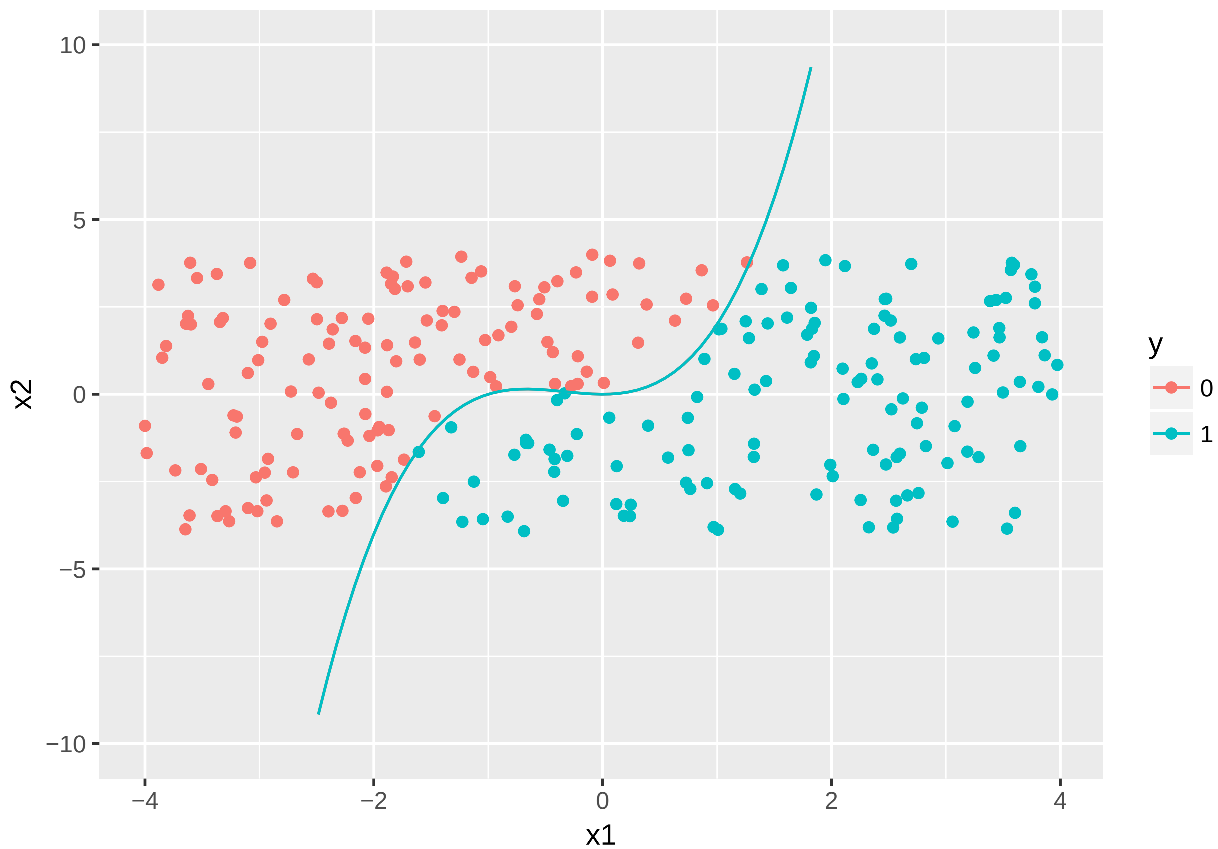
$$K(x_1, x_2) = (1+\sum_{j=1}^{p} x_{1j}x_{2j})^d \quad [1] K(x_1, x_2) = exp(-\gamma \sum_{j=1}^{p} (x_{1j}-x_{2j})^2) \quad [2] K(x_1, x_2) = tanh(\gamma \sum_{j=1}^{p} x_{1j}x_{2j}+\delta) \quad [3]$$

Support Vector Machines - Kernels

- [1] is called a *polynomial kernel* of degree d
- [2] is the *radial basis function* and is very good at describing points close to a training observation
- [3] is the *hyperbolic tangent* function

Support Vector Machines - Example

- We use an artificial data set made to work well with a polynomial kernel

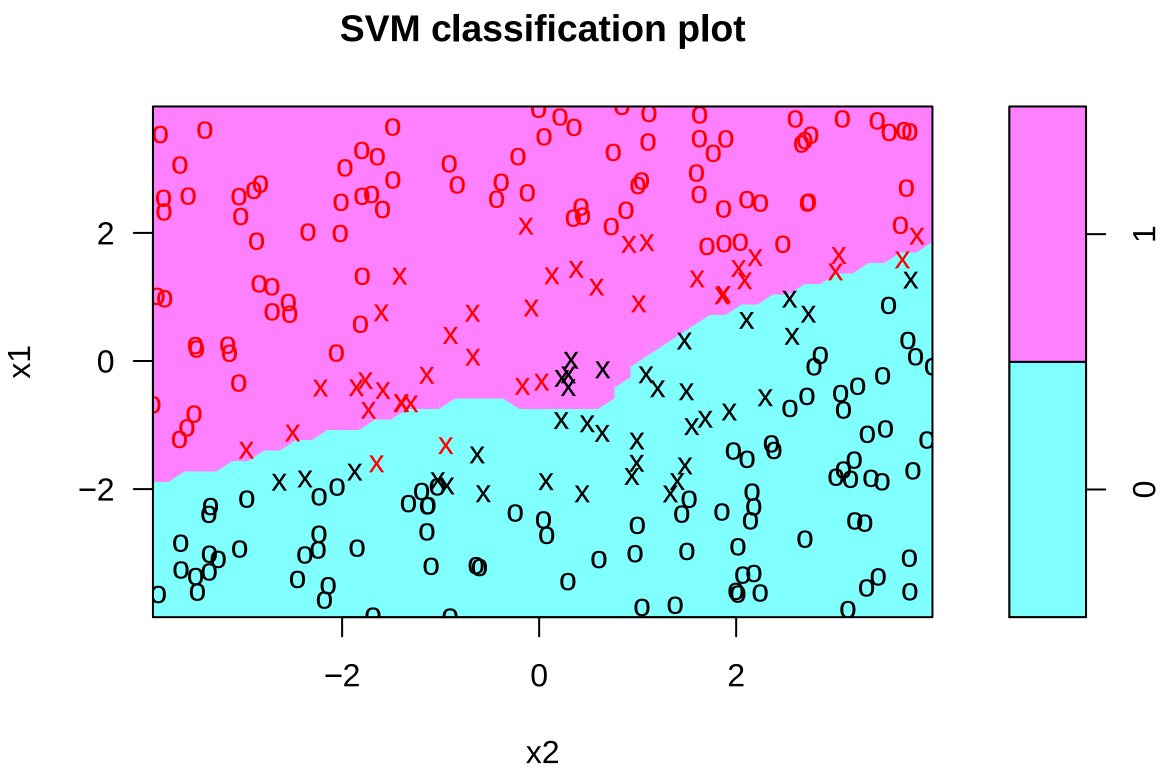


Support Vector Machines - Example

- SVM with a polynomial kernel of degree 3

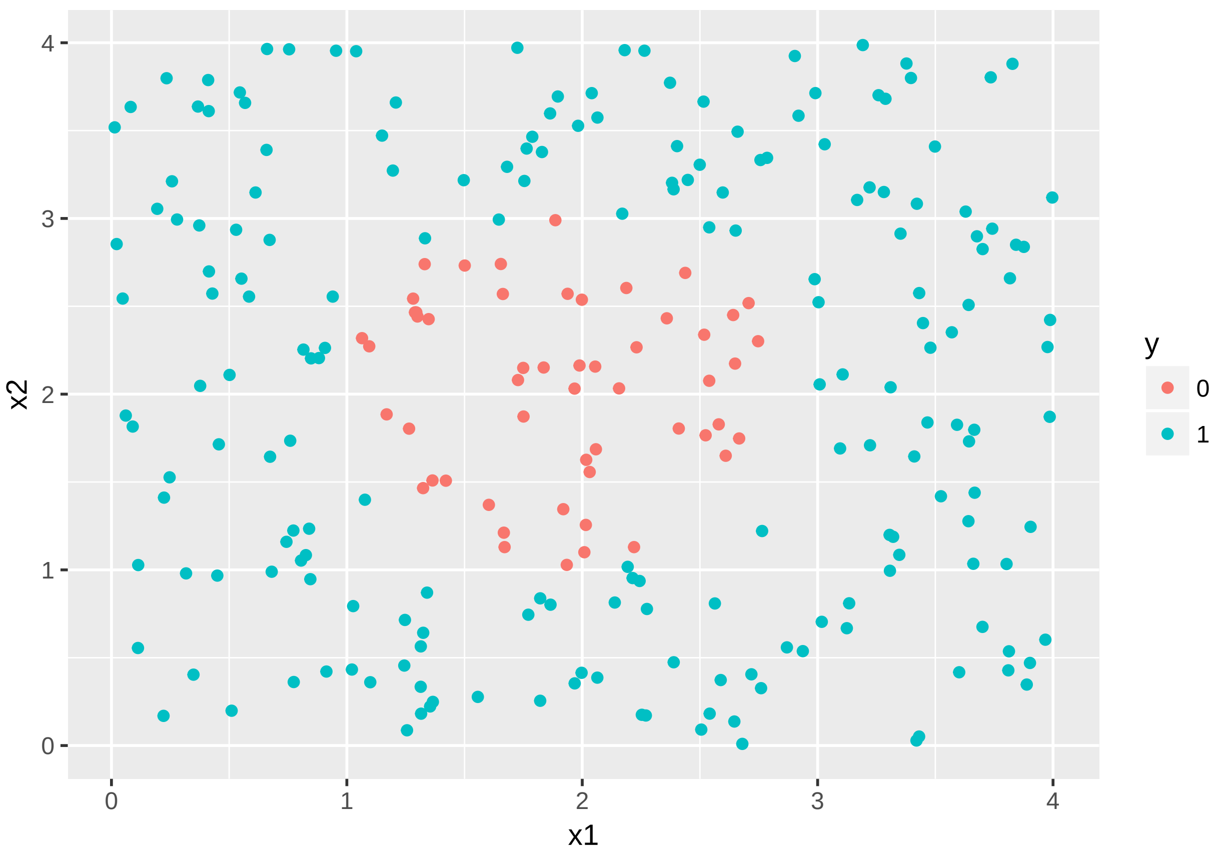
```
svm_poly <-  svm(y ~., data = poly_dt, kernel = "polynomial")
```

Support Vector Machines - Example



Support Vector Machines - Example

- New data to predict:

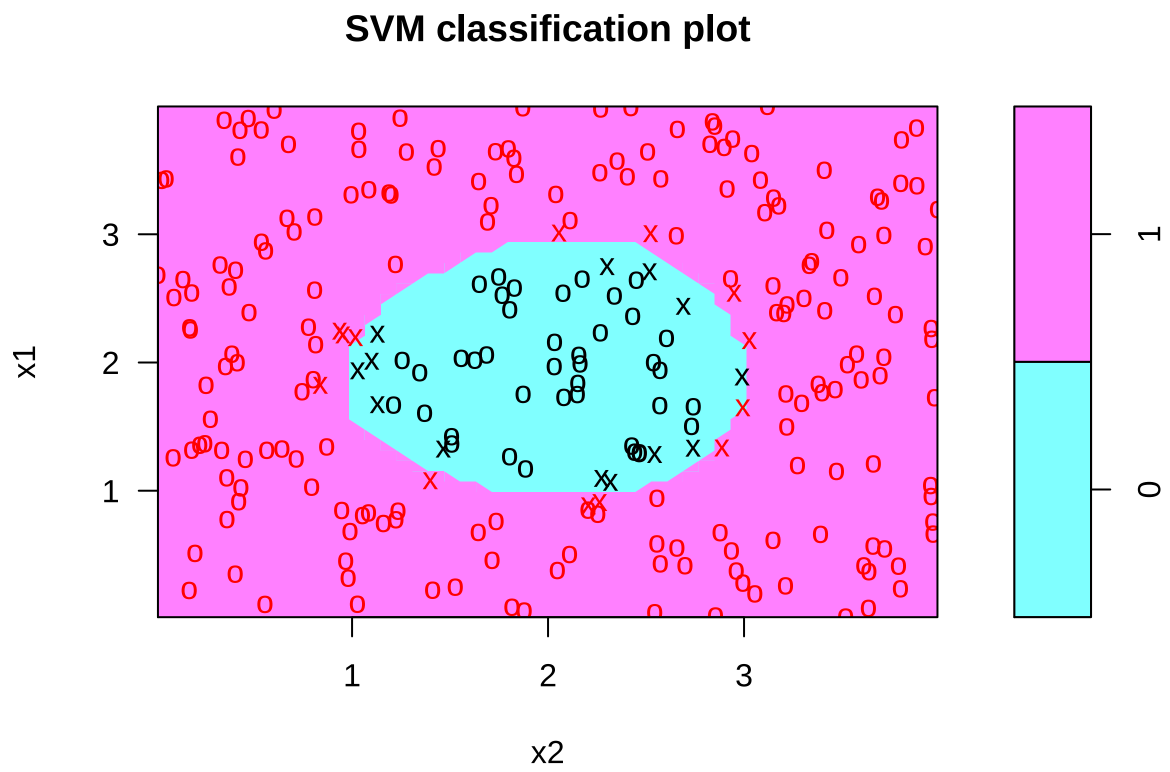


Support Vector Machines - Example

- SVM with radial kernel

```
svm_rad <-  svm(y ~ ., data = rad_dt, kernel = "radial",
                cost = 10)
```

Support Vector Machines - Example



Support Vector Machines - Tuning

- These non-linear kernel functions have new parameters that you have to choose yourself
  - Let CV do it for you!

```
tune(svm, y ~ ., data = train, kernel = 'radial',
                ranges = list(cost = c(.1, 1, 10, 100, 1000),
                              gamma = c(.5, 1, 2, 3, 4)))
```

Support Vector Machines - Evaluating

- Basic Workflow:
  - Define training and testing sets
  - Decide on a model (predictors, kernel, classes)
  - Use cross-validation to find hyperparameters with best training results (optional)
  - Evaluate best model using test set (ROC Curves, Classification Error, etc.)