

3 LDA "linear discriminant analysis"

Logistic regression involves ^{directly} ~~direction~~ modeling $P(Y = k|X = x)$ using the logistic function for the case of two response classes. We now consider a less direct approach.

Idea:

$P(X=x|Y=y)$: Model the distribution of the predictors X separately in each of the response classes \hookrightarrow (given Y) and then use Bayes theorem to flip these and get estimates for $P(Y=k|X=x)$

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Why do we need another method when we have logistic regression?

1. When classes are well-separated, the parameter estimates for logistic regression are surprisingly unstable.
2. If n is small and the distribution of predictors is approximately normal in each class, LDA is more stable than logistic regression.
3. We might have more than 2 response classes.

3.1 Bayes' Theorem for Classification

Suppose we wish to classify an observation into one of K classes, where $K \geq 2$.

Categorical Y can take on K possible distinct and unordered values.

π_k - overall or "prior" probability that a randomly chosen observation comes from the k^{th} class.

$$f_k(x) = P(X=x | Y=k) \text{ (discrete)}$$

probability that X takes value x given Y of class k .

density function of X for an observation that comes from class k .

probability that X falls in a small region around x given $Y=k$.

$$P(Y = k | X = x) = \frac{f_k(x) \pi_k}{\sum_{l=1}^K \pi_l f_l(x)} \quad (\text{Bayes Theorem})$$

$$\frac{P(A)P(B|A)}{P(A)P(B|A) + P(B)P(A|B)}$$

We will use the abbreviation $p_k(x)$ as before.

> Called the "posterior probability" that an observation comes from k^{th} class given $X=x$.

In general, estimating π_k is easy if we have a random sample of Y 's from the population.

Compute the fraction of training observations that come from the k^{th} class.

Estimating $f_k(x)$ is more difficult unless we assume some particular forms.

If we can estimate $f_k(x)$ we can develop a classifier that is close to the "best" classifier (more later).

3.2 p = 1

Let's (for now) assume we only have 1 predictor. We would like to obtain an estimate for $f_k(x)$ that we can plug into our formula to estimate $p_k(x)$. We will then classify an observation to the class for which $\hat{p}_k(x)$ is greatest.

assign to class w/ $P_k(x)$ highest is called the "Bayes classifier" and is known to be the optimal solution, i.e. we can do no better!

Suppose we assume that $f_k(x)$ is normal. In the one-dimensional setting, the normal density takes the form

$$f_k(x) = \frac{1}{\sqrt{2\pi}\sigma_k} \exp\left[-\frac{1}{2\sigma_k^2}(x-\mu_k)^2\right]$$

σ_k^2 and μ_k variance and mean parameters for k^{th} class.

Let's also (for now) assume $\sigma_1^2 = \dots = \sigma_K^2 = \sigma^2$ (shared variance term).

Plugging this into our formula to estimate $p_k(x)$,

$$p_k(x) = \frac{\pi_k \frac{1}{\sqrt{2\pi}\sigma^2} \exp\left[-\frac{1}{2\sigma^2}(x-\mu_k)^2\right]}{\sum_{l=1}^K \pi_l \frac{1}{\sqrt{2\pi}\sigma^2} \exp\left[-\frac{1}{2\sigma^2}(x-\mu_l)^2\right]}$$

↑ prior probability that an observation falls into l^{th} class.

We then assign an observation $X = x$ to the class which makes $p_k(x)$ the largest. This is equivalent to

(log and rearrange)

assign obs. to class for which

$$\delta_k(x) = x \frac{\mu_k}{\sigma^2} - \frac{\mu_k^2}{2\sigma^2} + \log(\pi_k).$$

is largest.

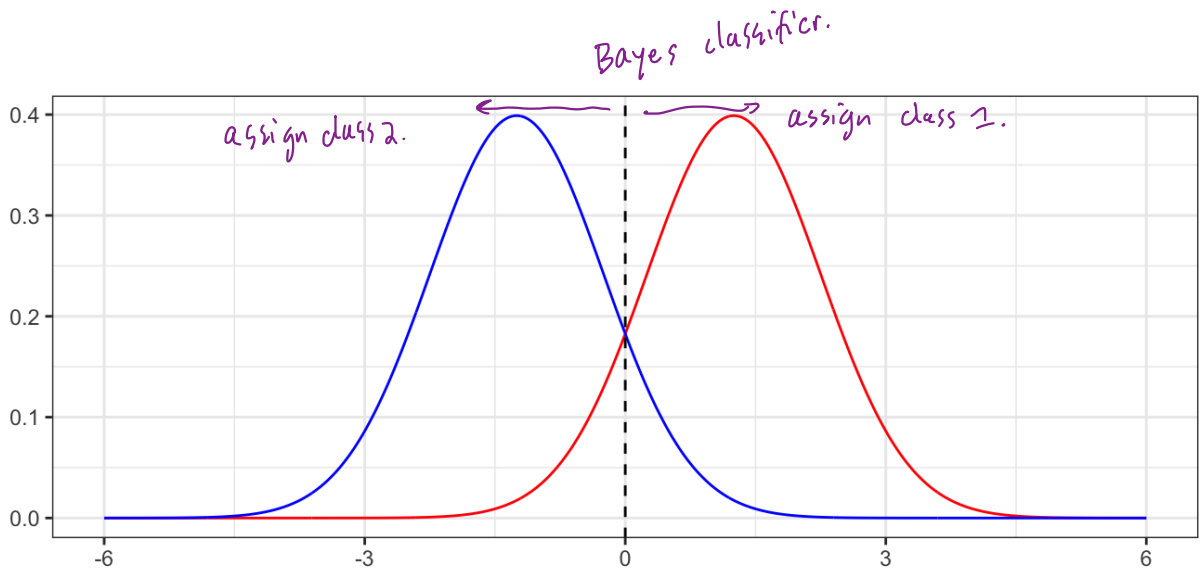
Example 3.1 Let $K = 2$ and $\pi_1 = \pi_2$. When does the Bayes classifier assign an observation to class 1?

When $\delta_1(x) > \delta_2(x)$?

$$\Leftrightarrow x \frac{\mu_1}{\sigma^2} - \frac{\mu_1^2}{2\sigma^2} + \log(\pi_1) > x \frac{\mu_2}{\sigma^2} - \frac{\mu_2^2}{2\sigma^2} + \log(\pi_2)$$

$$\Leftrightarrow 2x(\mu_1 - \mu_2) > \mu_1^2 - \mu_2^2$$

$$\Leftrightarrow x > \frac{\mu_1 + \mu_2}{2} \text{ decision boundary}$$



example where $\pi_1 = \pi_2 = 0.5$

$$\left. \begin{array}{l} \mu_2 = -1.25 \\ \mu_1 = 1.25 \\ \sigma = 1 \end{array} \right\} \text{decision boundary at } 0$$

In this case, we know

$$f_k(x) \sim N(\mu_k, \sigma^2).$$

\Rightarrow We can create the Bayes classifier!

In practice, even if we are certain of our assumption that X is drawn from a Gaussian distribution within each class, we still have to estimate the parameters

$\mu_1, \dots, \mu_K, \pi_1, \dots, \pi_K, \sigma^2$. to estimate Bayes classifier!

The linear discriminant analysis (LDA) method approximated the Bayes classifier by plugging estimates in for π_k, μ_k, σ^2 .

$$\hat{\mu}_k = \frac{1}{n_k} \sum_{i: y_i=k} x_i \quad \leftarrow \text{average of training observations in class } k.$$

$$\hat{\sigma}^2 = \frac{1}{n-K} \sum_{k=1}^K \sum_{i: y_i=k} (x_i - \hat{\mu}_k)^2 \quad \leftarrow \text{weighted average of class variances.}$$

n = total # training obs

n_k = # training obs. in class k

Sometimes we have knowledge of class membership probabilities π_1, \dots, π_K that can be used directly. If we do not, LDA estimates π_k using the proportion of training observations that belong to the k th class.

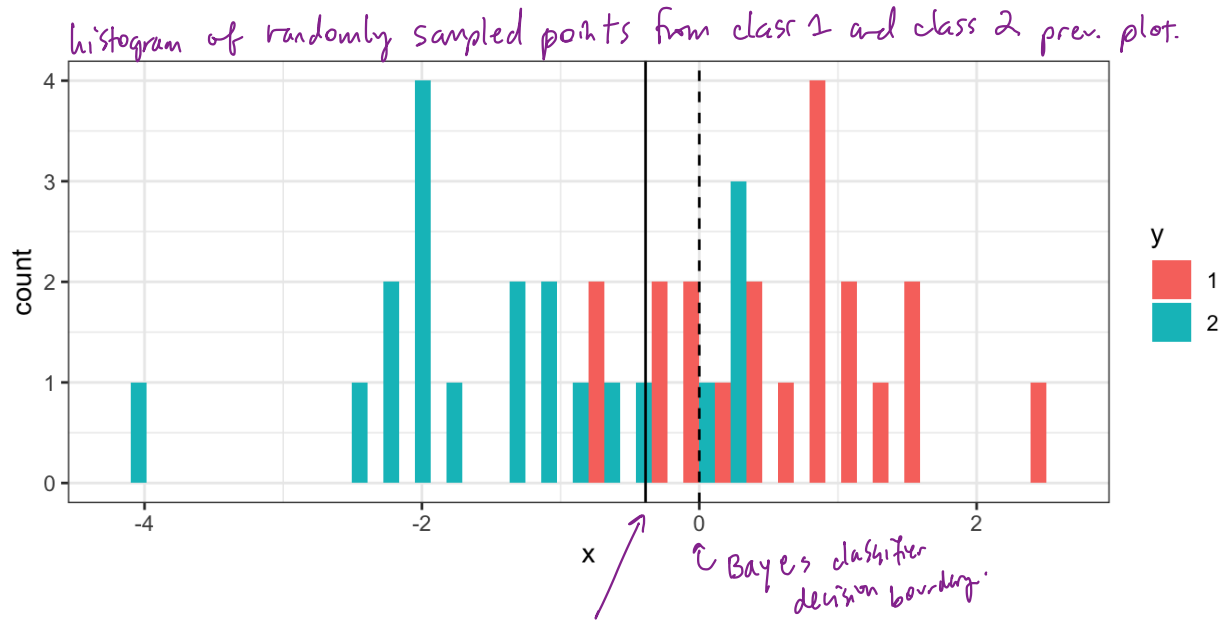
$$\hat{\pi}_k = \frac{n_k}{n}$$

The LDA classifier assigns an observation $X = x$ to the class with the highest value of

$$\hat{\delta}_k(x) = x \frac{\hat{\mu}_k}{\hat{\sigma}^2} - \frac{\hat{\mu}_k^2}{2\hat{\sigma}^2} + \log(\hat{\pi}_k).$$

\nearrow from "science" or from the problem.

$n_1 = n_2 = 20$



LDA decision boundary (based on data). $\frac{\hat{\mu}_1 + \hat{\mu}_2}{2}$

Bayes classifier decision boundary.

“Confusion matrix” on many many simulated test points (20k from each class).

##	pred	1	2
## y			
##	1	18966	1034
##	2	3855	16145

predicted values
 true values
 got wrong
 got right

The LDA test error rate is approximately 12.22% while the Bayes classifier error rate is approximately 10.52%.

The Bayes error rate is the best we can possibly do with this problem! (we can only estimate it because this is a simulated example).

The LDA approach did almost as well!

The LDA classifier results from assuming that the observations within each class come from a normal distribution with a class-specific mean vector and a common variance σ^2 and plugging estimates for these parameters into the Bayes classifier.

We will relax this assumption later.

3.3 $p > 1$

We now extend the LDA classifier to the case of multiple predictors. We will assume

$X = (X_1, \dots, X_p)$ drawn from multivariate Gaussian dsn w/ class specific mean vector & common covariance matrix.
 \rightarrow Each component follows a Normal dsn and same covariance between components.

$p \times 1$ vector \downarrow $p \times p$ matrix

$$X|Y=k \sim N_p(\underline{\mu}_k, \Sigma)$$

$$E[X|Y=k] = \mu_k$$

$$\text{Cov}[X|Y=k] = \Sigma$$

Formally the multivariate Gaussian density is defined as

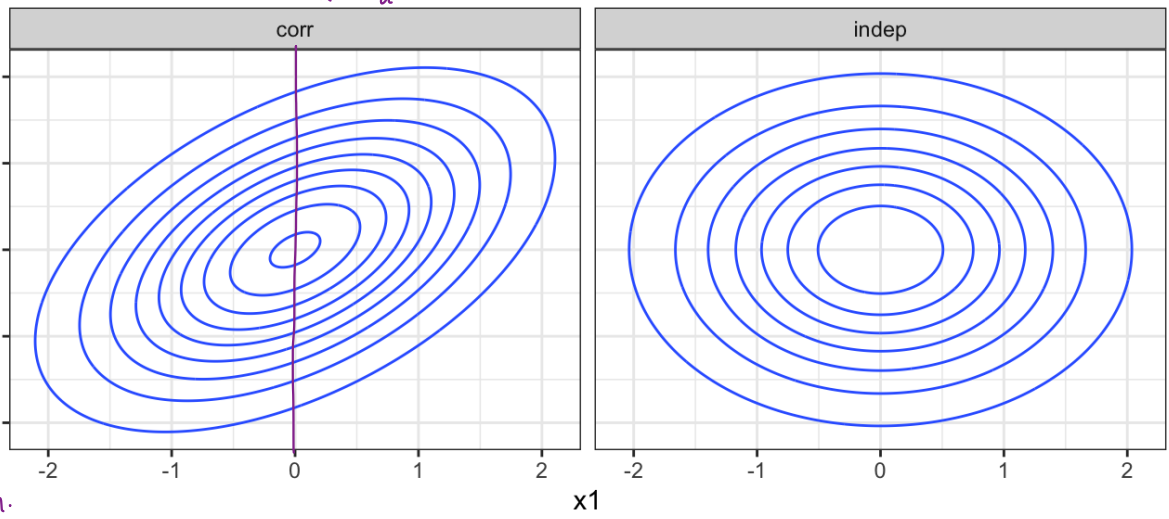
$$f_k(\underline{x}) = \left[\frac{1}{(2\pi)^{p/2} |\Sigma|^{1/2}} \right] \exp \left(-\frac{1}{2} (\underline{x} - \mu_k)^T \Sigma^{-1} (\underline{x} - \mu_k) \right)$$

transpose matrix inverse \rightarrow
 "trace" \rightarrow = sum of diagonal elements of Σ .

if we sliced across the dsn \Rightarrow Normal

$\text{Cov}(X_1, X_2) = \frac{1}{2}$
 results in more oval shape

If we morpholize out X_1 or X_2 we get Normal dsn.



independence \Rightarrow
 $\text{Cov}(X_1, X_2) = 0$
 results in round/oval shape.

$p=2$ Gaussian density w/ $\mu = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ and 2 Σ_s .

In the case of $p > 1$ predictors, the LDA classifier assumes the observations in the k th class are drawn from a multivariate Gaussian distribution $N(\mu_k, \Sigma)$.
Common variance.

Plugging in the density function for the k th class, results in a Bayes classifier
↑ class specific mean vector

assign an observation $X=x$ to the class which maximizes

$$\delta_k(x) = x^T \Sigma^{-1} \mu_k - \frac{1}{2} \mu_k^T \Sigma^{-1} \mu_k + \log \pi_k$$

↑

this decision rule is linear in x . (hence the name LDA).

Once again, we need to estimate the unknown parameters $\mu_1, \dots, \mu_K, \pi_1, \dots, \pi_K, \Sigma$.

use similar formulas as $p=1$ case.

To classify a new value $X = x$, LDA plugs in estimates into $\delta_k(x)$ and chooses the class which maximized this value.

⇒ get $\hat{\delta}_k(x)$ choose class k maximizes this quantity

Let's perform LDA on the `Default` data set to predict if an individual will default on their CC payment based on balance and student status.

(i.e. estimating Bayes classifier)

```
library(MASS) # package containing lda function
lda_fit <- lda(default ~ student + balance, data = Default)
lda_fit
```

specify formula just like `lm` & `glm`.

```
## Call:
## lda(default ~ student + balance, data = Default)
##
## Prior probabilities of groups:
##      No      Yes
## 0.9667 0.0333
##
## Group means:
##      studentYes  balance
## No      0.2914037 803.9438
## Yes     0.3813814 1747.8217
##
## Coefficients of linear discriminants:
##                      LD1
## studentYes -0.249059498
## balance    0.002244397
```

← estimates of π_k based on class membership in training data

average of each predictor within each class

used to estimate μ_k

linear combinations of student & balance used to form the LDA decision boundary.

```
# training data confusion matrix
table(predict(lda_fit)$class, Default$default)
```

training or test data y value.

get LDA predictions of either training or test data

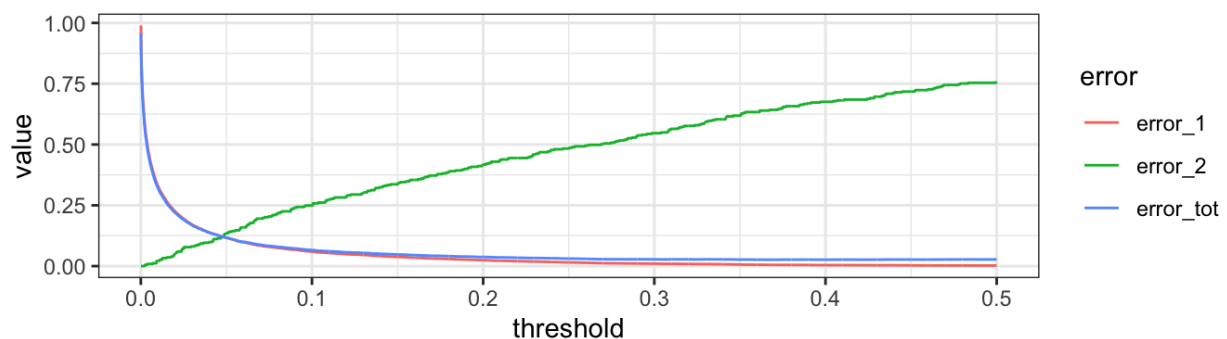
```
##          True
##          No  Yes
## Predicted No 9644 252
##           Yes  23  81
```

Compare predictions to actual values.

Why does the LDA classifier do such a poor job of classifying the customers who default?

```
table(predict(lda_fit)$posterior[, "Yes"] > 0.2, Default$default)
```

```
##          No  Yes
## FALSE 9432 138
## TRUE  235 195
```



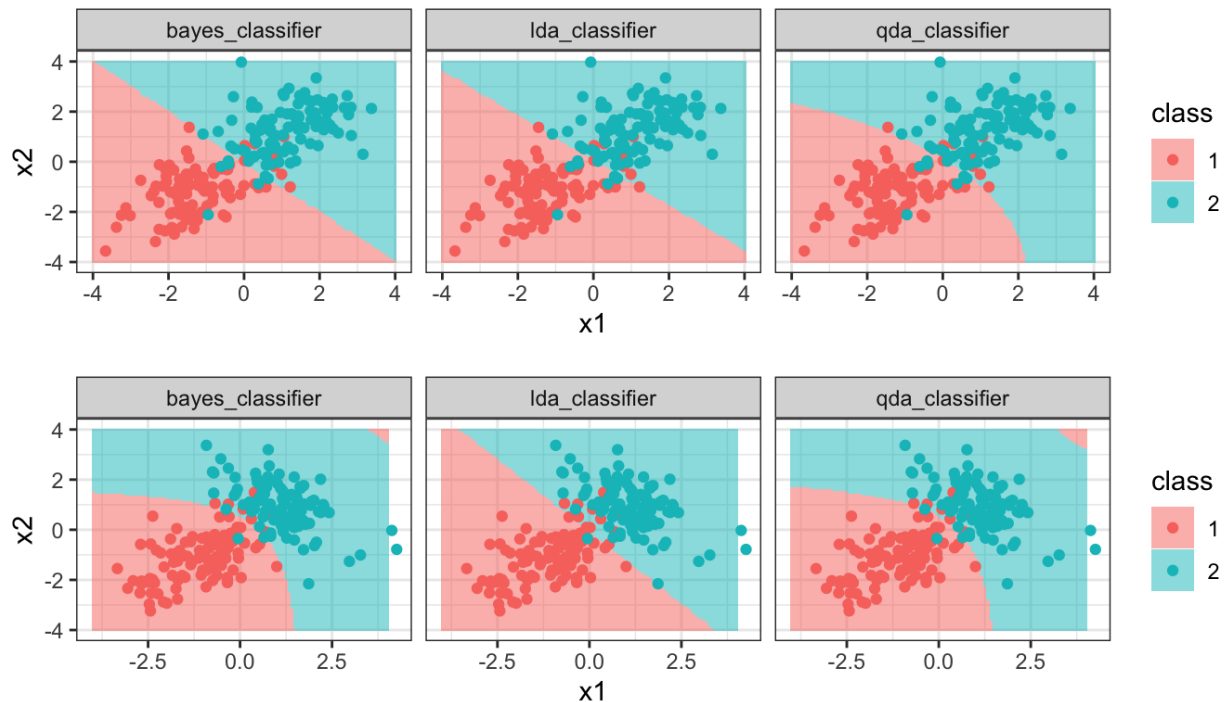
3.4 QDA

LDA assumes that the observations within each class are drawn from a multivariate Gaussian distribution with a class-specific mean vector and a common covariance matrix across all K classes.

Quadratic Discriminant Analysis (QDA) also assumes the observations within each class are drawn from a multivariate Gaussian distribution with a class-specific mean vector but now each class has its own covariance matrix.

Under this assumption, the Bayes classifier assigns observation $X = x$ to class k for whichever k maximizes

When would we prefer QDA over LDA?

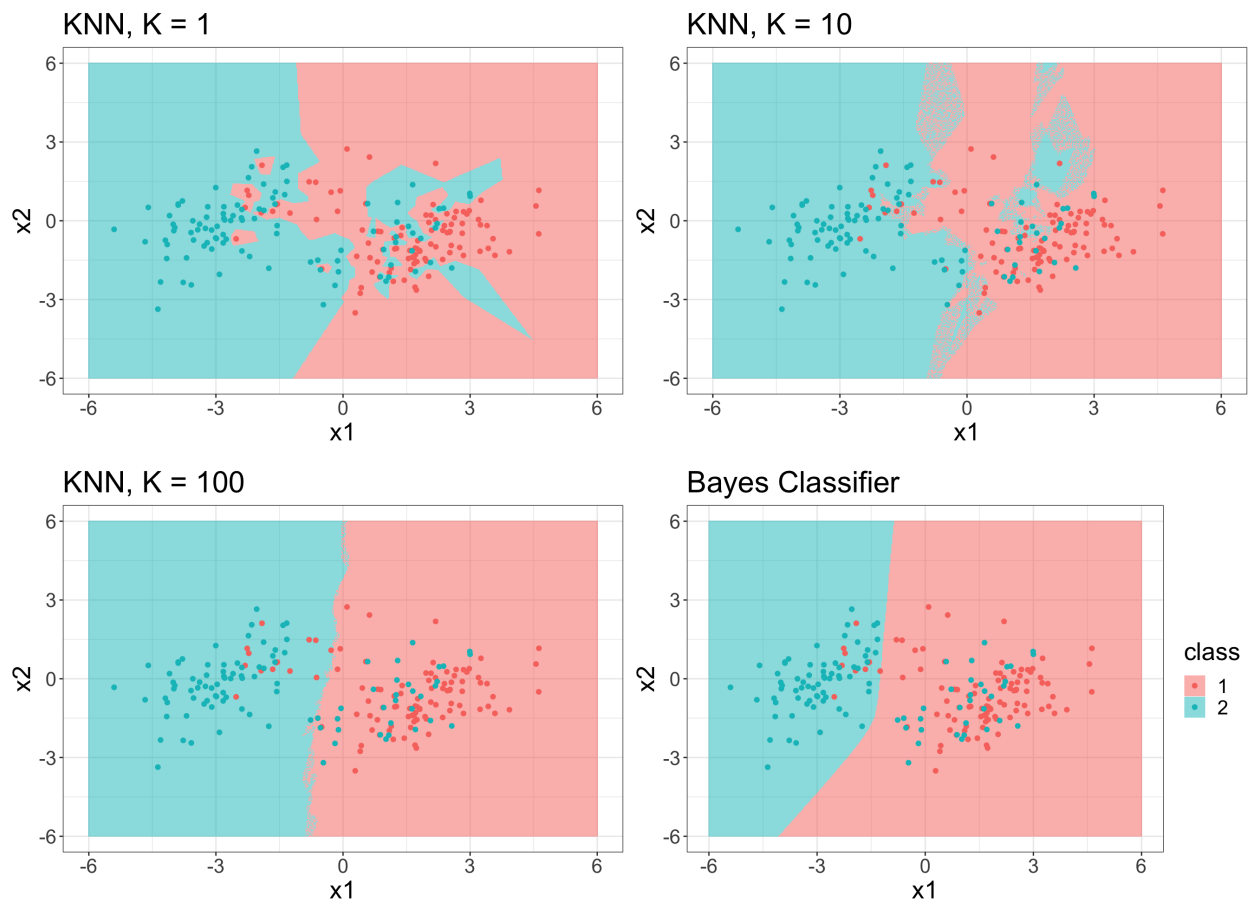


4 KNN

Another method we can use to estimate $P(Y = k|X = x)$ (and thus estimate the Bayes classifier) is through the use of K -nearest neighbors.

The KNN classifier first identifies the K points in the training data that are closest to the test data point $X = x$, called $\mathcal{N}(x)$.

Just as with regression tasks, the choice of K (neighborhood size) has a drastic effect on the KNN classifier obtained.



5 Comparison

LDA vs. Logistic Regression

(LDA & Logistic Regression) vs. KNN

QDA