

Elements of Statistical Learning, Solutions

Marios

Exercises for Section 2

1. Suppose each of K -classes has an associated target t_k , which is a vector of all zeros, except a one in the k th position. Show that classifying to the largest element of \hat{y} amounts to choosing the closest target, $\min_k \|t_k - \hat{y}\|$, if the elements of \hat{y} sum to one.

Solution. Let $k^* = \arg \max_k \hat{y}_k$ and suppose that there is $k' \leq k^*$ such that $\|t_{k'} - \hat{y}\| < \|t_{k^*} - \hat{y}\|$.

- ℓ_1 norm. It holds that $\|t_k - \hat{y}\|_1 = \sum_i |t_{k,i} - \hat{y}_i| = \sum_{i \neq k} |\hat{y}_i| + |1 - \hat{y}_k|$. Hence, we get

$$\sum_{i \neq k'} |\hat{y}_i| + |1 - \hat{y}_{k'}| < \sum_{i \neq k^*} |\hat{y}_i| + |1 - \hat{y}_{k^*}| \Rightarrow |\hat{y}_{k^*}| - |1 - \hat{y}_{k^*}| < |\hat{y}_{k'}| - |1 - \hat{y}_{k'}|. \quad (1)$$

But the function $f(y) = |y| - |1 - y|$ is increasing in $[0, 1]$ hence Equation (1) implies that $\hat{y}_{k^*} < \hat{y}_{k'}$, reaching a contradiction.

- ℓ_2 norm. Similarly, we get that $\hat{y}_{k^*}(1 - \hat{y}_{k^*}) < \hat{y}_{k'}(1 - \hat{y}_{k'})$ and since the function $f(y) = y(1 - y)$ is increasing in $[0, 1]$, we get that $\hat{y}_{k^*} < \hat{y}_{k'}$, reaching a contradiction.

2. Show how to compute the Bayes decision boundary for the simulation example in Figure 2.5.

Solution. If we know the exact probability distribution $\Pr[G, X]$, $X \in \mathbb{R}^p$, $G \in \mathcal{G} = \{B, O\}$, then we can probably also derive $f(X) = \Pr[B|X] = \Pr[B, X]/\Pr[X]$, namely the probability that X maps to blue in reality. This assume that we also know $\Pr[X]$ which is not necessary. Of course, $\Pr[O|X] = 1 - \Pr[B|X]$. So now, all we have to do is to check for each $x \in \mathbb{R}^p$, whether $f(x) > 1/2$. For the case where $x \in \mathbb{R}$, this is trivial. We simply solve the equation $f(x) = 1/2$. This also hold in general. So the points (in \mathbb{R}), the line (in \mathbb{R}^2), and the $(p - 1)$ -dimensional hyperplane (in \mathbb{R}^p), is the solution to the equation $f(x) = \Pr[B|X] = 1/2$. See Figure 2 for another example.

3. Derive equation 2.24. Consider N data points uniformly sampled in a p -dimensional unit ball centered at the origin. Show that the median distance from the origin to the closest data point is given by the expression

$$d(p, N) = \left(1 - \frac{1}{2^{1/N}}\right)^{1/p}.$$

Solution. We start with the cumulative distribution function (CDF) of the distance of a random point from the origin. The volume of a p -dimensional ball of radius d is $V_p(d) = c_p d^p$, where c_p is a value that does not depend on d . Therefore,

$$F_D(d) = \Pr[D \leq d] = \frac{V_p(d)}{V_p(1)} = d^p. \quad (\text{First trick to remember})$$

Now it is useful to compute the CDF of the distance of the closest point $C = \min_{i \in [N]} D_i$. We have

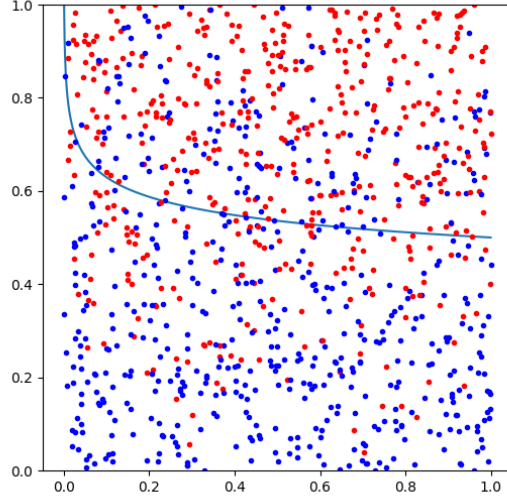


Figure 1: In this example we have computed the Bayes decision boundary when $X \sim U(0, 1)^2$ and $\Pr[Y = \text{red}|X] = X_1^{1/10}X_2$. Therefore, the line is the solution to the equation $X_1^{1/10}X_2 = 1/2$.

that

$$\begin{aligned}
 F_C(d) &= \Pr[C \leq d] \\
 &= 1 - \Pr[C \geq d] \\
 &= 1 - \Pr\left[\min_{i \in [N]} D_i \geq d\right] \\
 &= 1 - \Pr[\forall i \in [N], D_i \geq d] \\
 &= 1 - \prod_{i \in [N]} \Pr[D_i \geq d] \\
 &= 1 - \Pr[D \geq d]^N \\
 &= 1 - (1 - \Pr[D \leq d])^N \\
 &= 1 - (1 - d^p)^N.
 \end{aligned} \tag{2}$$

By definition, the median m is defined as $F_C(m) = 1/2$. Hence, we get that $(1 - m^p)^N = 1/2$ and solving for m , we get

$$m = \left(1 - \frac{1}{2}^{1/N}\right)^{1/p}.$$

4. Consider inputs drawn from a spherical multinormal distribution $X \sim N(0, \mathbf{I}_p)$. The squared distance from any sample point to the origin has a χ_p^2 distribution with mean p . Consider a prediction point x_0 drawn from this distribution, and let $a = x_0/\|x_0\|$ be an associated unit vector. Let $z_i = a^T x_i$ be the projection of each of the training points on this direction.

Show that the z_i are distributed according to $N(0, 1)$ with expected squared distance from the origin 1, while the target point has expected squared distance p from the origin.

Solution. We use the fact that for any $a \in \mathbb{R}^p$, if $x \sim N(0, \mathbf{I}_p)$, then $a^T x \sim N\left(\sum_j a_j \mu_j, \sum_j a_j^2 \sigma_j^2\right)$, where $\mu_j = E(x_j)$ and $\sigma_j = V(x_j)$ and $j \in [p]$. Since $\sigma_j = 1$ and $\mu_j = 0$, we get that $a^T x \sim$

$N(0, \sum_j a_j^2)$. Given that $\|a\|$ is a unit vector, we get that $a^T x \sim N(0, 1)$. Hence $|z| = |a^T x| \sim \chi_1^2$ and $E[|z|] = 1$.

5. Suppose that we know that the true relationship between Y and X is linear,

$$Y = X^T \beta + \varepsilon, \quad (2.26)$$

where $\varepsilon \sim N(0, \sigma^2)$ and we fit the model by least squares to the training data. For an arbitrary test point x_0 , we have $\hat{y}_0 = x_0^T \hat{\beta}$, which can be written as $\hat{y}_0 = x_0^T \beta + \sum_{i=1}^N \ell_i(x_0) \varepsilon_i$, where $\ell_i(x_0)$ is the i th element of $\mathbf{X}(\mathbf{X}^T \mathbf{X})^{-1} x_0$. Show that

$$\text{EPE}(x_0) = \sigma^2 + E_{\mathcal{T}} x_0^T (\mathbf{X}^T \mathbf{X})^{-1} x_0 \sigma^2 + 0^2, \quad (2.27)$$

where you can use the fact that for any \mathbf{X} ,

$$\text{Cov}[\hat{\beta}] = (\mathbf{X}^T \mathbf{X})^{-1} \sigma^2. \quad (3.8)$$

Additionally, suppose N is large and \mathcal{T} were selected at random. Assuming $E(X) = 0$, then $\mathbf{X}^T \mathbf{X} \rightarrow N \text{Cov}(X)$. Show that

$$\begin{aligned} E_{x_0} \text{EPE}(x_0) &\approx E_{x_0} x_0^T \text{Cov}[X]^{-1} x_0 \sigma^2 / N + \sigma^2 \\ &= \text{trace}[\text{Cov}[X]^{-1} \text{Cov}[x_0]] \sigma^2 / N + \sigma^2 \\ &= \sigma^2 (p/N) + \sigma^2. \end{aligned} \quad (2.28)$$

Make use of the cyclic property of the trace operator ($\text{trace}(AB) = \text{trace}(BA)$), and its linearity (which allows us to interchange the order of trace and expectation).

Solution. In the first question, the test point x_0 is arbitrary and not sampled from the distribution. Thus the randomness is only over:

- the samples \mathcal{T} ,
- the error ε .

In the second part, we also sample x_0 and hence we consider the expectation of $\text{EPE}(x_0)$.

- (a) We start by showing that the expected prediction error equals the sum of the variance of the system, the variance of the model and the squared bias of the model:

$$\begin{aligned} \text{EPE}(x_0) &= E_{\mathcal{T}, \varepsilon} [(y_0 - \hat{y}_0)^2] \\ &= E_{\mathcal{T}, \varepsilon} [y_0^2 - 2y_0 \hat{y}_0 + \hat{y}_0^2] \\ &= E_{\mathcal{T}, \varepsilon} [y_0^2] - 2E_{\mathcal{T}, \varepsilon} [y_0 \hat{y}_0] + E_{\mathcal{T}, \varepsilon} [\hat{y}_0^2] \\ &= E_{\mathcal{T}, \varepsilon} [y_0^2] - 2x_0^T \beta E_{\mathcal{T}, \varepsilon} [\hat{y}_0] + E_{\mathcal{T}, \varepsilon} [\hat{y}_0^2] \\ &= E_{\mathcal{T}, \varepsilon} [y_0^2] - \boxed{-E_{\mathcal{T}, \varepsilon} [y_0]^2 + E_{\mathcal{T}, \varepsilon} [y_0]^2} - 2x_0^T \beta E_{\mathcal{T}, \varepsilon} [\hat{y}_0] + E_{\mathcal{T}, \varepsilon} [\hat{y}_0^2] - \boxed{E_{\mathcal{T}, \varepsilon} [\hat{y}_0]^2 + E_{\mathcal{T}, \varepsilon} [\hat{y}_0]^2} \\ &= \text{Var}[y_0] + \text{Var}[\hat{y}_0] + (E_{\mathcal{T}, \varepsilon} [\hat{y}_0] - x_0^T \beta)^2, \end{aligned}$$

where the third line follows from the fact that

$$E_{\mathcal{T}, \varepsilon} [y_0 \hat{y}_0] = E_{\mathcal{T}, \varepsilon} [(x_0^T \beta + \varepsilon) \hat{y}_0] = x_0^T \beta E_{\mathcal{T}, \varepsilon} [\hat{y}_0] + E_{\mathcal{T}, \varepsilon} [\varepsilon \hat{y}_0]$$

and $E_{\mathcal{T}, \varepsilon} [\varepsilon \hat{y}_0] = E_{\mathcal{T}, \varepsilon} [\varepsilon] E_{\mathcal{T}, \varepsilon} [\hat{y}_0] = 0$, since ε is independent from \hat{y}_0 . Now, we have that $\text{Var}[y_0] =$

σ^2 . Moreover,

$$\begin{aligned}
E_{\mathcal{T},\varepsilon}[\hat{y}_0] &= E_{\mathcal{T},\varepsilon} \left[x_0^T \beta + \sum_{i=1}^N \ell_i(x_0) \varepsilon_i \right] \\
&= x_0^T \beta + \sum_{i=1}^N E_{\mathcal{T},\varepsilon}[\ell_i(x_0) \varepsilon_i] \\
&= x_0^T \beta + \sum_{i=1}^N E_{\mathcal{T},\varepsilon}[\ell_i(x_0)] E_{\mathcal{T},\varepsilon}[\varepsilon_i] \\
&= x_0^T \beta,
\end{aligned} \tag{3}$$

since ε_i is independent of x_0 and \mathbf{X} . Hence, $\text{Bias}(\hat{y}_0) = (E_{\mathcal{T},\varepsilon}[\hat{y}_0] - x_0^T \beta) = 0$. Last, we want to calculate the variance of our prediction $\text{Var}[\hat{y}_0]$. We have

$$\begin{aligned}
\text{Var}[\hat{y}_0] &= \text{Var}[x_0^T \hat{\beta}] \\
&= x_0^T \text{Cov}[\hat{\beta}] x_0 \\
&= x_0^T (\mathbf{X}^T \mathbf{X})^{-1} \sigma^2 x_0,
\end{aligned} \tag{4}$$

where the last line comes from eq. (3.8).

(b) Now we have that

$$\begin{aligned}
E_{x_0} \text{EPE}(x_0) &\approx E_{x_0} [x_0^T \text{Cov}[X]^{-1} x_0] \sigma^2 / N + \sigma^2 \\
&= E_{x_0} [\text{trace}[x_0^T \text{Cov}[X]^{-1} x_0]] \sigma^2 / N + \sigma^2 \\
&= E_{x_0} [\text{trace}[\text{Cov}[X]^{-1} x_0 x_0^T]] \sigma^2 / N + \sigma^2 \\
&= \text{trace}[E_{x_0} [\text{Cov}[X]^{-1} x_0 x_0^T]] \sigma^2 / N + \sigma^2 \\
&= \text{trace}[\text{Cov}[X]^{-1} E_{x_0} [x_0 x_0^T]] \sigma^2 / N + \sigma^2 \\
&= \text{trace}[\text{Cov}[X]^{-1} \text{Cov}[x_0]] \sigma^2 / N + \sigma^2 \\
&= \text{trace}[\mathbf{I}_p] \sigma^2 / N + \sigma^2 \\
&= p \sigma^2 / N + \sigma^2
\end{aligned} \tag{5}$$

We see that the function $f(p) = E_{x_0} \text{EPE}(x_0) = \sigma^2(p/N) + \sigma^2$ increases linearly with p , with slope $f'(p) = \sigma^2/N$. Hence as long as we have sufficiently many samples N this increase becomes negligible. In other words, even if we have a lot of dimensions, the expected EPE remains constant. Of course, the reason is that we imposed heavy restrictions on the class of models being fitted.

6. Consider a regression problem with inputs x_i and outputs y_i , and a parameterized model $f_\theta(x)$ to be fit by least squares. Show that if there are observations with *tied* or *identical* values of x , then the fit can be obtained from a reduced weighted least squares problem.

Solution. The weighted least squares problem is defined as the problem of minimizing the value

$$\text{WRSS}_{(x_i, y_i, w_i)}(\beta) = \sum_{i=1}^N w_i (y_i - \hat{f}_\beta(x_i))^2.$$

It generalizes RSS since by setting $w_i = 1$ we get the RSS. The idea behind WRSS is that some pairs (x_i, y_i) may have errors and some may be more accurate. By giving them weights, we reward the more accurate ones and we penalize the less accurate.

A reduced least squares problem is one that uses fewer observations than available; $N' < N$.

Suppose that we have N observations (x_i, y_i) with some of them sharing the same x_i . Suppose we have N' distinct x_i s and for each distinct x_i , we have N_i observations, so $N = \sum_{i=1}^{N'} N_i$. We wish to compute the value $\arg \min_{\beta} \text{RSS}(\beta)$. We will show that

$$\arg \min_{\beta} \text{RSS}_{(x_i, y_i)}(\beta) = \arg \min_{\beta} \text{WRSS}_{(x_i, \bar{y}_i, N_i)}(\beta).$$

We have

$$\begin{aligned} \arg \min_{\beta} \text{RSS}_{(x_i, y_i)}(\beta) &= \arg \min_{\beta} \sum_{i=1}^N (y_i - \hat{f}_{\beta}(x_i))^2 \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} \sum_{j=1}^{N_i} (y_i - \hat{f}_{\beta}(x_i))^2 \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} \sum_{j=1}^{N_i} (y_i^2 - 2y_i \hat{f}_{\beta}(x_i) + \hat{f}_{\beta}^2(x_i)) \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} \sum_{j=1}^{N_i} (-2y_i \hat{f}_{\beta}(x_i) + \hat{f}_{\beta}^2(x_i)) \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} (-2N_i \bar{y}_i \hat{f}_{\beta}(x_i) + N_i \hat{f}_{\beta}^2(x_i)) \tag{6} \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} N_i (-2\bar{y}_i \hat{f}_{\beta}(x_i) + \hat{f}_{\beta}^2(x_i)) \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} N_i (\bar{y}_i^2 - 2\bar{y}_i \hat{f}_{\beta}(x_i) + \hat{f}_{\beta}^2(x_i)) \\ &= \arg \min_{\beta} \sum_{i=1}^{N'} N_i (\bar{y}_i - \hat{f}_{\beta}(x_i))^2 \\ &= \arg \min_{\beta} \text{WRSS}_{(x_i, \bar{y}_i, N_i)}(\beta), \end{aligned}$$

where the fourth and the seventh lines come from the fact that for any function f and $c \in \mathbb{R}$, it holds that $\arg \min_{\beta} (f(\beta) + c) = \arg \min_{\beta} f(\beta)$.

7. Suppose we have a sample of N pairs x_i, y_i drawn i.i.d from the distribution characterized as follows:

$$\begin{aligned} x_i &\sim h(x), \text{ the design density} \\ y_i &= f(x_i) + \varepsilon_i, f \text{ is the regression function} \\ \varepsilon_i &\sim (0, \sigma^2) \text{ (mean zero, variance } \sigma^2) \end{aligned}$$

We construct an estimator for f linear in the y_i ,

$$\hat{f}(x_0) = \sum_{i=1}^N \ell_i(x_0; \mathcal{X}) y_i,$$

where the weights $\ell_i(x_0; \mathcal{X})$ do not depend on the y_i , but do depend on the entire training sequence of x_i , denoted here by \mathcal{X} .

(a) Show that the linear regression and k -nearest-neighbor regression are members of this class of estimators. Describe explicitly the weights $\ell_i(x_0; \mathcal{X})$ in each of these cases.

- (b) Decompose the conditional mean-squared error

$$E_{\mathcal{Y}|\mathcal{X}}(f(x_0) - \hat{f}(x_0))^2$$

into a conditional squared bias and a conditional variance component. Like \mathcal{X} , \mathcal{Y} represents the entire training sequence of y_i .

- (c) Decompose the mean-squared error $E_{\mathcal{X},\mathcal{Y}}(f(x_0) - \hat{f}(x_0))^2$ into a squared bias and a variance component.
- (d) Establish a relationship between the squared biases and variances in the above two cases.

Solution. (a) For linear regression, we have that $\hat{f}(x_0) = x^T(\mathcal{X}^T\mathcal{X})^{-1}\mathcal{X}y = \sum_{i=1}^N \ell_i(x_0; \mathcal{X})y_i$, where $\ell_i(x_0; \mathcal{X})$ is the i th element of the vector $x^T(\mathcal{X}^T\mathcal{X})^{-1}\mathcal{X}$. For the k -nearest neighbor, we have that $\ell_i(x_0; \mathcal{X}) = \frac{1}{k}I(x_i \in N_k(x_0, \mathcal{X}))$, where $N_k(x_0, \mathcal{X})$ is the set of the k closest points to x_0 .

- (b) We have that

$$\begin{aligned} E_{\mathcal{Y}|\mathcal{X}}[(f(x_0) - \hat{f}(x_0))^2] &= E_{\mathcal{Y}|\mathcal{X}}[f^2(x_0) - 2f(x_0)\hat{f}(x_0) + \hat{f}^2(x_0)] \\ &= \text{Var}_{\mathcal{Y}|\mathcal{X}}(f(x_0)) + \text{Var}_{\mathcal{Y}|\mathcal{X}}(\hat{f}(x_0)) + E_{\mathcal{Y}|\mathcal{X}}[(f(x_0) - \hat{f}(x_0))^2] \\ &= \text{Var}_{\mathcal{Y}|\mathcal{X}}(f(x_0)) + \text{Var}_{\mathcal{Y}|\mathcal{X}}(\hat{f}(x_0)) + \text{Bias}_{\mathcal{Y}|\mathcal{X}}[\hat{f}(x_0)]^2 \\ &= \text{Var}_{\mathcal{Y}|\mathcal{X}}(\hat{f}(x_0)) + \text{Bias}_{\mathcal{Y}|\mathcal{X}}[\hat{f}(x_0)]^2 \end{aligned} \quad (7)$$

since $f(x_0)$ does not have any randomness.

- (c) Similarly,

$$E_{\mathcal{Y},\mathcal{X}}[(f(x_0) - \hat{f}(x_0))^2] = \text{Var}_{\mathcal{Y},\mathcal{X}}(\hat{f}(x_0)) + \text{Bias}_{\mathcal{Y},\mathcal{X}}[\hat{f}(x_0)]^2. \quad (8)$$

- (d) We have that

$$\begin{aligned} \text{Var}_{\mathcal{Y},\mathcal{X}}(\hat{f}(x_0)) &= E_{\mathcal{X} \sim h}[\text{Var}_{\mathcal{Y},\mathcal{X}}(\hat{f}(x_0))] \\ \text{Bias}_{\mathcal{Y},\mathcal{X}}(\hat{f}(x_0)) &= E_{\mathcal{X} \sim h}[\text{Bias}_{\mathcal{Y},\mathcal{X}}(\hat{f}(x_0))] \end{aligned}$$

8. Compare the classification performance of linear regression and k -nearest neighbor classification on the `zipcode` data. In particular, consider only the 2's and 3's and $k = 1, 3, 5, 7, 15$. Show both the training and test error for each choice. The `zipcode` data are available from the book website <https://hastie.su.domains/ElemStatLearn/>.

Solution. We use the `sklearn` library of Python.

```
Linear Regression
Training Error
2.48%
Testing Error
15.17%
k-nearest neighbors classifier
k = 1
Training Error
0.00%
Testing Error
2.47%
k = 3
Training Error
0.50%
Testing Error
3.02%
k = 5
Training Error
0.58%
Testing Error
3.02%
```

k = 7
 Training Error
 0.65%
 Testing Error
 3.30%
 k = 15
 Training Error
 0.94%
 Testing Error
 3.85%

9. Consider a linear regression model with p parameters, fit by least squares to a set of training data $(x_1, y_1), \dots, (x_N, y_N)$ drawn at random from a population. Let $\hat{\beta}$ be the least squares estimate. Suppose we have some test data $(\tilde{x}_1, \tilde{y}_1), \dots, (\tilde{x}_M, \tilde{y}_M)$ drawn at random from the same population as the training data. If $R_{\text{tr}}(\beta) = \frac{1}{N} \sum_{i=1}^N (y_i - \beta^T x_i)^2$ and $R_{\text{te}}(\beta) = \frac{1}{M} \sum_{i=1}^M (\tilde{y}_i - \beta^T \tilde{x}_i)^2$, prove that

$$E[R_{\text{tr}}(\hat{\beta})] \leq E[R_{\text{te}}(\hat{\beta})],$$

where the expectations are over all that is random in each expression (meaning the population).

Solution. We will prove a more general result. Let S be the training set and T be the testing set. Moreover, let $f(S, \beta) = E_i[f(S_i, \beta)]$ be the function we want to minimize (in our case it will be the RSS or its normalized version, the mean squared error MSE). Observe that for any β ,

$$\begin{aligned}
 E_S[f(S, \beta)] &= E_S E_i[f(S_i, \beta)] \\
 &= E_i E_S[f(S_i, \beta)] \\
 &= E_i E_S[f(S_1, \beta)] \\
 &= E_S[f(S_1, \beta)],
 \end{aligned} \tag{9}$$

since all S_i are i.i.d.. Let $\beta_S = \arg \min_{\beta} f(S, \beta)$ and observe that for any β , it holds that $f(S, \beta_S) \leq f(S, \beta)$. Let T' be the set T , truncated or augmented by sampling more data to match the size of S . We have

$$\begin{aligned}
 E_{S,T}[f(T, \beta_S)] &= E_S E_{T/S}[f(T, \beta_S)] \\
 &\geq E_S E_{T/S}[f(T, \beta_{T'})] \\
 &= E_S E_T[f(T, \beta_{T'})] \\
 &= E_T[f(T, \beta_{T'})] \\
 &= E_T[f(T_1, \beta_{T'})] \\
 &= E_{T'}[f(T_1, \beta_{T'})] \\
 &= E_S[f(S_1, \beta_S)] \\
 &= E_S[f(S, \beta_S)]
 \end{aligned} \tag{10}$$

where the second line comes from the above inequality and the 5th and the 8th lines come from Equation (9).

For our case, S is the training set and T is the testing set. Moreover, we have that

$$\arg \min_{\beta} (\text{RSS}(\beta)) = \arg \min_{\beta} \left(\frac{1}{N} \text{RSS}(\beta) \right) = \arg \min_{\beta} (\text{MSE}(\beta)).$$

Hence it is enough to consider the function $f(S, \beta) = \text{MSE}(\beta)$, $\text{tr} = S$, $\text{te} = T$ and $\hat{\beta} = \beta_S$.

We see that this inequality is illustrated in Exercise 8.

Exercises for Section 3

1. Show that the F statistic (3.13) for dropping a single coefficient from a model is equal to the square of the corresponding z -score (3.12).

Solution. The z -score for dropping the variable $j \in [p]$ is defined as

$$z_j = \frac{\hat{\beta}_j}{\hat{\sigma}\sqrt{v_j}},$$

where v_j is the j th diagonal element of $(\mathbf{X}^T \mathbf{X})^{-1}$. Moreover, the F statistic for dropping variable j is

$$F = \frac{(\text{RSS}_0 - \text{RSS}_1)/(p_1 - p_0)}{\text{RSS}_1/(N - p_1 - 1)} = \frac{\text{RSS}_0 - \text{RSS}_1}{\text{RSS}_1/(N - p - 1)} = \frac{\text{RSS}_0 - \text{RSS}_1}{\hat{\sigma}^2}$$

Hence, it suffices to show that $\frac{\hat{\beta}_j^2}{u_j} = \text{RSS}_0 - \text{RSS}_1$.

Letting $V = (X^T X)^{-1}$, we have that $X^T y = V^{-1} \hat{\beta}$ and

$$\begin{aligned} \text{RSS} &= y^T y - y^T X \hat{\beta} - \hat{\beta}^T X^T y + \hat{\beta}^T X^T X \hat{\beta} \\ &= y^T y - \hat{\beta}^T V^{-1} \hat{\beta} \end{aligned} \quad (11)$$

$$\text{and } \text{RSS}_0 - \text{RSS}_1 = \hat{\beta}_0^T V_0^{-1} \hat{\beta}_0 - \hat{\beta}_1^T V_1^{-1} \hat{\beta}_1 = \hat{\beta}_j u_j^{-1} \hat{\beta}_j.$$

2. Given data on two variables X and Y , consider fitting a cubic polynomial regression model $f(X) = \sum_{j=0}^3 \beta_j X^j$. In addition to plotting the fitted curve, you would like a 95% confidence band about the curve. Consider the following two approaches:

- (a) At each point x_0 , form a 95% confidence interval for the linear function $a^T \beta = \sum_{j=0}^3 \beta_j x_0^j$.
- (b) For a 95% confidence set for β as in (3.15), which in turn generates confidence intervals for all $f(x_0)$.

How do these approaches differ? Which band is likely to be wider? Conduct a small simulation experiment to compare the two methods.

Solution. We consider design matrix

$$\mathbf{X} = \begin{bmatrix} 1 & x_0 & x_0^2 & x_0^3 \\ 1 & x_1 & x_1^2 & x_1^3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_N & x_N^2 & x_N^3 \end{bmatrix} \quad (12)$$

response matrix

$$\mathbf{y} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_N \end{bmatrix} \quad (13)$$

and that the true model is $y = x^T \beta + \varepsilon$, where $x^T = [1, x, x^2, x^3]$ and $\varepsilon \sim N(0, \sigma^2)$.

By applying ordinary least squares we get

$$\hat{\beta} = (X^T X)^{-1} X^T \mathbf{y}$$

with $\hat{\beta} \sim N(\beta, (\mathbf{X}^T \mathbf{X})^{-1} \sigma^2)$.

- (a) For any a^T , it holds that $a^T \hat{\beta}$ is a univariate normal distribution:

$$a^T \hat{\beta} \sim N(a^T \beta, a^T (\mathbf{X}^T \mathbf{X})^{-1} \sigma^2 a).$$

Therefore, the confidence interval for $a^T \beta$ is

$$C_{a^T \beta} = a^T \hat{\beta} \pm 2 \cdot \hat{\sigma} \sqrt{a^T (\mathbf{X}^T \mathbf{X})^{-1} a}$$

(b) For a confidence interval of the whole β , we apply (3.15) and we get that

$$C_\beta = \left\{ \beta \mid (\hat{\beta} - \beta)^T \mathbf{X}^T \mathbf{X} (\hat{\beta} - \beta) \leq \hat{\sigma}^2 \chi_4^2(1-0.05) \right\}$$

and therefore

$$C_{a^T \beta} = \left\{ a^T \beta \mid (\hat{\beta} - \beta)^T \mathbf{X}^T \mathbf{X} (\hat{\beta} - \beta) \leq \hat{\sigma}^2 \chi_4^2(1-0.05) \right\}$$

Since $\chi_4^2(1-0.05) > 2$, we expect the second band to be wider.

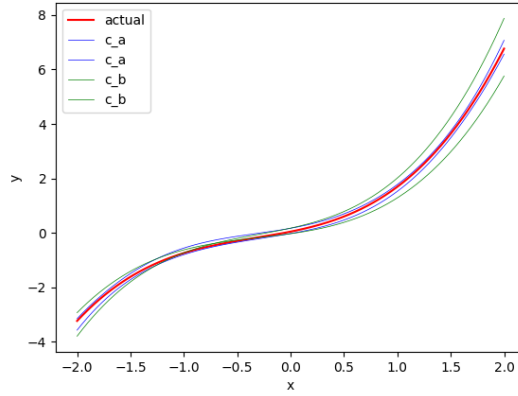


Figure 2: The actual curve together with the two confidence bands.

3. Gauss-Markov theorem:

- (a) Prove the Gauss-Markov theorem: the least squares estimate of a parameter $a^T \beta$ has variance no bigger than that of any other linear unbiased estimate of $a^T \beta$.
- (b) The matrix inequality $\mathbf{B} \preceq \mathbf{A}$ holds if $\mathbf{A} - \mathbf{B}$ is positive semidefinite. Show that if $\hat{\mathbf{V}}$ is the variance-covariance matrix of the least squares estimate $\hat{\beta}$ and $\tilde{\mathbf{V}}$ is the variance-covariance matrix of any other linear unbiased estimate, then $\hat{\mathbf{V}} \preceq \tilde{\mathbf{V}}$.

Solution. (a) Let $\hat{\beta} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y}$ be the least squares estimate and consider the estimator of $a^T \beta$ to be

$$\hat{\theta} = a^T \hat{\beta} = \mathbf{c}_0^T \mathbf{y}.$$

Now consider any other unbiased linear estimator $\tilde{\theta} = \mathbf{c}^T \mathbf{y}$ of $a^T \beta$; i.e., $E[\mathbf{c}^T \mathbf{y}] = a^T \beta$. We write $\mathbf{c}^T = \mathbf{c}_0^T + d^T$ for some d and we have:

$$\begin{aligned} E[\tilde{\theta}] &= E[(\mathbf{c}_0^T + d^T) \mathbf{y}] \\ &= E[a^T (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{y} + d^T \mathbf{y}] \\ &= a^T \beta + d^T E[\mathbf{y}] \\ &= a^T \beta + d^T \mathbf{X} \beta \end{aligned} \tag{14}$$

From which, we conclude that

$$d^T \mathbf{X} = 0$$

We now compute the variance of $\tilde{\theta}$:

$$\begin{aligned}
\text{Var}[\tilde{\theta}] &= \text{Var}[\mathbf{c}^T \mathbf{y}] \\
&= \mathbf{c}^T \text{Var}[\mathbf{y}] \mathbf{c} \\
&= \sigma^2 \mathbf{c}^T \mathbf{c} \\
&= \sigma^2 (\mathbf{c}_0^T + d^T) (\mathbf{c}_0 + d) \\
&= \sigma^2 (a^T (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T + d^T) (\mathbf{X} (\mathbf{X}^T \mathbf{X})^{-1} a + d) \\
&= \sigma^2 a^T (\mathbf{X}^T \mathbf{X})^{-1} a + \sigma^2 d^T d \\
&= a^T \sigma^2 (\mathbf{X}^T \mathbf{X})^{-1} a + \sigma^2 d^T d \\
&= a^T \text{Var}[\hat{\beta}] a + \sigma^2 d^T d \\
&= \text{Var}[\hat{\theta}] + \sigma^2 \|d\|^2 \\
&\geq \text{Var}[\hat{\theta}].
\end{aligned} \tag{15}$$

- (b) We can show that this extends to the whole variance-covariance matrix. Letting the above $a = I$ the identity matrix and $d = \mathbf{D}$ any $(p+1) \times (p+1)$ matrix, we get that

$$\text{Var}[\tilde{\beta}] = \text{Var}[\hat{\beta}] + \sigma^2 \mathbf{D}^T \mathbf{D} \tag{16}$$

Therefore, $\text{Var}[\hat{\beta}] - \text{Var}[\tilde{\beta}] = \sigma^2 \mathbf{D}^T \mathbf{D}$ is a Gram matrix and therefore positive-semidefinite.

Note. Another way of stating the Gauss-Markov theorem is that the least squares estimator $\hat{\beta}$ is *BLUE*: best linear unbiased estimator.

4. Show how the vector of least squares coefficients can be obtained from a single pass of the Gram-Schmidt procedure (Algorithm 3.1). Represent your solution in terms of the QR decomposition of \mathbf{X} .

Solution. After having computed the residual vectors \mathbf{z}_j using Gram-Schmidt, it is straightforward to compute the least squares coefficients, by computing

$$\hat{\beta}_j = \frac{\langle \mathbf{z}_j, \mathbf{y} \rangle}{\langle \mathbf{z}_j, \mathbf{z}_j \rangle}.$$

In other words, $\hat{\beta} = (\mathbf{DR})^{-1} \mathbf{Z}^T \mathbf{y}$ and

$$\begin{aligned}
\hat{\beta} &= (\mathbf{DR})^{-1} \mathbf{Z}^T \mathbf{y} \\
&= \mathbf{R}^{-1} \mathbf{D}^{-1} \mathbf{Z}^T \mathbf{y} \\
&= \mathbf{R}^{-1} \mathbf{Q}^T \mathbf{y}
\end{aligned} \tag{17}$$