

Principles of statistical inference project - Part 1

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1 Question 1

Consider a random variable X that follows an exponential distribution with scale parameter λ .

The **Exponential Distribution** is a continuous probability distribution that represents the time intervals between consecutive events in a Poisson process, where events happen independently and at a constant average rate. It is defined by a single parameter, λ , referred to as the rate parameter.

1.1 Give reference to a publication in which the exponential distribution has been used in practise. Explain the context in which this distribution has been used in this publication.

Mahmud et al. presented a study where they analyzed and estimated response times to questions on Twitter [1]. The authors developed predictive models to estimate response wait times, exploring three different approaches:

- **Personalized wait time models:** These models estimate the wait time for a specific user based on their individual history of response wait times. They assume each response event for a user occurs continuously and independently at a constant average rate, modelled by an exponential distribution. Each user's rate parameter λ is estimated as the inverse of their average past response wait times.

These models demonstrated a promising ability to estimate response times on Twitter. They generally outperformed generalized models and showed reasonable accuracy, especially for an hour or more time limits. The choice of cut-off probability (a threshold used to determine whether a user is considered sufficiently likely to respond to a question on Twitter within a given period) significantly influenced the precision and recall of the predictions.

- **Generalized wait time models:** Instead of individual models, a single model is built using the previous responses of all users in the dataset, again using

the exponential distribution. The rate parameter λ is estimated from the responses of all users. This model underperformed compared to the personalized models in estimating response times on Twitter.

- Time-sensitive wait time models: These models incorporate sensitivity to the time of day or day of the week when questions are sent for both generalized and personalized models by calculating the rate parameter based on responses to questions sent during a specific day or hour. Personalized time-sensitive models only considered users with at least five responses during the modelled time interval. Incorporating time sensitivity had a modest positive impact on the generalized models but did not consistently improve the performance of the personalized models.

1.2 State the mean and the variance of X .

As X follows an exponential distribution with scale parameter, $X \sim \text{Exp}(X)$, the expected value or mean is:

$$E[X] = \frac{1}{\lambda} \quad (1)$$

and the variance is:

$$\text{Var}(X) = \frac{1}{\lambda^2} \quad (2)$$

1.3 Derive the moment estimator of λ .

The p.d.f. for an exponential distribution is:

$$f(x) = \lambda e^{-\lambda x}, x \geq 0, \lambda > 0 \quad (3)$$

The first moment, or expected value:

$$\begin{aligned} E[X] &= \int_0^{\infty} x f(x) dx \\ &= \int_0^{\infty} x \lambda e^{-\lambda x} dx \\ &= \lambda \int_0^{\infty} x e^{-\lambda x} dx \end{aligned}$$

Integrating by parts, we let:

$$\begin{aligned} u &= x & du &= (1)dx \\ v &= -\frac{e^{-\lambda x}}{\lambda} & dv &= e^{-\lambda x} dx \end{aligned}$$

As $\int u dv = uv - \int v du$:

$$\begin{aligned}
E[X] &= \lambda \left(\left[-\frac{xe^{-\lambda x}}{\lambda} \right]_0^\infty - \int_0^\infty -\frac{e^{-\lambda x}}{\lambda} (1) dx \right) \\
&= \left[-xe^{-\lambda x} \right]_0^\infty + \int_0^\infty -e^{-\lambda x} dx
\end{aligned}$$

Let us consider $\left[xe^{-\lambda x} \right]_0^\infty$:

- $-xe^{-\lambda x} = 0$, when $x = 0$
- $\lim_{x \rightarrow \infty} xe^{-\lambda x} = 0$, as exponential decay dominates polynomial growth

So the first term is removed;

$$\begin{aligned}
E[X] &= \int_0^\infty -e^{-\lambda x} dx \\
&= \left[-\frac{1}{\lambda} - e^{-\lambda x} \right]_0^\infty \\
&= 0 - \left(-\frac{1}{\lambda} \right) \\
&= \frac{1}{\lambda}
\end{aligned}$$

As in the method of moments the sample mean is equal to theoretical expectation;

$$E[X] = \frac{1}{\lambda} = \bar{X}$$

and solving for λ

$$\hat{\lambda} = \frac{1}{\bar{X}} \quad (4)$$

1.4 Use the second moment to obtain another estimator of λ

For an exponential distribution with rate parameter λ , the second moment,

$$\begin{aligned}
E[X^2] &= \int_0^\infty x^2 f(x) dx \\
&= \int_0^\infty x^2 \lambda e^{-\lambda x} dx \\
&= \lambda \int_0^\infty x^2 e^{-\lambda x} dx
\end{aligned}$$

We let:

$$\begin{aligned} u &= x^2 & du &= 2x dx \\ v &= -\frac{e^{-\lambda x}}{\lambda} & dv &= e^{-\lambda x} dx \end{aligned}$$

$$\begin{aligned} E[X^2] &= \lambda \left(\left[-\frac{x^2 e^{-\lambda x}}{\lambda} \right]_0^\infty - \int_0^\infty -\frac{e^{-\lambda x}}{\lambda} 2x dx \right) \\ &= \left[-x^2 e^{-\lambda x} \right]_0^\infty + \int_0^\infty 2x e^{-\lambda x} dx \end{aligned}$$

Let us consider $\left[x^2 e^{-\lambda x} \right]_0^\infty$:

- $-x^2 e^{-\lambda x} = 0$, when $x = 0$
- $\lim_{x \rightarrow \infty} x^2 e^{-\lambda x} = 0$, as exponential decay dominates polynomial growth

Then

$$E[X^2] = \int_0^\infty 2x e^{-\lambda x} dx$$

We let:

$$\begin{aligned} u &= x & du &= dx \\ v &= -\frac{e^{-\lambda x}}{\lambda} & dv &= e^{-\lambda x} dx \end{aligned}$$

$$E[X^2] = 2 \left(\left[-\frac{x e^{-\lambda x}}{\lambda} \right] - \int_0^\infty e^{-\lambda x} dx \right)$$

We have seen previously that the first term will equate to zero.

$$\begin{aligned} E[X^2] &= 2 \int_0^\infty \frac{e^{-\lambda x}}{\lambda} dx \\ &= \left[-\frac{2e^{-\lambda x}}{\lambda^2} \right]_0^\infty \\ &= 0 - \left(-\frac{2}{\lambda^2} \right) \\ &= \frac{2}{\lambda^2} \end{aligned}$$

The variance of the exponential distribution is given by:

$$\begin{aligned} Var(X) &= E[X^2] - E[X]^2 \\ &= \frac{2}{\lambda^2} - \left(\frac{1}{\lambda} \right)^2 \\ &= \frac{1}{\lambda^2} \end{aligned}$$

We can estimate the sample variance

$$\hat{\sigma}^2 = \frac{1}{\hat{\lambda}^2}$$

and solving for λ

$$\hat{\lambda} = \frac{1}{\sqrt{\hat{\sigma}^2}} \quad (5)$$

1.5 Comment on the unbiasedness and consistency of the moment estimator for λ derived in Q1iii. State any assumption/s that need to be made to check for unbiasedness and consistency.

The moment estimator $\hat{\lambda}$ is both unbiased and consistent.

Unbiasedness: The estimator $\hat{\lambda}$ is unbiased if its expectation equals the true parameter λ :

$$E[\hat{\lambda}] = E\left[\frac{1}{\bar{X}}\right] = \lambda. \quad (6)$$

Since the expectation of the sample mean \bar{X} for an exponential distribution satisfies $E[\bar{X}] = \frac{1}{\lambda}$, applying Jensen's inequality confirms that the moment estimator is unbiased.

Consistency: The estimator $\hat{\lambda}$ is consistent if its variance decreases to zero as $n \rightarrow \infty$. The variance of $\hat{\lambda}$ is given by:

$$\text{Var}(\hat{\lambda}) = \frac{\lambda^2}{n}. \quad (7)$$

Since $\frac{\lambda^2}{n} \rightarrow 0$ as $n \rightarrow \infty$, it follows that $\hat{\lambda}$ is a consistent estimator of λ .

1.6 Use R software to generate 1000 data points from an exponential distributed random variable using any admissible parameter value for λ

The R script generates 1000 points from an exponentially distributed random variable with a rate parameter λ of 1.5. It then plots a histogram of these points and overlays the theoretical density function of the exponential distribution. The result is shown in Figure 1.

```

1 library(ggplot2)
2 library(glue)
3
4 set.seed(50)
5 lambda <- 1.5
6 x <- rexp(n = 1000, rate = lambda)
7
8 data <- data.frame(x = x)
9
10 p <- ggplot(data,
11             aes(x = x)) +
12     geom_histogram(
13         aes(y = after_stat(density)),
14         bins = 50, fill = "blue",
15         color = "black",
16         alpha = 0.6) +
17     stat_function(
18         fun = function(x) lambda * exp(-lambda * x),
19         color = "red",
20         size = 1) +
21     labs(title = glue("Histogram of exponentially distributed
22 random variable with lambda = {lambda}"),
23          x = "x", y = "Density") +
24     theme_minimal() +
25     theme(plot.title = element_text(hjust = 0.5))

```

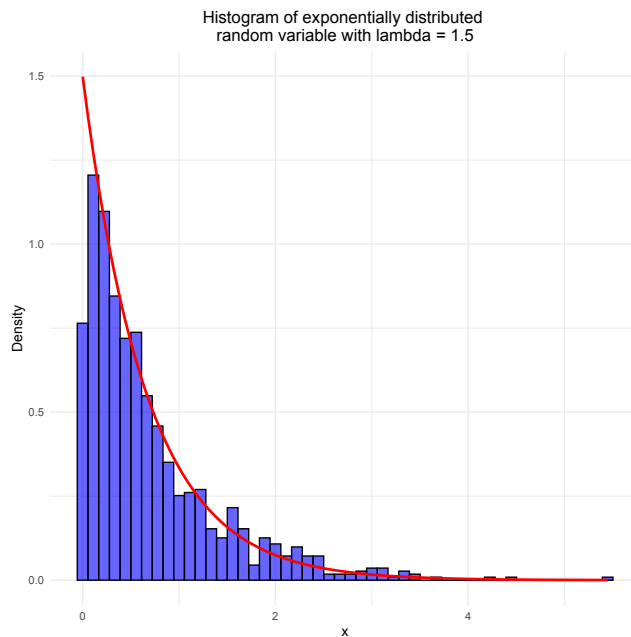


Figure 1: Exponential distributed random variable; histogram of 1000 generated points and theoretical distribution

1.6.1 Write down the log-likelihood function for this exponentially distributed random variable.

For sample $\mathbf{x} = (x_1, \dots, x_n)^T$ obtained on an exponential distributed random variable X , with parameter vector $\theta = (\lambda)$, the likelihood

$$\begin{aligned} L(\mathbf{x}, \theta) &= \prod_{i=1}^n f(x_i, \theta) \\ &= \prod_{i=1}^n \lambda e^{-\lambda x_i} \\ &= \lambda^n e^{\sum_{i=1}^n -\lambda x_i} \end{aligned}$$

The log-likelihood is then

$$l(\mathbf{x}, \theta) = n \log(\lambda) - \lambda \sum_{i=1}^n x_i$$

Taking the derivative with respect to λ ,

$$\frac{\partial l(\mathbf{x}, \theta)}{\partial \lambda} = \frac{n}{\lambda} - \sum_{i=1}^n x_i$$

for maximum $\frac{\partial l(\mathbf{x}, \theta)}{\partial \lambda}$

$$\begin{aligned} L \frac{\partial l(\mathbf{x}, \theta)}{\partial \lambda} &= 0 \\ \frac{n}{\lambda} - \sum_{i=1}^n x_i &= 0 \\ \frac{n}{\lambda} &= \sum_{i=1}^n x_i \end{aligned}$$

So that

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^n x_i} = \frac{1}{\bar{x}} \quad (8)$$

1.6.2 Evaluate the log-likelihood function for the generated data as a function of λ , and plot the resulting log-likelihood function against different values of λ . Present the plot together with the answers.

The following listing calculates and plots the log-likelihood values for an exponential distribution with varying λ values. The resulting plot can be examined in Figure 2

```

1 lambda_values <- seq(0.1, 5, by = 0.01)
2 log_likelihood_values <- sapply(lambda_values,
3 function(lambda) LL_exponential(lambda, x))
4
5 df <- data.frame(lambda_values, log_likelihood_values)
6
7 p <- ggplot(df,
8   aes(x = lambda_values,
9     y = log_likelihood_values)) +
10 geom_point(
11   color = "blue",
12   alpha = 0.6) +
13   labs(
14     title = "Log-Likelihood with varying
15     lambda values",
16     x = "Lambda",
17     y = "Log-Likelihood") +
18   theme_bw()
19
20 quartz()
21 print(p)

```

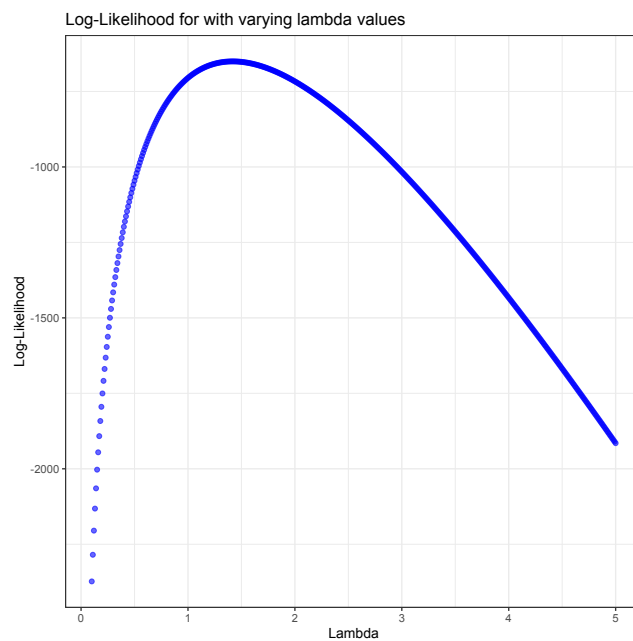


Figure 2: Log-likelihood plot for an exponential distribution with varying λ

1.6.3 Using the plot or otherwise, which estimate for λ is the MLE? Give a reason for your answer.

As we have seen in the previous question, the maximum likelihood estimation is the value for which the derivative of the log-likelihood with respect to lambda is zero, that is the peak of the curve shown in Figure 2. This can be easily calculated using the code below. The value obtained for $\hat{\lambda}$ was **1.43**.

```
1 max_ll <- max(log_likelihood_values)
2 max_lambda <- lambda_values[log_likelihood_values == max_ll]
3 print(glue("Lambda value for maximum log-likelihood is
  {max_lambda}"))
```

2 title

3 title

4 Question 4 - Jackknife and bootstrap

Consider 50 observations of bivariate pair (X, Y) in `resampling.xlsx`. Use the `nls` command in R to estimate the nonlinear regression $Y = \frac{aX}{b+X} + \epsilon$.

The code in Listing 1 performs nonlinear regression on the dataset. The resulting plots are presented in Figure 3. The estimated parameters are $\hat{a} = 14.56$ and $\hat{b} = 7.10$.

```

1 library(openxlsx)
2 library(ggplot2)
3
4 # load file
5 script_dir <- getwd()
6 file_path <- file.path(script_dir, "resampling.xlsx")
7 df <- read.xlsx(file_path, colNames = TRUE)
8
9 print(c("number of rows: ", nrow(df)))
10
11 # estimate the parameters of the model
12 init_a <- 1
13 init_b <- 1
14
15 nls_model <- nls(y ~ (a * x) / (b + x),
16 data = df,
17 start = list(a = init_a, b = init_b))
18
19
20 estimated_params <- coef(nls_model)
21 a_hat <- estimated_params["a"]
22 b_hat <- estimated_params["b"]
23 cat("Estimated a:", a_hat, "\n")
24 cat("Estimated b:", b_hat, "\n")
25
26 # predict the values of y
27 df$Predicted <- predict(nls_model)
28 print(head(df))
29
30 # plot the data
31 p <- ggplot(df, aes(x = x , y = y)) +
32 geom_point(color = "blue", alpha = 0.5) +
33 geom_line(aes(
34     y = Predicted),
35     color = "red",
36     linewidth = 1) +
37 labs(title = "Nonlinear Regression: Y = (aX) / (b+X)",
38 x = "X", y = "Y") +
39 theme_minimal()
40
41 print(p)

```

Listing 1: Non linear regression code in R

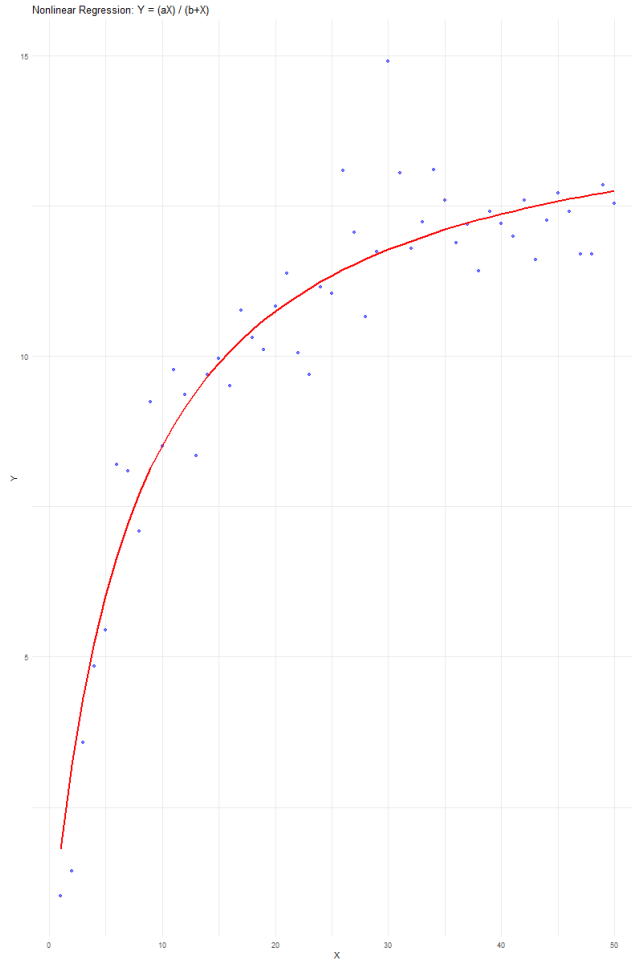


Figure 3: Nonlinear regression fit: observed vs. predicted values

4.1 Construct a computer code in R to find the Jackknife and Bootstrap estimators of a and b . In the case of Jackknife, section randomly the sampling into 5 partitions of size 10. In the case of Bootstrap, generate 1000 samples of size 100 with replacement.

The code in Listing 2 executes the following steps on the data to implement Jackknife resampling with non linear regression. The resulting plots are presented in Figure 4. The estimated parameters are $\hat{a}_{jk} = 14.504$ and $\hat{b}_{jk} = 6.996$. The code executes the following steps to estimate the parameters:

1. **Shuffle the dataset:** We randomly shuffle the data to remove any or-

dering bias:

2. **Divide the data into m Jackknife partitions:** We split the dataset into $m = 5$ partitions, each missing a unique subset of 5 elements.
3. **Fit the NLS model for each Jackknife sample:** We fit a nonlinear regression model to each Jackknife sample using Nonlinear Least Squares (NLS) to estimate parameters a and b . The model is defined as:

$$Y = \frac{aX}{b + X} \quad (9)$$

and is refitted for each sample S_{-a} , which excludes partition P_a .

4. **Compute Jackknife bias-corrected estimates:** The Jackknife estimate for each parameter is calculated using the bias correction formula:

$$\hat{\theta}_{\text{jack}} = m\hat{\theta} - (m-1)\hat{\theta}_{(-a)} \quad (10)$$

where:

- $m = 5$ is the number of partitions.
- $\hat{\theta}$ is the parameter estimate from the full dataset.
- $\hat{\theta}_{(-a)}$ is the parameter estimate from the jackknife sample with partition a removed.

5. **Compute final Jackknife estimates for a and b :** The final Jackknife estimates for a and b are obtained by averaging the bias-corrected values across all jackknife samples:

$$\hat{a}_{jk} = \frac{1}{m} \sum_{a=1}^m \hat{a}_{\text{jack},a}, \quad \hat{b}_{jk} = \frac{1}{m} \sum_{a=1}^m \hat{b}_{\text{jack},a} \quad (11)$$

```

1 partition_size <- 5
2
3 #shuffle the dataframe
4 set.seed(123)
5 df_shuf <- df[sample(nrow(df)), ]
6
7 # Generate jackknife samples by removing each fold of 5 elements
8 # lapply applies a function to each element of a list
9 # my list is from 1:5
10 # the function will
11 # for a = 1 remove element 1 to 5 (5*(1-1)+1):(5*1)
12 # and so on
13 # note the - sign -- I am removing the elements
14 # so the return for each a is y without the elements 1 to 5, 6 to
    10, etc.
15 jackknife_samples <- lapply(1:partition_size,
16 function(a) df_shuf[-((partition_size * (a - 1) +
    1):(partition_size * a)), ])
17
18 # we have calculated theta_hat_m before
19 theta_hat_m <- estimated_params
20
21 theta_m_a <- function(data) {
22     model <- nls(y ~ (a * x) / (b + x),
23     data = data,
24     start = list(a = theta_hat_m["a"],
25     b = theta_hat_m["b"]))
26     return(coef(model)) }
27
28 # jackknife estimator for each partition
29 nlsjk <- sapply(jackknife_samples, function(y_a) partition_size *
    theta_hat_m - (partition_size - 1) * theta_m_a(y_a))
30
31 #evaluating the jackknife estimator of the parametrs
32 jackknife_estimates <- rowMeans(nlsjk)
33
34 a_hat_jk <- jackknife_estimates["a"]
35 b_hat_jk <- jackknife_estimates["b"]
36
37 df$predicted_jk <- (a_hat_jk * df$x) / (b_hat_jk + df$x)
38
39 # Plot with Jackknife predictions and legend
40 p_jk <- ggplot(df, aes(x = x, y = y)) +
41 geom_point(color = "blue", alpha = 0.5, size = 3) +
42 geom_line(aes(y = Predicted, color = "Full Sample Prediction"),
43 linewidth = 1, linetype = "dashed") +
44 geom_line(aes(y = predicted_jk, color = "Jackknife Prediction"),
45 linewidth = 1) +
46 labs(title = "Nonlinear Regression: Full Sample vs. Jackknife",
47 x = "X", y = "Y", color = "Legend") +
48 theme_minimal() +
49 scale_color_manual(values = c("Full Sample Prediction" = "red",
50 "Jackknife Prediction" = "green"))

```

Listing 2: Jackknife resampling code in R

The resulting plot is shown below in Figure 4

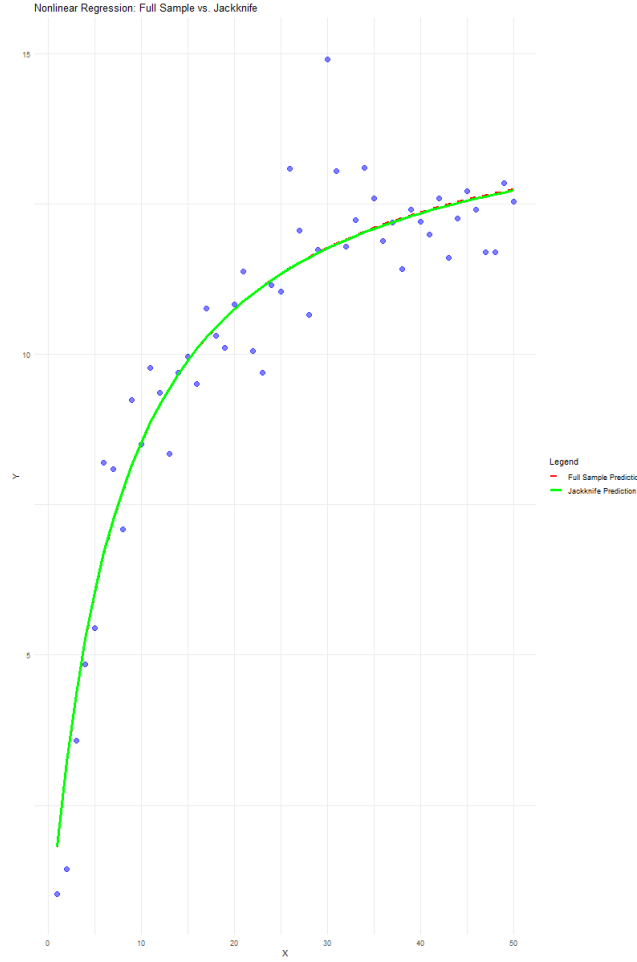


Figure 4: Nonlinear regression fit: observed vs. predicted values including Jackknife predictions

The code in Listing 3 executes the following steps on the data to implement Bootstrap resampling with non linear regression. The resulting plots are presented in Figure 5. The estimated parameters are $\hat{a}_{bs} = 14.566$ and $\hat{b}_{bs} = 7.110$. The code executes the following steps to estimate the parameters:

- **Generate Bootstrap Samples:** WE create 1000 resampled datasets of size 100 by drawing with replacement from the 50 original observations.
- **Fit a Nonlinear Regression Model:** For each bootstrap sample, we estimate parameters a and b using Nonlinear Least Squares (NLS) with the model.

- **Compute Bootstrap Estimates:** The final bootstrap estimates are obtained by averaging the parameter estimates from all bootstrap samples:
- **Predict Values Using Bootstrap Estimates:** Using the estimated parameters $\hat{a}_{\text{bs}}, \hat{b}_{\text{bs}}$, we compute the predicted values:

$$\hat{y}_{\text{bs}} = \frac{\hat{a}_{\text{bs}}x}{\hat{b}_{\text{bs}} + x} \quad (12)$$

```

1 num_samples <- 1000
2 sample_size <- 100
3
4 # 1000 bootstrap samples of size 100 with replacement
5 bootstrap_samples <- lapply(1:num_samples, function(i)
6   df[sample(nrow(df), sample_size, replace = TRUE), ])
7
8 fit_bootstrap_nls <- function(data) {
9   model <- nls(y ~ (a * x) / (b + x),
10    data = data,
11    start = list(a = 1, b = 1)) # Initial guesses
12   return(coef(model))
13 }
14
15 # Apply NLS to each bootstrap sample
16 nlsbs <- lapply(bootstrap_samples, fit_bootstrap_nls)
17
18 # Convert list of bootstrap estimates to a matrix
19 bootstrap_estimates <- do.call(rbind, nlsbs)
20 colnames(bootstrap_estimates) <- c("a", "b")
21
22 # Compute mean estimates for a and b
23 a_hat_bs <- mean(bootstrap_estimates[, "a"], na.rm = TRUE)
24 b_hat_bs <- mean(bootstrap_estimates[, "b"], na.rm = TRUE)
25
26 # Print results
27 cat("Bootstrap Estimated a:", a_hat_bs, "\n")
28 cat("Bootstrap Estimated b:", b_hat_bs, "\n")
29
30 df$predicted_bs <- (a_hat_bs * df$x) / (b_hat_bs + df$x)
31
32
33 # Plot with Jackknife predictions and legend
34 p_bs <- ggplot(df, aes(x = x, y = y)) +
35   geom_point(color = "blue", alpha = 0.5, size = 3) +
36   geom_line(aes(y = Predicted, color = "Full Sample Prediction"),
37     linewidth = 1, linetype = "dashed") +
38   geom_line(aes(y = predicted_jk, color = "Jackknife Prediction"),
39     linewidth = 1) +
40   geom_line(aes(y = predicted_bs, color = "Bootstrap Prediction"),
41     linewidth = 1) +
42   labs(title = "Nonlinear Regression: Full Sample vs. Jackknife vs.
43     Bootstrap",
44     x = "X", y = "Y", color = "Legend") +
45   theme_minimal() +
46   scale_color_manual(values = c("Full Sample Prediction" = "red",
47     "Jackknife Prediction" = "green",
48     "Bootstrap Prediction" = "blue"))

```

Listing 3: Bootstrap resampling code in R

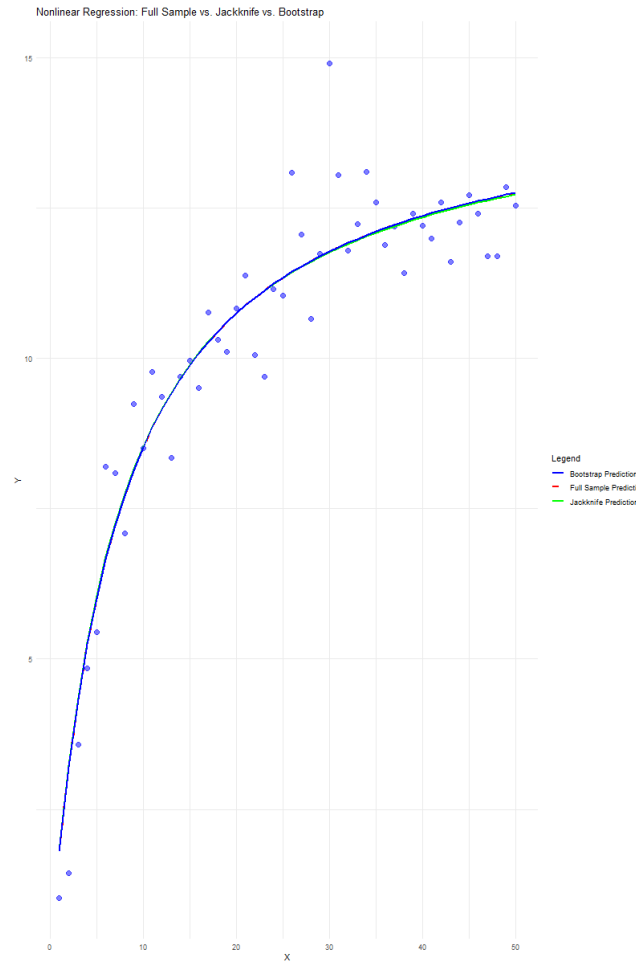


Figure 5: Nonlinear regression fit: observed vs. predicted values including Jackknife and Bootstrap predictions

4.2 For the Jackknife estimator, find a 95% confidence interval using the normal distribution and the t-distribution. For the Bootstrap estimator, find a 95% normal, t and empirical confidence intervals.

The following results were obtained for the Jackknife resampling method:

- 95% conf. interval for a using normal distribution: [14.14397 , 14.86412]
- 95% conf. interval for b using normal distribution: [6.356596 , 7.635241]
- 95% conf. interval for a using t-distribution: [13.99397 , 15.01412]

- 95% conf. interval for b using t-distribution: [6.090267 , 7.90157]

The following results were obtained for the Bootstrap resampling method:

- conf. interval for a using normal distribution: [14.07722 , 15.05515]
- conf. interval for b using normal distribution: [6.111358 , 8.109172]
- conf. interval for a using t-distribution: [14.07663 , 15.05575]
- conf. interval for b using t-distribution: [6.110146 , 8.110384]
- conf. interval for a using empirical distribution: [14.08458 , 15.08578]
- conf. interval for b using empirical distribution: [6.132766 , 8.113393]

| Method | Confidence Interval for a | Confidence Interval for b |
|-----------------------------|-----------------------------|-----------------------------|
| Jackknife Resampling | | |
| Normal Distribution | [14.14397, 14.86412] | [6.356596, 7.635241] |
| t-Distribution | [13.99397, 15.01412] | [6.090267, 7.90157] |
| Bootstrap Resampling | | |
| Normal Distribution | [14.07722, 15.05515] | [6.111358, 8.109172] |
| t-Distribution | [14.07663, 15.05575] | [6.110146, 8.110384] |
| Empirical Distribution | [14.08458, 15.08578] | [6.132766, 8.113393] |

Table 1: Confidence Intervals for Parameters a and b Using Jackknife and Bootstrap Methods

5 Question 5 – The EM Algorithm

Consider a univariate K -Gaussian mixture model with probability density function:

$$f(x) = \sum_{l=1}^K \pi_l \phi(x, \mu_l, \sigma_l)$$

such that $\sum_{l=1}^K \pi_l = 1$ and $\pi_l > 0$ for all l , and where $\phi(x, \mu, \sigma)$ is the Gaussian density function. The EM algorithm for this works as follows:

1. Initialise $\mu_1^{(0)}, \dots, \mu_K^{(0)}, \sigma_1^{(0)}, \dots, \sigma_K^{(0)}, \pi_1^{(0)}, \dots, \pi_K^{(0)}$.
2. Let

$$\gamma_n^{(j,k)} = \frac{\pi_k \phi(x_n | \mu_k^{(j-1)}, \sigma_k^{(j-1)})}{\sum_{i=1}^K \pi_i \phi(x_n | \mu_i^{(j-1)}, \sigma_i^{(j-1)})}.$$

3. Let

$$\mu_k^{(J)} = \frac{1}{N_k} \sum_{n=1}^N \gamma_n^{(j,k)} x_n,$$

$$\sigma_k^{(J)} = \sqrt{\frac{1}{N_k} \sum_{n=1}^N \gamma_n^{(j,k)} (x_n - \mu_k^{(J)})^2},$$

and

$$\pi_k^{(J)} = \frac{N_{jk}}{N},$$

where

$$N_{jk} = \sum_{n=1}^N \gamma_n^{(j,k)}.$$

5.1 Simulate 1000 readings from a mixture Gaussian distribution with 3 or more Gaussians.

The following function generalizes the code provided in the question so that an arbitrary number of samples are generated from any number of Gaussian distributions. The function also lists the number of samples selected from each Gaussian to ensure that acceptable proportions were attained for each sample and plots a distribution of the data and plots of the Gaussians.

```

1 library(ggplot2)
2
3 generate_samples <- function(
4   mixing_coefficients,
5   means,
6   standard_deviations,
7   number_of_samples = 1000) {
8
9     # should check that lengths are equal
10
11     data <- c()
12     choices_count <- rep(0, length(mixing_coefficients))
13
14     # select one of the gaussian distributions according
15     # to the mixing coefficients
16     choices <- sample(
17       x = seq_along(mixing_coefficients),
18       size = number_of_samples,
19       prob = mixing_coefficients,
20       replace = TRUE)
21
22     # let us see that the number of selections make sense
23     for (i in 1:number_of_samples){
24       choices_count[choices[i]] <-
25         choices_count[choices[i]] + 1
26     }
27     print(choices_count)
28
29     # for each selection, sample from the gaussian
30     data <- c(
31       data,
32       rnorm(
33         n = number_of_samples,
34         mean = means[choices],
35         sd = standard_deviations[choices]))
36
37     # plot histogram and gaussian curves
38     df <- data.frame(data)
39
40     p <- ggplot(df, aes(x = data)) +
41       geom_histogram(
42         aes(y = ..density..),
43         bins = 30,
44         fill = "blue",
45         alpha = 0.6) +
46       stat_function(fun = function(x) {
47         Reduce('+', lapply(1:length(means), function(i) {
48           dnorm(
49             x = x,
50             mean = means[i],
51             sd = standard_deviations[i]) *
52             mixing_coefficients[i]
53         })
54       }, color = "red") +
55       labs(title = "Histogram of Mixture of Gaussians",
56            x = "Value",
57            y = "Density") +
58       theme_bw()
59
60     print(p)
61 }

```

Listing 4: Gaussian mixture sample generation code in R

Data from the mixed Gaussian distributions was subsequently generated using the parameters below. The plot that was obtained as a result of this process is shown in Figure 6

| | | |
|---------------|--------------|------------------|
| $\pi_1 = 0.2$ | $\mu_1 = 6$ | $\sigma_1 = 2.0$ |
| $\pi_2 = 0.5$ | $\mu_2 = 0$ | $\sigma_2 = 1.0$ |
| $\pi_3 = 0.3$ | $\mu_3 = -7$ | $\sigma_3 = 1.5$ |

```

1 mixing_coefficients <- c(0.2, 0.5, 0.3)
2 means <- c(6, 0, -7)
3 standard_deviations <- c(2, 1, 1.5)
4
5 generate_samples(mixing_coefficients, means,
  standard_deviations)

```

Listing 5: Generation of data for this question

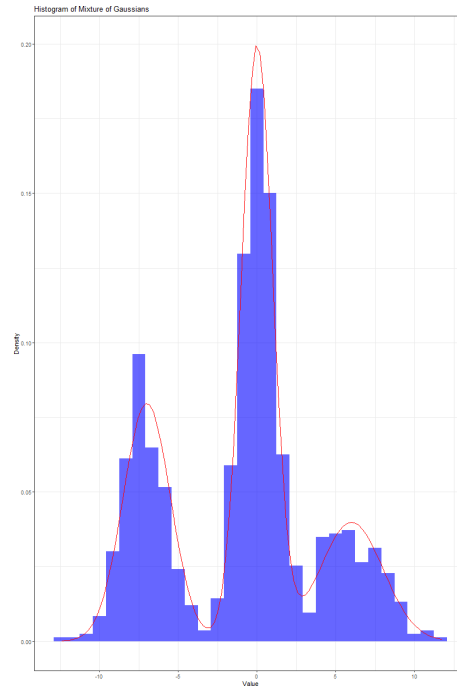


Figure 6: Distribution of generated data

5.2 Determine initial values $\mu_1^{(0)}, \dots, \mu_K^{(0)}, \sigma_1^{(0)}, \dots, \sigma_K^{(0)}, \pi_1^{(0)}, \dots, \pi_K^{(0)}$ using a K-means clustering approach or otherwise.

The function in Listing 6 is a custom implementation of a k-means algorithm to initialize parameters($\mu^{(0)}$, $\sigma^{(0)}$, and $\pi^{(0)}$) for a Gaussian mixture model. Its salient features are the following:

- After the initial centroids are randomly selected, the k-means algorithm iteratively assigns the data point to the closest centroid based on the absolute distance. The cluster centroids are then updated as the means of the points assigned to each cluster until the change in centroids is small or the threshold number of iterations is reached.
- The means of each centroid is, as we have discussed above, the centroid of each cluster.
- the standard deviation is calculated as follows

$$\sigma_j = \begin{cases} \sqrt{\frac{1}{n_j} \sum_{x_i \in C_j} (x_i - \mu_j)^2}, & \text{if } n_j > 0 \\ 0, & \text{otherwise} \end{cases}$$

Where:

- σ_j is the standard deviation for cluster j ,
- C_j is the set of points in cluster j ,
- n_j is the number of points in cluster j ,
- x_i are the individual data points in cluster j ,
- μ_j is the centroid (mean) of cluster j ,
- The initial values for the mixing coefficients of the Gaussian Mixture Model are computed as:

$$\pi_j = \begin{cases} \frac{n_j}{N}, & \text{if } n_j > 0 \\ 0, & \text{otherwise} \end{cases}$$

Where:

- π_j is the mixing coefficient for cluster j ,
- n_j is the number of data points in cluster j ,
- N is the total number of data points in the dataset,

```

1 initial_values_knn <- function(data, k = 3) {
2   set.seed(42) # For reproducibility
3
4   # Randomly select k initial centroids
5   centroids <- sample(x = data, size = k, replace = FALSE)
6
7   # Initialize empty clusters
8   clusters <- vector(mode = "list", length = k)
9
10  for (iteration in 1:100) {
11    # Reset clusters
12    clusters <- vector(mode = "list", length = k)
13
14    # Assign each data point to the closest centroid
15    for (item in data) {
16      distances <- abs(item - centroids)
17      closest_centroid <- which.min(distances)
18      clusters[[closest_centroid]] <-
19        c(clusters[[closest_centroid]], item)
20    }
21
22    # Compute new centroids
23    new_centroids <- sapply(1:k, function(i) {
24      if (length(clusters[[i]]) > 0) {
25        mean(clusters[[i]])
26      } else {
27        centroids[i] # Keep old centroid
28        if no points are assigned
29      }
30    })
31
32    # Check for convergence
33    if (max(abs(new_centroids - centroids)) < 0.0001) {
34      break
35    }
36
37    centroids <- new_centroids
38
39    # Compute standard deviations
40    clusters_standard_devs <- sapply(1:k,
41      function(cluster_idx) {
42        if (length(clusters[[cluster_idx]]) > 0) {
43          sqrt(sum((clusters[[cluster_idx]] -
44            centroids[cluster_idx])^2) /
45            length(clusters[[cluster_idx]]))
46        } else {
47          0
48        }
49      })
50
51    # Compute mixing coefficients for each cluster
52    mixing_coefficients <- sapply(1:k, function(cluster_idx) {
53      length(clusters[[cluster_idx]]) / length(data)
54    })
55
56    return(list(
57      centroids = centroids,
58      standard_devs = clusters_standard_devs,
59      mixing_coefficients = mixing_coefficients))
60  }

```

Listing 6: k-means algorithm to compute the initial values of the mixed Gaussian model parameters

The results obtained from this function are as follows:

| | | |
|-----------------|------------------|--------------------|
| $\pi_1 = 0.179$ | $\mu_1 = 6.353$ | $\sigma_1 = 1.685$ |
| $\pi_2 = 0.545$ | $\mu_2 = 0.104$ | $\sigma_2 = 1.107$ |
| $\pi_3 = 0.276$ | $\mu_3 = -6.942$ | $\sigma_3 = 1.508$ |

Table 2: Estimated parameters for the initial values of Gaussian mixture model

5.3 Run the EM algorithm for a number of iterations. Print $\mu_1^{(j)}, \dots, \mu_k^{(j)}, \sigma_1^{(j)}, \dots, \sigma_k^{(j)}, \pi_1^{(j)}, \dots, \pi_k^{(j)}$ for each iteration, and also the log-likelihood, which is given by: $\sum_{n=1}^N \ln \left(\sum_{l=1}^K \phi(x_n | \mu_l^{(j)}, \sigma_l^{(j)}) \right)$. Determine when to stop the EM algorithm, either via a maximum number of iterations or through a convergence criterion. However, ensure that the EM algorithm has converged. Plot the trajectory of the estimates and the likelihood by iteration to illustrate this.

We start by examining the code created to execute this question, which is presented below in four listings.

- Listing 7 contains the estimation step code that computes the responsibility of each Gaussian component for each data point as:

$$\gamma_{n,k} = \frac{\pi_k \phi(x_n | \mu_k, \sigma_k)}{\sum_{j=1}^K \pi_j \phi(x_n | \mu_j, \sigma_j)}$$

Where:

- $\gamma_{n,k}$ is the responsibility of Gaussian k for data point x_n .
- π_k is the mixing coefficient for Gaussian k .
- $\phi(x_n | \mu_k, \sigma_k)$ is the Gaussian probability density function:

$$\phi(x_n | \mu_k, \sigma_k) = \frac{1}{\sigma_k \sqrt{2\pi}} \exp \left(-\frac{(x_n - \mu_k)^2}{2\sigma_k^2} \right).$$

- Listing 8 illustrates the maximization step of the EM algorithm that updates the parameters as follows:
 - We update the mixing coefficients to calculate the proportion of data points that belong to a given Gaussian distribution:

$$\pi_k^{(j)} = \frac{N_k^{(j)}}{N}$$

Where:

$$N_k^{(j)} = \sum_{n=1}^N \gamma_{n,k}^{(j)}$$

Is the total responsibility weight assigned to Gaussian k ?

- We update the means to compute the weighted mean of the data points assigned to each Gaussian:

$$\mu_k^{(j)} = \frac{\sum_{n=1}^N \gamma_{n,k}^{(j)} x_n}{N_k^{(j)}}$$

- We update the standard deviations to calculate the spread of the data points around the updated mean for each Gaussian:

$$\sigma_k^{(j)} = \sqrt{\frac{\sum_{n=1}^N \gamma_{n,k}^{(j)} (x_n - \mu_k^{(j)})^2}{N_k^{(j)}}}$$

- We then calculate the log-likelihood function for our Gaussian mixture model using the code in Listing 9 using the suggested formulation:

$$\mathcal{L} = \sum_{n=1}^N \ln \left(\sum_{k=1}^K \pi_k \phi(x_n | \mu_k, \sigma_k) \right)$$

Where:

- \mathcal{L} is the log-likelihood of the data.
- K is the number of Gaussian components.
- N is the number of data points.
- π_k is the mixing coefficient for Gaussian k .
- $\phi(x_n | \mu_k, \sigma_k)$ is the Gaussian probability density function:

$$\phi(x_n | \mu_k, \sigma_k) = \frac{1}{\sigma_k \sqrt{2\pi}} \exp \left(-\frac{(x_n - \mu_k)^2}{2\sigma_k^2} \right)$$

- Listing 10 shows the execution of the EM algorithm, starting from the generation of data to the estimation of the initial values and ending with the actual estimates using the EM algorithm. We notice that EM is allowed a maximum of execution 100 steps, but optimization will stop if the change in log-likelihood is smaller than 10^{-5} .

```

1 expectation_step <- function(data, means, standard_deviations,
2   mixing_coefficients) {
3     number_of_gaussians <- length(mixing_coefficients)
4
5     # Initialize gamma matrix
6     gamma <- matrix(0, nrow = length(data), ncol =
7       number_of_gaussians)
8
9     # Calculate denominator (total probability for each data
10    point)
11    den_total <- 0
12    for (k in 1:number_of_gaussians) {
13      den_total <- den_total + mixing_coefficients[k] *
14        dnorm(data, mean = means[k], sd =
15          standard_deviations[k])
16    }
17
18    # Calculate numerator and compute gamma
19    for (k in 1:number_of_gaussians) {
20      gamma[, k] <- (mixing_coefficients[k] *
21        dnorm(data, mean = means[k], sd =
22          standard_deviations[k])) / den_total
23    }
24
25    return(gamma)
26  }

```

Listing 7: Estimation step code in R

```

1 maximization_step <- function(data, gamma, means,
2   standard_deviations, mixing_coefficients) {
3
4     no_gaussians <- length(mixing_coefficients)
5     m <- length(data)
6
7     # Compute cluster responsibilities
8     m_c <- colSums(gamma) # Sum of responsibilities for each
      Gaussian
9
10    # Compute new mixing coefficients
11    new_mixing_coefficients <- m_c / m
12
13    # Initialize new means and standard deviations
14    new_means <- numeric(no_gaussians)
15    new_standard_deviations <- numeric(no_gaussians)
16
17    # Compute new means and standard deviations for each
      Gaussian
18    for (k in 1:no_gaussians) {
19      new_means[k] <- sum(gamma[, k] * data) / m_c[k]
20      new_standard_deviations[k] <- sqrt(sum(gamma[, k]
      * (data - means[k])^2) / m_c[k])
21    }
22
23    return(list(
24      means = new_means,
25      standard_devs = new_standard_deviations,
26      mixing_coefficients = new_mixing_coefficients
27    ))
28 }

```

Listing 8: Maximization step code in R

```

1 log_likelihood <- function(data, means, standard_deviations,
2   mixing_coefficients) {
3     number_of_gaussians <- length(mixing_coefficients)
4
5     # Initialize likelihood matrix
6     likelihood <- matrix(0, nrow = length(data), ncol =
7       number_of_gaussians)
8
9     # Compute likelihood for each Gaussian component
10    for (k in 1:number_of_gaussians) {
11      likelihood[, k] <- mixing_coefficients[k] *
12        dnorm(data, mean = means[k], sd =
13          standard_deviations[k])
14    }
15
16    # Compute the log-likelihood
17    log_likelihood_value <- sum(log(rowSums(likelihood)))
18
19    return(log_likelihood_value)
20 }

```

Listing 9: Log-likelihood code in R

```

1 mixing_coefficients <- c(0.2, 0.5, 0.3)
2 means <- c(6, 0, -7)
3 standard_deviations <- c(2, 1, 1.5)
4
5 # generate the data
6 data <- generate_samples(mixing_coefficients, means,
7                           standard_deviations)
8
9 # initial values
10 kmeans_ret <- initial_values_kmeans(data)
11
12 centroids <- kmeans_ret$centroids
13 standard_devs <- kmeans_ret$standard_devs
14 mixing_coefficients <- kmeans_ret$mixing_coefficients
15
16 print("initial values")
17 print(centroids)
18 print(standard_devs)
19 print(mixing_coefficients)
20
21 log_likelihoods <- c()
22 for (i in 1:100) {
23     gamma <- expectation_step(data, centroids, standard_devs,
24                               mixing_coefficients)
25
26     max_ret <- maximization_step(data, gamma, centroids,
27                                  standard_devs, mixing_coefficients)
28
29     centroids <- max_ret$means
30     standard_devs <- max_ret$standard_devs
31     mixing_coefficients <- max_ret$mixing_coefficients
32
33     ll <- log_likelihood(data, means, standard_devs,
34                          mixing_coefficients)
35
36     log_likelihoods <- c(log_likelihoods, ll)
37
38     if (i>2 && abs(ll - log_likelihoods[i-1]) < 1e-5) {
39         print("converged")
40         break
41     }
42 }
43 # form string
44 iteration_result_str <- paste( "iteration: ", i)
45 for (j in 1:length(centroids)) {
46     iteration_result_str <-
47         paste(iteration_result_str, " c",j,": ",
48               format(centroids[j],3))
49     iteration_result_str <-
50         paste(iteration_result_str, " s",j,": ",
51               format(standard_devs[j],3))
52     iteration_result_str <-
53         paste(iteration_result_str, " m",j,": ",
54               format(mixing_coefficients[j],3))
55 }
56 print(iteration_result_str)
57 }

```

Listing 10: Execution code for this question

The parameters obtained after each iteration are shown in Table 3. The algorithm converged after 28 iterations. A plot of the log likelihood at each iteration can be observed in Figure 7

| Step | π_1 | σ_1 | μ_1 | π_2 | σ_2 | μ_2 | π_3 | σ_3 | μ_3 | \mathcal{L} |
|------|---------|------------|---------|---------|------------|---------|---------|------------|---------|---------------|
| 1 | 6.259 | 1.780 | 0.183 | 0.088 | 1.101 | 0.541 | -6.936 | 1.519 | 0.276 | -2666.447 |
| 2 | 6.208 | 1.824 | 0.186 | 0.078 | 1.090 | 0.538 | -6.935 | 1.520 | 0.276 | -2665.715 |
| 3 | 6.176 | 1.850 | 0.187 | 0.071 | 1.084 | 0.537 | -6.935 | 1.521 | 0.276 | -2665.371 |
| 4 | 6.155 | 1.868 | 0.188 | 0.067 | 1.079 | 0.536 | -6.934 | 1.521 | 0.276 | -2665.192 |
| 5 | 6.142 | 1.880 | 0.189 | 0.065 | 1.077 | 0.535 | -6.934 | 1.521 | 0.276 | -2665.092 |
| 6 | 6.132 | 1.888 | 0.189 | 0.063 | 1.075 | 0.534 | -6.934 | 1.522 | 0.276 | -2665.033 |
| 7 | 6.126 | 1.893 | 0.189 | 0.062 | 1.074 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.996 |
| 8 | 6.122 | 1.897 | 0.190 | 0.061 | 1.073 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.973 |
| 9 | 6.119 | 1.900 | 0.190 | 0.061 | 1.073 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.958 |
| 10 | 6.117 | 1.901 | 0.190 | 0.061 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.947 |
| 11 | 6.115 | 1.903 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.941 |
| 12 | 6.114 | 1.903 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.936 |
| 13 | 6.114 | 1.904 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.933 |
| 14 | 6.113 | 1.904 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.931 |
| 15 | 6.113 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.929 |
| 16 | 6.113 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.928 |
| 17 | 6.113 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.928 |
| 18 | 6.113 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.927 |
| 19 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.927 |
| 20 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.927 |
| 21 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 22 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 23 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 24 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 25 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 26 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 27 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |
| 28 | 6.112 | 1.905 | 0.190 | 0.060 | 1.072 | 0.534 | -6.934 | 1.522 | 0.276 | -2664.926 |

Table 3: EM iterations results table

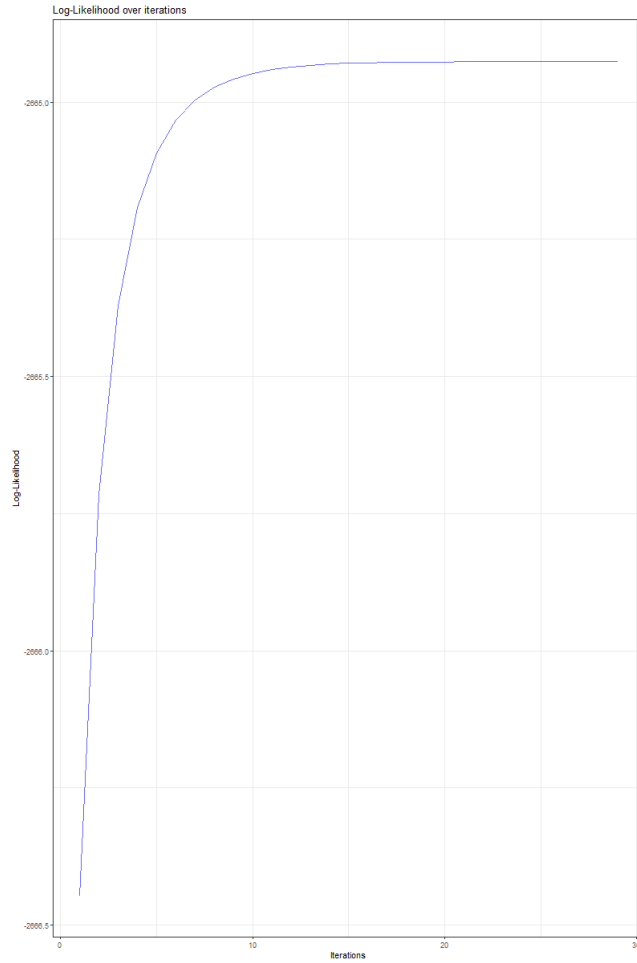


Figure 7: Log-likelihood vs iterations for the execution of the EM algorithm until convergence

5.4 Give the final estimated μ_k 's, σ_k 's and π_k 's. How do these compare with the coefficients you chose in the simulation?

The final estimated values compared to the chosen ones are listed in Table 4. The estimated values are very close to the initially chosen values, confirming that the initial assumptions were reasonable. The final log-likelihood value of -2664.926 indicates that the EM algorithm successfully converged to a stable solution. The minor parameter adjustments demonstrate that the algorithm effectively fine-tuned the initial estimates based on the data. The estimated values align closely with the assumed mixture structure, validating the underlying-

ing data distribution. Minor shifts in mixing coefficients, means, and standard deviations suggest that while the clusters generally adhered to the expected patterns, some exhibited slightly different densities than initially assumed. The successful convergence of the model indicates that the algorithm reached a local maximum of the likelihood function, further confirming the robustness of the estimation process.

| Distribution | Parameter | Chosen Value | Estimated Value |
|----------------|------------|--------------|-----------------|
| Distribution 1 | π_1 | 0.200000 | 0.1901318 |
| | μ_1 | 6.000000 | 6.112331 |
| | σ_1 | 2.000000 | 1.905292 |
| Distribution 2 | π_2 | 0.500000 | 0.5335142 |
| | μ_2 | 0.000000 | 0.05972212 |
| | σ_2 | 1.000000 | 1.071750 |
| Distribution 3 | π_3 | 0.300000 | 0.276354 |
| | μ_3 | -7.000000 | -6.933639 |
| | σ_3 | 1.500000 | 1.521854 |

Table 4: Chosen vs. estimated parameters

References

- [1] Jalal Mahmud, Jilin Chen, and Jeffrey Nichols. When will you answer this? estimating response time in twitter. In *Proceedings of the International AAAI Conference on Web and Social Media*, volume 7, pages 697–700, 2013.