

---

## *Half Title*

---

Solution Manual  
Introduction to Bayesian Inference:  
A GUIDed toolkit using R



---

# *Title Page*

---

Solution Manual  
Introduction to Bayesian Inference:  
A GUIDed toolkit using R

by Andrés Ramírez-Hassan, PhD. Statistical Science.



*To my parents, Nancy and Orlando.*



---

# *Contents*

---

Foreword	ix
Preface	xi
Symbols	xiii
<b>I Foundations: Theory, simulation methods and programming</b>	<b>1</b>
1 Basic formal concepts	3
1.1 Solutions of Exercises	3
2 Conceptual differences of the Bayesian and Frequentist approaches	23
2.1 Solutions of Exercises	23
3 Cornerstone models: Conjugate families	29
3.1 Solutions of Exercises	29
4 Simulation methods	53
4.1 Solutions of Exercises	53
<b>II Regression models: A GUIDed toolkit</b>	<b>55</b>
5 Graphical user interface	57
5.1 Introduction	57
5.2 Univariate models	59
5.3 Multivariate models	62
5.4 Time series model	64
5.5 Longitudinal/panel models	64
5.6 Bayesian model average	65
5.7 Warning	67
6 Univariate models	69
6.1 Solutions of Exercises	69
7 Multivariate models	91
7.1 Solutions of Exercises	91

<b>8 Time series models</b>	<b>115</b>
8.1 Solutions of Exercises . . . . .	115
<b>9 Longitudinal/Panel data models</b>	<b>121</b>
9.1 Solutions of Exercises . . . . .	121
<b>10 Bayesian model average</b>	<b>149</b>
10.1 Solutions of Exercises . . . . .	149
<b>III <i>Advanced</i> methods: A brief introduction</b>	<b>171</b>
<b>Bibliography</b>	<b>173</b>
<b>Appendix</b>	<b>175</b>



---

## *Foreword*





---

## *Preface*

---



---

# *Symbols*

---

## Symbol Description

$\neg$	Negation symbol.	$\mathcal{R}$	The Real set.
$\propto$	Proportional symbol.	$\emptyset$	Empty set.
$\perp$	Independence symbol.	$\mathbb{1}$	Indicator function.



## Part I

# Foundations: Theory, simulation methods and programming





# 1

## *Basic formal concepts*

### 1.1 Solutions of Exercises

#### 1. *The court case: the blue or green cap*

A cab was involved in a hit and run accident at night. There are two cab companies in the town: blue and green. The former has 150 cabs, and the latter 850 cabs. A witness said that a blue cab was involved in the accident; the court tested his/her reliability under the same circumstances, and got that 80% of the times the witness correctly identified the color of the cab. *What is the probability that the color of the cab involved in the accident was blue given that the witness said it was blue?*

#### **Answer**

Set  $WB$  and  $WG$  equal to the events that the witness said the cab was blue and green, respectively. Set  $B$  and  $G$  equal to the events that the cabs are blue and green, respectively. We need to calculate  $P(B|WB)$ , then:

$$\begin{aligned} P(B|WB) &= \frac{P(B, WB)}{P(WB)} \\ &= \frac{P(WB|B) \times P(B)}{P(WB|B) \times P(B) + (1 - P(WB|B)) \times (1 - P(B))} \\ &= \frac{0.8 \times 0.15}{0.8 \times 0.15 + 0.2 \times 0.85} \\ &= 0.41 \end{aligned} \tag{1.1}$$

#### 2. *The Monty Hall problem*

What is the probability of winning a car in the *Monty Hall problem* switching the decision if there are four doors, where there are three goats and one car? Solve this problem analytically and computationally. What if there are  $n$  doors,  $n - 1$  goats and one car?

#### **Answer**

Let's name  $P_i$  the event *contestant picks door No.  $i$* ,  $H_i$  the event *host picks door No.  $i$* , and  $C_i$  the event *car is behind door No.  $i$* . Let's assume that the

contestant picked door number 1, and the host picked door number 3, then the contestant is interested in the probability of the event  $P(C_i|H_3, P_1)$ ,  $i = 2$  or  $4$ . Then,  $P(H_3|C_3, P_1) = 0$ ,  $P(H_3|C_2, P_1) = P(H_3|C_4, P_1) = 1/2$  and  $P(H_3|C_1, P_1) = 1/3$ . Then,

$$\begin{aligned}
 P(C_i|H_3, P_1) &= \frac{P(C_i, H_3, P_1)}{P(H_3, P_1)} \\
 &= \frac{P(H_3|C_i, P_1)P(C_i|P_1)P(P_1)}{P(H_3|P_1) \times P(P_1)} \\
 &= \frac{P(H_3|C_i, P_1)P(C_i)}{P(H_3|P_1)} \\
 &= \frac{1/2 \times 1/4}{1/3} \\
 &= \frac{3}{8},
 \end{aligned} \tag{1.2}$$

where the third equation uses the fact that  $C_i$  and  $P_i$  are independent events, and  $P(H_3|P_1) = 1/3$  due to this depending just on  $P_1$  (not on  $C_i$ ).

Therefore, changing the initial decision increases the probability of getting the car from  $1/4$  to  $3/8$ !

Let's check the case with  $n$  doors, and assume that the contestant picks the door No. 1, the car is behind the door No.  $n$ , and the host, who knows what is behind each door, opens any of the remaining  $n - 2$  doors, where there is a goat. The contestant is interested in the probability of the event:

$$\begin{aligned}
 P(C_n|(H_2 \cup \dots \cup H_{n-1}) \cap P_1) &= \frac{P((H_2 \cup H_3 \cup \dots \cup H_{n-1})|C_n \cap P_1)P(C_n|P_1)P(P_1)}{P((H_2 \cup H_3 \cup \dots \cup H_{n-1})|P_1)P(P_1)} \\
 &= \frac{[P(H_2|C_n \cap P_1) + \dots + P(H_{n-1}|C_n \cap P_1)]P(C_n)}{P(H_2|P_1) + P(H_3|P_1) + \dots + P(H_{n-1}|P_1)} \\
 &= \frac{1 \times (\frac{1}{n})}{\frac{1}{n-1} + \frac{1}{n-1} + \dots + \frac{1}{n-1}} \\
 &= \left(\frac{1}{n}\right) \left(\frac{n-1}{n-2}\right).
 \end{aligned} \tag{1.3}$$

In general, the probability of winning the car changing the pick is  $\frac{1}{n} \frac{n-1}{n-2}$ , while the probability of winning given no change is  $\frac{1}{n}$ . Given that  $\frac{1}{n} \frac{n-1}{n-2} > \frac{1}{n}$  for all  $n \geq 3$ , where the difference between both probabilities is  $\frac{1}{n(n-2)}$ . We observe that as the number of doors increases, the difference between the two probabilities becomes zero.

Let's see a code for the general setting,

*R code. The Monty Hall Problem*

```

1 set.seed(0101) # Set simulation seed
2 S <- 100000 # Simulations
3 Game <- function(opt = 3){
4   # opt: number of options. opt > 2
5   opts <- 1:opt
6   car <- sample(opts, 1) # car location
7   guess1 <- sample(opts, 1) # Initial guess
8   if(opt == 3 && car != guess1) {
9     host <- opts[-c(car, guess1)]
10    } else {
11    host <- sample(opts[-c(car, guess1)], 1)
12  }
13  win1 <- guess1 == car # Win given no change
14  if(opt == 3) {
15    guess2 <- opts[-c(host, guess1)]
16  } else {
17    guess2 <- sample(opts[-c(host, guess1)], 1)
18  }
19  win2 <- guess2 == car # Win given change
20  return(c(win1, win2))
21 }
22 #Win probabilities
23 Prob <- rowMeans(replicate(S, Game(opt = 4)))
24 #Winning probabilities no changing door
25 Prob[1]
26 0.25151
27 #Winning probabilities changing door
28 Prob[2]
29 0.37267

```

3. Solve the health insurance example using a Gamma prior in the rate parametrization, that is,  $\pi(\lambda) = \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \lambda^{\alpha_0-1} \exp\{-\lambda\beta_0\}$ .

**Answer**

First, we get the posterior distribution,

$$\pi(\lambda|\mathbf{y}) = \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \lambda^{\alpha_0-1} e^{-\lambda\beta_0} \right) \left( \prod_{i=1}^N \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \right) \quad (1.4)$$

$$\begin{aligned}
&= \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \lambda^{\alpha_0-1} e^{-\lambda\beta_0} \right) \left( \frac{\lambda^{\sum_{i=1}^N y_i} e^{-N\lambda}}{\prod_{i=1}^N y_i!} \right) \\
&= \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \frac{1}{\prod_{i=1}^N y_i!} \right) \lambda^{\sum_{i=1}^N y_i + \alpha_0 - 1} e^{-\lambda(\beta_0 + N)} \\
&\propto \lambda^{\sum_{i=1}^N y_i + \alpha_0 - 1} e^{-\lambda(\beta_0 + N)}.
\end{aligned} \tag{1.5}$$

The last expression is the kernel of a Gamma distribution with parameters  $\alpha_n = \sum_{i=1}^N y_i + \alpha_0$  and  $\beta_n = \beta_0 + N$ .

Given that  $\int_0^\infty \pi(\lambda|\mathbf{y}) d\lambda = 1$ , then the constant of proportionality in the last expression is  $\Gamma(\alpha_n) / \beta_n^{\alpha_n}$ . Therefore the posterior density function  $\pi(\lambda|\mathbf{y})$  is  $G(\alpha_n, \beta_n)$ .

The posterior mean is

$$\begin{aligned}
E[\lambda|\mathbf{y}] &= \frac{\alpha_n}{\beta_n} \\
&= \frac{\sum_{i=1}^N y_i + \alpha_0}{\beta_0 + N} \\
&= \left( \frac{N}{\beta_0 + N} \right) \bar{y} + \left( \frac{\beta_0}{\beta_0 + N} \right) \frac{\alpha_0}{\beta_0} \\
&= w\bar{y} + (1-w) E[\lambda],
\end{aligned} \tag{1.6}$$

where  $w = \frac{N}{\beta_0 + N}$ ,  $\bar{y}$  is the sample mean, and  $E[\lambda] = \frac{\alpha_0}{\beta_0}$ .

The posterior predictive distribution is given by

$$\begin{aligned}
\pi(Y_0|\mathbf{y}) &= \int_0^\infty \frac{\lambda^{y_0} e^{-\lambda}}{y_0!} \pi(\lambda|\mathbf{y}) d\lambda \\
&= \int_0^\infty \left( \frac{\lambda^{y_0} e^{-\lambda}}{y_0!} \right) \left( \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n)} \lambda^{\alpha_n-1} e^{-\lambda\beta_n} \right) d\lambda \\
&= \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n) y_0!} \int_0^\infty \lambda^{y_0 + \alpha_n - 1} e^{-\lambda(1+\beta_n)} d\lambda \\
&= \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n) y_0!} \frac{\Gamma(y_0 + \alpha_n)}{(1 + \beta_n)^{y_0 + \alpha_n}} \\
&= \frac{\Gamma(y_0 + \alpha_n)}{\Gamma(\alpha_n) y_0!} \left( \frac{1}{1 + \beta_n} \right)^{y_0} \left( \frac{\beta_n}{1 + \beta_n} \right)^{\alpha_n}
\end{aligned} \tag{1.7}$$

$$\begin{aligned}
&= \frac{(y_0 + \alpha_n - 1)!}{(\alpha_n - 1)! y_0!} \left( \frac{1}{1 + \beta_n} \right)^{y_0} \left( \frac{\beta_n}{1 + \beta_n} \right)^{\alpha_n} \\
&= \binom{y_0 + \alpha_n - 1}{y_0} \left( \frac{1}{1 + \beta_n} \right)^{y_0} \left( \frac{\beta_n}{1 + \beta_n} \right)^{\alpha_n}.
\end{aligned}$$

Therefore  $Y_0|y \sim NB(\alpha_n, p_n)$  where  $p_n = \frac{1}{1+\beta_n}$ .

To use empirical Bayes, we have the following setting

$$[\hat{\alpha}_0, \hat{\beta}_0] = \arg \max_{\alpha_0, \beta_0} \ln(p(\mathbf{y})),$$

where

$$\begin{aligned}
p(y) &= \int_0^\infty \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \lambda^{\alpha_0-1} e^{-\lambda\beta_0} \right) \left( \prod_{i=1}^N \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \right) d\lambda \quad (1.8) \\
&= \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0) \prod_{i=1}^N y_i!} \right) \int_0^\infty \lambda^{\sum_{i=1}^N y_i + \alpha_0 - 1} e^{-\lambda(\beta_0 + N)} d\lambda \\
&= \left( \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0) \prod_{i=1}^N y_i!} \right) \left( \frac{\Gamma(\sum_{i=1}^N y_i + \alpha_0)}{(\beta_0 + N)^{\sum_{i=1}^N y_i + \alpha_0}} \right) \\
&= \frac{\Gamma(\sum_{i=1}^N y_i + \alpha_0)}{\Gamma(\alpha_0) \prod_{i=1}^N y_i!} \left( \frac{1}{\beta_0 + N} \right)^{\sum_{i=1}^N y_i} \left( \frac{\beta_0}{\beta_0 + N} \right)^{\alpha_0}.
\end{aligned}$$

*R code. Health insurance, predictive distribution  
using vague hyperparameters*

---

```

1 set.seed(010101)
2 y <- c(0, 3, 2, 1, 0) # Data
3 N <- length(y)
4
5 # Predictive distribution
6 ProbBo <- function(y, a0, b0){
7   N <- length(y)
8   #sample size
9   aN <- a0 + sum(y)
10  # Posterior shape parameter
11  bN <- b0 + N
12  # Posterior scale parameter
13  p <- 1 / (bN + 1)
14  # Probability negative binomial density
15  Pr <- 1 - pbinom(0, size = aN, prob = (1 - p))
16  # Probability of visiting the Doctor
17  # Observe that in R there is a slightly
18  # different parametrization.
19  return(Pr)
20 }
21
22 # Using a vague prior:
23 a0 <- 0.001 # Prior shape parameter
24 b0 <- 0.001 # Prior scale parameter
25 PriMeanV <- a0 / b0 # Prior mean
26 PriVarV <- a0 / b0^2 # Prior variance
27 Pp <- ProbBo(y, a0 = 0.001, b0 = 0.001)
28 # This setting is vague prior information.
29 Pp
30 0.67

```

---

*R code. Health insurance, predictive distribution  
using empirical Bayes*

```

1 # Using Empirical Bayes
2 LogMgLik <- function(theta, y){
3   N <- length(y)
4   #sample size
5   a0 <- theta[1]
6   # prior shape hyperparameter
7   b0 <- theta[2]
8   # prior scale hyperparameter
9   aN <- sum(y) + a0
10  # posterior shape parameter
11  if(a0 <= 0 || b0 <= 0){
12    #Avoiding negative values
13    lnp <- -Inf
14  }else{lnp <- lgamma(aN) - sum(y)*log(b0+1) + a0*log(b0/(b0
15    +1)) - lgamma(a0)}
16    # log marginal likelihood
17    return(-lnp)
18  }
19  theta0 <- c(0.01, 0.01)
20  # Initial values
21  control <- list(maxit = 1000)
22  EmpBay <- optim(theta0, LogMgLik, method = "BFGS", control =
23    control, hessian = TRUE, y = y)
24  # Optimization
25  EmpBay$convergence
26  # Checking convergence
27  EmpBay$value # Maximum
28  a0EB <- EmpBay$par[1]
29  # Prior shape using empirical Bayes
30  a0EB
31  128.383
32  b0EB <- EmpBay$par[2]
33  # Prior scale using empirical Bayes
34  b0EB
35  106.801
36  PriMeanEB <- a0EB / b0EB
37  # Prior mean
38  PriVarEB <- a0EB / b0EB^2
39  # Prior variance
40  PpEB <- ProbBo(y, a0 = a0EB, b0 = b0EB)
41  # This setting is using empirical Bayes.
42  PpEB
43  0.69

```

4. Suppose that you are analyzing to buy a car insurance next year. To make

a better decision you want to know *what is the probability that you have a car claim next year?* You have the records of your car claims in the last 15 years,  $\mathbf{y} = \{0, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 1, 0\}$ .

Assume that this is a random sample from a data generating process (statistical model) that is Bernoulli,  $Y_i \sim \text{Ber}(p)$ , and your probabilistic prior beliefs about  $p$  are well described by a beta distribution with parameters  $\alpha_0$  and  $\beta_0$ ,  $p \sim B(\alpha_0, \beta_0)$ , then, you are interested in calculating the probability of a claim the next year  $P(Y_0 = 1|\mathbf{y})$ .

Solve this using an empirical Bayes approach and a non-informative approach where  $\alpha_0 = \beta_0 = 1$  (uniform distribution).

**Answer**

The posterior distribution is given by

$$\begin{aligned} \pi(p|\mathbf{y}) &= \left[ \frac{\Gamma(\alpha_0 + \beta_0)}{\Gamma(\alpha_0)\Gamma(\beta_0)} p^{\alpha_0-1} (1-p)^{\beta_0-1} \right] \left[ \prod_{i=1}^N p^{y_i} (1-p)^{1-y_i} \right] \quad (1.9) \\ &= \frac{\Gamma(\alpha_0 + \beta_0)}{\Gamma(\alpha_0)\Gamma(\beta_0)} p^{\sum_{i=1}^N y_i + \alpha_0 - 1} (1-p)^{\beta_0 + N - \sum_{i=1}^N y_i - 1} \\ &\propto p^{\sum_{i=1}^N y_i + \alpha_0 - 1} (1-p)^{\beta_0 + N - \sum_{i=1}^N y_i - 1}. \end{aligned}$$

The last expression is the kernel of a Beta distribution with parameters  $\alpha_n = \sum_{i=1}^N y_i + \alpha_0$  and  $\beta_n = \beta_0 + N - \sum_{i=1}^N y_i$ . Thus, the posterior mean is

$$\begin{aligned} E[p|\mathbf{y}] &= \frac{\alpha_n}{\alpha_n + \beta_n} \\ &= \frac{\sum_{i=1}^N y_i + \alpha_0}{\alpha_0 + \beta_0 + N} \quad (1.10) \\ &= \frac{N\bar{y}}{\alpha_0 + \beta_0 + N} + \frac{\alpha_0}{\alpha_0 + \beta_0 + N} \\ &= \frac{N}{\alpha_0 + \beta_0 + N} (\bar{y}) + \frac{\alpha_0 + \beta_0}{\alpha_0 + \beta_0 + N} \left( \frac{\alpha_0}{\alpha_0 + \beta_0} \right) \\ &= w(\bar{y}) + (1-w)E[p], \end{aligned}$$

where  $w = \frac{N}{\alpha_0 + \beta_0 + N}$ ,  $\bar{y}$  is the sample mean, and  $E[p] = \frac{\alpha_0}{\alpha_0 + \beta_0}$  is the prior mean.

The posterior predictive distribution of claim the next year is given by



$$\begin{aligned}
\pi(Y_0 = 1|\mathbf{y}) &= \int_0^1 P(Y_0 = 1|\mathbf{y}, p) \pi(p|\mathbf{y}) dp \\
&= \int_0^1 p \times \pi(p|\mathbf{y}) dp \\
&= \mathbb{E}[p|\mathbf{y}] \\
&= \frac{\alpha_n}{\alpha_n + \beta_n}.
\end{aligned} \tag{1.11}$$

To use empirical Bayes, we have the following setting

$$[\hat{\alpha}_0 \ \hat{\beta}_0] = \arg \max_{\alpha_0, \beta_0} \ln(p(\mathbf{y})),$$

where

$$\begin{aligned}
p(\mathbf{y}) &= \int_0^1 \left[ \frac{\Gamma(\alpha_0 + \beta_0)}{\Gamma(\alpha_0) \Gamma(\beta_0)} p^{\alpha_0-1} (1-p)^{\beta_0-1} \right] \left[ \prod_{i=1}^N (1-p)^{1-y_i} \right] dp \tag{1.12} \\
&= \frac{\Gamma(\alpha_0 + \beta_0)}{\Gamma(\alpha_0) \Gamma(\beta_0)} \int_0^1 p^{\sum_{i=1}^N y_i + \alpha_0 - 1} (1-p)^{\beta_0 + N - \sum_{i=1}^N y_i - 1} dp \\
&= \frac{\Gamma(\alpha_0 + \beta_0)}{\Gamma(\alpha_0) \Gamma(\beta_0)} \frac{\Gamma\left(\sum_{i=1}^N y_i + \alpha_0\right) \Gamma\left(\beta_0 + N - \sum_{i=1}^N y_i\right)}{\Gamma(\alpha_0 + \beta_0 + N)}.
\end{aligned}$$

*R code. Car claim, predictive distribution using vague hyperparameters*

---

```

1 set.seed(010101)
2 y <- c(0, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 1, 0)
3 # Data
4 N <- length(y)
5 #require(TailRank)
6 # Predictive distribution
7 ProbBo <- function(y, a0, b0){
8   N <- length(y)
9   #sample size
10  aN <- a0 + sum(y)
11  # Posterior shape parameter
12  bN <- b0 + N - sum(y)
13  # Posterior scale parameter
14  pr <- aN / (aN + bN)
15  # Probability of a claim the next year
16  return(pr)
17 }
18 # Using a vague prior:
19 a0 <- 1 # Prior shape parameter
20 b0 <- 1 # Prior scale parameter
21 PriMeanV <- a0 / (a0 + b0)
22 # Prior mean
23 PriVarV <- (a0*b0) / (((a0+b0)^2)*(a0+b0+1))
24 # Prior variance
25 Pp <- ProbBo(y, a0 = 1, b0 = 1)
26 # This setting is defining vague prior information.
27 # The probability of a claim
28 Pp
29 0.47

```

---

*R code. Car claim, predictive distribution using empirical Bayes*

```

1 # Using Empirical Bayes
2 LogMgLik <- function(theta, y){
3   N <- length(y)
4   #sample size
5   a0 <- theta[1]
6   # prior shape hyperparameter
7   b0 <- theta[2]
8   # prior scale hyperparameter
9   aN <- sum(y) + a0
10  # posterior shape parameter
11  if(a0 <= 0 || b0 <= 0){
12    #Avoiding negative values
13    lnp <- -Inf
14  }else{lnp <- lgamma(a0+b0) + lgamma(aN) + lgamma(b0+N-sum(
15    y)) -lgamma(a0) - lgamma(b0) - lgamma(a0+b0+N)}
16  # log marginal likelihood
17  return(-lnp)
18 }
19 theta0 <- c(0.1, 0.1)
20 # Initial values
21 control <- list(maxit = 1000)
22 # Number of iterations in optimization
23 EmpBay <- optim(theta0, LogMgLik, method = "BFGS", control =
24   control, hessian = TRUE, y = y)
25 # Optimization
26 EmpBay$convergence
27 # Checking convergence
28 EmpBay$value # Maximum
29 a0EB <- EmpBay$par[1]
30 # Prior shape using empirical Bayes
31 b0EB <- EmpBay$par[2]
32 # Prior scale using empirical Bayes
33 PriMeanEB <- a0EB / (a0EB + b0EB)
34 # Prior mean
35 PriVarEB <- (a0EB*b0EB) / (((a0EB+b0EB)^2)*(a0EB+b0EB+1))
36 # Prior variance
37 PpEB <- ProbBo(y, a0 = a0EB, b0 = b0EB)
38 # This setting is using empirical Bayes.
39 PpEB
40 0.47

```

*R code. Car claim, density plots*

```

1 # Density figures
2 lambda <- seq(0.001, 1, 0.001)
3 # Values of lambda
4 VaguePrior <- dbeta(lambda, shape1 = a0, shape2 = b0)
5 EBPrior <- dbeta(lambda, shape1 = a0EB, shape2 = b0EB)
6 PosteriorV <- dbeta(lambda, shape1 = a0 + sum(y), shape2 =
  b0 + N - sum(y))
7 PosteriorEB <- dbeta(lambda, shape1 = a0EB + sum(y), shape2
  = b0EB + N - sum(y))
8 # Likelihood function
9 Likelihood <- function(theta, y){
10   LogL <- dbinom(y, 1, theta, log = TRUE)
11   # LogL <- dbern(y, theta)
12   Lik <- prod(exp(LogL))
13   return(Lik)
14 }
15 Liks <- sapply(lambda, function(par) {Likelihood(par, y = y)
  })
16 Sc <- max(PosteriorEB)/max(Liks)
17 #Scale for displaying in figure
18 LiksScale <- Liks * Sc
19 data <- data.frame(cbind(lambda, VaguePrior, EBPrior,
  PosteriorV, PosteriorEB, LiksScale))
20 #Data frame
21 require(ggplot2)
22 # Cool figures
23 require(latex2exp)
24 # LaTeX equations in figures
25 require(ggpubr)
26 # Multiple figures in one page
27 fig1 <- ggplot(data = data, aes(lambda, VaguePrior)) +
  geom_line() +
  xlab(TeX("$p$")) + ylab("Density") + ggtitle("Prior: Vague
  Beta")
28 fig2 <- ggplot(data = data, aes(lambda, EBPrior)) +
  geom_line() +
  xlab(TeX("$p$")) + ylab("Density") +
  ggtitle("Prior: Empirical Bayes Beta")
29 fig3 <- ggplot(data = data, aes(lambda, PosteriorV)) +
  geom_line() +
  xlab(TeX("$p$")) + ylab("Density") +
  ggtitle("Posterior: Vague Beta")
30 fig4 <- ggplot(data = data, aes(lambda, PosteriorEB)) +
  geom_line() +
  xlab(TeX("$p$")) + ylab("Density") +
  ggtitle("Posterior: Empirical Bayes Beta")
31 FIG <- ggarrange(fig1, fig2, fig3, fig4,
32 ncol = 2, nrow = 2)
33 annotate_figure(FIG,
34 top = text_grob("Vague versus Empirical Bayes: Beta-
  Bernoulli model", color = "black", face = "bold", size =
  14))

```

**FIGURE 1.1**

Vague versus Empirical Bayes: Bernoulli-Beta model.

*R code. Car claim, prior, likelihood and posterior  
density plots*

```

1 # Prior, likelihood and posterior:
2 #Empirical Bayes Binomial-Beta model
3 dataNew <- data.frame(cbind(rep(lambda, 3),
4 c(EBPrior, PosteriorEB, Likelihood),
5 rep(1:3, each = 1000)))
6 #Data frame
7
8 colnames(dataNew) <- c("Lambda", "Density", "Factor")
9 dataNew$Factor <- factor(dataNew$Factor, levels=c("1", "3",
10 "2"), labels=c("Prior", "Likelihood", "Posterior"))
11
12 ggplot(data = dataNew, aes_string(x = "Lambda",
13 y = "Density", group = "Factor")) +
14 geom_line(aes(color = Factor)) +
15 xlab(TeX("$\\lambda$")) + ylab("Density") +
16 ggtitle("Prior, likelihood and posterior: Empirical Bayes
17 Poisson-Gamma model") +
18 guides(color=guide_legend(title="Information")) +
19 scale_color_manual(values = c("red", "yellow", "blue"))

```

**FIGURE 1.2**

Prior, likelihood and posterior: Bernoulli-Beta model.

### *R code. Car claim, predictive probabilities plots*

```

1 # Predictive distributions
2 require(TailRank)
3 PredDen <- function(y, y0, a0, b0){
4   N <- length(y)
5   aN <- a0 + sum(y) # Posterior shape parameter
6   bN <- b0 + N - sum(y) # Posterior scale parameter
7   Pr <- aN/(aN+bN)
8   Probs <- dbinom(y0, 1, prob = Pr)
9   return(Probs)
10 }
11 y0 <- 0:1
12 PredVague <- PredDen(y = y, y0 = y0, a0 = a0, b0 = b0)
13 PredEB <- PredDen(y = y, y0 = y0, a0 = a0EB, b0 = b0EB)
14 dataPred <- as.data.frame(cbind(y0, PredVague, PredEB))
15 colnames(dataPred) <- c("y0", "PredictiveVague",
16   "PredictiveEB")
17 ggplot(data = dataPred) +
18   geom_point(aes(y0, PredictiveVague, color = "red")) +
19   xlab(TeX("$y_0$")) + ylab("Density") +
20   ggtitle("Predictive density: Vague and Empirical Bayes
21     priors") + geom_point(aes(y0, PredictiveEB, color = "
22     yellow")) +
23   guides(color = guide_legend(title="Prior")) +
24   scale_color_manual(labels = c("Vague", "Empirical Bayes"),
25     values = c("red", "yellow")) +
26   scale_x_continuous(breaks=seq(0,1,by=1))

```

**FIGURE 1.3**

Predictive probabilities: Bernoulli-Beta model.

*R code. Car claim, Bayesian model average*

```

1 # Posterior odds: Vague vs Empirical Bayes
2 P012 <- exp(-LogMgLik(c(a0EB, b0EB), y = y))/exp(-LogMgLik(c
  (a0, b0), y = y))
3 PostProMEM <- P012/(1 + P012)
4 # Posterior model probability Empirical Bayes
5 PostProMEM
6 0.757
7 PostProbMV <- 1 - PostProMEM
8 # Posterior model probability vague prior
9 PostProbMV
10 0.242
11 # Bayesian model average (BMA)
12 PostMeanEB <- (a0EB + sum(y)) / (a0EB + b0EB + N)
13 # Posterior mean Empirical Bayes
14 PostMeanV <- (a0 + sum(y)) / (a0 + b0 + N)
15 # Posterior mean vague priors
16 BMAMean <- PostProMEM * PostMeanEB + PostProbMV * PostMeanV
17 # BMA posterior mean
18 PostVarEB <- (a0EB + sum(y))*(b0EB + N - sum(y)) / ((a0EB +
  b0EB + N)^2)*(a0EB + b0EB + N - 1)
19 # Posterior variance Empirical Bayes
20 PostVarV <- (a0 + sum(y))*(b0 + N - sum(y)) / ((a0 + b0 + N)
  ^2)*(a0 + b0 + N - 1)
21 # Posterior variance vague prior
22 BMAVar <- PostProMEM * PostVarEB + PostProbMV * PostVarV +
  PostProMEM * (PostMeanEB - BMAMean)^2 + PostProbMV * (
  PostMeanV - BMAMean)^2
23 # BMA posterior variance
24 # BMA: Predictive
25 BMAPred <- PostProMEM * PredEB + PostProbMV * PredVague
26 dataPredBMA <- as.data.frame(cbind(y0, BMAPred))
27 colnames(dataPredBMA) <- c("y0", "PredictiveBMA")
28 ggplot(data = dataPredBMA) +
29   geom_point(aes(y0, PredictiveBMA, color = "red")) +
30   xlab(TeX("$y_0$")) + ylab("Density") +
31   ggtitle("Predictive density: BMA") +
32   guides(color = guide_legend(title="BMA")) +
33   scale_color_manual(labels = c("Probability"), values = c("
  red")) + scale_x_continuous(breaks=seq(0,1,by=1))

```



*R code. Car claim, Bayesian updating plots*

```

1 # Bayesian updating
2 BayUp <- function(y, lambda, a0, b0){
3   N <- length(y)
4   aN <- a0 + sum(y)
5   # Posterior shape parameter
6   bN <- b0 + N - sum(y)
7   # Posterior scale parameter
8   p <- dbeta(lambda, shape1 = aN, shape2 = bN)
9   # Posterior density
10  return(list(Post = p, a0New = aN, b0New = bN))
11 }
12 PostUp <- NULL
13 for(i in 1:N){
14   if(i == 1){
15     PostUpi <- BayUp(y[i], lambda, a0 = 1, b0 = 1)}
16   else{
17     PostUpi <- BayUp(y[i], lambda,
18       a0 = PostUpi$a0New, b0 = PostUpi$b0New)
19   }
20   PostUp <- cbind(PostUp, PostUpi$Post)
21 }
22 DataUp <- data.frame(cbind(rep(lambda, 15), c(PostUp), rep
23   (1:15, each = 1000))) #Data frame
24 colnames(DataUp) <- c("Lambda", "Density", "Factor")
25 DataUp$Factor <- factor(DataUp$Factor, levels=c("1","2","3",
26   "4","5","6","7","8","9","10","11","12","13","14","15"),
27   labels=c("Iter_1","Iter_2","Iter_3","Iter_4","Iter_5","
28   Iter_6","Iter_7","Iter_8","Iter_9","Iter_10","Iter_11","
29   Iter_12","Iter_13","Iter_14","Iter_15"))
30 ggplot(data = DataUp, aes_string(x = "Lambda",
31   y = "Density", group = "Factor")) +
32   geom_line(aes(color = Factor)) +
33   xlab(TeX("$p$")) + ylab("Density") +
34   ggtitle("Bayesian updating:
35   Beta-Binomial model with vague prior") +
36   guides(color=guide_legend(title="Update"))

```

5. Show that given the loss function,  $L(\theta, a) = |\theta - a|$ , then the optimal decision rule minimizing the risk function,  $a^*(\mathbf{y})$ , is the median.

**Answer**

$\int_{\Theta} |\theta - a| \pi(\theta|\mathbf{y}) d\theta = \int_{-\infty}^a (a - \theta) \pi(\theta|\mathbf{y}) d\theta + \int_a^{\infty} (\theta - a) \pi(\theta|\mathbf{y}) d\theta$ . Differentiating with respect to  $a$ , and equating to zero,

$$\int_{-\infty}^a \pi(\theta|\mathbf{y}) d\theta = \int_a^{\infty} \pi(\theta|\mathbf{y}) d\theta, \quad (1.13)$$

**FIGURE 1.4**

Predictive probabilities: Bernoulli-Beta Bayesian model average.

**FIGURE 1.5**

Predictive probabilities: Bernoulli-Beta Bayesian model updating.

then,

$$2 \int_{-\infty}^a \pi(\theta|\mathbf{y}) d\theta = \int_{-\infty}^{\infty} \pi(\theta|\mathbf{y}) d\theta = 1, \quad (1.14)$$

that is,  $a^*(\mathbf{y})$  is the median.



## 2

---

### *Conceptual differences of the Bayesian and Frequentist approaches*

---

#### 2.1 Solutions of Exercises

##### 1. Jeffreys-Lindley's paradox

The **Jeffreys-Lindley's paradox** [7, 12] is an apparent disagreement between the Bayesian and Frequentist frameworks to a hypothesis testing situation.

In particular, assume that in a city 49,581 boys and 48,870 girls have been born in 20 years. Assume that the male births is distributed Binomial with probability  $\theta$ . We want to test the null hypothesis  $H_0$ .  $\theta = 0.5$  versus  $H_1$ .  $\theta \neq 0.5$ .

- Show that the posterior model probability for the model under the null is approximately 0.95. Assume  $\pi(H_0) = \pi(H_1) = 0.5$ , and  $\pi(\theta)$  equal to  $U(0, 1)$  under  $H_1$ .
- Show that the  $p$ -value for this hypothesis test is equal to 0.023 using the normal approximation,  $Y \sim N(N \times \theta, N \times \theta \times (1 - \theta))$ .

##### Answer

- The marginal likelihood under the null hypothesis is  $p(y|H_0) = \binom{n}{y} \theta^y (1 - \theta)^{n-y} \approx 1.95 \times 10^{-4}$  given  $\theta = 0.5$  under  $H_0$ ,  $N = 49,581 + 48,870$  and  $y = 49,581$ . On the other hand, the marginal likelihood under the alternative hypothesis is

$$\begin{aligned}
p(y|H_1) &= \int_0^1 \binom{n}{y} \theta^y (1-\theta)^{n-y} d\theta \\
&= \binom{n}{y} B(y+1, n-k+1) \\
&= \frac{\Gamma(N+1)}{\Gamma(y+1)\Gamma(n-y+1)} \frac{\Gamma(y+1)\Gamma(N-y+1)}{\Gamma(N+2)} \\
&= \frac{N!}{(N+1)!} \\
&= \frac{1}{N+1} \\
&\approx 1.016 \times 10^{-5}.
\end{aligned}$$

Then,  $PO_{01} = \frac{1.95 \times 10^{-4}}{1.016 \times 10^{-5}} = 19.19$ , this implies that the posterior model probability under the null hypothesis is  $\pi(H_0|y) = \frac{19.19}{1+19.19} = 0.95$ .

- Under the null hypothesis,

$$\begin{aligned}
p &= 2 \int_{49,581}^{\infty} (2\pi\sigma^2)^{-1/2} \exp \left\{ -\frac{1}{2\sigma^2} (y - \mu)^2 \right\} dy \\
&= 0.0235,
\end{aligned}$$

where  $\mu = N \times \theta = 49,225.5$ , and  $\sigma^2 = N \times \theta \times (1 - \theta) = 24,612.75$  under the null hypothesis ( $\theta = 0.5$ ).

Observe that the posterior model probability supports the null hypothesis, whereas the p-value implies rejection of the null hypothesis using a 5% significance level.

Observe that actually this is not a paradox, as we are answering two different questions. The Bayes factor is comparing two models ( $\theta = 0.5$  versus  $\theta \sim U(0,1)$ ), whereas the p-value is checking the compatibility between  $\theta = 0.5$  and the sample information. Despite that  $\theta = 0.5$  is not compatible with sample information, it is better than the models assuming  $\theta \sim U(0,1)$  as most of these values of  $\theta$  are far away from the sample mean. Thus, the model under the null is a bad description of the data, but it is better than the model under the alternative hypothesis.<sup>1</sup>

---

<sup>1</sup>Observe that there are at least another two issues in this example. First, the prior under the alternative is non-informative, this implies problems for Bayes factors, and second, the prior under the alternative is positive at  $\theta = 0.5$ , which is the null ([9] propose non-local prior densities in Bayesian hypothesis tests to tackle these issues).

2. We want to test  $H_0: \mu = \mu_0$  vs  $H_1: \mu \neq \mu_0$  given  $y_i \stackrel{iid}{\sim} N(\mu, \sigma^2)$ .

Assume  $\pi(H_0) = \pi(H_1) = 0.5$ , and  $\pi(\mu, \sigma) \propto 1/\sigma$  under the alternative hypothesis.

Show that

$$p(\mathbf{y}|\mathcal{M}_1) = \frac{\pi^{-N/2}}{2} \Gamma(N/2) 2^{N/2} \left( \frac{1}{\alpha_n \hat{\sigma}^2} \right)^{N/2} \left( \frac{N}{\alpha_n \hat{\sigma}^2} \right)^{-1/2} \frac{\Gamma(1/2) \Gamma(\alpha_n/2)}{\Gamma((\alpha_N+1)/2)} \text{ and}$$

$$p(\mathbf{y}|\mathcal{M}_0) = (2\pi)^{-N/2} \left[ \frac{2}{\Gamma(N/2)} \left( \frac{N}{2} \frac{\sum_{i=1}^N (y_i - \mu_0)^2}{N} \right)^{N/2} \right]^{-1}. \text{ Then,}$$

$$PO_{01} = \frac{p(\mathbf{y}|\mathcal{M}_0)}{p(\mathbf{y}|\mathcal{M}_1)}$$

$$= \frac{\Gamma((\alpha_n + 1)/2)}{\Gamma(1/2) \Gamma(\alpha_N/2)} (\alpha_n \hat{\sigma}^2 / N)^{-1/2} \left[ 1 + \frac{(\mu_0 - \bar{y})^2}{\alpha_n \hat{\sigma}^2 / N} \right]^{-\left(\frac{\alpha_n + 1}{2}\right)},$$

where  $\alpha_N = N - 1$  and  $\hat{\sigma}^2 = \frac{\sum_{i=1}^N (y_i - \bar{y})^2}{N - 1}$ .

Find the relationship between the posterior odds and the classical test statistic for the null hypothesis.

**Answer**

$$\begin{aligned} p(\mathbf{y}|\mathcal{M}_1) &= \int_{-\infty}^{\infty} \int_0^{\infty} (2\pi)^{-N/2} \sigma^{-N} \exp \left\{ -\frac{1}{2\sigma^2} \sum_{i=1}^N (y_i - \mu)^2 \right\} \frac{1}{\sigma} d\sigma d\mu \\ &= (2\pi)^{-N/2} \int_{-\infty}^{\infty} \int_0^{\infty} \sigma^{-(N+1)} \exp \left\{ -\frac{N}{2\sigma^2} \frac{\sum_{i=1}^N (y_i - \mu)^2}{N} \right\} d\sigma d\mu \\ &= (2\pi)^{-N/2} \frac{\Gamma(N/2)}{2} 2^{N/2} \int_{-\infty}^{\infty} \left[ \sum_{i=1}^N (y_i - \mu)^2 \right]^{-N/2} d\mu \\ &= (2\pi)^{-N/2} \frac{\Gamma(N/2)}{2} 2^{N/2} \int_{-\infty}^{\infty} \left[ \sum_{i=1}^N [(y_i - \bar{y}) - (\mu - \bar{y})]^2 \right]^{-N/2} d\mu \\ &= (2\pi)^{-N/2} \frac{\Gamma(N/2)}{2} 2^{N/2} \int_{-\infty}^{\infty} [\alpha_n \hat{\sigma}^2 + N(\mu - \bar{y})^2]^{-N/2} d\mu \\ &= (2\pi)^{-N/2} \frac{\Gamma(N/2)}{2} 2^{N/2} \left( \frac{\alpha_n \hat{\sigma}^2}{\alpha_n \hat{\sigma}^2} \right)^{-N/2} \int_{-\infty}^{\infty} [\alpha_n \hat{\sigma}^2 + N(\mu - \bar{y})^2]^{-N/2} d\mu \\ &= (2\pi)^{-N/2} \frac{\Gamma(N/2)}{2} 2^{N/2} (\alpha_n \hat{\sigma}^2)^{-N/2} \int_{-\infty}^{\infty} \left[ 1 + \frac{N(\mu - \bar{y})^2}{\alpha_n \hat{\sigma}^2} \right]^{-N/2} d\mu \\ &= \frac{\pi^{-N/2}}{2} \Gamma(N/2) 2^{N/2} \left( \frac{1}{\alpha_n \hat{\sigma}^2} \right)^{N/2} \left( \frac{N}{\alpha_n \hat{\sigma}^2} \right)^{-1/2} \frac{\Gamma(1/2) \Gamma(\alpha_n/2)}{\Gamma((\alpha_N + 1)/2)}. \end{aligned}$$

The third line takes into account that the integral in the second line is the kernel of an inverted-gamma distribution, and the last line takes into account that the integral in the previous line is the kernel of a student's t distribution [28].

$$\begin{aligned}
p(\mathbf{y}|\mathcal{M}_0) &= \int_0^\infty (2\pi)^{-N/2} \sigma^{-N} \exp \left\{ -\frac{1}{2\sigma^2} \sum_{i=1}^N (y_i - \mu_0)^2 \right\} \frac{1}{\sigma} d\sigma \\
&= (2\pi)^{-N/2} \int_0^\infty \sigma^{-(N+1)} \exp \left\{ -\frac{N}{2\sigma^2} \frac{\sum_{i=1}^N (y_i - \mu_0)^2}{N} \right\} d\sigma \\
&= (2\pi)^{-N/2} \left[ \frac{2}{\Gamma(N/2)} \left( \frac{N}{2} \frac{\sum_{i=1}^N (y_i - \mu_0)^2}{N} \right)^{N/2} \right]^{-1}.
\end{aligned}$$

The third line takes into account that the integral in the second line is the kernel of an inverted-gamma distribution [28].

Given these results is easy to get  $PO_{01}$ .

In addition,

$$\begin{aligned}
PO_{01} &= \frac{\Gamma((\alpha_n + 1)/2)}{\Gamma(1/2)\Gamma(\alpha_N/2)} (\alpha_n \hat{\sigma}^2/N)^{-1/2} \left[ 1 + \frac{(\mu_0 - \bar{y})^2}{\alpha_n \hat{\sigma}^2/N} \right]^{-\left(\frac{\alpha_n+1}{2}\right)} \\
&= \frac{\Gamma((\alpha_n + 1)/2)}{\Gamma(1/2)\Gamma(\alpha_N/2)} (\alpha_n \hat{\sigma}^2/N)^{-1/2} \left[ 1 + \frac{1}{\alpha_n} \left( \frac{\mu_0 - \bar{y}}{\hat{\sigma}/\sqrt{N}} \right)^2 \right]^{-\left(\frac{\alpha_n+1}{2}\right)} \\
&= \frac{\Gamma((\alpha_n + 1)/2)}{\Gamma(1/2)\Gamma(\alpha_N/2)} (\alpha_n \hat{\sigma}^2/N)^{-1/2} \left[ 1 + \frac{1}{\alpha_n} t^2 \right]^{-\left(\frac{\alpha_n+1}{2}\right)},
\end{aligned}$$

where  $t = \frac{\bar{y} - \mu_0}{\hat{\sigma}/\sqrt{N}}$  is the classical statistical test. Then, as  $t$  increases then the  $PO_{01}$  decreases, both indicating support against the null hypothesis  $H_0$ .  $\mu = \mu_0$ . However, there are other terms affecting the posterior odds, then, there is no necessary agreement between the classical test statistic and the posterior odds.

### 3. Math test continues

Using the setting of the **Example: Math test** in subsection 2.6.1 in the book, test  $H_0$ .  $\mu = \mu_0$  vs  $H_1$ .  $\mu \neq \mu_0$  where  $\mu_0 = \{100, 100.5, 101, 101.5, 102\}$ .

- What is the  $p$ -value for these hypothesis tests?
- Find the posterior model probability of the null model for each  $\mu_0$ .

**Answer**



*R code. Example: Math test*

```
1 N <- 50 # Sample size
2 y_bar <- 102 # Sample mean
3 s2 <- 10 # Sample variance
4 alpha <- N - 1
5 serror <- (s2/N)^0.5
6 y.H0 <- c(100, 100.5, 101, 101.5, 102)
7 test <- (y.H0 - y_bar)/serror
8 pval <- 2*pt(test, alpha)
9 pval
10 0.0000459 0.0015431 0.0299338 0.2690040 1
11 # p-values
12 P001 <- (gamma(N/2)*((N-1)*serror^2)^(-0.5)*(1+test^2/alpha)
13         ^(-N/2))/(gamma(1/2)*gamma((N-1)/2))
14 P001/(1+P001)
15 0.0001705 0.0050345 0.0725330 0.3210223 0.4702050
16 # Posterior model probability of the null hypothesis.
```



# 3

## Cornerstone models: Conjugate families

### 3.1 Solutions of Exercises

1. Write in the canonical form the distribution of the Bernoulli example, and find the mean and variance of the sufficient statistic.

**Answer**

Given  $p(\mathbf{y}|\theta) = (1-\theta)^N \exp \left\{ \sum_{i=1}^N y_i \log \left( \frac{\theta}{1-\theta} \right) \right\}$  where  $\eta = \log \frac{\theta}{1-\theta}$  which implies  $\theta = \frac{\exp(\eta)}{1+\exp(\eta)}$ , then  $p(\mathbf{y}|\theta) = \exp \left\{ \sum_{i=1}^N y_i \eta - N \log(1 + \exp(\eta)) \right\}$ . Thus  $B(\eta) = N \log(1 + \exp(\eta))$ ,  $\nabla(B(\eta)) = N \frac{\exp(\eta)}{1+\exp(\eta)} = N\theta$  and  $\nabla^2(B(\eta)) = N \left\{ \frac{\exp(\eta)(1+\exp(\eta))}{(1+\exp(\eta))^2} - \frac{\exp(\eta)\exp(\eta)}{(1+\exp(\eta))^2} \right\} = N\theta(1-\theta)$ .

2. Given a random sample  $\mathbf{y} = [y_1, y_2, \dots, y_N]^\top$  from  $N$  binomial experiments each having known size  $n_i$  and same unknown probability  $\theta$ . Show that  $p(\mathbf{y}|\theta)$  is in the exponential family, and find the posterior distribution, the marginal likelihood and the predictive distribution of the binomial-beta model assuming the number of trials is known.

**Answer**

The density function is

$$\begin{aligned} p(\mathbf{y}|\theta) &= \prod_{i=1}^N \binom{n_i}{y_i} \theta^{y_i} (1-\theta)^{n_i-y_i} \\ &= \prod_{i=1}^N \binom{n_i}{y_i} \theta^{\sum_{i=1}^N y_i} (1-\theta)^{\sum_{i=1}^N n_i - \sum_{i=1}^N y_i} \\ &= \prod_{i=1}^N \binom{n_i}{y_i} \exp \left\{ \sum_{i=1}^N y_i \log \left( \frac{\theta}{1-\theta} \right) + \sum_{i=1}^N n_i \log(1-\theta) \right\} \\ &= \prod_{i=1}^N \binom{n_i}{y_i} (1-\theta)^{\sum_{i=1}^N n_i} \exp \left\{ \sum_{i=1}^N y_i \log \left( \frac{\theta}{1-\theta} \right) \right\}, \end{aligned}$$

Observe that  $\sum_{i=1}^N n_i$  is the total sample size of Bernoulli experiments.

Using Theorem 1 in Chapter 4, the prior distribution is

$$\begin{aligned}\pi(\theta) &\propto (1-\theta)^{B_0} \exp \left\{ a_0 \log \left( \frac{\theta}{1-\theta} \right) \right\} \\ &= \theta^{a_0} (1-\theta)^{B_0-a_0} \\ &= \theta^{\alpha_0-1} (1-\theta)^{\beta_0-1},\end{aligned}$$

where  $\alpha_0 = a_0 + 1$  and  $\beta_0 = B_0 - a_0 + 1$ . This is the kernel of a beta distribution. Thus, the posterior distribution is

$$\begin{aligned}\pi(\theta|\mathbf{y}) &\propto \theta^{\alpha_0-1} (1-\theta)^{\beta_0-1} \times \theta^{\sum_{i=1}^N y_i} (1-\theta)^{\sum_{i=1}^N n_i - \sum_{i=1}^N y_i} \\ &= \theta^{\alpha_0 + \sum_{i=1}^N y_i - 1} (1-\theta)^{\beta_0 + \sum_{i=1}^N n_i - \sum_{i=1}^N y_i - 1} \\ &= \theta^{\alpha_n-1} (1-\theta)^{\beta_n-1},\end{aligned}$$

where  $\alpha_n = \alpha_0 + \sum_{i=1}^N y_i$  and  $\beta_n = \beta_0 + \sum_{i=1}^N n_i - \sum_{i=1}^N y_i$ .

The marginal likelihood is

$$\begin{aligned}p(\mathbf{y}) &= \int_0^1 \frac{\theta^{\alpha_0-1} (1-\theta)^{\beta_0-1}}{B(\alpha_0, \beta_0)} \times \prod_{i=1}^N \binom{n_i}{y_i} \theta^{\sum_{i=1}^N y_i} (1-\theta)^{\sum_{i=1}^N n_i - \sum_{i=1}^N y_i} d\theta \\ &= \frac{\prod_{i=1}^N \binom{n_i}{y_i}}{B(\alpha_0, \beta_0)} \int_0^1 \theta^{\alpha_0 + \sum_{i=1}^N y_i - 1} (1-\theta)^{\beta_0 + \sum_{i=1}^N n_i - \sum_{i=1}^N y_i - 1} d\theta \\ &= \frac{\prod_{i=1}^N \binom{n_i}{y_i} B(\alpha_n, \beta_n)}{B(\alpha_0, \beta_0)}.\end{aligned}$$

The third line due to having the kernel of a Beta distribution.

Finally, the predictive distribution is

$$\begin{aligned}p(Y_0|\mathbf{y}) &= \int_0^1 \binom{n_{y_0}}{y_0} \theta^{y_0} (1-\theta)^{n_{y_0}-y_0} \frac{\theta^{\alpha_n-1} (1-\theta)^{\beta_n-1}}{B(\alpha_n, \beta_n)} d\theta \\ &= \frac{\binom{n_{y_0}}{y_0}}{B(\alpha_n, \beta_n)} \int_0^1 \theta^{\alpha_n+y_0-1} (1-\theta)^{\beta_n+n_{y_0}-y_0-1} d\theta \\ &= \binom{n_{y_0}}{y_0} \frac{B(\alpha_n+y_0, \beta_n+n_{y_0}-y_0)}{B(\alpha_n, \beta_n)},\end{aligned}$$

where  $n_{y_0}$  is the known size associated with  $y_0$ , and the last line due to having the kernel of a beta distribution. The predictive is a *beta-binomial distribution*.

3. Given a random sample  $\mathbf{y} = [y_1, y_2, \dots, y_N]^\top$  from a *exponential distribution*. Show that  $p(\mathbf{y}|\lambda)$  is in the exponential family, and find the posterior distribution, marginal likelihood and predictive distribution of the exponential-gamma model.

**Answer**

We see that the exponential distribution belongs to the exponential family as  $p(\mathbf{y}|\lambda) = \prod_{i=1}^N \lambda \exp(-\lambda y_i) = \lambda^N \exp(-\lambda \sum_{i=1}^N y_i)$ .

Using the gamma distribution in the rate parametrization, we see that  $\pi(\lambda|\mathbf{y}) \propto \lambda^{\alpha_0-1} \exp(-\lambda\beta_0) \times \lambda^N \exp(-\lambda \sum_{i=1}^N y_i) = \lambda^{\alpha_0+N-1} \exp(-\lambda(\beta_0 + \sum_{i=1}^N y_i))$ . This is the kernel of a gamma distribution, that is,  $\lambda|\mathbf{y} \sim G(\alpha_n, \beta_n)$  where  $\alpha_n = \alpha_0 + N$  and  $\beta_n = \beta_0 + \sum_{i=1}^N y_i$ .

The marginal likelihood is

$$\begin{aligned} p(\mathbf{y}) &= \int_0^\infty \lambda^N \exp\left\{-\lambda \sum_{i=1}^N y_i\right\} \lambda^{\alpha_0-1} \exp\{-\beta_0 \lambda\} \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} d\lambda \\ &= \frac{\beta_0^{\alpha_0}}{\Gamma(\alpha_0)} \int_0^\infty \lambda^{\alpha_0+N-1} \exp\left\{-\lambda \left(\beta_0 + \sum_{i=1}^N y_i\right)\right\} d\lambda \\ &= \frac{\beta_0^{\alpha_0} \Gamma(\alpha_n)}{\Gamma(\alpha_0) \beta_n^{\alpha_n}}. \end{aligned}$$

Finally, the predictive distribution is

$$\begin{aligned} p(Y_0|\mathbf{y}) &= \int_0^\infty \lambda \exp\{-\lambda y_0\} \lambda^{\alpha_n-1} \exp\{-\beta_n \lambda\} \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n)} d\lambda \\ &= \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n)} \int_0^\infty \lambda^{\alpha_n+1-1} \exp\{-\lambda(\beta_n + y_0)\} d\lambda \\ &= \frac{\beta_n^{\alpha_n}}{\Gamma(\alpha_n)} \times \frac{\Gamma(\alpha_n + 1)}{(\beta_n + y_0)^{\alpha_n+1}} \\ &= \frac{\alpha_n \beta_n^{\alpha_n}}{(\beta_n + y_0)^{\alpha_n+1}}. \end{aligned}$$

This is a *Lomax distribution*.

4. Given  $\mathbf{y} \sim N_N(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ , that is, a *multivariate normal distribution* show that  $p(\mathbf{y}|\boldsymbol{\mu}, \boldsymbol{\Sigma})$  is in the exponential family.

**Answer**

$$\begin{aligned}
p(\mathbf{y}|\boldsymbol{\mu}, \boldsymbol{\Sigma}) &= (2\pi)^{-N/2} |\boldsymbol{\Sigma}|^{-1/2} \exp \left\{ -\frac{1}{2} (\mathbf{y} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}^{-1} (\mathbf{y} - \boldsymbol{\mu}) \right\} \\
&= (2\pi)^{-N/2} \exp \left\{ -\frac{1}{2} (\mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \mathbf{y} - 2\mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \boldsymbol{\mu}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \log(|\boldsymbol{\Sigma}|)) \right\} \\
&= (2\pi)^{-N/2} \exp \left\{ -\frac{1}{2} (tr \{ \mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \mathbf{y} \} - 2\mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \boldsymbol{\mu}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \log(|\boldsymbol{\Sigma}|)) \right\} \\
&= (2\pi)^{-N/2} \exp \left\{ -\frac{1}{2} (vec(\mathbf{y}\mathbf{y}^\top)^\top vec(\boldsymbol{\Sigma}^{-1}) - 2\mathbf{y}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \boldsymbol{\mu}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \log(|\boldsymbol{\Sigma}|)) \right\},
\end{aligned}$$

where  $tr$  and  $vec$  are the trace and vectorization operators, respectively.

Then,  $h(\mathbf{y}) = (2\pi)^{-N/2}$ ,  $\eta(\boldsymbol{\mu}, \boldsymbol{\Sigma}) = [\boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} \quad vec(\boldsymbol{\Sigma}^{-1})]$ ,  $T(\mathbf{y}) = [\mathbf{y} \quad \frac{1}{2} vec(\mathbf{y}\mathbf{y}^\top)]$  and  $C(\boldsymbol{\mu}, \boldsymbol{\Sigma}) = \exp \left\{ -\frac{1}{2N} (\boldsymbol{\mu}^\top \boldsymbol{\Sigma}^{-1} \boldsymbol{\mu} + \log(|\boldsymbol{\Sigma}|)) \right\}$ .

5. Find the marginal likelihood in the normal/inverse-Wishart model.

**Answer**

$$\begin{aligned}
p(\mathbf{Y}) &= \int_{\mathcal{R}^p} \int_{\mathcal{S}} (2\pi)^{-pN/2} |\boldsymbol{\Sigma}|^{-N/2} \exp \left\{ -\frac{1}{2} tr[(\mathbf{S} + N(\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})(\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^\top) \boldsymbol{\Sigma}^{-1}] \right\} \\
&\quad \times (2\pi)^{-p/2} \beta_0^{p/2} |\boldsymbol{\Sigma}|^{-1/2} \exp \left\{ -\frac{\beta_0}{2} tr[(\boldsymbol{\mu} - \boldsymbol{\mu}_0)(\boldsymbol{\mu} - \boldsymbol{\mu}_0)^\top \boldsymbol{\Sigma}^{-1}] \right\} \\
&\quad \times |\boldsymbol{\Sigma}|^{-(\alpha_0 + p + 1)/2} \frac{2^{-\alpha_0 p/2} |\boldsymbol{\Psi}_0|^{\alpha_0/2}}{\Gamma_p(\alpha_0/2)} \exp \left\{ -\frac{1}{2} tr(\boldsymbol{\Psi}_0 \boldsymbol{\Sigma}^{-1}) \right\} d\boldsymbol{\Sigma} d\boldsymbol{\mu} \\
&= \frac{(2\pi)^{-frac{1}{2}(pN + p)} |\boldsymbol{\Psi}_0|^{\alpha_0/2} \beta_0^{p/2} 2^{-\alpha_0 p/2}}{\Gamma_p(\alpha_0/2)} \int_{\mathcal{R}^p} \int_{\mathcal{S}} |\boldsymbol{\Sigma}|^{-\frac{1}{2}(N + 1 + \alpha_0 + p + 1)} \\
&\quad \times \exp \left\{ -\frac{1}{2} tr[(\mathbf{S} + N(\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})(\boldsymbol{\mu} - \hat{\boldsymbol{\mu}})^\top + \beta_0(\boldsymbol{\mu} - \boldsymbol{\mu}_0)(\boldsymbol{\mu} - \boldsymbol{\mu}_0)^\top + \boldsymbol{\Psi}_0) \boldsymbol{\Sigma}^{-1}] \right\} d\boldsymbol{\Sigma} d\boldsymbol{\mu}.
\end{aligned}$$

We have in the integral the kernel of an Inverse-Wishart distribution, then

$$\begin{aligned}
p(\mathbf{Y}) &= \frac{\Gamma_p\left(\frac{N+1+\alpha_0}{2}\right) |\Psi_0|^{\alpha_0/2} \beta_0^{p/2}}{\Gamma_p(\alpha_0/2) \pi^{p(N+1)/2}} \\
&\quad \times \int_{\mathcal{R}^p} |\mathbf{S} + \Psi_0 + (N + \beta_0)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top \\
&\quad + N\beta_0/(N + \beta_0)(\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}_0)(\hat{\boldsymbol{\mu}} - \boldsymbol{\mu}_0)^\top| d\boldsymbol{\mu} \\
&= \frac{\Gamma_p\left(\frac{N+1+\alpha_0}{2}\right) |\Psi_0|^{\alpha_0/2} \beta_0^{p/2}}{\Gamma_p(\alpha_0/2) \pi^{p(N+1)/2}} \\
&\quad \times \int_{\mathcal{R}^p} |\Psi_n| |1 + \beta_n(\boldsymbol{\mu} - \boldsymbol{\mu}_n) \Psi_n^{-1}(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top|^{-\frac{1}{2}(\alpha_n+1)} d\boldsymbol{\mu} \\
&= \frac{\Gamma_p\left(\frac{\alpha_n+1}{2}\right) |\Psi_0|^{\alpha_0/2} \beta_0^{p/2}}{\Gamma_p(\alpha_0/2) \pi^{p(N+1)/2}} |\Psi_n|^{-\frac{1}{2}(\alpha_n+1)} \\
&\quad \times \int_{\mathcal{R}^p} [1 + \beta_n(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top \Psi_n^{-1}(\boldsymbol{\mu} - \boldsymbol{\mu}_n)]^{-\frac{1}{2}(\alpha_n+1)} d\boldsymbol{\mu}.
\end{aligned}$$

The last equality uses the definition of  $\Psi_n$ ,  $\beta_n$  and  $\alpha_n$ , and the Sylvester's determinant theorem. Observe that we have the kernel of a multivariate t distribution. Then,

$$\begin{aligned}
p(\mathbf{Y}) &= \frac{\Gamma_p\left(\frac{\alpha_n+1}{2}\right) |\Psi_0|^{\alpha_0/2} \beta_0^{p/2}}{\Gamma_p(\alpha_0/2) \pi^{p(N+1)/2}} |\Psi_n|^{-\frac{1}{2}(\alpha_n+1)} \\
&\quad \times \int_{\mathcal{R}^p} \left[ 1 + \frac{1}{\alpha_n + 1 - p} (\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top \left( \frac{\Psi_n}{\beta_n(\alpha_n + 1 - p)} \right)^{-1} (\boldsymbol{\mu} - \boldsymbol{\mu}_n) \right]^{-\frac{1}{2}(\alpha_n+1-p+p)} d\boldsymbol{\mu} \\
&= \frac{\Gamma_p\left(\frac{\alpha_n+1}{2}\right) \Gamma_p\left(\frac{\alpha_n+1-p}{2}\right) |\Psi_0|^{\alpha_0/2} \beta_0^{p/2} (\alpha_n + 1 - p)^{p/2} \pi^{p/2} |\Psi_n|^{-\frac{1}{2}(\alpha_n+1)}}{\Gamma_p(\alpha_0/2) \pi^{p(N+1)/2} \Gamma_p\left(\frac{\alpha_n+1-p+p}{2}\right) \left( \frac{\Psi_n}{\alpha_n+1-p} \right)^{-1/2}} \\
&= \frac{\Gamma_p\left(\frac{v_n}{2}\right) |\Psi_0|^{\alpha_0/2}}{\Gamma_p\left(\frac{\alpha_0}{2}\right) |\Psi_n|^{\alpha_n/2}} \left( \frac{\beta_0}{\beta_n} \right)^{p/2} (2\pi)^{-Np/2},
\end{aligned}$$

where  $v_n = \alpha_n + 1 - p$ .

6. Find the posterior predictive distribution in the normal/inverse-Wishart model, and show that  $\mathbf{Y}_0|\mathbf{Y} \sim T_{N_0,M}(\alpha_n - M + 1, \mathbf{X}_0\mathbf{B}_n, \mathbf{I}_{N_0} + \mathbf{X}_0\mathbf{V}_n\mathbf{X}_0^\top, \Psi_n)$  in the multivariate regression linear model.

**Answer**

$$\begin{aligned}
p(\mathbf{Y}_0|\mathbf{Y}) &\propto \int_{\mathcal{R}^p} \int_S |\Sigma|^{-1/2} \exp \left\{ -\frac{1}{2} \text{tr}[(\mathbf{y}_0 - \boldsymbol{\mu})(\mathbf{y}_0 - \boldsymbol{\mu})^\top \Sigma^{-1}] \right\} \\
&\quad \times |\Sigma|^{-1/2} \exp \left\{ -\frac{\beta_n}{2} \text{tr}[(\boldsymbol{\mu} - \boldsymbol{\mu}_n)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top \Sigma^{-1}] \right\} \\
&\quad \times |\Sigma|^{-(\alpha_n + p + 1)/2} \exp \left\{ -\frac{1}{2} \text{tr}(\Psi_n \Sigma^{-1}) \right\} d\Sigma d\boldsymbol{\mu} \\
&\propto \int_{\mathcal{R}^p} |(\mathbf{y}_0 - \boldsymbol{\mu})(\mathbf{y}_0 - \boldsymbol{\mu})^\top + (\boldsymbol{\mu} - \boldsymbol{\mu}_n)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top + \Psi_n|^{-(\alpha_n + 2)/2} d\boldsymbol{\mu}.
\end{aligned}$$

The last equality uses that there is the kernel of an Inverse Wishart distribution.

Taking into account that

$$\begin{aligned}
(\mathbf{y}_0 - \boldsymbol{\mu})(\mathbf{y}_0 - \boldsymbol{\mu})^\top + (\boldsymbol{\mu} - \boldsymbol{\mu}_n)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top &= (1 + \beta_n) \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right) \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right)^\top \\
&\quad + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top.
\end{aligned}$$

Then,

$$\begin{aligned}
p(\mathbf{Y}_0|\mathbf{Y}) &\propto \int_{\mathcal{R}^p} |(\mathbf{y}_0 - \boldsymbol{\mu})(\mathbf{y}_0 - \boldsymbol{\mu})^\top + (\boldsymbol{\mu} - \boldsymbol{\mu}_n)(\boldsymbol{\mu} - \boldsymbol{\mu}_n)^\top + \Psi_n|^{-(\alpha_n + 2)/2} d\boldsymbol{\mu} \\
&= \int_{\mathcal{R}^p} \left| (1 + \beta_n) \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right) \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right)^\top \right. \\
&\quad \left. + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top + \Psi_n \right|^{-(\alpha_n + 2)/2} d\boldsymbol{\mu} \\
&= \int_{\mathcal{R}^p} \left| \underbrace{\Psi_n + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top}_{\Lambda_n} \right| \\
&\quad \left| 1 + (1 + \beta_n) \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right)^\top \frac{1}{\alpha_n + 2 - p} \left( \frac{\Lambda_n}{\alpha_n + 2 - p} \right)^{-1} \left( \boldsymbol{\mu} - \frac{(\mathbf{y}_0 + \beta_n \boldsymbol{\mu}_n)}{1 + \beta_n} \right) \right|^{-(\alpha_n + 2 - p + p)/2} d\boldsymbol{\mu} \\
&\propto \left| \Psi_n + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top \right|^{-(\alpha_n + 2)/2} \\
&\quad \times \left| \Psi_n + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top \right|^{1/2} \\
&= \left| \Psi_n + \frac{\beta_n}{1 + \beta_n} (\mathbf{y}_0 - \boldsymbol{\mu}_n)(\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top \right|^{-(\alpha_n + 1)/2} \\
&\propto \left[ 1 + (\mathbf{y}_0 - \boldsymbol{\mu}_n)^\top \frac{1}{\alpha_n + 1 - p} \left( \frac{\Psi_n (1 + \beta_n)}{(\alpha_n + 1 - p) \beta_n} \right)^{-1} (\mathbf{y}_0 - \boldsymbol{\mu}_n) \right]^{-(\alpha_n + 1 - p + p)}.
\end{aligned}$$

The second equality and last line use the Sylvester's determinant theorem, and the second equality uses that there is the kernel of a multivariate t distribution.



Then, we have that the predictive distribution is a multivariate t distribution centered at  $\boldsymbol{\mu}_n$ ,  $\alpha_n + 1 - p$  degrees of freedom, and scale matrix  $\frac{\boldsymbol{\Psi}_n(1+\beta_n)}{(\alpha_n+1-p)\beta_n}$ .

To show the second statement, let's start by the definition of the predictive density to show that  $\mathbf{Y}_0|\mathbf{Y} \sim T_{N_0,M}(\alpha_n - M + 1, \mathbf{X}_0\mathbf{B}_n, \mathbf{I}_{N_0} + \mathbf{X}_0\mathbf{V}_n\mathbf{X}_0^\top, \boldsymbol{\Psi}_n)$ .

$$\begin{aligned} \pi(\mathbf{Y}_0|\mathbf{Y}) &\propto \int_{\mathcal{S}} \int_{\mathcal{B}} \left\{ |\boldsymbol{\Sigma}|^{-N_0/2} \exp \left\{ -\frac{1}{2} \text{tr}[(\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B})^\top (\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B}) \boldsymbol{\Sigma}^{-1}] \right\} \right. \\ &\quad \times |\boldsymbol{\Sigma}|^{-K/2} \exp \left\{ -\frac{1}{2} \text{tr}[(\mathbf{B} - \mathbf{B}_n)^\top \mathbf{V}_n^{-1} (\mathbf{B} - \mathbf{B}_n) \boldsymbol{\Sigma}^{-1}] \right\} \\ &\quad \times |\boldsymbol{\Sigma}|^{-(\alpha_n+M+1)/2} \exp \left\{ -\frac{1}{2} \text{tr}[\boldsymbol{\Psi}_n \boldsymbol{\Sigma}^{-1}] \right\} \Big\} d\mathbf{B} d\boldsymbol{\Sigma} \\ &= \int_{\mathcal{S}} \int_{\mathcal{B}} \left\{ |\boldsymbol{\Sigma}|^{-(N_0+K+\alpha_n+M+1)/2} \exp \left\{ -\frac{1}{2} \text{tr} [((\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B})^\top (\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B}) \right. \right. \\ &\quad \left. \left. + (\mathbf{B} - \mathbf{B}_n)^\top \mathbf{V}_n^{-1} (\mathbf{B} - \mathbf{B}_n) + \boldsymbol{\Psi}_n) \boldsymbol{\Sigma}^{-1}] \right\} \right\} d\mathbf{B} d\boldsymbol{\Sigma}. \end{aligned}$$

Setting  $\mathbf{M} = (\mathbf{X}_0^\top \mathbf{X}_0 + \mathbf{V}_n^{-1})$ , and  $\mathbf{B}_* = \mathbf{M}^{-1}(\mathbf{V}_n \mathbf{B}_n + \mathbf{X}_0^\top \mathbf{Y}_0)$ , we have that  $(\mathbf{B} - \mathbf{B}_*)^\top \mathbf{M} (\mathbf{B} - \mathbf{B}_*) + \mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n + \mathbf{Y}_0^\top \mathbf{Y}_0 - \mathbf{B}_*^\top \mathbf{M} \mathbf{B}_* = (\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B})^\top (\mathbf{Y}_0 - \mathbf{X}_0\mathbf{B}) + (\mathbf{B} - \mathbf{B}_n)^\top \mathbf{V}_n^{-1} (\mathbf{B} - \mathbf{B}_n)$ . Then,

$$\begin{aligned} \pi(\mathbf{Y}_0|\mathbf{Y}) &\propto \int_{\mathcal{S}} |\boldsymbol{\Sigma}|^{-(N_0+K+\alpha_n+M+1)/2} \\ &\quad \times \exp \left\{ -\frac{1}{2} \text{tr}[(\boldsymbol{\Psi}_n + \mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n + \mathbf{Y}_0^\top \mathbf{Y}_0 - \mathbf{B}_*^\top \mathbf{M} \mathbf{B}_*) \boldsymbol{\Sigma}^{-1}] \right\} \\ &\quad \times \int_{\mathcal{B}} \exp \left\{ -\frac{1}{2} \text{tr}[(\mathbf{B} - \mathbf{B}_*)^\top \mathbf{M} (\mathbf{B} - \mathbf{B}_*) \boldsymbol{\Sigma}^{-1}] \right\} d\mathbf{B} d\boldsymbol{\Sigma}. \end{aligned}$$

The latter is the kernel of a matrix normal distribution, thus

$$\begin{aligned} \pi(\mathbf{Y}_0|\mathbf{Y}) &\propto \int_{\mathcal{S}} |\boldsymbol{\Sigma}|^{-(N_0+\alpha_n+M+1)/2} \\ &\quad \times \exp \left\{ -\frac{1}{2} \text{tr}[(\boldsymbol{\Psi}_n + \mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n + \mathbf{Y}_0^\top \mathbf{Y}_0 - \mathbf{B}_*^\top \mathbf{M} \mathbf{B}_*) \boldsymbol{\Sigma}^{-1}] \right\} d\boldsymbol{\Sigma} \end{aligned}$$

This is the kernel of an inverse-Wishart distribution, then

$$\pi(\mathbf{Y}_0|\mathbf{Y}) \propto |\boldsymbol{\Psi}_n + \mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n + \mathbf{Y}_0^\top \mathbf{Y}_0 - \mathbf{B}_*^\top \mathbf{M} \mathbf{B}_*|^{-(N_0+\alpha_n)/2}.$$

Setting  $\mathbf{C}^{-1} = \mathbf{I}_{N_0} + \mathbf{X}_0 \mathbf{V}_n \mathbf{X}_0^\top$  such that  $\mathbf{C} = \mathbf{I}_{N_0} - \mathbf{X}_0 (\mathbf{X}_0^\top \mathbf{X}_0 + \mathbf{V}_n^{-1})^{-1} \mathbf{X}_0^\top$  (see footnote 4 in Chapter 4), then  $\mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n + \mathbf{Y}_0^\top \mathbf{Y}_0 - \mathbf{B}_*^\top \mathbf{M} \mathbf{B}_* = (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n)^\top \mathbf{C} (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n)$ . This is done following exactly same procedure as deducing the predictive distribution in the linear regression model in the book. Thus,

$$\begin{aligned} \pi(\mathbf{Y}_0 | \mathbf{Y}) &\propto |\boldsymbol{\Psi}_n + (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n)^\top \mathbf{C} (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n)|^{-(N_0 + \alpha_n)/2} \\ &\propto |\mathbf{I}_{N_0} + \mathbf{C} (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n) \boldsymbol{\Psi}^{-1} (\mathbf{Y}_0 - \mathbf{X}_0 \mathbf{B}_n)^\top|^{-(\alpha_n + 1 - M + N_0 + M - 1)/2}. \end{aligned}$$

The second proportionality follows from the Sylvester's theorem. Observe that this is the kernel of a matrix t distribution with  $\alpha_n + 1 - M$  degrees of freedom, location  $\mathbf{X}_0 \mathbf{B}_n$  and scale matrices  $\boldsymbol{\Psi}_n$  and  $\mathbf{C}^{-1} = \mathbf{I}_{N_0} + \mathbf{X}_0 \mathbf{V}_n \mathbf{X}_0^\top$ .

7. Show that  $\delta_n = \delta_0 + (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})^\top (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) + (\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}_0)^\top ((\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0)^{-1} (\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}_0)$  in the linear regression model, and that  $\boldsymbol{\Psi}_n = \boldsymbol{\Psi}_0 + \mathbf{S} + (\hat{\mathbf{B}} - \mathbf{B}_0)^\top \mathbf{V}_n (\hat{\mathbf{B}} - \mathbf{B}_0)$  in the linear multivariate regression model.

**Answer**

Taking into account that

$$\begin{aligned} \delta^* &= \delta_0 + \mathbf{y}^\top \mathbf{y} + \boldsymbol{\beta}_0^\top \mathbf{B}_0^{-1} \boldsymbol{\beta}_0 - \boldsymbol{\beta}_n^\top \mathbf{B}_n^{-1} \boldsymbol{\beta}_n \\ &= \delta_0 + \mathbf{y}^\top \mathbf{y} + \boldsymbol{\beta}_0^\top \mathbf{B}_0^{-1} \boldsymbol{\beta}_0 - (\mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}})^\top \mathbf{B}_n (\mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}}) \\ &= \delta_0 + \mathbf{y}^\top \mathbf{y} - \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \mathbf{B}_n \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} - 2\hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \mathbf{B}_n \mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \boldsymbol{\beta}_0^\top (\mathbf{B}_0^{-1} - \mathbf{B}_0^{-1} \mathbf{B}_n \mathbf{B}_0^{-1}) \boldsymbol{\beta}_0 \\ &\quad - \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} + \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} \\ &= \delta_0 + \mathbf{y}^\top \mathbf{y} - \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} + \hat{\boldsymbol{\beta}}^\top (\mathbf{X}^\top \mathbf{X} - \mathbf{X}^\top \mathbf{X} \mathbf{B}_n \mathbf{X}^\top \mathbf{X}) \hat{\boldsymbol{\beta}} \\ &\quad - 2\hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \mathbf{B}_n \mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \boldsymbol{\beta}_0^\top (\mathbf{B}_0^{-1} - \mathbf{B}_0^{-1} \mathbf{B}_n \mathbf{B}_0^{-1}) \boldsymbol{\beta}_0. \end{aligned}$$

Observe that

$$\begin{aligned} (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})^\top (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) &= \mathbf{y}^\top \mathbf{y} - 2\hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{y} + \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} \\ &= \mathbf{y}^\top \mathbf{y} - 2\hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top (\mathbf{X}\hat{\boldsymbol{\beta}} + \hat{\boldsymbol{\mu}}) + \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}} \\ &= \mathbf{y}^\top \mathbf{y} - \hat{\boldsymbol{\beta}}^\top \mathbf{X}^\top \mathbf{X} \hat{\boldsymbol{\beta}}, \end{aligned}$$

where  $\mathbf{y} = \mathbf{X}\hat{\boldsymbol{\beta}} + \hat{\boldsymbol{\mu}}$ , and  $\mathbf{X}^\top \hat{\boldsymbol{\mu}} = 0$ .

The following matrix identities are useful [24]:

$$(\mathbf{D} + \mathbf{E})^{-1} = \mathbf{D}^{-1} - \mathbf{D}^{-1} (\mathbf{D}^{-1} + \mathbf{E}^{-1})^{-1} \mathbf{D}^{-1},$$

and

$$(\mathbf{D} + \mathbf{E})^{-1} = \mathbf{D}^{-1} (\mathbf{E}^{-1} + \mathbf{D}^{-1}) \mathbf{E}^{-1}.$$

Using these identities,

$$\begin{aligned} [(\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0]^{-1} &= \mathbf{X}^\top \mathbf{X} - \mathbf{X}^\top \mathbf{X}(\mathbf{X}^\top \mathbf{X} + \mathbf{B}_0^{-1})^{-1} \mathbf{X}^\top \mathbf{X} \\ &= \mathbf{B}_0^{-1} - \mathbf{B}_0^{-1}(\mathbf{X}^\top \mathbf{X} + \mathbf{B}_0^{-1})^{-1} \mathbf{B}_0^{-1} \\ &= \mathbf{X}^\top \mathbf{X}(\mathbf{X}^\top \mathbf{X} + \mathbf{B}_0^{-1})^{-1} \mathbf{B}_0^{-1}. \end{aligned}$$

Then,

$$\begin{aligned} \delta^* &= \delta_0 + (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})^\top (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) + \hat{\boldsymbol{\beta}}^\top [(\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0]^{-1} \hat{\boldsymbol{\beta}} \\ &\quad - 2\hat{\boldsymbol{\beta}}^\top [(\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0]^{-1} \boldsymbol{\beta}_0 + \boldsymbol{\beta}_0^\top [(\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0]^{-1} \boldsymbol{\beta}_0 \\ &= \delta_0 + (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})^\top (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) \\ &\quad + (\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}_0)^\top [(\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{B}_0]^{-1} (\hat{\boldsymbol{\beta}} - \boldsymbol{\beta}_0). \end{aligned}$$

In a similar way for the second part,

$$\begin{aligned} (\mathbf{V}_0 + (\mathbf{X}^\top \mathbf{X})^{-1})^{-1} &= \mathbf{V}_0^{-1} - \mathbf{V}_0^{-1}(\mathbf{V}_0^{-1} + \mathbf{X}^\top \mathbf{X})^{-1} \mathbf{V}_0^{-1} \\ &= \mathbf{X}^\top \mathbf{X} - \mathbf{X}^\top \mathbf{X}(\mathbf{V}_0^{-1} + \mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{X} \\ &= \mathbf{X}^\top \mathbf{X}((\mathbf{X}^\top \mathbf{X})^{-1} + \mathbf{V}_0)^{-1} \mathbf{V}_0^{-1}, \end{aligned}$$

we use these results and some algebra to show that  $\mathbf{B}_0^\top \mathbf{V}_0^{-1} \mathbf{B}_0 + \hat{\mathbf{B}}^\top \mathbf{X}^\top \mathbf{X} \hat{\mathbf{B}} - \mathbf{B}_n^\top \mathbf{V}_n^{-1} \mathbf{B}_n = (\hat{\mathbf{B}} - \mathbf{B}_0)^\top \mathbf{V}_n (\hat{\mathbf{B}} - \mathbf{B}_0)$  taking into account that  $\mathbf{V}_n = (\mathbf{V}_0^{-1} + \mathbf{X}^\top \mathbf{X})^{-1}$  and  $\hat{\mathbf{B}} = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{Y}$ .

8. Show that in the linear regression model  $\boldsymbol{\beta}_n^\top (\mathbf{B}_n^{-1} - \mathbf{B}_n^{-1} \mathbf{M}^{-1} \mathbf{B}_n^{-1}) \boldsymbol{\beta}_n = \boldsymbol{\beta}_{**}^\top \mathbf{C} \boldsymbol{\beta}_{**}$  and  $\boldsymbol{\beta}_{**} = \mathbf{X}_0 \boldsymbol{\beta}_n$ .

**Answer**

Taking into account that  $(\mathbf{A} + \mathbf{B})^{-1} = \mathbf{A}^{-1} - \mathbf{A}^{-1}(\mathbf{A}^{-1} + \mathbf{B}^{-1})^{-1} \mathbf{A}^{-1}$  [24], then we observe that  $(\mathbf{B}_n^{-1} - \mathbf{B}_n^{-1} \mathbf{M}^{-1} \mathbf{B}_n^{-1}) = (\mathbf{B}_n + (\mathbf{X}_0^\top \mathbf{X}_0)^{-1})^{-1}$ , where  $(\mathbf{B}_n + (\mathbf{X}_0^\top \mathbf{X}_0)^{-1})^{-1} = \mathbf{X}_0^\top \mathbf{X}_0 - \mathbf{X}_0^\top \mathbf{X}_0 (\mathbf{B}_n^{-1} + \mathbf{X}_0^\top \mathbf{X}_0)^{-1} \mathbf{X}_0^\top \mathbf{X}_0 = \mathbf{X}_0^\top \mathbf{X}_0 - \mathbf{X}_0^\top \mathbf{X}_0 \mathbf{M}^{-1} \mathbf{X}_0^\top \mathbf{X}_0$ , thus

$$\begin{aligned} \boldsymbol{\beta}_n^\top (\mathbf{B}_n^{-1} - \mathbf{B}_n^{-1} \mathbf{M}^{-1} \mathbf{B}_n^{-1}) \boldsymbol{\beta}_n &= \boldsymbol{\beta}_n^\top (\mathbf{X}_0^\top \mathbf{X}_0 - \mathbf{X}_0^\top \mathbf{X}_0 \mathbf{M}^{-1} \mathbf{X}_0^\top \mathbf{X}_0) \boldsymbol{\beta}_n \\ &= \boldsymbol{\beta}_n^\top \mathbf{X}_0^\top (\mathbf{I}_{N_0} - \mathbf{X}_0 \mathbf{M}^{-1} \mathbf{X}_0^\top) \mathbf{X}_0 \boldsymbol{\beta}_n \\ &= \boldsymbol{\beta}_n^\top \mathbf{X}_0^\top \mathbf{C} \mathbf{X}_0 \boldsymbol{\beta}_n \\ &= \boldsymbol{\beta}_{**}^\top \mathbf{C} \boldsymbol{\beta}_{**}. \end{aligned}$$

Let's show that  $\boldsymbol{\beta}_{**} = \mathbf{X}_0 \boldsymbol{\beta}_n$ ,

$$\begin{aligned}
\beta_{**} &= \mathbf{C}^{-1} \mathbf{X}_0 \mathbf{M}^{-1} \mathbf{B}_n^{-1} \beta_n \\
&= (\mathbf{I}_{N_0} + \mathbf{X}_0 \mathbf{B}_n \mathbf{X}_0^\top) \mathbf{X}_0 \mathbf{M}^{-1} \mathbf{B}_n^{-1} \beta_n \\
&= (\mathbf{I}_{N_0} + \mathbf{X}_0 \mathbf{B}_n \mathbf{X}_0^\top) \mathbf{X}_0 (\mathbf{B}_n - \mathbf{B}_n ((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1} \mathbf{B}_n) \mathbf{B}_n^{-1} \beta_n \\
&= (\mathbf{I}_{N_0} + \mathbf{X}_0 \mathbf{B}_n \mathbf{X}_0^\top) (\mathbf{X}_0 \beta_n - \mathbf{X}_0 \mathbf{B}_n ((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1} \beta_n) \\
&= \mathbf{X}_0 \beta_n - \mathbf{X}_0 \mathbf{B}_n ((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1} \beta_n + \mathbf{X}_0 \mathbf{B}_n \mathbf{X}_0^\top \mathbf{X}_0 \beta_n \\
&\quad - \mathbf{X}_0 \mathbf{B}_n \mathbf{X}_0^\top \mathbf{X}_0 \mathbf{B}_n ((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1} \beta_n \\
&= \mathbf{X}_0 \beta_n - \mathbf{X}_0 \mathbf{B}_n [((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1} - \mathbf{X}_0^\top \mathbf{X}_0 + \mathbf{X}_0^\top \mathbf{X}_0 \mathbf{B}_n ((\mathbf{X}_0^\top \mathbf{X}_0)^{-1} + \mathbf{B}_n)^{-1}] \beta_n.
\end{aligned}$$

Using that  $(\mathbf{A} + \mathbf{B})^{-1} = \mathbf{A}^{-1} - \mathbf{A}^{-1} \mathbf{B} (\mathbf{A} + \mathbf{B})^{-1}$ , we observe that the expression in brackets is equal to  $\mathbf{0}$ , then we have the result.

9. Show that  $(\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}}) = \mathbf{S} + (\mathbf{B} - \hat{\mathbf{B}})^\top \mathbf{X}^\top \mathbf{X} (\mathbf{B} - \hat{\mathbf{B}})$  where  $\mathbf{S} = (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})$ ,  $\hat{\mathbf{B}} = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{Y}$  in the multivariate regression model.

**Answer**

$$\begin{aligned}
(\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}}) &= (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}} + \mathbf{X}\hat{\mathbf{B}} - \mathbf{X}\mathbf{B})^\top (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}} + \mathbf{X}\hat{\mathbf{B}} - \mathbf{X}\mathbf{B}) \\
&= (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}}) + 2(\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{X}\hat{\mathbf{B}} - \mathbf{X}\mathbf{B}) \\
&\quad + (\mathbf{X}\mathbf{B} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{X}\mathbf{B} - \mathbf{X}\hat{\mathbf{B}}) \\
&= \mathbf{S} + (\mathbf{B} - \hat{\mathbf{B}})^\top \mathbf{X}^\top \mathbf{X} (\mathbf{B} - \hat{\mathbf{B}}),
\end{aligned}$$

given that  $(\mathbf{Y} - \mathbf{X}\hat{\mathbf{B}})^\top (\mathbf{X}\hat{\mathbf{B}} - \mathbf{X}\mathbf{B}) = \hat{\mathbf{U}}^\top \mathbf{X} (\hat{\mathbf{B}} - \mathbf{B})$ , using that  $\hat{\mathbf{B}} = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{Y}$  which implies  $\mathbf{X}^\top \mathbf{X}\hat{\mathbf{B}} = \mathbf{X}^\top \mathbf{Y} = \mathbf{X}^\top \mathbf{X}\hat{\mathbf{B}} + \mathbf{X}^\top \hat{\mathbf{U}}$ , then  $\mathbf{X}^\top \hat{\mathbf{U}} = \mathbf{0}$ .

10. What is the probability that the Sun will rise tomorrow?

This is the most famous Richard Price's example developed in the Appendix of the Bayes' theorem paper [2]. Here, we implicitly use *Laplace's Rule of Succession* to solve this question. In particular, if we were a priori uncertain about the probability the Sun will rise on a specified day, we can assume a prior uniform distribution over  $(0,1)$ , that is, a beta  $(1,1)$  distribution. Then, what is the probability that the Sun will rise tomorrow?

**Answer**

This exercise is an application of the Bernoulli-beta model. Thus, the likelihood is given by a binomial distribution where the probability of success is  $\theta$ ,  $p(\mathbf{y}|\theta) \propto \theta^{\sum_{i=1}^N y_i} (1-\theta)^{N-\sum_{i=1}^N y_i}$ . In addition, the prior distribution is beta, that is,  $\pi(\theta) \propto \theta^{\alpha_0-1} (1-\theta)^{\beta_0-1}$ , where  $\alpha_0 = \beta_0 = 1$ . Then, the predictive distribution that the sun will rise tomorrow is  $p(Y_0 = 1|\mathbf{y}) = \frac{1+S}{2+N}$ , where  $S = \sum_{i=1}^N y_i$  is the number of successes (the Sun rise).  $\frac{1+S}{2+N}$  is known

as the *Laplace's Rule of Succession* that was introduced by Laplace in the 18<sup>th</sup> century in the course of treating the sunrise problem.

11. Using information from Public Policy Polling in September 27th-28th for the 2016 presidential five-way race in USA, there are 411, 373 and 149 sampled people supporting Hillary Clinton, Donald Trump and other, respectively.
  - Find the posterior probability of the percentage difference of people supporting Hillary versus Trump according to this data using a non-informative prior, that is,  $\alpha_0 = [1 \ 1 \ 1]$  in the multinomial-Dirichlet model. What is the probability of having more supporters of Hillary vs Trump?
  - What is the probability that sampling one hundred independent individuals 44, 40 and 16 support Hillary, Trump and other, respectively?

**Answer**

### *R code. Multinomial-Dirichlet model: Polling 2016 USA presidential race*

```

1 set.seed(010101)
2 # Multinomial-Dirichlet example:
3 # Polling 2016 USA presidential race
4 y <- c(411, 373, 149)
5 # Clinton, Trump, Other
6 # Public Policy Polling September 27-28,
7 # 2016 five-way race
8 alpha0 <- rep(1, 3)
9 # Hyperparameters: non-informative distribution
10 alphan <- alpha0 + y
11 S <- 100000
12 # Sample draws of posterior
13 thetas <- MCMCpack::rdirichlet(S, alphan)
14 colnames(thetas) <- c("Clinton", "Trump", "Other")
15 head(thetas)
16      Clinton      Trump      Other
17 [1,] 0.4211346 0.4188607 0.1600046
18 [2,] 0.4244207 0.4224523 0.1531270
19 [3,] 0.4349268 0.3843953 0.1806779
20 [4,] 0.4533499 0.4005530 0.1460972
21 [5,] 0.4381799 0.3968502 0.1649699
22 [6,] 0.4436852 0.3971321 0.1591827
23 dif <- thetas[,1] - thetas[,2]
24 # Difference of shares Hillary vs Trump
25 data <- data.frame(dif)
26 names(data) <- c("Difference")
27 library(ggplot2)
28 p <- ggplot(data) +
29   geom_histogram(aes(x = Difference), binwidth = 0.01) +
30   geom_vline(xintercept=0.0, lwd=1, colour="red") +
31   ggtitle("Percentage difference Clinton vs Trump 2016
32     presidential race") + xlab("Percentage Difference") +
33     ylab("")
34 difmcmc <- coda::mcmc(dif)
35 # Declaring a MCMC object
36 summary(difmcmc)
37
38 Iterations = 1:1e+05
39 Thinning interval = 1
40 Number of chains = 1
41 Sample size per chain = 1e+05
42
43 1. Empirical mean and standard deviation for each
44 variable, plus standard error of the mean:
45
46      Mean          SD      Naive SE Time-series SE
47 4.062e-02  2.996e-02  9.474e-05  9.474e-05
48
49 2. Quantiles for each variable:
50
51      2.5%      25%      50%      75%      97.5%
52 -0.01817  0.02033  0.04058  0.06089  0.09923
53
54 CW <- mean(difmcmc>0)
55 CW
56 0.91339

```

**FIGURE 3.1**

Percentage difference: Hillary Clinton vs Donald Trump, five-way race.

There is a 95% probability that the percentage difference between Hillary and Trump according to this poll is (-1.8%, 9.9%). The probability of Hillary having more supporters is 91.3%

***R code. Multinomial-Dirichlet model: Polling 2016  
USA presidential race***

```

1 # Predictive distribution by simulation
2 y0 <- c(44, 40, 16)
3 Pred <- apply(thetas, 1, function(p) {rmultinom(1, size =
4   sum(y0), prob = p)})
5 sum(sapply(1:S, function(s) {sum(Pred[,s] == y0) == 3}))/S
6 # Predictive distribution by analytical expression
7 PredY0 <- function(y0){
8   n <- sum(y0)
9   Res1 <- sum(sapply(1:length(y), function(l){lgamma(alphan[
10     l]+y0[l]) - lgamma(alphan[l])-lfactorial(y0[l]))}))
11   Res <- lfactorial(n)+lgamma(sum(alphan))-lgamma(sum(alphan
12     )+n) + Res1
13   return(exp(Res))
14 }
15 PredY0(y0)
16 0.00850

```

The probability that from one hundred random selected people 44 support Hillary, 40 support Trump and 16 support other candidate is 0.85%.

## 12. Math test example continues

You have a random sample of math scores of size  $N = 50$  from a normal distribution,  $Y_i \sim \mathcal{N}(\mu, \sigma)$ . The sample mean and variance are equal to 102 and 10, respectively. Using the normal-normal/inverse-gamma model where  $\mu_0 = 100$ ,  $\beta_0 = 1$ ,  $\alpha_0 = \delta_0 = 0.001$

- Get 95% confidence and credible intervals for  $\mu$ .
- What is the posterior probability that  $\mu > 103$ ?

**Answer**



*R code. Math test example continues*

```

1  set.seed(010101)
2  N <- 50
3  # Sample size
4  muhat <- 102
5  # Sample mean
6  sig2hat <- 10
7  # Sample variance
8  # Hyperparameters
9  mu0 <- 100
10 beta0 <- 1
11 delta0 <- 0.001
12 alpha0 <- 0.001
13 S <- 100000
14 # Posterior draws
15 alphan <- alpha0 + N
16 deltan <- sig2hat*(N - 1) + delta0 + beta0*N/(beta0 + N)*(
    muhat - mu0)^2
17 sig2Post <- invgamma::rinvgamma(S, shape = alphan, rate =
    deltan)
18 summary(sig2Post)
19 betan <- beta0 + N
20 mun <- (beta0*mu0 + N*muhat)/betan
21 muPost <- sapply(sig2Post, function(s2){rnorm(1, mun, sd = (
    s2/betan)^0.5)})
22 muPostq <- quantile(muPost, c(0.025, 0.5, 0.975))
23 muPostq
24      2.5%      50%      97.5%
25 101.0929 101.9625 102.8311
26 cutoff <- 103
27 PmuPostcutoff <- mean(muPost > cutoff)
28 PmuPostcutoff
29 0.00994
30 # Using Student's t
31 muPost_t <- ((deltan/(alphan*betan))^0.5)*rt(S, alphan) +
    mun
32 c1 <- rgb(173,216,230,max = 255, alpha = 50, names = "lt.
    blue")
33 c2 <- rgb(255,192,203, max = 255, alpha = 50, names = "lt.
    pink")
34 hist(muPost, main = "Histogram: Posterior mean", xlab = "
    Posterior mean", col = c2)
35 hist(muPost_t, main = "Histogram: Posterior mean", xlab = "
    Posterior mean", add = T, col = c1)
36 muPost_tq <- quantile(muPost_t, c(0.025, 0.5, 0.975))
37 muPost_tq
38      2.5%      50%      97.5%
39 101.0837 101.9608 102.8435
40 PmuPost_tcutoff <- mean(muPost_t > cutoff)
41 PmuPost_tcutoff
42 0.01087

```

We perform our calculations using the conditional posterior distribution, and the marginal posterior distribution. Both procedures give similar results as we can observe from Figure 3.2.



**FIGURE 3.2**

Histogram using the conditional posterior distribution and the marginal posterior distribution

We have that the 95% credible interval is  $(101.08, 102.84)$ , and the probability of having a value greater than 103 is 1.09%.

### 13. Demand of electricity example continues

Set  $c_0$  such that maximizes the marginal likelihood in the specifications with and without electricity price in the example of demand of electricity (empirical Bayes). Then, calculate the Bayes factor, and conclude if there is evidence supporting the inclusion of the price of electricity in the demand equation.

**Answer**

*R code. Demand of electricity*

```

1 rm(list = ls())
2 set.seed(010101)
3 # Electricity demand
4 DataUt <- read.csv("https://raw.githubusercontent.com/
    besmarter/BSTApp/refs/heads/master/DataApp/Utilities.csv",
    sep = ",", header = TRUE, quote = "")
5 DataUtEst <- DataUt %>%
6 filter(Electricity != 0)
7 attach(DataUtEst)
8 # Dependent variable: Monthly consumption (kWh) in log
9 Y <- log(Electricity)
10 N <- length(Y)
11 # Regressors quantity including intercept
12 X <- cbind(LnPriceElect, IndSocio1, IndSocio2, Altitude,
    Nrooms, HouseholdMem, Children, Lnincome, 1)
13 # Regressor without price
14 Xnew <- cbind(IndSocio1, IndSocio2, Altitude, Nrooms,
    HouseholdMem, Children, Lnincome, 1)
15 # Log marginal function (multiply by -1 due to minimization)
16 LogMarLikLM <- function(X, c0){
17   k <- dim(X)[2]
18   N <- dim(X)[1]
19   # Hyperparameters
20   B0 <- c0*diag(k)
21   b0 <- rep(0, k)
22   # Posterior parameters
23   bhat <- solve(t(X)%*%X)%*%t(X)%*%Y
24   # Force this matrix to be symmetric
25   Bn <- as.matrix(Matrix::forceSymmetric(solve(solve(B0) + t
    (X)%*%X)))
26   bn <- Bn%*(solve(B0)%*%b0 + t(X)%*%X)%*%bhat)
27   dn <- as.numeric(d0 + t(Y)%*%Y+t(b0)%*%solve(B0)%*%b0-t(bn
    )%*%solve(Bn)%*%bn)
28   an <- a0 + N
29   # Log marginal likelihood
30   logpy <- (N/2)*log(1/pi)+(a0/2)*log(d0)-(an/2)*log(dn) +
    0.5*log(det(Bn)/det(B0)) + lgamma(an/2)-lgamma(a0/2)
31   return(-logpy)
32 }
33 # Hyperparameters
34 d0 <- 0.001
35 a0 <- 0.001
36 # Empirical Bayes: Obtain c0 maximizing the log marginal
    likelihood
37 c0 <- 1000
38 EB <- optim(c0, fn = LogMarLikLM, method = "Brent", lower =
    0.0001, upper = 10^6, X = X)
39 EBnew <- optim(c0, fn = LogMarLikLM, method = "Brent", lower
    = 0.0001, upper = 10^6, X = Xnew)
40 # Change of order to take into account the -1 in the
    LogMarLikLM function
41 BFEM <- exp(EBnew$value - EB$value)
42 BFEM
43 71897025

```

The Bayes factor based on the empirical Bayes of the model with electricity price versus the model without electricity price is equal to 71897938, this gives very strong evidence to include the price in the specification.

#### 14. Utility demand

Use the file *Utilities.csv* to estimate a multivariate linear regression model where  $\mathbf{Y}_i = [\log(\text{electricity}_i) \log(\text{water}_i) \log(\text{gas}_i)]$  as function of  $\log(\text{electricity price}_i)$ ,  $\log(\text{water price}_i)$ ,  $\log(\text{gas price}_i)$ ,  $\text{IndSocio1}_i$ ,  $\text{IndSocio2}_i$ ,  $\text{Altitude}_i$ ,  $\text{Nrooms}_i$ ,  $\text{HouseholdMem}_i$ ,  $\text{Children}_i$ , and  $\log(\text{Income}_i)$ , where electricity, water and gas are monthly consumption of electricity (kWh), water ( $\text{m}^3$ ) and gas ( $\text{m}^3$ ), and other definitions are given in the Example of Section 4.3. Omit households that do not consume any of the utilities in this exercise.

Set a non-informative prior framework,  $\mathbf{B}_0 = [0]_{11 \times 3}$ ,  $\mathbf{V}_0 = 1000\mathbf{I}_{11}$ ,  $\boldsymbol{\Psi}_0 = 1000\mathbf{I}_3$  and  $\alpha_0 = 3$ , where we have  $K = 11$  (regressors plus intercept) and  $M = 3$  (equations) in this exercise.

- (a) Find the posterior mean estimates and the highest posterior density intervals at 95% of  $\mathbf{B}$  and  $\boldsymbol{\Sigma}$ . Use the marginal distribution and the conditional distribution to obtain the posterior estimates of  $\mathbf{B}$ , and compare the results.
- (b) Find the Bayes factor comparing the baseline model in this exercise with the same specification but using the income in dollars. Now, calculate the Bayes factor using the income in thousand dollars. Is there any difference?
- (c) Find the predictive distribution for the monthly demand of electricity, water and gas in the baseline specification of a household located in the lowest socioeconomic condition in a municipality located below 1000 meters above the sea level, 2 rooms, 3 members with children, a monthly income equal to USD 500, an electricity price equal to USD/kWh 0.15, a water price equal to USD/ $\text{M}^3$  0.70, and a gas price equal to USD/ $\text{M}^3$  0.75.

#### Answer

We see that the posterior estimates of the location parameters based on the marginal distribution and the conditional distribution are very similar (conditional on  $\boldsymbol{\Sigma}$ ). This is important as many times there is no analytical solutions in well-known forms of marginal posterior distributions, and consequently, we should get draws of the posterior distributions based on conditional distributions of block of parameters (See Chapter 4).

We find that the Bayes factor of the baseline model ( $\log(\text{Income})$ ) versus the two alternative models using income in dollars and thousand dollars are 108925764 and 0.1089261. The former gives strong evidence in favor of the baseline model, whereas the latter gives positive evidence for the

model using the income in thousand dollars. This result despite that the location coefficients are the same in the two alternative specifications, except for the change in scale of the coefficients associated with income. This example shows that Bayes factors are sensitive to units of measure, and consequently, it is relevant to think carefully about the priors when performing hypothesis testing using a Bayesian framework. Observe that a nice feature in Bayesian inference is that we followed the same conceptual framework (Bayes factor) in the previous exercise and this exercise. In one hand, the previous exercise is an example of nested models, that is, one model is a restricted version of a more general model. On the other hand, this exercise is an example of non-nested models. This is not the case in the Frequentist approach. The statistical framework is not the same when testing nested and non-nested models.

*R code. Utilities demand: Multivariate regression,  
posterior inference*

```

1 rm(list = ls())
2 set.seed(010101)
3 library(dplyr)
4 # Electricity demand
5 DataUt <- read.csv("https://raw.githubusercontent.com/
    besmarter/BSTApp/refs/heads/master/DataApp/Utilities.csv
    ", sep = ",", header = TRUE, quote = "")
6 DataUtEst <- DataUt %>%
7 filter(Electricity != 0 & Water != 0 & Gas != 0)
8 attach(DataUtEst)
9 Y <- cbind(log(Electricity), log(Water), log(Gas))
10 X <- cbind(LnPriceElect, LnPriceWater, LnPriceGas, IndSocio1
    , IndSocio2, Altitude, Nrooms, HouseholdMem, Children,
    Lnincome, 1)
11 M <- dim(Y)[2]
12 K <- dim(X)[2]
13 N <- dim(Y)[1]
14 # Hyperparameters
15 B0 <- matrix(0, K, M)
16 c0 <- 1000
17 V0 <- c0*diag(K)
18 Psi0 <- c0*diag(M)
19 a0 <- M
20 # Posterior parameters
21 Bhat <- solve(t(X)%*%X)%*%t(X)%*%Y
22 S <- t(Y - X%*%Bhat)%*%(Y - X%*%Bhat)
23 Vn <- solve(solve(V0) + t(X)%*%X)
24 Bn <- Vn%*(solve(V0)%*%B0 + t(X)%*%X)%*%Bhat
25 Psin <- Psi0 + S + t(B0)%*%solve(V0)%*%B0 + t(Bhat)%*%t(X)%*
    %X)%*%Bhat - t(Bn)%*%solve(Vn)%*%Bn
26 an <- a0 + N
27 #Posterior draws
28 s <- 10000 #Number of posterior draws
29 SIGs <- replicate(s, LaplacesDemon::rinvwishart(an, Psin))
30 BsCond <- sapply(1:s, function(s) {MixMatrix::rmatrixnorm(n
    = 1, mean=Bn, U = Vn, V = SIGs[,s])})
31 summary(coda::mcmc(t(BsCond)))
32 Bs <- sapply(1:s, function(s) {MixMatrix::rmatrixt(n = 1,
    mean=Bn, U = Vn, V = Psin, df = an + 1 - M)})
33 summary(coda::mcmc(t(Bs)))
34 SIGMs <- t(sapply(1:s, function(l) {gdata::lowerTriangle(
    SIGs[,l], diag=TRUE, byrow=FALSE)}))
35 summary(coda::mcmc(SIGMs))
36 hdiBs <- HDInterval::hdi(t(BsCond), credMass = 0.95) #
    Highest posterior density credible interval
37 hdiBs
38 hdiSIG <- HDInterval::hdi(SIGMs, credMass = 0.95) # Highest
    posterior density credible interval
39 hdiSIG
40

```

***R code. Utilities demand: Multivariate regression,  
Bayes factors***

```

1 # Log marginal function (multiply by -1 due to minimization)
2 LogMarLikLM <- function(X, c0){
3   c10 <- c0[1]; c20 <- c0[2]
4   k <- dim(X)[2]
5   N <- dim(X)[1]
6   # Hyperparameters
7   V0 <- c10*diag(k)
8   Psi0 <- c20*diag(M)
9   # Posterior parameters
10  Bhat <- solve(t(X)%*%X)%*%t(X)%*%Y
11  S <- t(Y - X)%*%Bhat)%*%(Y - X)%*%Bhat)
12  Vn <- solve(solve(V0) + t(X)%*%X)
13  Bn <- Vn%*(solve(V0)%*%B0 + t(X)%*%X)%*%Bhat)
14  Psin <- Psi0 + S + t(B0)%*%solve(V0)%*%B0 + t(Bhat)%*%t(X)
    %*%X)%*%Bhat - t(Bn)%*%solve(Vn)%*%Bn
15  # Log marginal likelihood
16  logpy <- (N*M/2)*log(1/pi)+(a0/2)*log(det(Psi0)) - (an/2)*
    log(det(Psin)) + (M/2)*(log(det(Vn)) - log(det(V0))) +
    lgamma(an/2)-lgamma(a0/2)
17  return(-logpy)
18 }
19 c0 <- rep(1000, 2)
20 LogML <- LogMarLikLM(X=X, c0 = c0)
21 # Using income in dollars as regressor
22 Xnew <- cbind(LnPriceElect, LnPriceWater, LnPriceGas,
    IndSocio1, IndSocio2, Altitude, Nrooms, HouseholdMem,
    Children, exp(Lnincome), 1)
23 LogMLnew <- LogMarLikLM(X=Xnew, c0 = c0)
24 # Bayes factor
25 BF12 <- exp(LogMLnew - LogML)
26 BF12
27 # Using income in thousand dollars as regressor
28 XnewT <- cbind(LnPriceElect, LnPriceWater, LnPriceGas,
    IndSocio1, IndSocio2, Altitude, Nrooms, HouseholdMem,
    Children, exp(Lnincome)/1000, 1)
29 LogMLnewT <- LogMarLikLM(X=XnewT, c0 = c0)
30 # Bayes factor
31 BF13 <- exp(LogMLnewT - LogML)
32 BF13
33

```

*R code. Utilities demand: Multivariate regression, predictive distribution*

```

1 # Predictive distribution
2 Xpred <- c(log(0.15), log(0.70), log(0.75), 1, 0, 0, 2, 3,
3           1, log(500), 1)
4 Mean <- Xpred%%Bn
5 Hn <- 1+t(Xpred)%%Vn%%Xpred
6 UtilDemand <- exp(replicate(s, MixMatrix::rmatrixt(n = 1,
7             mean=Mean, U = Hn, V = Psin, df = an + 1 - M)))
8 ElePred <- UtilDemand[1,1,]
9 WatPred <- UtilDemand[1,2,]
10 GasPred <- UtilDemand[1,3,]
11 data <- data.frame(cbind(ElePred, WatPred, GasPred)) #Data
12           frame
13 annotations1 <- data.frame(
14   x = round(quantile(data$ElePred, c(0.025, 0.5, 0.975)),1),
15   y = c(600, 1000, 600),
16   label = c("2.5%", "50%", "97.5%:")
17 )
18 annotations2 <- data.frame(
19   x = round(quantile(data$WatPred, c(0.025, 0.5, 0.975)),1),
20   y = c(600, 1000, 600),
21   label = c("2.5%", "50%", "97.5%:")
22 )
23 annotations3 <- data.frame(
24   x = round(quantile(data$GasPred, c(0.025, 0.5, 0.975)),1),
25   y = c(600, 1000, 600),
26   label = c("2.5%", "50%", "97.5%:")
27 )
28 require(ggplot2) # Cool figures
29 require(ggpubr) # Multiple figures in one page
30 require(latex2exp) # LaTeX equations in figures
31 fig1 <- ggplot(data = data, aes(ElePred)) + geom_histogram(
32   bins = 40, color = "#000000", fill = "#0099F8") + xlab(
33     "kWh") + ylab("Frequency") + ggtitle("Electricity") +
34     xlim(0, 1050) + geom_text(data = annotations1, aes(x = x,
35       y = y, label = paste(label, x)), size = 3, fontface = "
36     bold")
37 fig2 <- ggplot(data = data, aes(WatPred)) + geom_histogram(
38   bins = 40, color = "#000000", fill = "#0099F8") + xlab(
39     TeX("$M^3$")) + ylab("Frequency") + ggtitle("Water") +
40     xlim(0, 100) + geom_text(data = annotations2, aes(x = x,
41       y = y, label = paste(label, x)), size = 3, fontface = "
42     bold")
43 fig3 <- ggplot(data = data, aes(GasPred)) + geom_histogram(
44   bins = 40, color = "#000000", fill = "#0099F8") + xlab(
45     TeX("$M^3$")) + ylab("Frequency") + ggtitle("Gas") +
46     xlim(0, 80) + geom_text(data = annotations3, aes(x = x,
47       y = y, label = paste(label, x)), size = 3, fontface = "
48     bold")

```



Figures 3.3, 3.4 and 3.5 show the marginal predictive distributions of electricity, water and gas for the reference household. The median predictive values are kWh 168.8, M<sup>3</sup> 12.3 and M<sup>3</sup> 10.1, respectively. In addition, the 95% credible intervals are (27.7, 1028.9), (1.5, 98.7) and (1.5, 67.5) for electricity, water and gas.



**FIGURE 3.3**

Histogram using the posterior predictive distribution of electricity demand

**FIGURE 3.4**

Histogram using the posterior predictive distribution of water demand

**FIGURE 3.5**

Histogram using the posterior predictive distribution of gas demand

# 4

## *Simulation methods*

### 4.1 Solutions of Exercises

1. The inverse transform method ...

#### *R code. Example: Math test*

```
1 N <- 50 # Sample size
2 y_bar <- 102 # Sample mean
3 s2 <- 10 # Sample variance
4 alpha <- N - 1
5 serror <- (s2/N)^0.5
6 y.H0 <- c(100, 100.5, 101, 101.5, 102)
7 test <- (y.H0 - y_bar)/serror
8 pval <- 2*pt(test, alpha)
9 pval
10 0.0000459 0.0015431 0.0299338 0.2690040 1
11 # p-values
12 P001 <- (gamma(N/2)*((N-1)*serror^2)^(-0.5)*(1+test^2/alpha)
13 ^(-N/2))/(gamma(1/2)*gamma((N-1)/2))
14 P001/(1+P001)
15 0.0001705 0.0050345 0.0725330 0.3210223 0.4702050
16 # Posterior model probability of the null hypothesis.
```



## Part II

# Regression models: A GUIded toolkit



# 5

---

## Graphical user interface

---

This chapter presents our graphical user interface (GUI) to carry out Bayesian regression analysis in a very friendly environment without any programming skills (drag and drop). Our GUI is based on an interactive web application using *shiny* [3], and packages like *MCMCpack* [13] and *bayesm* [21] from **R** software [16], and is designed for teaching and applied purposes at an introductory level. In the next chapters of the second part of this book we carry out some applications to highlight the potential of our GUI for applied researchers and practitioners.

---

### 5.1 Introduction

Our GUI allows performing inference using Bayesian regression analysis without requiring programming skills. The latter seems to be a significant impediment to increasing the use of the Bayesian framework [26, 10].

There are other available graphical user interfaces for carrying out Bayesian regression analysis. *ShinyStan* [25] is a very flexible open source program, but users are required to have some programming skills. *BugsXLA* [26] is open source, but less flexible. However, users do not need to have programming skills. *Bayesian regression: Nonparametric and parametric models* [10] is a very flexible and friendly GUI that is based on *MATLAB Compiler* for a 64-bit Windows computer. Its focus is on Bayesian nonparametric regressions, and it can be thought of for users who have mastered basic parametric models, such as the ones that we show in our GUI. There are also *MATLAB toolkit*, *Stata* and *BayES*, but these are not open sources.

We developed our GUI based on an interactive web application using shiny [3], and some libraries in **R** [15]. The specific libraries and commands that are used in our GUI can be seen in Table 10.1. It has ten univariate models, four multivariate, **time series models**, three hierarchical longitudinal, and seven Bayesian model averaging frameworks. In addition, it gives basic summaries and diagnostics of the posterior chains, as well as the posterior chains themselves, and different plots, such as trace, autocorrelation and densities.

In terms of its flexibility and possibilities, our GUI lies between *ShinyStan* and *BugsXLA*: users are not required to have any programming skills, but it

is not as advanced as [10]’s software. However, our GUI can be run in any operating system. Our GUI, which we call BESmarter,<sup>1</sup> is freely available at <https://github.com/besmarter/BSTApp>; so users have access to all our code and datasets.

Simulated and applied datasets are in the folders **DataSim** (see Table 10.2 for details), and **DataApp** (see Table 10.3 for details) of our **GitHub** repository. The former folder also includes the files that were used to simulate different processes, so, the population parameters are available, and as a consequence these files can be used as a pedagogical tool to show some statistical properties of the inferential frameworks available in our GUI. The latter folder contains the datasets used in the applications of this second part of the book. Users should use these datasets as templates to structure their own datasets.

There are three ways to install our GUI. The easiest way, but that requires installation of **R**, and potentially a **R** code editor, is to type

***R code. How to display our graphical user interface***

```
1 shiny::runGitHub("besmarter/BSTApp", launch.browser = T)
```

in the **R** package console or any **R** code editor. We strongly recommend to type this directly, rather than copy and paste. This is due to a potential issue with the quotation mark.

The second option is to visit <https://posit.cloud/content/4328505>, log in or sign up for **Posit Cloud**, and access the project titled **GUIDed Bayesian regression app BSTApp**. In the right-bottom window, click on the **BSTApp-master** folder under **Files**, open the **app.R** file, and finally, click the **Run App** button. However, inactivity will cause the window to close.

The third approach, and our recommendation, is using a **Docker** image by running:

1. `docker pull magralo95/besmartergui:latest`
2. `docker run -rm -p 3838:3838 magralo95/besmartergui`

in your **Command Prompt**. This creates an isolated environment for our GUI, ensuring consistent performance across systems. Note that **Docker** must be installed to deploy our GUI this way.

After implementing any of the three ways to run our GUI, users can see

<sup>1</sup>Bayesian econometrics: Simulations, models and applications to research, teaching and encoding with responsibility.





FIGURE 5.1  
Display of our graphical user interface.



FIGURE 5.2  
Univariate models: Specification.

a new window where a presentation of our research team is displayed (see Figure 5.1). In addition, the top panel in Figure 5.1 shows the class of models that can be estimated in our GUI.

## 5.2 Univariate models

After our GUI is deployed (see Figure 5.1), the user should select *Univariate Models* in the top panel. Then, the Figure 5.2 is displayed, and the user can see the radio button on the left hand side that shows the specific models inside this generic class. In particular, users can see that the normal model is selected from inside the class of univariate models.

Then, the right hand side panel displays a widget to upload the input



**FIGURE 5.3**  
Univariate models: Results.

dataset, which should be a *csv* file with headers in the first row. Users also should select the kind of separator used in the input file: comma, semicolon, or tab (use the folders **DataSim** and **DataApp** for the input file templates). Once users upload the dataset, they can see a data preview. Range sliders help to set the number of iterations of the Markov chain Monte Carlo algorithm, the amount of burn-in, and the thinning parameter can be selected as well (see next chapters of this second part of the book for technical details). After this, users should specify the equation. This can be done with the formula builder, where users can select the dependent variable, and the independent variables, and then click on the *Build formula* tab. Users can see in the *Main Equation* space the formula expressed in the format used by **R** software (see Main equation box in Figure 5.2,  $y \sim x1 + x2 + x3$ ). Users can modify this if necessary, for instance, including higher order or interaction terms, other transformations are also allowed. This is done directly in the *Main Equation* space taking into account that this extra terms should follow formula command structure.<sup>2</sup> Note that the class of univariate models includes the intercept by default, except ordered probit, where the specification has to do this explicitly, that is, ordered probit models do not admit an intercept, for *identification* issues (see details below).<sup>3</sup> Hence, users should write down specifically this fact ( $y \sim x1 + x2 + x3 - 1$ ). Finally, users should define the hyperparameters of the prior; for instance, in the normal-inverse gamma model, these are the mean vector, covariance matrix, shape, and scale parameters (see Figure 5.3). However, users should take into account that our GUI has *non-informative* hyperparameters by default in all our modelling frameworks, so the last part is not a requirement.

After this specification process, users should click the *Go!* button to initi-

<sup>2</sup>See <https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/formula>

<sup>3</sup>An *identification* issue means that multiple values for the model parameters give rise to the same value for the likelihood function.



**FIGURE 5.4**  
Univariate models: Multinomial.

ate the estimation. Our GUI displays the summary statistics and convergence diagnostics after this process is finished (see Figure 5.3). There are also widgets to download posterior chains (*csv* file) and graphs (*pdf* and *eps* files). Note that the order of the coefficients in the results (summary, posterior chains, and graphs) is first for the location parameters, and then for the scale parameters.

Multinomial models (probit and logit) require a dataset file to have in the first column the dependent variable, then alternative specific regressors (for instance alternatives' prices), and finally, non-alternative regressors (for instance, income). The formula builder specifies the dependent variable, and independent variables that are alternative specific and non-alternative specific (see technical details in next chapter). Specification also requires defining the base category, number of alternatives (this is also required in ordered probit), number of alternative specific regressors, and number of non-alternative regressors (see Figure 5.4). Multinomial logit also allows defining a tuning parameter, the number of degrees of freedom in this case, for the Metropolis–Hastings algorithm (see technical details in next chapter). This is a feature in our GUI when the estimation of the models is based on the Metropolis–Hastings algorithm. The order of the coefficients in the results of these models is first the intercepts ( $\text{cte}_l$  appearing in the summary display,  $l$ -th alternative), and then the non-alternative specific regressors ( $\text{NAS}_{jl}$  appearing in the summary display,  $l$ -th alternative and  $j$ -th non-alternative regressor), and lastly, the coefficients for the alternative specific regressors ( $\text{AS}_j$  appearing in the summary display,  $j$ -th alternative specific regressor). Note that the non-alternative specific regressors associated with the base category are equal to zero (they do not appear in the results). In addition, some coefficients of the main diagonal of the covariance matrix are constant due to identification issues in multinomial and multivariate probit models.

In the case of the negative binomial model, users should set a dispersion parameter (see the negative binomial model in the next chapter). User should



**FIGURE 5.5**  
Univariate models: Bootstrap.

also set the censorship points and quantiles in the Tobit and quantile models, respectively.

Bayesian bootstrap only requires uploading a dataset, specifying the number of iterations of the MCMC, the resampling size, and the equation (see Figure 5.5). The input file has the same structure as the file used in the univariate normal model.

### 5.3 Multivariate models

After our GUI is deployed (see Figure 5.1), the user should select *Multivariate Models* in the top panel. Then, the Figure 5.6 is displayed, and the user can see the radio button on the left hand side that shows the specific models inside this generic class.

Figure 5.6 displays the multivariate regression setting. In this case, the input file should have first the dependent variables, and then the regressors. If there are intercepts in each equation, there should be a column of 1's after the dependent variables in the input file. The user also has to set the number of dependent variables, the number of regressors, if necessary include the intercept, and the values of the hyperparameters (see Figure 5.6).

The input file in seemingly unrelated regressions should have first the dependent variables, and then the regressors by equation, including the intercept in each equation if necessary (column of 1's). Users should define the number of dependent variables (equations), the number of total regressors, that is, the sum of all regressors associated with the equation (if necessary include intercepts, each intercept is an additional regressor), and the number of regressors



**FIGURE 5.6**  
Multivariate models: Simple multivariate.

by equation (if necessary include the intercept). Users can also set the values of the hyperparameters if there is prior information.

The results of the simple multivariate and seemingly unrelated regressions show first the posterior location parameters by equation, and then the posterior covariance matrix.

In the instrumental variable setting, users should specify the main equation and the instrumental equation. This setting includes intercepts by default. The first variable on the right hand side in the main equation has to be the variable with endogeneity issues. In the instrumental equation box, the dependent variable is the variable with endogeneity issues as a function of the instruments. Users can also specify the values of the hyperparameters if they have prior information. The input file should have the dependent variable, the endogenous regressor, the instruments, and the exogenous regressors. The results first list the posterior estimates of the endogenous regressor, then the location parameters of the auxiliary regression (instrumental equation), and the location parameters of the exogenous regressors. Last is the posterior covariance matrix.

The multivariate probit model requires an input dataset ordered by unit, for instance three choices implies repeat each unit three times. The first column has to be the identification of each unit; users should use ordered integers, then the dependent variable, just one vector, composed of 0's and 1's, then the regressors, which should include a column of 1's for the intercepts. Users should set the number of units, number of regressors, and number of choices (see Figure 5.7). The results first display the posterior location parameters by equation, and then the posterior covariance matrix.



**FIGURE 5.7**  
Multivariate models: Multivariate probit.

## 5.4 Time series model

## 5.5 Longitudinal/panel models

After our GUI is deployed (see Figure 5.1), the user should select *Hierarchical Longitudinal Models* in the top panel. Then, the Figure 5.8 is displayed, and the user can see the radio button on the left hand side that shows the specific models inside this generic class.

The hierarchical longitudinal models tab allows for estimating models that account for within-subject correlation when the dependent variable is continuous (Normal), binary (Logit), or a count (Poisson).

The input files for hierarchical longitudinal models should have first the dependent variable, then the regressors and a cross sectional identifier ( $i = 1, 2, \dots, N$ ). It is not a requirement to have a balanced dataset:  $T_i$  can be different for each  $i$  (see Chapter 9 for technical details). Users can see templates of datasets in the folders **DataSim** (see Table 10.2 for details), and **DataApp** (see Table 10.3 for details) of our *GitHub* repository. Users should also specify the fixed part equation and the random part equation, both in **R** format. In case of only requiring random intercepts, do not introduce anything in the latter part (see Figure 5.8). Users should also type the name of the cross sectional identifier variable. The results displayed and the posterior graphs are associated with the fixed effects and covariance matrix. However, users can download the posterior chains of all posterior estimates: fixed and random effects, and covariance matrix.



**FIGURE 5.8**  
Hierarchical longitudinal models: Specification.

## 5.6 Bayesian model average

After our GUI is deployed (see Figure 5.1), the user should select *Bayesian Model Averaging* in the top panel. Then, the Figure 5.9 is displayed, and the user can see the radio button on the left hand side that shows the specific models inside this generic class.

Bayesian model averaging based on a Gaussian distribution can be carried out using the Bayesian information criterion (BIC) approximation, Markov chain Monte Carlo model composition (MC3), or instrumental variables (see Figure 5.9). The former two approaches require an input dataset where the first column is the dependent variable, and then, the potentially important regressors. Users should set the band width model selection parameter ( $O_R$ ) and number of iterations for BIC and MC3, respectively (see Chapter 10 for technical details). The results include the posterior inclusion probability ( $p^! = 0$ ), expected value (EV), and standard deviation (SD) of the coefficients associated with each regressor. The BIC framework also displays the most relevant models, including the number of regressors, the coefficient of determination ( $R^2$ ), the BIC, and the posterior model probability. Users can download two *csv* files: *Best models* and *Descriptive statistics coefficients*. The former is a 0-1 matrix such that the columns are the regressors and the rows are the models; a 1 indicates the presence of a specific regressor in a specific model, 0 otherwise. Note that the last column of this file is the posterior model probability for each model (row). The latter file shows the posterior inclusion probabilities, expected values, and standard deviations associated with each regressor, taking into account the BMA procedure based on the best models.

Bayesian model averaging with endogeneity issues requires two input files. The first one has the dependent variable in the first column, the next columns are the regressors with endogeneity issues, and then the exogeneous regressors.



**FIGURE 5.9**  
Bayesian model averaging: Specification and results.



**FIGURE 5.10**  
Bayesian model averaging: Instrumental variable specification.

The user should include a column of 1's if an intercept is required. The second input file has all the instruments. Users should also introduce the number of regressors with endogeneity issues (see Figure 5.10).

The results include the posterior inclusion probabilities and expected values for each regressor. The user can find the results of the main equation, and then of the auxiliary equations. Users can download *csv* files of BMA results for both the second stage (main equation) and the first stage (auxiliary equations). In addition, users can download the posterior chains of the location parameters of the main equation,  $\beta_l$ ,  $l = 1, 2, \dots, \dim\{\beta\}$ , the location parameters of the auxiliary equations,  $\gamma_{j,i}$ ,  $j = 1, 2, \dots, \dim\{\beta_s\}$  where  $\dim\{\beta_s\}$  is the number of regressors with endogeneity issues,  $i = 1, 2, \dots, \dim\{\gamma\}$ , where  $\dim\{\gamma\}$  is the number of regressors in the auxiliary regressors (exogeneous regressors + instruments), and the elements of the covariance matrix  $\sigma_{j,k}$  (see Chapter 10 for technical details).

Bayesian model averaging based on BIC approximation for non-linear mod-



els, Logit, Gamma, and Poisson, requires an input dataset where the first column is the dependent variable, and the other columns are the potentially relevant regressors. Users should specify the band width model selection parameters, which are also referred to as Occam's window parameters ( $O_R$  and  $O_L$ ). Our GUI displays the posterior inclusion probabilities ( $p^! = 0$ ), the expected value of the posterior coefficients (EV), and the standard deviation (SD). In addition, users can see the results associated with the models with the highest posterior model probabilities, and download *csv* files with the results of specifications of the best models, and descriptive statistics of the posterior coefficients from the BMA procedure. These files are similar to the results of the BIC approximation of the Gaussian model.

---

## 5.7 Warning

Users should also note that sometimes our GUI shuts down. In our experience, this is due to computational issues using the implicit commands that we call when estimating some models, for instance, computationally singular systems, missing values where TRUE/FALSE needed, L-BFGS-B needs finite values of "fn", NA/NaN/Inf values, or Error in backsolve. Sometimes these issues can be solved by adjusting the dataset, for instance, avoiding high levels of multicollinearity. It should also be taken into account that when warning messages are displayed in our GUI, there is a high chance that there are convergence issues of the posterior chains. So, the results are not trustworthy. Users can identify these problems by checking the console of their *RStudio* sections, where the specific folder/file where the issue happened is specified. In any case, we would appreciate your feedback to improve and enhance our GUI.

We also should say there are many ways to improve the codes that we present in the following five chapters. For instance, the *MCMCpack* and *bayesm* packages perform most of the matrix operations in C++ using the *rcpp* package. This substantially speeds up the algorithms compared with the codes that we present in the next chapters. We could improve the computational times of our codes using parallel computing and the *rcpp* package, but this requires more advanced skills that we do not cover in this book.



# 6

## Univariate models

### 6.1 Solutions of Exercises

1. Get the conditional posterior distributions of the Gaussian linear model assuming independent priors  $\pi(\boldsymbol{\beta}, \sigma^2) = \pi(\boldsymbol{\beta}) \times \pi(\sigma^2)$ , where  $\boldsymbol{\beta} \sim N(\boldsymbol{\beta}_0, \mathbf{B}_0)$  and  $\sigma^2 \sim IG(\alpha_0/2, \delta_0/2)$ .

**Answer**

The joint posterior distribution of the parameters is

$$\begin{aligned}\pi(\boldsymbol{\beta}, \sigma^2 | \mathbf{y}, \mathbf{X}) &\propto p(\mathbf{y} | \boldsymbol{\beta}, \sigma^2, \mathbf{X}) \pi(\boldsymbol{\beta}) \pi(\sigma^2) \\ &\propto (\sigma^2)^{-\frac{N}{2}} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}\boldsymbol{\beta}) \right\} \\ &\quad \times \exp \left\{ -\frac{1}{2} (\boldsymbol{\beta} - \boldsymbol{\beta}_0)^\top \mathbf{B}_0^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_0) \right\} \\ &\quad \times \frac{(\delta_0/2)^{(\alpha_0/2)}}{\Gamma(\alpha_0/2)} \frac{1}{(\sigma^2)^{(\alpha_0/2+1)}} \exp \left\{ -\frac{\delta_0}{2\sigma^2} \right\} \\ &\propto \exp \left\{ -\frac{1}{2} (\boldsymbol{\beta} - \boldsymbol{\beta}_0)^\top \mathbf{B}_0^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_0) \right\} \\ &\quad \times \frac{1}{(\sigma^2)^{(\alpha_0+N)/2+1}} \exp \left\{ -\frac{\delta_0 + (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})}{2\sigma^2} \right\} \\ &= \exp \left\{ -\frac{1}{2} (\boldsymbol{\beta} - \boldsymbol{\beta}_0)^\top \mathbf{B}_0^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_0) \right\} \times \underbrace{\frac{1}{(\sigma^2)^{(\frac{\alpha_n}{2}+1)}} \exp \left\{ -\frac{\delta_n}{2\sigma^2} \right\}}_1.\end{aligned}$$

Observe that (1) is the kernel of an inverse-gamma density function. Thus,  $\sigma^2 | \boldsymbol{\beta}, \mathbf{y}, \mathbf{X} \sim IG(\alpha_n/2, \delta_n/2)$ , where  $\alpha_n = \alpha_0 + N$  and  $\delta_n = \delta_0 + (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})$ .

Let's see the posterior distribution of  $\beta$ ,

$$\begin{aligned}
\pi(\beta, \sigma^2 | \mathbf{y}, \mathbf{X}) &\propto p(\mathbf{y} | \beta, \sigma^2, \mathbf{X}) \pi(\beta) \pi(\sigma^2) \\
&\propto (\sigma^2)^{-\frac{N}{2}} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y} - \mathbf{X}\beta)^\top (\mathbf{y} - \mathbf{X}\beta) \right\} \\
&\times \exp \left\{ -\frac{1}{2} (\beta - \beta_0)^\top \mathbf{B}_0^{-1} (\beta - \beta_0) \right\} \\
&\times \frac{(\delta_0/2)^{(\alpha_0/2)}}{\Gamma(\alpha_0/2)} \frac{1}{(\sigma^2)^{(\alpha_0/2+1)}} \exp \left\{ -\frac{\delta_0}{2\sigma^2} \right\} \\
&= (\sigma^2)^{-\frac{N}{2}} \exp \left\{ -\frac{\sigma^{-2}}{2} [\mathbf{y}^\top \mathbf{y} - \mathbf{y}^\top \mathbf{X}\beta - \beta^\top \mathbf{X}^\top \mathbf{y} + \beta^\top \mathbf{X}^\top \mathbf{X}\beta] \right\} \\
&\times \exp \left\{ -\frac{1}{2} [\beta^\top \mathbf{B}_0^{-1} \beta - \beta^\top \mathbf{B}_0^{-1} \beta_0 - \beta_0^\top \mathbf{B}_0^{-1} \beta + \beta_0^\top \mathbf{B}_0^{-1} \beta_0] \right\} \\
&\times \frac{(\delta_0/2)^{(\alpha_0/2)}}{\Gamma(\alpha_0/2)} \frac{1}{(\sigma^2)^{(\alpha_0/2+1)}} \exp \left\{ -\frac{\delta_0}{2\sigma^2} \right\} \\
&\propto \exp \left\{ -\frac{1}{2} [\beta^\top (\mathbf{B}_0^{-1} + \sigma^{-2} \mathbf{X}^\top \mathbf{X}) \beta - 2\beta^\top (\mathbf{B}_0^{-1} \beta_0 + \sigma^{-2} \mathbf{X}^\top \mathbf{X} \hat{\beta})] \right\} \\
&\times \frac{1}{(\sigma^2)^{(\alpha_0+N)/2+1}} \exp \left\{ -\frac{\delta_0 + \mathbf{y}^\top \mathbf{y}}{2\sigma^2} \right\},
\end{aligned}$$

where  $\hat{\beta} = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{y}$ .

Adding and subtracting  $\beta_n^\top \mathbf{B}_n^{-1} \beta_n$  where

$$\begin{aligned}
\mathbf{B}_n &= (\mathbf{B}_0^{-1} + \sigma^{-2} \mathbf{X}^\top \mathbf{X})^{-1} \\
\beta_n &= \mathbf{B}_n (\mathbf{B}_0^{-1} \beta_0 + \sigma^{-2} \mathbf{X}^\top \mathbf{X} \hat{\beta}) = \mathbf{B}_n (\mathbf{B}_0^{-1} \beta_0 + \sigma^{-2} \mathbf{X}^\top \mathbf{y}),
\end{aligned}$$

and completing the square

$$\begin{aligned}
\pi(\beta, \sigma^2 | \mathbf{y}, \mathbf{X}) &\propto \exp \left\{ -\frac{1}{2} [\beta^\top (\mathbf{B}_0^{-1} + \sigma^{-2} \mathbf{X}^\top \mathbf{X}) \beta - 2\beta^\top \mathbf{B}_n^{-1} \mathbf{B}_n (\mathbf{B}_0^{-1} \beta_0 + \sigma^{-2} \mathbf{X}^\top \mathbf{X} \hat{\beta}) \right. \\
&\quad \left. + \beta_n^\top \mathbf{B}_n^{-1} \beta_n - \beta_n^\top \mathbf{B}_n^{-1} \beta_n] \right\} \times \frac{1}{(\sigma^2)^{(\alpha_0+N)/2+1}} \exp \left\{ -\frac{\delta_0 + \mathbf{y}^\top \mathbf{y}}{2\sigma^2} \right\} \\
&= \exp \left\{ -\frac{1}{2} [\beta^\top \mathbf{B}_n^{-1} \beta - 2\beta^\top \mathbf{B}_n^{-1} \beta_n + \beta_n^\top \mathbf{B}_n^{-1} \beta_n] \right\} \\
&\times \frac{1}{(\sigma^2)^{(\alpha_0+N)/2+1}} \exp \left\{ -\frac{\delta_0 + \mathbf{y}^\top \mathbf{y} - \sigma^2 \beta_n^\top \mathbf{B}_n^{-1} \beta_n}{2\sigma^2} \right\} \\
&= \exp \left\{ -\frac{1}{2} (\beta - \beta_n)^\top \mathbf{B}_n^{-1} (\beta - \beta_n) \right\} \\
&\quad \underbrace{\hspace{10em}}_1 \\
&\times (\sigma^2)^{-(\frac{\alpha_n}{2}+1)} \exp \left\{ -\frac{\delta^*}{2\sigma^2} \right\},
\end{aligned}$$

where  $\delta^* = \delta_0 + \mathbf{y}^\top \mathbf{y} + \sigma^2 \boldsymbol{\beta}_n^\top \mathbf{B}_n^{-1} \boldsymbol{\beta}_n$  does not depend on  $\boldsymbol{\beta}$ .

We can see that (1) is the kernel of a multivariate normal distribution with mean equal to  $\boldsymbol{\beta}_n$  and covariance matrix  $\mathbf{B}_n$ , that is,  $\boldsymbol{\beta} | \sigma^2, \mathbf{y}, \mathbf{X} \sim N(\boldsymbol{\beta}_n, \mathbf{B}_n)$ .

We see that the posterior distributions are from the same family as the prior distributions.

2. Given the model  $y_i \sim N(\mathbf{x}_i^\top \boldsymbol{\beta}, \sigma^2 / \tau_i)$  (Gaussian linear model with heteroskedasticity) with independent priors,  $\pi(\boldsymbol{\beta}, \sigma^2, \boldsymbol{\tau}) = \pi(\boldsymbol{\beta}) \times \pi(\sigma^2) \times \prod_{i=1}^N \pi(\tau_i)$ , where  $\boldsymbol{\beta} \sim N(\boldsymbol{\beta}_0, \mathbf{B}_0)$ ,  $\sigma^2 \sim IG(\alpha_0/2, \delta_0/2)$  and  $\tau_i \sim G(v/2, v/2)$ . Show that  $\boldsymbol{\beta} | \sigma^2, \boldsymbol{\tau}, \mathbf{y}, \mathbf{X} \sim N(\boldsymbol{\beta}_n, \mathbf{B}_n)$ ,  $\sigma^2 | \boldsymbol{\beta}, \boldsymbol{\tau}, \mathbf{y}, \mathbf{X} \sim IG(\alpha_n/2, \delta_n/2)$  and  $\tau_i | \boldsymbol{\beta}, \sigma^2, \mathbf{y}, \mathbf{X} \sim G(v_{1n}/2, v_{2in}/2)$ , where  $\boldsymbol{\tau} = [\tau_1, \dots, \tau_n]^\top$ ,  $\mathbf{B}_n = (\mathbf{B}_0^{-1} + \sigma^{-2} \mathbf{X}^\top \Psi \mathbf{X})^{-1}$ ,  $\boldsymbol{\beta}_n = \mathbf{B}_n (\mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \sigma^{-2} \mathbf{X}^\top \Psi \mathbf{y})$ ,  $\alpha_n = \alpha_0 + N$ ,  $\delta_n = \delta_0 + (\mathbf{y} - \mathbf{X} \boldsymbol{\beta})^\top \Psi (\mathbf{y} - \mathbf{X} \boldsymbol{\beta})$ ,  $v_{1n} = v + 1$ ,  $v_{2in} = v + \sigma^{-2} (y_i - \mathbf{x}_i^\top \boldsymbol{\beta})^2$ , and  $\Psi = \text{diagonal}\{\tau_i\}$ .

**Answer**

The joint posterior distribution of the parameters is

$$\begin{aligned} \pi(\boldsymbol{\beta}, \sigma^2, \boldsymbol{\tau} | \mathbf{y}, \mathbf{X}) &\propto p(\mathbf{y} | \boldsymbol{\beta}, \sigma^2, \boldsymbol{\tau}, \mathbf{X}) \pi(\boldsymbol{\beta}) \pi(\sigma^2) \prod_{i=1}^N \pi(\tau_i) \\ &\propto \left( \prod_{i=1}^N \tau_i^{1/2} \right) (\sigma^2)^{-\frac{N}{2}} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y} - \mathbf{X} \boldsymbol{\beta})^\top \Psi (\mathbf{y} - \mathbf{X} \boldsymbol{\beta}) \right\} \\ &\quad \times \exp \left\{ -\frac{1}{2} (\boldsymbol{\beta} - \boldsymbol{\beta}_0)^\top \mathbf{B}_0^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_0) \right\} \\ &\quad \times \frac{1}{(\sigma^2)^{(\alpha_0/2+1)}} \exp \left\{ -\frac{\delta_0}{2\sigma^2} \right\} \prod_{i=1}^N \tau_i^{v/2-1} \exp \{ -v\tau_i/2 \}. \end{aligned}$$

Thus, the conditional posterior distribution of  $\sigma^2 | \boldsymbol{\beta}, \boldsymbol{\tau}, \mathbf{y}, \mathbf{X}$  is given by

$$\pi(\sigma^2 | \boldsymbol{\beta}, \boldsymbol{\tau}, \mathbf{y}, \mathbf{X}) \propto (\sigma^2)^{-\frac{N+\alpha_0}{2}} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y} - \mathbf{X} \boldsymbol{\beta})^\top \Psi (\mathbf{y} - \mathbf{X} \boldsymbol{\beta}) + \delta_0 \right\}.$$

This is the kernel of an inverse-gamma distribution with shape parameter  $\alpha_n/2$  and rate parameter  $\delta_n/2$ .

The conditional posterior distribution of  $\tau_i | \boldsymbol{\beta}, \sigma^2, \mathbf{y}, \mathbf{X}$  is

$$\pi(\tau_i | \boldsymbol{\beta}, \sigma^2, \mathbf{y}, \mathbf{X}) \propto \tau_i^{(v+1)/2-1} \exp \left\{ -\frac{\tau_i}{2} [\sigma^{-2} (y_i - \mathbf{x}_i^\top \boldsymbol{\beta})^2 + v] \right\}.$$

This is the kernel of a gamma distribution with parameter  $(v+1)/2$  and  $(\sigma^{-2} (y_i - \mathbf{x}_i^\top \boldsymbol{\beta})^2 + v)/2$ .

The conditional posterior distribution of  $\beta|\sigma^2, \tau, \mathbf{y}, \mathbf{X}$  is given by

$$\pi(\beta|\sigma^2, \tau, \mathbf{y}, \mathbf{X}) \propto \exp \left\{ -\frac{1}{2} [\sigma^{-2}(\mathbf{y} - \mathbf{X}\beta)^\top \Psi(\mathbf{y} - \mathbf{X}\beta) + (\beta - \beta_0)^\top \mathbf{B}_0^{-1}(\beta - \beta_0)] \right\}.$$

Following same steps as in the previous exercise we get  $\beta|\sigma^2, \tau, \mathbf{y}, \mathbf{X} \sim N(\beta_n, \mathbf{B}_n)$ .

### 3. The market value of soccer players in Europe continues

Use the setting of the previous exercise to perform inference using a Gibbs sampling algorithm of the the market value of soccer players in Europe setting  $v = 5$  and same other hyperparameters as the homoscedastic case. Is there any meaningful difference for the coefficient associated with the national team compared to the application in the homoscedastic case?

**Answer**

*R. code. The value of soccer players, programming our Gibbs sampler (heteroskedastic case)*

```

1 rm(list = ls())
2 set.seed(010101)
3 ##### Linear regression: Value of
  soccer players #####
4 Data <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/1
  ValueFootballPlayers.csv", sep = ",", header = TRUE,
  quote = "")
5 attach(Data)
6 y <- log(Value)
7 # Value: Market value in Euros (2017) of soccer players
8 # Regressors quantity including intercept
9 X <- cbind(1, Perf, Age, Age2, NatTeam, Goals, Exp, Exp2)
10 # Perf: Performance. Perf2: Performance squared. Age: Age;
  Age2: Age squared.
11 # NatTeam: Indicator of national team. Goals: Scored goals.
  Goals2: Scored goals squared
12 # Exp: Years of experience. Exp2: Years of experience
  squared. Assists: Number of assists
13 k <- dim(X)[2]
14 N <- dim(X)[1]
15 # Hyperparameters
16 d0 <- 0.001
17 a0 <- 0.001
18 b0 <- rep(0, k)
19 c0 <- 1000
20 B0 <- c0*diag(k)
21 B0i <- solve(B0)
22 v <- 5
23 # MCMC parameters
24 mcmc <- 5000
25 burnin <- 5000
26 tot <- mcmc + burnin
27 thin <- 1
28 # Posterior distributions programming the Gibbs sampling
29 # Auxiliary parameters
30 an <- a0 + N
31 v1n <- v + 1
32 # Gibbs sampling functions
33 PostSig2 <- function(Beta, tau){
34   dn <- d0 + t(y - X%%Beta)%%diag(tau)%(y - X%%Beta)
35   sig2 <- invgamma::rinvgamma(1, shape = an/2, rate = dn/2)
36   return(sig2)
37 }
38 PostBeta <- function(sig2, tau){
39   Bn <- solve(B0i + sig2^(-1)*t(X)%%diag(tau)%%X)
40   bn <- Bn%%(B0i%%b0 + sig2^(-1)*t(X)%%diag(tau)%%y)
41   Beta <- MASS::mvrnorm(1, bn, Bn)
42   return(Beta)
43 }
44 PostTau <- function(sig2, Beta, i){
45   v2n <- v + sig2^(-1)*(y[i]-X[i,]%%Beta)^2
46   taui <- rgamma(1, v1n/2, v2n/2)
47   return(tau)
48 }

```

*R. code. The value of soccer players, programming our Gibbs sampler (heteroskedastic case)*

```

1 PostBetas <- matrix(0, mcmc+burnin, k)
2 PostSigma2 <- rep(0, mcmc+burnin)
3 Beta <- rep(0, k)
4 tau <- rep(1, N)
5 # create progress bar in case that you want to see
  iterations progress
6 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
7 for(s in 1:tot){
8   sig2 <- PostSig2(Beta = Beta, tau = tau)
9   PostSigma2[s] <- sig2
10  Beta <- PostBeta(sig2 = sig2, tau = tau)
11  PostBetas[s,] <- Beta
12  tau <- sapply(1:N, function(i){PostTau(sig2 = sig2, Beta =
    Beta, i)})
13  setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
14 }
15 close(pb)
16 keep <- seq((burnin+1), tot, thin)
17 PosteriorBetas <- PostBetas[keep,]
18 colnames(PosteriorBetas) <- c("Intercept", "Perf", "Age", "
  Age2", "NatTeam", "Goals", "Exp", "Exp2")
19 summary(coda::mcmc(PosteriorBetas))
20 PosteriorSigma2 <- PostSigma2[keep]
21 summary(coda::mcmc(PosteriorSigma2))
22 summary(coda::mcmc(exp(PosteriorBetas[,5])-1))
23 Iterations = 1:5000
24 Thinning interval = 1
25 Number of chains = 1
26 Sample size per chain = 5000
27 1. Empirical mean and standard deviation for each variable,
28 plus standard error of the mean:
29 Mean          SD          Naive SE Time-series SE
30 1.256091      0.254974      0.003606      0.004579
31 2. Quantiles for each variable:
32 2.5%      25%      50%      75%      97.5%
33 0.8078 1.0746 1.2367 1.4189 1.7959

```

We see in this application that the value of a top soccer player in Europe increases 124% ( $\exp(0.80) - 1$ ) on average when he has played in the national team, the credible interval at 95% is (81%, 180%). These values are not very different from the application assuming homoscedasticity in the book.



**4. Example: Determinants of hospitalization continues**

Program a Gibbs sampling algorithm in the application of determinants of hospitalization.

**Answer**

### *R. code. Determinants of hospitalization, programming our Gibbs sampler*

```

1 set.seed(010101)
2 Data <- read.csv("https://raw.githubusercontent.com/
   besmarter/BSTApp/refs/heads/master/DataApp/2HealthMed.
   csv", sep = ",", header = TRUE, quote = "")
3 attach(Data)
4 str(Data)
5 y <- Hosp # Dependent variables
6 X <- cbind(1, SHI, Female, Age, Age2, Est2, Est3, Fair, Good
   , Excellent) # Regressors
7 K <- dim(X)[2]
8 N <- dim(X)[1]
9 # Hyperparameters
10 b0 <- rep(0, K) # Prio mean
11 B0 <- diag(K) # Prior covariance
12 B0i <- solve(B0)
13 mcmc <- 1000; burnin <- 500; thin <- 2; tot <- mcmc + burnin
   ; keep <- seq(burnin, tot, thin)
14 # Posterior distributions programming the Gibbs sampling
15 # Auxiliary parameters
16 XtX <- t(X)%*%X
17 # Gibbs sampling functions
18 PostBeta <- function(Yl){
19   Bn <- solve(B0i + XtX)
20   bn <- Bn%*%(B0i%*%b0 + t(X)%*%Yl)
21   Beta <- MASS::mvrnorm(1, bn, Bn)
22   return(Beta)
23 }
24 PostYl <- function(Beta, i){
25   Ylmean <- X[i,]%*%Beta
26   if(y[i] == 1){
27     Yli <- truncnorm::rtruncnorm(1, a = 0, b = Inf, mean =
   Ylmean, sd = 1)
28   }else{
29     Yli <- truncnorm::rtruncnorm(1, a = -Inf, b = 0, mean =
   Ylmean, sd = 1)
30   }
31   return(Yli)
32 }
33 PostBetas <- matrix(0, mcmc+burnin, K)
34 Beta <- rep(0, K)
35 # create progress bar in case that you want to see
   iterations progress
36 pb <- winProgressBar(title = "progress bar", min = 0, max =
   tot, width = 300)
37 for(s in 1:tot){
38   Yl <- sapply(1:N, function(i){PostYl(Beta = Beta, i)})
39   Beta <- PostBeta(Yl = Yl)
40   PostBetas[s,] <- Beta
41   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
   "% done"))
42 }
43 close(pb)
44 keep <- seq((burnin+1), tot, thin)
45 PosteriorBetas <- PostBetas[keep,]
46 colnames(PosteriorBetas) <- c("Intercept", "SHI", "Female",
   "Age", "Age2", "Est2", "Est3", "Fair", "Good", "
   Excellent")
47 summary(coda::mcmc(PosteriorBetas))

```

**5. Choice of the fishing mode continues**

- Run the Algorithm 3 of the book to show the results of the Geweke [5], Raftery [18] and Heidelberger [6] tests using our GUI.
- Use the command *rmnpGibbs* to do the example of the choice of the fishing mode.

**Answer**

### *R. code. Fishing choice mode, results our GUI*

```

1 GewekeTestLocationCoef
2 Fraction in 1st window = 0.1
3 Fraction in 2nd window = 0.5
4 cte_1 cte_2 cte_3 NAS_1_1 NAS_1_2 NAS_1_3 AS_1 AS_2
5 -1.821 -0.714 0.792 2.275 -3.944 -2.071 1.627 -2.729
6
7 RafteryTestLocationCoef
8 Quantile (q) = 0.5
9 Accuracy (r) = +/- 0.025
10 Probability (s) = 0.95
11 Burn-in Total Lower bound Dependence
12 (M) (N) (Nmin) factor (I)
13 cte_1 780 365690 1537 238.0
14 cte_2 360 193950 1537 126.0
15 cte_3 660 340120 1537 221.0
16 NAS_1_1 120 70320 1537 45.8
17 NAS_1_2 475 243960 1537 159.0
18 NAS_1_3 440 248930 1537 162.0
19 AS_1 3010 1438135 1537 936.0
20 AS_2 550 297770 1537 194.0
21
22 HeidelTestLocationCoef
23 Stationarity start p-value
24 test iteration
25 cte_1 passed 6001 6.54e-01
26 cte_2 failed NA 3.72e-02
27 cte_3 failed NA 4.99e-02
28 NAS_1_1 failed NA 4.77e-07
29 NAS_1_2 failed NA 1.82e-05
30 NAS_1_3 failed NA 1.19e-04
31 AS_1 passed 2001 3.71e-01
32 AS_2 passed 8001 4.48e-01
33 Halfwidth Mean Halfwidth
34 test
35 cte_1 passed -0.34236 0.017025
36 cte_2 <NA> NA NA
37 cte_3 <NA> NA NA
38 NAS_1_1 <NA> NA NA
39 NAS_1_2 <NA> NA NA
40 NAS_1_3 <NA> NA NA
41 AS_1 passed -0.00708 0.000306
42 AS_2 passed 0.27982 0.009994

```

*R. code. Fishing choice mode, library bayesm*

```

1 remove(list = ls()); set.seed(12345)
2 Data <- read.csv("https://raw.githubusercontent.com/
   besmarter/BSTApp/refs/heads/master/DataApp/3Fishing.csv"
   , sep = ",", header = TRUE, quote = "")
3 attach(Data); str(Data)
4 p <- 4; na <- 2; nd <- 1; N <- dim(Data)[1]
5 Xa <- Data[,2:9]
6 Xd <- matrix(income, N, 1)
7 X <- bayesm::createX(p = p, na = na, nd = nd, Xa = Xa, Xd =
   Xd, INT = TRUE, base = p, DIFF = TRUE)
8 df <- list(y = mode, X = X, p = 4)
9 # Hyperparameters
10 k <- dim(X)[2]; b0 <- rep(0, k); c0 <- 1000
11 B0 <- c0*diag(k); B0i <- solve(B0)
12 a0 <- p - 1 + 3; Psi0 <- a0*diag(p-1)
13 Prior <- list(betabar = b0, A = B0i, nu = a0, V = Psi0)
14 # MCMC parameters
15 mcmc <- 100000; thin <- 5
16 Mcmc <- list(R = mcmc, keep = thin)
17 Results <- bayesm::rmnpGibbs(Data = df, Prior = Prior, Mcmc
   = Mcmc)
18 betatilde <- Results$betadraw / sqrt(Results$sigmadraw[,1])
19 attributes(betatilde)$class <- "bayesm.mat"
20 summary(coda::mcmc(betatilde))
21 Quantiles for each variable:
22      2.5%      25%      50%      75%      97.5%
23 var1 -6.371e-01 -4.670e-01 -3.834e-01 -3.028e-01 -1.422e-01
24 var2 -2.149e-01 -6.681e-02 -7.870e-03  4.414e-02  1.493e-01
25 var3 -8.873e-01 -6.071e-01 -4.982e-01 -4.040e-01 -2.446e-01
26 var4  1.859e-05  4.577e-05  5.952e-05  7.326e-05  9.861e-05
27 var5 -2.589e-05 -3.050e-06  8.212e-06  2.089e-05  5.330e-05
28 var6  4.549e-05  7.451e-05  9.144e-05  1.098e-04  1.555e-04
29 var7 -9.425e-03 -7.612e-03 -6.586e-03 -5.573e-03 -3.136e-03
30 var8  1.214e-01  2.068e-01  2.592e-01  3.154e-01  4.477e-01
31 sigmadraw <- Results$sigmadraw / Results$sigmadraw[,1]
32 attributes(sigmadraw)$class = "bayesm.var"
33 summary(coda::mcmc(sigmadraw))

```

## 6. Simulation exercise of the multinomial logit model continues

Perform inference in the simulation of the multinomial logit model using the command *rmnlIndepMetrop* from the *bayesm* package of **R** and using our GUI.

**Answer**

### *R. code. Simulation of the multinomial logit model*

```

1  remove(list = ls())
2  set.seed(12345)
3  # Simulation of data
4  N<-1000 # Sample Size
5  B<-c(0.5,0.8,-3)
6  B1<-c(-2.5,-3.5,0)
7  B2<-c(1,1,0)
8  # Alternative specific attributes of choice 1, for instance,
   price, quality and duration of choice 1
9  X1<-matrix(cbind(rnorm(N,0,1),rnorm(N,0,1),rnorm(N,0,1)),N,
   length(B))
10 # Alternative specific attributes of choice 2, for instance,
   price, quality and duration of choice 2
11 X2<-matrix(cbind(rnorm(N,0,1),rnorm(N,0,1),rnorm(N,0,1)),N,
   length(B))
12 # Alternative specific attributes of choice 3, for instance,
   price, quality and duration of choice 3
13 X3<-matrix(cbind(rnorm(N,0,1),rnorm(N,0,1),rnorm(N,0,1)),N,
   length(B))
14 X4<-matrix(rnorm(N,1,1),N,1)
15 V1<-B2[1]+X1%*%B+B1[1]*X4
16 V2<-B2[2]+X2%*%B+B1[2]*X4
17 V3<-B2[3]+X3%*%B+B1[3]*X4
18 suma<-exp(V1)+exp(V2)+exp(V3)
19 p1<-exp(V1)/suma
20 p2<-exp(V2)/suma
21 p3<-exp(V3)/suma
22 p<-cbind(p1,p2,p3)
23 y<- apply(p,1, function(x) sample(1:3, 1, prob = x, replace =
   TRUE))
24 table(y)
25 L <- length(table(y))
26 dat <-data.frame(mode,X1[,1],X2[,1],X3[,1],X1[,2],X2[,2],X3
   [,2],X1[,3],X2[,3],X3[,3],X4)
27 colnames(dat) <- c("mode","V1.1","V1.2","V1.3","V2.1","V2.2"
   ,"V2.3","V3.1","V3.2","V3.3","V4")
28 attach(dat)
29 LongData <- mlogit::mlogit.data(dat, shape = "wide", varying
   =2:10, choice = "mode")
30 Xa <- cbind(LongData$V1, LongData$V2, LongData$V3)
31 Xa <- cbind(X1[,1],X2[,1],X3[,1],X1[,2],X2[,2],X3[,2],X1
   [,3],X2[,3],X3[,3])
32 na <- 3
33 Xd <- X4
34 X <- bayesm::createX(p = L, na = na, nd = 1, Xa = Xa, Xd =
   Xd, base = L)
35 DataMlogit <- list(y=y, X = X, p = L)
36 # MCMC parameters
37 mcmc <- 11000+1
38 thin <- 5
39 df <- 6
40 mcmcpair <- list(R = mcmc, keep = 5, nu = df)
41 PostBeta <- bayesm::rmnlIndepMetrop(Data = DataMlogit, Mcmc
   = mcmcpair)
42 summary(PostBeta[["betadraw"]])

```

**7. Simulation of the ordered probit model**

Simulate an ordered probit model where the first regressor distributes  $N(6, 5)$  and the second distributes  $G(1, 1)$ , the location parameter is  $\beta = [0.5 \ -0.25 \ 0.5]^\top$ , and the cutoffs is the vector  $\alpha = [0 \ 1 \ 2.5]^\top$ . Program from scratch a Metropolis-within-Gibbs sampling algorithm to perform inference in this simulation.

**Answer**

### *R. code. Simulation of the ordered probit model*

```

1 rm(list = ls()); set.seed(010101); N <- 1000
2 x1 <- rnorm(N, 6, 5); x2 <- rgamma(N, shape = 1, scale = 1)
3 X <- cbind(1, x1, x2)
4 beta <- c(0.5, -0.25, 0.5); cutoffs <- c(0, 1, 2.5)
5 e <- rnorm(N,0,1)
6 y_latent <- X%*%beta + e; y <- rep(0,N)
7 for (i in 1:N) {
8   if (y_latent[i] < cutoffs[1]){
9     y[i] <- 0}else{
10    if (y_latent[i] >= cutoffs[1] & y_latent[i] < cutoffs
11      [2]) {
12      y[i] <- 1
13    }else{
14      if (y_latent[i] >= cutoffs[2] & y_latent[i] < cutoffs
15        [3]) {
16        y[i] <- 2
17      }else{y[i] <- 3
18      }
19    }
20  }
21 }
22 # Likelihood function
23 LogLikOP <- function(param){
24   beta_g <- param[1:ncol(X)]
25   delta <- param[(ncol(X)+1):(ncol(X) + dplyr::n_distinct(y)
26     - 1)]
27   Xbeta <- X%*%beta_g
28   logLik <- 0
29   for (i in 1:length(y)){
30     if (y[i]==0){logLiki <- log(pnorm(-Xbeta[i]))}
31     }else if (y[i]==1){
32       logLiki <- log(pnorm(exp(delta[1]) - Xbeta[i]) - pnorm
33         (-Xbeta[i]))
34     }else if (y[i]==2){
35       logLiki <- log(pnorm(exp(delta[2]) + exp(delta[1]) -
36         Xbeta[i]) - pnorm(exp(delta[1]) - Xbeta[i]))
37     }else {logLiki <- log(1 - pnorm(exp(delta[2]) + exp(
38       delta[1]) - Xbeta[i]))
39     }
40     logLik <- logLik + logLiki
41   }
42   return(-logLik)
43 }
44 # ML Estimation
45 param0 <- rep(0, ncol(X) + n_distinct(y)-2)
46 mle <- optim(param0, LogLikOP, hessian = T, method = "BFGS")
47 mle$par
48 exp(mle$par[length(beta)+1])
49 exp(mle$par[length(beta)+1])+exp(mle$par[length(beta)+2])
50 CovarML <- solve(mle$hessian)

```



*R. code. Simulation of the ordered probit model*

```

1 # M-H within Gibbs
2 mhop <- function(param0, G){
3   betasamples <- matrix(c(0), nrow = G, ncol = ncol(X))
4   betasamples[1,] <- param0[1:ncol(X)]
5   tau <- matrix(c(0), nrow = G, ncol = dplyr::n_distinct(y)
6     - 2)
7   tau[1,] <- param0[(ncol(X)+1):(ncol(X) + dplyr::n_distinct(
8     y) - 2)]
9   y1 <- rep(0,length(y)); ar <- rep(0,G); B1 <- solve(t(X)%*
10     %X+solve(B0))
11   pb <- winProgressBar(title = "progress bar", min = 0, max
12     = G, width = 300)
13   for(g in 2:G){
14     bg <- betasamples[g-1,]; tg <- tau[g-1,]
15     #Random walk M-H for delta
16     delta_prime <- tg + mvtnorm::rmvnorm(1, mean = rep(0,2),
17       sigma = VarProp)
18     alpha <- min(1,(mvtnorm::dmvnorm(delta_prime, mean = d0,
19       sigma = D0)*exp(-LogLikOP(c(bg, delta_prime)) +
20       LogLikOP(c(bg, tg)))/mvtnorm::dmvnorm(tg, mean = d0,
21       sigma = D0))
22     if(is.nan(alpha) | is.na(alpha)) {
23       alpha <- 0
24     }
25     #Acceptance step
26     u <- runif(1, min = 0, max = 1)
27     if(u<=alpha){tau[g,] <- delta_prime; ar[g] <- 1
28     }else{tau[g,] <- tg
29     }
30     #Generation of latent variables
31     for (i in 1:length(y)){
32       if (y[i]==0) {
33         y1[i] <- EnvStats::rnormTrunc(1, mean = X[i,]%*%bg,
34         sd = 1, max = 0)
35       }else if(y[i]==1){
36         y1[i] <- EnvStats::rnormTrunc(1, mean = X[i,]%*%bg,
37         sd = 1, min = 0, max = exp(tau[g,1]))
38       }else if(y[i]==2){
39         y1[i] <- EnvStats::rnormTrunc(1, mean = X[i,]%*%bg,
40         sd = 1, min = exp(tau[g,1]), max = exp(tau[g,2])+exp(tau
41         [g,1]))
42       }else{
43         y1[i] <- EnvStats::rnormTrunc(1, mean = X[i,]%*%bg,
44         sd = 1, min = exp(tau[g,2])+exp(tau[g,1]))
45       }
46     }
47     #Gibbs sampling for beta
48     if(sum(is.nan(y1))>0 | sum(is.na(y1))>0 | sum(y1)==Inf){
49       betasamples[g,] <- betasamples[g-1,]
50     }else{
51       b1 <- B1%*(t(X)%*%y1 + solve(B0)%*%b0)
52       betasamples[g,] <- mvrnorm(1, mu = b1, Sigma = B1)
53     }
54     setWinProgressBar(pb, g, title=paste( round(g/G*100, 0),
55       "% done"))
56   }
57   close(pb)
58   return(cbind(betasamples, tau, ar))
59 }

```

*R. code. Simulation of the ordered probit model*

```

1 #Hyperparameters
2 d0 <- rep(0,2)
3 D0 <- diag(2)*10000
4 b0 <- rep(0,ncol(X))
5 B0 <- diag(ncol(X))*10000
6 #Estimation
7 param0 <- rep(0, ncol(X) + dplyr::n_distinct(y)-1)
8 G <- 1000
9 tun <- 1
10 VarProp <- tun*solve(solve(CovarML[4:5, 4:5]) + solve(D0))
11 param_sample <- mhop(param0, G)
12 #Burn in
13 B <- round(0.2*G)
14 param_sample <- param_sample[(B+1):G,]
15 mcmc0 <- coda::mcmc(param_sample[, 1:(ncol(X) + dplyr::n_
    distinct(y) - 2)])
16 summary(mcmc0)
17 Iterations = 1:800
18 Thinning interval = 1
19 Number of chains = 1
20 Sample size per chain = 800
21 1. Empirical mean and standard deviation for each variable,
22 plus standard error of the mean:
23 Mean      SD Naive SE Time-series SE
24 0.49120 0.08465 0.0029929      0.007140
25 -0.24919 0.01222 0.0004319      0.001269
26 0.49440 0.03942 0.0013937      0.002739
27 0.06716 0.06419 0.0022695      0.008479
28 0.41926 0.07414 0.0026212      0.009479
29 2. Quantiles for each variable:
30 2.5%      25%      50%      75%      97.5%
31 0.31947 0.43558 0.49710 0.5479 0.6496
32 -0.27180 -0.25740 -0.24948 -0.2408 -0.2238
33 0.42229 0.46706 0.49253 0.5189 0.5762
34 -0.06338 0.02328 0.06819 0.1104 0.1932
35 0.25857 0.37195 0.41742 0.4672 0.5558
36 summary(coda::mcmc(cbind(exp(param_sample[, 4]),exp(param_
    sample[, 4])+exp(param_sample[, 5]))))
37 Iterations = 1:800
38 Thinning interval = 1
39 Number of chains = 1
40 Sample size per chain = 800
41 1. Empirical mean and standard deviation for each variable,
42 plus standard error of the mean:
43 Mean      SD Naive SE Time-series SE
44 [1,] 1.072 0.06854 0.002423      0.008999
45 [2,] 2.597 0.13593 0.004806      0.019700
46 2. Quantiles for each variable:
47 2.5%      25%      50%      75% 97.5%
48 var1 0.9386 1.024 1.071 1.117 1.213
49 var2 2.3224 2.500 2.603 2.686 2.877

```

All posterior mean estimates are close to the population parameters, and the 95% credible intervals encompass the population parameters. We use the definition of  $\gamma$  in the last line of the code.

#### 8. Simulation of the negative binomial model continues

Perform inference in the simulation of the negative binomial model using the *bayesm* package in R software.

**Answer**

#### *R. code. Simulation of the negative binomial model*

```

1 rm(list = ls())
2 set.seed(010101)
3 N <- 2000 # Sample size
4 x1 <- runif(N); x2 <- rnorm(N)
5 X <- cbind(1, x1, x2)
6 k <- dim(X)[2]
7 B <- rep(1, k)
8 alpha <- 1.2
9 gamma <- exp(alpha)
10 lambda <- exp(X%*%B)
11 y <- rbinom(N, mu = lambda, size = gamma)
12 table(y)
13 # MCMC parameters
14 mcmc <- 10000
15 burnin <- 1000
16 thin <- 5
17 iter <- mcmc + burnin
18 keep <- seq(burnin, iter, thin)
19 sbeta <- 2.93/sqrt(k); salpha <- 2.93
20 # Hyperparameters: Priors
21 B0 <- 1000*diag(k); b0 <- rep(0, k)
22 alpha0 <- 0.5; delta0 <- 0.1
23 DataNB <- list(y = y, X = X)
24 mcmcNB <- list(R = mcmc, keep = thin, s_beta = sbeta, s_
      alpha = salpha)
25 PriorNB <- list(betabar = b0, A = solve(B0), a = alpha0, b =
      delta0)
26 ResultBayesm <- bayesm::rnegbinRw(Data = DataNB, Mcmc =
      mcmcNB, Prior = PriorNB)
27 summary(ResultBayesm$alphadraw)
28 summary(ResultBayesm$betadraw)

```

#### 9. The market value of soccer players in Europe continues

Perform the application of the value of soccer players with left censoring

at one million Euros in our GUI using the Algorithm A7, and the hyperparameters of the example.

### Answer

These are the results of running the application in our GUI. These are very similar compared with the results in the book.

### *R. code. The value of soccer players with left censoring in our GUI*

```

1 Summary
2 Iterations = 10001:60000
3 Thinning interval = 1
4 Number of chains = 1
5 Sample size per chain = 50000
6 1. Empirical mean and standard deviation for each variable,
7 plus standard error of the mean:
8
9      Mean      SD Naive SE Time-series SE
10 (Intercept)  1.014765 2.626395 1.175e-02      1.659e-02
11 Perf         0.033935 0.004529 2.025e-05      2.245e-05
12 Age          1.027285 0.212413 9.499e-04      1.326e-03
13 Age2         -0.021914 0.003989 1.784e-05      2.528e-05
14 NatTeam      0.847412 0.124884 5.585e-04      6.423e-04
15 Goals        0.010092 0.001644 7.351e-06      7.712e-06
16 Exp          0.175324 0.069653 3.115e-04      3.727e-04
17 Exp2         -0.005696 0.002950 1.319e-05      1.527e-05
18 sigma2       0.983337 0.096194 4.302e-04      6.724e-04
19 2. Quantiles for each variable:
20      2.5%      25%      50%      75%      97.5%
21 (Intercept) -4.212563 -0.732856 1.038281 2.796603 6.051e
22      +00
23 Perf         0.025121 0.030873 0.033896 0.036988 4.286e
24      -02
25 Age          0.618743 0.883011 1.026760 1.168860 1.450e
26      +00
27 Age2         -0.029854 -0.024580 -0.021886 -0.019203 -1.424e
28      -02
29 NatTeam      0.605030 0.763154 0.846671 0.930593 1.095e
30      +00
31 Goals        0.006893 0.008987 0.010097 0.011201 1.330e
32      -02
33 Exp          0.038522 0.128032 0.175261 0.222110 3.118e
34      -01
35 Exp2         -0.011484 -0.007671 -0.005685 -0.003706 5.502e
36      -05
37 sigma2       0.813118 0.915664 0.977298 1.043661 1.189e
38      +00

```

**10. The market value of soccer players in Europe continues**

Program from scratch the Gibbs sampling algorithm in the example of the market value of soccer players at the 0.75 quantile.

**Answer**

### *R. code. The value of soccer players, quantile regression*

```

1 rm(list = ls()); set.seed(010101)
2 Data <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/1
  ValueFootballPlayers.csv", sep = ",", header = TRUE,
  quote = "")
3 attach(Data)
4 y <- log(Value); X <- cbind(1, Perf, Age, Age2, NatTeam,
  Goals, Exp, Exp2)
5 RegLS <- lm(y ~ X -1)
6 k <- dim(X)[2]; N <- dim(X)[1]
7 # Hyperparameters
8 b0 <- rep(0, k); c0 <- 1000
9 B0 <- c0*diag(k); B0i <- solve(B0)
10 # MCMC parameters
11 mcmc <- 5000; burnin <- 1000
12 tot <- mcmc + burnin; thin <- 1
13 # Quantile
14 tau <- 0.5; theta <- (1-2*tau)/(tau*(1-tau))
15 psi2 <- 2/(tau*(1-tau)); an2 <- 2+theta^2/psi2
16 # Gibbs sampler
17 PostBeta <- function(e){
18   Bn <- solve(B0i + psi2^(-1)*t(X)%*%diag(1/e)%*%X)
19   bn <- Bn%*%(B0i%*%b0 + psi2^(-1)*t(X)%*%diag(1/e)%*%(y-
     theta*e))
20   Beta <- MASS::mvrnorm(1, bn, Bn)
21   return(Beta)
22 }
23 PostE <- function(Beta, i){
24   dn2 <- (y[i]-X[i,]%*%Beta)^2/psi2
25   ei <- GIGrvg::rgig(1, chi = dn2, psi = an2, lambda = 1/2)
26   return(ei)
27 }
28 PostBetas <- matrix(0, mcmc+burnin, k)
29 Beta <- RegLS$coefficients
30 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
31 for(s in 1:tot){
32   e <- sample(1:N, function(i){PostE(Beta = Beta, i)})
33   Beta <- PostBeta(e = e)
34   PostBetas[s,] <- Beta
35   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
     "% done"))
36 }
37 close(pb)
38 keep <- seq((burnin+1), tot, thin)
39 PosteriorBetas <- PostBetas[keep,]
40 colnames(PosteriorBetas) <- c("Intercept", "Perf", "Age", "
  Age2", "NatTeam", "Goals", "Exp", "Exp2")
41 summary(coda::mcmc(PosteriorBetas))

```

11. Use the *bayesboot* package to perform inference in the simulation exercise of Section 7.10, and compared the results with the ones that we get using our GUI setting  $S = 10000$ .

**Answer**

*R. code. The value of soccer players, quantile regression*

```
1 ##### Bayesian bootstrap: Simulation
2 #####
3 rm(list = ls())
4 set.seed(010101)
5 N <- 1000 # Sample size
6 x1 <- runif(N); x2 <- rnorm(N)
7 X <- cbind(x1, x2)
8 k <- dim(X)[2]
9 B <- rep(1, k+1)
10 sig2 <- 1
11 u <- rnorm(N, 0, sig2)
12 y <- cbind(1, X)%*%B + u
13 data <- as.data.frame(cbind(y, X))
14 names(data) <- c("y", "x1", "x2")
15 Reg <- function(d){
16   Reg <- lm(y ~ x1 + x2, data = d)
17   Bhat <- Reg$coef
18   return(Bhat)
19 }
20 Reg(data)
21 S <- 10000
22 BB <- bayesboot::bayesboot(data = data, statistic = Reg, R =
  S)
23 plot(BB)
```





# 7

## Multivariate models

### 7.1 Solutions of Exercises

1. Show that  $\mathbb{E}[u_1 \text{PAER}] = \frac{\alpha_1}{1-\beta_1\alpha_1}\sigma_1^2$  assuming that  $\mathbb{E}[u_1 u_2] = 0$  where  $\text{Var}(u_1) = \sigma_1^2$  in the effect of institutions on per capita GDP.

**Answer**

The point of departure is the following *simultaneous structural* economic model:

$$\log(\text{pcGDP95}_i) = \beta_1 + \beta_2 \text{PAER}_i + \beta_3 \text{Africa} + \beta_4 \text{Asia} + \beta_5 \text{Other} + u_{1i}, \quad (7.1)$$

$$\text{PAER}_i = \alpha_1 + \alpha_2 \log(\text{pcGDP95}_i) + \alpha_3 \log(\text{Mort}_i) + u_{2i}, \quad (7.2)$$

where *pcGDP95*, *PAER* and *Mort* are the per capita gross domestic product (GDP) in 1995, the average index of protection against expropriation between 1985 and 1995, and the settler mortality rate during the time of colonization. *Africa*, *Asia* and *Other* are dummies for continents, with *America* as the baseline group.

Replacing Equation 7.2 into Equation 7.1, and solving for  $\log(\text{pcGDP95})$ ,

$$\log(\text{pcGDP95}_i) = \pi_1 + \pi_2 \log(\text{Mort}_i) + \pi_3 \text{Africa} + \pi_4 \text{Asia} + \pi_5 \text{Other} + e_{1i}, \quad (7.3)$$

where  $\pi_1 = \frac{\beta_1 + \beta_2 \alpha_1}{1 - \beta_2 \alpha_2}$ ,  $\pi_2 = \frac{\beta_2 \alpha_3}{1 - \beta_2 \alpha_2}$ ,  $\pi_3 = \frac{\beta_3}{1 - \beta_2 \alpha_2}$ ,  $\pi_4 = \frac{\beta_4}{1 - \beta_2 \alpha_2}$ ,  $\pi_5 = \frac{\beta_5}{1 - \beta_2 \alpha_2}$ , and  $e_1 = \frac{\beta_2 u_1 + u_2}{1 - \beta_2 \alpha_2}$ .

Then, replacing Equation 7.3 into Equation 7.2, and solving for *PAER*,

$$\text{PAER}_i = \gamma_1 + \gamma_2 \log(\text{Mort}_i) + \gamma_3 \text{Africa} + \gamma_4 \text{Asia} + \gamma_5 \text{Other} + e_{2i}, \quad (7.4)$$

where  $\gamma_1 = \frac{\alpha_1 + \alpha_2 \beta_1}{1 - \beta_2 \alpha_2}$ ,  $\gamma_2 = \frac{\alpha_3}{1 - \beta_2 \alpha_2}$ ,  $\gamma_3 = \frac{\alpha_2 \beta_3}{1 - \beta_2 \alpha_2}$ ,  $\gamma_4 = \frac{\alpha_2 \beta_4}{1 - \beta_2 \alpha_2}$ ,  $\gamma_5 = \frac{\alpha_2 \beta_5}{1 - \beta_2 \alpha_2}$ , and  $e_2 = \frac{\alpha_2 u_1 + u_2}{1 - \beta_2 \alpha_2}$ .

Then,  $\mathbb{E}[u_1 \text{PAER}] = \mathbb{E}[u_1(\gamma_1 + \gamma_2 \log(\text{Mort}_i) + \gamma_3 \text{Africa} + \gamma_4 \text{Asia} + \gamma_5 \text{Other} + e_{2i})] = \mathbb{E}\left[u_1 \left(\frac{\alpha_2 u_1 + u_2}{1 - \beta_2 \alpha_2}\right)\right] = \frac{\alpha_2}{1 - \beta_2 \alpha_2} \sigma_1^2$  given the assumptions.

2. Show that  $\beta_2 = \pi_2/\gamma_2$  in the effect of institutions on per capita GDP.

**Answer**

Given that  $\pi_2 = \frac{\beta_2 \alpha_3}{1 - \beta_2 \alpha_2}$  and  $\gamma_2 = \frac{\alpha_3}{1 - \beta_2 \alpha_2}$  from the previous exercise, consequently,  $\beta_2 = \pi_2/\gamma_2$ .

3. **The effect of institutions on per capita gross domestic product continues**

Use the *rmultireg* command from the *bayesm* package to perform inference in the example of the effect of institutions on per capita GDP.

**Answer**

### *R code. The effect of institutions on per capita GDP*

```

1 rm(list = ls())
2 set.seed(010101)
3 DataInst <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/4Institutions
  .csv", sep = ",", header = TRUE, quote = "")
4 attach(DataInst)
5 Y <- cbind(logpcGDP95, PAER)
6 X <- cbind(1, logMort, Africa, Asia, Other)
7 M <- dim(Y)[2]
8 K <- dim(X)[2]
9 # Hyperparameters
10 B0 <- matrix(0, K, M)
11 c0 <- 100
12 V0 <- c0*diag(K)
13 Psi0 <- 5*diag(M)
14 a0 <- 5
15 S <- 10000 #Number of posterior draws
16 betadraw = matrix(double(S*K*M), ncol=K*M)
17 Sigmadraw = matrix(double(S*M*M), ncol=M*M)
18 pb <- winProgressBar(title = "progress bar", min = 0, max =
  S, width = 300)
19 for (s in 1:S) {
20   Results <- bayesm::rmultireg(Y, X, Bbar = B0, A = solve(V0
    ), nu = a0, V = Psi0)
21   betadraw[s,] <- Results$B
22   Sigmadraw[s,] <- Results$Sigma
23   setWinProgressBar(pb, s, title=paste( round(s/S*100, 0), "
    % done"))
24 }
25 close(pb)
26 summary(coda::mcmc(betadraw))
27 summary(coda::mcmc(Sigmadraw))

```

#### 4. Demand and supply simulation

Given the structural demand-supply model:

$$\begin{aligned} q_i^d &= \beta_1 + \beta_2 p_i + \beta_3 y_i + \beta_4 pc_i + \beta_5 ps_i + u_{i1} \\ q_i^s &= \alpha_1 + \alpha_2 p_i + \alpha_3 er_i + u_{i2}, \end{aligned}$$

where  $q^d$  is demand,  $q^s$  is supply,  $p$ ,  $y$ ,  $pc$ ,  $ps$  and  $er$  are price, income, complementary price, substitute price, and exchange rate. Complementary and substitute prices are prices of a complementary and substitute goods of  $q$ . Assume that  $\beta = [5 \ -0.5 \ 0.8 \ -0.4 \ 0.7]^\top$ ,  $\alpha = [-2 \ 0.5 \ -0.4]^\top$ ,  $u_1 \sim N(0, 0.5^2)$  and  $u_2 \sim N(0, 0.5^2)$ . In addition, assume that  $y \sim N(10, 1)$ ,  $pc \sim N(5, 1)$ ,  $ps \sim N(5, 1)$  and  $tc \sim N(15, 1)$ .

- Find the *reduce-form* model using that in equilibrium demand and supply are equal, that is,  $q^d = q^s$ . This condition defines the observable quantity ( $q$ ).
- Simulate  $p$  and  $q$  from the *reduce-form* equations.
- Perform inference of the *reduce-form* model using the *rmultireg* command from the *bayesm* package.
- Use the posterior draws of the *reduce-form* parameters to perform inference of the *structural* parameters. Any issue? Hint: Are all *structural* parameters exactly identified?

#### Answer

We should equal demand and supply, and solve for price,

$$p = \pi_1 + \pi_2 er + \pi_3 y + \pi_4 pc + \pi_5 ps + v_1,$$

where  $\pi_1 = \frac{\alpha_1 - \beta_1}{\beta_2 - \alpha_2}$ ,  $\pi_2 = \frac{\alpha_3}{\beta_2 - \alpha_2}$ ,  $\pi_3 = \frac{-\beta_3}{\beta_2 - \alpha_2}$ ,  $\pi_4 = \frac{-\beta_4}{\beta_2 - \alpha_2}$ ,  $\pi_5 = \frac{-\beta_5}{\beta_2 - \alpha_2}$ , and  $v_1 = \frac{u_2 - u_1}{\beta_2 - \alpha_2}$  given  $\beta_2 \neq \alpha_2$ , that is, the equations should be independent. This condition is given by economic theory due to  $\beta_2 < 0$  and  $\alpha_2 > 0$ , the effect of price on demand and supply should be negative and positive, respectively.

The equation of price into the demand equation gives

$$q = \tau_1 + \tau_2 er + \tau_3 y + \tau_4 pc + \tau_5 ps + v_2,$$

where  $\tau_1 = \beta_1 + \beta_2 \pi_1$ ,  $\tau_2 = \beta_2 \pi_2$ ,  $\tau_3 = \beta_2 \pi_3 + \beta_3$ ,  $\tau_4 = \beta_2 \pi_4 + \beta_4$ ,  $\tau_5 = \beta_2 \pi_5 + \beta_5$ , and  $v_2 = \beta_2 v_1 + u_1$ . We can use the equations para  $\pi_k$  and  $\tau_k$ ,  $k = \{1, 2, 3, 4, 5\}$  to simulate the *reduced-form* equations.

Observe that estimating the *reduced-form* equations, we can get the *structural* parameters for the demand equation,  $\beta_2 = \tau_2 / \pi_2$  ( $\pi_2 \neq 0$ ),  $\beta_3 = \tau_3 - \beta_2 \pi_3$ ,  $\beta_4 = \tau_4 - \beta_2 \pi_4$  and  $\beta_5 = \tau_5 - \beta_2 \pi_5$ , whereas the *structural* parameters of the supply equation cannot be recovered just in one way,

$\alpha_2 = \beta_2 + \beta_3/\pi_3 = \beta_2 + \beta_4/\pi_4 = \beta_2 + \beta_5/\pi_5$ . This in turn implies different values for  $\alpha_3 = \pi_2(\beta_2 - \alpha_2)$ . This is because the demand equation is *exactly identified*, whereas the supply equation is *over identified*.

In this exercise,  $K = 5$ ,  $M = 2$ ,  $K_1 = 4$ ,  $K_2 = 2$ ,  $M_1 = 2$  and  $M_2 = 2$ . This means that  $K - K_1 = 1 = M - 1$  and  $K - K_2 = 3 > M - 1 = 1$ , that is, the order condition says that both equations (demand and supply) satisfy the necessary condition of identification, the demand would be *exactly identified*, and the supply equation would be *over identified*.

Regarding the rank condition (necessary and sufficient), let's see the identification matrix:

**TABLE 7.1**

Identification matrix.

q	p	constant	er	y	pc	ps
1	$-\beta_2$	$-\beta_1$	0	$-\beta_3$	$-\beta_4$	$-\beta_5$
1	$-\alpha_2$	$-\alpha_1$	$-\alpha_3$	0	0	0

The demand equation excludes the exchange rate (*exclusion restriction*), and given  $\alpha_3 \neq 0$ , that is, the exchange rate is relevant in the supply equation, then the rank condition is satisfied in the demand equation. The supply equation excludes the income, the complementary price and substitute price (*exclusion restrictions*), then as far as  $\beta_k \neq 0$  for any  $k = \{3, 4, 5\}$ , the rank condition is satisfied in the supply equation.

The following code shows how to do the simulation, and perform inference in this exercise. We can see that all 95% credible intervals encompass the population parameters, and the posterior means are very close to them.

*R code. Demand and supply simulation*

```

1 rm(list = ls()); set.seed(12345)
2 B0 <- 5; B1 <- -0.5; B2 <- 0.8; B3 <- -0.4; B4 <- 0.7; SD <-
  0.5
3 A0 <- -2; A1 <- 0.5; A2 <- -0.4; SS <- 0.5
4 P0 <- (A0-B0)/(B1-A1); P2 <- -B2/(B1-A1); P3 <- -B3/(B1-A1);
  P1 <- A2/(B1-A1); P4 <- -B4/(B1-A1)
5 T0 <- B0+B1*P0; T2 <- B2+B1*P2; T3 <- B3+B1*P3; T1 <- B1*P1;
  T4 <- B4+B1*P4;
6 n <- 5000
7 ED <- rnorm(n, 0, SD); ES <- rnorm(n, 0, SS)
8 VP <- (ES-ED)/(B1-A1); UQ <- B1*VP+ED
9 y <- rnorm(n, 10, 1); pc <- rnorm(n, 5, 1); er <- rnorm(n,
  15, 1); ps <- rnorm(n, 5, 1);
10 p <- P0+P1*er+P2*y+P3*pc+P4*ps+VP
11 q <- T0+T1*er+T2*y+T3*pc+T4*ps+UQ
12 #Inference
13 Y <- cbind(p, q); X <- cbind(1, er, y, pc, ps)
14 M <- dim(Y)[2]; K <- dim(X)[2]
15 # Hyperparameters
16 B0 <- matrix(0, K, M); c0 <- 100; V0 <- c0*diag(K)
17 Psi0 <- 5*diag(M); a0 <- 5; S <- 10000 #Posterior draws
18 betadraw = matrix(double(S*K*M), ncol=K*M)
19 Sigmadraw = matrix(double(S*M*M), ncol=M*M)
20 pb <- winProgressBar(title = "progress bar", min = 0, max =
  S, width = 300)
21 for (s in 1:S) {
22   Results <- bayesm::rmultireg(Y, X, Bbar = B0, A = solve(V0
    ), nu = a0, V = Psi0)
23   betadraw[s,] <- Results$B
24   Sigmadraw[s,] <- Results$Sigma
25   setWinProgressBar(pb, s, title=paste( round(s/S*100, 0), "
    % done"))
26 }
27 close(pb)
28 summary(coda::mcmc(betadraw))
29 summary(coda::mcmc(Sigmadraw))
30 beta2 <- betadraw[,7]/betadraw[,2] # Effect of price on
  demand
31 summary(coda::mcmc(beta2))
32 beta3 <- betadraw[,8] - beta2*betadraw[,3] # Effect of
  income on demand
33 summary(coda::mcmc(beta3))
34 beta4 <- betadraw[,9] - beta2*betadraw[,4] # Effect of
  complementary price on demand
35 summary(coda::mcmc(beta4))
36 beta5 <- betadraw[,10] - beta2*betadraw[,5] # Effect of
  substitute price on demand
37 summary(coda::mcmc(beta5))

```

### 5. Utility demand continues

- Run the **Utility demand** application using our GUI and the information in the dataset *Utilities.csv*. Hint: This file should be modified to agree the structure that requires our GUI (see the dataset *5Institutions.csv* in the folder *DataApp* of our GitHub repository - <https://github.com/besmarter/BSTApp>- for a template).
- Program from scratch the Gibbs sampler algorithm in this application.

**Answer**

### *R code. Utility demand in Colombia, Gibbs sampler*

```

1 rm(list = ls()); set.seed(010101); library(dplyr)
2 DataUt <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/Utilities.csv",
  sep = ",", header = TRUE, quote = "")
3 DataUtEst <- DataUt %>% filter(Electricity != 0 & Water != 0
  & Gas != 0)
4 attach(DataUtEst)
5 y1 <- log(Electricity); y2 <- log(Water); y3 <- log(Gas)
6 X1 <- cbind(1, LnPriceElect, LnPriceWater, LnPriceGas,
  IndSocio1, IndSocio2, Altitude, Nrooms, HouseholdMem,
  Lnincome)
7 X2 <- cbind(1, LnPriceElect, LnPriceWater, LnPriceGas,
  IndSocio1, IndSocio2, Nrooms, HouseholdMem)
8 X3 <- cbind(1, LnPriceElect, LnPriceWater, LnPriceGas,
  IndSocio1, IndSocio2, Altitude, Nrooms, HouseholdMem)
9 y <- c(y1, y2, y3)
10 X <- as.matrix(Matrix::bdiag(X1, X2, X3))
11 M <- 3; K1 <- dim(X1)[2]; K2 <- dim(X2)[2]; K3 <- dim(X3)[2]
12 K <- K1 + K2 + K3; N <- length(y1)
13 # Hyperparameters
14 b0 <- rep(0, K); c0 <- 100; B0 <- c0*diag(K)
15 B0i <- solve(B0); Psi0 <- 5*diag(M); Psi0i <- solve(Psi0)
16 a0 <- M; IN <- diag(N); an <- a0 + N
17 #Posterior draws
18 S <- 6000; burnin <- 1000; thin <- 1
19 tot <- S+burnin
20 # Gibbs functions
21 PostBeta <- function(Sigma){
22   Aux <- solve(Sigma)%x%IN
23   Bn <- solve(B0i + t(X)%*%Aux%*%X)
24   bn <- Bn%*%(B0i%*%b0 + t(X)%*%Aux%*%y)
25   Beta <- MASS::mvrnorm(1, bn, Bn)
26   return(Beta)
27 }
28 PostSigma <- function(Beta){
29   B1 <- Beta[1:K1]; B2 <- Beta[(K1+1):(K1+K2)]; B3 <- Beta[(
  K1+K2+1):(K1+K2+K3)]
30   U1 <- y1 - X1%*%B1; U2 <- y2 - X2%*%B2; U3 <- y3 - X3%*%B3
31   U <- cbind(U1, U2, U3)
32   Psin <- solve(Psi0i + t(U)%*%U)
33   Sigmai <- rWishart::rWishart(1, df = an, Sigma = Psin)
34   Sigma <- solve(Sigmai[, ,1])
35   return(Sigma)
36 }
37 PostBetas <- matrix(0, tot, K)
38 PostSigmas <- matrix(0, tot, M*(M+1)/2); Beta <- rep(1, K)
39 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
40 for(s in 1:tot){
41   Sigma <- PostSigma(Beta = Beta); PostSigmas[s,] <-
  matrixcalc::vech(Sigma)
42   Beta <- PostBeta(Sigma = Sigma); PostBetas[s,] <- Beta
43   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
  "% done"))
44 }
45 close(pb)
46 keep <- seq((burnin+1), tot, thin)
47 Bs <- PostBetas[keep,]; summary(coda::mcmc(Bs))
48 Sigmas <- PostSigmas[keep,]; summary(coda::mcmc(Sigmas))

```

### *R code. Utility demand in Colombia, results*

```

1 keep <- seq((burnin+1), tot, thin)
2 Bs <- PostBetas[keep,]; summary(coda::mcmc(Bs))
3 Sigmas <- PostSigmas[keep,]; summary(coda::mcmc(Sigmas))
4 Quantiles for each variable:
5
6      2.5%    25%    50%    75%    97.5%
7 Const      0.43304  1.04508  1.337751  1.64728  2.25228
8 LnPriceElect -2.40343 -2.05533 -1.882159 -1.70463 -1.35979
9 LnPriceWater -0.44027 -0.38524 -0.356049 -0.32676 -0.27021
10 LnPriceGas -0.21665 -0.13807 -0.098877 -0.05712  0.01673
11 IndSocio1 -0.87408 -0.78454 -0.736561 -0.68898 -0.59137
12 IndSocio2 -0.24504 -0.18344 -0.150827 -0.11845 -0.06029
13 Altitude -0.27153 -0.23866 -0.221539 -0.20468 -0.17325
14 Nrooms 0.04598 0.06191 0.069971 0.07837 0.09379
15 HouseholdMem 0.06610 0.07999 0.087320 0.09406 0.10708
16 Lnincome 0.03897 0.05516 0.063130 0.07152 0.08751
17 Const 0.88247 1.73546 2.162290 2.60793 3.48450
18 LnPriceElect -0.83128 -0.31258 -0.051838 0.20446 0.72087
19 LnPriceWater -0.49760 -0.40946 -0.363138 -0.31943 -0.23498
20 LnPriceGas 0.05880 0.16932 0.228734 0.28677 0.39226
21 IndSocio1 -0.63928 -0.50417 -0.427978 -0.35529 -0.21024
22 IndSocio2 -0.50363 -0.40976 -0.359576 -0.30929 -0.21097
23 Nrooms 0.05733 0.08126 0.093291 0.10550 0.12935
24 HouseholdMem 0.09984 0.12098 0.132126 0.14265 0.16290
25 Const -2.26403 -1.57842 -1.201124 -0.84494 -0.15985
26 LnPriceElect -2.41128 -2.00330 -1.786150 -1.57292 -1.17185
27 LnPriceWater -0.10791 -0.03978 -0.003399 0.03329 0.10082
28 LnPriceGas -0.76450 -0.67575 -0.627062 -0.57949 -0.48807
29 IndSocio1 -0.91346 -0.80094 -0.743421 -0.68334 -0.57228
30 IndSocio2 -0.31613 -0.24086 -0.202828 -0.16367 -0.08824
31 Altitude 0.24986 0.28987 0.310784 0.33183 0.37126
32 Nrooms 0.06071 0.07899 0.089606 0.09949 0.11842
33 HouseholdMem 0.14485 0.16148 0.169509 0.17797 0.19467
34 Sigmas <- PostSigmas[keep,]
35 summary(coda::mcmc(Sigmas))
36      2.5%    25%    50%    75%    97.5%
37 var1 0.19664 0.20567 0.21072 0.21593 0.22636
38 var2 0.08201 0.09289 0.09865 0.10447 0.11623
39 var3 0.05222 0.06015 0.06452 0.06903 0.07799
40 var4 0.47390 0.49575 0.50789 0.52046 0.54446
41 var5 0.07355 0.08672 0.09381 0.10061 0.11427
42 var6 0.29259 0.30618 0.31384 0.32140 0.33700

```

## 6. Simulation exercise of instrumental variables continues

- (a) Use the setting of the simulation exercise of instrumental variables to analyze what happens when the instrument is weak, for instance,



setting  $\gamma_2 = 0.2$ , and compare the performance of the posterior means of the ordinary and instrumental models.

- (b) Perform a simulation that helps to analyze how the degree of exogeneity of the instrument affects the performance of the posterior mean of the instrumental variable model.

**Answer**

*R code. Simulation exercise, sampling properties  
of instrumental variable*

```

1 rm(list = ls())
2 set.seed(010101)
3 N <- 100
4 k <- 2
5 B <- rep(1, k)
6 G <- c(1, 0.2)
7 s12 <- 0.8
8 SIGMA <- matrix(c(1, s12, s12, 1), 2, 2)
9 z <- rnorm(N); # w <- rnorm(N)
10 Z <- cbind(1, z); w <- matrix(1,N,1)
11 S <- 100
12 U <- replicate(S, MASS::mvrnorm(n = N, mu = rep(0, 2), SIGMA
   ))
13 x <- G[1] + G[2]*z + U[,2,]
14 y <- B[1] + B[2]*x + U[,1,]
15 VarX <- G[2]^2+1 # Population variance of x
16 EU1U2 <- s12 # Covariance U1
17 BiasPopB2 <- EU1U2/VarX
18 # Hyperparameters
19 d0 <- 0.001/2
20 a0 <- 0.001/2
21 b0 <- rep(0, k)
22 c0 <- 1000
23 B0 <- c0*diag(k)
24 B0i <- solve(B0)
25 g0 <- rep(0, 2)
26 G0 <- 1000*diag(2)
27 G0i <- solve(G0)
28 nu <- 3
29 Psi0 <- nu*diag(2)
30 # MCMC parameters
31 mcmc <- 5000
32 burnin <- 1000
33 tot <- mcmc + burnin
34 thin <- 1
35 # Gibbs sampling
36 Gibbs <- function(x, y){
37   Data <- list(y = y, x = x, w = w, z = Z)
38   Mcmc <- list(R = mcmc, keep = thin, nprint = 0)
39   Prior <- list(md = g0, Ad = G0i, mbg = b0, Abg = B0i, nu =
     nu, V = Psi0)
40   RestIV <- bayesm::rivGibbs(Data = Data, Mcmc = Mcmc, Prior
     = Prior)
41   PostBIV <- mean(RestIV[["betadraw"]])
42   ResLM <- MCMCpack::MCMCregress(y ~ x + w - 1, b0 = b0, B0
     = B0i, c0 = a0, d0 = d0)
43   PostB <- mean(ResLM[,1])
44   Res <- c(PostB, PostBIV)
45   return(Res)
46 }
47 PosteriorMeans <- sapply(1:S, function(s) {Gibbs(x = x[,s],
   y = y[,s])})
48 rowMeans(PosteriorMeans)
49 1.781513 1.470648

```

**FIGURE 7.1**

Histogram of posterior means to assess the effects of *weakness* of the instrument: Ordinary and instrumental models.

Figure 7.1 shows that having a *weak instrument* generates poor performance of the posterior means of the variable instrumental model. Observe that the mean of the posterior means is less precise and biased. This is due to an identification problem in the likelihood function of  $y$  and  $x_s$  given  $z$  (see [22, Chap. 7]).

*R code. Simulation exercise, sampling properties  
of instrumental variable*

```

1 # Endogenous instruments
2 rm(list = ls())
3 set.seed(010101)
4 N <- 100
5 k <- 2
6 B <- rep(1, k)
7 G <- c(1, 1)
8 delta <- 0.2 # Effect of instrument on y
9 s12 <- 0.8
10 SIGMA <- matrix(c(1, s12, s12, 1), 2, 2)
11 z <- rnorm(N); # w <- rnorm(N)
12 Z <- cbind(1, z); w <- matrix(1,N,1)
13 S <- 100
14 U <- replicate(S, MASS::mvrnorm(n = N, mu = rep(0, 2), SIGMA
  ))
15 x <- G[1] + G[2]*z + U[,2,]
16 y <- B[1] + B[2]*x + delta*z + U[,1,]
17 VarX <- G[2]^2+1 # Population variance of x
18 EU1U2 <- s12 # Covariance U1
19 BiasPopB2 <- EU1U2/VarX
20 # Hyperparameters
21 d0 <- 0.001/2
22 a0 <- 0.001/2
23 b0 <- rep(0, k)
24 c0 <- 1000
25 B0 <- c0*diag(k)
26 B0i <- solve(B0)
27 g0 <- rep(0, 2)
28 G0 <- 1000*diag(2)
29 G0i <- solve(G0)
30 nu <- 3
31 Psi0 <- nu*diag(2)
32 # MCMC parameters
33 mcmc <- 5000
34 burnin <- 1000
35 tot <- mcmc + burnin
36 thin <- 1
37 # Gibbs sampling
38 Gibbs <- function(x, y){
39   Data <- list(y = y, x = x, w = w, z = Z)
40   Mcmc <- list(R = mcmc, keep = thin, nprint = 0)
41   Prior <- list(md = g0, Ad = G0i, mbg = b0, Abg = B0i, nu =
     nu, V = Psi0)
42   RestIV <- bayesm::rivGibbs(Data = Data, Mcmc = Mcmc, Prior
     = Prior)
43   PostBIV <- mean(RestIV[["betadraw"]])
44   ResLM <- MCMCpack::MCMCregress(y ~ x + w - 1, b0 = b0, B0
     = B0i, c0 = a0, d0 = d0)
45   PostB <- mean(ResLM[,1])
46   Res <- c(PostB, PostBIV)
47   return(Res)
48 }
49 PosteriorMeans <- sapply(1:S, function(s) {Gibbs(x = x[,s],
     y = y[,s])})
50 rowMeans(PosteriorMeans)
51 1.508009 1.217419

```

**FIGURE 7.2**

Histogram of posterior means to assess the effects of *endogeneity* of the instrument: Ordinary and instrumental models.

A simple way to assess the effects of *endogeneity* of the instrument in the instrumental variable model is to introduce the instrument into the *structural equation*, but assume that  $E[yz|x_s] = 0$ . In particular, we generate  $y_i = \beta_1 + \beta_2 x_{si} + \beta_3 z_i + \mu_i$ , but estimate  $y_i = \beta_1 + \beta_2 x_{si} + \mu_i$ . Figure 7.2 shows that assuming that an instrument is exogenous, when actually it is not, generates bias in the posterior mean of the instrumental variable model. Observe that *exogeneity* of the instrument is equivalent to the dogmatic prior belief that the instrument does not affect the structural equation. Thus, [4] propose to assess the plausibility of the *exclusion restrictions* ( $\beta_3 = 0$  and  $\gamma_2 \neq 0$ ) defining *plausible exogeneity* as having prior information that the effect of the instrument in the *structural equation* is near zero, but perhaps not exactly zero.

## 7. Simulation exercise of instrumental variables continues II

Program from scratch the Gibbs sampling algorithm of the instrumental model for the simulation exercise of the instrumental variables.

### Answer

The following code shows how to implement the Gibbs sampling algorithm from scratch. We observe that all posterior means are close to the population values, and 95% credible intervals encompass them.

*R code. Simulation exercise, Gibbs sampling  
instrumental model*

```

1 rm(list = ls()); set.seed(010101)
2 N <- 100; k <- 2; kz <- 2
3 B <- rep(1, k); G <- rep(1, kz)
4 s12 <- 0.8; SIGMA <- matrix(c(1, s12, s12, 1), 2, 2)
5 z <- rnorm(N); Z <- cbind(1, z); w <- matrix(1, N, 1)
6 S <- 100; U <- MASS::mvrnorm(n = N, mu = rep(0, 2), SIGMA)
7 x <- G[1] + G[2]*z + U[,2]; y <- B[1] + B[2]*x + U[,1]
8 X <- cbind(w, x)
9 # Hyperparameters
10 b0 <- rep(0, k); c0 <- 1000; B0 <- c0*diag(k)
11 B0i <- solve(B0); g0 <- rep(0, kz)
12 G0 <- 1000*diag(kz); G0i <- solve(G0)
13 nu <- 3; Psi0 <- nu*diag(2); Psi0i <- solve(Psi0)
14 # MCMC parameters
15 mcmc <- 5000; burnin <- 1000; tot <- mcmc + burnin
16 thin <- 1
17 # Auxiliary elements
18 XtX <- t(X)%*%X; ZtZ <- t(Z)%*%Z; nun <- nu + N
19 # Gibbs sampling
20 PostBeta <- function(Sigma, Gamma){
21   w1 <- Sigma[1,1] - Sigma[1,2]^2/Sigma[2,2]
22   Bn <- solve(w1^(-1)*XtX + B0i)
23   yaux <- y - (Sigma[1,2]/Sigma[2,2])*(x - Z%*%Gamma)
24   bn <- Bn%*%(B0i%*%b0 + w1^(-1)*t(X)%*%yaux)
25   Beta <- MASS::mvrnorm(1, bn, Bn)
26   return(Beta)
27 }
28 PostGamma <- function(Sigma, Beta){
29   w2 <- Sigma[2,2] - Sigma[1,2]^2/Sigma[1,1]
30   Gn <- solve(w2^(-1)*ZtZ + G0i)
31   xaux <- x - (Sigma[1,2]/Sigma[1,1])*(y - X%*%Beta)
32   gn <- Gn%*%(G0i%*%g0 + w2^(-1)*t(Z)%*%xaux)
33   Gamma <- MASS::mvrnorm(1, gn, Gn)
34   return(Gamma)
35 }
36 PostSigma <- function(Beta, Gamma){
37   Uy <- y - X%*%Beta; Ux <- x - Z%*%Gamma
38   U <- cbind(Uy, Ux)
39   Psin <- solve(Psi0i + t(U)%*%U)
40   Sigmai <- rWishart::rWishart(1, df = nun, Sigma = Psin)
41   Sigma <- solve(Sigmai[, , 1])
42   return(Sigma)
43 }

```

*R code. Simulation exercise, Gibss sampling  
instrumental model*

```

1 PostBetas <- matrix(0, tot, k); PostGammas <- matrix(0, tot,
  kz)
2 PostSigmas <- matrix(0, tot, 2*(2+1)/2); Beta <- rep(0, k);
  Gamma <- rep(0, kz)
3 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
4 for(s in 1:tot){
5   Sigma <- PostSigma(Beta = Beta, Gamma = Gamma)
6   Beta <- PostBeta(Sigma = Sigma, Gamma = Gamma)
7   Gamma <- PostGamma(Sigma = Sigma, Beta = Beta)
8   PostBetas[s,] <- Beta; PostGammas[s,] <- Gamma;
    PostSigmas[s,] <- matrixcalc::vech(Sigma)
9   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
10 }
11 close(pb)
12 keep <- seq((burnin+1), tot, thin)
13 Bs <- PostBetas[keep,]
14 Gs <- PostGammas[keep,]
15 Sigmas <- PostSigmas[keep,]
16 summary(coda::mcmc(Bs))
17 1. Empirical mean and standard deviation for each variable,
18 plus standard error of the mean:
19 Mean      SD Naive SE Time-series SE
20 [1,]  1.1519 0.1683  0.00238      0.006321
21 [2,]  0.9896 0.1146  0.00162      0.005177
22 summary(coda::mcmc(Gs))
23 1. Empirical mean and standard deviation for each variable,
24 plus standard error of the mean:
25 Mean      SD Naive SE Time-series SE
26 [1,]  1.133 0.1068  0.001511      0.003096
27 [2,]  1.030 0.1066  0.001507      0.004193
28 summary(coda::mcmc(Sigmas))
29 1. Empirical mean and standard deviation for each variable,
30 plus standard error of the mean:
31 Mean      SD Naive SE Time-series SE
32 [1,]  1.3883 0.3149  0.004454      0.012707
33 [2,]  0.9992 0.2133  0.003017      0.007166
34 [3,]  1.1637 0.1685  0.002382      0.002481

```

8. The effect of institutions on per capita gross domestic product continues II

Estimate the structural Equation 7.1 using the instrumental variable model where the instrument of PAER is  $\log(Mort)$ . Compare the effect of prop-

erty rights on per capita GDP of this model with the effect estimated in the example of the effect of institutions on per capita gross domestic product. Use the file *6Institutions.csv* to do this exercise in our GUI, and set  $\mathbf{B}_0 = 100\mathbf{I}_5$ ,  $\boldsymbol{\beta}_0 = \mathbf{0}_5$ ,  $\boldsymbol{\gamma}_0 = \mathbf{0}_2$ ,  $\mathbf{G}_0 = 100\mathbf{I}_2$ ,  $\alpha_0 = 3$  and  $\boldsymbol{\Psi}_0 = 3\mathbf{I}_2$ . The MCMC iterations, burn-in and thinning parameters are 50000, 1000 and 5, respectively.

### Answer

The following code shows how to do this using the command *rivGibbs* from the *bayesm* package. We see that the posterior mean of the effect of property rights on per capita GDP is 0.72, and the 95% credible interval is (0.47, 1.00). The posterior mean estimate of this effect was 0.98 in the example, and the 95% credible interval was (0.56, 2.87) (see Section 8.1 in the book). We can observe that the indirect approach, where the *reduced-form* parameters are estimated, and then, plug into the equations of the *structural parameters* produce less efficient posterior estimations.



***R code. The effects of institutions on GDP,  
variable instrumental model***

```

1 rm(list = ls()); set.seed(010101)
2 DataInst <- read.csv("https://raw.githubusercontent.com/
   besmarter/BSTApp/refs/heads/master/DataApp/6Institutions
   .csv", sep = ",", header = TRUE, quote = "")
3 attach(DataInst)
4 y <- logpcGDP95; x <- PAER
5 w <- cbind(1, Africa, Asia, Other); Z <- cbind(1, logMort)
6 # Hyperparameters
7 k <- 5; kz <- 2; b0 <- rep(0, k); c0 <- 100
8 B0 <- c0*diag(k); B0i <- solve(B0); g0 <- rep(0, kz)
9 G0 <- 100*diag(kz); G0i <- solve(G0); nu <- 5
10 Psi0 <- nu*diag(2)
11 # MCMC parameters
12 mcmc <- 50000; burnin <- 10000; tot <- mcmc + burnin; thin
   <- 5
13 # Gibbs sampling
14 Data <- list(y = y, x = x, w = w, z = Z)
15 Mcmc <- list(R = mcmc, keep = thin, nprint = 100)
16 Prior <- list(md = g0, Ad = G0i, mbg = b0, Abg = B0i, nu =
   nu, V = Psi0)
17 RestIV <- bayesm::rivGibbs(Data = Data, Mcmc = Mcmc, Prior =
   Prior)
18 summary(RestIV[["deltadraw"]])
19 summary(coda::mcmc(RestIV[["betadraw"]]))
20 Iterations = 1:10000
21 Thinning interval = 1
22 Number of chains = 1
23 Sample size per chain = 10000
24 1. Empirical mean and standard deviation for each variable,
25 plus standard error of the mean:
26 Mean          SD          Naive SE Time-series SE
27 0.759497      0.140874      0.001409      0.002477
28 2. Quantiles for each variable:
29 2.5%    25%    50%    75%   97.5%
30 0.5110 0.6654 0.7502 0.8424 1.0707
31 summary(RestIV[["gammadraw"]])
32 summary(RestIV[["sigmadraw"]])

```

### 9. Multivariate probit with different regressors

Let's do a simulation exercise where  $y_{i1}^* = 0.5 - 1.2x_{i11} + 0.7x_{i12} + 0.8x_{i13} + \mu_{i1}$  and  $y_{i2}^* = 1.5 - 0.8x_{i21} + 0.5x_{i22} + \mu_{i2}$ ,  $\Sigma = \begin{Bmatrix} 1 & 0.5 \\ 0.5 & 1 \end{Bmatrix}$ , where all regressors distribute standard normal, and  $N = 5000$ . Use  $\beta_0 = \mathbf{0}$ ,  $B_0 = 1000B$ ,

$\alpha_0 = 4$  and  $\Psi_0 = 4\mathbf{I}_2$ . Set number of iterations 2000 and a thinning parameter equal to 5.

- Perform inference using the setting of Section 7.4, that is, assuming that  $x_{i3}$  could have an effect on  $y_{i2}$ .
- Program a Gibbs sampling algorithm taking into account that there are different regressors in each binary decision, that is,  $x_{i3}$  does not have an effect on  $y_{i2}$ .

**Answer**

The following code shows how to perform inference assuming same number of regressors in both binary results. We can check that all 95% credible intervals encompass the population values, and the posterior mean estimates are very close to the population parameters.

*R code. Multivariate probit model: Same number of regressors in each binary response*

```

1 remove(list = ls())
2 n <- 5000 #Individuals
3 p <- 2 #Number dependent variables (For instance to buy or
4       #not to buy different products)
5 xo <- 2 #Number of choice dependent variables (For instance
6       #price of products)
7 xi <- 1 #Number of regressors that dependt on individuals (
8       #For instance income)
9 B1 <- c(0.5, -1.2, 0.7, 0.8)
10 B2 <- c(1.5, -0.8, 0.5, 0) # The last regressor is not relevant
11    #for the second product
12 Cor <- matrix(c(1, 0.5, 0.5, 1), p, p)
13 yX <- NULL; y1 <- NULL
14 for (i in 1:n){
15   ei <- MASS::mvrnorm(1, c(0,0), Cor); xs <- rnorm(xi)
16   x1i <- c(1, rnorm(xo), xs); y11i <- sum(x1i*B1)
17   y1i <- y11i + ei[1] > 0; x2i <- c(1, rnorm(xo), xs)
18   y12i <- sum(x2i*B2); y2i <- y12i + ei[2] > 0
19   yXi <- rbind(c(y1i, x1i), c(y2i, x2i))
20   yXi <- cbind(i, yXi)
21   colnames(yXi) <- c("id", "y", "cte", "x1o", "x2o", "xi")
22   yX <- rbind(yX, yXi)
23   y1 <- c(y1, c(y11i + ei[1], y12i + ei[2]))
24 }
25 nd <- 4 # Number of regressors
26 Xd <- as.matrix(yX[,3:6])
27 XcreateMP <- function(p, nxs, nind, Data){
28   pandterm = function(message) {
29     stop(message, call. = FALSE)
30   }
31   if (missing(nxs))
32     pandterm("requires number of regressors: include intercept
33             #if required")
34   if (missing(nind))
35     pandterm("requires number of units (individuals)")
36   if (missing(Data))
37     pandterm("requires dataset")
38   if (nrow(Data) != nind*2)
39     pandterm("check dataset! number of units times number
40             #alternatives should be equal to dataset rows")
41   XXDat <- array(0, c(p, 1+nxs, nind))
42   XX <- array(0, c(p, nxs*p, nind))
43   YY <- array(0, c(p, 1, nind))
44   is <- seq(p, nind*p, p)
45   cis <- seq(nxs, nxs*p+1, nxs)
46   for(i in is){
47     j <- which(i==is)
48     XXDat[,j] <- as.matrix(Data[c((i-(p-1)):i), -1])
49     YY[,j] <- XXDat[,1,j]
50     for(l in 1:p){
51       XX[l, (cis[l]-(nxs-1)):cis[l], j] <- XXDat[l, -1, j]
52     }
53   }
54   return(list(y=YY, X=XX))
55 }
56 Dat <- XcreateMP(p = p, nxs = nd, nind = n, Data = yX)

```

*R code. Multivariate probit model: Same number of regressors in each binary response*

```

1 y<-NULL
2 X<-NULL
3 for(i in 1:dim(Dat$y)[3]){
4   y<-c(y,Dat$y[,i])
5   X<-rbind(X,Dat$X[,i])
6 }
7 DataMP = list(p=p, y=y, X=X)
8 # Hyperparameters
9 k <- dim(X)[2]
10 b0 <- rep(0, k)
11 c0 <- 1000
12 B0 <- c0*diag(k)
13 B0i <- solve(B0)
14 a0 <- p - 1 + 3
15 Psi0 <- a0*diag(p)
16 Prior <- list(betabar = b0, A = B0i, nu = a0, V = Psi0)
17 # MCMC parameters
18 mcmc <- 2000
19 burnin <- 1000
20 thin <- 5
21 Mcmc <- list(R = mcmc, keep = thin)
22 Results <- bayesm::rmvpGibbs(Data = DataMP, Mcmc = Mcmc,
   Prior = Prior)
23 betatildeEq1 <- Results$betadraw[,1:4] / sqrt(Results$
   sigmadraw[,1])
24 summary(coda::mcmc(betatildeEq1))
25 betatildeEq2 <- Results$betadraw[,5:8] / sqrt(Results$
   sigmadraw[,4])
26 summary(coda::mcmc(betatildeEq2))
27 sigmadraw12 <- Results$sigmadraw[,2] / (Results$sigmadraw
   [,1]*Results$sigmadraw[,4])^0.5
28 summary(coda::mcmc(sigmadraw12))

```

The following code shows the implementation of a Gibbs sampling algorithm using the *bayesm* package, particularly, the *rmvpGibbs* command.

***R code. Multivariate probit model: Different number of regressors in each binary response, the rmvpGibbs command***

```

1 # Omitting last regressor for y2
2 Xnew <- X[,-8]
3 DataMP = list(p=p, y=y, X=Xnew)
4 # Hyperparameters
5 k <- dim(Xnew)[2]
6 b0 <- rep(0, k)
7 c0 <- 1000
8 B0 <- c0*diag(k)
9 B0i <- solve(B0)
10 Prior <- list(betabar = b0, A = B0i, nu = a0, V = Psi0)
11 Results <- bayesm::rmvpGibbs(Data = DataMP, Mcmc = Mcmc,
    Prior = Prior)
12 betatildeEq1 <- Results$betadraw[,1:4] / sqrt(Results$
    sigmadraw[,1])
13 summary(coda::mcmc(betatildeEq1))
14 betatildeEq2 <- Results$betadraw[,5:7] / sqrt(Results$
    sigmadraw[,4])
15 summary(coda::mcmc(betatildeEq2))
16 sigmadraw12 <- Results$sigmadraw[,2] / (Results$sigmadraw
    [,1]*Results$sigmadraw[,4])^0.5
17 summary(coda::mcmc(sigmadraw12))

```

The following code shows how to implement a Gibbs sampling algorithm from scratch.

*R code. Multivariate probit model: Different number of regressors in each binary response, Gibbs from scratch*

```

1 PostBetaNew <- function(Sigma, Yl){
2   Sigmai <- solve(Sigma); C <- chol(Sigmai)
3   Xstar <- matrix(0, n*p, k); Ystar <- matrix(0, n*p, 1)
4   for(i in seq(1, n*p, 2)){
5     Xstari <- C%%Xnew[i:(i+1),]
6     Xstar[i:(i+1),] <- Xstari
7     Ystari <- C%%Yl[i:(i+1)]
8     Ystar[i:(i+1)] <- Ystari
9   }
10  Bn <- solve(B0i + t(Xstar)%%Xstar)
11  bn <- Bn%*(B0i%%b0 + t(Xstar)%%Ystar)
12  Beta <- MASS::mvrnorm(1, bn, Bn)
13  return(Beta)
14 }
15 PostSigmaNew <- function(Beta, Yl){
16  U <- matrix(0, p, p)
17  for(i in seq(1, n*p, 2)){
18    Ui <- (Yl[i:(i+1)] - Xnew[i:(i+1),]%%Beta)%%t(Yl[i:(i+1)] - Xnew[i:(i+1),]%%Beta)
19    U <- U + Ui
20  }
21  Psin <- solve(Psi0i + U)
22  Sigmai <- rWishart::rWishart(1, df = an, Sigma = Psin)
23  Sigma <- solve(Sigmai[, ,1])
24 }
25 PostYlNew <- function(Beta, Sigma, Yl){
26  w1 <- Sigma[1, ]
27  w2 <- Sigma[2, ]
28  f1 <- w1[-1]*Sigma[2, 2]^(-1)
29  f2 <- w2[-2]*Sigma[1, 1]^(-1)
30  t11 <- Sigma[1, 1] - w1[-1]*Sigma[2, 2]^(-1)*w1[-1]
31  t22 <- Sigma[2, 2] - w2[-2]*Sigma[1, 1]^(-1)*w2[-2]
32  Ylnew <- Yl
33  for(i in seq(1, n*p, 2)){
34    Ylmean1 <- Xnew[i,]%%Beta + f1*(Yl[i+1] - Xnew[i+1,]%%Beta)
35    if(y[i] == 1){
36      Ylnew[i] <- truncnorm::rtruncnorm(1, a = 0, b = Inf,
37        mean = Ylmean1, sd = t11^0.5)
38    }else{
39      Ylnew[i] <- truncnorm::rtruncnorm(1, a = -Inf, b = 0,
40        mean = Ylmean1, sd = t11^0.5)
41    }
42    Ylmean2 <- Xnew[i+1,]%%Beta + f2*(Ylnew[i] - Xnew[i,]%%Beta)
43    if(y[i+1] == 1){
44      Ylnew[i+1] <- truncnorm::rtruncnorm(1, a = 0, b = Inf,
45        mean = Ylmean2, sd = t22^0.5)
46    }else{
47      Ylnew[i+1] <- truncnorm::rtruncnorm(1, a = -Inf, b = 0,
48        mean = Ylmean2, sd = t22^0.5)
49    }
50  }
51  return(Ylnew)
52 }

```

***R code. Multivariate probit model: Different number of regressors in each binary response, Gibbs from scratch***

```

1 an <- a0 + n
2 Psi0i <- solve(Psi0)
3 K1 <- 4; K2 <- 3; K <- K1 + K2
4 tot <- mcmc + burnin
5 PostBetas <- matrix(0, tot, K)
6 PostSigmas <- matrix(0, tot, p*(p+1)/2)
7 Beta <- rep(1, K)
8 Sigma <- diag(p)
9 pb <- winProgressBar(title = "progress bar", min = 0, max =
    tot, width = 300)
10 for(s in 1:tot){
11   Yl <- PostYlNew(Beta = Beta, Sigma = Sigma, Yl = yl)
12   Sigma <- PostSigmaNew(Beta = Beta, Yl = Yl)
13   Beta <- PostBetaNew(Sigma = Sigma, Yl = Yl)
14   PostBetas[s,] <- Beta
15   PostSigmas[s,] <- matrixcalc::vech(Sigma)
16   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
17 }
18 close(pb)
19 keep <- seq((burnin+1), tot, thin)
20 Bs <- PostBetas[keep,]
21 betatilde1 <- Bs[,1:K1] / sqrt(PostSigmas[keep,1])
22 summary(coda::mcmc(betatilde1))
23 betatilde2 <- Bs[, (K1+1):(K1+K2)] / sqrt(PostSigmas[keep,3])
24 summary(coda::mcmc(betatilde2))
25 sigmadraw12 <- PostSigmas[keep,2] / (PostSigmas[keep,1] *
    PostSigmas[keep,3])^0.5
26 summary(coda::mcmc(sigmadraw12))

```





# 8

## *Time series models*

### 8.1 Solutions of Exercises

1. Simulate the *dynamic linear model* assuming  $X_t \sim N(1, 0.1\sigma^2)$ ,  $w_t \sim N(0, 0.5\sigma^2)$ ,  $\mu_t \sim N(0, \sigma^2)$ ,  $\beta_0 = 1$ ,  $B_0 = 0.5\sigma^2$ ,  $\sigma^2 = 0.25$ , and  $G_t = 1$ ,  $t = 1, \dots, 100$ . Then, perform the filtering recursion fixing  $\Sigma = 25 \times 0.25$ ,  $\Omega_1 = 0.5\Sigma$  (high signal-to-noise ratio) and  $\Omega_2 = 0.1\Sigma$  (low signal-to-noise ratio). Plot and compare the results.

#### **Answer**

The following code shows how to perform this simulation and perform the filtering recursion using the *dln* package in **R**.

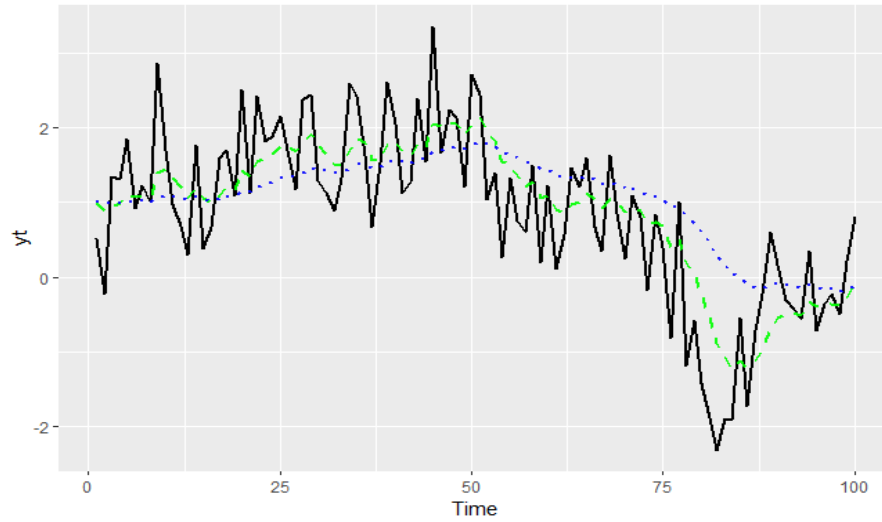
### *R code. Simulation: Scenarios signal-to-noise ratio*

```

1 rm(list = ls()); set.seed(010101)
2 T <- 100; sig2 <- 0.5^2; r <- 0.5; sigW2 <- sig2*r
3 x <- rnorm(T, mean = 1, sd = 0.1*sig2^0.5)
4 e <- rnorm(T, mean = 0, sd = sig2^0.5)
5 w <- rnorm(T, mean = 0, sd = sigW2^0.5)
6 K <- 1
7 Bt <- matrix(NA, T, K); Bt[1] <- 1
8 yt <- rep(NA, T)
9 yt[1] <- x[1]*Bt[1] + e[1]
10 for(t in 2:T){
11   Bt[t,] <- Bt[t-1,] + w[t]
12   yt[t] <- x[t]*Bt[t] + e[t]
13 }
14 # State spece model
15 ModelReg <- function(par){
16   Mod <- dlm::dlmModReg(x, dV = exp(par[1]), dW = exp(par
17     [2]), m0 = rep(1, K),
18   CO = sigW2*diag(K), addInt = FALSE)
19   return(Mod)
20 }
21 sig2New <- sig2*25
22 RegFilter1 <- dlm::dlmFilter(yt, ModelReg(c(sig2New, sig2New
23   *0.5)))
24 ytfil1 <- RegFilter1[["m"]][-1]
25 RegFilter2 <- dlm::dlmFilter(yt, ModelReg(c(sig2New, sig2New
26   *0.1)))
27 ytfil2 <- RegFilter2[["m"]][-1]
28 Time <- 1:T
29 df1 <- as.data.frame(cbind(Time,yt, ytfil1, ytfil2))
30 library(ggplot2)
31 ggplot(df1, aes(x=Time)) +
32   geom_line(aes(y=yt), colour="black", linewidth=1, linetype
33     =1) +
34   geom_line(aes(y=ytfil1), colour="green", linewidth=1, alpha
35     =0.9, linetype=2) +
36   geom_line(aes(y=ytfil2), color="blue", linewidth=1, alpha
37     =0.9, linetype=3)

```

Figure 8.1 shows the results of the filtering recursion. We see in this figure that the filtered recursion associated with the high signal-to-noise ratio (green dashed line) follows closer the data than the low signal-to-noise ratio scenario (blue dotted line). We see that the latter is smoother as it gives more weight to the prior mean, which takes into account historical information.

**FIGURE 8.1**

Signal-to-noise ratio: Dynamic linear model.

2. Simulate the *dynamic linear model*  $y_t = \beta_t x_t + \mu_t$ ,  $\beta_t = \beta_{t-1} + w_t$ , where  $x_t \sim N(1, 0.1\sigma^2)$ ,  $w_t \sim N(0, 0.5\sigma^2)$ ,  $\mu_t \sim N(0, \sigma^2)$ ,  $\beta_0 = 0$ ,  $B_0 = 0.5\sigma^2$ , and  $\sigma^2 = 1$ ,  $t = 1, \dots, 100$ . Perform the filtering and smoothing recursions from scratch.

**Answer**

The following code shows how to perform this simulation and perform the filtering recursion from scratch in **R**.

*R code. Simulation: Filtering and smoothing recursions from scratch*

```

1 rm(list = ls()); set.seed(010101)
2 T <- 100; sig2 <- 1; r <- 0.5; sigW2 <- sig2*r
3 xt <- rnorm(T, mean = 1, sd = 0.1*sig2^0.5)
4 e <- rnorm(T, mean = 0, sd = sig2^0.5)
5 w <- rnorm(T, mean = 0, sd = sigW2^0.5)
6 K <- 1; Bt <- matrix(NA, T, K); Bt[1] <- 0
7 yt <- rep(NA, T); yt[1] <- xt[1]*Bt[1] + e[1]
8 for(t in 2:T){
9   Bt[t,] <- Bt[t-1,] + w[t]
10  yt[t] <- xt[t]*Bt[t] + e[t]
11 }
12 # Filtering
13 KFR <- function(y, x, b1, B1, Omega, sig2){
14   e <- as.numeric(y - t(x)%*%b1) # Error
15   R <- B1 + Omega
16   q <- as.numeric(t(x)%*%R)%*%x + sig2)
17   K <- (R)%*%x)/q
18   bt <- b1 + K*e
19   Bt <- R - R)%*%x)%*%t(x)%*%R/q
20   Result <- list(bt = bt, Bt = Bt)
21   return(Result)
22 }
23 KFresb <- list(); KFresB <- list()
24 b0 <- 0; B0 <- sigW2
25 for(t in 1:T){
26   KFrest <- KFR(y = yt[t], x = xt[t], b1 = b0, B1 = B0,
27     Omega = sigW2, sig2 = sig2)
28   b0 <- KFrest[["bt"]]; B0 <- KFrest[["Bt"]]
29   KFresb[[t]] <- b0; KFresB[[t]] <- B0
30 }
31 ModelReg <- function(par){
32   Mod <- dlm::dlmModReg(xt, dV = exp(par[1]), dW = exp(par
33     [2]), m0 = rep(0, K),
34   C0 = sigW2*diag(K), addInt = FALSE)
35   return(Mod)
36 }
37 RegFilter1 <- dlm::dlmFilter(yt, ModelReg(c(sig2, sigW2)))
38 plot(Bt, type = "l")
39 lines(unlist(KFresb), type = "l", col = "red")
40 lines(RegFilter1[["m"]][-1], type = "l", col = "blue")

```

***R code. Simulation: Filtering and smoothing recursions from scratch***

```

1 # Smoothing
2 BSR <- function(b, B, slead, Slead, Omega){
3   b = bfilter[t]; B = Bfilter[t]; slead = slead; Slead =
4     slead; Omega = sigW2
5   R1 <- B + Omega
6   s <- b + B%*%solve(R1)%*%(slead - b)
7   S <- B - B%*%solve(R1)%*%(R1 - Slead)%*%solve(R1)%*%B
8   Result <- list(st = s, St = S)
9   return(Result)
10 }
11 bfilter <- unlist(KFresb); Bfilter <- unlist(KFresB)
12 slead <- bfilter[T]; Slead <- Bfilter[T]
13 smooth <- rep(slead, T); Smooth <- rep(Slead, T);
14 for(t in (T-1):1){
15   BSRrest <- BSR(b = bfilter[t], B = Bfilter[t], slead =
16     slead, Slead = Slead, Omega = sigW2)
17   slead <- BSRrest[["st"]]; Slead <- BSRrest[["St"]]
18   smooth[t] <- slead
19 }
20 RegSmoth <- dlm::dlmSmooth(yt, ModelReg(c(sig2, sigW2)))
21 VarSmooth <- dlm::dlmSvd2var(u = RegSmoth[["U.S"]], RegSmoth
22   [["D.S"]])
23 SDVarSmoothB2 <- sapply(2:(T+1), function(t){VarSmooth[[t]][
24   K,K]^0.5})
25 plot(Bt, type = "l")
26 lines(smooth, type = "l", col = "orange")
27 lines(RegSmoth[["s"]][-1], type = "l", col = "green")

```

3. Show that in the  $AR(2)$  stationary process,  $y_t = \mu + \phi_1 y_{t-1} + \phi_2 y_{t-2} + e_t$ , where  $e_t \sim N(0, \sigma^2)$ ,  $\mathbb{E}[y_t] = \frac{\mu}{1-\phi_1-\phi_2}$ , and  $Var[y_t] = \frac{\sigma^2(1-\phi_2)}{1-\phi_2-\phi_1^2-\phi_1^2\phi_2-\phi_2^2+\phi_2^3}$ .

**Answer**

A necessary condition to achieve second-order stationarity in the  $AR(2)$  process is that roots of the polynomial  $1 - \phi_1 L - \phi_2 L^2 = 0$  lie outside the unit circle. This is achieved if  $|\phi_2| < 1$ ,  $\phi_1 + \phi_2 < 1$  and  $\phi_2 - \phi_1 < 1$ .

Let's calculate the expected value:

$$\begin{aligned}
 \mathbb{E}[y_t] &= \bar{\mu} \\
 &= \mathbb{E}[\mu + \phi_1 y_{t-1} + \phi_2 y_{t-2} + e_t] \\
 &= \mu + \phi_1 \mathbb{E}[y_{t-1}] + \phi_2 \mathbb{E}[y_{t-2}] + \mathbb{E}[e_t] \\
 &= \mu + \phi_1 \bar{\mu} + \phi_2 \bar{\mu},
 \end{aligned}$$

then,  $\bar{\mu}(1 - \phi_1 - \phi_2) = \mu$ , then,  $\mathbb{E}[y_t] = \bar{\mu} = \frac{\mu}{1 - \phi_1 - \phi_2}$ .

See that  $y_t = \mu + \phi_1 y_{t-1} + \phi_2 y_{t-2} + e_t$  implies that  $y_t = \bar{\mu}(1 - \phi_1 - \phi_2) + \phi_1 y_{t-1} + \phi_2 y_{t-2} + e_t$ , which means that  $y_t - \bar{\mu} = \phi_1(y_{t-1} - \bar{\mu}) + \phi_2(y_{t-2} - \bar{\mu}) + e_t$ , and setting  $z_t = y_t - \bar{\mu}$ , we have  $z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + e_t$  where  $\mathbb{E}[z_t] = 0$ . Then, we can calculate the variance of  $y_t$  using  $z_t$ , given that both have same variance.

Let's define  $\gamma_s = \text{Cov}(z_t, z_{t-s}) = \mathbb{E}[z_t z_{t-s}]$ , then the Yule-Walker equations are:

$$\begin{aligned}\gamma_0 &= \phi_1 \gamma_1 + \phi_2 \gamma_2 + \sigma^2 \\ \gamma_1 &= \phi_1 \gamma_0 + \phi_2 \gamma_1 \\ \gamma_2 &= \phi_1 \gamma_1 + \phi_2 \gamma_0.\end{aligned}$$

Solving this system of equations for  $\gamma_0$ ,  $\gamma_1$  and  $\gamma_2$ , we find that  $\gamma_0 = \frac{\sigma^2(1 - \phi_2)}{1 - \phi_2 - \phi_1^2 - \phi_1^2 \phi_2 - \phi_2^2 + \phi_2^3}$ .

4. Show that the posterior distribution of  $\phi | \beta, \sigma^2, \mathbf{y}, \mathbf{X}$  in the model  $y_t = \mathbf{x}_t^\top \beta + \mu_t$  where  $\phi(L)\mu_t = e_t$  and  $e_t \stackrel{iid}{\sim} N(0, \sigma^2)$  is  $N(\phi_n, \Phi_n) \mathbb{1}[\phi \in S_\phi]$ , where  $\Phi_n = (\Phi_0^{-1} + \sigma^{-2} \mathbf{U}^\top \mathbf{U})$ ,  $\phi_n = \Phi_n(\Phi_0^{-1} \phi_0 + \sigma^{-2} \mathbf{U}^\top \mu)$ , and  $S_\phi$  is the stationary region of  $\phi$ .

**Answer**

The conditional posterior distribution can be got as follows:

$$\begin{aligned}\pi(\phi | \beta, \sigma^2, \mathbf{y}) &\propto \exp \left\{ -\frac{1}{2\sigma^2} (\mu - \mathbf{U}\phi)^\top (\mu - \mathbf{U}\phi) \right\} \\ &\times \exp \left\{ -\frac{1}{2} (\phi - \phi_0)^\top \Phi_0^{-1} (\phi - \phi_0) \right\} \\ &\propto \exp \left\{ -\frac{1}{2} [\phi^\top (\sigma^{-2} \mathbf{U}^\top \mathbf{U} + \Phi_0^{-1}) \phi - 2\phi^\top (\sigma^{-2} \mathbf{U}^\top \mu + \Phi_0^{-1} \phi_0) \right. \\ &\quad \left. + \phi_n^\top \Phi_n^{-1} \phi_n - \phi_n^\top \Phi_n^{-1} \phi_n] \right\} \\ &\propto \exp \left\{ -\frac{1}{2} [(\phi - \phi_n)^\top \Phi_n^{-1} (\phi - \phi_n)] \right\},\end{aligned}$$

where  $\Phi_n = (\sigma^{-2} \mathbf{U}^\top \mathbf{U} + \Phi_0^{-1})^{-1}$  and  $\phi_n = \Phi_n(\sigma^{-2} \mathbf{U}^\top \mu + \Phi_0^{-1} \phi_0)$ . The last expression is the kernel of a multivariate normal distribution with mean  $\phi_n$  and variance matrix  $\Phi_n$ .

# 9

## Longitudinal/Panel data models

### 9.1 Solutions of Exercises

1. Show that the posterior distribution of  $\beta|\sigma^2, \mathbf{D}$  is  $N(\beta_n, \mathbf{B}_n)$ , where  $\mathbf{B}_n = (\mathbf{B}_0^{-1} + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{X}_i)^{-1}$  and  $\beta_n = \mathbf{B}_n(\mathbf{B}_0^{-1}\beta_0 + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{y}_i)$ .

**Answer**

$$\begin{aligned}
 \pi(\beta|\sigma^2, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W}) &\propto \exp \left\{ -\frac{1}{2} \sum_{i=1}^N (\mathbf{y}_i - \mathbf{X}_i \beta)^\top \mathbf{V}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \beta) \right\} \\
 &\quad \times \exp \left\{ -\frac{1}{2} (\beta - \beta_0)^\top \mathbf{B}_0^{-1} (\beta - \beta_0) \right\} \\
 &\propto \exp \left\{ -\frac{1}{2} \left( -2\beta^\top \left( \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{y}_i + \mathbf{B}_0^{-1} \beta_0 \right) + \beta^\top \left( \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{X}_i + \mathbf{B}_0^{-1} \right) \beta \right) \right\} \\
 &= \exp \left\{ -\frac{1}{2} (-2\beta^\top \mathbf{B}_n^{-1} \mathbf{B}_n \left( \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{y}_i + \mathbf{B}_0^{-1} \beta_0 \right) + \beta^\top \mathbf{B}_n^{-1} \beta) \right\} \\
 &= \exp \left\{ -\frac{1}{2} (-2\beta^\top \mathbf{B}_n^{-1} \beta_n + \beta^\top \mathbf{B}_n^{-1} \beta) \right\}.
 \end{aligned}$$

We can complete the square in this expression by adding and subtracting  $\beta_n^\top \mathbf{B}_n^{-1} \beta_n$ . Thus,

$$\begin{aligned}
 \pi(\beta|\sigma^2, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W}) &\propto \exp \left\{ -\frac{1}{2} (-2\beta^\top \mathbf{B}_n^{-1} \beta_n + \beta^\top \mathbf{B}_n^{-1} \beta + \beta_n^\top \mathbf{B}_n^{-1} \beta_n - \beta_n^\top \mathbf{B}_n^{-1} \beta_n) \right\} \\
 &\propto \exp \left\{ -\frac{1}{2} (\beta - \beta_n)^\top \mathbf{B}_n^{-1} (\beta - \beta_n) \right\}.
 \end{aligned}$$

This is the kernel of a multivariate random variable with mean  $\beta_n$  and variance matrix  $\mathbf{B}_n$ .

2. **The relation between productivity and public investment example continues**

- Perform inference of this example using our GUI.

- Program from scratch a Gibbs sampling algorithm to perform this application. Set  $\beta_0 = \mathbf{0}_5$ ,  $B_0 = I_5$ ,  $\alpha_0 = \delta_0 = 0.001$ ,  $d_0 = 5$  and  $D_0 = I_1$ .
- Perform inference in this example assuming that  $\mu_{it}|\tau_{it} \sim N(0, \sigma^2/\tau_{it})$  and  $\tau_{it} \sim G(v/2, v/2)$  setting  $v = 5$ .

**Answer**



***R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler***

```

1 rm(list = ls())
2 set.seed(12345)
3 DataGSP <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/8PublicCap.
  csv", sep = ",", header = TRUE, quote = "")
4 attach(DataGSP)
5 N <- length(unique(id))
6 y <- log(gsp)
7 NT <- length(y)
8 X <- cbind(1, log(pcap), log(pc), log(emp), unemp)
9 K1 <- dim(X)[2]
10 W <- matrix(rep(1, NT), NT, 1)
11 K2 <- dim(W)[2]
12 mcmc <- 10000; burnin <- 5000; thin <- 1; tot <- mcmc +
  burnin
13 b0 <- rep(0, K1); B0 <- diag(K1); B0i <- solve(B0)
14 r0 <- 5; R0 <- diag(K2); a0 <- 0.001; d0 <- 0.001
15 PostBeta <- function(sig2, D){
16   XVX <- matrix(0, K1, K1)
17   XVy <- matrix(0, K1, 1)
18   for(i in 1:N){
19     ids <- which(id == i)
20     Ti <- length(ids)
21     Wi <- W[ids, ]
22     Vi <- sig2*diag(Ti) + Wi*%D%*t(Wi)
23     ViInv <- solve(Vi)
24     Xi <- X[ids, ]
25     XVXi <- t(Xi)*%ViInv%*Xi
26     XVX <- XVX + XVXi
27     yi <- y[ids]
28     XVyi <- t(Xi)*%ViInv%*yi
29     XVy <- XVy + XVyi
30   }
31   Bn <- solve(B0i + XVX)
32   bn <- Bn*%(B0i*%b0 + XVy)
33   Beta <- MASS::mvrnorm(1, bn, Bn)
34   return(Beta)
35 }

```

***R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler***

```

1 Postb <- function(Beta, sig2, D){
2   Di <- solve(D)
3   bis <- matrix(0, N, K2)
4   for(i in 1:N){
5     ids <- which(id == i)
6     Wi <- W[ids, ]
7     Xi <- X[ids, ]
8     yi <- y[ids]
9     Wtei <- sig2^(-1)*t(Wi)%*(yi - Xi%*Beta)
10    Bni <- solve(sig2^(-1)*t(Wi)%*Wi + Di)
11    bni <- Bni%*Wtei
12    bi <- MASS::mvrnorm(1, bni, Bni)
13    bis[i, ] <- bi
14  }
15  return(as.matrix(bis))
16 }
17 PostSig2 <- function(Beta, bs){
18   an <- a0 + 0.5*NT
19   ete <- 0
20   for(i in 1:N){
21     ids <- which(id == i)
22     Xi <- X[ids, ]
23     yi <- y[ids]
24     Wi <- W[ids, ]
25     ei <- yi - Xi%*Beta - Wi*bs[i, ]
26     etei <- t(ei)%*ei
27     ete <- ete + etei
28   }
29   dn <- d0 + 0.5*ete
30   sig2 <- MCMCpack::rinvgamma(1, shape = an, scale = dn)
31   return(sig2)
32 }
33 PostD <- function(bs){
34   rn <- r0 + N
35   btb <- matrix(0, K2, K2)
36   for(i in 1:N){
37     bsi <- bs[i, ]
38     btbi <- bsi%*t(bsi)
39     btb <- btb + btbi
40   }
41   Rn <- d0*R0 + btb
42   Sigma <- MCMCpack::riwish(v = rn, S = Rn)
43   return(Sigma)
44 }

```

***R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler***

```

1 PostBetas <- matrix(0, tot, K1); PostDs <- matrix(0, tot, K2
  *(K2+1)/2)
2 PostSig2s <- rep(0, tot); Postbs <- array(0, c(N, K2, tot))
3 RegLS <- lm(y ~ X - 1); SumLS <- summary(RegLS)
4 Beta <- SumLS[["coefficients"]][,1]
5 sig2 <- SumLS[["sigma"]]^2; D <- diag(K2)
6 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
7 for(s in 1:tot){
8   bs <- Postb(Beta = Beta, sig2 = sig2, D = D)
9   D <- PostD(bs = bs)
10  Beta <- PostBeta(sig2 = sig2, D = D)
11  # Beta <- PostBetaNew(sig2 = sig2, D = D)
12  sig2 <- PostSig2(Beta = Beta, bs = bs)
13  PostBetas[s,] <- Beta
14  PostDs[s,] <- matrixcalc::vech(D)
15  PostSig2s[s] <- sig2
16  Postbs[, , s] <- bs
17  setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
18 }
19 close(pb)
20 keep <- seq((burnin+1), tot, thin)
21 Bs <- PostBetas[keep,]; Ds <- PostDs[keep,]
22 bs <- Postbs[, , keep]; sig2s <- PostSig2s[keep]
23 summary(coda::mcmc(Bs))
24 Quantiles for each variable:
25      2.5%      25%      50%      75%      97.5%
26 var1  1.727227  1.934457  2.037411  2.138829  2.325961
27 var2 -0.033664  0.001015  0.018974  0.037977  0.076626
28 var3  0.274521  0.303619  0.318302  0.332881  0.363323
29 var4  0.652937  0.692479  0.712605  0.730885  0.768415
30 var5 -0.008724 -0.007265 -0.006548 -0.005844 -0.004508
31 summary(coda::mcmc(Ds))
32 summary(coda::mcmc(sig2s))
33 # Convergence diagnostics
34 coda::geweke.diag(Bs)
35 coda::raftery.diag(Bs,q=0.5,r=0.05,s = 0.95)
36 coda::heidel.diag(Bs)

```

The likelihood function in the case with heteroskedasticity is proportional

to

$$p(\boldsymbol{\beta}, \mathbf{b}, \sigma^2, \boldsymbol{\tau} | \mathbf{y}, \mathbf{X}, \mathbf{W}) \propto \prod_{i=1}^N |\sigma^2 \boldsymbol{\Psi}_i|^{-1/2} \\ \times \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta} - \mathbf{W}_i \mathbf{b}_i)^\top \boldsymbol{\Psi}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta} - \mathbf{W}_i \mathbf{b}_i) \right\},$$

where  $\mathbf{b} = [\mathbf{b}_1^\top, \mathbf{b}_2^\top, \dots, \mathbf{b}_N^\top]^\top$ ,  $\boldsymbol{\tau} = [\tau_{it}]^\top$  and  $\boldsymbol{\Psi}_i = \text{diag} \{ \tau_{it}^{-1} \}$ .

Following the same procedure as in Section 9.1 of the book, and Exercise 1 of this chapter, we have that

$$\boldsymbol{\beta} | \sigma^2, \boldsymbol{\tau}, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W} \sim N(\boldsymbol{\beta}_n, \mathbf{B}_n),$$

where  $\mathbf{B}_n = (\mathbf{B}_0^{-1} + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{X}_i)^{-1}$ ,  $\boldsymbol{\beta}_n = \mathbf{B}_n (\mathbf{B}_0^{-1} \boldsymbol{\beta}_0 + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{y}_i)$  and  $\mathbf{V}_i = \sigma^2 \boldsymbol{\Psi}_i + \sigma_b^2 \mathbf{i}_{T_i} \mathbf{i}_{T_i}^\top$ .

$$\mathbf{b}_i | \boldsymbol{\beta}, \sigma^2, \boldsymbol{\tau}, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W} \sim N(\mathbf{b}_{ni}, \mathbf{B}_{ni}),$$

where  $\mathbf{B}_{ni} = (\sigma^{-2} \mathbf{W}_i^\top \boldsymbol{\Psi}_i^{-1} \mathbf{W}_i + \mathbf{D}^{-1})^{-1}$  and  $\mathbf{b}_{ni} = \mathbf{B}_{ni} (\sigma^{-2} \mathbf{W}_i^\top \boldsymbol{\Psi}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta}))$ .

$$\sigma^2 | \boldsymbol{\beta}, \mathbf{b}, \boldsymbol{\tau}, \mathbf{y}, \mathbf{X}, \mathbf{W} \sim IG(\alpha_n, \delta_n),$$

where  $\alpha_n = \alpha_0 + \frac{1}{2} \sum_{i=1}^N T_i$  and  $\delta_n = \delta_0 + \frac{1}{2} \sum_{i=1}^N (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta} - \mathbf{W}_i \mathbf{b}_i)^\top \boldsymbol{\Psi}_i^{-1} (\mathbf{y}_i - \mathbf{X}_i \boldsymbol{\beta} - \mathbf{W}_i \mathbf{b}_i)$ .

$$\mathbf{D} | \mathbf{b} \sim IW(d_n, \mathbf{D}_n),$$

where  $d_n = d_0 + N$  and  $\mathbf{D}_n = d_0 \mathbf{D}_0 + \sum_{i=1}^N \mathbf{b}_i \mathbf{b}_i^\top$ . And

$$\tau_{it} | \sigma^2, \boldsymbol{\beta}, \mathbf{b}, \mathbf{y}, \mathbf{X}, \mathbf{W} \sim G(v_{1n}/2, v_{2ni}/2),$$

where  $v_{1n} = v + 1$  and  $v_{2ni} = v + \sigma^{-2} (\mathbf{y}_{it} - \mathbf{x}_{it}^\top \boldsymbol{\beta} - \mathbf{w}_{it}^\top \mathbf{b}_i)^2$ .

The following code shows to implement this for the productivity application. The results of the *fixed effects* are very similar compared to the results without taken into account heteroskedasticity.

***R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler with heteroskedasticity***

```

1 rm(list = ls())
2 set.seed(12345)
3 DataGSP <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/8PublicCap.
  csv", sep = ",", header = TRUE, quote = "")
4 attach(DataGSP)
5 N <- length(unique(id))
6 y <- log(gsp)
7 NT <- length(y)
8 X <- cbind(1, log(pcap), log(pc), log(emp), unemp)
9 K1 <- dim(X)[2]
10 W <- matrix(rep(1, NT), NT, 1)
11 K2 <- dim(W)[2]
12 mcmc <- 10000; burnin <- 5000; thin <- 1; tot <- mcmc +
  burnin
13 b0 <- rep(0, K1); B0 <- diag(K1); B0i <- solve(B0)
14 r0 <- 5; R0 <- diag(K2); a0 <- 0.001; d0 <- 0.001; v <- 5
15 # Gibbs by hand
16 PostBeta <- function(sig2, D, tau){
17   X VX <- matrix(0, K1, K1)
18   X Vy <- matrix(0, K1, 1)
19   for(i in 1:N){
20     ids <- which(id == i)
21     Ti <- length(ids)
22     Wi <- W[ids, ]
23     tau_i <- tau[ids]
24     Vi <- sig2*solve(diag(1/tau_i)) + Wi%*%D%*%t(Wi)
25     ViInv <- solve(Vi)
26     Xi <- X[ids, ]
27     VX Xi <- t(Xi)%*%ViInv%*%Xi
28     VX <- VX + VX Xi
29     yi <- y[ids]
30     XV yi <- t(Xi)%*%ViInv%*%yi
31     XV y <- XV y + XV yi
32   }
33   Bn <- solve(B0i + VX)
34   bn <- Bn%*%(B0i%*%b0 + XV y)
35   Beta <- MASS::mvrnorm(1, bn, Bn)
36   return(Beta)
37 }

```

*R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler with heteroskedasticity*

```

1 Postb <- function(Beta, sig2, D, tau){
2   Di <- solve(D);   bis <- matrix(0, N, K2)
3   for(i in 1:N){
4     ids <- which(id == i)
5     Wi <- W[ids, ]; Xi <- X[ids, ]
6     yi <- y[ids]; tau_i <- tau[ids]
7     Tau_i <- solve(diag(1/tau_i))
8     Wtei <- sig2^(-1)*t(Wi)%*%Tau_i%*(yi - Xi%*Beta)
9     Bni <- solve(sig2^(-1)*t(Wi)%*%Tau_i%*Wi + Di)
10    bni <- Bni%*%Wtei
11    bi <- MASS::mvrnorm(1, bni, Bni)
12    bis[i, ] <- bi
13  }
14  return(bis)
15 }
16 PostSig2 <- function(Beta, bs, tau){
17   an <- a0 + 0.5*NT; ete <- 0
18   for(i in 1:N){
19     ids <- which(id == i)
20     Xi <- X[ids, ]; yi <- y[ids]
21     Wi <- W[ids, ]; tau_i <- tau[ids]
22     Tau_i <- solve(diag(1/tau_i))
23     ei <- yi - Xi%*Beta - Wi*bs[i]
24     etei <- t(ei)%*%Tau_i%*ei
25     ete <- ete + etei
26   }
27   dn <- d0 + 0.5*ete
28   sig2 <- MCMCpack::rinvgamma(1, shape = an, scale = dn)
29   return(sig2)
30 }
31 PostD <- function(bs){
32   rn <- r0 + N
33   btb <- matrix(0, K2, K2)
34   for(i in 1:N){
35     bsi <- bs[i, ]
36     btbi <- bsi%*%t(bsi)
37     btb <- btb + btbi
38   }
39   Rn <- d0*R0 + btb
40   Sigma <- MCMCpack::riwish(v = rn, S = Rn)
41   return(Sigma)
42 }
43 PostTau <- function(sig2, Beta, bs){
44   v1n <- v + 1
45   v2n <- NULL
46   for(i in 1:NT){
47     Xi <- X[i, ]; yi <- y[i]
48     Wi <- W[i, ]; bi <- bs[id[i],]
49     v2ni <- v + sig2^(-1)*(yi - Xi%*Beta - Wi%*bi)^2
50     v2n <- c(v2n, v2ni)
51   }
52   tau <- rgamma(NT, shape = rep(v1n/2, NT), rate = v2n/2)
53   return(tau)
54 }

```

***R code. The relationship between productivity and public investment, programming from scratch the Gibbs sampler with heteroskedasticity***

```

1 PostBetas <- matrix(0, tot, K1); PostDs <- matrix(0, tot, K2
  *(K2+1)/2)
2 PostSig2s <- rep(0, tot); Postbs <- array(0, c(N, K2, tot))
3 PostTaus <- matrix(0, tot, NT); RegLS <- lm(y ~ X - 1)
4 SumLS <- summary(RegLS); Beta <- SumLS[["coefficients"]][,1]
5 sig2 <- SumLS[["sigma"]]^2; D <- diag(K2)
6 tau <- rgamma(NT, shape = v/2, rate = v/2)
7 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
8 for(s in 1:tot){
9   bs <- Postb(Beta = Beta, sig2 = sig2, D = D, tau = tau)
10  D <- PostD(bs = bs)
11  Beta <- PostBeta(sig2 = sig2, D = D, tau = tau)
12  sig2 <- PostSig2(Beta = Beta, bs = bs, tau = tau)
13  tau <- PostTau(sig2 = sig2, Beta = Beta, bs = bs)
14  PostBetas[s,] <- Beta
15  PostDs[s,] <- matrixcalc::vech(D)
16  PostSig2s[s] <- sig2
17  Postbs[, , s] <- bs
18  PostTaus[s,] <- tau
19  setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
20 }
21 close(pb)
22 keep <- seq((burnin+1), tot, thin)
23 Bs <- PostBetas[keep,]
24 Ds <- PostDs[keep,]
25 bs <- Postbs[, , keep]
26 sig2s <- PostSig2s[keep]
27 taus <- PostTaus[keep,]
28 summary(coda::mcmc(Bs))
29 Quantiles for each variable:
30      2.5%      25%      50%      75%      97.5%
31 var1  1.61764  1.891242  2.029985  2.165677  2.427349
32 var2 -0.07088 -0.016921  0.013080  0.044681  0.107360
33 var3  0.27259  0.312197  0.333106  0.353678  0.395123
34 var4  0.59507  0.664490  0.699526  0.734612  0.796977
35 var5 -0.01046 -0.008533 -0.007586 -0.006666 -0.004918
36 summary(coda::mcmc(Ds))
37 summary(coda::mcmc(sig2s))

```

### 3. Simulation exercise of the longitudinal normal model continues

Assume that  $y_{it} = \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 x_{it3} + \beta_4 z_{i1} + b_i + w_{it1} b_{i1} + \mu_{it}$  where  $x_{itk} \sim N(0, 1)$ ,  $k = 1, 2, 3$ ,  $z_{i1} \sim B(0.5)$ ,  $w_{it1} \sim N(0, 1)$ ,  $b_i \sim$

$N(0, 0.7^{1/2})$ ,  $b_{i1} \sim N(0, 0.6^{1/2})$ ,  $\mu_{it} \sim N(0, 0.1^{1/2})$   $\beta = [0.4 \ 0.6 \ -0.6 \ 0.7]^\top$ ,  $i = 1, 2, \dots, 50$ , and the sample size is 2000 in an *unbalanced panel structure*. In addition, we assume that  $\mathbf{b}_i$  depends on  $\mathbf{z}_i = [1 \ z_{i1}]^\top$  such that  $\mathbf{b}_i \sim N(\mathbf{Z}_i \boldsymbol{\gamma}, \mathbf{D})$  where  $\mathbf{Z}_i = \mathbf{I}_{K_2} \otimes \mathbf{z}_i^\top$ , and  $\boldsymbol{\gamma} = [1 \ 1 \ 1 \ 1]$ . The prior for  $\boldsymbol{\gamma}$  is  $N(\boldsymbol{\gamma}_0, \boldsymbol{\Gamma}_0)$  where we set  $\boldsymbol{\gamma}_0 = \mathbf{0}_4$  and  $\boldsymbol{\Gamma}_0 = \mathbf{I}_4$ . In addition, Set  $\beta_0 = \mathbf{0}_4$ ,  $\mathbf{B}_0 = \mathbf{I}_4$ ,  $\alpha_0 = \delta_0 = 0.001$ ,  $d_0 = 2$  and  $\mathbf{D}_0 = \mathbf{I}_2$ .

- Perform inference in this model without taking into account the dependence between  $\mathbf{b}_i$  and  $z_{i1}$ , and compare the posterior estimates with the population parameters.
- Perform inference in this model taking into account the dependence between  $\mathbf{b}_i$  and  $z_{i1}$ , and compare the posterior estimates with the population parameters.

### Answer

Following the same procedure as in Section 9.1 of the book, and Exercise 1 of this chapter, we have that

$$\beta | \sigma^2, \gamma, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W}, \mathbf{Z} \sim N(\beta_n, \mathbf{B}_n),$$

where  $\mathbf{B}_n = (\mathbf{B}_0^{-1} + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} \mathbf{X}_i)^{-1}$ ,  $\beta_n = \mathbf{B}_n(\mathbf{B}_0^{-1} \beta_0 + \sum_{i=1}^N \mathbf{X}_i^\top \mathbf{V}_i^{-1} (\mathbf{y}_i - \mathbf{W}_i \mathbf{Z}_i \boldsymbol{\gamma}))$  and  $\mathbf{V}_i = \sigma^2 \mathbf{I}_{T_i} + \sigma_b^2 \mathbf{i}_{T_i} \mathbf{i}_{T_i}^\top$ .

$$\mathbf{b}_i | \beta, \sigma^2, \gamma, \mathbf{D}, \mathbf{y}, \mathbf{X}, \mathbf{W}, \mathbf{Z} \sim N(\mathbf{b}_{ni}, \mathbf{B}_{ni}),$$

where  $\mathbf{B}_{ni} = (\sigma^{-2} \mathbf{W}_i^\top \mathbf{W}_i + \mathbf{D}^{-1})^{-1}$  and  $\mathbf{b}_{ni} = \mathbf{B}_{ni}(\sigma^{-2} \mathbf{W}_i^\top (\mathbf{y}_i - \mathbf{X}_i \beta) + \mathbf{D}^{-1} \mathbf{Z}_i \boldsymbol{\gamma})$ .

$$\sigma^2 | \beta, \mathbf{b}, \tau, \mathbf{y}, \mathbf{X}, \mathbf{W} \sim IG(\alpha_n, \delta_n),$$

where  $\alpha_n = \alpha_0 + \frac{1}{2} \sum_{i=1}^N T_i$  and  $\delta_n = \delta_0 + \frac{1}{2} \sum_{i=1}^N (\mathbf{y}_i - \mathbf{X}_i \beta - \mathbf{W}_i \mathbf{b}_i)^\top (\mathbf{y}_i - \mathbf{X}_i \beta - \mathbf{W}_i \mathbf{b}_i)$ .

$$\mathbf{D} | \mathbf{b}, \gamma, \mathbf{Z} \sim IW(d_n, \mathbf{D}_n),$$

where  $d_n = d_0 + N$  and  $\mathbf{D}_n = d_0 \mathbf{D}_0 + \sum_{i=1}^N (\mathbf{b}_i - \mathbf{Z}_i \boldsymbol{\gamma})(\mathbf{b}_i - \mathbf{Z}_i \boldsymbol{\gamma})^\top$ . And

$$\boldsymbol{\gamma} | \mathbf{b}, \mathbf{D}, \mathbf{Z} \sim N(\boldsymbol{\gamma}_n, \boldsymbol{\Gamma}_n),$$

where  $\boldsymbol{\Gamma}_n = (\sum_{i=1}^N \mathbf{Z}_i^\top \mathbf{D}^{-1} \mathbf{Z}_i + \boldsymbol{\Gamma}_0^{-1})^{-1}$  and  $\boldsymbol{\gamma}_n = \boldsymbol{\Gamma}_n(\sum_{i=1}^N \mathbf{Z}_i^\top \mathbf{D}^{-1} \mathbf{b}_i + \boldsymbol{\Gamma}_0^{-1} \boldsymbol{\gamma}_0)$ .

The following code shows how to implement this longitudinal normal model where *random effects* are correlated with regressors. We set MCMC iterations, burn-in and thinning parameters equal to 15000, 5000 and 5, respectively. In addition,  $\beta_0 = \mathbf{0}_5$ ,  $\mathbf{B}_0 = \mathbf{I}_5$ ,  $\alpha_0 = \delta_0 = 0.001$ ,  $d_0 = 2$ ,  $\mathbf{D}_0 = \mathbf{I}_2$ ,  $\boldsymbol{\gamma}_0 = \mathbf{0}_4$  and  $\boldsymbol{\Gamma}_0 = \mathbf{I}_4$ .



*R code. Simulation exercise: Longitudinal normal model with fixed effects correlated to regressors*

```

1 rm(list = ls())
2 set.seed(010101)
3 NT <- 2000
4 N <- 50
5 id <- c(1:N, sample(1:N, NT - N, replace=TRUE))
6 table(id)
7 x1 <- rnorm(NT); x2 <- rnorm(NT)
8 x3 <- rnorm(NT); z1 <- rbinom(N, 1, 0.5)
9 zdata <- NULL
10 for(i in 1:NT){
11   zdatai <- z1[id[i]]
12   zdata <- c(zdata, zdatai)
13 }
14 X <- cbind(x1, x2, x3, zdata)
15 K1 <- dim(X)[2]
16 w1 <- rnorm(NT)
17 W <- cbind(1, w1)
18 K2 <- dim(W)[2]
19 B <- c(0.5, 0.4, 0.6, -0.6, 0.7)
20 D <- c(0.7, 0.6)
21 sig2 <- 0.1
22 u <- rnorm(NT, 0, sd = sig2^0.5)
23 Z <- cbind(1, z1)
24 K3 <- dim(Z)[2]
25 G <- rep(1, K3*K2)
26 b <- matrix(0, N, K2)
27 for(i in 1:N){
28   ZGi <- t(kronecker(diag(K2), Z[i, ]))%*%G
29   b[i, ] <- MASS::mvrnorm(1, ZGi, diag(D))
30 }
31 y <- NULL
32 for(i in 1:NT){
33   yi <- X[i,]%*%B + W[i,]%*%b[id[i],] + u[i]
34   y <- c(y, yi)
35 }
36 Data <- as.data.frame(cbind(y, x1, x2, x3, zdata, w1, id))
37 mcmc <- 15000; burnin <- 5000; thin <- 10; tot <- mcmc +
   burnin
38 b0 <- rep(0, K1+1); B0 <- diag(K1+1); B0i <- solve(B0)
39 r0 <- K2; R0 <- diag(K2); a0 <- 0.001; d0 <- 0.001
40 g0 <- rep(0, K2*K3); G0 <- diag(K2*K3); G0i <- solve(G0)
41 Resultshreg <- MCMCpack::MCMChregress(fixed = y~x1 + x2 + x3
   + zdata, random = ~w1, group="id", data = Data, burnin
   = burnin, mcmc = mcmc, thin = thin,
42 mubeta = b0, Vbeta = B0, r = r0, R = R0, nu = a0, delta = d0
   )
43 Betas <- Resultshreg[["mcmc"]][,1:(K1+1)]
44 Sigma2RanEff <- Resultshreg[["mcmc"]][,c(K2*N+K1+2, 2*N+K1
   +1+K2^2)]
45 Sigma2 <- Resultshreg[["mcmc"]][,K2*N+K1+K2^2+2]
46 summary(Betas)
47 summary(Sigma2RanEff)
48 summary(Sigma2)

```

*R code. Simulation exercise: Longitudinal normal model with fixed effects correlated to regressors*

```

1 PostBeta <- function(sig2, Gamma, D){
2   XVX <- matrix(0, K1, K1)
3   XVy <- matrix(0, K1, 1)
4   for(i in 1:N){
5     ids <- which(id == i)
6     Ti <- length(ids)
7     Wi <- W[ids, ]
8     Vi <- sig2*diag(Ti) + Wi%*%D%*%t(Wi)
9     ViInv <- solve(Vi)
10    Xi <- X[ids, ]
11    XVXi <- t(Xi)%*%ViInv%*%Xi
12    XVX <- XVX + XVXi
13    Zi <- Z[i, ]
14    yi <- y[ids]
15    ZGi <- t(kronecker(diag(K2), Zi))%*%Gamma
16    XVyi <- t(Xi)%*%ViInv%*%(yi - Wi%*%ZGi)
17    XVy <- XVy + XVyi
18  }
19  Bn <- solve(B0i + XVX)
20  bn <- Bn%*%(B0i%*%b0 + XVy)
21  Beta <- MASS::mvrnorm(1, bn, Bn)
22  return(Beta)
23 }
24 Postb <- function(Beta, sig2, Gamma, D){
25   Di <- solve(D)
26   bis <- matrix(0, N, K2)
27   for(i in 1:N){
28     ids <- which(id == i)
29     Wi <- W[ids, ]
30     Xi <- X[ids, ]
31     yi <- y[ids]
32     Wtei <- sig2^(-1)*t(Wi)%*%(yi - Xi%*%Beta)
33     Bni <- solve(sig2^(-1)*t(Wi)%*%Wi + Di)
34     Zi <- Z[i, ]
35     ZGi <- t(kronecker(diag(K2), Zi))%*%Gamma
36     bni <- Bni%*%(Wtei + Di%*%ZGi)
37     bi <- MASS::mvrnorm(1, bni, Bni)
38     bis[i, ] <- bi
39   }
40   return(bis)
41 }
42 PostSig2 <- function(Beta, bs){
43   an <- a0 + 0.5*NT
44   ete <- 0
45   for(i in 1:N){
46     ids <- which(id == i)
47     Xi <- X[ids, ]
48     yi <- y[ids]
49     Wi <- W[ids, ]
50     ei <- yi - Xi%*%Beta - Wi%*%bs[i, ]
51     etei <- t(ei)%*%ei
52     ete <- ete + etei
53   }
54   dn <- d0 + 0.5*ete
55   sig2 <- MCMCpack::rinvgamma(1, shape = an, scale = dn)
56   return(sig2)
57 }

```

*R code. Simulation exercise: Longitudinal normal model with fixed effects correlated to regressors*

```

1 PostGamma <- function(bs, D){
2   Di <- solve(D)
3   ZDZ <- matrix(0, K2*K3, K2*K3)
4   ZDb <- matrix(0, K2*K3, 1)
5   for(i in 1:N){
6     Zi <- Z[i, ]
7     ZZi <- t(kronecker(diag(K2), Zi))
8     ZDZi <- t(ZZi)%*%Di%*%ZZi
9     ZDZ <- ZDZ + ZDZi
10    bi <- bs[i,]
11    ZDbi <- t(ZZi)%*%Di%*%bi
12    ZDb <- ZDb + ZDbi
13  }
14  Gn <- solve(G0i + ZDZ); gn <- Gn%*%(G0i%*%g0 + ZDb)
15  Gamma <- MASS::mvrnorm(1, gn, Gn)
16  return(Gamma)
17 }
18 PostD <- function(bs, Gamma){
19   rn <- r0 + N
20   btb <- matrix(0, K2, K2)
21   for(i in 1:N){
22     bsi <- bs[i, ]
23     Zi <- Z[i, ]
24     ZGi <- t(kronecker(diag(K2), Zi))%*%Gamma
25     btbi <- (bsi-ZGi)%*%t(bsi-ZGi)
26     btb <- btb + btbi
27   }
28   Rn <- d0*R0 + btb
29   Sigma <- MCMCpack::riwish(v = rn, S = Rn)
30   return(Sigma)
31 }
32 PostBetas <- matrix(0, tot, K1); PostGammas <- matrix(0, tot,
33   , K2*K3)
34 PostDs <- matrix(0, tot, K2*(K2+1)/2); PostSig2s <- rep(0,
35   tot)
36 Postbs <- array(0, c(N, K2, tot)); RegLS <- lm(y ~ X - 1)
37 SumLS <- summary(RegLS); Beta <- SumLS[["coefficients"]][,1]
38 sig2 <- SumLS[["sigma"]]2; Gamma <- rep(0, K2*K3)
39 D <- diag(K2); b0 <- rep(0, K1); B0 <- diag(K1); B0i <-
40   solve(B0)
41 pb <- winProgressBar(title = "progress bar", min = 0, max =
42   tot, width = 300)
43 for(s in 1:tot){
44   bs <- Postb(Beta = Beta, sig2 = sig2, Gamma = Gamma, D = D)
45   D <- PostD(bs = bs, Gamma = Gamma)
46   Beta <- PostBeta(sig2 = sig2, Gamma = Gamma, D = D)
47   sig2 <- PostSig2(Beta = Beta, bs = bs)
48   Gamma <- PostGamma(bs = bs, D = D)
49   PostBetas[s,] <- Beta; PostDs[s,] <- matrixcalc::vech(D)
50   PostSig2s[s] <- sig2; Postbs[, , s] <- bs
51   PostGammas[s,] <- Gamma
52   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
53     "% done"))
54 }

```

***R code. Simulation exercise: Longitudinal normal model with fixed effects correlated to regressors***

```

1 close(pb)
2 keep <- seq((burnin+1), tot, thin)
3 Bs <- PostBetas[keep,]
4 Ds <- PostDs[keep,]
5 bs <- Postbs[, , keep]
6 sig2s <- PostSig2s[keep]
7 Gs <- PostGammas[keep, ]
8 summary(coda::mcmc(Bs))
9 Quantiles for each variable:
10      2.5%      25%      50%      75%      97.5%
11 var1  0.3629  0.3812  0.3880  0.3945  0.4120
12 var2  0.5844  0.6032  0.6098  0.6176  0.6381
13 var3 -0.6114 -0.5950 -0.5880 -0.5809 -0.5605
14 var4 -0.4455  0.4155  0.8598  1.3047  2.0654
15 summary(coda::mcmc(Ds))
16 Quantiles for each variable:
17      2.5%      25%      50%      75%      97.5%
18 var1  0.5858  0.7798  0.9173  1.13381  2.0153
19 var2 -0.3914 -0.1901 -0.1104 -0.03585  0.1250
20 var3  0.4285  0.5495  0.6314  0.72342  0.9662
21 summary(coda::mcmc(sig2s))
22 Quantiles for each variable:
23 Quantiles for each variable:
24      2.5%      25%      50%      75%      97.5%
25 0.09609 0.11486 0.17790 0.35215 1.12537
26 summary(coda::mcmc(Gs))
27 Quantiles for each variable:
28      2.5%      25%      50%      75%      97.5%
29 var1  0.6552  0.8998  1.0288  1.162  1.402
30 var2 -0.4463  0.4056  0.7882  1.242  2.144
31 var3  0.8583  1.0599  1.1623  1.271  1.482
32 var4  0.5525  0.8430  1.0038  1.147  1.416

```

In one hand, the 95% credible intervals of the model without taking into account the dependence between the *random effects* and  $z_{i1}$  overestimates the posterior mean of  $\beta_4$  and the variance of  $b_{i1}$ . In addition, the credible intervals are very narrow. However, the variance of  $\mu_i$  is well estimated. On the other hand, all the 95% credible intervals of the model taking into account the dependence between the *random effects* and  $z_{i1}$  encompass the population parameters. However, there is a lot of variability in  $\beta_4$  posterior estimates. The posterior mean estimate of the variance of  $b_{i1}$  is close to the population value, and the location parameters associated with  $z_{i1}$  in the mean of the *random effects* are also well estimated by the posterior mean. However, the variance of the model is overestimated.

**4. Doctor visits in Germany continues I**

Replicate this example using our GUI, which by default does not fix the over-dispersion parameter ( $\sigma^2$ ), and compare the results with the results of this example in Section 9.2.

**Answer**

This code replicates what we get using our GUI.

*R code. Doctor visits in Germany, results*

```

1 rm(list = ls())
2 set.seed(12345)
3 Data <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/9VisitDoc.csv",
  sep = ",", header = TRUE, quote = "\"")
4 attach(Data)
5 K1 <- 7; K2 <- 2; N <- 9197
6 b0 <- rep(0, K1); B0 <- diag(K1)
7 r0 <- 5; R0 <- diag(K2)
8 a0 <- 0.001; d0 <- 0.001
9 RegLogit <- glm(DocVis ~ Age + Male + Sport + LogInc +
  GoodHealth + BadHealth, family = binomial(link = "logit"
  ))
10 SumLogit <- summary(RegLogit)
11 Beta0 <- SumLogit[["coefficients"]][,1]
12 mcmc <- 10000; burnin <- 1000; thin <- 10
13 # MCMChlogit
14 Resultshlogit <- MCMCpack::MCMChlogit(fixed = DocVis ~ Age +
  Male + Sport + LogInc + GoodHealth + BadHealth, random
  = ~Sozh, group="id", data = Data, burnin = burnin, mcmc
  = mcmc, thin = thin, mubeta = b0, Vbeta = B0, r = r0, R
  = R0, nu = a0, delta = d0, beta.start = Beta0, FixOD =
  0)
15 Betas <- Resultshlogit[["mcmc"]][,1:K1]
16 Sigma2RanEff <- Resultshlogit[["mcmc"]][,c(K2*N+K1+1, 2*N+K1
  +K2^2)]
17 summary(Betas)
18 summary(Sigma2RanEff)
19 summary(Sigma2)
20 Quantiles for each variable:
21      2.5%      25%      50%      75%      97.5%
22 Intercept -9.48e-01 -5.27e-01 -2.86e-01 -6.28e-02 2.99e-01
23 Age        4.88e-03 7.27e-03 8.35e-03 9.31e-03 1.09e-02
24 Male      -9.90e-01 -9.52e-01 -9.31e-01 -9.10e-01 -8.75e-01
25 Sport      1.80e-01 2.25e-01 2.55e-01 2.85e-01 3.47e-01
26 LogInc     1.38e-01 1.85e-01 2.15e-01 2.49e-01 3.01e-01
27 GoodHealth -9.56e-01 -9.18e-01 -8.97e-01 -8.75e-01 -8.36e-01
28 BadHealth  1.08e+00 1.14e+00 1.19e+00 1.23e+00 1.28e+00
29 D11        1.43e+00 1.53e+00 1.58e+00 1.62e+00 1.70e+00
30 D21       -2.67e-01 1.94e-02 1.85e-01 4.08e-01 5.81e-01
31 D12       -2.67e-01 1.94e-02 1.85e-01 4.08e-01 5.81e-01
32 D22        6.05e-01 7.99e-01 9.75e-01 1.21e+00 1.62e+00
33 sigma2     6.37e-02 7.76e-02 1.01e-01 1.15e-01 1.58e-01

```

We see in this example running our GUI that we get qualitatively same results as the results fixing the over-dispersion parameter in Section 9.2 in the book. However, there small numerical differences in the *fixed effects*,

and the differences are greater in the posterior results of the covariance matrix of the *random effects*.

### 5. Simulation exercise of the longitudinal logit model

Perform a simulation exercise to assess the performance of the hierarchical longitudinal logit model. The point of departure is to assume that  $y_{it}^* = \beta_0 + \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 x_{it3} + b_i + w_{it1} b_{i1}$  where  $x_{itk} \sim N(0, 1)$ ,  $k = 1, 2, 3$ ,  $w_{it1} \sim N(0, 1)$ ,  $b_i \sim N(0, 0.7^{1/2})$ ,  $b_{i1} \sim N(0, 0.6^{1/2})$ ,  $\beta = [0.5 \ 0.4 \ 0.6 \ -0.6]^\top$ ,  $i = 1, 2, \dots, 50$ , and  $y_{it} \sim B(\pi_{it})$ , where  $\pi_{it} = 1/(1 + \exp(-y_{it}^*))$ . The sample size is 1000 in an *unbalanced panel structure*.

- Perform inference using the command *MCMChlogit* fixing the over-dispersion parameter, and using  $\beta_0 = \mathbf{0}_4$ ,  $\mathbf{B}_0 = \mathbf{I}_4$ ,  $\alpha_0 = \delta_0 = 0.001$ ,  $d_0 = 2$  and  $\mathbf{D}_0 = \mathbf{I}_2$ .
- Program from scratch a Metropolis-within-Gibbs algorithm to perform inference in this simulation.

### Answer

The following code shows the simulation setting, and the results using the *MCMChlogit* command. We see that all posterior estimates encompass the population values.

*R code. Simulation exercise: Hierarchical longitudinal logit model using MCMChlogit*

```

1 rm(list = ls()); set.seed(010101)
2 NT <- 1000; N <- 50
3 id <- c(1:N, sample(1:N, NT - N, replace=TRUE))
4 x1 <- rnorm(NT); x2 <- rnorm(NT); x3 <- rnorm(NT)
5 X <- cbind(1, x1, x2, x3); K1 <- dim(X)[2]
6 w1 <- rnorm(NT); W <- cbind(1, w1); K2 <- dim(W)[2]
7 B <- c(0.5, 0.4, 0.6, -0.6); D <- c(0.7, 0.6)
8 sig2 <- 0.1
9 b1 <- rnorm(N, 0, sd = D[1]^0.5)
10 b2 <- rnorm(N, 0, sd = D[2]^0.5)
11 b <- cbind(b1, b2)
12 yl <- NULL
13 for(i in 1:NT){
14   ylmeani <- X[i,]%*%B + W[i,]%*%b[id[i],]
15   yli <- rnorm(1, ylmeani, sig2^0.5)
16   yl <- c(yl, yli)
17 }
18 pit <- 1/(1+exp(-yl))
19 y <- rbinom(NT, 1, prob = pit)
20 Data <- as.data.frame(cbind(y, x1, x2, x3, w1, id))
21 mcmc <- 15000; burnin <- 5000; thin <- 10; tot <- mcmc +
   burnin
22 b0 <- rep(0, K1); B0 <- diag(K1); B0i <- solve(B0)
23 r0 <- K2; R0 <- diag(K2); a0 <- 0.001; d0 <- 0.001
24 RegLogit <- glm(y ~ X - 1, family = binomial(link = "logit")
   )
25 SumLogit <- summary(RegLogit)
26
27 Beta0 <- SumLogit[["coefficients"]][,1]
28 sig20 <- sum(SumLogit[["deviance.resid"]]^2)/SumLogit[["df.
   residual"]]
29 Resultshlogit <- MCMCpack::MCMChlogit(fixed = y~x1 + x2 + x3
   , random = ~w1, group="id", data = Data, burnin = burnin
   , mcmc = mcmc, thin = thin,
30   mubeta = b0, Vbeta = B0, r = r0, R = R0, nu = a0, delta = d0
   ,
31   beta.start = Beta0, FixOD = 1, sigma2.start = sig20)
32 Betas <- Resultshlogit[["mcmc"]][,1:K1]
33 Sigma2RanEff <- Resultshlogit[["mcmc"]][,c(K2*N+K1+1, 2*N+K1
   +K2^2)]
34 Sigma2 <- Resultshlogit[["mcmc"]][,K2*N+K1+K2^2+1]
35 summary(Betas)
36 Quantiles for each variable:
37      2.5%      25%      50%      75%      97.5%
38 beta.(Intercept)  0.4258  0.6165  0.7140  0.8155  1.0041
39 beta.x1           0.3294  0.4372  0.4999  0.5617  0.6684
40 beta.x2           0.5555  0.6763  0.7388  0.8062  0.9377
41 beta.x3          -0.9327 -0.7957 -0.7276 -0.6591 -0.5383
42 summary(Sigma2RanEff)
43 Quantiles for each variable:
44      2.5%      25%      50%      75% 97.5%
45 D11 0.3394 0.5366 0.6962 0.8652 1.338
46 D22 0.4101 0.6478 0.8091 1.0039 1.611

```



The following code shows the algorithm step by step.

***R code. Simulation exercise: Hierarchical longitudinal logit model from scratch***

```

1 LatentMHV1 <- function(tuning, Beta, bs, sig2){
2   ylhat <- rep(0, NT)
3   accept <- NULL
4   for(i in 1:NT){
5     ids <- which(id == i)
6     yi <- y[i]
7     ylhatmean1 <- X[i,]%*Beta + W[i,]%*bs[id[i],]
8     ylhati <- rnorm(1, ylhatmean1, sd = sig2^0.5)
9     pihati <- 1/(1+exp(-ylhati))
10    ei <- rnorm(1, 0, sd = tuning)
11    ylpropi <- ylhati + ei; pipropi <- 1/(1+exp(-ylpropi))
12    logPosthati <- sum(dbinom(yi, 1, prob = pihati, log =
13    TRUE) + dnorm(ylhati, ylhatmean1, sig2^0.5, log = TRUE))
14    logPostpropi <- sum(dbinom(yi, 1, prob = pipropi, log =
15    TRUE) + dnorm(ylpropi, ylhatmean1, sig2^0.5, log = TRUE)
16    )
17    alphai <- min(1, exp(logPostpropi - logPosthati))
18    ui <- runif(1)
19    if(ui <= alphai){
20      ylhati <- ylpropi; accepti <- 1
21    }else{
22      ylhati <- ylhati; accepti <- 0
23    }
24    ylhat[i] <- ylhati; accept <- c(accept, accepti)
25  }
26  res <- list(ylhat = ylhat, accept = mean(accept))
27  return(res)
28 }
29
30 PostBeta <- function(D, ylhat, sig2){
31   XVX <- matrix(0, K1, K1); XVy <- matrix(0, K1, 1)
32   for(i in 1:N){
33     ids <- which(id == i); Ti <- length(ids)
34     Wi <- W[ids, ]; Vi <- diag(Ti)*sig2 + Wi%*D%*t(Wi)
35     ViInv <- solve(Vi); Xi <- X[ids, ]
36     XVXi <- t(Xi)%*ViInv%*Xi; XVX <- XVX + XVXi
37     yi <- ylhat[ids]; XVyi <- t(Xi)%*ViInv%*yi
38     XVy <- XVy + XVyi
39   }
40   Bn <- solve(B0i + XVX)
41   bn <- Bn%*(B0i%*b0 + XVy)
42   Beta <- MASS::mvrnorm(1, bn, Bn)
43   return(Beta)
44 }
45
46 Postb <- function(Beta, D, ylhat, sig2){
47   Di <- solve(D); bis <- matrix(0, N, K2)
48   for(i in 1:N){
49     ids <- which(id == i)
50     Wi <- W[ids, ]; Xi <- X[ids, ]
51     yi <- ylhat[ids]
52     Wtei <- sig2^(-1)*t(Wi)%*(yi - Xi%*Beta)
53     Bni <- solve(sig2^(-1)*t(Wi)%*Wi + Di)
54     bni <- Bni%*Wtei; bi <- MASS::mvrnorm(1, bni, Bni)
55     bis[i, ] <- bi
56   }
57   return(bis)
58 }

```

***R code. Simulation exercise: Hierarchical longitudinal logit model from scratch***

```

1 PostD <- function(bs){
2   rn <- r0 + N
3   btb <- matrix(0, K2, K2)
4   for(i in 1:N){
5     bsi <- bs[i, ]; btb_i <- bsi%*%t(bsi)
6     btb <- btb + btb_i
7   }
8   Rn <- d0*R0 + btb
9   Sigma <- MCMCpack::riwish(v = rn, S = Rn)
10  return(Sigma)
11 }
12 PostSig2 <- function(Beta, bs, ylhat, ss){
13   an <- a0 + 0.5*NT; ete <- 0
14   for(i in 1:N){
15     ids <- which(id == i)
16     Xi <- X[ids, ]; yi <- ylhat[ids]
17     Wi <- W[ids, ]
18     ei <- yi - Xi%*%Beta - Wi%*%bs[i, ]
19     etei <- t(ei)%*%ei; ete <- ete + etei
20   }
21   dn <- d0 + 0.5*ete
22   sig2 <- MCMCpack::rinvgamma(1, shape = an, scale = dn)
23   if(sig2 > ss){
24     sig2 <- ss
25   }else{
26     sig2 <- sig2
27   }
28   return(sig2)
29 }
30 PostBetas <- matrix(0, tot, K1)
31 PostDs <- matrix(0, tot, K2*(K2+1)/2)
32 Postbs <- array(0, c(N, K2, tot))
33 PostSig2s <- rep(0, tot)
34 Accepts <- rep(NULL, tot)
35 RegLogit <- glm(y ~ X - 1, family = binomial(link = "logit")
36 )
37 SumLogit <- summary(RegLogit)
38 Beta <- SumLogit[["coefficients"]][,1]
39 sig2 <- sum(SumLogit[["deviance.resid"]]^2)/SumLogit[["df.
40 residual"]]
41 ss0 <- sig2; D <- diag(K2)
42 bs1 <- rnorm(N, 0, sd = D[1]^0.5)
43 bs2 <- rnorm(N, 0, sd = D[2]^0.5)
44 bs <- cbind(bs1, bs2)
45 tuning <- 0.1; ropt <- 0.44
46 tuneapariter <- seq(round(tot/10, 0), tot, round(tot/10, 0));
47   l <- 1
48 pb <- winProgressBar(title = "progress bar", min = 0, max =
49   tot, width = 300)

```

*R code. Simulation exercise: Hierarchical longitudinal logit model from scratch*

```

1 for(s in 1:tot){
2   LatY <- LatentMHV1(tuning = tuning, Beta = Beta, bs = bs,
3     sig2 = sig2)
4   ylhat <- LatY[["ylhat"]]
5   bs <- Postb(Beta = Beta, D = D, ylhat = ylhat, sig2 = sig2
6     )
7   D <- PostD(bs = bs)
8   Beta <- PostBeta(D = D, ylhat = ylhat, sig2 = sig2)
9   sig2 <- PostSig2(Beta = Beta, bs = bs, ylhat = ylhat, ss =
10     ss0)
11   PostBetas[s,] <- Beta
12   PostDs[s,] <- matrixcalc::vech(D)
13   Postbs[, , s] <- bs
14   PostSig2s[s] <- sig2
15   AcceptRate <- LatY[["accept"]]
16   Accepts[s] <- AcceptRate
17   if(AcceptRate > ropt){
18     tuning = tuning*(2-(1-AcceptRate)/(1-ropt))
19   }else{
20     tuning = tuning/(2-AcceptRate/ropt)
21   }
22   if(s == tunepariter[1]){
23     print(AcceptRate)
24     l <- l + 1
25   }
26   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
27     "% done"))
28 }
29 close(pb)
30 keep <- seq((burnin+1), tot, thin)
31 Bs <- PostBetas[keep,]
32 Ds <- PostDs[keep,]
33 bs <- Postbs[, , keep]
34 sig2s <- PostSig2s[keep]
35 summary(coda::mcmc(Bs))
36 Quantiles for each variable:
37   2.5%   25%   50%   75%   97.5%
38 var1  0.3195  0.5266  0.6325  0.7452  0.9427
39 var2  0.1780  0.3563  0.4521  0.5436  0.7352
40 var3  0.3596  0.5197  0.6140  0.7165  0.9149
41 var4 -0.8994 -0.7153 -0.6125 -0.5135 -0.3240
42 summary(coda::mcmc(Ds))
43 Quantiles for each variable:
44   2.5%   25%   50%   75%   97.5%
45 var1  0.0002003  0.0007473  0.0022547  0.0124378  0.09575
46 var2 -0.0534437 -0.0029207 -0.0001433  0.0009905  0.02296
47 var3  0.0002150  0.0009101  0.0026712  0.0119391  0.14863
48 summary(coda::mcmc(sig2s))
49 Quantiles for each variable:
50   2.5%   25%   50%   75%   97.5%
51 0.1321  0.5174  0.8674  1.0788  1.1909

```

The 95% credible intervals of the *fixed effects* encompass all the population values. However, we do not get good posterior estimates of the covariance matrix and over-dispersion parameters.

#### 6. Doctor visits in Germany continues II

Take a sub-sample of the first 500 individuals of the dataset *9VisitDoc.csv* to perform inference in the number of visits to doctors (*DocNum*) with the same specification of the example of **Doctor visits in Germany** of Section 9.2.

##### **Answer**

This algorithm shows how to perform inference in this application programming from scratch the algorithm.

### *R code. Doctor visits in Germany: Hierarchical longitudinal Poisson model from scratch*

```

1 rm(list = ls())
2 set.seed(12345)
3 Data <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/9VisitDoc.csv",
  sep = ",", header = TRUE, quote = "")
4 library(dplyr)
5 Data <- Data %>%
6 filter(id <= 500)
7 attach(Data)
8 K1 <- 7; K2 <- 2; N <- 9197
9 b0 <- rep(0, K1); B0 <- diag(K1)
10 r0 <- 5; R0 <- diag(K2)
11 a0 <- 0.001; d0 <- 0.001
12 NT <- dim(Data)[1]
13 N <- length(unique(id))
14 X <- cbind(1, Age, Male, Sport, LogInc, GoodHealth,
  BadHealth)
15 K1 <- dim(X)[2]
16 W <- cbind(1, Sozh)
17 K2 <- dim(W)[2]
18 y <- DocNum
19 mcmc <- 15000; burnin <- 5000; thin <- 10; tot <- mcmc +
  burnin
20 b0 <- rep(0, K1); B0 <- diag(K1); B0i <- solve(B0)
21 r0 <- K2; R0 <- diag(K2); a0 <- 0.001; d0 <- 0.001
22 LatentMHV1 <- function(tuning, Beta, bs, sig2){
23   ylhat <- rep(0, NT)
24   accept <- NULL
25   for(i in 1:NT){
26     ids <- which(id == i)
27     yi <- y[ids]
28     ylhatmean1 <- X[ids,]%*%Beta + W[ids,]%*%bs[id[ids],]
29     ylhati <- rnorm(1, ylhatmean1, sd = sig2^0.5)
30     lambdahati <- exp(ylhati)
31     ei <- rnorm(1, 0, sd = tuning)
32     ylpropi <- ylhati + ei
33     lambdapropi <- exp(ylpropi)
34     logPosthati <- sum(dpois(yi, lambdahati, log = TRUE) +
35       dnorm(ylhati, ylhatmean1, sig2^0.5, log = TRUE))
36     logPostpropi <- sum(dpois(yi, lambdapropi, log = TRUE) +
37       dnorm(ylpropi, ylhatmean1, sig2^0.5, log = TRUE))
38     alphai <- min(1, exp(logPostpropi - logPosthati))
39     ui <- runif(1)
40     if(ui <= alphai){
41       ylhati <- ylpropi; accepti <- 1
42     }else{
43       ylhati <- ylhati; accepti <- 0
44     }
45     ylhat[i] <- ylhati
46     accept <- c(accept, accepti)
47   }
48   res <- list(ylhat = ylhat, accept = mean(accept))
49   return(res)
50 }

```

*R code. Doctor visits in Germany: Hierarchical longitudinal Poisson model from scratch*

```

1 PostBeta <- function(D, ylhat, sig2){
2   XVX <- matrix(0, K1, K1); XVy <- matrix(0, K1, 1)
3   for(i in 1:N){
4     ids <- which(id == i); Ti <- length(ids)
5     Wi <- matrix(W[ids, ], Ti, K2)
6     Vi <- diag(Ti)*sig2 + Wi%*%D%*%t(Wi)
7     ViInv <- solve(Vi); Xi <- matrix(X[ids, ], Ti, K1)
8     XVXi <- t(Xi)%*%ViInv%*%Xi
9     XVX <- XVX + XVXi; yi <- ylhat[ids]
10    XVyi <- t(Xi)%*%ViInv%*%yi; XVy <- XVy + XVyi
11  }
12  Bn <- solve(B0i + XVX); bn <- Bn%*%(B0i%*%b0 + XVy)
13  Beta <- MASS::mvrnorm(1, bn, Bn)
14  return(Beta)
15 }
16 Postb <- function(Beta, D, ylhat, sig2){
17   Di <- solve(D); bis <- matrix(0, N, K2)
18   for(i in 1:N){
19     ids <- which(id == i); Ti <- length(ids)
20     Wi <- matrix(W[ids, ], Ti, K2)
21     Xi <- matrix(X[ids, ], Ti, K1)
22     yi <- ylhat[ids]
23     Wtei <- sig2^(-1)*t(Wi)%*%(yi - Xi%*%Beta)
24     Bni <- solve(sig2^(-1)*t(Wi)%*%Wi + Di)
25     bni <- Bni%*%Wtei
26     bi <- MASS::mvrnorm(1, bni, Bni)
27     bis[i, ] <- bi
28   }
29   return(bis)
30 }
31 PostD <- function(bs){
32   rn <- r0 + N; btb <- matrix(0, K2, K2)
33   for(i in 1:N){
34     bsi <- bs[i, ]; btbi <- bsi%*%t(bsi)
35     btb <- btb + btbi
36   }
37   Rn <- d0*R0 + btb; Sigma <- MCMCpack::riwish(v = rn, S =
38     Rn)
39   return(Sigma)
40 }
41 PostSig2 <- function(Beta, bs, ylhat){
42   an <- a0 + 0.5*NT; ete <- 0
43   for(i in 1:N){
44     ids <- which(id == i)
45     Ti <- length(ids)
46     Xi <- matrix(X[ids, ], Ti, K1); yi <- ylhat[ids]
47     Wi <- matrix(W[ids, ], Ti, K2)
48     ei <- yi - Xi%*%Beta - Wi%*%bs[i, ]
49     etei <- t(ei)%*%ei; ete <- ete + etei
50   }
51   dn <- d0 + 0.5*ete
52   sig2 <- MCMCpack::rinvgamma(1, shape = an, scale = dn)
53   return(sig2)
54 }

```

### *R code. Doctor visits in Germany: Hierarchical longitudinal Poisson model from scratch*

```

1 PostBetas <- matrix(0, tot, K1)
2 PostDs <- matrix(0, tot, K2*(K2+1)/2)
3 Postbs <- array(0, c(N, K2, tot))
4 PostSig2s <- rep(0, tot); ccepts <- rep(NULL, tot)
5 RegPois <- glm(DocNum ~ Age + Male + Sport + LogInc +
  GoodHealth + BadHealth, family = poisson(link = "log"))
6 SumPois <- summary(RegPois)
7 Beta <- SumPois[["coefficients"]][,1]
8 sig2 <- sum(SumPois[["deviance.resid"]]2)/SumPois[["df.
  residual"]]
9 D <- diag(K2)
10 bs1 <- rnorm(N, 0, sd = D[1,1]0.5)
11 bs2 <- rnorm(N, 0, sd = D[2,2]0.5)
12 bs <- cbind(bs1, bs2); tuning <- 0.1; ropt <- 0.44
13 tuneapariter <- seq(round(tot/10, 0), tot, round(tot/10, 0));
  l <- 1
14 pb <- winProgressBar(title = "progress bar", min = 0, max =
  tot, width = 300)
15 for(s in 1:tot){
16   LatY <- LatentMHV1(tuning = tuning, Beta = Beta, bs = bs,
    sig2 = sig2)
17   ylhat <- LatY[["ylhat"]]
18   bs <- Postb(Beta = Beta, D = D, ylhat = ylhat, sig2 = sig2
    )
19   D <- PostD(bs = bs)
20   Beta <- PostBeta(D = D, ylhat = ylhat, sig2 = sig2)
21   sig2 <- PostSig2(Beta = Beta, bs = bs, ylhat = ylhat)
22   PostBetas[s,] <- Beta; PostDs[s,] <- matrixcalc::vech(D)
23   Postbs[, , s] <- bs; PostSig2s[s] <- sig2
24   AcceptRate <- LatY[["accept"]]; Accepts[s] <- AcceptRate
25   if(AcceptRate > ropt){
26     tuning = tuning*(2-(1-AcceptRate)/(1-ropt))
27   }else{
28     tuning = tuning/(2-AcceptRate/ropt)
29   }
30   if(s == tuneapariter[l]){
31     print(AcceptRate)
32     l <- l + 1
33   }
34   setWinProgressBar(pb, s, title=paste( round(s/tot*100, 0),
    "% done"))
35 }
36 close(pb)
37 keep <- seq((burnin+1), tot, thin)
38 Bs <- PostBetas[keep,]; Ds <- PostDs[keep,]
39 bs <- Postbs[, , keep]; sig2s <- PostSig2s[keep]
40 summary(coda::mcmc(Bs))
41 Quantiles for each variable:
42 2.5%      25%      50%      75%      97.5%
43 var1 -1.250036 -0.269211  0.1995811  0.69139  1.59234
44 var2 -0.001542  0.004852  0.0083935  0.01147  0.01815
45 var3 -0.484097 -0.331748 -0.2586891 -0.19011 -0.04787
46 var4 -0.023677  0.123336  0.1973927  0.26883  0.41314
47 var5 -0.196732 -0.071421 -0.0001036  0.06601  0.19356
48 var6 -0.815499 -0.657182 -0.5784964 -0.49969 -0.36882
49 var7  0.613990  0.799534  0.8982645  1.00161  1.18880

```



We see that males with good perception of health status visit less frequently the physicians, and women with bad perception of health status visit more frequently the physicians.



# 10

## Bayesian model average

### 10.1 Solutions of Exercises

- The Gaussian linear model specifies  $\mathbf{y} = \alpha \mathbf{i}_N + \mathbf{X}_m \boldsymbol{\beta}_m + \boldsymbol{\mu}_m$  such that  $\boldsymbol{\mu}_m \sim N(\mathbf{0}, \sigma^2 \mathbf{I}_n)$ , and  $\mathbf{X}_m$  does not have the column of ones. Assuming that  $\pi(\sigma^2) \propto 1/\sigma^2$ ,  $\pi(\alpha) \propto 1$ , and  $\boldsymbol{\beta}_m | \sigma^2 \sim N(\mathbf{0}_{k_m}, \sigma^2 (g_m \mathbf{X}_m^\top \mathbf{X}_m)^{-1})$ .
  - Show that the conditional posterior distribution of  $\boldsymbol{\beta}_m$  is  $N(\boldsymbol{\beta}_{mn}, \sigma^2 \mathbf{B}_{mn})$ , where  $\boldsymbol{\beta}_{mn} = \mathbf{B}_{mn} \mathbf{X}_m^\top \mathbf{y}$  and  $\mathbf{B}_{mn} = ((1 + g_m) \mathbf{X}_m^\top \mathbf{X}_m)^{-1}$ .
  - Show that the marginal the marginal likelihood associated with model  $\mathcal{M}_m$  is proportional to

$$p(\mathbf{y} | \mathcal{M}_m) \propto \left( \frac{g_m}{1 + g_m} \right)^{k_m/2} \left[ (\mathbf{y} - \bar{y} \mathbf{i}_N)^\top (\mathbf{y} - \bar{y} \mathbf{i}_N) - \frac{1}{1 + g_m} (\mathbf{y}^\top \mathbf{P}_{X_m} \mathbf{y}) \right]^{-(N-1)/2},$$

where all parameter are indexed to model  $\mathcal{M}_m$ ,  $\mathbf{P}_{X_m} = \mathbf{X}_m (\mathbf{X}_m^\top \mathbf{X}_m)^{-1} \mathbf{X}_m$  is the projection matrix on the space generated by the columns of  $\mathbf{X}_m$ , and  $\bar{y}$  is the sample mean of  $\mathbf{y}$ .

Hint: Take into account that  $\mathbf{i}_N^\top \mathbf{X}_m = \mathbf{0}_{k_m}$  due to all columns being centered with respect to their means.

#### Answer

The marginal likelihood of this model is

$$\begin{aligned} p(\mathbf{y}) &= \int_0^\infty \int_{R^K} \int_R \pi(\boldsymbol{\beta} | \sigma^2) \pi(\sigma^2) \pi(\alpha) p(\mathbf{y} | \boldsymbol{\beta}, \sigma^2, \alpha) d\alpha d\boldsymbol{\beta} d\sigma^2 \\ &\propto \int_0^\infty \int_{R^K} \int_R (\sigma^2)^{-k_m/2} |g_m \mathbf{X}_m^\top \mathbf{X}_m|^{1/2} \exp \left\{ -\frac{1}{2\sigma^2} (\boldsymbol{\beta}^\top (g_m \mathbf{X}_m^\top \mathbf{X}_m) \boldsymbol{\beta}) \right\} (\sigma^2)^{-1} \\ &\quad \times (\sigma^2)^{-N/2} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y} - \alpha \mathbf{i}_N - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \alpha \mathbf{i}_N - \mathbf{X}_m \boldsymbol{\beta}) \right\} d\alpha d\boldsymbol{\beta} d\sigma^2. \end{aligned}$$

Taking into account that  $(\mathbf{y} - \alpha \mathbf{i}_N - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \alpha \mathbf{i}_N - \mathbf{X}_m \boldsymbol{\beta}) = (\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta}) + N(\alpha - \bar{y})^2 - N\bar{y}^2$ ,

$$\begin{aligned}
p(\mathbf{y}) &\propto \int_0^\infty \int_{R^K} (\sigma^2)^{-k_m/2} |g_m \mathbf{X}_m^\top \mathbf{X}_m|^{1/2} \exp \left\{ -\frac{1}{2\sigma^2} (\boldsymbol{\beta}^\top (g_m \mathbf{X}_m^\top \mathbf{X}_m) \boldsymbol{\beta}) \right\} (\sigma^2)^{-1} \\
&\quad \times (\sigma^2)^{-N/2} \exp \left\{ -\frac{1}{2\sigma^2} [(\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta}) - N\bar{y}^2] \right\} \\
&\quad \times \int_R \exp \left\{ -\frac{1}{2\sigma^2} (N(\alpha - \bar{y})^2) \right\} d\alpha d\boldsymbol{\beta} d\sigma^2.
\end{aligned}$$

The last term is the kernel of a normal density function with mean  $\bar{y}$  and variance  $\sigma^2/N$ , then

$$\begin{aligned}
p(\mathbf{y}) &\propto \int_0^\infty \int_{R^K} (\sigma^2)^{-k_m/2} |g_m \mathbf{X}_m^\top \mathbf{X}_m|^{1/2} \exp \left\{ -\frac{1}{2\sigma^2} (\boldsymbol{\beta}^\top (g_m \mathbf{X}_m^\top \mathbf{X}_m) \boldsymbol{\beta}) \right\} (\sigma^2)^{-1} \\
&\quad \times (\sigma^2)^{-N/2} (\sigma^2)^{1/2} \exp \left\{ -\frac{1}{2\sigma^2} [(\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta}) - N\bar{y}^2] \right\} d\boldsymbol{\beta} d\sigma^2.
\end{aligned}$$

Collecting terms for  $\boldsymbol{\beta}$ , we have  $(\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta})^\top (\mathbf{y} - \mathbf{X}_m \boldsymbol{\beta}) - N\bar{y}^2 + \boldsymbol{\beta}^\top (g_m \mathbf{X}_m^\top \mathbf{X}_m) \boldsymbol{\beta} = (\boldsymbol{\beta} - \boldsymbol{\beta}_{mn})^\top \mathbf{B}_{mn}^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_{mn}) + \mathbf{y}^\top \mathbf{y} - N\bar{y}^2 - \boldsymbol{\beta}_{mn}^\top \mathbf{B}_{mn} \boldsymbol{\beta}_{mn}$  where  $\boldsymbol{\beta}_{mn} = \mathbf{B}_{mn} \mathbf{X}_m^\top \mathbf{y}$  and  $\mathbf{B}_{mn} = ((1 + g_m) \mathbf{X}_m^\top \mathbf{X}_m)^{-1}$ . Then,

$$\begin{aligned}
p(\mathbf{y}) &\propto \int_0^\infty (\sigma^2)^{-k_m/2} |g_m \mathbf{X}_m^\top \mathbf{X}_m|^{1/2} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y}^\top \mathbf{y} - N\bar{y}^2 - \boldsymbol{\beta}_{mn}^\top \mathbf{B}_{mn} \boldsymbol{\beta}_{mn}) \right\} (\sigma^2)^{-1} \\
&\quad \times (\sigma^2)^{-N/2} (\sigma^2)^{1/2} \int_{R^K} \exp \left\{ -\frac{1}{2\sigma^2} (\boldsymbol{\beta} - \boldsymbol{\beta}_{mn})^\top \mathbf{B}_{mn}^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_{mn}) \right\} d\boldsymbol{\beta} d\sigma^2.
\end{aligned}$$

The last term is the kernel of a multivariate normal density with mean  $\boldsymbol{\beta}_{mn}$  and variance  $\mathbf{B}_{mn}$  (proof of the first bullet). Then,

$$p(\mathbf{y}) \propto \int_0^\infty \left( \frac{g_m}{1 + g_m} \right)^{k_m/2} (\sigma^2)^{-(N-1)/2-1} \exp \left\{ -\frac{1}{2\sigma^2} (\mathbf{y}^\top \mathbf{y} - N\bar{y}^2 - \boldsymbol{\beta}_{mn}^\top \mathbf{B}_{mn} \boldsymbol{\beta}_{mn}) \right\} d\sigma^2.$$

This is the kernel of an inverse-gamma density with parameters  $\alpha_n = (N-1)/2$  and  $\delta_n = \mathbf{y}^\top \mathbf{y} - N\bar{y}^2 - \boldsymbol{\beta}_{mn}^\top \mathbf{B}_{mn} \boldsymbol{\beta}_{mn}$ , where  $\mathbf{y}^\top \mathbf{y} - N\bar{y}^2 - \boldsymbol{\beta}_{mn}^\top \mathbf{B}_{mn} \boldsymbol{\beta}_{mn} = (\mathbf{y} - \mathbf{i}_N \bar{y})^\top (\mathbf{y} - \mathbf{i}_N \bar{y}) - (1 + g_m)^{-1} \mathbf{y}^\top (\mathbf{X} (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top) \mathbf{y}$ . Then,

$$p(\mathbf{y} | \mathcal{M}_m) \propto \left( \frac{g_m}{1 + g_m} \right)^{k_m/2} \left[ (\mathbf{y} - \bar{y} \mathbf{i}_N)^\top (\mathbf{y} - \bar{y} \mathbf{i}_N) - \frac{1}{1 + g_m} (\mathbf{y}^\top \mathbf{P}_{X_m} \mathbf{y}) \right]^{-(N-1)/2},$$

## 2. Determinants of export diversification I

[8] use BMA to study the determinants of export diversification. Use the dataset *10ExportDiversificationHHI.csv* to perform BMA using the BIC approximation and MC3 with 10000 iterations to check if these two approaches agree.

### Answer

The first aspect to note is that the BIC approximation is faster by far than the MC3 algorithm. We see from the results that the two approaches show that the most relevant variables to determine export diversification are *avgedu5* (primary education) and *avgnatres* (natural resources). See [8] for details of all variables. The model with the highest PMP using MC3 includes these two variables (PMP = 0.16), while the model with the highest PMP using the BIC approximation in addition to these two variables also includes Portugal former colony and population (PMP = 0.03). Both methods agree that export diversification increases with primary education, and decreases with natural resources.

*R code. Determinants of export diversification*

```

1 rm(list = ls()); set.seed(010101)
2 Data <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/10
  ExportDiversificationHHI.csv", sep = ",", header = TRUE,
  quote = "")
3 attach(Data)
4 y <- Data[,1]; X <- as.matrix(Data[, -1]); K <- dim(X)[2]
5 BMAglm <- BMA::bicreg(X, y, strict = FALSE, OR = 50)
6 summary(BMAglm)
7 BMAreg <- BMA::MC3.REG(y, X, num.its=10000)
8 Models <- unique(BMAreg[["variables"]])
9 nModels <- dim(Models)[1]
10 nVistModels <- dim(BMAreg[["variables"]])[1]
11 PMPmc3 <- NULL
12 for(m in 1:nModels){
13   idModm <- NULL
14   for(j in 1:nVistModels){
15     if(sum(Models[m,] == BMAreg[["variables"]][j,]) == K){
16       idModm <- c(idModm, j)
17     }else{
18       idModm <- idModm
19     }
20   }
21   PMPm <- sum(BMAreg[["post.prob"]][idModm])
22   PMPmc3 <- c(PMPmc3, PMPm)
23 }
24 PMPmc3
25 PIPmc3 <- NULL
26 for(k in 1:K){
27   PIPk <- sum(PMPmc3[which(Models[,k] == 1)])
28   PIPmc3 <- c(PIPmc3, PIPk)
29 }
30 plot(PIPmc3)
31 Meansmc3 <- matrix(0, nModels, K)
32 Varsmc3 <- matrix(0, nModels, K)
33 for(m in 1:nModels){
34   idXs <- which(Models[m,] == 1)
35   if(length(idXs) == 0){
36     Regm <- lm(y ~ 1)
37   }else{
38     Xm <- X[, idXs]
39     Regm <- lm(y ~ Xm)
40     SumRegm <- summary(Regm)
41     Meansmc3[m, idXs] <- SumRegm[["coefficients"]][-1,1]
42     Varsmc3[m, idXs] <- SumRegm[["coefficients"]][-1,2]^2
43   }
44 }
45 BMAmeansmc3 <- colSums(Meansmc3*PMPmc3)
46 BMAstdmc3 <- (colSums(PMPmc3*Varsmc3) + colSums(PMPmc3*(
  Meansmc3-matrix(rep(BMAmeansmc3, each = nModels),
  nModels, K))^2))^0.5
47 plot(BMAmeansmc3)
48 plot(BMAstdmc3)
49 Ratio <- BMAmeansmc3/BMAstdmc3
50 ResselMC3 <- as.data.frame(cbind(PIPmc3, Models[1,],
  BMAmeansmc3, BMAstdmc3, Ratio))
51 PMPmc3

```

**3. Simulation exercise of the Markov chain Monte Carlo model composition continues**

Program an algorithm to perform MC3 where the final  $S$  models are unique. Use the simulation setting of Section 10.2 of the book increasing the number of regressors to 40, this implies approximately  $1.1 \times 10^{12}$  models.

**Answer**

The following code shows how to perform BMA using MC3 with the consideration that all final  $S$  models should be different.

After running the algorithm 50000 ( $\ll 2^{40}$ ) times, we can see that the PIP is 1 for variables  $x_1$ ,  $x_5$  and  $x_{10}$ , which are the variables in the data generating process (population statistical model). However, we can see that variable  $x_{23}$  has a high PIP (0.49), this makes that the PMP of the model including  $x_1$ ,  $x_5$ ,  $x_{10}$  and  $x_{23}$  is the highest, followed by the model including  $x_1$ ,  $x_5$  and  $x_{10}$ , which is the population statistical model. This highlights the relevance of performing BMA; selecting just one model based on the highest PMP would induce a mistake. Although selecting the median probability model would uncover the population statistical model.

Estimating the BMA mean shows that we get values very close to the population values, a remarkable results is all other BMA posterior means are close to 0, including the mean coefficient of  $x_{23}$  despite that its PIP is almost 0.5. We calculate the posterior ratio between the mean and standard deviation, and get values higher than 2 just for  $x_1$ ,  $x_5$  and  $x_{10}$ , again given evidence for the data generating process.

*R code. Markov chain Monte Carlo model  
composition*

```

1 rm(list = ls()); set.seed(010101)
2 N <- 1000
3 K1 <- 6; K2 <- 4; K3 <- 30; K <- K1 + K2 + K3
4 X1 <- matrix(rnorm(N*K1,1,1), N, K1)
5 X2 <- matrix(rbinom(N*K2, 1, 0.5), N, K2)
6 X3 <- matrix(rnorm(N*K3,1,1), N, K3)
7 X <- cbind(X1, X2, X3); e <- rnorm(N, 0, 0.5)
8 B <- c(1,0,0,0,0.5,0,0,0,0,-0.7, rep(0, 30))
9 y <- 1 + X%B + e
10 LogMLfunt <- function(Model){
11   indr <- Model == 1
12   kr <- sum(indr)
13   if(kr > 0){
14     gr <- ifelse(N > kr^2, 1/N, kr^(-2))
15     Xr <- matrix(Xnew[, indr], ncol = kr)
16     # PX <- diag(N) - Xr%*%solve(t(Xr)%*%Xr)%*%t(Xr)
17     # s2pos <- c(t(y)%*%PX%*%y/(1 + gr) + gr*(t(y - mean(y))
18     # %*%(y - mean(y)))/(1 + gr))
19     PX <- Xr%*%solve(t(Xr)%*%Xr)%*%t(Xr)
20     s2pos <- c((t(y - mean(y))%*%(y - mean(y))) - t(y)%*%PX%
21     # %*%y/(1 + gr))
22     mllMod <- (kr/2)*log(gr/(1+gr))-(N-1)/2*log(s2pos)
23   }else{
24     gr <- ifelse(N > kr^2, 1/N, kr^(-2))
25     # PX <- diag(N)
26     # s2pos <- c(t(y)%*%PX%*%y/(1 + gr) + gr*(t(y - mean(y))
27     # %*%(y - mean(y)))/(1 + gr))
28     s2pos <- c((t(y - mean(y))%*%(y - mean(y))))
29     mllMod <- (kr/2)*log(gr/(1+gr))-(N-1)/2*log(s2pos)
30   }
31   return(mllMod)
32 }
33 Xnew <- apply(X, 2, scale); M <- 100
34 Models <- matrix(rbinom(K*M, 1, p = 0.5), ncol = K, nrow = M
35 + 800)
36 Models <- unique(Models)[1:M,]
37 mllnew <- sapply(1:M, function(s){LogMLfunt(matrix(Models[s
38 ], 1, K))})
39 oind <- order(mllnew, decreasing = TRUE)
40 mllnew <- mllnew[oind, ]
41 Models <- Models[oind, ]
42 iter <- 50000; s <- 1
43 pb <- winProgressBar(title = "progress bar", min = 0, max =
44   iter, width = 300)

```



*R code. Markov chain Monte Carlo model  
composition*

```

1 while(s <= iter){
2   ActModel <- Models[M,]
3   idK <- which(ActModel == 1)
4   Kact <- length(idK)
5   Continue <- 0
6   while(Continue == 0){
7     if(Kact < K & Kact > 1){
8       CardMol <- K
9       opt <- sample(1:3, 1)
10      if(opt == 1){ # Same
11        CandModel <- ActModel
12      }else{
13        if(opt == 2){ # Add
14          All <- 1:K
15          NewX <- sample(All[-idK], 1)
16          CandModel <- ActModel
17          CandModel[NewX] <- 1
18        }else{ # Subtract
19          LessX <- sample(idK, 1)
20          CandModel <- ActModel
21          CandModel[LessX] <- 0
22        }
23      }
24    }else{
25      CardMol <- K + 1
26      if(Kact == K){
27        opt <- sample(1:2, 1)
28        if(opt == 1){ # Same
29          CandModel <- ActModel
30        }else{ # Subtract
31          LessX <- sample(1:K, 1)
32          CandModel <- ActModel
33          CandModel[LessX] <- 0
34        }
35      }else{
36        if(K == 1){
37          opt <- sample(1:3, 1)
38          if(opt == 1){ # Same
39            CandModel <- ActModel
40          }else{
41            if(opt == 2){ # Add
42              All <- 1:K
43              NewX <- sample(All[-idK], 1)
44              CandModel <- ActModel
45              CandModel[NewX] <- 1
46            }else{ # Subtract
47              LessX <- sample(idK, 1)
48              CandModel <- ActModel
49              CandModel[LessX] <- 0
50            }
51          }
52        }else{ # Add
53          NewX <- sample(1:K, 1)
54          CandModel <- ActModel
55          CandModel[NewX] <- 1
56        }
57      }
58    }

```

*R code. Markov chain Monte Carlo model composition*

```

1      check <- NULL
2      for(j in 1:M){
3          if(sum(Models[j,] == CandModel) == K){
4              checkj <- 0
5              check <- c(check, checkj)
6          }else{
7              checkj <- 1
8              check <- c(check, checkj)
9          }
10     }
11     dimUniModels <- sum(check)
12     if(dimUniModels == M){
13         Continue <- 1
14     }else{
15         Continue <- 0
16     }
17 }
18 LogMLact <- LogMLfunt(matrix(ActModel, 1, K))
19 LogMLcand <- LogMLfunt(matrix(CandModel, 1, K))
20 alpha <- min(1, exp(LogMLcand-LogMLact)); u <- runif(1)
21 if(u <= alpha){
22     mllnew[M] <- LogMLcand
23     Models[M, ] <- CandModel
24     oind <- order(mllnew, decreasing = TRUE)
25     mllnew <- mllnew[oind]
26     Models <- Models[oind, ]
27 }else{
28     mllnew <- mllnew
29     Models <- Models
30 }
31 s <- s + 1
32 setWinProgressBar(pb, s, title=paste( round(s/iter*100, 0), "%
    done"))
33 }
34 close(pb)
35 ModelsUni <- unique(Models)
36 mllnewUni <- sapply(1:dim(ModelsUni)[1], function(s){
37     LogMLfunt(matrix(ModelsUni[s,], 1, K))})
38 StMarLik <- exp(mllnewUni-mllnewUni[1])
39 PMP <- StMarLik/sum(StMarLik)
40 PIP <- NULL
41 for(k in 1:K){
42     PIPk <- sum(PMP[which(ModelsUni[,k] == 1)])
43     PIP <- c(PIP, PIPk)
44 }
45 PIP

```

***R code. Markov chain Monte Carlo model composition***

```

1 Means <- matrix(0, M, K)
2 Vars <- matrix(0, M, K)
3 for(m in 1:M){
4   idXs <- which(ModelsUni[m,] == 1)
5   if(length(idXs) == 0){
6     Regm <- lm(y ~ 1)
7   }else{
8     Xm <- X[, idXs]
9     Regm <- lm(y ~ Xm)
10    SumRegm <- summary(Regm)
11    Means[m, idXs] <- SumRegm[["coefficients"]][-1,1]
12    Vars[m, idXs] <- SumRegm[["coefficients"]][-1,2]^2
13  }
14 }
15 BMameans <- colSums(Means*PMP)
16 BMAsd <- (colSums(PMP*Vars) + colSums(PMP*(Means-matrix(rep
17   (BMameans, each = M), M, K))^2))^0.5
18 plot(BMameans)
19 plot(BMAsd)
20 plot(BMameans/BMAsd)

```

#### 4. Simulation exercise of IV BMA continues

Use the simulation setting with endogeneity in Section 10.2 to perform BMA based on the BIC approximation and MC3.

**Answer**

The following code shows how to perform BMA using the BIC approximation and MC3 in this simulation setting with endogeneity. We see from the results that the BIC approximation and MC3 do a good job with the PMP and the PIP, as the data generating process gets the highest PMP using both approaches, and the PIPs of the variables in the data generating process are equal 1. The critical point is the BMA posterior means of the endogenous regressors, as these are far from the population values. The population values of  $x_{i1}$  and  $x_{i2}$  are 0.5 and -1, whereas the posterior means are 0.97 and -0.52.

*R code. BIC and MC3 in model with endogeneity*

```

1 rm(list = ls())
2 set.seed(010101)
3 simIV <- function(delta1,delta2,beta0,betas1,betas2,beta2,
4   Sigma,n,z) {
5   eps <- matrix(rnorm(3*n),ncol=3) %%% chol(Sigma)
6   xs1 <- z%*%delta1 + eps[,1]
7   xs2 <- z%*%delta2 + eps[,2]
8   x2 <- rnorm(dim(z)[1])
9   y <- beta0+betas1*xs1+betas2*xs2+beta2*x2 + eps[,3]
10  X <- as.matrix(cbind(xs1,xs2,1,x2))
11  colnames(X) <- c("x1en","x2en","cte","xex")
12  y <- matrix(y,dim(z)[1],1)
13  colnames(y) <- c("y")
14  list(X=X,y=y)
15 }
16 n <- 1000 ; p <- 3
17 z <- matrix(runif(n*p),ncol=p)
18 rho31 <- 0.8; rho32 <- 0.5;
19 Sigma <- matrix(c(1,0,rho31,0,1,rho32,rho31,rho32,1),ncol=3)
20 delta1 <- c(4,-1,2); delta2 <- c(-2,3,-1); betas1 <- .5;
21 betas2 <- -1; beta2 <- 1; beta0 <- 2
22 simiv <- simIV(delta1,delta2,beta0,betas1,betas2,beta2,Sigma,
23   n,z)
24 nW <- 18
25 W <- matrix(rnorm(nW*dim(z)[1]),dim(z)[1],nW)
26 YXW<-cbind(simiv$y, simiv$X, W)
27 y <- YXW[,1]; X <- YXW[,2:3]; W <- YXW[,-c(1:4)]
28 Xnew <- cbind(X, W)
29 BMAGlm <- BMA::bicreg(Xnew, y, strict = FALSE, OR = 50)
30 summary(BMAGlm)
31 BMAREg <- BMA::MC3.REG(y, Xnew, num.its=10000)
32 Models <- unique(BMAREg[["variables"]])
33 nModels <- dim(Models)[1]
34 nVistModels <- dim(BMAREg[["variables"]])[1]
35 K <- dim(Xnew)[2]
36 PMP <- NULL
37 for(m in 1:nModels){
38   idModm <- NULL
39   for(j in 1:nVistModels){
40     if(sum(Models[m,] == BMAREg[["variables"]][j,]) == K){
41       idModm <- c(idModm, j)
42     }else{
43       idModm <- idModm
44     }
45   }
46   PMPm <- sum(BMAREg[["post.prob"]][idModm])
47   PMP <- c(PMP, PMPm)
48 }
49 PMP
50 PIP <- NULL
51 for(k in 1:K){
52   PIPk <- sum(PMP[which(Models[,k] == 1)])
53   PIP <- c(PIP, PIPk)
54 }
55 plot(PIP)

```

*R code. BIC and MC3 in model with endogeneity*

```

1 Means <- matrix(0, nModels, K)
2 Vars <- matrix(0, nModels, K)
3 for(m in 1:nModels){
4   idXs <- which(Models[m,] == 1)
5   if(length(idXs) == 0){
6     Regm <- lm(y ~ 1)
7   }else{
8     Xm <- Xnew[, idXs]
9     Regm <- lm(y ~ Xm)
10    SumRegm <- summary(Regm)
11    Means[m, idXs] <- SumRegm[["coefficients"]][-1,1]
12    Vars[m, idXs] <- SumRegm[["coefficients"]][-1,2]^2
13  }
14 }
15 BMameans <- colSums(Means*PMP)
16 BMAsd <- (colSums(PMP*Vars) + colSums(PMP*(Means-matrix(rep
17   (BMameans, each = nModels), nModels, K))^2))^0.5
18 plot(BMameans)
19 plot(BMAsd)
20 plot(BMameans/BMAsd)

```

The previous results are intuitive, as the PMP are calculated based on fit (and penalty for complexity), for instance,  $BIC = k_m \log(N) - 2\log(p(\hat{\theta}_m|\mathbf{y}))$ , where  $\hat{\theta}_m$  is the maximum likelihood estimator. Observe that the fit is not affected by endogeneity. Thus, the PMP are well calculated. However, the coefficients are not well identified.

This suggests a simple strategy to perform BMA taking into account endogeneity, calculate the PMPs using standard BMA approaches, for instance, BIC approximation, and then estimate the BMA means using these PMPs, but estimating the different models using instrumental variables. This approach is easily implemented using packages from **R**. The following code does this:

*R code. Easy IV BMA*

```

1 BMAglm <- BMA::bicreg(Xnew, y, strict = FALSE, OR = 50)
2 summary(BMAglm)
3 PMPBIC <- BMAglm[["postprob"]]
4 ModelsBIC <- BMAglm[["which"]]
5 nModels <- dim(ModelsBIC)[1]
6 K <- dim(Xnew)[2]
7 Means <- matrix(0, nModels, K)
8 Vars <- matrix(0, nModels, K)
9 for(m in 1:nModels){
10   idXs <- which(ModelsBIC[m,] == 1)
11   if(length(idXs) == 0){
12     Regm <- lm(y ~ 1)
13   }else{
14     Xm <- Xnew[, idXs]
15     Regm <- ivreg::ivreg(y ~ Xm | z + W)
16     SumRegm <- summary(Regm)
17     Means[m, idXs] <- SumRegm[["coefficients"]][-1,1]
18     Vars[m, idXs] <- SumRegm[["coefficients"]][-1,2]^2
19   }
20 }
21 BMAMEANS <- colSums(Means*PMPBIC)
22 BMASD <- (colSums(PMPBIC*Vars) + colSums(PMPBIC*(Means -
23   matrix(rep(BMAMEANS, each = nModels), nModels, K))^2))
24   ^0.5
25 BMAMEANS
26 5.589366e-01 -9.431664e-01 1.035593e+00 -1.967444e-05
27 -1.429801e-04 -3.310215e-04 4.036846e-04 4.651796e-03
28 -2.673730e-03 6.462503e-05 4.286529e-04 -1.829889e-04
29 5.073229e-03 -1.007356e-04 -5.377972e-04 1.644475e-03
30 -4.029205e-04 -1.457381e-04 6.421582e-04 2.211994e-04
31 2.216503e-04
32
33 plot(BMASD)
34 plot(BMAMEANS/BMASD)
35 17.764095075 -23.233601133 34.734610916 -0.005600369
36 -0.039168667 -0.071895067 0.080909448 0.274994618
37 -0.210854131 0.018790592 0.061271650 -0.047117887
38 0.305639285 -0.028830411 -0.092463544 0.169455952
39 -0.058299940 -0.038099792 0.102373567 0.056074670
40 0.055500343

```

We observe that the Easy IV BMA means of the endogenous regressors are 0.59 and -0.94, which are closer to the population values (0.5 and -1) than the exogenous BMA means (0.97 and -0.52) and align closely with the IV BMA means calculated using conditional Bayes factors (0.51 and -0.98; see Section 10.2 in the book). Additionally, the ratios between the Easy IV

BMA means and their standard deviations exceed 2 in absolute value for these variables, and the t-intervals encompass the population values

#### 5. Determinants of export diversification II

Use the datasets *11ExportDiversificationHHI.csv* and *12ExportDiversificationHHIInstr.csv* to perform IV BMA assuming that the log of per capita gross domestic product is endogenous (*avglgdpcap*). See [8] for details.

##### **Answer**

The results show that primary education (*avgedu5*) and natural resources (*avgnatres*) have again the highest PIP, 0.77 and 0.92, respectively. The former variable increases export diversification, and the latter decreases export diversification. However, it seems that endogeneity is not a concern in this application, as the 95% credible interval of  $\sigma_{12}$  is (-0.014, 0.024).

### *R code. IV BMA in export diversification*

```

1 rm(list = ls())
2 set.seed(010101)
3 DataMain <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/11
  ExportDiversificationHHI.csv", sep = ",", header = TRUE,
  quote = "")
4 DataInst <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/12
  ExportDiversificationHHIInstr.csv", sep = ",", header =
  TRUE, quote = "")
5 attach(DataMain)
6 attach(DataInst)
7 y <- DataMain[,1]
8 X <- as.matrix(DataMain[,2])
9 W <- as.matrix(DataMain[,c(1:2)])
10 Z <- as.matrix(DataInst)
11 S <- 10000; burnin <- 1000
12 regivBMA <- ivbma::ivbma(Y = y, X = X, Z = Z, W = W, s = S+
  burnin, b = burnin, odens = S, print.every = round(S/10)
  , run.diagnostics = FALSE)
13 PIPmain <- regivBMA[["L.bar"]] # PIP outcome
14 PIPmain
15 EVmain <- regivBMA[["rho.bar"]] # Posterior mean outcome
16 EVmain
17 PIPaux <- regivBMA[["M.bar"]] # PIP auxiliary
18 PIPaux
19 EVaux <- regivBMA[["lambda.bar"]] # Posterior mean auxiliary
20 plot(EVaux[,1])
21 EVsigma <- regivBMA[["Sigma.bar"]] # Posterior mean variance
  matrix
22 EVsigma
23 summary(coda::mcmc(regivBMA[["Sigma"]][1,2,]))
24 Iterations = 1:10000
25 Thinning interval = 1
26 Number of chains = 1
27 Sample size per chain = 10000
28 1. Empirical mean and standard deviation for each variable,
29 plus standard error of the mean:
30 Mean          SD          Naive SE Time-series SE
31 3.944e-03      9.592e-03      9.592e-05      4.043e-04
32 2. Quantiles for each variable:
33 2.5%          25%          50%          75%          97.5%
34 -0.014155     -0.002415     0.003592     0.009988     0.024047

```

6. Show that the link function in the case of the Bernoulli distribution is  $\log\left(\frac{\theta}{1-\theta}\right)$ .



**Answer**

$$\begin{aligned}
 p(\mathbf{y}|\theta) &= \theta^y(1-\theta)^{1-y} \\
 &= (1-\theta) \exp \left\{ y \log \left( \frac{\theta}{1-\theta} \right) \right\} \\
 &= \exp \left\{ y \log \left( \frac{\theta}{1-\theta} \right) + \log(1-\theta) \right\},
 \end{aligned}$$

then  $\eta(\theta) = \log \left( \frac{\theta}{1-\theta} \right)$ , and this density in the canonical form is  $p(y|\eta) = \exp \{ y\eta - \log(1 + \exp(\eta)) \}$  consequently,  $\mathbb{E}[Y|\mathbf{x}] = \nabla (\log(1 + \exp(\eta))) = \frac{\exp(\eta)}{1+\exp(\eta)} = \theta = \frac{\exp(\mathbf{x}^\top \boldsymbol{\beta})}{1+\exp(\mathbf{x}^\top \boldsymbol{\beta})}$ . Then, the link function in the Bernoulli case is the *logit* function.

7. [19, 20] perform variable selection using the file *13InternetMed.csv*. In this data set, the dependent variable is an indicator of Internet adoption (internet) for 5000 households in Medellín (Colombia) during the period 2006–2014. This dataset contains information about 18 potential determinants, which means 262144 ( $2^{18}$ ) potential models just taking into account variable uncertainty (see these papers for details about the data set). Perform BMA using the logit link function using this data set.

**Answer***R code. BMA logit in internet adoption*

```

1 rm(list = ls())
2 set.seed(010101)
3 DataMain <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/13InternetMed
  .csv", sep = ",", header = TRUE, quote = "")
4 attach(DataMain)
5 ### BIC approximation
6 y <- DataMain[,1]
7 X <- as.matrix(DataMain[, -1])
8 BMAglm <- BMA::bic.glm(X, y, strict = FALSE, OR = 50, glm.
  family = binomial(link="logit"))
9 summary(BMAglm)
10

```

The results show that the best model has a posterior model probability equal to 31%, and the second best model has a PMP equal to 30%. It seems that age, squared age, years of education of the head of the household, total expenses, having pay TV, any household member studying, and number of children in the household are relevant determinants of Internet adoption.

8. [23] use the file *14ValueFootballPlayers.csv* to analyze the market value of soccer players in the most important leagues in Europe. In particular, there are 26 potential determinants of the market value (dependent variable) of a stratified sample of 335 soccer players in the five most important leagues in Europe (see [23] for details). Use this data set to perform BMA using the gamma distribution with the log link function, and setting default values for Occam's window.

**Answer**

*R code. BMA gamma in market value of soccer players in Europe*

```

1 rm(list = ls())
2 set.seed(010101)
3 DataMain <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/14
  ValueFootballPlayers.csv", sep = ",", header = TRUE,
  quote = "")
4 attach(DataMain)
5 ### BIC approximation
6 y <- DataMain[,1]
7 X <- as.matrix(DataMain[, -1])
8 BMAGlm <- BMA::bic.glm(X, y, strict = FALSE, OR = 50, glm.
  family = Gamma(link="log"))
9 summary(BMAGlm)

```

The results show that performance, age, squared age, participation in national team, scored goals, and appearance in the UEFA champions league have PIPs equal 1. All these variables increase the market value of soccer players, except squared age.

9. Use the dataset *15Fertile2.csv* from [27, p. 547] to perform BMA using the Poisson model with the log link. This data set has information about 1,781 women from Botswana in 1988 (for details, see <https://rdrr.io/cran/wooldridge/man/fertil2.html>, and take into account that we deleted some variables and omitted observations with NA values). The dependent variable is the number of children ever born (ceb), which is a count variable, as a function of 19 potential determinants.

**Answer**

***R code. BMA Poisson in determinants of fertility  
in Bostwana***

```

1 rm(list = ls())
2 set.seed(010101)
3 DataMain <- read.csv("https://raw.githubusercontent.com/
  besmarter/BSTApp/refs/heads/master/DataApp/15Fertil2.csv",
  sep = ",", header = TRUE, quote = "")
4 attach(DataMain)
5 ### BIC approximation
6 y <- DataMain[,1]
7 X <- as.matrix(DataMain[,-1])
8 BMAGlm <- BMA::bic.glm(X, y, strict = FALSE, OR = 50, glm.
  family = poisson(link="log"))
9 summary(BMAGlm)

```

We found that the best model, for which the PMP is equal to 27%, has as regressors age, squared age, age at first birth, use birth control, husband's years of education, woman's years of education, and living in an urban area. The first five variables have PIPs equal to 100. For instance, we found that women using birth control have approximately 15% fewer children on average than women who are not using birth control.

10. Perform BMA in the logit model using MC3 and the BIC approximation using the simulation setting of Section 10.3.

**Answer**

*R code. BMA Logit model*

```

1 rm(list = ls()); set.seed(010101)
2 n<-1000; B<-c(0.5,0.8,-1.2)
3 X<-matrix(cbind(rep(1,n),rnorm(n,0,1),rnorm(n,0,1)),n,length
  (B))
4 p <- exp(X%*%B)/(1+exp(X%*%B))
5 y <- rbinom(n, 1, p); table(y)
6 nXgar<-25; Xgar<-matrix(rnorm(nXgar*n),n,nXgar)
7 df<-as.data.frame(cbind(y,X[, -1],Xgar))
8 colnames(df) <- c("y", "x1", "x2", "x3", "x4", "x5", "x6", "
  x7", "x8", "x9", "x10", "x11", "x12", "x13", "x14", "x15
  ", "x16", "x17", "x18", "x19", "x20", "x21", "x22", "x23
  ", "x24", "x25", "x26", "x27")
9 Xnew <- apply(df[, -1], 2, scale)
10 BICfunt <- function(Model){
11   indr <- Model == 1
12   kr <- sum(indr)
13   if(kr > 0){
14     Xr <- as.matrix(Xnew[, indr])
15     model <- glm(y ~ Xr, family = binomial(link = "logit"))
16     model_bic <- BIC(model)
17     mllMod <- -model_bic/2
18   }else{
19     model <- glm(y ~ 1, family = binomial(link = "logit"))
20     model_bic <- BIC(model)
21     mllMod <- -model_bic/2
22   }
23   return(mllMod)
24 }
25 M <- 500; K <- dim(df)[2] - 1
26 Models <- matrix(rbinom(K*M, 1, p = 0.5), ncol = K, nrow = M
  )
27 mllnew <- sapply(1:M, function(s){BICfunt(matrix(Models[s,],
  1, K))})
28 oind <- order(mllnew, decreasing = TRUE)
29 mllnew <- mllnew[oind]; Models <- Models[oind, ]
30 iter <- 25000; s <- 1
31 pb <- winProgressBar(title = "progress bar", min = 0, max =
  iter, width = 300)
32 while(s <= iter){
33   ActModel <- Models[M,]
34   idK <- which(ActModel == 1)
35   Kact <- length(idK)
36   if(Kact < K & Kact > 1){
37     CardMol <- K; opt <- sample(1:3, 1)
38     if(opt == 1){ # Same
39       CandModel <- ActModel
40     }else{
41       if(opt == 2){ # Add
42         All <- 1:K; NewX <- sample(All[-idK], 1)
43         CandModel <- ActModel; CandModel[NewX] <- 1
44       }else{ # Subtract
45         LessX <- sample(idK, 1)
46         CandModel <- ActModel; CandModel[LessX] <- 0
47       }
48     }
49   }
50 }

```

*R code. BMA Logit model*

```

1   }else{
2   CardMol <- K + 1
3   if(Kact == K){
4     opt <- sample(1:2, 1)
5     if(opt == 1){ # Same
6       CandModel <- ActModel
7     }else{ # Subtract
8       LessX <- sample(1:K, 1)
9       CandModel <- ActModel
10      CandModel[LessX] <- 0
11    }
12  }else{
13    if(K == 1){
14      opt <- sample(1:3, 1)
15      if(opt == 1){ # Same
16        CandModel <- ActModel
17      }else{
18        if(opt == 2){ # Add
19          All <- 1:K
20          NewX <- sample(All[-idK], 1)
21          CandModel <- ActModel
22          CandModel[NewX] <- 1
23        }else{ # Subtract
24          LessX <- sample(idK, 1)
25          CandModel <- ActModel
26          CandModel[LessX] <- 0
27        }
28      }
29    }else{ # Add
30      NewX <- sample(1:K, 1)
31      CandModel <- ActModel
32      CandModel[NewX] <- 1
33    }
34  }
35 }
36 LogMLact <- BICfunt(matrix(ActModel, 1, K))
37 LogMLcand <- BICfunt(matrix(CandModel, 1, K))
38 alpha <- min(1, exp(LogMLcand-LogMLact)) # Let's reasonably
39      assume same prior model probability for candidate and
40      actual, and same carnality of neighbor models
41 u <- runif(1)
42 if(u <= alpha){
43   mllnew[M] <- LogMLcand
44   Models[M, ] <- CandModel
45   oind <- order(mllnew, decreasing = TRUE)
46   mllnew <- mllnew[oind]
47   Models <- Models[oind, ]
48 }else{
49   mllnew <- mllnew
50   Models <- Models
51 }
52 s <- s + 1
53 setWinProgressBar(pb, s, title=paste( round(s/iter*100, 0),"%
54      done"))
55 }
56 close(pb)

```

*R code. BMA Logit model*

```

1 ModelsUni <- unique(Models)
2 mllnewUni <- sapply(1:dim(ModelsUni)[1], function(s){BICfunt
  (matrix(ModelsUni[s,], 1, K))})
3 StMarLik <- exp(mllnewUni-mllnewUni[1])
4 PMP <- StMarLik/sum(StMarLik) # PMP based on unique selected
  models
5 plot(PMP)
6 ModelsUni[1,]
7 PIP <- NULL
8 for(k in 1:K){
9   PIPk <- sum(PMP[which(ModelsUni[,k] == 1)])
10  PIP <- c(PIP, PIPk)
11 }
12 plot(PIP)
13 Xnew <- df[,-1]
14 nModels <- dim(ModelsUni)[1]
15 Means <- matrix(0, nModels, K)
16 Vars <- matrix(0, nModels, K)
17 for(m in 1:nModels){
18   idXs <- which(ModelsUni[m,] == 1)
19   if(length(idXs) == 0){
20     Regm <- glm(y ~ 1, family = binomial(link = "logit"))
21   }else{
22     Xm <- as.matrix(Xnew[, idXs])
23     Regm <- glm(y ~ Xm, family = binomial(link = "logit"))
24     SumRegm <- summary(Regm)
25     Means[m, idXs] <- SumRegm[["coefficients"]][-1,1]
26     Vars[m, idXs] <- SumRegm[["coefficients"]][-1,2]^2
27   }
28 }
29 BMAMEANS <- colSums(Means*PMP)
30 BMASD <- (colSums(PMP*Vars) + colSums(PMP*(Means-matrix(rep
  (BMAMEANS, each = nModels), nModels, K))^2))^0.5
31 plot(BMAMEANS)
32 plot(BMASD)
33 plot(BMAMEANS/BMASD)

```

The simulation setting implies  $2^{27}$  models, which implies approximately 135 million models in the model space. We run our MC3 algorithm using the BIC approximation with 25000 iterations. This takes by far more time than the BIC approximation from the *BMA* package, but it seems to do a good job finding the data generating process as the highest PMP is associated with it, the PIPs of  $x_{i1}$  and  $x_{i2}$  are 1, the posterior means are 0.85 and -1.1, which are very close to the population values (0.8 and -1.2), and the

t-ratios are by far higher than 2. The PIPs of the other regressors are lower than 20%, and the BMA means are close to 0.

11. Show that

$$\mathbb{E} \left[ \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta}|\mathcal{M}_m)p(\mathbf{y}|\boldsymbol{\theta}_m, \mathcal{M}_m)} \middle| \mathbf{y}, \mathcal{M}_m \right] = \frac{1}{p(\mathbf{y}|\mathcal{M}_m)},$$

where the expected value is with respect to the posterior distribution given the model  $\mathcal{M}_m$ .

**Answer**

Given a probability density function  $p(\boldsymbol{\theta})$ , whose support is in  $\boldsymbol{\Theta}$ , then

$$\begin{aligned} \mathbb{E} \left[ \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta}|\mathcal{M}_m)p(\mathbf{y}|\boldsymbol{\theta}_m, \mathcal{M}_m)} \middle| \mathbf{y}, \mathcal{M}_m \right] &= \int_{\boldsymbol{\Theta}} \left[ \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta}|\mathcal{M}_m)p(\mathbf{y}|\boldsymbol{\theta}_m, \mathcal{M}_m)} \right] \pi(\boldsymbol{\theta}|\mathbf{y}, \mathcal{M}_m) d\boldsymbol{\theta} \\ &= \int_{\boldsymbol{\Theta}} \left[ \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta}|\mathcal{M}_m)p(\mathbf{y}|\boldsymbol{\theta}_m, \mathcal{M}_m)} \right] \frac{\pi(\boldsymbol{\theta}|\mathcal{M}_m)p(\mathbf{y}|\boldsymbol{\theta}_m, \mathcal{M}_m)}{p(\mathbf{y}|\mathcal{M}_m)} d\boldsymbol{\theta} \\ &= \frac{1}{p(\mathbf{y}|\mathcal{M}_m)} \int_{\boldsymbol{\Theta}} p(\boldsymbol{\theta}) d\boldsymbol{\theta} \\ &= \frac{1}{p(\mathbf{y}|\mathcal{M}_m)}. \end{aligned}$$





## Part III

### *Advanced* methods: A brief introduction



---

## ***Bibliography***

---

- [1] R. Baath. *Package bayesboot*, 2018.
- [2] Thomas Bayes. LII. an essay towards solving a problem in the doctrine of chances. by the late rev. mr. bayes, FRS communicated by Mr. Price, in a letter to John Canton, AMFR S. *Philosophical transactions of the Royal Society of London*, 53:370–418, 1763.
- [3] W. Chang. *Web Application Framework for R: Package shiny*. R Studio, 2018.
- [4] T. Conley, C. Hansen, and P. Rossi. Plausibly exogenous. *The Review of Economics and Statistics*, 94(1):260–272, 2012.
- [5] J. Geweke. *Bayesian Statistics*, chapter Evaluating the accuracy of sampling-based approaches to calculating posterior moments. Clarendon Press, Oxford, UK., 1992.
- [6] P. Heidelberger and P. D. Welch. Simulation run length control in the presence of an initial transient. *Operations Research*, 31(6):1109–1144, 1983.
- [7] H. Jeffreys. *Theory of Probability*. Oxford University Press, London, 1961.
- [8] M. Jetter and A. Ramírez Hassan. Want export diversification? Educate the kids first. *Economic Inquiry*, 53(4):1765–1782, 2015.
- [9] Valen E Johnson and David Rossell. On the use of non-local prior densities in bayesian hypothesis tests. *Journal of the Royal Statistical Society Series B: Statistical Methodology*, 72(2):143–170, 2010.
- [10] G. Karabatsos. A menu-driven software package of Bayesian nonparametric (and parametric) mixed models for regression analysis and density estimation. *Behavior Research Methods*, 49:335–362, 2016.
- [11] Alex Lenkoski, Anna Karl, and Andreas Neudecker. *Package ivbma*, 2013.
- [12] Dennis V Lindley. A statistical paradox. *Biometrika*, 44(1/2):187–192, 1957.
- [13] Andrew D. Martin, Kevin M. Quinn, and Jong Hee Park. *Package MCMCpack*, 2018.

- [14] Martyn Plummer, Nicky Best, Kate Cowles, Karen Vines, Deepayan Sarkar, Douglas Bates, Russell Almond, and Arni Magnusson. *Output Analysis and Diagnostics for MCMC*, 2016.
- [15] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2021.
- [16] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2023.
- [17] Adrian Raftery, Jennifer Hoeting, Chris Volinsky, Ian Painter, and Ka Yee Yeung. *Package BMA*, 2012.
- [18] A.E. Raftery and S.M. Lewis. One long run with diagnostics: Implementation strategies for Markov chain Monte Carlo. *Statistical Science*, 7:493–497, 1992.
- [19] Andrés Ramírez-Hassan. Dynamic variable selection in dynamic logistic regression: an application to internet subscription. *Empirical Economics*, 59(2):909–932, 2020.
- [20] Andrés Ramírez-Hassan and Daniela A Carvajal-Rendón. Specification uncertainty in modeling internet adoption: A developing city case analysis. *Utilities Policy*, 70:101218, 2021.
- [21] P. Rossi. *Package bayesm*, 2017.
- [22] Peter E. Rossi, Greg M. Allenby, and Robert McCulloch. *Bayesian Statistics and Marketing*. John Wiley and Sons, Hoboken, NJ, 2005.
- [23] M. Serna Rodríguez, A. Ramírez Hassan, and A. Coad. Uncovering value drivers of high performance soccer players. *Journal of Sport Economics*, 20(6):819–849, 2019.
- [24] A. F. M. Smith. A General Bayesian Linear Model. *Journal of the Royal Statistical Society. Series B (Methodological)*., 35(1):67–75, 1973.
- [25] Stan Development Team. shinystan: Interactive visual and numerical diagnostics and posterior analysis for Bayesian models., 2017. R package version 2.3.0.
- [26] P. Woodward. BugsXLA: Bayes for the common man. *Journal of Statistical Software*, 14(5):1–18, 2005.
- [27] Jeffrey M. Wooldridge. *Introductory Econometrics: A Modern Approach*. Cengage Learning, Mason, Ohio: South-Western, fifth edition, 2012.
- [28] A. Zellner. *Introduction to Bayesian inference in econometrics*. John Wiley & Sons Inc., 1996.

## **Appendix**

**TABLE 10.1**

Libraries and commands in BEsmarter GUI.

Univariate models			
Model	Library	Command	Reference
Normal	MCMCpack	MCMCregress	[13]
Logit	MCMCpack	MCMClogit	[13]
Probit	bayesm	rbprobitGibbs	[21]
Multinomial(Mixed) Probit	bayesm	rmnpGibbs	[21]
Multinomial(Mixed) Logit	bayesm	rmnlIndepMetrop	[21]
Ordered Probit	bayesm	rordprobitGibbs	[21]
Negative Binomial(Poisson)	bayesm	rnegbinRw	[21]
Tobit	MCMCpack	MCMCtobit	[13]
Quantile	MCMCpack	MCMCquantreg	[13]
Bayesian bootstrap	bayesboot	bayesboot	[1]
Multivariate models			
Model	Library	Command	Reference
Multivariate	bayesm	rmultireg	[21]
Seemingly Unrelated Regression	bayesm	rsurGibbs	[21]
Instrumental Variable	bayesm	rivGibbs	[21]
Bivariate Probit	bayesm	rmvpGibbs	[21]
Hierarchical longitudinal models			
Model	Library	Command	Reference
Normal	MCMCpack	MCMChregress	[13]
Logit	MCMCpack	MCMChlogit	[13]
Poisson	MCMCpack	MCMChpoisson	[13]
Bayesian model averaging			
Model	Library	Command	Reference
Normal (BIC)	BMA	bic.glm	[17]
Normal (MC <sup>3</sup> )	BMA	MC3.REG	[17]
Normal (instrumental variables)	ivbma	ivbma	[11]
Logit (BIC)	BMA	bic.glm	[17]
Gamma (BIC)	BMA	bic.glm	[17]
Poisson (BIC)	BMA	bic.glm	[17]
Diagnostics			
Diagnostic	Library	Command	Reference
Trace plot	coda	traceplot	[14]
Autocorrelation plot	coda	autocorr.plot	[14]
Geweke test	coda	geweke.diag	[14]
Raftery & Lewis test	coda	raftery.diag	[14]
Heidelberger & Welch test	coda	heidel.diag	[14]

**TABLE 10.2**Datasets templates in folder *DataSim*.

Univariate models		
Model	Data set file	Data set simulation
Normal	11SimNormalmodel.csv	11SimNormal.R
Logit	12SimLogitmodel.csv	12SimLogit
Probit	13SimProbitmodel.csv	13SimProbit.R
Multinomial(Mixed) Probit	14SimMultProbmodel.csv	14SimMultinomialProbit.R
Multinomial(Mixed) Logit	15SimMultLogitmodel.csv	15SimMultinomialLogit.R
Ordered Probit	16SimOrderedProbitmodel.csv	16SimOrderedProbit.R
Negative Binomial(Poisson)	17SimNegBinmodel.csv	17SimNegBin.R
Tobit	18SimTobitmodel.csv	18SimTobit.R
Quantile	19SimQuantilemodel.csv	19SimQuantile.R
Bayesian bootstrap	41SimBootstrapmodel.csv	41SimBootstrapmodel.R
Multivariate models		
Model	Data set file	Data set simulation
Multivariate	21SimMultivariate.csv	21SimMultReg.R
Seemingly Unrelated Regression	22SimSUR.csv	22SimSUR.R
Instrumental Variable	23SimIV.csv	23SimIV.R
Bivariate Probit	24SimMultProbit.csv	24SimMultProbit.R
Hierarchical longitudinal models		
Model	Data set file	Data set simulation
Normal	31SimLogitudinalNormal.csv	31SimLogitudinalNormal.R
Logit	32SimLogitudinalLogit.csv	32SimLogitudinalLogit.R
Poisson	33SimLogitudinalPoisson.csv	33SimLogitudinalPoisson.R
Bayesian model averaging		
Model	Data set file	Data set simulation
Normal (BIC)	511SimNormalBMA.csv	511SimNormalBMA.R
Normal (MC <sup>3</sup> )	512SimNormalBMA.csv	512SimNormalBMA.R
Normal (instrumental variables)	513SimNormalBMAivYXW.csv	513SimNormalBMAiv.R
	513SimNormalBMAivZ.csv	
Logit (BIC)	52SimLogitBMA.csv	52SimLogitBMA.R
Gamma (BIC)	53SimGammaBMA.csv	53SimGammaBMA.R
Poisson (BIC)	53SimPoissonBMA.csv	53SimPoissonBMA.R

**TABLE 10.3**Real datasets in folder *DataApp*.

Univariate models		
Model	Data set file	Dependent variable
Normal	1ValueFootballPlayers.csv	log(Value)
Logit	2HealthMed.csv	Hosp
Probit	2HealthMed.csv	Hosp
Multinomial(Mixed) Probit	Fishing.csv	mode
Multinomial(Mixed) Logit	Fishing.csv	mode
Ordered Probit	2HealthMed.csv	MedVisPrevOr
Negative Binomial(Poisson)	2HealthMed.csv	MedVisPrev
Tobit	1ValueFootballPlayers.csv	log(ValueCens)
Quantile	1ValueFootballPlayers.csv	log(Value)
Bayesian bootstrap	1ValueFootballPlayers.csv	log(Value)
Multivariate models		
Model	Data set file	Dependent variable
Multivariate	4Institutions.csv	logpcGDP95 and PAER
Seemingly Unrelated Regression	5Institutions.csv	logpcGDP95 and PAER
Instrumental Variable	6Institutions.csv	logpcGDP95 and PAER
Bivariate Probit	7HealthMed.csv	$y = [\text{Hosp SHI}]'$
Hierarchical longitudinal models		
Model	Data set file	Dependent variable
Normal	8PublicCap.csv	log(gsp)
Logit	9VisitDoc.csv	DocVis
Poisson	9VisitDoc.csv	DocNum
Bayesian model averaging		
Model	Data set file	Dependent variable
Normal (BIC)	10ExportDiversificationHHI.csv	avghhi
Normal (MC <sup>3</sup> )	10ExportDiversificationHHI.csv	avghhi
Normal (instrumental variables)	11ExportDiversificationHHI.csv	avghhi and avglgdp
Logit (BIC)	12ExportDiversificationHHIInstr.csv	cap
Gamma (BIC)	13InternetMed.csv	internet
Poisson (BIC)	14ValueFootballPlayers.csv	log market value
	15Fertile2.csv	ceb