

SDS 383D: Exercises 2 – Bayes and the Gaussian linear model

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Problem 1

The conjugate Gaussian linear model

We have a model where

$$\begin{aligned}(y_i|\theta, \sigma^2) &\stackrel{\text{iid}}{\sim} \mathcal{N}(\theta, \omega^{-1}), \quad i = 1, \dots, n, \\ (\theta|\sigma) &\sim \mathcal{N}(\mu, \tau^2 \sigma^2), \\ \sigma^2 &\sim \text{IG}(\frac{d}{2}, \frac{\eta}{2}).\end{aligned}$$

Define $\omega = \frac{1}{\sigma^2}$ and $\kappa = \frac{1}{\tau^2}$, so now

$$(\theta|\omega) \sim \mathcal{N}(\mu, (\omega\kappa)^{-1}),$$

and

$$\omega \sim \text{Gamma}\left(\frac{d}{2}, \frac{\eta}{2}\right).$$

(A) Taking advantage that (1) below is the integral of the kernel of a gamma distribution, the marginal prior distribution of θ is

$$\begin{aligned}p(\theta) &= \int_0^\infty p(\theta, \omega) d\omega \\ &\propto \int_0^\infty p(\theta|\omega) p(\omega) d\omega \\ &\propto \int_0^\infty (\omega\kappa)^{1/2} \exp\left[-\frac{1}{2}\omega\kappa(\theta - \mu)^2\right] \omega^{d/2-1} \exp\left[-\frac{\eta}{2}\omega\right] d\omega \\ &= \int_0^\infty \omega^{(d+1)/2-1} \exp\left[-\left(\frac{1}{2}\kappa(\theta - \mu)^2 + \frac{\eta}{2}\right)\omega\right] d\omega \\ &\propto \left(\frac{1}{2}\kappa(\theta - \mu)^2 + \frac{\eta}{2}\right)^{-\left(\frac{d+1}{2}\right)} \\ &\propto \left(1 + \frac{1}{d} \cdot \frac{(\theta - \mu)^2}{\frac{\eta}{d\kappa}}\right)^{-\left(\frac{d+1}{2}\right)},\end{aligned}$$

which is the kernel of the Student's t -distribution with degrees of freedom d , center parameter μ , and scale parameter $\sqrt{\frac{\eta}{d\kappa}}$.

(B) In this exercise, recall that the likelihood may be written as

$$p(y|\theta, \omega) \propto \omega^{n/2} \exp\left[-\omega \left(\frac{S_y + n(\bar{y} - \theta)^2}{2}\right)\right]$$

where $S_y = \sum_{i=1}^n (y_i - \bar{y})^2 = \sum_{i=1}^n y_i^2 - n\bar{y}^2$ is the sum of squares. Here we calculate the joint posterior

density,

$$\begin{aligned}
 p(\theta, \omega | y) &\propto p(y | \theta, \omega) p(\theta, \omega) \\
 &\propto \left(\omega^{n/2} \exp \left[-\omega \left(\frac{S_y + n(\bar{y} - \theta)^2}{2} \right) \right] \right) \left(\omega^{(d+1)/2} \exp \left[-\frac{1}{2} \omega \kappa (\theta - \mu)^2 \right] \exp \left[-\frac{\eta}{2} \omega \right] \right) \\
 &= \omega^{(d+n+1)/2-1} \exp \left[-\omega \left(\frac{S_y + n(\bar{y} - \theta)^2}{2} \right) - \frac{1}{2} \omega \kappa (\theta - \mu)^2 - \frac{\eta}{2} \omega \right] \\
 &= \omega^{(d+n+1)/2-1} \exp \left(-\frac{1}{2} \omega \left[S_y + n(\bar{y} - \theta)^2 + \kappa (\theta - \mu)^2 + \eta \right] \right) \\
 &= \omega^{(d+n+1)/2-1} \exp \left(-\frac{1}{2} \omega \left[n\theta^2 - 2n\bar{y}\theta + n\bar{y}^2 + \kappa\theta^2 - 2\mu\kappa\theta + \kappa\mu^2 + \eta + S_y \right] \right) \\
 &= \omega^{(d+n+1)/2-1} \exp \left(-\frac{1}{2} \omega \left[(n + \kappa)\theta^2 - 2(n\bar{y} + \mu\kappa)\theta + n\bar{y}^2 + \kappa\mu^2 + \eta + S_y \right] \right) \\
 &= \omega^{(d+n+1)/2-1} \exp \left(-\frac{1}{2} \omega(n + \kappa) \left[\theta^2 - 2\frac{n\bar{y} + \mu\kappa}{n + \kappa}\theta + \frac{n\bar{y}^2 + \kappa\mu^2 + \eta + S_y}{n + \kappa} \right] \right) \\
 &= \omega^{(d+n+1)/2-1} \exp \left(-\frac{1}{2} \omega(n + \kappa) \left[\left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 - \left(\frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 + \frac{n\bar{y}^2 + \kappa\mu^2 + \eta + S_y}{n + \kappa} \right] \right) \\
 &= \dots \times \exp \left[-\frac{1}{2} \omega(n + \kappa) \left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right] \exp \left[-\frac{1}{2} (n + \kappa) \left(\frac{n\bar{y}^2 + \kappa\mu^2 + \eta + S_y}{n + \kappa} - \left(\frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right) \omega \right] \\
 &= \dots \times \exp \left[-\frac{1}{2} \omega(n + \kappa) \left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right] \exp \left[-\frac{1}{2} \left(n\bar{y}^2 + \kappa\mu^2 + \eta + S_y - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa} \right) \omega \right] \\
 &= \omega^{(d+n+1)/2-1} \exp \left[-\frac{1}{2} \omega(n + \kappa) \left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right] \exp \left[-\frac{1}{2} \left(\eta + \sum_{i=1}^n y_i^2 + \kappa\mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa} \right) \omega \right].
 \end{aligned}$$

This expression looks very much like the joint prior, but now with

$$\begin{aligned}
 \mu &\rightarrow \mu^* = \frac{n\bar{y} + \mu\kappa}{n + \kappa} \\
 \kappa &\rightarrow \kappa^* = \kappa + n \\
 d &\rightarrow d^* = d + n \\
 \eta &\rightarrow \eta^* = \eta + \sum_{i=1}^n y_i^2 + \kappa\mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa}.
 \end{aligned}$$

We can also rewrite the joint posterior as

$$\begin{aligned}
 p(\theta, \omega | y) &\propto \omega^{(d+n+1)/2-1} \exp \left[-\frac{1}{2} \omega(n + \kappa) \left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right] \exp \left[-\frac{1}{2} \left(\eta + \sum_{i=1}^n y_i^2 + \kappa\mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa} \right) \omega \right] \\
 &= \underbrace{\omega^{1/2} \exp \left[-\frac{1}{2} \omega(n + \kappa) \left(\theta - \frac{n\bar{y} + \mu\kappa}{n + \kappa} \right)^2 \right]}_{p(\theta | \omega, y) \sim \mathcal{N} \left(\frac{n\bar{y} + \mu\kappa}{n + \kappa}, [(n + \kappa)\omega]^{-1} \right)} \underbrace{\omega^{(d+n)/2-1} \exp \left[-\frac{1}{2} \left(\eta + \sum_{i=1}^n y_i^2 + \kappa\mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa} \right) \omega \right]}_{p(\omega | y) \sim \text{Gamma} \left(\frac{d+n}{2}, \frac{1}{2} \left[\eta + \sum_{i=1}^n y_i^2 + \kappa\mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n + \kappa} \right] \right)}.
 \end{aligned}$$

(C) It is easy to read off the conditional posterior of θ ,

$$p(\theta | \omega, y) \sim \mathcal{N} \left(\frac{n\bar{y} + \mu\kappa}{n + \kappa}, [(n + \kappa)\omega]^{-1} \right).$$

- (D) Getting the marginal posterior is not too much more difficult. We have separated the joint posterior into two kernels, and once we integrate out the normal kernel to get

$$p(\omega|y) \sim \text{Gamma} \left(\frac{d+n}{2}, \frac{1}{2} \left[\eta + \sum_{i=1}^n y_i^2 + \kappa \mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n+\kappa} \right] \right).$$

- (E) The marginal posterior distribution $p(\theta|y)$ will follow a Student's t -distribution, following a similar argument used in (A), but now with updated parameters. The degrees of freedom is

$$\nu' = d + n,$$

the center parameter is

$$m' = \frac{n\bar{y} + \mu\kappa}{n + \kappa},$$

and the scale parameter is

$$s' = \sqrt{\frac{\eta + \sum_{i=1}^n y_i^2 + \kappa \mu^2 - \frac{(n\bar{y} + \mu\kappa)^2}{n+\kappa}}{(d+n)(\kappa+n)}}.$$

- (F) Suppose $\kappa \rightarrow 0$, $d \rightarrow 0$, and $\eta \rightarrow 0$. The priors of $\theta|\omega$ and ω become

$$\begin{aligned} p(\theta|\omega) &\rightarrow \mathcal{N}(\mu, 0^{-1}) \\ p(\omega) &\rightarrow \text{Gamma}(0, 0), \end{aligned}$$

neither of which is a proper PDF.

- (G) Suppose $\kappa \rightarrow 0$, $d \rightarrow 0$, and $\eta \rightarrow 0$. The marginal posteriors $p(\theta|y)$ and $p(\omega|y)$ become

$$\begin{aligned} p(\theta|\omega, y) &\rightarrow \mathcal{N}(\bar{y}, (n\omega)^{-1}) \\ p(\omega|y) &\rightarrow \text{Gamma} \left(\frac{n}{2}, \frac{1}{2} \left[\sum_{i=1}^n y_i^2 - n\bar{y}^2 \right] \right) \\ &= \text{Gamma} \left(\frac{n}{2}, \frac{S_y}{2} \right) \end{aligned}$$

- (H) A Bayesian credible interval for θ , having observed y , is

$$\theta \in m' \pm t^* s',$$

for some critical value t^* from the Student's t -distribution with ν' degrees of freedom. Suppose $\kappa \rightarrow 0$, $d \rightarrow 0$, and $\eta \rightarrow 0$. The parameters of this Student's t -distribution become

$$\begin{aligned} \nu' &\rightarrow n \\ m' &\rightarrow \bar{y} \\ s' &\rightarrow \sqrt{\frac{S_y}{n^2}}, \end{aligned}$$

so the credible interval becomes identical to the frequentist confidence interval at the same confidence level.

Problem 2

The conjugate Gaussian linear model

(A) We have the Gaussian linear model,

$$(y|\beta, \omega) \sim \mathcal{N}_n(X\beta, (\omega\Lambda)^{-1})$$

with priors

$$\begin{aligned} (\beta|\omega) &\sim \mathcal{N}_p(m, (\omega K)^{-1}) \\ \omega &\sim \text{Gamma}\left(\frac{d}{2}, \frac{\eta}{2}\right). \end{aligned}$$

Having observed y , the joint posterior for β and ω is

$$\begin{aligned} p(\beta, \omega|y) &\propto p(y|\beta, \omega)p(\beta, \omega) \\ &= p(y|\beta, \omega)p(\beta|\omega)p(\omega) \\ &= \left(\omega^{n/2} \exp \left[-\frac{1}{2}(y - X\beta)^T \omega \Lambda (y - X\beta) \right] \right) \left(\omega^{p/2} \exp \left[-\frac{1}{2}(\beta - m)^T \omega K (\beta - m) \right] \right) \left(\omega^{d/2-1} \exp \left[-\frac{\eta}{2} \right] \right) \\ &= \omega^{(d+p+n)/2-1} \exp \left(-\frac{1}{2} \omega \left[(y - X\beta)^T \Lambda (y - X\beta) + (\beta - m)^T K (\beta - m) + \eta \right] \right) \\ &= \omega^{(d+p+n)/2-1} \exp \left(-\frac{1}{2} \omega \left[y^T \Lambda y - 2y^T \Lambda X \beta + \beta^T X^T \Lambda X \beta + \beta^T K \beta - 2m^T K \beta + m^T K m + \eta \right] \right) \\ &= \omega^{(d+p+n)/2-1} \exp \left(-\frac{1}{2} \omega \underbrace{\left[\beta^T (X^T \Lambda X + K) \beta - 2(y^T \Lambda X + m^T K) \beta + y^T \Lambda y + m^T K m + \eta \right]}_{(i)} \right) \end{aligned}$$

Now, let

$$\begin{aligned} A &= X^T \Lambda X + K \\ b^T &= y^T \Lambda X + m^T K \\ \Rightarrow b &= X^T \Lambda y + K m \\ c &= y^T \Lambda y + m^T K m + \eta, \end{aligned}$$

so now the expression in (i) becomes, once the square is completed,

$$\begin{aligned} \beta^T A \beta - 2b^T \beta + c &= \beta^T A \beta - 2b^T \beta + b^T A^{-1} b - b^T A^{-1} b + c \\ &= (\beta - A^{-1} b)^T A (\beta - A^{-1} b) - b^T A^{-1} b + c, \end{aligned}$$

Now let

$$\begin{aligned} m^* &= A^{-1} b = (X^T \Lambda X + K)^{-1} (X^T \Lambda y + K m) \\ K^* &= A = X^T \Lambda X + K, \end{aligned}$$

and we can also simplify the term

$$\begin{aligned} b^T A^{-1} b &= b^T I A^{-1} \\ &= b^T A^{-1} A A^{-1} b \\ &= m^{*T} K^* m^*, \end{aligned}$$

and finally let

$$\begin{aligned}\eta^* &= c - m^{*T} K^* m^* \\ &= \eta + y^T \Lambda y + m^T K m - m^{*T} K^* m^*\end{aligned}$$

We can at last express (i) as

$$(\beta - m^*)^T K^* (\beta - m^*) + \eta^*.$$

Now the joint posterior distribution may be written as

$$\begin{aligned}p(\beta, \omega | y) &\propto \omega^{(d+p+n)/2-1} \exp \left(-\frac{1}{2} \omega \left[(\beta - m^*)^T K^* (\beta - m^*) + \eta^* \right] \right) \\ &= \underbrace{\omega^{p/2} \exp \left[-\frac{1}{2} (\beta - m^*)^T \omega K^* (\beta - m^*) \right]}_{p(\beta | y, \omega) \sim \mathcal{N}(m^*, (\omega K^*)^{-1})} \underbrace{\omega^{d^*/2-1} \exp \left[-\frac{1}{2} \eta^* \omega \right]}_{p(\omega | y) \sim \text{Gamma} \left(\frac{d^*}{2}, \frac{\eta^*}{2} \right)},\end{aligned}$$

with

$$\begin{aligned}m^* &= (X^T \Lambda X + K)^{-1} (X^T \Lambda y + K m) \\ K^* &= X^T \Lambda X + K \\ \eta^* &= \eta + y^T \Lambda y + m^T K m - m^{*T} K^* m^* \\ d^* &= d + n\end{aligned}$$

(B) $p(\omega | y) \sim \text{Gamma} \left(\frac{d^*}{2}, \frac{\eta^*}{2} \right)$

(C) The marginal posterior for β may be found with

$$\begin{aligned}p(\beta | y) &= \int_0^\infty p(\beta, \omega | y) d\omega \\ &\propto \int_0^\infty \omega^{(d+p+n)/2-1} \exp \left(-\frac{1}{2} \omega \left[(\beta - m^*)^T K^* (\beta - m^*) + \eta^* \right] \right) d\omega \\ &\propto \left[\frac{1}{2} \left[(\beta - m^*)^T K^* (\beta - m^*) + \eta^* \right] \right]^{-\frac{d+p+n}{2}} \\ &\propto \left[1 + (\beta - m^*)^T \frac{K^*}{\eta^*} (\beta - m^*) \right]^{-\frac{d+n+p}{2}} \\ &\propto \left[1 + \frac{1}{d+n} \cdot (\beta - m^*)^T \cdot \frac{d+n}{\eta^*} K^* \cdot (\beta - m^*) \right]^{-\frac{d+n+p}{2}},\end{aligned}$$

which we may recognize as the p -dimensional Student's t -distribution with $d + n$ degrees of freedom, mean vector m^* , and precision matrix $\frac{d+n}{\eta^*} K^*$.

A heavy-tailed model

Now we have a model with

$$\begin{aligned}(y | \beta, \omega, \Lambda) &\sim \mathcal{N}(X\beta, (\omega\Lambda)^{-1}) \\ \Lambda &= \text{diag}(\lambda_1, \dots, \lambda_n) \\ \lambda_i &\stackrel{\text{iid}}{\sim} \text{Gamma} \left(\frac{h}{2}, \frac{h}{2} \right) \\ (\beta | \omega) &\sim \mathcal{N}(m, (\omega K)^{-1}) \\ \omega &\sim \text{Gamma} \left(\frac{d}{2}, \frac{\eta}{2} \right)\end{aligned}$$

(A) The conditional distribution $p(y_i|X, \beta, \omega)$, once the λ_i has been marginalized out, is

$$\begin{aligned}
 p(y_i|X, \beta, \omega) &= \int_0^\infty p(y_i|X, \beta, \omega, \lambda_i) p(\lambda_i) d\lambda_i \\
 &\propto \int_0^\infty (\omega \lambda_i)^{1/2} \exp \left[-\frac{1}{2} \omega \lambda_i (y_i - x_i^T \beta)^2 \right] \lambda_i^{h/2-1} \exp \left[-\frac{h}{2} \lambda_i \right] d\lambda_i \\
 &= \int_0^\infty \lambda_i^{(h+1)/2-1} \exp \left[-\frac{1}{2} \left(\omega (y_i - x_i^T \beta)^2 + h \right) \lambda_i \right] d\lambda_i \\
 &\propto \left[\frac{1}{2} \left(\omega (y_i - x_i^T \beta)^2 + h \right) \right]^{-(h+1)/2} \\
 &\propto \left[1 + \frac{1}{h} \cdot \frac{(y_i - x_i^T \beta)^2}{\omega^{-1}} \right]^{-(h+1)/2},
 \end{aligned}$$

which follows the Student's t -distribution with h degrees of freedom, center parameter x_i^T , and scale parameter $\omega^{-1/2}$.

(B) The conditional posterior distribution of each λ_i is

$$\begin{aligned}
 p(\lambda_i|y, \beta, \omega) &\propto p(y|\lambda_i, \beta, \omega) \cdot p(\lambda_i|\beta, \omega) \cdot p(\beta, \omega) \\
 &\propto p(y|\lambda_i, \beta, \omega) \cdot p(\lambda_i|\beta, \omega) \\
 &= p(y|\lambda_i, \beta, \omega) \cdot p(\lambda_i) \\
 &\propto \lambda_i^{(h+1)/2-1} \exp \left[-\frac{1}{2} \left(\omega (y_i - x_i^T \beta)^2 + h \right) \lambda_i \right] \\
 &\sim \text{Gamma} \left(\frac{h+1}{2}, \frac{h + \omega (y_i - x_i^T \beta)^2}{2} \right)
 \end{aligned}$$

(C) To run a Gibbs sampler with the heavy-tails model, we have the three conditional distributions

$$p(\beta|y, \omega) \sim \mathcal{N}(m^*, (\omega K^*)^{-1}) \quad (1)$$

$$p(\omega|y) \sim \text{Gamma} \left(\frac{d^*}{2}, \frac{\eta^*}{2} \right) \quad (2)$$

$$p(\lambda_i|y, \beta, \omega) \sim \text{Gamma} \left(\frac{h+1}{2}, \frac{h + \omega (y_i - x_i^T \beta)^2}{2} \right). \quad (3)$$

The figure below shows the comparison between frequentist, Bayesian, and Bayesian heavy-tail models for the GDP growth data.

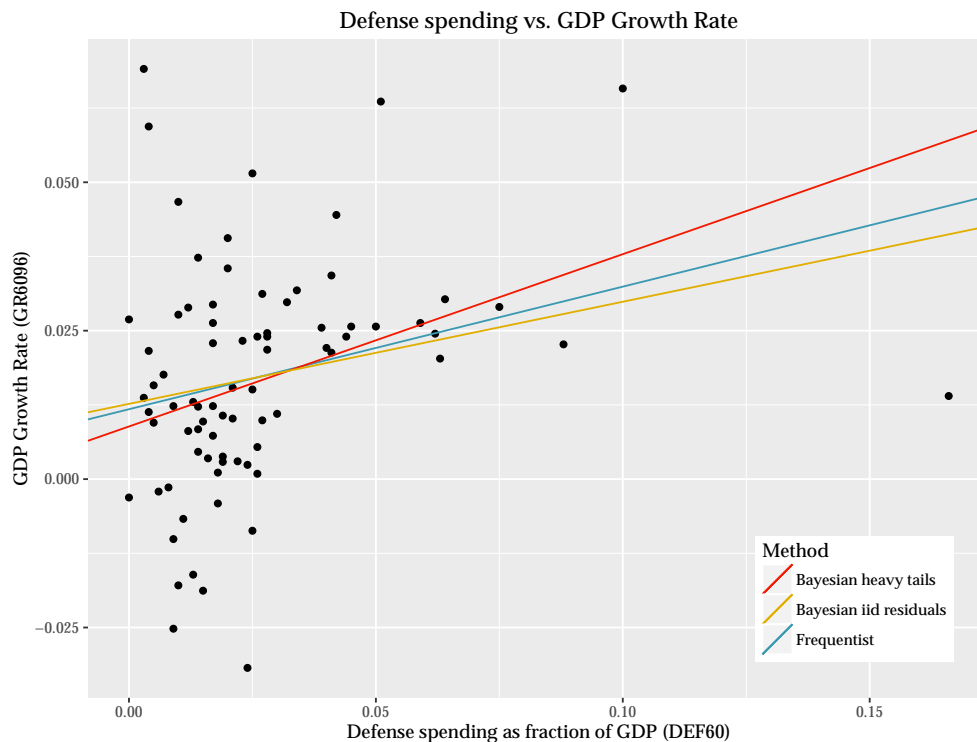


Figure 1: Comparison of three methods

R code for myfuns02.R

```
#####
##### Created by Spencer Woody on 04 Feb 2017 #####
#####

5 my.lm <- function(X, y) {
  # Custom function for linear regression
  #
  # Note: this function assumes that X already has an intercept term
10 # (or doesn't, if we want to force OLS through the origin)
  #
  # INPUTS:
  # X is the design matrix
  # y is the response vector
15 #
  # OUTPUTS
  # a list of...
  # Beta.hat is a vector of estimates of the coefficients
  # Beta.SE is a vector of the standard errors of the coefficients
20 # Beta.t is a vector of t-scores of the coefficients
  # Beta.p is the p-value for each coefficient
  # RSS is the residual sum of squares
  # Var.hat is the estimated variance of homoscedastic residuals
  # R.sq is the R-squared value
25 # R.sqadj is the adjusted R-squared value
}
```



```

#

N <- nrow(X)
p <- ncol(X)

XtX <- crossprod(X)

# Calculate beta.hat
beta.hat <- solve(XtX, crossprod(X, y))

# Calculate predicted values and residuals
y.hat <- crossprod(t(X), beta.hat)
res <- y - y.hat

rss <- sum(res^2)

# Calculate \hat{\sigma}^2
var.hat <- rss / (N - p)

# Calculate covariance matrix of beta and SE's of beta
var.beta <- var.hat * solve(XtX)
beta.SE <- diag(var.beta) ^ 0.5

# Calculate t-score of each beta
beta.t <- beta.hat / beta.SE

# Calculate p-values for coefficients
beta.p <- 2 * (1 - pt(abs(beta.t), N - p))

# Calculate r-squared and adjusted r-squared
r.sq <- 1 - rss / sum((y - mean(y))^2)
r.sqadj <- r.sq - (1 - r.sq) * (p - 1) / (N - p - 2)

# Create a list of calculated values, return it back
mylist <- list(Beta.hat = beta.hat, Beta.SE = beta.SE,
              Beta.t = beta.t, Beta.p = beta.p, RSS = rss, Var.hat = var.hat,
              R.sq = r.sq, R.sqadj = r.sqadj, Res = res)
return(mylist)
}

my.mvn <- function(n, mu, Sigma) {
  # Simulate n draws from MVN(mu, Sigma)
  #
  # Note: this function assumes that X already has an intercept term
  # (or doesn't, if we want to force OLS through the origin)
  #
  # INPUTS:
  # n is the number of draws
  # mu is the mean vector
  # Sigma is the covariance matrix
  #
  # OUTPUT:

```

```
80  # x is matrix of n draws from MVN(mu, Sigma) [with n rows, p columns]
    #
    # dimension of MVN
    p <- length(mu)

85  # Check if inputs are valid (dimensions match, Sigma is square and p.s.d.)
    # if ( (ncol(Sigma) != p) | (nrow(Sigma) != p) | (max(eigen(Sigma)$values) <= 0) ) {
    #   return("Try again...")
    # }
    #
90  # Generate n*p univariate standard normal variables
    z <- matrix(rnorm(n*p), nrow = p)

    # Create a matrix containing copies of mu
    mumat <- matrix(rep(mu, n), nrow = p)

95  # Decompose Sigma into Sigma = L %*% Lt
    Lt <- chol(Sigma)

    # Generate sample with affine transformation of z
100 x <- crossprod(Lt, z) + mumat

    return(t(x))
}
```

R code for exercises02.R

```
#####
##### Created by Spencer Woody on 04 Feb 2017 #####
#####

5 library(ggplot2)
  library(mvtnorm)
  library(wesanderson)
  library(extrafont)

10 source("myfuns02.R")

  # Prep color palette
  pal <- wes_palette("Zissou", 5)
  col1 <- pal[1]
15 col2 <- pal[4]
  col3 <- pal[5]

  # _____
  # Read in the data _____
20 # _____

GDP <- read.csv("gdpgrowth.csv", header = T)

y <- matrix(GDP$GR6096, ncol = 1)
25 X <- matrix(GDP$DEF60, ncol = 1)

n <- length(y)

X <- cbind(rep(1, n), X)
30 colnames(X) <- c("int", "DEF60")

  # _____
  # Specify prior model _____
  # _____

35 freq.lm <- my.lm(X, y)
  freq.beta <- freq.lm$Beta.hat

  # _____
40 # Specify prior model _____
  # _____

  # Hyperparameters: K = diag(k1, k2), Lambda, d, eta, m

45 k1 <- 0.01
  k2 <- 0.01

m <- matrix(c(0, 0), ncol = 1)
K <- diag(c(k1, k2))

50 Lambda <- diag(n)
```

```

d <- 0.02
eta <- 0.02

55 # For heavy tails only
h <- 0.02

# -----
60 # Obtain posterior model (no heavy tails) -----
# -----

XtLambda <- crossprod(X, Lambda)

65 K.star <- crossprod(t(XtLambda), X) + K
m.star <- solve(K.star, crossprod(t(XtLambda), y) + crossprod(K, m))
eta.star <- eta + crossprod(Lambda %*% y, y) +
              crossprod(K %*% m, m) - crossprod(K.star %*% m.star, m.star)
d.star <- d + n

70 m.star

# Prep for Gibbs sampler for model with heavy tails

75 nruns <- 1e4
burn <- 2e3

beta.post <- matrix(nrow = nruns, ncol = 2)
omega.post <- rep(NA, nruns)
80 lambda.post <- matrix(nrow = nruns, ncol = n)

beta.post[1, ] <- c(0, 0)
omega.post[1] <- 1
lambda.post[1, ] <- rep(1, n)

85 # Gibbs sampler
for (i in 2:nruns) {
  # Create lambda matrix
  Lambda.i <- diag(lambda.post[i - 1, ])

90 # Precache this crossproduct
  XtLambda.i <- crossprod(X, Lambda.i)

  # Update parameters of posterior conditionals
95 K.star.i <- crossprod(t(XtLambda.i), X) + K
  m.star.i <- solve(K.star.i, crossprod(t(XtLambda.i), y) + crossprod(K, m))
  eta.star.i <- eta + crossprod(Lambda.i %*% y, y) +
                  crossprod(K %*% m, m) - crossprod(K.star.i %*% m.star.i, m.star.i)

  # Draw from conditional posterior
100 omega.post[i] <- rgamma(1, d.star / 2, eta.star.i / 2)
  beta.post[i, ] <- rmvnorm(1, m.star.i,
                           sigma = solve(omega.post[i] * K.star.i))
  lambda.post[i, ] <- rgamma(n, rep(h/2 + 1/2, n),
105 h/2 + omega.post[i] * (y - X %*% beta.post[i, ] )^2 / 2)

```

```

}

# Burn-out
beta.post <- beta.post[-(1:burn), ]
110 omega.post <- omega.post[-(1:burn)]
lambda.post <- lambda.post[-(1:burn), ]

# Mean posterior for betas
115 m.star2 <- colMeans(beta.post)

# Plot Frequentist, Bayesian, and Bayesian heavy-tail linear models
r <- ggplot(GDP, aes(DEF60, GR6096)) + geom_point() +
  geom_abline(mapping = aes(colour = "Frequentist",
120 intercept = freq.beta[1],
slope = freq.beta[2]),
show.legend = T) +
geom_abline(mapping = aes(colour = "Bayesian heavy tails",
intercept = m.star2[1],
125 slope = m.star2[2]),
show.legend = T) +
geom_abline(mapping = aes(colour = "Bayesian iid residuals",
intercept = m.star[1],
slope = m.star[2]),
130 show.legend = T) +
xlab("Defense spending as fraction of GDP (DEF60)") +
ylab("GDP Growth Rate (GR6096)") +
ggtitle("Defense spending vs. GDP Growth Rate") +
scale_color_manual(name = "Method",
135 values = c("Frequentist" = col1,
"Bayesian iid residuals" = col2, "Bayesian heavy tails" = col3)) +
theme(legend.position = c(0.85, 0.15),
text = element_text(family="Palatino"))

r

140 # Save this plotr
pdf("img/compplot.pdf", width = 8, height = 6)
r
dev.off()

145 # Plot of reciprocals of lambdas
plot(sort(1 / colMeans(lambda.post)))

plot(sort(colMeans(lambda.post)))

150 # Plot gibbs sampler results
plot(omega.post,
type = "l")

q <- qplot(1:length(beta.post[, 1]), beta.post[, 1], geom = "blank") +
155 geom_line() +
ggtitle("Traceplot of Gibbs sampler for intercept term") +
xlab("iteration") +
ylab("Intercept") +

```

```
160   theme(text = element_text(family="Palatino"))  
w <- qplot(1:length(beta.post[, 2]), beta.post[, 1], geom = "blank") +  
  geom_line() +  
  ggtitle("Traceplot of Gibbs sampler for DEF60 term") +  
  xlab("iteration") +  
165  ylab("Intercept") +  
  theme(text = element_text(family="Palatino"))
```