

HW2

STAT 651

RJ Cass

2026-01-26

Foreword: I fully acknowledge this HW is incomplete (see #4), and in parts, probably just completely wrong. I feel like I have no idea what I'm doing in this class, and eventually just got tired of banging my head against the metaphorical wall and decided to call it quits for my wellbeing.

1: BDA3 2.10ab

$$\pi(N) = (.01)(.99)^{N-1} \quad (N > 1, 2, 3\dots)$$

a)

We see 203. What is the posterior for actual number of roadcars? Thinking about what the distribution of $P(203|N)$, if there were 203 cars, $P(203|N) = 1/203$. If there were 204, it would be $1/204$, etc. For any N less than 203 we couldn't have seen a 203, so it's 0. Thus:

$$P(203|N) = \frac{1}{N} \text{ for } N \geq 203$$

$$P(N|203) \propto P(203|N)\pi(N) = \frac{1}{N}(.01)(.99)^{N-1} = \frac{1}{N}(.01)(.99)(.99)^N \propto \underline{\frac{1}{N}(.99)^N}$$

b)

What are mean and sd of N?

To determine those, we must first find the normalizing constant. We know $\sum_N P(N|203) = \sum_N \frac{c}{N}(.99)^N = 1 \implies \frac{1}{c} = \sum_N \frac{1}{N}(.99)^N \implies c = \frac{1}{\sum_N \frac{1}{N}(.99)^N}$. This is solved via R below:

```
N_list <- c(203:1000)
c <- round(1/sum(sapply(N_list, \(N) 1/N*.99^N)), 4)
```

Giving us $c \approx 21.4701$.

$$E(N|203) = \sum_{N=203}^{\infty} N * P(N|203) = \sum_{N=203}^{\infty} \frac{cN}{N}(.99)^N = c \sum_{N=203}^{\infty} (.99)^N$$

```
E <- round(c*sum(sapply(N_list, \(N) .99^N)), 4)
```

$$\underline{E(N|203) \approx 279.0203}$$

$$\sigma(N|203) = \sqrt{\sum_{N=203}^{\infty} (N - E(N|203))^2 P(N|203)} = \sqrt{\sum_{N=203}^{\infty} (N - 279.0203)^2 \frac{21.4701}{N} (.99)^N}$$

```
sd <- round(sqrt(sum(sapply(N_list, \(N) (N - E)^2 * c / N * .99^N))), 4)
```

$$\underline{\sigma(N|203) \approx 79.6154.}$$

c)

Find the MLE and compare to the Bayes estimate.

Just thinking about this, as explained above, for $N = 203$, $P(203|N) = \frac{1}{203} = \frac{1}{N}$. As N increases, the probability only decreases, meaning the MLE for N is the smallest possible value, which in our case, is 203.

I think both methods have their benefits, but the Bayes method allows a bit more leeway for there to be more than the exact number we saw and is likely a better reflection of reality (as long as our prior is actually reasonable).

2

Assume $\theta = Beta(\alpha, \beta)$

a)

We observe $x_1|\theta \sim Binom(n_1, \theta)$. Find $\pi(\theta|x_1)$.

$$\begin{aligned}\pi(\theta|x_1) &= f(x_1|\theta)f(\theta) = Binom(n_1, \theta) * Beta(\alpha, \beta) = \binom{n}{x_1} \theta^{x_1} (1-\theta)^{n-x_1} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha-1} (1-\theta)^{\beta-1} \\ &= \binom{n}{x_1} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha+x_1-1} (1-\theta)^{\beta+n-x_1-1}\end{aligned}$$

b)

We observe $x_2|\theta \sim Binom(n_2, \theta)$. Use $\pi(\theta|x_1)$ as the prior for the second day. Find $\pi(\theta|x_1, x_2)$

$$\begin{aligned}\pi(\theta|x_1, x_2) &= f(x_2|\theta)f(\theta|x_1) = Binom(n_2, \theta) * \pi(\theta|x_1) = \binom{n}{x_2} \theta^{x_2} (1-\theta)^{n-x_2} \binom{n}{x_1} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha+x_1-1} (1-\theta)^{\beta+n-x_1-x_2-1} \\ &= \binom{n}{x_1+x_2} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha+x_1+x_2-1} (1-\theta)^{\beta+2n-x_1-x_2-1}\end{aligned}$$

c)

Let $y = x_1 + x_2$. What is $\pi(\theta|y)$. How does this compare to answer from (b)?

$$f(y|\theta) = \binom{n}{x_1+x_2} \theta^{x_1+x_2} (1-\theta)^{n-(x_1+x_2)}$$

Thus,

$$\begin{aligned}\pi(\theta|y) &= f(y|\theta) * f(\theta) = \binom{n}{x_1+x_2} \theta^{x_1+x_2} (1-\theta)^{n-(x_1+x_2)} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha-1} (1-\theta)^{\beta-1} \\ &= \binom{n}{x_1+x_2} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha+x_1+x_2-1} (1-\theta)^{\beta+2n-x_1-x_2}\end{aligned}$$

This is the same answer which, as stated in the problem, indicates that using a hierarchical model gives the same answer as multiple step Bayesian if you use the posterior of step 1 as the prior for step 2.

3

$$f(y_i|\lambda) = \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \text{ for } y_i \in 0, 1, 2, \dots$$

a)

Show the conjugate prior for λ is the gamma distribution

$$\begin{aligned}L(y_i|\lambda) f(\lambda) &\propto \lambda^{\sum y_i} e^{-n\lambda} [\lambda^{\alpha-1} e^{\lambda\beta}] \\ &= \lambda^{\sum y_i + \alpha - 1} e^{\lambda(n+\beta)}\end{aligned}$$

This is another Gamma distribution with $\alpha = \sum y_i + \alpha$, $\beta = n + \beta$

b)

Identify the sufficient statistic for λ

The sufficient statistic for λ is just $\sum y_i$

c)

Derive the prior predictive distribution for one month's failure count y

$$\begin{aligned}\mathbb{P}(y_i) &= \int_{\Lambda} f(y_i|\lambda)\pi(\lambda) \\ &= \int_{\Lambda} \frac{\lambda^{y_i} e^{-\lambda}}{y_i!} \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda} d\lambda \\ &= \frac{\beta^\alpha}{\Gamma(\alpha)y_i!} \int_{\Lambda} \lambda^{\alpha+y_i-1} e^{-\lambda(\beta+1)} d\lambda \text{ This is a Gamma Kernel} \\ &= \frac{\beta^\alpha}{\Gamma(\alpha)y_i!} \frac{\Gamma(\alpha+y_i)}{(\beta+1)^{\alpha+y_i}}\end{aligned}$$

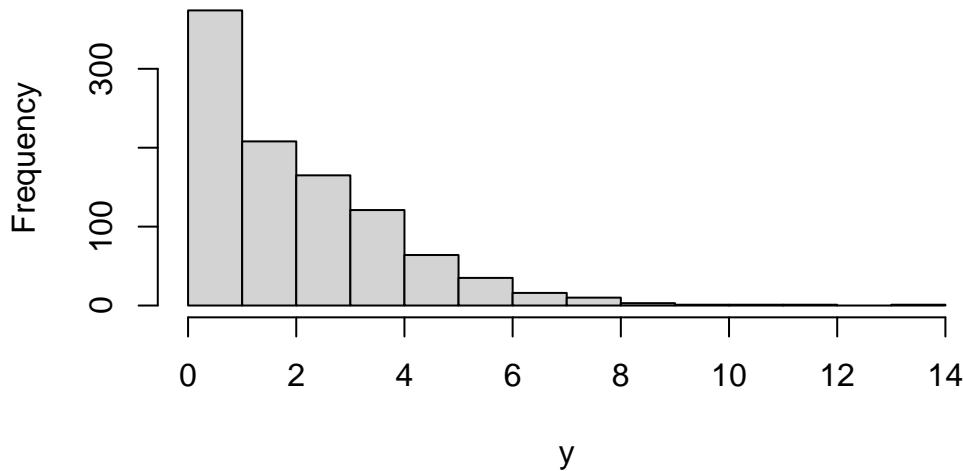
In talking with classmates, they helped me see that this reduces down to a $\underline{\text{Neg.Binom.}(\alpha, \frac{\beta}{1+\beta})}$

d)

Verify the prior predictive by simulating (λ, y) pairs

```
n <- 1000
lambda <- rgamma(n, 3.5, 1.5)
y <- rpois(n, lambda)
hist(y)
```

Histogram of y



Picking just some values (also tried to see values for part (e)) for the prior on λ , this does indeed appear to be a Negative Binomial on y .

e)

Use my prior predictive to calibrate the against the expert's opinion

Expert says there should rarely more than 10 failures in one month, so we'll use $\alpha = 3.5, \beta = -3$

f)

Find posterior using: $y = (3, 4, 3, 1, 1, 4, 1, 4, 2, 1, 1, 3, 1, 1, 4)$

```
y <- c(3, 4, 3, 1, 1, 4, 1, 4, 2, 1, 1, 3, 1, 1, 4)
sum_y <- sum(y)
```

$$\text{Posterior} \propto \lambda^{34} e^{-n\lambda} [\lambda^{3.5-1} e^{-\lambda 3}]$$

g)

Use posterior predictive to find prob. that num. failures in any given month exceeds 3

This is one of those parts I'm not too sure what to do. I've obviously done something wrong prior (pun intended) to this. Theoretically, I would just take my posterior distribution and integrate from 3 to infinity.

4

a)

$$f(y_i|\theta) = \theta e^{-y_i\theta}, y_i > 0$$

i. Conjugate Prior

The conjugate prior for this is the Gamma distribution.

ii. Prove conjugate prior

$$\begin{aligned} p(y_i|\theta) * \Gamma(\alpha, \beta) \\ &= \prod \theta e^{-\theta y_i} \Gamma(\alpha, \beta) \\ &\propto \theta^n e^{-\theta \sum y_i} \theta^{\alpha-1} e^{-\beta \theta} \\ &= \theta^{n+\alpha-1} e^{-\theta(\beta+\sum y_i)} \end{aligned}$$

This is a $\Gamma(n + \alpha, \beta \sum y_i)$

iii. Choose values for prior and justify

Looking online, Google says that many of the major rivers fall in the 600-1000 mile range, so I'll pick a mean of ~ 750 , and a standard deviation of 350 (the max values are around 2500 miles). This gives what I believe to be a reasonable representation of the expected distribution. To get an average of the distribution of ~ 750 , we need $\theta = 1/750$, so I will set that as my average, and just some small value like $1/500$ as my variance, and use those to calculate the actual parameters for the prior.

```
avg <- 1/750
var <- 1/500
beta <- var/avg
alpha <- avg/beta
```

This gives an $\alpha \approx 9 \times 10^{-4}$, $\beta \approx 1.5$

iv. Find MLE and Bayesian Posterior Mean

$$l(\theta|y) = \sum [ln(\theta) - y_i \theta] = n ln(\theta) - \theta \sum y_i$$
$$\frac{d}{d\theta} l(\theta|y) = \frac{n}{\theta} - \sum y_i = 0 \implies \theta = \frac{n}{\sum y_i} = \frac{1}{\bar{y}}$$

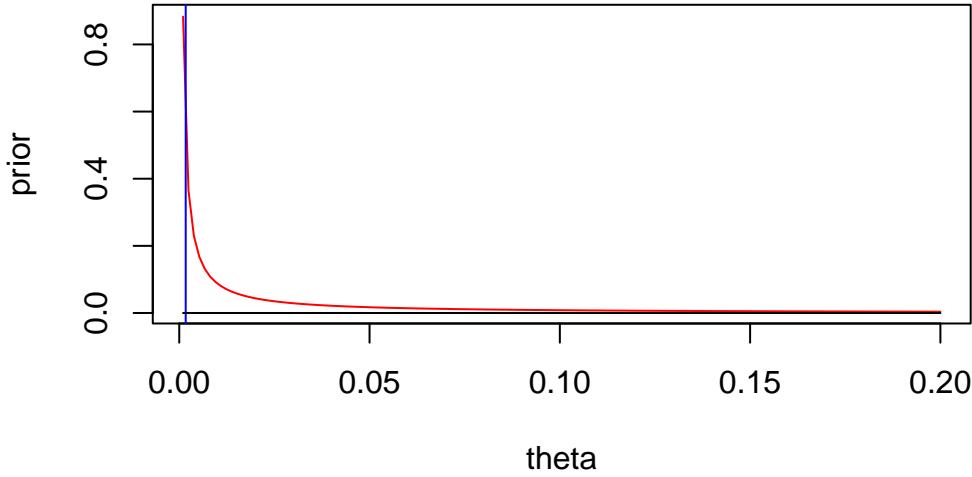
Mean of a $\Gamma(\alpha, \beta)$ is $\alpha\beta$, so for the Bayesian Posterior Mean I first need to find the normalizing constant.

$c = \frac{1}{\Gamma(\alpha)\beta^\alpha}$. Thus the BPM is $(n + \alpha)(\beta \sum y_i)^{\frac{1}{\Gamma(\alpha)\beta^\alpha}}$

v. Plot prior and posterior densities with MLE and Bayesian mean included

```
y <- as.numeric(readLines("rivers.dat"))

n <- 141
theta <- seq(.001, .2, length = n)
prior <- dgamma(theta, shape = alpha, scale = beta)
posterior <- dgamma(theta, shape = n+alpha, scale = beta*sum(y))
mle <- 1/mean(y)
bpm <- (n+alpha)*(beta*sum(y))/(gamma(alpha)*beta^alpha)
plot(theta, prior, type = 'l', col = 'red')
abline(v = mle, col = 'blue')
abline(v = bpm, col = 'green')
lines(theta, posterior)
```



vi. Find Posterior Mean, Median, Mode, Var, SD, and 95% CI for parameter

```
post_mean <- mean(posterior)
post_med <- median(posterior)
post_mode <- mode(posterior)
post_var <- var(posterior)
post_sd <- sd(posterior)
```

vii. Propose 2 other priors, plot all 3 priors on same graph, find the same summary stats, put all in table

My posterior stuff wasn't working. I genuinely don't really understand this and just want to turn something in.

b)

$$f(y_i|\mu, \tau) = \tau^{1/2} (2\pi)^{-1/2} \exp(-\frac{\tau}{2}(y_i - \mu)^2), y_i \in \mathbb{R}$$

$$\mu \text{ unknown}, \tau = 1/81$$

i. Conjugate Prior

The conjugate prior is the Normal

ii. Prove conjugate prior

$$\begin{aligned}
 p(y_i|\mu, \tau) * N(\mu, \sigma) &\propto \prod e^{-\frac{\tau}{2}(y_i - \mu)^2} * e^{-1/(2\sigma^2)(x - \mu)^2} \\
 &= \prod e^{-\frac{\tau}{2}(y_i^2 - 2\mu y_i + \mu^2)} * e^{-1/(2\sigma^2)(x^2 - 2\mu x + \mu^2)} \\
 &= e^{-\frac{n\tau}{2}(y_i^2 - 2\mu y_i + \mu^2)} * e^{-1/(2\sigma^2)(x^2 - 2\mu x + \mu^2)} \\
 &= e^{-\mu^2(-\frac{n\tau}{2} + \frac{1}{2\sigma^2}) + 2\mu(n\tau + 1/\sigma^2)}
 \end{aligned}$$

At this point you would complete the square which I'm not going to do. Too exhausted already.

iii. Choose values for prior and justify

iv. Find MLE and Bayesian Posterior Mean

v. Plot prior and posterior densities with MLE and Bayesian mean included

vi. Find Posterior Mean, Median, Mode, Var, SD, and 95% CI for parameter

vii. Propose 2 other priors, plot all 3 priors on same graph, find the same summary stats, put all in table

c)

$$f(y_i|\mu, \tau) = \tau^{1/2}(2\pi)^{-1/2} \exp(-\frac{\tau}{2}(y_i - \mu)^2), y_i \in \mathbb{R}$$

τ unknown, $\mu = 87$

i. Conjugate Prior

The conjugate prior is the Gamma.

ii. Prove conjugate prior

$$\begin{aligned} p(y_i|\mu, \tau) * N(\mu, \sigma) &\propto \prod e^{-\frac{\tau}{2}(y_i - \mu)^2} * e^{-1/(2\sigma^2)(x - \mu)^2} \\ &= \prod e^{-\frac{\tau}{2}(y_i^2 - 2\mu y_i + \mu^2)} * e^{-1/(2\sigma^2)(x^2 - 2\mu x + \mu^2)} \\ &= e^{-\frac{n\tau}{2}(y_i^2 - 2\mu y_i + \mu^2)} * e^{-1/(2\sigma^2)(x^2 - 2\mu x + \mu^2)} \\ &= e^{-\mu^2(-\frac{n\tau}{2} + \frac{1}{2\sigma^2}) + 2\mu(n\tau + 1/\sigma^2)} \end{aligned}$$

iii. Choose values for prior and justify

iv. Find MLE and Bayesian Posterior Mean

v. Plot prior and posterior densities with MLE and Bayesian mean included

vi. Find Posterior Mean, Median, Mode, Var, SD, and 95% CI for parameter

vii. Propose 2 other priors, plot all 3 priors on same graph, find the same summary stats, put all in table

5

$$Y|\theta, Z \sim \text{Binom}(n, \theta Z)$$

$$\pi(\theta) \sim \text{Unif}(0, 1)$$

$$\pi(Z) \sim \text{Bern}(.5)$$

When $Z = 0$, $Y = 0$. Otherwise, for $Z = 1$, $Y|\theta, Z \sim \text{Binom}(n, \theta)$

a)

What is posterior that the frog is in the forest ($\mathbb{P}(Z = 1|Y)$)

$$\begin{aligned} f(y, z, \theta) &= f(Y|\theta, Z) * \pi(\theta) * \pi(Z) \\ &= \text{Binom}(n, \theta Z) * \text{Unif}(0, 1) * \text{Bern}(.5) \\ &= \binom{n}{y} \theta^y (1 - \theta)^{n-y} I_{Z=1} P(Z=1) + I_{Z=0} P(Z=0) I_{Y=0} \\ &= .5 \binom{n}{y} \theta^y (1 - \theta)^{n-y} I_{Z=1} + .5 I_{Z=0} I_{Y=0} \end{aligned}$$

$$\begin{aligned} f(y, z) &= \int_0^1 .5 \binom{n}{y} \theta^y (1 - \theta)^{n-y} I_{Z=1} + .5 I_{Z=0} I_{Y=0} d\theta \\ &= .5 \binom{n}{y} I_{Z=1} \int_0^1 \theta^y (1 - \theta)^{n-y} + .5 I_{Z=0} I_{Y=0} \int_0^1 d\theta \\ &= .5 I_{Z=1} \binom{n}{y} \frac{\Gamma(y+1)\Gamma(n-y+1)}{\Gamma(y+1+n-y+1)} + .5 I_{Z=0} I_{Y=0} \\ &= .5 I_{Z=1} \frac{n!}{y!(n-y)!} \frac{y!(n-y)!}{\Gamma(n+2)} + .5 I_{Z=0} I_{Y=0} \\ &= .5 I_{Z=1} \frac{n!}{(n+1)!} + .5 I_{Z=0} I_{Y=0} \\ &= .5 I_{Z=1} \frac{n!}{(n+1)!} + .5 I_{Z=0} I_{Y=0} \\ &= \frac{.5}{n+1} I_{Z=1} + .5 I_{Z=0} I_{Y=0} \end{aligned}$$

$$f(y) = \frac{.5}{n+1} + .5 I_{Y=0}$$

$$\mathbb{P}(Z = 1|Y) = \frac{\frac{.5}{n+1} I_{Z=1} + .5 I_{Z=0} I_{Y=0}}{\frac{.5}{n+1} + .5 I_{Y=0}}$$

b)

What is the smallest sample size such that $\mathbb{P}(Z = 1|Y = 0) < .05$

```
n <- 1:10
pz_y <- .5/(n+1) / (.5/n+1 + .5)
smallest_n <- min(n[which(pz_y < .05)])
```

Smallest sample size to use is 6.

Homework Statements

Estimate of Time Taken

I estimate this homework took about 14 hours in total.

Disclosure of Resources Used

I used some online helps (Google, StackOverflow) for some help with debugging. In particular, I used Google to identify the Conjugate distributions for (4). Doing Priors and everything is still really hard for me (this is my first exposure to them), so I also used them to help me understand how to setup the problems (ie. get the Likelihood, know what to multiply, etc.). Definitely worked with some classmates to help me understand how to setup some problems, such as number 5.