

# CompStat 1

## Problem A

1)

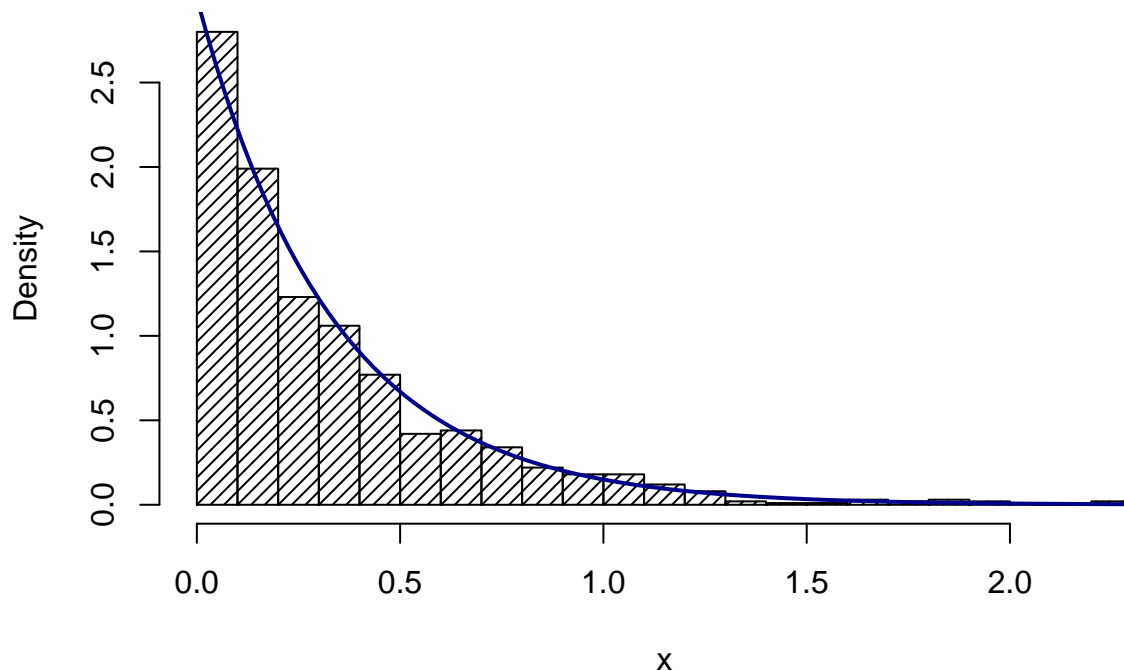
Here using the inversion method, we get:

$$x = F^{-1}(u) = -\frac{1}{\lambda} \log(u), \quad u \sim U(0,1).$$

Thus we get a exponential samples, by sampling from the uniform distribution, and use the inversion method. Under it a function that generates a vector of  $n$  samples from an exponentially distributed random variable with rate  $\lambda$ .

```
# Generate samples from exponential distribution
rate <- 3 #Rate parameter
n <- 1000 #Number of samples
generate.exponential <- function(rate, n){
  u <- runif(n)
  x <- - 1/rate * log(u)
  return(x)
}
x <- generate.exponential(rate, n)
hist(x, density=20, breaks = 30, prob=TRUE)
curve(dexp(x, rate=rate), add=TRUE, col="darkblue", lwd=2)
```

**Histogram of x**



2)

The cdf  $G(x)$  of  $g(x)$  and its inverse  $G^{-1}$  are

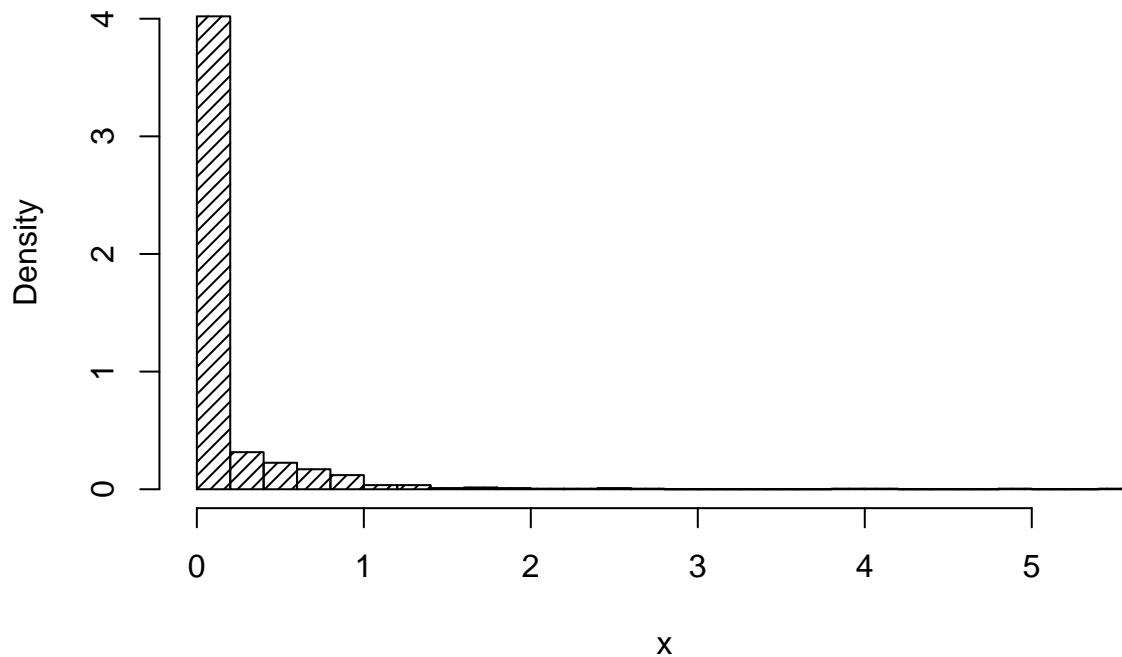
$$G(x) = \begin{cases} \int_0^1 cx^{\alpha-1}dx & , 0 < x \leq 1 \\ \int_1^\infty ce^x dx & , 1 \leq x \\ 0 & , x \leq 0 \end{cases} = \begin{cases} c(\alpha-1)x^\alpha & , 0 < x \leq 1 \\ c(e^{-1} - e^{-x}) & , 1 \leq x \\ 0 & , x \leq 0 \end{cases}$$

$$G^{-1}(u) = \begin{cases} \left(\frac{u}{c(\alpha-1)}\right)^{\frac{1}{\alpha}} & , \text{SJEKK GRENSER } 0 < \left(\frac{u}{c(\alpha-1)}\right)^{\frac{1}{\alpha}} \leq 1 \\ -\log(e^{-1} - \frac{u}{c}) & , 1 \leq -\log(e^{-1} - \frac{u}{c}) \\ 0 & , u \leq 0 \end{cases}$$

Writing a function that returns  $g$ -samples.

```
# Generate samples from g(X)
rate <- 3 #Rate parameter
n <- 1000 #Number of samples
alpha <- 0.1
generate.samples.g<- function(alpha, n){
  c <- alpha*exp(1)/(alpha+exp(1))
  u <- runif(n, 0,1)
  x <- c()
  for (i in 1:n){
    if (u[i] < c/(alpha)){
      x <- c(x, (u[i]*(alpha)/c)^(1/alpha))
    }
    else{
      x <- c(x, 1-log(exp(1)/c*(1-u[i])))
    }
  }
  return(x)
}
x <- generate.samples.g(alpha, n)
hist(x, density=20, breaks = 20, prob=TRUE)
```

## Histogram of x

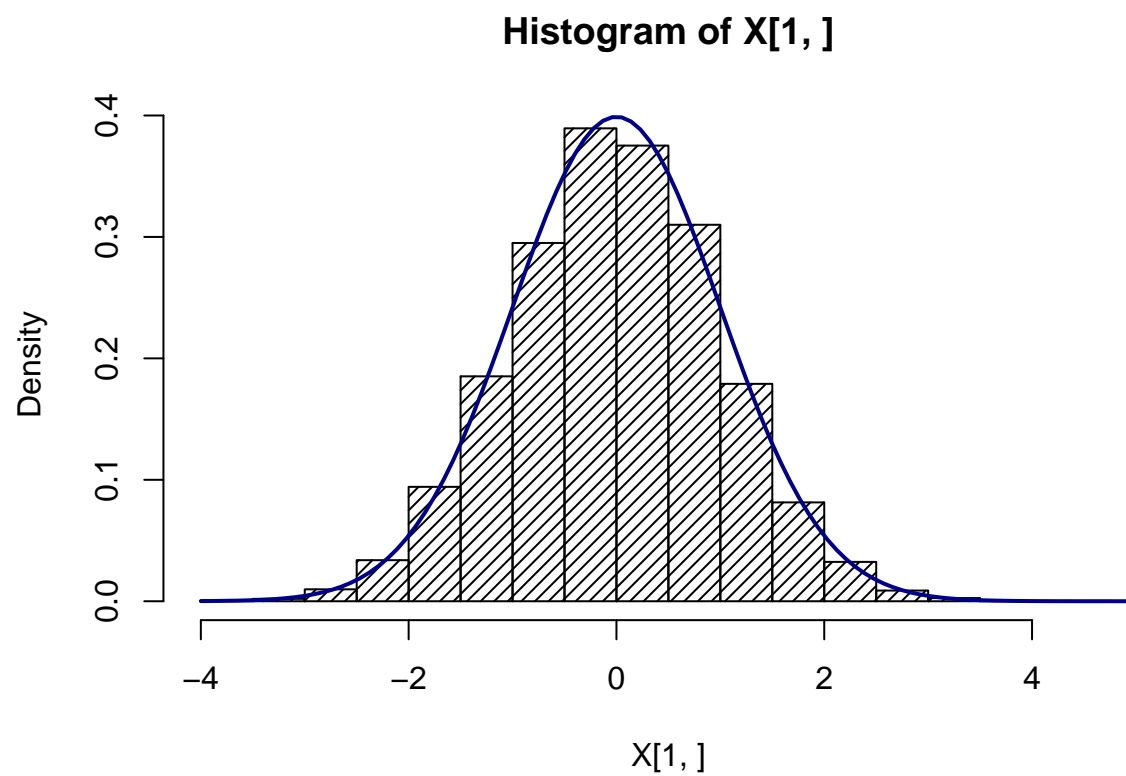


The histogram is used to check that `generate.samples.g` returns the correct value. As we see here, ...

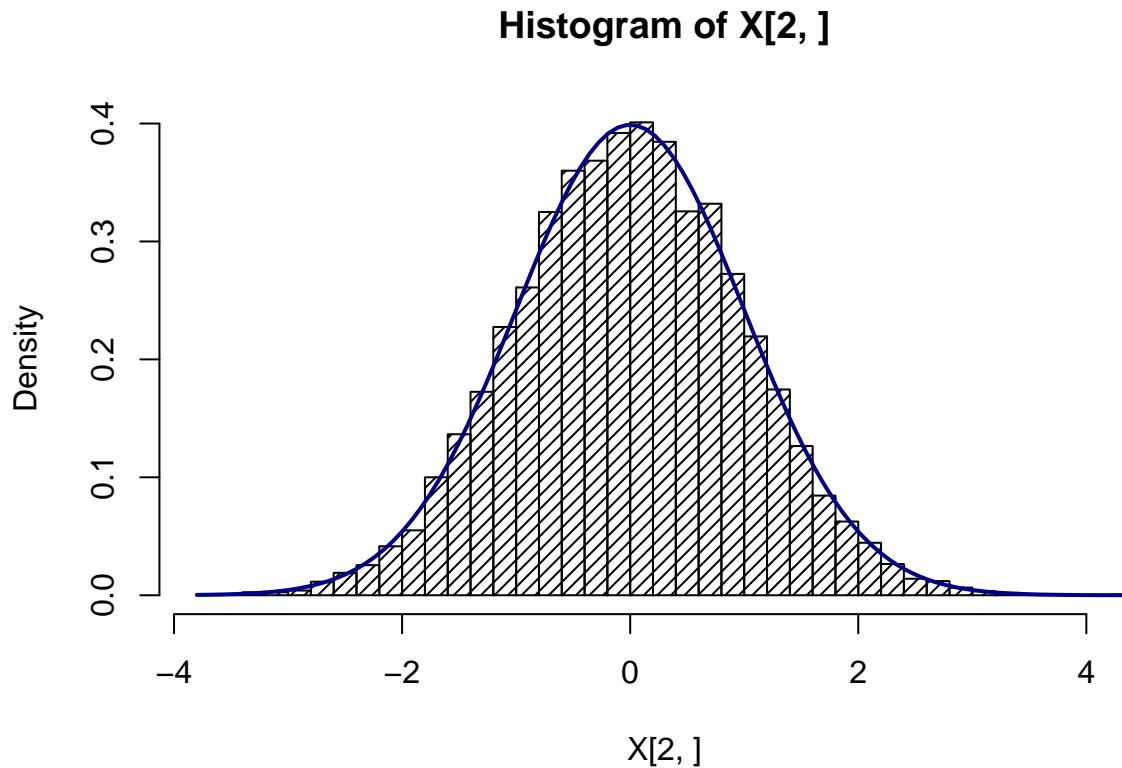
### 3)

The function `generate.normal` uses Box-Muller to generate an  $n$ -vector of independent samples from the standard normal distribution.

```
# Generate samples from normal distribution with Box-Muller
n <- 10000 #Number of samples
generate.normal <- function(n){
  u1 <- runif(n)
  u2 <- runif(n)
  x1 <- sqrt(-2*log(u1))*cos(2*pi*u2)
  x2 <- sqrt(-2*log(u1))*sin(2*pi*u2)
  X <- rbind(x1, x2)
  return (X)
}
X <- generate.normal(n)
hist(X[1,], density=20, breaks = 30, prob=TRUE)
curve(dnorm, add=TRUE, col="darkblue", lwd=2)
```



```
hist(X[2,], density=20, breaks = 30, prob=TRUE)  
curve(dnorm, add=TRUE, col="darkblue", lwd=2)
```



```
print("Observed: ")
```

```
## [1] "Observed: "
```

```
mean(X)
```

```
## [1] -0.007784062
```

```
cov(t(X))
```

```
##           x1           x2
## x1  0.99986674 -0.01497694
## x2 -0.01497694  0.98772750
```

As we see, the observed mean and variance is fairly close to the moments of the standard normal distribution, which are zero and one. The empirical covariance  $Cov(x_1, x_2)$  is also close to zero, as expected.

4)

Writing function `generate.d.normal` that generates samples from a  $d$ -variate normal distribution with mean vector  $\mu$  and covariance matrix  $\Sigma$ .

```
# Generate n samples from d variate normal distribution
n <- 10000 #Number of samples
mu <- c(0,0)
sigma <- cbind(c(1,0.5),c(0.5,1))
generate.d.normal <- function(n, mu, sigma){
  A <- chol(sigma)
  d <- length(mu)
```

```

X <- generate.normal(n*d)
x <- matrix(X[1,], nrow=d, ncol=n)
Z <- mu+t(A)%*%x
}
Z <- generate.d.normal(n, mu, sigma)
print("Expected: ")

```

```
## [1] "Expected: "
```

```
mu
```

```
## [1] 0 0
```

```
sigma
```

```
##      [,1] [,2]
```

```
## [1,]  1.0  0.5
```

```
## [2,]  0.5  1.0
```

```
print('Observed: ')
```

```
## [1] "Observed: "
```

```
mean(Z)
```

```
## [1] -0.006273658
```

```
cov(t(Z))
```

```
##      [,1]      [,2]
```

```
## [1,] 1.0078294 0.4911569
```

```
## [2,] 0.4911569 0.9891390
```

As we see,  $\mu$  is close to ER MU KUN 2-VARIAT?

## B

```

#Function f(x)
function.f <- function(x, alpha){
  if (x>0){
    return (x^(alpha-1)*exp(-x)/gamma(alpha))
  }
  else{
    return(0)
  }
}

```

```

#Function g(x)
function.g <- function(x, alpha){
  c = alpha*exp(1)/(alpha+exp(1))
  if (x>0 && x<1){
    return (c*x^(alpha-1))
  }
  else if(x >= 1){
    return(c*exp(-x))
  }
  else{

```

```

    return(0)
  }
}

# Generate n samples from d variate normal distribution
n <- 1000 #Number of samples
alpha <- 0.3
rejection.sampling <- function(n, alpha){
  c <- (alpha+exp(1))/(gamma(alpha)*alpha*exp(1))
  samples <- c()
  for (i in 1:n){
    repeat{
      x <- generate.samples.g(alpha, 1)
      acceptance.prob <- function.f(x, alpha)/(c*function.g(x, alpha))
      if(runif(1) <= acceptance.prob){
        samples <- c(samples, x)
        break
      }
    }
  }
  return(samples)
}
y <- rejection.sampling(n, alpha)
print("Expected: ")

```

```
## [1] "Expected: "
```

```
cat("Mean: ", alpha, "\n")
```

```
## Mean: 0.3
```

```
cat("Variance: ", alpha, "\n")
```

```
## Variance: 0.3
```

```
print("Observed: ")
```

```
## [1] "Observed: "
```

```
cat("Mean: ", mean(y), "\n")
```

```
## Mean: 0.2995217
```

```
cat("Variance: ", var(y), "\n")
```

```
## Variance: 0.2646554
```

```

log.gamma <- function(x, alpha){
  return((alpha-1)*log(x)-x)
}

# Ratio-of-uniforms method
n <- 1000
alpha <- 30
ratio.of.uniforms <- function(n, alpha){
  sample.counter <- 0
  b.minus <- 0
  log.b.plus <- (alpha+1)/2*(log(alpha+1)-1)
  log.a <- (alpha-1)/2*(log(alpha-1)-1)

```

```

samples <- c()
for(i in 1:n){
  repeat{
    sample.counter <- sample.counter + 1
    log.x1 <- -generate.exponential(1, rate=1) + log.a
    log.x2 <- -generate.exponential(1, rate=1) + log.b.plus
    log.y <- log.x2 - log.x1
    y <- exp(log.y)
    if (2*log.x1 <= log.gamma(y, alpha)){
      samples <- c(samples, y)
      break
    }
  }
}
cat("Rejection ratio: ", (sample.counter-n)/n , "\n")
return (samples)
}
y <- ratio.of.uniforms(n, alpha)

```

```
## Rejection ratio: 3.322
```

```
print("Expected: ")
```

```
## [1] "Expected: "
```

```
cat("Mean: ", alpha, "\n")
```

```
## Mean: 30
```

```
cat("Variance: ", alpha, "\n")
```

```
## Variance: 30
```

```
print("Observed: ")
```

```
## [1] "Observed: "
```

```
cat("Mean: ", mean(y), "\n")
```

```
## Mean: 29.96807
```

```
cat("Variance: ", var(y), "\n")
```

```
## Variance: 30.12334
```

```
n = 1000
```

```
alpha = 0.1
```

```
beta = 2
```

```

sample.gamma <- function(n, alpha, beta){
  if(alpha < 1){
    return(rejection.sampling(n, alpha)/beta)
  }
  else if (alpha == 1){
    return(generate.exponential(1, n)/beta)
  }
  else if (alpha > 1){
    return(ratio.of.uniforms(n, alpha)/beta)
  }
  else{

```



```

    return(0)
  }
}
y <- sample.gamma(n, alpha, beta)
print("Expected: ")

## [1] "Expected: "
cat("Mean: ", alpha/beta, "\n")

## Mean:  0.05
cat("Variance: ", alpha/beta^2, "\n")

## Variance:  0.025
print("Observed: ")

## [1] "Observed: "
cat("Mean: ", mean(y), "\n")

## Mean:  0.05287266
cat("Variance: ", var(y), "\n")

## Variance:  0.02397319

```

## Problem C

1)

Claim: Given independent variables  $z_k \sim \text{gamma}(\alpha_k, \beta = 1)$  for  $k = 1, \dots, K$ , define  $x_k = z_k \cdot (\sum_{k=1}^K z_k)^{-1}$  for  $k = 1, \dots, K$ . Then vector  $(x_1, \dots, x_K)$  has the Dirichlet distribution with parameter vector  $\alpha = (\alpha_1, \dots, \alpha_K)$ .  
 Demonstration: Consider vector  $x = (x_1, \dots, x_{K-1})$  with  $x_k$  as before and variable  $v = \sum_{k=1}^K z_k$ . Express the transformation

$$Z_k = X_k \cdot V \text{ for } k = 1, \dots, K-1 ; Z_K = V \cdot X_K = V(1 - X_1 - \dots - X_{K-1})$$

$X, V$  now has joint distribution  $f_{X,V} = |J| \cdot f_Z(z) = |J| \cdot \prod_{k=1}^K e^{-z_k} z_k^{\alpha_k-1} \cdot \frac{1}{\Gamma(\alpha_k)}$

$$f_{X,V} = |J| \cdot f_Z(z) = |J| \cdot \prod_{k=1}^K e^{-z_k} z_k^{\alpha_k-1} \cdot \frac{1}{\Gamma(\alpha_k)}$$

with

$$J = \begin{bmatrix} V & 0 & \dots & X_1 \\ 0 & V & \dots & \vdots \\ \vdots & \vdots & \ddots & X_{K-1} \\ -V & \dots & -V & X_K \end{bmatrix} \sim \begin{bmatrix} V & 0 & \dots & X_1 \\ 0 & V & \dots & \vdots \\ \vdots & \vdots & \ddots & X_{K-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \Rightarrow |J| = V^{K-1}$$

Here we have used row reduction on the bottom row, along with the fact that  $X_K = \sum_{k=1}^{K-1} X_k$  and determinant rule for triangular matrices.

Isolate the  $v$ -part of  $f_{X,V}$  and integrate with respect to  $v$ , yielding the marginal distribution  $f_X$ .

$$f_{X,V} = v^{K-1} \prod_{k=1}^K e^{-x_k v} (x_k v)^{\alpha_k - 1} \cdot \frac{1}{\Gamma(\alpha_k)} = v^{\sum \alpha_k - 1} e^{-v} \prod_{k=1}^K x_k^{\alpha_k - 1} \cdot \frac{1}{\Gamma(\alpha_k)}$$

$$f_X(x) = \prod_{k=1}^K x_k^{\alpha_k - 1} \cdot \frac{1}{\Gamma(\alpha_k)} \cdot \int_0^\infty v^{\sum \alpha_k - 1} e^{-v} dv$$

$$f_X(x) = \left( \prod_{k=1}^K x_k^{\alpha_k - 1} \cdot \frac{1}{\Gamma(\alpha_k)} \right) \cdot \Gamma\left(\sum_{k=1}^K \alpha_k\right) = \frac{\Gamma\left(\sum_{k=1}^K \alpha_k\right)}{\prod_{k=1}^K \Gamma(\alpha_k)} \prod_{k=1}^{K-1} x_k^{\alpha_k - 1} \cdot \left(1 - \sum_{k=1}^{K-1} x_k\right)^{\alpha_K - 1}$$

where the integral resolves from the fact that the Gamma distribution with shape  $\sum_{k=1}^K \alpha_k$  and rate one integrates to one. We again used that  $X_K = 1 - \sum_{k=1}^{K-1} x_k$ . ## 2)

*# Here, the user can manually change the alpha vector*

*# in order to draw a sample from any chosen Dirichlet distribution.*

`alphas.from.user=c(1.34534,0.9345,0.6356,20,14,5,2)`

```
gammas.in.dirichlet <- function(alpha){
  n=length(alpha)
  gammas <- c()
  for(i in 1:n){
    gammas <- c(gammas, sample.gamma(1,alpha[i],1))
  }
  return(gammas)
}

generate.dirichlet <- function(alpha){ # Creates Dirichlet distributed vector
  g<-gammas.in.dirichlet(alpha)       # with the K chosen alphas
  print(g)                            # as K-variate parameter vector.
  v<-sum(g)
  z=g/v
  return(z)
}

dirich.var<-generate.dirichlet(alphas.from.user)
```

```
## Rejection ratio: 0
## Rejection ratio: 5
## Rejection ratio: 0
## Rejection ratio: 0
## Rejection ratio: 0
## [1] 3.44660911 2.01231621 0.05635422 22.18572735 12.89698797 4.77014094
## [7] 0.31303884
```

`dirich.var` *# The elements in the Dirichlet distribution*

```
## [1] 0.075449223 0.044051324 0.001233642 0.485664555 0.282326102 0.104422467
## [7] 0.006852688
```

`print(sum(dirich.var))` *# The sum of the elements in the Dirichlet distribution*

```
## [1] 1
```

In the code, the normalising of the Dirichlet distributed vector  $x$  occurs after the gammas  $z$  have been sampled, so  $\|x\|_1$  is always one, which is equal to the joint expected value of  $x$ 's elements.

## Problem D

### D1)

Given a prior Beta(1, 1), which is equal to the uniform distribution on (0, 1), and a multinomial density function:

$$f(\mathbf{y}|\theta) \propto (2 + \theta)^{y_1} (1 - \theta)^{y_2 + y_3} \theta^{y_4},$$

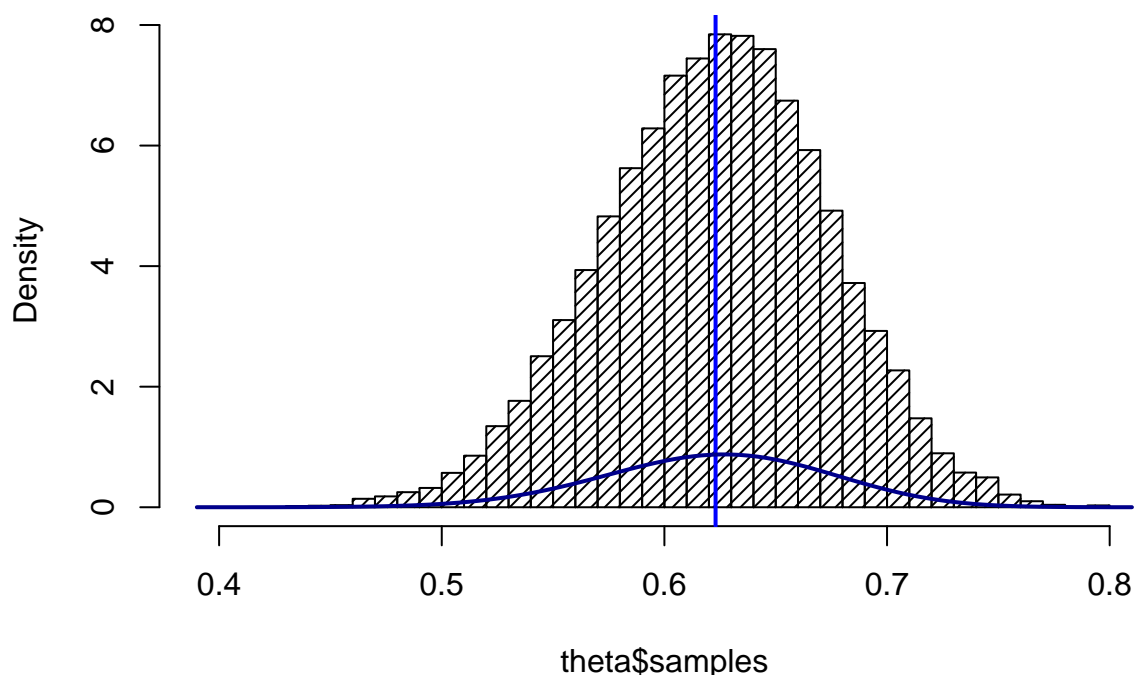
we have that the posterior is distributed with:

$$f(\theta, \mathbf{y}) \propto (2 + \theta)^{y_1} (1 - \theta)^{y_2 + y_3} \theta^{y_4}, \quad \theta \in (0, 1).$$

We also have the values for  $\mathbf{y}$ :  $y_1 = 125$ ,  $y_2 = 18$ ,  $y_3 = 20$ ,  $y_4 = 34$ . Thus we can use a rejection sample method, where we sample thetas from the prior, compute the acceptance probability, and then reject/include a random number into sample. To find the constant c, we have optimized over the posterior distribution. This will not be the real c value, but c times the proportional constant of the posterior distribution and the multinomial distribution. There is however no need to find this constant as when dividing the posterior by c, it would cancel.

```
# Rejection sampling
n <- 20000 #Number of samples
posterior.f <- function(theta){
  y <- c(125, 18, 20, 34)
  return ((2+theta)^y[1]*(1-theta)^(y[2]+y[3])*theta^y[4])
}
rejection.sampling.multinomial <- function(n){
  sample.counter <- 0
  c <- optimize(posterior.f, c(0, 1), maximum=TRUE)$objective
  samples <- c()
  for(i in 1:n){
    repeat{
      sample.counter <- sample.counter + 1
      theta <- runif(1)
      acceptance.prob <- posterior.f(theta)/c
      u <- runif(1)
      if (u <= acceptance.prob){
        samples <- c(samples, theta)
        break
      }
    }
  }
  li <- list("samples" = samples, "number.samples" = sample.counter)
  return (li)
}
theta <- rejection.sampling.multinomial(n)
hist(theta$samples, density=20, breaks = 30, prob=TRUE)
abline(v = mean(theta$samples), col = "blue", lwd = 2)
curve(posterior.f(x)*sum(theta$samples)/sum(posterior.f(theta$samples)), add=TRUE, col="darkblue", lwd=2)
```

## Histogram of theta\$samples



```
cat("Theta sample mean", mean(theta$samples))
```

```
## Theta sample mean 0.6229804
```

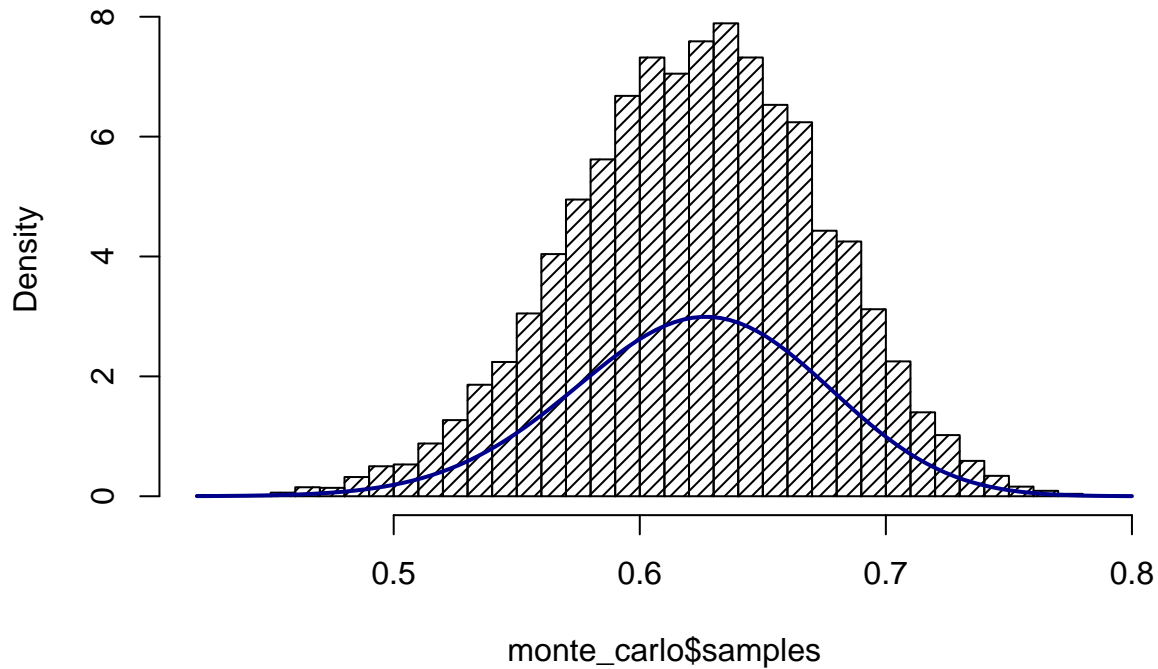
Here is a plot over the density of the sampled  $\theta$ 's as well as the sampled mean. As we can see the sample mean of  $\theta$  is circa 0.623, which may suggest that the prior was not right (as we would expect mean close to 0.5 from a uniform (0, 1) distribution).

## D2)

Here we have

```
monte.carlo.integration <- function(){
  m <- 10000 # Number of samples
  samples <- rejection.sampling.multinomial(m)$samples
  mu <- sum(samples)/m
  li <- list("observed_mean" = mu, "samples" = samples)
  return (li)
}
monte_carlo <- monte.carlo.integration()
hist(monte_carlo$samples, density=20, breaks = 30, prob=TRUE)
curve(posterior.f(x)/mean(posterior.f(x)), add=TRUE, col="darkblue", lwd=2)
```

## Histogram of monte\_carlo\$samples



```
numerical.integration <- function(theta){
  return (theta*posterior.f(theta))
}
Analytic_mean <- integrate(numerical.integration, lower=0,upper=1)$value/integrate(posterior.f, lower=0,
cat("Observed mean: ", monte_carlo$observed_mean, "\n")

## Observed mean: 0.6226724
cat("Analytic mean: ", Analytic_mean, "\n")

## Analytic mean: 0.6228061
n = 20000 #number of samples
rejection.sampling.multinomial(n)$number.samples/n

## [1] 7.81675
optimize(posterior.f, c(0, 1), maximum=TRUE)$objective/integrate(posterior.f, lower=0, upper=1)$value

## [1] 7.799308
beta.distribution <- function(x, alpha, beta){
  return(x^(alpha-1)*(1-x)^(beta-1)/beta(alpha, beta))
}
importance.sampling <- function(n){
  samples <- rejection.sampling.multinomial(n)$samples
  w = (1-samples)^4
  mu.is <- sum(samples*w)/sum(w)
  return(mu.is)
```

```
}  
importance.sampling(20000)  
## [1] 0.5956244
```