

# Lab 3: Intro to Decision Theory

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## Task 1

```
# set seed
set.seed(123)

# data
sum_x = 1
n = 30
# prior parameters
a = 0.05; b = 1
# posterior parameters
an = a + sum_x
bn = b + n - sum_x
th = seq(0,1,length.out = 100)
like = dbeta(th, sum_x+1,n-sum_x+1)
prior = dbeta(th,a,b)
post = dbeta(th,sum_x+a,n-sum_x+b)
```

We now consider the loss function.

```
# compute the loss given theta and c
loss_function = function(theta, c){
  if (c < theta){
    return(10*abs(theta - c))
  } else{
    return(1 = abs(theta - c))
  }
}
```

We now write a function **posterior\_risk** which is a function of  $c$ , parameters  $a\_prior$  and  $b\_prior$  for the prior distribution of  $\theta$ , the summation of  $x_i$   $sum\_x$ , the number of observations  $n$ , and also the number of random draws  $s$ .

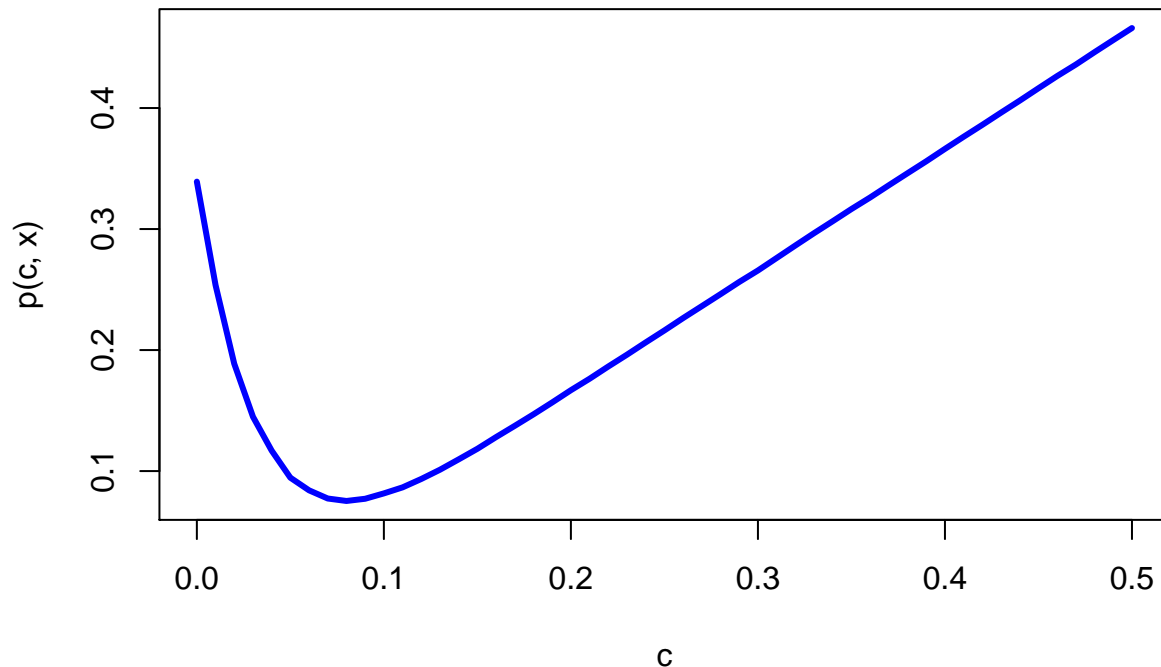
```
# compute the posterior risk given c
# s is the number of random draws
posterior_risk = function(c, a_prior, b_prior, sum_x, n, s = 30000){
  # random draws from beta distribution
  a_post = a_prior + sum_x
  b_post = b_prior + n - sum_x
  theta = rbeta(s, a_post, b_post)
  loss <- apply(as.matrix(theta),1,loss_function,c)
  # average values from the loss function
  risk = mean(loss)
}
# a sequence of c in [0, 0.5]
```

```
c = seq(0, 0.5, by = 0.01)
post_risk <- apply(as.matrix(c), 1, posterior_risk, a, b, sum_x, n)
head(post_risk)
```

```
## [1] 0.33917940 0.25367603 0.18868962 0.14489894 0.11693106 0.09453471
```

We then look at the Posterior expected loss (posterior risk) for disease prevalence versus  $c$ .

```
# plot posterior risk against c
plot(c, post_risk, type = 'l', col='blue',
     lwd = 3, ylab = 'p(c, x)' )
```



```
# minimum of posterior risk occurs at c = 0.08
(c[which.min(post_risk)])
```

```
## [1] 0.08
```

## Task 2

We now consider task 2. We set  $a = 0.05, 1, 0.05$  and  $b = 1, 2, 10$ . If we have different prior, the posterior risk is minimized at different  $c$  values. The optimal  $c$  depends on not only the data, but also the prior setting.

```
# set prior
as = c(0.05, 1, 0.05); bs = c(1, 1, 10)
post_risk = matrix(NA, 3, length(c))

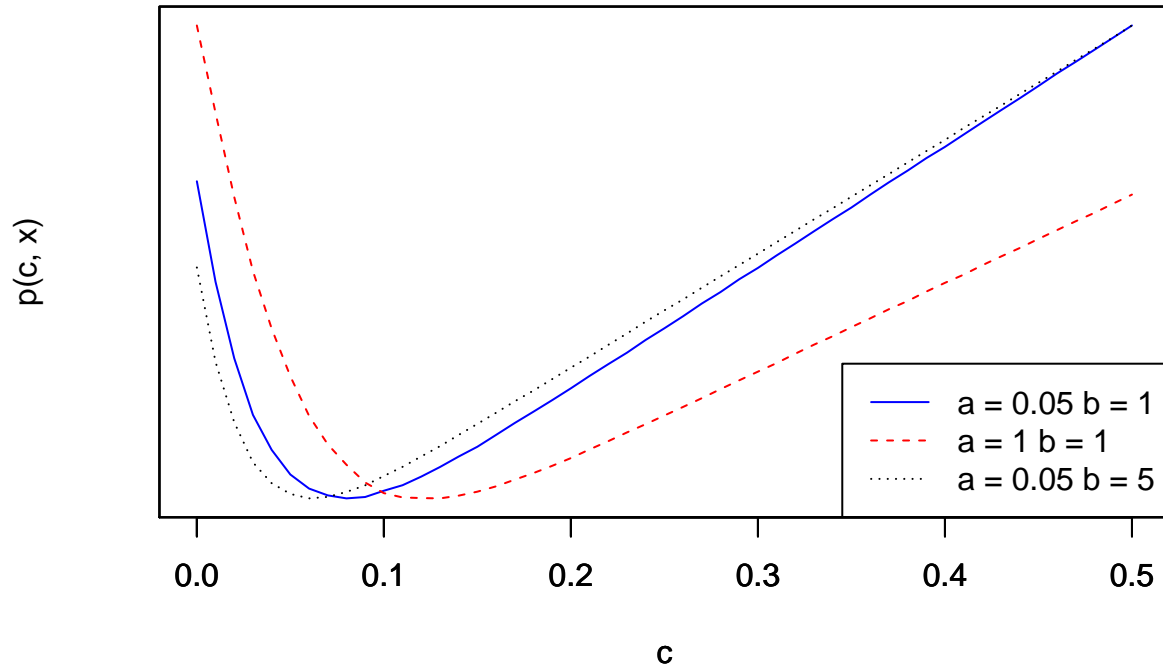
# for each pair of a and b, compute the posterior risks
for (i in 1:3){
  a_prior = as[i]
  b_prior = bs[i]

  post_risk[i,] = apply(as.matrix(c), 1, posterior_risk, a_prior, b_prior, sum_x, n)
}
```

```

plot(c, post_risk[1,], type = 'l', col='blue', lty = 1, yaxt = "n", ylab = "p(c, x)")
par(new = T)
plot(c, post_risk[2,], type = 'l', col='red', lty = 2, yaxt = "n", ylab = "")
par(new = T)
plot(c, post_risk[3,], type = 'l', lty = 3, yaxt = "n", ylab = "")
legend("bottomright", lty = c(1,2,3), col = c("blue", "red", "black"),
      legend = c("a = 0.05 b = 1", "a = 1 b = 1", "a = 0.05 b = 5"))

```



Note there is a more automated solution but this is the most simple one and is completely correct.

### Task 3

The Bayes procedure always picks  $c$  to be a little bigger than  $\bar{x}$ .

```

sum_xs = seq(0, 30)
min_c = matrix(NA, 3, length(sum_xs))

# find_optimal_C finds the optimal c under Bayes procedure
# function of sum of x, parameters for prior, number of observations, and number of random draws
find_optimal_C = function(sum_x, a_prior, b_prior, n, s = 500){
  c = seq(0, 1, by = 0.01)
  post_risk = apply(as.matrix(c), 1, posterior_risk, a_prior, b_prior, sum_x, n, s)
  c[which.min(post_risk)]
}

min_c[1,] = apply(as.matrix(sum_xs), 1, find_optimal_C, a, b, n)
# find optimal c under sample mean
min_c[2,] = (sum_xs)/n
# constant c
min_c[3,] = 0.1

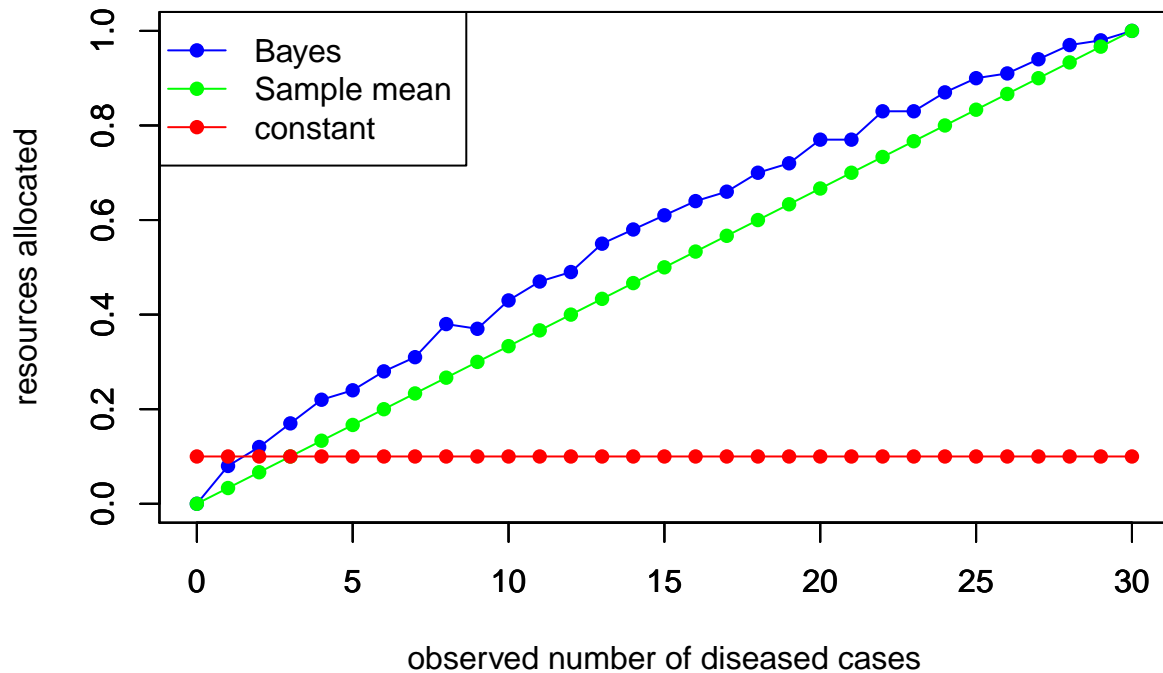
# plot

```

```

plot(sum_xs, min_c[1,], col='blue', type = 'o', pch = 16,
     ylab = "resources allocated", xlab = 'observed number of diseased cases',
     ylim = c(0,1))
par(new = T)
plot(sum_xs, min_c[2,], type = 'o', col='green',
     pch = 16, ylab = "", xlab = '', ylim = c(0,1))
par(new = T)
plot(sum_xs, min_c[3,], type = 'o', col = 'red',
     pch = 16, ylab = "", xlab = '', ylim = c(0,1))
legend("topleft", lty = c(1,1,1), pch = c(16,16,16),
     col = c("blue", "green", "red"),
     legend = c("Bayes", "Sample mean", "constant"))

```



## Task 4

For all  $\theta$ , the Bayes procedure has the lower frequentist risk than the sample mean.

```

thetas = seq(0, 1, by=0.1)

# frequentist risk for the 3 estimators given a theta
frequentist_risk = function(theta){
  sum_xs = rbinom(100, 30, theta)
  Bayes_optimal = apply(as.matrix(sum_xs), 1, find_optimal_C, a, b, n, s = 100)
  mean_c = sum_xs / 30

  loss1 = apply(as.matrix(Bayes_optimal), 1, loss_function, theta = theta)
  loss2 = apply(as.matrix(mean_c), 1, loss_function, theta = theta)
  risk1 = mean(loss1)
  risk2 = mean(loss2)
  risk3 = loss_function(theta, 0.1)
  return(c(risk1, risk2, risk3))
}

```

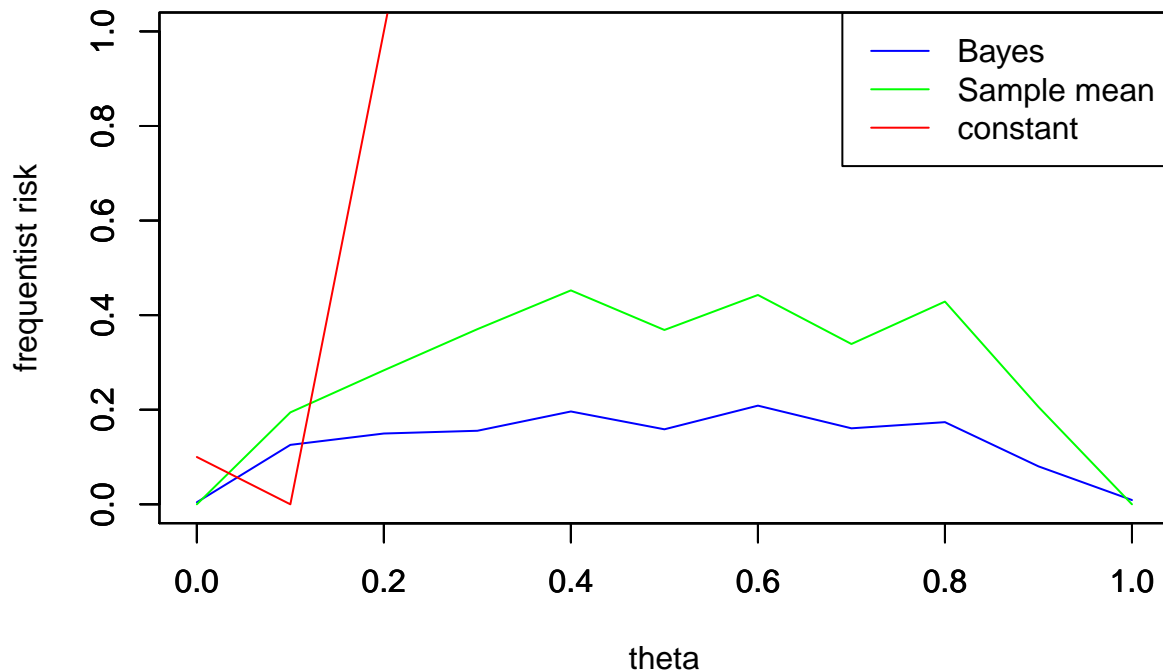
```

}

# given a sequence a theta, compute frequentist risk for each theta
R = apply(as.matrix(thetas), 1, frequentist_risk)

# plot
plot(thetas, R[1,], col='blue', type = "l",
      ylab = "frequentist risk", xlab = 'theta', ylim = c(0,1))
par(new = T)
plot(thetas, R[2,], type = 'l', col='green',
      ylab = "", xlab = '', ylim = c(0,1))
par(new = T)
plot(thetas, R[3,], type = 'l', col = 'red',
      ylab = "", xlab = '', ylim = c(0,1))
legend("topright", lty = c(1,1,1), col = c("blue", "green", "red"),
      legend = c("Bayes", "Sample mean", "constant"))

```



Please see a few remarks about Task 4 that will help you with interpreting the plot.

1. If you zoom into see the plot for Task 4, you will notice that the Bayes risk is not always smaller than the sample mean. Specifically, the issue is occurring around  $\theta = 0$  and  $\theta = 1$ .
2. One observation that we can make is that when  $x$  is very small (say 0), Bayes estimator tends to overestimate  $\theta$  and hence sample mean has lower risk. What other observations can you make?

I am including some code that Xu Chen has written that is much faster, where the resulting plot is much more clear.

```

# code by Xu Chen
loss <- function(theta, c){
  if (c >= theta) {
    return(c - theta)
  } else {
    return(10*(theta - c))
  }
}

```

```

}
}

delta1 <- function(x){
  return(rep(0.1,length(x)))
}

delta2 <- function(x){
  return(x/30)
}

delta3 <- function(x, a = 0.05, b = 1){
  a.post <- a + x
  b.post <- b + 30 - x
  c <- seq(0,1,0.01)
  theta <- matrix(rbeta(1e4*length(c), a.post, b.post), nrow = 1e4, ncol = length(c))

  return(c[which.min(sapply(c, function(u) mean(sapply(theta[,as.integer(100*u+1)], loss, c = u))))])
}

risk <- function(theta, c){
  return(sum(dbinom(x = 0:30, size = 30, prob = theta) * sapply(c, loss, theta = theta)))
}

theta.grid <- seq(0,1,0.01)
x <- 0:30

c3 <- sapply(x, delta3)
plot(theta.grid, sapply(theta.grid, risk, c3), ylim = c(0,1), type = 'l', col = 'red', xlab = expression(theta))

c1 <- delta1(x)
points(theta.grid, sapply(theta.grid, risk, c1), ylim = c(0,1), type = 'l')

c2 <- delta2(x)
points(theta.grid, sapply(theta.grid, risk, c2), ylim = c(0,1), type = 'l', col='green')

legend('topright', legend = c('Bayes', 'sample mean', 'constant'), col = c('red', 'green', 'black'), lty = c(1, 1, 1))

```

