

### Solution 1: Risk Minimization and Gradient Descent

- (a) Write a function in R implementing a gradient descent routine for the optimization of the linear model defined in the previous exercise sheet. Start with:

```
#' @param step_size the step_size in each iteration
#' @param X the feature input matrix X
#' @param y the outcome vector y
#' @param beta a starting value for the coefficients
#' @param eps a small constant measuring the changes in each update step.
#' Stop the algorithm if the estimated model parameters do not change
#' more than \code{eps}.

#' @return a set of optimal coefficients beta
gradient_descent <- function(step_size, X, y, beta = rep(0,ncol(X)),
                             eps = 1e-8){

  change <- 1 # something larger eps

  XtX <- crossprod(X)
  Xty <- crossprod(X,y)

  while(sum(abs(change)) > eps){

    # Use standard gradient descent:
    change <- + step_size * (Xty - XtX%*%beta)

    # update beta in the end
    beta <- beta + change

  }

  return(beta)
}
```

- (b) Run a small simulation study by creating 20 data sets as indicated below and test different step sizes  $\alpha$  (fixed across iterations) against each other and against the state-of-the-art routine for linear models (in R, using the function `lm`, in Python, e.g., `sklearn.linear_model.LinearRegression`).

- Compare the difference in estimated coefficients  $\beta_j, j = 1, \dots, p$  using the mean squared error, i.e.

$$p^{-1} \sum_{j=1}^p (\beta_j^{truth} - \hat{\beta}_j)^2$$

and summarize the difference over all 20 simulation repetitions.

- Compare the run times of your implementation and the one given by the state-of-the-art method by wrapping the function calls into a timer (e.g., `system.time()` in R).

```

n <- 10000
p <- 100
nr_sims <- 20

# define mse
mse <- function(x,y) mean((x-y)^2)

# create data (only once)
X <- matrix(rnorm(n*p), ncol=p)
beta_truth <- runif(p, -2, 2)
f_truth <- X%%beta_truth

# create result object
result_list <- vector("list", nr_sims)

# make it all reproducible
set.seed(2020-4-6)

for(sim_nr in seq_len(nr_sims))
{

  # create response
  y <- f_truth + rnorm(n, sd = 2)

  time_lm <- system.time(
    coef_lm <- coef(lm(y~1+X))
  )["elapsed"]

  time_gd_1 <- system.time(
    coef_gd_1 <- gradient_descent(step_size = 0.0001, X = X, y = y)
  )["elapsed"]

  time_gd_2 <- system.time(
    coef_gd_2 <- gradient_descent(step_size = 0.00001, X = X, y = y)
  )["elapsed"]

  mse_lm <- mse(coef_lm, beta_truth)
  mse_gd_1 <- mse(coef_gd_1, beta_truth)
  mse_gd_2 <- mse(coef_gd_2, beta_truth)

  # save results in list (performance, time)
  result_list[[sim_nr]] <- data.frame(mse_lm = mse_lm,
                                     mse_gd_1 = mse_gd_1,
                                     mse_gd_2 = mse_gd_2,
                                     time_lm = time_lm,
                                     time_gd_1 = time_gd_1,
                                     time_gd_2 = time_gd_2)

}

library(ggplot2)
library(dplyr)
library(tidyr)

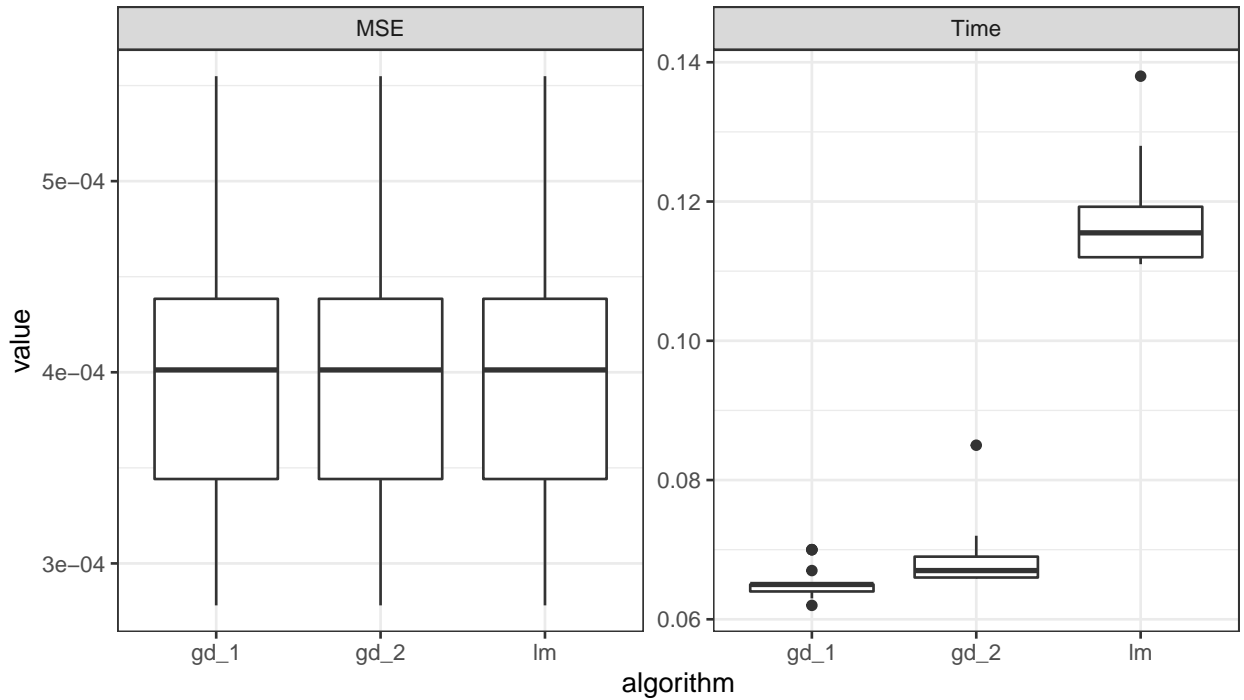
do.call("rbind", result_list) %>%
  gather() %>%
  mutate(what = ifelse(grepl("mse", key), "MSE", "Time"),

```

```

algorithm = gsub("(mse|time)\\_(.*)", "\\2", key)) %>%
ggplot(aes(x = algorithm, y = value)) +
geom_boxplot() + theme_bw() +
facet_wrap(~ what, scales = "free")

```



- (c) There exists an analytic solution to this problem, namely  $\hat{\beta} = (\mathbf{X}^\top \mathbf{X})^{-1} \mathbf{X}^\top \mathbf{y}$ . Gradient descent might sometimes be slower and less exact. However, for very large data sets, a numerical optimization might be the preferred solution (in this case, you would rather apply **stochastic** gradient descent). Analytically solving the problem involves inverting the matrix  $\mathbf{X}^\top \mathbf{X}$ , which should never be done explicitly, but rather by solving the linear equation  $\mathbf{X}^\top \mathbf{y} = \mathbf{X}^\top \mathbf{X} \beta$  or by decomposing  $\mathbf{X}^\top \mathbf{X}$  first, e.g., using Cholesky or QR decomposition.
- (d) Our learning algorithm  $\mathcal{I}$  will always have an approximation error if  $f^* \notin \mathcal{H}$ , and is thus not consistent.