

# Project Bioinformatic Resources

Annalisa Xamin, Nicola Perotti

## Introduction

The following analysis focus on RNA-seq count data extracted from different cancer datasets from the Cancer Genome Atlas (TCGA). From the original TCGA data 50 cases (tumor samples) and 50 controls (normal samples) were randomly selected.

## Analysis

The packages needed for the analysis are the following:

```
library(tidyverse)
library(biomaRt)
library(MotifDb)  # large collection of motifs across different species
library(seqLogo)
library(PWMEnrich)
library(PWMEnrich.Hsapiens.background)
library(GEOquery)
library(oligo)
library(pd.hg.u133.plus.2)
library(hgu133plus2.db)
library(genefilter)
library(limma)
library(pheatmap)
library(stringr)
library(GenomicFeatures) # to build object with specific information such as genomic coordinates
library(ggplot2)
library(edgeR)  # designed to perform Differential Expression Analysis from RNA-Seq data
library(fgsea)  # computation of enrichment scores and other statistics
library(org.Hs.eg.db) # database annotation human specific transcript from Ensembl
library(clusterProfiler) # uses Fisher test, explore gene list of interest against a reference
library(enrichplot) # build enrich map
library(ggnewscale)
library(DOSE)
library(pathview) # contains cartoons of pathways and we project on them our genes of interest
library(igraph)
```

## Task 1: Load data

In particular, we consider data coming from **Lung adenocarcinoma**.

```
load("./RData/Lung_adenocarcinoma.RData")
```

After loading the data, the following three data-frames are available:

- `raw_counts_df` which contains the raw RNA-seq counts;
- `c_anno_df`, which contains sample name and condition (case and control);
- `r_anno_df`, which contains the ENSEMBL genes ids, the length of the genes and the genes symbols.

## Task 2: Filter protein coding genes

To extract only protein coding genes from `raw_counts_df` and `r_anno_df`, we use the `biomaRt` package.

First, we retrieve the information about the protein coding genes from Ensembl.

```
database <- useMart("ensembl")
datasetHuman <- useDataset("hsapiens_gene_ensembl", mart = database)
query <- getBM(attributes = c("ensembl_gene_id", "external_gene_name", "gene_biotype"),
  filters = c("ensembl_gene_id", values = r_anno_df$ensembl_gene_id, mart = datasetHuman)

query_protein_coding <- query[which(query$gene_biotype == "protein_coding"), ]
```

Then, we filter the data frames containing the raw counts and the annotation to keep only the protein coding genes.

```
indexes_r_anno_df <- which(r_anno_df$ensembl_gene_id %in% query_protein_coding$ensembl_gene_id)
r_anno_df_protein_coding <- r_anno_df[indexes_r_anno_df, ]

indexes_raw_counts_df <- which(rownames(raw_counts_df) %in% query_protein_coding$ensembl_gene_id)
raw_counts_df_protein_coding <- raw_counts_df[indexes_raw_counts_df, ]
```

## Task 3: Differential expression analysis

To perform the differential expression analysis, we will use the `edgeR` package.

It is important to remove genes with low signal that will have low statistical power. Since, we want to focus on the transcripts we can use to perform the analysis, we can filter raw counts data using a threshold of raw count  $> 20$  in at least 5 replicates.

```
# count threshold
count_thr <- 20

# number of replicates with more counts than the count threshold
repl_thr <- 5

filter_vec <- apply(raw_counts_df_protein_coding, 1, # go through all count matrices by rows
  function(y) max(by(y, c_anno_df$condition, function(x) sum(x>=count_thr))))
# groups the values on each condition and sum all the values above the count
```

Then, we filter the previously updated data frames.



```
long_counts_df <- gather(as.data.frame(filter_counts_df), key = "sample", value = "read_number")

ggplot(data = long_counts_df, aes(sample, read_number + 1)) + geom_boxplot(colour = "deeppink4",
  fill = "deeppink4", alpha = 0.7) + theme_bw() + scale_y_log10()
```

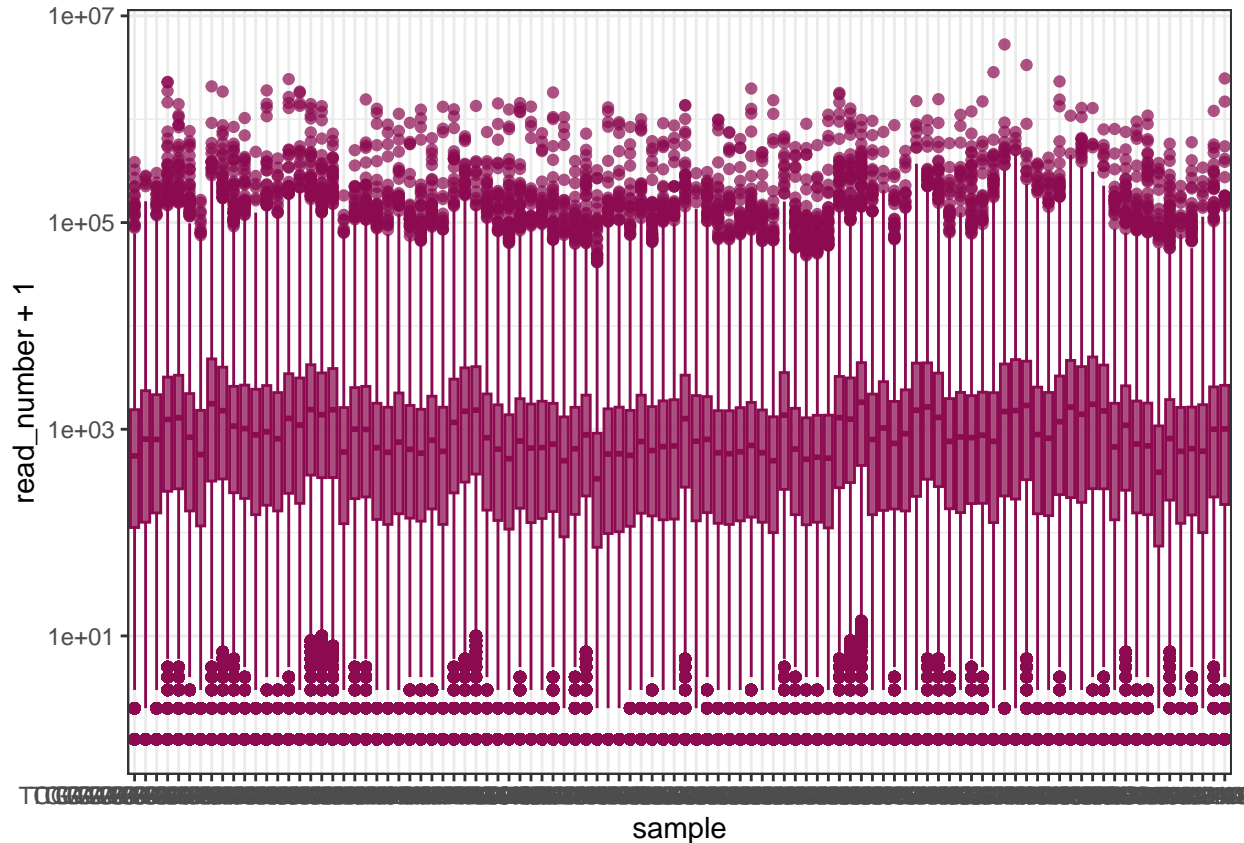


Figure 2: Boxplot of gene counts before normalization.

As we can see from the plots, there is a significant variability across samples in term of library sizes (reads per million). We have to take into account this aspect because the expected size of each count is the product of the relative abundance of that gene in that sample but also of the library size.

As we can see from the boxplot, we need to normalize our data before testing for differential expression. Normalization can be obtained using different methodologies. Among them, TMM (the default method) is a method that consider in the normalization also variables related to the library size.

To perform the DEG analysis, we first need to create a `DGRLIST` object containing information about counts, annotation, samples and genes. To do that, we use the function `DGELIST` to create the input for the following normalization step. This object contains information about counts, samples and genes.

The normalization intra- and inter-sample is done using the function `calcNormFactors` and specifying `method = "TMM"`, which is the weighted trimmed mean of M-values approach.

```
edge_c <- DGELIST(counts = filter_counts_df, group = c_anno_df$condition, samples = c_anno_df,
  genes = filter_anno_df)

# computing norm factors for TMM normalization
edge_n <- calcNormFactors(edge_c, method = "TMM")
```

Then, we create a cpm table containing the normalized expression values for each transcript expressed as counts per million (CPM).

```
# create a cpm table (normalized expression values)  
cpm_table <- as.data.frame(round(cpm(edge_n), 2))
```

To see the effect of the normalization, we look at the boxplot distribution of gene expression signals after normalization.

```
# look at the boxplot distribution of gene expression signals after  
# normalization  
long_cpm_df <- gather(cpm_table, key = "sample", value = "CPM")  
  
ggplot(data = long_cpm_df, aes(sample, CPM + 1)) + geom_boxplot(colour = "olivedrab",  
  fill = "olivedrab", alpha = 0.7) + theme_bw() + scale_y_log10()
```

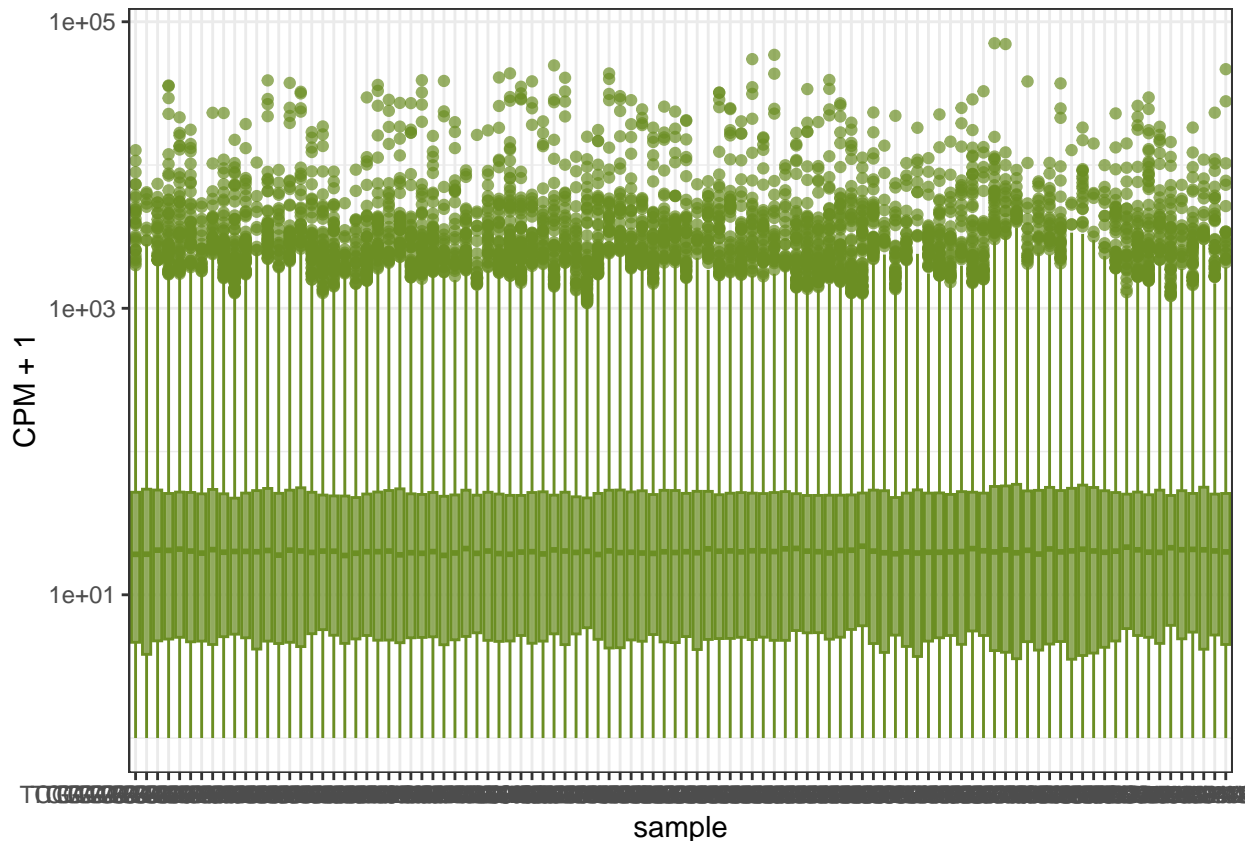


Figure 3: Boxplot distribution of gene expression signals after normalization.

We notice that, with respect to the previous boxplot, after the normalization, the distributions are comparable. That means that now our data is ready to be tested for DE analysis.

We define the experimental design matrix, later needed to calculate the dispersion and fit. This matrix is based on the experimental design, so we define the conditions we want to test (case VS control).

```
design <- model.matrix(~0 + group, data = edge_n$samples)
colnames(design) <- levels(edge_n$samples$group)
rownames(design) <- edge_n$samples$sample
```

Once we normalized the data and the design, we proceed by calculating the dispersion fit.

```
# calculate dispersion and fit with edgeR (necessary for differential
# expression analysis)
edge_d <- estimateDisp(edge_n, design)
edge_f <- glmQLFit(edge_d, design)
```

The `estimateDisp` function tries to estimate the variability at different levels: in the data, inter sample and intra sample. The over dispersion of counts across the samples can be modeled as a Poisson distribution, which can be approximated using a negative binomial distribution by using `glmQLFit` function.

We define the contrasts (conditions to be compared).

```
contro <- makeContrasts("control-case", levels = design)
```

We performed a test through function `glmQLFTest` to determine which genes are differentially expressed. Then, we selected genes based on a 0.01 p-value cutoff and ordered them based on the log2 fold change.

```
# fit the model with generalized linear models
edge_t <- glmQLFTest(edge_f, contrast = contro)
DEGs <- as.data.frame(topTags(edge_t, n = 20000, p.value = 0.01, sort.by = "logFC"))
```

Then, we improve the selection, considering not only the p-value, but also the average expression of the genes (logCPM). We used the logFC value to assign genes to different classes:

- up-regulated genes if  $\log FC > 1.5$
- down-regulated genes if  $\log FC < -1.5$
- not significant genes (unchanged) otherwise.

```
DEGs$class <- "="
DEGs$class[which(DEGs$logCPM > 1 & DEGs$logFC > 1.5 & DEGs$FDR < 0.25)] = "+" # upregulated genes
DEGs$class[which(DEGs$logCPM > 1 & DEGs$logFC < (-1.5) & DEGs$FDR < 0.25)] = "-" # downregulated genes
DEGs <- DEGs[order(DEGs$logFC, decreasing = T), ]
```

```
head(DEGs)
```

##	ensembl_gene_id	external_gene_name	length	logFC	logCPM	
##	ENSG00000179914	ENSG00000179914	ITLN1	8640	6.684901	5.8661078
##	ENSG00000108576	ENSG00000108576	SLC6A4	41683	6.084705	6.6338451
##	ENSG00000180440	ENSG00000180440	SERTM1	23819	5.663190	3.2093449
##	ENSG00000108342	ENSG00000108342	CSF3	2452	5.588520	5.2512424
##	ENSG00000034971	ENSG00000034971	MYOC	17271	5.397462	1.5811486
##	ENSG00000178084	ENSG00000178084	HTR3C	7626	5.325742	0.5517057
##	F	PValue	FDR	class		
##	ENSG00000179914	75.57703	6.388727e-14	4.459213e-13	+	
##	ENSG00000108576	122.16543	3.992071e-19	7.518401e-18	+	

```
## ENSG00000180440 181.47838 2.383659e-24 1.325115e-22 +
## ENSG00000108342 90.91727 8.943402e-16 8.552128e-15 +
## ENSG00000034971 170.30732 1.866103e-23 8.293843e-22 +
## ENSG00000178084 120.55392 5.781068e-19 1.046585e-17 =
```

```
table(DEGs$class) # 1193-, 877+, 14949=
```

```
##
##      -      +      =
## 1199  884  9258
```

From the results, we saw that 1193 genes are down-regulated, 877 genes are up-regulated and 14949 genes have no changes in their regulation.

We then create the volcano plot.

```
input_df <- DEGs
xlabel <- "log2 FC case vs control"
ylabel <- "-log10 p-value"

par(fig = c(0, 1, 0, 1), mar = c(4, 4, 1, 2), mgp = c(2, 0.75, 0))
plot(input_df$logFC, -log(input_df$PValue, base = 10), xlab = xlabel, ylab = ylabel,
     col = ifelse(input_df$class == "=", "grey70", "olivedrab4"), pch = 20, frame.plot = TRUE,
     cex = 0.8, main = "Volcano plot")
abline(v = 0, lty = 2, col = "grey20")
```

The volcano plot allows to have a quick visual identification of genes with large fold changes that are also statistically significant.

We also report the heatmap of only up and down-regulated genes.

To create an annotated heatmap focusing only on up- and down-regulated genes we need first of all a matrix in which we select genes with class “+” or “-”. Moreover, we also need to assign a color to each sample. In this case, we assign green to the case condition and beige to the control, and save the corresponding color into the variable `cols`. In this way, we can then set the `ColSideColors` parameter in order to have a color code to recognize the sample condition.

```
# plot only up and down regulated genes
cols <- c(ifelse(c_anno_df$condition == "case", "chartreuse4", "burlywood3"))
pal <- c("blue", "white", "red")
pal <- colorRampPalette(pal)(100)
heatmap(as.matrix(cpm_table[which(rownames(cpm_table) %in% DEGs$ensembl_gene_id[which(DEGs$class !=
    "=")]), ]), ColSideColors = cols, cexCol = 0.5, margins = c(4, 4), col = pal,
    cexRow = 0.2)
```

On the top of the heatmap, we can see the dendrogram indicating how distant our samples are, while on the left the dendrogram related to genes. The dendrogram is built by hierarchical clustering, a method based on the concept of dissimilarity.

To simplify the later analysis, we save the list of differentially expressed genes in a text file.

```
up_DEGs <- DEGs[which(DEGs$class == "+"), ]
down_DEGs <- DEGs[which(DEGs$class == "-"), ]
```

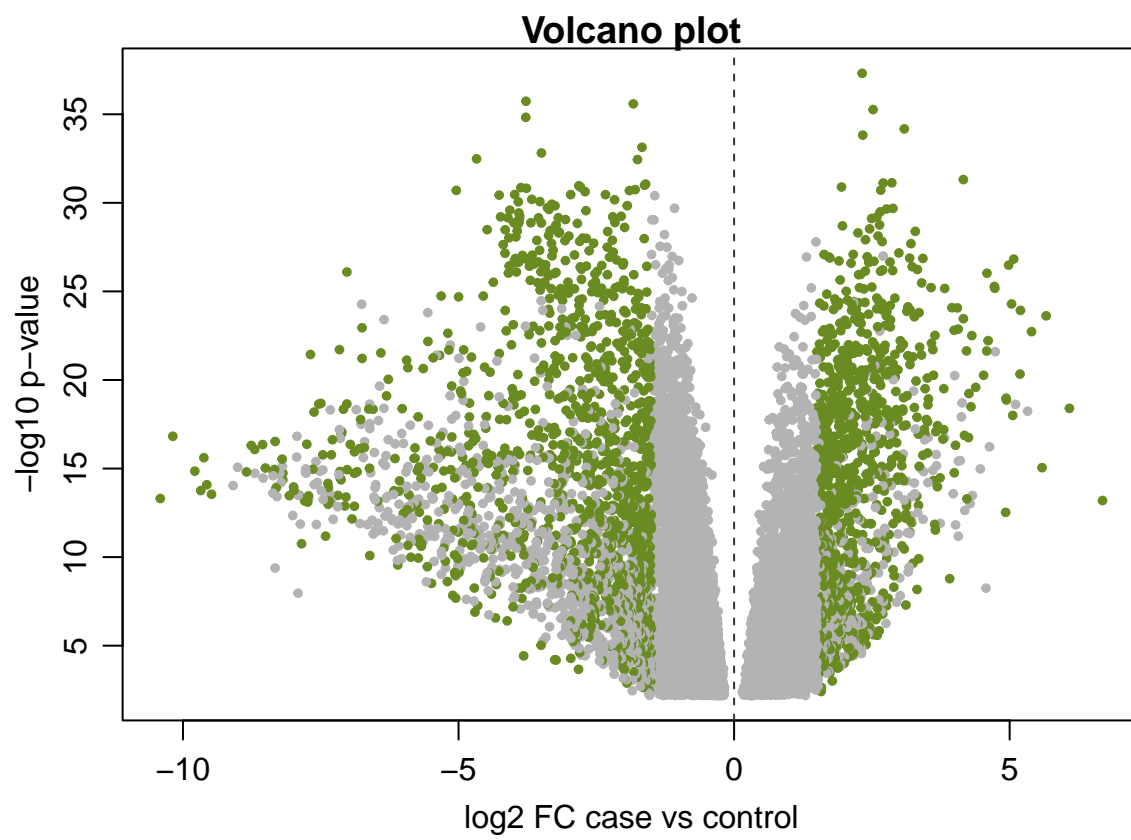


Figure 4: Volcano plot





```
write.table(up_DEGs, file = "output/up_DEGs.txt", row.names = F, col.names = T, sep = "\t",
           quote = F)
write.table(down_DEGs, file = "output/down_DEGs.txt", row.names = F, col.names = T,
           sep = "\t", quote = F)
write.table(DEGs, file = "output/DEGs.txt", row.names = F, col.names = T, sep = "\t",
           quote = F)
```

## Task 4: Gene set enrichment analysis

To perform the gene set enrichment analysis, we will use the `clusterProfiler` package.

```
DEGs <- read.table("output/DEGs.txt", header = T, sep = "\t", as.is = T)
table(DEGs$class)
```

```
##
##      -      +      =
## 1199  884 9258
```

We use the `biomaRt` package to retrieve the `entrezgene_id` for all the genes in the DEGs dataset.

```
ensembl <- useEnsembl(biomart = "ensembl", dataset = "hsapiens_gene_ensembl")
convert <- getBM(attributes = c("ensembl_gene_id", "entrezgene_id"), filters = c("ensembl_gene_id"),
                 values = DEGs$ensembl_gene_id, mart = ensembl)

DEGs <- merge(DEGs, convert, by.x = "ensembl_gene_id", by.y = "ensembl_gene_id") # include the new info
DEGs <- DEGs[which(!is.na(DEGs$entrezgene_id)), ]
DEGs <- DEGs[-which(duplicated(DEGs$entrezgene_id)), ]
```

We removed all the NA and duplicates in the dataset DEGs.

We created new lists for the down and up-regulated genes.

```
# list of up-regulated genes
upDEGs <- DEGs %>%
  filter(class == "+")
# list of down-regulated genes
downDEGs <- DEGs %>%
  filter(class == "-")
```

## Performing enrichment analysis for GO biological process

```
# biological process up regulated genes
ego_BP_up <- enrichGO(gene = upDEGs$external_gene_name, OrgDb = org.Hs.eg.db, keyType = "SYMBOL",
                     ont = "BP", pAdjustMethod = "BH", pvalueCutoff = 0.05, qvalueCutoff = 0.05)

# biological process down regulated genes
ego_BP_down <- enrichGO(gene = downDEGs$external_gene_name, OrgDb = org.Hs.eg.db,
                      keyType = "SYMBOL", ont = "BP", pAdjustMethod = "BH", pvalueCutoff = 0.05, qvalueCutoff = 0.05)
```

We report the top 10 enriched GO terms related to the Biological Process for both up and down regulated genes.

In the barplots we can see that the elements are ordered by adjusted p-value (where the most significant is placed on the top) and on the x-axis we have the gene counts, so the number of elements of our lists were found in the category.

```
barplot(ego_BP_up, showCategory = 10, main = "Up-regulated gene list: top 10 enriched BP terms")
```

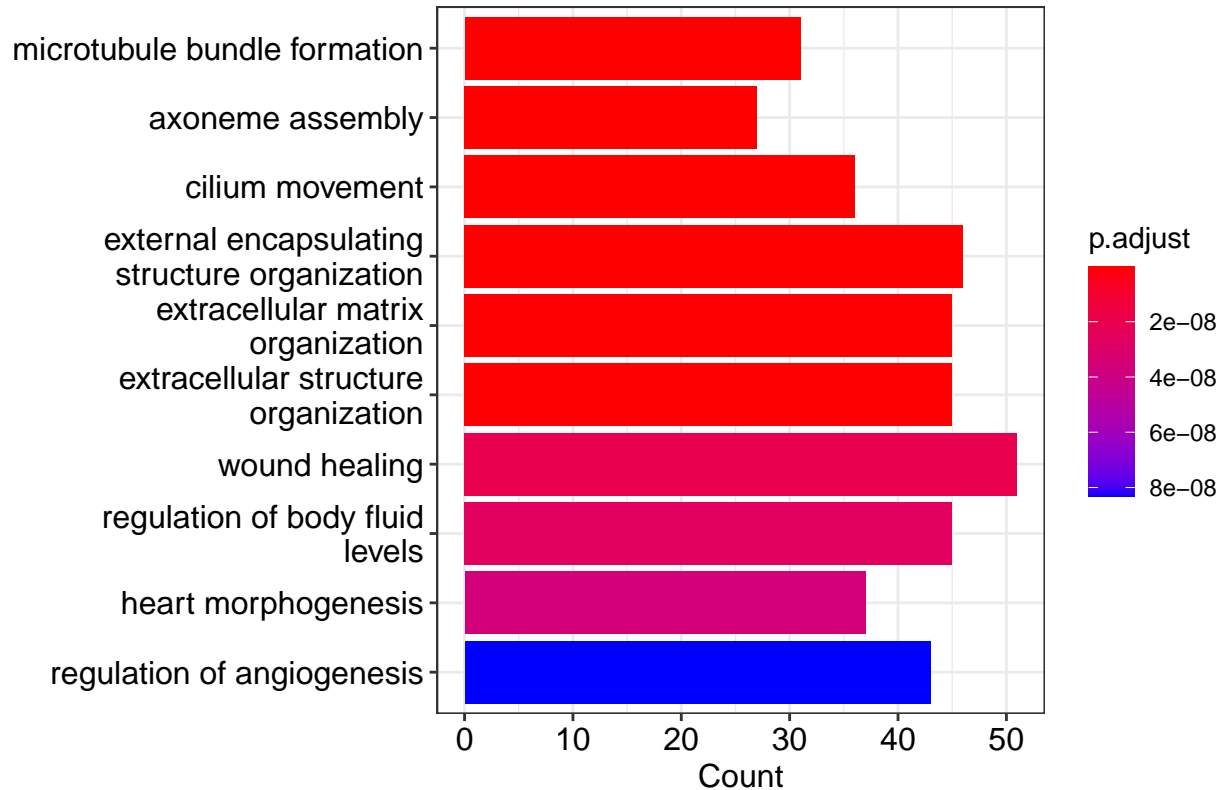


Figure 6: Biological process up regulated genes

Both the first two biological processes are related to the microtubules, which might be explained by the fact that tumour cells have a high growth rate thus the cytoskeleton is assembled over and over again. We also notice that angiogenesis is among the most enriched biological processes as we expected. In fact, angiogenesis is particularly important in tumorigenesis to allow the growth of the tumour tissue, providing nutrients to cells.

```
barplot(ego_BP_down, showCategory = 10, main = "Down-regulated gene list: top 10 enriched BP terms")
```

We would expect most of these biological processes to be enriched in the up-regulated genes since tumour cells tend to replicate more than normal cells. A possible explanation is that tumour cells genes accumulate numerous mutations usually ending up in loss of function or downregulation. These mutations might occur on transcription factors binding sites or RNA binding sites, reducing their expression.

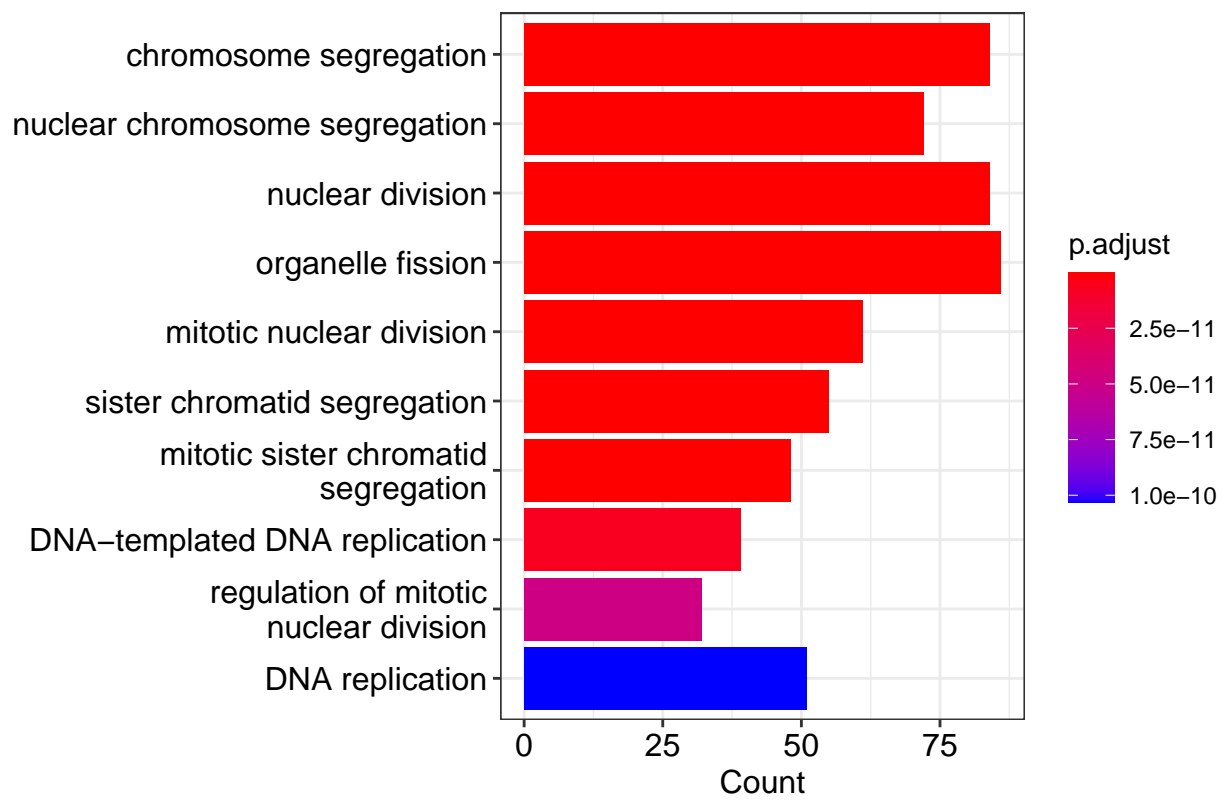


Figure 7: Biological process down regulated genes

## Performing enrichment analysis for GO molecular function

The same analysis was done also for the molecular function.

```
# molecular function up regulated genes
ego_MF_up <- enrichGO(gene = upDEGs$external_gene_name, OrgDb = org.Hs.eg.db, keyType = "SYMBOL",
  ont = "MF", pAdjustMethod = "BH", pvalueCutoff = 0.05, qvalueCutoff = 0.05)

# molecular function down regulated genes
ego_MF_down <- enrichGO(gene = downDEGs$external_gene_name, OrgDb = org.Hs.eg.db,
  keyType = "SYMBOL", ont = "MF", pAdjustMethod = "BH", pvalueCutoff = 0.05, qvalueCutoff = 0.05)
```

```
barplot(ego_MF_up, showCategory = 10, main = "Up-regulated gene list: top 10 enriched MP terms")
```

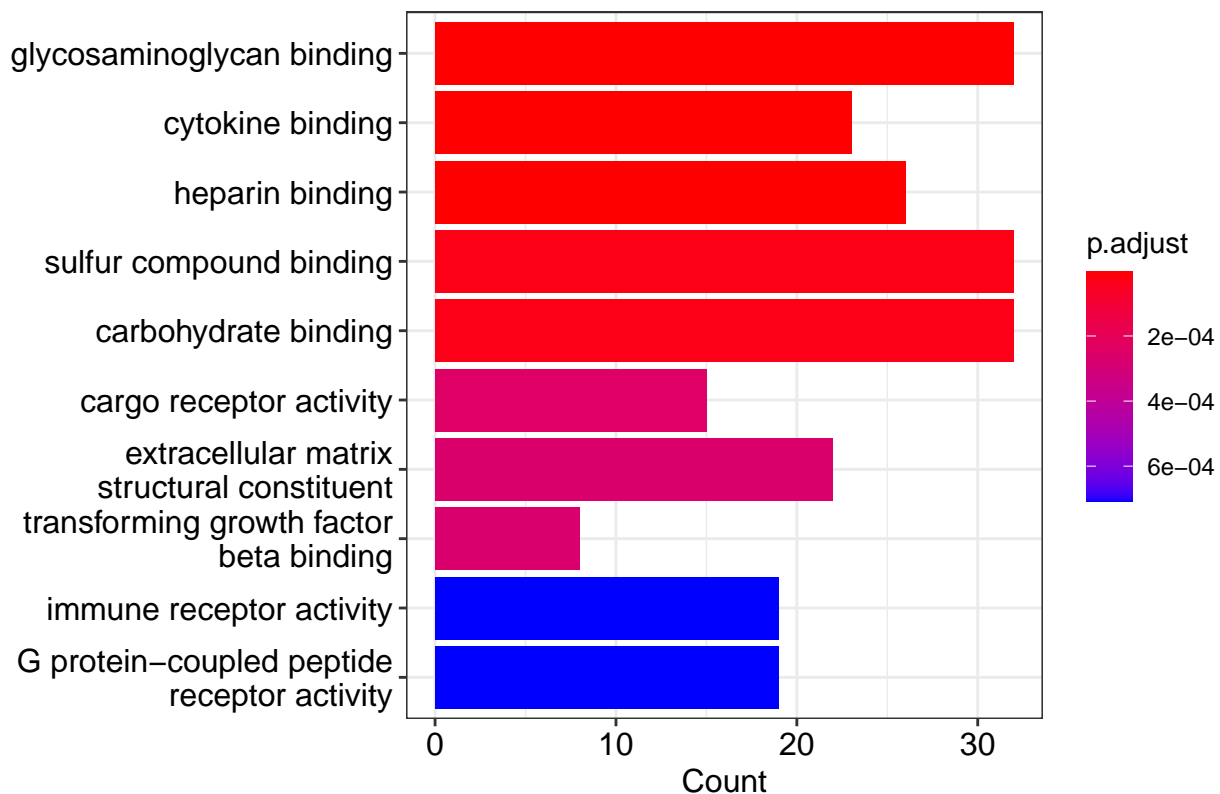


Figure 8: Molecular function up regulated genes

```
barplot(ego_MF_down, showCategory = 10, main = "Down-regulated gene list: top 10 enriched MP terms")
```

```
eWP_up <- enrichWP(gene = upDEGs$entrezgene_id, organism = "Homo sapiens", pvalueCutoff = 0.05,
  qvalueCutoff = 0.1)

head(eWP_up, n = 10)
```

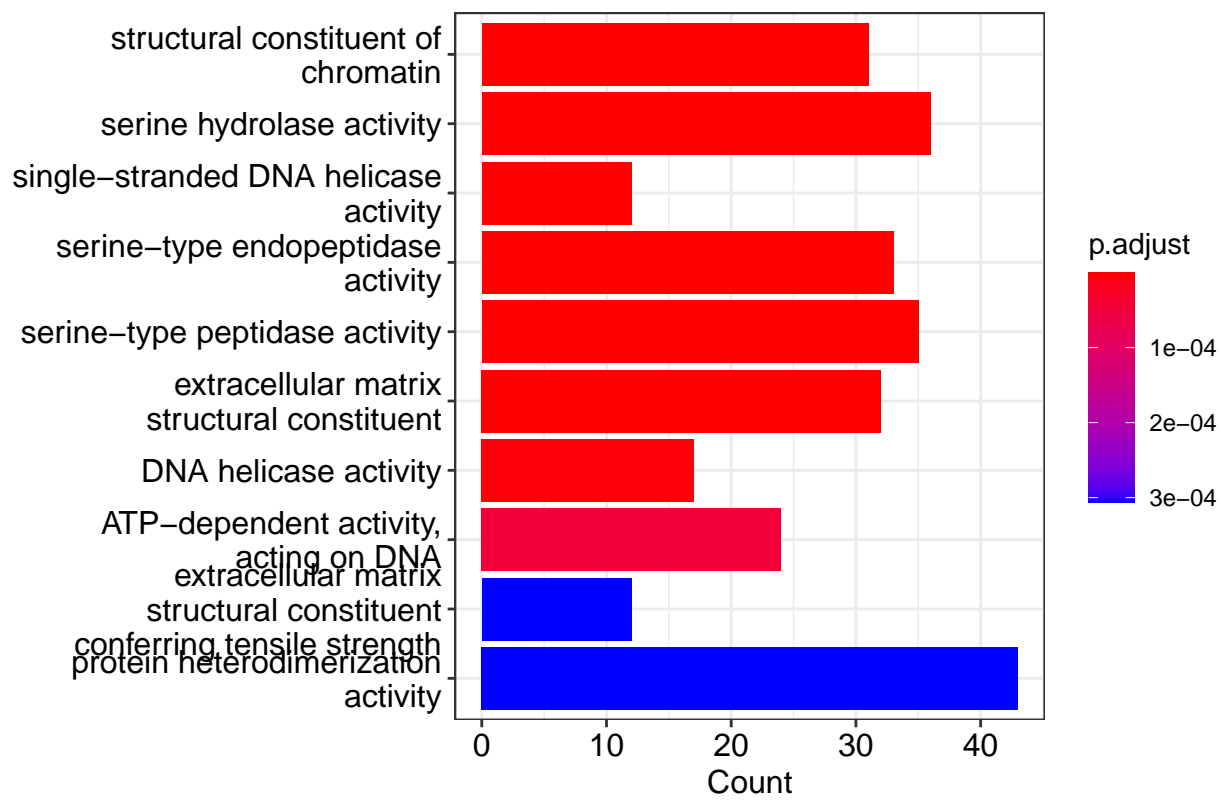


Figure 9: Molecular function down regulated genes

##	ID	Description			
## WP2806	WP2806	Complement system			
## WP545	WP545	Complement activation			
## WP558	WP558	Complement and coagulation cascades			
## WP2431	WP2431	Spinal cord injury			
## WP5094	WP5094	Orexin receptor pathway			
## WP5090	WP5090	Complement system in neuronal development and plasticity			
##	GeneRatio	BgRatio	pvalue	p.adjust	qvalue
## WP2806	19/436	97/8442	3.960197e-07	0.0001892974	0.0001725812
## WP545	8/436	23/8442	1.171095e-05	0.0027989174	0.0025517547
## WP558	12/436	58/8442	3.152788e-05	0.0050234421	0.0045798393
## WP2431	18/436	121/8442	4.427616e-05	0.0052910008	0.0048237708
## WP5094	24/436	201/8442	1.015995e-04	0.0087342052	0.0079629178
## WP5090	16/436	107/8442	1.096344e-04	0.0087342052	0.0079629178
##					
## WP2806			6401/729/2219/2160/7448/6404/730/653509/22918/5199/5648/11326/5806/235		
## WP545				732/729	
## WP558				729/1361/7450/730/5648/713/	
## WP2431			2920/4842/57556/6347/1958/3164/7538/3569/7099/9353/2353/361		
## WP5094			6401/862/2920/4616/1839/8013/1958/1959/3164/2354/3949/5468/3569/9314/2890/1346/2353/5581/3400		
## WP5090				732/729/2219/7448/730/5199/5648/8547/81035/1524	
##	Count				
## WP2806	19				
## WP545	8				
## WP558	12				
## WP2431	18				
## WP5094	24				
## WP5090	16				

```
eWP_down <- enrichWP(gene = downDEGs$entrezgene_id, organism = "Homo sapiens", pvalueCutoff = 0.05,
  qvalueCutoff = 0.1)
head(eWP_down, n = 10)
```

##	ID	Description
## WP2446	WP2446	Retinoblastoma gene in cancer
## WP2361	WP2361	Gastric cancer network 1
## WP179	WP179	Cell cycle
## WP1604	WP1604	Codeine and morphine metabolism
## WP45	WP45	G1 to S cell cycle control
## WP466	WP466	DNA replication
## WP4240	WP4240	Regulation of sister chromatid separation at the metaphase-anaphase transition
## WP698	WP698	Glucuronidation

```

## WP4016 DNA IR-damage and cellular response via ATR
## WP2525 Trans-sulfuration, one-carbon metabolism and related pathways
##      GeneRatio  BgRatio      pvalue    p.adjust      qvalue
## WP2446    26/618   90/8442  5.976882e-10  3.107978e-07  2.850029e-07
## WP2361    13/618   28/8442  2.054960e-08  4.361461e-06  3.999477e-06
## WP179     28/618  120/8442  2.516227e-08  4.361461e-06  3.999477e-06
## WP1604     9/618   16/8442  4.091055e-07  4.391632e-05  4.027145e-05
## WP45      18/618   64/8442  4.222724e-07  4.391632e-05  4.027145e-05
## WP466     13/618   42/8442  5.366172e-06  4.650682e-04  4.264694e-04
## WP4240     7/618   15/8442  4.168136e-05  3.096330e-03  2.839347e-03
## WP698     9/618   26/8442  5.735318e-05  3.541417e-03  3.247494e-03
## WP4016    17/618   81/8442  6.129375e-05  3.541417e-03  3.247494e-03
## WP2525    15/618   68/8442  9.059661e-05  4.711024e-03  4.320028e-03
##
## WP2446 1870/54443/4175/4998/24137/8318/5427/1869/4173/898/1871/7272/7153/891/10733/890/1111/9133/
## WP2361 6790/22974/4605/4173/1894/1063/71
## WP179 1870/4171/4175/4998/23594/8318/990/1869/4173/898/1871/7272/991/9088/891/9700/890/1029/1111/91
## WP1604 1244/1565/8
## WP45 1870/4171/4175/4998/23594/8318/5427/1869/4173/898/
## WP466 55388/4171/4175/4998/23594/83
## WP4240
## WP698 7358/7363/545
## WP4016 672/5888/4171/63967/8318/1869/2305/83990/55215
## WP2525 2729/2730/10797/1789/2571/23743/29968/570/5
##      Count
## WP2446    26
## WP2361    13
## WP179     28
## WP1604     9
## WP45      18
## WP466     13
## WP4240     7
## WP698     9
## WP4016    17
## WP2525    15

```

## Task 5: Visualization of the enriched pathway

KEGG analysis was performed using the function `enrichKEGG`.

```
eWP_KEGG <- enrichKEGG(gene = upDEGs$entrezgene_id, organism = "human", pvalueCutoff = 0.05,
                        qvalueCutoff = 0.1)
```

Here are reported the top 10 enriched KEGG pathways resulting from the up-regulated list of genes.

```
knitr::kable(head(eWP_KEGG[, 1:6], n = 10))
```

ID	Description	GeneRatio	BgRatio	pvalue	p.adjust
hsa05144	hsa05144 Malaria	13/382	50/8464	0.0000002	0.0000306
hsa04610	hsa04610 Complement and coagulation cascades	17/382	86/8464	0.0000002	0.0000306
hsa04270	hsa04270 Vascular smooth muscle contraction	17/382	134/8464	0.0001035	0.0098968



ID	Description	GeneRatio	BgRatio	pvalue	p.adjust
hsa04061	hsa04061 Viral protein interaction with cytokine and cytokine receptor	14/382	100/8464	0.0001464	0.0105063
hsa04614	hsa04614 Renin-angiotensin system	6/382	23/8464	0.0004262	0.0237535
hsa03320	hsa03320 PPAR signaling pathway	11/382	75/8464	0.0004966	0.0237535
hsa04380	hsa04380 Osteoclast differentiation	15/382	128/8464	0.0006213	0.0249197
hsa04514	hsa04514 Cell adhesion molecules	17/382	157/8464	0.0006946	0.0249197
hsa04060	hsa04060 Cytokine-cytokine receptor interaction	26/382	297/8464	0.0008879	0.0280393
hsa04924	hsa04924 Renin secretion	10/382	69/8464	0.0009770	0.0280393

The more enriched pathway (using the list of up-regulated genes) is related to malaria (and has ID **hsa05144**). We then visualized it using the package **pathview**:

```
# set working directory to save output
setwd("~/Documents/Repo_Git/Project_BR/output")

logFC <- upDEGs$logFC
names(logFC) <- upDEGs$entrezgene_id
pathview(gene.data = logFC, pathway.id = "hsa05144", species = "human")
```

Here is reported the network representing the pathway, with the up-regulated genes colored in red:

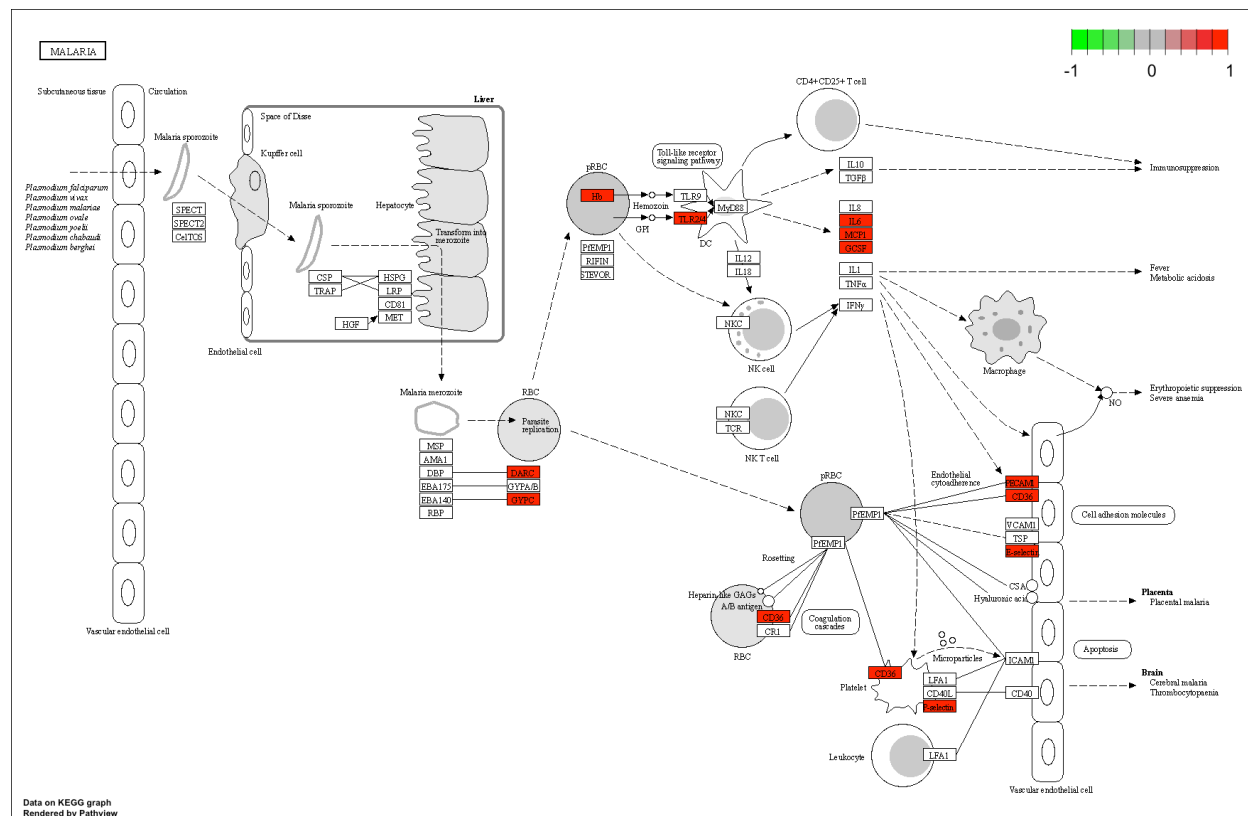


Figure 10: Most enriched pathway

## Task 6: Enrichment score transcription factors

First of all, we retrieve the promoter sequence for all the genes in the list of those down-regulated using ensembl gene id as identifier.

```
promoter_regions <- getSequence(id = downDEGs$ensembl_gene_id, type = "ensembl_gene_id",
  seqType = "gene_flank", upstream = 500, mart = ensembl)
```

Then we load the background for MotifDb human PWMs and convert the obtained sequence into a DNASTring object.

```
data(PWMLogn.hg19.MotifDb.Hsap)
seq <- lapply(promoter_regions$gene_flank, function(x) DNASTring(x))
```

motifEnrichment function performs enrichment analysis on the promoter sequences we obtained a few chunks above.



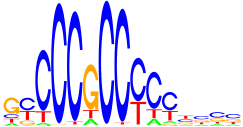


```
enriched_TFs = motifEnrichment(seq, PWMLogn.hg19.MotifDb.Hsap, score = "affinity")
```

```
## Calculating motif enrichment scores ...
```

```
report = groupReport(enriched_TFs)
```

Here we plot the top 5 enriched transcription factors resulted from our analysis:

```
plot(report[1:5])
```

Rank	Target	PWM	Motif ID	Raw score	Adjusted value	In top motifs
1	PGAM2		PGAM2	7.472.41e-868	6.8	8 %
2	TFAP4		M2944_1.02	3.423.37e-848	4	8 %
3	SP2		SP2	1206.25e-849	9	%
4	CEBPB		M4556_1.02	2.311.71e-837	7	%
5	JUND		M4506_1.02	6.861.5e-8119	%	

## Task 7

We select one among the top enriched TFs (TFAP4), compute the empirical distributions of scores for all PWMs that you find in MotifDB for the selected TF and determine for all of them the distribution (log2) threshold cutoff at 99.75%.

```
tfs <- report$target[2] # contains TFAP4
tfs_motifs = subset(MotifDb, organism == "Hsapiens" & geneSymbol == tfs)

# transformation to a PWM matrix
PWM = toPWM(as.list(tfs_motifs))
```

For the selected TF we found 15 PWMs:

- Hsapiens-cisbp\_1.02-M2943\_1.02
- Hsapiens-cisbp\_1.02-M2944\_1.02
- Hsapiens-cisbp\_1.02-M2947\_1.02
- Hsapiens-cisbp\_1.02-M5926\_1.02
- Hsapiens-cisbp\_1.02-M5927\_1.02
- Hsapiens-cisbp\_1.02-M6513\_1.02
- Hsapiens-HOCOMOCov10-TFAP4\_HUMAN.H10MO.C
- Hsapiens-HOCOMOCov11-core-A-TFAP4\_HUMAN.H11MO.0.A
- Hsapiens-jaspar2016-TFAP4-MA0691.1
- Hsapiens-jaspar2018-TFAP4-MA0691.1
- Hsapiens-jaspar2022-TFAP4-MA0691.1
- Hsapiens-jaspar2022-TFAP4-MA1570.1
- Hsapiens-jolma2013-TFAP4
- Hsapiens-jolma2013-TFAP4-2
- Hsapiens-SwissRegulon-TFAP4.SwissRegulon

To get the empirical distribution we used the function `motifEcdf`, which associates to each PWM a distribution. Then, for each score we computed the scores with a cutoff threshold of 99.75%.

```
ecdf = motifEcdf(PWM, organism = "hg19", quick = TRUE)

thresholds = lapply(ecdf, function(x) log2(quantile(x, 0.9975)))
# for each of the distribution, take the quantile as reference

scores = motifScores(seq, PWM, raw.scores = FALSE, cutoff = unlist(thresholds))
```

In the following table are reported the calculated scores for each PWM of the first 10 motifs.

```
head(scores, n = 10)
```

```
##      Hsapiens-cisbp_1.02-M2943_1.02 Hsapiens-cisbp_1.02-M2944_1.02
## [1,]                                2                                2
## [2,]                                3                                2
## [3,]                                3                                4
## [4,]                                6                                6
## [5,]                                2                                3
## [6,]                                0                                0
## [7,]                                4                                4
## [8,]                                4                                3
## [9,]                                1                                3
## [10,]                               3                                4
##      Hsapiens-cisbp_1.02-M2947_1.02 Hsapiens-cisbp_1.02-M5926_1.02
## [1,]                                3                                2
## [2,]                                2                                0
## [3,]                                1                                2
## [4,]                                6                                5
## [5,]                                5                                2
## [6,]                                1                                4
## [7,]                                4                                6
## [8,]                                4                                0
## [9,]                                3                                3
## [10,]                               1                                0
##      Hsapiens-cisbp_1.02-M5927_1.02 Hsapiens-cisbp_1.02-M6513_1.02
## [1,]                                6                                2
## [2,]                                0                                4
## [3,]                                1                                3
## [4,]                                4                                4
## [5,]                                2                                4
## [6,]                                4                                0
## [7,]                                4                                3
## [8,]                                1                                10
## [9,]                                4                                6
## [10,]                               0                                2
##      Hsapiens-HOCOMOCv10-TFAP4_HUMAN.H10M0.C
## [1,]                                2
## [2,]                                4
## [3,]                                3
## [4,]                                4
## [5,]                                4
## [6,]                                0
## [7,]                                3
## [8,]                                9
## [9,]                                7
## [10,]                               2
##      Hsapiens-HOCOMOCv11-core-A-TFAP4_HUMAN.H11M0.0.A
## [1,]                                1
## [2,]                                3
## [3,]                                1
## [4,]                                3
## [5,]                                2
## [6,]                                2
```

##	[7,]		6
##	[8,]		4
##	[9,]		5
##	[10,]		2
##		Hsapiens-jaspar2016-TFAP4-MA0691.1	Hsapiens-jaspar2018-TFAP4-MA0691.1
##	[1,]	6	6
##	[2,]	0	0
##	[3,]	1	1
##	[4,]	4	4
##	[5,]	2	2
##	[6,]	4	4
##	[7,]	4	4
##	[8,]	1	1
##	[9,]	4	4
##	[10,]	0	0
##		Hsapiens-jaspar2022-TFAP4-MA0691.1	Hsapiens-jaspar2022-TFAP4-MA1570.1
##	[1,]	6	5
##	[2,]	0	0
##	[3,]	1	2
##	[4,]	4	8
##	[5,]	2	0
##	[6,]	4	6
##	[7,]	4	11
##	[8,]	1	6
##	[9,]	4	4
##	[10,]	0	3
##		Hsapiens-jolma2013-TFAP4	Hsapiens-jolma2013-TFAP4-2
##	[1,]	2	6
##	[2,]	0	0
##	[3,]	2	1
##	[4,]	5	4
##	[5,]	2	2
##	[6,]	4	4
##	[7,]	6	4
##	[8,]	0	1
##	[9,]	3	4
##	[10,]	0	0
##		Hsapiens-SwissRegulon-TFAP4	SwissRegulon
##	[1,]	2	
##	[2,]	0	
##	[3,]	2	
##	[4,]	5	
##	[5,]	2	
##	[6,]	4	
##	[7,]	6	
##	[8,]	0	
##	[9,]	3	
##	[10,]	0	

## Task 8: Pattern matching

We identify which down-regulated genes have a region in their promoter (defined as previously) with binding scores above the computed thresholds for any of the previously selected PWMs.

To do that, we use the table of scores displayed before. We selected only genes having a region in their promoter with binding scores above the computed thresholds for any of the previously selected PWMs.

```
highscore_seq <- which(apply(scores, 1, function(x) {
  sum(x == 0)
}) == 0)
genes_id <- promoter_regions$ensembl_gene_id[highscore_seq]
```

The resulting list contains 510 genes.

```
length(genes_id)
```

```
## [1] 510
```

```
head(genes_id, n = 5)
```

```
## [1] "ENSG000000001084" "ENSG000000004848" "ENSG000000002726" "ENSG000000006118"
## [5] "ENSG000000005001"
```

## Task 9: PPI interactions

We use STRING database to find PPI interactions among differentially expressed genes. The network is exported in TSV format.

```
dat <- read.table("output/down_DEGs.txt", sep = "\t", header = TRUE)
write.table(dat$ensembl_gene_id, file = "output/ens_gene_id_down.txt", row.names = FALSE,
  col.names = FALSE)
```

## Task 10: visualize the network

We import the network in R and, using `igraph` package, we identify and plot the largest connected component.

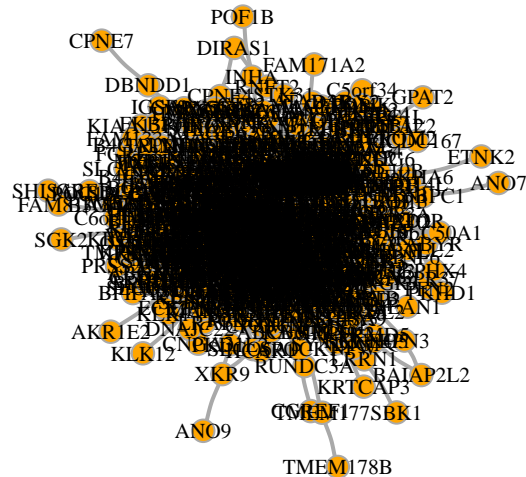
```
links_high_conf <- read.delim("string_interactions_short_high_conf.tsv")
links <- read.delim("string_interactions_short.tsv")
downDEGs <- read.table("output/down_DEGs.txt", sep = "\t", header = TRUE)

ensembl <- useMart(biomart = "ensembl", dataset = "hsapiens_gene_ensembl")
nodes <- getBM(attributes = c("external_gene_name", "ensembl_gene_id", "description",
  "gene_biotype", "start_position", "end_position", "chromosome_name", "strand"),
  filters = c("ensembl_gene_id"), values = downDEGs[, 1], mart = ensembl) # search info about nodes
nodes <- unique(nodes[, c(1, 3:6)])

nodes <- nodes[nodes$external_gene_name %in% links$X.node1 & nodes$external_gene_name %in%
  links$X.node1, ]

links <- links[links$X.node1 %in% nodes$external_gene_name & links$node2 %in% nodes$external_gene_name,
  ]
```





```
deg <- degree(net.c, mode = "all")
names_nodes <- names(deg[which(deg > 150)])

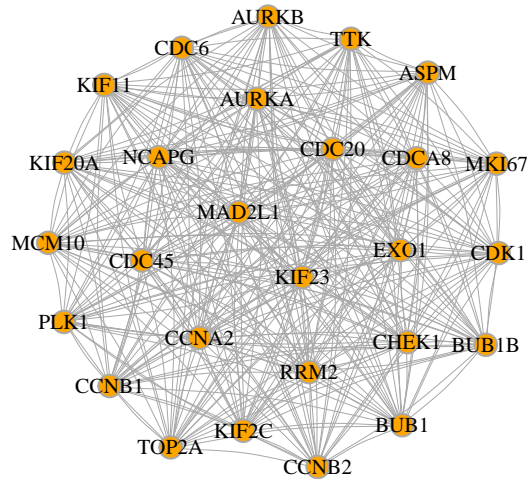
nodes.deg <- nodes[nodes$external_gene_name %in% names_nodes, ]

nodes.deg <- nodes.deg[nodes.deg$external_gene_name %in% links$X.node1 & nodes.deg$external_gene_name %in%
  links$node2, ]
links.deg <- links[links$X.node1 %in% nodes.deg$external_gene_name & links$node2 %in%
  nodes.deg$external_gene_name, ]

net.deg <- graph_from_data_frame(d = links.deg, vertices = nodes.deg, directed = FALSE)

plot(net.deg, edge.width = 0.5, vertex.color = "orange", vertex.size = 10, vertex.frame.color = "darkgreen",
  vertex.label.color = "black", vertex.label.cex = 0.7, edge.curved = 0.1)
```





```

links_high_conf <- read.delim("string_interactions_short_high_conf.tsv")
downDEGs <- read.table("output/down_DEGs.txt", sep = "\t", header = TRUE)

ensembl <- useMart(biomart = "ensembl", dataset = "hsapiens_gene_ensembl")
nodes <- getBM(attributes = c("external_gene_name", "ensembl_gene_id", "description",
  "gene_biotype", "start_position", "end_position", "chromosome_name", "strand"),
  filters = c("ensembl_gene_id"), values = downDEGs[, 1], mart = ensembl) # search info about nodes
nodes <- unique(nodes[, c(1, 3:6)])

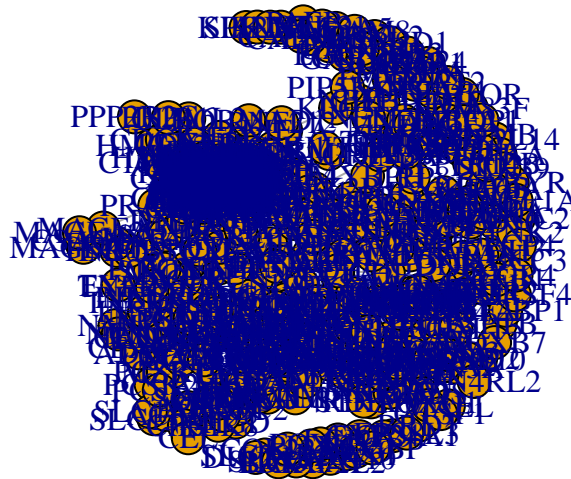
nodes <- nodes[nodes$external_gene_name %in% links_high_conf$X.node1 & nodes$external_gene_name %in%
  links_high_conf$X.node1, ]

links_high_conf <- links_high_conf[links_high_conf$X.node1 %in% nodes$external_gene_name &
  links_high_conf$node2 %in% nodes$external_gene_name, ]

# create network
net <- graph_from_data_frame(d = links_high_conf, vertices = nodes, directed = FALSE)

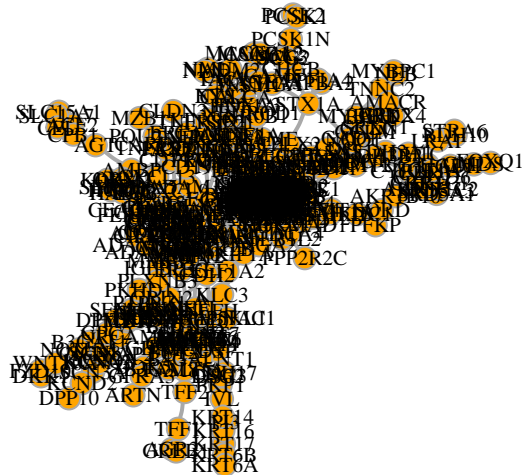
plot(net)

```



```
c <- components(net, mode = "strong")
net.c <- induced_subgraph(net, V(net)[which(c$membership == 1)])

plot(net.c, edge.width = 2, vertex.color = "orange", vertex.size = 10, vertex.frame.color = "darkgray",
      vertex.label.color = "black", vertex.label.cex = 0.7, edge.curved = 0.1)
```



```
deg <- degree(net.c, mode = "all")
names_nodes <- names(deg[which(deg > 110)])

nodes.deg <- nodes[nodes$external_gene_name %in% names_nodes, ]

nodes.deg <- nodes.deg[nodes.deg$external_gene_name %in% links_high_conf$X.node1 &
  nodes.deg$external_gene_name %in% links_high_conf$node2, ]
links.deg.high <- links_high_conf[links_high_conf$X.node1 %in% nodes.deg$external_gene_name &
  links_high_conf$node2 %in% nodes.deg$external_gene_name, ]

net.deg <- graph_from_data_frame(d = links.deg.high, vertices = nodes.deg, directed = FALSE)

plot(net.deg, edge.width = 0.5, vertex.color = "orange", vertex.size = 10, vertex.frame.color = "darkgreen",
  vertex.label.color = "black", vertex.label.cex = 0.7, edge.curved = 0.1)
```

