

Questions for Lab 1, 2 and 3

Leo lahti & Rajesh Shigdel

2022-04-23

Contents

1	Overview	4
1.1	Introduction	4
1.2	Learning goals	4
1.3	Schedule	5
1.4	Material	6
2	Organizers	7
2.1	Acknowledgments	7
3	Program	9
3.1	Day 1: from raw sequences to ecological data analysis	9
3.2	Day 2 - Alpha diversity	9
3.3	Day 3 - Beta diversity	10
3.4	Day 4 - Differential abundance	10
3.5	Day 5 : Presentations & closing	10
4	Getting started	11
4.1	Checklist (before the course)	11
4.2	Support and resources	11
4.3	Installing and loading the required R packages	11
5	Reproducible reporting with Rmarkdown	13
6	Importing microbiome data	14
6.1	Data access	14
6.2	Importing microbiome data in R	15
6.3	Example solutions	15

<i>CONTENTS</i>	2
7 Microbiome data exploration	19
7.1 Data structure	19
7.2 Visualization	22
7.3 Exercises (optional)	24
8 Alpha diversity	29
8.1 Visualization	32
8.2 Statistical testing and comparisons	33
8.3 Exercises	34
9 Beta diversity	37
9.1 Examples of PCoA with different settings	37
9.2 Highlighting external variables	41
9.3 Estimating associations with an external variable	44
9.4 Community typing	47
9.5 Exercises	47
10 Differential abundance analysis	49
10.1 Wilcoxon test	49
10.2 ANCOM-BC	51
10.3 Comparison of the methods	53
10.4 Comparison of abundance	53
11 Study material	58
11.1 Lecture slides	58
11.2 R programming resources	58
11.3 Resources for TreeSummarizedExperiment	58
11.4 Resources for phyloseq	59
11.5 Further reading	59
12 Additional Community Typing	60
12.1 Community composition	60
12.2 Cluster into CSTs	62
12.3 Holmes and McMurdie Workflow	72
12.4 CST Analysis	83
12.5 Session Info	84
12.6 Bibliography	86

<i>CONTENTS</i>	3
13 Exercise Solutions	88
13.1 Section 5	88
13.2 Section 6	88
13.3 Section 7	88
13.4 Section 8	88
14 Tutorial Aims	89
15 Lab 1	90
15.1 unsupervised learning: Feature selection & dimension reduction	90
15.2 Load the data	90
16 Lab 2	91
16.1 unsupervised learning: clustering & visualization	91
17 Lab 3	92
17.1 unsupervised learning: Analysis and interpretation	92

Chapter 1

Overview

Welcome to Oulu Summer School, June 2022

Venue University of Oulu. June 20-23, 2022. Organized together with University of Turku, Finland.

Figure source: Moreno-Indias *et al.* (2021) Statistical and Machine Learning Techniques in Human Microbiome Studies: Contemporary Challenges and Solutions. *Frontiers in Microbiology* 12:11.

1.1 Introduction

This course is based on data science with R, a popular open source environment for scientific data analysis. It provides general capabilities for the analysis, integration, and visualization of multi-omic data from biomedical studies.

The course is based on *miaverse* (mia = **MI**crobiome **A**nalyses), an R/Bioconductor framework for microbiome data science.

The data science framework consists of the following elements:

- efficient multi-omic data container
- a package ecosystem, providing algorithmic data analysis methods
- demonstration data sets
- open documentation

The framework is explained in a greater depth in the online book *Orchestrating Microbiome Analysis*. The book is currently a development version.

1.2 Learning goals

The course aims to provide the basic understanding and skills for biomedical data analysis with R and Bioconductor. The course provides an overview of reproducible data analysis and reporting workflow in multi-omic studies, with recent example data sets published microbiome studies.

The participants become familiar with standard concepts and methods in multi-omic data analysis, in particular in human microbiome research. This includes better understanding of the specific statistical challenges, practical hands-on experience with the commonly used methods, and reproducible research with R.

After the course you will know how to approach new tasks in microbiome data science by utilizing available documentation and R tools.

Target audience Advanced MSc and PhD students, Postdocs, and biomedical researchers who wish to develop their skills in scientific programming and biomedical data analysis.

1.3 Schedule

The course takes place daily between 9am – 5pm, including coffee and lunch breaks.

The course will be organized in a live format but the material will be openly available online during and after the course.

A priority will be given to local students from Oulu. Participants from other higher education institutions are welcome to apply.

The mornings will start with lectures, and afternoons are mainly dedicated to hands-on sessions that consist of practical tasks and example data from recent research literature. Students will solve the exercises based on available online examples and resources that are pointed out in the study material. There is often more than one way to solve a given task, and the teachers will be available for assistance.

Monday:

- Orientation
- Best practices in reproducible reporting and open science
- Hands-on: Introduction to R

Tuesday:

- Key concepts and challenges in biomedical data analysis
- Hands-on: Biomedical data exploration

Wednesday:

- Key concepts in biomedical data visualization
- Hands-on: Biomedical data visualization

Thursday:

- Advanced topics: common machine learning techniques
- Hands-on: multi-omic data integration and reproducible workflows

Friday:

- Student presentations
- Summary & Conclusions

1.4 Material

The teaching material follows open online documentation created by the course teachers, extending the online book *Orchestrating Microbiome Analysis* (<https://microbiome.github.io/OMA>). We will teach generic data analytical skills that are applicable to common data analysis tasks encountered in modern omics research.

The training material walks through example workflows that go through standard steps of biomedical data analysis covering data access, exploration, analysis, visualization, reproducible reporting, and best practices in open science. The teaching format allows adaptations according to the student's learning speed.

You can run the workflow by simply copy-pasting the examples. For further, advanced material, you can test and modify further examples from the OMA book, or try to apply the techniques to your own data.

We expect that the students will install the necessary software in advance. Online support will be available.

Chapter 2

Organizers

Jointly organized by:

- Health and Biosciences Doctoral Programme, University of Oulu Graduate School (HBS-DP)
- Department of Computing, University of Turku

Supported by:

- IT Center for Science (CSC), Finland

Teachers

- Leo Lahti is the main teacher and Associate Professor in Data Science at the University of Turku, with specialization on biomedical data analysis.
- Tuomas Borman is research assistant and one of the main developers of the open training material covered by the course.
- Jenni Hekkala is a local PhD researchers from Oulu who will coordinate the local arrangements and contribute to course teaching.

2.1 Acknowledgments

Citation “Introduction to microbiome data science (2021). URL: <https://microbiome.github.io>”.

Borman et al. (2022)

We thank all miaverse developers and contributors who have contributed open resources that supported the development of the training material.

Contact Leo Lahti, University of Turku, Finland

License All material is released under the open CC BY-NC-SA 3.0 License and available online during and after the course, following the recommendations on open teaching materials of the national open science coordination in Finland**.

Source code

The source code of this repository is fully reproducible and contains the Rmd files with executable code. All files can be rendered at one go by running the file main.R. You can check the file for details on how to clone the repository and convert it into a gitbook, although this is not necessary for the training.

- Source code (github): [miaverse teaching material](#)
- Course page (html): [miaverse teaching material](#)

Chapter 3

Program

The course takes place on each working day from 9am – 1pm (CEST). Short breaks will be scheduled between sessions.

The hands-on sessions consist of a set of questions and example data. Solve the exercises by taking advantage of the online examples and resources that are pointed out in the study material. There is often more than one way to solve a given task. It is assumed that you have already installed the required software. Do not hesitate to ask support from the course assistants.

3.1 Day 1: from raw sequences to ecological data analysis

Lectures

- Microbiota analysis: association studies vs. causality; microbiota sequencing methods (16S, shotgun, metagenomics) - by dr. Tom Ederveen (Radboud UMC Nijmegen, The Netherlands)
- DNA isolation and 16S rRNA gene sequencing; bioinformatics step 1: from raw sequences to OTU table in a biom file – by Tom Ederveen (Radboudumc Nijmegen, The Netherlands)

Demo & Practical

- Importing data to R for interactive data analysis
 - Task: initialize reproducible report
-

3.2 Day 2 - Alpha diversity

Demo

- Microbiome data exploration

Lecture

- Key concepts in microbiome data science

Practical

- Alpha diversity: estimation, analysis, and visualization
-

3.3 Day 3 - Beta diversity

Demo

- Community similarity

Practical

- Beta diversity: estimation, analysis, and visualization
-

3.4 Day 4- Differential abundance

Lecture

- Differential abundance analysis methods

Practical

- Differential abundance in practice

Lecture

- Overview of microbiota data science methods & concepts
-

3.5 Day 5 : Presentations & closing

Student presentations on microbiome data analytics

Chapter 4

Getting started

4.1 Checklist (before the course)

Install the following software in advance in order to avoid unnecessary delays and leaving more time for the course contents.

- R (version >4.1.0)
- RStudio; choose “Rstudio Desktop” to download the latest version. Optional but preferred. For further details, check the Rstudio home page.
- Install and load the required R packages
- After a successful installation you can start with the case study examples in this training material

4.2 Support and resources

For additional reading and online material, see Material section

For online support on installation and other matters, you can join us at:

- Users: miaverse Gitter channel
- Developers: Bioconductor Slack [#microbiomeexperiment](#) channel (ask for an invitation)

4.3 Installing and loading the required R packages

This section shows how to install and load all required packages into the R session. Only uninstalled packages are installed.

```
# List of packages that we need from cran and bioc
cran_pkg <- c("BiocManager", "bookdown", "dplyr", "ecodist", "ggplot2",
             "gridExtra", "kableExtra", "knitr", "scales", "vegan", "matrixStats")
bioc_pkg <- c("yulab.utils", "ggtree", "ANCOMBC", "ape", "DESeq2", "DirichletMultinomial", "mia", "miaViz")
```

```

# Gets those packages that are already installed
cran_pkg_already_installed <- cran_pkg[ cran_pkg %in% installed.packages() ]
bioc_pkg_already_installed <- bioc_pkg[ bioc_pkg %in% installed.packages() ]

# Gets those packages that need to be installed
cran_pkg_to_be_installed <- setdiff(cran_pkg, cran_pkg_already_installed)
bioc_pkg_to_be_installed <- setdiff(bioc_pkg, bioc_pkg_already_installed)

# If there are packages that need to be installed, installs them from CRAN
if( length(cran_pkg_to_be_installed) ) {
  install.packages(cran_pkg_to_be_installed)
}

# If there are packages that need to be installed, installs them from Bioconductor
if( length(bioc_pkg_to_be_installed) ) {
  BiocManager::install(bioc_pkg_to_be_installed, ask = F)
}

```

Now all required packages are installed, so let's load them into the session. Some function names occur in multiple packages. That is why *miaverse*'s packages *mia* and *miaViz* are prioritized. Packages that are loaded first have higher priority.

```

# Reorders bioc packages, so that mia and miaViz are first
bioc_pkg <- c(bioc_pkg[ bioc_pkg %in% c("mia", "miaViz") ],
             bioc_pkg[ !bioc_pkg %in% c("mia", "miaViz") ] )

# Loading all packages into session. Returns true if package was successfully loaded.
loaded <- sapply(c(bioc_pkg, cran_pkg), require, character.only = TRUE)
as.data.frame(loaded)

```

##	loaded
## mia	TRUE
## miaViz	TRUE
## yulab.utils	TRUE
## ggtree	TRUE
## ANCOMBC	TRUE
## ape	TRUE
## DESeq2	TRUE
## DirichletMultinomial	TRUE
## BiocManager	TRUE
## bookdown	TRUE
## dplyr	TRUE
## ecodist	TRUE
## ggplot2	TRUE
## gridExtra	TRUE
## kableExtra	TRUE
## knitr	TRUE
## scales	TRUE
## vegan	TRUE
## matrixStats	TRUE

Chapter 5

Reproducible reporting with Rmarkdown

Reproducible reporting is the starting point for robust interactive data science. Perform the following tasks:

- Create a Rmarkdown template in RStudio, and render it into a document (markdown, PDF, docx or other format)
- If you are entirely new to Markdown, take this 10 minute tutorial to get introduced to the most important functions within Markdown. Then experiment with different options with Rmarkdown

In case you are new to Rmarkdown Rstudio provides resources to learn about the use cases and the basics of Rmarkdown. A good online tutorial to reproducible reporting is available by Dr. C Titus Brown.

Chapter 6

Importing microbiome data

This section demonstrates how to import microbiome profiling data in R.

6.1 Data access

Option 1

ADHD-associated changes in gut microbiota and brain in a mouse model

Tengeler AC *et al.* (2020) **Gut microbiota from persons with attention-deficit/hyperactivity disorder affects the brain in mice.** Microbiome 8:44.

In this study, mice are colonized with microbiota from participants with ADHD (attention deficit hyperactivity disorder) and healthy participants. The aim of the study was to assess whether the mice display ADHD behaviors after being inoculated with ADHD microbiota, suggesting a role of the microbiome in ADHD pathology.

Download the data from data subfolder.

Option 2

Western diet intervention study in serotonin transporter modified mouse model

Mice received three weeks of Western (high fat, high sugar) or Control diet in three Genotype groups, a wild-type group and 2 groups with either partial or complete knock-out of the serotonin transporter (SERT), leading to an excess of serotonin in the gut, brain and blood circulation. Mice were measured before and after the intervention. In total there are three factors in this design, Time (pre-,post-intervention), Diet (Control, Western diet) and Genotype group (WT, HET, KO). There are about 6-8 mice per group.

Data can be found from Summer School's Brightspace.

Option 3

Open data set of your own choice, see e.g.:

- Bioconductor microbiomeDataSets

6.2 Importing microbiome data in R

Import example data by modifying the examples in the online book section on data exploration and manipulation. The data files in our example are in *biom* format, which is a standard file format for microbiome data. Other file formats exist as well, and import details vary by platform.

Here, we import *biom* data files into a specific data container (structure) in R, *TreeSummarizedExperiment* (TSE) Huang et al. (2020). This provides the basis for downstream data analysis in the *miaverse* data science framework.

In this course, we focus on downstream analysis of taxonomic profiling data, and assume that the data has already been appropriately preprocessed and available in the TSE format. In addition to our example data, further demonstration data sets are readily available in the TSE format through *microbiomeDataSets*.

Figure sources:

Original article - Huang R *et al.* (2021) *TreeSummarizedExperiment*: a S4 class for data with hierarchical structure. *F1000Research* 9:1246.

Reference Sequence slot extension - Lahti L *et al.* (2020) Upgrading the R/Bioconductor ecosystem for microbiome research *F1000Research* 9:1464 (slides).

6.3 Example solutions

- Example code for data import: `import.Rmd`

```
## Loading required package: SummarizedExperiment

## Loading required package: MatrixGenerics

## Loading required package: matrixStats

##
## Attaching package: 'MatrixGenerics'

## The following objects are masked from 'package:matrixStats':
##
##   colAlls, colAnyNAs, colAnys, colAvgsPerRowSet, colCollapse,
##   colCounts, colCummaxs, colCummins, colCumprods, colCumsums,
##   colDiffs, colIQRDiffs, colIQRs, colLogSumExps, colMadDiffs,
##   colMads, colMaxs, colMeans2, colMedians, colMins, colOrderStats,
##   colProds, colQuantiles, colRanges, colRanks, colSdDiffs, colSds,
##   colSums2, colTabulates, colVarDiffs, colVars, colWeightedMads,
##   colWeightedMeans, colWeightedMedians, colWeightedSds,
##   colWeightedVars, rowAlls, rowAnyNAs, rowAnys, rowAvgsPerColSet,
##   rowCollapse, rowCounts, rowCummaxs, rowCummins, rowCumprods,
##   rowCumsums, rowDiffs, rowIQRDiffs, rowIQRs, rowLogSumExps,
##   rowMadDiffs, rowMads, rowMaxs, rowMeans2, rowMedians, rowMins,
##   rowOrderStats, rowProds, rowQuantiles, rowRanges, rowRanks,
##   rowSdDiffs, rowSds, rowSums2, rowTabulates, rowVarDiffs, rowVars,
##   rowWeightedMads, rowWeightedMeans, rowWeightedMedians,
##   rowWeightedSds, rowWeightedVars
```



```
## Loading required package: GenomicRanges

## Loading required package: stats4

## Loading required package: BiocGenerics

##
## Attaching package: 'BiocGenerics'

## The following objects are masked from 'package:stats':
##
##     IQR, mad, sd, var, xtabs

## The following objects are masked from 'package:base':
##
##     anyDuplicated, append, as.data.frame, basename, cbind, colnames,
##     dirname, do.call, duplicated, eval, evalq, Filter, Find, get, grep,
##     grepl, intersect, is.unsorted, lapply, Map, mapply, match, mget,
##     order, paste, pmax, pmax.int, pmin, pmin.int, Position, rank,
##     rbind, Reduce, rownames, sapply, setdiff, sort, table, tapply,
##     union, unique, unsplit, which.max, which.min

## Loading required package: S4Vectors

##
## Attaching package: 'S4Vectors'

## The following objects are masked from 'package:base':
##
##     expand.grid, I, unname

## Loading required package: IRanges

## Loading required package: GenomeInfoDb

## Loading required package: Biobase

## Welcome to Bioconductor
##
##     Vignettes contain introductory material; view with
##     'browseVignettes()'. To cite Bioconductor, see
##     'citation("Biobase")', and for packages 'citation("pkgname)".

##
## Attaching package: 'Biobase'

## The following object is masked from 'package:MatrixGenerics':
##
##     rowMedians
```

```
## The following objects are masked from 'package:matrixStats':  
##  
##    anyMissing, rowMedians  
  
## Loading required package: SingleCellExperiment  
  
## Loading required package: TreeSummarizedExperiment  
  
## Loading required package: Biostrings  
  
## Loading required package: XVector  
  
##  
## Attaching package: 'Biostrings'  
  
## The following object is masked from 'package:base':  
##  
##    strsplit  
  
## Loading required package: MultiAssayExperiment  
  
## Loading required package: ggplot2  
  
## Loading required package: ggraph  
  
##  
## Attaching package: 'dplyr'  
  
## The following objects are masked from 'package:Biostrings':  
##  
##    collapse, intersect, setdiff, setequal, union  
  
## The following object is masked from 'package:XVector':  
##  
##    slice  
  
## The following object is masked from 'package:Biobase':  
##  
##    combine  
  
## The following objects are masked from 'package:GenomicRanges':  
##  
##    intersect, setdiff, union  
  
## The following object is masked from 'package:GenomeInfoDb':  
##  
##    intersect
```

```
## The following objects are masked from 'package:IRanges':  
##  
## collapse, desc, intersect, setdiff, slice, union  
  
## The following objects are masked from 'package:S4Vectors':  
##  
## first, intersect, rename, setdiff, setequal, union  
  
## The following objects are masked from 'package:BiocGenerics':  
##  
## combine, intersect, setdiff, union  
  
## The following object is masked from 'package:matrixStats':  
##  
## count  
  
## The following objects are masked from 'package:stats':  
##  
## filter, lag  
  
## The following objects are masked from 'package:base':  
##  
## intersect, setdiff, setequal, union
```

Chapter 7

Microbiome data exploration

Now we have loaded the data set into R. Next, let us walk through some basic operations for data exploration to confirm that the data has all the necessary components.

7.1 Data structure

Let us now investigate how taxonomic profiling data is organized in R.

Dimensionality tells us how many taxa and samples the data contains. As we can see, there are 151 taxa and 27 samples.

```
dim(tse)
```

```
## [1] 151 27
```

The `rowData` slot contains a taxonomic table. This includes taxonomic information for each of the 151 entries. With the `head()` command, we can print just the beginning of the table.

The `rowData` seems to contain information from 6 different taxonomy classes.

```
knitr::kable(head(rowData(tse))) %>%  
  kableExtra::kable_styling("striped",  
                             latex_options="scale_down") %>%  
  kableExtra::scroll_box(width = "100%")
```

The `colData` slot contains sample metadata. It contains information for all 27 samples. However, here only the 6 first samples are shown as we use the `head()` command. There are 4 columns, that contain information, e.g., about patients' status, and cohort.

	Kingdom	Phylum	Class	Order	Family	Genus
1726470	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	Bacteroidaceae	Bacteroides
1726471	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	Bacteroidaceae	Bacteroides
17264731	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	Porphyromonadaceae	Parabacteroides
17264726	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	Bacteroidaceae	Bacteroides
1726472	Bacteria	Verrucomicrobia	Verrucomicrobiae	Verrucomicrobiales	Verrucomicrobiaceae	Akkermansia
17264724	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales	Bacteroidaceae	Bacteroides

	patient_status	cohort	patient_status_vs_cohort	sample_name
A110	ADHD	Cohort_1	ADHD_Cohort_1	A110
A12	ADHD	Cohort_1	ADHD_Cohort_1	A12
A15	ADHD	Cohort_1	ADHD_Cohort_1	A15
A19	ADHD	Cohort_1	ADHD_Cohort_1	A19
A21	ADHD	Cohort_2	ADHD_Cohort_2	A21
A23	ADHD	Cohort_2	ADHD_Cohort_2	A23

```
knitr::kable(head(colData(tse))) %>%
  kableExtra::kable_styling("striped",
                             latex_options="scale_down") %>%
  kableExtra::scroll_box(width = "100%")
```

From here, we can draw summaries of the sample (column) data, for instance to see what is the patient status distribution.

The command `colData(tse)$patient_status` fetches the data from the column, and `table()` creates a table that shows how many times each class is present, and `sort()` sorts the table to ascending order.

There are 13 samples from patients having ADHD, and 14 control samples.

```
sort(table(colData(tse)$patient_status))
```

```
##
##      ADHD Control
##      13       14
```

7.1.1 Transformations

Microbial abundances are typically ‘compositional’ (relative) in the current microbiome profiling data sets. This is due to technical aspects of the data generation process (see e.g. Gloor et al., 2017).

The next example calculates relative abundances as these are usually easier to interpret than plain counts. For some statistical models we need to transform the data into other formats as explained in above link (and as we will see later).

```
# Calculates relative abundances, and stores the table to assays
tse <- transformCounts(tse, method = "relabundance")
```

A variety of standard transformations for microbiome data are available for TSE data objects through mia R package.

7.1.2 Aggregation

Microbial species can be called at multiple taxonomic resolutions. We can easily agglomerate the data based on taxonomic ranks. Here, we agglomerate the data at Phylum level.

	Kingdom	Phylum	Class	Order	Family	Genus
Bacteroidetes	Bacteria	Bacteroidetes	NA	NA	NA	NA
Verrucomicrobia	Bacteria	Verrucomicrobia	NA	NA	NA	NA
Proteobacteria	Bacteria	Proteobacteria	NA	NA	NA	NA
Firmicutes	Bacteria	Firmicutes	NA	NA	NA	NA
Cyanobacteria	Bacteria	Cyanobacteria	NA	NA	NA	NA

	Kingdom	Phylum	Class	Order	Family	Genus
Family:Lachnospiraceae	Bacteria	Firmicutes	Clostridia	Clostridiales	Lachnospiraceae	
Order:Bacteroidales	Bacteria	Bacteroidetes	Bacteroidia	Bacteroidales		
Order:Clostridiales	Bacteria	Firmicutes	Clostridia	Clostridiales		
Family:Enterobacteriaceae	Bacteria	Proteobacteria	Gammaproteobacteria	Enterobacteriales	Enterobacteriaceae	
Order:Gastranaerophilales	Bacteria	Cyanobacteria	Melainabacteria	Gastranaerophilales		

```
tse_phylum <- agglomerateByRank(tse, rank = "Phylum")
```

```
# Show dimensionality
dim(tse_phylum)
```

```
## [1] 5 27
```

Now there are 5 taxa and 27 samples, meaning that there are 5 different Phylum level taxonomic groups. Looking at the `rowData` after agglomeration shows all Firmicutes are combined together, and all lower rank information is lost.

From the assay we can see that all abundances of taxa that belong to Firmicutes are summed up.

```
knitr::kable(head(rowData(tse_phylum))) %>%
  kableExtra::kable_styling("striped",
                           latex_options="scale_down") %>%
  kableExtra::scroll_box(width = "100%")
```

If you are sharp, you have by now noticed that all the aggregated values in the above example are NA's (missing data). This is because the agglomeration is missing abundances for certain taxa, and in that case the sum is not defined by default (`na.rm = FALSE`). We can ignore the missing values in summing up the data by setting `na.rm = TRUE`; then the taxa that do not have information in specified level will be removed. Those taxa that do not have information in specified level are agglomerated at lowest possible level that is left after agglomeration.

```
temp <- rowData(agglomerateByRank(tse, rank = "Genus"))

# Prints those taxa that do not have information at the Genus level
knitr::kable(head(temp[temp$Genus == "",])) %>%
  kableExtra::kable_styling("striped",
                           latex_options="scale_down") %>%
  kableExtra::scroll_box(width = "100%")
```

Here agglomeration is done similarly, but `na.rm = TRUE`

```
temp2 <- rowData(agglomerateByRank(tse, rank = "Genus", na.rm = TRUE))

print(paste0("Agglomeration with na.rm = FALSE: ", dim(temp)[1], " taxa."))

## [1] "Agglomeration with na.rm = FALSE: 54 taxa."

print(paste0("Agglomeration with na.rm = TRUE: ", dim(temp2)[1], " taxa."))

## [1] "Agglomeration with na.rm = TRUE: 49 taxa."
```

The mia package contains further examples on various data agglomeration and splitting options.

7.2 Visualization

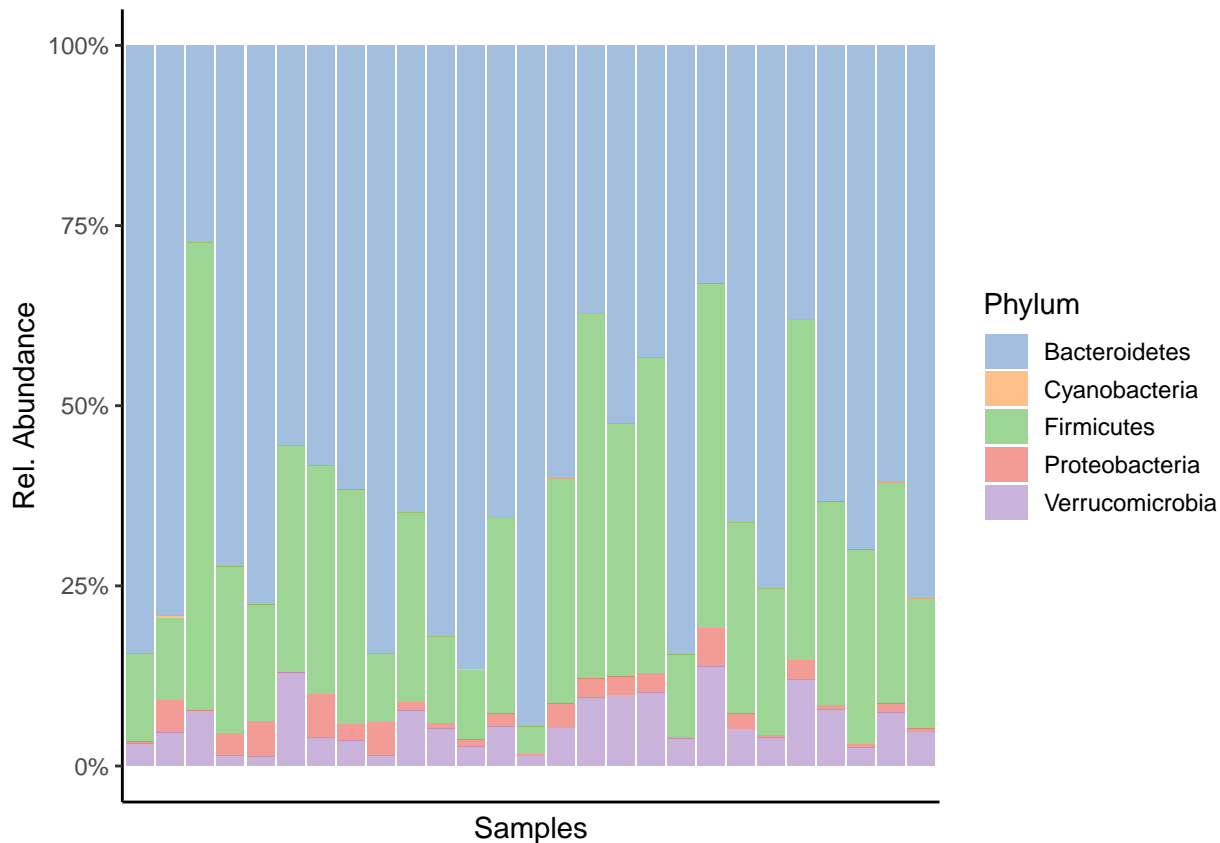
The miaViz package facilitates data visualization. Let us plot the Phylum level abundances.

```
# Here we specify "relabundance" to be abundance table that we use for plotting.
# Note that we can use agglomerated or non-agglomerated tse as an input, because
# the function agglomeration is built-in option.

# Legend does not fit into picture, so its height is reduced.
plot_abundance <- plotAbundance(tse, abund_values="relabundance", rank = "Phylum") +
  theme(legend.key.height = unit(0.5, "cm")) +
  scale_y_continuous(label = scales::percent)

## Scale for 'y' is already present. Adding another scale for 'y', which will
## replace the existing scale.

plot_abundance
```



Density plot shows the overall abundance distribution for a given taxonomic group. Let us check the relative abundance of Firmicutes across the sample collection. The density plot is a smoothed version of a standard histogram.

The plot shows peak abundances around 30 %.

```
# Subset data by taking only Firmicutes
tse_firmicutes <- tse_phylum["Firmicutes"]

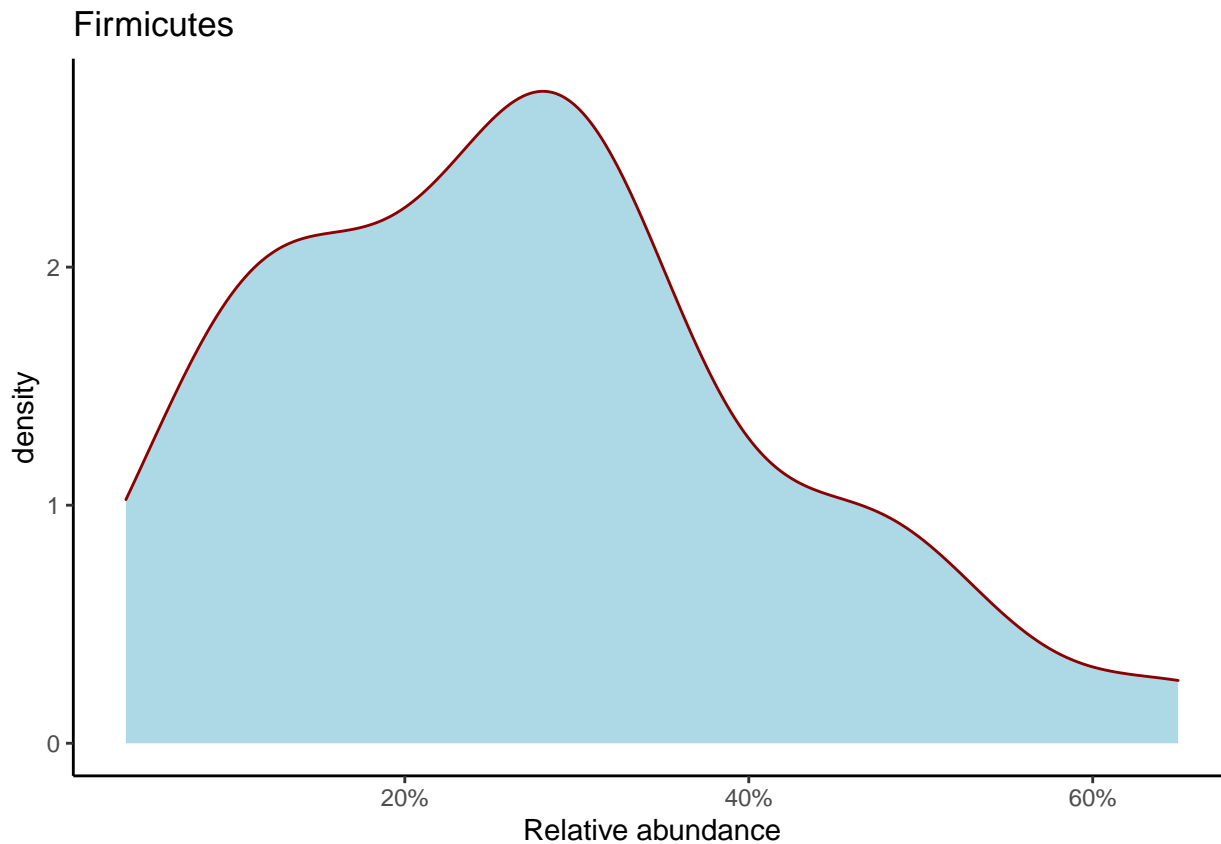
# Gets the abundance table
abundance_firmicutes <- assay(tse_firmicutes, "relabundance")

# Creates a data frame object, where first column includes abundances
firmicutes_abund_df <- as.data.frame(t(abundance_firmicutes))
# Rename the first and only column
colnames(firmicutes_abund_df) <- "abund"

# Creates a plot. Parameters inside feom_density are optional. With
# geom_density(bw=1000), it is possible to adjust bandwidth.
firmicutes_abund_plot <- ggplot(firmicutes_abund_df, aes(x = abund)) +
  geom_density(color="darkred", fill="lightblue") +
  labs(x = "Relative abundance", title = "Firmicutes") +
  theme_classic() + # Changes the background
  scale_x_continuous(label = scales::percent)
```



```
firmicutes_abund_plot
```



For more visualization options and examples, see the miaViz vignette.

7.3 Exercises (optional)

Explore some of the following questions on your own by following online examples. Prepare a reproducible report (Rmarkdown), and include the code that you use to import the data and generate the analyses.

- **Abundance table** Retrieve the taxonomic abundance table from the example data set (TSE object). Tip: check “assays” in data import section
- How many different samples and genus-level groups this phyloseq object has? Tips: see `dim()`, `rowData()`
- What is the maximum abundance of *Akkermansia* in this data set? Tip: aggregate the data to Genus level with `agglomerateByRank`, pick abundance assay, and check a given genus (row) in the assay
- Draw a histogram of library sizes (total number of reads per sample). Tip: Library size section in OMA. You can use the available function, or count the sum of reads per sample by using the `colSums` command applied on the abundance table. Check Vandeputte et al. 2017 for further discussion on the differences between absolute and relative quantification of microbial abundances.

- **Taxonomy table** Retrieve the taxonomy table and print out the first few lines of it with the R command `head()`. Investigate how many different phylum-level groups this phyloseq object has? Tips: `rowData`, `taxonomicRanks` in OMA.
- **Sample metadata** Retrieve sample metadata. How many patient groups this data set has? Draw a histogram of sample diversities. Tips: `colData`
- **Subsetting** Pick a subset of the data object including only ADHD individuals from Cohort 1. How many there are? Tips: subsetting in OMA
- **Transformations** The data contains read counts. We can convert these into relative abundances and other formats. Compare abundance of a given taxonomic group using the example data before and after the compositionality transformation (with a cross-plot, for instance). You can also compare the results to CLR-transformed data (see e.g. Gloor et al. 2017)
- **Visual exploration** Visualize the population distribution of abundances for certain taxonomic groups. Do the same for CLR-transformed abundances. Tip: `assays`, `transformCounts`
- Experiment with other data manipulation tools from OMA.
- Example solution: Solutions

```
## Loading required package: SummarizedExperiment

## Loading required package: MatrixGenerics

## Loading required package: matrixStats

##
## Attaching package: 'MatrixGenerics'

## The following objects are masked from 'package:matrixStats':
##
##   colAlls, colAnyNAs, colAnys, colAvesPerRowSet, colCollapse,
##   colCounts, colCummaxs, colCummins, colCumprods, colCumsums,
##   colDiffs, colIQRDiffs, colIQRs, colLogSumExps, colMadDiffs,
##   colMads, colMaxs, colMeans2, colMedians, colMins, colOrderStats,
##   colProds, colQuantiles, colRanges, colRanks, colSdDiffs, colSds,
##   colSums2, colTabulates, colVarDiffs, colVars, colWeightedMads,
##   colWeightedMeans, colWeightedMedians, colWeightedSds,
##   colWeightedVars, rowAlls, rowAnyNAs, rowAnys, rowAvesPerColSet,
##   rowCollapse, rowCounts, rowCummaxs, rowCummins, rowCumprods,
##   rowCumsums, rowDiffs, rowIQRDiffs, rowIQRs, rowLogSumExps,
##   rowMadDiffs, rowMads, rowMaxs, rowMeans2, rowMedians, rowMins,
##   rowOrderStats, rowProds, rowQuantiles, rowRanges, rowRanks,
##   rowSdDiffs, rowSds, rowSums2, rowTabulates, rowVarDiffs, rowVars,
##   rowWeightedMads, rowWeightedMeans, rowWeightedMedians,
##   rowWeightedSds, rowWeightedVars

## Loading required package: GenomicRanges

## Loading required package: stats4
```

```
## Loading required package: BiocGenerics

##
## Attaching package: 'BiocGenerics'

## The following objects are masked from 'package:stats':
##
##     IQR, mad, sd, var, xtabs

## The following objects are masked from 'package:base':
##
##     anyDuplicated, append, as.data.frame, basename, cbind, colnames,
##     dirname, do.call, duplicated, eval, evalq, Filter, Find, get, grep,
##     grepl, intersect, is.unsorted, lapply, Map, mapply, match, mget,
##     order, paste, pmax, pmax.int, pmin, pmin.int, Position, rank,
##     rbind, Reduce, rownames, sapply, setdiff, sort, table, tapply,
##     union, unique, unsplit, which.max, which.min

## Loading required package: S4Vectors

##
## Attaching package: 'S4Vectors'

## The following objects are masked from 'package:base':
##
##     expand.grid, I, unname

## Loading required package: IRanges

## Loading required package: GenomeInfoDb

## Loading required package: Biobase

## Welcome to Bioconductor
##
##     Vignettes contain introductory material; view with
##     'browseVignettes()'. To cite Bioconductor, see
##     'citation("Biobase")', and for packages 'citation("pkgname)".

##
## Attaching package: 'Biobase'

## The following object is masked from 'package:MatrixGenerics':
##
##     rowMedians

## The following objects are masked from 'package:matrixStats':
##
##     anyMissing, rowMedians
```

```
## Loading required package: SingleCellExperiment

## Loading required package: TreeSummarizedExperiment

## Loading required package: Biostrings

## Loading required package: XVector

##
## Attaching package: 'Biostrings'

## The following object is masked from 'package:base':
##
##      strsplit

## Loading required package: MultiAssayExperiment

## Loading required package: ggplot2

## Loading required package: ggraph

##
## Attaching package: 'dplyr'

## The following objects are masked from 'package:Biostrings':
##
##      collapse, intersect, setdiff, setequal, union

## The following object is masked from 'package:XVector':
##
##      slice

## The following object is masked from 'package:Biobase':
##
##      combine

## The following objects are masked from 'package:GenomicRanges':
##
##      intersect, setdiff, union

## The following object is masked from 'package:GenomeInfoDb':
##
##      intersect

## The following objects are masked from 'package:IRanges':
##
##      collapse, desc, intersect, setdiff, slice, union
```

```
## The following objects are masked from 'package:S4Vectors':  
##  
##   first, intersect, rename, setdiff, setequal, union  
  
## The following objects are masked from 'package:BiocGenerics':  
##  
##   combine, intersect, setdiff, union  
  
## The following object is masked from 'package:matrixStats':  
##  
##   count  
  
## The following objects are masked from 'package:stats':  
##  
##   filter, lag  
  
## The following objects are masked from 'package:base':  
##  
##   intersect, setdiff, setequal, union
```

Chapter 8

Alpha diversity

This section demonstrates the analysis of alpha diversity. This quantity measures microbial diversity within each sample. Higher numbers of unique taxa, and more even abundance distributions within a sample yield larger values for alpha diversity.

Alpha diversity is a key quantity in a microbiome research. The *mia* package provides access to a wide variety of alpha diversity indices. For more background information and examples with various alpha diversity indices, see the online book.

Let us show how to calculate to different diversity indices, Shannon and Faith. Shannon index reflects how many different taxa there are and how evenly they are distributed within a sample. Faith index additionally takes into account the phylogenetic relations into account.

```
# Indices to be calculated.
# Every index is calculated by default if we don't specify indices.
indices <- c("shannon", "faith")

# Indices are stored in colData (i.e., sample metadata). We can specify the name
# of column, or we can use the default name which is the name of index
# (i.e., "shannon" and "faith").
names <- c("Shannon_diversity", "Faith_diversity")

# Calculates indices
tse <- estimateDiversity(tse, index = indices, name = names)

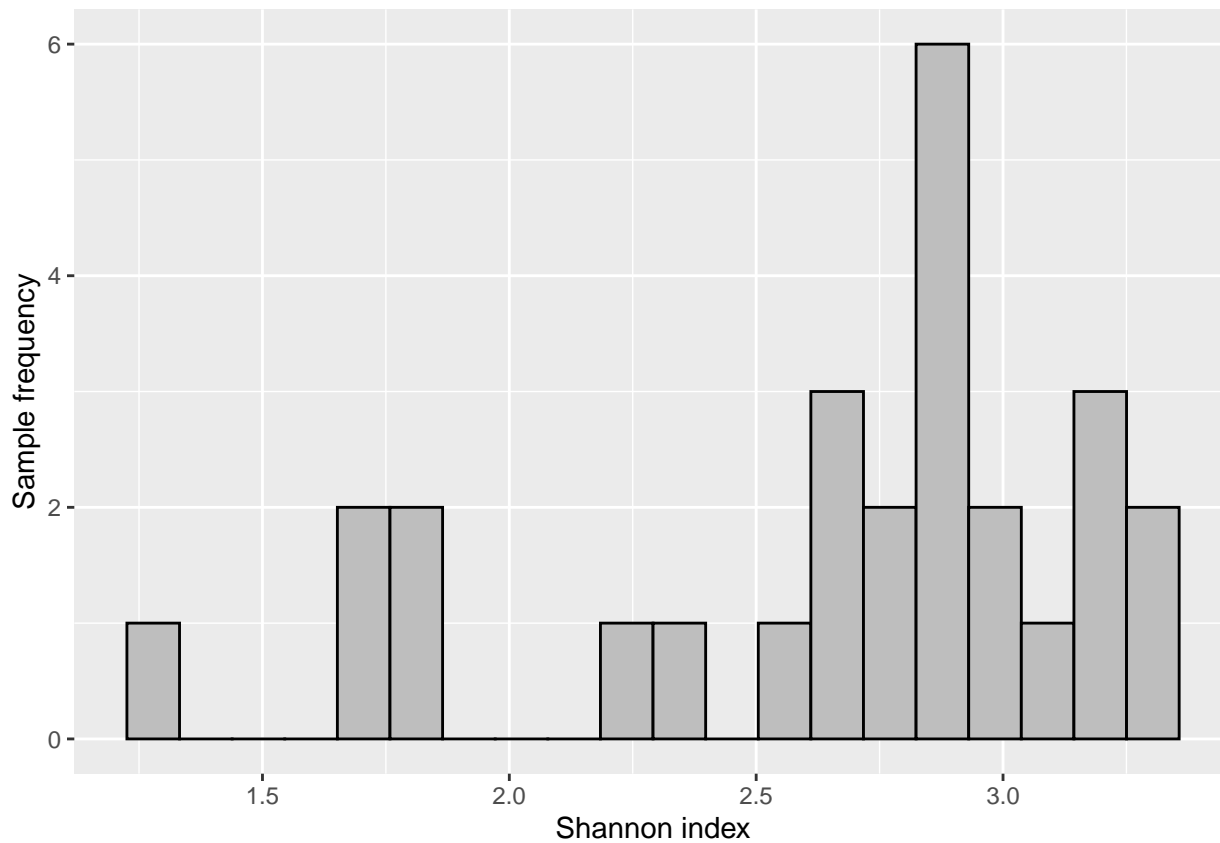
# Shows the calculated indices
knitr::kable(head(colData(tse)[names])) %>%
  kableExtra::kable_styling("striped",
    latex_options="scale_down") %>%
  kableExtra::scroll_box(width = "100%")
```

Next we can visualize Shannon index with histogram.

```
# ggplot needs data.frame format as input.
# Here, colData is Dataframe, therefore it needs to be converted to data.frame
shannon_hist <- ggplot(as.data.frame(colData(tse)),
```

	Shannon_diversity	Faith_diversity
A110	1.765407	7.39224
A12	2.716438	6.29378
A15	3.178103	6.60608
A19	2.891987	6.79708
A21	2.841979	6.65110
A23	2.797942	5.96246

```
    aes(x = Shannon_diversity)) +  
geom_histogram(bins = 20, fill = "gray", color = "black") +  
labs(x = "Shannon index", y = "Sample frequency")  
  
shannon_hist
```

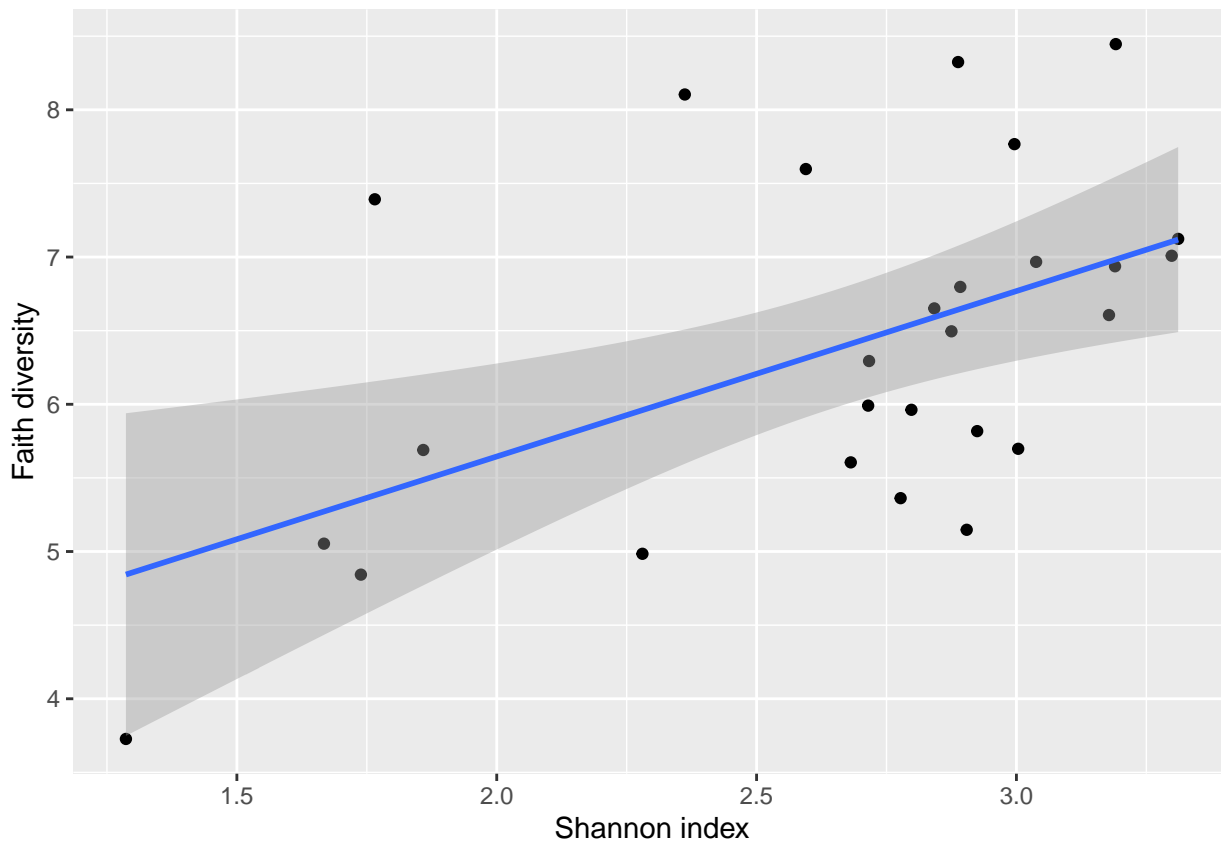


Next, let us compare the indices based on a scatter-plot.

```
cross_plot <- ggplot2::ggplot(as.data.frame(colData(tse)),
                              aes(x = Shannon_diversity, y = Faith_diversity)) +
  geom_point() + # Adds points
  geom_smooth(method=lm) + # Adds regression line
  labs(x = "Shannon index", y = "Faith diversity")

cross_plot
```

```
## `geom_smooth()` using formula 'y ~ x'
```

8.1 Visualization

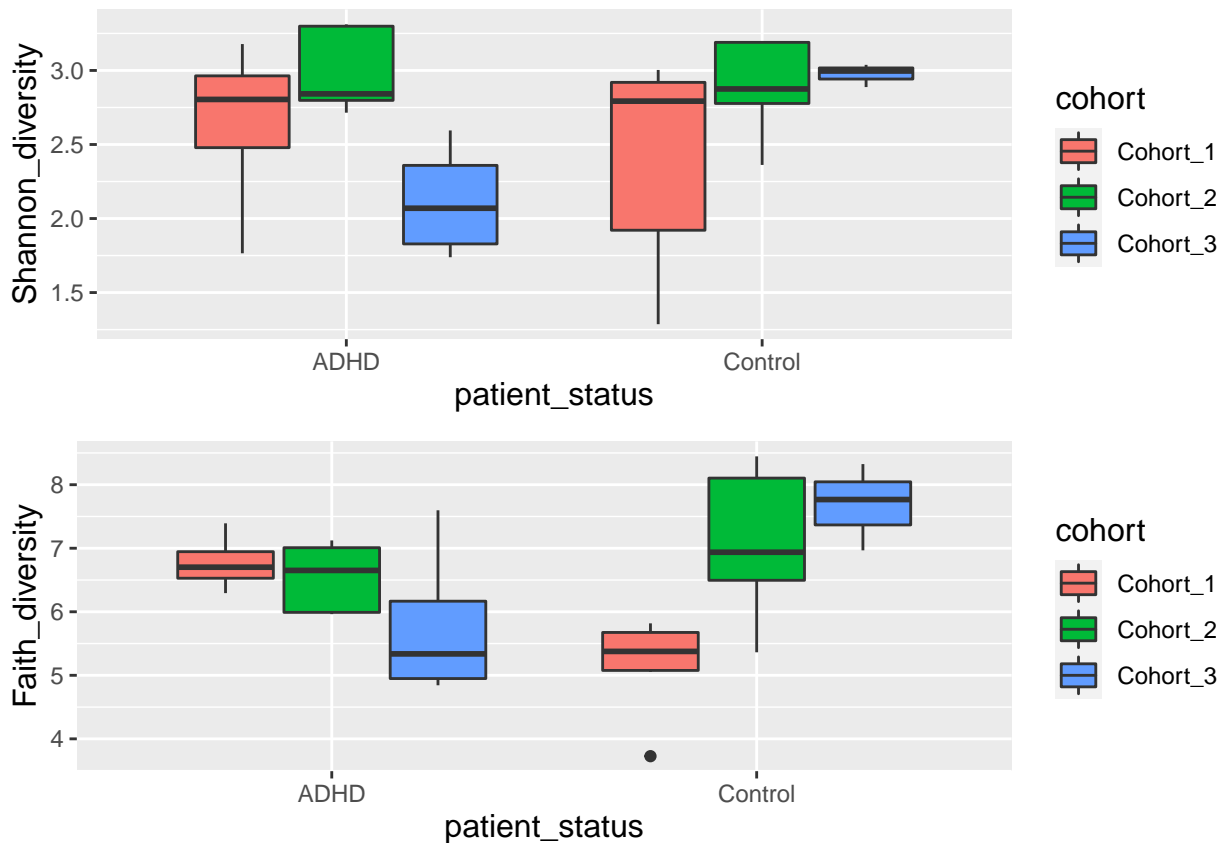
Next let us compare indices between different patient status and cohorts. Boxplot is suitable for that purpose.

```
# Creates Shannon boxplot
shannon_box <- ggplot(as.data.frame(colData(tse)),
  aes(x = patient_status,
      y = Shannon_diversity,
      fill = cohort)) +
  geom_boxplot() +
  theme(title = element_text(size = 12)) # makes titles smaller

# Creates Faith boxplot
faith_box <- ggplot(as.data.frame(colData(tse)), aes(x = patient_status,
                                                    y = Faith_diversity,
                                                    fill = cohort)) +

  geom_boxplot() +
  theme(title = element_text(size = 12)) # makes titles smaller

# Puts them into same picture
gridExtra::grid.arrange(shannon_box, faith_box, nrow = 2)
```



For an alternative visualization, see examples with `scatter::plotColData`.

8.2 Statistical testing and comparisons

To further investigate if patient status could explain the variation of Shannon index, let's do a Wilcoxon test. This is a non-parametric test that doesn't make specific assumptions about the distribution, unlike popular parametric tests, such as the t test, which assumes normally distributed observations.

Wilcoxon test can be used to estimate whether the differences between two groups is statistically significant. Here the ADHD and control groups are not significantly different between groups (p-value is over 0.05).

```
# Wilcoxon test, where Shannon index is the variable that we are comparing.
# Patient status - ADHD or control - is the factor that we use for grouping.
wilcoxon_shannon <- wilcox.test(Shannon_diversity ~ patient_status, data = colData(tse))

wilcoxon_shannon
```

```
##
## Wilcoxon rank sum exact test
##
## data: Shannon_diversity by patient_status
## W = 76, p-value = 0.4879
```

```
## alternative hypothesis: true location shift is not equal to 0
```

Another test that we can make is to test if ADHD samples differs between different cohorts. From boxplot that we made in previous step, we can see that there might be statistically significant difference between different cohorts.

Let's compare Shannon index of ADHD samples between cohort 2 and cohort 3.

As we can see, there is statistically significant difference between the cohorts.

```
# Takes subset of colData. Takes only ADHD samples
ADHD_shannon <- colData(tse)[ colData(tse)[, "patient_status"] == "ADHD" , ]

# Takes subset of colData. Takes only samples that are in cohort 2 or cohort 3.
ADHD_shannon <- ADHD_shannon[ ADHD_shannon[, "cohort"] %in% c("Cohort_2", "Cohort_3") , ]

# Wilcoxon test, where Shannon index is the variable that we are comparing.
# Cohort - 2 or 3 - is the factor that we use for grouping.
wilcoxon_shannon_ADHD_cohorts <- wilcox.test(Shannon_diversity ~ cohort, data = ADHD_shannon)

wilcoxon_shannon_ADHD_cohorts

##
## Wilcoxon rank sum exact test
##
## data: Shannon_diversity by cohort
## W = 20, p-value = 0.01587
## alternative hypothesis: true location shift is not equal to 0
```

For more examples, see a dedicated section on alpha diversity in the online book.

8.3 Exercises

Add the following in the reproducible summary report.

- Estimate alpha diversity for each sample and draw a histogram. Tip: `estimateDiversity`
- Compare the results between two or more alpha diversity indices (visually and/or statistically).
- See online book for further examples.
- Example Solutions

```
## Loading required package: SummarizedExperiment
```

```
## Loading required package: MatrixGenerics
```

```
## Loading required package: matrixStats
```

```
##
## Attaching package: 'MatrixGenerics'

## The following objects are masked from 'package:matrixStats':
##
##   colAlls, colAnyNAs, colAnys, colAvgsPerRowSet, colCollapse,
##   colCounts, colCummaxs, colCummins, colCumprods, colCumsums,
##   colDiffs, colIQRDiffs, colIQRs, colLogSumExps, colMadDiffs,
##   colMads, colMaxs, colMeans2, colMedians, colMins, colOrderStats,
##   colProds, colQuantiles, colRanges, colRanks, colSdDiffs, colSds,
##   colSums2, colTabulates, colVarDiffs, colVars, colWeightedMads,
##   colWeightedMeans, colWeightedMedians, colWeightedSds,
##   colWeightedVars, rowAlls, rowAnyNAs, rowAnys, rowAvgsPerColSet,
##   rowCollapse, rowCounts, rowCummaxs, rowCummins, rowCumprods,
##   rowCumsums, rowDiffs, rowIQRDiffs, rowIQRs, rowLogSumExps,
##   rowMadDiffs, rowMads, rowMaxs, rowMeans2, rowMedians, rowMins,
##   rowOrderStats, rowProds, rowQuantiles, rowRanges, rowRanks,
##   rowSdDiffs, rowSds, rowSums2, rowTabulates, rowVarDiffs, rowVars,
##   rowWeightedMads, rowWeightedMeans, rowWeightedMedians,
##   rowWeightedSds, rowWeightedVars

## Loading required package: GenomicRanges

## Loading required package: stats4

## Loading required package: BiocGenerics

##
## Attaching package: 'BiocGenerics'

## The following objects are masked from 'package:stats':
##
##   IQR, mad, sd, var, xtabs

## The following objects are masked from 'package:base':
##
##   anyDuplicated, append, as.data.frame, basename, cbind, colnames,
##   dirname, do.call, duplicated, eval, evalq, Filter, Find, get, grep,
##   grepl, intersect, is.unsorted, lapply, Map, mapply, match, mget,
##   order, paste, pmax, pmax.int, pmin, pmin.int, Position, rank,
##   rbind, Reduce, rownames, sapply, setdiff, sort, table, tapply,
##   union, unique, unsplit, which.max, which.min

## Loading required package: S4Vectors

##
## Attaching package: 'S4Vectors'
```

```
## The following objects are masked from 'package:base':
##
##   expand.grid, I, unname

## Loading required package: IRanges

## Loading required package: GenomeInfoDb

## Loading required package: Biobase

## Welcome to Bioconductor
##
##   Vignettes contain introductory material; view with
##   'browseVignettes()'. To cite Bioconductor, see
##   'citation("Biobase")', and for packages 'citation("pkgname)".

##
## Attaching package: 'Biobase'

## The following object is masked from 'package:MatrixGenerics':
##
##   rowMedians

## The following objects are masked from 'package:matrixStats':
##
##   anyMissing, rowMedians

## Loading required package: SingleCellExperiment

## Loading required package: TreeSummarizedExperiment

## Loading required package: Biostrings

## Loading required package: XVector

##
## Attaching package: 'Biostrings'

## The following object is masked from 'package:base':
##
##   strsplit

## Loading required package: MultiAssayExperiment

## Loading required package: ggplot2

## Loading required package: ggraph
```

Chapter 9

Beta diversity

Beta diversity is another name for sample dissimilarity. It quantifies differences in the overall taxonomic composition between two samples.

Common indices include Bray-Curtis, Unifrac, Jaccard index, and the Aitchison distance. Each of these (dis)similarity measures emphasizes different aspects. For example, UniFrac incorporates phylogenetic information, and Jaccard index ignores exact abundances and considers only presence/absence values. For more background information and examples, you can check the dedicated section in online book.

9.1 Examples of PCoA with different settings

Beta diversity estimation generates a (dis)similarity matrix that contains for each sample (rows) the dissimilarity to any other sample (columns).

This complex set of pairwise relations can be visualized in informative ways, and even coupled with other explanatory variables. As a first step, we compress the information to a lower dimensionality, or fewer principal components, and then visualize sample similarity based on that using ordination techniques, such as Principal Coordinate Analysis (PCoA). PCoA is a non-linear dimension reduction technique, and with Euclidean distances it is identical to the linear PCA (except for potential scaling).

We typically retain just the two (or three) most informative top components, and ignore the other information. Each sample has a score on each of these components, and each component measures the variation across a set of correlated taxa. The top components are then easily visualized on a two (or three) dimensional display.

Let us next look at some concrete examples.

9.1.1 PCoA for ASV-level data with Bray-Curtis

Let us start with PCoA based on a Bray-Curtis dissimilarity matrix calculated at Genus level abundances.

```
# Pick the relative abundance table
rel_abund_assay <- assays(tse)$relabundance

# Calculates Bray-Curtis distances between samples. Because taxa is in
# columns, it is used to compare different samples. We transpose the
```

```

# assay to get taxa to columns
bray_curtis_dist <- vegan::vegdist(t(rel_abund_assay), method = "bray")

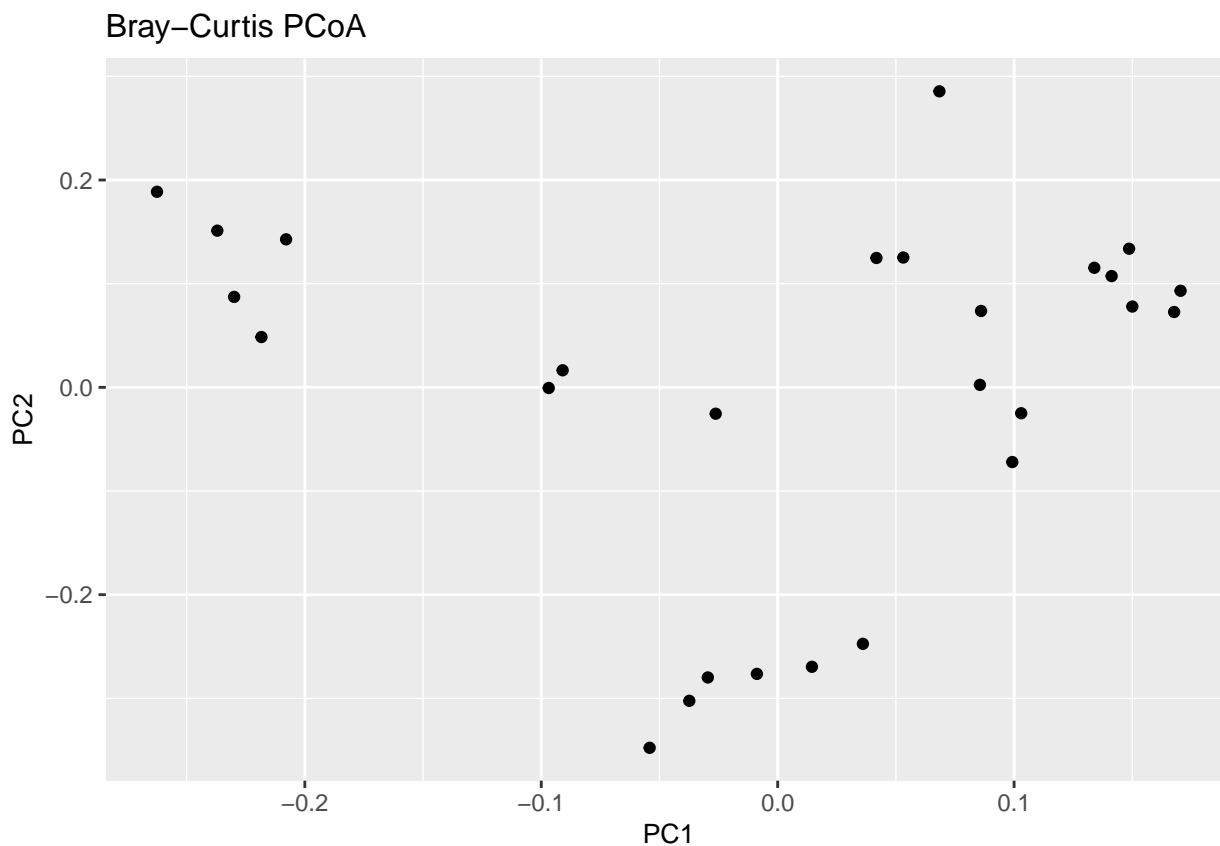
# PCoA
bray_curtis_pcoa <- ecodist::pco(bray_curtis_dist)

# All components could be found here:
# bray_curtis_pcoa$vectors
# But we only need the first two to demonstrate what we can do:
bray_curtis_pcoa_df <- data.frame(pcoa1 = bray_curtis_pcoa$vectors[,1],
                                pcoa2 = bray_curtis_pcoa$vectors[,2])

# Create a plot
bray_curtis_plot <- ggplot(data = bray_curtis_pcoa_df, aes(x=pcoa1, y=pcoa2)) +
  geom_point() +
  labs(x = "PC1",
       y = "PC2",
       title = "Bray-Curtis PCoA") +
  theme(title = element_text(size = 10)) # makes titles smaller

bray_curtis_plot

```



9.1.2 PCoA for ASV-level data with Aitchison distance

Now the same using Aitchison distance. This metric corresponds to Euclidean distances between CLR transformed sample abundance vectors.

```
# Does clr transformation. Pseudocount is added, because data contains zeros.
tse <- transformCounts(tse, method = "clr", pseudocount = 1)

# Gets clr table
clr_assay <- assays(tse)$clr

# Transposes it to get taxa to columns
clr_assay <- t(clr_assay)

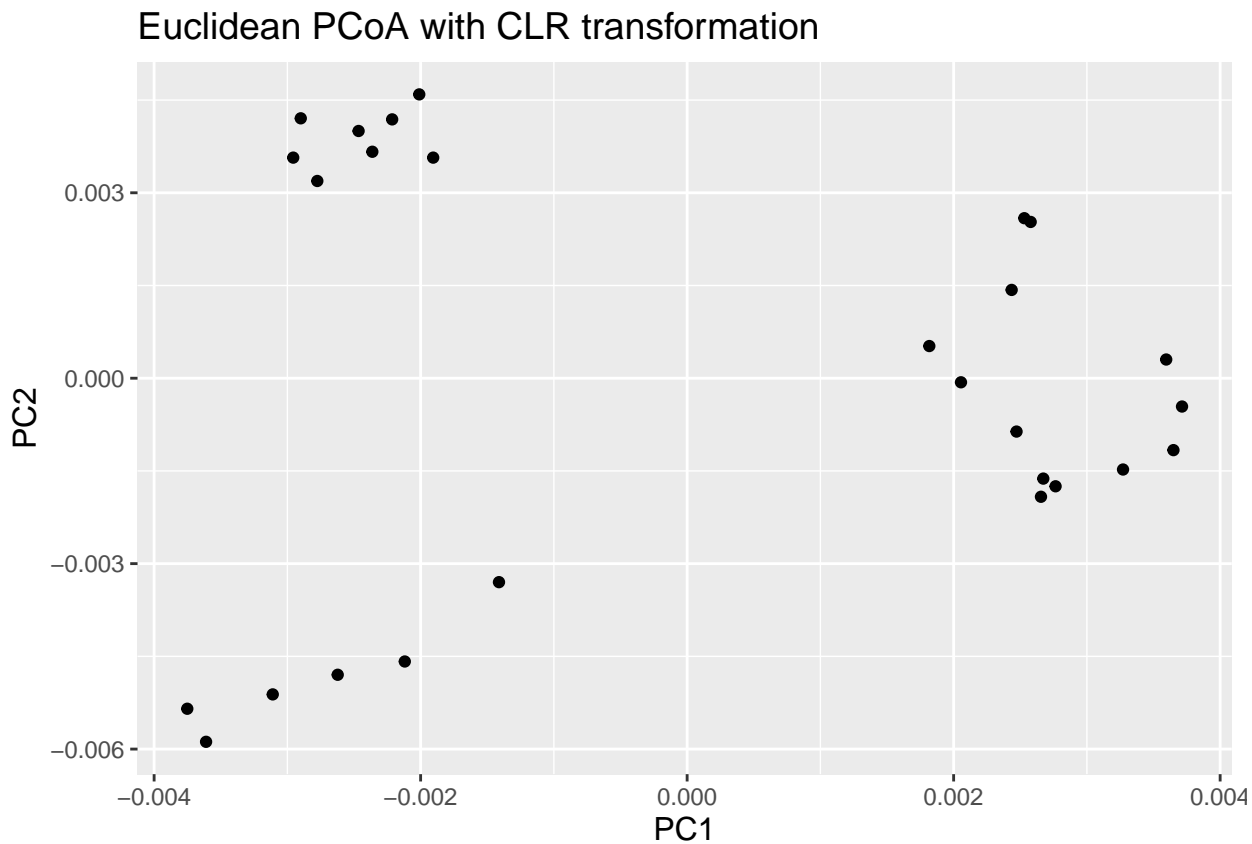
# Calculates Euclidean distances between samples. Because taxa is in columns,
# it is used to compare different samples.
euclidean_dist <- vegan::vegdist(clr_assay, method = "euclidean")

# Does principal coordinate analysis
euclidean_pcoa <- ecodist::pco(euclidean_dist)

# Creates a data frame from principal coordinates
euclidean_pcoa_df <- data.frame(pcoa1 = euclidean_pcoa$vectors[,1],
                               pcoa2 = euclidean_pcoa$vectors[,2])

# Creates the plot
euclidean_plot <- ggplot(data = euclidean_pcoa_df, aes(x=pcoa1, y=pcoa2)) +
  geom_point() +
  labs(x = "PC1",
       y = "PC2",
       title = "Euclidean PCoA with CLR transformation") +
  theme(title = element_text(size = 12)) # makes titles smaller

euclidean_plot
```

9.1.3 PCoA aggregated to Phylum level

We use again the Aitchison distances in this example but this time applied to the phylum level.

```
# Does clr transformation. Psuedocount is added, because data contains zeros.
tse_phylum <- transformCounts(tse_phylum, method = "clr", pseudocount = 1)

# Gets clr table
clr_phylum_assay <- assays(tse_phylum)$clr

# Transposes it to get taxa to columns
clr_phylum_assay <- t(clr_phylum_assay)

# Calculates Euclidean distances between samples. Because taxa is in columns,
# it is used to compare different samples.
euclidean_phylum_dist <- vegan::vegdist(clr_assay, method = "euclidean")

# Does principal coordinate analysis
euclidean_phylum_pcoa <- ecodist::pco(euclidean_phylum_dist)

# Creates a data frame from principal coordinates
euclidean_phylum_pcoa_df <- data.frame(
```

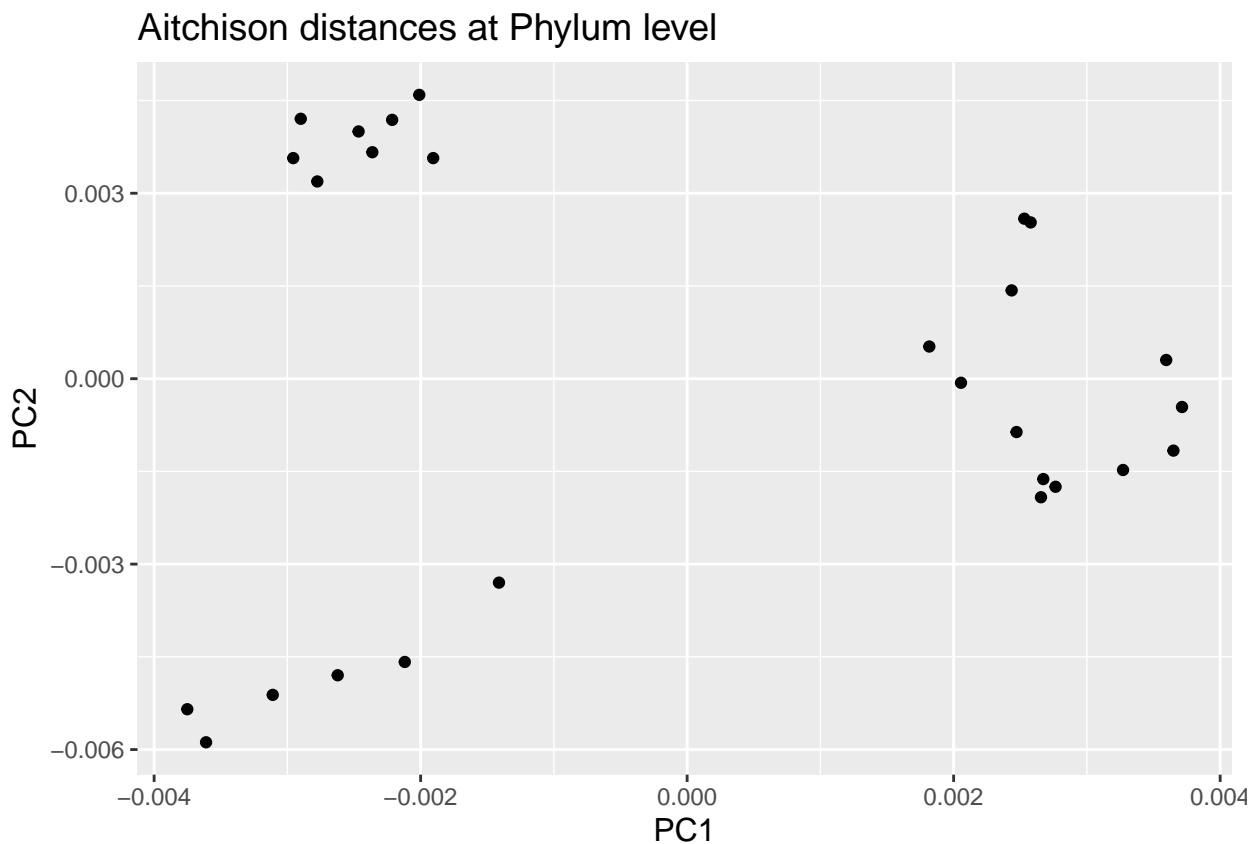
```

pcoa1 = euclidean_phylum_pcoa$vectors[,1],
pcoa2 = euclidean_phylum_pcoa$vectors[,2])

# Creates a plot
euclidean_phylum_plot <- ggplot(data = euclidean_phylum_pcoa_df,
  aes(x=pcoa1, y=pcoa2)) +
  geom_point() +
  labs(x = "PC1",
       y = "PC2",
       title = "Aitchison distances at Phylum level") +
  theme(title = element_text(size = 12)) # makes titles smaller

euclidean_phylum_plot

```



9.2 Highlighting external variables

We can map other variables on the same plot for example by coloring the points accordingly.

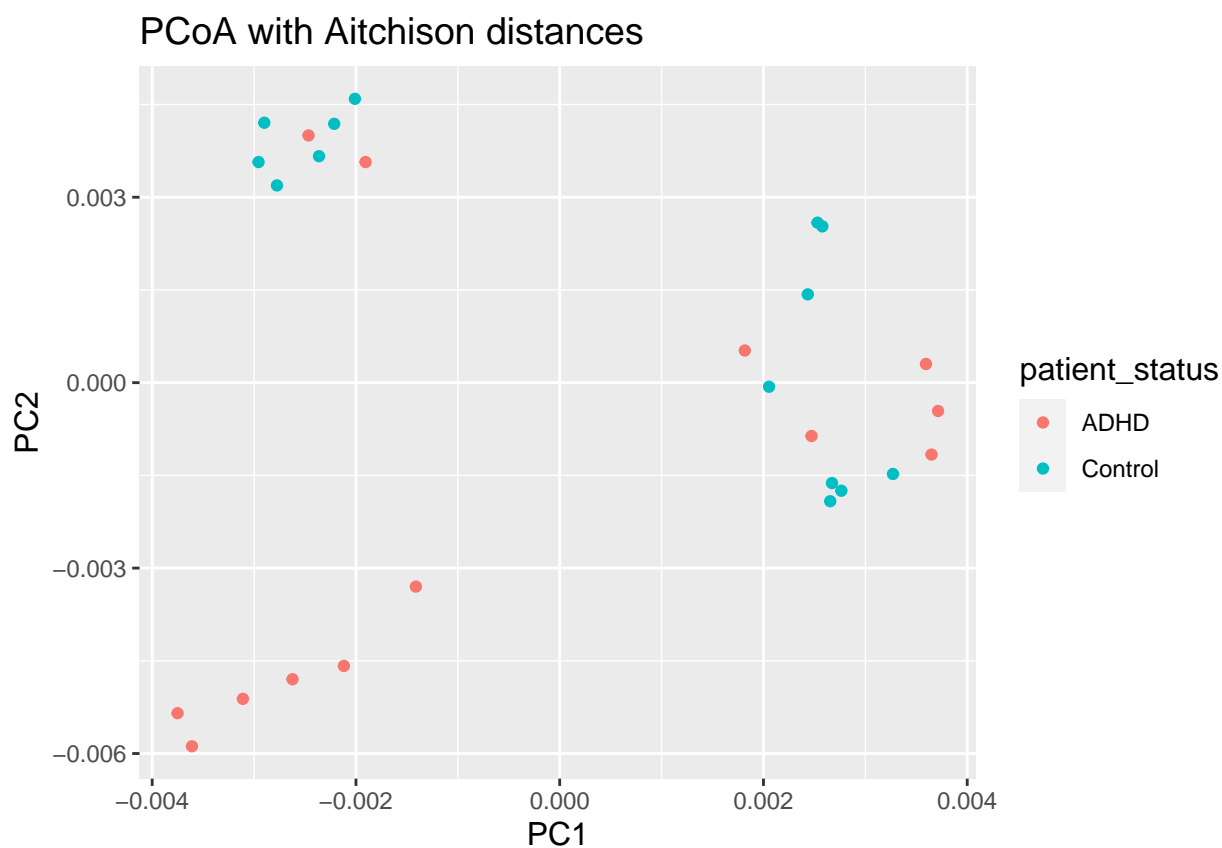
9.2.1 Discrete grouping variable shown with colors

```
# Adds the variable we later use for coloring to the data frame
euclidean_patient_status_pcoa_df <- cbind(euclidean_pcoa_df,
                                           patient_status = colData(tse)$patient_status)

# Creates a plot
euclidean_patient_status_plot <- ggplot(data = euclidean_patient_status_pcoa_df,
                                         aes(x=pcoa1, y=pcoa2,
                                              color = patient_status)) +

  geom_point() +
  labs(x = "PC1",
       y = "PC2",
       title = "PCoA with Aitchison distances") +
  theme(title = element_text(size = 12)) # makes titles smaller

euclidean_patient_status_plot
```



9.2.2 PCoA plot with continuous variable

We can also overlay a continuous variable on a PCoA plot. E.g. let us use the alcohol study dataset from `curatedMetagenomicData`. Perform PCoA and use the BMI as our continuous variable:

```
# Retrieving data as a TreeSummarizedExperiment object, and agglomerating to a genus level.
library(curatedMetagenomicData)
library(dplyr)
library(DT)
# Querying the data
tse_data <- sampleMetadata %>%
  filter(age >= 18) %>% # taking only data of age 18 or above
  filter(!is.na(alcohol)) %>% # excluding missing values
  returnSamples("relative_abundance")

# Agglomeration
tse_genus <- agglomerateByRank(tse_data, rank="genus")
```

Performing PCoA with Bray-Curtis dissimilarity.

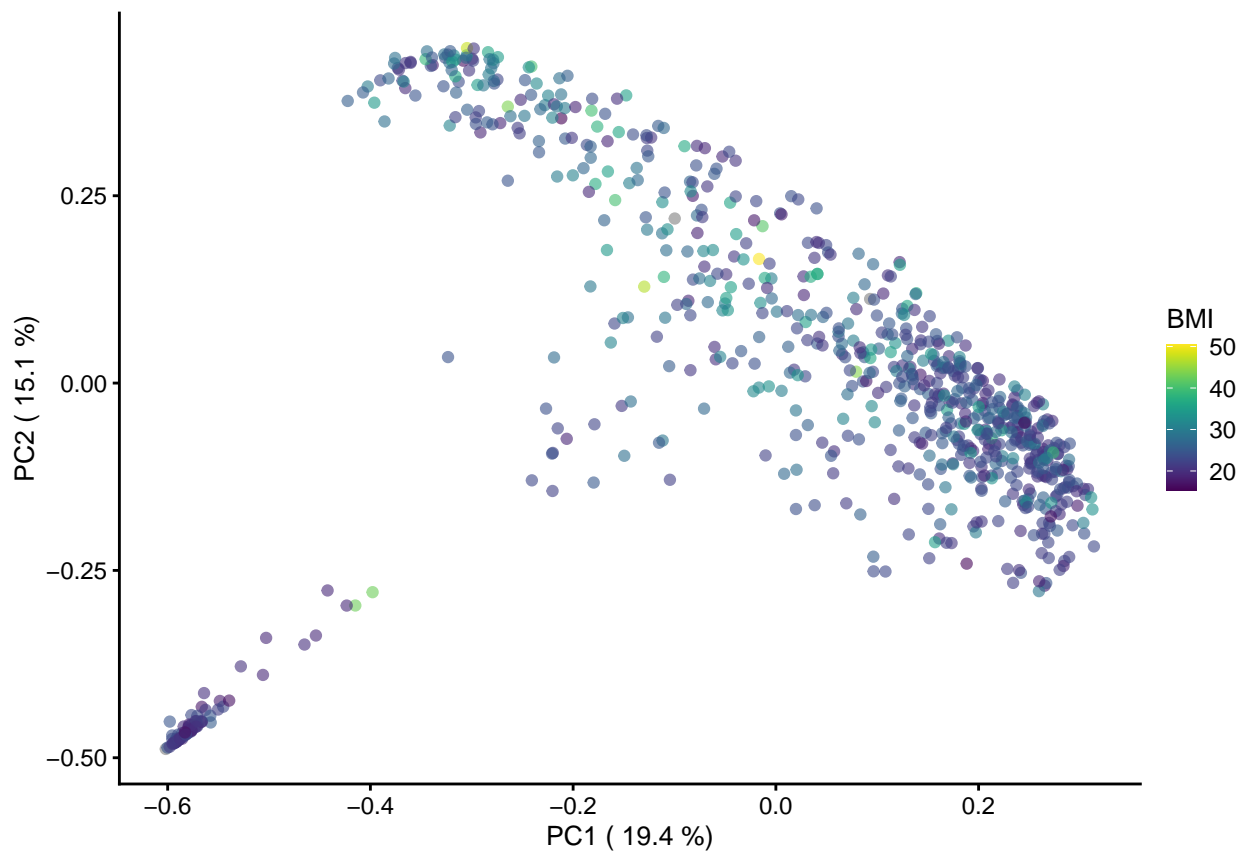
```
library(scater)

## Loading required package: scuttle

tse_genus <- runMDS(tse_genus, FUN = vegan::vegdist,
  name = "PCoA_BC", exprs_values = "relative_abundance")

# Retrieving the explained variance
e <- attr(reducedDim(tse_genus, "PCoA_BC"), "eig");
var_explained <- e/sum(e[e>0])*100

# Visualization
plot <- plotReducedDim(tse_genus, "PCoA_BC", colour_by = "BMI")+
  labs(x=paste("PC1 (",round(var_explained[1],1),"%)" ),
    y=paste("PC2 (",round(var_explained[2],1),"%)" ),
    color="")
plot
```



9.3 Estimating associations with an external variable

Next to visualizing whether any variable is associated with differences between samples, we can also quantify the strength of the association between community composition (beta diversity) and external factors.

The standard way to do this is to perform a so-called permutational multivariate analysis of variance (PERMANOVA). This method takes as input the abundance table, which measure of distance you want to base the test on and a formula that tells the model how you think the variables are associated with each other.

```
# First we get the relative abundance table
rel_abund_assay <- assays(tse)$relabundance

# again transpose it to get taxa to columns
rel_abund_assay <- t(rel_abund_assay)

# then we can perform the method
permanova_cohort <- vegan::adonis(rel_abund_assay ~ cohort,
                                  data = colData(tse),
                                  permutations = 9999)
```

```
## 'adonis' will be deprecated: use 'adonis2' instead
```

```
# we can obtain a the p value for our predictor:
print(paste0("Different different cohorts and variance of abundance ",
             "between samples, p-value: ",
             as.data.frame(permanova_cohort$aov.tab)["cohort", "Pr(>F)"]))
```

```
## [1] "Different different cohorts and variance of abundance between samples, p-value: 0.7419"
```

The cohort variable is not significantly associated with microbiota composition (p-value is over 0.05).

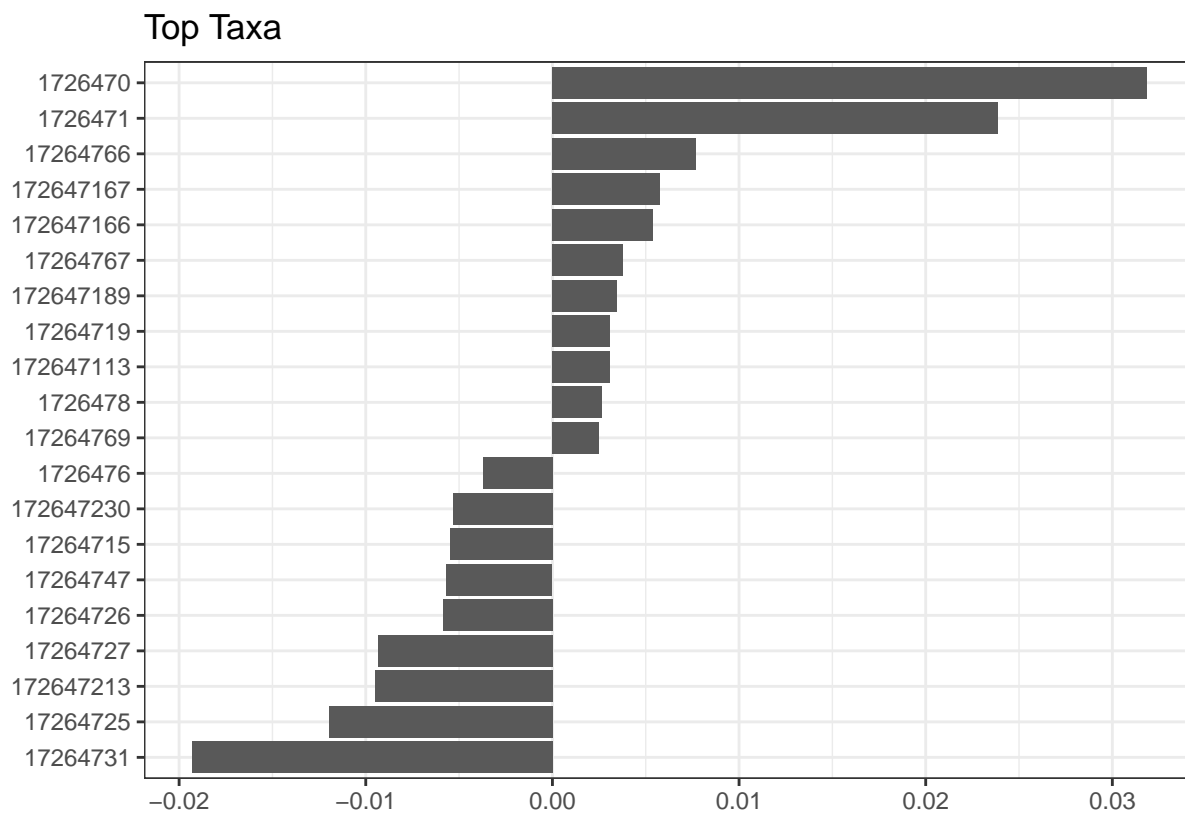
We can, however, visualize those taxa whose abundances drive the differences between cohorts. We first need to extract the model coefficients of taxa:

```
# Gets the coefficients
coef <- coefficients(permanova_cohort)["cohort1",]

# Gets the highest coefficients
top_coef <- sort(head(coef[rev(order(abs(coef)))],20))

# Plots the coefficients
top_taxa_coefficient_plot <- ggplot(data.frame(x = top_coef,
                                              y = factor(names(top_coef),
                                              unique(names(top_coef)))),
                                aes(x = x, y = y)) +
  geom_bar(stat="identity") +
  labs(x="", y="", title="Top Taxa") +
  theme_bw()

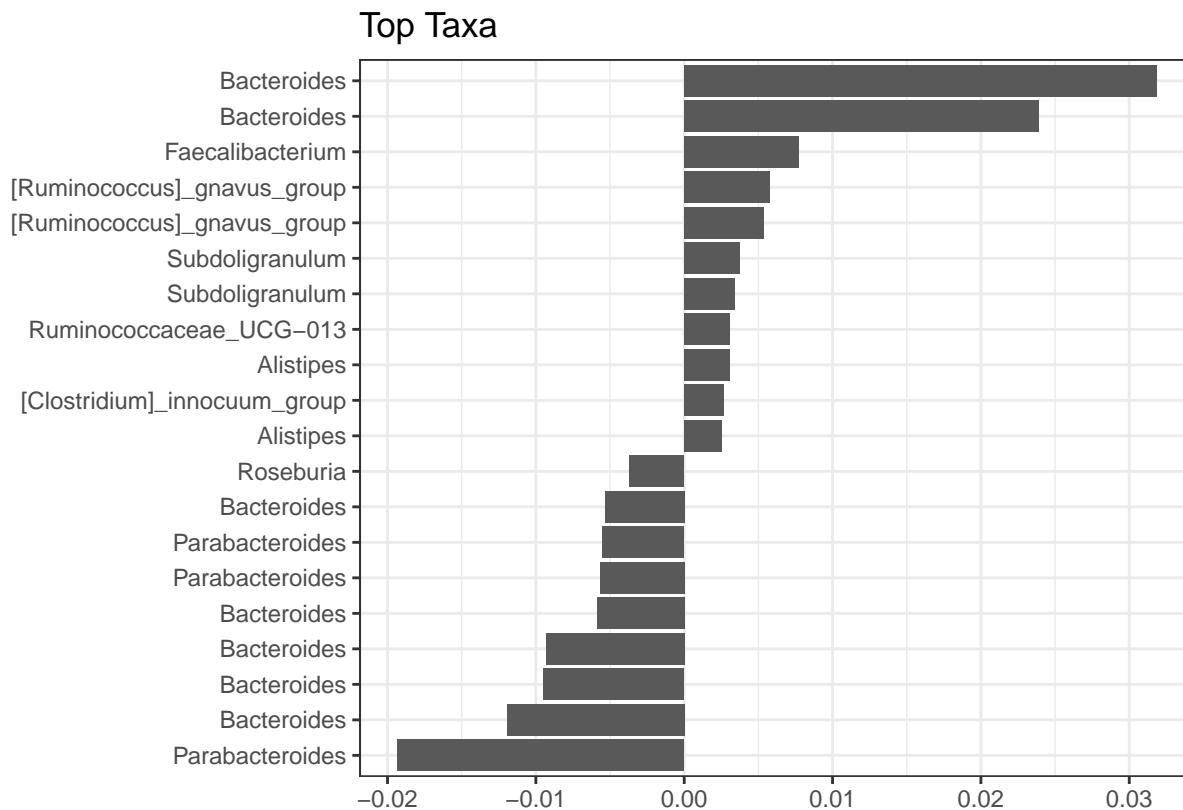
top_taxa_coefficient_plot
```



The above plot shows taxa as code names, and it is hard to tell which bacterial groups they represent. However, it is easy to add human readable names. We can fetch those from our `rowData`. Here we use Genus level names:

```
# Gets corresponding Genus level names and stores them to top.coef
names <- rowData(tse)[names(top.coef), ][, "Genus"]

# Adds new labels to the plot
top_taxa_coefficient_plot <- top_taxa_coefficient_plot +
  scale_y_discrete(labels = names) # Adds new labels
top_taxa_coefficient_plot
```



There are many alternative and complementary methods for analysing community composition. For more examples, see a dedicated section on beta diversity in the online book.

9.4 Community typing

A dedicated section presenting examples on community typing is in the online book.

9.5 Exercises

- Visualize community variation with different methods (PCA, MDS, t-SNE...) by using the options in the alternative method, `plotReducedDim OMA`. Compare results obtained with different dissimilarities (Euclidean, Bray-Curtis, Unifrac..) and transformations (CLR, compositional..) of your own choice.”
- Investigate the influence of the data transformations on statistical analysis: Visualize community variation with PCoA with the following options: 1) Bray-Curtis distances for compositional data; 2) Euclidean distances for CLR-transformed data.
- Community-level comparisons: Use PERMANOVA to investigate whether the community composition differs between two groups of individuals (e.g. males and females, or some other grouping of your choice). You can also include covariates such as age and gender, and see how this affects the results.

- Perform community typing for the data using the DMM method OMA
- Example Solutions

Chapter 10

Differential abundance analysis

Here, we analyse abundances with two different methods: **Wilcoxon test** (CLR), and **ANCOM-BC**. All of these test statistical differences between groups. We will analyse Genus level abundances.

We might want to first perform prevalence filtering to reduce the amount of multiple tests. In this particular dataset, all genera pass a prevalence threshold of 10%, therefore, we do not perform filtering.

10.1 Wilcoxon test

A Wilcoxon test estimates the difference in an outcome between two groups. It is a non-parametric alternative to a t-test, which means that the Wilcoxon test does not make any assumptions about the data.

Let's first combine the data for the testing purpose.

```
# Agglomerates data to Genus level
tse_genus <- agglomerateByRank(tse, rank = "Genus")

# Perform clr transformation. A Pseudocount of 1 needs to be added,
# because the data contains zeros and the clr transformation includes a
# log transformation.
tse_genus <- transformCounts(tse_genus, method = "clr", pseudocount = 1)

# Does transpose, so samples are in rows, then creates a data frame.
abundance_analysis_data <- data.frame(t(assay(tse_genus, "clr")))
# We will analyse whether abundances differ depending on the "patient_status".
# There are two groups: "ADHD" and "control".
# Let's include that to the data frame.
abundance_analysis_data <- cbind(
  abundance_analysis_data,
  patient_status = colData(tse_genus)$patient_status
)
```

Now we can start with the Wilcoxon test. We test all the taxa by looping through columns, and store individual p-values to a vector. Then we create a data frame from collected data.

The code below does the Wilcoxon test only for columns that contain abundances, not for columns that contain patient status.

```
genera <- names(abundance_analysis_data[, !names(abundance_analysis_data) %in% "patient_status"])

wilcoxon_p <- c() # Initialize empty vector for p-values

# Do "for loop" over selected column names
for (i in genera) {

  result <- wilcox.test(abundance_analysis_data[, i] ~ patient_status,
                        data = abundance_analysis_data)

  # Stores p-value to the vector with this column name
  wilcoxon_p[[i]] <- result$p.value

}

wilcoxon_p <- data.frame(taxa = names(wilcoxon_p),
                        p_raw = unlist(wilcoxon_p))
```

Multiple tests were performed. These are not independent, so we need to adjust p-values for multiple testing. Otherwise, we would increase the chance of a type I error drastically depending on our p-value threshold. By applying a p-value adjustment, we can keep the false positive rate at a level that is acceptable. What is acceptable depends on our research goals. Here we use the fdr method, but there are several other methods as well.

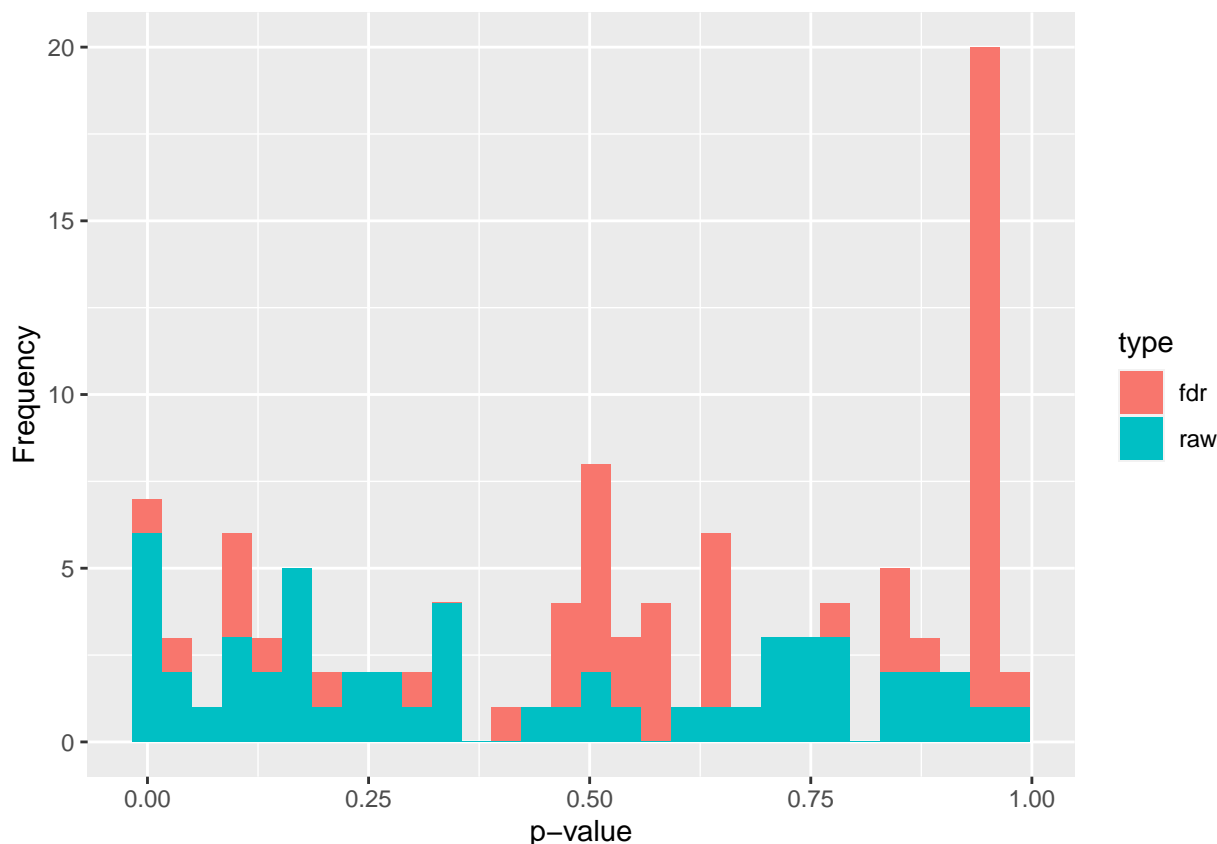
```
wilcoxon_p$p_adjusted <- p.adjust(wilcoxon_p$p_raw, method = "fdr")

# prepare a dataframe to plot p values
df <- data.frame(x = c(wilcoxon_p$p_raw, wilcoxon_p$p_adjusted),
                 type=rep(c("raw", "fdr"),
                        c(length(wilcoxon_p$p_raw),
                          length(wilcoxon_p$p_adjusted))))

# make a histogram of p values and adjusted p values
wilcoxon_plot <- ggplot(df) +
  geom_histogram(aes(x=x, fill=type)) +
  labs(x = "p-value", y = "Frequency")

wilcoxon_plot
```

```
## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.
```



10.2 ANCOM-BC

The analysis of composition of microbiomes with bias correction (ANCOM-BC) is a recently developed method for differential abundance testing. It is based on an earlier published approach. The former version of this method could be recommended as part of several approaches: A recent study compared several mainstream methods and found that among another method, ANCOM produced the most consistent results and is probably a conservative approach. Please note that based on this and other comparisons, no single method can be recommended across all datasets. Rather, it could be recommended to apply several methods and look at the overlap/differences.

As the only method, ANCOM-BC incorporates the so called *sampling fraction* into the model. The latter term could be empirically estimated by the ratio of the library size to the microbial load. Variations in this sampling fraction would bias differential abundance analyses if ignored. Furthermore, this method provides p-values, and confidence intervals for each taxon. It also controls the FDR and it is computationally simple to implement.

As we will see below, to obtain results, all that is needed is to pass a `phyloseq` object to the `ancombc()` function. Therefore, below we first convert our `tse` object to a `phyloseq` object. Then, we specify the formula. In this formula, other covariates could potentially be included to adjust for confounding. Please check the function documentation to learn about the additional arguments that we specify below. Also, see here for another example for more than 1 group comparison.

	patient_statusControl
172647198	FALSE
1726478	FALSE
172647201	FALSE
17264798	FALSE
172647195	FALSE
1726472	FALSE

```
# currently, ancombc requires the phyloseq format, but we can convert this easily
pseq <- makePhyloseqFromTreeSummarizedExperiment(tse)
pseq_genus <- phyloseq::tax_glom(pseq, taxrank = "Genus")

out = ancombc(
  phyloseq = pseq_genus,
  formula = "patient_status",
  p_adj_method = "fdr",
  zero_cut = 0.90, # by default prevalence filter of 10% is applied
  lib_cut = 0,
  group = "patient_status",
  struc_zero = TRUE,
  neg_lb = TRUE,
  tol = 1e-5,
  max_iter = 100,
  conserve = TRUE,
  alpha = 0.05,
  global = TRUE
)
res <- out$res
```

The object `out` contains all relevant information. Again, see the documentation of the function under **Value** for an explanation of all the output objects. Our question can be answered by looking at the `res` object, which now contains dataframes with the coefficients, standard errors, p-values and q-values. Conveniently, there is a dataframe `diff_abn`. Here, we can find all differentially abundant taxa. Below we show the first 6 entries of this dataframe:

```
knitr::kable(head(res$diff_abn)) %>% kableExtra::kable_styling("striped") %>%
  kableExtra::scroll_box(width = "100%")
```

In total, this method detects 14 differentially abundant taxa.

```
print(paste0("Wilcoxon test p-values under 0.05: ", sum(wilcoxon_p$p_adjusted<0.05, na.rm = TRUE), "/", length(wilcoxon_p)))
```

```
## [1] "Wilcoxon test p-values under 0.05: 2/54"
```

```
print(paste0("ANCOM p-values under 0.05: ", sum(out$res$diff_abn$patient_statusControl), "/", length(out$res$diff_abn)))
```

```
## [1] "ANCOM p-values under 0.05: 14/49"
```

10.3 Comparison of the methods

TO DO: More difference abundance methods are upcoming. Comparison will be made later.

10.4 Comparison of abundance

In previous steps, we got information which taxa vary between ADHD and control groups. Let's plot those taxa in the boxplot, and compare visually if abundances of those taxa differ in ADHD and control samples. For comparison, let's plot also taxa that do not differ between ADHD and control groups.

Let's first gather data about taxa that have highest p-values.

```
#we used the results from the wilcoxon test
df <- wilcoxon_p
# renaming row names and taxa column
df$taxa <- rownames(assay(tse_genus, "clr"))

# There are some taxa that do not include Genus level information. They are
# excluded from analysis.
# str_detect finds if the pattern is present in values of "taxon" column.
# Subset is taken, only those rows are included that do not include the pattern.
df <- df[ !stringr::str_detect(df$taxa, "Genus:uncultured"), ]

# Sorts p-values in decreasing order. Takes 3 first ones. Takes those rows that match
# with p-values. Takes taxa.
highest3 <- df[df$p_adjusted %in% sort(df$p_adjusted, decreasing = TRUE)[1:3], ]$taxa

# From clr transformed table, takes only those taxa that had highest p-values
highest3 <- assay(tse_genus, "clr")[highest3, ]

# Transposes the table
highest3 <- t(highest3)

# Adds colData that includes patient status information
highest3 <- data.frame(highest3, as.data.frame(colData(tse_genus)))

# Some taxa names are that long that they don't fit nicely into title. So let's add there
# a line break after e.g. "Genus". Here the dot after e.g. Genus is replaced with
# ": \n"
colnames(highest3)[1:3] <- lapply(colnames(highest3)[1:3], function(x){
  # Replaces the first dot
  temp <- stringr::str_replace(x, "[.]", ": ")

  # Replace all other dots and underscores with space
  temp <- stringr::str_replace_all(temp, c("[.]" = " ", "_" = " "))

  # Adds line break so that 25 characters is the maximal width
  temp <- stringr::str_wrap(temp, width = 25)
})
```

Next, let's do the same but for taxa with lowest p-values.

```
# Sorts p-values in increasing order. Takes 3rd first ones. Takes those rows that match
# with p-values. Takes taxa.
lowest3 <- df[df$p_adjusted %in% sort(df$p_adjusted, decreasing = FALSE)[1:3], ]$taxa

# From clr transformed table, takes only those taxa that had lowest p-values
lowest3 <- assay(tse_genus, "clr")[lowest3, ]

# Transposes the table
lowest3 <- t(lowest3)

# Adds colData that includes patient status information
lowest3 <- data.frame(lowest3, as.data.frame(colData(tse_genus)))

# Some taxa names are that long that they don't fit nicely into title. So let's add there
# a line break after e.g. "Genus". Here the dot after e.g. Genus is replaced with
# ": \n"
colnames(lowest3)[1:3] <- lapply(colnames(lowest3)[1:3], function(x){
  # Replaces the first dot
  temp <- stringr::str_replace(x, "[.]", ": ")

  # Replace all other dots and underscores with space
  temp <- stringr::str_replace_all(temp, c("[.]" = " ", "_" = " "))

  # Adds line break so that 25 characters is the maximal width
  temp <- stringr::str_wrap(temp, width = 25)
})
```

Then we can plot these six different taxa. Let's arrange them into the same picture.

```
# Puts plots in the same picture
gridExtra::grid.arrange(

  # Plot 1
  ggplot(highest3, aes(x = patient_status, y = highest3[,1])) +
    geom_boxplot() +
    ylab("CLR abundances") + # y axis title
    ggtitle(names(highest3)[1]) + # main title
    theme(title = element_text(size = 7),
          axis.text = element_text(size = 7),
          axis.title.x=element_blank()), # makes titles smaller, removes x axis title

  # Plot 2
  ggplot(highest3, aes(x = patient_status, y = highest3[,2])) +
    geom_boxplot() +
    ylab("CLR abundances") + # y axis title
    ggtitle(names(highest3)[2]) + # main title
    theme(title = element_text(size = 7),
          axis.text = element_text(size = 7),
```

```

    axis.title.x=element_blank()), # makes titles smaller, removes x axis title

# Plot 3
ggplot(highest3, aes(x = patient_status, y = highest3[,3])) +
  geom_boxplot() +
  ylab("CLR abundances") + # y axis title
  ggtitle(names(highest3)[3]) + # main title
  theme(title = element_text(size = 7),
        axis.text = element_text(size = 7),
        axis.title.x=element_blank()), # makes titles smaller, removes x axis title

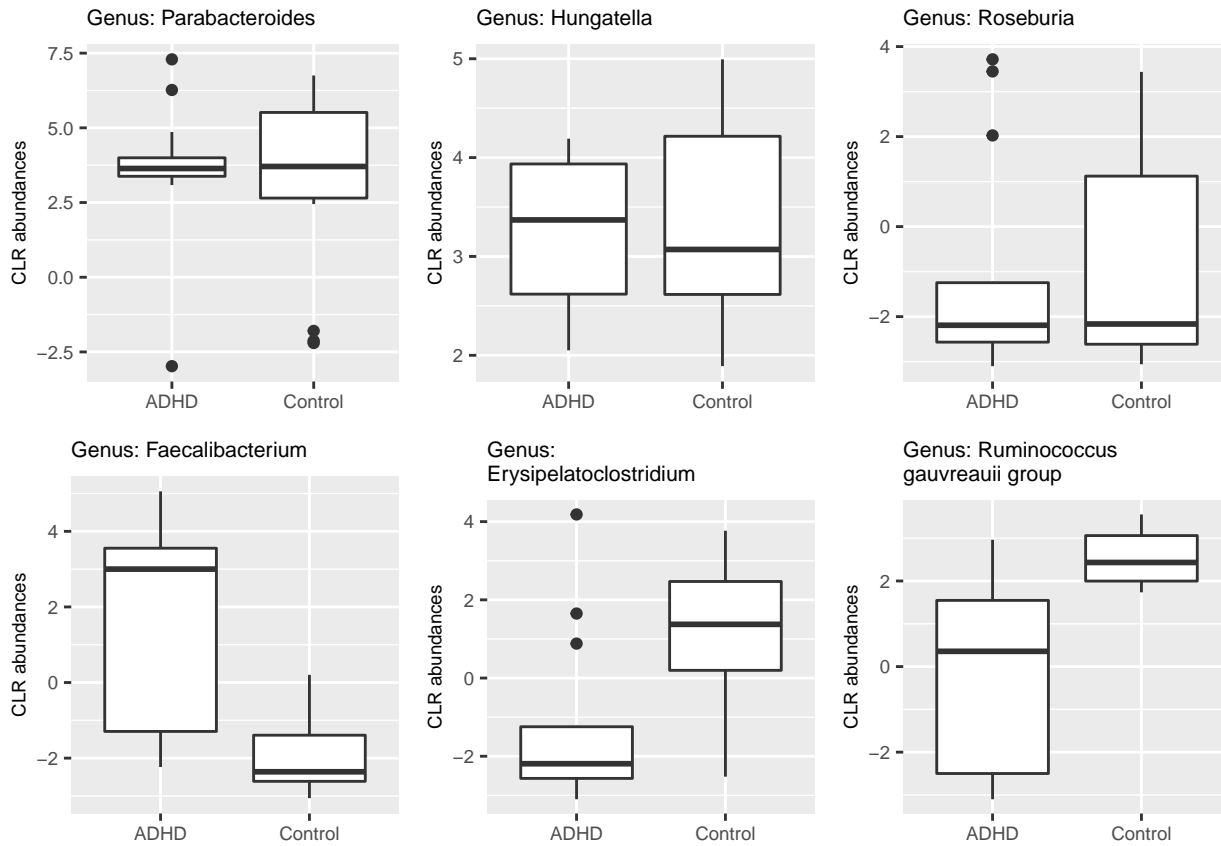
# Plot 4
ggplot(lowest3, aes(x = patient_status, y = lowest3[,1])) +
  geom_boxplot() +
  ylab("CLR abundances") + # y axis title
  ggtitle(names(lowest3)[1]) + # main title
  theme(title = element_text(size = 7),
        axis.text = element_text(size = 7),
        axis.title.x=element_blank()), # makes titles smaller, removes x axis title

# Plot 5
ggplot(lowest3, aes(x = patient_status, y = lowest3[,2])) +
  geom_boxplot() +
  ylab("CLR abundances") + # y axis title
  ggtitle(names(lowest3)[2]) + # main title
  theme(title = element_text(size = 7),
        axis.text = element_text(size = 7),
        axis.title.x=element_blank()), # makes titles smaller, removes x axis title

# Plot 6
ggplot(lowest3, aes(x = patient_status, y = lowest3[,3])) +
  geom_boxplot() +
  ylab("CLR abundances") + # y axis title
  ggtitle(names(lowest3)[3]) + # main title
  theme(title = element_text(size = 7),
        axis.text = element_text(size = 7),
        axis.title.x=element_blank()), # makes titles smaller, removes x axis title

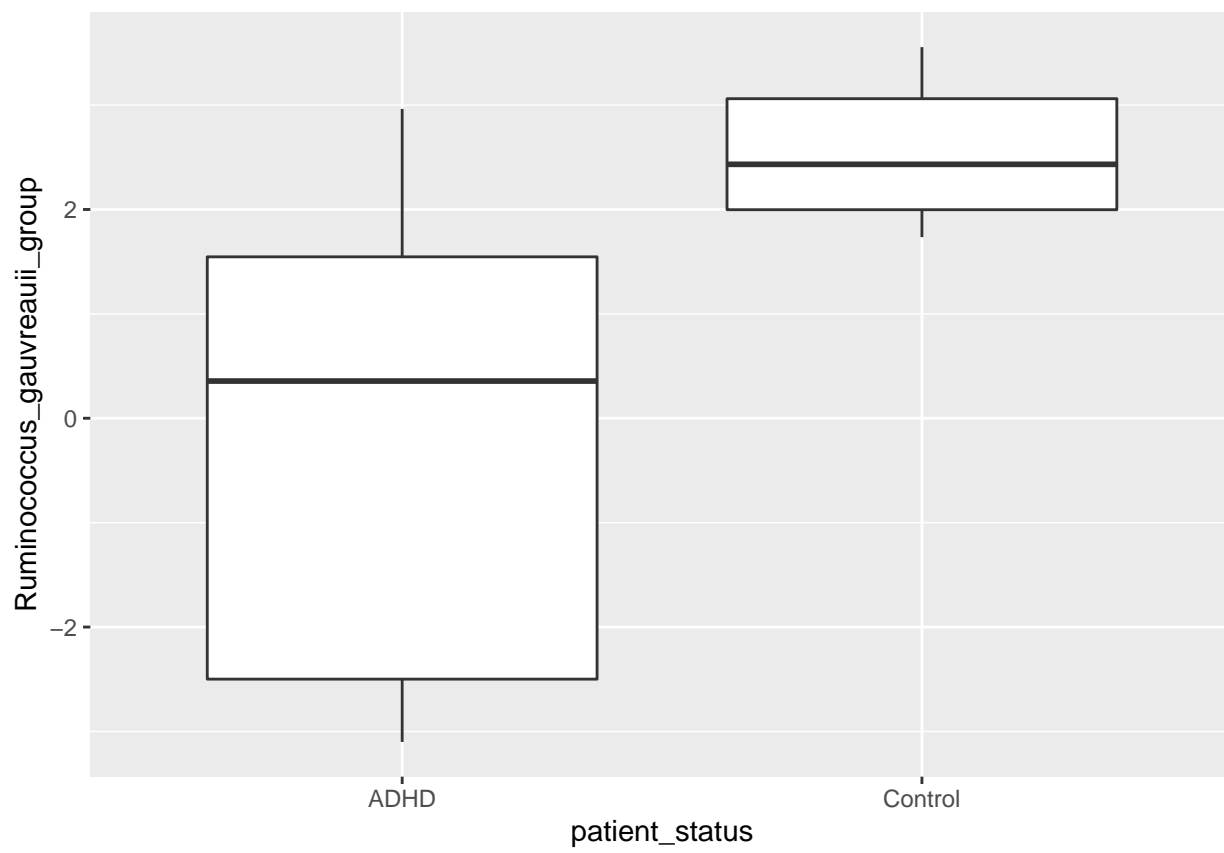
# 3 columns and 2 rows
ncol = 3,
nrow = 2
)

```

We plotted those taxa that have the highest and lowest p values according to DESeq2. Can you create a plot that shows the difference in abundance in “[Ruminococcus]_gauvreauii_group”, which is the other taxon that was identified by all tools. Try for yourself! Below you find one way how to do it.

```
select(
  abundance_analysis_data,
  patient_status,
  Ruminococcus_gauvreauii_group = contains("gauvreauii_group")) %>%
  ggplot(aes(patient_status, Ruminococcus_gauvreauii_group)) +
  geom_boxplot()
```



Chapter 11

Study material

11.1 Lecture slides

See slides.

11.2 R programming resources

R programming

- [Base R cheat sheet](#)
- [Base R cheat sheet 2](#)
- [Cheat sheet collection](#)

Visualization

- [ggplot2 cheat sheet](#)
- [R graphics cookbook](#)

Rmarkdown

- [Rmarkdown tips](#)

RStudio

- [RStudio cheat sheet](#)

11.3 Resources for TreeSummarizedExperiment

SummarizedExperiment

- Publication
- Project page

TreeSummarizedExperiment

- Publication
- Project page

SingleCellExperiment

- Publication
- Project page

11.4 Resources for phyloseq

- List of R tools for microbiome analysis
- phyloseq
- microbiome tutorial
- microbiomeutilities
- Bioconductor Workflow for Microbiome Data Analysis: from raw reads to community analyses (Callahan et al. F1000, 2016).

11.5 Further reading

- Data Analysis and Visualization in R for Ecologists by Data Carpentry
- Modern Statistics for Modern Biology. Holmes & Huber (2018) for background in statistical analysis
- Microbiome Data Science. Shetty & Lahti, 2019

Chapter 12

Additional Community Typing

```
# Load data
library(mia)
data(enterotype)
tse <- enterotype
```

12.1 Community composition

12.1.1 Composition barplot

The typical way to visualise the microbiome compositions is by using a composition barplot. In the following, we calculate the relative abundances and the top 10 taxa. The barplot is ordered by “Bacteroidetes”:

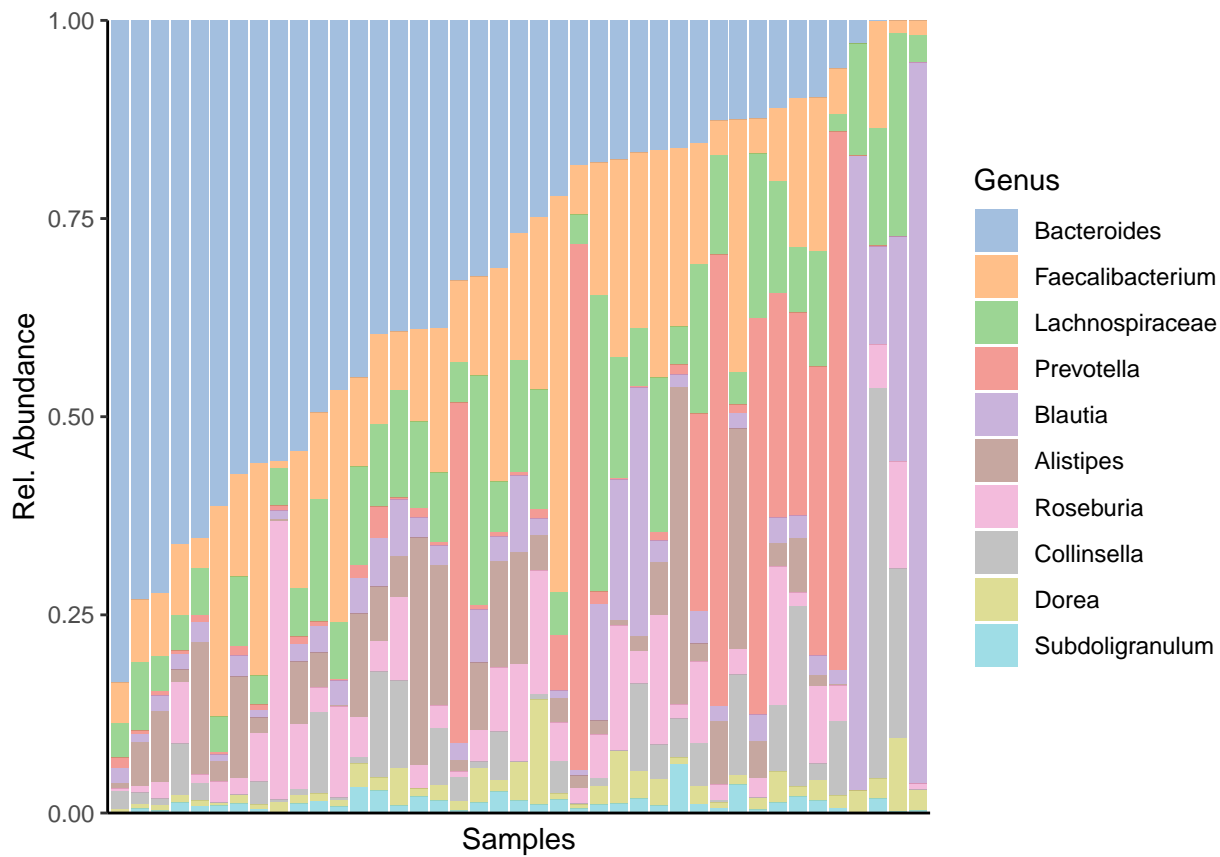
```
library(miaViz)

# Remove unwanted taxon
tse <- subsetTaxa(tse, rownames(tse) != "-1")
# Only consider Sanger technique
mat <- subsetSamples(tse, colData(tse)$SeqTech == "Sanger")

# Get top taxa
rel_taxa <- getTopTaxa(tse, top = 10, abund_values = "counts")

# Take only the top taxa
mat <- subsetTaxa(mat, is.element(rownames(tse), rel_taxa))

# Visualise composition barplot, with samples order by "Bacteroides"
plotAbundance(mat, abund_values = "counts",
              order_rank_by = "abund", order_sample_by = "Bacteroides")
```



12.1.2 Composition heatmap

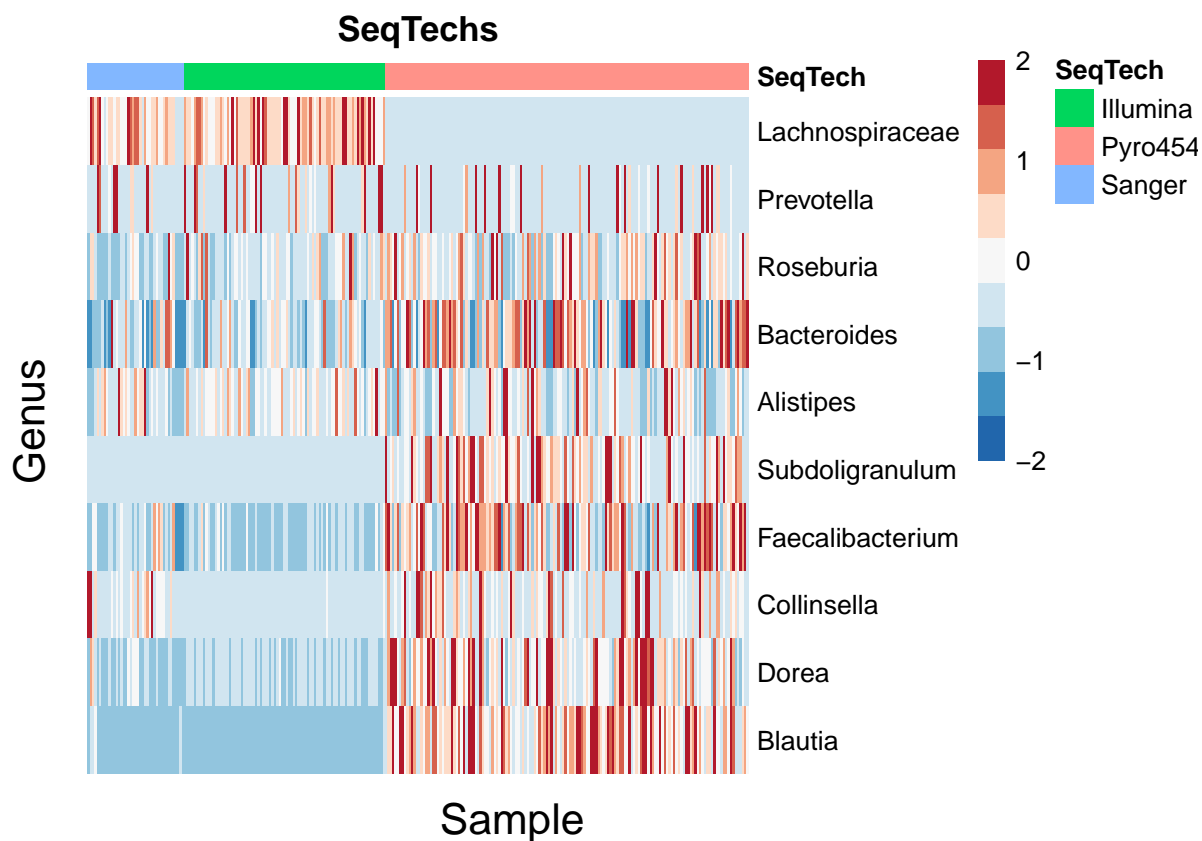
Community composition can be visualised with a heatmap. The colour of each intersection point represents the abundance of a taxon in a specific sample.

Here, the CLR + Z-transformed abundances are shown.

```
library(pheatmap)
library(grid)
library(RColorBrewer)
# CLR and Z transforms
mat <- transformCounts(tse, abund_values = "counts", method = "clr", pseudocount = 1)
mat <- transformFeatures(mat, abund_values = "clr", method = "z")
# Take only the top taxa
mat <- subsetTaxa(mat, is.element(rownames(tse), rel_taxa))

# For annotating heat map
SeqTechs <- data.frame("SeqTech" = colData(mat)$SeqTech)
rownames(SeqTechs) <- colData(mat)$Sample_ID
# count matrix for pheatmap
mat <- assays(mat)$z
```

```
# Make grid for heatmap
breaks <- seq(-2, 2, length.out = 10)
setHook("grid.newpage", function() pushViewport(viewport(x = 1, y = 1, width = 0.9,
                                                         height = 0.9, name = "vp",
                                                         just = c("right", "top"))),
        action = "prepend")
pheatmap(mat, color = rev(brewer.pal(9, "RdBu")), breaks = breaks, main = "SeqTechs", treeheight_row = 0, treeheight_col = 0,
         setHook("grid.newpage", NULL, "replace"))
grid.text("Sample", x = 0.39, y = -0.04, gp = gpar(fontsize = 16))
grid.text("Genus", x = -0.04, y = 0.47, rot = 90, gp = gpar(fontsize = 16))
```



12.2 Cluster into CSTs

The burden of specifying the number of clusters falls on the researcher. To help make an informed decision, we turn to previously established methods for doing so. In this section we introduce three such methods (aside from DMM analysis) to cluster similar samples. They include the Elbow Method, Silhouette Method, and Gap Statistic Method. All of them will utilise the 'kmeans' algorithm which essentially assigns clusters and minimises the distance within clusters (a sum of squares calculation). The default distance metric used is the Euclidean metric.

The scree plot allows us to see how much of the variance is captured by each dimension in the MDS ordination.

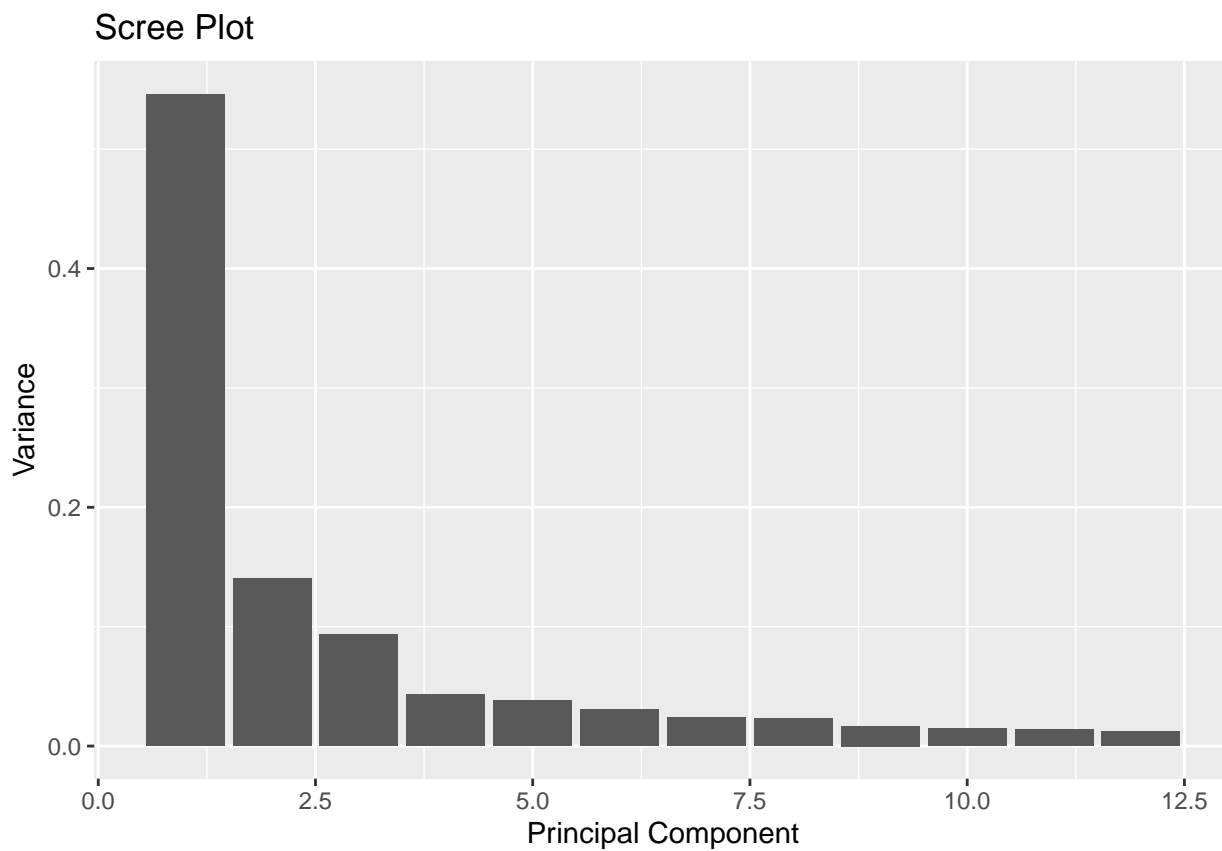
```
library(ggplot2); th <- theme_bw()

# reset data
tse <- enterotype

# MDS analysis with the first 20 dimensions
tse <- scatter::runMDS(tse, FUN = vegan::vegdist, method = "bray",
                      name = "MDS_BC", exprs_values = "counts", ncomponents = 20)
ord <- reducedDim(tse, "MDS_BC", withDimnames = TRUE)
# retrieve eigenvalues
eigs <- attr(ord, "eig")

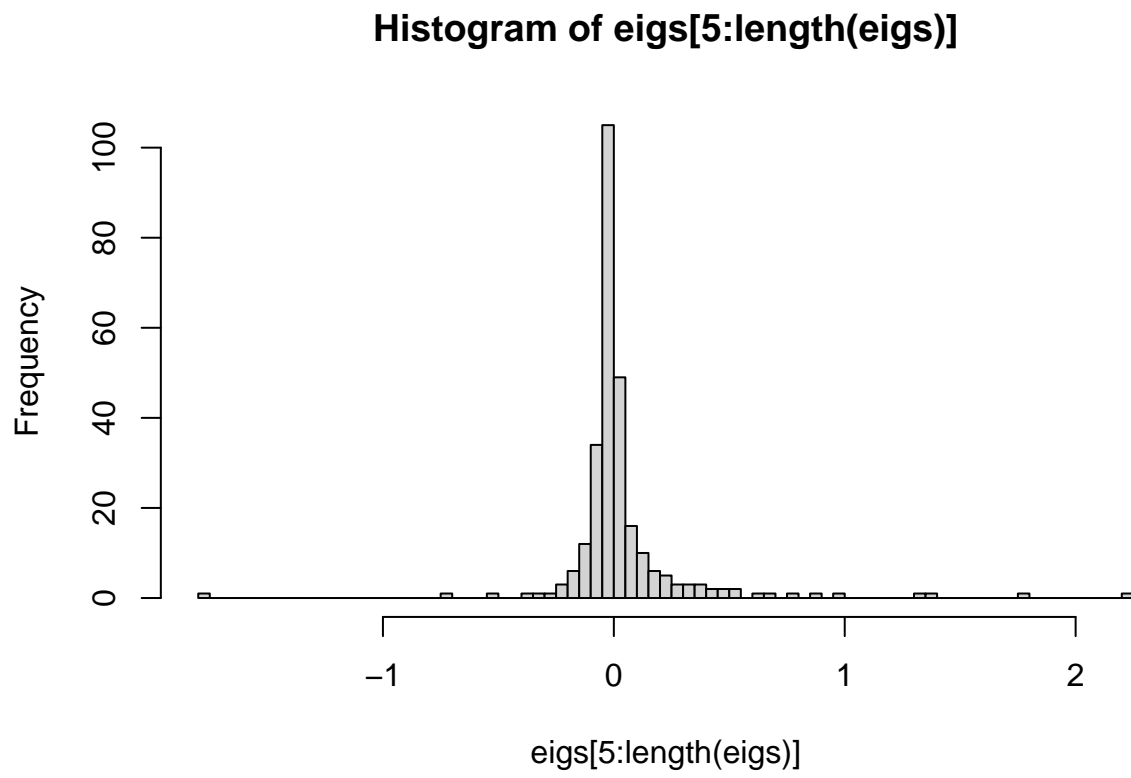
# variance in each of the axes
var <- eigs / sum(eigs)
# first 12 values
df <- data.frame(x = c(1:12), y = var[1:12])

# create scree plot
p <- ggplot(df, aes(x, y)) +
  geom_bar(stat="identity") +
  xlab("Principal Component") +
  ylab("Variance") +
  ggtitle("Scree Plot")
p
```

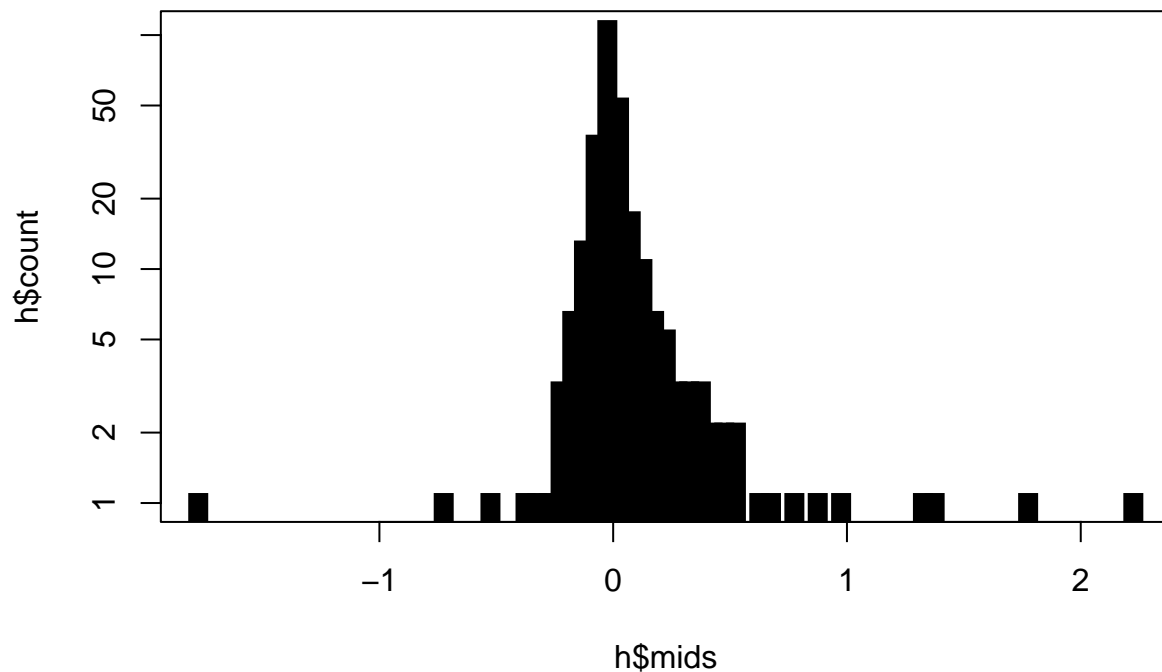



From the scree plot (above), we can see that the two principal dimensions can account for 68% of the total variation, but at least the top 4 eigenvalues are considerable. Dimensions beyond 3 and 4 may be useful so let's try to remove the less relevant dimensions.

```
# histogram of MDS eigenvalues from the fifth dimension onward  
h <- hist(eigs[5:length(eigs)], 100)
```



```
plot(h$mids, h$count, log = "y", type = "h", lwd = 10, lend = 2)
```



As you can see, dimensions 5, 6, and 7 still stand out so we will include 7 MDS dimensions.

12.2.1 Elbow Method

This method graphs the sum of the sum of squares for each k (number of clusters), where k ranges between 1 and 10. Where the bend or ‘elbow’ occurs is the optimal value of k .

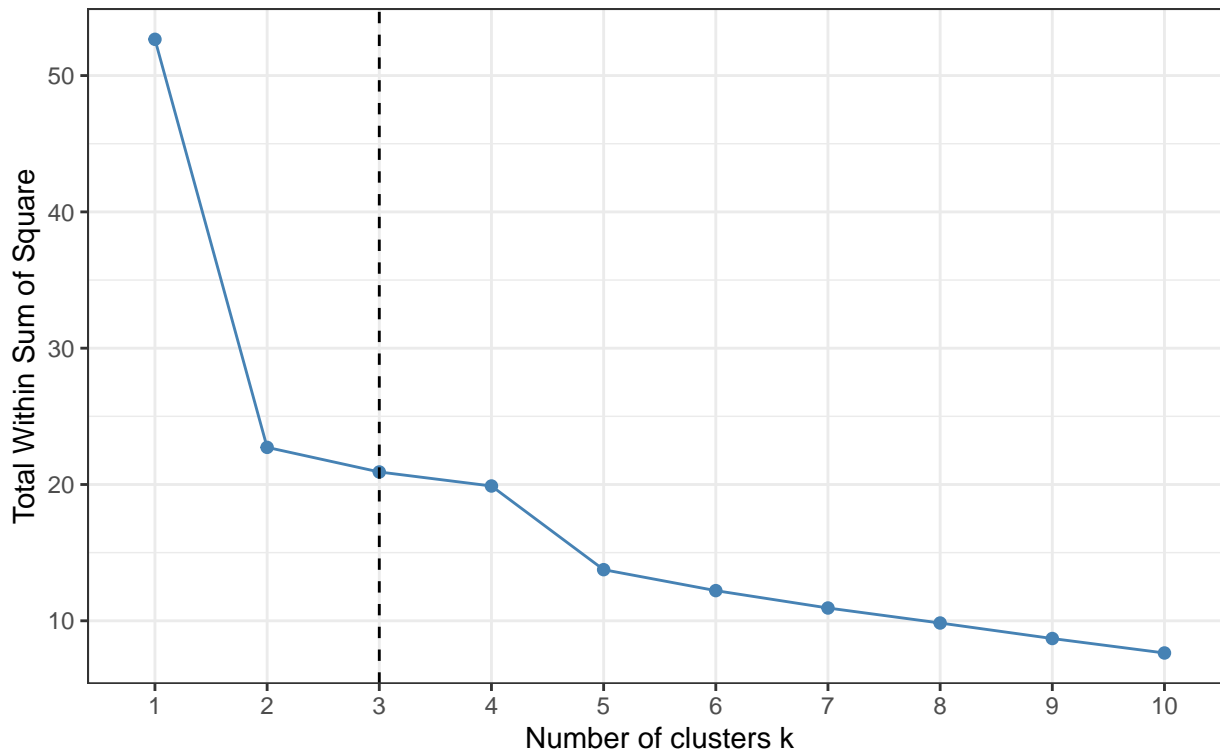
```
library(factoextra)

# take only first 7 dimensions
NDIM <- 7
x <- ord[, 1:NDIM]

# Elbow Method
factoextra::fviz_nbclust(x, kmeans, method = "wss") +
  geom_vline(xintercept = 3, linetype = 2) +
  labs(subtitle = "Elbow Method") + th
```

Optimal number of clusters

Elbow Method

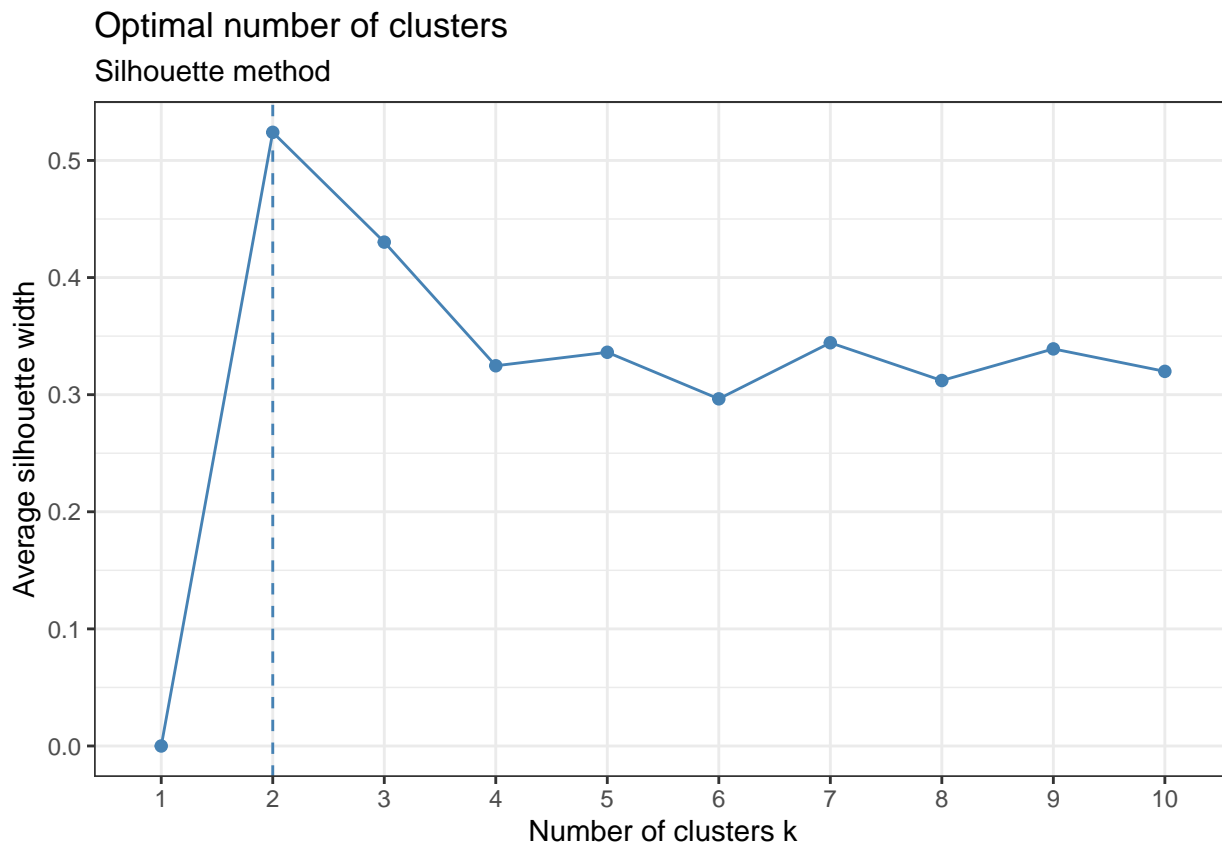


As you can see, the bend occurs at $k = 3$, implying there are three clusters present in the enterotype data.

12.2.2 Silhouette Method

This method on the otherhand returns a width for each k . In this case, we want the k that maximises the width.

```
# Silhouette method
factoextra::fviz_nbclust(x, kmeans, method = "silhouette") +
  labs(subtitle = "Silhouette method") + th
```



The graph shows the maximum occurring at $k = 2$. $k = 3$ is also strongly suggested by the plot and is consistent with what we obtained from the elbow method.

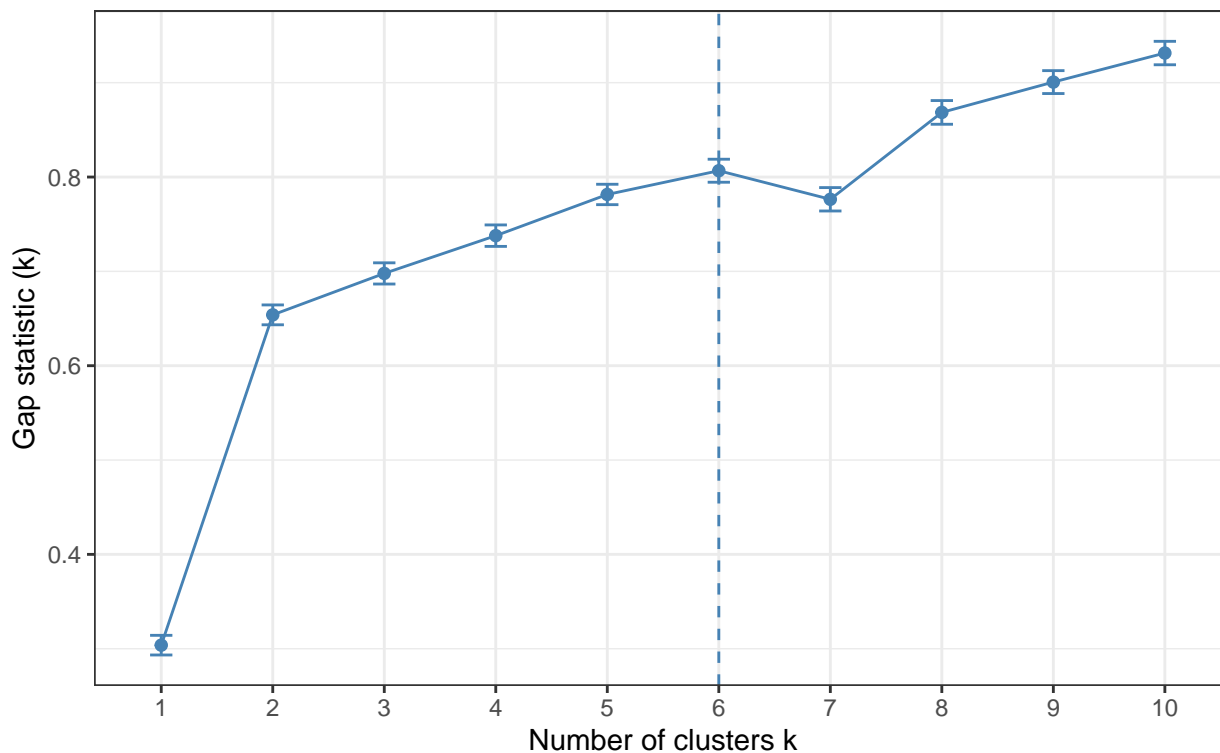
12.2.3 Gap-Statistic Method

The Gap-Statistic Method is the most complicated among the methods discussed here. In the plot produced, we want the k value that maximises the output (local and global maxima), but we also want to pay attention to where the plot jumps if the maximum value doesn't turn out to be helpful.

```
# Gap Statistic Method
factoextra::fviz_nbclust(x, kmeans, method = "gap_stat", nboot = 50)+
  labs(subtitle = "Gap Statistic Method") + th
```

Optimal number of clusters

Gap Statistic Method



$k = 6$ clusters, as the peak suggests, would not be very revealing since having too many clusters can cease to be revealing and so we look to the points where the graph jumps. We can see this occurs at $k = 2$ and $k = 8$. The output indicates that there are at least two clusters present. Since we have previous evidence for the existence of three clusters and $k = 3$ yields a higher gap statistic than $k = 2$, $k = 3$ seems to be a good choice.

One could argue for the existence of two or three clusters as they are both good candidates. At times like these it helps to visualise the clustering in an MDS or NMDS plot.

Now let's divide the subjects into their respective clusters.

```
library(cluster)

# assume 3 clusters
K <- 3
x <- ord[, 1:NDIM]

clust <- as.factor(pam(x, k = K, cluster.only = T))
# swapping the assignment of 2 and 3 to match ravel cst enumeration
clust[clust == 2] <- NA
clust[clust == 3] <- 2
clust[is.na(clust)] <- 3

colData(tse)$CST <- clust
```

```
CSTs <- as.character(seq(K))
```

Let's take a look at the MDS ordination with the Bray-Curtis dissimilarity in the first four dimensions.

```
library(scater)
library(RColorBrewer)
library(cowplot)

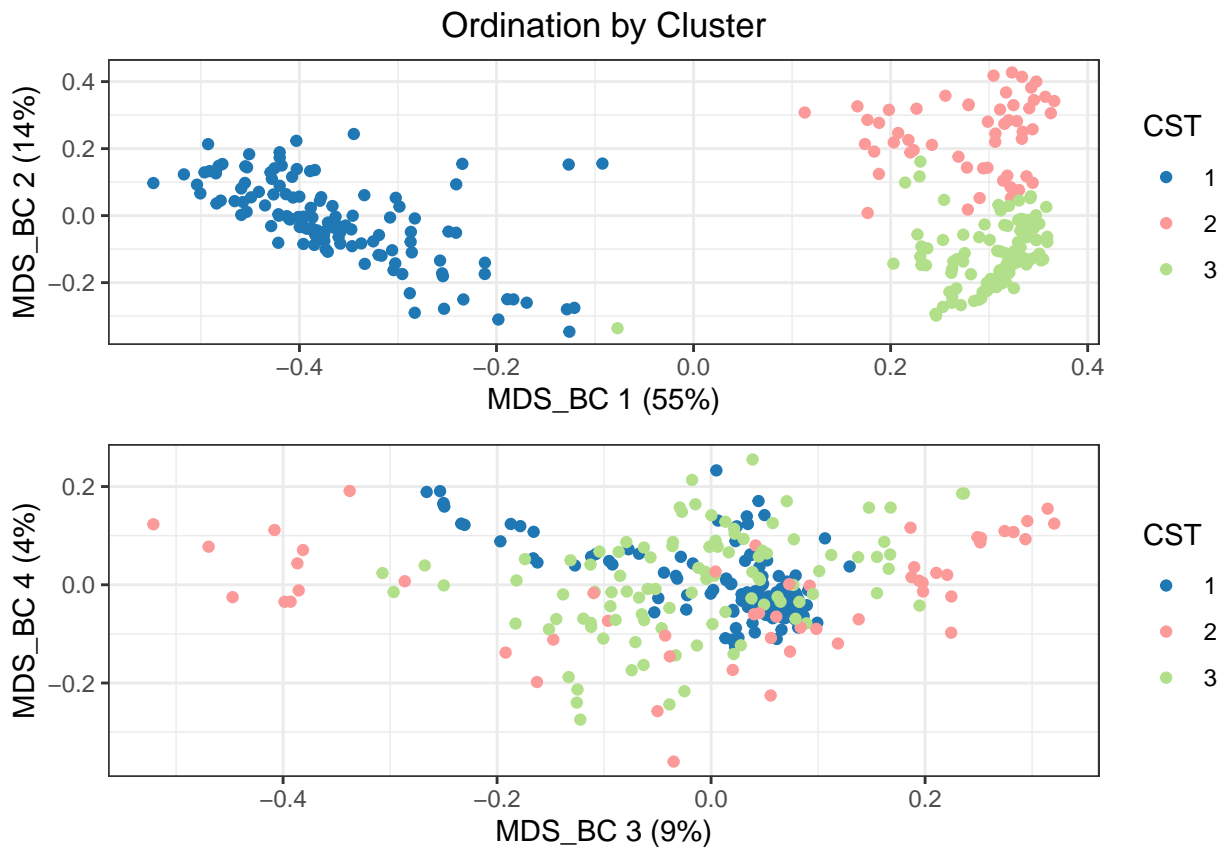
# set up colours
CSTColors <- brewer.pal(6, "Paired")[c(2, 5, 3)] # Length 6 for consistency with pre-revision CST+ colouration
names(CSTColors) <- CSTs

CSTColorScale <- scale_colour_manual(name = "CST", values = CSTColors)
CSTFillScale <- scale_fill_manual(name = "CST", values = CSTColors)

# plot MDS with Bray-Curtis dimensions 1 and 2
p1 <- scater::plotReducedDim(tse, "MDS_BC", colour_by = "CST", point_alpha = 1,
                             percentVar = var[c(1, 2)]*100) + th + labs(title = "Ordination by Cluster") +
  theme(plot.title = element_text(hjust = 0.5))

# plot MDS with Bray-Curtis dimensions 3 and 4
p2 <- scater::plotReducedDim(tse, "MDS_BC", colour_by = "CST", point_alpha = 1,
                             ncomponents = c(3, 4), percentVar = var[c(1, 2, 3, 4)]*100) + th

plot_grid(p1 + CSTColorScale, p2 + CSTColorScale, nrow = 2)
```

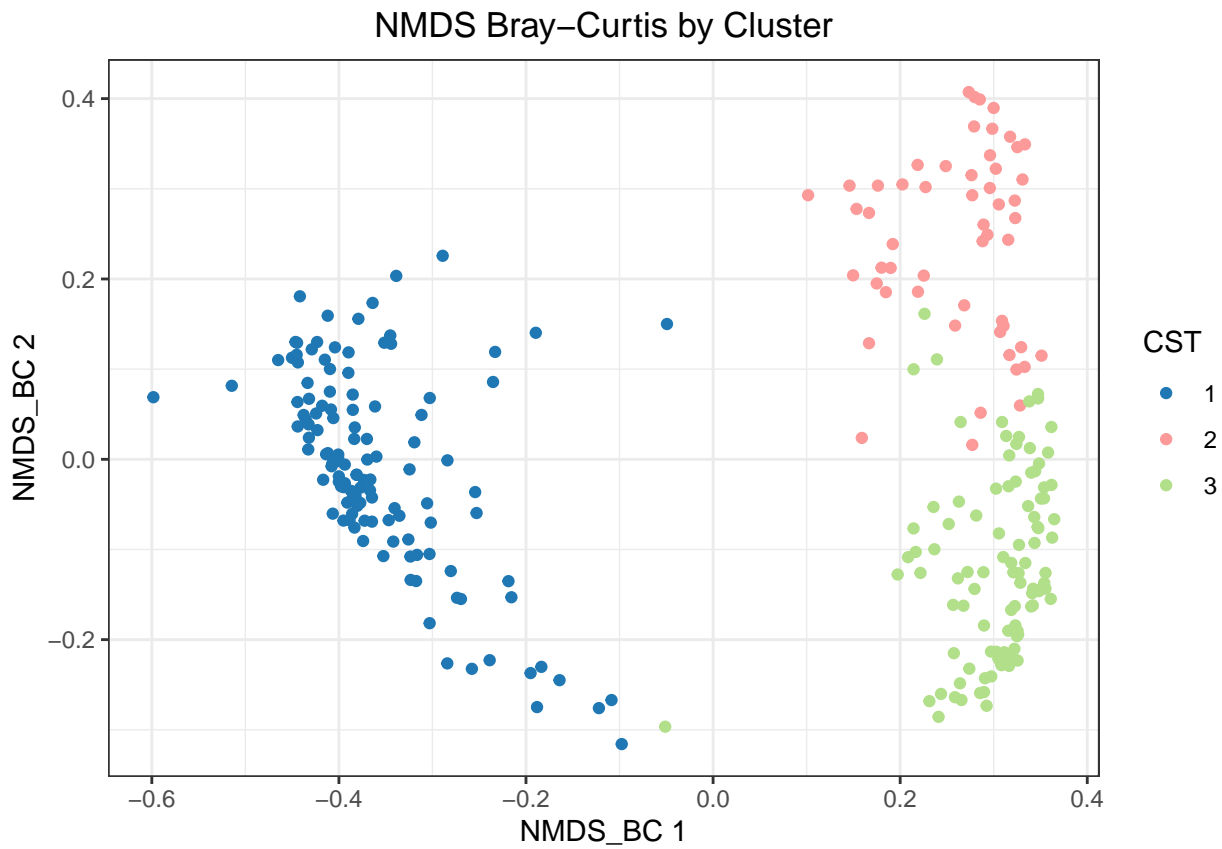


And now nMDS.

```
tse <- runNMDS(tse, FUN = vegan::vegdist, method = "bray",
               name = "NMDS_BC", exprs_values = "counts", ncomponents = 20)
```

```
## initial value 4.717325
## iter 5 value 2.138115
## iter 10 value 1.879881
## iter 15 value 1.787953
## iter 20 value 1.750342
## iter 25 value 1.730981
## iter 30 value 1.719617
## iter 30 value 1.717980
## iter 30 value 1.717898
## final value 1.717898
## converged
```

```
scatter::plotReducedDim(tse, "NMDS_BC", colour_by = "CST", point_alpha = 1) + th +
  labs(title = "NMDS Bray-Curtis by Cluster") +
  theme(plot.title = element_text(hjust = 0.5)) + CSTColorScale
```

We can also look at a multitude of other distance metrics and subsets of the data.

12.3 Holmes and McMurdie Workflow

For the following distance measures, we will only consider the sequencing technique “Sanger” from the enterotype data.

```
dim(tse)
```

```
## [1] 553 280
```

```
# Subset data
tse2 <- subsetSamples(tse, colData(tse)$SeqTech == "Sanger")

# Change NAs to 0
x <- as.vector(colData(tse2)$Enterotype)
x[is.na(x)] <- 0
x <- factor(x, levels = c("1", "2", "3", "0"))
colData(tse2)$Enterotype <- x
```

```
dim(tse2)
```

```
## [1] 553 41
```

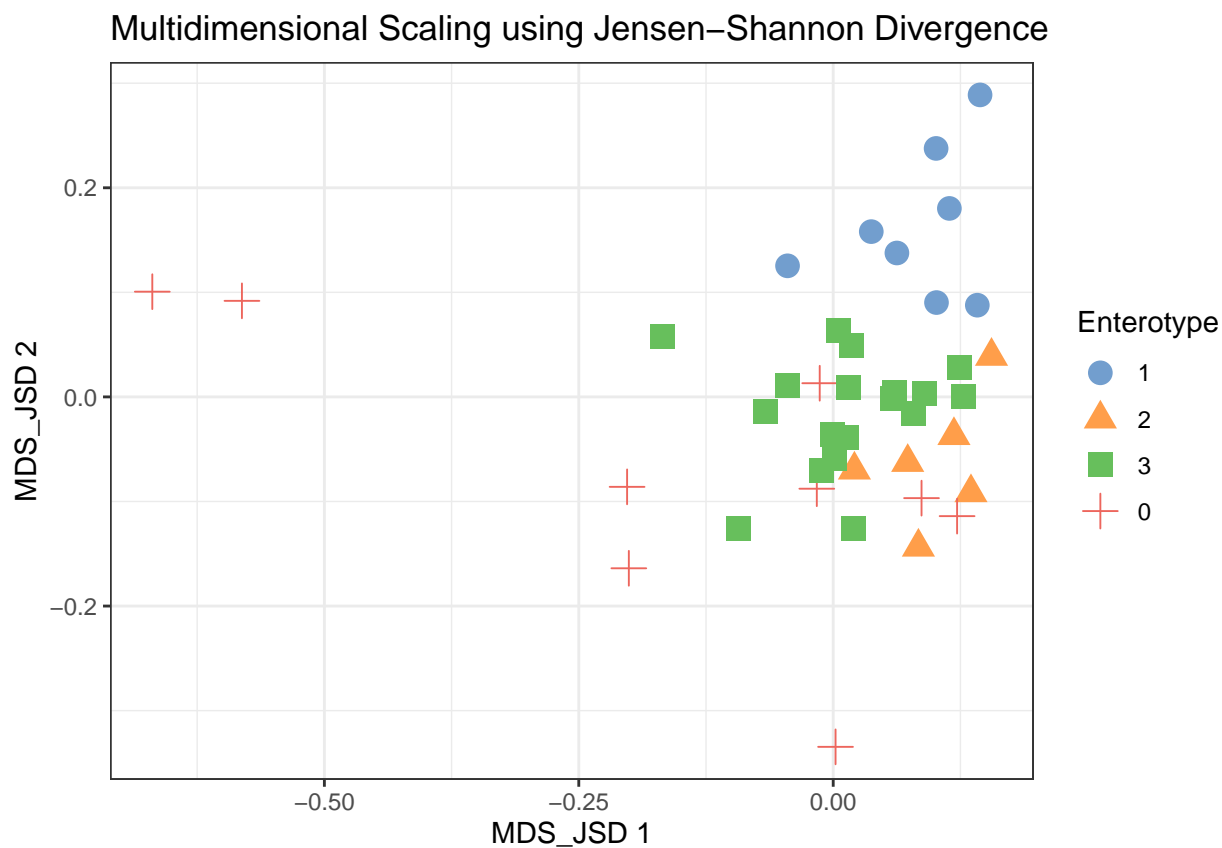
```
table(colData(tse2)$Enterotype)
```

```
##
##  1  2  3  0
##  8  6 18  9
```

12.3.1 Jensen-Shannon Distance

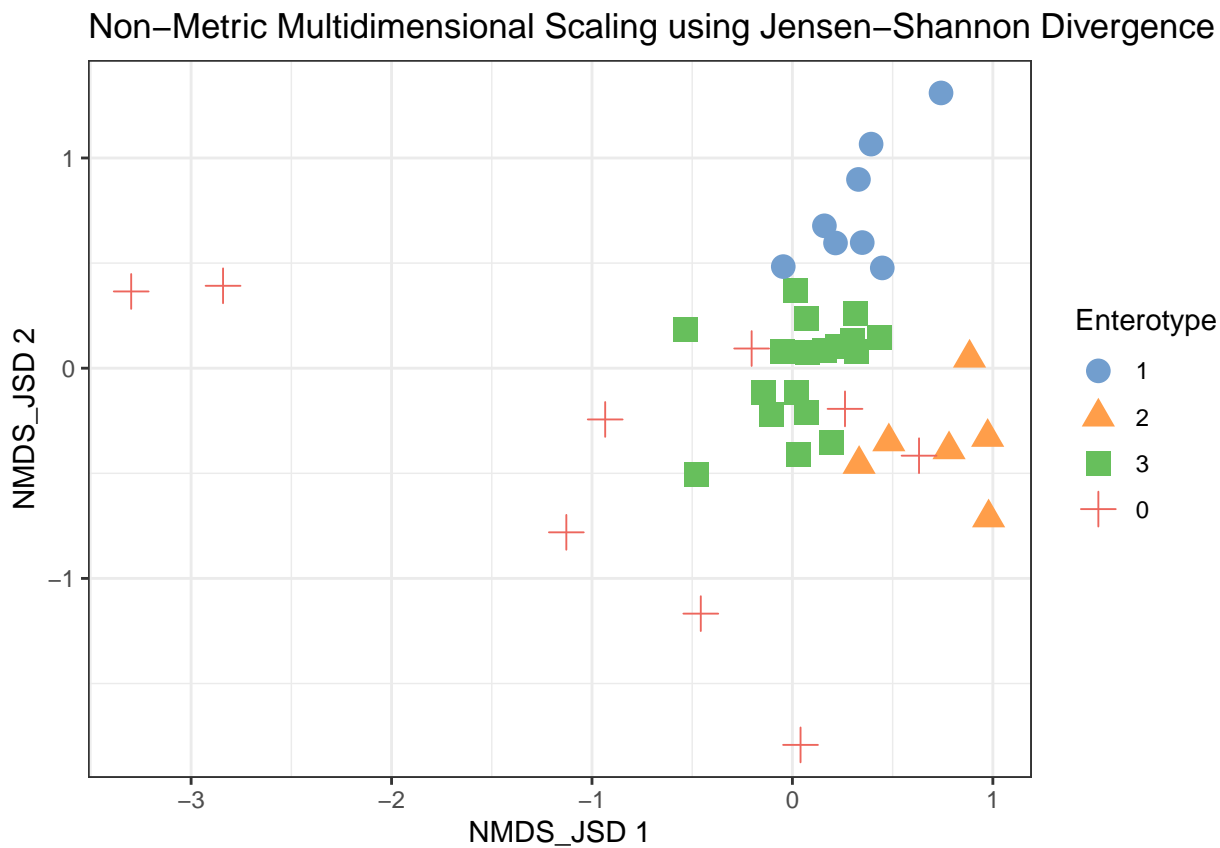
```
library(philentropy)

custom_FUN <- function(x) as.dist(philentropy::JSD(x))
tse2 <- scater::runMDS(tse2, FUN = custom_FUN, name = "MDS_JSD", exprs_values = "counts")
scater::plotReducedDim(tse2, "MDS_JSD", colour_by = "Enterotype",
  shape_by = "Enterotype", point_size = 4, point_alpha = 1) +
  ggtitle("Multidimensional Scaling using Jensen-Shannon Divergence") + th
```



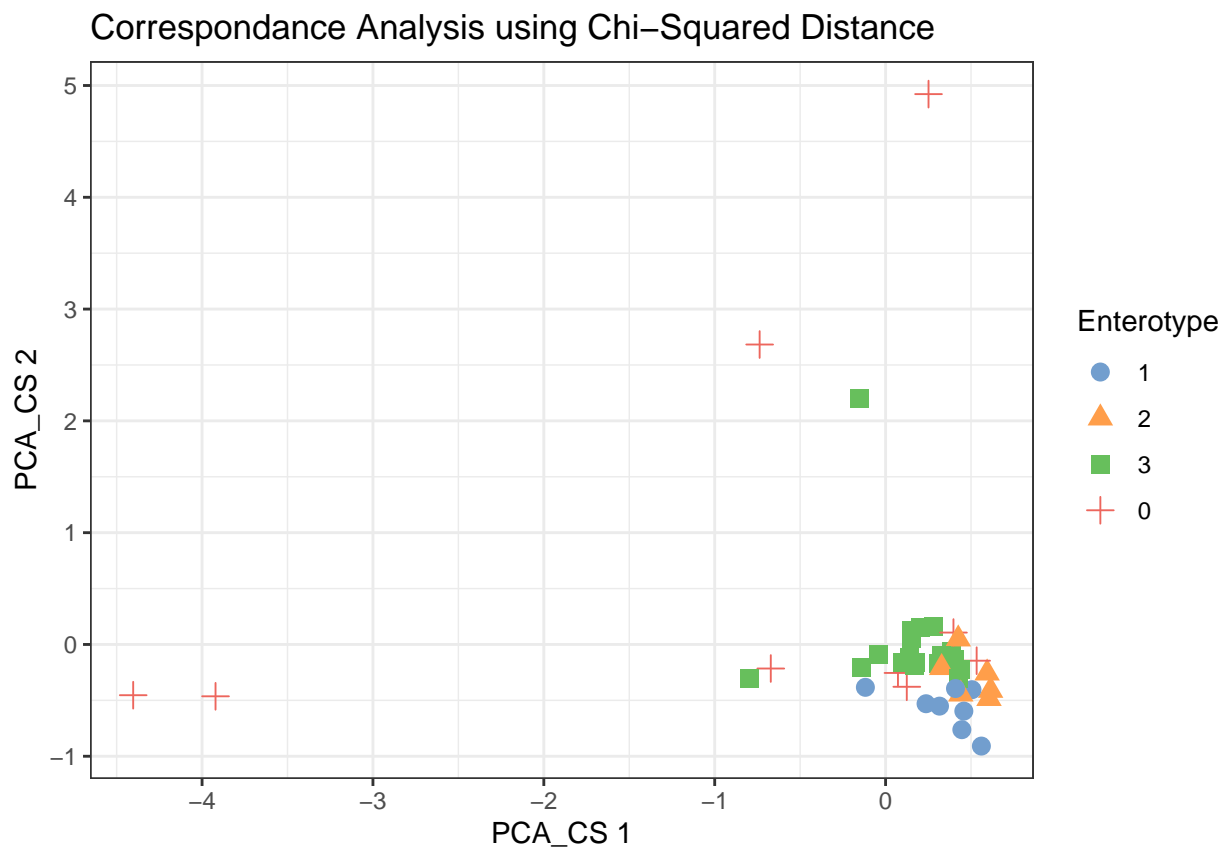
12.3.2 NonMetric Multidimensional Scaling

```
tse2 <- mia::runNMDS(tse2, FUN = custom_FUN, nmbsFUN = "monoMDS", name = "NMDS_JSD")
scater::plotReducedDim(tse2, "NMDS_JSD", colour_by = "Enterotype",
  shape_by = "Enterotype", point_size = 4, point_alpha = 1) +
  ggtitle("Non-Metric Multidimensional Scaling using Jensen-Shannon Divergence") + th
```



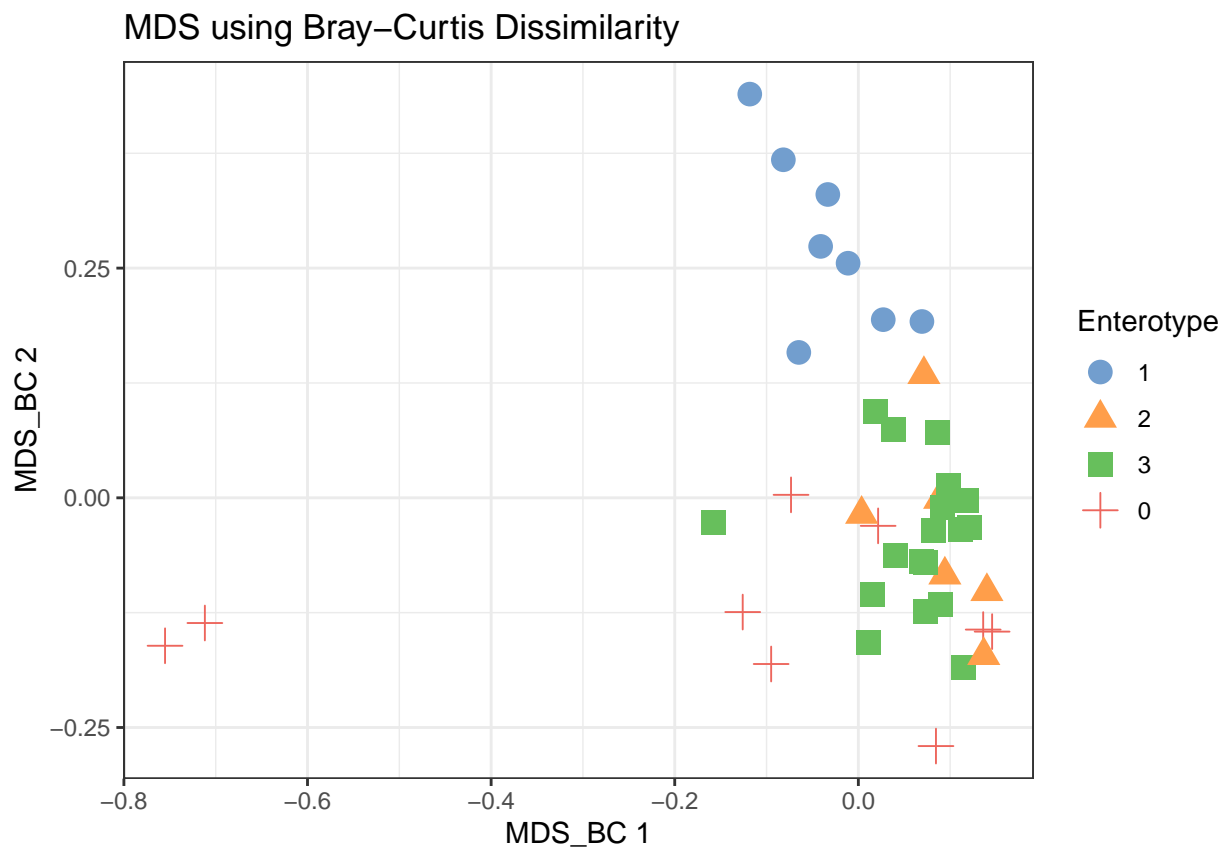
12.3.3 Chi-Squared Correspondence Results

```
tse2 <- mia::runCCA(tse2, name = "PCA_CS", exprs_values = "counts")
scater::plotReducedDim(tse2, "PCA_CS", colour_by = "Enterotype",
  shape_by = "Enterotype", point_size = 3, point_alpha = 1) +
  ggtitle("Correspondance Analysis using Chi-Squared Distance") + th
```



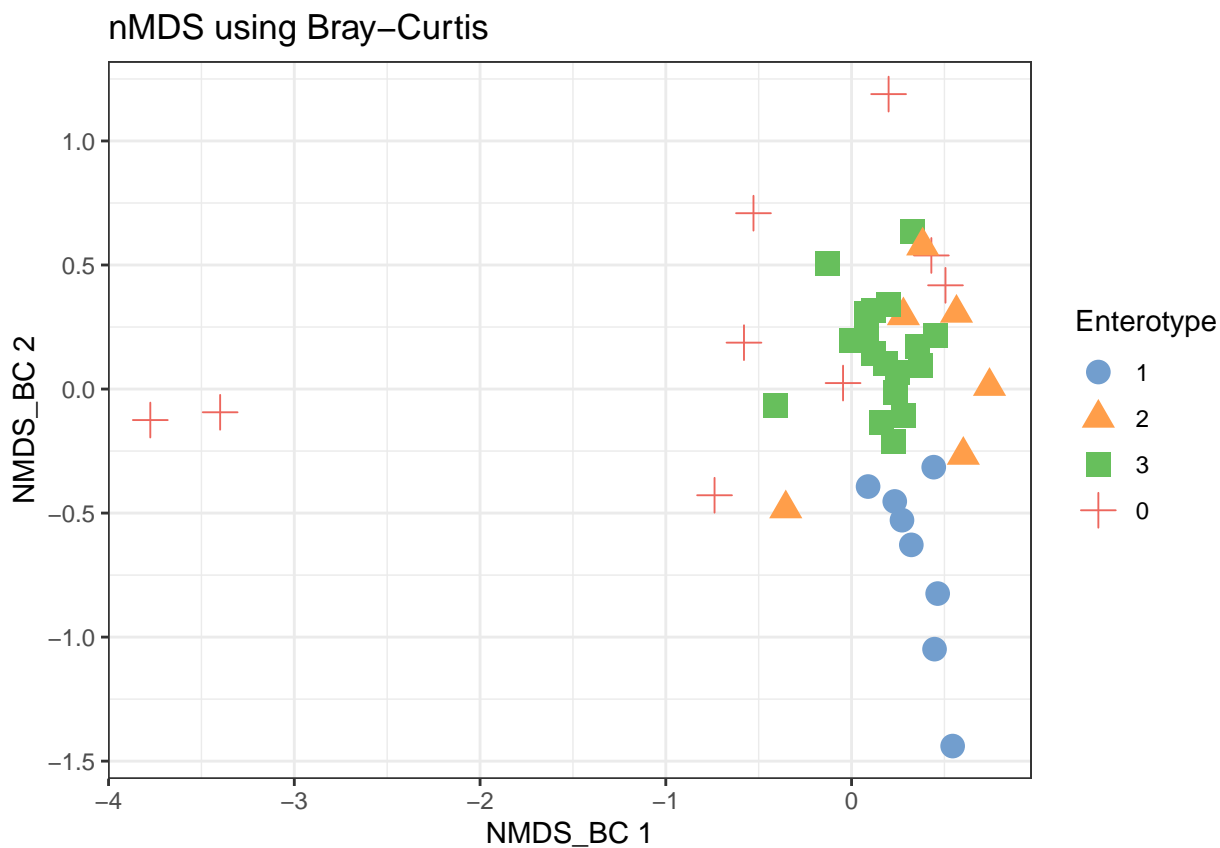
12.3.4 Bray-Curtis MDS

```
tse2 <- scater::runMDS(tse2, FUN = vegan::vegdist, name = "MDS_BC", exprs_values = "counts")
scater::plotReducedDim(tse2, "MDS_BC", colour_by = "Enterotype",
  shape_by = "Enterotype", point_size = 4, point_alpha = 1) +
  ggtitle("MDS using Bray-Curtis Dissimilarity") + th
```



12.3.5 Bray-Curtis NMDS

```
tse2 <- mia::runNMDS(tse2, FUN = vegan::vegdist, nmdsFUN = "monoMDS", method = "bray", name = "NMDS_BC")
scater::plotReducedDim(tse2, "NMDS_BC", colour_by = "Enterotype",
  shape_by = "Enterotype", point_size = 4, point_alpha = 1) +
  ggtitle("nMDS using Bray-Curtis") + th
```



12.3.6 Other distances from the Philentropy package

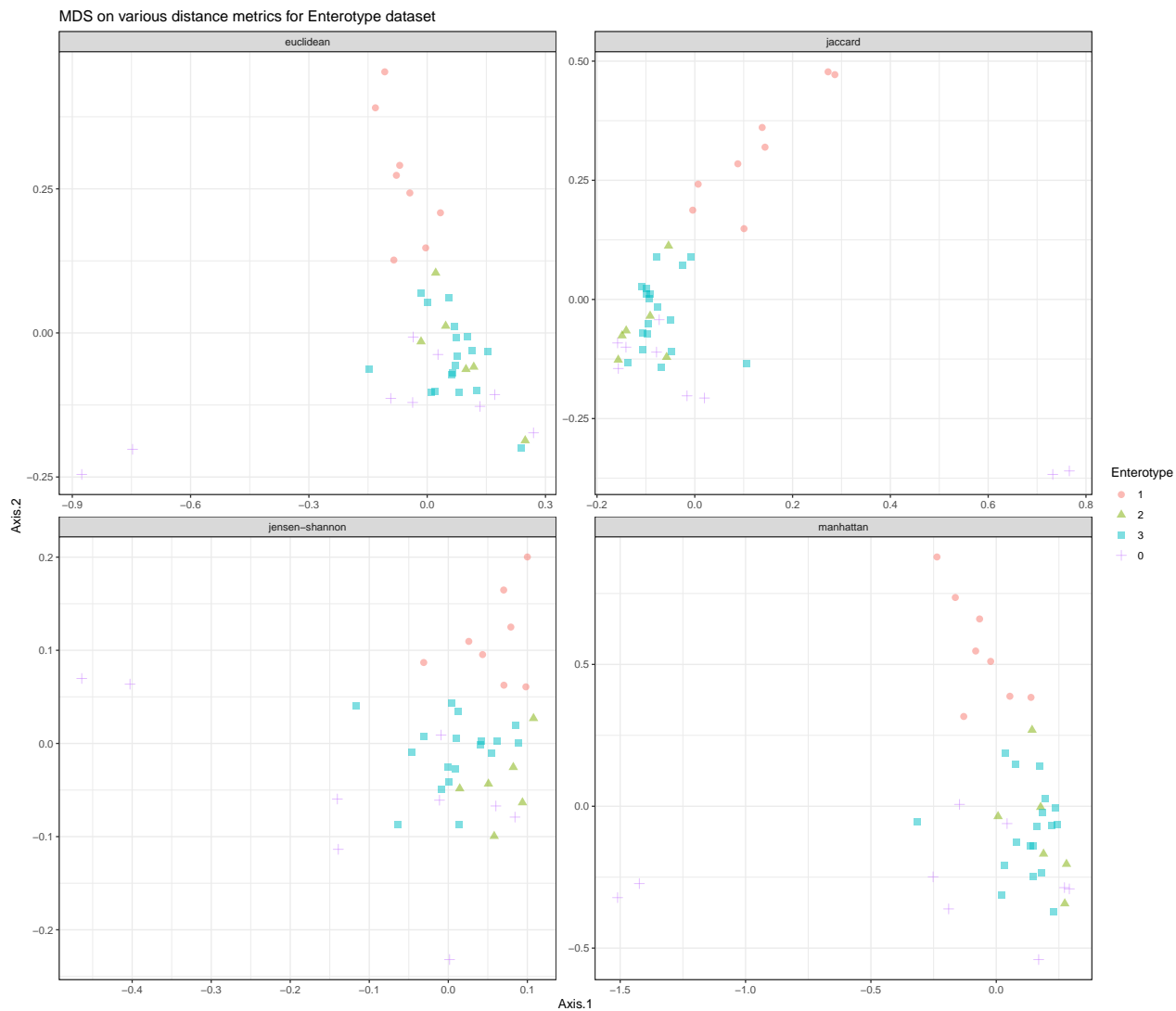
```
library(gridExtra)
# take distances that more or less match Holmes and McMurdie
distances <- getDistMethods()[c(1, 2, 23, 42)]
# variable to store results
plist <- vector("list", length(distances))
names(plist) <- distances

# calculate each distance measure
for (i in distances[1:length(distances)]) {
  custom_FUN <- function(x) as.dist(philentropy::distance(x, method = i, p = 1))
  tse2 <- scater::runMDS(tse2, FUN = custom_FUN, name = i, exprs_values = "counts")
  # store result in plist
  plist[[i]] <- scater::plotReducedDim(tse2, i, colour_by = "Enterotype")
}

library(plyr)

# plot
df <- ldply(plist, function(x) x$data)
```

```
names(df) <- c("distance", "Axis.1", "Axis.2", "Enterotype")
p <- ggplot(df, aes(Axis.1, Axis.2, color = Enterotype, shape = Enterotype)) +
  geom_point(size = 2.5, alpha = 0.5) +
  facet_wrap(~distance, scales = "free") +
  theme(strip.text = element_text(size = 8)) +
  ggtitle("MDS on various distance metrics for Enterotype dataset") + th
p
```



12.3.7 Add a Clustering Variable

It may be revealing to see the full data (with subsetting) clustered according to a `colData` variable.

```
# remove taxon
tse3 <- subsetTaxa(tse, rownames(tse) != "-1")
```

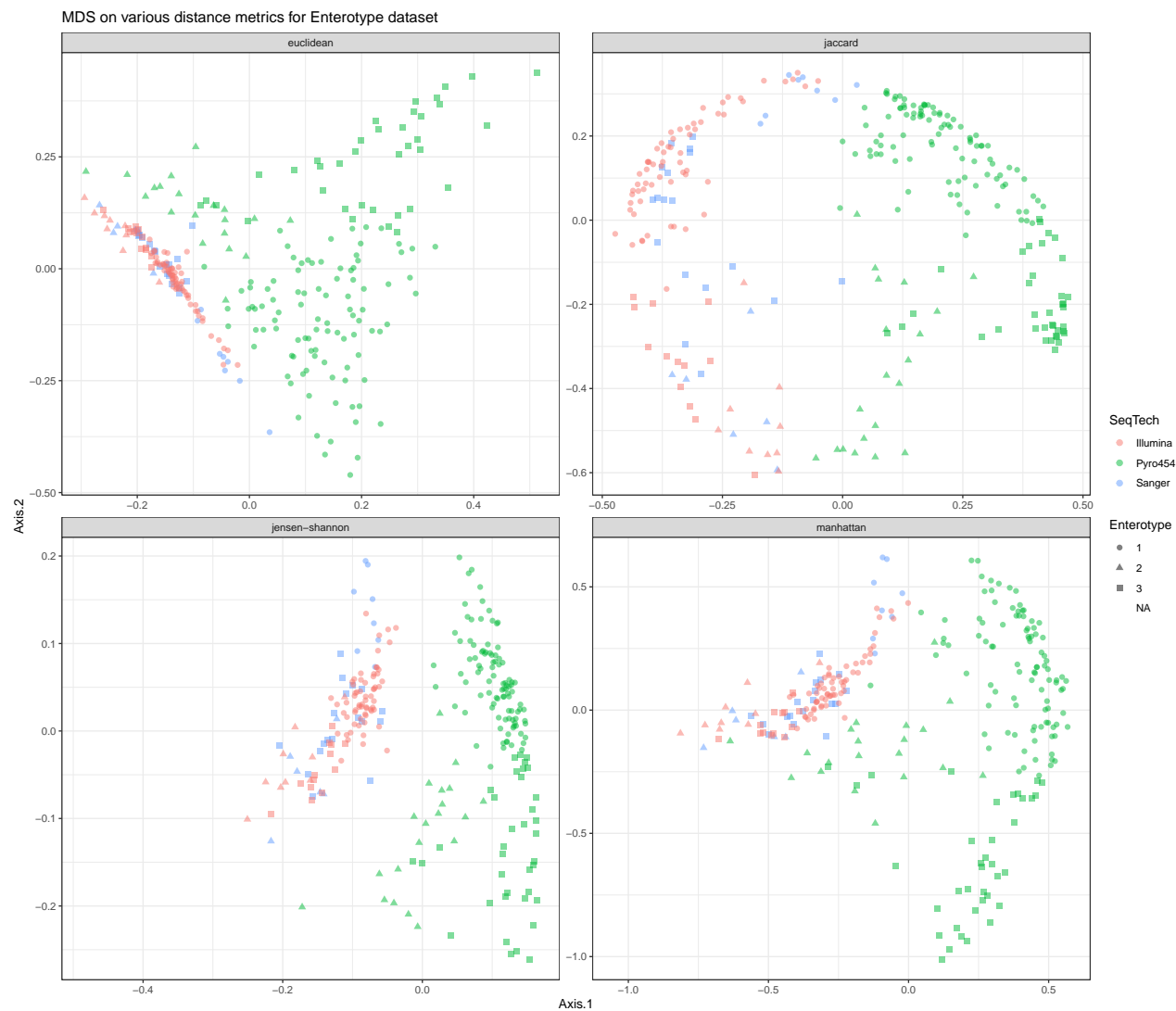
```

# Remove NAs
x <- as.vector(colData(tse3)$Enterotype)
x <- factor(x)
colData(tse3)$Enterotype <- x

# loop over distances
for (i in distances[1:length(distances)]) {
  custom_FUN <- function(x) as.dist(philentropy::distance(x, method = i, p = 1))
  tse3 <- scater::runMDS(tse3, FUN = custom_FUN, name = i, exprs_values = "counts")

  plist[[i]] <- scater::plotReducedDim(tse3, i, colour_by = "SeqTech", shape_by = "Enterotype")
}
# plot
df <- ldply(plist, function(x) x$data)
names(df) <- c("distance", "Axis.1", "Axis.2", "SeqTech", "Enterotype")
p <- ggplot(df, aes(Axis.1, Axis.2, color = SeqTech, shape = Enterotype)) +
  geom_point(size = 2, alpha = 0.5) +
  facet_wrap(~distance, scales = "free") +
  theme(strip.text = element_text(size = 8)) +
  ggtitle("MDS on various distance metrics for Enterotype dataset") + th
p

```

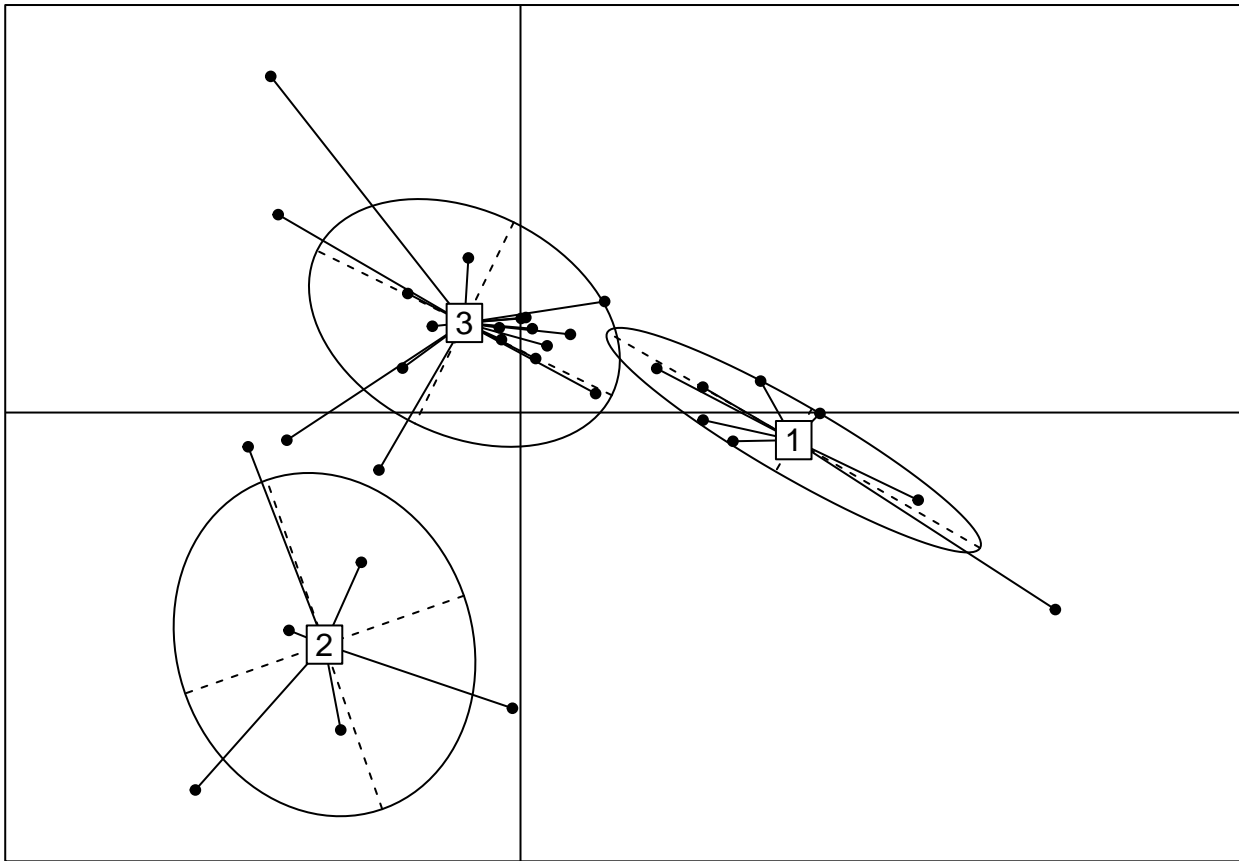



12.3.8 More Clustering

Dropping 9 outliers (the 0 enterotype), let's visualise the clustering in a different manner. Based on our analysis above, we concluded there were 3 distinct clusters. The authors of the Nature paper published on the enterotype data created a figure similar to the following:

```
library(ade4)
# remove 9 outliers
tse2 <- subsetSamples(tse2, colData(tse2)$Enterotype != 0)
colData(tse2)$Enterotype <- factor(colData(tse2)$Enterotype)

clus <- colData(tse2)$Enterotype
dist <- calculateJSD(tse2)
pcoa <- dudi.pco(dist, scannf = F, nf = 3)
s.class(pcoa$li, grid = F, fac = clus)
```

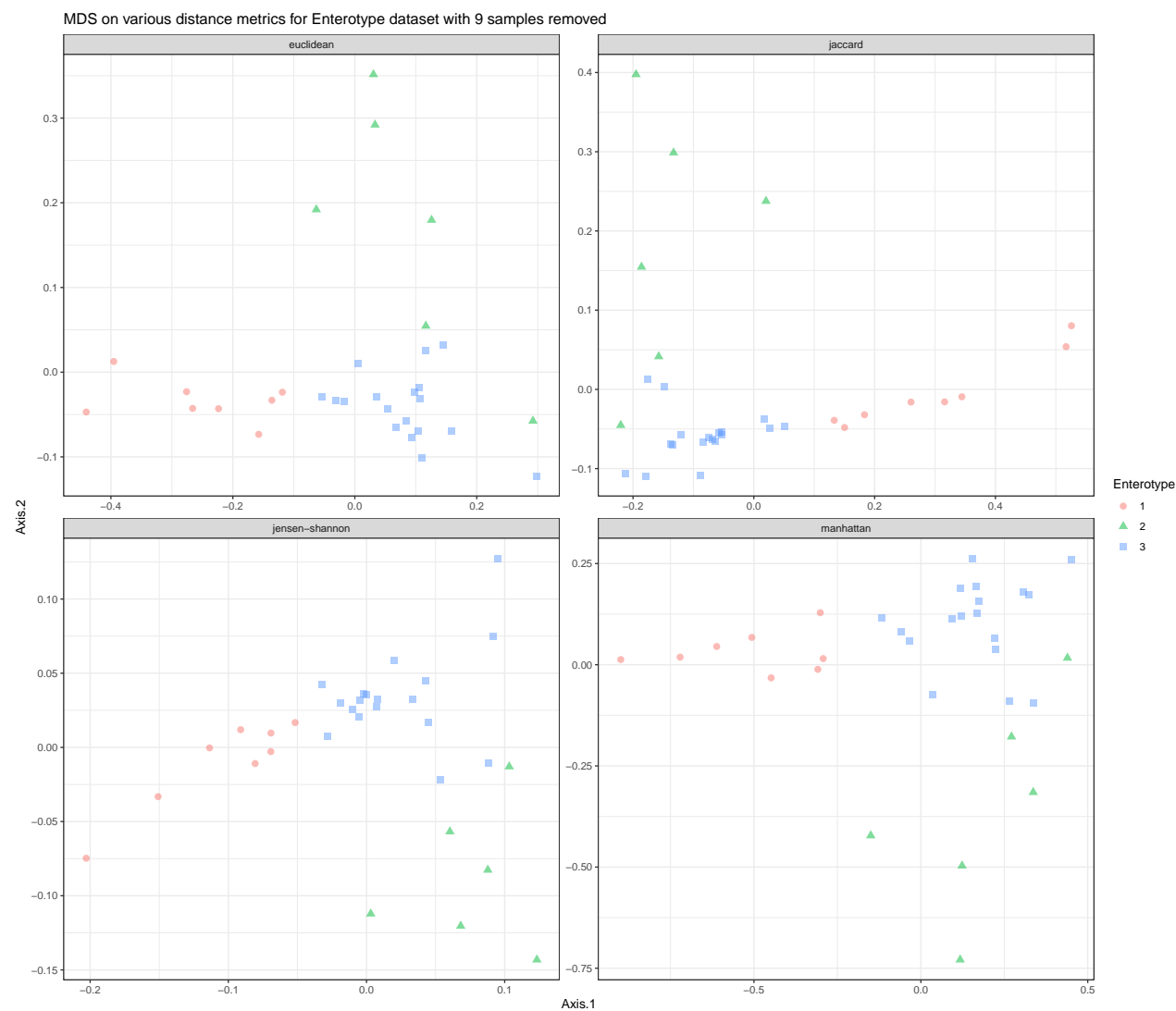


Revisit the distances without the 9 outlier values.

```
# loop over distances
for (i in distances[1:length(distances)]) {
  custom_FUN <- function(x) as.dist(phileentropy::distance(x, method = i, p = 1))
  tse2 <- scater::runMDS(tse2, FUN = custom_FUN, name = i, exprs_values = "counts")

  plist[[i]] <- scater::plotReducedDim(tse2, i, colour_by = "Enterotype")
}

# plot
df <- ldply(plist, function(x) x$data)
names(df) <- c("distance", "Axis.1", "Axis.2", "Enterotype")
p <- ggplot(df, aes(Axis.1, Axis.2, color = Enterotype, shape = Enterotype)) +
  geom_point(size = 2.5, alpha = 0.5) +
  facet_wrap(~distance, scales = "free") +
  theme(strip.text = element_text(size = 8)) +
  ggtitle("MDS on various distance metrics for Enterotype dataset with 9 samples removed") + th
p
```

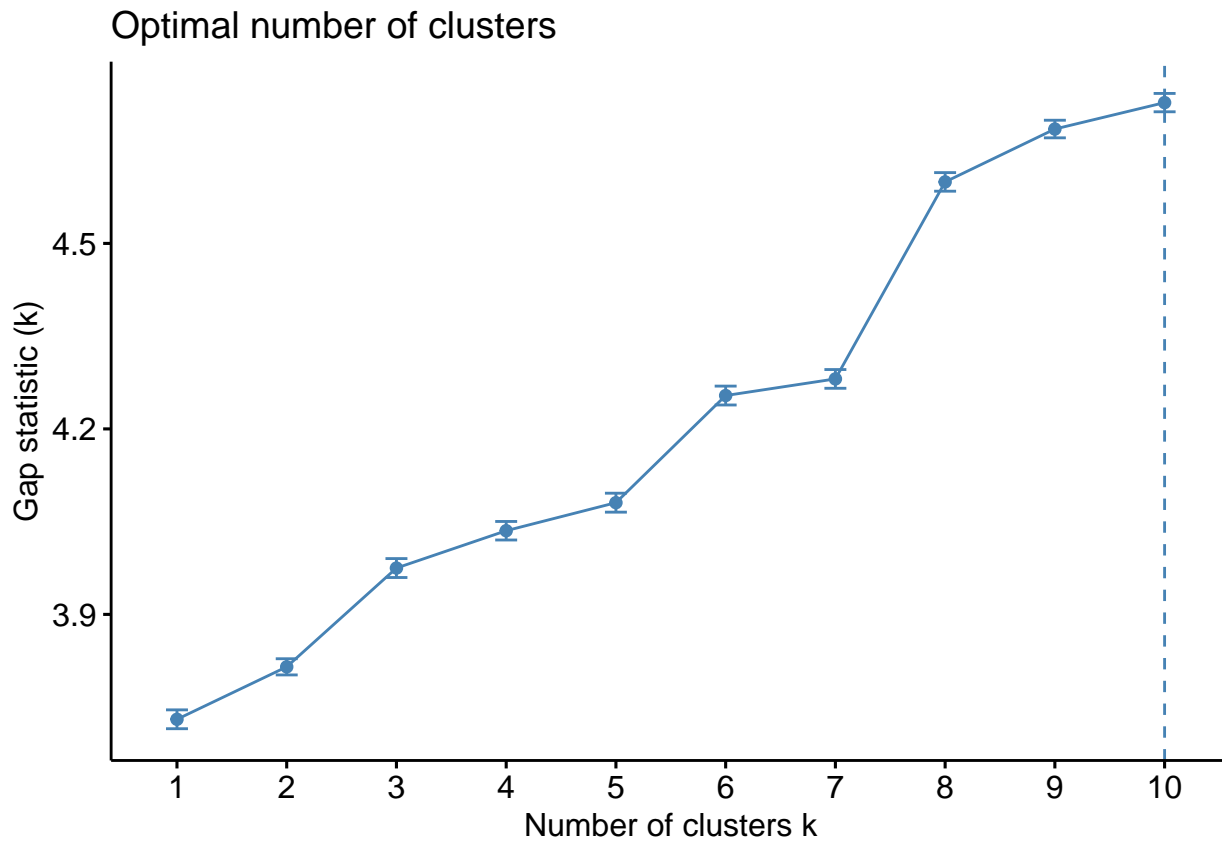


Would we use the same number of clusters as before with 9 values missing?

```
## Slightly faster way to use pam
pam1 <- function(x,k) list(cluster = pam(x,k, cluster.only=TRUE))

pamPCoA = function(x, k) {
  list(cluster = pam(x[,1:2], k, cluster.only = TRUE))
}

# gap statistic method
gs <- clusGap(assays(tse2)$counts, FUN = pamPCoA, K.max = 10)
fviz_gap_stat(gs)
```



We still see a jump at three so it is still a good choice for the number of clusters.

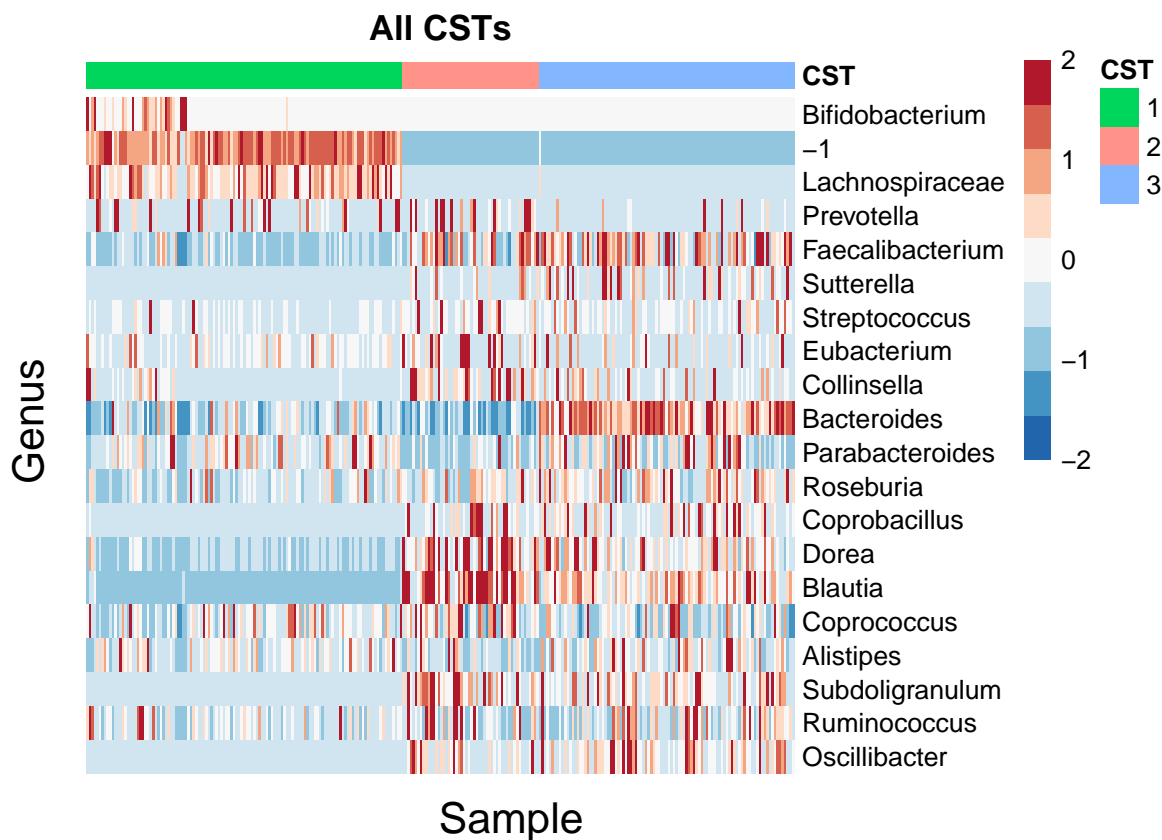
12.4 CST Analysis

Looking at heat maps of the CSTs can reveal structure on a different level. Using all of the data again (for the top 20 taxa) and taking the z transformation of the clr transformed counts, we have

```
# Find top 20 taxa
rel_taxa <- getTopTaxa(tse, top = 20)
# Z transform of CLR counts
mat <- transformCounts(tse, abund_values = "counts", method = "clr", pseudocount = 1)
mat <- transformFeatures(mat, abund_values = "clr", method = "z")
# Select top 20 taxa
mat <- subsetTaxa(mat, is.element(rownames(tse), rel_taxa))
mat <- assays(mat)$z

# Order CSTs
mat <- mat[, order(clust)]
colnames(mat) <- names(sort(clust))
```

```
# Plot
CSTs      <- as.data.frame(sort(clust))
names(CSTs) <- "CST"
breaks <- seq(-2, 2, length.out = 10)
# Make grid for heatmap
setHook("grid.newpage", function() pushViewport(viewport(x = 1, y = 1, width = 0.9,
                                                         height = 0.9, name = "vp",
                                                         just = c("right", "top"))),
        action = "prepend")
pheatmap(mat, color = rev(brewer.pal(9, "RdBu")), breaks = breaks, main = "All CSTs", treeheight_row = 0, treeheight_col = 0,
         setHook("grid.newpage", NULL, "replace"))
grid.text("Sample", x = 0.39, y = -0.04, gp = gpar(fontsize = 16))
grid.text("Genus", x = -0.04, y = 0.47, rot = 90, gp = gpar(fontsize = 16))
```



12.5 Session Info

```
sessionInfo()
```

```
## R Under development (unstable) (2022-03-14 r81896)
```

```

## Platform: x86_64-pc-linux-gnu (64-bit)
## Running under: Ubuntu 20.04.4 LTS
##
## Matrix products: default
## BLAS/LAPACK: /usr/lib/x86_64-linux-gnu/openblas-pthread/libopenblas-p-r0.3.8.so
##
## locale:
##  [1] LC_CTYPE=en_US.UTF-8      LC_NUMERIC=C
##  [3] LC_TIME=en_US.UTF-8      LC_COLLATE=en_US.UTF-8
##  [5] LC_MONETARY=en_US.UTF-8  LC_MESSAGES=en_US.UTF-8
##  [7] LC_PAPER=en_US.UTF-8     LC_NAME=C
##  [9] LC_ADDRESS=C             LC_TELEPHONE=C
## [11] LC_MEASUREMENT=en_US.UTF-8 LC_IDENTIFICATION=C
##
## attached base packages:
## [1] grid      stats4      stats      graphics  grDevices  utils      datasets
## [8] methods  base
##
## other attached packages:
##  [1] ade4_1.7-19                plyr_1.8.7
##  [3] gridExtra_2.3             philentropy_0.6.0
##  [5] cowplot_1.1.1             scatter_1.23.6
##  [7] scuttle_1.5.2             cluster_2.1.3
##  [9] factoextra_1.0.7          RColorBrewer_1.1-3
## [11] pheatmap_1.0.12           miaViz_1.3.3
## [13] ggraph_2.0.5              ggplot2_3.3.5
## [15] mia_1.3.20                MultiAssayExperiment_1.21.7
## [17] TreeSummarizedExperiment_2.3.0 Biostrings_2.63.3
## [19] XVector_0.35.0            SingleCellExperiment_1.17.2
## [21] SummarizedExperiment_1.25.3 Biobase_2.55.2
## [23] GenomicRanges_1.47.6      GenomeInfoDb_1.31.10
## [25] IRanges_2.29.1            S4Vectors_0.33.17
## [27] BiocGenerics_0.41.2       MatrixGenerics_1.7.0
## [29] matrixStats_0.62.0
##
## loaded via a namespace (and not attached):
##  [1] backports_1.4.1           igraph_1.3.1
##  [3] lazyeval_0.2.2           splines_4.2.0
##  [5] BiocParallel_1.29.21     digest_0.6.29
##  [7] yulab.utils_0.0.4        htmltools_0.5.2
##  [9] viridis_0.6.2            fansi_1.0.3
## [11] magrittr_2.0.3           memoise_2.0.1
## [13] ScaledMatrix_1.3.0       DECIPHER_2.23.0
## [15] graphlayouts_0.8.0       colorspace_2.0-3
## [17] blob_1.2.3               ggrepel_0.9.1
## [19] xfun_0.30                dplyr_1.0.8
## [21] crayon_1.5.1             RCurl_1.98-1.6
## [23] jsonlite_1.8.0           ape_5.6-2
## [25] glue_1.6.2               polyclip_1.10-0
## [27] gtable_0.3.0             zlibbioc_1.41.0
## [29] DelayedArray_0.21.2      car_3.0-12

```

```

## [31] BiocSingular_1.11.0      abind_1.4-5
## [33] scales_1.2.0             DBI_1.1.2
## [35] rstatix_0.7.0           Rcpp_1.0.8.3
## [37] viridisLite_0.4.0       decontam_1.15.0
## [39] gridGraphics_0.5-1      tidytree_0.3.9
## [41] bit_4.0.4               rsvd_1.0.5
## [43] ellipsis_0.3.2          pkgconfig_2.0.3
## [45] farver_2.1.0            utf8_1.2.2
## [47] ggplotify_0.1.0         tidyselect_1.1.2
## [49] labeling_0.4.2          rlang_1.0.2
## [51] reshape2_1.4.4          munsell_0.5.0
## [53] tools_4.2.0             cachem_1.0.6
## [55] cli_3.2.0               DirichletMultinomial_1.37.0
## [57] generics_0.1.2          RSQLite_2.2.12
## [59] broom_0.8.0             evaluate_0.15
## [61] stringr_1.4.0           fastmap_1.1.0
## [63] yaml_2.3.5              ggtree_3.3.2
## [65] knitr_1.38              bit64_4.0.5
## [67] tidygraph_1.2.1         purrr_0.3.4
## [69] nlme_3.1-157            sparseMatrixStats_1.7.0
## [71] aplot_0.1.3             compiler_4.2.0
## [73] beeswarm_0.4.0          ggsignif_0.6.3
## [75] treeio_1.19.2           tibble_3.1.6
## [77] tweenr_1.0.2            stringi_1.7.6
## [79] highr_0.9               lattice_0.20-45
## [81] Matrix_1.4-1            vegan_2.6-2
## [83] permute_0.9-7           vctrs_0.4.1
## [85] pillar_1.7.0            lifecycle_1.0.1
## [87] BiocNeighbors_1.13.0    bitops_1.0-7
## [89] irlba_2.3.5             patchwork_1.1.1
## [91] R6_2.5.1                bookdown_0.26
## [93] vipor_0.4.5             MASS_7.3-57
## [95] assertthat_0.2.1        withr_2.5.0
## [97] GenomeInfoDbData_1.2.8  mgcv_1.8-40
## [99] parallel_4.2.0          ggfun_0.0.6
## [101] beachmat_2.11.0         tidyr_1.2.0
## [103] rmarkdown_2.13          DelayedMatrixStats_1.17.0
## [105] carData_3.0-5           ggpubr_0.4.0
## [107] ggnewscale_0.4.7        ggforce_0.3.3
## [109] ggbeeswarm_0.6.0

```

12.6 Bibliography

Robert L. Thorndike. 1953. “Who Belongs in the Family?”. *Psychometrika*. 18 (4): 267–276. doi:10.1007/BF02289263

Peter J. Rousseeuw. 1987. “Silhouettes: a Graphical Aid to the Interpretation and Validation of Cluster Analysis”. *Computational and Applied Mathematics*. 20: 53–65. doi:10.1016/0377-0427(87)90125-7.

Robert Tibshirani, Guenther Walther, and Trevor Hastie. 2002. Estimating the number of clusters in a data set via the gap statistic method. (63): 411-423. doi:10.1111/1467-9868.00293.

Susan Holmes and Joey McMurdie. 2015. Reproducible Research: Enterotype Example. <http://statweb.stanford.edu/~susan/papers/EnterotypeRR.html>.

Daniel B. DiGiulio et al. 2015. Temporal and spatial variation of the human microbiota during pregnancy. (112): 11060–11065. doi:10.1073/pnas.1502875112

Arumugam, M., et al. (2011). Enterotypes of the human gut microbiome.

Chapter 13

Exercise Solutions

This section includes exemplary solutions to the exercises presented earlier.

13.1 Section 5

Link:

- [Rmd](#)

13.2 Section 6

Links:

- [Rmd](#)

13.3 Section 7

Links:

- [Rmd](#)

13.4 Section 8

Links:

- [Rmd](#)

Chapter 14

Tutorial Aims

In this tutorial we will learn feature selection, dimension reduction, clustering, visualization, analysis and interpretation using `miaverse` (`mia` = `MI`crobiome `A`nalysis) and `miaViz` - (`MI`crobiome `A`nalysis `P`lotting and `V`isualization) to explore patterns in human gut microbiome datasets.

The examples in this tutorial are mainly based on this online book `Orchestrating Microbiome Analysis`

In this tutorial we use data from The Human Gut Microbiome Atlas (HGMA)

Chapter 15

Lab 1

15.1 unsupervised learning: Feature selection & dimension reduction

1. Make the tse (TreeSummarizedExperiment) Object for the further analysis (use the provided script to make a tse)

15.2 Load the data

2. Aggregate the data to Phylum level (agglomerateByRank)
 3. Subset the data at the Species level with only taking bacterial Species that are greater than 10% of prevalence in the total sample
 4. Subset a tse object which consist only two phyla i.e Actinobacteria”, “Cyanobacteria
 5. Calculate relative abundances, and store the table to assays
- 6.Perform a centred log-ratio transformation (clr) (i.e. mia::transformSamples)

Chapter 16

Lab 2

16.1 unsupervised learning: clustering & visualization

1. Visualize beta diversity using principal coordinate analysis (PCoA);based on the Bray-Curtis dissimilarities
2. Visualize beta diversity using principal coordinates analysis (PCoA); with Aitchison distance (clr transformation+ Euclidean distance)
3. Cluster the samples using Dirichlet- multinomial mixture model
4. Visualize the clusters in the PCoA plot

Chapter 17

Lab 3

17.1 unsupervised learning: Analysis and interpretation

1. What taxa are driving the axis? Calculate the Spearman correlation between PC1 and the relative abundance of the bacteria and visualize the results in a bar plot.
2. Visualize the dominant taxonomic group of each sample by colour on PCoA plot
3. Visualize gender by colour on PCoA plot

Bibliography

Borman, T., Hekkala, J., Reunanen, J., and Lahti, L. (2022). *Multi-omic data science with R/Bioconductor. Oulu Summer School.*