

Statistical Methods for Quantitative MS-based Proteomics: Part I. Preprocessing

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This is part of the online course [Proteomics Data Analysis \(PDA\)](#)

- [Playlist PDA Preprocessing](#)

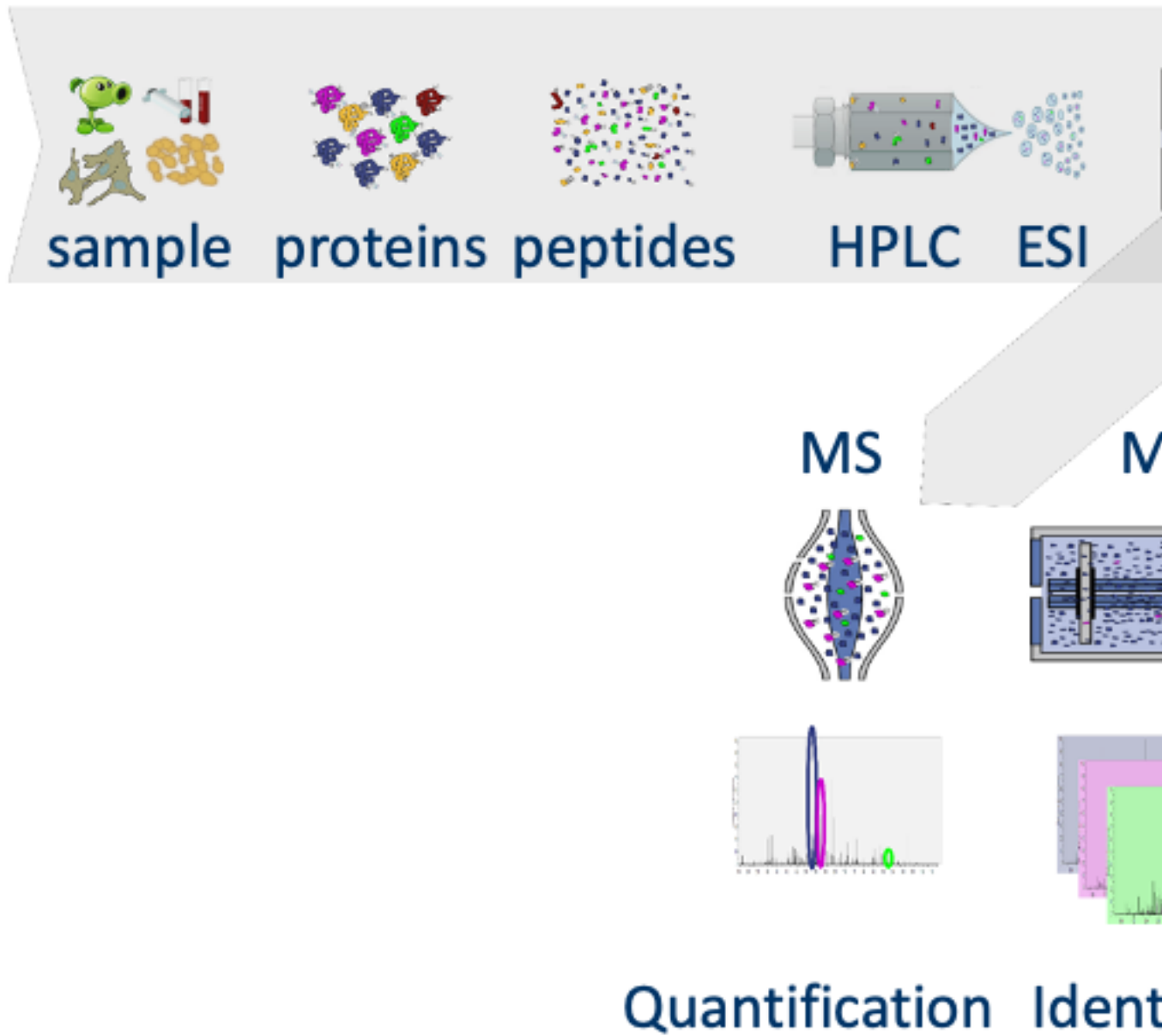
Outline

1. Introduction
2. Preprocessing
 - Log-transformation
 - Filtering
 - Normalization
 - Summarization

Note, that the R-code is included for learners who are aiming to develop R/markdown scripts to automate their quantitative proteomics data analyses. According to the target audience of the course we either work with a graphical user interface (GUI) in a R/shiny App `msqrob2gui` (e.g. Proteomics Bioinformatics course of the EBI and the Proteomics Data Analysis course at the Gulbenkian institute) or with R/markdowns scripts (e.g. Bioinformatics Summer School at UCLouvain or the Statistical Genomics Course at Ghent University).

1 Intro: Challenges in Label-Free Quantitative Proteomics

1.1 MS-based workflow



- Peptide Characteristics
 - Modifications

- Ionisation Efficiency: huge variability
- Identification
 - * Misidentification → outliers
 - * MS² selection on peptide abundance
 - * Context depending missingness
 - * Non-random missingness

→ Unbalanced peptide identifications across samples and messy data

1.2 Level of quantification

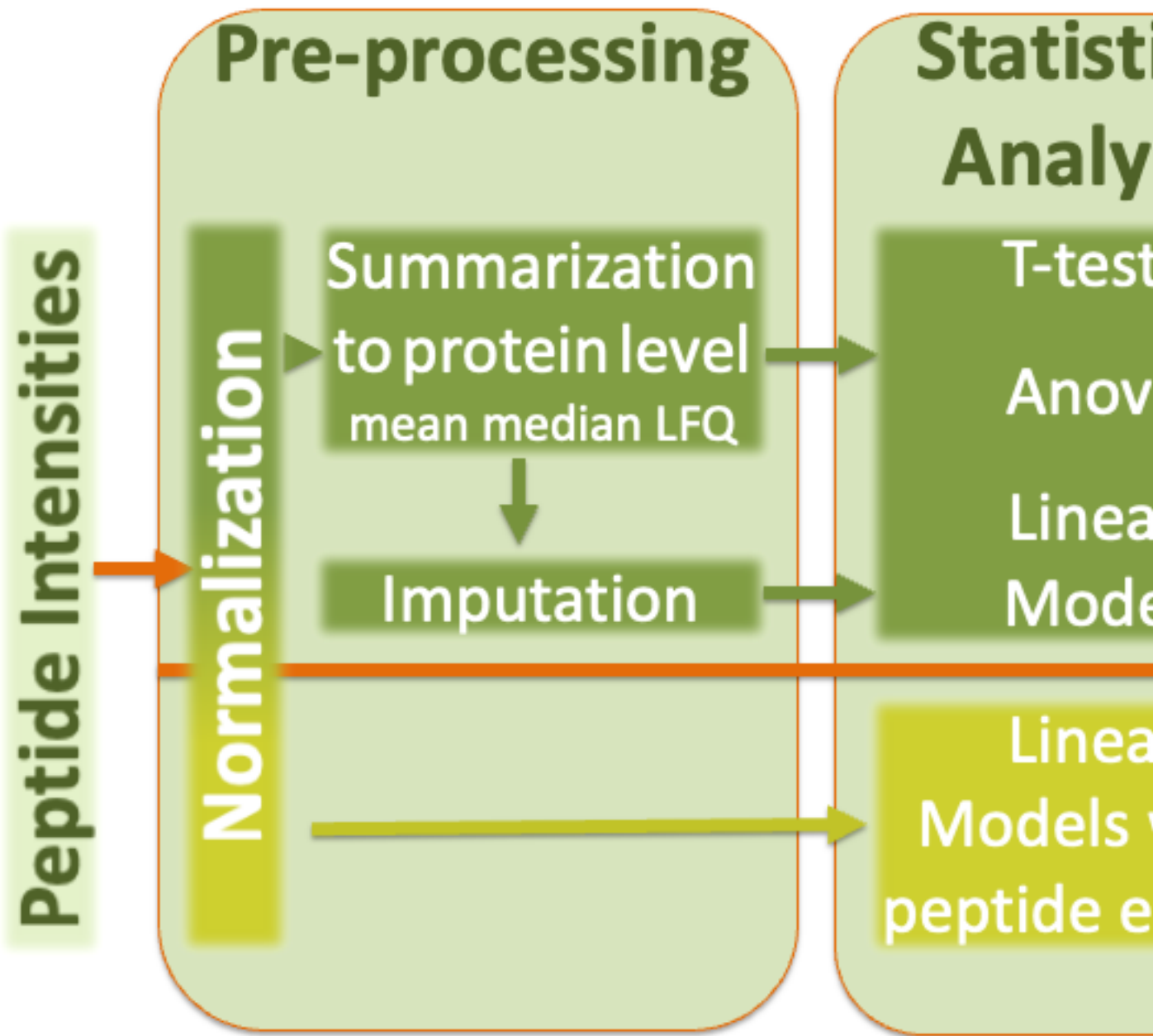
- MS-based proteomics returns peptides: pieces of proteins



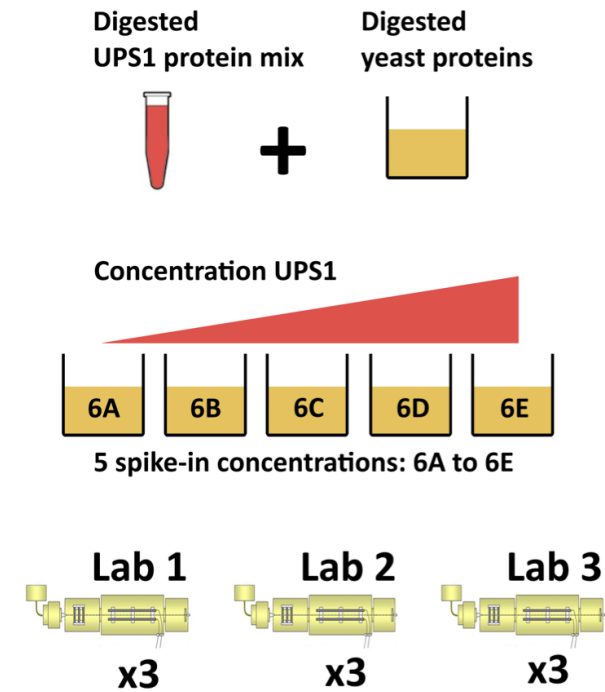
- Quantification commonly required on the protein level



1.3 Label-free Quantitative Proteomics Data Analysis Workflows



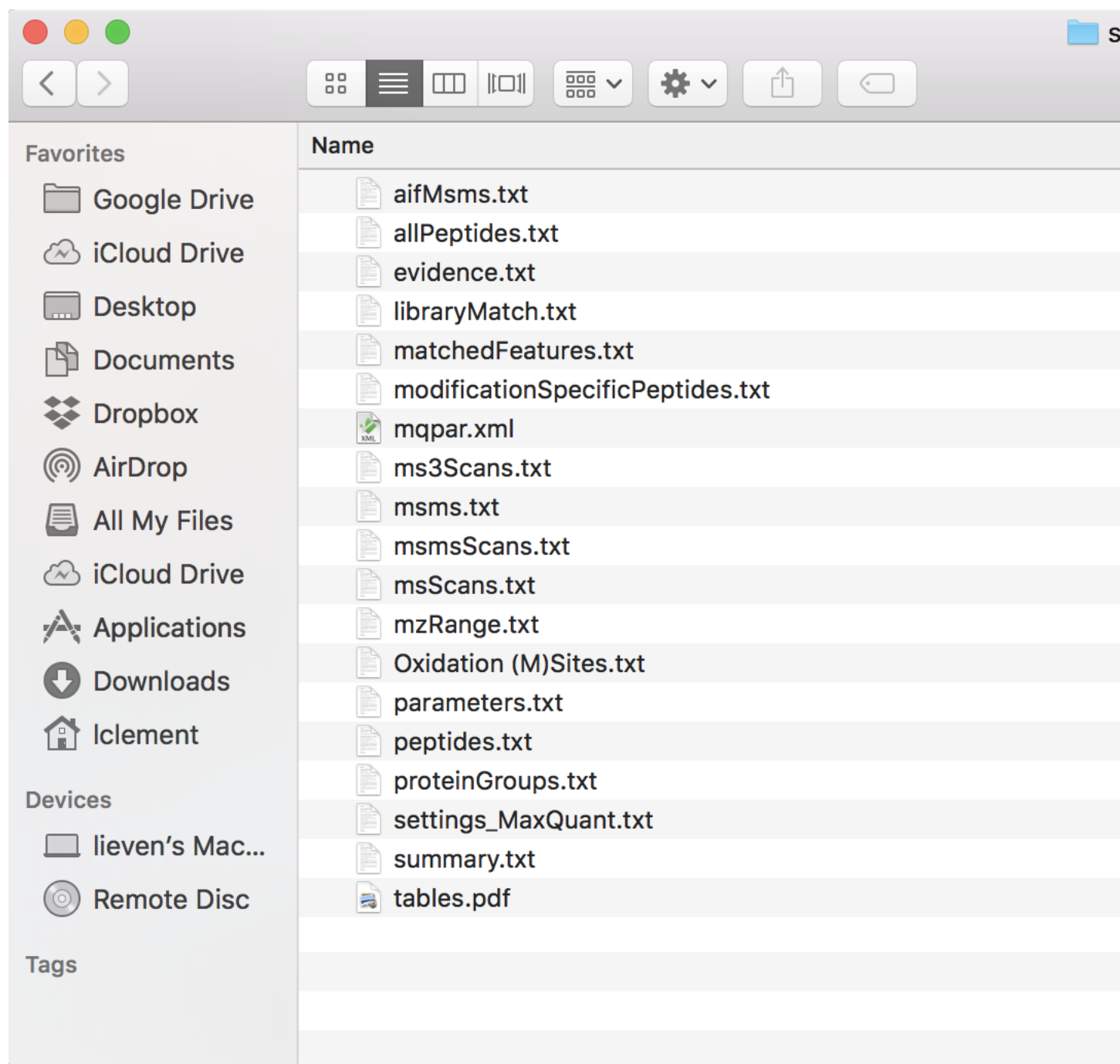
1.4 CPTAC Spike-in Study



- Same trypsin-digested yeast proteome background in each sample
- Trypsin-digested Sigma UPS1 standard: 48 different human proteins spiked in at 5 different concentrations (treatment A-E)
- Samples repeatedly run on different instruments in different labs
- After MaxQuant search with match between runs option
 - 41% of all proteins are quantified in all samples
 - 6.6% of all peptides are quantified in all samples

→ vast amount of missingness

1.5 Maxquant output



2 Import the data in R

2.1 Data infrastructure

Click to see background on data infrastructure used in R to store proteomics data

- We use the `QFeatures` package that provides the infrastructure to
 - store,
 - process,
 - manipulate and
 - analyse quantitative data/features from mass spectrometry experiments.
- It is based on the `SummarizedExperiment` and `MultiAssayExperiment` classes.
- Assays in a `QFeatures` object have a hierarchical relation:
 - proteins are composed of peptides,
 - themselves produced by spectra
 - relations between assays are tracked and recorded throughout data processing

2.2 Import data in R

2.2.1 Load libraries

Click to see code

```
library(tidyverse)
library(limma)
library(QFeatures)
library(msqrob2)
library(plotly)
library(ggplot2)
```

2.2.2 Read data

Click to see background and code

1. We use a `peptides.txt` file from MS-data quantified with `maxquant` that contains MS1 intensities summarized at the peptide level.

```
peptidesFile <- "https://raw.githubusercontent.com/statOmics/PDA22GTPB/data/quantification/fullCptacData"
```

2. `Maxquant` stores the intensity data for the different samples in columns that start with `Intensity`. We can retrieve the column names with the intensity data with the code below:

```
ecols <- grep("Intensity\\.", names(read.delim(peptidesFile)))
```

3. Read the data and store it in `QFeatures` object

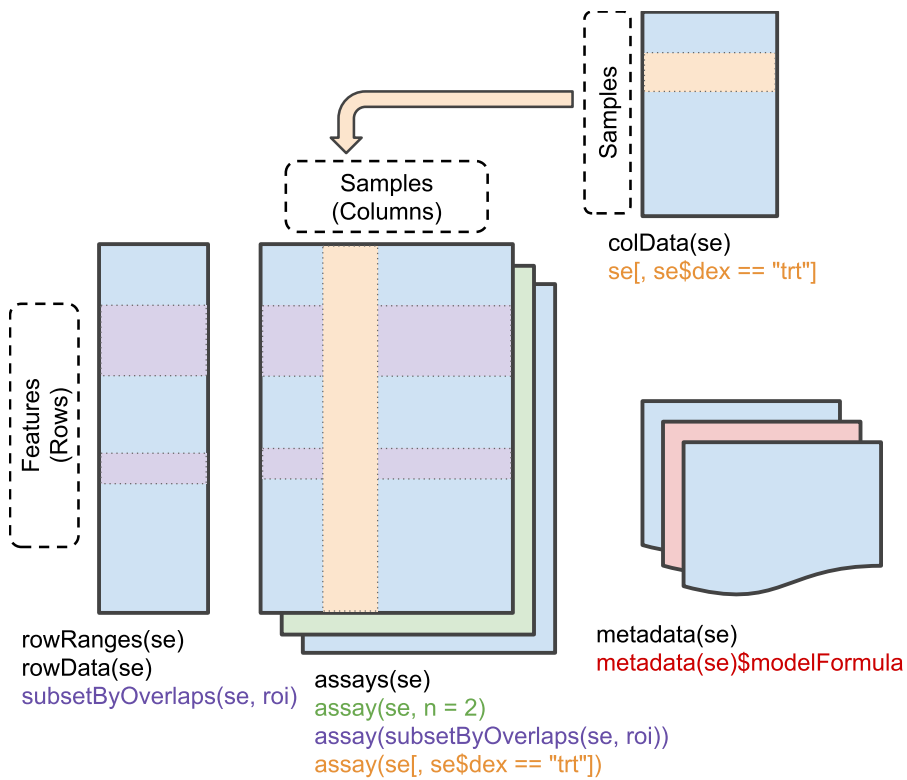


Figure 1: Conceptual representation of a ‘SummarizedExperiment’ object. Assays contain information on the measured omics features (rows) for different samples (columns). The ‘rowData’ contains information on the omics features, the ‘colData’ contains information on the samples, i.e. experimental design etc.

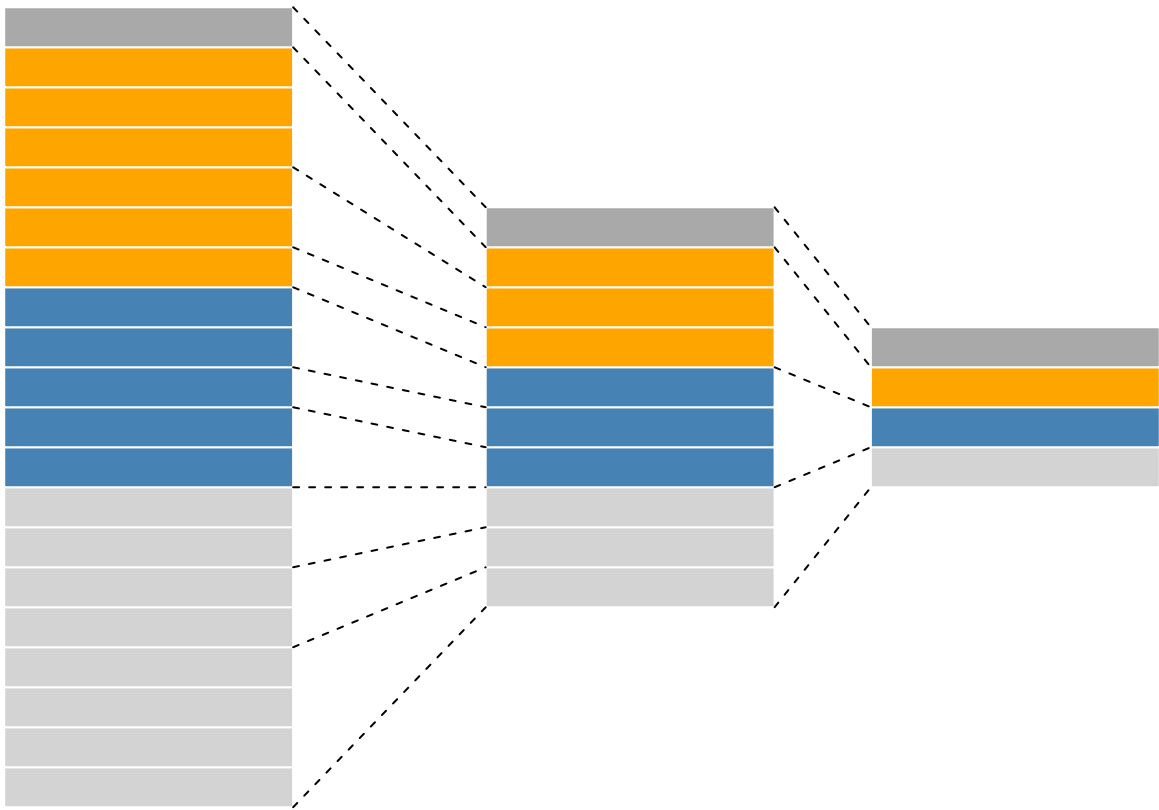


Figure 2: Conceptual representation of a `QFeatures` object and the aggregative relation between different assays.

```
pe <- readQFeatures(
  table = peptidesFile,
  fnames = 1,
  ecol = ecols,
  name = "peptideRaw", sep="\t")
```

2.2.3 Explore object

Click to see background and code

- The rowData contains information on the features (peptides) in the assay. E.g. Sequence, protein, ...

```
rowData(pe[["peptideRaw"]])
```

```
## DataFrame with 11466 rows and 143 columns
##           Sequence N.term.cleavage.window C.term.cleavage.window
##           <character>                 <character>                 <character>
## AAAAGAGGAGDSGDAVTK AAAAGAGGAG...           EHQHDEQKAA...           DSGDAVTKIG...
## AAAALAGGK           AAAALAGGK           QQLSKAAKAA...           AAALAGGKKS...
## AAAALAGGKK           AAAALAGGKK           QQLSKAAKAA...           AALAGGKKS...
## AAADALSDLEIK           AAADALSDLE...           MPKETPSKAA...           ALSDLEIKDS...
## AAADALSDLEIKDSK           AAADALSDLE...           MPKETPSKAA...           DLEIKDSKSN...
## ...           ...           ...           ...
## YYSIYDLGNNAVGLAK           YYSIYDLGNN...           VGDAFLRKYY...           NNAVGLAKAI...
## YYTFNGPNYNENETIR           YYTFNGPNYN...           FKDGSYPKYY...           YNENETIRHI...
## YYTITEVATR           YYTITEVATR           QEWDINERY...           TITEVATR...
## YYTVFDRDNNR           YYTVFDRDNN...           LGDVFIGRYY...           VFDRDNNRVG...
## YYTVFDRDNNRVGFAEAAAR           YYTVFDRDNN...           LGDVFIGRYY...           VGFAEAARL_...
##           Amino.acid.before First.amino.acid Second.amino.acid
##           <character>           <character>           <character>
## AAAAGAGGAGDSGDAVTK           K           A           A
## AAAALAGGK           K           A           A
## AAAALAGGKK           K           A           A
## AAADALSDLEIK           K           A           A
## AAADALSDLEIKDSK           K           A           A
## ...           ...           ...           ...
## YYSIYDLGNNAVGLAK           K           Y           Y
## YYTFNGPNYNENETIR           K           Y           Y
## YYTITEVATR           R           Y           Y
## YYTVFDRDNNR           R           Y           Y
## YYTVFDRDNNRVGFAEAAAR           R           Y           Y
##           Second.last.amino.acid Last.amino.acid Amino.acid.after
##           <character>           <character>           <character>
## AAAAGAGGAGDSGDAVTK           T           K           I
## AAAALAGGK           G           K           K
## AAAALAGGKK           K           K           S
## AAADALSDLEIK           I           K           D
## AAADALSDLEIKDSK           S           K           S
## ...           ...           ...           ...
## YYSIYDLGNNAVGLAK           A           K           A
## YYTFNGPNYNENETIR           I           R           H
## YYTITEVATR           T           R           A
```

	N			R		V	
	A			R		L	
##	A.Count	R.Count	N.Count	D.Count	C.Count	Q.Count	
##	<integer>	<integer>	<integer>	<integer>	<integer>	<integer>	
## AAAAGAGGAGDSGDAVTK	7	0	0	2	0	0	
## AAAALAGGK	5	0	0	0	0	0	
## AAAALAGGKK	5	0	0	0	0	0	
## AAADALSDLEIK	4	0	0	2	0	0	
## AAADALSDLEIKDSK	4	0	0	3	0	0	
##	
## YYSIYDLGNNAVGLAK	2	0	2	1	0	0	
## YYTFNGPNYNENETIR	0	1	4	0	0	0	
## YYTITEVATR	1	1	0	0	0	0	
## YYTVFDRDNNR	0	2	2	2	0	0	
## YYTVFDRDNNRVGFAEAAR	3	3	2	2	0	0	
##	E.Count	G.Count	H.Count	I.Count	L.Count	K.Count	
##	<integer>	<integer>	<integer>	<integer>	<integer>	<integer>	
## AAAAGAGGAGDSGDAVTK	0	5	0	0	0	1	
## AAAALAGGK	0	2	0	0	1	1	
## AAAALAGGKK	0	2	0	0	1	2	
## AAADALSDLEIK	1	0	0	1	2	1	
## AAADALSDLEIKDSK	1	0	0	1	2	2	
##	
## YYSIYDLGNNAVGLAK	0	2	0	1	2	1	
## YYTFNGPNYNENETIR	2	1	0	1	0	0	
## YYTITEVATR	1	0	0	1	0	0	
## YYTVFDRDNNR	0	0	0	0	0	0	
## YYTVFDRDNNRVGFAEAAR	1	1	0	0	0	0	
##	M.Count	F.Count	P.Count	S.Count	T.Count	W.Count	
##	<integer>	<integer>	<integer>	<integer>	<integer>	<integer>	
## AAAAGAGGAGDSGDAVTK	0	0	0	1	1	0	
## AAAALAGGK	0	0	0	0	0	0	
## AAAALAGGKK	0	0	0	0	0	0	
## AAADALSDLEIK	0	0	0	1	0	0	
## AAADALSDLEIKDSK	0	0	0	2	0	0	
##	
## YYSIYDLGNNAVGLAK	0	0	0	1	0	0	
## YYTFNGPNYNENETIR	0	1	1	0	2	0	
## YYTITEVATR	0	0	0	0	3	0	
## YYTVFDRDNNR	0	1	0	0	1	0	
## YYTVFDRDNNRVGFAEAAR	0	2	0	0	1	0	
##	Y.Count	V.Count	U.Count	Length	Missed.cleavages		
##	<integer>	<integer>	<integer>	<integer>	<integer>		
## AAAAGAGGAGDSGDAVTK	0	1	0	18	0		
## AAAALAGGK	0	0	0	9	0		
## AAAALAGGKK	0	0	0	10	1		
## AAADALSDLEIK	0	0	0	12	0		
## AAADALSDLEIKDSK	0	0	0	15	1		
##		
## YYSIYDLGNNAVGLAK	3	1	0	16	0		
## YYTFNGPNYNENETIR	3	0	0	16	0		
## YYTITEVATR	2	1	0	10	0		
## YYTVFDRDNNR	2	1	0	11	1		
## YYTVFDRDNNRVGFAEAAR	2	2	0	19	2		

##	Mass	Proteins	Leading.razor.protein
##	<numeric>	<character>	<character>
## AAAAGAGGAGDSGDAVTK	1445.675	sp P38915 ...	sp P38915 ...
## AAAALAGGK	728.418	sp Q3E792 ...	sp Q3E792 ...
## AAAALAGGKK	856.513	sp Q3E792 ...	sp Q3E792 ...
## AAADALSDLEIK	1215.635	sp P09938 ...	sp P09938 ...
## AAADALSDLEIKDSK	1545.789	sp P09938 ...	sp P09938 ...
##
## YYSIYDLGNNAVGLAK	1759.88	sp P07267 ...	sp P07267 ...
## YYTFNGPNYNENETIR	1993.88	sp Q00955 ...	sp Q00955 ...
## YYTITEVATR	1215.61	sp P38891 ...	sp P38891 ...
## YYTVFDRDNNR	1461.66	P07339ups ...	P07339ups ...
## YYTVFDRDNNRVGFAEAAR	2263.08	P07339ups ...	P07339ups ...
##	Start.position	End.position	Unique..Groups.
##	<integer>	<integer>	<character>
## AAAAGAGGAGDSGDAVTK	97	114	yes
## AAAALAGGK	13	21	yes
## AAAALAGGKK	13	22	yes
## AAADALSDLEIK	9	20	yes
## AAADALSDLEIKDSK	9	23	yes
##
## YYSIYDLGNNAVGLAK	388	403	yes
## YYTFNGPNYNENETIR	1275	1290	yes
## YYTITEVATR	311	320	yes
## YYTVFDRDNNR	225	235	yes
## YYTVFDRDNNRVGFAEAAR	225	243	yes
##	Unique..Proteins.	Charges	PEP
##	<character>	<character>	<numeric>
## AAAAGAGGAGDSGDAVTK	yes	2	1.1843e-05
## AAAALAGGK	no	2	7.4562e-06
## AAAALAGGKK	no	2	3.3094e-09
## AAADALSDLEIK	yes	2	9.1593e-23
## AAADALSDLEIKDSK	yes	3	1.5319e-04
##
## YYSIYDLGNNAVGLAK	yes	2	7.7415e-37
## YYTFNGPNYNENETIR	yes	2	4.2208e-21
## YYTITEVATR	yes	2	1.3566e-04
## YYTVFDRDNNR	yes	2	6.1425e-04
## YYTVFDRDNNRVGFAEAAR	yes	3	8.9859e-04
##	Score		
##	<numeric>		
## AAAAGAGGAGDSGDAVTK	82.942		
## AAAALAGGK	134.810		
## AAAALAGGKK	143.730		
## AAADALSDLEIK	182.230		
## AAADALSDLEIKDSK	73.927		
##		
## YYSIYDLGNNAVGLAK	174.240		
## YYTFNGPNYNENETIR	147.750		
## YYTITEVATR	109.160		
## YYTVFDRDNNR	110.930		
## YYTVFDRDNNRVGFAEAAR	59.728		
##	Identification.type.6A_1	Identification.type.6A_2	
##	<character>	<character>	
## AAAAGAGGAGDSGDAVTK	By matchin...	By MS/MS	
## AAAALAGGK	By matchin...	By matchin...	
## AAAALAGGKK	By matchin...	By matchin...	
## AAADALSDLEIK	By MS/MS	By MS/MS	
## AAADALSDLEIKDSK	By matchin...	By matchin...	
##	
## YYSIYDLGNNAVGLAK	By matchin...	By matchin...	
## YYTFNGPNYNENETIR	By matchin...	By matchin...	
## YYTITEVATR	By MS/MS	By matchin...	
## YYTVFDRDNNR	By matchin...	By matchin...	
## YYTVFDRDNNRVGFAEAAR	By matchin...	By matchin...	
##	Identification.type.6A_3	Identification.type.6A_4	
##	<character>	<character>	

```

## AAAAGAGGAGDSGDAVTK          By matchin...          By MS/MS
## AAAALAGGK                    By matchin...          By MS/MS
## AAAALAGGKK                   By matchin...          By MS/MS
## AAADALSDLEIK                 By matchin...          By MS/MS
## AAADALSDLEIKDSK              By matchin...          By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK           By matchin...          By MS/MS
## YYTFNGPNYNENETIR            By matchin...          By MS/MS
## YYTITEVATR                    By matchin...          By matchin...
## YYTVFDRDNNR                  By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR         By matchin...          By matchin...
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## AAAALAGGK                    By matchin...          By matchin...
## AAAALAGGKK                   By matchin...          By matchin...
## AAADALSDLEIK                 By MS/MS                By MS/MS
## AAADALSDLEIKDSK              By MS/MS                By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK           By MS/MS                By MS/MS
## YYTFNGPNYNENETIR            By MS/MS                By MS/MS
## YYTITEVATR                    By matchin...          By matchin...
## YYTVFDRDNNR                  By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR         By matchin...          By matchin...
##                               Identification.type.6A_7 Identification.type.6A_8
##                               <character>          <character>
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## AAAALAGGK                    By MS/MS                By MS/MS
## AAAALAGGKK                   By MS/MS                By MS/MS
## AAADALSDLEIK                 By MS/MS                By matchin...
## AAADALSDLEIKDSK              By MS/MS                By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK           By matchin...          By matchin...
## YYTFNGPNYNENETIR            By matchin...          By matchin...
## YYTITEVATR                    By MS/MS                By matchin...
## YYTVFDRDNNR                  By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR         By matchin...          By matchin...
##                               Identification.type.6A_9 Identification.type.6B_1
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK          By MS/MS                By matchin...
## AAAALAGGK                    By MS/MS                By MS/MS
## AAAALAGGKK                   By MS/MS                By matchin...
## AAADALSDLEIK                 By MS/MS                By MS/MS
## AAADALSDLEIKDSK              By MS/MS                By matchin...
## ...                          ...
## YYSIYDLGNNNAVGLAK           By matchin...          By matchin...
## YYTFNGPNYNENETIR            By matchin...          By matchin...
## YYTITEVATR                    By matchin...          By MS/MS
## YYTVFDRDNNR                  By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR         By matchin...          By matchin...
##                               Identification.type.6B_2 Identification.type.6B_3
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK          By matchin...          By matchin...
## AAAALAGGK                    By matchin...          By matchin...

```

```

## AAAALAGGKK                               By MS/MS                               By MS/MS
## AAADALSDLEIK                             By MS/MS                               By matchin...
## AAADALSDLEIKDSK                           By matchin...                           By matchin...
## ...                                         ...                                     ...
## YYSIYDLGNNNAVGLAK                         By matchin...                           By matchin...
## YYTFNGPNYNENETIR                          By matchin...                           By matchin...
## YYTITEVATR                                By matchin...                           By matchin...
## YYTVFDRDNNR                               By matchin...                           By matchin...
## YYTVFDRDNNRVGFAEAAR                       By matchin...                           By matchin...
## Identification.type.6B_4 Identification.type.6B_5
## <character>                               <character>
## AAAAGAGGAGDSGDAVTK                       By matchin...                           By matchin...
## AAAALAGGK                                 By matchin...                           By matchin...
## AAAALAGGKK                                By matchin...                           By matchin...
## AAADALSDLEIK                             By MS/MS                               By MS/MS
## AAADALSDLEIKDSK                           By MS/MS                               By MS/MS
## ...                                         ...                                     ...
## YYSIYDLGNNNAVGLAK                         By MS/MS                               By matchin...
## YYTFNGPNYNENETIR                          By MS/MS                               By MS/MS
## YYTITEVATR                                By MS/MS                               By MS/MS
## YYTVFDRDNNR                               By matchin...                           By matchin...
## YYTVFDRDNNRVGFAEAAR                       By matchin...                           By matchin...
## Identification.type.6B_6 Identification.type.6B_7
## <character>                               <character>
## AAAAGAGGAGDSGDAVTK                       By matchin...                           By matchin...
## AAAALAGGK                                 By matchin...                           By MS/MS
## AAAALAGGKK                                By matchin...                           By MS/MS
## AAADALSDLEIK                             By MS/MS                               By MS/MS
## AAADALSDLEIKDSK                           By MS/MS                               By MS/MS
## ...                                         ...                                     ...
## YYSIYDLGNNNAVGLAK                         By matchin...                           By matchin...
## YYTFNGPNYNENETIR                          By MS/MS                               By matchin...
## YYTITEVATR                                By matchin...                           By matchin...
## YYTVFDRDNNR                               By matchin...                           By matchin...
## YYTVFDRDNNRVGFAEAAR                       By matchin...                           By matchin...
## Identification.type.6B_8 Identification.type.6B_9
## <character>                               <character>
## AAAAGAGGAGDSGDAVTK                       By MS/MS                               By MS/MS
## AAAALAGGK                                 By MS/MS                               By MS/MS
## AAAALAGGKK                                By MS/MS                               By MS/MS
## AAADALSDLEIK                             By matchin...                           By matchin...
## AAADALSDLEIKDSK                           By MS/MS                               By MS/MS
## ...                                         ...                                     ...
## YYSIYDLGNNNAVGLAK                         By matchin...                           By matchin...
## YYTFNGPNYNENETIR                          By matchin...                           By matchin...
## YYTITEVATR                                By MS/MS                               By matchin...
## YYTVFDRDNNR                               By matchin...                           By matchin...
## YYTVFDRDNNRVGFAEAAR                       By matchin...                           By matchin...
## Identification.type.6C_1 Identification.type.6C_2
## <character>                               <character>
## AAAAGAGGAGDSGDAVTK                       By matchin...                           By matchin...
## AAAALAGGK                                 By matchin...                           By MS/MS
## AAAALAGGKK                                By matchin...                           By MS/MS
## AAADALSDLEIK                             By MS/MS                               By matchin...

```

```

## AAADALSDLEIKDSK          By matchin...          By matchin...
## ...                      ...                      ...
## YYSIYDLGNNAVGLAK        By matchin...          By matchin...
## YYTFNGPNYNENETIR        By matchin...          By matchin...
## YYTITEVATR               By matchin...          By matchin...
## YYTVFDRDNNR             By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR     By matchin...          By matchin...
## Identification.type.6C_3  Identification.type.6C_4
## <character>              <character>
## AAAAGAGGAGDSGDAVTK      By matchin...          By matchin...
## AAAALAGGK                By matchin...          By MS/MS
## AAAALAGGK                By matchin...          By MS/MS
## AAADALSDLEIK            By MS/MS                By MS/MS
## AAADALSDLEIKDSK         By matchin...          By MS/MS
## ...                      ...                      ...
## YYSIYDLGNNAVGLAK        By matchin...          By MS/MS
## YYTFNGPNYNENETIR        By matchin...          By MS/MS
## YYTITEVATR               By MS/MS                By matchin...
## YYTVFDRDNNR             By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR     By matchin...          By matchin...
## Identification.type.6C_5  Identification.type.6C_6
## <character>              <character>
## AAAAGAGGAGDSGDAVTK      By MS/MS                By matchin...
## AAAALAGGK                By matchin...          By matchin...
## AAAALAGGK                By matchin...          By matchin...
## AAADALSDLEIK            By MS/MS                By MS/MS
## AAADALSDLEIKDSK         By MS/MS                By MS/MS
## ...                      ...                      ...
## YYSIYDLGNNAVGLAK        By MS/MS                By MS/MS
## YYTFNGPNYNENETIR        By matchin...          By matchin...
## YYTITEVATR               By matchin...          By matchin...
## YYTVFDRDNNR             By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR     By matchin...          By matchin...
## Identification.type.6C_7  Identification.type.6C_8
## <character>              <character>
## AAAAGAGGAGDSGDAVTK      By MS/MS                By matchin...
## AAAALAGGK                By MS/MS                By MS/MS
## AAAALAGGK                By MS/MS                By MS/MS
## AAADALSDLEIK            By matchin...          By MS/MS
## AAADALSDLEIKDSK         By MS/MS                By MS/MS
## ...                      ...                      ...
## YYSIYDLGNNAVGLAK        By matchin...          By matchin...
## YYTFNGPNYNENETIR        By matchin...          By matchin...
## YYTITEVATR               By matchin...          By MS/MS
## YYTVFDRDNNR             By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR     By matchin...          By matchin...
## Identification.type.6C_9  Identification.type.6D_1
## <character>              <character>
## AAAAGAGGAGDSGDAVTK      By matchin...          By matchin...
## AAAALAGGK                By MS/MS                By matchin...
## AAAALAGGK                By MS/MS                By matchin...
## AAADALSDLEIK            By MS/MS                By MS/MS
## AAADALSDLEIKDSK         By MS/MS                By MS/MS
## ...                      ...                      ...

```



```

## YYSIYDLGNNNAVGLAK          By matchin...          By matchin...
## YYTFNGPNYNENETIR          By matchin...          By matchin...
## YYTITEVATR                  By MS/MS              By matchin...
## YYTVFDRDNNR                By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR       By matchin...          By matchin...
##                               Identification.type.6D_2 Identification.type.6D_3
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK        By matchin...          By matchin...
## AAAALAGGK                   By matchin...          By matchin...
## AAAALAGGK                   By matchin...          By matchin...
## AAADALSDLEIK               By matchin...          By matchin...
## AAADALSDLEIKDSK            By MS/MS              By matchin...
## ...                          ...
## YYSIYDLGNNNAVGLAK          By matchin...          By matchin...
## YYTFNGPNYNENETIR          By matchin...          By matchin...
## YYTITEVATR                  By MS/MS              By MS/MS
## YYTVFDRDNNR                By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR       By matchin...          By matchin...
##                               Identification.type.6D_4 Identification.type.6D_5
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK        By matchin...          By matchin...
## AAAALAGGK                   By matchin...          By matchin...
## AAAALAGGK                   By MS/MS              By matchin...
## AAADALSDLEIK               By MS/MS              By MS/MS
## AAADALSDLEIKDSK            By MS/MS              By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK          By MS/MS              By MS/MS
## YYTFNGPNYNENETIR          By MS/MS              By MS/MS
## YYTITEVATR                  By matchin...          By matchin...
## YYTVFDRDNNR                By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR       By matchin...          By matchin...
##                               Identification.type.6D_6 Identification.type.6D_7
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK        By MS/MS              By matchin...
## AAAALAGGK                   By matchin...          By MS/MS
## AAAALAGGK                   By matchin...          By MS/MS
## AAADALSDLEIK               By MS/MS              By matchin...
## AAADALSDLEIKDSK            By matchin...          By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK          By MS/MS              By matchin...
## YYTFNGPNYNENETIR          By MS/MS              By matchin...
## YYTITEVATR                  By matchin...          By matchin...
## YYTVFDRDNNR                By matchin...          By MS/MS
## YYTVFDRDNNRVGFAEAAR       By matchin...          By matchin...
##                               Identification.type.6D_8 Identification.type.6D_9
##                               <character>          <character>
## AAAAGAGGAGDSGDAVTK        By matchin...          By matchin...
## AAAALAGGK                   By MS/MS              By MS/MS
## AAAALAGGK                   By MS/MS              By MS/MS
## AAADALSDLEIK               By MS/MS              By MS/MS
## AAADALSDLEIKDSK            By MS/MS              By MS/MS
## ...                          ...
## YYSIYDLGNNNAVGLAK          By matchin...          By matchin...
## YYTFNGPNYNENETIR          By matchin...          By matchin...

```

```

## YYTITEVATR                By MS/MS                By matchin...
## YYTVFDRDNNR               By MS/MS                By matchin...
## YYTVFDRDNNRVGFAEAAR      By matchin...          By matchin...
##                               Identification.type.6E_1 Identification.type.6E_2
##                               <character>           <character>
## AAAAGAGGAGDSGDAVTK       By matchin...          By matchin...
## AAAALAGGK                 By matchin...          By matchin...
## AAAALAGGK                 By matchin...          By matchin...
## AAADALSDLEIK             By MS/MS                By MS/MS
## AAADALSDLEIKDSK          By MS/MS                By MS/MS
## ...                       ...
## YYSIYDLGNNNAVGLAK        By matchin...          By matchin...
## YYTFNGPNYNENETIR         By matchin...          By matchin...
## YYTITEVATR                By matchin...          By matchin...
## YYTVFDRDNNR               By matchin...          By matchin...
## YYTVFDRDNNRVGFAEAAR      By matchin...          By matchin...
##                               Identification.type.6E_3 Identification.type.6E_4
##                               <character>           <character>
## AAAAGAGGAGDSGDAVTK       By matchin...          By matchin...
## AAAALAGGK                 By matchin...          By MS/MS
## AAAALAGGK                 By matchin...          By matchin...
## AAADALSDLEIK             By matchin...          By MS/MS
## AAADALSDLEIKDSK          By MS/MS                By matchin...
## ...                       ...
## YYSIYDLGNNNAVGLAK        By matchin...          By MS/MS
## YYTFNGPNYNENETIR         By matchin...          By MS/MS
## YYTITEVATR                By matchin...          By matchin...
## YYTVFDRDNNR               By matchin...          By MS/MS
## YYTVFDRDNNRVGFAEAAR      By matchin...          By matchin...
##                               Identification.type.6E_5 Identification.type.6E_6
##                               <character>           <character>
## AAAAGAGGAGDSGDAVTK       By matchin...          By matchin...
## AAAALAGGK                 By matchin...          By matchin...
## AAAALAGGK                 By matchin...          By matchin...
## AAADALSDLEIK             By MS/MS                By matchin...
## AAADALSDLEIKDSK          By MS/MS                By MS/MS
## ...                       ...
## YYSIYDLGNNNAVGLAK        By MS/MS                By MS/MS
## YYTFNGPNYNENETIR         By MS/MS                By MS/MS
## YYTITEVATR                By matchin...          By matchin...
## YYTVFDRDNNR               By MS/MS                By matchin...
## YYTVFDRDNNRVGFAEAAR      By matchin...          By MS/MS
##                               Identification.type.6E_7 Identification.type.6E_8
##                               <character>           <character>
## AAAAGAGGAGDSGDAVTK       By matchin...          By matchin...
## AAAALAGGK                 By MS/MS                By MS/MS
## AAAALAGGK                 By MS/MS                By MS/MS
## AAADALSDLEIK             By MS/MS                By MS/MS
## AAADALSDLEIKDSK          By matchin...          By MS/MS
## ...                       ...
## YYSIYDLGNNNAVGLAK        By matchin...          By matchin...
## YYTFNGPNYNENETIR         By matchin...          By matchin...
## YYTITEVATR                By matchin...          By matchin...
## YYTVFDRDNNR               By MS/MS                By MS/MS

```

```

## YYTVFDRDNNRVGFAEAAR          By matchin...          By matchin...
##                               Identification.type.6E_9 Experiment.6A_1 Experiment.6A_2
##                               <character>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          By matchin...          NA          1
## AAAALAGGK                    By MS/MS          NA          1
## AAAALAGGKK                   By MS/MS          NA          1
## AAADALSDLEIK                By MS/MS          1          1
## AAADALSDLEIKDSK            By MS/MS          1          1
## ...                          ...          ...          ...
## YYSIYDLGNNNAVGLAK          By matchin...          NA          NA
## YYTFNGPNYNENETIR           By MS/MS          NA          NA
## YYTITEVATR                   By matchin...          1          NA
## YYTVFDRDNNR                 By MS/MS          NA          NA
## YYTVFDRDNNRVGFAEAAR          By matchin...          NA          NA
##                               Experiment.6A_3 Experiment.6A_4 Experiment.6A_5
##                               <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          NA          1          1
## AAAALAGGK                    2          1          1
## AAAALAGGKK                   NA          1          NA
## AAADALSDLEIK                1          1          1
## AAADALSDLEIKDSK            NA          1          1
## ...                          ...          ...          ...
## YYSIYDLGNNNAVGLAK          NA          1          1
## YYTFNGPNYNENETIR           NA          1          1
## YYTITEVATR                   1          NA          NA
## YYTVFDRDNNR                 NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##                               Experiment.6A_6 Experiment.6A_7 Experiment.6A_8
##                               <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          1          1          1
## AAAALAGGK                    1          2          1
## AAAALAGGKK                   1          1          1
## AAADALSDLEIK                1          1          1
## AAADALSDLEIKDSK            1          1          1
## ...                          ...          ...          ...
## YYSIYDLGNNNAVGLAK          1          NA          NA
## YYTFNGPNYNENETIR           1          1          NA
## YYTITEVATR                   1          1          NA
## YYTVFDRDNNR                 NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##                               Experiment.6A_9 Experiment.6B_1 Experiment.6B_2
##                               <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          1          NA          NA
## AAAALAGGK                    1          1          1
## AAAALAGGKK                   1          NA          1
## AAADALSDLEIK                1          1          1
## AAADALSDLEIKDSK            1          NA          1
## ...                          ...          ...          ...
## YYSIYDLGNNNAVGLAK          NA          NA          NA
## YYTFNGPNYNENETIR           1          NA          NA
## YYTITEVATR                   NA          1          1
## YYTVFDRDNNR                 NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##                               Experiment.6B_3 Experiment.6B_4 Experiment.6B_5

```

```

##          <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          NA          NA          1
## AAAALAGGK          1          2          1
## AAAALAGGK          1          1          NA
## AAADALSDLEIK          1          1          1
## AAADALSDLEIKDSK          NA          1          1
## ...          ...          ...          ...
## YYSIYDLGNNAVGLAK          NA          1          1
## YYTFNGPNYNENETIR          NA          1          1
## YTTITEVATR          1          1          1
## YYTVFDRDNNR          NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##          Experiment.6B_6 Experiment.6B_7 Experiment.6B_8
##          <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          1          NA          1
## AAAALAGGK          NA          2          1
## AAAALAGGK          NA          1          1
## AAADALSDLEIK          1          1          1
## AAADALSDLEIKDSK          1          1          1
## ...          ...          ...          ...
## YYSIYDLGNNAVGLAK          1          NA          NA
## YYTFNGPNYNENETIR          1          1          NA
## YTTITEVATR          1          NA          1
## YYTVFDRDNNR          NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##          Experiment.6B_9 Experiment.6C_1 Experiment.6C_2
##          <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          1          NA          NA
## AAAALAGGK          2          NA          1
## AAAALAGGK          1          NA          1
## AAADALSDLEIK          1          1          1
## AAADALSDLEIKDSK          1          1          1
## ...          ...          ...          ...
## YYSIYDLGNNAVGLAK          NA          NA          NA
## YYTFNGPNYNENETIR          NA          NA          NA
## YTTITEVATR          NA          1          1
## YYTVFDRDNNR          NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##          Experiment.6C_3 Experiment.6C_4 Experiment.6C_5
##          <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          NA          1          1
## AAAALAGGK          2          2          NA
## AAAALAGGK          NA          1          NA
## AAADALSDLEIK          1          1          1
## AAADALSDLEIKDSK          1          1          1
## ...          ...          ...          ...
## YYSIYDLGNNAVGLAK          NA          1          1
## YYTFNGPNYNENETIR          NA          1          1
## YTTITEVATR          1          1          NA
## YYTVFDRDNNR          NA          NA          NA
## YYTVFDRDNNRVGFAEAAR          NA          NA          NA
##          Experiment.6C_6 Experiment.6C_7 Experiment.6C_8
##          <integer>          <integer>          <integer>
## AAAAGAGGAGDSGDAVTK          1          1          1

```

## AAAALAGGK	NA	2	1
## AAAALAGGKK	NA	1	1
## AAADALSDLEIK	1	1	1
## AAADALSDLEIKDSK	1	1	1
##
## YYSIYDLGNNAVGLAK	1	NA	NA
## YYTFNGPNYNENETIR	1	1	1
## YYTITEVATR	1	NA	1
## YYTVFDRDNNR	1	NA	1
## YYTVFDRDNNRVGFAEAAR	NA	NA	NA
##	Experiment.6C_9	Experiment.6D_1	Experiment.6D_2
##	<integer>	<integer>	<integer>
## AAAAGAGGAGDSGDAVTK	1	NA	NA
## AAAALAGGK	1	NA	1
## AAAALAGGKK	1	NA	NA
## AAADALSDLEIK	1	1	1
## AAADALSDLEIKDSK	1	1	1
##
## YYSIYDLGNNAVGLAK	NA	NA	NA
## YYTFNGPNYNENETIR	1	NA	NA
## YYTITEVATR	1	NA	1
## YYTVFDRDNNR	NA	NA	NA
## YYTVFDRDNNRVGFAEAAR	NA	NA	NA
##	Experiment.6D_3	Experiment.6D_4	Experiment.6D_5
##	<integer>	<integer>	<integer>
## AAAAGAGGAGDSGDAVTK	NA	1	1
## AAAALAGGK	1	1	1
## AAAALAGGKK	NA	1	NA
## AAADALSDLEIK	1	1	1
## AAADALSDLEIKDSK	1	1	1
##
## YYSIYDLGNNAVGLAK	NA	1	1
## YYTFNGPNYNENETIR	NA	1	1
## YYTITEVATR	1	1	1
## YYTVFDRDNNR	NA	1	1
## YYTVFDRDNNRVGFAEAAR	NA	1	NA
##	Experiment.6D_6	Experiment.6D_7	Experiment.6D_8
##	<integer>	<integer>	<integer>
## AAAAGAGGAGDSGDAVTK	1	1	NA
## AAAALAGGK	NA	2	1
## AAAALAGGKK	NA	1	1
## AAADALSDLEIK	1	1	1
## AAADALSDLEIKDSK	1	1	1
##
## YYSIYDLGNNAVGLAK	1	1	NA
## YYTFNGPNYNENETIR	1	1	1
## YYTITEVATR	1	NA	1
## YYTVFDRDNNR	1	1	1
## YYTVFDRDNNRVGFAEAAR	NA	NA	NA
##	Experiment.6D_9	Experiment.6E_1	Experiment.6E_2
##	<integer>	<integer>	<integer>
## AAAAGAGGAGDSGDAVTK	NA	NA	1
## AAAALAGGK	2	NA	1
## AAAALAGGKK	1	NA	NA

```

## AAADALSDLEIK          1          1          1
## AAADALSDLEIKDSK      1          1          1
## ...                   ...         ...         ...
## YYSIYDLGNNAVGLAK    NA         NA         NA
## YYTFNGPNYNENETIR    1          NA         NA
## YYTITEVATR           NA         NA          1
## YYTVFDRDNNR         1          1         NA
## YYTVFDRDNNRVGFAEAAR NA         NA         NA
## Experiment.6E_3 Experiment.6E_4 Experiment.6E_5
## <integer>           <integer>           <integer>
## AAAAGAGGAGDSGDAVTK  NA         NA          1
## AAAALAGGK            2          2          1
## AAAALAGGKK          NA         1          NA
## AAADALSDLEIK        1          1          1
## AAADALSDLEIKDSK    1          1          1
## ...                   ...         ...         ...
## YYSIYDLGNNAVGLAK    1          1          1
## YYTFNGPNYNENETIR    NA         1          1
## YYTITEVATR           1          1          1
## YYTVFDRDNNR         1          1          1
## YYTVFDRDNNRVGFAEAAR NA         1          1
## Experiment.6E_6 Experiment.6E_7 Experiment.6E_8
## <integer>           <integer>           <integer>
## AAAAGAGGAGDSGDAVTK  1          NA         NA
## AAAALAGGK            NA         2          2
## AAAALAGGKK          NA         1          1
## AAADALSDLEIK        1          1          1
## AAADALSDLEIKDSK    1          NA         1
## ...                   ...         ...         ...
## YYSIYDLGNNAVGLAK    1          NA         NA
## YYTFNGPNYNENETIR    1          1          1
## YYTITEVATR           NA         NA         NA
## YYTVFDRDNNR         1          1          1
## YYTVFDRDNNRVGFAEAAR 1          1          1
## Experiment.6E_9 Intensity Reverse Potential.contaminant
## <integer> <numeric> <character> <character>
## AAAAGAGGAGDSGDAVTK  NA 1190800
## AAAALAGGK            1 280990000
## AAAALAGGKK          1 333600000
## AAADALSDLEIK        1 546220000
## AAADALSDLEIKDSK    1 189100000
## ...                   ...         ...         ...
## YYSIYDLGNNAVGLAK    NA 2145900
## YYTFNGPNYNENETIR    1 5608800
## YYTITEVATR           NA 13034000
## YYTVFDRDNNR         1 8702500
## YYTVFDRDNNRVGFAEAAR 1 2391100
## id Protein.group.IDs Mod..peptide.IDs Evidence.IDs
## <integer> <character> <character> <character>
## AAAAGAGGAGDSGDAVTK  0 859 0 0;1;2;3;4;...
## AAAALAGGK            1 230 1 24;25;26;2...
## AAAALAGGKK          2 230 2 74;75;76;7...
## AAADALSDLEIK        3 229 3 99;100;101...
## AAADALSDLEIKDSK    4 229 4 144;145;14...

```

```

## ...
## YYSIYDLGNNAVGLAK      11461      196      12240 331367;331...
## YYTFNGPNYNENETIR     11462     1254      12241 331384;331...
## YYTITEVATR            11463      854      12242 331411;331...
## YYTVFDRDNNR          11464       34      12243 331439;331...
## YYTVFDRDNNRVGFAEAAR  11465       34      12244 331455;331...
##
##           MS.MS.IDs Best.MS.MS Oxidation..M..site.IDs MS.MS.Count
##           <character> <integer>           <character>   <integer>
## AAAAGAGGAGDSGDAVTK  0;1;2;3;4;...           0                10
## AAAALAGGK           10;11;12;1...           21               18
## AAAALAGGKK          30;31;32;3...           31               21
## AAADALSLEIK         51;52;53;5...           72               29
## AAADALSLEIKDSK      85;86;87;8...           94               32
## ...
## YYSIYDLGNNAVGLAK    169138;169...      169147            13
## YYTFNGPNYNENETIR   169151;169...      169159            14
## YYTITEVATR          169165;169...      169173            12
## YYTVFDRDNNR         169177;169...      169180             7
## YYTVFDRDNNRVGFAEAAR 169184            169184             1

```

- The colData contains information on the samples

```
colData(pe)
```

```
## DataFrame with 45 rows and 0 columns
```

- No information is stored yet on the design.

```
pe %>% colnames
```

```
## CharacterList of length 1
## [["peptideRaw"]] Intensity.6A_1 Intensity.6A_2 ... Intensity.6E_9
```

- Note, that the sample names include the spike-in condition.
- They also end on a number.
 - 1-3 is from lab 1,
 - 4-6 from lab 2 and
 - 7-9 from lab 3.
- We update the colData with information on the design

```
colData(pe)$lab <- rep(rep(paste0("lab",1:3),each=3),5) %>% as.factor
colData(pe)$condition <- pe[["peptideRaw"]] %>% colnames %>% substr(12,12) %>% as.factor
colData(pe)$spikeConcentration <- rep(c(A = 0.25, B = 0.74, C = 2.22, D = 6.67, E = 20),each = 9)
```

- We explore the colData again

```
colData(pe)
```

```
## DataFrame with 45 rows and 3 columns
##           lab condition spikeConcentration
##           <factor> <factor>           <numeric>
## Intensity.6A_1  lab1      A             0.25
## Intensity.6A_2  lab1      A             0.25
## Intensity.6A_3  lab1      A             0.25
## Intensity.6A_4  lab2      A             0.25
## Intensity.6A_5  lab2      A             0.25
## ...           ...      ...           ...
## Intensity.6E_5  lab2      E             20
## Intensity.6E_6  lab2      E             20
## Intensity.6E_7  lab3      E             20
## Intensity.6E_8  lab3      E             20
## Intensity.6E_9  lab3      E             20
```

3 Preprocessing

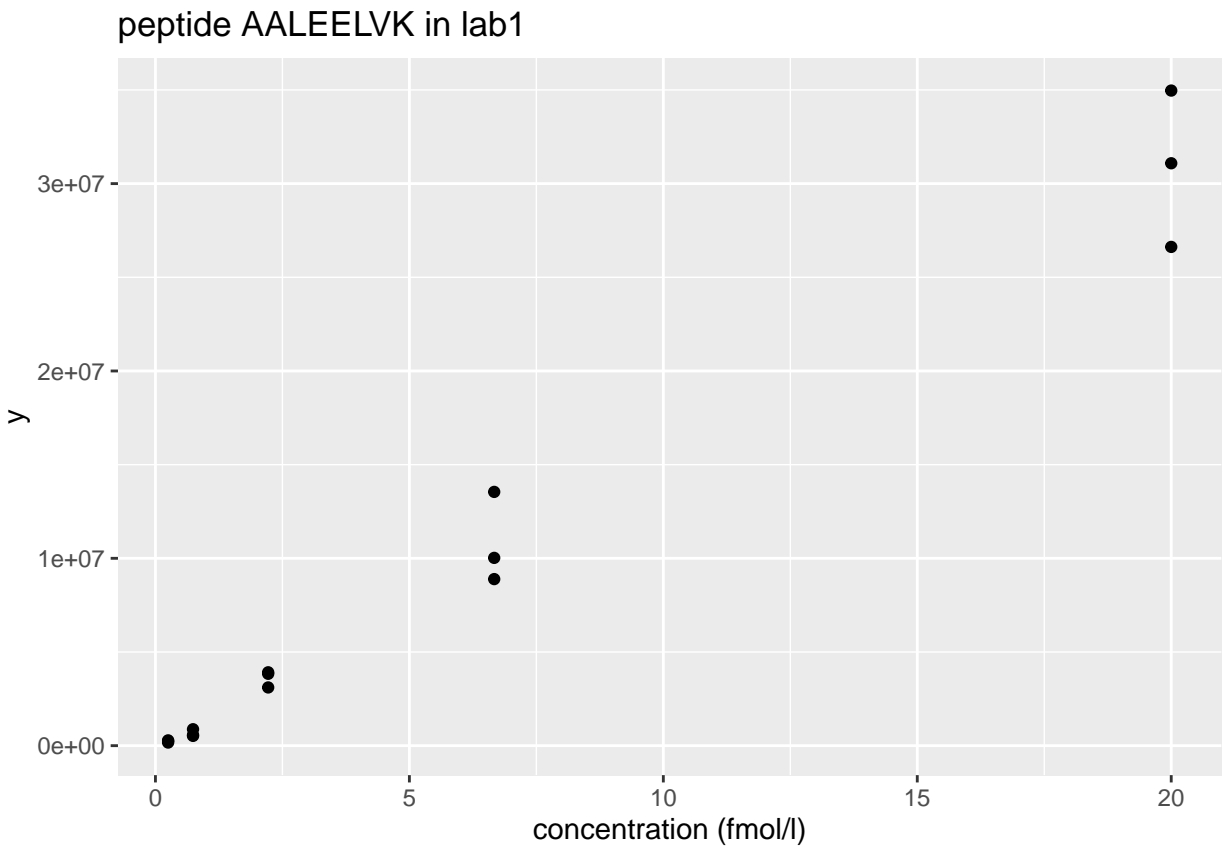
3.1 Log-transformation

3.1.1 Explore the data with plots

Peptide AALEELVK from spiked-in UPS protein P12081. We only show data from lab1.

[Click to see code to make plot](#)

```
subset <- pe["AALEELVK", colData(pe)$lab=="lab1"]
plotWhyLog <- data.frame(concentration = colData(subset)$spikeConcentration,
  y = assay(subset[["peptideRaw"]]) %>% c
) %>%
  ggplot(aes(concentration, y)) +
  geom_point() +
  xlab("concentration (fmol/l)") +
  ggtitle("peptide AALEELVK in lab1")
```

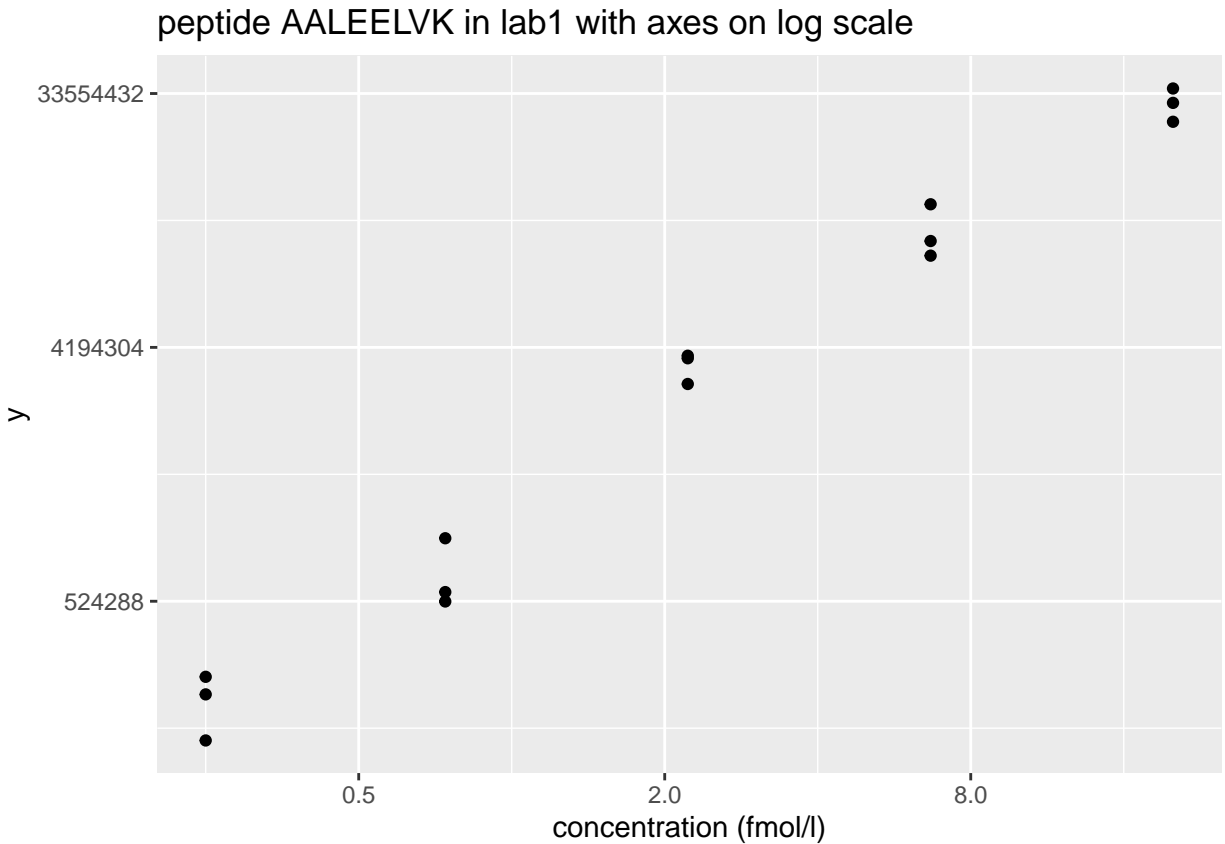



- Variance increases with the mean → Multiplicative error structure

Click to see code to make plot

```
plotLog <- data.frame(concentration = colData(subset)$spikeConcentration,
  y = assay(subset[["peptideRaw"]]) %>% c
) %>%
ggplot(aes(concentration, y)) +
  geom_point() +
  scale_x_continuous(trans='log2') +
  scale_y_continuous(trans='log2') +
  xlab("concentration (fmol/l)") +
  ggtitle("peptide AALEELVK in lab1 with axes on log scale")
```

plotLog



- Data seems to be homoscedastic on log-scale → log transformation of the intensity data
- In quantitative proteomics analysis on \log_2

→ Differences on a \log_2 scale: \log_2 fold changes

$$\log_2 B - \log_2 A = \log_2 \frac{B}{A} = \log FC_{B-A}$$

$$\log_2 FC = 1 \rightarrow FC = 2^1 = 2$$

$$\log_2 FC = 2 \rightarrow FC = 2^2 = 4$$

3.1.2 log-transformation of the data

Click to see code to log-transfrom the data

- We calculate how many non zero intensities we have for each peptide and this can be useful for filtering.

```
rowData(pe[["peptideRaw"]])$nNonZero <- rowSums(assay(pe[["peptideRaw"]]) > 0)
```

- Peptides with zero intensities are missing peptides and should be represent with a NA value rather than 0.

```
pe <- zeroIsNA(pe, "peptideRaw") # convert 0 to NA
```

- Logtransform data with base 2

```
pe <- logTransform(pe, base = 2, i = "peptideRaw", name = "peptideLog")
```

3.2 Filtering

- Reverse sequences
- Only identified by modification site (only modified peptides detected)
- Razor peptides: non-unique peptides assigned to the protein group with the most other peptides
- Contaminants
- Peptides few identifications
- Proteins that are only identified with one or a few peptides

Filtering does not induce bias if the criterion is independent from the downstream data analysis!

Click to see code to filter the data

1. Handling overlapping protein groups

In our approach a peptide can map to multiple proteins, as long as there is none of these proteins present in a smaller subgroup.

```
pe <- filterFeatures(pe, ~ Proteins %in% smallestUniqueGroups(rowData(pe[["peptideLog"]])$Proteins))
```

2. Remove reverse sequences (decoys) and contaminants

We now remove the contaminants, peptides that map to decoy sequences, and proteins which were only identified by peptides with modifications.

```
pe <- filterFeatures(pe, ~Reverse != "+")  
pe <- filterFeatures(pe, ~ Potential.contaminant != "+")
```

3. Drop peptides that were only identified in one sample

We keep peptides that were observed at last twice.

```
pe <- filterFeatures(pe, ~ nNonZero >=2)  
nrow(pe[["peptideLog"]])
```

```
## [1] 10478
```

We keep 10478 peptides upon filtering.

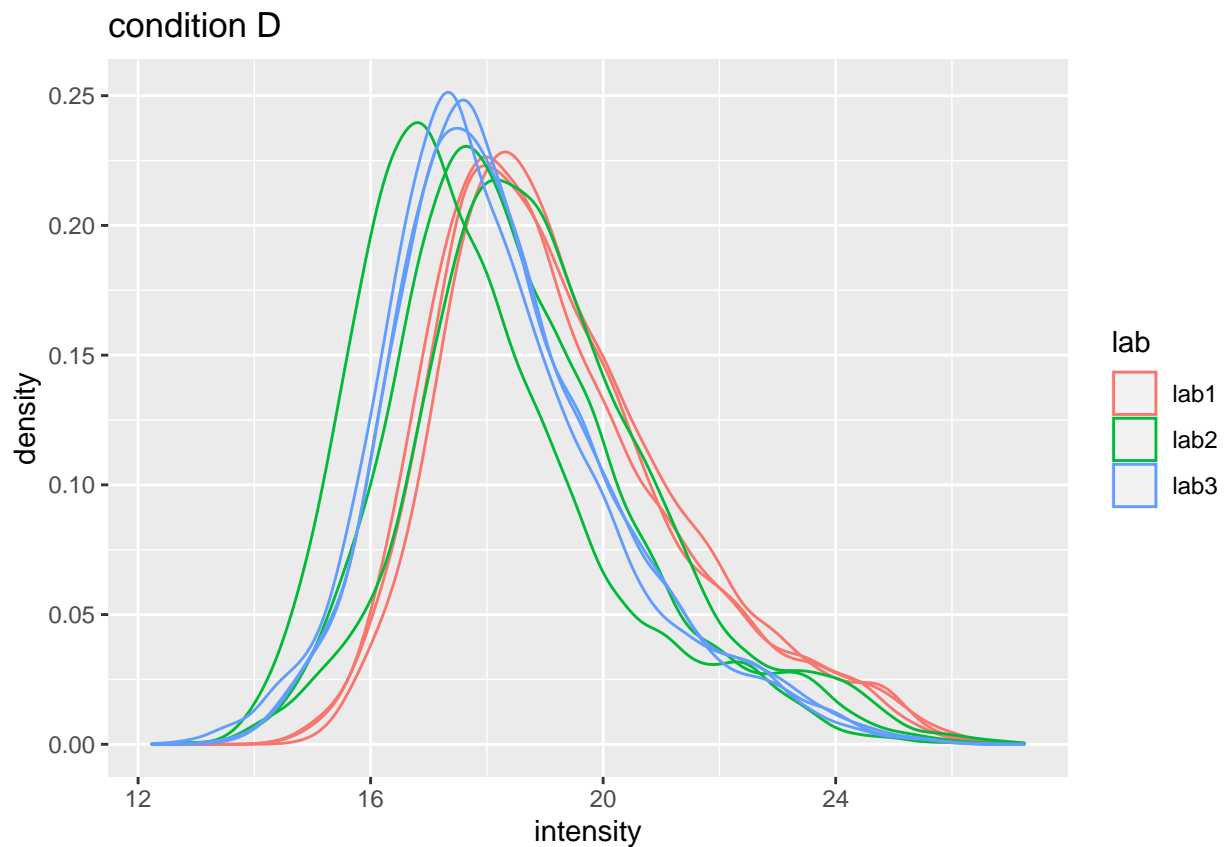
3.3 Normalization

Click to see code to make plot

```
densityConditionD <- pe[["peptideLog"]][,colData(pe)$condition=="D"] %>%  
  assay %>%  
  as.data.frame() %>%  
  gather(sample, intensity) %>%  
  mutate(lab = colData(pe)[sample,"lab"]) %>%  
  ggplot(aes(x=intensity,group=sample,color=lab)) +  
    geom_density() +  
    ggtitle("condition D")  
  
densityLab2 <- pe[["peptideLog"]][,colData(pe)$lab=="lab2"] %>%  
  assay %>%  
  as.data.frame() %>%  
  gather(sample, intensity) %>%  
  mutate(condition = colData(pe)[sample,"condition"]) %>%  
  ggplot(aes(x=intensity,group=sample,color=condition)) +  
    geom_density() +  
    ggtitle("lab2")
```

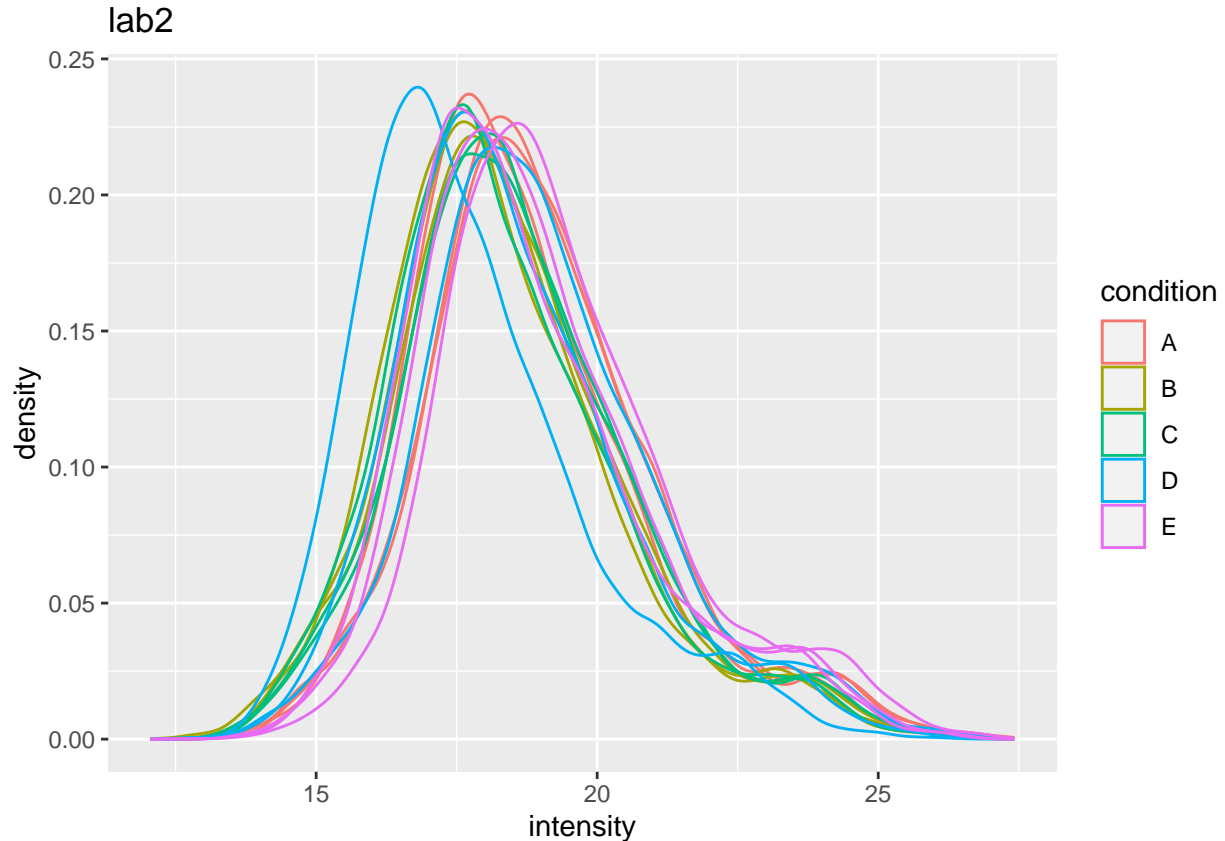
```
densityConditionD
```

```
## Warning: Removed 39179 rows containing non-finite values (stat_density).
```



densityLab2

```
## Warning: Removed 44480 rows containing non-finite values (stat_density).
```



- Even in very clean synthetic dataset (same background, only 48 UPS proteins can be different) the marginal peptide intensity distribution across samples can be quite distinct

- Considerable effects between and within labs for replicate samples
- Considerable effects between samples with different spike-in concentration

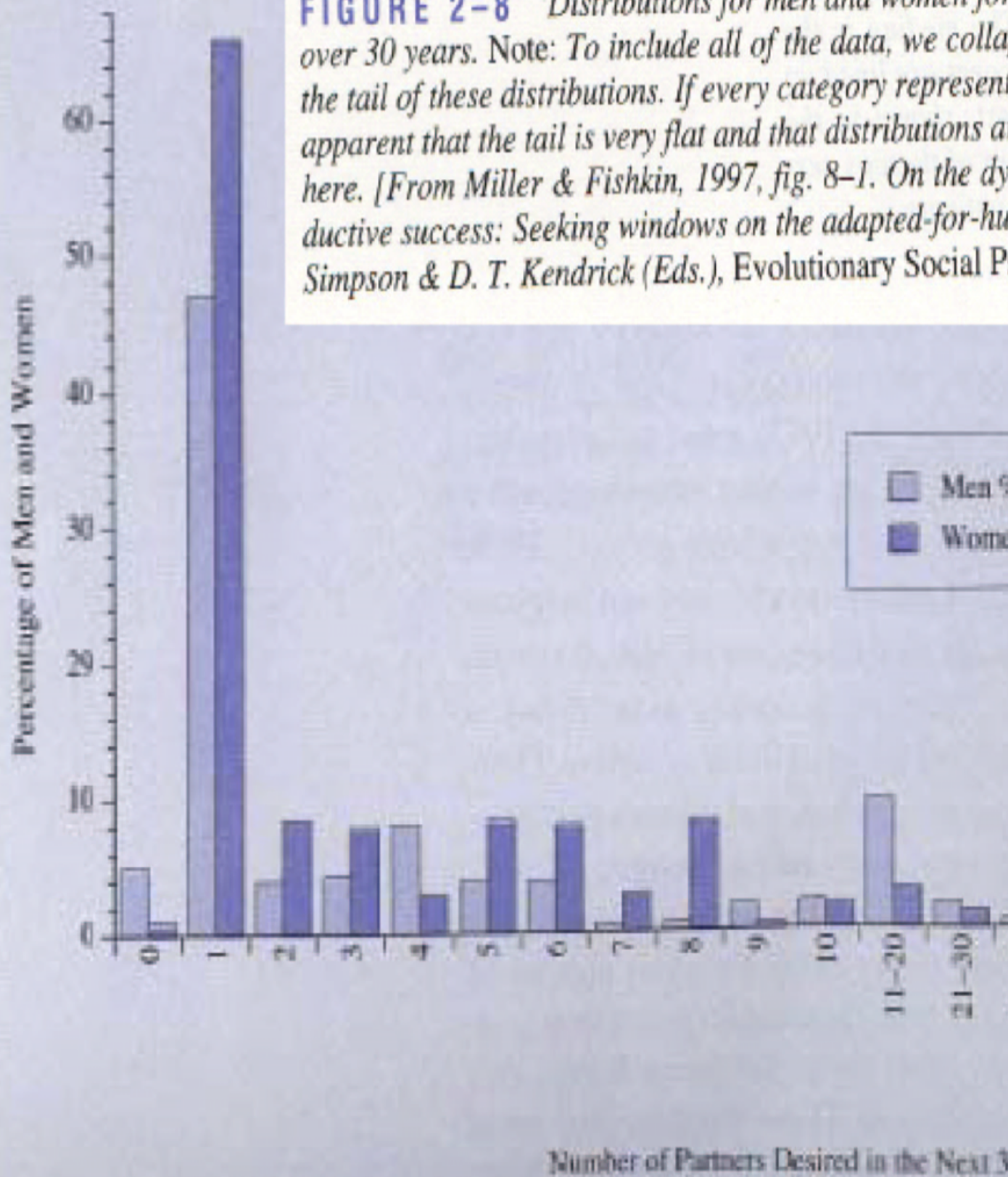
→ Normalization is needed

3.3.1 Mean or median?

- Miller and Fishkin (1997) reported that over a period of 30 years males would like to have on average 64.3 partners and females 2.8.
- Miller and Fishkin (1997) reported that the median number of partners someone would like to have over a period of 30 years males is 1 for both males and females.

Mean is very sensitive to outliers!

FIGURE 2-8 Distributions for men and women for over 30 years. Note: To include all of the data, we collate the tail of these distributions. It is apparent that the tail is very flat and that distributions are different here. [From Miller & Fishkin, 1997, fig. 8-1. On the dynamics of reproductive success: Seeking windows on the adapted-for-humans. In J. Simpson & D. T. Kendrick (Eds.), *Evolutionary Social Psychology*]



3.3.2 Normalization of the data by median centering

$$y_{ip}^{\text{norm}} = y_{ip} - \hat{\mu}_i$$

with $\hat{\mu}_i$ the median intensity over all observed peptides in sample i .

[Click to see R-code to normalize the data](#)

```
pe <- normalize(pe,
  i = "peptideLog",
  name = "peptideNorm",
  method = "center.median")
```

3.3.3 Plots of normalized data

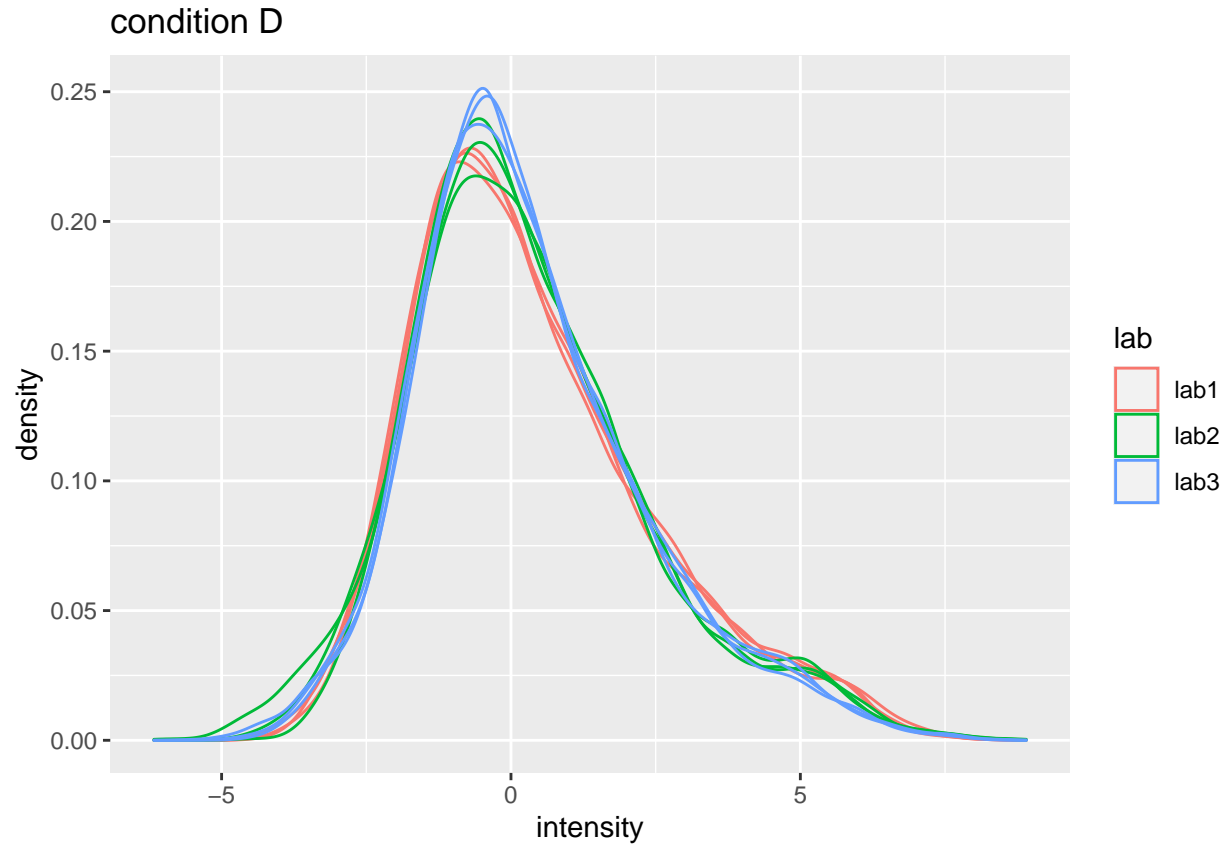
[Click to see code to make plot](#)

```
densityConditionDNorm <- pe[["peptideNorm"]][,colData(pe)$condition=="D"] %>%
  assay %>%
  as.data.frame() %>%
  gather(sample, intensity) %>%
  mutate(lab = colData(pe)[sample,"lab"]) %>%
  ggplot(aes(x=intensity,group=sample,color=lab)) +
  geom_density() +
  ggtitle("condition D")

densityLab2Norm <- pe[["peptideNorm"]][,colData(pe)$lab=="lab2"] %>%
  assay %>%
  as.data.frame() %>%
  gather(sample, intensity) %>%
  mutate(condition = colData(pe)[sample,"condition"]) %>%
  ggplot(aes(x=intensity,group=sample,color=condition)) +
  geom_density() +
  ggtitle("lab2")
```

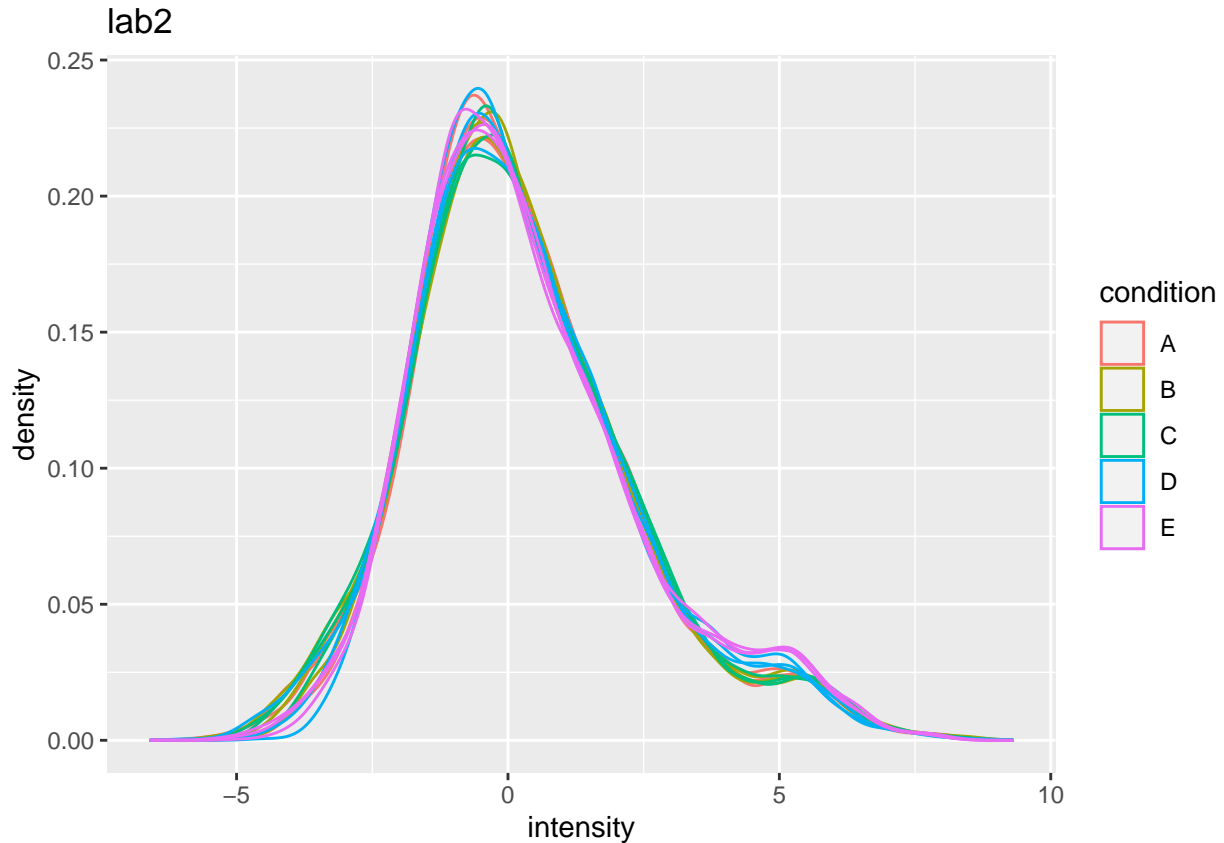
```
densityConditionDNorm
```

```
## Warning: Removed 39179 rows containing non-finite values (stat_density).
```



```
densityLab2Norm
```

```
## Warning: Removed 44480 rows containing non-finite values (stat_density).
```

- Upon normalization the marginal distributions of the peptide intensities across samples are much more comparable
- We still see deviations
- This can be due to technical variability
- In micro-array literature, quantile normalisation is used to force the median and all other quantiles to be equal across samples
- In proteomics quantile normalisation often introduces artifacts due to a difference in missing peptides across samples
- More advanced methods should be developed for normalizing proteomics data
- If there are differences in the width of the marginal distributions of the data across samples. They can also be standardized by using a robust estimator for location and scale, i.e.

$$y_{ip}^{\text{norm}} = \frac{y_{ip} - \mu_i}{s_i}$$

3.4 Summarization

- We illustrate summarization issues using a subset of the cptac study (Lab 2, condition A and E) for a spiked protein (UPS P12081).

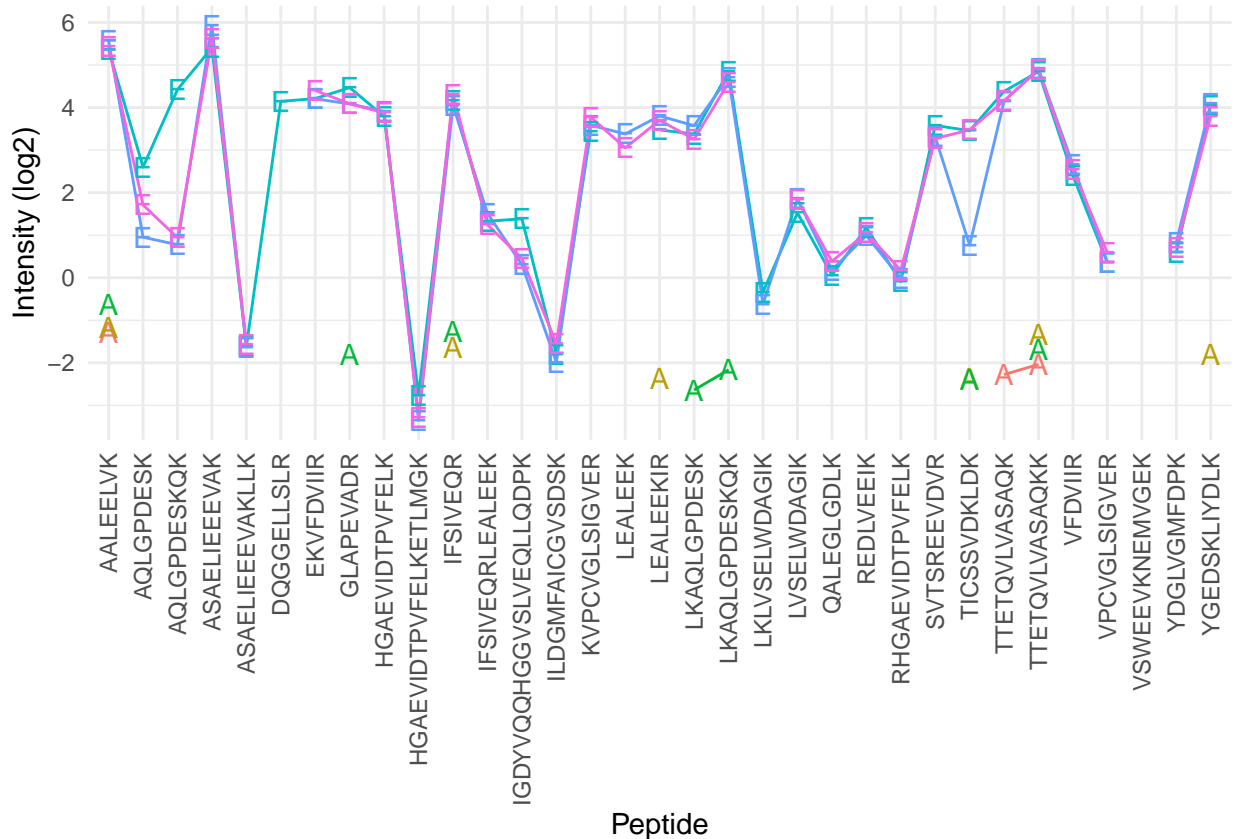
[Click to see code to make plot](#)

```
summaryPlot <- pe[["peptideNorm"]][
  rowData(pe[["peptideNorm"]])$Proteins == "P12081ups|SYHC_HUMAN_UPS",
  colData(pe)$lab=="lab2"&colData(pe)$condition %in% c("A","E")] %>%
  assay %>%
  as.data.frame %>%
  rownames_to_column(var = "peptide") %>%
  gather(sample, intensity, -peptide) %>%
  mutate(condition = colData(pe)[sample,"condition"]) %>%
  ggplot(aes(x = peptide, y = intensity, color = sample, group = sample, label = condition), show.legend = FALSE) +
  geom_line(show.legend = FALSE) +
  geom_text(show.legend = FALSE) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 90, vjust = 0.5, hjust = 1)) +
  xlab("Peptide") +
  ylab("Intensity (log2)")
```

summaryPlot

Warning: Removed 10 row(s) containing missing values (geom_path).

Warning: Removed 90 rows containing missing values (geom_text).



We observe:

- intensities from multiple peptides for each protein in a sample

- Strong peptide effect -Unbalanced peptide identification
- Pseudo-replication: peptide intensities from a particular protein in the same sample are correlated, i.e. they more alike than peptide intensities from a particular protein between samples.

→ Summarize all peptide intensities from the same protein in a sample into a single protein expression value

Commonly used methods are

- Mean summarization

$$y_{ip} = \beta_i^{\text{samp}} + \epsilon_{ip}$$

- Median summarization
- Maxquant's maxLFQ summarization (in protein groups file)
- Model based summarization:

$$y_{ip} = \beta_i^{\text{samp}} + \beta_p^{\text{pep}} + \epsilon_{ip}$$

Click to see R-code to normalize the data

We use the standard summarization in `aggregateFeatures`, which is robust model based summarization.

```
pe <- aggregateFeatures(pe,
  i = "peptideNorm",
  fcol = "Proteins",
  na.rm = TRUE,
  name = "protein")
```

```
## Your quantitative and row data contain missing values. Please read the
## relevant section(s) in the aggregateFeatures manual page regarding the
## effects of missing values on data aggregation.
```

Other summarization methods can be implemented by using the `fun` argument in the `aggregateFeatures` function.

- `fun = MsCoreUtils::medianPolish()` to fits an additive model (two way decomposition) using Tukey's median polish_ procedure using `stats::medpolish()`
- `fun = MsCoreUtils::robustSummary()` to calculate a robust aggregation using `MASS::rlm()` (default)
- `fun = base::colMeans()` to use the mean of each column
- `fun = matrixStats::colMedians()` to use the median of each column
- `fun = base::colSums()` to use the sum of each column

4 Exercise

1. We will evaluate different summarization methods (Maxquant maxLFQ, median and robust model based) in the tutorial session before discussing on their advantages/disadvantages.
2. Can you anticipate on potential problems related to the summarization?

5 Software & code

- Our R/Bioconductor package [msqrob2](#) can be used in R markdown scripts or with a GUI/shinyApp in the [msqrob2gui](#) package.
- The GUI is intended as a introduction to the key concepts of proteomics data analysis for users who have no experience in R.
- However, learning how to code data analyses in R markdown scripts is key for open en reproducible science and for reporting your proteomics data analyses and interpretation in a reproducible way.
- More information on our tools can be found in our papers (L. J. Goeminne, Gevaert, and Clement 2016), (L. J. E. Goeminne et al. 2020) and (Sticker et al. 2020). Please refer to our work when using our tools.

5.1 Code

1. Data infrastructure
2. Import proteomics data
3. Preprocessing
 - Log-transformation
 - Filtering
 - Normalisation
 - Summarization

5.2 Data analysis with the GUI/shinyApp msqrob2gui

References

- Goeminne, L. J. E., A. Sticker, L. Martens, K. Gevaert, and L. Clement. 2020. “MSqRob Takes the Missing Hurdle: Uniting Intensity- and Count-Based Proteomics.” *Anal Chem* 92 (9): 6278–87.
- Goeminne, L. J., K. Gevaert, and L. Clement. 2016. “Peptide-level Robust Ridge Regression Improves Estimation, Sensitivity, and Specificity in Data-dependent Quantitative Label-free Shotgun Proteomics.” *Mol Cell Proteomics* 15 (2): 657–68.
- Sticker, A., L. Goeminne, L. Martens, and L. Clement. 2020. “Robust Summarization and Inference in Proteome-wide Label-free Quantification.” *Mol Cell Proteomics* 19 (7): 1209–19.