

Analysis of flow cytometry data with R

Training for life scientists

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Translational Data Science – Facility

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Outline & Schedule

Day 3

01

Importing data from Excel and arranging plots in a grid

02

Differential state analysis using a paired design

03

Normalization / batch correction

04

Working with gated data in R

Outline & Schedule

Day 4

05

Generate HTML or PDF reports

Examples and exercises are integrated in the chapters

01

- A. Importing data from Excel**
- B. Arranging plots in grids**

Importing data from an Excel file

Package xlsx

<https://cran.r-project.org/web/packages/xlsx/index.html>

```
> data <- read.xlsx2(file = "excelfile.xlsx",  
sheetName = "Sheet1")
```

	A	B
1	sample	id
2	1	3
3	2	
4		4
5	3	5
6	4	
7		5
8		5
9		

The function *read.xlsx2* considers the empty cells as "" character.

```
> str(data)  
'data.frame': 7 obs. of 2 variables:  
 $ sample: chr  "1" "2" "" "3" ...  
 $ id     : chr  "3" "" "4" "5" ...
```

The function *read.xlsx* considers the empty cells as NA

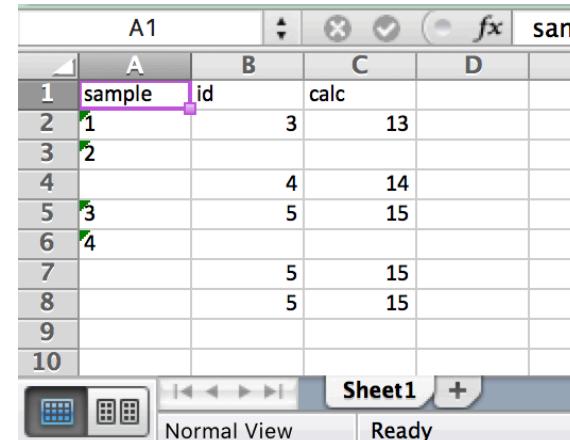
```
> str(data)  
'data.frame': 7 obs. of 2 variables:  
 $ sample: num  1 2 NA 3 4 NA NA  
 $ id     : num  3 NA 4 5 NA 5 5
```

Exporting data to an Excel file

Advantage: no risk of gene name conversion to date like with csv files

Package `xlsx` can be used to export a `data.frame` after manipulating it within R:

```
> data$id<-as.numeric(data$id)  
> data$calc<-data$id+10  
> write.xlsx2(x=data,  
           file = "exclfile2.xlsx",  
           row.names = FALSE,  
           SheetName = "Sheet1")
```



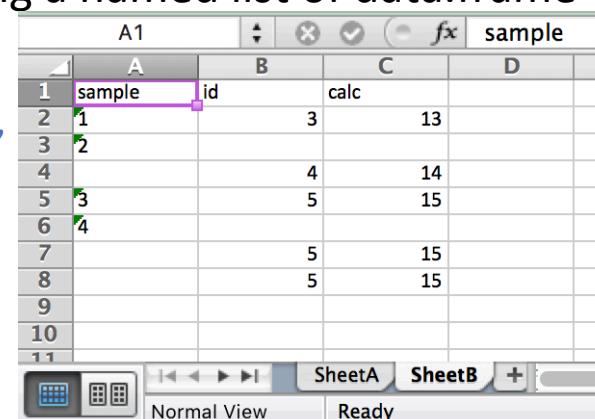
	A1	B	C	D	
1	sample	id	calc		
2	1		3	13	
3	2				
4			4	14	
5	3		5	15	
6	4				
7			5	15	
8			5	15	
9					
10					

Another package: `openxlsx`

<https://cran.r-project.org/web/packages/openxlsx/index.html>

Allows to generate several separate sheets providing a named list of `data.frame` objects:

```
> openxlsx::write.xlsx(x = list(SheetA=data[, c(1,2)],  
                           SheetB=data),  
                           file = "exclfile3.xlsx")
```



	A1	B	C	D	
1	sample	id	calc		
2	1		3	13	
3	2				
4			4	14	
5	3		5	15	
6	4				
7			5	15	
8			5	15	
9					
10					
11					

Doesn't export rownames by default.

Arranging ggplot2 plots in a grid

Can be useful to compare distribution of values before and after transformation, or to compare a UMAP with cells colored according to different markers.

Package *cowplot*

<https://cran.r-project.org/web/packages/cowplot/index.html>

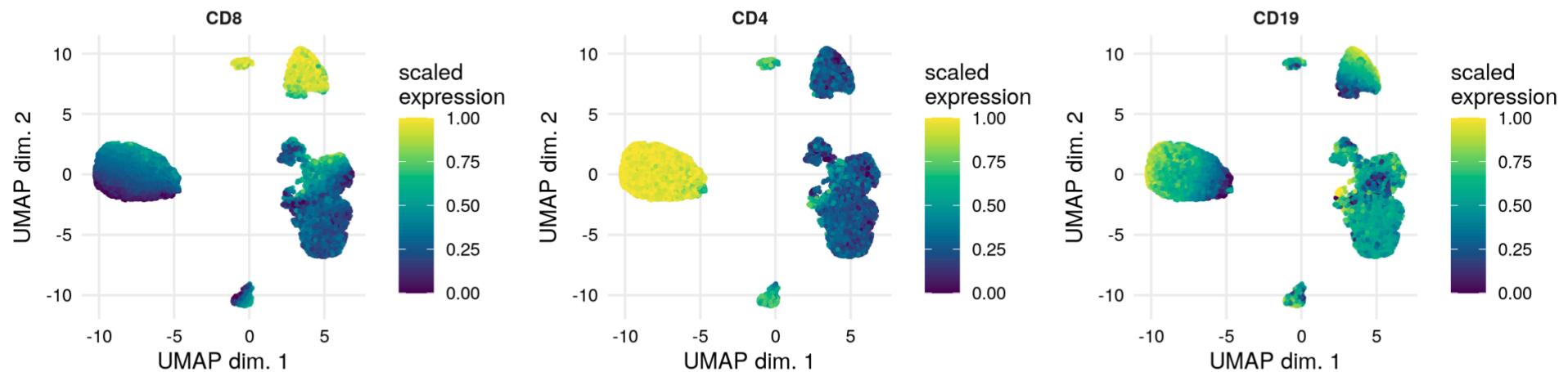
First save each ggplot2 plot to an object:

```
> p1 <- plotDR(sce, dr = "UMAP",
  assay = "exprs", color_by="CD8" )
> p2 <- plotDR(sce, dr = "UMAP",
  assay = "exprs", color_by="CD4")
> p3<-plotDR(sce, dr = "UMAP",
  assay = "exprs", color_by="CD19")
```

Arranging ggplot2 plots in a grid

Use the *plot_grid* function to arrange them in a grid, e.g. all on the same row:

```
> plot_grid(p1, p2, p3, nrow = 1)
```



02

Differential state analysis with a paired design

Differential state (DS) analysis with paired design

Differential expression of cell state markers within clusters

```
> res_DS <- diffcyt(sce_PBMC,  
                      clustering_to_use = "final_annotation",  
                      analysis_type = "DS",  
                      method_DS = "diffcyt-DS-limma",  
                      design = design,  
                      contrast = contrast,  
                      block_id = patient_id)
```

Methods for DS: uses the **limma** package

Vector of patient IDs

How to create a vector of patient IDs from the fcs file names?

```
> ei(sce)$sample_id  
# [1] 0BF51C_0.fcs 0BF51C_14.fcs 0BF51C_7.fcs 0E1F8E_0.fcs 0E1F8E_14.fcs  
# [6] 0E1F8E_7.fcs 180E1A_0.fcs 180E1A_14.fcs 180E1A_7.fcs 1A9B20_0.fcs  
# [11] 1A9B20_14.fcs 1A9B20_7.fcs 61BBAD_0.fcs 61BBAD_14.fcs 61BBAD_7.fcs
```

Using gsub() :

This function replaces all characters having a same pattern with other characters.
We can replace the *_0.fcs*, *_14.fcs* and *_7.fcs* extensions by an empty character:

Create a vector of patient IDs for block design:

```
> patient_id <- ei(sce)$sample_id
```

Use gsub to replace the extensions for the matching elements within the vector:

```
> patient_id <- gsub("_0.fcs", "", patient_id)  
> patient_id <- gsub("_14.fcs", "", patient_id)  
> patient_id <- gsub("_7.fcs", "", patient_id)
```

```
> patient_id
```

```
[1] "0BF51C" "0BF51C" "0BF51C" "0E1F8E" "0E1F8E" "0E1F8E" "180E1A" "180E1A"  
[9] "180E1A" "1A9B20" "1A9B20" "1A9B20" "61BBAD" "61BBAD" "61BBAD"
```

Differential state analysis

Extract results table - same method as for unpaired design:

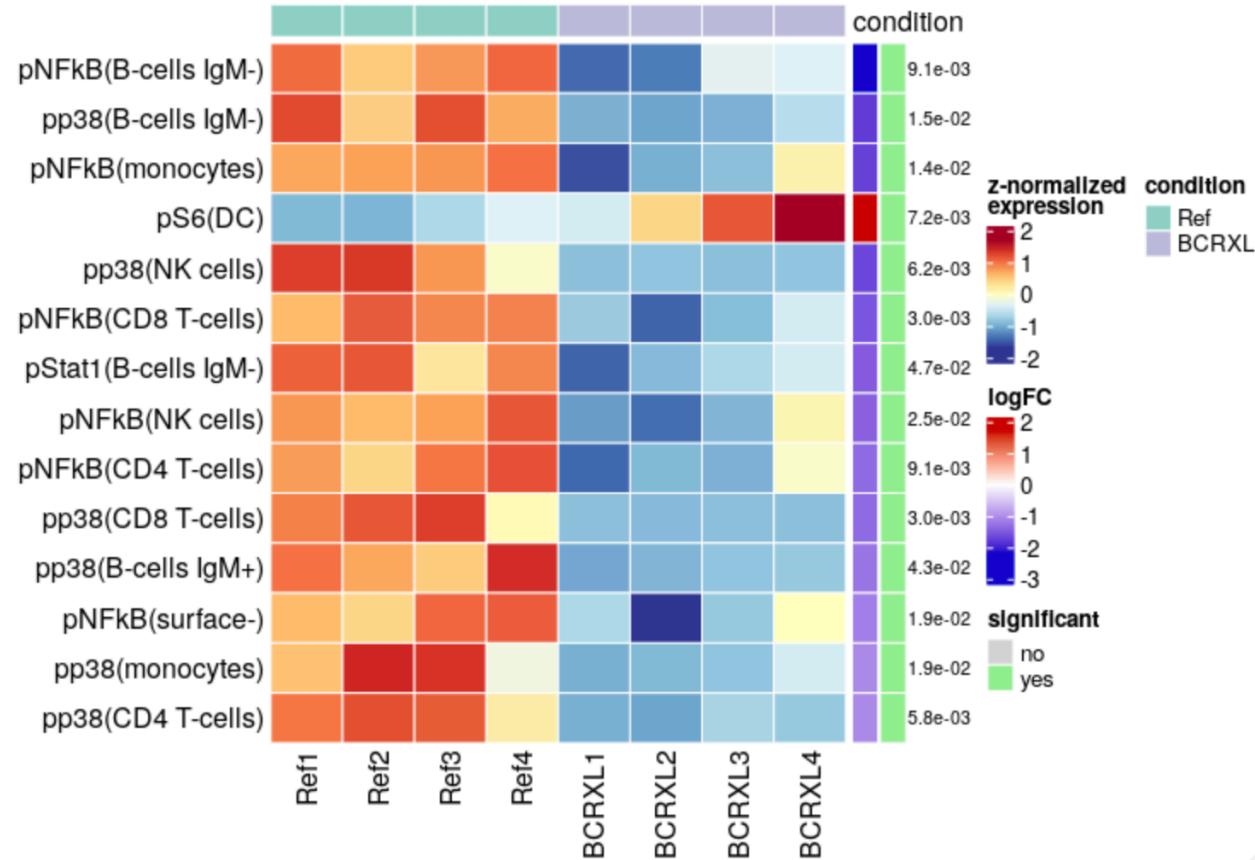
```
> tbl_DS <- rowData(res_DS$res)  
> tbl_DS
```

DataFrame with 20 rows and 4 columns					
		cluster_id	marker_id	p_val	p_adj
		<factor>	<factor>	<numeric>	<numeric>
Other	Other		CD38	0.000883343	0.128085
Other	Other		TCR gd	0.006609759	0.479208
CD4 T cells	CD4 T cells		CD141	0.027918113	0.481051
CD8 T cells	CD8 T cells		CCR5	0.026749683	0.481051
Monocytes	Monocytes		CCR5	0.027850828	0.481051
...
CD4 T cells	CD4 T cells		CD16	0.0703599	0.534035
CD8 T cells	CD8 T cells		CD16	0.0629339	0.534035
Other	Other		CD16	0.0688253	0.534035
CD8 T cells	CD8 T cells		IgD	0.0704875	0.534035
Other	Other		CD161	0.0684019	0.534035
...

Differential state analysis

Plot results for all markers Sorts results by absolute value of logFoldChange

```
> plotDiffHeatmap(sce_PBMC, tbl_DS, all=T, sort_by = "lfc", col_anno = "condition")
```



Let's practice – 7 bis

In this exercise we will test if markers were differentially expressed between two time points (D14 compared to D0), **using a paired design**

Create a new script in which you will

- 1) Load the sce object from exercise number 6 ("sce.annotated.RData").
- 2) Create a vector of patient IDs from the fcs file names using gsub()
- 3) Set up the design and contrast matrices.
- 4) Test for differences in marker expression between D14 and D0, including argument block_id
- 5) View table of results

03

Normalization / batch correction

Spectral flow cytometry analysis workflow

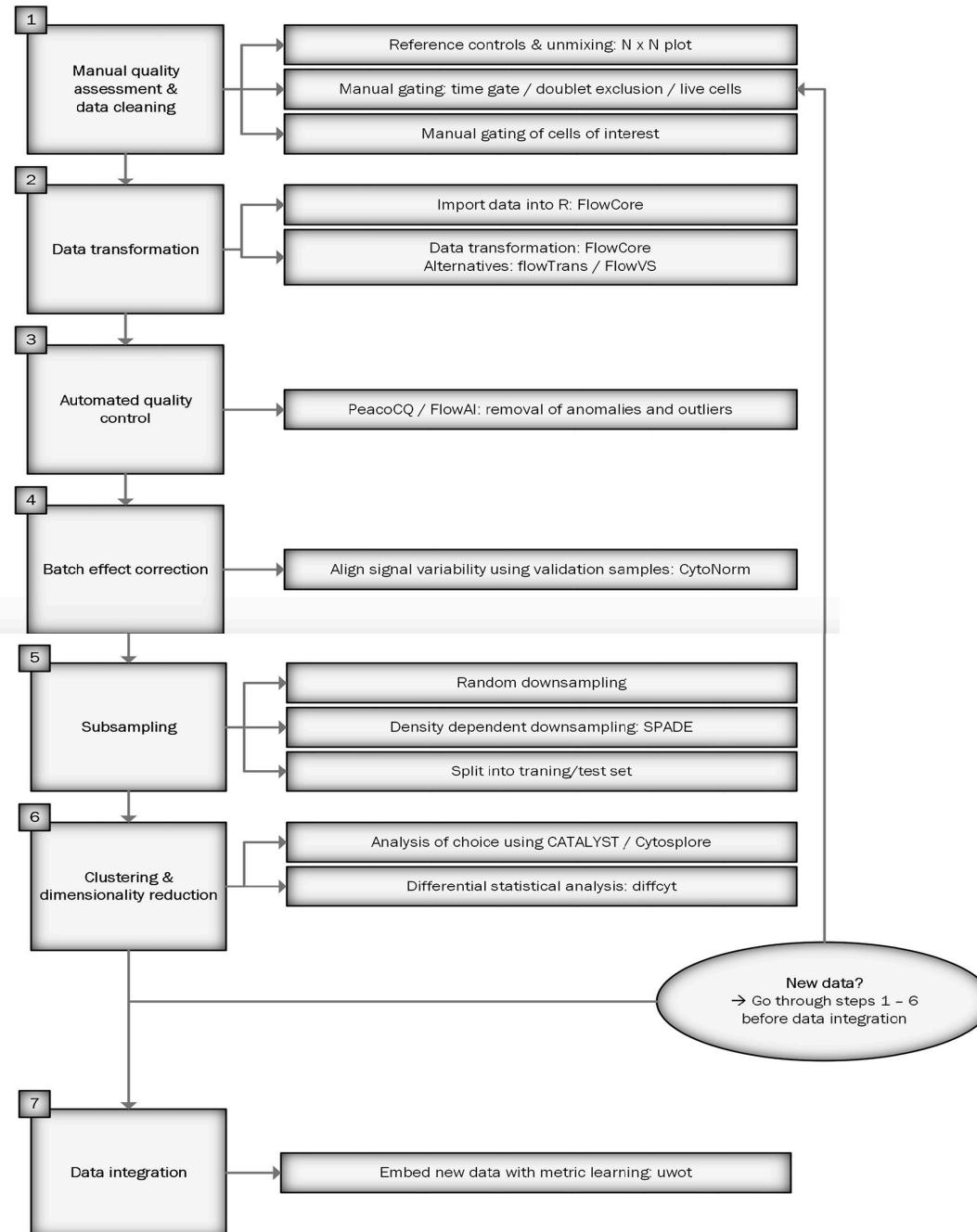
- Workflow based on

The screenshot shows a website layout for a journal article. At the top, there is a navigation bar with the 'frontiers' logo, 'Immunology', and links for 'Sections', 'Articles', 'Research Topics', and 'Editorial Board'. Below the navigation bar, the article title is displayed: 'METHODS article' followed by 'Front. Immunol., 19 November 2021' and 'Sec. Systems Immunology'. The volume information is 'Volume 12 - 2021 | <https://doi.org/10.3389/fimmu.2021.768113>'. To the right of this information, it states 'This article is part of the Research Topic Re-Using Cytometry Datasets in Immunology: "Old Wine into New Wineskins"' and a link 'View all 7 Articles >'. The main title of the article is 'How to Prepare Spectral Flow Cytometry Datasets for High Dimensional Data Analysis: A Practical Workflow'. Below the title, three author names are listed with their corresponding profile icons: Hannah den Braanker^{1,2,3†}, Margot Bongenaar^{1,2†}, and Erik Lubberts^{1,2*}. Below the authors, three footnotes are provided: ¹ Department of Rheumatology, Erasmus University Medical Center, Rotterdam, Netherlands; ² Department of Immunology, Erasmus University Medical Center, Rotterdam, Netherlands; ³ Department of Clinical Immunology and Rheumatology, Maasstad Hospital, Rotterdam, Netherlands. A brief abstract at the bottom states: 'Spectral flow cytometry is an upcoming technique that allows for extensive multicolor panels, enabling simultaneous investigation of a large number of'.

Provide R code to perform the proposed workflow

<https://doi.org/10.3389/fimmu.2021.768113>

Suggested workflow: Figure 1, den Braanker et al



Planning and Preparation

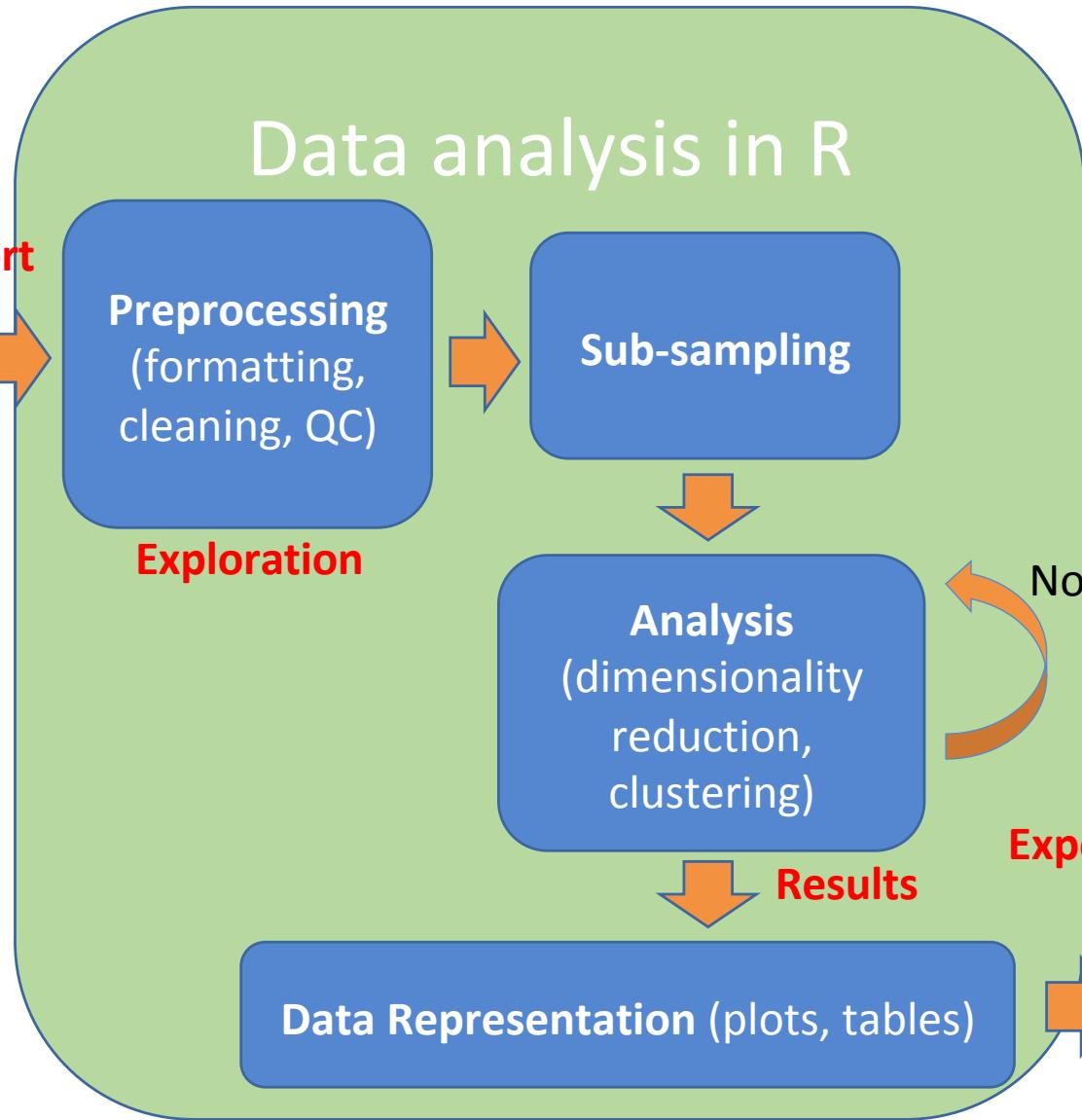


Data acquisition



Manual analysis
(QC, gating)

Import



Simplified workflow presented in day 1 and 2

Communicate (reports)

Spectral flow cytometry analysis workflow

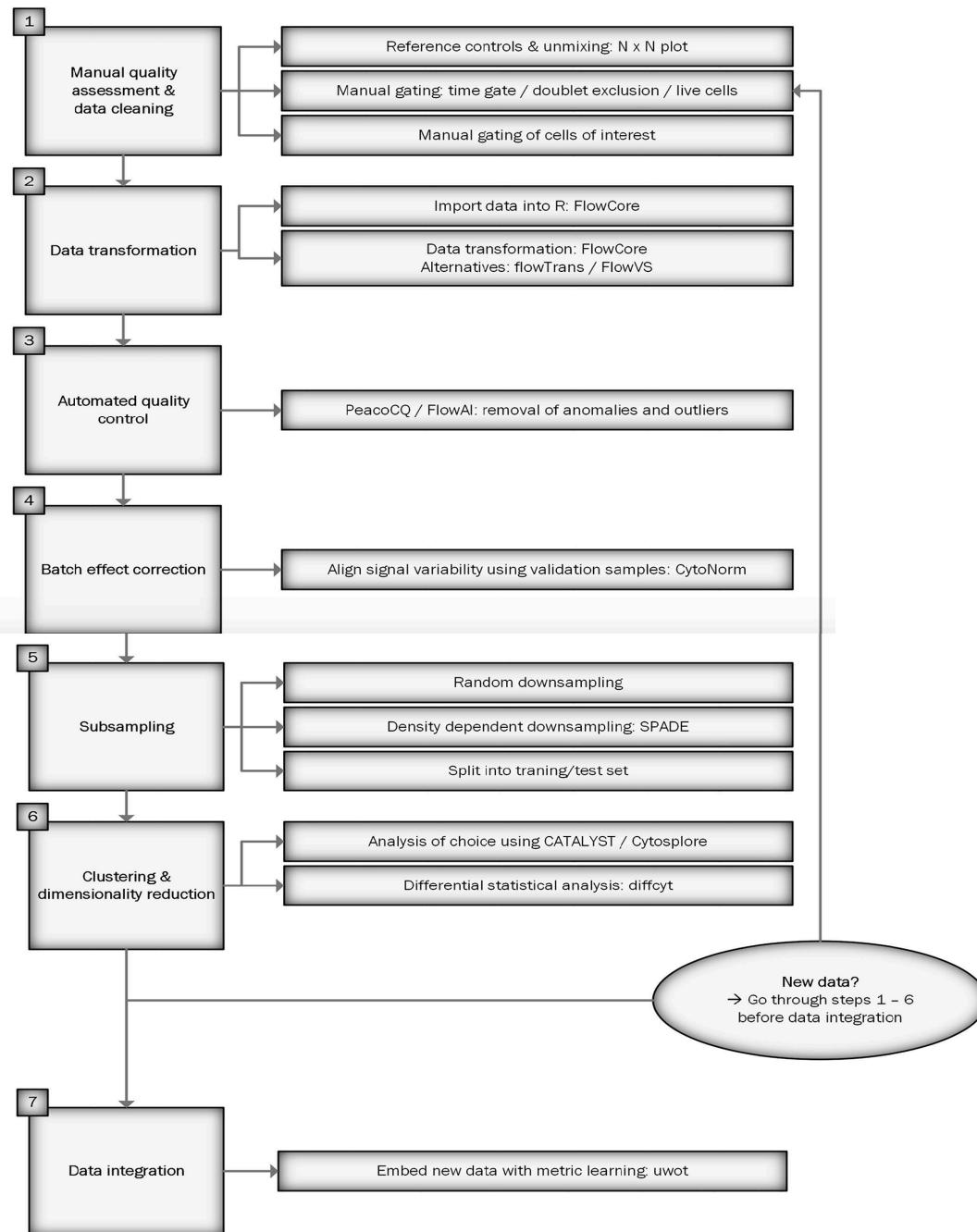
- Workflow based on

The screenshot shows a website layout for a scientific publication. At the top, there is a navigation bar with the 'frontiers' logo, followed by 'Immunology' and other menu items: 'Sections', 'Articles', 'Research Topics', and 'Editorial Board'. Below the navigation bar, the page title is 'METHODS article'. The article details are: 'Front. Immunol., 19 November 2021', 'Sec. Systems Immunology', 'Volume 12 - 2021 | <https://doi.org/10.3389/fimmu.2021.768113>'. To the right, it states 'This article is part of the Research Topic Re-Using Cytometry Datasets in Immunology: "Old Wine into New Wineskins"' and a link 'View all 7 Articles >'. The main title of the article is 'How to Prepare Spectral Flow Cytometry Datasets for High Dimensional Data Analysis: A Practical Workflow'. Below the title, author information is listed: 'Hannah den Braanker^{1,2,3†}', 'Margot Bongenaar^{1,2†}', and 'Erik Lubberts^{1,2*}'. Below the authors, three footnotes are provided: ¹ Department of Rheumatology, Erasmus University Medical Center, Rotterdam, Netherlands; ² Department of Immunology, Erasmus University Medical Center, Rotterdam, Netherlands; ³ Department of Clinical Immunology and Rheumatology, Maasstad Hospital, Rotterdam, Netherlands. A descriptive paragraph at the bottom states: 'Spectral flow cytometry is an upcoming technique that allows for extensive multicolor panels, enabling simultaneous investigation of a large number of'.

Provide R code to perform the proposed workflow

<https://doi.org/10.3389/fimmu.2021.768113>

Suggested workflow: Figure 1, den Braanker et al



<https://doi.org/10.3389/fimmu.2021.768113>

Planning and Preparation



Data acquisition



Manual analysis
(QC, gating)

Import

Data analysis in R

Preprocessing
(formatting,
cleaning, QC)

Exploration

Sub-sampling

Analysis
(dimensionality
reduction,
clustering)

Normalization

Export

Results

Data Representation (plots, tables)

Communicate
(reports)

Simplified workflow
presented in day 1 and 2

CytoNorm

Available on github: <https://github.com/saeyslab/CytoNorm>

van Gassen et al, 2020 <https://onlinelibrary.wiley.com/doi/epdf/10.1002/cyto.a.23904>

Install using devtools package:

```
> library(devtools)
```

```
> install_github('saeyslab/CytoNorm')
```

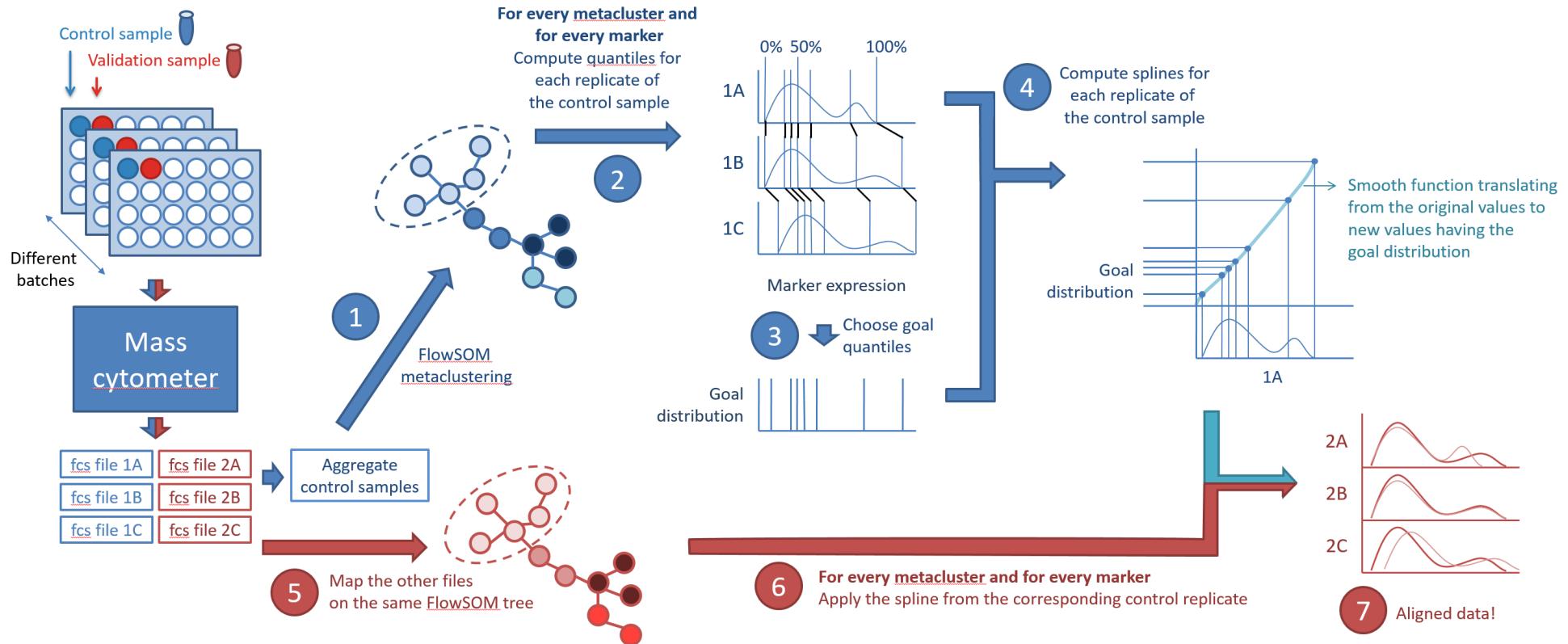
Why do we need to normalize?

Shifts that occur because of batch can have effects on DR for example.

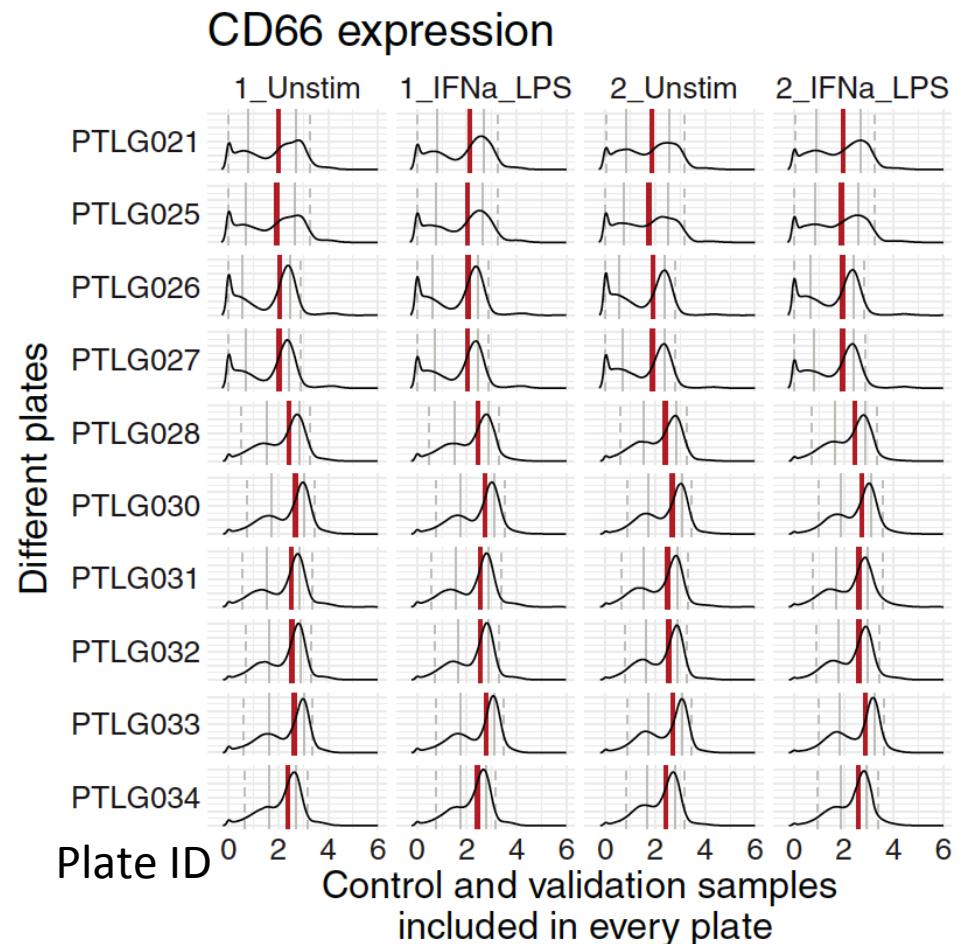
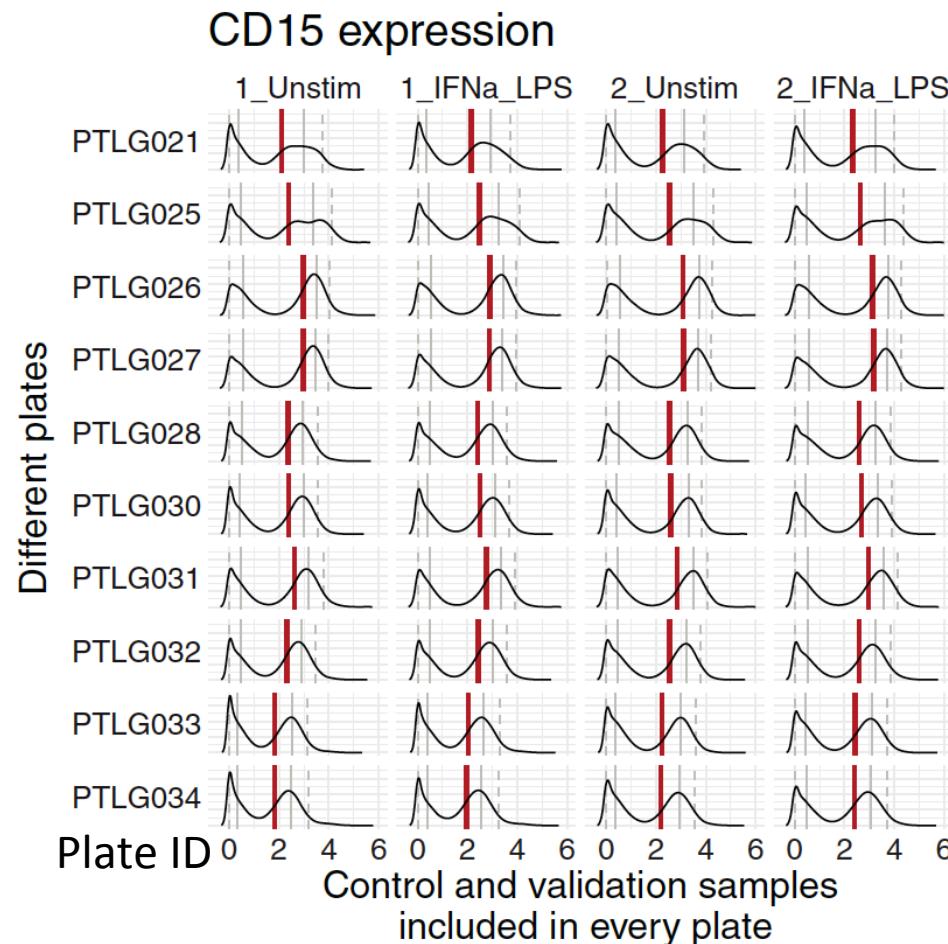
Computational methods can align the distribution of markers across samples.

Normalization methods without a reference sample can hide biologically relevant differences in cell subsets. Different cell types are impacted differently by batch effects (Finak et al, 2014, Cytom. Part A)

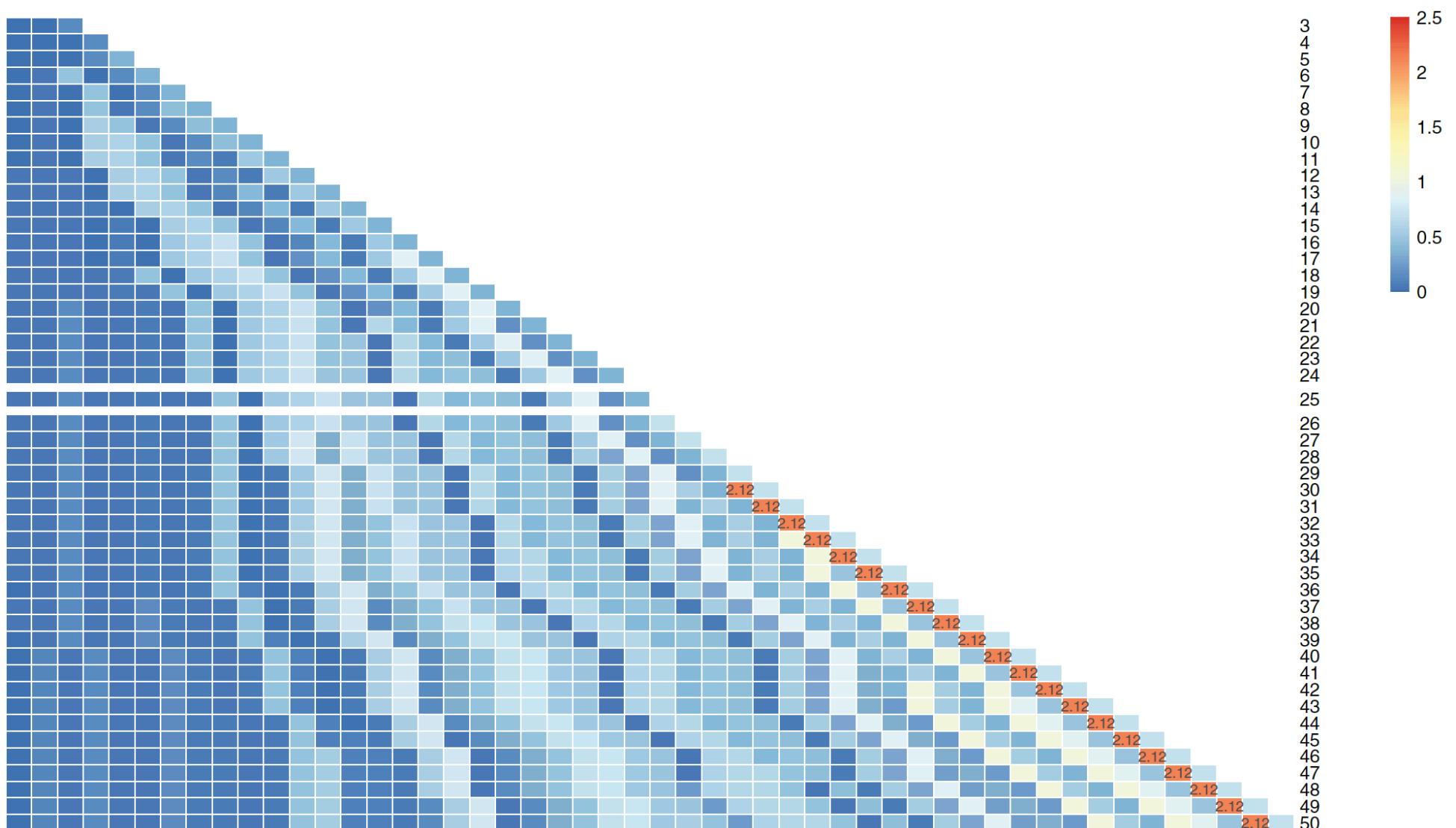
CytoNorm – algorithm overview



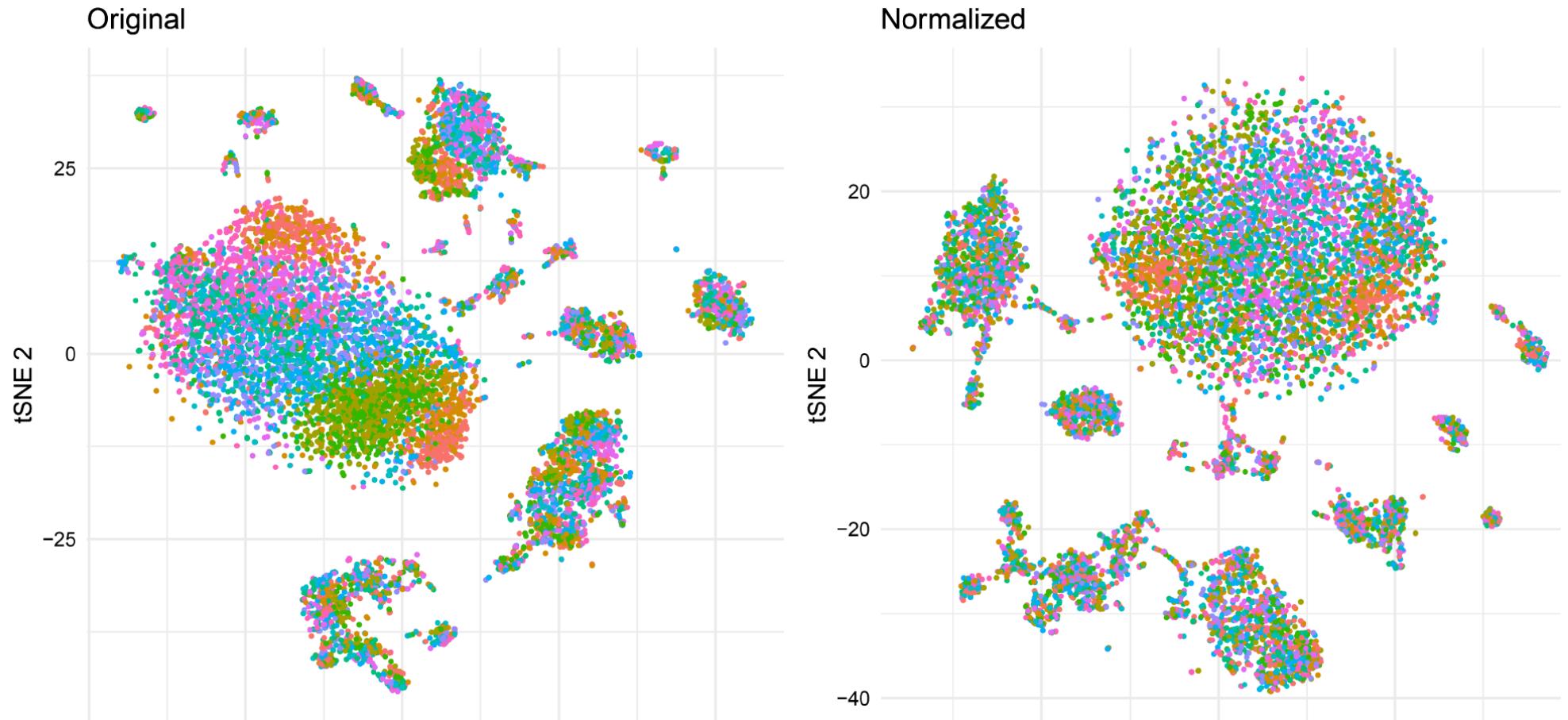
An example of shifts across plates



Assumption: clusters are not affected by batch



Normalization enhances DR plot



1,000 randomly sampled cells for each of 10 samples

Functions of CytoNorm

Functions use flowSet objects containing transformed data (eg arcsinh with fixed cofactor).

Generate pre-clustering with flowSOM:

```
> fsom <- prepareFlowSOM(train_files, ←  
    colsToUse = markerstotransf, ←  
    transformList = NULL,  
    FlowSOM.params = list(xdim=10,  
                          ydim=10,  
                          nClus=20, scale=FALSE)) ←  
    flowSet with technical replicates of a  
    single sample  
    Markers to use for clustering (eg. "type"  
    marker_class)  
    FlowSOM parameters: number of  
    grids and of metaclusters
```

Test for coefficient of variation within clusters:

```
> cvs <- CytoNorm::testCV(fsom, cluster_values = c(5,10,15,20), plot=TRUE)  
> range(cvs$cvs$`20`) # 0.05758965 1.43114512
```

If the clusters are impacted by batch effects, CV values of >1.5 - 2 will occur, then you can choose to put FlowSOM.params to NULL and skip clustering.

Functions of CytoNorm

Train the model, i.e. evaluate quantiles from technical replicates:

```
model <- CytoNorm.train(files = train_files, ← flowSet with technical replicates of a
  labels = labels_train, ← single sample
  channels = markerstotransf, ← Vector of batch ID labels for each technical
  transformList = NULL, ← replicate within the train flowSet
  FlowSOM.params = list(nCells = 6000, ← Markers to use for clustering
    xdim = 10, ← (eg. "type" marker_class)
    ydim = 10, ←
    nClus = 5, ←
    scale = FALSE), ← FlowSOM parameters: number of
                      grids and of metaclusters
  normMethod.train = QuantileNorm.train,
  normParams = list(nQ = 101, ←
    goal = "mean"),
  seed = 1,
  verbose = TRUE)
```

Compute quantiles to describe the distribution of the data, and infer spline functions to equalize these distributions over the files.

Functions of CytoNorm

Normalize the rest of the samples:

```
> CytoNorm.normalize(model = model,  
                      files = validation_files,  
                      labels = label_norm,  
                      transformList = NULL,  
                      transformList.reverse = NULL,  
                      normMethod.normalize = QuantileNorm.normalize,  
                      outputDir = "course_datasets/FR_FCM_Z4KT/Normalized",  
                      prefix = "Norm_",  
                      clean = TRUE,  
                      verbose = TRUE)
```

Model with quantiles obtained using CytoNorm.train()
flowSet with the rest of the samples
Vector of batch ID labels for each sample of the samples to be normalized
Compute quantiles and infer spline functions to equalize these distributions over the files.
Output folder where new fcs files will be created with prefix "Norm_"

Before the exercise: the grep() function

It allows to search for a pattern of characters within a vector:

```
> grep("pattern", myvector)
```

Will return numbers of elements within the vector that correspond to that pattern:

```
> myvector <- c("abc", "xyz", "abcd", "abxyz", "cdy")
> grep("abc", myvector)
# [1] 1 3
```

Use it on flowSet sampleNames to split a flowSet based on sample ID:

```
> train_files <- fcs_transform[grep("REU271", sampleNames(fcs_transform))]
> validation_files <- fcs_transform[-c(grep("REU271", sampleNames(fcs_transform)))]
```

Let's practice – 8

In this exercise we will perform normalization (i.e. batch correction) for fcs files provided in accession **FR_FCM_Z4KT** of the FlowRepository.

Create a new script in which you will:

- 1) Create a flowSet called `fcs_data` of all samples within the `/course_dataset/FR_FCM_Z4KT` folder
- 2) Generate a panel data.frame using `colnames(fcs_data)` antigen names extracted with `pData(parameters(fcs_data[[1]]))$desc`. Create a new column called `marker_class` that will contain the type of markers: all that are not NA should be labeled as "type", except PD-1 which should be labeled as "state". Make sure that the antigen "Zombie UV" is labeled as "none" and not as "type". Save the panel to an Excel file using `write.xlsx2()`.
- 3) Transform the data: extract a vector from the panel data.frame which are the channels to be transformed, which are not labeled with "none". Perform asinh transformation with a cofactor of 3000 for all channels to be transformed, using `transFlowVS()` from the `flowVS` package.
- 4) Split the flowSet resulting from transformation into a *training* flowSet containing all flowFrames from the sample "REU271", and a flowSet with the rest of the flowFrames not corresponding to sample "REU271". Use the `grep()` function on the `sampleNames` of the flowSet.

Let's practice – 8 - continued

- 5) Perform pre-clustering with flowSOM with function `prepareFlowSOM()`, providing the flowSet with the training flowFrames, the vector of channels to transform, and `FlowSOM.params = list(xdim=10, ydim=10, nClus=20, scale=FALSE)`
- 6) Test the coefficient of variation within clusters with the `testCV()` function.
- 7) Import the metadata with the batch label of each sample contained in the excel file md.xlsx, using `read.xlsx2()`. Create 2 vectors using the column "batch" in the md.xlsx file. One vector contains the batch labels of the samples that correspond to sample "REU271", and another vector contains the batch labels of the other samples (i.e. not "REU271").
- 8) Estimate quantiles from the training flowSet using `CytoNorm.train()`. Use `FlowSOM.params = list(nCells = 6000, xdim = 10, ydim = 10, nClus = 5, scale = FALSE)`
- 9) Normalize the rest of the samples using `CytoNorm.normalize()`, and using `outputDir = "course_datasets/FR_FCM_Z4KT/Normalized"` ; Make sure this is a new folder.
- 10) Choosing one channel, create a ridge plot of its distribution within samples before normalization (without the training samples), and one for the normalized samples. For this, you need to create a new flowSet with the created Norm_fcs files. Use the `densityplot()` function for each flowSet, storing the output in 2 objects, then use the cowplot `plot_grid()` function to plot one above the other.

04

Working with gated data in R

Gating data in R

- The *GatingSet* class of objects (*flowWorkspace*) for working with gating data in R
- Import a *FlowJo* or *Cytobank* workspace (xml file) with gating data into R
- Manual gating from scratch
 - Using functions from the *flowWorkspace* package
 - Using a graphic-based, interactive tool (*flowGate* package)
- Automated gating methods
 - *FlowClust* package
 - *OpenCyto* package

flowWorkspace

<https://bioconductor.org/packages/release/bioc/html/flowWorkspace.html>

- Provides the *GatingSet* class of objects as an efficient data structure to store, query and visualize gated flow data
- A *GatingSet* (**gs**) stores multiple *GatingHierarchy* (**gh**) objects associated with individual samples

GatingSet ~ *flowSet*

GatingHierarchy ~ *flowFrame*

- Unlike *flowSets*, functions that operate on a *GatingSet* have the potential side-effect of modifying the object (all the modifications are made to the *external pointer*, rather than the R object itself)

flowWorkspaceData

<https://bioconductor.org/packages/release/bioc/html/flowWorkspace.html>

- Contains FCS data files, XML workspaces and GatingSets for testing the *flowWorkspace* and *openCyto* packages
- Data from whole blood

Installation

To install this package, start R (version "4.3") and enter:

```
if (!require("BiocManager", quietly = TRUE))
  install.packages("BiocManager")

BiocManager::install("flowWorkspaceData")
```

Create a *gatingSet*

Ways to generate a *gatingSet*:

- Imported from workspace XML files from FlowJo, CytoBank or other software using *CytoML* package
- Built from scratch within R (**manual gating**)
- Generated by **automated gating** methods (e.g. *openCyto* package)

Import a workspace using *CytoML*

<https://bioconductor.org/packages/release/bioc/html/CytoML.html>

- Uses platform-specific implementations of the GatingML2.0 standard to exchange gated cytometry data



Published in final edited form as:
Cytometry A. 2015 July ; 87(7): 683–687. doi:10.1002/cyto.a.22690.

ISAC's Gating-ML 2.0 data exchange standard for gating description

Josef Spidlen¹, Wayne Moore², ISAC Data Standards Task Force³, and Ryan R. Brinkman^{†, 1,4}

¹Terry Fox Laboratory, BC Cancer Agency, Vancouver, British Columbia, Canada

²Genetics Department, Stanford University School of Medicine, Stanford, California, United States of America

³Full lists of members and affiliations appear at the end of the paper

⁴Department of Medical Genetics, University of British Columbia, Vancouver, British Columbia, Canada

```
# import workspace from FlowJo
> ws <- open_flowjo_xml("course_datasets/flowWorspaceData/manual.xml")
> gs <- flowjo_to_gatingset(ws, name = "T-cell")
```

flowWorkspace: basics on *GatingSet* objects

List the samples stored in the GatingSet

```
> sampleNames(gs)
[1] "CytoTrol_CytoTrol_1.fcs_119531" "CytoTrol_CytoTrol_2.fcs_115728"
```

Access metadata

```
> pData(gs)
```

	name	condition
CytoTrol_CytoTrol_1.fcs_119531	CytoTrol_CytoTrol_1.fcs	treatment
CytoTrol_CytoTrol_2.fcs_115728	CytoTrol_CytoTrol_2.fcs	control

Add metadata

```
pData(gs)$condition <- c("treatment","control")
```

Subset a GatingSet by metadata column

```
> subset(gs, subset = treatment == "control")
```

A GatingSet with 1 samples

Retrieve a GatingHierarchical (one sample)

```
> gh <- gs[[1]]
```

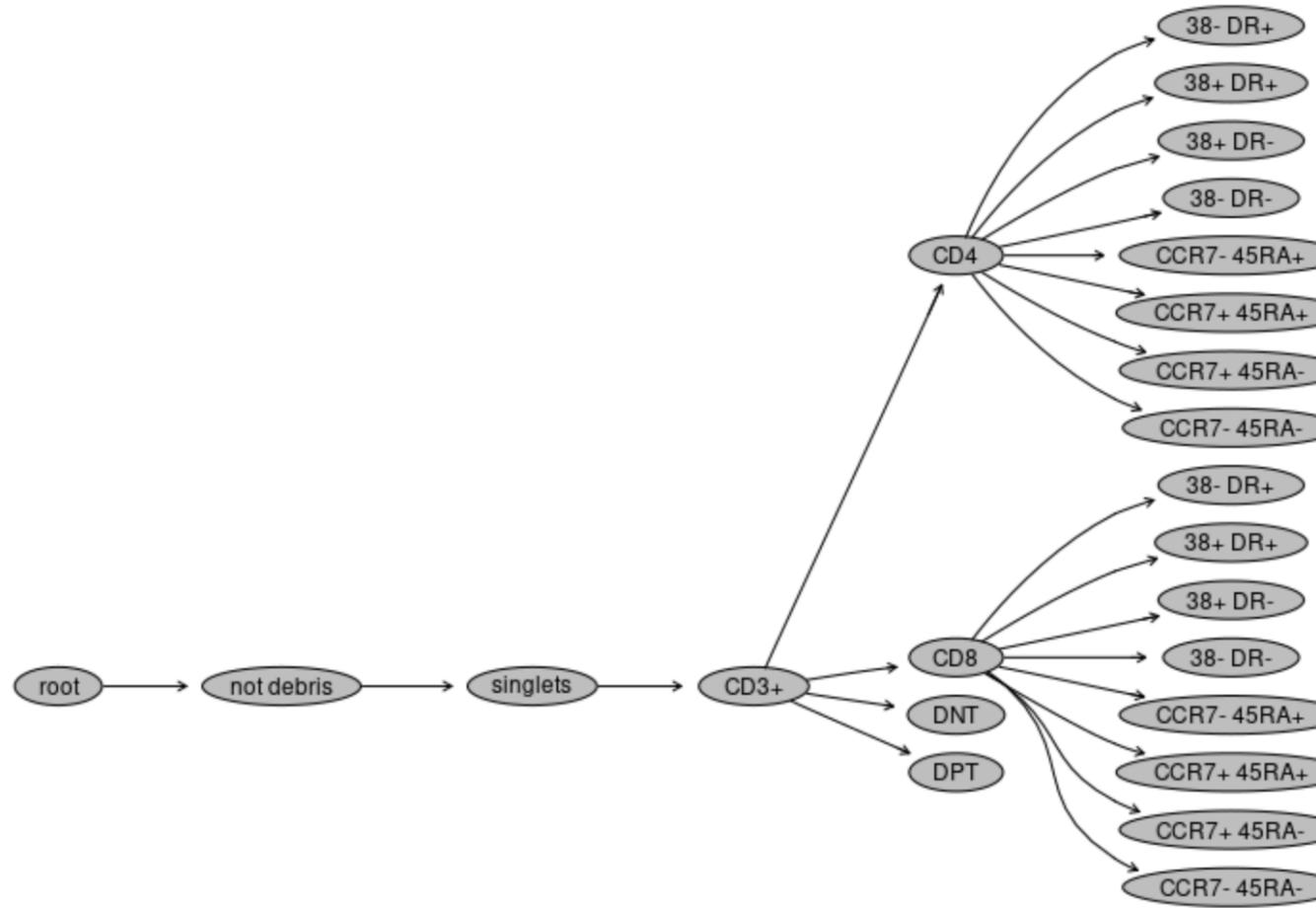
```
> gh
```

Sample:	CytoTrol_CytoTrol_1.fcs_119531
GatingHierarchy	with 24 gates

flowWorkspace: basics on *GatingSet* objects

```
# plot the gating hierarchy (tree)
```

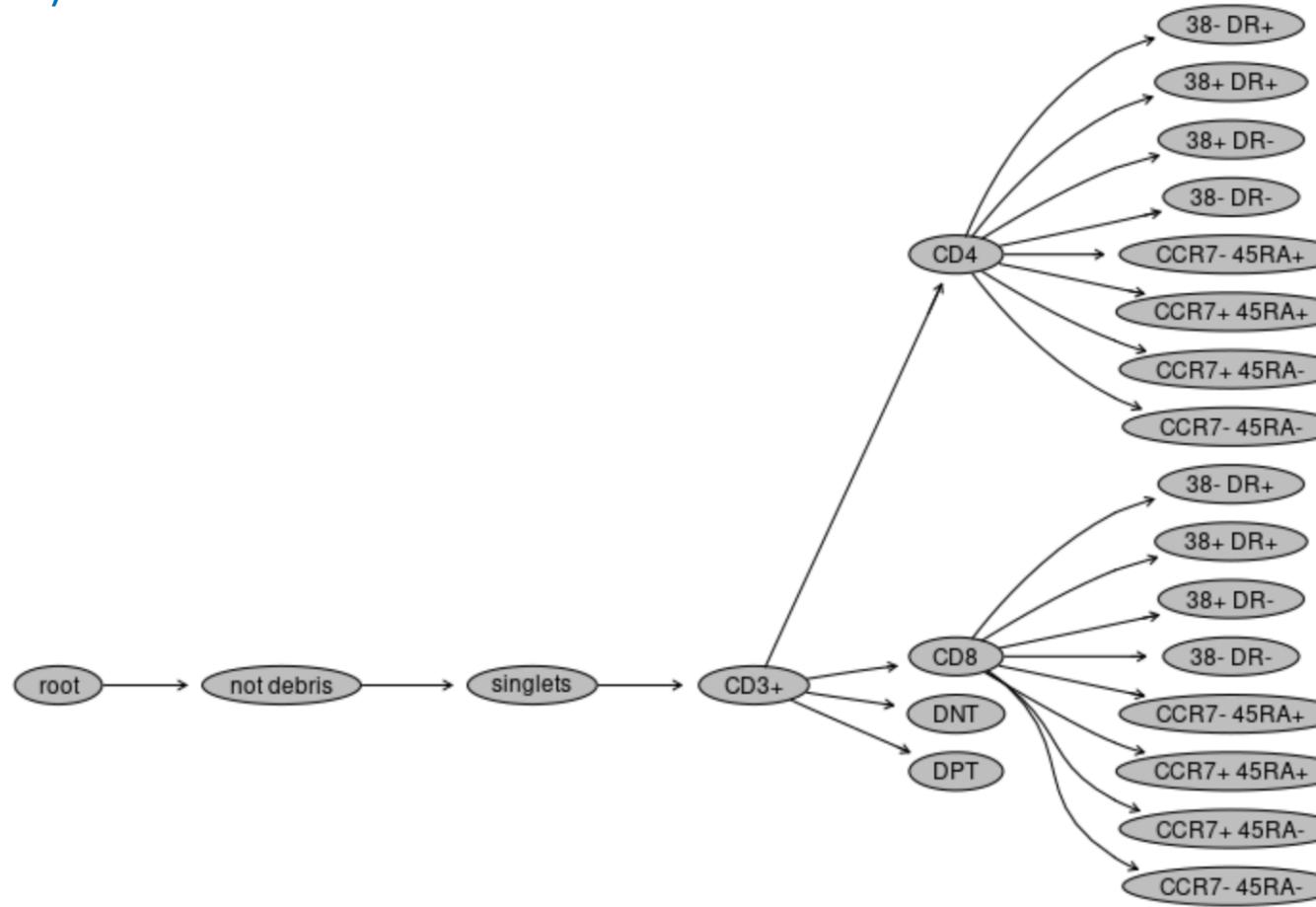
```
> plot(gs)
```



flowWorkspace: basics on *GatingSet* objects

Delete a gate

```
> Rm(gs, "DPT")  
> plot(gs)
```



flowWorkspace: basics on *GatingSet* objects

list nodes (cell populations)

```
> gs_get_pop_paths(gs, path = 2)
```

```
[1] "root"                 "not debris"          "not debris/singlets" "singlets/CD3+"      "CD3+/CD4"
[6] "CD4/38- DR+"         "CD4/38+ DR+"        "CD4/38+ DR-"       "CD4/38- DR-"      "CD4/CCR7- 45RA+"
[11] "CD4/CCR7+ 45RA+"     "CD4/CCR7+ 45RA-"    "CD4/CCR7- 45RA-"   "CD3+/CD8"        "CD8/38- DR+"
[16] "CD8/38+ DR+"         "CD8/38+ DR-"        "CD8/38- DR-"       "CD8/CCR7- 45RA+"  "CD8/CCR7+ 45RA+"
[21] "CD8/CCR7+ 45RA-"     "CD8/CCR7- 45RA-"    "CD3+/DNT"         "CD3+/DPT"
```

```
> gs_get_pop_paths(gs, path = "full")
```

```
[1] "root"                 "/not debris"
[3] "/not debris/singlets" "/not debris/singlets/CD3+"
[5] "/not debris/singlets/CD3+/CD4" "/not debris/singlets/CD3+/CD4/38- DR+"
[7] "/not debris/singlets/CD3+/CD4/38+ DR+" "/not debris/singlets/CD3+/CD4/38+ DR-"
[9] "/not debris/singlets/CD3+/CD4/38- DR-" "/not debris/singlets/CD3+/CD4/CCR7- 45RA+"
[11] "/not debris/singlets/CD3+/CD4/CCR7+ 45RA+" "/not debris/singlets/CD3+/CD4/CCR7+ 45RA-"
[13] "/not debris/singlets/CD3+/CD4/CCR7- 45RA-" "/not debris/singlets/CD3+/CD8"
[15] "/not debris/singlets/CD3+/CD8/38- DR+" "/not debris/singlets/CD3+/CD8/38+ DR+"
[17] "/not debris/singlets/CD3+/CD8/38+ DR-" "/not debris/singlets/CD3+/CD8/38- DR-"
[19] "/not debris/singlets/CD3+/CD8/CCR7- 45RA+" "/not debris/singlets/CD3+/CD8/CCR7+ 45RA+"
[21] "/not debris/singlets/CD3+/CD8/CCR7+ 45RA-" "/not debris/singlets/CD3+/CD8/CCR7- 45RA-"
[23] "/not debris/singlets/CD3+/DNT"           "/not debris/singlets/CD3+/DPT"
```

```
> gs_get_pop_paths(gs, path = "auto")
```

```
[1] "root"                 "not debris"          "singlets"          "CD3+"            "CD4"              "CD4/38- DR+"      "CD4/38+ DR+"
[8] "CD4/38+ DR-"         "CD4/38- DR-"        "CD4/CCR7- 45RA+"  "CD4/CCR7+ 45RA+"  "CD4/CCR7+ 45RA- " "CD4/CCR7- 45RA-"  "CD8"
[15] "CD8/38- DR+"         "CD8/38+ DR+"        "CD8/38+ DR-"       "CD8/38- DR-"      "CD8/CCR7- 45RA+"  "CD8/CCR7+ 45RA+"  "CD8/CCR7+ 45RA-"
[22] "CD8/CCR7- 45RA-"     "DNT"                "DPT"
```

FlowWorkspace: basics on *GatingSet*

```
# retrieve data from all nodes as a cytoset
```

```
> cs <- gs_pop_get_data(gs)
```

```
> class(cs)
```

```
[1] "cytoset"
```

```
attr(,"package")
```

```
[1] "flowWorkspace"
```

```
# convert the cytoset to a flowSet
```

```
> fs <- cytoset_to_flowSet(cs)
```

```
# check the number of cells in the flowSet
```

```
> fsApply(fs, nrow)
```

```
[,1]
```

```
CytoTrol_CytoTrol_1.fcs_119531 119531
```

```
CytoTrol_CytoTrol_2.fcs_115728 115728
```

```
# retrieve data associated to one node (gate)
```

```
> cs <- gs_pop_get_data(gs, "CD4")
```

```
[,1]
```

```
> fs <- cytoset_to_flowSet(cs)
```

```
CytoTrol_CytoTrol_1.fcs_119531 34032
```

```
> fsApply(fs, nrow)
```

```
CytoTrol_CytoTrol_2.fcs_115728 33751
```

FlowWorkspace: basics on *GatingSet* object

```
# Get membership indices with respect to a gate
```

```
> gh_pop_get_indices(gs[[1]], "CD4")
```

```
[1] TRUE FALSE FALSE FALSE FALSE TRUE FA  
[16] TRUE FALSE TRUE TRUE TRUE FALSE FA  
[31] FALSE FALSE FALSE FALSE TRUE FALSE FA  
[46] FALSE FALSE FALSE FALSE TRUE TRUE FA
```

```
> table(gh_pop_get_indices(gs[[1]], "CD4"))
```

	FALSE	TRUE
85499	34032	

```
# save / load a GatingSet
```

```
> save_gs(gs, path = "course_datasets/flowWorspaceData/gs")
```

```
> gs2 <- load_gs("course_datasets/flowWorspaceData/gs")
```

The regular R assignment (`<-`) or `save()` routine doesn't work for *GatingSet* objects

Build a *GatingSet* from scratch

Start from a *flowSet* (*flowCore*)

Read the FCS files

```
> fs <- read.flowSet(path="course_datasets/flowWorspaceData/", pattern = "*.fcs")
```

Arcsinh transform with *flowVS*

```
> panel <- pData(parameters(fs[[1]]))  
> markerstotransf <- as.character(panel$name[!is.na(panel$desc)])  
> fs <- transFlowVS(fs, channels = markerstotransf,  
                      cofactors = rep(3000,length(markerstotransf)))
```

Convert to a *GatingSet*

```
> gs <- GatingSet(fcs_transform) # convert the flowSet to GatingSet
```

Start from a single cell experiment object (*CATALYST*)

```
> load("course_datasets/FR_FCM_Z4KT/DA_example_sce_PBMC.RData") # load the sce  
> fs <- sce2fcs(sce_PBMC, assay = "exprs") # convert sce to flowSet (CATALYST)  
> gs <- GatingSet(fs) # convert flowSet to GatingSet
```

Manual gating : rectangle gate

```
# Create a rectangle gate
```

```
> rg1 <- rectangleGate("FSC-A"=c(60000,260000),  
                         "SSC-A"=c(1, 250000),  
                         filterId="NotDebris")
```

```
# Add the gate to the GatingSet object
```

```
> gs_pop_add(gs, rg1, parent = "root")
```

```
# Apply the gate to the data
```

```
> recompute(gs)
```

```
# Plot the gate
```

```
> autoplot(gs[[1]], gate = "NotDebris")
```

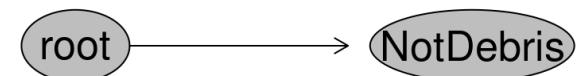
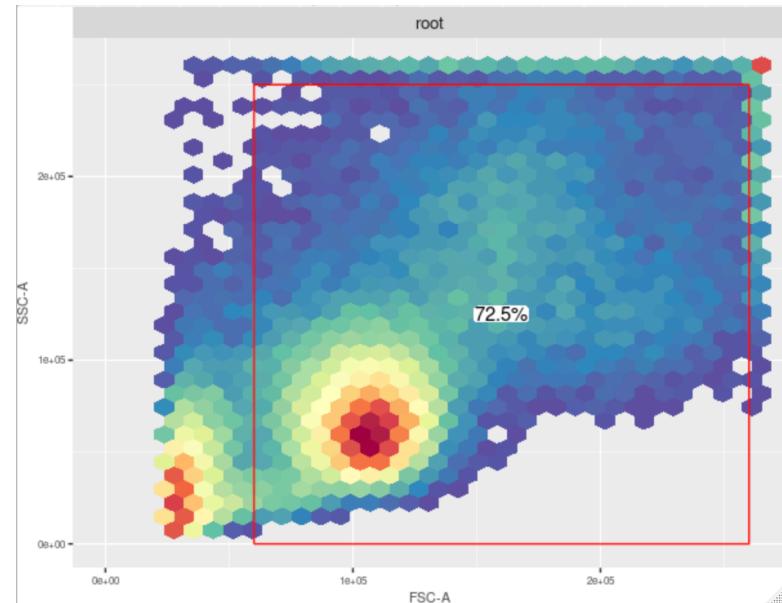
```
# Check gating hierarchy
```

```
> plot(gs)
```

```
# Get statistics
```

```
> gs_pop_get_stats(gs[[1]], "NonDebris") # counts
```

```
> gs_pop_get_stats(gs[[1]], "NonDebris", type = "percent") # proportions
```



	sample	pop count
1:	CytoTrol_CytoTrol_1.fcs	NotDebris 86699
2:	CytoTrol_CytoTrol_2.fcs	NotDebris 86689

	sample	pop percent
1:	CytoTrol_CytoTrol_1.fcs	NotDebris 0.7253265
2:	CytoTrol_CytoTrol_2.fcs	NotDebris 0.7490754

Manual gating: polygon gate

```
# Define the vertices of the polygon
```

```
my_vertices <- matrix(c(1,0.6,1,2,2.3,2.2,  
                      25000,65000,120000,120000,75000,25000),  
                      ncol=2,nrow=6)  
colnames(my_vertices) <- c("V450-A","SSC-A")
```

```
# Create polygon gate "singlets"
```

```
rg2 <- polygonGate( boundaries= my_vertices,  
                     filterId="CD3")
```

```
# Add the gate to the GatingSet
```

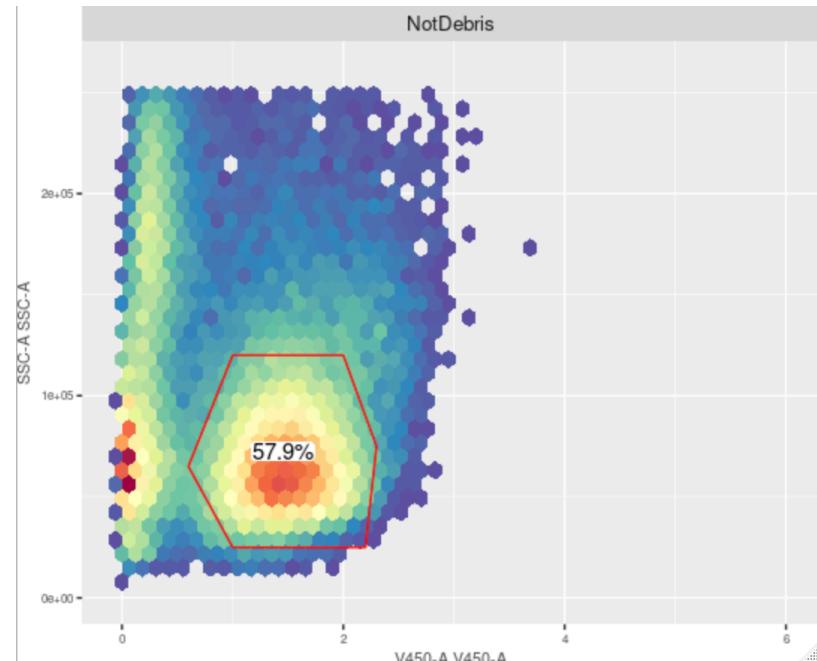
```
gs_pop_add(gs, rg2, parent = "NotDebris")
```

```
# Recompute the GatingSet
```

```
recompute(gs)
```

```
# Check
```

```
autoplots(gs[[1]], gate = "CD3")  
plot(gs)
```



Manual gating: quadrant gate

```
# Create quadrant gate "CD4 CD8"
```

```
> rg3 <- quadGate("B710-A"= 1.5,  
                    "R780-A"= 3,  
                    filterId = "CD4 CD8")
```

```
# Add the gate to the GatingSet
```

```
> gs_pop_add(gs, rg3, parent = "CD3")
```

```
# Recompute the GatingSet
```

```
> recompute(gs)
```

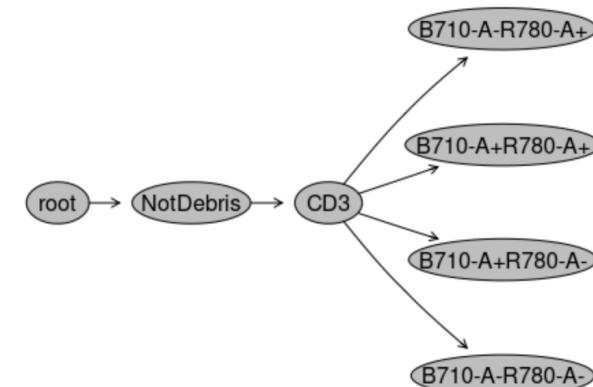
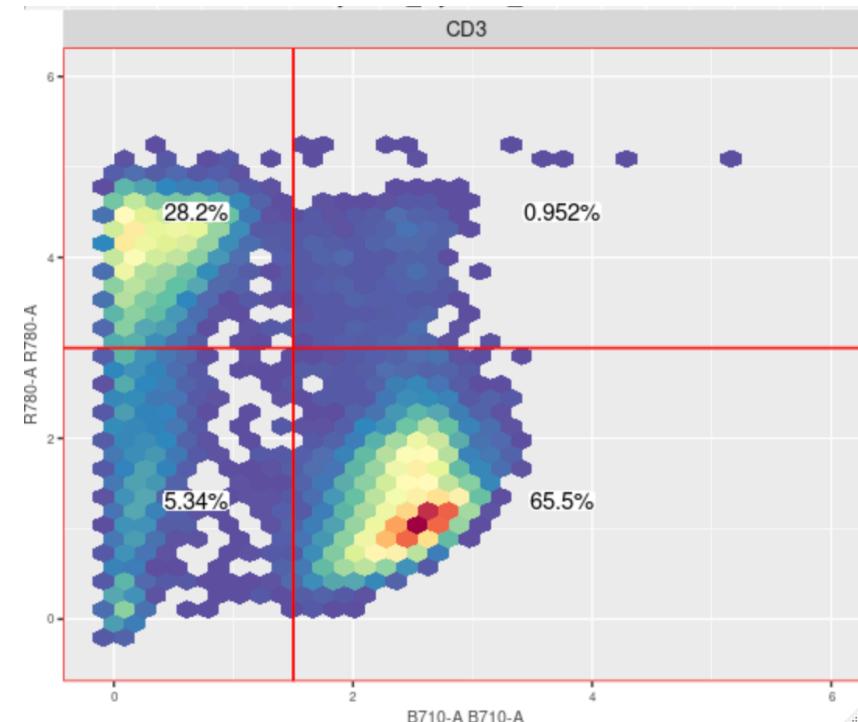
```
# Check
```

```
> gs_get_pop_paths(gs)
```

```
[1] "root"  
[2] "/NotDebris"  
[3] "/NotDebris/CD3"  
[4] "/NotDebris/CD3/B710-A-R780-A+"  
[5] "/NotDebris/CD3/B710-A+R780-A+" "  
[6] "/NotDebris/CD3/B710-A+R780-A-"  
[7] "/NotDebris/CD3/B710-A-R780-A-"
```

```
# Plot
```

```
> autoplot(gs[[1]], gate = gs_get_pop_paths(gs)[4:7])  
> plot(gs)
```

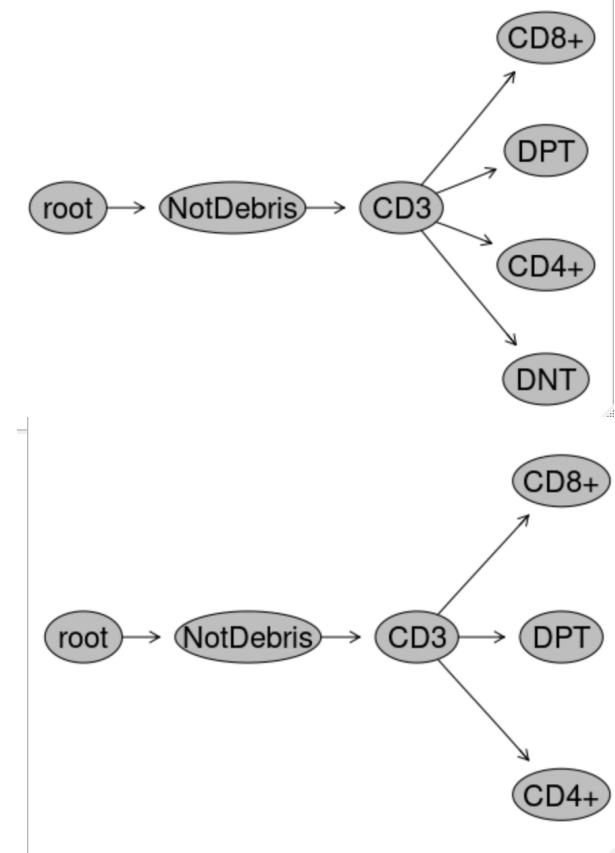


FlowWorkspace: other utilities

```
# Rename nodes (gates)
> gs_pop_set_name(gs, "B710-A-R780-A+", "CD8+")
> gs_pop_set_name(gs, "B710-A+R780-A-", "CD4+")
> gs_pop_set_name(gs, "B710-A-R780-A-", "DNT")
> gs_pop_set_name(gs, "B710-A+R780-A+", "DPT")
> plot(gs)
```

```
# Remove a node
> gs_pop_remove(gs, "DNT")
> plot(gs)
```

```
# retrieve the flow data for a node
> fs_CD8 <- gs_pop_get_data(gs, "CD8+")
```



Interactive gating with *flowGate*

<https://bioconductor.org/packages/release/bioc/html/flowGate.html>

```
if (!require("BiocManager", quietly = TRUE))
  install.packages("BiocManager")

BiocManager::install("flowGate")
```

- Interactive cytometry gating in R
- Based on a shiny app (web application using R)
- Especially geared toward wet-lab cytometerists looking to take advantage of R without having a lot of experience
- Uses GatingSet objects
- You can use transformed data, but flowGate was designed to apply desired transformations at the plotting level only

Interactive gating with *FlowGate*

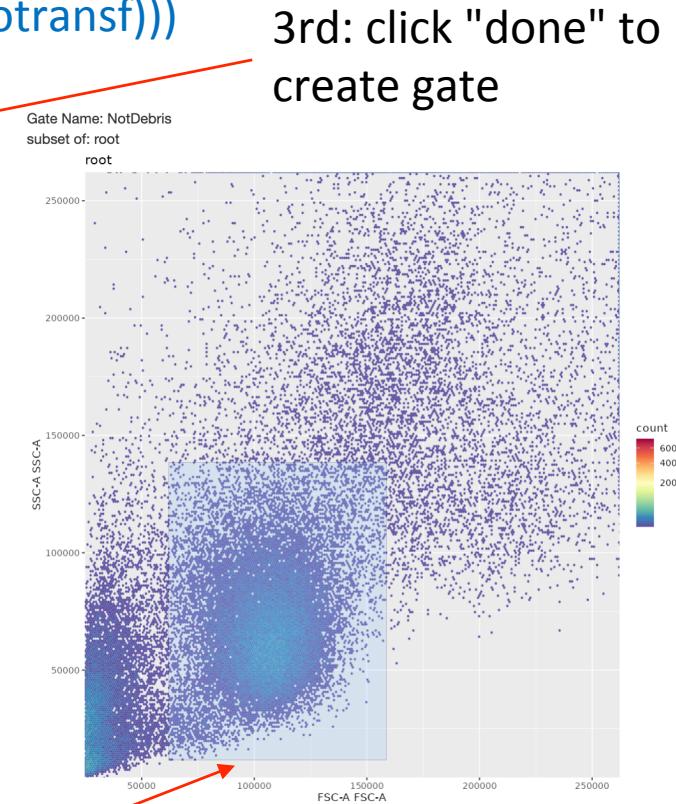
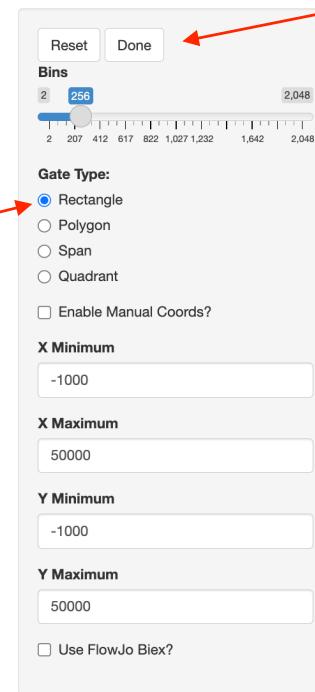
Load FCS files and preprocess

```
> fs <- read.flowSet(path="course_datasets/flowWorspaceData/", pattern = "*.fcs")
> panel <- pData(parameters(fs[[1]]))
> markerstotransf <- as.character(panel$name[!is.na(panel$desc)])
> fs <- transFlowVS(fs, channels = markerstotransf,
  cofactors = rep(3000,length(markerstotransf)))
```

Convert to GatingSet

```
> gs <- GatingSet(fs)
```

1st: chose type of gate



3rd: click "done" to create gate

Start the interactive gating

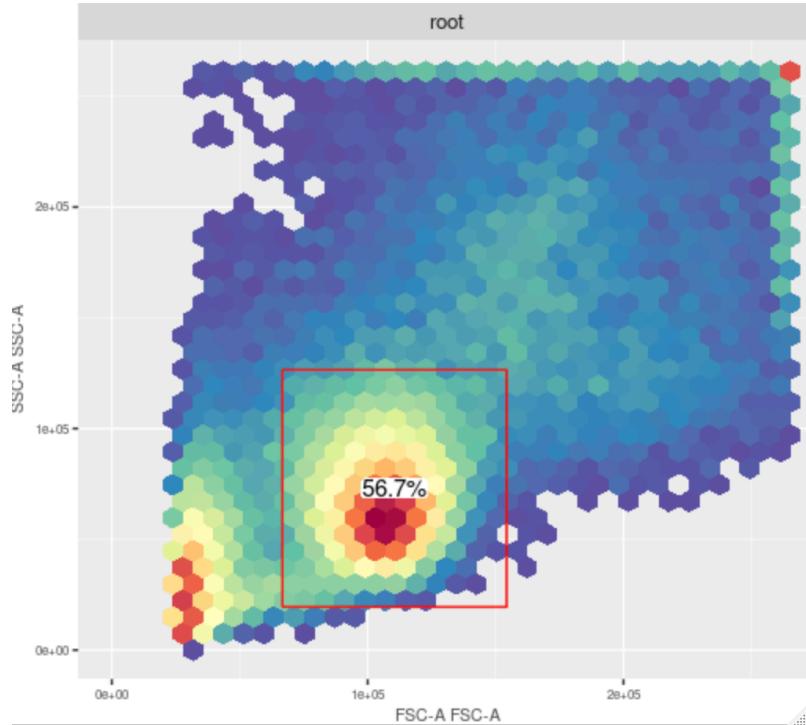
```
> gs_gate_interactive(gs,
  filterId = "NotDebris",
  dims = list("FSC-A", "SSC-A"))
```

2nd drag pointer to create gate

Interactive gating with *FlowGate*

```
# Plot the data with the new gate  
> autoplot(gs[[1]], gate = "NotDebris")
```

```
# Plot hierarchy  
> plot(gs)
```

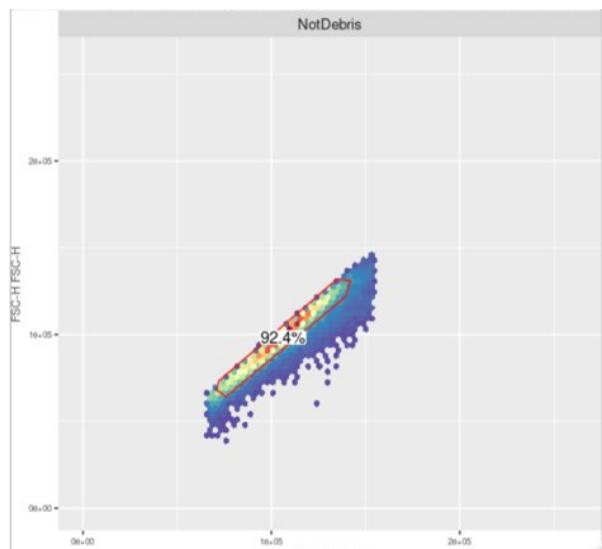


Interactive gating with *FlowGate*

Create a 2-D *polygon* gate

```
# Create a polygon gate  
> gs_gate_interactive(gs,  
                      filterId = "singlets",  
                      dims = list("FSC-A", "FSC-H"),  
                      subset = "NotDebris")
```

```
# check  
> autoplot(gs[[1]], gate = "singlets")
```



Draw your gate

Reset Done

Bins 2 256 2,048

Gate Type: Polygon Rectangle Span Quadrant

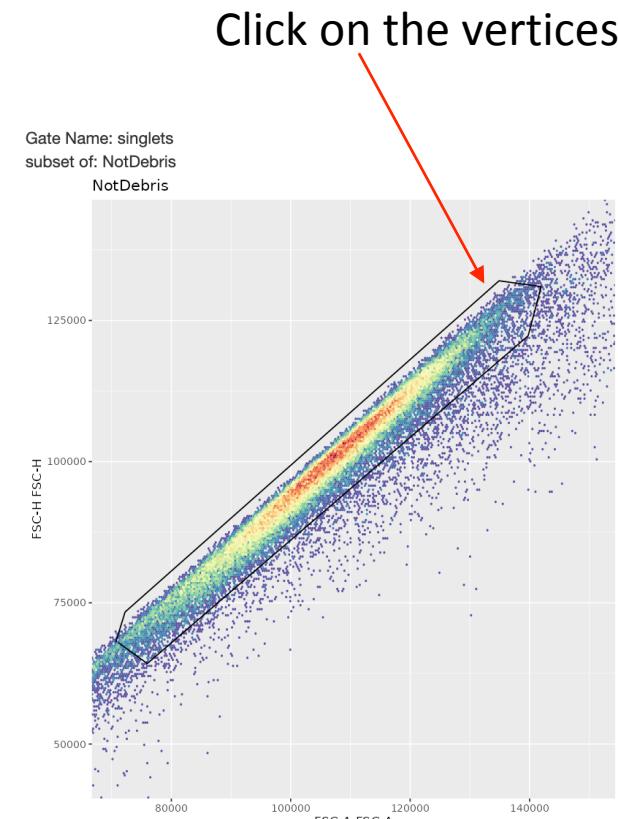
Enable Manual Coords?

X Minimum: -1000

X Maximum: 50000

Y Minimum: -1000

Y Maximum: 50000



```
> plot(gs)
```



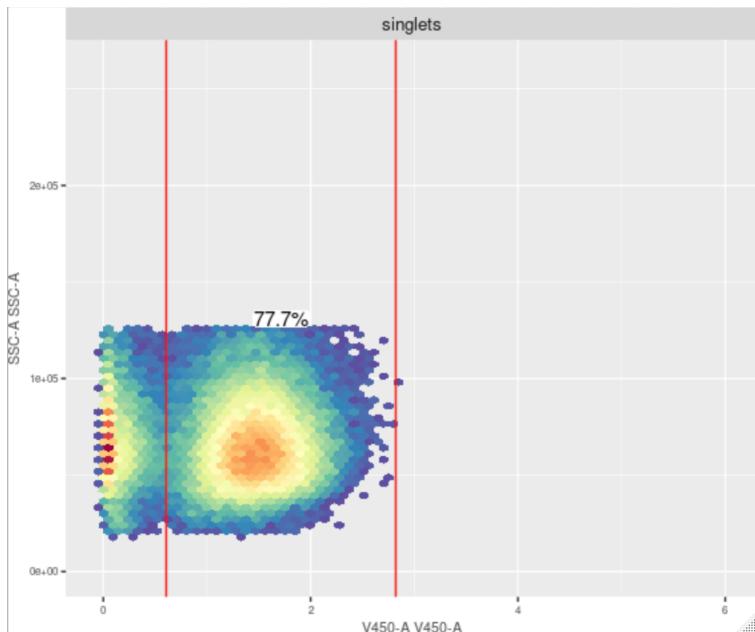
Interactive gating with *FlowGate*

Create a 1-D *span* gate

```
> gs_gate_interactive(gs,  
                      filterId = "CD3",  
                      dims = "V450-A",  
                      subset = "singlets")
```

Check the gate

```
> autoplot(gs[[1]], gate = "CD3")
```



Draw your gate

Reset Done

Bins 2 256 2,048

Gate Type:

Rectangle
 Polygon
 Span
 Quadrant

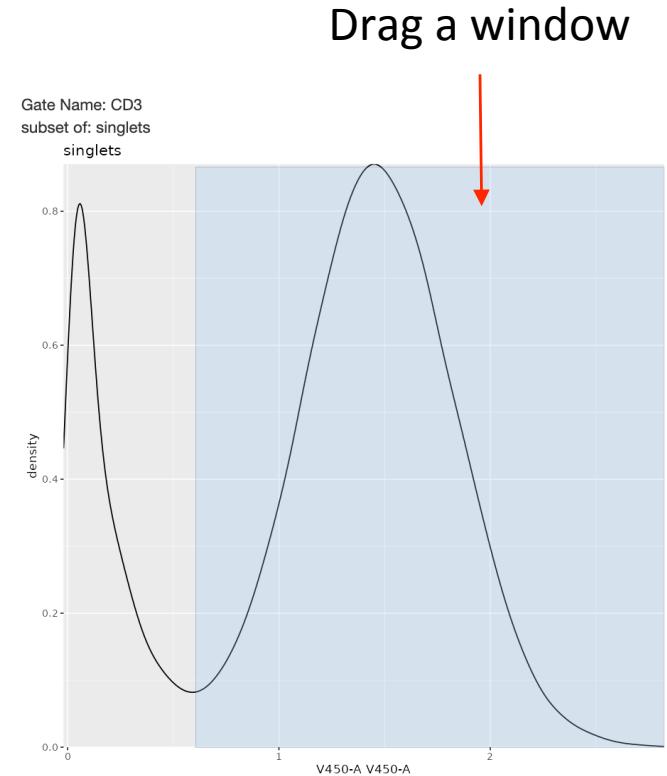
Enable Manual Coords?

X Minimum -1000

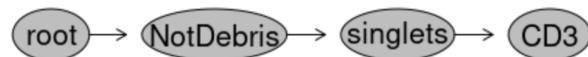
X Maximum 50000

Y Minimum -1000

Y Maximum 50000



```
> plot(gs)
```

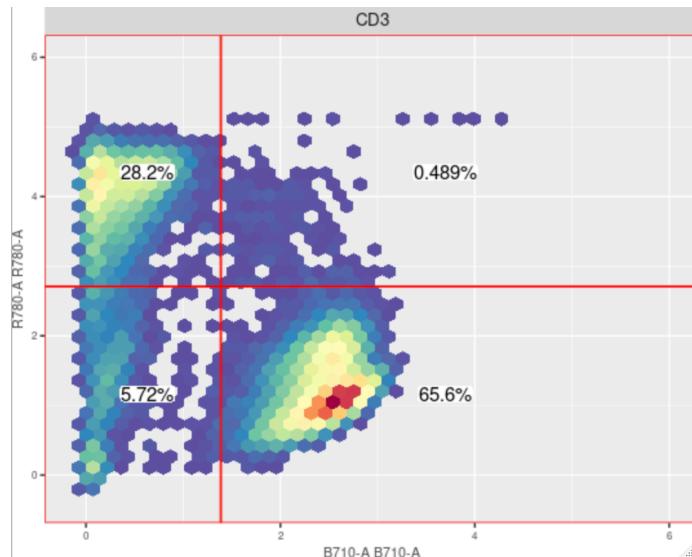


Interactive gating with *FlowGate*

Create a 2-D quadrant gate

```
> gs_gate_interactive(gs,  
  filterId = "CD4 CD8",  
  dims = c("B710-A",  
          "R780-A"),  
  subset = "CD3")
```

```
# check  
my_nodes <- gs_pop_get_children(gs,"CD3")  
autoplot(gs[[1]], my_nodes)
```



Draw your gate

Reset Done

Bins: 2 256 2,048

Gate Type:

- Rectangle
- Polygon
- Span
- Quadrant

Enable Manual Coords?

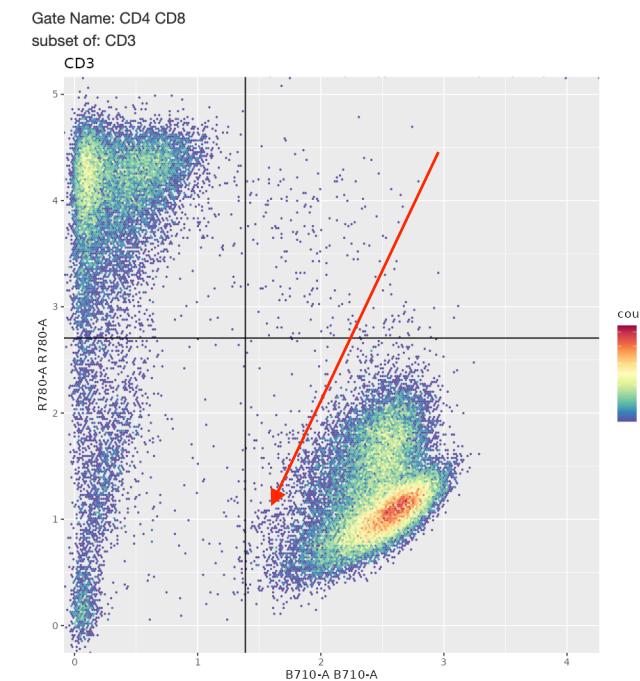
X Minimum: -1000

X Maximum: 50000

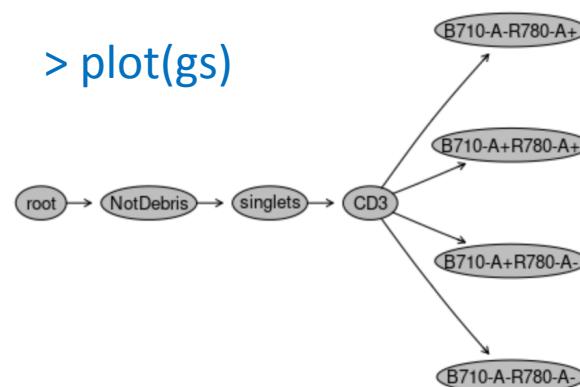
Y Minimum: -1000

Y Maximum: 50000

Select the origin of the quadrant



```
> plot(gs)
```



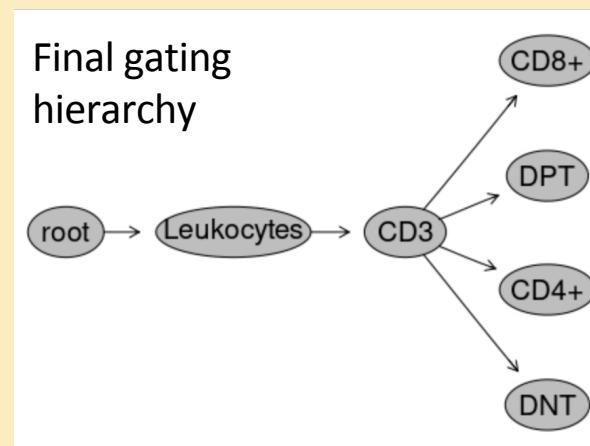
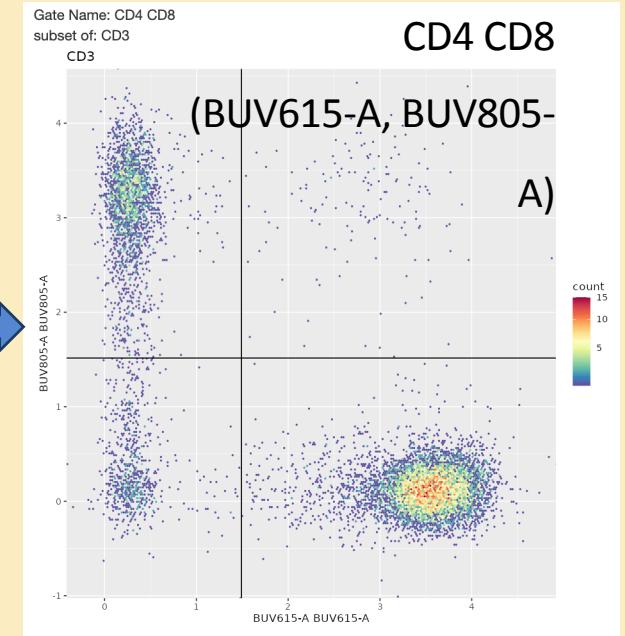
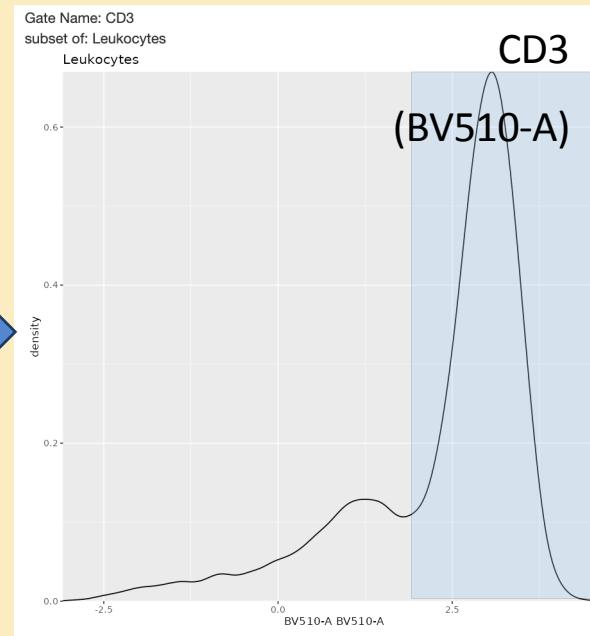
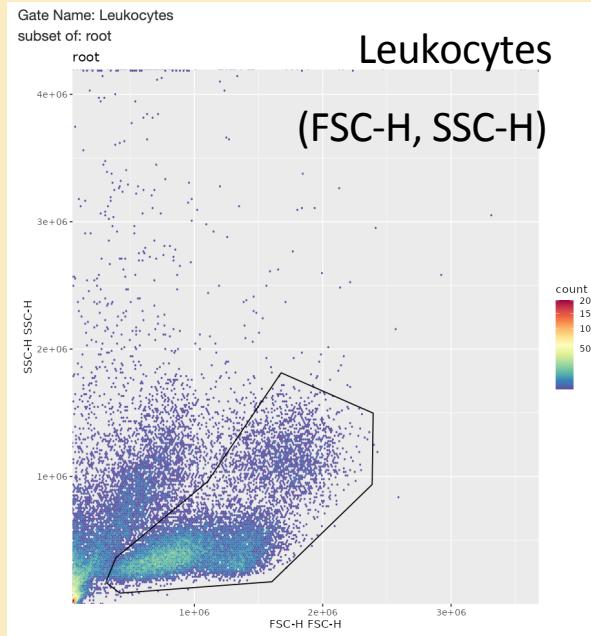
Let's practice – 9

In this exercise we will do some gating using flowGate and data from the **FR_FCM_Z3WR** of the FlowRepository.

Create a new script in which you will:

- 1) Create a flowSet of all samples within the `/course_dataset/FR_FCM_Z3WR` folder
- 2) Perform asinh transformation with a cofactor of 3000 for all channels not labeled with "none", using `transFlowVS()` from the `flowVS` package. Use the csv file with the panel previously created (`/course_datasets/FR_FCM_Z3WR/panel_with_marker_classes.csv`)
- 3) Convert the `flowSet` to a *GatingSet*
- 4) Using `flowGate`, create a gating hierarchy according to the scheme depicted in the following slide.
Don't forget to check your gating with scatter or density plots.
- 5) Do necessary adjustments so that your gating hierarchy looks like the one depicted in the next slide
- 6) What is the percentage of CD8+ T cells among T cells ("CD3")

Let's practice – 9 : Gates



04

Automated Gating

Automated gating with *flowClust*

<https://www.bioconductor.org/packages/release/bioc/html/flowClust.html>

```
if (!require("BiocManager", quietly = TRUE))
  install.packages("BiocManager")

BiocManager::install("flowClust")
```

- Robust Model-based Clustering of Flow Cytometry Data (Lo et al. 2008)
- Identify cell populations in flow cytometry data
- Based on a multivariate t mixture model with Box-Cox transformation
- Two options for **estimating the number of clusters when it is unknown**
- **Input are *flowFrames***

Automated gating with *openCyto*

<https://bioconductor.org/packages/release/bioc/html/openCyto.html>

```
if (!require("BiocManager", quietly = TRUE))
  install.packages("BiocManager")

BiocManager::install("openCyto")
```

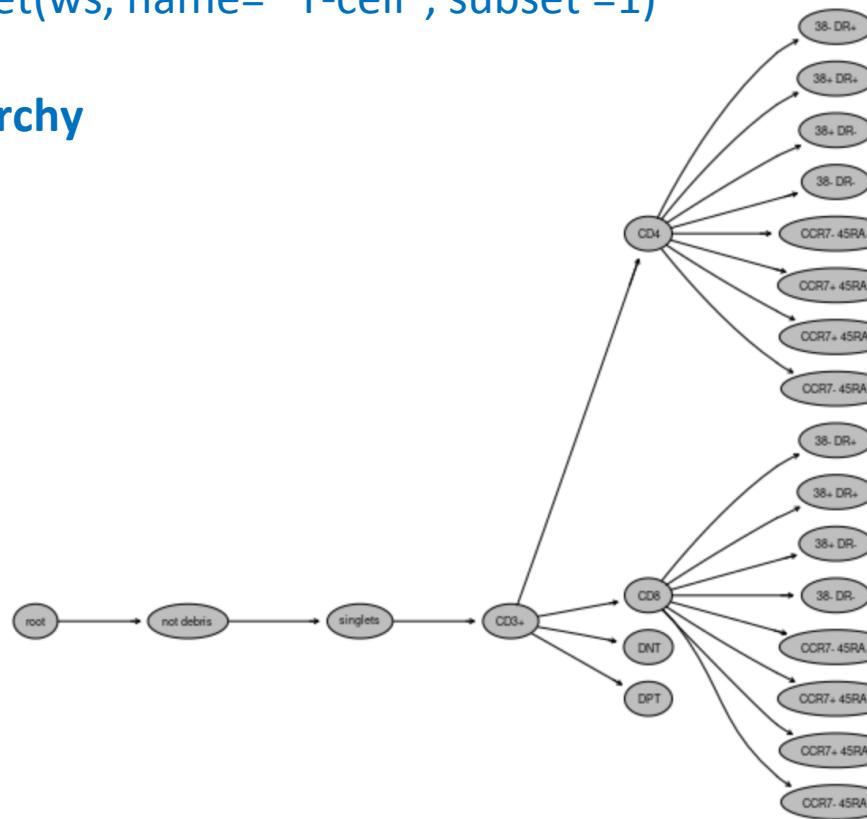
- Hierarchical gating pipeline for flow cytometry data
- Based on *GatingSet* objects
- Wide variety of methods, including *flowClust*
- Automated gating using a *gatingTemplate* (hierarchical gating scheme)
- Possibility of step-by-step gating without a template

Automated gating with *openCyto*

Example from flowWorkspaceData (gated data)

```
# Load example gatingSet from FlowJo workspace (xml file)
> library(CytoML)
> ws <- open_flowjo_xml("course_datasets/flowWorspaceData/manual.xml")
> gs_final <- flowjo_to_gatingset(ws, name= "T-cell", subset =1)
```

```
# Check complete gating hierarchy  
> plot(gs_final[[1]])
```

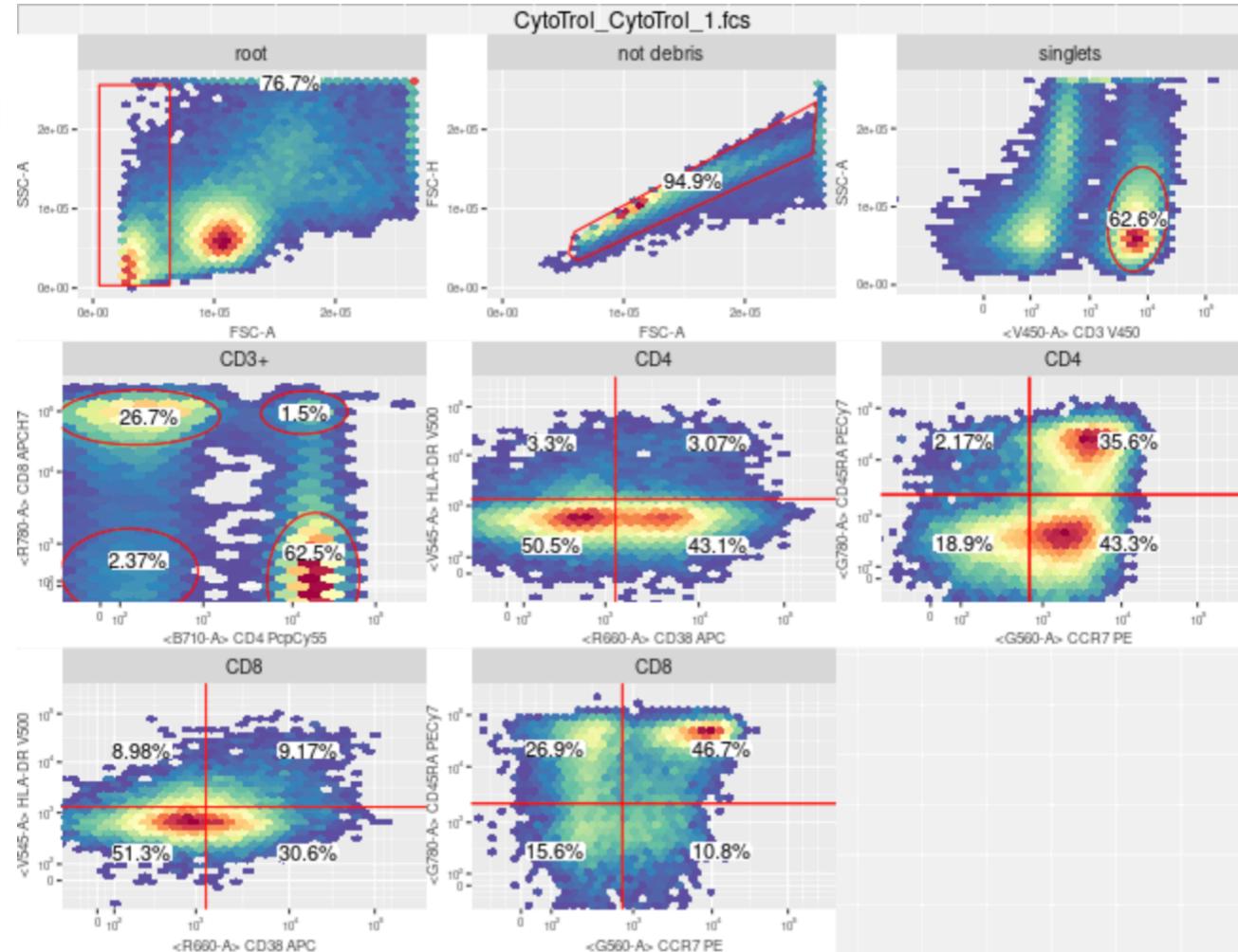


Automated gating with *openCyto*

Example from flowWorkspaceData (gated data)

Plot gates

```
> autoplot(gs_final[[1]])
```

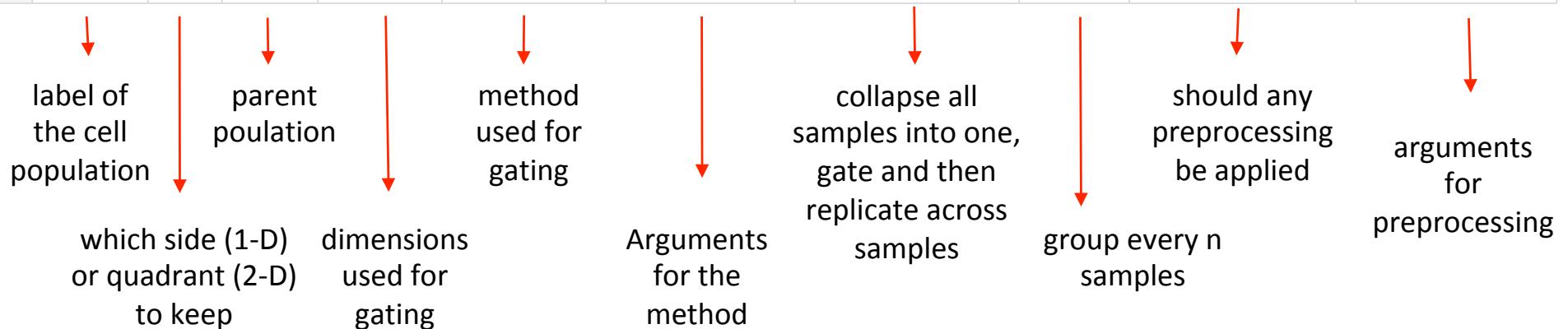


gatingTemplate

Check the structure of the *gatingTemplate*

```
> my_gt <- read.csv("course_datasets/flowWorkspaceData/tcell.csv")
> view(my_gt)
```

▲	alias	pop	parent	dims	gating_method	gating_args	collapseDataForGating	groupBy	preprocessing_method	preprocessing_args
1	nonDebris	+	root	FSC-A	gate_mindensity		NA	NA		NA
2	singlets	+	nonDebris	FSC-A,FSC-H	singletGate		NA	NA		NA
3	lymph	+	singlets	FSC-A,SSC-A	flowClust	K=2,target=c(1e5,5e4)	NA	NA	prior_flowClust	NA
4	cd3	+	lymph	CD3	gate_mindensity		TRUE	4		NA
5	*	-/+/-	cd3	cd4,cd8	gate_mindensity	gate_range=c(1,3)	NA	NA		NA
6	activated cd4	++	cd4+cd8-	CD38,HLA	gate_mindensity		NA	NA	standardize_flowset	NA
7	activated cd8	++	cd4-cd8+	CD38,HLA	gate_mindensity		NA	NA	standardize_flowset	NA
8	CD45_neg	-	cd4+cd8-	CD45RA	gate_mindensity	gate_range=c(2,3)	NA	NA		NA
9	CCR7_gate	+	CD45_neg	CCR7	flowClust	neg=1,pos=1	NA	NA		NA
10	*	+/-/-	cd4+cd8-	CCR7,CD45RA	refGate	CD45_neg:CCR7_gate	NA	NA		NA
11	*	+/-/-	cd4-cd8+	CCR7,CD45RA	gate_mindensity		NA	NA		NA



<https://bioconductor.org/packages/release/bioc/vignettes/openCyto/inst/doc/HowToWriteCSVTemplate.html>

gatingTemplate

Example of a 1-D scan gate

▲	alias	pop	parent	dims	gating_method	gating_args	collapseDataForGating	groupBy	preprocessing_method	preprocessing_args
1	nonDebris	+	root	FSC-A	gate_mindensity		NA	NA		NA

- The population name will be "nonDebris"
- The parent node is "root"
- The gating method is *mindensity*
- It will generate a scan gate on FSC-A and keep the only the positive cells

gatingTemplate

Example of a *singlet* gate

2	singlets	+	nonDebris	FSC-A,FSC-H	singletGate	NA	NA	NA
---	----------	---	-----------	-------------	-------------	----	----	----

- The population name will be "singlets"
- The parent node is "nonDebris"
- It will use FSC-A and FSC-H
- The gating method is *singletGate*
- It will generate a polygon gate on FSC-A and FSC-H to keep only the singlets

gatingTemplate

Example of a *flowClust* gate

3	lymph	+	singlets	FSC-A,SSC-A	flowClust	K=2,target=c(1e5,5e4)	NA	NA	prior_flowClust	NA
---	-------	---	----------	-------------	-----------	-----------------------	----	----	-----------------	----

- The population name will be "lymph"
- The parent node is "singlets"
- Use the method from *flowClust*
- It will generate an ellipsoid gate on FSC-A and SSC-A and split the cells in "peaks" (high density areas)
- There are parameters to be passed to *flowClust*: apply some preprocessing before gating; it should identify populations, centered

gatingTemplate

Example of a quadrant gate

5	*	-/+/-	cd3	cd4,cd8	gate_mindensity	gate_range=c(1,3)	NA	NA	NA	NA
---	---	-------	-----	---------	-----------------	-------------------	----	----	----	----

- Quadrant gate
- Based on mindesity for determining the origin of the quadrant
- Specifies that population CD4+/-CD8+/- should be expanded into 6 cell populations
 - The first two gates are span gates on each channel (CD4 and CD8)
 - The other four gates are rectangle gates that correspond to the four quadrants in the 2-D projection

openCyto

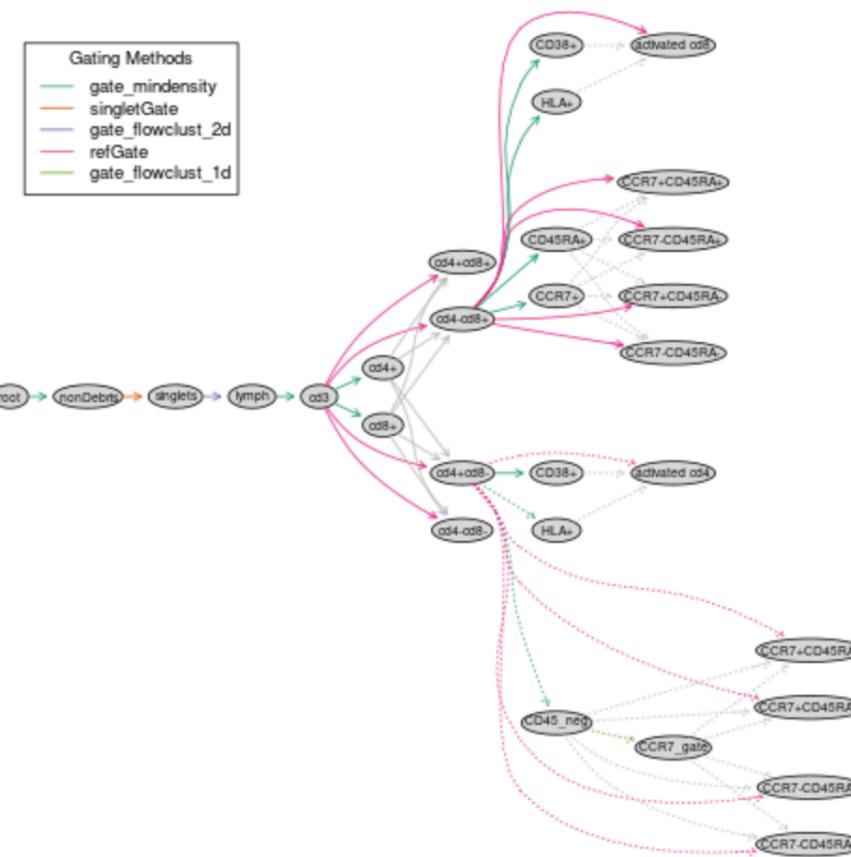
Create the gatingTemplate from the csv file

```
# Create the gatingTemplate from a file
```

```
> gt_tcell <- gatingTemplate("course_datasets/flowWorkspaceData/tcell.csv")
```

```
# Examine the gating scheme
```

```
> plot(gt_tcell)
```

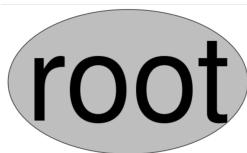


openCyto: run the gating pipeline

Load the raw data and convert to gatingSet

```
# Load the preprocessed but ungated data  
# The code used to preprocess this data is available in  
# /Code_slides/Code_preprocessing_data_openCyto.R  
> gs <- load_gs("course_datasets/flowWorspaceData/gs_preprocessed")
```

```
# Check  
> plot(gs)
```



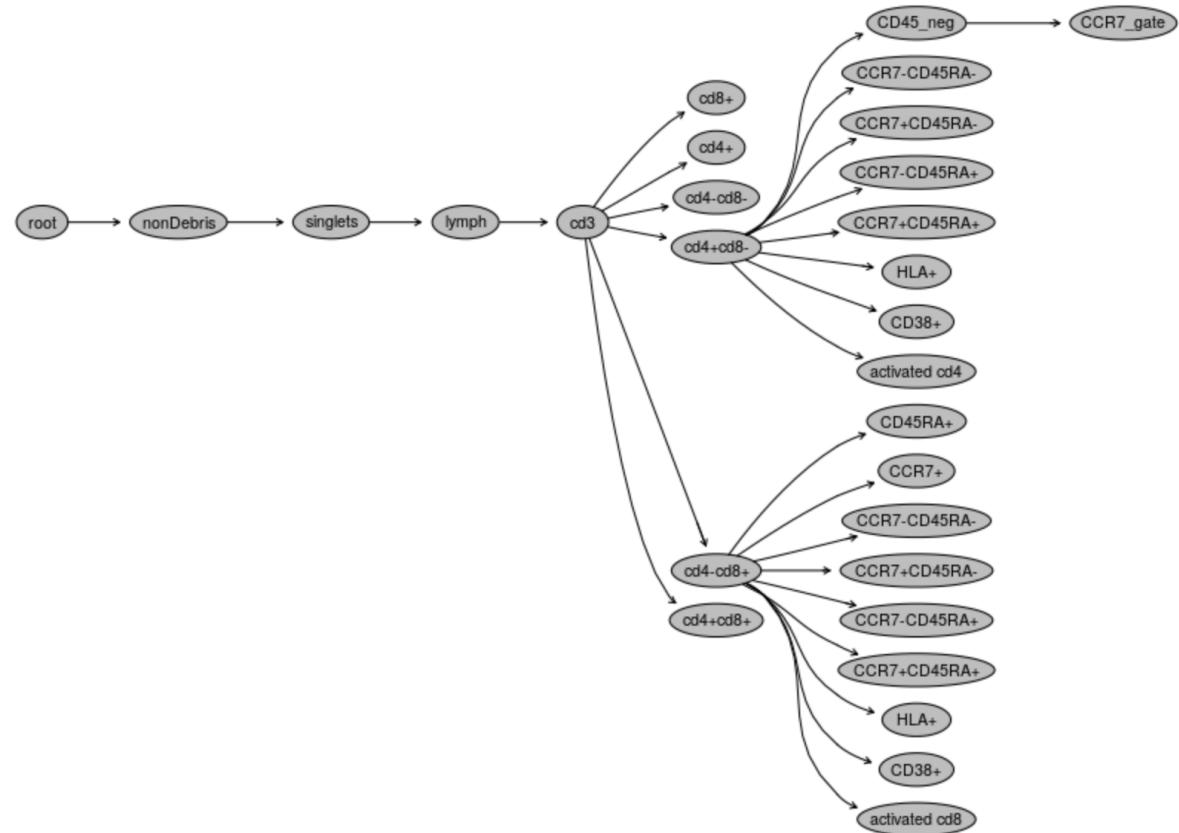
Apply the gating template

```
# Run the gating  
> gt_gating(gt_tcell, gs)
```

openCyto: run the gating pipeline

Check the gating

```
# Check the gating  
> plot(gs[[1]])
```



openCyto

Hide populations we are not interested in

```
# Define nodes to hide
```

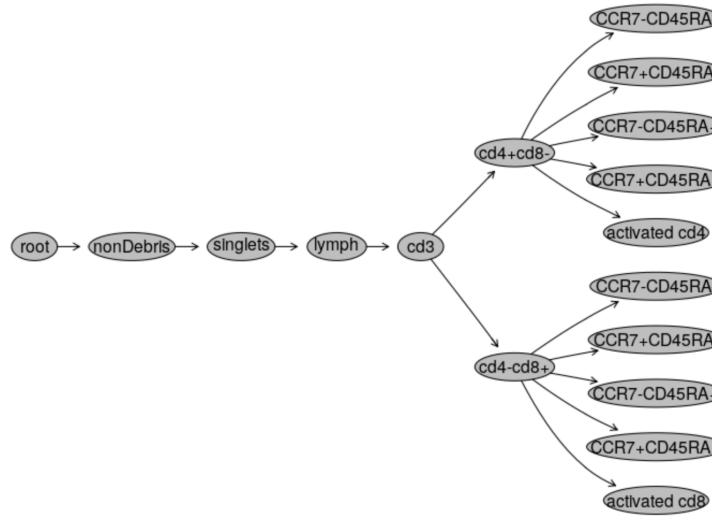
```
> nodesToHide <- c("cd8+", "cd4+", "cd4-cd8", "cd4+cd8+", "cd4+cd8-/HLA+",  
  "cd4+cd8-/CD38+", "cd4-cd8+/HLA+", "cd4-cd8+/CD38+",  
  "CD45_neg/CCR7_gate", "cd4+cd8-/CD45_neg",  
  "cd4-cd8+/CCR7+", "cd4-cd8+/CD45RA+" )
```

```
# Apply the gs_pop_set_visibility() function to the nodes to hide
```

```
> lapply(nodesToHide, function(thisNode) gs_pop_set_visibility(gs, thisNode, FALSE))
```

```
# Check after hiding nodes
```

```
> plot(gs[[1]])
```



openCyto

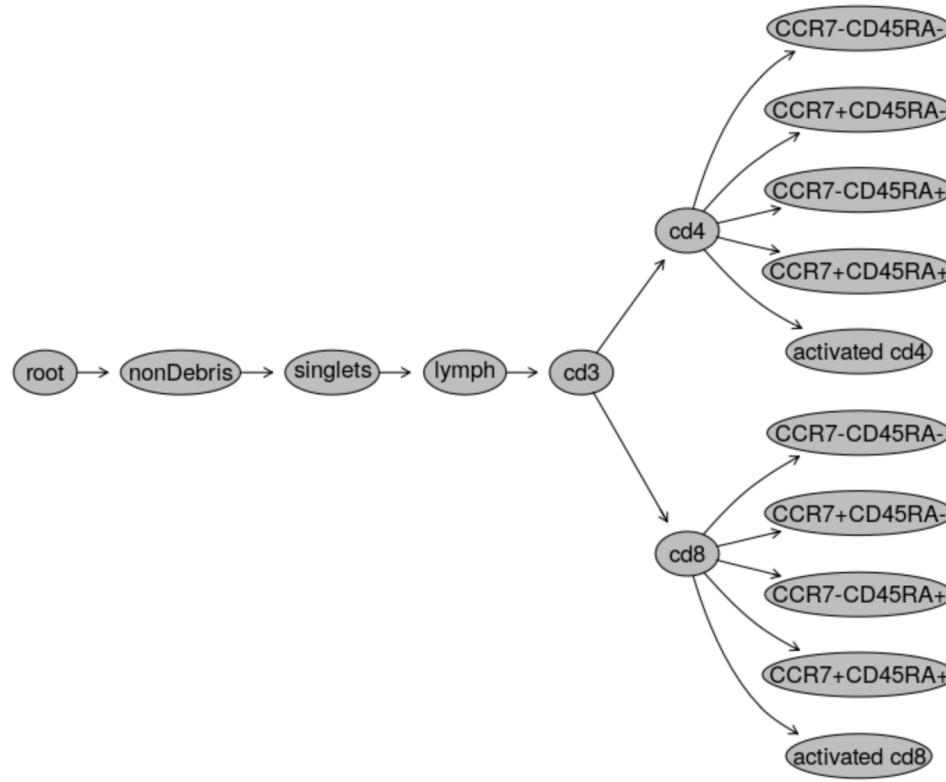
Rename some populations

Rename

```
> gs_pop_set_name(gs,"cd4+cd8-","cd4")
> gs_pop_set_name(gs,"cd4-cd8+","cd8")
```

Check

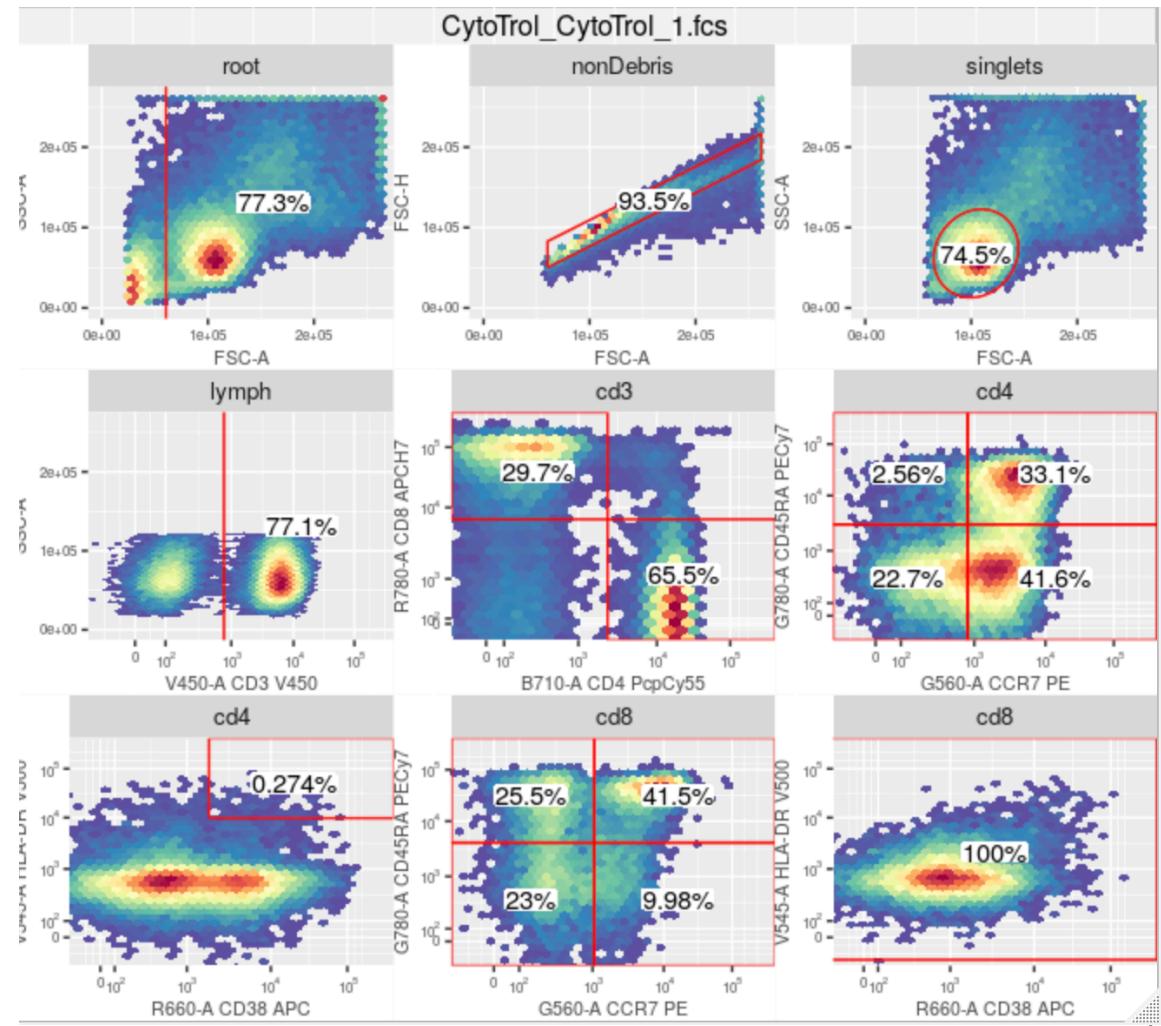
```
> plot(gs[[1]])
```



openCyto

Visualize the gates with *ggcyto*

```
> autoplot(gs[[1]])
```



openCyto: gating without a template

We can apply each automated gating step using the same fields as in the template

```
> gs_add_gating_method(gs,  
                        alias = "non-activated cd4",  
                        pop = "--",  
                        parent = "cd4",  
                        dims = "CD38,HLA",  
                        gating_method = "tailgate")
```

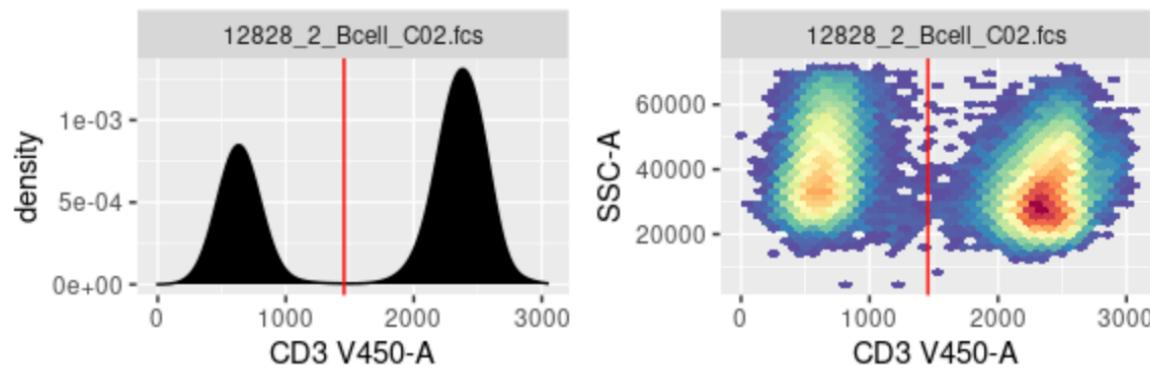
```
# check  
> plot(gs[[1]])
```

openCyto: overview of gating methods

<https://bioconductor.org/packages/release/bioc/vignettes/openCyto/inst/doc/HowToAutoGating.html>

mindensity

Finds the minimum as the cutpoint between positive and negative peaks in a 1-D density plot



- Fast, robust and easy to use
- For markers with a good separation between + and – peaks
- Needs more guidance when there are more than 2 peaks

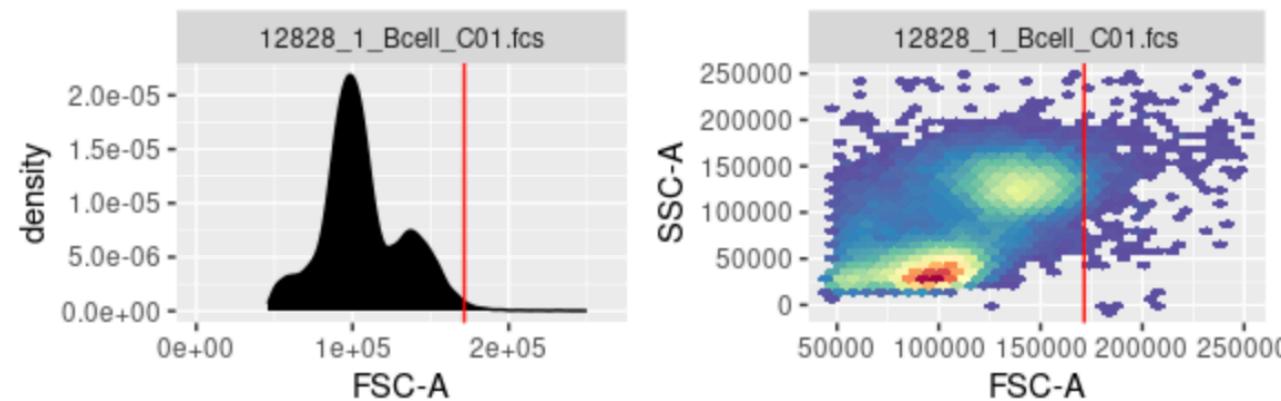
openCyto: overview of gating methods

tailgate

Gates the right side or left side of the 1-D density based on a cutpoint (estimated) in the tail

quantileGate

Alternative to tailgate and it determines the cutpoint by the events quantile

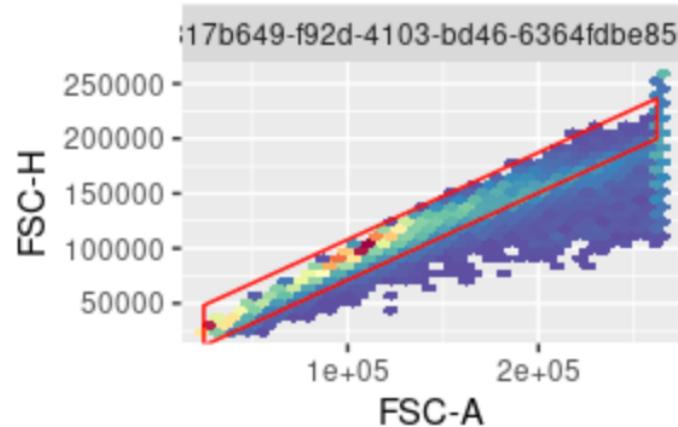


- More commonly used for rare populations (peak is not prominent enough)

openCyto: overview of gating methods

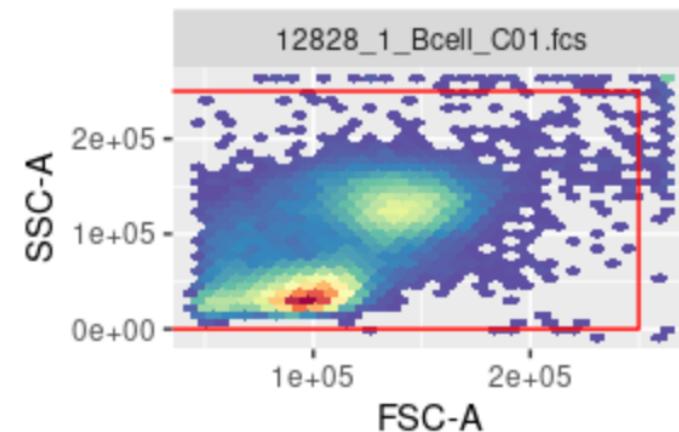
singletGate

Use the area vs height to gate out the singlets



boundary

Constructs a rectangle gate from input range (min and max)

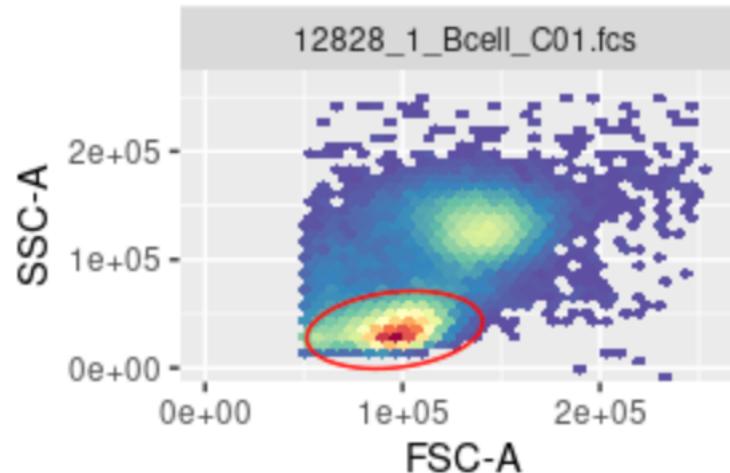


- Used for filtering out very extreme signals at the boundary

openCyto: overview of gating methods

flowClust

1-D or 2-D automated gating methods from flowClust (more details in ?flowClust)



- k = how many cell populations are expected
- $target$ = center of target population (by default the most prominent cluster)
- $quantile$ = how large the ellipse should be

Let's practice – 10

In this exercise we will repeat the gating previously done with *flowGate* on the data from **FR_FCM_Z3WR** of the FlowRepository, but this time using automated gating with *openCyto*.

Create a new script in which you will:

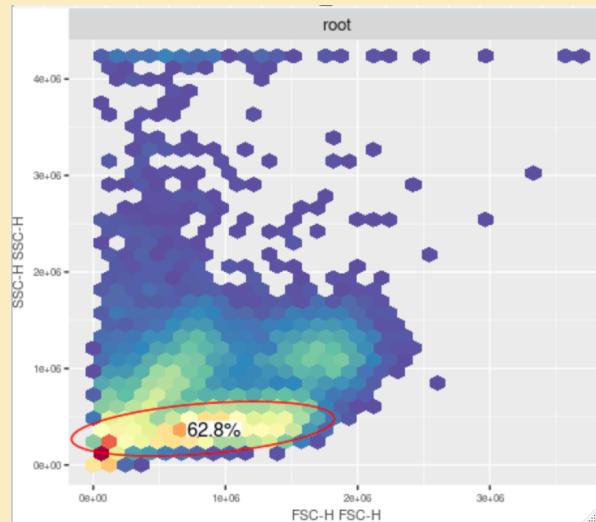
- 1) Repeat steps 1 to 4 from previous exercise (loading data from fcs files and preprocessing). You can also load the preprocessed GatingSet from `/course_dataset/FR_FCM_Z3WR/gs_preprocessed/`.
- 2) Using the `gs_add_gating_method()` function (i.e., without a template), create a gating hierarchy according to the scheme depicted in the following slide. Don't forget to check your gating with scatter or density plots.
- 3) Do necessary adjustments so that your gating hierarchy looks like the one depicted in the next slide (hide the "BUV805-A+" and "BUV615-A+" nodes from the tree, and rename the CD4, CD8, DNT and DPT nodes)
- 4) Create boxplots showing the percentage of CD8+ T cells among T cells ("CD3") as a function of time points

Let's practice – 10 : Gates

Leukocytes

(FSC-H, SSC-H)

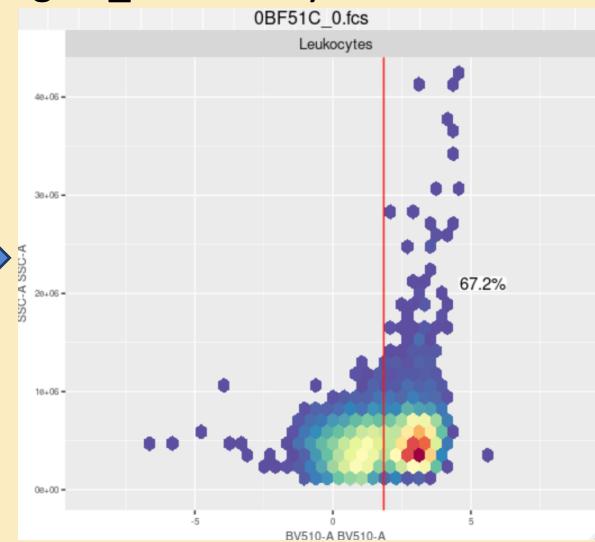
flowClust (K = 3)



CD3 +

(BV510-A)

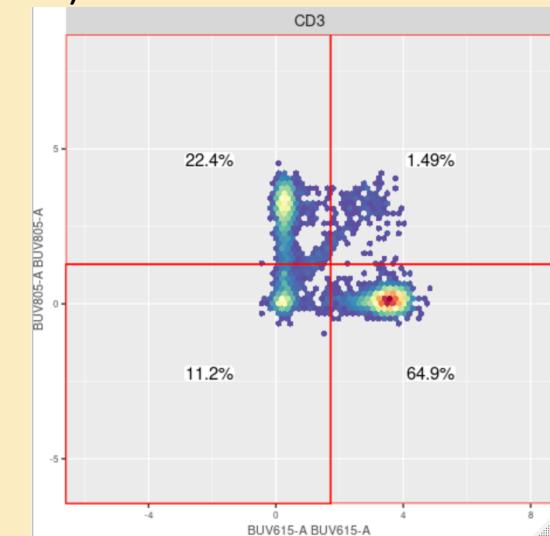
gate_mindensity



CD4 CD8

(BUV615-A, BUV805-

A)



Final gating hierarchy

