edgeR: differential expression analysis of digital gene expression data

User’s Guide

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First edition 17 September 2008
Last revised 20 April 2016
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Chapter 1

Introduction

1.1 Scope

This guide provides an overview of the Bioconductor package edgeR for differential expression analyses of read counts arising from RNA-Seq, SAGE or similar technologies [25]. The package can be applied to any technology that produces read counts for genomic features. Of particular interest are summaries of short reads from massively parallel sequencing technologies such as Illumina™, 454 or ABI SOLiD applied to RNA-Seq, SAGE-Seq or ChIP-Seq experiments and pooled shRNA-seq or CRISPR-Cas9 genetic screens. edgeR provides statistical routines for assessing differential expression in RNA-Seq experiments or differential marking in ChIP-Seq experiments.

The package implements exact statistical methods for multigroup experiments developed by Robinson and Smyth [27, 28]. It also implements statistical methods based on generalized linear models (glms), suitable for multifactor experiments of any complexity, developed by McCarthy et al. [17], Lund et al. [15], Chen et al. [5] and Lun et al. [14]. Sometimes we refer to the former exact methods as classic edgeR, and the latter as glm edgeR. However the two sets of methods are complementary and can often be combined in the course of a data analysis. Most of the glm functions can be identified by the letters “glm” as part of the function name. The glm functions can test for differential expression using either likelihood ratio tests [17, 5] or quasi-likelihood F-tests [15, 14].

A particular feature of edgeR functionality, both classic and glm, are empirical Bayes methods that permit the estimation of gene-specific biological variation, even for experiments with minimal levels of biological replication.

edgeR can be applied to differential expression at the gene, exon, transcript or tag level. In fact, read counts can be summarized by any genomic feature. edgeR analyses at the exon level are easily extended to detect differential splicing or isoform-specific differential expression.

This guide begins with brief overview of some of the key capabilities of package, and then gives a number of fully worked case studies, from counts to lists of genes.
1.2 Citation

The edgeR package implements statistical methods from the following publications. Please try to cite the appropriate articles when you publish results obtained using the software, as such citation is the main means by which the authors receive credit for their work.


Proposed the idea of sharing information between genes by estimating the negative binomial variance parameter globally across all genes. This made the use of negative binomial models practical for RNA-Seq and SAGE experiments with small to moderate numbers of replicates. Introduced the terminology *dispersion* for the variance parameter. Proposed conditional maximum likelihood for estimating the dispersion, assuming common dispersion across all genes. Developed an exact test for differential expression appropriate for the negative binomially distributed counts. Despite the official publication date, this was the first of the papers to be submitted and accepted for publication.


Introduced empirical Bayes moderated dispersion parameter estimation. This is a crucial improvement on the previous idea of estimating the dispersions from a global model, because it permits gene-specific dispersion estimation to be reliable even for small samples. Gene-specific dispersion estimation is necessary so that genes that behave consistently across replicates should rank more highly than genes that do not.


Announcement of the edgeR software package. Introduced the terminology *coefficient of biological variation*.


Introduced the idea of model-based scale normalization of RNA-Seq data. Proposed TMM normalization.


Extended negative binomial differential expression methods to glms, making the methods applicable to general experiments. Introduced the use of Cox-Reid approximate
conditional maximum likelihood for estimating the dispersion parameters, and used this for empirical Bayes moderation. Developed fast algorithms for fitting glms to thousands of genes in parallel. Gives a more complete explanation of the concept of \textit{biological coefficient of variation}.


This book chapter explains the \texttt{glmQLFTest} function, which is an alternative to \texttt{glmLRT}, and which replaces the chi-square approximation to the likelihood ratio statistic with a quasi-likelihood F-test.


This book chapter explains the \texttt{estimateDisp} function and the weighted likelihood empirical Bayes method.


This paper explains the \texttt{processAmplicons} function for obtaining counts from the fastq files of shRNA-seq and CRISPR-Cas9 genetic screens and outlines a general workflow for analyzing data from such screens.

1.3 How to get help

Most questions about edgeR will hopefully be answered by the documentation or references. If you’ve run into a question that isn’t addressed by the documentation, or you’ve found a conflict between the documentation and what the software does, then there is an active support community that can offer help.

The edgeR authors always appreciate receiving reports of bugs in the package functions or in the documentation. The same goes for well-considered suggestions for improvements. All other questions or problems concerning edgeR should be posted to the Bioconductor support site \url{https://support.bioconductor.org}. Please send requests for general assistance and advice to the support site rather than to the individual authors. Posting questions to the Bioconductor support site has a number of advantages. First, the support site includes a community of experienced edgeR users who can answer most common questions. Second, the edgeR authors try hard to ensure that any user posting to Bioconductor receives assistance. Third, the support site allows others with the same sort of questions to gain from the answers.
Users posting to the support site for the first time will find it helpful to read the posting guide at [http://www.bioconductor.org/help/support/posting-guide](http://www.bioconductor.org/help/support/posting-guide).

Note that each function in edgeR has its own online help page. For example, a detailed description of the arguments and output of the `exactTest` function can be read by typing `?exactTest` or `help(exactTest)` at the R prompt. If you have a question about any particular function, reading the function’s help page will often answer the question very quickly. In any case, it is good etiquette to check the relevant help page first before posting a question to the support site.

The authors do occasionally answer questions posted to other forums, such as SEQAnswers or Biostar, but it is not possible to do this on a regular basis.

### 1.4 Quick start

edgeR offers many variants on analyses. In general, the glm pipeline is recommended as it offers great flexibilities. There are two testing methods under the glm framework: likelihood ratio test and quasi-likelihood F-test. The details of these two methods are described in Chapter 2.

A typical edgeR analysis might look like the following. Here we assume there are four RNA-Seq libraries in two groups, and the counts are stored in a tab-delimited text file, with gene symbols in a column called `Symbol`.

To perform quasi-likelihood F-tests:

```r
> x <- read.delim("fileofcounts.txt",row.names="Symbol")
> group <- factor(c(1,1,2,2))
> y <- DGEList(counts=x,group=group)
> y <- calcNormFactors(y)
> design <- model.matrix(~group)
> y <- estimateDisp(y,design)
> fit <- glmQLFit(y,design)
> qlf <- glmQLFTest(fit,coef=2)
> topTags(qlf)
```

To perform likelihood ratio tests:

```r
> fit <- glmFit(y,design)
> lrt <- glmLRT(fit,coef=2)
> topTags(lrt)
```
Chapter 2

Overview of capabilities

2.1 Terminology

edgeR performs differential abundance analysis for pre-defined genomic features. Although not strictly necessary, it usually desirable that these genomic features are non-overlapping. For simplicity, we will henceforth refer to the genomic features as “genes”, although they could in principle be transcripts, exons, general genomic intervals or some other type of feature. For ChIP-seq experiments, abundance might relate to transcription factor binding or to histone mark occupancy, but we will henceforth refer to abundance as in terms of gene expression. In other words, the remainder of this guide will use terminology as for a gene-level analysis of an RNA-seq experiment, although the methodology is more widely applicable than that.

2.2 Aligning reads to a genome

The first step in an RNA-seq analysis is usually to align the raw sequence reads to a reference genome, although there are many variations on this process. Alignment needs to allow for the fact that reads may span multiple exons which may align to well separated locations on the genome. We find the subread-featureCounts pipeline [11, 12] to be very fast and effective for this purpose, but the Bowtie-TopHat-htseq pipeline is also very popular [1].

2.3 Producing a table of read counts

edgeR works on a table of integer read counts, with rows corresponding to genes and columns to independent libraries. The counts represent the total number of reads aligning to each gene (or other genomic locus).

Such counts can be produced from aligned reads by a variety of short read software tools. We find the featureCounts function of the Rsubread package [12] to be particularly effective
and convenient, but other tools are available such as `findOverlaps` in the GenomicRanges package or the Python software `htseq-counts`.

Reads can be counted in a number of ways. When conducting gene-level analyses, the counts could be for reads mapping anywhere in the genomic span of the gene or the counts could be for exons only. We usually count reads that overlap any exon for the given gene, including the UTR as part of the first exon [12].

For data from pooled shRNA-seq or CRISPR-Cas9 genetic screens, the `processAmplicons` function [7] can be used to obtain counts directly from fastq files.

Note that edgeR is designed to work with actual read counts. We not recommend that predicted transcript abundances are input the edgeR in place of actual counts.

## 2.4 Reading the counts from a file

If the table of counts has been written to a file, then the first step in any analysis will usually be to read these counts into an R session.

If the count data is contained in a single tab-delimited or comma-separated text file with multiple columns, one for each sample, then the simplest method is usually to read the file into R using one of the standard R read functions such as `read.delim`. See the quick start above, or the case study on LNCaP Cells, or the case study on oral carcinomas later in this guide for examples.

If the counts for different samples are stored in separate files, then the files have to be read separately and collated together. The edgeR function `readDGE` is provided to do this. Files need to contain two columns, one for the counts and one for a gene identifier.

## 2.5 The DGEList data class

dger stores data in a simple list-based data object called a `DGEList`. This type of object is easy to use because it can be manipulated like any list in R. The function `readDGE` makes a `DGEList` object directly. If the table of counts is already available as a matrix or a `data.frame`, `x` say, then a `DGEList` object can be made by

> `y <- DGEList(counts=x)`

A grouping factor can be added at the same time:

> `group <- c(1,1,2,2)`
> `y <- DGEList(counts=x, group=group)`

The main components of an `DGEList` object are a matrix `counts` containing the integer counts, a `data.frame` `samples` containing information about the samples or libraries, and a optional `data.frame` `genes` containing annotation for the genes or genomic features. The `data.frame` `samples` contains a column `lib.size` for the library size or sequencing depth for
each sample. If not specified by the user, the library sizes will be computed from the column sums of the counts. For classic edgeR the data.frame samples must also contain a column group, identifying the group membership of each sample.

2.6 Filtering

Genes with very low counts across all libraries provide little evidence for differential expression. In the biological point of view, a gene must be expressed at some minimal level before it is likely to be translated into a protein or to be biologically important. In addition, the pronounced discreteness of these counts interferes with some of the statistical approximations that are used later in the pipeline. These genes should be filtered out prior to further analysis.

As a rule of thumb, genes are dropped if they can’t possibly be expressed in all the samples for any of the conditions. Users can set their own definition of genes being expressed. Usually a gene is required to have a count of 5-10 in a library to be considered expressed in that library. Users should also filter with count-per-million (CPM) rather than filtering on the counts directly, as the latter does not account for differences in library sizes between samples.

Here is a simple example. Suppose the sample information of a DGEList object y is shown as follows:

```r
> y$samples

       group lib.size norm.factors
Sample1    1 10880519          1
Sample2    1  9314747          1
Sample3    1 11959792          1
Sample4    2  7460595          1
Sample5    2  6714958          1
```

We filter out lowly expressed genes using the following commands:

```r
> keep <- rowSums(cpm(y)>1) >= 2
> y <- y[keep, , keep.lib.sizes=FALSE]
```

Here, a CPM of 1 corresponds to a count of 6-7 in the smallest sample. A requirement for expression in two or more libraries is used as the minimum number of samples in each group is two. This ensures that a gene will be retained if it is only expressed in both samples in group 2. It is also recommended to recalculate the library sizes of the DGEList object after the filtering though the difference is usually negligible.
2.7 Normalization

2.7.1 Normalization is only necessary for sample-specific effects

edgeR is concerned with differential expression analysis rather than with the quantification of expression levels. It is concerned with relative changes in expression levels between conditions, but not directly with estimating absolute expression levels. This greatly simplifies the technical influences that need to be taken into account, because any technical factor that is unrelated to the experimental conditions should cancel out of any differential expression analysis. For example, read counts can generally be expected to be proportional to length as well as to expression for any transcript, but edgeR does not generally need to adjust for gene length because gene length has the same relative influence on the read counts for each RNA sample. For this reason, normalization issues arise only to the extent that technical factors have sample-specific effects.

2.7.2 Sequencing depth

The most obvious technical factor that affects the read counts, other than gene expression levels, is the sequencing depth of each RNA sample. edgeR adjusts any differential expression analysis for varying sequencing depths as represented by differing library sizes. This is part of the basic modeling procedure and flows automatically into fold-change or p-value calculations. It is always present, and doesn’t require any user intervention.

2.7.3 RNA composition

The second most important technical influence on differential expression is one that is less obvious. RNA-seq provides a measure of the relative abundance of each gene in each RNA sample, but does not provide any measure of the total RNA output on a per-cell basis. This commonly becomes important when a small number of genes are very highly expressed in one sample, but not in another. The highly expressed genes can consume a substantial proportion of the total library size, causing the remaining genes to be under-sampled in that sample. Unless this RNA composition effect is adjusted for, the remaining genes may falsely appear to be down-regulated in that sample [26].

The calcNormFactors function normalizes for RNA composition by finding a set of scaling factors for the library sizes that minimize the log-fold changes between the samples for most genes. The default method for computing these scale factors uses a trimmed mean of M-values (TMM) between each pair of samples [26]. We call the product of the original library size and the scaling factor the effective library size. The effective library size replaces the original library size in all downstream analyses.
2.7.4 GC content

The GC-content of each gene does not change from sample to sample, so it can be expected to have little effect on differential expression analyses to a first approximation. Recent publications, however, have demonstrated that sample-specific effects for GC-content can be detected [24, 9]. The EDASeq [24] and cqn [9] packages estimate correction factors that adjust for sample-specific GC-content effects in a way that is compatible with edgeR. In each case, the observation-specific correction factors can be input into the glm functions of edgeR as an offset matrix.

2.7.5 Gene length

Like GC-content, gene length does not change from sample to sample, so it can be expected to have little effect on differential expression analyses. Nevertheless, sample-specific effects for gene length have been detected [9], although the evidence is not as strong as for GC-content.

2.7.6 Model-based normalization, not transformation

In edgeR, normalization takes the form of correction factors that enter into the statistical model. Such correction factors are usually computed internally by edgeR functions, but it is also possible for a user to supply them. The correction factors may take the form of scaling factors for the library sizes, such as computed by calcNormFactors, which are then used to compute the effective library sizes. Alternatively, gene-specific correction factors can be entered into the glm functions of edgeR as offsets. In the latter case, the offset matrix will be assumed to account for all normalization issues, including sequencing depth and RNA composition.

Note that normalization in edgeR is model-based, and the original read counts are not themselves transformed. This means that users should not transform the read counts in any way before inputting them to edgeR. For example, users should not enter RPKM or FPKM values to edgeR in place of read counts. Such quantities will prevent edgeR from correctly estimating the mean-variance relationship in the data, which is a crucial to the statistical strategies underlying edgeR. Similarly, users should not add artificial values to the counts before inputting them to edgeR.

edgeR is not designed to work with estimated expression levels, for example as might be output by Cufflinks. edgeR can work with expected counts as output by RSEM, but raw counts are still preferred.

2.7.7 Pseudo-counts

The classic edgeR functions estimateCommonDisp and exactTest produce a matrix of pseudo-counts as part of the output object. The pseudo-counts are used internally to speed up computation of the conditional likelihood used for dispersion estimation and exact tests
in the classic edgeR pipeline. The pseudo-counts represent the equivalent counts would have been observed had the library sizes all been equal, assuming the fitted model. The pseudo-counts are computed for a specific purpose, and their computation depends on the experimental design as well as the library sizes, so users are advised not to interpret the pseudo-counts as general-purpose normalized counts. They are intended mainly for internal use in the edgeR pipeline.

Disambiguation. Note that some other software packages use the term pseudo-count to mean something analogous to prior counts in edgeR, i.e., a starting value that is added to a zero count to avoid missing values when computing logarithms. In edgeR, a pseudo-count is a type of normalized count and a prior count is a starting value used to offset small counts.

2.8 Negative binomial models

2.8.1 Introduction

The starting point for an RNA-Seq experiment is a set of \( n \) RNA samples, typically associated with a variety of treatment conditions. Each sample is sequenced, short reads are mapped to the appropriate genome, and the number of reads mapped to each genomic feature of interest is recorded. The number of reads from sample \( i \) mapped to gene \( g \) will be denoted \( y_{gi} \). The set of genewise counts for sample \( i \) makes up the expression profile or library for that sample. The expected size of each count is the product of the library size and the relative abundance of that gene in that sample.

2.8.2 Biological coefficient of variation (BCV)

RNA-Seq profiles are formed from \( n \) RNA samples. Let \( \pi_{gi} \) be the fraction of all cDNA fragments in the \( i \)th sample that originate from gene \( g \). Let \( G \) denote the total number of genes, so \( \sum_{g=1}^{G} \pi_{gi} = 1 \) for each sample. Let \( \sqrt{\phi_{g}} \) denote the coefficient of variation (CV) (standard deviation divided by mean) of \( \pi_{gi} \) between the replicates \( i \). We denote the total number of mapped reads in library \( i \) by \( N_{i} \) and the number that map to the \( g \)th gene by \( y_{gi} \). Then

\[
E(y_{gi}) = \mu_{gi} = N_{i}\pi_{gi}.
\]

Assuming that the count \( y_{gi} \) follows a Poisson distribution for repeated sequencing runs of the same RNA sample, a well known formula for the variance of a mixture distribution implies:

\[
\text{var}(y_{gi}) = \mu_{gi} \left[ \text{var}(\pi) \right] + \text{var}\left[ E(y|\pi) \right] = \mu_{gi} + \phi_{g}\mu_{gi}^{2}.
\]

Dividing both sides by \( \mu_{gi}^{2} \) gives

\[
\text{CV}^{2}(y_{gi}) = 1/\mu_{gi} + \phi_{g}.
\]
The first term $1/\mu_{gi}$ is the squared CV for the Poisson distribution and the second is the squared CV of the unobserved expression values. The total $\text{CV}^2$ therefore is the technical $\text{CV}^2$ with which $\pi_{gi}$ is measured plus the biological $\text{CV}^2$ of the true $\pi_{gi}$. In this article, we call $\phi_g$ the dispersion and $\sqrt{\phi_g}$ the biological CV although, strictly speaking, it captures all sources of the inter-library variation between replicates, including perhaps contributions from technical causes such as library preparation as well as true biological variation between samples.

Two levels of variation can be distinguished in any RNA-Seq experiment. First, the relative abundance of each gene will vary between RNA samples, due mainly to biological causes. Second, there is measurement error, the uncertainty with which the abundance of each gene in each sample is estimated by the sequencing technology. If aliquots of the same RNA sample are sequenced, then the read counts for a particular gene should vary according to a Poisson law [16]. If sequencing variation is Poisson, then it can be shown that the squared coefficient of variation (CV) of each count between biological replicate libraries is the sum of the squared CVs for technical and biological variation respectively,

$$\text{Total CV}^2 = \text{Technical CV}^2 + \text{Biological CV}^2.$$  

Biological CV (BCV) is the coefficient of variation with which the (unknown) true abundance of the gene varies between replicate RNA samples. It represents the CV that would remain between biological replicates if sequencing depth could be increased indefinitely. The technical CV decreases as the size of the counts increases. BCV on the other hand does not. BCV is therefore likely to be the dominant source of uncertainty for high-count genes, so reliable estimation of BCV is crucial for realistic assessment of differential expression in RNA-Seq experiments. If the abundance of each gene varies between replicate RNA samples in such a way that the genewise standard deviations are proportional to the genewise means, a commonly occurring property of measurements on physical quantities, then it is reasonable to suppose that BCV is approximately constant across genes. We allow however for the possibility that BCV might vary between genes and might also show a systematic trend with respect to gene expression or expected count.

The magnitude of BCV is more important than the exact probabilistic law followed by the true gene abundances. For mathematical convenience, we assume that the true gene abundances follow a gamma distributional law between replicate RNA samples. This implies that the read counts follow a negative binomial probability law.

### 2.8.3 Estimating BCVs

When a negative binomial model is fitted, we need to estimate the BCV(s) before we carry out the analysis. The BCV, as shown in the previous section, is the square root of the dispersion parameter under the negative binomial model. Hence, it is equivalent to estimating the dispersion(s) of the negative binomial model.
The parallel nature of sequencing data allows some possibilities for borrowing information from the ensemble of genes which can assist in inference about each gene individually. The easiest way to share information between genes is to assume that all genes have the same mean-variance relationship, in other words, the dispersion is the same for all the genes [28]. An extension to this “common dispersion” approach is to put a mean-dependent trend on a parameter in the variance function, so that all genes with the same expected count have the same variance.

However, the truth is that the gene expression levels have non-identical and dependent distribution between genes, which makes the above assumptions too naive. A more general approach that allows genewise variance functions with empirical Bayes shrinkage was introduced several years ago [27] and has recently been extended to generalized linear models and thus more complex experimental designs [17]. Only when using tagwise dispersion will genes that are consistent between replicates be ranked more highly than genes that are not. It has been seen in many RNA-Seq datasets that allowing gene-specific dispersion is necessary in order that differential expression is not driven by outliers. Therefore, the tagwise dispersions are strongly recommended in model fitting and testing for differential expression.

In edgeR, we first estimate a common dispersion for all the tags and then apply an empirical Bayes strategy for squeezing the tagwise dispersions towards the common dispersion. The amount of shrinkage is determined by the prior weight given to the common dispersion (or the dispersion trend) and the precision of the tagwise estimates, and can be considered as the prior degrees of freedom. This prior degrees of freedom is estimated by examining the heteroskedasticity of the data [5].

2.8.4 Quasi negative binomial

The NB model can be extended with quasi-likelihood (QL) methods to account for gene-specific variability from both biological and technical sources [15, 14]. Under the QL framework, the variance of the count \( y_{gi} \) is a quadratic function of the mean,

\[
\text{var}(y_{gi}) = \sigma^2_g (\mu_{gi} + \phi \mu^2_{gi}),
\]

where \( \phi \) is the NB dispersion parameter and \( \sigma^2_g \) is the QL dispersion parameter.

Any increase in the observed variance of \( y_{gi} \) will be modelled by an increase in the estimates for \( \phi \) and/or \( \sigma^2_g \). In this model, the NB dispersion \( \phi \) is a global parameter whereas the QL is gene-specific, so the two dispersion parameters have different roles. The NB dispersion describes the overall biological variability across all genes. It represents the observed variation that is attributable to inherent variability in the biological system, in contrast to the Poisson variation from sequencing. The QL dispersion picks up any gene-specific variability above and below the overall level.

The common NB dispersion for the entire data set can be used for the global parameter. In practice, we use the trended dispersions to account for the empirical mean-variance re-
relationships. Since the NB dispersion under the QL framework reflects the overall biological variability, it does not make sense to use the tagwise dispersions.

Estimation of the gene-specific QL dispersion is difficult as most RNA-seq data sets have limited numbers of replicates. This means that there is often little information to stably estimate the dispersion for each gene. To overcome this, an empirical Bayes (EB) approach is used whereby information is shared between genes [30, 15, 21]. Briefly, a mean-dependent trend is fitted to the raw QL dispersion estimates. The raw estimates are then squeezed towards this trend to obtain moderated EB estimates, which can be used in place of the raw values for downstream hypothesis testing. This EB strategy reduces the uncertainty of the estimates and improves testing power.

2.9 Pairwise comparisons between two or more groups (classic)

2.9.1 Estimating dispersions

edgeR uses the quantile-adjusted conditional maximum likelihood (qCML) method for experiments with single factor.

Compared against several other estimators (e.g. maximum likelihood estimator, Quasi-likelihood estimator etc.) using an extensive simulation study, qCML is the most reliable in terms of bias on a wide range of conditions and specifically performs best in the situation of many small samples with a common dispersion, the model which is applicable to Next-Gen sequencing data. We have deliberately focused on very small samples due to the fact that DNA sequencing costs prevent large numbers of replicates for SAGE and RNA-seq experiments.

The qCML method calculates the likelihood by conditioning on the total counts for each tag, and uses pseudo counts after adjusting for library sizes. Given a table of counts or a DGEList object, the qCML common dispersion and tagwise dispersions can be estimated using the estimateDisp() function. Alternatively, one can estimate the qCML common dispersion using the estimateCommonDisp() function, and then the qCML tagwise dispersions using the estimateTagwiseDisp() function.

However, the qCML method is only applicable on datasets with a single factor design since it fails to take into account the effects from multiple factors in a more complicated experiment. When an experiment has more than one factor involved, we need to seek a new way of estimating dispersions.

Here is a simple example of estimating dispersions using the qCML method. Given a DGEList object y, we estimate the dispersions using the following commands.

To estimate common dispersion and tagwise dispersions in one run (recommended):

\[
y <- \text{estimateDisp}(y)
\]

Alternatively, to estimate common dispersion:

\[
y <- \text{estimateDisp}(y)
\]
y <- estimateCommonDisp(y)

Then to estimate tagwise dispersions:

y <- estimateTagwiseDisp(y)

Note that common dispersion needs to be estimated before estimating tagwise dispersions if they are estimated separately.

### 2.9.2 Testing for DE genes

For all the Next-Gen sequencing data analyses we consider here, people are most interested in finding differentially expressed genes/tags between two (or more) groups. Once negative binomial models are fitted and dispersion estimates are obtained, we can proceed with testing procedures for determining differential expression using the exact test.

The exact test is based on the qCML methods. Knowing the conditional distribution for the sum of counts in a group, we can compute exact $p$-values by summing over all sums of counts that have a probability less than the probability under the null hypothesis of the observed sum of counts. The exact test for the negative binomial distribution has strong parallels with Fisher’s exact test.

As we discussed in the previous section, the exact test is only applicable to experiments with a single factor. The testing can be done by using the function `exactTest()`, and the function allows both common dispersion and tagwise dispersion approaches. For example:

```r
> et <- exactTest(y)
> topTags(et)
```

### 2.10 More complex experiments (glm functionality)

#### 2.10.1 Generalized linear models

Generalized linear models (GLMs) are an extension of classical linear models to nonnormally distributed response data [20, 19]. GLMs specify probability distributions according to their mean-variance relationship, for example the quadratic mean-variance relationship specified above for read counts. Assuming that an estimate is available for $\phi_g$, so the variance can be evaluated for any value of $\mu_{gi}$, GLM theory can be used to fit a log-linear model

$$
\log \mu_{gi} = x_i^T \beta_g + \log N_i
$$

for each gene [13, 4]. Here $x_i$ is a vector of covariates that specifies the treatment conditions applied to RNA sample $i$, and $\beta_g$ is a vector of regression coefficients by which the covariate effects are mediated for gene $g$. The quadratic variance function specifies the negative binomial GLM distributional family. The use of the negative binomial distribution is equivalent to treating the $\pi_{gi}$ as gamma distributed.
2.10.2 Estimating dispersions

For general experiments (with multiple factors), edgeR uses the Cox-Reid profile-adjusted likelihood (CR) method in estimating dispersions. The CR method is derived to overcome the limitations of the qCML method as mentioned above. It takes care of multiple factors by fitting generalized linear models (GLM) with a design matrix.

The CR method is based on the idea of approximate conditional likelihood which reduces to residual maximum likelihood. Given a table counts or a DGEList object and the design matrix of the experiment, generalized linear models are fitted. This allows valid estimation of the dispersion, since all systematic sources of variation are accounted for.

The CR method can be used to calculate a common dispersion for all the tags, trended dispersion depending on the tag abundance, or separate dispersions for individual tags. These can be done by calling the function estimateDisp() with a specified design. Alternatively, one can estimate the common, trended and tagwise dispersions separately using estimateGLMCommonDisp(), estimateGLMTrendedDisp() and estimateGLMTagwiseDisp(), respectively. The tagwise dispersion approach is strongly recommended in multi-factor experiment cases.

Here is a simple example of estimating dispersions using the GLM method. Given a DGEList object y and a design matrix, we estimate the dispersions using the following commands.

To estimate common dispersion, trended dispersions and tagwise dispersions in one run (recommended):

\[
y \leftarrow \text{estimateDisp}(y, \text{design})
\]

Alternatively, one can use the following calling sequence to estimate them one by one.

To estimate common dispersion:

\[
y \leftarrow \text{estimateGLMCommonDisp}(y, \text{design})
\]

To estimate trended dispersions:

\[
y \leftarrow \text{estimateGLMTrendedDisp}(y, \text{design})
\]

To estimate tagwise dispersions:

\[
y \leftarrow \text{estimateGLMTagwiseDisp}(y, \text{design})
\]

Note that we need to estimate either common dispersion or trended dispersions prior to the estimation of tagwise dispersions. When estimating tagwise dispersions, the empirical Bayes method is applied to squeeze tagwise dispersions towards common dispersion or trended dispersions, whichever exists. If both exist, the default is to use the trended dispersions.

For more detailed examples, see the case study in section 4.1 (Tuch’s data), section 4.2 (arabidopsis data), section 4.3 (Nigerian data) and section 4.4 (Fu’s data).
2.10.3 Testing for DE genes

For general experiments, once dispersion estimates are obtained and negative binomial models are fitted, we can proceed with testing procedures for determining differential expression using either the generalized linear model (GLM) likelihood ratio test or the quasi-likelihood (QL) F-test.

The GLM likelihood ratio test is based on the idea of fitting negative binomial GLMs with the Cox-Reid dispersion estimates. The testing can be done by using the functions \texttt{glmFit()} and \texttt{glmLRT()}. Given raw counts, dispersion(s) and a design matrix, \texttt{glmFit()} fits the negative binomial GLM for each tag and produces an object of class \texttt{DGEGLM} with some new components. This \texttt{DGEGLM} object can then be passed to \texttt{glmLRT()} to carry out the likelihood ratio test. User can select one or more coefficients to drop from the full design matrix. This gives the null model against which the full model is compared using the likelihood ratio test. Tags can then be ranked in order of evidence for differential expression, based on the \(p\)-value computed for each tag.

As a brief example, consider a situation in which are three treatment groups, each with two replicates, and the researcher wants to make pairwise comparisons between them. A generalized linear model representing the study design can be fitted to the data with commands such as:

\begin{verbatim}
> group <- factor(c(1,1,2,2,3,3))
> design <- model.matrix(~group)
> fit <- glmFit(y, design)
\end{verbatim}

The fit has three parameters. The first is the baseline level of group 1. The second and third are the 2 vs 1 and 3 vs 1 differences.

To compare 2 vs 1:

\begin{verbatim}
> lrt.2vs1 <- glmLRT(fit, coef=2)
> topTags(lrt.2vs1)
\end{verbatim}

To compare 3 vs 1:

\begin{verbatim}
> lrt.3vs1 <- glmLRT(fit, coef=3)
\end{verbatim}

To compare 3 vs 2:

\begin{verbatim}
> lrt.3vs2 <- glmLRT(fit, contrast=c(0,-1,1))
\end{verbatim}

The contrast argument in this case requests a statistical test of the null hypothesis that coefficient3 − coefficient2 is equal to zero.

To find genes different between any of the three groups:

\begin{verbatim}
> lrt <- glmLRT(fit, coef=2:3)
> topTags(lrt)
\end{verbatim}
For more detailed examples, see the case study in section 4.1 (Tuch’s data).

Alternatively, one can perform QL F-test to test for differential expression. While the likelihood ratio test is a more obvious choice for inferences with GLMs, the QL F-test is preferred as it reflects the uncertainty in estimating the dispersion for each gene. It provides more robust and reliable error rate control when the number of replicates is small. The QL dispersion estimation and hypothesis testing can be done by using the functions `glmQLFit()` and `glmQLFTest()`.

To apply the QL method to the above example and compare 2 vs 1:

```r
> fit <- glmQLFit(y, design)
> qlf.2vs1 <- glmQLFTest(fit, coef=2)
> topTags(qlf.2vs1)
```

Similarly for the other comparisons.

For more detailed examples, see the case study in section 4.2 (arabidopsis data), section 4.3 (Nigerian data) and section 4.4 (Fu’s data).

### 2.11 What to do if you have no replicates

edgeR is primarily intended for use with data including biological replication. Nevertheless, RNA-Seq and ChIP-Seq are still expensive technologies, so it sometimes happens that only one library can be created for each treatment condition. In these cases there are no replicate libraries from which to estimate biological variability. In this situation, the data analyst is faced with the following choices, none of which are ideal. We do not recommend any of these choices as a satisfactory alternative for biological replication. Rather, they are the best that can be done at the analysis stage, and options 2–4 may be better than assuming that biological variability is absent.

1. Be satisfied with a descriptive analysis, that might include an MDS plot and an analysis of fold changes. Do not attempt a significance analysis. This may be the best advice.

2. Simply pick a reasonable dispersion value, based on your experience with similar data, and use that for `exactTest` or `glmFit`. Typical values for the common BCV (square-root-dispersion) for datasets arising from well-controlled experiments are 0.4 for human data, 0.1 for data on genetically identical model organisms or 0.01 for technical replicates. Here is a toy example with simulated data:

```r
> bcv <- 0.2
> counts <- matrix(rnbinom(40, size=1/bcv^2, mu=10), 20, 2)
> y <- DGEList(counts=counts, group=1:2)
> et <- exactTest(y, dispersion=bcv^2)
```

Note that the p-values obtained and the number of significant genes will be very sensitive to the dispersion value chosen, and be aware that less well controlled datasets,
with unaccounted-for batch effects and so on, could have in reality much larger disper-
sions than are suggested here. Nevertheless, choosing a nominal dispersion value may
be more realistic than ignoring biological variation entirely.

3. Remove one or more explanatory factors from the linear model in order to create
some residual degrees of freedom. Ideally, this means removing the factors that are
least important but, if there is only one factor and only two groups, this may mean
removing the entire design matrix or reducing it to a single column for the intercept.
If your experiment has several explanatory factors, you could remove the factor with
smallest fold changes. If your experiment has several treatment conditions, you could
try treating the two most similar conditions as replicates. Estimate the dispersion from
this reduced model, then insert these dispersions into the data object containing the
full design matrix, then proceed to model fitting and testing with \texttt{glmFit} and \texttt{glmLRT}.
This approach will only be successful if the number of DE genes is relatively small.

In conjunction with this reduced design matrix, you could try \texttt{estimateGLMCommonDisp}
with \texttt{method=\textasciitilde\textquoteleft\textquoteleft deviance\textquoteright\textquoteright}, \texttt{robust=TRUE} and \texttt{subset=NULL}. This is our current best at-
ttempt at an automatic method to estimate dispersion without replicates, although it
will only give good results when the counts are not too small and the DE genes are a
small proportion of the whole. Please understand that this is only our best attempt
to return something useable. Reliable estimation of dispersion generally requires repli-
cates.

4. If there exist a sizeable number of control transcripts that should not be DE, then the
dispersion could be estimated from them. For example, suppose that \texttt{housekeeping}
is an index variable identifying housekeeping genes that do not respond to the treatment
used in the experiment. First create a copy of the data object with only one treatment
group:

```r
> y1 <- y
> y1$samples$group <- 1
```

Then estimate the dispersion from the housekeeping genes and all the libraries as one
group:

```r
> y0 <- estimateCommonDisp(y1[housekeeping,])
```

Then insert this into the full data object and proceed:

```r
> y$common.dispersion <- y0$common.dispersion
> et <- exactTest(y)
```

and so on. A reasonably large number of control transcripts is required, at least a few
dozen and ideally hundreds.
2.12 Differential expression above a fold-change threshold

All the above testing methods identify differential expression based on statistical significance regardless of how small the difference might be. On the other hand, one might be more interested in studying genes of which the expression levels change by a certain amount. A commonly used approach is to conduct DE tests, apply a fold-change cut-off and then rank all the genes above that fold-change threshold by $p$-value. In some other cases genes are first chosen according to a $p$-value cut-off and then sorted by their fold-changes. These combinations of $p$-value and fold-change threshold criteria seem to give more biological meaningful sets of genes than using either of them alone. However, they are both ad hoc and do not give meaningful $p$-values for testing differential expressions relative to a fold-change threshold. They favour lowly expressed but highly variable genes and destroy the control of FDR in general.

edgeR offers a rigorous statistical test for thresholded hypotheses under the GLM framework. It is analogous to TREAT [18] but much more powerful than the original TREAT method. Given a fold-change (or log-fold-change) threshold, the thresholded testing can be done by calling the function `glmTreat()` on a `DGEGLM` object produced by either `glmFit()` or `glmQLFit()`.

In the example shown in section 2.10.3, suppose we are detecting genes of which the log2-fold-changes for 1 vs 2 are significantly greater than 1, i.e., fold-changes significantly greater than 2, we use the following commands:

```r
> fit <- glmFit(y, design)
> tr <- glmTreat(fit, coef=2, lfc=1)
> topTags(tr)
```

Note that the fold-change threshold in `glmTreat()` is not the minimum value of the fold-change expected to see from the testing results. Genes will need to exceed this threshold by some way before being declared statistically significant. It is better to interpret the threshold as “the fold-change below which we are definitely not interested in the gene” rather than “the fold-change above which we are interested in the gene”. In the presence of a huge number of DE genes, a relatively large fold-change threshold may be appropriate to narrow down the search to genes of interest. In the lack of DE genes, on the other hand, a small or even no fold-change threshold shall be used.

For more detailed examples, see the case study in section 4.4 (Fu’s data).

2.13 Gene ontology (GO) and pathway analysis

The gene ontology (GO) enrichment analysis and the KEGG pathway enrichment analysis are the common downstream procedures to interpret the differential expression results in a biological context. Given a set of genes that are up- or down-regulated under a certain
contrast of interest, a GO (or pathway) enrichment analysis will find which GO terms (or pathways) are over- or under-represented using annotations for the genes in that set.

The GO analysis can be performed using the `goana()` function in edgeR. The KEGG pathway analysis can be performed using the `kegga()` function in edgeR. Both `goana()` and `kegga()` take a `DGEList` or `DGEExact` object. They both use the NCBI RefSeq annotation. Therefore, the Entrez Gene identifier (ID) should be supplied for each gene as the row names of the input object. Also users should set `species` according to the organism being studied. The top set of most enriched GO terms can be viewed with the `topGO()` function, and the top set of most enriched KEGG pathways can be viewed with the `topKEGG()` function.

Suppose we want to identify GO terms and KEGG pathways that are over-represented in group 1 compared to group 2 from the previous example in section 2.10.3 assuming the samples are collected from mice. We use the following commands:

```r
> qlf <- glmQLFTest(fit, coef=2)
> go <- goana(qlf, species="Mm")
> topGO(go)
> keg <- kegga(qlf, species="Mm")
> topKEGG(keg)
```

For more detailed examples, see the case study in section 4.1 (Tuch’s data) and section 4.4 (Fu’s data).

### 2.14 Gene set testing

In addition to the GO and pathway analysis, edgeR offers different types of gene set tests for RNA-Seq data. These gene set tests are the extensions of the original gene set tests in limma in order to handle `DGEList` objects.

The `roast()` function performs ROAST gene set tests [33]. It is a self-contained gene set test. Given a gene set, it tests whether the majority of the genes in the set are DE across the comparison of interest.

The `mroast()` function does ROAST tests for multiple sets, including adjustment for multiple testing.

The `fry()` function is a fast version of `mroast()`. It assumes all the genes in a set have equal variances. Since edgeR uses the z-score equivalents of NB random deviates for the gene set tests, the above assumption is always met. Hence, `fry()` is recommended over `roast()` and `mroast()` in edgeR. It gives the same result as `mroast()` with an infinite number of rotations.

The `camera()` function performs a competitive gene set test accounting for inter-gene correlation. It tests whether a set of genes is highly ranked relative to other genes in terms of differential expression [34].

The `romer()` function performs a gene set enrichment analysis. It implements a GSEA approach [31] based on rotation instead of permutation.
Unlike `goana()` and `kegga()`, the gene set tests are not limited to GO terms or KEGG pathways. Any pre-defined gene set can be used, for example MSigDB gene sets. A common application is to use a set of DE genes that was defined from an analysis of an independent data set.

For more detailed examples, see the case study in section 4.3 (Nigerian’s data) and section 4.4 (Fu’s data).

### 2.15 Clustering, heatmaps etc

The function `plotMDS` draws a multi-dimensional scaling plot of the RNA samples in which distances correspond to leading log-fold-changes between each pair of RNA samples. The leading log-fold-change is the average (root-mean-square) of the largest absolute log-fold-changes between each pair of samples. This plot can be viewed as a type of unsupervised clustering. The function also provides the option of computing distances in terms of BCV between each pair of samples instead of leading logFC.

Inputing RNA-seq counts to clustering or heatmap routines designed for microarray data is not straight-forward, and the best way to do this is still a matter of research. To draw a heatmap of individual RNA-seq samples, we suggest using moderated log-counts-per-million. This can be calculated by `cpm` with positive values for `prior.count`, for example

```r
> logcpm <- cpm(y, prior.count=2, log=TRUE)
```

where `y` is the normalized `DGEList` object. This produces a matrix of log_{2} counts-per-million (logCPM), with undefined values avoided and the poorly defined log-fold-changes for low counts shrunk towards zero. Larger values for `prior.count` produce more shrinkage. The logCPM values can optionally be converted to RPKM or FPKM by subtracting log_{2} of gene length, see `rpkm()`.

### 2.16 Alternative splicing

`edgeR` can also be used to analyze RNA-Seq data at the exon level to detect differential splicing or isoform-specific differential expression. Alternative splicing events are detected by testing for differential exon usage for each gene, that is testing whether the log-fold-changes differ between exons for the same gene.

Both exon-level and gene-level tests can be performed simultaneously using the `diffSpliceDGE()` function in `edgeR`. The exon-level test tests for the significant difference between the exon’s logFC and the overall logFC for the gene. Two testing methods at the gene-level are provided. The first is to conduct a gene-level statistical test using the exon-level test statistics. Whether it is a likelihood ratio test or a QL F-test depends on the pipeline chosen. The second is to convert the exon-level p-values into a genewise p-value by the Simes’ method. The first method is likely to be powerful for genes in which several exons are differentially
spliced. The Simes’ method is likely to be more powerful when only a minority of the exons for a gene are differentially spliced.

The top set of most significant spliced genes can be viewed by the `topSpliceDGE()` function. The exon-level testing results for a gene of interest can be visualized by the `plotSpliceDGE()` function.

For more detailed examples, see the case study in section 4.5 (Pasilla’s data).

2.17 CRISPR-Cas9 and shRNA-seq screen analysis

dger can also be used to analyze data from CRISPR-Cas9 and shRNA-seq genetic screens as described in Dai et al. (2014) [7]. Screens of this kind typically involve the comparison of two or more cell populations either in the presence or absence of a selective pressure, or as a time-course before and after a selective pressure is applied. The goal is to identify sgRNAs (or shRNAs) whose representation changes (either increases or decreases) suggesting that disrupting the target gene’s function has an effect on the cell.

To begin, the `processAmplicons` function can be used to obtain counts for each sgRNA (or shRNA) in the screen in each sample and organise them in a `DGEList` for down-stream analysis using either the classic edgeR or GLM pipeline mentioned above. Next, gene set testing methods such as `camera` and `roast` can be used to summarize results from multiple sgRNAs or shRNAs targeting the same gene to obtain gene-level results.

For a detailed example, see the case study in section 4.6 (CRISPR-Cas9 knockout screen analysis).
Chapter 3

Specific experimental designs

3.1 Introduction

In this chapter, we outline the principles for setting up the design matrix and forming contrasts for some typical experimental designs.

3.2 Two or more groups

3.2.1 Introduction

The simplest and most common type of experimental design is that in which a number of experimental conditions are compared on the basis of independent biological replicates of each condition. Suppose that there are three experimental conditions to be compared, treatments A, B and C, say. The samples component of the DGEList data object might look like:

```r
> y$samples
   group  lib.size norm.factors
sample.1 A       100001       1
sample.2 A       100002       1
sample.3 B       100003       1
sample.4 B       100004       1
sample.5 C       100005       1
```

Note that it is not necessary to have multiple replicates for all the conditions, although it is usually desirable to do so. By default, the conditions will be listed in alphabetical order, regardless of the order that the data were read:

```r
> levels(y$samples$group)
[1] "A" "B" "C"
```
3.2.2 Classic approach

The classic edgeR approach is to make pairwise comparisons between the groups. For example,

```r
> et <- exactTest(y, pair=c("A","B"))
> topTags(et)
```

will find genes differentially expressed (DE) in B vs A. Similarly

```r
> et <- exactTest(y, pair=c("A","C"))
```

for C vs A, or

```r
> et <- exactTest(y, pair=c("C","B"))
```

for B vs C.

Alternatively, the conditions to be compared can be specified by number, so that

```r
> et <- exactTest(y, pair=c(3,2))
```

is equivalent to `pair=c("C","B")`, given that the second and third levels of `group` are B and C respectively.

Note that the levels of `group` are in alphabetical order by default, but can be easily changed. Suppose for example that C is a control or reference level to which conditions A and B are to be compared. Then one might redefine the group levels, in a new data object, so that C is the first level:

```r
> y2 <- y
> y2$samples$group <- relevel(y2$samples$group, ref="C")
> levels(y2$samples$group)
[1] "C" "A" "B"
```

Now

```r
> et <- exactTest(y2, pair=c("A","B"))
```

would still compare B to A, but

```r
> et <- exactTest(y2, pair=c(1,2))
```

would now compare A to C.

When `pair` is not specified, the default is to compare the first two group levels, so

```r
> et <- exactTest(y)
```

compares B to A, whereas

```r
> et <- exactTest(y2)
```

compares A to C.
3.2.3 GLM approach

The glm approach to multiple groups is similar to the classic approach, but permits more general comparisons to be made. The glm approach requires a design matrix to describe the treatment conditions. We will usually use the `model.matrix` function to construct the design matrix, although it could be constructed manually. There are always many equivalent ways to define this matrix. Perhaps the simplest way is to define a coefficient for the expression level of each group:

```r
> design <- model.matrix(~0+group, data=y$samples)
> colnames(design) <- levels(y$samples$group)
> design
```

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample.1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>sample.2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>sample.3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>sample.4</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>sample.5</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Here, the `0+` in the model formula is an instruction not to include an intercept column and instead to include a column for each group.

One can compare any of the treatment groups using the `contrast` argument of the `glmLRT` function. For example,

```r
> fit <- glmFit(y, design)
> lrt <- glmLRT(fit, contrast=c(-1,1,0))
> topTags(lrt)
```

will compare B to A. The meaning of the contrast is to make the comparison \(-1*A + 1*B + 0*C\), which is of course is simply \(B-A\).

The contrast vector can be constructed using `makeContrasts` if that is convenient. The above comparison could have been made by

```r
> BvsA <- makeContrasts(B-A, levels=design)
> lrt <- glmLRT(fit, contrast=BvsA)
```

One could make three pairwise comparisons between the groups by

```r
> my.contrasts <- makeContrasts(BvsA=B-A, CvsB=C-B, CvsA=A-C, levels=design)
> lrt.BvsA <- glmLRT(fit, contrast=my.contrasts[,"BvsA"])
> topTags(lrt.BvsA)
> lrt.CvsB <- glmLRT(fit, contrast=my.contrasts[,"CvsB"])
> topTags(lrt.CvsB)
> lrt.CvsA <- glmLRT(fit, contrast=my.contrasts[,"CvsA"])
> topTags(lrt.CvsA)
```

which would compare B to A, C to B and C to A respectively.

Any comparison can be made. For example,
would compare C to the average of A and B. Alternatively, this same contrast could have been specified by

> my.contrast <- makeContrasts(C-(A+B)/2, levels=design)
> lrt <- glmLRT(fit, contrast=my.contrast)

with the same results.

### 3.2.4 Questions and contrasts

The glm approach allows an infinite variety of contrasts to be tested between the groups. This embarrassment of riches leads to the question, which specific contrasts should we test? This answer is that we should form and test those contrasts that correspond to the scientific questions that we want to answer. Each statistical test is an answer to a particular question, and we should make sure that our questions and answers match up.

To clarify this a little, we will consider a hypothetical experiment with four groups. The groups correspond to four different types of cells: white and smooth, white and furry, red and smooth and red furry. We will think of white and red as being the major group, and smooth and furry as being a sub-grouping. Suppose the RNA samples look like this:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Color</th>
<th>Type</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>White</td>
<td>Smooth</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>White</td>
<td>Smooth</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>White</td>
<td>Furry</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>White</td>
<td>Furry</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>Red</td>
<td>Smooth</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>Red</td>
<td>Smooth</td>
<td>C</td>
</tr>
<tr>
<td>7</td>
<td>Red</td>
<td>Furry</td>
<td>D</td>
</tr>
<tr>
<td>8</td>
<td>Red</td>
<td>Furry</td>
<td>D</td>
</tr>
</tbody>
</table>

To decide which contrasts should be made between the four groups, we need to be clear what are our scientific hypotheses. In other words, what are we seeking to show?

First, suppose that we wish to find genes that are always higher in red cells than in white cells. Then we will need to form the four contrasts \( C-A \), \( C-B \), \( D-A \) and \( D-B \), and select genes that are significantly up for all four contrasts.

Or suppose we wish to establish that the difference between Red and White is large compared to the differences between Furry and Smooth. An efficient way to establish this would be to form the three contrasts \( B-A \), \( D-C \) and \( (C+D)/2-(A+B)/2 \). We could confidently make this assertion for genes for which the third contrast is far more significant than the first two. Even if \( B-A \) and \( D-C \) are statistically significant, we could still look for genes for which the fold changes for \( (C+D)/2-(A+B)/2 \) are much larger than those for \( B-A \) or \( D-C \).
We might want to find genes that are more highly expressed in Furry cells regardless of color. Then we would test the contrasts B-A and D-C, and look for genes that are significantly up for both contrasts.

Or we want to assert that the difference between Furry over Smooth is much the same regardless of color. In that case you need to show that the contrast \((B+D)/2-(A+C)/2\) (the average Furry effect) is significant for many genes but that \((D-C)-(B-A)\) (the interaction) is not.

### 3.2.5 A more traditional glm approach

A more traditional way to create a design matrix in R is to include an intercept term that represents the first level of the factor. We included 0+ in our model formula above. Had we omitted it, the design matrix would have had the same number of columns as above, but the first column would be the intercept term and the meanings of the second and third columns would change:

```r
> design <- model.matrix(~group, data=y$samples)
> design
   (Intercept) groupB groupC
sample.1     1      0      0
sample.2     1      0      0
sample.3     1      1      0
sample.4     1      1      0
sample.5     1      0      1
```

Now the first coefficient will measure the baseline logCPM expression level in the first treatment condition (here group A), and the second and third columns are relative to the baseline. Here the second and third coefficients represent B vs A and C vs A respectively. In other words, coef=2 now means B-A and coef=3 means C-A, so

```r
> fit <- glmFit(y, design)
> lrt <- glmLRT(fit, coef=2)
```

would test for differential expression in B vs A and

```r
> lrt <- glmLRT(fit, coef=3)
```

would test for differential expression in C vs A.

This parametrization makes good sense when the first group represents a reference or control group, as all comparison are made with respect to this condition. If we releveled the factor to make level C the first level (see Section 3.2.2), then the design matrix becomes:

```r
> design2 <- model.matrix(~group, data=y2$samples)
> design2
   (Intercept) groupA groupB
sample.1    1      1      0
sample.2    1      1      0
```

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> fit2 <- glmFit(y2, design2)
> lrt <- glmLRT(fit2, coef=2)

compares A to C, and

> lrt <- glmLRT(fit2, coef=3)

compares B to C. With this parametrization, one could still compare B to A using

> lrt <- glmLRT(fit2, contrast=c(0,-1,1))

Note that

> lrt <- glmLRT(fit2, coef=1)

should not be used. It would test whether the first coefficient is zero, but it is not meaningful to compare the logCPM in group A to zero.

### 3.2.6 An ANOVA-like test for any differences

It might be of interest to find genes that are DE between any of the groups, without specifying before-hand which groups might be different. This is analogous to a one-way ANOVA test. In edgeR, this is done by specifying multiple coefficients to glmLRT, when the design matrix includes an intercept term. For example, with fit as defined in the previous section,

> lrt <- glmLRT(fit, coef=2:3)
> topTags(lrt)

will find any genes that differ between any of the treatment conditions A, B or C. Technically, this procedure tests whether either of the contrasts B-A or C-A are non-zero. Since at least one of these must be non-zero when differences exist, the test will detect any differences. To have this effect, the coef argument should specify all the coefficients except the intercept.

Note that this approach does not depend on how the group factor was defined, or how the design matrix was formed, as long as there is an intercept column. For example

> lrt <- glmLRT(fit2, coef=2:3)

gives exactly the results, even though fit2 and fit were computed using different design matrices. Here fit2 is as defined in the previous section.
3.3 Experiments with all combinations of multiple factors

3.3.1 Defining each treatment combination as a group

We now consider experiments with more than one experimental factor, but in which every combination of experiment conditions can potentially have a unique effect. For example, suppose that an experiment has been conducted with an active drug and a placebo, at three times from 0 hours to 2 hours, with all samples obtained from independent subjects. The data frame `targets` describes the treatment conditions applied to each sample:

```r
> targets
   Treat Time
Sample1 Placebo 0h
Sample2 Placebo 0h
Sample3 Placebo 1h
Sample4 Placebo 1h
Sample5 Placebo 2h
Sample6 Placebo 2h
Sample7    Drug 0h
Sample8    Drug 0h
Sample9    Drug 1h
Sample10   Drug 1h
Sample11   Drug 2h
Sample12   Drug 2h
```

As always, there are many ways to setup a design matrix. A simple, multi-purpose approach is to combine all the experimental factors into one combined factor:

```r
> Group <- factor(paste(targets$Treat, targets$Time, sep="."))
> cbind(targets, Group=Group)
   Treat  Time Group
Sample1 Placebo 0h Placebo.0h
Sample2 Placebo 0h Placebo.0h
Sample3 Placebo 1h Placebo.1h
Sample4 Placebo 1h Placebo.1h
Sample5 Placebo 2h Placebo.2h
Sample6 Placebo 2h Placebo.2h
Sample7    Drug 0h   Drug.0h
Sample8    Drug 0h   Drug.0h
Sample9    Drug 1h   Drug.1h
Sample10   Drug 1h   Drug.1h
Sample11   Drug 2h   Drug.2h
Sample12   Drug 2h   Drug.2h
```

Then we can take the same approach as in the previous section on two or more groups. Each treatment time for each treatment drug is a group:
> design <- model.matrix(~0+Group)
> colnames(design) <- levels(Group)
> fit <- glmFit(y, design)

Then we can make any comparisons we wish. For example, we might wish to make the following contrasts:

```r
> my.contrasts <- makeContrasts(
+   Drug.1vs0 = Drug.1h-Drug.0h,
+   Drug.2vs0 = Drug.2h-Drug.0h,
+   Placebo.1vs0 = Placebo.1h-Placebo.0h,
+   Placebo.2vs0 = Placebo.2h-Placebo.0h,
+   DrugvsPlacebo.0h = Drug.0h-Placebo.0h,
+   DrugvsPlacebo.1h = (Drug.1h-Drug.0h)-(Placebo.1h-Placebo.0h),
+   DrugvsPlacebo.2h = (Drug.2h-Drug.0h)-(Placebo.2h-Placebo.0h),
+   levels=design)
```

To find genes responding to the drug at 1 hour:

```r
> lrt <- glmLRT(fit, contrast=my.contrasts[,"Drug.1vs0"])
```

or at 2 hours:

```r
> lrt <- glmLRT(fit, contrast=my.contrasts[,"Drug.2vs0"])
```

To find genes with baseline differences between the drug and the placebo at 0 hours:

```r
> lrt <- glmLRT(fit, contrast=my.contrasts[,"DrugvsPlacebo.0h"])
```

To find genes that have responded *differently* to the drug and the placebo at 2 hours:

```r
> lrt <- glmLRT(fit, contrast=my.contrasts[,"DrugvsPlacebo.2h"])
```

Of course, it is not compulsory to use `makeContrasts` to form the contrasts. The coefficients are the following:

```r
> colnames(fit)
[1] "Drug.0h"  "Drug.1h"  "Drug.2h"  "Placebo.0h"  "Placebo.1h"  "Placebo.2h"
```

so

```r
> lrt <- glmLRT(fit, contrast=c(-1,0,1,0,0,0))
```

would find the `Drug.2vs0` contrast, and

```r
> lrt <- glmLRT(fit, contrast=c(-1,0,1,0,-1))
```

is another way of specifying the `DrugvsPlacebo.2h` contrast.
3.3.2 Nested interaction formulas

We generally recommend the approach of the previous section, because it is so explicit and easy to understand. However it may be useful to be aware of more short-hand approach to form the same contrasts in the previous section using a model formula. First, make sure that the placebo is the reference level:

```r
> targets$Treat <- relevel(targets$Treat, ref="Placebo")
```

Then form the design matrix:

```r
> design <- model.matrix(~Treat + Treat:Time, data=targets)
> fit <- glmFit(y, design)
```

The meaning of this formula is to consider all the levels of time for each treatment drug separately. The second term is a nested interaction, the interaction of Time within Treat. The coefficient names are:

```r
> colnames(fit)
[1] "(Intercept)" "TreatDrug"
[3] "TreatPlacebo:Time1h" "TreatDrug:Time1h"
[5] "TreatPlacebo:Time2h" "TreatDrug:Time2h"
```

Now most of the above contrasts are directly available as coefficients:

```r
> lrt <- glmLRT(fit, coef=2)
```

is the baseline drug vs placebo comparison,

```r
> lrt <- glmLRT(fit, coef=4)
```

is the drug effect at 1 hour,

```r
> lrt <- glmLRT(fit, coef=6)
```

is the drug effect at 2 hours, and finally

```r
> lrt <- glmLRT(fit, contrast=c(0,0,0,0,-1,1))
```

is the DrugvsPlacebo.2h contrast.

3.3.3 Treatment effects over all times

The nested interaction model makes it easy to find genes that respond to the treatment at any time, in a single test. Continuing the above example,

```r
> lrt <- glmLRT(fit, coef=c(4,6))
```

finds genes that respond to the treatment at either 1 hour or 2 hours versus the 0 hour baseline. This is analogous to an ANOVA \( F \)-test for a normal linear model.
### 3.3.4 Interaction at any time

The full interaction formula is

```r
design <- model.matrix(~Treat * Time, data=targets)
```

which is equivalent to

```r
design <- model.matrix(~Treat + Time + Treat:Time, data=targets)
fit <- glmFit(y, design)
```

This formula is primarily useful as a way to conduct an overall test for interaction. The coefficient names are:

```r
colnames(design)
```

```
[1] "(Intercept)" "TreatDrug"    
[3] "Time1h"     "Time2h"     
[5] "TreatDrug:Time1h" "TreatDrug:Time2h"
```

Now

```r
lrt <- glmLRT(fit, coef=2)
```

is again the baseline drug vs placebo comparison, but

```r
lrt <- glmLRT(fit, coef=3)
```

and

```r
lrt <- glmLRT(fit, coef=4)
```

are the effects of the reference drug, i.e., the effects of the placebo at 1 hour and 2 hours. The last two coefficients give the `DrugvsPlacebo.1h` and `DrugvsPlacebo.2h` contrasts, so that

```r
lrt <- glmLRT(fit, coef=5:6)
```

is useful because it detects genes that respond *differently* to the drug, relative to the placebo, at either of the times.

### 3.4 Additive models and blocking

#### 3.4.1 Paired samples

Paired samples occur whenever we compare two treatments and each independent subject in the experiment receives both treatments. Suppose for example that an experiment is conducted to compare a new treatment (T) with a control (C). Suppose that both the control and the treatment are administered to each of three patients. This produces the sample data:
This is a paired design in which each subject receives both the control and the active treatment. We can therefore compare the treatment to the control for each patient separately, so that baseline differences between the patients are subtracted out.

The design matrix is formed from an additive model formula without an interaction term:

```r
> Subject <- factor(targets$Subject)
> Treat <- factor(targets$Treatment, levels=c("C","T"))
> design <- model.matrix(~Subject+Treat)
```

The omission of an interaction term is characteristic of paired designs. We are not interested in the effect of the treatment on an individual patient (which is what an interaction term would examine). Rather we are interested in the average effect of the treatment over a population of patients.

As always, the dispersion has to be estimated:

```r
> y <- estimateGLMCommonDisp(y,design)
> y <- estimateGLMTrendedDisp(y,design)
> y <- estimateGLMTagwiseDisp(y,design)
```

We proceed to fit a linear model and test for the treatment effect. Note that we can omit the `coef` argument to `glmLRT` because the treatment effect is the last coefficient in the model.

```r
> fit <- glmFit(y, design)
> lrt <- glmLRT(fit)
> topTags(lrt)
```

This test detects genes that are differentially expressed in response to the active treatment compared to the control, adjusting for baseline differences between the patients. This test can be viewed as a generalization of a paired \( t \)-test.

See the oral carcinomas case study of Section 4.1 for a fully worked analysis with paired samples.

### 3.4.2 Blocking

Paired samples are a simple example of what is called “blocking” in experimental design. The idea of blocking is to compare treatments using experimental subjects that are as similar as possible, so that the treatment difference stands out as clearly as possible.
Suppose for example that we wish to compare three treatments A, B and C using experimental animals. Suppose that animals from the same litter are appreciably more similar than animals from different litters. This might lead to an experimental setup like:

<table>
<thead>
<tr>
<th>FileName</th>
<th>Litter</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>File1</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>File2</td>
<td>1</td>
<td>B</td>
</tr>
<tr>
<td>File3</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>File4</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>File5</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>File6</td>
<td>2</td>
<td>C</td>
</tr>
<tr>
<td>File7</td>
<td>3</td>
<td>C</td>
</tr>
<tr>
<td>File8</td>
<td>3</td>
<td>B</td>
</tr>
<tr>
<td>File9</td>
<td>3</td>
<td>A</td>
</tr>
</tbody>
</table>

Here it is the differences between the treatments that are of interest. The differences between the litters are not of primary interest, nor are we interested in a treatment effect that occurs for in only one litter, because that would not be reproducible.

We can compare the three treatments adjusting for any baseline differences between the litters by fitting an additive model:

```r
> Litter <- factor(targets$Litter)
> Treatment <- factor(targets$Treatment)
> design <- model.matrix(~Litter+Treatment)
```

This creates a design matrix with five columns: three for the litters and two more for the differences between the treatments.

If `fit` is the fitted model with this design matrix, then we may proceed as follows. To detect genes that are differentially expressed between any of the three treatments, adjusting for litter differences:

```r
> lrt <- glmLRT(fit, coef=4:5)
> topTags(lrt)
```

To detect genes that are differentially expressed in treatment B vs treatment A:

```r
> lrt <- glmLRT(fit, coef=4)
> topTags(lrt)
```

To detect genes that are differentially expressed in treatment C vs treatment A:

```r
> lrt <- glmLRT(fit, coef=5)
> topTags(lrt)
```

To detect genes that are differentially expressed in treatment C vs treatment B:

```r
> lrt <- glmLRT(fit, contrast=c(0,0,0,-1,1))
> topTags(lrt)
```
The advantage of using litter as a blocking variable in the analysis is that this will make the comparison between the treatments more precise, if litter-mates are more alike that animals from different litters. On the other hand, if litter-mates are no more alike than animals from different litters, which might be so for genetically identical inbred laboratory animals, then the above analysis is somewhat inefficient because the litter effects are being estimated unnecessarily. In that case, it would be better to omit litter from the model formula.

3.4.3 Batch effects

Another situation in which additive model formulas are used is when correcting for batch effects in an experiment. The situation here is analogous to blocking, the only difference being that the batch effects were probably unintended rather than a deliberate aspect of the experimental design. The analysis is the same as for blocking. The treatments can be adjusted for differences between the batches by using an additive model formula of the form:

```r
> design <- model.matrix(~Batch+Treatment)
```

In this type of analysis, the treatments are compared only within each batch. The analysis is corrected for baseline differences between the batches.

The Arabidopsis case study in Section 4.2 gives a fully worked example with batch effects.

3.5 Comparisons both between and within subjects

Here is a more complex scenario, posed by a poster to the Bioconductor mailing list. The experiment has 18 RNA samples collected from 9 subjects. The samples correspond to cells from 3 healthy patients, either treated or not with a hormone; cells from 3 patients with disease 1, either treated or not with the hormone; and cells from 3 patients with disease 2, either treated or not with the hormone. The targets frame looks like this:

```r
> targets
   Disease Patient Treatment
1    Healthy     1     None
2    Healthy     1   Hormone
3    Healthy     2     None
4    Healthy     2   Hormone
5    Healthy     3     None
6    Healthy     3   Hormone
7    Disease1    4     None
8    Disease1    4   Hormone
9    Disease1    5     None
10   Disease1    5   Hormone
11   Disease1    6     None
12   Disease1    6   Hormone
13   Disease2    7     None
```

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If all the RNA samples were collected from independent subjects, then this would be nested factorial experiment, from which we would want to estimate the treatment effect for each disease group. As it is, however, we have a paired comparison experiment for each disease group. The feature that makes this experiment complex is that some comparisons (between the diseases) are made between patients while other comparisons (hormone treatment vs no treatment) are made within patients.

The design matrix will be easier to construct in R if we re-number the patients within each disease group:

```r
> Patient <- gl(3,2,length=18)
```

We also define Disease and Treatment to be factors, with the control state as the first level in each case:

```r
> Disease <- factor(targets$Disease, levels=c("Healthy","Disease1","Disease2"))
> Treatment <- factor(targets$Treatment, levels=c("None","Hormone"))
```

This gives us a revised targets frame:

```r
> data.frame(Disease,Patient,Treatment)
  Disease Patient Treatment
  1 Healthy 1 None
  2 Healthy 1 Hormone
  3 Healthy 2 None
  4 Healthy 2 Hormone
  5 Healthy 3 None
  6 Healthy 3 Hormone
  7 Disease1 1 None
  8 Disease1 1 Hormone
  9 Disease1 2 None
 10 Disease1 2 Hormone
11 Disease1 3 None
12 Disease1 3 Hormone
13 Disease2 1 None
14 Disease2 1 Hormone
15 Disease2 2 None
16 Disease2 2 Hormone
17 Disease2 3 None
18 Disease2 3 Hormone
```

Now we can construct the design matrix. The critical feature to appreciate is that Patient and Treatment are of interest within each disease group, so we use the nested factorial formula
discussed in a previous section. The patients are nested with the disease groups, because we have different patients in each group. The treatment is nested within disease groups, because we are interested in the disease-specific treatment effects. The model formula has the main effect for disease plus nested interactions with Patient and Treatment:

```r
> design <- model.matrix(~Disease+Disease:Patient+Disease:Treatment)
> colnames(design)
[1] "(Intercept)" "DiseaseDisease1"
[3] "DiseaseDisease2" "DiseaseHealthy:Patient2"
[5] "DiseaseDisease1:Patient2" "DiseaseDisease2:Patient2"
[7] "DiseaseHealthy:Patient3" "DiseaseDisease1:Patient3"
[9] "DiseaseDisease2:Patient3" "DiseaseHealthy:TreatmentHormone"
[11] "DiseaseDisease1:TreatmentHormone" "DiseaseDisease2:TreatmentHormone"
```

After estimating the dispersions (code not shown), we can fit a linear model:

```r
> fit <- glmFit(y, design)
```

To find genes responding to the hormone in healthy patients:

```r
> lrt <- glmLRT(fit, coef="DiseaseHealthy:TreatmentHormone")
> topTags(lrt)
```

To find genes responding to the hormone in disease1 patients:

```r
> lrt <- glmLRT(fit, coef="DiseaseDisease1:TreatmentHormone")
> topTags(lrt)
```

To find genes responding to the hormone in disease2 patients:

```r
> lrt <- glmLRT(fit, coef="DiseaseDisease2:TreatmentHormone")
> topTags(lrt)
```

To find genes that respond to the hormone in any disease group:

```r
> lrt <- glmLRT(fit, coef=10:12)
> topTags(lrt)
```

To find genes that respond differently to the hormone in disease1 vs healthy patients:

```r
> lrt <- glmLRT(fit, contrast=c(0,0,0,0,0,0,0,0,-1,1,0))
> topTags(lrt)
```

To find genes that respond differently to the hormone in disease2 vs healthy patients:

```r
> lrt <- glmLRT(fit, contrast=c(0,0,0,0,0,0,0,0,0,-1,0,1))
> topTags(lrt)
```

To find genes that respond differently to the hormone in disease2 vs disease1 patients:

```r
> lrt <- glmLRT(fit, contrast=c(0,0,0,0,0,0,0,0,0,0,-1,1))
> topTags(lrt)
```
Chapter 4
Case studies

4.1 RNA-Seq of oral carcinomas vs matched normal tissue

4.1.1 Introduction
This section provides a detailed analysis of data from a paired design RNA-seq experiment, featuring oral squamous cell carcinomas and matched normal tissue from three patients [32]. The aim of the analysis is to detect genes differentially expressed between tumor and normal tissue, adjusting for any differences between the patients. This provides an example of the GLM capabilities of edgeR.

RNA was sequenced on an Applied Biosystems SOLiD System 3.0 and reads mapped to the UCSC hg18 reference genome [32]. Read counts, summarised at the level of refSeq transcripts, are available in Table S1 of Tuch et al. [32].

4.1.2 Reading in the data
The read counts for the six individual libraries are stored in one tab-delimited file. To make this file, we downloaded Table S1 from Tuch et al. [32], deleted some unnecessary columns and edited the column headings slightly:

```r
> rawdata <- read.delim("TableS1.txt", check.names=FALSE, stringsAsFactors=FALSE)
> head(rawdata)
   RefSeqID Symbol NbrOfExons 8N 8T 33N 33T 51N 51T
1 NM_182502 TMPRSS11B  10    2592   3  7805   321   3372   9
2 NM_003280 TNNC1       6    1684   0  1787   7    4894  559
3 NM_152381 XIRP2        10   9915  15 10396  48  23309  7181
4 NM_022438 MAL           3   2496   2  3585  239  1596   7
5 NM_001100112 MYH2       40   4389   7  7944  16  9262  1818
6 NM_017534 MYH2          40   4402   7  7943  16  9244  1815
```

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For easy manipulation, we put the data into a \texttt{DGEList} object:

\begin{verbatim}
> library(edgeR)
> y <- DGEList(counts=rawdata[,4:9], genes=rawdata[,1:3])
\end{verbatim}

\subsection*{4.1.3 Annotation}

The study by Tuch et al. [32] was undertaken a few years ago, so not all of the RefSeq IDs provided by match RefSeq IDs currently in use. We retain only those transcripts with IDs in the current NCBI annotation, which is provided by the \texttt{org.Hs.eg.db} package:

\begin{verbatim}
> library(org.Hs.eg.db)
> idfound <- y$genes$RefSeqID %in% mappedRkeys(org.Hs.egREFSEQ)
> y <- y[idfound,]
> dim(y)
[1] 15559 6
\end{verbatim}

We add Entrez Gene IDs to the annotation:

\begin{verbatim}
> egREFSEQ <- toTable(org.Hs.egREFSEQ)
> head(egREFSEQ)

<table>
<thead>
<tr>
<th>gene_id</th>
<th>accession</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NM_130786</td>
</tr>
<tr>
<td>2</td>
<td>NP_570602</td>
</tr>
<tr>
<td>3</td>
<td>NM_000014</td>
</tr>
<tr>
<td>4</td>
<td>NP_000005</td>
</tr>
<tr>
<td>5</td>
<td>XM_006719056</td>
</tr>
<tr>
<td>6</td>
<td>XP_006719119</td>
</tr>
</tbody>
</table>

> m <- match(y$genes$RefSeqID, egREFSEQ$accession)
> y$genes$EntrezGene <- egREFSEQ$gene_id[m]
\end{verbatim}

Now use the Entrez Gene IDs to update the gene symbols:

\begin{verbatim}
> egSYMBOL <- toTable(org.Hs.egSYMBOL)
> head(egSYMBOL)

<table>
<thead>
<tr>
<th>gene_id</th>
<th>symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1BG</td>
</tr>
<tr>
<td>2</td>
<td>A2M</td>
</tr>
<tr>
<td>3</td>
<td>A2MP1</td>
</tr>
<tr>
<td>4</td>
<td>NAT1</td>
</tr>
<tr>
<td>5</td>
<td>NAT2</td>
</tr>
<tr>
<td>6</td>
<td>NATP</td>
</tr>
</tbody>
</table>

> m <- match(y$genes$EntrezGene, egSYMBOL$gene_id)
> y$genes$Symbol <- egSYMBOL$symbol[m]
> head(y$genes)
\end{verbatim}
<table>
<thead>
<tr>
<th>RefSeqID</th>
<th>Symbol</th>
<th>NbrOfExons</th>
<th>EntrezGene</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM_182502</td>
<td>TMPRSS11B</td>
<td>10</td>
<td>132724</td>
</tr>
<tr>
<td>NM_003280</td>
<td>TNNC1</td>
<td>6</td>
<td>7134</td>
</tr>
<tr>
<td>NM_152381</td>
<td>XIRP2</td>
<td>10</td>
<td>129446</td>
</tr>
<tr>
<td>NM_022438</td>
<td>MAL</td>
<td>3</td>
<td>4118</td>
</tr>
<tr>
<td>NM_001100112</td>
<td>MYH2</td>
<td>40</td>
<td>4620</td>
</tr>
<tr>
<td>NM_017534</td>
<td>MYH2</td>
<td>40</td>
<td>4620</td>
</tr>
</tbody>
</table>

### 4.1.4 Filtering and normalization

Different RefSeq transcripts for the same gene symbol count predominantly the same reads. So we keep one transcript for each gene symbol. We choose the transcript with highest overall count:

```r
> o <- order(rowSums(y$count), decreasing=TRUE)
> y <- y[o,]
> d <- duplicated(y$genes$Symbol)
> y <- y[!d,]
> nrow(y)
[1] 10523
```

Normally we would also filter lowly expressed genes. For this data, all transcripts already have at least 50 reads for all samples of at least one of the tissues types.

Recompute the library sizes:

```r
> y$samples$lib.size <- colSums(y$count)
```

Use Entrez Gene IDs as row names:

```r
> rownames(y$count) <- rownames(y$genes) <- y$genes$EntrezGene
> y$genes$EntrezGene <- NULL
```

TMM normalization is applied to this dataset to account for compositional difference between the libraries:

```r
> y <- calcNormFactors(y)
> y$samples

<table>
<thead>
<tr>
<th>group</th>
<th>lib.size</th>
<th>norm.factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>8N</td>
<td>1 7992800</td>
<td>1.146</td>
</tr>
<tr>
<td>8T</td>
<td>1 7374090</td>
<td>1.086</td>
</tr>
<tr>
<td>33N</td>
<td>1 15759922</td>
<td>0.673</td>
</tr>
<tr>
<td>33T</td>
<td>1 14050463</td>
<td>0.974</td>
</tr>
<tr>
<td>51N</td>
<td>1 21547308</td>
<td>1.032</td>
</tr>
<tr>
<td>51T</td>
<td>1 15199698</td>
<td>1.190</td>
</tr>
</tbody>
</table>
```

44
4.1.5 Data exploration

The first step of an analysis should be to examine the samples for outliers and for other relationships. The function plotMDS produces a plot in which distances between samples correspond to leading biological coefficient of variation (BCV) between those samples:

```r
> plotMDS(y)
```

In the plot, dimension 1 separates the tumor from the normal samples, while dimension 2 roughly corresponds to patient number. This confirms the paired nature of the samples. The tumor samples appear more heterogeneous than the normal samples.

4.1.6 The design matrix

Before we fit negative binomial GLMs, we need to define our design matrix based on the experimental design. Here we want to test for differential expression between tumor and normal tissues within patients, i.e. adjusting for differences between patients. In statistical terms, this is an additive linear model with patient as the blocking factor:

```r
> Patient <- factor(c(8,8,33,33,51,51))
> Tissue <- factor(c("N","T","N","T","N","T"))
> data.frame(Sample=colnames(y),Patient,Tissue)
```

<table>
<thead>
<tr>
<th>Sample</th>
<th>Patient</th>
<th>Tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8N</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>8T</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>33N</td>
<td>33 N</td>
</tr>
</tbody>
</table>

45
> design <- model.matrix(~Patient+Tissue)
> rownames(design) <- colnames(y)
> design

   (Intercept) Patient33 Patient51 TissueT
     8N    1     0     0     0
     8T    1     0     0     1
    33N    1     1     0     0
    33T    1     1     0     1
    51N    1     0     1     0
    51T    1     0     1     1

attr("assign")
 [1] 0 1 1 2
attr("contrasts")
attr("contrasts")$Patient
 [1] "contr.treatment"

attr("contrasts")$Tissue
 [1] "contr.treatment"

This sort of additive model is appropriate for paired designs, or experiments with batch effects.

### 4.1.7 Estimating the dispersion

We estimate the NB dispersion for the dataset.

> y <- estimateDisp(y, design, robust=TRUE)
> y$common.dispersion

[1] 0.159

The square root of the common dispersion gives the coefficient of variation of biological variation. Here the common dispersion is found to be 0.159, so the coefficient of biological variation is around 0.4.

The dispersion estimates can be viewed in a BCV plot:

> plotBCV(y)
4.1.8 Differential expression

Now proceed to determine differentially expressed genes. Fit genewise glms:

> fit <- glmFit(y, design)

Conduct likelihood ratio tests for tumour vs normal tissue differences and show the top genes:

> lrt <- glmLRT(fit)
> topTags(lrt)

Coefficient: TissueT

<table>
<thead>
<tr>
<th>RefSeqID</th>
<th>Symbol</th>
<th>NbrOfExons</th>
<th>logFC</th>
<th>logCPM</th>
<th>LR</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>5737</td>
<td>PTGFR</td>
<td>4</td>
<td>-5.18</td>
<td>4.74</td>
<td>98.7</td>
<td>2.98e-23</td>
<td>3.14e-19</td>
</tr>
<tr>
<td>5744</td>
<td>PTHLH</td>
<td>4</td>
<td>3.97</td>
<td>6.21</td>
<td>92.1</td>
<td>8.10e-22</td>
<td>4.26e-18</td>
</tr>
<tr>
<td>3479</td>
<td>IGF1</td>
<td>5</td>
<td>-3.99</td>
<td>5.71</td>
<td>86.5</td>
<td>1.38e-20</td>
<td>4.83e-17</td>
</tr>
<tr>
<td>1288</td>
<td>COL4A6</td>
<td>45</td>
<td>3.66</td>
<td>5.71</td>
<td>77.5</td>
<td>1.32e-18</td>
<td>3.47e-15</td>
</tr>
<tr>
<td>10351</td>
<td>ABCA8</td>
<td>38</td>
<td>-3.98</td>
<td>4.94</td>
<td>75.9</td>
<td>2.97e-18</td>
<td>6.24e-15</td>
</tr>
<tr>
<td>5837</td>
<td>PYGM</td>
<td>20</td>
<td>-5.48</td>
<td>5.99</td>
<td>75.4</td>
<td>3.82e-18</td>
<td>6.70e-15</td>
</tr>
<tr>
<td>487</td>
<td>ATP2A1</td>
<td>23</td>
<td>-4.62</td>
<td>5.96</td>
<td>74.8</td>
<td>5.16e-18</td>
<td>7.75e-15</td>
</tr>
<tr>
<td>27179</td>
<td>IL36A</td>
<td>4</td>
<td>-6.17</td>
<td>5.40</td>
<td>72.2</td>
<td>1.96e-17</td>
<td>2.58e-14</td>
</tr>
<tr>
<td>196374</td>
<td>KRT78</td>
<td>9</td>
<td>-4.25</td>
<td>7.61</td>
<td>70.8</td>
<td>3.98e-17</td>
<td>4.66e-14</td>
</tr>
<tr>
<td>83699</td>
<td>SH3BGRL2</td>
<td>4</td>
<td>-3.93</td>
<td>5.53</td>
<td>67.8</td>
<td>1.83e-16</td>
<td>1.93e-13</td>
</tr>
</tbody>
</table>

Note that \texttt{glmLRT} has conducted a test for the last coefficient in the linear model, which we can see is the tumor vs normal tissue effect:

> colnames(design)
The genewise tests are for tumor vs normal differential expression, adjusting for baseline differences between the three patients. The tests can be viewed as analogous to paired \( t \)-tests. The top DE tags have tiny \( p \)-values and FDR values, as well as large fold changes.

Here’s a closer look at the counts-per-million in individual samples for the top genes:

```r
> o <- order(lrt$table$PValue)
> cpm(y)[o[1:10],]
```

<table>
<thead>
<tr>
<th></th>
<th>8N</th>
<th>8T</th>
<th>33N</th>
<th>33T</th>
<th>51N</th>
<th>51T</th>
</tr>
</thead>
<tbody>
<tr>
<td>5737</td>
<td>49.69</td>
<td>0.874</td>
<td>27.08</td>
<td>0.877</td>
<td>78.10</td>
<td>2.5425</td>
</tr>
<tr>
<td>5744</td>
<td>7.32</td>
<td>95.799</td>
<td>11.79</td>
<td>204.034</td>
<td>6.88</td>
<td>116.2917</td>
</tr>
<tr>
<td>3479</td>
<td>50.24</td>
<td>3.123</td>
<td>32.36</td>
<td>1.901</td>
<td>211.59</td>
<td>14.2048</td>
</tr>
<tr>
<td>1288</td>
<td>12.12</td>
<td>140.138</td>
<td>6.32</td>
<td>94.378</td>
<td>4.86</td>
<td>56.8193</td>
</tr>
<tr>
<td>10351</td>
<td>52.64</td>
<td>3.123</td>
<td>39.43</td>
<td>2.120</td>
<td>79.18</td>
<td>6.0799</td>
</tr>
<tr>
<td>5837</td>
<td>152.80</td>
<td>2.748</td>
<td>119.53</td>
<td>1.170</td>
<td>97.67</td>
<td>5.6930</td>
</tr>
<tr>
<td>487</td>
<td>107.91</td>
<td>3.123</td>
<td>146.98</td>
<td>3.801</td>
<td>102.80</td>
<td>8.8987</td>
</tr>
<tr>
<td>27179</td>
<td>40.08</td>
<td>1.249</td>
<td>172.08</td>
<td>3.290</td>
<td>36.08</td>
<td>0.0553</td>
</tr>
<tr>
<td>196374</td>
<td>372.22</td>
<td>20.733</td>
<td>580.96</td>
<td>47.737</td>
<td>145.05</td>
<td>4.5323</td>
</tr>
<tr>
<td>83699</td>
<td>96.22</td>
<td>5.121</td>
<td>117.08</td>
<td>5.410</td>
<td>48.18</td>
<td>5.4166</td>
</tr>
</tbody>
</table>

We see that all the top genes have consistent tumour vs normal changes for the three patients.

The total number of differentially expressed genes at 5% FDR is given by:

```r
> summary(de <- decideTestsDGE(lrt))
```

```
[,1]
-1   938
 0  9255
 1   330
```

Plot log-fold change against log-counts per million, with DE genes highlighted:

```r
> detags <- rownames(y)[as.logical(de)]
> plotSmear(lrt, de.tags=detags)
> abline(h=c(-1, 1), col="blue")
```
The blue lines indicate 2-fold changes.

### 4.1.9 Gene ontology analysis

We perform a gene ontology analysis focusing on the ontology of biological process (BP). The genes up-regulated in the tumors tend to be associated with cell differentiation, cell migration and tissue morphogenesis:

```r
> go <- goana(lrt)
> topGO(go, ont="BP", sort="Up", n=30)
```

<table>
<thead>
<tr>
<th>Term</th>
<th>Ont</th>
<th>N</th>
<th>Up</th>
<th>Down</th>
<th>P.Up</th>
<th>P.Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>GO:0040011 locomotion BP</td>
<td>BP</td>
<td>1142</td>
<td>87</td>
<td>163</td>
<td>3.13e-15</td>
<td>2.39e-10</td>
</tr>
<tr>
<td>GO:006928 movement of cell or subcellular component BP</td>
<td>BP</td>
<td>1235</td>
<td>85</td>
<td>182</td>
<td>2.38e-12</td>
<td>8.40e-13</td>
</tr>
<tr>
<td>GO:0016477 cell migration BP</td>
<td>BP</td>
<td>791</td>
<td>61</td>
<td>128</td>
<td>7.08e-11</td>
<td>7.34e-12</td>
</tr>
<tr>
<td>GO:0048870 cell motility BP</td>
<td>BP</td>
<td>832</td>
<td>62</td>
<td>130</td>
<td>1.99e-10</td>
<td>5.96e-11</td>
</tr>
<tr>
<td>GO:0051674 localization of cell BP</td>
<td>BP</td>
<td>832</td>
<td>62</td>
<td>130</td>
<td>1.99e-10</td>
<td>5.96e-11</td>
</tr>
<tr>
<td>GO:0030154 cell differentiation BP</td>
<td>BP</td>
<td>2249</td>
<td>121</td>
<td>285</td>
<td>3.12e-10</td>
<td>9.69e-12</td>
</tr>
<tr>
<td>GO:009888 tissue development BP</td>
<td>BP</td>
<td>1130</td>
<td>74</td>
<td>179</td>
<td>9.87e-10</td>
<td>1.33e-15</td>
</tr>
<tr>
<td>GO:0030198 extracellular matrix organization BP</td>
<td>BP</td>
<td>278</td>
<td>31</td>
<td>52</td>
<td>1.23e-09</td>
<td>2.04e-07</td>
</tr>
<tr>
<td>GO:0043062 extracellular structure organization BP</td>
<td>BP</td>
<td>278</td>
<td>31</td>
<td>52</td>
<td>1.23e-09</td>
<td>2.04e-07</td>
</tr>
<tr>
<td>GO:0007155 cell adhesion BP</td>
<td>BP</td>
<td>876</td>
<td>62</td>
<td>149</td>
<td>1.60e-09</td>
<td>1.26e-15</td>
</tr>
<tr>
<td>GO:0044707 single-multicellular organism process BP</td>
<td>BP</td>
<td>3532</td>
<td>165</td>
<td>439</td>
<td>1.65e-09</td>
<td>9.00e-19</td>
</tr>
<tr>
<td>GO:0022610 biological adhesion BP</td>
<td>BP</td>
<td>880</td>
<td>62</td>
<td>150</td>
<td>1.91e-09</td>
<td>8.15e-16</td>
</tr>
<tr>
<td>GO:0048699 generation of neurons BP</td>
<td>BP</td>
<td>987</td>
<td>66</td>
<td>116</td>
<td>4.39e-09</td>
<td>1.06e-03</td>
</tr>
<tr>
<td>GO:0060429 epithelium development BP</td>
<td>BP</td>
<td>712</td>
<td>53</td>
<td>96</td>
<td>5.48e-09</td>
<td>2.22e-05</td>
</tr>
<tr>
<td>GO:0022008 neurogenesis BP</td>
<td>BP</td>
<td>1042</td>
<td>68</td>
<td>122</td>
<td>6.61e-09</td>
<td>9.04e-04</td>
</tr>
<tr>
<td>GO:0007275 multicellular organism development BP</td>
<td>BP</td>
<td>2921</td>
<td>141</td>
<td>353</td>
<td>9.92e-09</td>
<td>4.67e-12</td>
</tr>
<tr>
<td>GO:0048859 cellular developmental process BP</td>
<td>BP</td>
<td>2418</td>
<td>122</td>
<td>296</td>
<td>1.59e-08</td>
<td>2.06e-10</td>
</tr>
</tbody>
</table>
4.1.10 Setup

This analysis was conducted on:

```r
> sessionInfo()
R version 3.3.0 beta (2016-04-14 r70486)
Platform: x86_64-w64-mingw32/x64 (64-bit)
Running under: Windows 7 x64 (build 7601) Service Pack 1

locale:
[1] LC_COLLATE=English_Australia.1252 LC_CTYPE=English_Australia.1252
[3] LC_MONETARY=English_Australia.1252 LC_NUMERIC=C
[5] LC_TIME=English_Australia.1252

attached base packages:
[1] parallel  stats4   stats   graphics  grDevices  utils    datasets  methods  base

other attached packages:
[1] RSQLite_1.0.0  DBI_0.3.1  AnnotationDbi_1.33.11
[5] S4Vectors_0.9.51 Biobase_2.31.3 BiocGenerics_0.17.5
[9] edgeR_3.13.9   limma_3.27.19

loaded via a namespace (and not attached):
[1] grid_3.3.0 GO.db_3.3.0 grid_3.3.0 splines_3.3.0 statmod_1.4.24
[7] tools_3.3.0
```
4.2 RNA-Seq of pathogen inoculated arabidopsis with batch effects

4.2.1 Introduction

This case study re-analyses Arabidopsis thaliana RNA-Seq data described by Cumbie et al. [6]. Summarized count data is available as a data object in the CRAN package NBPSeg comparing ΔhrcC challenged and mock-inoculated samples [6]. Samples were collected in three batches, and adjustment for batch effects proves to be important. The aim of the analysis therefore is to detect genes differentially expressed in response to ΔhrcC challenge, while correcting for any differences between the batches.

4.2.2 RNA samples

Pseudomonas syringae is a bacterium often used to study plant reactions to pathogens. In this experiment, six-week old Arabidopsis plants were inoculated with the ΔhrcC mutant of P. syringae, after which total RNA was extracted from leaves. Control plants were inoculated with a mock pathogen.

Three biological replicates of the experiment were conducted at separate times and using independently grown plants and bacteria.

The six RNA samples were sequenced one per lane on an Illumina Genome Analyzer. Reads were aligned and summarized per gene using GENE-counter. The reference genome was derived from the TAIR9 genome release (www.arabidopsis.org).

4.2.3 Loading the data

Load the data from the NBPSeg package:

```r
> library(NBPSeg)
> library(edgeR)
> data(arab)
> head(arab)

mock1  mock2  mock3  hrcc1  hrcc2  hrcc3
AT1G01010  35     77     40     46     64     60
AT1G01020  43     45     32     43     39     49
AT1G01030  16     24     26     27     35     20
AT1G01040  72     43     64     66     25     90
AT1G01050  49     78     90     67     45     60
AT1G01060  0      15     2      0      21     8
```

There are two experimental factors, treatment (hrcc vs mock) and the time that each replicate was conducted:
We then create a DGEList object:

```r
> y <- DGEList(counts=arab, group=Treat)
```

### 4.2.4 Filtering and normalization

There is no purpose in analysing genes that are not expressed in either experimental condition. We consider a gene to be expressed at a reasonable level in a sample if it has at least two counts for each million mapped reads in that sample. This cutoff is ad hoc, but serves to require at least 4–6 reads in this case. Since this experiment has three replicates for each condition, a gene should be expressed in at least three samples if it responds to at least one condition. Hence we keep genes with at least two counts per million (CPM) in at least three samples:

```r
> keep <- rowSums(cpm(y)>2) >= 3
> table(keep)
keep
FALSE   TRUE
 9696  16526
> y <- y[keep, , keep.lib.sizes=FALSE]
```

Note that the filtering does not use knowledge of what treatment corresponds to each sample, so the filtering does not bias the subsequent differential expression analysis.

The TMM normalization is applied to account for the compositional biases:

```r
> y <- calcNormFactors(y)
> y$samples
         group lib.size norm.factors
mock1    mock  1896802 0.979
mock2    mock  1898690 1.054
mock3    mock  3249396 0.903
hrcc1   hrcc  2119367 1.051
hrcc2   hrcc  1264927 1.096
hrcc3   hrcc  3516253 0.932
```

### 4.2.5 Data exploration

An MDS plot shows the relative similarities of the six samples.

```r
> plotMDS(y)
```
Distances on an MDS plot of a DGEList object correspond to *leading log-fold-change* between each pair of samples. Leading log-fold-change is the root-mean-square average of the largest log₂-fold-changes between each pair of samples. Each pair of samples extracted at each time tend to cluster together, suggesting a batch effect. The hrcc treated samples tend to be below the mock samples for each time, suggesting a treatment effect within each time. The two samples at time 1 are less consistent than at times 2 and 3.

To examine further consistency of the three replicates, we compute predictive log₂-fold-changes (logFC) for the treatment separately for the three times.

```r
> design <- model.matrix(~Time+Time:Treat)
> logFC <- predFC(y,design,prior.count=1,dispersion=0.05)
```

The logFC at the three times are positively correlated with one another, as we would hope:

```r
> cor(logFC[,4:6])

Time1:Treathrcc Time2:Treathrcc Time3:Treathrcc
Time1:Treathrcc 1.000 0.315 0.400
Time2:Treathrcc 0.315 1.000 0.437
Time3:Treathrcc 0.400 0.437 1.000
```

The correlation is highest between times 2 and 3.

### 4.2.6 The design matrix

Before we fit GLMs, we need to define our design matrix based on the experimental design. We want to test for differential expressions between ∆hrcC challenged and mock-inoculated samples within batches, i.e. adjusting for differences between batches. In statistical terms, this is an additive linear model. So the design matrix is created as:
4.2.7 Estimating the dispersion

Estimate the genewise dispersion estimates over all genes, allowing for a possible abundance trend. The estimation is also robustified against potential outlier genes.

> y <- estimateDisp(y, design, robust=TRUE)
> y$common.dispersion
[1] 0.0705
> plotBCV(y)
The square root of dispersion is the coefficient of biological variation (BCV). The common BCV is on the high side, considering that this is a designed experiment using genetically identical plants. The trended dispersion shows a decreasing trend with expression level. At low logCPM, the dispersions are very large indeed.

Note that only the trended dispersion is used under the quasi-likelihood (QL) pipeline. The tagwise and common estimates are shown here but will not be used further.

The QL dispersions can be estimated using the `glmQLFit` function, and then be visualized with the `plotQLDisp` function.

```r
> fit <- glmQLFit(y, design, robust=TRUE)
> plotQLDisp(fit)
```

![Diagram showing trended dispersion and QL dispersions](image)

### 4.2.8 Differential expression

Now we test for significant differential expression in each gene using the QL F-test.

First we check whether there was a genuine need to adjust for the experimental times. We do this by testing for differential expression between the three times. There is considerable differential expression, justifying our decision to adjust for the batch effect:

```r
> qlf <- glmQLFTest(fit, coef=2:3)
> topTags(qlf)
```

<table>
<thead>
<tr>
<th>Coefficient: Time2 Time3</th>
<th>logFC.Time2</th>
<th>logFC.Time3</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT5G66800</td>
<td>5.58</td>
<td>-1.065</td>
<td>5.48</td>
<td>150.1</td>
<td>8.93e-10</td>
<td>1.48e-05</td>
</tr>
<tr>
<td>AT5G23000</td>
<td>5.58</td>
<td>-0.292</td>
<td>5.71</td>
<td>127.5</td>
<td>2.48e-09</td>
<td>2.05e-05</td>
</tr>
</tbody>
</table>
> FDR <- p.adjust(qlf$table$PValue, method="BH")
> sum(FDR < 0.05)
[1] 1628

Now conduct QL F-tests for the pathogen effect and show the top genes. By default, the test is for the last coefficient in the design matrix, which in this case is the treatment effect:

> qlf <- glmQLFTest(fit)
> topTags(qlf)

Coefficient: Treathrc

<table>
<thead>
<tr>
<th>logFC</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT2G19190</td>
<td>4.50</td>
<td>7.37</td>
<td>304</td>
<td>1.83e-10</td>
</tr>
<tr>
<td>AT2G39530</td>
<td>4.34</td>
<td>6.71</td>
<td>278</td>
<td>3.17e-10</td>
</tr>
<tr>
<td>AT3G46280</td>
<td>4.78</td>
<td>8.10</td>
<td>247</td>
<td>6.70e-10</td>
</tr>
<tr>
<td>AT2G39380</td>
<td>4.94</td>
<td>5.77</td>
<td>209</td>
<td>9.92e-09</td>
</tr>
<tr>
<td>AT1G51800</td>
<td>3.97</td>
<td>7.71</td>
<td>232</td>
<td>1.89e-09</td>
</tr>
<tr>
<td>AT1G51850</td>
<td>5.32</td>
<td>5.42</td>
<td>203</td>
<td>1.89e-09</td>
</tr>
<tr>
<td>AT5G48430</td>
<td>6.32</td>
<td>6.73</td>
<td>203</td>
<td>2.30e-09</td>
</tr>
<tr>
<td>AT2G44370</td>
<td>5.41</td>
<td>5.20</td>
<td>200</td>
<td>2.50e-09</td>
</tr>
<tr>
<td>AT1G51820</td>
<td>4.34</td>
<td>6.37</td>
<td>198</td>
<td>2.64e-09</td>
</tr>
<tr>
<td>AT3G55150</td>
<td>5.78</td>
<td>4.90</td>
<td>196</td>
<td>2.80e-09</td>
</tr>
</tbody>
</table>

Here’s a closer look at the individual counts-per-million for the top genes. The top genes are very consistent across the three replicates:

> top <- rownames(topTags(qlf))
> cpm(y)[top,]

<table>
<thead>
<tr>
<th>mock1</th>
<th>mock2</th>
<th>mock3</th>
<th>hrcc1</th>
<th>hrcc2</th>
<th>hrcc3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT2G19190</td>
<td>16.696</td>
<td>12.0</td>
<td>13.29</td>
<td>341.3</td>
<td>254.7</td>
</tr>
<tr>
<td>AT2G39530</td>
<td>7.001</td>
<td>9.0</td>
<td>13.29</td>
<td>158.1</td>
<td>191.9</td>
</tr>
<tr>
<td>AT3G46280</td>
<td>18.850</td>
<td>17.0</td>
<td>18.40</td>
<td>384.8</td>
<td>374.5</td>
</tr>
<tr>
<td>AT2G39380</td>
<td>2.154</td>
<td>3.0</td>
<td>4.77</td>
<td>91.6</td>
<td>84.4</td>
</tr>
<tr>
<td>AT1G51800</td>
<td>29.083</td>
<td>16.5</td>
<td>30.66</td>
<td>362.4</td>
<td>347.8</td>
</tr>
<tr>
<td>AT1G51850</td>
<td>1.077</td>
<td>1.0</td>
<td>3.75</td>
<td>78.1</td>
<td>56.3</td>
</tr>
<tr>
<td>AT5G48430</td>
<td>4.309</td>
<td>4.5</td>
<td>0.00</td>
<td>189.1</td>
<td>314.6</td>
</tr>
<tr>
<td>AT2G44370</td>
<td>2.154</td>
<td>1.0</td>
<td>1.70</td>
<td>57.0</td>
<td>67.1</td>
</tr>
<tr>
<td>AT1G51820</td>
<td>9.694</td>
<td>7.5</td>
<td>6.13</td>
<td>121.2</td>
<td>156.6</td>
</tr>
<tr>
<td>AT3G55150</td>
<td>0.539</td>
<td>1.0</td>
<td>1.36</td>
<td>43.1</td>
<td>64.9</td>
</tr>
</tbody>
</table>
The total number of genes significantly up-regulated or down-regulated at 5% FDR is summarized as follows:

```r
> summary(dt <- decideTestsDGE(qlf))
   [,1]
  -1   837
   0  14797
   1   892
```

We can pick out which genes are DE:

```r
> isDE <- as.logical(dt)
> DEnames <- rownames(y)[isDE]
```

Then we can plot all the logFCs against average count size, highlighting the DE genes:

```r
> plotSmear(qlf, de.tags=DEnames)
> abline(h=c(-1,1), col="blue")
```

The blue lines indicate 2-fold up or down.

### 4.2.9 Setup

This analysis was conducted on:

```r
> sessionInfo()
```
4.3 Profiles of Yoruba HapMap individuals

4.3.1 Background

RNA-Seq profiles were made of cell lines derived from lymphoblastoid cells from 69 different Yoruba individuals from Ibadan, Nigeria [22] [23]. The profiles were generated as part of the International HapMap project [10]. RNA from each individual was sequenced on at least two lanes of an Illumina Genome Analyser 2, and mapped reads to the human genome using MAQ v0.6.8.

The study group here is essentially an opportunity sample and the individuals are likely to be genetically diverse. In this analysis we look at genes that are differentially expressed between males and female.

4.3.2 Loading the data

Read counts summarized by Ensembl gene identifiers are available in the tweeDEseqCountData package:

```r
> library(tweeDEseqCountData)
> data(pickrell1)
> Counts <- exprs(pickrell1.eset)
> dim(Counts)
```
In this analysis we will compare female with male individuals.

> Gender <- pickrell1.eset$gender
> table(Gender)

Gender
female  male
   40    29

> rm(pickrell1.eset)

Annotation for each Ensemble gene is also available from the tweeDEseqCountData package:

> data(annotEnsembl63)
> annot <- annotEnsembl63[,c("Symbol","Chr")]
> annot[1:5,]

Symbol Chr
ENSG000000252775   U7   5
ENSG000000207459   U6   5
ENSG000000252899   U7   5
ENSG000000201298   U6   5
ENSG000000222266   U6   5

> rm(annotEnsembl63)

Form a DGEList object combining the counts and associated annotation:

> library(edgeR)
> y <- DGEList(counts=Counts, genes=annot[rownames(Counts),])
4.3.3 Filtering and normalization

Keep genes with at least 1 count-per-million reads (cpm) in at least 20 samples:

> isexpr <- rowSums(cpm(y)>1) >= 20

Keep only genes with defined annotation, and recompute library sizes:

> hasannot <- rowSums(is.na(y$genes))==0
> y <- y[isexpr & hasannot, , keep.lib.sizes=FALSE]
> dim(y)
[1] 17310 69

The library sizes vary from about 5 million to over 15 million:

> barplot(y$samples$lib.size*1e-6, names=1:69, ylab="Library size (millions)")

Apply TMM normalization to account for the composition biases:

> y <- calcNormFactors(y)
> head(y$samples)

<table>
<thead>
<tr>
<th>group</th>
<th>lib.size</th>
<th>norm.factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA18486</td>
<td>7749527</td>
<td>0.939</td>
</tr>
<tr>
<td>NA18498</td>
<td>13612983</td>
<td>1.110</td>
</tr>
<tr>
<td>NA18499</td>
<td>8569631</td>
<td>0.963</td>
</tr>
<tr>
<td>NA18501</td>
<td>8595024</td>
<td>1.201</td>
</tr>
<tr>
<td>NA18502</td>
<td>13375275</td>
<td>0.938</td>
</tr>
<tr>
<td>NA18504</td>
<td>9881732</td>
<td>0.979</td>
</tr>
</tbody>
</table>
4.3.4 Estimating the dispersion

We are interested in the differences between male and female. Hence, we create a design matrix using the gender factor. We estimate the NB dispersion using `estimateDisp`. The estimation is robustified against potential outlier genes.

```r
> design <- model.matrix(~Gender)
> y <- estimateDisp(y, design, robust=TRUE)
> plotBCV(y)
```

We then estimate the QL dispersions around the dispersion trend using `glmQLFit`. The large number of cases and the high variability means that the QL dispersions are not squeezed very heavily from the raw values:

```r
> fit <- glmQLFit(y, design, robust=TRUE)
> plotQLDisp(fit)
```
4.3.5 Differential expression

Now find genes differentially expressed between male and females. Positive log-fold-changes mean higher expression in males. The highly ranked genes are mostly on the X or Y chromosomes. Top ranked is the famous XIST gene, which is known to be expressed only in females.

```r
> qlf <- glmQLFTest(fit)
> topTags(qlf, n=15)
```

<table>
<thead>
<tr>
<th>Coefficient: Gendermale</th>
<th>Symbol</th>
<th>Chr</th>
<th>logFC</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENSG000000229807</td>
<td>XIST</td>
<td>X</td>
<td>-9.49</td>
<td>7.249</td>
<td>1213</td>
<td>1.03e-46</td>
<td>1.78e-42</td>
</tr>
<tr>
<td>ENSG00000099749</td>
<td>CYorf15A</td>
<td>Y</td>
<td>4.28</td>
<td>1.757</td>
<td>857</td>
<td>1.19e-41</td>
<td>1.03e-37</td>
</tr>
<tr>
<td>ENSG00000131002</td>
<td>CYorf15B</td>
<td>Y</td>
<td>5.63</td>
<td>2.055</td>
<td>587</td>
<td>2.66e-36</td>
<td>1.31e-32</td>
</tr>
<tr>
<td>ENSG00000157828</td>
<td>RPS4Y2</td>
<td>Y</td>
<td>3.18</td>
<td>4.207</td>
<td>585</td>
<td>3.02e-36</td>
<td>1.31e-32</td>
</tr>
<tr>
<td>ENSG00000233864</td>
<td>TTTY15</td>
<td>Y</td>
<td>4.84</td>
<td>1.254</td>
<td>538</td>
<td>4.42e-35</td>
<td>1.53e-31</td>
</tr>
<tr>
<td>ENSG00000198692</td>
<td>EIF1AY</td>
<td>Y</td>
<td>2.36</td>
<td>3.247</td>
<td>376</td>
<td>3.04e-30</td>
<td>8.78e-27</td>
</tr>
<tr>
<td>ENSG00000165246</td>
<td>NLGN4Y</td>
<td>Y</td>
<td>5.09</td>
<td>1.676</td>
<td>303</td>
<td>1.70e-27</td>
<td>4.21e-24</td>
</tr>
<tr>
<td>ENSG00000183878</td>
<td>UTY</td>
<td>Y</td>
<td>1.86</td>
<td>3.137</td>
<td>253</td>
<td>3.24e-25</td>
<td>7.01e-22</td>
</tr>
<tr>
<td>ENSG00000243209</td>
<td>AC010889.1</td>
<td>Y</td>
<td>2.66</td>
<td>0.797</td>
<td>232</td>
<td>3.63e-24</td>
<td>6.29e-21</td>
</tr>
<tr>
<td>ENSG00000129824</td>
<td>RPS4Y1</td>
<td>Y</td>
<td>2.53</td>
<td>5.401</td>
<td>232</td>
<td>3.63e-24</td>
<td>6.29e-21</td>
</tr>
<tr>
<td>ENSG00000012817</td>
<td>KDM5D</td>
<td>Y</td>
<td>1.47</td>
<td>4.950</td>
<td>222</td>
<td>1.16e-23</td>
<td>1.82e-20</td>
</tr>
<tr>
<td>ENSG00000213318</td>
<td>RP11-331F4.1</td>
<td>16</td>
<td>3.67</td>
<td>3.688</td>
<td>217</td>
<td>2.87e-23</td>
<td>4.13e-20</td>
</tr>
<tr>
<td>ENSG00000067048</td>
<td>DDX3Y</td>
<td>Y</td>
<td>1.62</td>
<td>5.621</td>
<td>181</td>
<td>2.48e-21</td>
<td>3.30e-18</td>
</tr>
<tr>
<td>ENSG00000146938</td>
<td>NLGN4X</td>
<td>X</td>
<td>3.94</td>
<td>1.048</td>
<td>139</td>
<td>1.81e-18</td>
<td>2.24e-15</td>
</tr>
<tr>
<td>ENSG00000232928</td>
<td>RP13-204A15.4</td>
<td>X</td>
<td>1.44</td>
<td>3.558</td>
<td>111</td>
<td>3.19e-16</td>
<td>3.68e-13</td>
</tr>
</tbody>
</table>
4.3.6 Gene set testing

The tweeDEseqCountData package includes a list of genes belonging to the male-specific region of chromosome Y, and a list of genes located in the X chromosome that have been reported to escape X-inactivation. We expect genes in the first list to be up-regulated in males, whereas genes in the second list should be up-regulated in females.

```
> data(genderGenes)
> Ymale <- rownames(y) %in% msYgenes
> Xescape <- rownames(y) %in% XiEgenes
```

Roast gene set tests by `fry()` confirm that the male-specific genes are significantly up as a group in our comparison of males with females, whereas the X genes are significantly down as a group [33].

```
> index <- list(Y=Ymale, X=Xescape)
> fry(y, index=index, design=design)
```

<table>
<thead>
<tr>
<th>NGenes</th>
<th>Direction</th>
<th>PValue</th>
<th>FDR</th>
<th>PValue.Mixed</th>
<th>FDR.Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>12</td>
<td>Up</td>
<td>7.04e-46</td>
<td>1.41e-45</td>
<td>5.86e-11</td>
</tr>
<tr>
<td>X</td>
<td>46</td>
<td>Down</td>
<td>7.25e-17</td>
<td>7.25e-17</td>
<td>2.28e-66</td>
</tr>
</tbody>
</table>

A barcode plot can be produced to visualize the results. Genes are ranked from left to right by decreasing log-fold-change in the background of the barcode plot. Genes in the set of `msYgenes` are represented by red bars whereas genes in the set of `XiEgenes` are represented by blue bars. The line above the barcode shows the relative local enrichment of the vertical bars in each part of the plot. This particular plot suggests that the male-specific genes tend to have large positive log-fold-changes, whereas the X genes tend to have large negative log-fold-changes.

```
> barcodeplot(qlf$table$logFC, index[[1]], index[[2]])
```
The results from competitive camera gene sets tests are even more convincing [34]. The positive intergene correlations here show that the genes in each set tend to be biologically correlated:

```r
> camera(y, index, design)

  NGenes Correlation Direction PValue      FDR
Y    12   0.0846       Up 4.18e-39 8.36e-39
X    46   0.0239      Down 1.34e-12 1.34e-12
```

See where the X and Y genes fall on the MA plot:

```r
> with(qlf$table, plot(logCPM,logFC,pch=16,cex=0.2))
> with(qlf$table, points(logCPM[Xescape],logFC[Xescape],pch=16,col="blue"))
> with(qlf$table, points(logCPM[Ymale],logFC[Ymale],pch=16,col="red"))
> legend("bottomleft",legend=c("Ymale genes","Xescape genes"),pch=16,,col=c("red","blue"))
```
4.3.7 Setup

This analysis was conducted on:

> sessionInfo()

R version 3.3.0 beta (2016-04-14 r70486)
Platform: x86_64-w64-mingw32/x64 (64-bit)
Running under: Windows 7 x64 (build 7601) Service Pack 1

locale:
[1] LC_COLLATE=English_Australia.1252 LC_CTYPE=English_Australia.1252
[3] LC_MONETARY=English_Australia.1252 LC_NUMERIC=C
[5] LC_TIME=English_Australia.1252

attached base packages:
[1] parallel stats4 stats graphics grDevices utils datasets methods base

other attached packages:
[1] tweeDEseqCountData_1.9.0 NBPSeq_0.3.0 org.Hs.eg.db_3.3.0
[4] RSQLite_1.0.0 DBI_0.3.1 AnnotationDbi_1.33.11
[7] IRanges_2.5.46 S4Vectors_0.9.51 Biobase_2.31.3
[10] BiocGenerics_0.17.5 edgeR_3.13.9 limma_3.27.19

loaded via a namespace (and not attached):
[1] Rcpp_0.12.4.5 magrittr_1.5 splines_3.3.0 munsell_0.4.3 statmod_1.4.24
[6] colorspace_1.2-6 lattice_0.20-33 stringr_1.0.0 plyr_1.8.3 tools_3.3.0
4.4 RNA-Seq profiles of mouse mammary gland

4.4.1 Introduction

The RNA-Seq data of this case study is described in Fu et al. [8]. The sequence and count data are publicly available from the Gene Expression Omnibus (GEO) at the series accession number GSE60450. This study examines the expression profiles of basal stem-cell enriched cells (B) and committed luminal cells (L) in the mammary gland of virgin, pregnant and lactating mice. Six groups are present, with one for each combination of cell type and mouse status. Each group contains two biological replicates. This is summarized in the table below, where the basal and luminal cell types are abbreviated with B and L respectively.

```r
> targets <- read.delim("targets.txt", header=TRUE)
> targets

             FileName GEOAccession CellType Status
   1 SRR1552450.fastq GSM1480297     B     virgin
   2 SRR1552451.fastq GSM1480298     B     virgin
   3 SRR1552452.fastq GSM1480299     B    pregnant
   4 SRR1552453.fastq GSM1480300     B    pregnant
   5 SRR1552454.fastq GSM1480301     B     lactate
   6 SRR1552455.fastq GSM1480302     B     lactate
   7 SRR1552444.fastq GSM1480291     L     virgin
   8 SRR1552445.fastq GSM1480292     L     virgin
   9 SRR1552446.fastq GSM1480293     L    pregnant
  10 SRR1552447.fastq GSM1480294     L    pregnant
  11 SRR1552448.fastq GSM1480295     L     lactate
  12 SRR1552449.fastq GSM1480296     L     lactate
```

The name of the file containing the read sequences for each library is also shown. Each file is downloaded from the Sequence Read Archive and has an accession number starting with SRR, e.g., SRR1552450 for the first library in targets.

4.4.2 Read alignment and processing

Prior to read alignment, these files are converted into the FASTQ format using the `fastq-dump` utility from the SRA Toolkit. See [http://www.ncbi.nlm.nih.gov/books/NBK158900](http://www.ncbi.nlm.nih.gov/books/NBK158900) for how to download and use the SRA Toolkit.
Before the differential expression analysis can proceed, these reads must be aligned to the mouse genome and counted into annotated genes. This can be achieved with functions in the Rsubread package [11]. We assume that an index of the mouse genome is already available - if not, this can be constructed from a FASTA file of the genome sequence with the `buildindex` command. In this example, we assume that the prefix for the index files is `mm10`. The reads in each FASTQ file are then aligned to the mouse genome, as shown below.

```r
> library(Rsubread)
> output.files <- sub(".fastq", ".bam", targets$FileName)
> align("mm10", readfile1=targets$FileName, phredOffset=33,
+ input_format="FASTQ", output_file=output.files)
```

This produces a set of BAM files, where each file contains the read alignments for each library. The mapped reads can be counted into mouse genes by using the `featureCounts` function. It uses the exon intervals defined in the NCBI annotation of the mm10 genome.

```r
> fc <- featureCounts(output.files, annot.inbuilt="mm10")
> colnames(fc$counts) <- 1:12
> head(fc$counts)
```

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>497097</td>
<td>438</td>
<td>300</td>
<td>65</td>
<td>237</td>
<td>354</td>
<td>287</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100503874</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100038431</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19888</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20671</td>
<td>106</td>
<td>182</td>
<td>82</td>
<td>105</td>
<td>43</td>
<td>82</td>
<td>16</td>
<td>25</td>
<td>18</td>
<td>8</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>27395</td>
<td>309</td>
<td>234</td>
<td>337</td>
<td>300</td>
<td>290</td>
<td>270</td>
<td>560</td>
<td>464</td>
<td>489</td>
<td>328</td>
<td>307</td>
<td>342</td>
</tr>
</tbody>
</table>
```

The row names of the matrix represent the Entrez gene identifiers for each gene. In the output from `featureCounts`, the column names of `fc$counts` are the output file names from `align`. Here, we simplify them for brevity.

### 4.4.3 Count loading and annotation

We create a `DGEList` object as follows

```r
> group <- factor(paste0(targets$CellType, ",", targets$Status))
> y <- DGEList(fc$counts, group=group)
> colnames(y) <- targets$GEO
```

Human-readable gene symbols can also be added to complement the Entrez identifiers for each gene, using the annotation in the `org.Mm.eg.db` package.
> require(org.Mm.eg.db)
> y$genes <- select(org.Mm.eg.db, keys=rownames(y), columns="SYMBOL")
> head(y$genes)

<table>
<thead>
<tr>
<th>ENTREZID</th>
<th>SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>497097</td>
<td>Xkr4</td>
</tr>
<tr>
<td>100503874</td>
<td>Gm19938</td>
</tr>
<tr>
<td>100038431</td>
<td>Gm10568</td>
</tr>
<tr>
<td>19888</td>
<td>Rp1</td>
</tr>
<tr>
<td>20671</td>
<td>Sox17</td>
</tr>
<tr>
<td>27395</td>
<td>Mrpl15</td>
</tr>
</tbody>
</table>

### 4.4.4 Filtering and normalization

Here, a gene is only retained if it is expressed at a count-per-million (CPM) above 0.5 in at least two samples.

> keep <- rowSums(cpm(y) > 0.5) >= 2
> summary(keep)

```
   Mode FALSE  TRUE  NA's
   logical   11375 15804     0
```

> y <- y[keep, , keep.lib.sizes=FALSE]

TMM normalization is performed to eliminate composition biases between libraries.

> y <- calcNormFactors(y)
> y$samples

<table>
<thead>
<tr>
<th>group</th>
<th>lib.size</th>
<th>norm.factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM1480297</td>
<td>B.virgin</td>
<td>23218026</td>
</tr>
<tr>
<td>GSM1480298</td>
<td>B.virgin</td>
<td>21768136</td>
</tr>
<tr>
<td>GSM1480299</td>
<td>B.pregnant</td>
<td>24091588</td>
</tr>
<tr>
<td>GSM1480300</td>
<td>B.pregnant</td>
<td>22656713</td>
</tr>
<tr>
<td>GSM1480301</td>
<td>B.lactate</td>
<td>21522033</td>
</tr>
<tr>
<td>GSM1480302</td>
<td>B.lactate</td>
<td>20008326</td>
</tr>
<tr>
<td>GSM1480291</td>
<td>L.virgin</td>
<td>20384562</td>
</tr>
<tr>
<td>GSM1480292</td>
<td>L.virgin</td>
<td>21698793</td>
</tr>
<tr>
<td>GSM1480293</td>
<td>L.pregnant</td>
<td>22235847</td>
</tr>
<tr>
<td>GSM1480294</td>
<td>L.pregnant</td>
<td>21982745</td>
</tr>
<tr>
<td>GSM1480295</td>
<td>L.lactate</td>
<td>24719697</td>
</tr>
<tr>
<td>GSM1480296</td>
<td>L.lactate</td>
<td>24652963</td>
</tr>
</tbody>
</table>
The performance of the TMM normalization procedure can be examined using mean-difference (MD) plots. This visualizes the library size-adjusted log-fold change between two libraries (the difference) against the average log-expression across those libraries (the mean). The following MD plot is generated by comparing sample 1 against an artificial library constructed from the average of all other samples.

```r
> plotMD(cpm(y, log=TRUE), column=1)
> abline(h=0, col="red", lty=2, lwd=2)
```

Ideally, the bulk of genes should be centred at a log-fold change of zero. This indicates that any composition bias between libraries has been successfully removed. This quality check should be repeated by constructing a MD plot for each sample.

### 4.4.5 Data exploration

The data can be explored by generating multi-dimensional scaling (MDS) plots. This visualizes the differences between the expression profiles of different samples in two dimensions.

```r
> points <- c(0,1,2,15,16,17)
> colors <- rep(c("blue", "darkgreen", "red"), 2)
> plotMDS(y, col=colors[group], pch=points[group])
> legend("topleft", legend=levels(group), pch=points, col=colors, ncol=2)
```
Replicate samples from the same group cluster together in the plot, while samples from different groups form separate clusters. This indicates that the differences between groups are larger than those within groups, i.e., differential expression is greater than the variance and can be detected. The distance between basal samples on the left and luminal cells on the right is about 6 units, corresponding to a leading fold change of about 64-fold \(2^6 = 64\) between basal and luminal. The expression differences between virgin, pregnant and lactating are greater for luminal cells than for basal.

4.4.6 The design matrix

The experimental design for this study can be parametrized with a one-way layout, whereby one coefficient is assigned to each group. The design matrix contains the predictors for each sample and is constructed using the code below.

```r
> design <- model.matrix(~ 0 + group)
> colnames(design) <- levels(group)
> design

<table>
<thead>
<tr>
<th></th>
<th>B.lactate</th>
<th>B.pregnant</th>
<th>B.virgin</th>
<th>L.lactate</th>
<th>L.pregnant</th>
<th>L.virgin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
```

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4.4.7 Estimating the dispersion

The NB dispersion is estimated using the \texttt{estimateDisp} function. This returns the \texttt{DGEList} object with additional entries for the estimated NB dispersions for all gene. These estimates can be visualized with \texttt{plotBCV}, which shows the root-estimate, i.e., the biological coefficient of variation for each gene.

```r
> y <- estimateDisp(y, design, robust=TRUE)
> y$common.dispersion
[1] 0.0134
> plotBCV(y)
```
Note that only the trended dispersion is used under the quasi-likelihood (QL) pipeline. The tagwise and common estimates are shown here but will not be used further.

For the QL dispersions, estimation can be performed using the \texttt{glmQLFit} function. This returns a \texttt{DGEGLM} object containing the estimated values of the GLM coefficients for each gene, as well as the fitted mean-QL dispersion trend, the squeezed QL estimates and the prior degrees of freedom (df). These can be visualized with the \texttt{plotQLDisp} function.

\begin{verbatim}
> fit <- glmQLFit(y, design, robust=TRUE)
> head(fit$coefficients)

  B.lactate B.pregnant B.virgin L.lactate L.pregnant L.virgin
20671   -12.77   -12.51   -12.15   -14.5   -14.31   -14.1
27395   -11.27   -11.30   -11.53   -10.6   -10.87   -10.9
18777   -10.15   -10.21   -10.77   -10.1   -10.39   -10.4
\end{verbatim}

\begin{verbatim}
> plotQLDisp(fit)
\end{verbatim}

Setting \texttt{robust=TRUE} in \texttt{glmQLFit} is strongly recommended [21]. Setting \texttt{robust=TRUE} in \texttt{estimateDisp} has no effect on the downstream analysis, but is nevertheless very useful as it identifies genes that are outliers from the mean-NB dispersion trend.
4.4.8 Differential expression

We test for significant differential expression in each gene, using the QL F-test. The contrast of interest can be specified using the `makeContrasts` function. Here, genes are tested for DE between the basal pregnant and lactating groups. This is done by defining the null hypothesis as $B.pregnant - B.lactate = 0$.

```r
> con <- makeContrasts(B.pregnant - B.lactate, levels=design)
> qlf <- glmQLFTest(fit, contrast=con)
```

The top set of most significant genes can be examined with `topTags`. Here, a positive log-fold change represents genes that are up in $B.pregnant$ over $B.lactate$. Multiplicity correction is performed by applying the Benjamini-Hochberg method on the $p$-values, to control the false discovery rate (FDR).

```r
> topTags(qlf)
```

<table>
<thead>
<tr>
<th>ENTREZID</th>
<th>SYMBOL</th>
<th>logFC</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>18071</td>
<td>Csn1s2b</td>
<td>-6.09</td>
<td>10.18</td>
<td>421</td>
<td>4.86e-11</td>
<td>7.67e-07</td>
</tr>
<tr>
<td>22881</td>
<td>Mrgprf</td>
<td>-5.15</td>
<td>2.74</td>
<td>345</td>
<td>1.30e-10</td>
<td>8.05e-07</td>
</tr>
<tr>
<td>12177</td>
<td>Myof</td>
<td>-2.32</td>
<td>6.44</td>
<td>322</td>
<td>1.97e-10</td>
<td>8.05e-07</td>
</tr>
<tr>
<td>851</td>
<td>Atp2b4</td>
<td>-2.14</td>
<td>6.14</td>
<td>320</td>
<td>1.30e-10</td>
<td>8.05e-07</td>
</tr>
<tr>
<td>9279</td>
<td>Muc4</td>
<td>7.17</td>
<td>6.05</td>
<td>308</td>
<td>2.64e-10</td>
<td>8.34e-07</td>
</tr>
<tr>
<td>18829</td>
<td>Mica12</td>
<td>6.25</td>
<td>5.18</td>
<td>282</td>
<td>4.47e-10</td>
<td>7.67e-07</td>
</tr>
<tr>
<td>2491</td>
<td>Wif1</td>
<td>1.82</td>
<td>6.76</td>
<td>260</td>
<td>7.30e-10</td>
<td>1.65e-06</td>
</tr>
<tr>
<td>18684</td>
<td>Cldn4</td>
<td>5.32</td>
<td>9.87</td>
<td>298</td>
<td>8.88e-10</td>
<td>1.71e-06</td>
</tr>
<tr>
<td>22829</td>
<td>Tnni2</td>
<td>-5.75</td>
<td>3.86</td>
<td>313</td>
<td>9.76e-10</td>
<td>1.71e-06</td>
</tr>
<tr>
<td>19483</td>
<td>Creb5</td>
<td>-2.57</td>
<td>4.87</td>
<td>241</td>
<td>1.16e-09</td>
<td>8.34e-07</td>
</tr>
</tbody>
</table>

The top gene Csn1s2b has a large negative log2-fold-change, showing that it is far more highly expressed in lactating than pregnant mice. This gene is known to be a major source of protein in milk.

The total number of DE genes in each direction at a FDR of 5% can be examined with `decideTestsDGE`. There are in fact nearly 4500 DE genes an FDR cut-off of 5% in this comparison:

```r
> is.de <- decideTestsDGE(qlf, p.value=0.05)
> summary(is.de)
```

<table>
<thead>
<tr>
<th>[,1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

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The differential expression test results can be visualized using a smear plot. The log-fold change for each gene is plotted against the average abundance, i.e., logCPM in the result table above. Significantly DE genes at a FDR of 5\% are highlighted in red.

> plotSmear(qlf, de.tags=rownames(qlf)[is.de!=0])

![Smear plot showing differential expression results](image)

We use `glmTreat` to narrow down the list of DE genes and focus on genes that are more biologically meaningful. We test whether the differential expression is significantly above a log2-fold-change of log₂ 1.2, i.e., a fold-change of 1.2.

> tr <- glmTreat(fit, contrast=con, lfc=log2(1.2))
> topTags(tr)

<table>
<thead>
<tr>
<th>ENTREZID</th>
<th>SYMBOL</th>
<th>logFC</th>
<th>unshrunk.logFC</th>
<th>logCPM</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>18071</td>
<td>Csn1s2b</td>
<td>-6.09</td>
<td>-6.09</td>
<td>10.18</td>
<td>5.08e-11</td>
<td>8.02e-07</td>
</tr>
<tr>
<td>22881</td>
<td>Mrgprf</td>
<td>-5.15</td>
<td>-5.15</td>
<td>2.74</td>
<td>1.38e-10</td>
<td>9.13e-07</td>
</tr>
<tr>
<td>12177</td>
<td>Myof</td>
<td>-2.32</td>
<td>-2.32</td>
<td>6.44</td>
<td>2.66e-10</td>
<td>9.13e-07</td>
</tr>
<tr>
<td>851</td>
<td>Atp2b4</td>
<td>-2.14</td>
<td>-2.14</td>
<td>6.14</td>
<td>2.89e-10</td>
<td>9.13e-07</td>
</tr>
<tr>
<td>9279</td>
<td>Muc4</td>
<td>7.17</td>
<td>7.17</td>
<td>6.05</td>
<td>2.89e-10</td>
<td>9.13e-07</td>
</tr>
<tr>
<td>18829</td>
<td>Micall2</td>
<td>2.25</td>
<td>2.25</td>
<td>5.18</td>
<td>6.15e-10</td>
<td>1.62e-06</td>
</tr>
<tr>
<td>18684</td>
<td>Cldn4</td>
<td>5.32</td>
<td>5.32</td>
<td>9.87</td>
<td>9.30e-10</td>
<td>2.00e-06</td>
</tr>
<tr>
<td>22829</td>
<td>Tnni2</td>
<td>-5.75</td>
<td>-5.76</td>
<td>3.86</td>
<td>1.01e-09</td>
<td>2.00e-06</td>
</tr>
<tr>
<td>2491</td>
<td>Wif1</td>
<td>1.82</td>
<td>1.82</td>
<td>6.76</td>
<td>1.18e-09</td>
<td>2.08e-06</td>
</tr>
<tr>
<td>19483</td>
<td>Creb5</td>
<td>-2.57</td>
<td>-2.57</td>
<td>4.87</td>
<td>1.47e-09</td>
<td>2.32e-06</td>
</tr>
</tbody>
</table>

We use `glmTreat` to narrow down the list of DE genes and focus on genes that are more biologically meaningful. We test whether the differential expression is significantly above a log2-fold-change of log₂ 1.2, i.e., a fold-change of 1.2.

> tr <- glmTreat(fit, contrast=con, lfc=log2(1.2))
> topTags(tr)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>ENTREZID</th>
<th>SYMBOL</th>
<th>logFC</th>
<th>unshrunk.logFC</th>
<th>logCPM</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1<em>B.lactate 1</em>B.pregnant</td>
<td>18071</td>
<td>Csn1s2b</td>
<td>-6.09</td>
<td>-6.09</td>
<td>10.18</td>
<td>5.08e-11</td>
<td>8.02e-07</td>
</tr>
<tr>
<td>22881</td>
<td>Mrgprf</td>
<td>-5.15</td>
<td>-5.15</td>
<td>2.74</td>
<td>1.38e-10</td>
<td>9.13e-07</td>
<td></td>
</tr>
<tr>
<td>12177</td>
<td>Myof</td>
<td>-2.32</td>
<td>-2.32</td>
<td>6.44</td>
<td>2.66e-10</td>
<td>9.13e-07</td>
<td></td>
</tr>
<tr>
<td>851</td>
<td>Atp2b4</td>
<td>-2.14</td>
<td>-2.14</td>
<td>6.14</td>
<td>2.89e-10</td>
<td>9.13e-07</td>
<td></td>
</tr>
<tr>
<td>9279</td>
<td>Muc4</td>
<td>7.17</td>
<td>7.17</td>
<td>6.05</td>
<td>2.89e-10</td>
<td>9.13e-07</td>
<td></td>
</tr>
<tr>
<td>18829</td>
<td>Micall2</td>
<td>2.25</td>
<td>2.25</td>
<td>5.18</td>
<td>6.15e-10</td>
<td>1.62e-06</td>
<td></td>
</tr>
<tr>
<td>18684</td>
<td>Cldn4</td>
<td>5.32</td>
<td>5.32</td>
<td>9.87</td>
<td>9.30e-10</td>
<td>2.00e-06</td>
<td></td>
</tr>
<tr>
<td>22829</td>
<td>Tnni2</td>
<td>-5.75</td>
<td>-5.76</td>
<td>3.86</td>
<td>1.01e-09</td>
<td>2.00e-06</td>
<td></td>
</tr>
<tr>
<td>2491</td>
<td>Wif1</td>
<td>1.82</td>
<td>1.82</td>
<td>6.76</td>
<td>1.18e-09</td>
<td>2.08e-06</td>
<td></td>
</tr>
<tr>
<td>19483</td>
<td>Creb5</td>
<td>-2.57</td>
<td>-2.57</td>
<td>4.87</td>
<td>1.47e-09</td>
<td>2.32e-06</td>
<td></td>
</tr>
</tbody>
</table>
Around 3000 genes are detected as DE with fold-change significantly above 1.2 at an FDR cut-off of 5%.

```r
> is.de <- decideTestsDGE(tr, p.value=0.05)
> summary(is.de)

[,1]
-1 1291
0 12827
1 1686
```

The test results are visualized in the following smear plot. Genes that are significantly DE above a fold-change of 1.2 at an FDR of 5% are highlighted in red.

```r
> plotSmear(tr, de.tags=rownames(tr)[is.de!=0])
```

4.4.9 ANOVA-like testing

The differential expression analysis of two-group comparison can be easily extended to comparisons between three or more groups. This is done by creating a matrix of contrasts, where which each column represents a contrast between two groups of interest. In this manner, users can perform a one-way analysis of variance (ANOVA) for each gene.

As an example, suppose we want to compare the three groups in the luminal population, i.e., virgin, pregnant and lactating. An appropriate contrast matrix can be created as shown below, to make pairwise comparisons between all three groups.
con <- makeContrasts(
+ L.PvsL = L.pregnant - L.lactate,
+ L.VvsL = L.virgin - L.lactate,
+ L.VvsP = L.virgin - L.pregnant, levels=design)

The QL F-test is then applied to identify genes that are DE among the three groups. This combines the three pairwise comparisons into a single F-statistic and \( p \)-value. The top set of significant genes can be displayed with topTags.

> anov <- glmQLFTest(fit, contrast=con)
> topTags(anov)

<table>
<thead>
<tr>
<th>ENTREZID</th>
<th>SYMBOL</th>
<th>logFC.L.PvsL</th>
<th>logFC.L.VvsL</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>19230</td>
<td>Ptn</td>
<td>-1.54</td>
<td>7.26</td>
<td>7.97</td>
<td>2387</td>
<td>3.77e-17</td>
<td>5.96e-13</td>
</tr>
<tr>
<td>15679</td>
<td>Egf</td>
<td>-5.36</td>
<td>-7.22</td>
<td>3.67</td>
<td>1126</td>
<td>4.46e-15</td>
<td>3.22e-11</td>
</tr>
<tr>
<td>21207</td>
<td>Kcnk6</td>
<td>-2.42</td>
<td>-7.00</td>
<td>7.91</td>
<td>1020</td>
<td>8.40e-15</td>
<td>3.22e-11</td>
</tr>
<tr>
<td>15439</td>
<td>Hp</td>
<td>1.08</td>
<td>5.42</td>
<td>4.93</td>
<td>992</td>
<td>8.40e-15</td>
<td>3.22e-11</td>
</tr>
<tr>
<td>18071</td>
<td>Csn1s2b</td>
<td>-8.55</td>
<td>-11.36</td>
<td>4.93</td>
<td>1050</td>
<td>7.97e-17</td>
<td>5.96e-13</td>
</tr>
<tr>
<td>22626</td>
<td>Fgfr2</td>
<td>-1.15</td>
<td>3.95</td>
<td>7.38</td>
<td>932</td>
<td>1.29e-14</td>
<td>3.22e-11</td>
</tr>
<tr>
<td>9083</td>
<td>Slc25a1</td>
<td>-4.13</td>
<td>-10.56</td>
<td>4.93</td>
<td>1133</td>
<td>1.79e-14</td>
<td>3.22e-11</td>
</tr>
</tbody>
</table>

Note that the three contrasts of pairwise comparisons are linearly dependent. Constructing the contrast matrix with any two of the contrasts would be sufficient to specify an ANOVA test. For instance, the contrast matrix shown below produces the same test results but with a different column of log-fold changes.

> con <- makeContrasts(
+ L.PvsL = L.pregnant - L.lactate,
+ L.VvsP = L.virgin - L.pregnant, levels=design)

If all three contrasts are present in the contrast matrix, then only the log-fold changes of the first two contrasts are shown in the output of topTags.

4.4.10 Gene ontology analysis

Further analyses are required to interpret the differential expression results in a biological context. One common downstream procedure is a gene ontology (GO) enrichment analysis.

Suppose we want to identify GO terms that are over-represented in the basal lactating group compared to the basal pregnancy group. This can be achieved by applying the goana function to the differential expression results of that comparison. The top set of most enriched GO terms can be viewed with the topGO function.
```r
> con <- makeContrasts(B.lactate - B.pregnant, levels=design)
> qlf <- glmQLFTest(fit, contrast=con)
> go <- goana(qlf, species = "Mm")
> topGO(go, n=30)
```

<table>
<thead>
<tr>
<th>Term</th>
<th>Ont</th>
<th>N</th>
<th>Up</th>
<th>Down</th>
<th>P.Up</th>
<th>P.Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>GO:0044822 poly(A) RNA binding</td>
<td>MF</td>
<td>1092</td>
<td>107</td>
<td>394</td>
<td>1.000</td>
<td>3.44e-53</td>
</tr>
<tr>
<td>GO:0003723 RNA binding</td>
<td>MF</td>
<td>1429</td>
<td>155</td>
<td>469</td>
<td>1.000</td>
<td>4.29e-50</td>
</tr>
<tr>
<td>GO:0042254 ribosome biogenesis</td>
<td>BP</td>
<td>223</td>
<td>7</td>
<td>127</td>
<td>1.000</td>
<td>1.13e-40</td>
</tr>
<tr>
<td>GO:0022613 ribonucleoprotein complex biogenesis</td>
<td>BP</td>
<td>336</td>
<td>24</td>
<td>161</td>
<td>1.000</td>
<td>1.58e-38</td>
</tr>
<tr>
<td>GO:0022626 cytosolic ribosome</td>
<td>CC</td>
<td>97</td>
<td>1</td>
<td>75</td>
<td>1.000</td>
<td>4.19e-38</td>
</tr>
<tr>
<td>GO:0030529 intracellular ribonucleoprotein complex</td>
<td>BP</td>
<td>646</td>
<td>43</td>
<td>246</td>
<td>1.000</td>
<td>3.87e-37</td>
</tr>
<tr>
<td>GO:1990904 ribonucleoprotein complex</td>
<td>CC</td>
<td>646</td>
<td>43</td>
<td>246</td>
<td>1.000</td>
<td>3.87e-37</td>
</tr>
<tr>
<td>GO:0005730 nucleolus</td>
<td>CC</td>
<td>663</td>
<td>79</td>
<td>239</td>
<td>1.000</td>
<td>9.61e-32</td>
</tr>
<tr>
<td>GO:0003676 nucleic acid binding</td>
<td>MF</td>
<td>2834</td>
<td>423</td>
<td>712</td>
<td>0.998</td>
<td>1.42e-30</td>
</tr>
<tr>
<td>GO:0006364 rRNA processing</td>
<td>BP</td>
<td>146</td>
<td>3</td>
<td>85</td>
<td>1.000</td>
<td>1.57e-28</td>
</tr>
<tr>
<td>GO:0016072 rRNA metabolic process</td>
<td>BP</td>
<td>149</td>
<td>5</td>
<td>85</td>
<td>1.000</td>
<td>1.17e-27</td>
</tr>
<tr>
<td>GO:0031974 membrane-enclosed lumen</td>
<td>CC</td>
<td>2850</td>
<td>409</td>
<td>698</td>
<td>1.000</td>
<td>2.62e-26</td>
</tr>
<tr>
<td>GO:0070013 intracellular organelle lumen</td>
<td>CC</td>
<td>2793</td>
<td>401</td>
<td>684</td>
<td>1.000</td>
<td>1.11e-25</td>
</tr>
<tr>
<td>GO:0005840 ribosome</td>
<td>CC</td>
<td>203</td>
<td>4</td>
<td>100</td>
<td>1.000</td>
<td>1.71e-25</td>
</tr>
<tr>
<td>GO:0043233 organelle lumen</td>
<td>CC</td>
<td>2797</td>
<td>402</td>
<td>684</td>
<td>1.000</td>
<td>1.72e-25</td>
</tr>
<tr>
<td>GO:0044391 cytosolic subunit</td>
<td>CC</td>
<td>157</td>
<td>1</td>
<td>84</td>
<td>1.000</td>
<td>9.64e-24</td>
</tr>
<tr>
<td>GO:0022625 cytosolic large ribosomal subunit</td>
<td>CC</td>
<td>52</td>
<td>0</td>
<td>43</td>
<td>1.000</td>
<td>1.49e-24</td>
</tr>
<tr>
<td>GO:0031981 nuclear lumen</td>
<td>CC</td>
<td>2558</td>
<td>384</td>
<td>631</td>
<td>0.996</td>
<td>2.88e-24</td>
</tr>
<tr>
<td>GO:1901363 heterocyclic compound binding</td>
<td>MF</td>
<td>4346</td>
<td>668</td>
<td>975</td>
<td>0.998</td>
<td>8.95e-24</td>
</tr>
<tr>
<td>GO:0044445 cytosolic part</td>
<td>CC</td>
<td>189</td>
<td>17</td>
<td>93</td>
<td>0.999</td>
<td>9.45e-24</td>
</tr>
<tr>
<td>GO:0032991 macromolecular complex</td>
<td>CC</td>
<td>3900</td>
<td>584</td>
<td>890</td>
<td>1.000</td>
<td>1.26e-23</td>
</tr>
<tr>
<td>GO:0097159 organic cyclic compound binding</td>
<td>MF</td>
<td>4393</td>
<td>676</td>
<td>980</td>
<td>0.998</td>
<td>5.15e-23</td>
</tr>
<tr>
<td>GO:0044446 intracellular organelle part</td>
<td>CC</td>
<td>5362</td>
<td>874</td>
<td>1158</td>
<td>0.871</td>
<td>7.88e-23</td>
</tr>
<tr>
<td>GO:0044428 nuclear part</td>
<td>CC</td>
<td>2955</td>
<td>452</td>
<td>700</td>
<td>0.992</td>
<td>4.74e-22</td>
</tr>
<tr>
<td>GO:0003735 structural constituent of ribosome</td>
<td>MF</td>
<td>190</td>
<td>8</td>
<td>90</td>
<td>1.000</td>
<td>1.43e-21</td>
</tr>
<tr>
<td>GO:0044222 organelle part</td>
<td>CC</td>
<td>5508</td>
<td>909</td>
<td>1176</td>
<td>0.740</td>
<td>3.05e-21</td>
</tr>
<tr>
<td>GO:0006396 RNA processing</td>
<td>BP</td>
<td>672</td>
<td>57</td>
<td>215</td>
<td>1.000</td>
<td>5.97e-21</td>
</tr>
<tr>
<td>GO:0005634 nucleus</td>
<td>CC</td>
<td>5357</td>
<td>881</td>
<td>1145</td>
<td>0.780</td>
<td>1.35e-20</td>
</tr>
<tr>
<td>GO:0034660 ncRNA metabolic process</td>
<td>BP</td>
<td>353</td>
<td>24</td>
<td>133</td>
<td>1.000</td>
<td>6.45e-20</td>
</tr>
<tr>
<td>GO:0034470 ncRNA processing</td>
<td>BP</td>
<td>269</td>
<td>14</td>
<td>110</td>
<td>1.000</td>
<td>8.47e-20</td>
</tr>
</tbody>
</table>

The row names of the output are the universal identifiers of the GO terms, with one term per row. The **Term** column gives the names of the GO terms. These terms cover three domains - biological process (BP), cellular component (CC) and molecular function (MF), as shown in the **Ont** column. The **N** column represents the total number of genes that are annotated with each GO term. The **Up** and **Down** columns represent the number of genes with the GO term that are significantly up- and down-regulated in this differential expression comparison, respectively. The **P.Up** and **P.Down** columns contain the p-values for over-representation of the GO term across the set of up- and down-regulated genes, respectively. The output table is sorted by the minimum of **P.Up** and **P.Down** by default.

The **goana** function uses the NCBI RefSeq annotation. Therefore, the Entrez Gene iden-
tifier (ID) should be supplied for each gene as the row names of qlf.

4.4.11 Gene set testing

Another downstream step uses the rotation gene set test (ROAST) [33]. Given a set of genes, we can test whether the majority of the genes in the set are DE across the contrast of interest. It is useful when the specified set contains all genes involved in some pathway or process.

In our case study, suppose we are interested in three GO terms related to cytokinesis. Each term will be used to define a set containing all genes that are annotated with that term. The names of these terms can be viewed as shown below.

```r
> library(GO.db)
> cyt.go <- c("GO:0032465", "GO:0000281", "GO:0000920")
> term <- select(GO.db, keys=cyt.go, columns="TERM")
> term

1  GO:0032465 regulation of cytokinesis
2  GO:0000281 mitotic cytokinesis
3  GO:0000920 cell separation after cytokinesis
```

We construct a list of three components, each of which is a vector of Entrez Gene IDs for all genes annotated with one of the GO terms. We then convert the Gene IDs into row indices of the fit object using the function ids2indices.

```r
> Rkeys(org.Mm.egGO2ALLEGS) <- cyt.go
> ind <- ids2indices(as.list(org.Mm.egGO2ALLEGS), fit$genes$ENTREZID)
```

We proceed to run ROAST on the defined gene sets for the contrast of interest. Suppose the comparison of interest is between the virgin and lactating groups in the basal population. We use fry to test for multiple gene sets.

```r
> con <- makeContrasts(B.virgin-B.lactate, levels=design)
> fr <- fry(y, index=ind, design=design, contrast=con)
> fr

373h

NGenes Direction PValue FDR PValue.Mixed FDR.Mixed
GO:0032465 48 Up 0.000471 0.00141 3.72e-06 6.96e-06
GO:0000920 16 Down 0.001839 0.00276 4.64e-06 6.96e-06
GO:0000281 30 Up 0.007394 0.00739 2.50e-05 2.50e-05
```

Each row corresponds to a single gene set, i.e., GO term. The NGenes column gives the number of genes in each set. The net direction of change is determined from the significance
of changes in each direction, and is shown in the Direction column. The PValue provides evidence for whether the majority of genes in the set are DE in the specified direction, whereas the PValue.Mixed tests for differential expression in any direction. FDRs are computed from the corresponding p-values across all sets.

A barcode plot can be produced with the barcodeplot function to visualize the results for any particular set. In this case, visualization is performed for the gene set defined by GO:0032465. Here, genes are represented by bars and are ranked from left to right by decreasing log-fold change. This forms the barcode-like pattern. The line above the barcode shows the relative local enrichment of the vertical bars in each part of the plot. This particular plot suggests that most genes in this set are up-regulated in the virgin group compared to the lactating group.

```r
> res <- glmQLFTest(fit, contrast=con)
> barcodeplot(res$table$logFC, ind[[1]], main=names(ind)[1])
```

![Barcode plot for GO:0032465](image)

4.4.12 Setup
This analysis was conducted on:

```r
> sessionInfo()
```

R version 3.3.0 beta (2016-04-14 r70486)
Platform: x86_64-w64-mingw32/x64 (64-bit)
Running under: Windows 7 x64 (build 7601) Service Pack 1

locale:
[1] LC_COLLATE=English_Australia.1252  LC_CTYPE=English_Australia.1252
[3] LC_MONETARY=English_Australia.1252  LC_NUMERIC=C

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4.5 Differential splicing after Pasilla knockdown

4.5.1 Introduction

The RNA-Seq data of this case study was produced by Brooks et al [3]. Drosophila melanogaster was used as a model system to study the proteins NOVA1 and NOVA2 which are known to regulate splicing in mammals. In particular, an RNA interference system (RNAi) was used to knock down the expression of the D. melanogaster ortholog of NOVA1 and NOVA2, which is Pasilla.

The experiment compared treated and untreated cells from the S2-DRSC cell line. In this case study we are interested in exons and genes that are differentially expressed after Pasilla knockdown, as well as genes that are differentially spliced in the knockdown samples as compared to wildtype.

4.5.2 RNA-Seq samples

The RNA-Seq data of the six samples were deposited on GEO [http://www.ncbi.nlm.nih.gov/geo]. The GEO accession numbers and titles were prepared in a csv file:

```r
> library(edgeR)
> GEO <- readTargets("GEO-samples.csv", sep="",")
> GEO

GEO                                               Title  Pasilla
1 GSM461176                                           S2_DRSC_Untreated-1   Normal
```
There are three untreated biological samples, in which Pasilla should be expressed at normal levels, and three treated biological samples, in which Pasilla should be expressed at reduced levels.

While GEO records the sample information, the sequencing data file are actually held on the NCBI Short Read Archive (SRA). The RNA samples were sequenced on an Illumina Genome Analyzer II. Multiple sequencing runs were used for several of the samples, resulting in a total of 20 SRA files:

```r
>SRA <- readTargets("SRA-Files.csv", sep="",")
>SRA
```

The last two columns of the above target file indicate whether the samples are single end (SE) sequencing with 45 base-pair reads or paired end (PE) sequencing with 37 bp reads.

### 4.5.3 Read alignment and processing

The SRA format files were first converted to FASTQ format using the SRA Toolkit. Then an index file of the D. melanogaster reference genome was built in Rsubread[11] using the FASTA

Next we counted the number of reads or fragments overlapping each annotated exon of each gene. GFF files containing gene and exon annotation were downloaded from ftp://ftp.ncbi.nlm.nih.gov/genomes/Drosophila_melanogaster/RELEASE_5_48. The five *.gff files, one for each chromosome, were concatenated into one file, and repeated exons instances of the same exon (same start and stop position) were removed to create a data frame of start/stop positions called unique.gff. The single end (SE) reads were counted by:

```r
> fc_SE <- featureCounts(SE_bam_files, annot.ext="unique.gff",
+   isGTFAnnotationFile=TRUE, GTF.featureType="exon", GTF.attrType="ID",
+   useMetaFeatures=FALSE, allowMultiOverlap=TRUE)
```

where SE_bam_files is a vector of BAM file names for the SE reads. The paired end (PE) reads were counted by:

```r
> fc_PE <- featureCounts(PE_bam_files, annot.ext="unique.gff",
+   isGTFAnnotationFile=TRUE, GTF.featureType="exon", GTF.attrType="ID",
+   useMetaFeatures=FALSE, allowMultiOverlap=TRUE, isPairedEnd=TRUE)
```

where PE_bam_files is a vector of BAM file names for the PE reads.

### 4.5.4 Count loading and annotation

We create a DGEList object as follows

```r
> y.all <- DGEList(counts=cbind(fc_SE$counts, fc_PE$counts), genes=fc_SE$annotation)
> dim(y.all)
[1] 74184  20
> head(y.all$genes)
```

<table>
<thead>
<tr>
<th>GeneID</th>
<th>Chr</th>
<th>Start</th>
<th>End</th>
<th>Strand</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>138088</td>
<td>NC_004354.3</td>
<td>138094</td>
<td>139379</td>
<td>-</td>
<td>1286</td>
</tr>
<tr>
<td>138087</td>
<td>NC_004354.3</td>
<td>139445</td>
<td>139611</td>
<td>-</td>
<td>167</td>
</tr>
<tr>
<td>138089</td>
<td>NC_004354.3</td>
<td>139889</td>
<td>139889</td>
<td>-</td>
<td>445</td>
</tr>
<tr>
<td>138086</td>
<td>NC_004354.3</td>
<td>139713</td>
<td>139889</td>
<td>-</td>
<td>177</td>
</tr>
<tr>
<td>138091</td>
<td>NC_004354.3</td>
<td>140011</td>
<td>141629</td>
<td>+</td>
<td>1619</td>
</tr>
<tr>
<td>138092</td>
<td>NC_004354.3</td>
<td>142415</td>
<td>144271</td>
<td>+</td>
<td>1857</td>
</tr>
</tbody>
</table>

The annotation includes Entrez ID and the length, chromosome and start and stop position of each exon. We resort the samples back to original SRA order and collapse the data so that there is a single column for each GEO sample by summing the counts over the technical replicates:
> y.all <- y.all[, SRA$SRA]
> y <- sumTechReps(y.all, ID=SRA$GEO)
> y$samples

<table>
<thead>
<tr>
<th>group</th>
<th>lib.size</th>
<th>norm.factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM461176</td>
<td>31007529</td>
<td>1</td>
</tr>
<tr>
<td>GSM461177</td>
<td>13040952</td>
<td>1</td>
</tr>
<tr>
<td>GSM461178</td>
<td>15030819</td>
<td>1</td>
</tr>
<tr>
<td>GSM461179</td>
<td>28143539</td>
<td>1</td>
</tr>
<tr>
<td>GSM461180</td>
<td>14901292</td>
<td>1</td>
</tr>
<tr>
<td>GSM461181</td>
<td>16264066</td>
<td>1</td>
</tr>
</tbody>
</table>

> colnames(y) <- c("N1","N3","N4","D1","D3","D4")

Annotation for D. melanogaster genes was downloaded from ftp://ftp.ncbi.nlm.nih.gov/gene/DATA/GENE_INFO/Invertebrates. We now add selected annotation columns to the DGEList object:

> ncbi.L1 <- readLines("Drosophila_melanogaster.gene_info", n = 1)
> ncbi.colname <- unlist(strsplit(substring(ncbi.L1, 10, 234), ' '))
> ncbi <- read.delim("Drosophila_melanogaster.gene_info", skip=1,
> +     header=FALSE, stringsAsFactors=FALSE)
> colnames(ncbi) <- ncbi.colname
> m <- match(y$genes$GeneID, ncbi$GeneID)
> y$genes$Chr <- ncbi$chromosome[m]
> y$genes$Symbol <- ncbi$Symbol[m]
> y$genes$Strand <- NULL
> head(y$genes)

<table>
<thead>
<tr>
<th>GeneID</th>
<th>Chr</th>
<th>Start</th>
<th>End</th>
<th>Length</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>138088</td>
<td>30970</td>
<td>138094</td>
<td>139379</td>
<td>1286</td>
<td>CG3038</td>
</tr>
<tr>
<td>138087</td>
<td>30970</td>
<td>139445</td>
<td>139611</td>
<td>167</td>
<td>CG3038</td>
</tr>
<tr>
<td>138089</td>
<td>30970</td>
<td>139445</td>
<td>139889</td>
<td>445</td>
<td>CG3038</td>
</tr>
<tr>
<td>138086</td>
<td>30970</td>
<td>139713</td>
<td>139889</td>
<td>177</td>
<td>CG3038</td>
</tr>
<tr>
<td>138091</td>
<td>30971</td>
<td>140011</td>
<td>141629</td>
<td>1619</td>
<td>G9a</td>
</tr>
<tr>
<td>138092</td>
<td>30971</td>
<td>142415</td>
<td>144271</td>
<td>1857</td>
<td>G9a</td>
</tr>
</tbody>
</table>

4.5.5 Filtering and normalization

Here, an exon is only retained if it is expressed at a count-per-million (CPM) above 1 in at least 3 samples.

> keep <- rowSums(cpm(y) > 1) >=3
> summary(keep)
Mode FALSE TRUE NA's
logical 36926 37258 0

> y <- y[keep, , keep.lib.sizes=FALSE]

TMM normalization is performed to eliminate composition biases between libraries.

> y <- calcNormFactors(y)
> y$samples

<table>
<thead>
<tr>
<th>group</th>
<th>lib.size</th>
<th>norm.factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>1 30872843</td>
<td>0.955</td>
</tr>
<tr>
<td>N3</td>
<td>1 12962245</td>
<td>1.031</td>
</tr>
<tr>
<td>N4</td>
<td>1 14908555</td>
<td>0.976</td>
</tr>
<tr>
<td>D1</td>
<td>1 27989806</td>
<td>1.005</td>
</tr>
<tr>
<td>D3</td>
<td>1 14760887</td>
<td>1.022</td>
</tr>
<tr>
<td>D4</td>
<td>1 16172265</td>
<td>1.014</td>
</tr>
</tbody>
</table>

### 4.5.6 Data exploration

The data can be explored by generating multi-dimensional scaling (MDS) plots. This visualizes the differences between the expression profiles of different samples in two dimensions.

> plotMDS(y)

![MDS plot](image)

The MDS plot shows clear separation of the Pasilla down vs normal samples, but also a batch effect associated with sequencing type and date.
4.5.7 The design matrix

To account for the batch effect observed from the MDS plot, we create a design matrix as follows:

```r
> Batch <- factor(c(1,3,4,1,3,4))
> Pasilla <- factor(GEO$Pasilla, levels=c("Normal","Down"))
> design <- model.matrix(~ Batch + Pasilla)
> design

 (Intercept) Batch3 Batch4 PasillaDown
 1    1   0   0     0
 2    1   1   0     0
 3    1   0   1     0
 4    1   0   0     1
 5    1   1   0     1
 6    1   0   1     1
attr("assign")
[1] 0 1 1 2
attr("contrasts")
attr("contrasts")$Batch
[1] "contr.treatment"
attr("contrasts")$Pasilla
[1] "contr.treatment"
```

4.5.8 Estimating the dispersion

We estimate NB dispersions using the `estimateDisp` function. The estimated dispersions can be visualized with `plotBCV`.

```r
> y <- estimateDisp(y, design, robust=TRUE)
> y$common.dispersion
[1] 0.0141
> plotBCV(y)
```
Note that only the trended dispersion is used under the quasi-likelihood (QL) pipeline. The tagwise and common estimates are shown here but will not be used further.

For the QL dispersions, estimation can be performed using the `glmQLFit` function. The results can be visualized with the `plotQLDisp` function.

```r
> fit <- glmQLFit(y, design, robust=TRUE)
> plotQLDisp(fit)
```
4.5.9 Differential expression

We test for differentially expressed exons between Pasilla knockdown and normal using the QL F-test.

\[ qlf \leftarrow \text{glmQLFTest}(\text{fit}, \text{coef}=4) \]

The top set of most significant exons can be examined with `topTags`. Here, a positive log-fold change represents exons that are up in Pasilla knockdown over normal. Multiplicity correction is performed by applying the Benjamini-Hochberg method on the \( p \)-values, to control the false discovery rate (FDR).

\[ \text{topTags}(qlf) \]

<table>
<thead>
<tr>
<th>Coefficient: PasillaDown</th>
<th>GeneID</th>
<th>Chr</th>
<th>Start</th>
<th>End</th>
<th>Length</th>
<th>Symbol</th>
<th>logFC</th>
<th>logCPM</th>
<th>F</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>150709</td>
<td>32007</td>
<td>X</td>
<td>10674926</td>
<td>10676128</td>
<td>1203</td>
<td>sesB</td>
<td>-3.26</td>
<td>7.21</td>
<td>949</td>
<td>7.41e-15</td>
<td>1.39e-10</td>
</tr>
<tr>
<td>150713</td>
<td>32007</td>
<td>X</td>
<td>10675026</td>
<td>10676128</td>
<td>1103</td>
<td>sesB</td>
<td>-3.26</td>
<td>7.21</td>
<td>948</td>
<td>7.46e-15</td>
<td>1.39e-10</td>
</tr>
<tr>
<td>150697</td>
<td>32008</td>
<td>X</td>
<td>10672987</td>
<td>10673728</td>
<td>742</td>
<td>Ant2</td>
<td>2.85</td>
<td>6.14</td>
<td>863</td>
<td>1.48e-14</td>
<td>1.84e-10</td>
</tr>
<tr>
<td>91614</td>
<td>42865</td>
<td>3R</td>
<td>19970915</td>
<td>19971592</td>
<td>678</td>
<td>Kal1</td>
<td>-4.43</td>
<td>3.81</td>
<td>756</td>
<td>3.88e-14</td>
<td>3.61e-10</td>
</tr>
<tr>
<td>107856</td>
<td>44030</td>
<td>3L</td>
<td>2561932</td>
<td>2562843</td>
<td>912</td>
<td>msn</td>
<td>-2.46</td>
<td>5.59</td>
<td>615</td>
<td>1.74e-13</td>
<td>1.30e-09</td>
</tr>
<tr>
<td>150702</td>
<td>32008</td>
<td>X</td>
<td>10674230</td>
<td>10674694</td>
<td>465</td>
<td>Ant2</td>
<td>2.97</td>
<td>4.55</td>
<td>575</td>
<td>2.83e-13</td>
<td>1.33e-09</td>
</tr>
<tr>
<td>150695</td>
<td>32008</td>
<td>X</td>
<td>10674230</td>
<td>10674559</td>
<td>330</td>
<td>Ant2</td>
<td>2.96</td>
<td>4.55</td>
<td>574</td>
<td>2.86e-13</td>
<td>1.33e-09</td>
</tr>
<tr>
<td>70750</td>
<td>44258</td>
<td>3R</td>
<td>5271691</td>
<td>5272628</td>
<td>938</td>
<td>ps</td>
<td>-2.27</td>
<td>5.95</td>
<td>572</td>
<td>2.97e-13</td>
<td>1.33e-09</td>
</tr>
<tr>
<td>11333</td>
<td>44548</td>
<td>2R</td>
<td>6407125</td>
<td>6408782</td>
<td>1658</td>
<td>lola</td>
<td>2.26</td>
<td>6.15</td>
<td>565</td>
<td>3.21e-13</td>
<td>1.33e-09</td>
</tr>
<tr>
<td>96433</td>
<td>43230</td>
<td>3R</td>
<td>22697648</td>
<td>22697717</td>
<td>70</td>
<td>BM-40-SPARC</td>
<td>-2.17</td>
<td>6.65</td>
<td>542</td>
<td>4.37e-13</td>
<td>1.63e-09</td>
</tr>
</tbody>
</table>

The total number of DE exons in each direction at a FDR of 5% can be examined with `decideTestsDGE`.

\[ \text{is.de} \leftarrow \text{decideTestsDGE}(qlf, \text{p.value}=0.05) \]

\[ \text{summary(is.de)} \]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>2059</td>
</tr>
<tr>
<td>0</td>
<td>33385</td>
</tr>
<tr>
<td>1</td>
<td>1814</td>
</tr>
</tbody>
</table>

4.5.10 Alternative splicing

We detect alternative splicing by testing for differential exon usage between Pasilla knockdown and normal in each gene.
> sp <- diffSpliceDGE(fit, coef=4, geneid="GeneID", exonid="Start")

Total number of exons:  37258
Total number of genes: 8192
Number of genes with 1 exon: 1619
Mean number of exons in a gene: 5
Max number of exons in a gene: 56

Two testing methods at the gene-level are provided. The Simes’ method is likely to be more powerful when only a minority of the exons for a gene are differentially spliced. The F-tests are likely to be powerful for genes in which several exons are differentially spliced.

The top spliced genes under the Simes’ method are shown below:

> topSpliceDGE(sp, test="Simes", n=20)

<table>
<thead>
<tr>
<th>GeneID</th>
<th>Chr</th>
<th>Symbol</th>
<th>NExons</th>
<th>P.Value</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>141235</td>
<td>45320</td>
<td>X trol</td>
<td>44</td>
<td>1.64e-30</td>
<td>1.08e-26</td>
</tr>
<tr>
<td>11214</td>
<td>44548</td>
<td>2R lola</td>
<td>30</td>
<td>4.28e-30</td>
<td>1.41e-26</td>
</tr>
<tr>
<td>95956</td>
<td>44448</td>
<td>3R scrib</td>
<td>35</td>
<td>1.10e-20</td>
<td>2.40e-17</td>
</tr>
<tr>
<td>107810</td>
<td>44030</td>
<td>3L msn</td>
<td>24</td>
<td>1.15e-18</td>
<td>1.89e-15</td>
</tr>
<tr>
<td>19880</td>
<td>36773</td>
<td>2R Dg</td>
<td>15</td>
<td>2.17e-18</td>
<td>2.86e-15</td>
</tr>
<tr>
<td>16060</td>
<td>36542</td>
<td>2R shot</td>
<td>38</td>
<td>2.03e-17</td>
<td>2.22e-14</td>
</tr>
<tr>
<td>82117</td>
<td>42130</td>
<td>3R osa</td>
<td>17</td>
<td>2.50e-17</td>
<td>2.35e-14</td>
</tr>
<tr>
<td>32242</td>
<td>37893</td>
<td>2R slik</td>
<td>19</td>
<td>2.59e-15</td>
<td>2.13e-12</td>
</tr>
<tr>
<td>131170</td>
<td>40205</td>
<td>3L CG42674</td>
<td>16</td>
<td>3.88e-15</td>
<td>2.84e-12</td>
</tr>
<tr>
<td>163416</td>
<td>32817</td>
<td>X CrebB-17A</td>
<td>12</td>
<td>1.00e-14</td>
<td>6.58e-12</td>
</tr>
<tr>
<td>150694</td>
<td>32008</td>
<td>X Ant2</td>
<td>5</td>
<td>1.02e-13</td>
<td>6.07e-11</td>
</tr>
<tr>
<td>110493</td>
<td>38491</td>
<td>3L ens</td>
<td>16</td>
<td>1.88e-13</td>
<td>1.03e-10</td>
</tr>
<tr>
<td>41795</td>
<td>3771968</td>
<td>2L Msp-300</td>
<td>33</td>
<td>2.80e-12</td>
<td>1.41e-09</td>
</tr>
<tr>
<td>115767</td>
<td>38879</td>
<td>3L pbl</td>
<td>12</td>
<td>3.84e-12</td>
<td>1.80e-09</td>
</tr>
<tr>
<td>2032</td>
<td>2768716</td>
<td>2R mim</td>
<td>25</td>
<td>8.98e-12</td>
<td>3.93e-09</td>
</tr>
<tr>
<td>526</td>
<td>35494</td>
<td>2R laccase2</td>
<td>9</td>
<td>2.81e-11</td>
<td>1.11e-08</td>
</tr>
<tr>
<td>150710</td>
<td>32007</td>
<td>X sesB</td>
<td>7</td>
<td>2.88e-11</td>
<td>1.11e-08</td>
</tr>
<tr>
<td>166094</td>
<td>33098</td>
<td>X CG32521</td>
<td>8</td>
<td>4.29e-11</td>
<td>1.57e-08</td>
</tr>
<tr>
<td>52823</td>
<td>34652</td>
<td>2L vir-1</td>
<td>7</td>
<td>8.31e-11</td>
<td>2.88e-08</td>
</tr>
<tr>
<td>85970</td>
<td>42428</td>
<td>3R Stat92E</td>
<td>14</td>
<td>4.41e-10</td>
<td>1.45e-07</td>
</tr>
</tbody>
</table>

The top spliced genes identified by F-tests are shown below:

> topSpliceDGE(sp, test="gene", n=20)

<table>
<thead>
<tr>
<th>GeneID</th>
<th>Chr</th>
<th>Symbol</th>
<th>NExons</th>
<th>gene.F</th>
<th>P.Value</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>141235</td>
<td>45320</td>
<td>X trol</td>
<td>44</td>
<td>52.5</td>
<td>2.53e-51</td>
<td>1.66e-47</td>
</tr>
<tr>
<td>11214</td>
<td>44548</td>
<td>2R lola</td>
<td>30</td>
<td>42.7</td>
<td>6.84e-34</td>
<td>2.25e-30</td>
</tr>
<tr>
<td>95956</td>
<td>44448</td>
<td>3R scrib</td>
<td>35</td>
<td>17.2</td>
<td>1.08e-24</td>
<td>1.78e-21</td>
</tr>
<tr>
<td>16060</td>
<td>36542</td>
<td>2R shot</td>
<td>38</td>
<td>11.1</td>
<td>6.90e-20</td>
<td>9.07e-17</td>
</tr>
</tbody>
</table>
We plot all the exons for the top two most differentially spliced genes. Exons that are individually significant are highlighted.

```r
> par(mfrow=c(1,2))
> plotSpliceDGE(sp, geneid="trol", genecol="Symbol")
> plotSpliceDGE(sp, geneid="lola", genecol="Symbol")
```

We can see that a block of five or six exons at the right end of the trol gene are relatively lost when Pasilla is down. Most exons in the first half of the gene behave similarly to each other. This gene is on the negative strand, so transcription is from right to left. The gene trol was identified by Brooks et al [3] to have a novel set of coordinately regulated exons.
4.5.11 Setup

This analysis was conducted on:

```r
> sessionInfo()
```

R version 3.3.0 beta (2016-04-14 r70486)
Platform: x86_64-w64-mingw32/x64 (64-bit)
Running under: Windows 7 x64 (build 7601) Service Pack 1

locale:
[1] LC_COLLATE=English_Australia.1252  LC_CTYPE=English_Australia.1252
[3] LC_MONETARY=English_Australia.1252  LC_NUMERIC=C
[5] LC_TIME=English_Australia.1252

attached base packages:
[1] parallel stats4  stats  graphics grDevices  utils  datasets  methods  base

other attached packages:
[1] GO.db_3.3.0  org.Mm.eg.db_3.3.0  tweeDEseqCountData_1.9.0
[4] NBPSeq_0.3.0  org.Hs.eg.db_3.3.0  RSQLite_1.0.0
[7] DBI_0.3.1  AnnotationDbi_1.33.11  IRanges_2.5.46
[10] S4Vectors_0.9.51  Biobase_2.31.3  BiocGenerics_0.17.5
[13] edgeR_3.13.9  limma_3.27.19

loaded via a namespace (and not attached):
[1] Rcpp_0.12.4.5  magrittr_1.5  splines_3.3.0  munsell_0.4.3  statmod_1.4.24
[6] colorspace_1.2-6  lattice_0.20-33  stringr_1.0.0  plyr_1.8.3  tools_3.3.0
[11] grid_3.3.0  gtable_0.2.0  reshape2_1.4.1  ggplot2_2.1.0  qvalue_2.3.2
[16] stringi_1.0-1  scales_0.4.0  locfit_1.5-9.1

4.5.12 Acknowledgements

Thanks to Yang Liao for mapping the reads and running featureCounts and Yifang Hu for the initial analysis of the data.

4.6 CRISPR-Cas9 knockout screen analysis

4.6.1 Introduction

Dai et al. (2014) [7] describe the use of edgeR to analyze data from pooled genetic screens utilizing either shRNAs or CRISPR-Cas9 to disrupt gene expression in a population of cells.

In this case study we analyze data from a pooled screen that uses CRISPR-Cas9 (clustered regularly interspaced short palindromic repeats-associated nuclease Cas9) knockout
4.6.2 Sequence processing

Multiple single guide RNAs (sgRNAs) per gene (generally between 3-6) were included in the screen. Below we read in the raw sequences from the paired end fastq files `screen4_R1.fastq` and `screen4_R2.fastq` using the `processAmplicons` function in edgeR. This screen employed a dual indexing strategy where the first 8 bases from each pair of reads contained an index sequence that uniquely identifies which sample a particular sgRNA sequence originated from. Matches between sample indexes and sgRNAs listed in the files `Samples4.txt` and `sgRNAs4.txt` are identified by `processAmplicons` to produce a `DGEList` of counts.

```R
> # Read in sample & sgRNA information
> sampleanno <- read.table("Samples4.txt", header=TRUE, sep="\t")
> sampleanno[1:5,]
> sgseqs <- read.table("sgRNAs4.txt", header=TRUE, sep="\t")
> sgseqs[1:5,]
> # Process raw sequences from fastq files
> x <- processAmplicons("screen4_R1.fastq", readfile2="screen4_R2.fastq",
+ barcodesfile="Samples4.txt", hairpinfile="sgRNAs4.txt",
+ barcodeStart=1, barcodeEnd=8, hairpinStart=33, hairpinEnd=52,
+ barcodeStartRev=1, barcodeEndRev=8, verbose=TRUE)
```

Note that this dual indexing strategy requires an additional column named ‘`Sequences-Rev`’ in the file that contains the sample annotation information. Also, `readFile2` must be specified, along with position information (`barcodeStartRev`, `barcodeEndRev`) for the second index in the second read from each pair (in this case the index can be found in the first 8 bases).

4.6.3 Filtering and data exploration

We next filter out sgRNAs and samples with low numbers of reads.

```R
> x
```

An object of class "DGEList"

```
$counts
 A1_1_1 A2_1_2 A3_1_3 A4_1_4 A5_1_5 A6_1_6 A7_2_1 A8_2_2 A9_2_3 A10_2_4 A11_2_5 A12_2_6
sgRNA1 0 14 0 0 3 36 1 55 0 23 0 62
sgRNA2 0 18 0 0 1 22 0 26 0 29 0 43
sgRNA3 0 50 0 0 4 52 1 98 0 60 0 111
```
<table>
<thead>
<tr>
<th>ID</th>
<th>lib.size</th>
<th>norm.factors</th>
<th>Sequences</th>
<th>Reverse</th>
<th>group</th>
<th>Infection</th>
<th>Replicate</th>
<th>IndexF</th>
<th>IndexR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1_1_1</td>
<td>188</td>
<td>1</td>
<td>TAAGGCGA</td>
<td>Drug</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A2_1_2</td>
<td>667530</td>
<td>1</td>
<td>CCGTACTAG</td>
<td>NoDrug</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A3_1_3</td>
<td>1340</td>
<td>1</td>
<td>AGGCAGAA</td>
<td>Drug</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>A4_1_4</td>
<td>2473</td>
<td>1</td>
<td>TCCTGAGC</td>
<td>NoDrug</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>A5_1_5</td>
<td>69161</td>
<td>1</td>
<td>GGACCTCCT</td>
<td>Drug</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

67 more rows ...

$\text{samples}$
$genes

<table>
<thead>
<tr>
<th>ID</th>
<th>Sequences</th>
<th>Gene</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sgRNA1 TACCCTGGGACTGTACCCCC</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>sgRNA2 ACCCTTGCTGACGACCTGC</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>sgRNA3 TCGCTGCCCCTCTTCCTC</td>
<td>99</td>
</tr>
<tr>
<td>4</td>
<td>sgRNA4 TGACCCTCGGAGCTGCTSG</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>sgRNA5 CGTCATAGCCATCTTCTTC</td>
<td>19</td>
</tr>
</tbody>
</table>

64746 more rows...

> table(x$samples$group)

```
Drug  NoDrug
  40     32
```

> # Filter sgRNAs and samples with low counts
> # Need a CPM greater than 5 in 15 or more samples to keep sgRNAs
> selr <- rowSums(cpm(x$counts)>5)>=15
> # Need at least 100,000 reads to keep a given sample
> selc <- colSums(x$counts)>=100000
> x <- x[selr,selc]

> # Set up drug treatment colours
> cols <- as.numeric(x$samples$group)+2
> # Plot number of sgRNAs that could be matched per sample
> # and total for each sgRNA across all samples
> par(mfrow=c(2,1))
> barplot(colSums(x$counts), las=2, main="Counts per index", col=cols, cex.names=0.5, cex.axis=0.8)
> legend("topright", legend=c("Control", "Drug"), col=c(3,4), pch=15)
> barplot(rowSums(x$counts), las=2, main="Counts per sgRNA", axisnames=FALSE, cex.axis=0.8)
A multidimensional scaling plot was generated to assess the consistency between replicate samples. There is a clear separation between the two infections, indicating the need to incorporate an effect for this in the GLM.

> # Make an MDS plot to visualise relationships between replicate samples
> # Set up infection colours
> cols2 <- x$samples$Infection
> par(mfrow=c(1,2))
> plotMDS(x, col=cols, main="MDS Plot: drug treatment colours")
> legend("topleft", legend=c("Control", "Drug"), col=c(3,4), pch=15)
> plotMDS(x, col=cols2, main="MDS Plot: infection colours")
> legend("topleft", legend=c("Inf#1", "Inf#2"), col=c(1,2), pch=15)

4.6.4 The design matrix and dispersion estimation

A design matrix is set up for the GLM analysis, and the sgRNA-specific variation is estimated and plotted (while taking into account both drug treatment and infection number).

> # Set up design matrix for GLM
> treatment <- relevel(as.factor(x$samples$group), "NoDrug")
> infection <- as.factor(x$samples$Infection)
> des <- model.matrix(~treatment+infection)
> des[1:5,]
(Intercept) treatmentDrug infection2
1 1 0 0
2 1 0 0
3 1 0 0
4 1 0 0
5 1 0 0

> colnames(des)[2:3] <- c("Drug", "Infection2")
> # Estimate dispersions
> xglm <- estimateDisp(x, des)
> sqrt(xglm$common.disp)

[1] 0.258

> # Plot BCVs versus abundance
> plotBCV(xglm, main="BCV Plot")

4.6.5 Differential representation analysis

We use the function glmFit to fit the sgRNA-specific models and glmLRT to do the testing between the drug treated and control samples. The top ranked sgRNAs are listed using the topTags function and sgRNAs with FDR < 0.0001 [2] and log-fold-change ≥ 1 are highlighted on a plot of log-fold-change versus log-counts-per-millions by the plotSmear function. Since this is a positive screen, we highlight over-represented sgRNAs (i.e. those with positive log-fold-changes) since the model is parameterized to compare drug treatment versus control (coefficient 2 in the design matrix).
# Fit negative bionomial GLM
fit <- glmFit(xglm, des)
# Carry out Likelihood ratio test
lrt <- glmLRT(fit, coef=2)
# Show top ranked sgRNAs
topTags(lrt)

<table>
<thead>
<tr>
<th>ID</th>
<th>Sequences</th>
<th>Gene</th>
<th>logFC</th>
<th>logCPM</th>
<th>LR</th>
<th>PValue</th>
<th>FDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>816</td>
<td>TCCGAACCTCCCCCTCCCCCA</td>
<td>269</td>
<td>4.36</td>
<td>7.32</td>
<td>699</td>
<td>4.41e-154</td>
<td>2.49e-149</td>
</tr>
<tr>
<td>4070</td>
<td>GTTGTGTCCAGTAGTAGGTCT</td>
<td>1252</td>
<td>2.94</td>
<td>8.00</td>
<td>659</td>
<td>2.11e-145</td>
<td>5.94e-141</td>
</tr>
<tr>
<td>6351</td>
<td>AAAACGTATCTTTTTTTTAC</td>
<td>1957</td>
<td>3.37</td>
<td>6.34</td>
<td>422</td>
<td>8.43e-94</td>
<td>1.58e-89</td>
</tr>
<tr>
<td>12880</td>
<td>CTCGACCCAGAGAGAGTCTG</td>
<td>3979</td>
<td>2.83</td>
<td>7.04</td>
<td>322</td>
<td>5.38e-72</td>
<td>7.58e-68</td>
</tr>
<tr>
<td>23015</td>
<td>CAATTTCATCTTCTACTG</td>
<td>6714</td>
<td>3.16</td>
<td>4.83</td>
<td>233</td>
<td>1.34e-52</td>
<td>1.51e-48</td>
</tr>
<tr>
<td>62532</td>
<td>AAACAGCTCCAGTGAGCAGCCC</td>
<td>19612</td>
<td>2.79</td>
<td>4.91</td>
<td>216</td>
<td>6.15e-49</td>
<td>5.78e-45</td>
</tr>
<tr>
<td>38819</td>
<td>TACGTTTACGGCGCGCGCCA</td>
<td>11531</td>
<td>2.42</td>
<td>6.54</td>
<td>204</td>
<td>2.93e-46</td>
<td>2.36e-42</td>
</tr>
<tr>
<td>3887</td>
<td>AAGCCTGACTGAGGAGGCC</td>
<td>1194</td>
<td>2.28</td>
<td>5.33</td>
<td>203</td>
<td>4.03e-46</td>
<td>2.84e-42</td>
</tr>
<tr>
<td>19299</td>
<td>GGAGTCTTACCGAGGCTCC</td>
<td>5732</td>
<td>1.94</td>
<td>5.63</td>
<td>202</td>
<td>7.64e-46</td>
<td>4.78e-42</td>
</tr>
<tr>
<td>52924</td>
<td>CCACCGGTCCACTTCTTGG</td>
<td>16395</td>
<td>2.87</td>
<td>6.64</td>
<td>193</td>
<td>5.49e-44</td>
<td>3.09e-40</td>
</tr>
</tbody>
</table>

# Select sgRNAs with FDR < 0.0001 and logFC <= -1 to highlight on plot
thresh <- 0.0001
lfc <- 1
top4 <- topTags(lrt, n=Inf)
top4ids <- top4$table[top4$table$FDR<thresh & top4$table$logFC>=lfc,1]
# Plot logFC versus logCPM
plotSmear(lrt, de.tags=top4ids, pch=20, cex=0.6, main="Drug treatment vs Control")
abline(h = c(-1, 0, 1), col = c("dodgerblue", "yellow", "dodgerblue"), lty=2)
4.6.6 Gene set tests to summarize over multiple sgRNAs targeting the same gene

We finish this analysis by summarising data across multiple sgRNAs that target the same gene in order to get a gene-by-gene ranking, rather than a sgRNA-specific one. The \textit{camera} gene-set test \cite{34} is used for this purpose. For this analysis, the collection of sgRNAs that target a specific gene can be regarded as a ‘set’. In the code below, we restrict our analysis to genes with more than 3 sgRNAs. A barcode plot, highlighting the rank of sgRNAs for a given gene relative to the entire data set is generated for the top-ranked gene (11531). Abundance of sgRNAs targeting this gene tend to increase with drug treatment (FDR=0.0003).

\begin{verbatim}
> # Carry out camera gene-set analysis
> genesymbols <- x$genes[,3]
> genesymbollist <- list()
> unq <- unique(genesymbols)
> unq <- unq[!is.na(unq)]
> for(i in unq) {
+   sel <- genesymbols==i & !is.na(genesymbols)
+   if(sum(sel)>3)
+     genesymbollist[[i]] <- which(sel)
+ }
> # Run camera for all genes
> camera.res <- camera(xglm, index=genesymbollist, des, contrast=2)
> # Display results for top ranked genes
> camera.res[1:10,]
\end{verbatim}

\begin{verbatim}
  NGenes Correlation Direction  PValue   FDR
  11531  4  -0.1744  Up  1.08e-07  0.00032
  19612  5  -0.0324  Up  1.16e-07  0.00032
  10784  4  -0.1885  Up  7.31e-07  0.00134
   8808  4  -0.1059  Up  1.65e-06  0.00228
   10386  4  -0.1050  Up  2.36e-05  0.02606
    3979  4  -0.0121  Up  4.16e-05  0.03823
    8493  4  -0.0959  Up  8.30e-05  0.06537
    4635  5  -0.0996  Up  1.05e-04  0.12951
    9860  5  -0.0240  Up  2.11e-04  0.12951

> # Make a barcode plot for an example that ranks highly
> # Gene 11531
> barcodeplot(lrt$table$logFC,index=genesymbollist[[11531]],
+           main="Barcodeplot for Gene 11531",
+           labels=c("Positive logFC", "Negative logFC"),
+           quantile=c(-0.5,0.5))
\end{verbatim}
The raw data from this example and several other case studies for this technology can be found at http://bioinf.wehi.edu.au/shRNAseq/.

4.6.7 Setup

This analysis was conducted on:

```r
> sessionInfo()
```

R version 3.3.0 beta (2016-04-14 r70486)
Platform: x86_64-w64-mingw32/x64 (64-bit)
Running under: Windows 7 x64 (build 7601) Service Pack 1

locale:
[1] LC_COLLATE=English_Australia.1252 LC_CTYPE=English_Australia.1252
[3] LC_MONETARY=English_Australia.1252 LC_NUMERIC=C
[5] LC_TIME=English_Australia.1252

attached base packages:
[1] parallel stats4 stats graphics grDevices utils datasets methods base

other attached packages:
[1] GO.db_3.3.0 org.Mm.eg.db_3.3.0 tweeDEseqCountData_1.9.0
[4] NBPSeg_0.3.0 org.Hs.eg.db_3.3.0 RSQLite_1.0.0
[7] DBI_0.3.1 AnnotationDbi_1.33.11 IRanges_2.5.46
[10] S4Vectors_0.9.51 Biobase_2.31.3 BiocGenerics_0.17.5
[13] edgeR_3.13.9 limma_3.27.19

loaded via a namespace (and not attached):
[1] Rcpp_0.12.4.5 magrittr_1.5 splines_3.3.0 munsell_0.4.3 statmod_1.4.24
[6] colorspace_1.2-6 lattice_0.20-33 stringr_1.0.0 plyr_1.8.3 tools_3.3.0
4.6.8 Acknowledgements

Thanks to Dr Sam Wormald from the WEHI for providing the data set used in this case study.


