Comparative analysis of RNA-Seq data with DESeq2

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Two applications of RNA-Seq

Discovery
• find new transcripts
• find transcript boundaries
• find splice junctions

Comparison
Given samples from different experimental conditions, find effects of the treatment on
• gene expression strengths
• isoform abundance ratios, splice patterns, transcript boundaries
Sequencing count data

<table>
<thead>
<tr>
<th></th>
<th>control-1</th>
<th>control-2</th>
<th>control-3</th>
<th>treated-1</th>
<th>treated-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBgn0000008</td>
<td>78</td>
<td>46</td>
<td>43</td>
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<tr>
<td>FBgn0000017</td>
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<td>1672</td>
<td>1859</td>
<td>2445</td>
<td>4615</td>
</tr>
<tr>
<td>FBgn0000018</td>
<td>369</td>
<td>150</td>
<td>176</td>
<td>288</td>
<td>383</td>
</tr>
</tbody>
</table>

[...]

- RNA-Seq
- Tag-Seq
- ChIP-Seq
- HiC
- Bar-Seq
- ...
Counting rules

• Count reads, not base-pairs
• Count each read at most once.
• Discard a read if
  • it cannot be uniquely mapped
  • its alignment overlaps with several genes
  • the alignment quality score is bad
  • (for paired-end reads) the mates do not map to the same gene
Why we discard non-unique alignments

gene A

control condition

treatment condition

gene B
Normalization for library size

• If sample A has been sampled deeper than sample B, we expect counts to be higher.

• Naive approach: Divide by the total number of reads per sample

• Problem: Genes that are strongly and differentially expressed may distort the ratio of total reads.
Normalization for library size
Normalization for library size

Histogram of $\log_2(\text{sample2/sample1})$
Normalization for library size

To compare more than two samples:

• Form a “virtual reference sample” by taking, for each gene, the geometric mean of counts over all samples

• Normalize each sample to this reference, to get one scaling factor (“size factor”) per sample.

Anders and Huber, 2010

similar approach: Robinson and Oshlack, 2010
Counting noise

In RNA-Seq, noise (and hence power) depends on count level.

Why?
The Poisson distribution

- This bag contains very many small balls, 10% of which are red.

- Several experimenters are tasked with determining the percentage of red balls.

- Each of them is permitted to draw 20 balls out of the bag, without looking.
3 / 20 = 15%
1 / 20 = 5%
2 / 20 = 10%
0 / 20 = 0%
7 / 100 = 7%

10 / 100 = 10%

8 / 100 = 8%

11 / 100 = 11%
## Poisson distribution: Counting uncertainty

<table>
<thead>
<tr>
<th>expected number of red balls</th>
<th>standard deviation of number of red balls</th>
<th>relative error in estimate for the fraction of red balls</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$\sqrt{10} = 3$</td>
<td>$1 / \sqrt{10} = 31.6%$</td>
</tr>
<tr>
<td>100</td>
<td>$\sqrt{100} = 10$</td>
<td>$1 / \sqrt{100} = 10.0%$</td>
</tr>
<tr>
<td>1,000</td>
<td>$\sqrt{1,000} = 32$</td>
<td>$1 / \sqrt{1000} = 3.2%$</td>
</tr>
<tr>
<td>10,000</td>
<td>$\sqrt{10,000} = 100$</td>
<td>$1 / \sqrt{10000} = 1.0%$</td>
</tr>
</tbody>
</table>
The negative binomial distribution

A commonly used generalization of the Poisson distribution with two parameters

\[ \Pr(Y = k) = \binom{k + r - 1}{r - 1} p^r (1 - p)^k \quad \text{for } k = 0, 1, 2, \ldots \]
The NB from a hierarchical model

Biological sample with mean $\mu$ and variance $\nu$

Poisson distribution with mean $q$ and variance $q$.

Negative binomial with mean $\mu$ and variance $q+\nu$. 
Testing: Generalized linear models

Two sample groups, treatment and control.

Assumption:
• Count value for a gene in sample $j$ is generated by NB distribution with mean $s_j \mu_j$ and dispersion $\alpha$.

Null hypothesis:
• All samples have the same $\mu_j$.

Alternative hypothesis:
• Mean is the same only within groups:
\[
\log \mu_j = \beta_0 + x_j \beta_T
\]
\[
x_j = 0 \text{ for if } j \text{ is control sample}
\]
\[
x_j = 1 \text{ for if } j \text{ is treatment sample}
\]
Testing: Generalized linear models

\[ \log \mu_j = \beta_0 + x_j \beta_T \]

- \( x_j = 0 \) for if \( j \) is control sample
- \( x_j = 1 \) for if \( j \) is treatment sample

Calculate the coefficients \( \beta \) that fit best the observed data.

Is the value for \( \beta_T \) significantly different from null?

Can we reject the null hypothesis that it is merely cause by noise?

The Wald test gives us a p value.
p values

The p value from the Wald test indicates the probability that the observed difference between treatment and control (as indicated by $\beta_T$), or an even stronger one, is observed even though there is no true treatment effect.
Multiple testing

• Consider: A genome with 10,000 genes
• We compare treatment and control. Unbeknownst to us, the treatment had no effect at all.
• How many genes will have $p < 0.05$?
Multiple testing

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• We compare treatment and control. Unbeknownst to us, the treatment had no effect at all.
• How many genes will have $p < 0.05$?

• $0.05 \times 10,000 = 500$ genes.
Multiple testing

• Consider: A genome with 10,000 genes
• We compare treatment and control
• Now, the treatment is real.

• 1,500 genes have $p < 0.05$.
• How many of these are false positives?
Multiple testing

• Consider: A genome with 10,000 genes
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• 1,500 genes have p < 0.05.
• How many of these are false positives?

• 500 genes, i.e., 33%
Dispersion

• A crucial input to the GLM procedure and the Wald test is the estimated strength of within-group variability.

• Getting this right is the hard part.
Replication at what level?

• Prepare several libraries from the same sample (technical replicates).
  → controls for measurement accuracy
  → allows conclusions about just this sample
Replication at what level?

• Prepare several samples from the same cell-line (biological replicates).
  → controls for measurement accuracy and variations in environment and the cells’ response to them.
  → allows for conclusions about the specific cell line
Replication at what level?

• Derive samples from different individuals (independent samples).
  → controls for measurement accuracy, variations in environment and variations in genotype.
  → allows for conclusions about the species
How much replication?

Two replicates permit to
• globally estimate variation

Sufficiently many replicates permit to
• estimate variation for each gene
• randomize out unknown covariates
• spot outliers
• improve precision of expression and fold-change estimates
Estimation of variability is the bottleneck

Example: A gene differs by 20% between samples within a group (CV=0.2)

What fold change gives rise to p=0.0001?

<table>
<thead>
<tr>
<th>Number of samples</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>20</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV known</td>
<td>55%</td>
<td>45%</td>
<td>39%</td>
<td>35%</td>
<td>35%</td>
<td>11%</td>
</tr>
<tr>
<td>CV estimated</td>
<td></td>
<td></td>
<td></td>
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(assuming normality and use of z or t test, resp.)
Estimation of variability is the bottleneck

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<tr>
<td>CV estimated</td>
<td>1400% (14x)</td>
<td>180% (1.8x)</td>
<td>91%</td>
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(assuming normality and use of z or t test, resp.)
Shrinkage estimation of variability

Comparison of normalized counts between two replicate samples

(Drosophila cell culture, treated with siRNA, data by Brooks et al., 2011)

Core assumption:
Genes of similar expression strength have similar sample-to-sample variance.

Under this assumption, we can estimate variance with more precision.

Baldi & Long (2001); Lönnsted & Speed (2002); Smyth (2004); Robinson, McCarthy & Smyth (2010); Wu et al (2013);...
Fisher’s exact test between two samples

Example data: fly cell culture, knock-down of pasilla
(Brooks et al., Genome Res., 2011)

knock-down sample T2
versus
control sample U3

red: significant genes according to Fisher test (at 10% FDR)
Fisher’s exact test between two samples

Example data: fly cell culture, knock-down of pasilla
(Brooks et al., Genome Res., 2011)

knock-down sample T2
versus
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control sample U2
versus
control sample U3

red: significant genes according to Fisher test (at 10% FDR)
Tasks in comparative RNA-Seq analysis

• Estimate fold-change between control and treatment

• Estimate variability within groups

• Determine significance

the hard part
Estimation of variability
Estimation of variability is the bottleneck

Example: A gene typically differs by 20% between replicate samples (CV=0.2)

What fold change gives rise to p=0.0001?

<table>
<thead>
<tr>
<th>Number of samples</th>
<th>2x2</th>
<th>2x3</th>
<th>2x4</th>
<th>2x5</th>
<th>2x10</th>
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(assuming normality and use of z or t test, resp.)
Estimation of variability is the bottleneck

Example: A gene differs by 20% between samples within a group (CV=0.2)

What fold change gives rise to p=0.0001?

<table>
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(assuming normality and use of z or t test, resp.)
Shrinkage estimation of variability

For each gene, estimate within-group variance/dispersion with Cox-Reid maximum-likelihood

[McCarthy et al., NAR, 2012]
Dispersion

• Minimum variance of count data:
  \[ v = \mu \quad \text{(Poisson)} \]

• Actual variance:
  \[ v = \mu + \alpha \mu^2 \]

• \( \alpha \) : “dispersion” \[ \alpha = \frac{\mu - v}{\mu^2} \]
  (squared coefficient of variation of extra-Poisson variability)
Shrinkage estimation of variability

Core assumption:
Genes of similar expression strength have similar sample-to-sample variance.

Under this assumption, we can estimate variance with more precision.

Baldi & Long (2001); Lönnsted & Speed (2002); Smyth (2004); Robinson, McCarthy & Smyth (2010); Wu et al (2013);...
Shrinkage estimation of variability
Shrinkage estimation of variability
Empirical Bayes shrinkage

Model:

• Estimates scatter around fit due to
  (i) uncertainty of dispersion estimation
  (ii) true differences in dispersion

• Fitting a log-normal to the residuals provides estimates the sum of both.

• After subtracting expected width for (i), we are left with an empirical prior for (ii).
Dispersion shrinkage in DESeq2

• Estimate dispersion for each gene (using only that gene’s count data)
• Fit dependence on mean.
• Fit log-normal empirical prior for true dispersion scatter around fitted values.
• Narrow prior to account for sampling width.
• Calculate maximum a-posteriori values as final dispersion estimates.
• Use raw values for high-dispersion outliers.

(Similar approach: DSS by Wu, Wang & Wu, 2013)
Testing

• DESeq2 fits a generalized linear model (GLM) of the negative binomial (NB) family.
Testing

• DESeq2 fits a generalized linear model (GLM) of the negative binomial (NB) family.

• Then, a Wald test is performed for the treatment coefficient
Outlier robustness

Cook’s distance: Change in fitted coefficients if the sample were removed
Testing and estimating

p values and effect sizes

or

What else to do with shrinkage?
All genes are differentially expressed
(but maybe only a very little bit)

No gene is perfectly decoupled from the other genes.

What do our p values really mean?
All genes are differentially expressed
(but maybe only a very little bit)

No gene is perfectly decoupled from the other genes.

What do our p values really mean?

Actually: “Have we got the sign right?”
Weak genes have exaggerated effect sizes
Shrinkage estimation of effect sizes

without shrinkage

with shrinkage
Shrinkage estimation of effect sizes

Procedure in DESeq2:

• Fit GLMs for all genes without shrinkage.
• Estimate normal empirical-Bayes prior from non-intercept coefficients.
• Adding log prior to the GLMs’ log likelihoods results in a ridge penalty term.
• Fit GLMs again, now with the penalized likelihood to get shrunken coefficients.
From testing to estimating

- **Testing:** Is the gene’s change noticeably different from zero? *Can we say whether it is up or down?*

- **Estimation:** *How strong* is the change?
From testing to estimating

- **Testing**: Is the gene’s change noticeably different from zero? *Can we say whether it is up or down?*

- **Estimation**: *How strong* is the change? *How precise* is this estimate?

→ Fold change estimates need information on their standard error.
From testing to estimating

→ Fold change estimates need information on their standard error.

It is convenient to have the same precision for all fold-change estimates.

Hence: Shrinkage. (variance-bias trade-off)
Gene ranking

How to rank a gene list to prioritize downstream experiments?

• by p value?
• by log fold change?
Gene ranking

How to rank a gene list to prioritize downstream experiments?
• by p value?
• by log fold change?
• by *shrunken* log fold change!
Gene-set enrichment analysis

Given the list of genes with strong effects in an experiment ("hits"): What do they mean?

Common approach: Take a collection of gene sets (e.g., GO, KEGG, Reactome, etc.), look for sets that are enriched in hits.
Gene-set enrichment analysis

Two approaches:

**Categorical test:** Is the gene set enriched for significantly differentially-expressed genes?

**Continuous test:** Are the fold changes of the genes in the set particularly strong?
Gene-set enrichment analysis: Worries

Power in RNA-Seq depends on counts. Hit lists are enriched for genes with high count values: strong genes, and genes with long transcripts.

This causes bias in categorical tests.

(e.g., Oshlack & Wakefield, 2009)
Gene-set enrichment analysis:

Worries

Fold-change estimates in RNA-Seq depends on counts.
Genes with low counts have exaggerated fold changes.

This causes bias in continuous tests.

(e.g., Oshlack & Wakefield, 2009)
Gene-set enrichment analysis: Shrinkage to the rescue

After shrinkage, log-fold-changes are homoskedastic. This makes a continuous test easy:
Gene-set enrichment analysis: Shrinkage to the rescue

After shrinkage, log-fold-changes (LFCs) are homoskedastic.

What about an ordinary t test:
• Is the mean of the LFCs of all the genes in the set non-zero?
GSEA with shrunken log fold changes

fly cell culture, knock-down of \textit{pasilla} versus control (Brooks et al., 2011)

turquoise circles: genes in Reactome Path 3717570
“APC/C-mediated degradation of cell cycle proteins”
56 genes, avg LFC: -0.15, p value: $4 \times 10^{-11}$ (t test)
Critique

• The t test assumes the genes to be independent.

• However, genes in the same category tend to be correlated

• Our p values will be overly optimistic.

• We are working on it ...
More things to do with shrinkage: 
The rlog transformation

Many useful methods want homoscedastic data:

• Hierarchical clustering
• PCA and MDS

But: RNA-Seq data is not homoscedastic.
Visualization of rlog-transformed data: Sample clustering and PCA

Data: Parathyroid samples from Haglung et al., 2012
Visualization of rlog-transformed data: Gene clustering
More things to do with shrinkage:
The rlog transformation

RNA-Seq data is not homoscedastic.

• On the count scale, large counts have large (absolute) variance.

• After taking the logarithm, small counts show excessive variance.
More things to do with shrinkage:

The rlog transformation

Conceptual idea of the rlog transform:

Log-transform the average across samples of each gene’s normalized count.

The “pull in” the log normalized counts towards the log averages. Pull more for weaker genes.
More things to do with shrinkage:
The rlog transformation

Procedure:
• Fit log-link GLM with intercept for average and one coefficient per sample.
• Estimate empirical-Bayes prior from sample coefficients.
• Fit again, now with ridge penalty from EB prior.
• Return fitted linear predictors.
Summary: Effect-size shrinkage

A simple method that makes many things easier, including:

• visualizing and interpreting effect sizes
• ranking genes
• performing GSEA
• performing clustering and ordination analyses
Complex designs

Simple: Comparison between two groups.

More complex:
- paired samples
- testing for interaction effects
- accounting for nuisance covariates
- ...

### GLMs: Blocking factor

<table>
<thead>
<tr>
<th>Sample</th>
<th>treated</th>
<th>sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>no</td>
<td>male</td>
</tr>
<tr>
<td>S2</td>
<td>no</td>
<td>male</td>
</tr>
<tr>
<td>S3</td>
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<td>S4</td>
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<tr>
<td>S9</td>
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<td>female</td>
</tr>
<tr>
<td>S10</td>
<td>yes</td>
<td>female</td>
</tr>
</tbody>
</table>
GLMs: Blocking factor

\[ K_{ij} \sim NB(s_j \mu_{ij}, \alpha_{ij}) \]

full model for gene \( i \):

\[
\log \mu_{ij} = \beta_i^0 + \beta_i^S x_j^S + \beta_i^T x_j^T
\]

reduced model for gene \( i \):

\[
\log \mu_{ij} = \beta_i^0 + \beta_i^S x_j^S
\]
GLMs: Interaction

\[ K_{ij} \sim NB(s_j \mu_{ij}, \alpha_{ij}) \]

full model for gene \( i \):

\[
\log \mu_{ij} = \beta_i^0 + \beta_i^S x_j^S + \beta_i^T x_j^T + \beta_i^I x_j^S x_j^T
\]

reduced model for gene \( i \):

\[
\log \mu_{ij} = \beta_i^0 + \beta_i^S x_j^S + \beta_i^T x_j^T
\]
GLMs: paired designs

- Often, samples are paired (e.g., a tumour and a healthy-tissue sample from the same patient).
- Then, using pair identity as blocking factor improves power.

**full model:**

$$\log \mu_{ijl} = \beta_i^0 + \begin{cases} 
0 & \text{for } l = 1 \text{(healthy)} \\
\beta_i^T & \text{for } l = 2 \text{(tumour)}
\end{cases}$$

**reduced model:**

$$\log \mu_{ij} = \beta_i^0$$

- \(i\): gene
- \(j\): subject
- \(l\): tissue state
GLMs: Dual-assay designs

How does the affinity of an RNA-binding protein to mRNA change under some drug treatment?

Prepare control and treated samples (in replicates) and perform on each sample RNA-Seq and CLIP-Seq.

For each sample, we are interested in the ratio of CLIP-Seq to RNA-Seq reads.

How is this ratio affected by treatment?
GLMs: CLIP-Seq/RNA-Seq assay

full model:
\[
\text{count} \sim \text{assayType} + \text{treatment} + \text{assayType: treatment}
\]

reduced model:
\[
\text{count} \sim \text{assayType} + \text{treatment}
\]
GLMs: CLIP-Seq/RNA-Seq assay

full model:
  \text{count} \sim \text{sample} + \text{assayType} + \text{assayType}:\text{treatment}

reduced model:
  \text{count} \sim \text{sample} + \text{assayType}
Summary

- Estimating fold-changes without estimating variability is pointless.
- Estimating variability from few samples requires information sharing across genes (shrinkage).
- Shrinkage can also regularize fold-change estimates. (New in DESeq2)
- This helps with interpretation, visualization, clustering, ordination, etc.
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