## 1 Introduction

### Overview

The Genominator package provides an interface to storing and retrieving genomic data, together with some additional functionality aimed at high-throughput sequence data. The intent is that retrieval and summarization will be fast enough to enable online experimentation with the data.

We have used the package to analyze tiling arrays and (perhaps more appropriate) RNA-Seq data consisting of more than 400 million reads.

The canonical use case at the core of the package is summarizing the data over a large number of genomic regions. The standard example is for each annotated exon in human, count the number of reads that lands in that exon, for all experimental samples.

Data is stored in a SQLite database, and as such the package makes it possible to work with very large datasets in limited memory. However, working with SQLite databases is limited by I/O (disk speed), and substantial performance gains are possible by using a fast disk.

Work using this package should cite [1].

### Limitations

While data may be stored in different ways using the experimental data model described below, typically (for sequencing data) we associate each read to a single location in the genome. This means that the package does not currently support paired-end reads, nor dealing with reads that span exon-exon junctions. Work is being done to include these important cases.

As mentioned above, the package uses a SQLite backend and the speed of its functionality is primarily limited by disk speed, which is unlike many other R packages. There is no gain in having multiple cores available and there is substantial slow down when accessing the data over a networked drive.

## 2 Data model

The core functionality of the package is the analysis of experimental data using genomic annotation, such as counting the number of reads falling in annotated exons. In the following we describe what we mean by experimental and annotation data.
Experimental data

The package utilizes RSQLite to store the data corresponding to an experiment. The SQL data model is:

```sql
chr INTEGER, strand INTEGER (-1,0,1), location INTEGER, [name NUMERIC]*
```

Specifically it means that each data unit has an associated (non-empty) genomic location triplet, namely `chr` (chromosome coded as an integer), `strand` (one of -1, 0, or 1 representing reverse strand, no strand information, and forward strand respectively) as well as a `location`. We also allow an unlimited number of additional numeric variables. (The requirement that the additional variables be numeric is purely an optimization.) There is no requirement that the location triplet (chr, strand, location) only occurs once in the data.

Examples are

```sql
chr INTEGER, strand INTEGER (-1,0,1), location INTEGER, chip_1 REAL, chip_2 REAL
chr INTEGER, strand INTEGER (-1,0,1), location INTEGER, counts INTEGER
```

The first data model could describe data from two tiling arrays, and in that case there would typically only be a single occurrence of each location triplet (chr, strand, location).

The second data model could describe

- data from a single sequencing experiment, each row corresponding to a read, such as

  ```
  chr, strand, location, counts
  1, 1, 1, 1
  1, 1, 1, 1
  1, 1, 2, 1
  (here two reads map to the same location)
  ```

- data from a single sequencing experiment, but where the reads have been aggregated such that each row corresponds to the number of reads mapped to that location.

  ```
  chr, strand, location, counts
  1, 1, 1, 2
  1, 1, 1, 1
  ```

Annotation data

Unlike experimental data, which is stored in an SQLite database, we represent annotation as an R `data.frame` with the following columns:

```sql
chr integer, strand integer (-1L,0L,1L), start integer, end integer, [name class]*
```

As in the experimental data representation, strand information is encoded as -1 for Reverse/Minus Strand, 0 for No Strand Information Available/Relevant, and 1 for Forward/Plus Strand. Each row is typically called a region (or region of interest, abbreviated ROI).

Since each region is consecutive, a transcript with multiple exons needs to be represented by multiple regions and one would typically have a column indicating transcript id, linking the different regions together. This data model is very similar to the genomic feature format (GFF).

A common example is

```sql
chr integer, strand integer (-1L,0L,1L), start integer, end integer, feature factor
```

3 Overview

There are 3 broad classes of functions within Genominator: functions that import and transform data, functions that retrieve and summarize data and finally functions that operate on retrieved data (focused on analysis of next generation sequencing data).

In the next two sections we will generate experimental data and annotation data for use in later examples.
Creating Experimental Data

We are going to walk through a very simple example using simulated experimental data to present the data import pipeline. This example uses a verbose setting of TRUE to illustrate activities performed in the SQLite databases. The example data will be used later in the vignette to illustrate other aspects of the package.

For an example of importing “real” next generation sequence data, see the companion vignette on working with the ShortRead package, which illustrates the use of importFromAlignedReads.

The data can be thought of as next generation sequencing data (\(N\) number of reads), in an organism with 16 chromosomes and a small number of annotated regions (\(K\) regions).

```r
> library(Genominator)
> options(verbose = TRUE) # to be used by Genominator functions.
> set.seed(123)
> N <- 100000L # the number of observations.
> K <- 100L # the number of annotation regions, not less than 10
> df <- data.frame(chr = sample(1:16, size = N, replace = TRUE),
+ location = sample(1:1000, size = N, replace = TRUE),
+ strand = sample(c(1L,-1L), size = N, replace = TRUE))
> head(df)

chr location strand
1 5 603 -1
2 13 23 -1
3 7 821 -1
4 15 37 -1
5 16 236 1
6 1 871 -1

> eDataRaw <- importToExpData(df, "my.db", tablename = "ex_tbl", overwrite = TRUE)

Writing table:
0.125 sec
Creating index:
0.054 sec

> eDataRaw

table: ex_tbl
database file: /tmp/RtmpGa1y6v/Rbuild198617b055d6/Genominator/vignettes/my.db
index columns: chr location strand
mode: w
schema:

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
</tr>
</thead>
</table>

"INTEGER" "INTEGER" "INTEGER"

> head(eDataRaw)

chr location strand
1 1 1 -1
2 1 1 -1
```
The `df` object contains unsorted reads, which is imported using `importToExpData`. `eDataRaw` is an example of an `ExpData` object, the core object in Genominator. Such an object essentially points to a specific table in a specific database (in SQLite a database is a file). The data in `eDataRaw` is ordered along the genome (unlike `df`), but there may be multiple rows with the same genomic location. The argument `overwrite = TRUE` indicates that if the table already exists in the database, overwrite it. This can be handy for scripts and vignettes.

The `eDataRaw` has a number of slots related to an internal bookkeeping of database connection. The `index columns` indicates what columns of the database are indexed. For “normal” uses this will always be (chr, location, strand). The `mode` indicates whether the database is in read or write mode (write implies read).

In a normal pipeline, the first thing we do is aggregate the reads. With default settings, this means counting the number of reads starting at each (chr, location, strand). The resulting database has only one row with a given (chr, location, strand).

```r
> eData <- aggregateExpData(eDataRaw, tablename = "counts_tbl", + deleteOriginal = FALSE, overwrite = TRUE)

Creating table: counts_tbl:
0.001 sec
inserting:
0.054 sec
creating index:
0.015 sec

> eData
table: counts_tbl
database file: /tmp/RtmpGa1y6v/Rbuild198617b055d6/Genominator/vignettes/my.db
index columns: chr location strand
mode: w
schema:

chr location strand counts
"INTEGER" "INTEGER" "INTEGER" "INTEGER"

> head(eData)
chr location strand counts
1 1 1 -1 7
2 1 1 1 2
3 1 2 -1 1
4 1 2 1 2
5 1 3 -1 3
6 1 3 1 4
```

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```r
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Creating table: counts_tbl:
0.001 sec
inserting:
0.054 sec
creating index:
0.015 sec

> eData
table: counts_tbl
database file: /tmp/RtmpGa1y6v/Rbuild198617b055d6/Genominator/vignettes/my.db
index columns: chr location strand
mode: w
schema:

chr location strand counts
"INTEGER" "INTEGER" "INTEGER" "INTEGER"

> head(eData)
chr location strand counts
1 1 1 -1 7
2 1 1 1 2
3 1 2 -1 1
4 1 2 1 2
5 1 3 -1 3
6 1 3 1 4
```
The return object is (as always) an ExpData object pointing to the table that was created. Note the addition of the counts column.

The input ExpData object points to table ex_tbl in database my.db. The output ExpData object (currently) always uses the same database as the input object, possibly with a different name (in this case counts_tbl). All functions that manipulate databases have the arguments overwrite and deleteOriginal. If deleteOriginal = TRUE, the original table (in this case ex_tbl) is deleted. If tablename = NULL (default), the function does a destructive in-place modification of the table.

It is possible to break ExpData objects. For example, if we had used the aggregateExpData function with deleteOriginal = TRUE, the table that eDataRaw points to would have been deleted. Or, if the function had been used with tablename = NULL (default), both eDataRaw and eData would point to the same table in the database, but the schema recorded in eDataRaw during instantiation would be out of date because it would not include the counts column. While this may seem problematic, it has not been cause for much concern. Remember, that ExpData objects are very cheap to create, so if something seems to break, delete and recreate it. With a bit of familiarity, this problem can be avoided. In general, we highly recommend carrying out the creation/manipulation of data in a script separate from the analysis, since creation/manipulation requires write access, whereas analysis is read only.

Each ExpData object has a mode that indicates whether the database is in read or write, which also implies read, mode. The eDataRaw and eData objects created above had a 'write' mode. To prevent unwanted modifications to the database, we will instantiate a new eData object in 'read' only mode.

```r
> eData <- ExpData(dbFilename = "my.db", tablename = "counts_tbl")
> eData
```

```
table: counts_tbl
database file: /tmp/RtmpGa1y6v/Rbuild198617b055d6/Genominator/vignettes/my.db
index columns: chr location strand
mode: r
schema:

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;INTEGER&quot;</td>
<td>&quot;INTEGER&quot;</td>
<td>&quot;INTEGER&quot;</td>
<td>&quot;INTEGER&quot;</td>
</tr>
</tbody>
</table>
```

```r
> head(eData)
```

```
chr location strand counts
1 1 1 -1 7
2 1 1 1 2
3 1 2 -1 1
4 1 2 1 2
5 1 3 -1 3
6 1 3 1 4
```

This used the constructor function ExpData, which is a standard way to instantiate ExpData objects in a new session.

It is possible to use the normal [ and $ operators on ExpData objects (although they do not have rownames). This is rarely necessary, and the return objects may be massive.

```r
> head(eData$chr)
```

```
chr
1 1
2 1
```
Creating Annotation

We now create a suitable annotation object. As described in earlier sections, annotation consists of consecutive genomic regions that may or may not be overlapping.

```r
annoData <- data.frame(chr = sample(1:16, size = K, replace = TRUE),
                        strand = sample(c(1L, -1L), size = K, replace = TRUE),
                        start = (st <- sample(1:1000, size = K, replace = TRUE)),
                        end = st + rpois(K, 75),
                        feature = c("gene", "intergenic")[sample(1:2, size = K, replace = TRUE)])
```

In this example, the `annoData` object needs to have distinct row names in order to maintain the link between annotation and returned data structures from the Genominator API. Also the `strand` column needs to have values in \{-1, 0, 1\}, and the `chr` column needs to have integer values. When you access "real" annotation, you will often need a post-processing step where the annotation gets massaged into this format. See the additional vignette on working with the ShortRead package for a real-life example.

4 Creating and managing data

For illustrative purposes, we generate another set of data:

```r
df2 <- data.frame(chr = sample(1:16, size = N, replace = TRUE),
                   location = sample(1:1000, size = N, replace = TRUE),
                   strand = sample(c(1L, -1L), size = N, replace = TRUE))
eData2 <- aggregateExpData(importToExpData(df2, dbFilename = "my.db", tablename = "ex2",
                                         overwrite = TRUE))
```

Writing table:
0.145 sec

Creating index:
0.09 sec
Aggregation

Aggregation refers to aggregation over rows of the database. This is typically used for sequencing data and is typically employed in order to go from a “one row, one read” type representation to a “one row, one genomic location with an associated number of reads”. The default arguments creates a new column counts using an “aggregator” that is the number of times a genomic location occurs in the data. Aggregation has also been discussed in an earlier section.

Merging

It is natural to store a number of experimental replicates in columns of a table. However, it is often the case that we receive the data in chunks over time, and that merging new values with old values is not trivial. For this reason we provide a joinExpData function to bind two tables together.
Essentially, merging consists of placing two (or more) columns next to each other. It is (somewhat) clear that (in general) it makes the most sense to merge two datasets when each dataset has only a single occurrence of each genomic location. Otherwise, how would we deal with/interpret the case where a genomic location occurs multiple times in each dataset? For that reason, joining two datasets typically happens after they have been aggregated.

It is possible to merge/join the datasets in R and then subsequently use the import facility to store the resulting object in a database. In general, that approach is less desirable because 1) it is slow(er) and 2) it requires all datasets to be present in memory.

```r
> ## eData1 <- aggregateExpData(importToExpData(df2, dbFilename = "my.db", tablename = "ex1",
> ## overwrite = TRUE))
> ## eData2 <- aggregateExpData(importToExpData(df, dbFilename = "my.db", tablename = "ex2",
> ## overwrite = TRUE))
> eDataJoin <- joinExpData(list(eData1, eData2), fields =
+ list(ex1 = c(counts = "counts_1"), ex2 = c(counts = "counts_2")),
+ tablename = "allcounts")

Creating union:
0.019 sec

Left outer join with table ex1:
0.039 sec

Left outer join with table ex2:
0.065 sec

Indexing:
0.015 sec

> head(eDataJoin)

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>counts_1</th>
<th>counts_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>3</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
```

In this example both `eData1` and `eData2` have a column named `counts` that we rename in the resulting object using the `fields` argument. Also missing values are introduced when the locations in one object are not present in the other. Finally, the `joinExpData` function supports joining an arbitrary number of `ExpData` objects.

We can examine the result using `summarizeExpData` (described later)

```r
> summarizeExpData(eDataJoin, fxs = c("total", "avg", "count"))

fetching summary:
0.015 sec

<table>
<thead>
<tr>
<th>total(counts_1)</th>
<th>total(counts_2)</th>
<th>avg(counts_1)</th>
<th>avg(counts_2)</th>
<th>count(counts_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000000e+05</td>
<td>1.000000e+05</td>
<td>3.267760e+00</td>
<td>3.267547e+00</td>
<td>3.060200e+04</td>
</tr>
<tr>
<td>3.060400e+04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Because of the way we store the data, the “total” column will be the total number of read, the “count” column will be the number of bases where a read starts, and the “avg” column will be average number of reads at a given genomic location (removing the genomic locations that were not sequenced).
Collapsing

Another common operation is collapsing data across columns. One use would be to join to experiments where the same sample was sequenced. One advantage of collapsing the data in this case is speed.

Collapsing is most often done using summation (the default):

```r
> head(collapseExpData(eDataJoin, tablename = "collapsed", collapse = "sum", overwrite = TRUE))
```

SQL query: CREATE TABLE collapsed (chr INTEGER, location INTEGER, strand INTEGER, COL)

creating table:
0.001 sec

SQL query: INSERT INTO collapsed SELECT chr, location, strand, CAST(TOTAL(counts_1) AS INTEGER)+CAST(TOTAL(counts_2) AS INTEGER) FROM allcounts GROUP BY chr,location,strand

inserting data:
0.035 sec

creating index:
0.016 sec

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>COL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>-1</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

But it could also be done using an “average” or a “weighted average” (weighted according to sequencing effort).

```r
> head(collapseExpData(eDataJoin, tablename = "collapsed", collapse = "weighted.avg", overwrite = TRUE))
```

fetching summary:
0.006 sec

SQL query: CREATE TABLE collapsed (chr INTEGER, location INTEGER, strand INTEGER, COL)

creating table:
0.002 sec

SQL query: INSERT INTO collapsed SELECT chr, location, strand, TOTAL(counts_1)*0.5+TOTAL(counts_2)*0.5 FROM allcounts GROUP BY chr,location,strand

inserting data:
0.036 sec

creating index:
0.016 sec

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>COL</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this case setting `collapse = "avg"` or `collapse = "weighted.avg"` respectively yields the exact same result, since the two experiments have the same number of reads.

## 5 Interface

In this section we describe the core functionality of the Genominator package.

We will use two examples: one ExpData consisting of a single (aggregated) experiment and one ExpData consisting of two aggregated, joined experiments.

```r
> eData <- ExpData("my.db", tablename = "counts_tbl", mode = "r")
> eDataJoin <- ExpData("my.db", tablename = "allcounts", mode = "r")
```

### Summarizing experimental data

We can use the function `summarizeExpData` to summarize ExpData objects. This function does not utilize annotation, so the summarization is in some sense “global”. The call to generate the total number of counts, i.e. the number of reads, in column “counts” is

```r
> ss <- summarizeExpData(eData, what = "counts")
```

fetching summary:

0.007 sec
The `what` argument is present in many of the following functions. It refers to which columns are being used, and in general the default depends on the type of function. If the function summarizes data, the default is “all columns, except the genomic location columns”, whereas if the function retrieves data, the default is “all columns”.

We can customize the summary by specifying the name of any SQLite function ([www.sqlite.org/lang_aggfunc.html](http://www.sqlite.org/lang_aggfunc.html)) in the `fxs` argument.

```r
> summarizeExpData(eData, what = "counts", fxs = c("MIN", "MAX"))
```

fetching summary:
0.007 sec

```
MIN(counts) MAX(counts)
1 14
```

This yields the maximum/minimum number of reads mapped to a single location. The minimum number of reads is not zero because we only store locations associated with reads.

### Selecting a region

We can access genomic data in a single genomic region using the function `getRegion`.

```r
> reg <- getRegion(eData, chr = 2L, strand = -1L, start = 100L, end = 105L)
```

SQL query: `SELECT * FROM counts_tbl WHERE chr = 2 AND (strand IN (-1) OR strand = 0) AND location between 100 AND 105 ORDER BY chr,location,strand`

fetching region query:
0.002 sec

```r
> class(reg)
[1] "data.frame"
```

```
> reg
chr location strand counts
1 2 100 -1 3
2 2 101 -1 5
3 2 102 -1 4
4 2 103 -1 6
5 2 104 -1 3
6 2 105 -1 4
```

It is possible exclude either `start` or `end` in which case the default values are 0 and 1e12.

### Using annotation with experimental data

The two previous sections show useful functions, but in general we want to summarize data over many genomic regions simultaneously, in order to:

- Summarize regions (means, lengths, sums, etc)
• Fit models on each region
• Perform operations over classes of regions (genes, intergenic regions, ncRNAs)

There are essentially two different strategies for this: retrieve the data as a big object and then use R functions to operate on the data (e.g. `splitByAnnotation`) or perform some operation on the different regions in the database (e.g. `summarizeByAnnotation`). The first approach is more flexible, but also slower and requires more memory. The second approach is faster, but limited to operations that can be expressed in SQL.

First, we demonstrate how to summarize over regions of interest. Here we are going to compute the SUM and COUNT of each region, which tell us the total number of sequencing reads at each location and the number of unique locations that were read respectively.

```r
> head(summarizeByAnnotation(eData, annoData, what = "counts", fxs = c("COUNT", "TOTAL"),
+   bindAnno = TRUE))
```

writing regions table: 0.013 sec

SQL query: 
```
SELECT __regions__.id, COUNT(counts), TOTAL(counts) FROM __regions__
LEFT OUTER JOIN counts_tbl ON __regions__.chr = counts_tbl.chr AND
counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND
(counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR
counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id
```

fetching summary table: 0.012 sec

<table>
<thead>
<tr>
<th>chr</th>
<th>strand</th>
<th>start</th>
<th>end</th>
<th>feature</th>
<th>COUNT(counts)</th>
<th>TOTAL(counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elt.1</td>
<td>13</td>
<td>-1</td>
<td>460</td>
<td>521</td>
<td>gene</td>
<td>58</td>
</tr>
<tr>
<td>elt.2</td>
<td>4</td>
<td>-1</td>
<td>332</td>
<td>405</td>
<td>gene</td>
<td>69</td>
</tr>
<tr>
<td>elt.3</td>
<td>13</td>
<td>1</td>
<td>177</td>
<td>236</td>
<td>gene</td>
<td>57</td>
</tr>
<tr>
<td>elt.4</td>
<td>3</td>
<td>1</td>
<td>390</td>
<td>472</td>
<td>gene</td>
<td>82</td>
</tr>
<tr>
<td>elt.5</td>
<td>15</td>
<td>1</td>
<td>130</td>
<td>203</td>
<td>gene</td>
<td>70</td>
</tr>
<tr>
<td>elt.6</td>
<td>1</td>
<td>1</td>
<td>885</td>
<td>964</td>
<td>intergenic</td>
<td>78</td>
</tr>
</tbody>
</table>

The result of `summarizeByAnnotation` is a `data.frame`. We use `bindAnno = TRUE` in order to keep the annotation as part of the result, which is often very useful.

The `fxs` argument takes the names of SQLite functions, see [www.sqlite.org/lang_aggfunc.html](http://www.sqlite.org/lang_aggfunc.html). One important note regarding summation: the standard SQL function `SUM` handles the sum of only missing values, which in R is expressed as `sum(NA)`, differently from the SQLite specific function `TOTAL`. In particular, the `SUM` function returns a missing value and the `TOTAL` function returns a zero. This is relevant when summarizing over a genomic region containing no reads in one experiment, but reads in another experiment.

This next example computes the number of reads mapping to the region for each annotated region, ignoring strand. Ignoring strand might be the right approach if the protocol does not retain strand information (e.g. the current standard protocol for Illumina RNA-Seq).

```r
> head(summarizeByAnnotation(eDataJoin, annoData, , fxs = c("SUM"),
+   bindAnno = TRUE, preserveColnames = TRUE, ignoreStrand = TRUE))
```

writing regions table: 0.039 sec

SQL query: 
```
SELECT __regions__.id, SUM(counts_1), SUM(counts_2) FROM __regions__
LEFT OUTER JOIN allcounts ON __regions__.chr = allcounts.chr AND
allcounts.location BETWEEN __regions__.start AND __regions__.end GROUP BY
```
Essentially, this output is the input to a simple differential expression analysis.

Note that if two regions in the annotation overlap, data falling in the overlap will be part of the end result for each region.

We can produce summarizes by category using the splitBy argument.

```r
> res <- summarizeByAnnotation(eData, annoData, what = "counts", fx$s = c("TOTAL", "COUNT"), + splitBy = "feature")
```

writing regions table:
0.012 sec

SQL query:
```
SELECT __regions__.id, TOTAL(counts), COUNT(counts) FROM __regions__
LEFT OUTER JOIN counts_tbl ON __regions__.chr = counts_tbl.chr AND
counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND
(counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR
counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id
```

fetching summary table:
0.013 sec

> class(res)
```
[1] "list"
```

> lapply(res, head)

$gene
```
TOTAL(counts) COUNT(counts)
elt.1 193 58
elt.2 219 69
elt.3 190 57
elt.4 258 82
elt.5 235 70
elt.7 301 86
```

$intergenic
```
TOTAL(counts) COUNT(counts)
elt.6 241 78
elt.8 283 86
elt.9 221 68
elt.11 206 62
elt.13 228 82
elt.16 235 72
```

Finally, we might want to join the relevant annotation to the summaries using the `bindAnno` argument.

```r
res <- summarizeByAnnotation(eData, annoData, what = "counts", fxs = c("TOTAL", "COUNT"),
          splitBy = "feature", bindAnno = TRUE)
```

writing regions table:
0.013 sec

SQL query: SELECT __regions__.id, TOTAL(counts), COUNT(counts) FROM __regions__
LEFT OUTER JOIN counts_tbl ON __regions__.chr = counts_tbl.chr AND
counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND
(counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR
counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

fetching summary table:
0.013 sec

```r
lapply(res, head)
```

$gene

<table>
<thead>
<tr>
<th>chr</th>
<th>strand</th>
<th>start</th>
<th>end</th>
<th>feature</th>
<th>TOTAL(counts)</th>
<th>COUNT(counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>-1</td>
<td>460</td>
<td>521</td>
<td>gene</td>
<td>193</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>332</td>
<td>405</td>
<td>gene</td>
<td>219</td>
<td>69</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>177</td>
<td>236</td>
<td>gene</td>
<td>190</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>390</td>
<td>472</td>
<td>gene</td>
<td>258</td>
<td>82</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>130</td>
<td>203</td>
<td>gene</td>
<td>235</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>24</td>
<td>109</td>
<td>gene</td>
<td>301</td>
<td>86</td>
</tr>
</tbody>
</table>

$intergenic

<table>
<thead>
<tr>
<th>chr</th>
<th>strand</th>
<th>start</th>
<th>end</th>
<th>feature</th>
<th>TOTAL(counts)</th>
<th>COUNT(counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>885</td>
<td>964</td>
<td>intergenic</td>
<td>241</td>
<td>78</td>
</tr>
<tr>
<td>16</td>
<td>-1</td>
<td>729</td>
<td>820</td>
<td>intergenic</td>
<td>283</td>
<td>86</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>656</td>
<td>726</td>
<td>intergenic</td>
<td>221</td>
<td>68</td>
</tr>
<tr>
<td>14</td>
<td>-1</td>
<td>550</td>
<td>612</td>
<td>intergenic</td>
<td>206</td>
<td>62</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>116</td>
<td>201</td>
<td>intergenic</td>
<td>228</td>
<td>82</td>
</tr>
<tr>
<td>8</td>
<td>-1</td>
<td>419</td>
<td>492</td>
<td>intergenic</td>
<td>235</td>
<td>72</td>
</tr>
</tbody>
</table>

(Both of these example might require `ignoreStrand = TRUE` in a real world application.)

Unfortunately, the `summarizeByAnnotation` function is only able to utilize the very small set of SQLite
functions, essentially limiting the function to computing very simple summaries.

We also mention the `groupBy` argument to `summarizeByAnnotation`. This argument allows for an
additional summarization level, used in the following way: assume that the `annoData` object has rows corre-
sponding to exons and that there is an additional column (say `gene_id`) describing how exons are grouped
into genes. If `groupBy = "gene_id"` the final object will have one line per gene, containing the summarized
data over each set of exons.

We will now examine the `splitByAnnotation` function that splits the data according to annotation and
returns the “raw” data. The return object of this function may be massive depending on the size of the data
and the size of the annotation. In general we advise to do as much computation as possible using SQLite
(essentially using `summarizeByAnnotation`), but sometimes it is necessary to access the raw data. Leaving
aside the problems with the size of the return object, `splitByAnnotation` is reasonably fast.

We start by only splitting on the annotated regions of type “gene”.

```r
dim(annoData[annoData$feature %in% "gene", ])
```

[1] 51 5
> a <- splitByAnnotation(eData, annoData[annoData$feature %in% "gene", ])

writing region table:
0.014 sec

SQL query: SELECT counts_tbl.* , __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) ORDER BY __regions__.id, counts_tbl.chr, counts_tbl.location, counts_tbl.strand

fetching splits table:
0.014 sec

SQL query: SELECT count(__regions__.id), __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

count query:
0.005 sec

performing split:
0.002 sec

> class(a)
[1] "list"

> length(a)
[1] 51

> names(a)[1:10]
[1] "elt.1" "elt.2" "elt.3" "elt.4" "elt.5" "elt.7" "elt.10" "elt.12"
[9] "elt.14" "elt.15"

> head(a[[1]])

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>460</td>
<td>-1</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>461</td>
<td>-1</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>462</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>463</td>
<td>-1</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>464</td>
<td>-1</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>465</td>
<td>-1</td>
<td>2</td>
</tr>
</tbody>
</table>

There are several notes here. For starters, the return object is named according to the rownames of the annotation data. Also, only annotated regions with data are represented in the return object, so in general the return object does not have an element for each annotated region. We provide several convenience functions for operating on the results of splitByAnnotation, which are discussed later.

Now we wish to compute a trivial function over the counts, such as a quantile.

> sapply(a, function(x) { quantile(x[,"counts"], .9) })[1:10]
Often we wish to use the annotation information when operating on the data in each region. The `applyMapped` function makes this easy by appropriately matching up the annotation and the data. Essentially, this function ensures that you are applying the right bit of annotation to the correct chunk of data.

```r
> applyMapped(a, annoData, FUN = function(region, anno) {
+   counts <- sum(region[,"counts"])
+   length <- anno$end - anno$start + 1
+   counts/length
+ })[1:10]

$elt.1
[1] 3.112903

$elt.2
[1] 2.959459

$elt.3
[1] 3.166667

$elt.4
[1] 3.108434

$elt.5
[1] 3.175676

$elt.7
[1] 3.5

$elt.10
[1] 3.405063

$elt.12
[1] 2.207317

$elt.14
[1] 3.068493

$elt.15
[1] 3.090909
```

This example computes the average number of reads per base, taking into account that bases without data exists. Note that `FUN` needs to be a function of two arguments.

What we see is that some of our regions are not present. This is a byproduct of the fact that some of our regions have no data within their bounds. One can successfully argue that the result of the example above ought to include such regions with a value of zero (see below for this).

When our data sets are large, it is often more convenient and significantly faster to return only some columns.

```r
> sapply(splitByAnnotation(eData, annoData, what = "counts"), median)[1:10]
```

This example computes the average number of reads per base, taking into account that bases without data exists. Note that `FUN` needs to be a function of two arguments.
Often we wish to “fill” in missing regions. In the case of a coding sequence there may be bases that have no reads, and so these bases will not appear in our resulting object. We can “expand” a region to include these bases by filling in 0 reads for them. There are different ways to do this expansion. For convenience, data are stratified by strand. Therefore expansion will produce a list-of-lists, where each sublist has possibly two elements corresponding to each strand. If the original annotation query is stranded, then expansion will produce a list, where each sublist only has one element. Finally, we provide a feature to collapse across strand for the common use case of combining reads occurring on either strand within the region. In this case the return value is a list, where each element is an expanded matrix representing the reads that occurred on either strand.

> ## This returns a list-of-lists
> x1 <- splitByAnnotation(eData, annoData, expand = TRUE, ignoreStrand = TRUE)
```r
> names(x1[[1]])
[1] "-1" "1"

> ## this returns a list-of-lists, however they are of length 1
> x2 <- splitByAnnotation(eData, annoData, expand = TRUE)

writing region table:
0.013 sec

SQL query: SELECT counts_tbl.chr, counts_tbl.location, counts_tbl.strand, counts_tbl.* , __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) ORDER BY __regions__.id, counts_tbl.chr, counts_tbl.location, counts_tbl.strand

fetching splits table:
0.034 sec

SQL query: SELECT count(__regions__.id), __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

count query:
0.008 sec

performing split:
0.003 sec

> names(x2[[1]])
[1] "-1"

> ## this returns a list where we have combined the two sublists
> x3 <- splitByAnnotation(eData, annoData, expand = TRUE, addOverStrand = TRUE)

writing region table:
0.014 sec

SQL query: SELECT counts_tbl.chr, counts_tbl.location, counts_tbl.strand, counts_tbl.* , __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) ORDER BY __regions__.id, counts_tbl.chr, counts_tbl.location, counts_tbl.strand
```

18
fetching splits table:
0.034 sec

SQL query: SELECT count(__regions__.id), __regions__.id FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

count query:
0.008 sec

performing split:
0.003 sec

> head(x3[[1]])

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>460</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>461</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>462</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>463</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>464</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>465</td>
<td>2</td>
</tr>
</tbody>
</table>

Leaving the `splitByAnnotation` function, sometimes we want to compute summaries of higher level entities, such as genes, pseudogenes, and intergenic regions. We can label each genomic location with its annotation using the `mergeWithAnnotation` convenience function.

> mergeWithAnnotation(eData, annoData)[1:3,]

writing regions table:
0.015 sec

SQL query: SELECT * FROM counts_tbl INNER JOIN __regions__ ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0)

fetching merge table:
0.035 sec

<table>
<thead>
<tr>
<th>chr</th>
<th>location</th>
<th>strand</th>
<th>counts</th>
<th>id</th>
<th>chr</th>
<th>start</th>
<th>end</th>
<th>strand</th>
<th>feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>460</td>
<td>-1</td>
<td>4</td>
<td>13</td>
<td>13</td>
<td>460</td>
<td>521</td>
<td>-1</td>
<td>gene</td>
</tr>
<tr>
<td>2</td>
<td>461</td>
<td>-1</td>
<td>5</td>
<td>13</td>
<td>13</td>
<td>460</td>
<td>521</td>
<td>-1</td>
<td>gene</td>
</tr>
<tr>
<td>3</td>
<td>462</td>
<td>-1</td>
<td>2</td>
<td>13</td>
<td>13</td>
<td>460</td>
<td>521</td>
<td>-1</td>
<td>gene</td>
</tr>
</tbody>
</table>

This will result in duplicated genomic locations in case a genomic location is annotated multiple times. There are a number of parameters that can make this more natural.

> par(mfrow=c(1,2))
> x <- lapply(mergeWithAnnotation(eData, annoData, splitBy = "feature", what = "counts"), + function(x) { + plot(density(x)) + })
6 Annotation

Annotation has been defined earlier as a data.frame satisfying certain requirements. This may be checked using validAnnotation which return TRUE or FALSE.

Genominator has a very useful function for dealing with annotation, makeGeneRepresentation. The input is a data.frame not unlike the result of a query to Ensembl or UCSC (using the biomaRt package of the rtracklayer package). The output of this function is a new set of gene models satisfying certain requirements detailed in the following. The typical output from such a query is an object where each row correspond to an exon and there are additional columns describing how exons are grouped into transcripts or genes.

An Ugene model (“Union gene”) consists of all bases annotated as belonging to a certain gene. Bases that are annotated as belonging to other genes as well, are removed.

An UIgene model (“Union-intersection”) is an approach to summarize a gene protecting against different splice forms. It consists of the bases that are annotated as belonging to every transcript of the gene. Bases that are annotated as belonging to other genes as well, are removed.

An ROCE model (“Region of Constant Expression”) are maximal intervals such that every base in the interval belongs to the same set of transcripts from the same gene. Bases that are annotated as belonging to other genes as well, are removed.

Finally Background models consists of the bases that are not annotated as belonging to any gene. Note: this function does not require chromosome lengths, so you may have to add an additional interval (row) for each chromosome, consisting of the interval from the last annotated base to the end of the chromosome.
7 Analysis tools

In the case of short read sequencing, the Genominator package offers a number of specific useful tools. They are presented in no particular order.

Coverage

The `computeCoverage` function can be used to assess the sequencing depth.

```r
> coverage <- computeCoverage(eData, annoData, effort = seq(100, 1000, by = 5),
+                              cutoff = function(e, anno, group) {e > 1})

writing regions table:
0.013 sec

SQL query: SELECT __regions__.id, TOTAL(counts) FROM __regions__ LEFT OUTER JOIN counts_tbl ON __regions__.chr = counts_tbl.chr AND counts_tbl.location BETWEEN __regions__.start AND __regions__.end AND (counts_tbl.strand = __regions__.strand OR __regions__.strand = 0 OR counts_tbl.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

fetching summary table:
0.012 sec

fetching summary:
0.006 sec

> plot(coverage, draw.legend = FALSE)
```
Statistical Functions: Goodness of Fit

You can conduct a goodness of fit analysis to the Poisson model across lanes using the following function. The result is assessed by a QQ-plot against the theoretical distribution (of either the p-values or the statistic).

```r
> plot(regionGoodnessOfFit(eDataJoin, annoData))
```

writing regions table:
0.013 sec

SQL query: SELECT __regions__.id, TOTAL(counts_1), TOTAL(counts_2) FROM __regions__ LEFT OUTER JOIN allcounts ON __regions__.chr = allcounts.chr AND allcounts.location BETWEEN __regions__.start AND __regions__.end AND (allcounts.strand = __regions__.strand OR __regions__.strand = 0 OR allcounts.strand = 0) GROUP BY __regions__.id ORDER BY __regions__.id

fetching summary table:
0.013 sec
We can also do this for subsets of the data, for example within condition.

```r
> plot(regionGoodnessOfFit(as.data.frame(matrix(rpois(1000, 100), ncol = 10)),
    + groups = rep(c("A", "B"), 5), denominator = rep(1, 10)))
```
SessionInfo

- R version 3.4.0 (2017-04-21), x86_64-pc-linux-gnu
- Locale: LC_CTYPE=en_US.UTF-8, LC_NUMERIC=C, LC_TIME=en_US.UTF-8, LC_COLLATE=C, LC_MONETARY=en_US.UTF-8, LC_MESSAGES=en_US.UTF-8, LC_PAPER=en_US.UTF-8, LC_NAME=C, LC_ADDRESS=C, LC_TELEPHONE=C, LC_MEASUREMENT=en_US.UTF-8, LC_IDENTIFICATION=C
- Running under: Ubuntu 16.04.2 LTS
- Matrix products: default
- BLAS: /home/biocbuild/bbs-3.5-bioc/R/lib/libRblas.so
- LAPACK: /home/biocbuild/bbs-3.5-bioc/R/lib/libRlapack.so
- Base packages: base, datasets, grDevices, graphics, grid, methods, parallel, stats, stats4, utils
- Other packages: BiocGenerics 0.22.0, DBI 0.6-1, GenomeGraphs 1.36.0, Genominator 1.30.0, IRanges 2.10.0, RSQLite 1.1-2, S4Vectors 0.14.0, biomaRt 2.32.0
- Loaded via a namespace (and not attached): AnnotationDbi 1.38.0, Biobase 2.36.0, RCurl 1.95-4.8, Repp 0.12.10, XML 3.98-1.6, bitops 1.0-6, compiler 3.4.0, digest 0.6.12, memoise 1.1.0, tools 3.4.0

References