An Introduction to the GenomicRanges Package

Marc Carlson, Patrick Aboyoun, Hervé Pagès, and Martin Morgan

February 25, 2018; updated 16 November, 2016

Contents

1 Introduction

The *GenomicRanges* package serves as the foundation for representing genomic locations within the *Bioconductor* project. In the *Bioconductor* package hierarchy, it builds upon the *IRanges* (infrastructure) package and provides support for the *BSgenome* (infrastructure), *Rsamtools* (I/O), *ShortRead* (I/O & QA), *rtracklayer* (I/O), *GenomicFeatures* (infrastructure), *GenomicAlignments* (sequence reads), *VariantAnnotation* (called variants), and many other *Bioconductor* packages.

This package lays a foundation for genomic analysis by introducing three classes (*GRanges*, *GPos*, and *GRangesList*), which are used to represent genomic ranges, genomic positions, and groups of genomic ranges. This vignette focuses on the *GRanges* and *GRangesList* classes and their associated methods.

The *GenomicRanges* package is available at https://bioconductor.org and can be installed via `biocLite`:

```
> source("https://bioconductor.org/biocLite.R")
> biocLite("GenomicRanges")
```

A package only needs to be installed once. Load the package into an *R* session with

```
> library(GenomicRanges)
```

2 *GRanges*: Genomic Ranges

The *GRanges* class represents a collection of genomic ranges that each have a single start and end location on the genome. It can be used to store the location of genomic features such as contiguous binding sites, transcripts, and exons. These objects can be created by using the `GRanges` constructor function. For example,

```
> gr <- GRanges(
+     seqnames = Rle(c("chr1", "chr2", "chr1", "chr3"), c(1, 3, 2, 4)),
+     ranges = IRanges(101:110, end = 111:120, names = head(letters, 10)),
+     strand = Rle(strand(c("-", "+", "*", "+", "-")), c(1, 2, 2, 3, 2)),
+     score = 1:10,
+     GC = seq(1, 0, length=10))
> gr

GRanges object with 10 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  .      ...        ...    ... .       ...               ...
  h     chr3 [108, 118]      + |         8 0.222222222222222
  i     chr3 [109, 119]      - |         9 0.111111111111111
  j     chr3 [110, 120]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome; no seqlengths

> options(warn=2)
```

creates a *GRanges* object with 10 genomic ranges. The output of the *GRanges* `show` method separates the information into a left and right hand region that are separated by `|` symbols. The genomic coordinates (seqnames, ranges, and strand) are located on the left-hand side and the metadata columns (annotation) are located on the right. For this example, the metadata is comprised of `score` and `GC` information, but almost anything can be stored in the metadata portion of a *GRanges* object.

The components of the genomic coordinates within a *GRanges* object can be extracted using the `seqnames`, `ranges`, and `strand` accessor functions.

```
> seqnames(gr)
```

```
factor-Rle of length 10 with 4 runs
  Lengths:    1    3    2    4
  Values : chr1 chr2 chr1 chr3
Levels(3): chr1 chr2 chr3
```

```
> ranges(gr)
```

```
IRanges object with 10 ranges and 0 metadata columns:
        start       end     width
    <integer> <integer> <integer>
  a       101       111        11
  b       102       112        11
  c       103       113        11
  .       ...       ...       ...
  h       108       118        11
  i       109       119        11
  j       110       120        11
```

```
> strand(gr)
```

```
factor-Rle of length 10 with 5 runs
  Lengths: 1 2 2 3 2
  Values : - + * + -
Levels(3): + - *
```

The genomic ranges can be extracted without corresponding metadata with `granges`

```
> granges(gr)
```

```
GRanges object with 10 ranges and 0 metadata columns:
    seqnames     ranges strand
       <Rle>  <IRanges>  <Rle>
  a     chr1 [101, 111]      -
  b     chr2 [102, 112]      +
  c     chr2 [103, 113]      +
  .      ...        ...    ...
  h     chr3 [108, 118]      +
  i     chr3 [109, 119]      -
  j     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome; no seqlengths
```

Annotations for these coordinates can be extracted as a *DataFrame* object using the `mcols` accessor.

```
> mcols(gr)
```

```
DataFrame with 10 rows and 2 columns
        score        GC
    <integer> <numeric>
1           1 1.0000000
2           2 0.8888889
3           3 0.7777778
...       ...       ...
```

```
8           8 0.2222222
9           9 0.1111111
10         10 0.0000000
```

```
> mcols(gr)$score
```

```
 [1]  1  2  3  4  5  6  7  8  9 10
```

Information about the lengths of the various sequences that the ranges are aligned to can also be stored in the *GRanges* object. So if this is data from *Homo sapiens*, we can set the values as:

```
> seqlengths(gr) <- c(249250621, 243199373, 198022430)
```

And then retrieves as:

```
> seqlengths(gr)
```

```
     chr1      chr2      chr3
249250621 243199373 198022430
```

Methods for accessing the `length` and `names` have also been defined.

```
> names(gr)
```

```
 [1] "a" "b" "c" "d" "e" "f" "g" "h" "i" "j"
```

```
> length(gr)
```

```
[1] 10
```

2.1 Splitting and combining *GRanges* objects

GRanges objects can be devided into groups using the `split` method. This produces a *GRangesList* object, a class that will be discussed in detail in the next section.

```
> sp <- split(gr, rep(1:2, each=5))
> sp
```

```
GRangesList object of length 2:
$1
GRanges object with 5 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  d     chr2 [104, 114]      * |         4 0.666666666666667
  e     chr1 [105, 115]      * |         5 0.555555555555556

$2
GRanges object with 5 ranges and 2 metadata columns:
    seqnames     ranges strand | score                GC
  f     chr1 [106, 116]      + |     6 0.444444444444444
```

```
  g     chr3 [107, 117]      + |     7 0.333333333333333
  h     chr3 [108, 118]      + |     8 0.222222222222222
  i     chr3 [109, 119]      - |     9 0.111111111111111
  j     chr3 [110, 120]      - |    10                 0

-------
seqinfo: 3 sequences from an unspecified genome
```

Separate *GRanges* instances can be concatenated by using the `c` and `append` methods.

```
> c(sp[[1]], sp[[2]])

GRanges object with 10 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  .      ...        ...    ... .       ...               ...
  h     chr3 [108, 118]      + |         8 0.222222222222222
  i     chr3 [109, 119]      - |         9 0.111111111111111
  j     chr3 [110, 120]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome
```

2.2 Subsetting *GRanges* objects

GRanges objects act like vectors of ranges, with the expected vector-like subsetting operations available

```
> gr[2:3]

GRanges object with 2 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  -------
  seqinfo: 3 sequences from an unspecified genome
```

A second argument to the `[` subset operator can be used to specify which metadata columns to extract from the *GRanges* object. For example,

```
> gr[2:3, "GC"]

GRanges object with 2 ranges and 1 metadata column:
    seqnames     ranges strand |                GC
       <Rle>  <IRanges>  <Rle> |         <numeric>
  b     chr2 [102, 112]      + | 0.888888888888889
  c     chr2 [103, 113]      + | 0.777777777777778
  -------
  seqinfo: 3 sequences from an unspecified genome
```

Elements can also be assigned to the *GRanges* object. Here is an example where the second row of a *GRanges* object is replaced with the first row of `gr`.

```
> singles <- split(gr, names(gr))
> grMod <- gr
> grMod[2] <- singles[[1]]
> head(grMod, n=3)

GRanges object with 3 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr1 [101, 111]      - |         1                 1
  c     chr2 [103, 113]      + |         3 0.777777777777778
  -------
  seqinfo: 3 sequences from an unspecified genome
```

Here is a second example where the metadata for score from the third element is replaced with the score from the second row etc.

```
> grMod[2,1] <- singles[[3]][,1]
> head(grMod, n=3)

GRanges object with 3 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr2 [103, 113]      + |         3                 1
  c     chr2 [103, 113]      + |         3 0.777777777777778
  -------
  seqinfo: 3 sequences from an unspecified genome
```

There are methods to repeat, reverse, or select specific portions of *GRanges* objects.

```
> rep(singles[[2]], times = 3)

GRanges object with 3 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  b     chr2 [102, 112]      + |         2 0.888888888888889
  b     chr2 [102, 112]      + |         2 0.888888888888889
  b     chr2 [102, 112]      + |         2 0.888888888888889
  -------
  seqinfo: 3 sequences from an unspecified genome

> rev(gr)

GRanges object with 10 ranges and 2 metadata columns:
    seqnames     ranges strand |     score                GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  j     chr3 [110, 120]      - |        10                 0
  i     chr3 [109, 119]      - |         9 0.111111111111111
  h     chr3 [108, 118]      + |         8 0.222222222222222
```

```
  .      ...        ...    ... .       ...                ...
  c     chr2 [103, 113]      + |         3 0.777777777777778
  b     chr2 [102, 112]      + |         2 0.888888888888889
  a     chr1 [101, 111]      - |         1                 1
  -------
  seqinfo: 3 sequences from an unspecified genome

> head(gr,n=2)

GRanges object with 2 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [101, 111]      - |         1                 1
  b     chr2 [102, 112]      + |         2 0.888888888888889
  -------
  seqinfo: 3 sequences from an unspecified genome

> tail(gr,n=2)

GRanges object with 2 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  i     chr3 [109, 119]      - |         9 0.111111111111111
  j     chr3 [110, 120]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome

> window(gr, start=2,end=4)

GRanges object with 3 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  d     chr2 [104, 114]      * |         4 0.666666666666667
  -------
  seqinfo: 3 sequences from an unspecified genome

> gr[IRanges(start=c(2,7), end=c(3,9))]

GRanges object with 5 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  b     chr2 [102, 112]      + |         2 0.888888888888889
  c     chr2 [103, 113]      + |         3 0.777777777777778
  g     chr3 [107, 117]      + |         7 0.333333333333333
  h     chr3 [108, 118]      + |         8 0.222222222222222
  i     chr3 [109, 119]      - |         9 0.111111111111111
  -------
  seqinfo: 3 sequences from an unspecified genome
```

2.3 Basic interval operations for *GRanges* objects

Basic interval characteristics of *GRanges* objects can be extracted using the `start`, `end`, `width`, and `range` methods.

```
> g <- gr[1:3]
> g <- append(g, singles[[10]])
> start(g)
[1] 101 102 103 110
> end(g)
[1] 111 112 113 120
> width(g)
[1] 11 11 11 11
> range(g)
GRanges object with 3 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr1 [101, 111]      -
  [2]     chr2 [102, 113]      +
  [3]     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome
```

The *GRanges* class also has many methods for manipulating the ranges. The methods can be classified as *intra-range methods*, *inter-range methods*, and *between-range methods*.

Intra-range methods operate on each element of a *GRanges* object independent of the other ranges in the object. For example, the `flank` method can be used to recover regions flanking the set of ranges represented by the *GRanges* object. So to get a *GRanges* object containing the ranges that include the 10 bases upstream of the ranges:

```
> flank(g, 10)
GRanges object with 4 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>        <numeric>
  a     chr1 [112, 121]      - |         1                1
  b     chr2 [ 92, 101]      + |         2 0.888888888888889
  c     chr2 [ 93, 102]      + |         3 0.777777777777778
  j     chr3 [121, 130]      - |        10                0
  -------
  seqinfo: 3 sequences from an unspecified genome
```

And to include the downstream bases:

```
> flank(g, 10, start=FALSE)
GRanges object with 4 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>        <numeric>
```

```
  a     chr1 [ 91, 100]      - |         1                 1
  b     chr2 [113, 122]      + |         2 0.888888888888889
  c     chr2 [114, 123]      + |         3 0.777777777777778
  j     chr3 [100, 109]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome
```

Other examples of intra-range methods include `resize` and `shift`. The `shift` method will move the ranges by a specific number of base pairs, and the `resize` method will extend the ranges by a specified width.

```
> shift(g, 5)

GRanges object with 4 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [106, 116]      - |         1                 1
  b     chr2 [107, 117]      + |         2 0.888888888888889
  c     chr2 [108, 118]      + |         3 0.777777777777778
  j     chr3 [115, 125]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome

> resize(g, 30)

GRanges object with 4 ranges and 2 metadata columns:
    seqnames     ranges strand |     score               GC
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric>
  a     chr1 [ 82, 111]      - |         1                 1
  b     chr2 [102, 131]      + |         2 0.888888888888889
  c     chr2 [103, 132]      + |         3 0.777777777777778
  j     chr3 [ 91, 120]      - |        10                 0
  -------
  seqinfo: 3 sequences from an unspecified genome
```

The *GenomicRanges* help page `?"intra-range-methods"` summarizes these methods.

Inter-range methods involve comparisons between ranges in a single *GRanges* object. For instance, the `reduce` method will align the ranges and merge overlapping ranges to produce a simplified set.

```
> reduce(g)

GRanges object with 3 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr1 [101, 111]      -
  [2]     chr2 [102, 113]      +
  [3]     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome
```

Sometimes one is interested in the gaps or the qualities of the gaps between the ranges represented by your *GRanges* object. The `gaps` method provides this information: reduced version of your ranges:

```
> gaps(g)

GRanges object with 12 ranges and 0 metadata columns:
       seqnames           ranges strand
          <Rle>        <IRanges>  <Rle>
   [1]     chr1 [  1, 249250621]      +
   [2]     chr1 [  1,       100]      -
   [3]     chr1 [112, 249250621]      -
   ...      ...              ...    ...
  [10]     chr3 [  1,       109]      -
  [11]     chr3 [121, 198022430]      -
  [12]     chr3 [  1, 198022430]      *
  -------
  seqinfo: 3 sequences from an unspecified genome
```

The `disjoin` method represents a *GRanges* object as a collection of non-overlapping ranges:

```
> disjoin(g)

GRanges object with 5 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr1 [101, 111]      -
  [2]     chr2 [102, 102]      +
  [3]     chr2 [103, 112]      +
  [4]     chr2 [113, 113]      +
  [5]     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome
```

The `coverage` method quantifies the degree of overlap for all the ranges in a *GRanges* object.

```
> coverage(g)

RleList of length 3
$chr1
integer-Rle of length 249250621 with 3 runs
  Lengths:       100        11 249250510
  Values :         0         1         0

$chr2
integer-Rle of length 243199373 with 5 runs
  Lengths:       101         1        10         1 243199260
  Values :         0         1         2         1         0

$chr3
integer-Rle of length 198022430 with 3 runs
  Lengths:       109        11 198022310
  Values :         0         1         0
```

See the *GenomicRanges* help page `?"inter-range-methods"` for additional help.

Between-range methods involve operations between two *GRanges* objects; some of these are summarized in the next section.

2.4 Interval set operations for *GRanges* objects

Between-range methods calculate relationships between different *GRanges* objects. Of central importance are `findOverlaps` and related operations; these are discussed below. Additional operations treat *GRanges* as mathematical sets of coordinates; `union(g, g2)` is the union of the coordinates in `g` and `g2`. Here are examples for calculating the `union`, the `intersect` and the asymmetric difference (using `setdiff`).

```
> g2 <- head(gr, n=2)
> union(g, g2)

GRanges object with 3 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr1 [101, 111]      -
  [2]     chr2 [102, 113]      +
  [3]     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome

> intersect(g, g2)

GRanges object with 2 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr1 [101, 111]      -
  [2]     chr2 [102, 112]      +
  -------
  seqinfo: 3 sequences from an unspecified genome

> setdiff(g, g2)

GRanges object with 2 ranges and 0 metadata columns:
      seqnames     ranges strand
         <Rle>  <IRanges>  <Rle>
  [1]     chr2 [113, 113]      +
  [2]     chr3 [110, 120]      -
  -------
  seqinfo: 3 sequences from an unspecified genome
```

Related methods are available when the structure of the *GRanges* objects are 'parallel' to one another, i.e., element 1 of object 1 is related to element 1 of object 2, and so on. These operations all begin with a `p`, which is short for parallel. The methods then perform element-wise, e.g., the union of element 1 of object 1 with element 1 of object 2, etc. A requirement for these operations is that the number of elements in each *GRanges* object is the same, and that both of the objects have the same seqnames and strand assignments throughout.

```
> g3 <- g[1:2]
> ranges(g3[1]) <- IRanges(start=105, end=112)
```

```
> punion(g2, g3)

GRanges object with 2 ranges and 0 metadata columns:
    seqnames     ranges strand
       <Rle>  <IRanges>  <Rle>
  a     chr1 [101, 112]      -
  b     chr2 [102, 112]      +
  -------
  seqinfo: 3 sequences from an unspecified genome

> pintersect(g2, g3)

GRanges object with 2 ranges and 3 metadata columns:
    seqnames     ranges strand |     score                GC       hit
       <Rle>  <IRanges>  <Rle> | <integer>         <numeric> <logical>
  a     chr1 [105, 111]      - |         1                 1         1
  b     chr2 [102, 112]      + |         2 0.888888888888889         1
  -------
  seqinfo: 3 sequences from an unspecified genome

> psetdiff(g2, g3)

GRanges object with 2 ranges and 0 metadata columns:
    seqnames     ranges strand
       <Rle>  <IRanges>  <Rle>
  a     chr1 [101, 104]      -
  b     chr2 [102, 101]      +
  -------
  seqinfo: 3 sequences from an unspecified genome
```

For more information on the `GRanges` classes be sure to consult the manual page.

```
> ?GRanges
```

A relatively comprehensive list of available methods is discovered with

```
> methods(class="GRanges")
```

3 *GRangesList*: Groups of Genomic Ranges

Some important genomic features, such as spliced transcripts that are are comprised of exons, are inherently compound structures. Such a feature makes much more sense when expressed as a compound object such as a *GRangesList*. Whenever genomic features consist of multiple ranges that are grouped by a parent feature, they can be represented as a *GRangesList* object. Consider the simple example of the two transcript `GRangesList` below created using the `GRangesList` constructor.

```
> gr1 <- GRanges(
+     seqnames = "chr2",
+     ranges = IRanges(103, 106),
+     strand = "+",
+     score = 5L, GC = 0.45)
```

```
> gr2 <- GRanges(
+     seqnames = c("chr1", "chr1"),
+     ranges = IRanges(c(107, 113), width = 3),
+     strand = c("+", "-"),
+     score = 3:4, GC = c(0.3, 0.5))
> grl <- GRangesList("txA" = gr1, "txB" = gr2)
> grl

GRangesList object of length 2:
$txA
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45

$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand | score  GC
  [1]     chr1 [107, 109]      + |     3 0.3
  [2]     chr1 [113, 115]      - |     4 0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

The `show` method for a *GRangesList* object displays it as a named list of *GRanges* objects, where the names of this list are considered to be the names of the grouping feature. In the example above, the groups of individual exon ranges are represented as separate *GRanges* objects which are further organized into a list structure where each element name is a transcript name. Many other combinations of grouped and labeled *GRanges* objects are possible of course, but this example is expected to be a common arrangement.

3.1 Basic *GRangesList* accessors

Just as with *GRanges* object, the components of the genomic coordinates within a *GRangesList* object can be extracted using simple accessor methods. Not surprisingly, the *GRangesList* objects have many of the same accessors as *GRanges* objects. The difference is that many of these methods return a list since the input is now essentially a list of *GRanges* objects. Here are a few examples:

```
> seqnames(grl)

RleList of length 2
$txA
factor-Rle of length 1 with 1 run
  Lengths:    1
  Values : chr2
Levels(2): chr2 chr1

$txB
factor-Rle of length 2 with 1 run
  Lengths:    2
```

```
  Values : chr1
Levels(2): chr2 chr1

> ranges(grl)

IRangesList of length 2
$txA
IRanges object with 1 range and 0 metadata columns:
          start       end     width
      <integer> <integer> <integer>
  [1]       103       106         4

$txB
IRanges object with 2 ranges and 0 metadata columns:
          start       end     width
      <integer> <integer> <integer>
  [1]       107       109         3
  [2]       113       115         3

> strand(grl)

RleList of length 2
$txA
factor-Rle of length 1 with 1 run
  Lengths: 1
  Values : +
Levels(3): + - *

$txB
factor-Rle of length 2 with 2 runs
  Lengths: 1 1
  Values : + -
Levels(3): + - *
```

The `length` and `names` methods will return the length or names of the list and the `seqlengths` method will return the set of sequence lengths.

```
> length(grl)

[1] 2

> names(grl)

[1] "txA" "txB"

> seqlengths(grl)

chr2 chr1
  NA   NA
```

The `elementNROWS` method returns a list of integers corresponding to the result of calling `NROW` on each individual *GRanges* object contained by the *GRangesList*. This is a faster alternative to calling `lapply` on the *GRangesList*.

```
> elementNROWS(grl)

txA txB
```

```
  1   2
```

`isEmpty` tests if a *GRangesList* object contains anything.

```
> isEmpty(grl)

[1] FALSE
```

In the context of a *GRangesList* object, the `mcols` method performs a similar operation to what it does on a *GRanges* object. However, this metadata now refers to information at the list level instead of the level of the individual *GRanges* objects.

```
> mcols(grl) <- c("Transcript A","Transcript B")
> mcols(grl)

DataFrame with 2 rows and 1 column
         value
   <character>
1 Transcript A
2 Transcript B
```

Element-level metadata can be retrieved by unlisting the `GRangesList`, and extracting the metadata

```
> mcols(unlist(grl))

DataFrame with 3 rows and 2 columns
      score        GC
  <integer> <numeric>
1         5      0.45
2         3      0.30
3         4      0.50
```

3.2 Combining *GRangesList* objects

GRangesList objects can be unlisted to combine the separate *GRanges* objects that they contain as an expanded *GRanges*.

```
> ul <- unlist(grl)
> ul

GRanges object with 3 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  txA     chr2 [103, 106]      + |         5      0.45
  txB     chr1 [107, 109]      + |         3       0.3
  txB     chr1 [113, 115]      - |         4       0.5
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

Append lists using `append` or `c`.

A support site user had two *GRangesList* objects with 'parallel' elements, and wanted to combined these element-wise into a single *GRangesList*. One solution is to use `pc()` – parallel (element-wise) `c()`. A more general solution is to concatenate the lists and then re-group by some factor, in this case the names of the elements.

```
> grl1 <- GRangesList(
+     gr1 = GRanges("chr2", IRanges(3, 6)),
+     gr2 = GRanges("chr1", IRanges(c(7,13), width = 3)))
> grl2 <- GRangesList(
+     gr1 = GRanges("chr2", IRanges(9, 12)),
+     gr2 = GRanges("chr1", IRanges(c(25,38), width = 3)))
> pc(grl1, grl2)

GRangesList object of length 2:
$gr1
GRanges object with 2 ranges and 0 metadata columns:
      seqnames    ranges strand
         <Rle> <IRanges>  <Rle>
  [1]     chr2   [3,  6]      *
  [2]     chr2   [9, 12]      *

$gr2
GRanges object with 4 ranges and 0 metadata columns:
      seqnames   ranges strand
  [1]     chr1 [ 7,  9]      *
  [2]     chr1 [13, 15]      *
  [3]     chr1 [25, 27]      *
  [4]     chr1 [38, 40]      *

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> grl3 <- c(grl1, grl2)
> regroup(grl3, names(grl3))

GRangesList object of length 2:
$gr1
GRanges object with 2 ranges and 0 metadata columns:
      seqnames    ranges strand
         <Rle> <IRanges>  <Rle>
  [1]     chr2   [3,  6]      *
  [2]     chr2   [9, 12]      *

$gr2
GRanges object with 4 ranges and 0 metadata columns:
      seqnames   ranges strand
  [1]     chr1 [ 7,  9]      *
  [2]     chr1 [13, 15]      *
  [3]     chr1 [25, 27]      *
  [4]     chr1 [38, 40]      *

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

3.3 Basic interval operations for *GRangesList* objects

For interval operations, many of the same methods exist for *GRangesList* objects that exist for *GRanges* objects.

```
> start(grl)

IntegerList of length 2
[["txA"]] 103
[["txB"]] 107 113

> end(grl)

IntegerList of length 2
[["txA"]] 106
[["txB"]] 109 115

> width(grl)

IntegerList of length 2
[["txA"]] 4
[["txB"]] 3 3
```

These operations return a data structure representing, e.g., *IntegerList*, a list where all elements are integers; it can be convenient to use mathematical and other operations on **List* objects that work on each element, e.g.,

```
> sum(width(grl))  # sum of widths of each grl element

txA txB
  4   6
```

Most of the intra-, inter- and between-range methods operate on *GRangesList* objects, e.g., to shift all the *GRanges* objects in a *GRangesList* object, or calculate the coverage. Both of these operations are also carried out across each *GRanges* list member.

```
> shift(grl, 20)

GRangesList object of length 2:
$txA
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [123, 126]      + |         5      0.45

$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand | score  GC
  [1]     chr1 [127, 129]      + |     3 0.3
  [2]     chr1 [133, 135]      - |     4 0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> coverage(grl)

RleList of length 2
```

```
$chr2
integer-Rle of length 106 with 2 runs
  Lengths: 102   4
  Values :   0   1

$chr1
integer-Rle of length 115 with 4 runs
  Lengths: 106   3   3   3
  Values :   0   1   0   1
```

3.4 Subsetting *GRangesList* objects

A *GRangesList* object is behaves like a `list`: `[` returns a *GRangesList* containing a subset of the original object; `[[` or `$` returns the *GRanges* object at that location in the list.

```
> grl[1]
> grl[[1]]
> grl["txA"]
> grl$txB
```

In addition, subsetting a *GRangesList* also accepts a second parameter to specify which of the metadata columns you wish to select.

```
> grl[1, "score"]

GRangesList object of length 1:
$txA
GRanges object with 1 range and 1 metadata column:
      seqnames     ranges strand |     score
         <Rle>  <IRanges>  <Rle> | <integer>
  [1]     chr2 [103, 106]      + |         5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> grl["txB", "GC"]

GRangesList object of length 1:
$txB
GRanges object with 2 ranges and 1 metadata column:
      seqnames     ranges strand |        GC
         <Rle>  <IRanges>  <Rle> | <numeric>
  [1]     chr1 [107, 109]      + |       0.3
  [2]     chr1 [113, 115]      - |       0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

The `head`, `tail`, `rep`, `rev`, and `window` methods all behave as you would expect them to for a list object. For example, the elements referred to by `window` are now list elements instead of *GRanges* elements.

```
> rep(grl[[1]], times = 3)

GRanges object with 3 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45
  [2]     chr2 [103, 106]      + |         5      0.45
  [3]     chr2 [103, 106]      + |         5      0.45
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths

> rev(grl)

GRangesList object of length 2:
$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr1 [107, 109]      + |         3       0.3
  [2]     chr1 [113, 115]      - |         4       0.5

$txA
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand | score   GC
  [1]     chr2 [103, 106]      + |     5 0.45

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> head(grl, n=1)

GRangesList object of length 1:
$txA
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> tail(grl, n=1)

GRangesList object of length 1:
$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr1 [107, 109]      + |         3       0.3
  [2]     chr1 [113, 115]      - |         4       0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths

> window(grl, start=1, end=1)
```

```
GRangesList object of length 1:
$txA
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

```
> grl[IRanges(start=2, end=2)]
```

```
GRangesList object of length 1:
$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr1 [107, 109]      + |         3       0.3
  [2]     chr1 [113, 115]      - |         4       0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

3.5 Looping over *GRangesList* objects

For *GRangesList* objects there is also a family of `apply` methods. These include `lapply`, `sapply`, `mapply`, `endoapply`, `mendoapply`, `Map`, and `Reduce`.

The different looping methods defined for *GRangesList* objects are useful for returning different kinds of results. The standard `lapply` and `sapply` behave according to convention, with the `lapply` method returning a list and `sapply` returning a more simplified output.

```
> lapply(grl, length)
```

```
$txA
[1] 1

$txB
[1] 2
```

```
> sapply(grl, length)
```

```
txA txB
  1   2
```

As with *IRanges* objects, there is also a multivariate version of `sapply`, called `mapply`, defined for *GRangesList* objects. And, if you don't want the results simplified, you can call the `Map` method, which does the same things as `mapply` but without simplifying the output.

```
> grl2 <- shift(grl, 10)
> names(grl2) <- c("shiftTxA", "shiftTxB")
> mapply(c, grl, grl2)
```

```
$txA
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45
  [2]     chr2 [113, 116]      + |         5      0.45
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths

$txB
GRanges object with 4 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr1 [107, 109]      + |         3       0.3
  [2]     chr1 [113, 115]      - |         4       0.5
  [3]     chr1 [117, 119]      + |         3       0.3
  [4]     chr1 [123, 125]      - |         4       0.5
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

```
> Map(c, grl, grl2)

$txA
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45
  [2]     chr2 [113, 116]      + |         5      0.45
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths

$txB
GRanges object with 4 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr1 [107, 109]      + |         3       0.3
  [2]     chr1 [113, 115]      - |         4       0.5
  [3]     chr1 [117, 119]      + |         3       0.3
  [4]     chr1 [123, 125]      - |         4       0.5
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

Sometimes you will want to get back a modified version of the *GRangesList* that you originally passed in.

An endomorphism is a transformation of an object to another instance of the same class . This is achieved using the `endoapply` method, which will return the results as a *GRangesList* object.

```
> endoapply(grl, rev)

GRangesList object of length 2:
$txA
```

```
GRanges object with 1 range and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45

$txB
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand | score  GC
  [1]     chr1 [113, 115]      - |     4 0.5
  [2]     chr1 [107, 109]      + |     3 0.3

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

```
> mendoapply(c, grl, grl2)
```

```
GRangesList object of length 2:
$txA
GRanges object with 2 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45
  [2]     chr2 [113, 116]      + |         5      0.45

$txB
GRanges object with 4 ranges and 2 metadata columns:
      seqnames     ranges strand | score  GC
  [1]     chr1 [107, 109]      + |     3 0.3
  [2]     chr1 [113, 115]      - |     4 0.5
  [3]     chr1 [117, 119]      + |     3 0.3
  [4]     chr1 [123, 125]      - |     4 0.5

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

The `Reduce` method will allow the *GRanges* objects to be collapsed across the whole of the *GRangesList* object.

```
> Reduce(c, grl)
```

```
GRanges object with 3 ranges and 2 metadata columns:
      seqnames     ranges strand |     score        GC
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>
  [1]     chr2 [103, 106]      + |         5      0.45
  [2]     chr1 [107, 109]      + |         3       0.3
  [3]     chr1 [113, 115]      - |         4       0.5
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

Explicit element-wise operations (`lapply()` and friends) on *GRangesList* objects with many elements can be slow. It is therefore beneficial to explore operations that work on `*List` objects directly (e.g., many of the 'group generic' operators, see `?S4groupGeneric`, and the

set and parallel set operators (e.g., `union`, `punion`). A useful and fast strategy is to `unlist` the *GRangesList* to a *GRanges* object, operate on the *GRanges* object, then `relist` the result, e.g.,

```
> gr <- unlist(grl)
> gr$log_score <- log(gr$score)
> grl <- relist(gr, grl)
> grl

GRangesList object of length 2:
$txA
GRanges object with 1 range and 3 metadata columns:
      seqnames     ranges strand |     score        GC       log_score
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>       <numeric>
  txA     chr2 [103, 106]      + |         5      0.45 1.6094379124341

$txB
GRanges object with 2 ranges and 3 metadata columns:
      seqnames     ranges strand | score  GC        log_score
  txB     chr1 [107, 109]      + |     3 0.3 1.09861228866811
  txB     chr1 [113, 115]      - |     4 0.5 1.38629436111989

-------
seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

See also `?extractList`.

For more information on the `GRangesList` classes be sure to consult the manual page and available methods

```
> ?GRangesList
> methods(class="GRangesList")   # _partial_ list
```

4 Interval overlaps involving *GRanges* and *GRanges-List* objects

Interval overlapping is the process of comparing the ranges in two objects to determine if and when they overlap. As such, it is perhaps the most common operation performed on *GRanges* and *GRangesList* objects. To this end, the *GenomicRanges* package provides a family of interval overlap functions. The most general of these functions is `findOverlaps`, which takes a query and a subject as inputs and returns a *Hits* object containing the index pairings for the overlapping elements.

```
> mtch <- findOverlaps(gr, grl)
> as.matrix(mtch)

     queryHits subjectHits
[1,]         1           1
[2,]         2           2
[3,]         3           2
```

As suggested in the sections discussing the nature of the *GRanges* and *GRangesList* classes, the index in the above matrix of hits for a *GRanges* object is a single range while for a *GRangesList* object it is the set of ranges that define a "feature".

Another function in the overlaps family is `countOverlaps`, which tabulates the number of overlaps for each element in the query.

```
> countOverlaps(gr, grl)

txA txB txB
  1   1   1
```

A third function in this family is `subsetByOverlaps`, which extracts the elements in the query that overlap at least one element in the subject.

```
> subsetByOverlaps(gr,grl)

GRanges object with 3 ranges and 3 metadata columns:
      seqnames     ranges strand |     score        GC        log_score
         <Rle>  <IRanges>  <Rle> | <integer> <numeric>        <numeric>
  txA     chr2 [103, 106]      + |         5      0.45  1.6094379124341
  txB     chr1 [107, 109]      + |         3       0.3 1.09861228866811
  txB     chr1 [113, 115]      - |         4       0.5 1.38629436111989
  -------
  seqinfo: 2 sequences from an unspecified genome; no seqlengths
```

Finally, you can use the `select` argument to get the index of the first overlapping element in the subject for each element in the query.

```
> findOverlaps(gr, grl, select="first")

[1] 1 2 2

> findOverlaps(grl, gr, select="first")

[1] 1 2
```

5 Session Information

All of the output in this vignette was produced under the following conditions:

```
> sessionInfo()

R version 3.4.3 (2017-11-30)
Platform: x86_64-pc-linux-gnu (64-bit)
Running under: Ubuntu 16.04.3 LTS

Matrix products: default
BLAS: /home/biocbuild/bbs-3.6-bioc/R/lib/libRblas.so
LAPACK: /home/biocbuild/bbs-3.6-bioc/R/lib/libRlapack.so

locale:
 [1] LC_CTYPE=en_US.UTF-8       LC_NUMERIC=C
 [3] LC_TIME=en_US.UTF-8        LC_COLLATE=C
 [5] LC_MONETARY=en_US.UTF-8    LC_MESSAGES=en_US.UTF-8
```

```
 [7] LC_PAPER=en_US.UTF-8       LC_NAME=C
 [9] LC_ADDRESS=C               LC_TELEPHONE=C
[11] LC_MEASUREMENT=en_US.UTF-8 LC_IDENTIFICATION=C

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

other attached packages:
 [1] BSgenome.Scerevisiae.UCSC.sacCer2_1.4.0
 [2] KEGGgraph_1.38.0
 [3] KEGG.db_3.2.3
 [4] BSgenome.Hsapiens.UCSC.hg19_1.4.0
 [5] BSgenome_1.46.0
 [6] rtracklayer_1.38.3
 [7] edgeR_3.20.8
 [8] limma_3.34.9
 [9] DESeq2_1.18.1
[10] AnnotationHub_2.10.1
[11] TxDb.Athaliana.BioMart.plantsmart22_3.0.1
[12] TxDb.Hsapiens.UCSC.hg19.knownGene_3.2.2
[13] TxDb.Dmelanogaster.UCSC.dm3.ensGene_3.2.2
[14] GenomicFeatures_1.30.3
[15] AnnotationDbi_1.40.0
[16] GenomicAlignments_1.14.1
[17] Rsamtools_1.30.0
[18] Biostrings_2.46.0
[19] XVector_0.18.0
[20] SummarizedExperiment_1.8.1
[21] DelayedArray_0.4.1
[22] matrixStats_0.53.1
[23] Biobase_2.38.0
[24] pasillaBamSubset_0.16.0
[25] GenomicRanges_1.30.3
[26] GenomeInfoDb_1.14.0
[27] IRanges_2.12.0
[28] S4Vectors_0.16.0
[29] BiocGenerics_0.24.0

loaded via a namespace (and not attached):
 [1] bitops_1.0-6                bit64_0.9-7
 [3] RColorBrewer_1.1-2          progress_1.1.2
 [5] httr_1.3.1                  rprojroot_1.3-2
 [7] tools_3.4.3                 backports_1.1.2
 [9] R6_2.2.2                    rpart_4.1-13
[11] Hmisc_4.1-1                 DBI_0.7
[13] lazyeval_0.2.1              colorspace_1.3-2
[15] nnet_7.3-12                 gridExtra_2.3
[17] prettyunits_1.0.2           RMySQL_0.10.13
[19] bit_1.1-12                  curl_3.1
[21] compiler_3.4.3              graph_1.56.0
[23] htmlTable_1.11.2            scales_0.5.0
[25] checkmate_1.8.5             genefilter_1.60.0
[27] stringr_1.3.0               digest_0.6.15
[29] foreign_0.8-69              rmarkdown_1.8
```

```
 [31] base64enc_0.1-3              pkgconfig_2.0.1
 [33] htmltools_0.3.6              htmlwidgets_1.0
 [35] rlang_0.2.0                  rstudioapi_0.7
 [37] RSQLite_2.0                  BiocInstaller_1.28.0
 [39] shiny_1.0.5                  BiocParallel_1.12.0
 [41] acepack_1.4.1                VariantAnnotation_1.24.5
 [43] RCurl_1.95-4.10              magrittr_1.5
 [45] GenomeInfoDbData_1.0.0       Formula_1.2-2
 [47] Matrix_1.2-12                Rcpp_0.12.15
 [49] munsell_0.4.3                stringi_1.1.6
 [51] yaml_2.1.16                  zlibbioc_1.24.0
 [53] plyr_1.8.4                   grid_3.4.3
 [55] blob_1.1.0                   lattice_0.20-35
 [57] splines_3.4.3                annotate_1.56.1
 [59] locfit_1.5-9.1               knitr_1.20
 [61] pillar_1.1.0                 geneplotter_1.56.0
 [63] biomaRt_2.34.2               XML_3.98-1.10
 [65] evaluate_0.10.1              latticeExtra_0.6-28
 [67] data.table_1.10.4-3          httpuv_1.3.5
 [69] gtable_0.2.0                 assertthat_0.2.0
 [71] ggplot2_2.2.1                mime_0.5
 [73] xtable_1.8-2                 survival_2.41-3
 [75] tibble_1.4.2                 memoise_1.1.0
 [77] cluster_2.0.6                interactiveDisplayBase_1.16.0
 [79] BiocStyle_2.6.1
```