

An Introduction to the GenomicRanges Package

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September 20, 2018; updated 11 January, 2018

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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.

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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	0.8888888888888889
c	chr2	103-113	+	3	0.7777777777777778
.
h	chr3	108-118	+	8	0.2222222222222222
i	chr3	109-119	-	9	0.1111111111111111
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)
```

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```
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
2      2 0.8888888888888889
3      3 0.7777777777777778
...      ...      ...
```

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```
8      8 0.222222222222222
9      9 0.111111111111111
10     10      0
> 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 divided 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
```

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```
g chr3 107-117 + | 7 0.3333333333333333
h chr3 108-118 + | 8 0.2222222222222222
i chr3 109-119 - | 9 0.1111111111111111
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 0.8888888888888889	
c	chr2 103-113	+	3 0.7777777777777778	
.
h	chr3 108-118	+	8 0.2222222222222222	
i	chr3 109-119	-	9 0.1111111111111111	
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 0.8888888888888889	
c	chr2 103-113	+	3 0.7777777777777778	

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	+	0.8888888888888889
c	chr2 103-113	+	0.7777777777777778

seqinfo: 3 sequences from an unspecified genome

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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
```

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
-----
```

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```
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
```

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```
> 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>
```


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```

a   chr1  106-116  - |      1      1
b   chr2  107-117  + |      2 0.8888888888888889
c   chr2  108-118  + |      3 0.7777777777777778
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 0.8888888888888889
c   chr2   103-132  + |      3 0.7777777777777778
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

```

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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      +
 [3]   chr2    103-112     +
 [4]   chr2      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
```

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```

      <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     +
[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      TRUE
b   chr2   102-112   + |         2 0.888888888888889  TRUE
-----
seqinfo: 3 sequences from an unspecified genome

```

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```
> 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 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
```

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```
[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
```

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```
> 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
```

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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      0.3
3      4      0.5
```

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      *
```

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```
[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
```


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```
> 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
      <Rle> <IRanges> <Rle> | <integer> <numeric>
[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 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)
```

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```
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
      <Rle> <IRanges> <Rle> | <integer> <numeric>
 [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)]
```

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```
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:
```

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```
      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, gr1, gr2)

$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(gr1, 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
```

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```
-----
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
  <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
```

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>
```

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```
      <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 *GRangesList* 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
```

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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 3.5.1 Patched (2018-07-12 r74967)
Platform: x86_64-pc-linux-gnu (64-bit)
Running under: Ubuntu 16.04.5 LTS

Matrix products: default
BLAS: /home/biocbuild/bbs-3.7-bioc/R/lib/libRblas.so
LAPACK: /home/biocbuild/bbs-3.7-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_1.40.0
```


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```
[3] KEGG.db_3.2.3
[4] BSgenome.Hsapiens.UCSC.hg19_1.4.0
[5] BSgenome_1.48.0
[6] rtracklayer_1.40.6
[7] edgeR_3.22.3
[8] limma_3.36.5
[9] DESeq2_1.20.0
[10] AnnotationHub_2.12.1
[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_1.32.2
[15] AnnotationDbi_1.42.1
[16] GenomicAlignments_1.16.0
[17] Rsamtools_1.32.3
[18] Biostrings_2.48.0
[19] XVector_0.20.0
[20] SummarizedExperiment_1.10.1
[21] DelayedArray_0.6.6
[22] BiocParallel_1.14.2
[23] matrixStats_0.54.0
[24] Biobase_2.40.0
[25] pasillaBamSubset_0.18.0
[26] GenomicRanges_1.32.7
[27] GenomeInfoDb_1.16.0
[28] IRanges_2.14.12
[29] S4Vectors_0.18.3
[30] BiocGenerics_0.26.0
```

loaded via a namespace (and not attached):

```
[1] bitops_1.0-6           bit64_0.9-7
[3] RColorBrewer_1.1-2     progress_1.2.0
[5] httr_1.3.1            rprojroot_1.3-2
[7] tools_3.5.1           backports_1.1.2
[9] R6_2.2.2              rpart_4.1-13
[11] Hmisc_4.1-1           DBI_1.0.0
[13] lazyeval_0.2.1        colorspace_1.3-2
[15] nnet_7.3-12           gridExtra_2.3
[17] tidyselect_0.2.4      prettyunits_1.0.2
[19] bit_1.1-14           curl_3.2
[21] compiler_3.5.1        graph_1.58.0
[23] htmlTable_1.12        checkmate_1.8.5
[25] scales_1.0.0          genefilter_1.62.0
[27] stringr_1.3.1         digest_0.6.17
[29] foreign_0.8-71        rmarkdown_1.10
[31] base64enc_0.1-3      pkgconfig_2.0.2
[33] htmltools_0.3.6      htmlwidgets_1.2
[35] rlang_0.2.2          rstudioapi_0.7
[37] RSQLite_2.1.1        BiocInstaller_1.30.0
[39] shiny_1.1.0          bindr_0.1.1
[41] acepack_1.4.1        dplyr_0.7.6
[43] VariantAnnotation_1.26.1 RCurl_1.95-4.11
[45] magrittr_1.5          GenomeInfoDbData_1.1.0
[47] Formula_1.2-3        Matrix_1.2-14
[49] Rcpp_0.12.18         munsell_0.5.0
```

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```
[51] stringi_1.2.4          yaml_2.2.0
[53] zlibbioc_1.26.0       plyr_1.8.4
[55] grid_3.5.1            blob_1.1.1
[57] promises_1.0.1        crayon_1.3.4
[59] lattice_0.20-35       splines_3.5.1
[61] annotate_1.58.0        hms_0.4.2
[63] locfit_1.5-9.1        knitr_1.20
[65] pillar_1.3.0          geneplotter_1.58.0
[67] biomaRt_2.36.1        XML_3.98-1.16
[69] glue_1.3.0            evaluate_0.11
[71] latticeExtra_0.6-28   data.table_1.11.6
[73] httpuv_1.4.5          gtable_0.2.0
[75] purrr_0.2.5           assertthat_0.2.0
[77] ggplot2_3.0.0         mime_0.5
[79] xtable_1.8-3          later_0.7.5
[81] survival_2.42-6       tibble_1.4.2
[83] memoise_1.1.0         bindrcpp_0.2.2
[85] cluster_2.0.7-1      interactiveDisplayBase_1.18.0
[87] BiocStyle_2.8.2
```