

An Introduction to Genomic Ranges Classes

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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), and *GenomicFeatures* (infrastructure) packages.

This package lays a foundation for genomic analysis by introducing three classes (*GRanges*, *GRangesList*, and *GappedAlignments*), which are used to represent single interval range features, multiple interval range features, and gapped alignments respectively. This vignette focuses on these classes and their associated methods.

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

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

> library(GenomicRanges)
```

2 *GRanges*: Single Interval Range Features

The *GRanges* class represents a collection of genomic features that each have a single start and end location on the genome. This includes 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(1:10, end = 7:16),
+ 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 with 10 ranges and 2 elementMetadata values

	seqnames	ranges	strand		score	GC
	<Rle>	<IRanges>	<Rle>		<integer>	<numeric>
a	chr1	[1, 7]	-		1	1.0000000
b	chr2	[2, 8]	+		2	0.8888889
c	chr2	[3, 9]	+		3	0.7777778
d	chr2	[4, 10]	*		4	0.6666667
e	chr1	[5, 11]	*		5	0.5555556
f	chr1	[6, 12]	+		6	0.4444444
g	chr3	[7, 13]	+		7	0.3333333
h	chr3	[8, 14]	+		8	0.2222222
i	chr3	[9, 15]	-		9	0.1111111
j	chr3	[10, 16]	-		10	0.0000000

seqlengths

chr1	chr2	chr3
NA	NA	NA

creates a *GRanges* object with 10 single interval features. 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 element metadata (annotation) columns 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 of length 10
  start end width names
[1]     1  7     7     a
[2]     2  8     7     b
[3]     3  9     7     c
```

```
[4] 4 10 7 d
[5] 5 11 7 e
[6] 6 12 7 f
[7] 7 13 7 g
[8] 8 14 7 h
[9] 9 15 7 i
[10] 10 16 7 j
```

```
> strand(gr)
```

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

Stored annotations for these coordinates can be extracted as a *DataFrame* object using the `elementMetadata` or the `values` accessor.

```
> elementMetadata(gr)[, "score"]
```

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

```
> values(gr)
```

```
DataFrame with 10 rows and 2 columns
```

	score	GC
	<integer>	<numeric>
a	1	1.0000000
b	2	0.8888889
c	3	0.7777778
d	4	0.6666667
e	5	0.5555556
f	6	0.4444444
g	7	0.3333333
h	8	0.2222222
i	9	0.1111111
j	10	0.0000000

Finally, the total 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 of length 2
```

```
$1
```

```
GRanges with 5 ranges and 2 elementMetadata values
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
a	chr1	[1, 7]	-	1	1.0000000
b	chr2	[2, 8]	+	2	0.8888889
c	chr2	[3, 9]	+	3	0.7777778
d	chr2	[4, 10]	*	4	0.6666667
e	chr1	[5, 11]	*	5	0.5555556

```
$2
```

```
GRanges with 5 ranges and 2 elementMetadata values
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
f	chr1	[6, 12]	+	6	0.4444444
g	chr3	[7, 13]	+	7	0.3333333
h	chr3	[8, 14]	+	8	0.2222222
i	chr3	[9, 15]	-	9	0.1111111
j	chr3	[10, 16]	-	10	0.0000000

```
seqlengths
```

	chr1	chr2	chr3
	249250621	243199373	198022430

If you then grab the components of this list, they can also be merged by using the `c` and `append` methods.

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

```
GRanges with 10 ranges and 2 elementMetadata values
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
a	chr1	[1, 7]	-	1	1.0000000
b	chr2	[2, 8]	+	2	0.8888889
c	chr2	[3, 9]	+	3	0.7777778
d	chr2	[4, 10]	*	4	0.6666667
e	chr1	[5, 11]	*	5	0.5555556
f	chr1	[6, 12]	+	6	0.4444444
g	chr3	[7, 13]	+	7	0.3333333
h	chr3	[8, 14]	+	8	0.2222222
i	chr3	[9, 15]	-	9	0.1111111
j	chr3	[10, 16]	-	10	0.0000000

```
seqlengths
```

```

      chr1      chr2      chr3
249250621 243199373 198022430

```

2.2 Subsetting *GRanges* objects

The expected subsetting operations are also available for *GRanges* objects.

```
> gr[2:3]
```

GRanges with 2 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
b	chr2	[2, 8]	+	2	0.8888889
c	chr2	[3, 9]	+	3	0.7777778

seqlengths

```

      chr1      chr2      chr3
249250621 243199373 198022430

```

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

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

GRanges with 2 ranges and 1 elementMetadata value

	seqnames	ranges	strand	GC
	<Rle>	<IRanges>	<Rle>	<numeric>
b	chr2	[2, 8]	+	0.8888889
c	chr2	[3, 9]	+	0.7777778

seqlengths

```

      chr1      chr2      chr3
249250621 243199373 198022430

```

You can also assign into elements of the *GRanges* object. Here is an example where the 2nd row of a *GRanges* object is replaced with the 1st row of *gr*.

```

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

```

GRanges with 3 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
a	chr1	[1, 7]	-	1	1.0000000
b	chr1	[1, 7]	-	1	1.0000000
c	chr2	[3, 9]	+	3	0.7777778

seqlengths

```

      chr1      chr2      chr3
249250621 243199373 198022430

```

Here is a second example where the metadata for score from the 3rd element is replaced with the score from the 2nd row etc.

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

GRanges with 3 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
a   chr1     [1, 7]   - |         1 1.0000000
b   chr2     [3, 9]   + |         3 1.0000000
c   chr2     [3, 9]   + |         3 0.7777778

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430
```

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

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

GRanges with 3 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
b   chr2     [2, 8]   + |         2 0.8888889
b.1 chr2     [2, 8]   + |         2 0.8888889
b.2 chr2     [2, 8]   + |         2 0.8888889

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430
```

```
> rev(gr)

GRanges with 10 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
j   chr3    [10, 16]   - |        10 0.0000000
i   chr3     [ 9, 15]   - |         9 0.1111111
h   chr3     [ 8, 14]   + |         8 0.2222222
g   chr3     [ 7, 13]   + |         7 0.3333333
f   chr1     [ 6, 12]   + |         6 0.4444444
e   chr1     [ 5, 11]   * |         5 0.5555556
d   chr2     [ 4, 10]   * |         4 0.6666667
c   chr2     [ 3,  9]   + |         3 0.7777778
b   chr2     [ 2,  8]   + |         2 0.8888889
a   chr1     [ 1,  7]   - |         1 1.0000000

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430
```

```
> head(gr, n = 2)
```

GRanges with 2 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
a	chr1	[1, 7]	-	1	1.0000000
b	chr2	[2, 8]	+	2	0.8888889

seqlengths

chr1	chr2	chr3
249250621	243199373	198022430

> tail(gr, n = 2)

GRanges with 2 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
i	chr3	[9, 15]	-	9	0.1111111
j	chr3	[10, 16]	-	10	0.0000000

seqlengths

chr1	chr2	chr3
249250621	243199373	198022430

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

GRanges with 3 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
b	chr2	[2, 8]	+	2	0.8888889
c	chr2	[3, 9]	+	3	0.7777778
d	chr2	[4, 10]	*	4	0.6666667

seqlengths

chr1	chr2	chr3
249250621	243199373	198022430

> seqselect(gr, start = c(2, 7), end = c(3, 9))

GRanges with 5 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
b	chr2	[2, 8]	+	2	0.8888889
c	chr2	[3, 9]	+	3	0.7777778
g	chr3	[7, 13]	+	7	0.3333333
h	chr3	[8, 14]	+	8	0.2222222
i	chr3	[9, 15]	-	9	0.1111111

seqlengths

chr1	chr2	chr3
249250621	243199373	198022430

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] 1 2 3 10

> end(g)

[1] 7 8 9 16

> width(g)

[1] 7 7 7 7

> range(g)

GRanges with 3 ranges and 0 elementMetadata values
  seqnames      ranges strand |
    <Rle> <IRanges> <Rle> |
[1]   chr1 [ 1, 7]     - |
[2]   chr2 [ 2, 9]     + |
[3]   chr3 [10, 16]    - |

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

The *GRanges* class also has many methods for manipulating the intervals. 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 with 4 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
a   chr1 [ 8, 17]     - |         1 1.0000000
b   chr2 [ 1, 1]      + |         2 0.8888889
c   chr2 [ 1, 2]      + |         3 0.7777778
j   chr3 [17, 26]    - |        10 0.0000000

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

And to include the downstream bases:

```

> flank(g, 10, start = FALSE)

GRanges with 4 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
a   chr1 [ 1, 0]      - |         1 1.0000000
b   chr2 [ 9, 18]     + |         2 0.8888889

```



```

c   chr2 [10, 19]   + |      3 0.7777778
j   chr3 [ 1,  9]   - |     10 0.0000000

```

```

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

Similar to `flank`, there are also operations to `resize` and `shift` our `GRanges` object. 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 with 4 ranges and 2 elementMetadata values
```

```

  seqnames  ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
a   chr1 [ 6, 12]   - |      1 1.0000000
b   chr2 [ 7, 13]   + |      2 0.8888889
c   chr2 [ 8, 14]   + |      3 0.7777778
j   chr3 [15, 21]   - |     10 0.0000000

```

```

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

```
> resize(g, 30)
```

```
GRanges with 4 ranges and 2 elementMetadata values
```

```

  seqnames  ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
a   chr1 [1,  7]   - |      1 1.0000000
b   chr2 [2, 31]  + |      2 0.8888889
c   chr2 [3, 32]  + |      3 0.7777778
j   chr3 [1, 16]  - |     10 0.0000000

```

```

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

The `reduce` will align the ranges and merge overlapping ranges to produce a simplified set.

```
> reduce(g)
```

```
GRanges with 3 ranges and 0 elementMetadata values
```

```

  seqnames  ranges strand |
  <Rle> <IRanges> <Rle> |
[1]   chr1 [ 1,  7]   - |
[2]   chr2 [ 2,  9]   + |
[3]   chr3 [10, 16]  - |

```

```

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

Sometimes you may be interested in the spaces or the qualities of the spaces between the ranges represented by your *GRanges* object. The `gaps` method will help you calculate the spaces between a reduced version of your ranges:

```
> gaps(g)
```

```
GRanges with 11 ranges and 0 elementMetadata values
```

	seqnames	ranges	strand
	<Rle>	<IRanges>	<Rle>
[1]	chr1	[1, 249250621]	+
[2]	chr1	[8, 249250621]	-
[3]	chr1	[1, 249250621]	*
[4]	chr2	[1, 1]	+
[5]	chr2	[10, 243199373]	+
[6]	chr2	[1, 243199373]	-
[7]	chr2	[1, 243199373]	*
[8]	chr3	[1, 198022430]	+
[9]	chr3	[1, 9]	-
[10]	chr3	[17, 198022430]	-
[11]	chr3	[1, 198022430]	*

```
seqlengths
```

chr1	chr2	chr3
249250621	243199373	198022430

And sometimes you also may want to know how many quantitatively unique fragments your ranges could possibly represent. For this task there is the `disjoin` method.

```
> disjoin(g)
```

```
GRanges with 5 ranges and 0 elementMetadata values
```

	seqnames	ranges	strand
	<Rle>	<IRanges>	<Rle>
[1]	chr1	[1, 7]	-
[2]	chr2	[2, 2]	+
[3]	chr2	[3, 8]	+
[4]	chr2	[9, 9]	+
[5]	chr3	[10, 16]	-

```
seqlengths
```

chr1	chr2	chr3
249250621	243199373	198022430

One of the most powerful methods for looking at *GRanges* objects is the `coverage` method. The `coverage` method quantifies the degree of overlap for all the ranges in a *GRanges* object.

```
> coverage(g)
```

```
SimpleRleList of length 3
```

```
$chr1
```

```
'integer' Rle of length 249250621 with 2 runs
```

Lengths:	7	249250614
Values :	1	0

```
$chr2
'integer' Rle of length 243199373 with 5 runs
  Lengths:      1      1      6      1 243199364
  Values :      0      1      2      1      0
```

```
$chr3
'integer' Rle of length 198022430 with 3 runs
  Lengths:      9      7 198022414
  Values :      0      1      0
```

2.4 Interval set operations for *GRanges* objects

There are also operations for calculating relationships between different *GRanges* objects. Here are a some examples for how you can calculate the union, the `intersect` and the asymmetric difference (using `setdiff`).

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

GRanges with 3 ranges and 0 elementMetadata values

```
  seqnames  ranges strand |
  <Rle> <IRanges> <Rle> |
[1]   chr1  [ 1, 7]   - |
[2]   chr2  [ 2, 9]   + |
[3]   chr3 [10, 16]   - |
```

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

```
> intersect(g, g2)
```

GRanges with 2 ranges and 0 elementMetadata values

```
  seqnames  ranges strand |
  <Rle> <IRanges> <Rle> |
[1]   chr1  [1, 7]   - |
[2]   chr2  [2, 8]   + |
```

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

```
> setdiff(g, g2)
```

GRanges with 2 ranges and 0 elementMetadata values

```
  seqnames  ranges strand |
  <Rle> <IRanges> <Rle> |
[1]   chr2  [ 9, 9]   + |
[2]   chr3 [10, 16]   - |
```

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

In addition, there is similar set of operations that act at the level of the individual ranges within each *GRanges*. These operations all begin with a “p”, which is short for parallel. A requirement for this set of operations is that the number of elements in each *GRanges* object has to be the same, and that both of the objects have to have the same seqnames and strand assignments throughout.

```
> g3 <- g[1:2]
> ranges(g3[1]) <- IRanges(start = 5, end = 12)
> punion(g2, g3)
```

```
GRanges with 2 ranges and 0 elementMetadata values
```

```
  seqnames  ranges strand |
    <Rle> <IRanges> <Rle> |
a   chr1    [1, 12]    - |
b   chr2    [2,  8]    + |
```

```
seqlengths
```

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

```
> pintersect(g2, g3)
```

```
GRanges with 2 ranges and 0 elementMetadata values
```

```
  seqnames  ranges strand |
    <Rle> <IRanges> <Rle> |
a   chr1    [5,  7]    - |
b   chr2    [2,  8]    + |
```

```
seqlengths
```

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

```
> psetdiff(g2, g3)
```

```
GRanges with 2 ranges and 0 elementMetadata values
```

```
  seqnames  ranges strand |
    <Rle> <IRanges> <Rle> |
a   chr1    [1,  4]    - |
b   chr2    [2,  1]    + |
```

```
seqlengths
```

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

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

```
> `?`(GRanges)
```

3 *GRangesList*: Multiple Interval Range Features

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 *GRangesList* object. Consider the simple example of the two transcript *GRangesList* below created using the *GRangesList* constructor.

```

> gr1 <- GRanges(seqnames = "chr2", ranges = IRanges(3, 6),
+   strand = "+", score = 5L, GC = 0.45)
> gr2 <- GRanges(seqnames = c("chr1", "chr1"), ranges = IRanges(c(7,
+   13), width = 3), strand = c("+", "-"), score = 3:4,
+   GC = c(0.3, 0.5))
> grl <- GRangesList(txA = gr1, txB = gr2)
> grl

```

```

GRangesList of length 2
$txA
GRanges with 1 range and 2 elementMetadata values
  seqnames  ranges strand |   score   GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2   [3, 6]     + |         5    0.45

```

```

$txB
GRanges with 2 ranges and 2 elementMetadata values
  seqnames  ranges strand |   score   GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1  [ 7,  9]     + |         3    0.3
[2]   chr1 [13, 15]     - |         4    0.5

```

```

seqlengths
chr2 chr1
NA   NA

```

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)

CompressedRleList 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(gr1)
```

```
CompressedIRangesList of length 2
```

```
$txA
```

```
IRanges of length 1
  start end width
[1]    3   6     4
```

```
$txB
```

```
IRanges of length 2
  start end width
[1]    7   9     3
[2]   13  15     3
```

```
> strand(gr1)
```

```
CompressedRleList 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(gr1)
```

```
[1] 2
```

```
> names(gr1)
```

```
[1] "txA" "txB"
```

```
> seqlengths(gr1)
```

```
chr2 chr1
NA   NA
```

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

```
> elementLengths(gr1)
```

```
txA txB
  1   2
```

You can also use `isEmpty` to test if a *GRangesList* object contains anything.

```
> isEmpty(grl)
[1] FALSE
```

Finally, in the context of a *GRangesList* object, the `elementMetadata` and `values` methods perform a similar operations to what they do on a *GRanges* object. However, this metadata refers to information at the list level instead of the level of the individual *GRanges* objects.

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

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

```
> values(grl)
```

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

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)
```

You can also append values together using `append` or `c`.

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)
```

```
CompressedIntegerList of length 2
[["txA"]] 3
[["txB"]] 7 13
```

```
> end(grl)
```

```
CompressedIntegerList of length 2
[["txA"]] 6
[["txB"]] 9 15
```

```
> width(gr1)
```

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

And as with *GRanges* objects, you can also 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(gr1, 20)
```

```
GRangesList of length 2
$txA
GRanges with 1 range and 2 elementMetadata values
  seqnames  ranges strand |   score   GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2  [23, 26]     + |         5    0.45
```

```
$txB
GRanges with 2 ranges and 2 elementMetadata values
  seqnames  ranges strand |   score   GC
    <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1  [27, 29]     + |         3    0.3
[2]   chr1  [33, 35]     - |         4    0.5
```

```
seqlengths
chr2 chr1
  NA  NA
```

```
> coverage(gr1)
```

```
SimpleRleList of length 2
$chr2
'integer' Rle of length 6 with 2 runs
  Lengths: 2 4
  Values : 0 1
```

```
$chr1
'integer' Rle of length 15 with 4 runs
  Lengths: 6 3 3 3
  Values : 0 1 0 1
```

3.4 Subsetting *GRangesList* objects

As you might guess, the subsetting of a *GRangesList* object is quite different from subsetting on a *GRanges* object in that it acts as if you are subsetting a list. If you try out the following you will notice that the standard conventions have been followed.

```
> gr1[1]
> gr1[[1]]
> gr1["txA"]
> gr1$txB
```


But in addition to this, when subsetting a *GRangesList*, you can also pass in a second parameter (as with a *GRanges* object) to again specify which of the *elementMetadata* columns you wish to select.

```
> grl[1, "score"]  
  
GRangesList of length 1  
$txA  
GRanges with 1 range and 1 elementMetadata value  
  seqnames      ranges strand |      score  
    <Rle> <IRanges> <Rle> | <integer>  
[1]   chr2     [3, 6]      + |         5
```

```
seqlengths  
chr2 chr1  
NA  NA
```

```
> grl["txB", "GC"]  
  
GRangesList of length 1  
$txB  
GRanges with 2 ranges and 1 elementMetadata value  
  seqnames      ranges strand |      GC  
    <Rle> <IRanges> <Rle> | <numeric>  
[1]   chr1 [ 7,  9]      + |     0.3  
[2]   chr1 [13, 15]     - |     0.5
```

```
seqlengths  
chr2 chr1  
NA  NA
```

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

```
> rep(grl[[1]], times = 3)  
  
GRanges with 3 ranges and 2 elementMetadata values  
  seqnames      ranges strand |      score      GC  
    <Rle> <IRanges> <Rle> | <integer> <numeric>  
[1]   chr2     [3, 6]      + |         5     0.45  
[2]   chr2     [3, 6]      + |         5     0.45  
[3]   chr2     [3, 6]      + |         5     0.45
```

```
seqlengths  
chr2 chr1  
NA  NA
```

```
> rev(grl)  
  
GRangesList of length 2  
$txB
```

GRanges with 2 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	chr1	[7, 9]	+	3	0.3
[2]	chr1	[13, 15]	-	4	0.5

\$txA

GRanges with 1 range and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	chr2	[3, 6]	+	5	0.45

seqlengths

chr2	chr1
NA	NA

> head(grl, n = 1)

GRangesList of length 1

\$txA

GRanges with 1 range and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	chr2	[3, 6]	+	5	0.45

seqlengths

chr2	chr1
NA	NA

> tail(grl, n = 1)

GRangesList of length 1

\$txB

GRanges with 2 ranges and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	chr1	[7, 9]	+	3	0.3
[2]	chr1	[13, 15]	-	4	0.5

seqlengths

chr2	chr1
NA	NA

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

GRangesList of length 1

\$txA

GRanges with 1 range and 2 elementMetadata values

	seqnames	ranges	strand	score	GC
--	----------	--------	--------	-------	----

```

      <Rle> <IRanges> <Rle> | <integer> <numeric>
[1] chr2 [3, 6] + | 5 0.45

```

```

seqlengths
chr2 chr1
NA NA

```

```
> seqselect(gr1, start = 2, end = 2)
```

```

GRangesList of length 1
$txB
GRanges with 2 ranges and 2 elementMetadata values
  seqnames ranges strand | score GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
[1] chr1 [7, 9] + | 3 0.3
[2] chr1 [13, 15] - | 4 0.5

```

```

seqlengths
chr2 chr1
NA NA

```

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(gr1, length)
```

```

$txA
[1] 1

```

```

$txB
[1] 2

```

```
> sapply(gr1, 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(gr1, 10)
> names(grl2) <- c("shiftTxA", "shiftTxB")
> mapply(c, gr1, grl2)

```

```
$txA
GRanges with 2 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
      <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2 [ 3,  6]      + |         5      0.45
[2]   chr2 [13, 16]      + |         5      0.45
```

```
seqlengths
chr2 chr1
NA   NA
```

```
$txB
GRanges with 4 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
      <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1 [ 7,  9]      + |         3      0.3
[2]   chr1 [13, 15]      - |         4      0.5
[3]   chr1 [17, 19]      + |         3      0.3
[4]   chr1 [23, 25]      - |         4      0.5
```

```
seqlengths
chr2 chr1
NA   NA
```

```
> Map(c, gr1, grl2)
```

```
$txA
GRanges with 2 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
      <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2 [ 3,  6]      + |         5      0.45
[2]   chr2 [13, 16]      + |         5      0.45
```

```
seqlengths
chr2 chr1
NA   NA
```

```
$txB
GRanges with 4 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
      <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1 [ 7,  9]      + |         3      0.3
[2]   chr1 [13, 15]      - |         4      0.5
[3]   chr1 [17, 19]      + |         3      0.3
[4]   chr1 [23, 25]      - |         4      0.5
```

```
seqlengths
chr2 chr1
NA   NA
```

Sometimes, you may not want to get back a simplified output or a list. Sometimes you will want to get back a modified version of the *GRangesList* that you originally passed in. This is conceptually similar to the

mathematical notion of an endomorphism. This is achieved using the `endoapply` method, which will return the results as a *GRangesList* object.

```
> endoapply(gr1, rev)

GRangesList of length 2
$txA
GRanges with 1 range and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2    [3, 6]     + |         5     0.45

$txB
GRanges with 2 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1  [13, 15]     - |         4     0.5
[2]   chr1   [ 7,  9]     + |         3     0.3

seqlengths
chr2 chr1
NA  NA
```

And, there is also a multivariate version of the `endoapply` method in the form of the `mendoapply` method.

```
> mendoapply(c, gr1, gr12)

GRangesList of length 2
$txA
GRanges with 2 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2 [ 3,  6]     + |         5     0.45
[2]   chr2 [13, 16]     + |         5     0.45

$txB
GRanges with 4 ranges and 2 elementMetadata values
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr1 [ 7,  9]     + |         3     0.3
[2]   chr1 [13, 15]     - |         4     0.5
[3]   chr1 [17, 19]     + |         3     0.3
[4]   chr1 [23, 25]     - |         4     0.5

seqlengths
chr2 chr1
NA  NA
```

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

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

```
GRanges with 3 ranges and 2 elementMetadata values
  seqnames   ranges strand |   score   GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
[1]   chr2 [ 3,  6]   + |     5     0.45
[2]   chr1 [ 7,  9]   + |     3     0.30
[3]   chr1 [13, 15]   - |     4     0.50
```

```
seqlengths
chr2 chr1
NA  NA
```

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

```
> `?`(GRangesList)
```

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 an *RangesMatching* object containing the index pairings for the overlapping elements.

```
> mtch <- findOverlaps(gr, grl)
> matchMatrix(mtch)
```

```
   query subject
[1,]    2      1
[2,]    3      1
[3,]    4      1
[4,]    5      2
[5,]    6      2
```

As suggested in the sections discussing the nature of the *GRanges* and *GRangesList* classes, the index in the `matchMatrix` 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)

[1] 0 1 1 1 1 1 0 0 0 0
```

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 with 5 ranges and 2 elementMetadata values
  seqnames   ranges strand |   score   GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
```

```

b   chr2  [2,  8]   + |      2 0.8888889
c   chr2  [3,  9]   + |      3 0.7777778
d   chr2  [4, 10]   * |      4 0.6666667
e   chr1  [5, 11]   * |      5 0.5555556
f   chr1  [6, 12]   + |      6 0.4444444

```

```

seqlengths
  chr1      chr2      chr3
249250621 243199373 198022430

```

Finally, you can also call the standard `match` methods on these objects.

```

> match(gr, gr1)
[1] NA  1  1  1  2  2 NA NA NA NA

> match(gr1, gr)
[1] 2 5

> gr %in% gr1
[1] FALSE TRUE TRUE TRUE TRUE TRUE FALSE FALSE FALSE FALSE

> gr1 %in% gr
[1] TRUE TRUE

```

5 Gapped Alignments

In addition to *GRanges* and *GRangesList* classes, the *GenomicRanges* package defines the *GappedAlignments* class, which is a more specialized container for storing a set of alignments. The class is intended to support alignments in general, not only those coming from a 'Binary Alignment Map' or 'BAM' files. Also alignments with gaps in the reference sequence (a.k.a. *gapped alignments*) are supported which, for example, makes the class suited for storing junction reads from an RNA-seq experiment.

More precisely, a *GappedAlignments* object is a vector-like object where each element describes an *alignment*, that is, how a given sequence (called *query* or *read*, typically short) aligns to a reference sequence (typically long).

As shown later in this document, a *GappedAlignments* object can be created from a 'BAM' file. In that case, each element in the resulting object will correspond to a record in the file. One important thing to note though is that not all the information present in the BAM/SAM records is stored in the object. In particular, for now, we discard the query sequences (SEQ field), the query ids (QNAME field), the query qualities (QUAL), the mapping qualities (MAPQ) and any other information that is not needed in order to support the basic set of operations described in this document. This also means that multi-reads (i.e. reads with multiple hits in the reference) don't receive any special treatment i.e. the various SAM/BAM records corresponding to a multi-read will show up in the *GappedAlignments* object as if they were coming from different/unrelated queries. Also paired-end reads will be treated as single-end reads and the pairing information will be lost. This might change in the future.

5.1 Load a ‘BAM’ file into a *GappedAlignments* object

First we use the `readGappedAlignments` function to load a toy ‘BAM’ file into a *GappedAlignments* object:

```
> library(Rsamtools)
> aln1_file <- system.file("extdata", "ex1.bam", package = "Rsamtools")
> aln1 <- readGappedAlignments(aln1_file)
> aln1
```

```
GappedAlignments of length 3271
      rname strand cigar qwidth start  end width ngap
[1]   seq1     +   36M    36     1   36   36   0
[2]   seq1     +   35M    35     3   37   35   0
[3]   seq1     +   35M    35     5   39   35   0
[4]   seq1     +   36M    36     6   41   36   0
[5]   seq1     +   35M    35     9   43   35   0
[6]   seq1     +   35M    35    13   47   35   0
[7]   seq1     +   36M    36    13   48   36   0
[8]   seq1     +   35M    35    15   49   35   0
[9]   seq1     -   35M    35    18   52   35   0
...     ...     ...     ...     ...     ...     ...     ...
[3263] seq2     +   35M    35  1520 1554   35   0
[3264] seq2     -   33M    33  1523 1555   33   0
[3265] seq2     -   35M    35  1524 1558   35   0
[3266] seq2     +   34M    34  1524 1557   34   0
[3267] seq2     +   35M    35  1524 1558   35   0
[3268] seq2     +   35M    35  1524 1558   35   0
[3269] seq2     -   35M    35  1528 1562   35   0
[3270] seq2     -   35M    35  1532 1566   35   0
[3271] seq2     -   35M    35  1533 1567   35   0
```

```
> length(aln1)
```

```
[1] 3271
```

3271 ‘BAM’ records were loaded into the object.

Note that `readGappedAlignments` would have discarded any ‘BAM’ record describing an unaligned query or a query that is a PCR or optical duplicate (see description of the `<flag>` field in the SAM Format Specification ¹ for more information). The reader interested in tracking down these events can always use the `scanBam` function but this goes beyond the scope of this document.

5.2 Simple accessor methods

There is one accessor per field displayed by the `show` method and it has the same name as the field. All of them return a vector or factor of the same length as the object:

```
> head(rname(aln1))

'factor' Rle of length 6 with 1 run
Lengths: 6
Values : seq1
Levels(2): seq1 seq2
```

¹<http://samtools.sourceforge.net/SAM1.pdf>


```

> levels(rname(aln1))
[1] "seq1" "seq2"
> head(strand(aln1))
'factor' Rle of length 6 with 1 run
  Lengths: 6
  Values : +
Levels(3): + - *
> head(cigar(aln1))
[1] "36M" "35M" "35M" "36M" "35M" "35M"
> head(qwidth(aln1))
[1] 36 35 35 36 35 35
> head(start(aln1))
[1] 1 3 5 6 9 13
> head(end(aln1))
[1] 36 37 39 41 43 47
> head(width(aln1))
[1] 36 35 35 36 35 35
> head(ngap(aln1))
[1] 0 0 0 0 0 0

```

5.3 More accessor methods