

A quick introduction to GRanges and GRangesList objects

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GRanges objects

- The `GRanges()` constructor

- `GRanges` accessors

- Vector operations on `GRanges` objects

- Range-based operations on `GRanges` objects

GRangesList objects

- The `GRangesList()` constructor

- `GRangesList` accessors

- Vector operations on `GRangesList` objects

- List operations on `GRangesList` objects

- Range-based operations on `GRangesList` objects

Other resources

The GRanges class is a container for...

... storing a set of *genomic ranges* (a.k.a. *genomic regions* or *genomic intervals*).

- ▶ Each genomic range is described by a chromosome name, a *start*, an *end*, and a strand.
- ▶ *start* and *end* are both **1-based** positions relative to the 5' end of the plus strand of the chromosome, even when the range is on the minus strand.
- ▶ *start* and *end* are both considered to be included in the interval (except when the range is empty).
- ▶ The *width* of the range is the number of genomic positions included in it. So $width = end - start + 1$.
- ▶ *end* is always $\geq start$, except for empty ranges (a.k.a. zero-width ranges) where $end = start - 1$.

Note that the *start* is always the leftmost position and the *end* the rightmost, even when the range is on the minus strand.

Gotcha: A TSS is at the *end* of the range associated with a transcript located on the minus strand.

The `GRanges()` constructor

```
> library(GenomicRanges)
> gr1 <- GRanges(seqnames=Rle(c("ch1", "chMT"), c(2, 4)),
+               ranges=IRanges(16:21, 20),
+               strand=rep(c("+", "-", "*"), 2))
> gr1
```

GRanges object with 6 ranges and 0 metadata columns:

	seqnames	ranges	strand
	<Rle>	<IRanges>	<Rle>
[1]	ch1	[16, 20]	+
[2]	ch1	[17, 20]	-
[3]	chMT	[18, 20]	*
[4]	chMT	[19, 20]	+
[5]	chMT	[20, 20]	-
[6]	chMT	[21, 20]	*

seqinfo: 2 sequences from an unspecified genome; no seqlengths

GRanges accessors: `length()`, `seqnames()`, `ranges()`

```
> length(gr1)
[1] 6
> seqnames(gr1)
factor-Rle of length 6 with 2 runs
  Lengths:    2    4
  Values  : ch1 chMT
Levels(2): ch1 chMT
> ranges(gr1)
IRanges object with 6 ranges and 0 metadata columns:
      start      end      width
  <integer> <integer> <integer>
 [1]      16      20         5
 [2]      17      20         4
 [3]      18      20         3
 [4]      19      20         2
 [5]      20      20         1
 [6]      21      20         0
```

GRanges accessors: `start()`, `end()`, `width()`, `strand()`

```
> start(gr1)
[1] 16 17 18 19 20 21
> end(gr1)
[1] 20 20 20 20 20 20
> width(gr1)
[1] 5 4 3 2 1 0
> strand(gr1)
factor-Rle of length 6 with 6 runs
  Lengths: 1 1 1 1 1 1
  Values  : + - * + - *
Levels(3): + - *
> strand(gr1) <- c("-", "-", "+")
> strand(gr1)
factor-Rle of length 6 with 4 runs
  Lengths: 2 1 2 1
  Values  : - + - +
Levels(3): + - *
```

GRanges accessors: `names()`

```
> names(gr1) <- LETTERS[1:6]
> gr1
GRanges object with 6 ranges and 0 metadata columns:
      seqnames      ranges strand
   <Rle> <IRanges> <Rle>
A      ch1  [16, 20]     -
B      ch1  [17, 20]     -
C      chMT [18, 20]     +
D      chMT [19, 20]     -
E      chMT [20, 20]     -
F      chMT [21, 20]     +
-----
seqinfo: 2 sequences from an unspecified genome; no seqlengths
> names(gr1)
[1] "A" "B" "C" "D" "E" "F"
```

GRanges accessors: `mcols()`

Like with most *Bioconductor* vector-like objects, *metadata columns* can be added to a GRanges object:

```
> mcols(gr1) <- DataFrame(score=11:16, GC=seq(1, 0, length=6))
> gr1
```

GRanges object with 6 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
E	chMT	[20, 20]	-	15	0.2
F	chMT	[21, 20]	+	16	0

seqinfo: 2 sequences from an unspecified genome; no seqlengths

```
> mcols(gr1)
```

DataFrame with 6 rows and 2 columns

	score	GC
	<integer>	<numeric>
1	11	1.0
2	12	0.8
3	13	0.6
4	14	0.4
5	15	0.2
6	16	0.0

GRanges accessors: `seqinfo()`, `seqlevels()`, `seqlengths()`

```
> seqinfo(gr1)
```

Seqinfo object with 2 sequences from an unspecified genome; no seqlengths:

seqnames	seqlengths	isCircular	genome
ch1	NA	NA	<NA>
chMT	NA	NA	<NA>

```
> seqlevels(gr1)
```

```
[1] "ch1" "chMT"
```

```
> seqlengths(gr1)
```

ch1	chMT
NA	NA

```
> seqlengths(gr1) <- c(50000, 800)
```

```
> seqlengths(gr1)
```

ch1	chMT
50000	800

Vector operations on GRanges objects

What we call *vector operations* are operations that work on any ordinary vector:

- ▶ `length()`, `names()`
- ▶ Single-bracket subsetting: `[`
- ▶ Combining: `c()`
- ▶ `split()`, `relist()`
- ▶ Comparing: `==`, `!=`, `match()`, `%in%`, `duplicated()`, `unique()`
- ▶ Ordering: `<=`, `>=`, `<`, `>`, `order()`, `sort()`, `rank()`

GRanges objects support all these *vector operations* ==> They're considered *vector-like* objects.

Vector operations on GRanges objects: Single-bracket subsetting

```
> gr1[c("F", "A")]
```

```
GRanges object with 2 ranges and 2 metadata columns:
```

seqnames	ranges	strand	score	GC
<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
F	chMT [21, 20]	+	16	0
A	ch1 [16, 20]	-	11	1

```
-----
```

```
seqinfo: 2 sequences from an unspecified genome
```

```
> gr1[strand(gr1) == "+"]
```

```
GRanges object with 2 ranges and 2 metadata columns:
```

seqnames	ranges	strand	score	GC
<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
C	chMT [18, 20]	+	13	0.6
F	chMT [21, 20]	+	16	0

```
-----
```

```
seqinfo: 2 sequences from an unspecified genome
```

Vector operations on GRanges objects: Single-bracket subsetting

```
> gr1 <- gr1[-5]
> gr1
```

GRanges object with 5 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[21, 20]	+	16	0

seqinfo: 2 sequences from an unspecified genome

Vector operations on GRanges objects: Combining

```
> gr2 <- GRanges(seqnames="ch2",
+               ranges=IRanges(start=c(2:1,2), width=6),
+               score=15:13,
+               GC=seq(0, 0.4, length=3))
> gr12 <- c(gr1, gr2)
> gr12
```

GRanges object with 8 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
.
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	13	0.4

seqinfo: 3 sequences from an unspecified genome

Vector operations on GRanges objects: Comparing

```
> gr12[length(gr12)] == gr12
[1] FALSE FALSE FALSE FALSE FALSE TRUE FALSE TRUE
> duplicated(gr12)
[1] FALSE FALSE FALSE FALSE FALSE FALSE FALSE TRUE
> unique(gr12)
```

GRanges object with 7 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[21, 20]	+	16	0
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2

seqinfo: 3 sequences from an unspecified genome

Vector operations on GRanges objects: Ordering

```
> sort(gr12)
```

GRanges object with 8 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
.
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	15	0
	ch2	[2, 7]	*	13	0.4

seqinfo: 3 sequences from an unspecified genome

Splitting a GRanges object

```
> split(gr12, seqnames(gr12))
```

```
GRangesList object of length 3:
```

```
$ch1
```

```
GRanges object with 2 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8

```
$chMT
```

```
GRanges object with 3 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[21, 20]	+	16	0

```
$ch2
```

```
GRanges object with 3 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	13	0.4

```
-----
```

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


Exercise 1

- a. Load the *GenomicRanges* package.
- b. Open the man page for the `GRanges` class and run the examples in it.
- c. Extract from `GRanges` object `gr` the elements (i.e. ranges) with a score between 4 and 8.
- d. Split `gr` by strand.

An overview of *range*-based operations

Intra range transformations

`shift()`, `narrow()`, `resize()`, `flank()`

Inter range transformations

`range()`, `reduce()`, `gaps()`, `disjoin()`

Range-based set operations

`union()`, `intersect()`, `setdiff()`,
`punion()`, `pintersect()`, `psetdiff()`,
`pgap()`

Coverage and slicing

`coverage()`, `slice()`

Finding/counting overlapping ranges

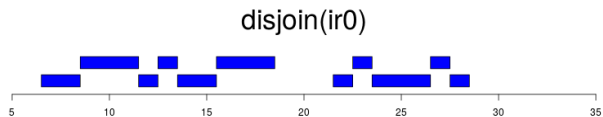
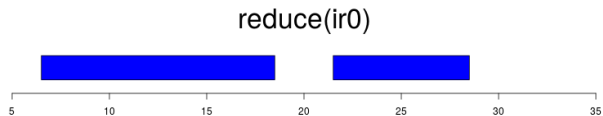
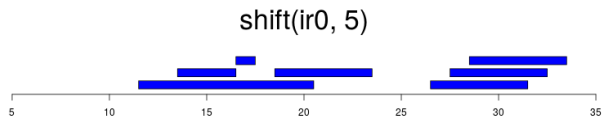
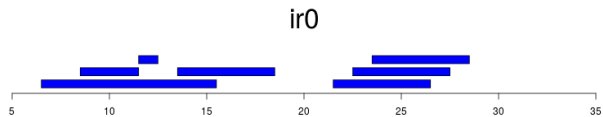
`findOverlaps()`, `countOverlaps()`

Finding the nearest range neighbor

`nearest()`, `precede()`, `follow()`

and more...

Examples of some common *range-based* operations



Range-based operations on GRanges objects

```
> gr2
```

```
GRanges object with 3 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	ch2	[2, 7]	*	15	0
[2]	ch2	[1, 6]	*	14	0.2
[3]	ch2	[2, 7]	*	13	0.4

```
-----  
seqinfo: 1 sequence from an unspecified genome; no seqlengths
```

```
> shift(gr2, 50)
```

```
GRanges object with 3 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
[1]	ch2	[52, 57]	*	15	0
[2]	ch2	[51, 56]	*	14	0.2
[3]	ch2	[52, 57]	*	13	0.4

```
-----  
seqinfo: 1 sequence from an unspecified genome; no seqlengths
```

Range-based operations on GRanges objects (continued)

```
> gr1
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[21, 20]	+	16	0

```
-----  
seqinfo: 2 sequences from an unspecified genome
```

```
> resize(gr1, 12)
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[9, 20]	-	11	1
B	ch1	[9, 20]	-	12	0.8
C	chMT	[18, 29]	+	13	0.6
D	chMT	[9, 20]	-	14	0.4
F	chMT	[21, 32]	+	16	0

```
-----  
seqinfo: 2 sequences from an unspecified genome
```

Range-based operations on GRanges objects (continued)

```
> gr1
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[16, 20]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 20]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[21, 20]	+	16	0

```
-----  
seqinfo: 2 sequences from an unspecified genome
```

```
> flank(gr1, 3)
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[21, 23]	-	11	1
B	ch1	[21, 23]	-	12	0.8
C	chMT	[15, 17]	+	13	0.6
D	chMT	[21, 23]	-	14	0.4
F	chMT	[18, 20]	+	16	0

```
-----  
seqinfo: 2 sequences from an unspecified genome
```

Range-based operations on GRanges objects (continued)

```
> gr3 <- shift(gr1, c(35000, rep(0, 3), 100))
> width(gr3)[c(3,5)] <- 117
> gr3
```

GRanges object with 5 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

seqinfo: 2 sequences from an unspecified genome

```
> range(gr3)
```

GRanges object with 3 ranges and 0 metadata columns:

	seqnames	ranges	strand
	<Rle>	<IRanges>	<Rle>
[1]	ch1	[17, 35020]	-
[2]	chMT	[18, 237]	+
[3]	chMT	[19, 20]	-

seqinfo: 2 sequences from an unspecified genome

Range-based operations on GRanges objects (continued)

```
> gr3
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

```
-----  
seqinfo: 2 sequences from an unspecified genome
```

```
> reduce(gr3)
```

```
GRanges object with 4 ranges and 0 metadata columns:
```

	seqnames	ranges	strand
	<Rle>	<IRanges>	<Rle>
[1]	ch1	[17, 20]	-
[2]	ch1	[35016, 35020]	-
[3]	chMT	[18, 237]	+
[4]	chMT	[19, 20]	-

```
-----  
seqinfo: 2 sequences from an unspecified genome
```


Range-based operations on GRanges objects (continued)

```
> gr3

GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A     ch1 [35016, 35020]   - |         11         1
B     ch1 [  17,    20]   - |         12        0.8
C     chMT [  18,   134]  + |         13        0.6
D     chMT [  19,    20]   - |         14        0.4
F     chMT [ 121,   237]  + |         16         0
-----
seqinfo: 2 sequences from an unspecified genome

> gaps(gr3)

GRanges object with 10 ranges and 0 metadata columns:
  seqnames      ranges strand
   <Rle>        <IRanges> <Rle>
[1]     ch1 [  1, 50000]   +
[2]     ch1 [  1,    16]   -
[3]     ch1 [21, 35015]   -
...     ...      ...     ...
[8]    chMT [  1,    18]   -
[9]    chMT [21,    80]   -
[10]   chMT [  1,    80]   *
-----
seqinfo: 2 sequences from an unspecified genome
```

Range-based operations on GRanges objects (continued)

```
> gr3
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A      ch1 [35016, 35020] - |         11         1
B      ch1 [  17,    20] - |         12        0.8
C     chMT [  18,   134] + |         13        0.6
D     chMT [  19,    20] - |         14        0.4
F     chMT [ 121,   237] + |         16         0
-----
seqinfo: 2 sequences from an unspecified genome

> disjoint(gr3)
GRanges object with 6 ranges and 0 metadata columns:
  seqnames      ranges strand
   <Rle>        <IRanges> <Rle>
[1]   ch1 [  17,    20] -
[2]   ch1 [35016, 35020] -
[3]  chMT [  18,   120] +
[4]  chMT [ 121,   134] +
[5]  chMT [ 135,   237] +
[6]  chMT [  19,    20] -
-----
seqinfo: 2 sequences from an unspecified genome
```

Exercise 2

Using `GRanges` object `gr` created at Exercise 1:

- a. Shift the ranges in `gr` by 1000 positions to the right.
- b. What method is called when doing `shift()` on a `GRanges` object? Find the man page for this method.

Coverage

```
> cvg12 <- coverage(gr12)
> cvg12

RleList of length 3
$ch1
integer-Rle of length 50000 with 4 runs
  Lengths: 15 1 4 49980
  Values : 0 1 2 0

$chMT
integer-Rle of length 800 with 4 runs
  Lengths: 17 1 2 780
  Values : 0 1 2 0

$ch2
integer-Rle of length 7 with 3 runs
  Lengths: 1 5 1
  Values : 1 3 2
```

Coverage (continued)

```
> mean(cvg12)
      ch1      chMT      ch2
0.000180 0.006250 2.571429
```

```
> max(cvg12)
 ch1 chMT ch2
  2   2   3
```

Slicing the coverage

```
> sl12 <- slice(cvg12, lower=1)
> sl12

RleViewsList of length 3
names(3): ch1 chMT ch2

> elementNROWS(sl12)

  ch1 chMT  ch2
  1   1   1

> sl12$chMT

Views on a 800-length Rle subject

views:
  start end width
[1]   18  20     3 [1 2 2]

> mean(sl12$chMT)

[1] 1.666667

> max(sl12$chMT)

[1] 2
```

findOverlaps()

Load aligned reads from a BAM file:

```
> library(pasillaBamSubset)
> untreated1_chr4()

[1] "/home/biocbuild/bbs-3.5-bioc/R/library/pasillaBamSubset/extdata/untreated1_chr4.bam"

> library(GenomicAlignments)
> reads <- readGAlignments(untreated1_chr4())
```

and store them in a GRanges object:

```
> reads <- as(reads, "GRanges")
> reads[1:4]

GRanges object with 4 ranges and 0 metadata columns:
      seqnames      ranges strand
      <Rle>      <IRanges> <Rle>
 [1]   chr4 [892, 966]     -
 [2]   chr4 [919, 993]     -
 [3]   chr4 [924, 998]     +
 [4]   chr4 [936, 1010]    +
-----
seqinfo: 8 sequences from an unspecified genome
```

findOverlaps() (continued)

Load the gene ranges from a *TxDb* package:

```
> library(TxDb.Dmelanogaster.UCSC.dm3.ensGene)
> txdb <- TxDb.Dmelanogaster.UCSC.dm3.ensGene
> dm3_genes <- genes(txdb)
```

and find the overlaps between the reads and the genes:

```
> hits <- findOverlaps(reads, dm3_genes)
> head(hits)

Hits object with 6 hits and 0 metadata columns:
      queryHits subjectHits
      <integer>  <integer>
 [1]      6296      11499
 [2]      6304      11499
 [3]      6305      11499
 [4]      6310      11499
 [5]      6311      11499
 [6]      6312      11499
-----
queryLength: 204355 / subjectLength: 15682
```


Exercise 3

- a. Recreate `GRanges` objects `reads` and `dm3_genes` from previous slides.
- b. What method is called when calling `findOverlaps()` on them? Open the man page for this method.
- c. Find the overlaps between the 2 objects but this time the strand should be ignored.

Exercise 4

In this exercise we want to get the exon sequences for the dm3 genome.

- a. Extract the exon ranges from `txdb`.
- b. Load the `BSgenome.Dmelanogaster.UCSC.dm3` package.
- c. Use `getSeq()` to extract the exon sequences from the `BSgenome` object in `BSgenome.Dmelanogaster.UCSC.dm3`.

The GRangesList class is a container for...

storing a list of *compatible* GRanges objects.

compatible means:

- ▶ they are relative to the same genome,
- ▶ AND they have the same metadata columns (accessible with the `mcols()` accessor).

The GRangesList() constructor

```
> gr1 <- GRangesList(gr3, gr2)
> gr1
```

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	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

```
[[2]]
```

GRanges object with 3 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	13	0.4

seqinfo: 3 sequences from an unspecified genome

GRangesList accessors

```
> length(grl)
```

```
[1] 2
```

```
> seqnames(grl)
```

```
RleList of length 2
```

```
[[1]]
```

```
factor-Rle of length 5 with 2 runs
```

```
  Lengths:  2  3
```

```
  Values :  ch1 chMT
```

```
Levels(3): ch1 chMT ch2
```

```
[[2]]
```

```
factor-Rle of length 3 with 1 run
```

```
  Lengths:  3
```

```
  Values :  ch2
```

```
Levels(3): ch1 chMT ch2
```

```
> strand(grl)
```

```
RleList of length 2
```

```
[[1]]
```

```
factor-Rle of length 5 with 4 runs
```

```
  Lengths: 2 1 1 1
```

```
  Values : - + - +
```

```
Levels(3): + - *
```

```
[[2]]
```

```
factor-Rle of length 3 with 1 run
```

```
  Lengths: 3
```

```
  Values : *
```

```
Levels(3): + - *
```

GRangesList accessors (continued)

```
> ranges(grl)
IRangesList of length 2
[[1]]
IRanges object with 5 ranges and 0 metadata columns
  start      end      width
  <integer> <integer> <integer>
A      35016    35020         5
B         17         20         4
C         18        134        117
D         19         20         2
F         121        237        117

[[2]]
IRanges object with 3 ranges and 0 metadata columns
  start      end      width
  <integer> <integer> <integer>
      2         7         6
      1         6         6
      2         7         6
```

```
> start(grl)
IntegerList of length 2
[[1]] 35016 17 18 19 121
[[2]] 2 1 2

> end(grl)
IntegerList of length 2
[[1]] 35020 20 134 20 237
[[2]] 7 6 7

> width(grl)
IntegerList of length 2
[[1]] 5 4 117 2 117
[[2]] 6 6 6
```

GRangesList accessors (continued)

```
> names(grl) <- c("TX1", "TX2")
> grl
```

GRangesList object of length 2:

\$TX1

GRanges object with 5 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

\$TX2

GRanges object with 3 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	13	0.4

seqinfo: 3 sequences from an unspecified genome

GRangesList accessors (continued)

```
> mcols(grl)$geneid <- c("GENE1", "GENE2")
> mcols(grl)

DataFrame with 2 rows and 1 column
  geneid
<character>
1      GENE1
2      GENE2

> grl

GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |   score   GC
  <Rle>         <IRanges> <Rle> | <integer> <numeric>
A      ch1 [35016, 35020]   - |      11     1
B      ch1 [ 17, 20]       - |      12    0.8
C      chMT [ 18, 134]     + |      13    0.6
D      chMT [ 19, 20]     - |      14    0.4
F      chMT [ 121, 237]   + |      16     0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
      ch2 [2, 7]   * | 15 0
      ch2 [1, 6]  * | 14 0.2
      ch2 [2, 7]  * | 13 0.4

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


GRangesList accessors (continued)

```
> seqinfo(grl)
```

Seqinfo object with 3 sequences from an unspecified genome:

seqnames	seqlengths	isCircular	genome
ch1	50000	NA	<NA>
chMT	800	NA	<NA>
ch2	NA	NA	<NA>

Vector operations on GRangesList objects

Only the following *vector operations* are supported on GRangesList objects:

- ▶ `length()`, `names()`
- ▶ Single-bracket subsetting: `[`
- ▶ Combining: `c()`

Vector operations on GRangesList objects

```
> grl[c("TX2", "TX1")]
GRangesList object of length 2:
$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
   ch2     [2, 7]   * |      15       0
   ch2     [1, 6]   * |      14      0.2
   ch2     [2, 7]   * |      13      0.4

$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   A      ch1 [35016, 35020] - |      11       1
   B      ch1 [ 17, 20]     - |      12      0.8
   C     chMT [ 18, 134]    + |      13      0.6
   D     chMT [ 19, 20]     - |      14      0.4
   F     chMT [ 121, 237]   + |      16       0

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

Vector operations on GRangesList objects (continued)

```
> c(gr1, GRangesList(gr3))
```

```
GRangesList object of length 3:
```

```
$TX1
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

```
$TX2
```

```
GRanges object with 3 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
	ch2	[2, 7]	*	15	0
	ch2	[1, 6]	*	14	0.2
	ch2	[2, 7]	*	13	0.4

```
[[3]]
```

```
GRanges object with 5 ranges and 2 metadata columns:
```

	seqnames	ranges	strand	score	GC
A	ch1	[35016, 35020]	-	11	1
B	ch1	[17, 20]	-	12	0.8
C	chMT	[18, 134]	+	13	0.6
D	chMT	[19, 20]	-	14	0.4
F	chMT	[121, 237]	+	16	0

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

List operations on GRangesList objects

What we call *list operations* are operations that work on an ordinary list:

- ▶ Double-bracket subsetting: `[[`
- ▶ `elementNROWS()`, `unlist()`
- ▶ `lapply()`, `sapply()`, `endoapply()`
- ▶ `mendoapply()` (not covered in this presentation)

`GRangesList` objects support all these *list operations* ==> They're considered *list-like* objects.

elementNROWS() and unlist()

```
> gr1[[2]]  
  
GRanges object with 3 ranges and 2 metadata columns:  
  seqnames      ranges strand |      score      GC  
  <Rle> <IRanges> <Rle> | <integer> <numeric>  
    ch2      [2, 7]   * |         15        0  
    ch2      [1, 6]   * |         14       0.2  
    ch2      [2, 7]   * |         13       0.4  
-----  
seqinfo: 3 sequences from an unspecified genome  
  
> elementNROWS(gr1)  
  
TX1 TX2  
  5   3  
  
> unlisted <- unlist(gr1, use.names=FALSE) # same as c(gr1[[1]], gr1[[2]])  
> unlisted  
  
GRanges object with 8 ranges and 2 metadata columns:  
  seqnames      ranges strand |      score      GC  
  <Rle> <IRanges> <Rle> | <integer> <numeric>  
A     ch1 [35016, 35020] - |         11        1  
B     ch1 [  17,   20] - |         12       0.8  
C     chMT [  18,   134] + |         13       0.6  
  ...     ...     ...     |         ...     ...  
     ch2      [2, 7]   * |         15        0  
     ch2      [1, 6]   * |         14       0.2  
     ch2      [2, 7]   * |         13       0.4  
-----  
seqinfo: 3 sequences from an unspecified genome
```

relist()

```
> grl100 <- relist(shift(unlisted, 100), grl)
> grl100
```

GRangesList object of length 2:

\$TX1

GRanges object with 5 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	<Rle>	<IRanges>	<Rle>	<integer>	<numeric>
A	ch1	[35116, 35120]	-	11	1
B	ch1	[117, 120]	-	12	0.8
C	chMT	[118, 234]	+	13	0.6
D	chMT	[119, 120]	-	14	0.4
F	chMT	[221, 337]	+	16	0

\$TX2

GRanges object with 3 ranges and 2 metadata columns:

	seqnames	ranges	strand	score	GC
	ch2	[102, 107]	*	15	0
	ch2	[101, 106]	*	14	0.2
	ch2	[102, 107]	*	13	0.4

seqinfo: 3 sequences from an unspecified genome

endoapply()

```
> grl100b <- endoapply(grl, shift, 100)
> grl100b

GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A     ch1 [35116, 35120]   - |         11         1
B     ch1 [ 117,  120]   - |         12        0.8
C     chMT [ 118,  234]   + |         13        0.6
D     chMT [ 119,  120]   - |         14        0.4
F     chMT [ 221,  337]   + |         16         0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
ch2 [102, 107]   * |         15         0
ch2 [101, 106]   * |         14        0.2
ch2 [102, 107]   * |         13        0.4

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

> mcols(grl100)

DataFrame with 2 rows and 0 columns

> mcols(grl100b)

DataFrame with 2 rows and 1 column
  geneid
<character>
1     GENE1
2     GENE2
```


Range-based operations on GRangesList objects

```
> gr1
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A    ch1 [35016, 35020] - |      11      1
B    ch1 [ 17, 20] - |      12     0.8
C    chMT [ 18, 134] + |      13     0.6
D    chMT [ 19, 20] - |      14     0.4
F    chMT [ 121, 237] + |      16      0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
ch2 [2, 7] * | 15 0
ch2 [1, 6] * | 14 0.2
ch2 [2, 7] * | 13 0.4

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

```
> shift(gr1, 100)
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A    ch1 [35116, 35120] - |      11      1
B    ch1 [ 117, 120] - |      12     0.8
C    chMT [ 118, 234] + |      13     0.6
D    chMT [ 119, 120] - |      14     0.4
F    chMT [ 221, 337] + |      16      0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
ch2 [102, 107] * | 15 0
ch2 [101, 106] * | 14 0.2
ch2 [102, 107] * | 13 0.4

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

`shift(gr1, 100)` is equivalent to `endoapply(gr1, shift, 100)`

Range-based operations on GRangesList objects (continued)

```
> gr1
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle>         <IRanges> <Rle> | <integer> <numeric>
A   ch1 [35016, 35020]   - |         11         1
B   ch1 [  17,   20]   - |         12         0.8
C   chMT [  18,  134]   + |         13         0.6
D   chMT [  19,   20]   - |         14         0.4
F   chMT [ 121,  237]   + |         16         0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
  ch2 [2, 7] * | 15 0
  ch2 [1, 6] * | 14 0.2
  ch2 [2, 7] * | 13 0.4

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

```
> flank(gr1, 10)
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle>         <IRanges> <Rle> | <integer> <numeric>
A   ch1 [35021, 35030]   - |         11         1
B   ch1 [  21,   30]   - |         12         0.8
C   chMT [  8,   17]   + |         13         0.6
D   chMT [ 21,   30]   - |         14         0.4
F   chMT [ 111,  120]   + |         16         0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
  ch2 [-8, 1] * | 15 0
  ch2 [-9, 0] * | 14 0.2
  ch2 [-8, 1] * | 13 0.4

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

`flank(gr1, 10)` is equivalent to `endoapply(gr1, flank, 10)`

Range-based operations on GRangesList objects (continued)

```
> gr1
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>      <IRanges> <Rle> | <integer> <numeric>
A    ch1 [35016, 35020]  - |         11         1
B    ch1 [  17,    20]  - |         12         0.8
C    chMT [  18,   134]  + |         13         0.6
D    chMT [  19,    20]  - |         14         0.4
F    chMT [ 121,   237]  + |         16         0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
ch2 [2, 7] * | 15 0
ch2 [1, 6] * | 14 0.2
ch2 [2, 7] * | 13 0.4

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

```
> range(gr1)
GRangesList object of length 2:
$TX1
GRanges object with 3 ranges and 0 metadata columns:
  seqnames      ranges strand
   <Rle>      <IRanges> <Rle>
[1]    ch1 [17, 35020]  -
[2]   chMT [18,  237]  +
[3]   chMT [19,   20]  -

$TX2
GRanges object with 1 range and 0 metadata columns:
  seqnames ranges strand
   <Rle> <IRanges> <Rle>
[1]    ch2 [1, 7] *

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

`range(gr1)` is equivalent to `endoapply(gr1, range)`

Range-based operations on GRangesList objects (continued)

```
> grl
GRangesList object of length 2:
$TX1
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>        <IRanges> <Rle> | <integer> <numeric>
A    ch1 [35016, 35020]   - |         11         1
B    ch1 [  17,    20]   - |         12         0.8
C    chMT [  18,   134]   + |         13         0.6
D    chMT [  19,    20]   - |         14         0.4
F    chMT [ 121,   237]   + |         16         0

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames ranges strand | score GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
ch2 [2, 7] * | 15 0
ch2 [1, 6] * | 14 0.2
ch2 [2, 7] * | 13 0.4

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

```
> reduce(grl)
GRangesList object of length 2:
$TX1
GRanges object with 4 ranges and 0 metadata columns:
  seqnames      ranges strand
   <Rle>        <IRanges> <Rle>
[1]    ch1 [  17,    20]   -
[2]    ch1 [35016, 35020]   -
[3]    chMT [  18,   237]   +
[4]    chMT [  19,    20]   -

$TX2
GRanges object with 1 range and 0 metadata columns:
  seqnames ranges strand
   <Rle>   <IRanges> <Rle>
[1]    ch2 [2, 7] *

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

`reduce(grl)` is equivalent to `endoapply(grl, reduce)`

Range-based operations on GRangesList objects (continued)

```
> gr12
GRangesList object of length 2:
$TX1
GRanges object with 1 range and 2 metadata columns:
  seqnames   ranges strand |   score   GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  C       chMT [18, 134]   + |      13    0.6
$TX2
GRanges object with 1 range and 2 metadata columns:
  seqnames ranges strand | score GC
  ch2 [2, 7]   * |   15  0
-----
seqinfo: 3 sequences from an unspecified genome

> gr13
GRangesList object of length 2:
[[1]]
GRanges object with 1 range and 2 metadata columns:
  seqnames   ranges strand |   score   GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  chMT [22, 130]   + |      13    0.6
[[2]]
GRanges object with 1 range and 2 metadata columns:
  seqnames ranges strand | score GC
  ch2 [2, 7]   * |   15  0
-----
seqinfo: 3 sequences from an unspecified genome
```

```
> setdiff(gr12, gr13)
GRangesList object of length 2:
$TX1
GRanges object with 2 ranges and 0 metadata columns:
  seqnames   ranges strand
  <Rle> <IRanges> <Rle>
  [1]   chMT [ 18, 21]   +
  [2]   chMT [131, 134]   +
$TX2
GRanges object with 0 ranges and 0 metadata columns:
  seqnames ranges strand
-----
seqinfo: 3 sequences from an unspecified genome
```

`setdiff(gr12, gr1)` is equivalent to `mendoapply(setdiff, gr12, gr1)`

Other resources

- ▶ Great slides from Michael on ranges sequences and alignments:
http://bioconductor.org/help/course-materials/2014/CSAMA2014/2_Tuesday/lectures/Ranges_Sequences_and_Alignments-Lawrence.pdf
- ▶ Vignettes in the *GenomicRanges* package (`browseVignettes("GenomicRanges")`).
- ▶ `GRanges` and `GRangesList` man pages in the *GenomicRanges* package.
- ▶ Vignettes and `GAlignments` man page in the *GenomicAlignments* package.
- ▶ *Bioconductor* support site: <http://support.bioconductor.org/>
- ▶ The *genomic ranges* paper: Michael Lawrence, Wolfgang Huber, Hervé Pagès, Patrick Aboyoun, Marc Carlson, Robert Gentleman, Martin T. Morgan, Vincent J. Carey. Software for Computing and Annotating Genomic Ranges. *PLOS Computational Biology*, 4(3), 2013.