

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	-
[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        -
  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	1.0
B	ch1	17-20	-	12	0.8
C	chMT	18-20	+	13	0.6
D	chMT	19-20	-	14	0.4
E	chMT	20	-	15	0.2
F	chMT	21-20	+	16	0.0

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

```
> mcols(gr1)
```

DataFrame with 6 rows and 2 columns

	score	GC
	<integer>	<numeric>
A	11	1.0
B	12	0.8
C	13	0.6
D	14	0.4
E	15	0.2
F	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         0.0  
-----  
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      1.0
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      0.0
-----
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	1.0
B	ch1	17-20	-	12	0.8
C	chMT	18-20	+	13	0.6
.
	ch2	2-7	*	15	0.0
	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	1.0
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	0.0
	ch2	2-7	*	15	0.0
	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	1.0
B	ch1	17-20	-	12	0.8
C	chMT	18-20	+	13	0.6
.
	ch2	1-6	*	14	0.2
	ch2	2-7	*	15	0.0
	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      1.0
B     ch1      17-20    - |         12      0.8
-----
seqinfo: 3 sequences from an unspecified genome

$chMT
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
C     chMT      18-20     + |         13      0.6
D     chMT      19-20     - |         14      0.4
F     chMT      21-20     + |         16      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$ch2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
   ch2      2-7     * |         15      0.0
   ch2      1-6     * |         14      0.2
   ch2      2-7     * |         13      0.4
-----
```


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

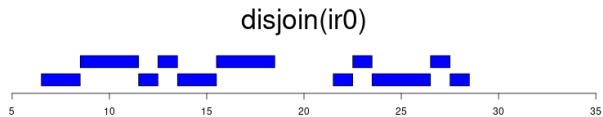
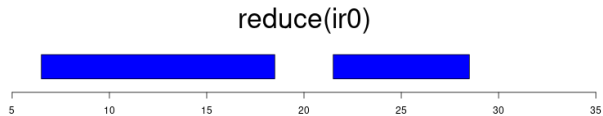
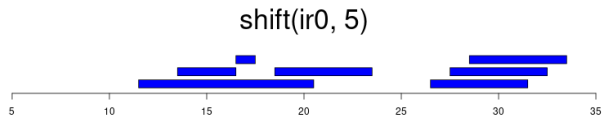
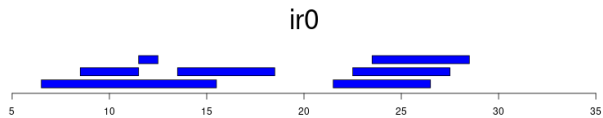
`findOverlaps()`, `countOverlaps()`

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     0.0
 [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     0.0
 [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	1.0
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	0.0

```
-----
```

```
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	1.0
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	0.0

```
-----
```

```
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	1.0
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	0.0

```
-----
```

```
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	1.0
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	0.0

```
-----
```

```
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     1.0
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     0.0
-----
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	1.0
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	0.0

```
-----
```

```
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      1.0
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      0.0
-----
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  21-800   -
[10]     chMT  1-800   *
```

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      1.0
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      0.0
-----
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

```
> s112 <- slice(cvg12, lower=1)
> s112
RleViewsList object of length 3:
$ch1
Views on a 50000-length Rle subject

views:
  start end width
[1]   16  20    5 [1 2 2 2 2]

$chMT
Views on a 800-length Rle subject

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

$ch2
Views on a 7-length Rle subject

views:
  start end width
[1]    1   7    7 [1 3 3 3 3 3 2]
> elementNROWS(s112)
  ch1 chMT ch2
  1   1   1
> s112$chMT
Views on a 800-length Rle subject
```

findOverlaps()

Load aligned reads from a BAM file:

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

[1] "/home/biocbuild/bbs-3.17-bioc/R/site-library/pasillaBamSubset/extdata/untreated1_chr4"

> 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     1.0
B     ch1   17-20     - |         12     0.8
C    chMT  18-134     + |         13     0.6
D    chMT  19-20     - |         14     0.4
F    chMT 221-237     + |         16     0.0
-----
seqinfo: 3 sequences from an unspecified genome

[[2]]
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  ch2      2-7     * |         15     0.0
  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 object of length 2:
[[1]]
IRanges object with 5 ranges and 0 metadata
  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
  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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
   ch2      2-7    * |         15     0.0
   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>
TX1      GENE1
TX2      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      1.0
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      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
ch2      2-7 * |      15      0.0
ch2      1-6 * |      14      0.2
ch2      2-7 * |      13      0.4
-----
seqinfo: 3 sequences from an unspecified genome
```


GRangesList accessors (continued)

```
> seqinfo(gr1)
```

```
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      0.0
   ch2      1-6     * |      14      0.2
   ch2      2-7     * |      13      0.4
-----
seqinfo: 3 sequences from an unspecified genome

$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      1.0
   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      0.0
-----
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      1.0
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      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
      ch2      2-7     * |         15      0.0
      ch2      1-6     * |         14      0.2
      ch2      2-7     * |         13      0.4
-----
seqinfo: 3 sequences from an unspecified genome

[[3]]
GRanges object with 5 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
A      ch1 35016-35020   - |         11      1.0
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      0.0
-----
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()

```
> grl[[2]]
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle> <IRanges> <Rle> | <integer> <numeric>
   ch2     2-7     * |      15      0.0
   ch2     1-6     * |      14      0.2
   ch2     2-7     * |      13      0.4
-----
seqinfo: 3 sequences from an unspecified genome
> elementNROWS(grl)
TX1 TX2
 5   3
> unlisted <- unlist(grl, use.names=FALSE) # same as c(grl[[1]], grl[[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      1.0
  B     ch1  17-20 - |      12      0.8
  C     chMT 18-134 + |      13      0.6
  .     ...  ...  ... |      ...      ...
  ch2     2-7     * |      15      0.0
  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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  ch2   102-107   * |         15     0.0
  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      1.0
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      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>    <IRanges> <Rle> | <integer> <numeric>
ch2  102-107 * |         15      0.0
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>
TX1      GENE1
TX2      GENE2
```


Range-based operations on GRangesList objects

```
> 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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
ch2      2-7 * |         15     0.0
ch2      1-6 * |         14     0.2
ch2      2-7 * |         13     0.4
-----
seqinfo: 3 sequences from an unspecified genome
```

```
> shift(grl, 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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
ch2     102-107 * |         15     0.0
ch2     101-106 * |         14     0.2
ch2     102-107 * |         13     0.4
-----
seqinfo: 3 sequences from an unspecified genome
```

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

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      1.0
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      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
   ch2      2-7 * |         15      0.0
   ch2      1-6 * |         14      0.2
   ch2      2-7 * |         13      0.4
-----
seqinfo: 3 sequences from an unspecified genome
```

```
> flank(grl, 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      1.0
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      0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
   ch2     -8-1 * |         15      0.0
   ch2     -9-0 * |         14      0.2
   ch2     -8-1 * |         13      0.4
-----
seqinfo: 3 sequences from an unspecified genome
```

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

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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
    ch2         2-7   * |         15     0.0
    ch2         1-6   * |         14     0.2
    ch2         2-7   * |         13     0.4
-----
seqinfo: 3 sequences from an unspecified genome
```

```
> range(grl)
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     -
-----
seqinfo: 3 sequences from an unspecified genome

$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(grl)` is equivalent to `endoapply(grl, 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     1.0
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     0.0
-----
seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 3 ranges and 2 metadata columns:
  seqnames      ranges strand |      score      GC
   <Rle>   <IRanges> <Rle> | <integer> <numeric>
    ch2         2-7   * |         15     0.0
    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     -
-----
seqinfo: 3 sequences from an unspecified genome

$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
```

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

Range-based operations on GRangesList objects (continued)

```
> grl2
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
-----
  seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 1 range and 2 metadata columns:
  seqnames   ranges strand |   score   GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  ch2        2-7     * |      15     0
-----
  seqinfo: 3 sequences from an unspecified genome

> grl3
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
-----
  seqinfo: 3 sequences from an unspecified genome

[[2]]
GRanges object with 1 range and 2 metadata columns:
  seqnames   ranges strand |   score   GC
  <Rle> <IRanges> <Rle> | <integer> <numeric>
  ch2        2-7     * |      15     0
-----
  seqinfo: 3 sequences from an unspecified genome
```

```
> setdiff(grl2, grl3)
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   +
-----
  seqinfo: 3 sequences from an unspecified genome

$TX2
GRanges object with 0 ranges and 0 metadata columns:
  seqnames   ranges strand
  <Rle> <IRanges> <Rle>
-----
  seqinfo: 3 sequences from an unspecified genome
```

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.