

# A quick introduction to GRanges and GRangesList objects

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July 2015

## 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

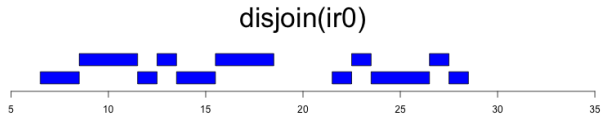
`findOverlaps()`, `countOverlaps()`

## 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

```
> sl12 <- slice(cvg12, lower=1)
> sl12
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 2]
> elementNROWS(sl12)
  ch1 chMT ch2
    1   1   1
> sl12$chMT
Views on a 800-length Rle subject
```

## findOverlaps()

Load aligned reads from a BAM file:

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

[1] "/Library/Frameworks/R.framework/Versions/4.5-x86_64/Resources/library/pasillaBamSubset"

> 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

```
> grl <- GRangesList(gr3, gr2)
> grl
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     121-237      + |         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(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        | 0.0       |
| 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()

```
> 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      0.0  
    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      1.0  
  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](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.