

Sequence manipulation and scanning

Benjamin Jean-Marie Tremblay*

4 May 2021

Abstract

Sequences stored as XStringSet objects (from the Biostrings package) can be used by several functions in the universalmotif package. These functions are demonstrated here and fall into two categories: sequence manipulation and motif scanning. Sequences can be generated, shuffled, and background frequencies of any order calculated. Scanning can be done simply to find locations of motif hits above a certain threshold, or to find instances of enriched motifs.

Contents

1	Introduction	2
2	Creating random sequences	2
3	Calculating sequence background	3
4	Clustering sequences by k-let composition	4
5	Shuffling sequences	5
6	Local shuffling	7
7	Miscellaneous string utilities	8
8	Scanning sequences for motifs	9
9	Visualizing motif hits across sequences	13
10	Enrichment analyses	15
11	Gapped motifs	15
12	Testing for motif positional preferences in sequences	17
13	Motif discovery with MEME	18
	Session info	20
	References	22

*benjamin.tremblay@uwaterloo.ca

1 Introduction

This vignette goes through generating your own sequences from a specified background model, shuffling sequences whilst maintaining a certain k -let size, and the scanning of sequences and scoring of motifs. For an introduction to sequence motifs, see the introductory vignette. For a basic overview of available motif-related functions, see the motif manipulation vignette. For a discussion on motif comparisons and P-values, see the motif comparisons and P-values vignette.

2 Creating random sequences

The **Biostrings** package offers an excellent suite of functions for dealing with biological sequences. The **universalmotif** package hopes to help extend these by providing the `create_sequences()` and `shuffle_sequences()` functions. The first of these, `create_sequences()`, generates a set of letters in random order, then passes these strings to the **Biostrings** package to generate the final **XStringSet** object. The number and length of sequences can be specified. The probabilities of individual letters can also be set.

The `freqs` option of `create_sequences()` also takes higher order backgrounds. In these cases the sequences are constructed in a Markov-style manner, where the probability of each letter is based on which letters precede it.

```
library(universalmotif)
library(Biostrings)

## Create some DNA sequences for use with an external program (default
## is DNA):

sequences.dna <- create_sequences(seqnum = 500,
                                freqs = c(A=0.3, C=0.2, G=0.2, T=0.3))

## writeXStringSet(sequences.dna, "dna.fasta")
sequences.dna
#> DNAStringSet object of length 500:
#>      width seq
#> [1] 100 ATGCTTTGTAGAGGCACGAGATTATTCTCCTTC...TCACAACAGCAACACGCAAGACAAGGCAAAAG
#> [2] 100 GGCAACATCCACAGTGCACGGTTCCTGGACATA...GAGGGTCTAGTTTTGAAGAACCATATAGATTT
#> [3] 100 TTAATGCCTTTTCTAAGCGTAACGGATGTGTCG...GCTAGCGATAGATTGTAAGCATGCAATCTTA
#> [4] 100 AATTCGATAAGCCGTTCCCAGGTAATCAAAGTG...GGCGTAGGCGTGCCACATGATTTAAACCGGTG
#> [5] 100 GCCCAATCATCGTTCTTCATTACCCCATGATCA...TTAGGGGCTGATAACCCAGTAGATACTCGAAT
#> ... ..
#> [496] 100 ATGGGCTTGTAACGAAGAACCAAGTTGCAACTA...CCACAAAAATTTAAACTCGACCCAGCAGAAAG
#> [497] 100 GTCAATGCTGTAAAGAATCGACAAACGCATCTG...GAGACGTATTGCAGACACGACCTAGACGCGGG
#> [498] 100 TGATCGGCTCTTACCTTCGTTAACCGCCAGCAC...CACATTAATCTTAGGCCCCGACGATTACGTTT
#> [499] 100 GCCATCAATTGACTTCATTACAACTTGGGTCAA...AAATTCGCAACAAAAAACAATGATCCTATTTT
#> [500] 100 ACAATTCGAGGTAACAGTTGGATCCGGATATCA...CCTACTCCTAGATTTCACTATAGGATTCAAAT

## Amino acid:

create_sequences(alphabet = "AA")
#> AAStringSet object of length 100:
#>      width seq
#> [1] 100 LHQWEGGWAPVYWWRSYMSFTEYKWHQPALTT...GMYFAPCSDTAAHAWWDQKKTWTIKSACKRIY
#> [2] 100 FQFSQGVSSMGPPRTFHREEHKWPIYGIQHSVP...ARPTCPQMYNWWVDFYNMLQRDIQGPNTTYF
#> [3] 100 HNQPPHVECLCCYHPLTDDWLEYTWGRADMTCK...WKEFEDCFHFSMWEDREYTHSFTGQMNGTNW
#> [4] 100 FFASANFYKHYARDAGWCLMYFHGGRNEAVCLS...LEMAITKHHYHFHTCHNTWQGRWKIETPDDWK
#> [5] 100 PIGHPVSVIEWYKCNSETYMLHYWKENCFGQTL...YMCKYDIVHVAEKGTGVGFFRINKQMTDSLEI
```

```
#> ... ...
#> [96] 100 YGTQSFPHAKSPWEIHVMWADFRICMPMFVDTF...YDQHMNHESDNMCDGQSKRAAREFYSWNIQRE
#> [97] 100 YFWIVIDMRVKRMYFSWMFKYEFIASYNWVIPS...IMWCASHCDVTSYHIWNWSTAVLKFFECEEEQ
#> [98] 100 CNLQSPSNWNRFTMAAAHKKRTFQLRGMQMVAG...YKFIWENMLCCDLHWGPQDSTWHWFQGLLYV
#> [99] 100 PSHISWMWARARMEPAYYSGFHVWSKCDFHLNT...RDMQPWTWSMQGHENPCGPSDYSLSCQCMVGY
#> [100] 100 HLSGNTIHQKKEMTYEAF TKPKGIWGGMEQSYT...NCCKENVGQRPWD AKIHEHYARGQGHHAHNNC

## Any set of characters can be used

create_sequences(alphabet = paste0(letters, collapse = ""))
#> BStringSet object of length 100:
#>      width seq
#> [1] 100 jryrszmvadpzotntqbesnwfczcojkoapd...fwopducnyttmtvcntqidæmogtsmlkfqa
#> [2] 100 wcyyhstgttjfgygktidvdlfrtyllgun...ktfsgmyszmbdrzrycqyhytamulyhumqf
#> [3] 100 yxzwjtjyuzzztwddihfkqobzaabvknbx...jæbwuueækdkgwsmæzrairmfdræmdix
#> [4] 100 lmkppgitdvæizdsufszæuæotrumicnh...ltzlæmleznædaqjabæcnpqwdjæmpjbms
#> [5] 100 zeapstmcmqvpuesttartdæskrulllhsg...vcmhofzeullvriuvuvugæxiuumujbdkq
#> ... ...
#> [96] 100 efapajojgnnafisqoolmdcqtctumjrtdg...rubærvrrdnæprhæzdfzegcatgkyohrti
#> [97] 100 qlkedgatgbybrlæwzæcobegchjæaetyyn...pbflæeehyæcpqkæddamipmoumriobfm
#> [98] 100 rgcmfnsfghguddæiehnztlpæedfmcmgæ...jywfryfymtdhpcqkwbeemocæædkskly
#> [99] 100 zæaqkdpsgoveelvfudjbnpædwææuvck...jetdzbjælhwiuhnzkvytægppcnhfvpæ
#> [100] 100 gbyewksnokuhozktæiszvuchmpnsvpsæ...swlyedbbkiææspopomwzthææejgyæ
```

3 Calculating sequence background

Sequence backgrounds can be retrieved for DNA and RNA sequences with `oligonucleotideFrequency()` from "Biostrings. Unfortunately, no such Biostrings function exists for other sequence alphabets. The `universalmotif` package proves `get_bkg()` to remedy this. Similarly, the `get_bkg()` function can calculate higher order backgrounds for any alphabet as well. It is recommended to use the original Biostrings for very long (e.g. billions of characters) DNA and RNA sequences whenever possible though, as it is much faster than `get_bkg()`.

```
library(universalmotif)

## Background of DNA sequences:
dna <- create_sequences()
get_bkg(dna, k = 1:2)
#> DataFrame with 20 rows and 3 columns
#>      klet      count probability
#>      <character> <numeric> <numeric>
#> 1          A      2541 0.2541000
#> 2          C      2448 0.2448000
#> 3          G      2415 0.2415000
#> 4          T      2596 0.2596000
#> 5         AA       604 0.0610101
#> ...      ...      ...      ...
#> 16         GT       608 0.0614141
#> 17         TA       634 0.0640404
#> 18         TC       628 0.0634343
#> 19         TG       613 0.0619192
#> 20         TT       697 0.0704040
```

```
## Background of non DNA/RNA sequences:
qwerty <- create_sequences("QWERTY")
get_bkg(qwerty, k = 1:2)
#> DataFrame with 42 rows and 3 columns
#>      klet      count probability
#>   <character> <numeric>   <numeric>
#> 1          E      1698      0.1698
#> 2          Q      1650      0.1650
#> 3          R      1621      0.1621
#> 4          T      1667      0.1667
#> 5          W      1695      0.1695
#> ...      ...      ...      ...
#> 38         YQ       271  0.0273737
#> 39         YR       261  0.0263636
#> 40         YT       292  0.0294949
#> 41         YW       273  0.0275758
#> 42         YY       252  0.0254545
```

4 Clustering sequences by k-let composition

One way to compare sequences is by k-let composition. The following example illustrates how one could go about doing this using only the `universalmotif` package and base graphics.

```
library(universalmotif)

## Generate three random sets of sequences:
s1 <- create_sequences(seqnum = 20,
  freqs = c(A = 0.3, C = 0.2, G = 0.2, T = 0.3))
s2 <- create_sequences(seqnum = 20,
  freqs = c(A = 0.4, C = 0.4, G = 0.1, T = 0.1))
s3 <- create_sequences(seqnum = 20,
  freqs = c(A = 0.2, C = 0.3, G = 0.3, T = 0.2))

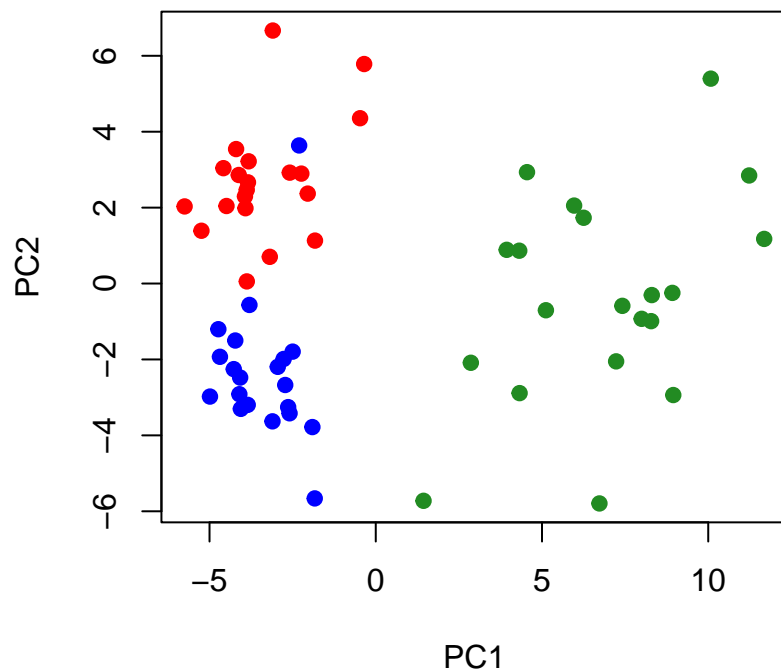
## Create a function to get properly formatted k-let counts:
get_klet_matrix <- function(seqs, k, groupName) {
  bkg <- get_bkg(seqs, k = k, merge.res = FALSE)
  bkg <- bkg[, c("sequence", "klet", "count")]
  bkg <- reshape(bkg, idvar = "sequence", timevar = "klet",
    direction = "wide")
  as.data.frame(cbind(Group = groupName, bkg))
}

## Calculate k-let content (up to you what size k you want!):
s1 <- get_klet_matrix(s1, 4, 1)
s2 <- get_klet_matrix(s2, 4, 2)
s3 <- get_klet_matrix(s3, 4, 3)

# Combine everything into a single object:
sAll <- rbind(s1, s2, s3)

## Do the PCA:
sPCA <- prcomp(sAll[, -(1:2)])
```

```
## Plot the PCA:
plot(sPCA$x, col = c("red", "forestgreen", "blue")[sAll$Group], pch = 19)
```



This example could be improved by using `tidyr::spread()` instead of `reshape()` (the former is much faster), and plotting the PCA using the `ggfortify` package to create a nicer `ggplot2` plot. Feel free to play around with different ways of plotting the data! Additionally, you could even try using t-SNE instead of PCA (such as via the `Rtsne` package).

5 Shuffling sequences

When performing *de novo* motif searches or motif enrichment analyses, it is common to do so against a set of background sequences. In order to properly identify consistent patterns or motifs in the target sequences, it is important that there be maintained a certain level of sequence composition between the target and background sequences. This reduces results which are derived purely from base differential letter frequency biases.

In order to avoid these results, typically it is desirable to use a set of background sequences which preserve a certain *k*-let size (such as dinucleotide or trinucleotide frequencies in the case of DNA sequences). Though for some cases a set of similar sequences may already be available for use as background sequences, usually background sequences are obtained by shuffling the target sequences, while preserving a desired *k*-let size. For this purpose, a commonly used tool is `uShuffle` (Jiang et al. 2008). The `universalmotif` package aims to provide its own *k*-let shuffling capabilities for use within R via `shuffle_sequences()`.

The `universalmotif` package offers three different methods for sequence shuffling: `euler`, `markov` and `linear`. The first method, `euler`, can shuffle sequences while preserving any desired *k*-let size. Furthermore 1-letter counts will always be maintained. However due to the nature of the method, the first and last letters will remain unshuffled. This method is based on the initial random Eulerian walk algorithm proposed by Altschul and Erickson (1985) and the subsequent cycle-popping algorithm detailed by Propp and Wilson (1998) for quickly and efficiently finding Eulerian walks.

The second method, `markov` can only guarantee that the approximate *k*-let frequency will be maintained, but not that the original letter counts will be preserved. The `markov` method involves determining the original *k*-let frequencies, then creating a new set of sequences which will have approximately similar *k*-let frequency.

As a result the counts for the individual letters will likely be different. Essentially, it involves a combination of determining k-let frequencies followed by `create_sequences()`. This type of pseudo-shuffling is discussed by Fitch (1983).

The third method `linear` preserves the original 1-letter counts exactly, but uses a more crude shuffling technique. In this case the sequence is split into sub-sequences every k-let (of any size), which are then re-assembled randomly. This means that while shuffling the same sequence multiple times with `method = "linear"` will result in different sequences, they will all have started from the same set of k-length sub-sequences (just re-assembled differently).

```
library(universalmotif)
library(Biostrings)
data(ArabidopsisPromoters)

## Potentially starting off with some external sequences:
# ArabidopsisPromoters <- readDNAStringSet("ArabidopsisPromoters.fasta")

euler <- shuffle_sequences(ArabidopsisPromoters, k = 2, method = "euler")
markov <- shuffle_sequences(ArabidopsisPromoters, k = 2, method = "markov")
linear <- shuffle_sequences(ArabidopsisPromoters, k = 2, method = "linear")
k1 <- shuffle_sequences(ArabidopsisPromoters, k = 1)
```

Let us compare how the methods perform:

```
o.letter <- get_bkg(ArabidopsisPromoters, 1)
e.letter <- get_bkg(euler, 1)
m.letter <- get_bkg(markov, 1)
l.letter <- get_bkg(linear, 1)

data.frame(original=o.letter$count, euler=e.letter$count,
            markov=m.letter$count, linear=l.letter$count, row.names = DNA_BASES)

#>   original euler markov linear
#> A    17384 17384  17498  17384
#> C     8081  8081   8110   8081
#> G     7583  7583   7555   7583
#> T    16952 16952  16887  16952

o.counts <- get_bkg(ArabidopsisPromoters, 2)
e.counts <- get_bkg(euler, 2)
m.counts <- get_bkg(markov, 2)
l.counts <- get_bkg(linear, 2)

data.frame(original=o.counts$count, euler=e.counts$count,
            markov=m.counts$count, linear=l.counts$count,
            row.names = get_klets(DNA_BASES, 2))

#>   original euler markov linear
#> AA     6893  6893   6243   6521
#> AC     2614  2614   2774   2677
#> AG     2592  2592   2590   2596
#> AT     5276  5276   5874   5580
#> CA     3014  3014   2726   2884
#> CC     1376  1376   1372   1384
#> CG     1051  1051   1282   1128
#> CT     2621  2621   2725   2677
#> GA     2734  2734   2570   2646
#> GC     1104  1104   1204   1169
```

```
#> GG      1176  1176   1227   1183
#> GT      2561  2561   2546   2575
#> TA      4725  4725   5939   5317
#> TC      2977  2977   2754   2843
#> TG      2759  2759   2450   2670
#> TT      6477  6477   5724   6100
```

6 Local shuffling

If you have a fairly heterogeneous sequence and wish to preserve the presence of local “patches” of differential sequence composition, you can set `window = TRUE` in the `shuffle_sequences()` function. In the following example, the sequence of interest has an AT rich first half followed by a second half with an even background. The impact on this specific sequence composition is observed after regular and local shuffling, using the per-window functionality of `get_bkg()` (via `window = TRUE`). Fine-tune the window size and overlap between windows with `window.size` and `window.overlap`.

```
library(Biostrings)
library(universalmotif)
library(ggplot2)

myseq <- DNASTringSet(paste0(
  create_sequences(seqlen = 500, freqs = c(A=0.4, T=0.4, C=0.1, G=0.1)),
  create_sequences(seqlen = 500)
))

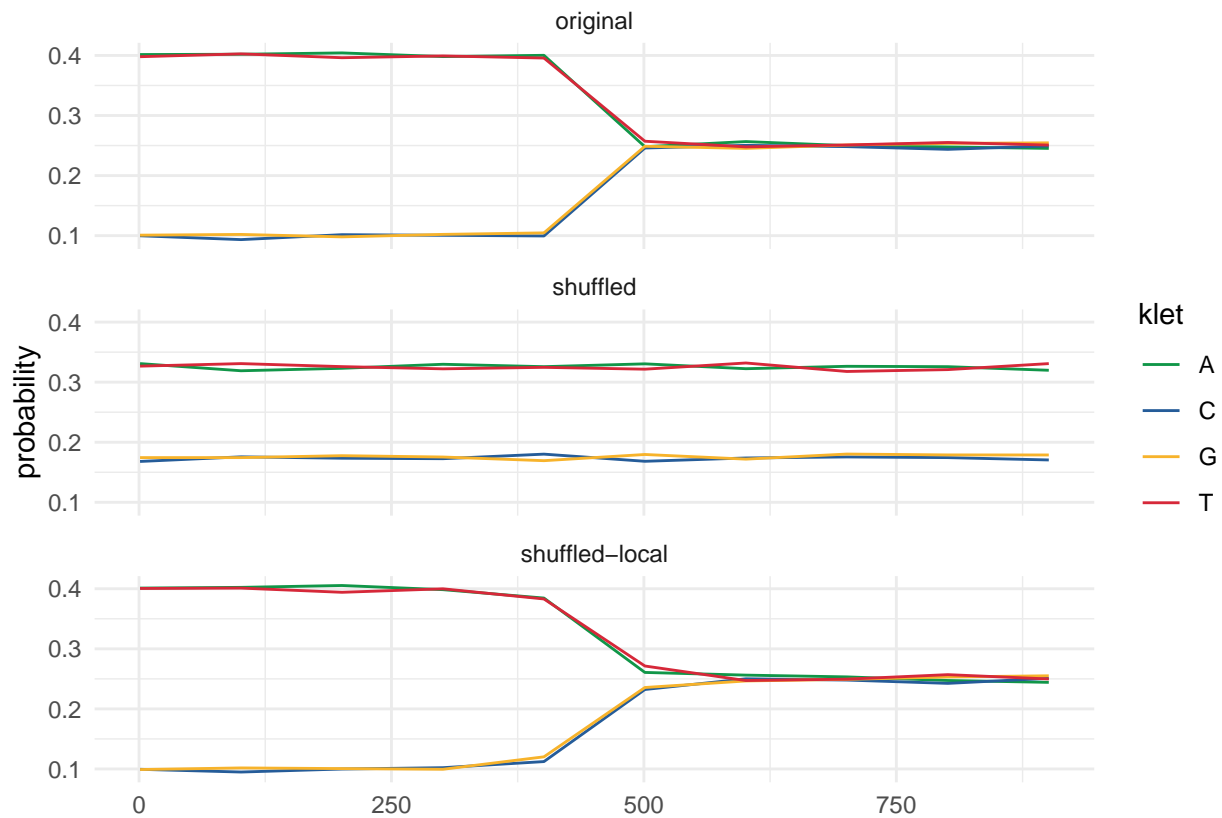
myseq_shuf <- shuffle_sequences(myseq)
myseq_shuf_local <- shuffle_sequences(myseq, window = TRUE)

myseq_bkg <- get_bkg(myseq, k = 1, window = TRUE)
myseq_shuf_bkg <- get_bkg(myseq_shuf, k = 1, window = TRUE)
myseq_shuf_local_bkg <- get_bkg(myseq_shuf_local, k = 1, window = TRUE)

myseq_bkg$group <- "original"
myseq_shuf_bkg$group <- "shuffled"
myseq_shuf_local_bkg$group <- "shuffled-local"

myseq_all <- as.data.frame(
  rbind(myseq_bkg, myseq_shuf_bkg, myseq_shuf_local_bkg)
)

ggplot(myseq_all, aes(x = start, y = probability, colour = klet)) +
  geom_line() +
  theme_minimal() +
  scale_colour_manual(values = universalmotif:::DNA_COLOURS) +
  xlab(element_blank()) +
  facet_wrap(~group, ncol = 1)
```



7 Miscellaneous string utilities

Since biological sequences are usually contained in `XStringSet` class objects, `get_bkg()` and `shuffle_sequences()` are designed to work with such objects. For cases when strings are not `XStringSet` objects, the following functions are available:

- `count_klets()`: alternative to `get_bkg()`
- `shuffle_string()`: alternative to `shuffle_sequences()`

```
library(universalmotif)

string <- "DASDSDSDASDSSA"

count_klets(string, 2)
#>   klets counts
#> 1   AA      0
#> 2   AD      0
#> 3   AS      2
#> 4   DA      1
#> 5   DD      1
#> 6   DS      3
#> 7   SA      2
#> 8   SD      3
#> 9   SS      1

shuffle_string(string, 2)
#> [1] "DSASSDSDASDDSA"
```


Finally, the `get_klets()` function can be used to get a list of all possible k-lets for any sequence alphabet:

```
library(universalmotif)

get_klets(c("A", "S", "D"), 2)
#> [1] "AA" "AS" "AD" "SA" "SS" "SD" "DA" "DS" "DD"
```

8 Scanning sequences for motifs

There are many motif-programs available with sequence scanning capabilities, such as HOMER and tools from the MEME suite. The `universalmotif` package does not aim to supplant these, but rather provide convenience functions for quickly scanning a few sequences without needing to leave the R environment. Furthermore, these functions allow for taking advantage of the higher-order (`multifreq`) motif format described here.

Two scanning-related functions are provided: `scan_sequences()` and `enrich_motifs()`. The latter simply runs `scan_sequences()` twice on a set of target and background sequences. Given a motif of length `n`, `scan_sequences()` considers every possible `n`-length subset in a sequence and scores it using the PWM format. If the match surpasses the minimum threshold, it is reported. This is case regardless of whether one is scanning with a regular motif, or using the higher-order (`multifreq`) motif format (the `multifreq` matrix is converted to a PWM).

Before scanning a set of sequences, one must first decide the minimum logodds threshold for retrieving matches. This decision is not always the same between scanning programs out in the wild, nor is it usually told to the user what the cutoff is or how it is decided. As a result, `universalmotif` aims to be as transparent as possible in this regard by allowing for complete control of the threshold. For more details on PWMs, see the introductory vignette.

One way is to set a cutoff between 0 and 1, then multiplying the highest possible PWM score to get a threshold. The `matchPWM()` function from the `Biostrings` package for example uses a default of 0.8 (shown as "80%"). This is quite arbitrary of course, and every motif will end up with a different threshold. For high information content motifs, there is really no right or wrong threshold, as they tend to have fewer non-specific positions. This means that incorrect letters in a match will be more punishing. To illustrate this, contrast the following PWMs:

```
library(universalmotif)
m1 <- create_motif("TATATATATA", nsites = 50, type = "PWM", pseudocount = 1)
m2 <- matrix(c(0.10,0.27,0.23,0.19,0.29,0.28,0.51,0.12,0.34,0.26,
               0.36,0.29,0.51,0.38,0.23,0.16,0.17,0.21,0.23,0.36,
               0.45,0.05,0.02,0.13,0.27,0.38,0.26,0.38,0.12,0.31,
               0.09,0.40,0.24,0.30,0.21,0.19,0.05,0.30,0.31,0.08),
             byrow = TRUE, nrow = 4)
m2 <- create_motif(m2, alphabet = "DNA", type = "PWM")
m1["motif"]
#>           T           A           T           A           T           A           T
#> A -5.672425  1.978626 -5.672425  1.978626 -5.672425  1.978626 -5.672425
#> C -5.672425 -5.672425 -5.672425 -5.672425 -5.672425 -5.672425 -5.672425
#> G -5.672425 -5.672425 -5.672425 -5.672425 -5.672425 -5.672425 -5.672425
#> T  1.978626 -5.672425  1.978626 -5.672425  1.978626 -5.672425  1.978626
#>           A           T           A
#> A  1.978626 -5.672425  1.978626
#> C -5.672425 -5.672425 -5.672425
#> G -5.672425 -5.672425 -5.672425
#> T -5.672425  1.978626 -5.672425
m2["motif"]
#>           S           H           C           N           N           N
```

```
#> A -1.3219281 0.09667602 -0.12029423 -0.3959287 0.2141248 0.1491434
#> C 0.5260688 0.19976951 1.02856915 0.6040713 -0.1202942 -0.6582115
#> G 0.8479969 -2.33628339 -3.64385619 -0.9434165 0.1110313 0.5897160
#> T -1.4739312 0.66371661 -0.05889369 0.2630344 -0.2515388 -0.4102840
#>      R      N      N      V
#> A 1.0430687 -1.0732490 0.4436067 0.04222824
#> C -0.5418938 -0.2658941 -0.1202942 0.51171352
#> G 0.0710831 0.5897160 -1.0588937 0.29598483
#> T -2.3074285 0.2486791 0.3103401 -1.65821148
```

In the first example, sequences which do not have a matching base in every position are punished heavily. The maximum logodds score in this case is approximately 20, and for each incorrect position the score is reduced approximately by 5.7. This means that a threshold of zero would allow for at most three mismatches. At this point, it is up to you how many mismatches you would deem appropriate.

This thinking becomes impossible for the second example. In this case, mismatches are much less punishing, to the point that one could ask: what even constitutes a mismatch? The answer to this question is much more difficult in such cases. An alternative to manually deciding upon a threshold is to instead start with maximum P-value one would consider appropriate for a match. If, say, we want matches with a P-value of at most 0.001, then we can use `motif_pvalue()` to calculate the appropriate threshold (see the comparisons and P-values vignette for details on motif P-values).

```
motif_pvalue(m2, pvalue = 0.001)
#> [1] 4.8583
```

Furthermore, the `scan_sequences()` function offers the ability to scan using the `multifreq` slot, if available. This allows to take into account inter-positional dependencies, and get matches which more faithfully represent the original sequences from which the motif originated.

```
library(universalmotif)
library(Biostrings)
data(ArabidopsisPromoters)

## A 2-letter example:

motif.k2 <- create_motif("CWWWCC", nsites = 6)
sequences.k2 <- DNASTringSet(rep(c("CAAAACC", "CTTTTCC"), 3))
motif.k2 <- add_multifreq(motif.k2, sequences.k2)
```

Regular scanning:

```
scan_sequences(motif.k2, ArabidopsisPromoters, RC = TRUE,
               threshold = 0.9, threshold.type = "logodds")
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
#> DataFrame with 94 rows and 12 columns
#>      motif motif.i sequence start stop score match
#>      <character> <integer> <character> <integer> <integer> <numeric> <character>
#> 1 motif 1 AT4G28150 621 627 9.08 CTAAACC
#> 2 motif 1 AT1G19380 139 145 9.08 CTTATCC
#> 3 motif 1 AT1G19380 204 210 9.08 CTAAACC
#> 4 motif 1 AT1G03850 203 209 9.08 CTAATCC
#> 5 motif 1 AT5G01810 821 827 9.08 CATATCC
#> ...
#> 90 motif 1 AT5G22690 58 52 9.08 CATTACC
#> 91 motif 1 AT1G05670 706 700 9.08 CTTTACC
```

```
#> 92      motif      1 AT1G06160      498      492      9.08      CTAAACC
#> 93      motif      1 AT5G24660      146      140      9.08      CATTACC
#> 94      motif      1 AT3G19200      421      415      9.08      CTAAACC
#>      thresh.score min.score max.score score.pct      strand
#>      <numeric> <numeric> <numeric> <numeric> <character>
#> 1      8.172      -19.649      9.08      100      +
#> 2      8.172      -19.649      9.08      100      +
#> 3      8.172      -19.649      9.08      100      +
#> 4      8.172      -19.649      9.08      100      +
#> 5      8.172      -19.649      9.08      100      +
#> ...      ...      ...      ...      ...      ...
#> 90      8.172      -19.649      9.08      100      -
#> 91      8.172      -19.649      9.08      100      -
#> 92      8.172      -19.649      9.08      100      -
#> 93      8.172      -19.649      9.08      100      -
#> 94      8.172      -19.649      9.08      100      -
```

Using 2-letter information to scan:

```
scan_sequences(motif.k2, ArabidopsisPromoters, use.freq = 2, RC = TRUE,
               threshold = 0.9, threshold.type = "logodds")
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
#> DataFrame with 8 rows and 12 columns
#>      motif motif.i sequence      start      stop      score      match
#>      <character> <integer> <character> <integer> <integer> <numeric> <character>
#> 1      motif      1 AT4G12690      938      943      17.827      CAAAAC
#> 2      motif      1 AT2G37950      751      756      17.827      CAAAAC
#> 3      motif      1 AT1G49840      959      964      17.827      CTTTTC
#> 4      motif      1 AT1G77210      184      189      17.827      CAAAAC
#> 5      motif      1 AT1G77210      954      959      17.827      CAAAAC
#> 6      motif      1 AT3G57640      917      922      17.827      CTTTTC
#> 7      motif      1 AT4G14365      977      982      17.827      CTTTTC
#> 8      motif      1 AT1G19510      960      965      17.827      CTTTTC
#>      thresh.score min.score max.score score.pct      strand
#>      <numeric> <numeric> <numeric> <numeric> <character>
#> 1      16.0443      -16.842      17.827      100      +
#> 2      16.0443      -16.842      17.827      100      +
#> 3      16.0443      -16.842      17.827      100      +
#> 4      16.0443      -16.842      17.827      100      +
#> 5      16.0443      -16.842      17.827      100      +
#> 6      16.0443      -16.842      17.827      100      +
#> 7      16.0443      -16.842      17.827      100      +
#> 8      16.0443      -16.842      17.827      100      +
```

Furthermore, sequence scanning can be further refined to avoid overlapping hits. Consider:

```
motif <- create_motif("AAAAAA")

## Leave in overlapping hits:

scan_sequences(motif, ArabidopsisPromoters, RC = TRUE, threshold = 0.9,
               threshold.type = "logodds")
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
```

```
#> DataFrame with 491 rows and 12 columns
#>      motif motif.i sequence start stop score match
#>      <character> <integer> <character> <integer> <integer> <numeric> <character>
#> 1      motif      1 AT4G28150    419  424  11.934  AAAAAA
#> 2      motif      1 AT1G19380    867  872  11.934  AAAAAA
#> 3      motif      1 AT1G19380    868  873  11.934  AAAAAA
#> 4      motif      1 AT1G03850    243  248  11.934  AAAAAA
#> 5      motif      1 AT1G03850    735  740  11.934  AAAAAA
#> ...      ...      ...      ...      ...      ...      ...
#> 487     motif      1 AT3G19200    246  241  11.934  AAAAAA
#> 488     motif      1 AT3G19200    247  242  11.934  AAAAAA
#> 489     motif      1 AT3G19200    248  243  11.934  AAAAAA
#> 490     motif      1 AT3G19200    668  663  11.934  AAAAAA
#> 491     motif      1 AT3G19200    669  664  11.934  AAAAAA
#>      thresh.score min.score max.score score.pct strand
#>      <numeric> <numeric> <numeric> <numeric> <character>
#> 1      10.7406  -39.948    11.934    100      +
#> 2      10.7406  -39.948    11.934    100      +
#> 3      10.7406  -39.948    11.934    100      +
#> 4      10.7406  -39.948    11.934    100      +
#> 5      10.7406  -39.948    11.934    100      +
#> ...      ...      ...      ...      ...      ...
#> 487     10.7406  -39.948    11.934    100      -
#> 488     10.7406  -39.948    11.934    100      -
#> 489     10.7406  -39.948    11.934    100      -
#> 490     10.7406  -39.948    11.934    100      -
#> 491     10.7406  -39.948    11.934    100      -

## Only keep the highest scoring hit amongst overlapping hits:

scan_sequences(motif, ArabidopsisPromoters, RC = TRUE, threshold = 0.9,
               threshold.type = "logodds", no.overlaps = TRUE)
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
#> DataFrame with 229 rows and 12 columns
#>      motif motif.i sequence start stop score match
#>      <character> <integer> <character> <integer> <integer> <numeric> <character>
#> 1      motif      1 AT4G28150    419  424  11.934  AAAAAA
#> 2      motif      1 AT1G19380    867  872  11.934  AAAAAA
#> 3      motif      1 AT1G03850    243  248  11.934  AAAAAA
#> 4      motif      1 AT1G03850    735  740  11.934  AAAAAA
#> 5      motif      1 AT5G01810    950  955  11.934  AAAAAA
#> ...      ...      ...      ...      ...      ...      ...
#> 225     motif      1 AT1G05670     78   73  11.934  AAAAAA
#> 226     motif      1 AT1G05670     85   80  11.934  AAAAAA
#> 227     motif      1 AT1G06160    404  399  11.934  AAAAAA
#> 228     motif      1 AT3G19200    246  241  11.934  AAAAAA
#> 229     motif      1 AT3G19200    668  663  11.934  AAAAAA
#>      thresh.score min.score max.score score.pct strand
#>      <numeric> <numeric> <numeric> <numeric> <character>
#> 1      10.7406  -39.948    11.934    100      +
#> 2      10.7406  -39.948    11.934    100      +
#> 3      10.7406  -39.948    11.934    100      +
```

```
#> 4      10.7406 -39.948 11.934 100 +
#> 5      10.7406 -39.948 11.934 100 +
#> ...      ...      ...      ...      ...
#> 225    10.7406 -39.948 11.934 100 -
#> 226    10.7406 -39.948 11.934 100 -
#> 227    10.7406 -39.948 11.934 100 -
#> 228    10.7406 -39.948 11.934 100 -
#> 229    10.7406 -39.948 11.934 100 -
```

Finally, the results can be returned as a `GRanges` object for further manipulation:

```
scan_sequences(motif.k2, ArabidopsisPromoters, RC = TRUE,
               threshold = 0.9, threshold.type = "logodds",
               return.granges = TRUE)
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
#> GRanges object with 94 ranges and 8 metadata columns:
#>      seqnames      ranges strand |      motif motif.i      score      match
#>      <Rle> <IRanges> <Rle> | <character> <integer> <numeric> <character>
#> [1] AT4G28150 621-627 + | motif 1 9.08 CTAAACC
#> [2] AT1G19380 139-145 + | motif 1 9.08 CTTATCC
#> [3] AT1G19380 204-210 + | motif 1 9.08 CTAAACC
#> [4] AT1G03850 203-209 + | motif 1 9.08 CTAATCC
#> [5] AT5G01810 821-827 + | motif 1 9.08 CATATCC
#> ...      ...      ...      ...      ...      ...      ...
#> [90] AT5G22690 52-58 - | motif 1 9.08 CATTACC
#> [91] AT1G05670 700-706 - | motif 1 9.08 CTTTACC
#> [92] AT1G06160 492-498 - | motif 1 9.08 CTAAACC
#> [93] AT5G24660 140-146 - | motif 1 9.08 CATTACC
#> [94] AT3G19200 415-421 - | motif 1 9.08 CTAAACC
#>      thresh.score min.score max.score score.pct
#>      <numeric> <numeric> <numeric> <numeric>
#> [1] 8.172 -19.649 9.08 100
#> [2] 8.172 -19.649 9.08 100
#> [3] 8.172 -19.649 9.08 100
#> [4] 8.172 -19.649 9.08 100
#> [5] 8.172 -19.649 9.08 100
#> ...      ...      ...      ...
#> [90] 8.172 -19.649 9.08 100
#> [91] 8.172 -19.649 9.08 100
#> [92] 8.172 -19.649 9.08 100
#> [93] 8.172 -19.649 9.08 100
#> [94] 8.172 -19.649 9.08 100
#> -----
#> seqinfo: 50 sequences from an unspecified genome
```

9 Visualizing motif hits across sequences

Using the `ggbio` package, it is rather trivial to generate nice visualizations of the output of `scan_sequences()`. This requires having the `GenomicRanges` and `ggbio` packages installed, and outputting the `scan_sequences()` result as a `GRanges` object (via `return.granges = TRUE`).

```
library(universalmotif)
library(GenomicRanges)
```

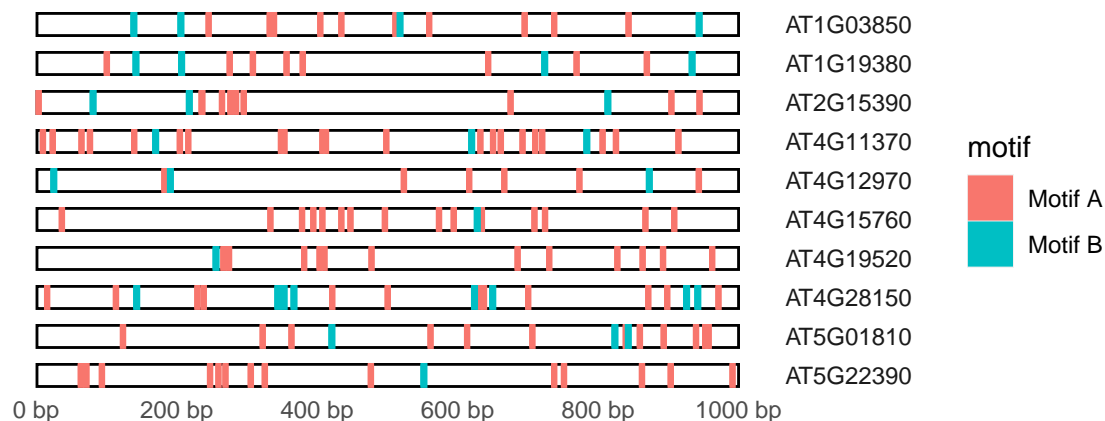
```
library(ggbio)

data(ArabidopsisPromoters)

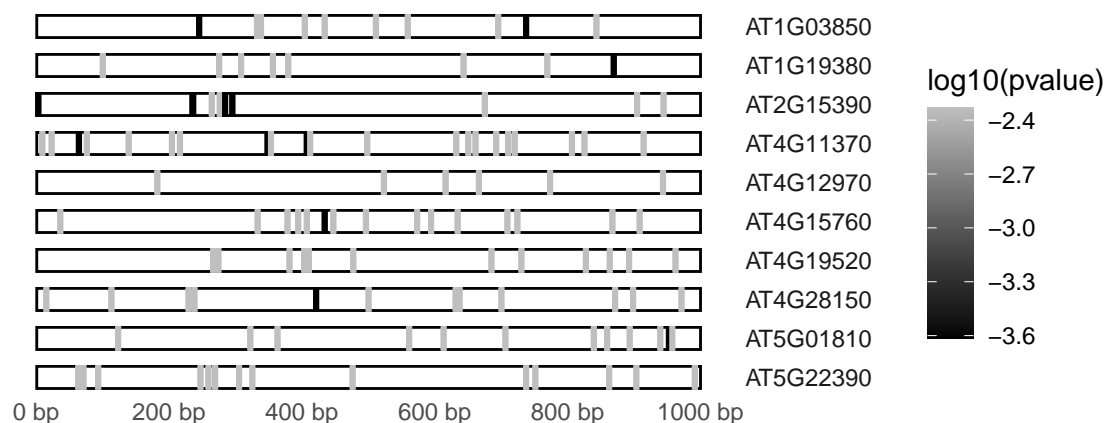
motif1 <- create_motif("AAAAAA", name = "Motif A")
motif2 <- create_motif("CWWWWCC", name = "Motif B")

res <- scan_sequences(c(motif1, motif2), ArabidopsisPromoters[1:10],
  return.ranges = TRUE, calc.pvals = TRUE, no.overlaps = TRUE)
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.

## Just plot the motif hits:
autoplot(res, layout = "karyogram", aes(fill = motif, color = motif)) +
  theme(
    strip.background = element_rect(fill = NA, colour = NA),
    panel.background = element_rect(fill = NA, colour = NA)
  )
#> Scale for 'x' is already present. Adding another scale for 'x', which will
#> replace the existing scale.
#> Scale for 'x' is already present. Adding another scale for 'x', which will
#> replace the existing scale.
```



```
## Plot Motif A hits by P-value:
autoplot(res[res$motif.i == 1, ], layout = "karyogram",
  aes(fill = log10(pvalue), colour = log10(pvalue))) +
  scale_fill_gradient(low = "black", high = "grey75") +
  scale_colour_gradient(low = "black", high = "grey75") +
  theme(
    strip.background = element_rect(fill = NA, colour = NA),
    panel.background = element_rect(fill = NA, colour = NA)
  )
#> Scale for 'x' is already present. Adding another scale for 'x', which will
#> replace the existing scale.
#> Scale for 'x' is already present. Adding another scale for 'x', which will
#> replace the existing scale.
```



10 Enrichment analyses

The `universalmotif` package offers the ability to search for enriched motif sites in a set of sequences via `enrich_motifs()`. There is little complexity to this, as it simply runs `scan_sequences()` twice: once on a set of target sequences, and once on a set of background sequences. After which the results between the two sequences are collated and run through enrichment tests. The background sequences can be given explicitly, or else `enrich_motifs()` will create background sequences on its own by using `shuffle_sequences()` on the target sequences.

Let us consider the following basic example:

```
library(universalmotif)
data(ArabidopsisMotif)
data(ArabidopsisPromoters)

enrich_motifs(ArabidopsisMotif, ArabidopsisPromoters, shuffle.k = 3,
              threshold = 0.001, RC = TRUE)
#> DataFrame with 1 row and 11 columns
#>      motif motif.i target.hits target.seq.hits target.seq.count
#>      <character> <integer> <integer> <integer> <integer>
#> 1 YTTYTTTTTYYY 1 675 50 50
#>      bkg.hits bkg.seq.hits bkg.seq.count Pval Qual Eval
#>      <integer> <integer> <integer> <numeric> <numeric> <numeric>
#> 1 292 49 50 4.65125e-36 4.65125e-36 9.3025e-36
```

Here we can see that the motif is significantly enriched in the target sequences. The `Pval` was calculated by calling `stats::fisher.test()`.

One final point: always keep in mind the `threshold` parameter, as this will ultimately decide the number of hits found. (A bad threshold can lead to a false negative.)

11 Gapped motifs

`universalmotif` class motifs can be gapped, which can be used by `scan_sequences()` and `enrich_motifs()`. Note that gapped motif support is currently limited to these two functions. All other functions will ignore the gap information, and even discard them in functions such as `merge_motifs()`.

First, obtain the component motifs:

```
library(universalmotif)
data(ArabidopsisPromoters)
```



```
m1 <- create_motif("TTTATAT", name = "PartA")
m2 <- create_motif("GGTTCGA", name = "PartB")
```

Then, combine them and add the desired gap. In this case, a gap will be added between the two motifs which can range in size from 4-6 bases.

```
m <- cbind(m1, m2)
m <- add_gap(m, gaploc = ncol(m1), mingap = 4, maxgap = 6)
m
#>
#>      Motif name:  PartA/PartB
#>      Alphabet:   DNA
#>      Type:       PCM
#>      Strands:    +-
#>      Total IC:   28
#>      Pseudocount: 0
#>      Consensus:  TTTATAT..GGTTCGA
#>      Gap locations: 7-8
#>      Gap sizes:   4-6
#>
#>   T T T A T A T   G G T T C G A
#> A 0 0 0 1 0 1 0 .. 0 0 0 0 0 0 1
#> C 0 0 0 0 0 0 0 .. 0 0 0 0 1 0 0
#> G 0 0 0 0 0 0 0 .. 1 1 0 0 0 1 0
#> T 1 1 1 0 1 0 1 .. 0 0 1 1 0 0 0
```

Now, it can be used directly in `scan_sequences()` or `enrich_motifs()`:

```
scan_sequences(m, ArabidopsisPromoters, threshold = 0.4, threshold.type = "logodds")
#> Note: found -Inf values in motif PWM(s), adding a pseudocount. Set
#> `allow.nonfinite = TRUE` to prevent this behaviour.
#> DataFrame with 75 rows and 12 columns
#>      motif motif.i sequence start stop score
#>      <character> <integer> <character> <integer> <integer> <numeric>
#> 1 PartA/PartB 1 AT4G19520 484 501 11.918
#> 2 PartA/PartB 1 AT5G20200 731 748 11.918
#> 3 PartA/PartB 1 AT2G04025 168 185 11.918
#> 4 PartA/PartB 1 AT1G06160 144 161 11.918
#> 5 PartA/PartB 1 AT1G03850 376 394 11.178
#> ...
#> 71 PartA/PartB 1 AT4G33970 272 291 11.428
#> 72 PartA/PartB 1 AT3G15610 402 421 11.428
#> 73 PartA/PartB 1 AT2G17450 233 252 11.428
#> 74 PartA/PartB 1 AT2G17450 891 910 11.428
#> 75 PartA/PartB 1 AT2G24240 355 374 11.428
#>
#>      match thresh.score min.score max.score score.pct strand
#>      <character> <numeric> <numeric> <numeric> <numeric> <character>
#> 1 GTTATAT...GATTCTA 11.1384 -93.212 27.846 42.7997 +
#> 2 TTCATTT...GGTTAGA 11.1384 -93.212 27.846 42.7997 +
#> 3 TGTTTAT...GGTTCGG 11.1384 -93.212 27.846 42.7997 +
#> 4 TTTATGT...GGTTTGT 11.1384 -93.212 27.846 42.7997 +
#> 5 TATATGT....GGTGCAA 11.1384 -93.212 27.846 40.1422 +
#> ...
#> 71 TTTACCA.....AGTTCGA 11.1384 -93.212 27.846 41.04 +
#> 72 TTAAAGT.....AGTTCTA 11.1384 -93.212 27.846 41.04 +
```



```
#> 73 TTTTAT.....TGATAGA 11.1384 -93.212 27.846 41.04 +
#> 74 TTATTAT.....GATTGA 11.1384 -93.212 27.846 41.04 +
#> 75 CTTATAT.....GGATTGT 11.1384 -93.212 27.846 41.04 +
```

12 Testing for motif positional preferences in sequences

The `universalmotif` package provides the `motif_peaks()` function, which can test for positionally preferential motif sites in a set of sequences. This can be useful, for example, when trying to determine whether a certain transcription factor binding site is more often than not located at a certain distance from the transcription start site (TSS). The `motif_peaks()` function finds density peaks in the input data, then creates a null distribution from randomly generated peaks to calculate peak P-values.

```
library(universalmotif)
data(ArabidopsisMotif)
data(ArabidopsisPromoters)

hits <- scan_sequences(ArabidopsisMotif, ArabidopsisPromoters, RC = FALSE)

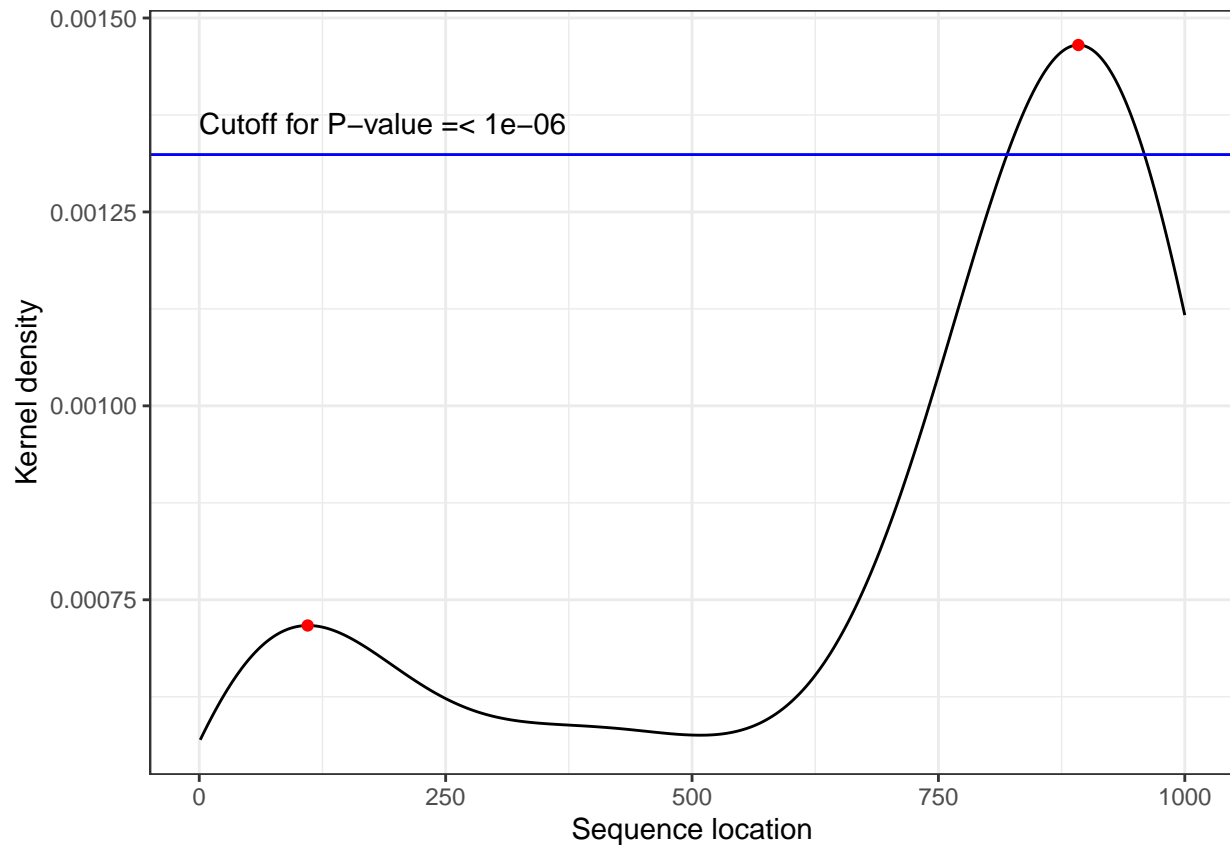
res <- motif_peaks(hits$start,
                   seq.length = unique(width(ArabidopsisPromoters)),
                   seq.count = length(ArabidopsisPromoters))

## Significant peaks:
res$Peaks
#> DataFrame with 1 row and 2 columns
#>      Peak      Pval
#> <numeric> <numeric>
#> 1      892 8.24913e-13
```

Using the datasets provided in this package, a significant motif peak was found about 100 bases away from the TSS. If you'd like to simply know the locations of any peaks, this can be done by setting `max.p = 1`.

The function can also output a plot:

```
res$Plot
```



In this plot, red dots are used to indicate density peaks and the blue line shows the P-value cutoff.

13 Motif discovery with MEME

The `universalmotif` package provides a simple wrapper to the powerful motif discovery tool **MEME** (Bailey and Elkan 1994). To run an analysis with **MEME**, all that is required is a set of `XStringSet` class sequences (defined in the `Biostrings` package), and `run_meme()` will take care of running the program and reading the output for use within R.

The first step is to check that R can find the **MEME** binary in your `$PATH` by running `run_meme()` without any parameters. If successful, you should see the default **MEME** help message in your console. If not, then you'll need to provide the complete path to the **MEME** binary. There are two options:

```
library(universalmotif)

## 1. Once per session: via `options()`
options(meme.bin = "/path/to/meme/bin/meme")

run_meme(...)

## 2. Once per run: via `run_meme()`
run_meme(..., bin = "/path/to/meme/bin/meme")
```

Now we need to get some sequences to use with `run_meme()`. At this point we can read sequences from disk or extract them from one of the Bioconductor `BSgenome` packages.

```

library(universalmotif)
data(ArabidopsisPromoters)

## 1. Read sequences from disk (in fasta format):

library(Biostrings)

# The following `read*()` functions are available in Biostrings:
# DNA: readDNAStringSet
# DNA with quality scores: readQualityScaledDNAStringSet
# RNA: readRNAStringSet
# Amino acid: readAAStringSet
# Any: readBStringSet

sequences <- readDNAStringSet("/path/to/sequences.fasta")

run_meme(sequences, ...)

## 2. Extract from a `BSgenome` object:

library(GenomicFeatures)
library(TxDb.Athaliana.BioMart.plantsmart28)
library(BSgenome.Athaliana.TAIR.TAIR9)

# Let us retrieve the same promoter sequences from ArabidopsisPromoters:
gene.names <- names(ArabidopsisPromoters)

# First get the transcript coordinates from the relevant `TxDb` object:
transcripts <- transcriptsBy(TxDb.Athaliana.BioMart.plantsmart28,
                             by = "gene")[gene.names]

# There are multiple transcripts per gene, we only care for the first one
# in each:

transcripts <- lapply(transcripts, function(x) x[1])
transcripts <- unlist(GRangesList(transcripts))

# Then the actual sequences:

# Unfortunately this is a case where the chromosome names do not match
# between the two databases

seqlevels(TxDb.Athaliana.BioMart.plantsmart28)
#> [1] "1" "2" "3" "4" "5" "Mt" "Pt"
seqlevels(BSgenome.Athaliana.TAIR.TAIR9)
#> [1] "Chr1" "Chr2" "Chr3" "Chr4" "Chr5" "ChrM" "ChrC"

# So we must first rename the chromosomes in `transcripts`:
seqlevels(transcripts) <- seqlevels(BSgenome.Athaliana.TAIR.TAIR9)

# Finally we can extract the sequences
promoters <- getPromoterSeq(transcripts,
                             BSgenome.Athaliana.TAIR.TAIR9,

```

```

upstream = 1000, downstream = 0)

run_meme(promoters, ...)

```

Once the sequences are ready, there are few important options to keep in mind. One is whether to conserve the output from MEME. The default is not to, but this can be changed by setting the relevant option:

```
run_meme(sequences, output = "/path/to/desired/output/folder")
```

The second important option is the search function (`objfun`). Some search functions such as the default `classic` do not require a set of background sequences, whilst some do (such as `de`). If you choose one of the latter, then you can either let MEME create them for you (it will shuffle the target sequences) or you can provide them via the `control.sequences` parameter.

Finally, choose how you'd like the data imported into R. Once the MEME program exits, `run_meme()` will import the results into R with `read_meme()`. At this point you can decide if you want just the motifs themselves (`readsites = FALSE`) or if you'd like the original sequence sites as well (`readsites = TRUE`, the default). Doing the latter gives you the option of generating higher order representations for the imported MEME motifs as shown here:

```

motifs <- run_meme(sequences)
motifs.k23 <- mapply(add_multifreq, motifs$motifs, motifs$sites)

```

There are a wealth of other MEME options available, such as the number of desired motifs (`nmotifs`), the width of desired motifs (`minw`, `maxw`), the search mode (`mod`), assigning sequence weights (`weights`), using a custom alphabet (`alph`), and many others. See the output from `run_meme()` for a brief description of the options, or visit the online manual for more details.

Session info

```

#> R version 4.1.0 (2021-05-18)
#> Platform: x86_64-w64-mingw32/x64 (64-bit)
#> Running under: Windows Server 2012 R2 x64 (build 9600)
#>
#> Matrix products: default
#>
#> locale:
#> [1] LC_COLLATE=C
#> [2] LC_CTYPE=English_United States.1252
#> [3] LC_MONETARY=English_United States.1252
#> [4] LC_NUMERIC=C
#> [5] LC_TIME=English_United States.1252
#>
#> attached base packages:
#> [1] stats4      parallel  stats      graphics  grDevices  utils      datasets
#> [8] methods    base
#>
#> other attached packages:
#> [1] ggbio_1.40.0      TFBSTools_1.30.0      cowplot_1.1.1
#> [4] dplyr_1.0.7       ggtree_3.0.2          ggplot2_3.3.5
#> [7] MotifDb_1.34.0    GenomicRanges_1.44.0  Biostrings_2.60.2
#> [10] GenomeInfoDb_1.28.1 XVector_0.32.0        IRanges_2.26.0
#> [13] S4Vectors_0.30.0  BiocGenerics_0.38.0   universalmotif_1.10.2
#>
#> loaded via a namespace (and not attached):

```

```

#> [1] backports_1.2.1           Hmisc_4.5-0
#> [3] BiocFileCache_2.0.0        plyr_1.8.6
#> [5] lazyeval_0.2.2            splines_4.1.0
#> [7] BiocParallel_1.26.1       digest_0.6.27
#> [9] ensemblldb_2.16.4         htmltools_0.5.1.1
#> [11] GO.db_3.13.0              fansi_0.5.0
#> [13] magrittr_2.0.1            checkmate_2.0.0
#> [15] memoise_2.0.0             BSgenome_1.60.0
#> [17] grImport2_0.2-0           cluster_2.1.2
#> [19] tzdb_0.1.2                readr_2.0.0
#> [21] annotate_1.70.0           matrixStats_0.60.0
#> [23] R.utils_2.10.1            prettyunits_1.1.1
#> [25] jpeg_0.1-9                colorspace_2.0-2
#> [27] rappdirs_0.3.3           blob_1.2.2
#> [29] xfun_0.24                 crayon_1.4.1
#> [31] RCurl_1.98-1.3           jsonlite_1.7.2
#> [33] graph_1.70.0              TFMPvalue_0.0.8
#> [35] VariantAnnotation_1.38.0  survival_3.2-11
#> [37] ape_5.5                   glue_1.4.2
#> [39] gtable_0.3.0             zlibbioc_1.38.0
#> [41] DelayedArray_0.18.0      scales_1.1.1
#> [43] DBI_1.1.1                 GGally_2.1.2
#> [45] Rcpp_1.0.7               progress_1.2.2
#> [47] xtable_1.8-4             htmlTable_2.2.1
#> [49] tidytree_0.3.4           foreign_0.8-81
#> [51] bit_4.0.4                OrganismDbi_1.34.0
#> [53] Formula_1.2-4            htmlwidgets_1.5.3
#> [55] httr_1.4.2               RColorBrewer_1.1-2
#> [57] ellipsis_0.3.2           pkgconfig_2.0.3
#> [59] reshape_0.8.8            XML_3.99-0.6
#> [61] R.methodsS3_1.8.1        farver_2.1.0
#> [63] dbplyr_2.1.1             nnet_7.3-16
#> [65] ggseqlogo_0.1            utf8_1.2.2
#> [67] tidyselect_1.1.1         labeling_0.4.2
#> [69] rlang_0.4.11             reshape2_1.4.4
#> [71] AnnotationDbi_1.54.1     munsell_0.5.0
#> [73] tools_4.1.0              cachem_1.0.5
#> [75] DirichletMultinomial_1.34.0 generics_0.1.0
#> [77] RSQLite_2.2.7            ade4_1.7-17
#> [79] evaluate_0.14            stringr_1.4.0
#> [81] fastmap_1.1.0            yaml_2.2.1
#> [83] knitr_1.33               bit64_4.0.5
#> [85] caTools_1.18.2           purrr_0.3.4
#> [87] AnnotationFilter_1.16.0  KEGGREST_1.32.0
#> [89] splitstackshape_1.4.8    RBGL_1.68.0
#> [91] nlme_3.1-152             R.oo_1.24.0
#> [93] powerLaw_0.70.6          aplot_0.0.6
#> [95] xml2_1.3.2               pracma_2.3.3
#> [97] biomaRt_2.48.2           rstudioapi_0.13
#> [99] compiler_4.1.0          filelock_1.0.2
#> [101] curl_4.3.2              png_0.1-7
#> [103] treeio_1.16.1            tibble_3.1.3
#> [105] stringi_1.7.3           highr_0.9
#> [107] GenomicFeatures_1.44.0   lattice_0.20-44

```

```

#> [109] ProtGenerics_1.24.0      CNEr_1.28.0
#> [111] Matrix_1.3-4             vctr_0.3.8
#> [113] pillar_1.6.2             lifecycle_1.0.0
#> [115] BiocManager_1.30.16      data.table_1.14.0
#> [117] bitops_1.0-7             patchwork_1.1.1
#> [119] rtracklayer_1.52.0       R6_2.5.0
#> [121] BiocIO_1.2.0             latticeExtra_0.6-29
#> [123] bookdown_0.22            gridExtra_2.3
#> [125] motifStack_1.36.0        dichromat_2.0-0
#> [127] MASS_7.3-54             gtools_3.9.2
#> [129] assertthat_0.2.1         seqLogo_1.58.0
#> [131] SummarizedExperiment_1.22.0 rjson_0.2.20
#> [133] withr_2.4.2             GenomicAlignments_1.28.0
#> [135] Rsamtools_2.8.0         GenomeInfoDbData_1.2.6
#> [137] hms_1.1.0               grid_4.1.0
#> [139] rpart_4.1-15            tidyr_1.1.3
#> [141] rmarkdown_2.9           rvcheck_0.1.8
#> [143] MatrixGenerics_1.4.1    biovizBase_1.40.0
#> [145] Biobase_2.52.0          base64enc_0.1-3
#> [147] tinytex_0.32            restfulr_0.0.13

```

References

- Altschul, Stephen F., and Bruce W. Erickson. 1985. "Significance of Nucleotide Sequence Alignments: A Method for Random Sequence Permutation That Preserves Dinucleotide and Codon Usage." *Molecular Biology and Evolution* 2 (6): 526–38.
- Bailey, T. L., and C. Elkan. 1994. "Fitting a Mixture Model by Expectation Maximization to Discover Motifs in Biopolymers." *Proceedings of the Second International Conference on Intelligent Systems for Molecular Biology* 2: 28–36.
- Fitch, Walter M. 1983. "Random Sequences." *Journal of Molecular Biology* 163 (2): 171–76.
- Jiang, M., J. Anderson, J. Gillespie, and M. Mayne. 2008. "uShuffle: A Useful Tool for Shuffling Biological Sequences While Preserving K-Let Counts." *BMC Bioinformatics* 9 (192).
- Propp, J. G., and D. W. Wilson. 1998. "How to Get a Perfectly Random Sample from a Generic Markov Chain and Generate a Random Spanning Tree of a Directed Graph." *Journal of Algorithms* 27: 170–217.