atSNP: affinity tests for regulatory SNP detection

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1 Introduction

This document provides an introduction to the affinity test for large sets of SNP-motif interactions using the `atSNP` package(**a**ffinity **t**est for regulatory **SNP** detection) [Chandler Zuo and Sunyoung Shin and Sündüz Keleş, 2014]. `atSNP` implements in-silico methods for identifying SNPs that potentially may affect binding affinity of transcription factors. Given a set of SNPs and a library of motif position weight matrices (PWMs), `atSNP` provides three main functions for analyzing SNP effects:

1. Computing the binding affinity score for each allele and each PWM;
2. Computing the p-values for allele-specific binding affinity scores;
3. Computing the p-values for affinity score changes between the two alleles for each SNP.

`atSNP` implements the importance sampling algorithm in [Chan et al., 2010] to compute the p-values. Compared to other bioinformatics tools, such as FIMO [Grant et al., 2011] and is-rSNP [Macintyre et al., 2010], that provides similar functionalities, `atSNP` avoides computing the p-values analytically. This reduces the execution time drastically because the probability sample space is a exponential order of the motif length. In one of our research projects, we have used atSNP to evaluate interactions between 26K SNPs and 2K motifs within 5 hours. We found no other existing tool can finish the analysis of such a scale.

2 Installation

We are working to make the package available through bioconductor. The developing version can be installed from the Github repository:

```
> library( devtools )
> install_github( "chandlerzuo/atSNP" )
```

The following dependent `R` packages are required:

- `data.table` is used for formatting results that are easy for users to query;
- `motifStack` is relied upon to draw sequence logo plots;

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- `doMC` is used for parallel computation;
- `Rcpp` interfaces the C++ codes that implements the importance sampling algorithm;
- `testthat` is used for unit testing.

In addition, users also need to install the annotation package from `www.bioconductor.org/packages/3.0/data/annotation/` that corresponds to the species type and genome version. Our example SNP data set in the subsequent sections corresponds to the hg19 version of human genome. To repeat the sample codes in this vignette, the `BSgenome.Hsapiens.UCSC.hg19` package is required.

3 Example

3.1 Load motif and SNP data

A text file including the PWMs of all motifs can be loaded via the 'LoadMotifLibrary' function. In this function, 'tag' specifies the string that marks the start of each block of PWM; 'skiprows' is the number of description lines before the PWM; 'skipcols' is the number of columns to be skipped in the PWM matrix; 'transpose' is TRUE if the PWM has 4 rows representing A, C, G, T or FALSE if otherwise; 'field' is the position of the motif name within the description line; 'sep' is the separator in the PWM. These arguments provide the flexibility of loading a number of varying formatted files. The PWMs are returned as a list object. Some examples are the following:

The data set for the SNP information must be a table including five columns:

- chr: the chromosome ID;
- snp: the genome coordinate of the SNP;
- snpid: the string for the SNP name;
- a1, a2: nucleobases for the two alleles at the SNP position.

This data set can be loaded using the 'LoadSNPData' function. The 'genome.lib' argument specifies the annotation package name corresponding to the SNP data set, with the default as 'BSgenome.Hsapiens.UCSC.hg19'. Each side of the SNP is extended by a number of base pairs specified by the 'half.window.size' argument. 'LoadSNPData' extracts the genome sequence within such windows around each SNP using the 'genome.lib' package. An example is the following:

'LoadSNPData' simultaneously estimates the parameters for the first order Markov model in the reference genome using the nucleobases within the SNP windows. It returns a list object with five fields:

- $sequence_matrix: a matrix with (2×'half.window.size' + 1), with each column corresponding to one SNP. The entries 1-4 represent the A, C, G, T nucleobases;
- $ref_base: a vector coding the reference allele nucleobases for all SNPs;
- $snp_base: a vector coding the SNP allele nucleobases for all SNPs;
- $prior: the stationary distribution parameters for the Markov model;
- $transition: the transition matrix for the first order Markov model.

A sample data set including a preloaded motif library and a SNP set is included in the package:

```
> library(atSNP)
> data(example)
> str(motif_library)
List of 7
 $ SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic  : num [1:10, 1:4] 8.51e-03 9.02e-01 4.55e
 $ USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic  : num [1:10, 1:4] 1.74e-01 1.00e-10 1.00e
 $ SRF_H1-hESC_encode-Myers_seq_hsa_r1:MDscan#2#Intergenic : num [1:10, 1:4] 1.00e-10 1.00e-10 4.95e
 $ JUND_K562_encode-Snyder_seq_hsa_r1:MEME#1#Intergenic    : num [1:10, 1:4] 4.18e-01 1.00e-10 1.00e
 $ SIX5_H1-hESC_encode-Myers_seq_hsa_r1:MDscan#1#Intergenic: num [1:10, 1:4] 1.00e-10 1.00e-10 1.00e
 $ ALX3_jolma_DBD_M449                                     : num [1:10, 1:4] 0.257 0.1356 0.0699 0.8
 $ AFP1_transfac_M00616                                    : num [1:11, 1:4] 1 0.2 0.2 1 1 ...
> str(snpInfo)
```

```
List of 5
 $ sequence_matrix: int [1:61, 1:1997] 4 3 1 4 3 2 2 1 3 3 ...
  ..- attr(*, "dimnames")=List of 2
  .. ..$ : NULL
  .. ..$ : chr [1:1997] "rs10910078" "rs4486391" "rs3748816" "rs2843401" ...
 $ ref_base       : int [1:1997] 4 1 1 4 4 4 4 1 1 4 ...
 $ snp_base       : int [1:1997] 2 4 3 2 2 2 2 2 3 2 ...
 $ transition     : num [1:4, 1:4] 0.317 0.354 0.292 0.214 0.177 ...
  ..- attr(*, "dimnames")=List of 2
  .. ..$ : chr [1:4] "A" "C" "G" "T"
  .. ..$ : chr [1:4] "A" "C" "G" "T"
 $ prior          : Named num [1:4] 0.289 0.207 0.207 0.297
  ..- attr(*, "names")= chr [1:4] "A" "C" "G" "T"
```

3.2 Affinity score tests

The binding affinity scores for all pairs of SNP and PWM can be computed by the 'ComputeMotifScore' function. It returns a list of two fields: 'snp.tbl' is a data.table containing the nucleobase sequences for each SNP; 'motif.scores' is a data.table containing the binding affinity scores for each SNP-motif pair.

```
> motif_score <- ComputeMotifScore(motif_library, snpInfo, ncores = 2)
> motif_score$snp.tbl
           snpid                                                          ref_seq
   1: rs10910078 TGATGCCAGGTGGTCAGTGGGTTTTTGCCATCCGCCAGGAGCTTCACTGGGCCTCCCGTTG
   2:  rs4486391 ATGGAGAATTCCACAGCTGATTGGAACCTAAACGAGAGAACCAAATGGACATCCCAGGGCT
   3:  rs3748816 TTGGAGTACTCCTCGTCCAGGCGCCTGTTCATCTCCTCCAGGATGTAGTCAGGGTGCCCGA
   4:  rs2843401 TCCTCCACCATTGTGCCAAACAGCGCCTGGTGGGGCCACCCGATCATCCCACGGGCCCCCA
   5:  rs2843402 CACCTTCTGGGCTGCAGGACTTCCTGCCCTTTAGGAAAGGGAGGCAGCCCTTTCTTCCTCC
  ---
1993:  rs3003207 CACCAAAACAGCTATGTCATTTTAGAAATGCAAATTGGACCCTAGAGTTTGATTATCAGCA
1994:  rs1173830 ATATAATCTATTCTTTCTTTCCCTTTCCTTCTCCAGAAACAGCTCAAATTATGAAATAACT
1995:   rs654873 GCTTCAGTAAAATTAACATTGATGAGTACCCTTATGGAATCTATCATGCATGTTCCAATTT
1996:  rs1768071 GGTGTCAGGGAATGCCAATCTCGCTGGTTCCGGTTTATTAGCTCGGGGAATCTCGTTAGAT
1997:  rs1538961 CTACCAGGTGCCAGTTGAGGATAGTCTAAACTACATTCTCAGCTTGAAATATTTTTGACCA
                                                                    snp_seq
   1: TGATGCCAGGTGGTCAGTGGGTTTTTGCCACCCGCCAGGAGCTTCACTGGGCCTCCCGTTG
   2: ATGGAGAATTCCACAGCTGATTGGAACCTATACGAGAGAACCAAATGGACATCCCAGGGCT
   3: TTGGAGTACTCCTCGTCCAGGCGCCTGTTCGTCTCCTCCAGGATGTAGTCAGGGTGCCCGA
   4: TCCTCCACCATTGTGCCAAACAGCGCCTGGCGGGGCCACCCGATCATCCCACGGGCCCCCA
   5: CACCTTCTGGGCTGCAGGACTTCCTGCCCTCTAGGAAAGGGAGGCAGCCCTTTCTTCCTCC
  ---
1993: CACCAAAACAGCTATGTCATTTTAGAAATGTAAATTGGACCCTAGAGTTTGATTATCAGCA
1994: ATATAATCTATTCTTTCTTTCCCTTTCCTTTTCCAGAAACAGCTCAAATTATGAAATAACT
1995: GCTTCAGTAAAATTAACATTGATGAGTACCTTTATGGAATCTATCATGCATGTTCCAATTT
1996: GGTGTCAGGGAATGCCAATCTCGCTGGTTCTGGTTTATTAGCTCGGGGAATCTCGTTAGAT
1997: CTACCAGGTGCCAGTTGAGGATAGTCTAAATTACATTCTCAGCTTGAAATATTTTTGACCA
                                                                ref_seq_rev
   1: CAACGGGAGGCCCAGTGAAGCTCCTGGCGGATGGCAAAAACCCACTGACCACCTGGCATCA
   2: AGCCCTGGGATGTCCATTTGGTTCTCTCGTTTAGGTTCCAATCAGCTGTGGAATTCTCCAT
   3: TCGGGCACCCTGACTACATCCTGGAGGAGATGAACAGGCGCCTGGACGAGGAGTACTCCAA
   4: TGGGGGCCCGTGGGATGATCGGGTGGCCCCACCAGGCGCTGTTTGGCACAATGGTGGAGGA
   5: GGAGGAAGAAAGGGCTGCCTCCCTTTCCTAAAGGGCAGGAAGTCCTGCAGCCCAGAAGGTG
  ---
1993: TGCTGATAATCAAACTCTAGGGTCCAATTTGCATTTCTAAAATGACATAGCTGTTTTGGTG
1994: AGTTATTTCATAATTTGAGCTGTTTCTGGAGAAGGAAAGGGAAAGAAAGAATAGATTATAT
1995: AAATTGGAACATGCATGATAGATTCCATAAGGGTACTCATCAATGTTAATTTTACTGAAGC
1996: ATCTAACGAGATTCCCCGAGCTAATAAACCGGAACCAGCGAGATTGGCATTCCCTGACACC
1997: TGGTCAAAAATATTTCAAGCTGAGAATGTAGTTTAGACTATCCTCAACTGGCACCTGGTAG
                                                            snp_seq_rev
   1: CAACGGGAGGCCCAGTGAAGCTCCTGGCGGGTGGCAAAAACCCACTGACCACCTGGCATCA
```

```
   2: AGCCCTGGGATGTCCATTTGGTTCTCTCGTATAGGTTCCAATCAGCTGTGGAATTCTCCAT
   3: TCGGGCACCCTGACTACATCCTGGAGGAGACGAACAGGCGCCTGGACGAGGAGTACTCCAA
   4: TGGGGGCCCGTGGGATGATCGGGTGGCCCCGCCAGGCGCTGTTTGGCACAATGGTGGAGGA
   5: GGAGGAAGAAAGGGCTGCCTCCCTTTCCTAGAGGGCAGGAAGTCCTGCAGCCCAGAAGGTG
  ---
1993: TGCTGATAATCAAACTCTAGGGTCCAATTTACATTTCTAAAATGACATAGCTGTTTTGGTG
1994: AGTTATTTCATAATTTGAGCTGTTTCTGGAAAAGGAAAGGGAAAGAAAGAATAGATTATAT
1995: AAATTGGAACATGCATGATAGATTCCATAAAGGTACTCATCAATGTTAATTTTACTGAAGC
1996: ATCTAACGAGATTCCCCGAGCTAATAAACCAGAACCAGCGAGATTGGCATTCCCTGACACC
1997: TGGTCAAAAATATTTCAAGCTGAGAATGTAATTTAGACTATCCTCAACTGGCACCTGGTAG
> motif_score$motif.scores[, list(snpid, motif, log_lik_ref,
+                                  log_lik_snp, log_lik_ratio)]
           snpid                                                motif
    1: rs10910078                                AFP1_transfac_M00616
    2:  rs4486391                                AFP1_transfac_M00616
    3:  rs3748816                                AFP1_transfac_M00616
    4:  rs2843401                                AFP1_transfac_M00616
    5:  rs2843402                                AFP1_transfac_M00616
   ---
13975:  rs3003207 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13976:  rs1173830 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13977:   rs654873 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13978:  rs1768071 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13979:  rs1538961 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
       log_lik_ref log_lik_snp log_lik_ratio
    1:  -117.69581  -116.93812    -0.7576857
    2:   -73.54122   -95.18078    21.6395566
    3:   -73.94669   -96.74940    22.8027074
    4:  -139.33536  -141.41480     2.0794415
    5:   -95.07542   -95.40392     0.3285041
   ---
13975:   -97.42420   -95.28965    -2.1345441
13976:   -94.64204  -115.49770    20.8556528
13977:   -75.86532   -94.23625    18.3709332
13978:  -117.30407  -119.09290     1.7888356
13979:   -98.55470   -75.52885   -23.0258509
```

The affinity scores for the reference and the SNP alleles are represented by the 'log_lik_ref' and 'log_lik_snp' columns in '$motif.scores'. The affinity score change is included in the 'log_lik_ratio' column. These three affinity scores are tested in the subsequent steps. '$motif.scores' also include other columns for the position of the best matching subsequence on each allele. For a complete description on all these columns, users can look up the help documentation.

After we have computed the binding affinity scores, they can be tested using the 'ComputePValues' function. The result is a data.table extending the affinity score table by three columns: 'pval_ref' is the p-value for the reference allele affinity score; 'pval_snp' is the p-value for the SNP allele affinity score; and 'pval_diff' is the p-value for the affinity score change between the two alleles.

```
> motif.scores <- ComputePValues(motif.lib = motif_library,
+                                snp.info = snpInfo,
+                                motif.scores = motif_scores$motif.scores,
+                                ncores = 7)
> motif.scores[, list(snpid, motif, pval_ref, pval_snp, pval_diff)]
           snpid                                                motif
    1: rs10910078                                AFP1_transfac_M00616
    2:  rs4486391                                AFP1_transfac_M00616
    3:  rs3748816                                AFP1_transfac_M00616
    4:  rs2843401                                AFP1_transfac_M00616
    5:  rs2843402                                AFP1_transfac_M00616
   ---
13975:  rs3003207 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13976:  rs1173830 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
```

```
13977:   rs654873 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13978:  rs1768071 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
13979:  rs1538961 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic
        pval_ref  pval_snp pval_diff
    1: 0.9774000 0.9634000 0.7867244
    2: 0.3883116 0.7523780 0.3120905
    3: 0.4399325 0.8721000 0.1914366
    4: 0.9995000 0.9998000 0.5894549
    5: 0.7468201 0.7859574 0.8601430
   ---
13975: 0.6630776 0.4690842 0.6505726
13976: 0.4348056 0.8260000 0.3578960
13977: 0.2578003 0.4060862 0.4883657
13978: 0.9006000 0.9705000 0.6926110
13979: 0.7130457 0.2417652 0.1857757
```

3.3 Additional analysis

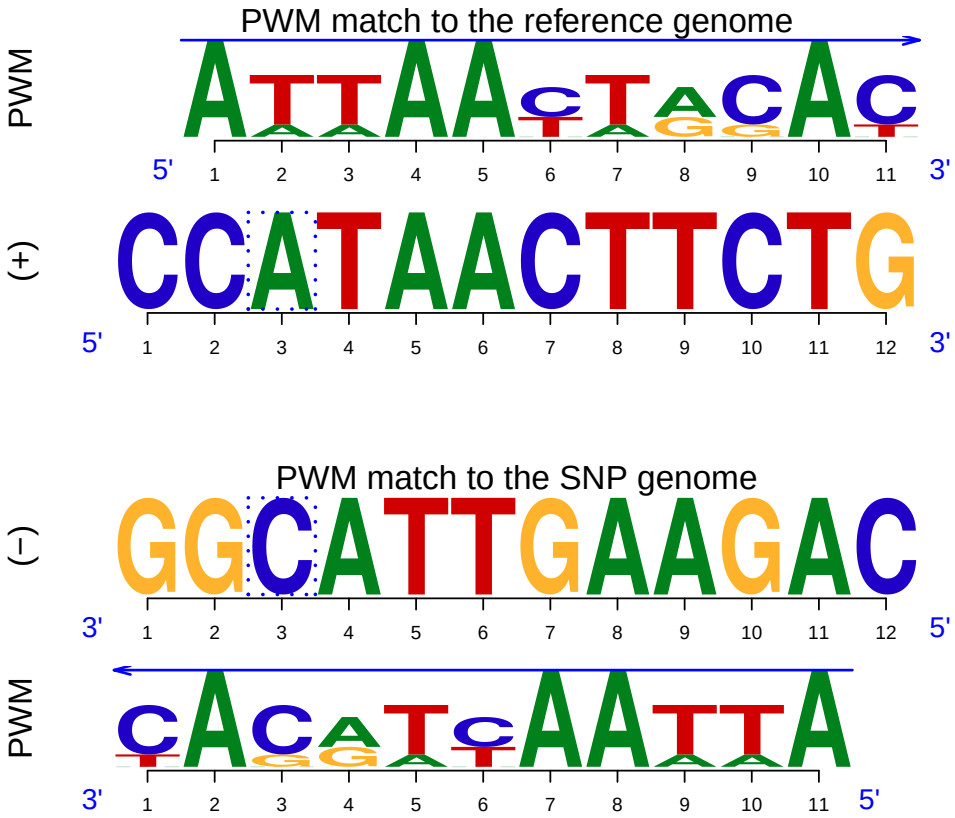
atSNP provides additional functions to extract the matched nucleobase subsequences that match to the motifs. Function 'MatchSubsequence' adds the subsequence matches to the affinity score table by using the motif library and the SNP set. The subsequences matching to the motif in the two alleles are returned in the 'ref_match_seq' and 'snp_match_seq' columns. The 'IUPAC' column returns the IUPAC letters of the motifs. Notice that if you have a large number of SNPs and motifs, the returned table can be very large.

```
> match_result <- MatchSubsequence(snp.tbl = motif_scores$snp.tbl,
+                                  motif.scores = motif.scores,
+                                  motif.lib = motif_library,
+                                  snpids = list("rs10910078", "rs4486391"),
+                                  motifs = names(motif_library)[1:2],
+                                  ncores = 2)
> match_result[, list(snpid, motif, IUPAC, ref_match_seq, snp_match_seq)]
        snpid                                                    motif      IUPAC
1: rs10910078 SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic GARWTGTAGT
2: rs10910078 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic GTCACGTGAC
3:  rs4486391 SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic GARWTGTAGT
4:  rs4486391 USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic GTCACGTGAC
   ref_match_seq snp_match_seq
1:    CTGGCGGATG    GGCGGGTGGC
2:    GGCGGATGGC    GCCACCCGCC
3:    CTCGTTTAGG    CTCGTATAGG
4:    TAAACGAGAG    CTCGTATAGG
```

We can also visualize how each motif is matched to each allele using the 'plotMotifMatch' function:

```
> plotMotifMatch(snp.tbl = motif_scores$snp.tbl,
+                motif.scores = motif_scores$motif.scores,
+                snpid = motif_scores$snp.tbl$snpid[50],
+                motif = motif_scores$motif.scores$motif[1])
```

AFP1_transfac_M00616 PWM Scan for rs301789



4 Session Information

```
R version 3.1.1 (2014-07-10)
Platform: x86_64-redhat-linux-gnu (64-bit)

locale:
 [1] LC_CTYPE=zh_TW.UTF-8       LC_NUMERIC=C
 [3] LC_TIME=en_US.UTF-8        LC_COLLATE=en_US.UTF-8
 [5] LC_MONETARY=en_US.UTF-8    LC_MESSAGES=en_US.UTF-8
 [7] LC_PAPER=en_US.UTF-8       LC_NAME=C
 [9] LC_ADDRESS=C               LC_TELEPHONE=C
[11] LC_MEASUREMENT=en_US.UTF-8 LC_IDENTIFICATION=C

attached base packages:
[1] grid      parallel  stats     graphics  grDevices utils     datasets
[8] methods   base

other attached packages:
 [1] atSNP_1.0          motifStack_1.6.5   ade4_1.6-2         MotIV_1.18.0
 [5] BiocGenerics_0.8.0 grImport_0.9-0     XML_3.98-1.1       testthat_0.9.1
 [9] doMC_1.3.3         iterators_1.0.7    foreach_1.4.2      data.table_1.9.4
[13] Rcpp_0.11.3

loaded via a namespace (and not attached):
 [1] Biostrings_2.30.1    BSgenome_1.30.0      chron_2.3-45
 [4] codetools_0.2-8      compiler_3.1.1       GenomicRanges_1.14.4
```

```
 [7] IRanges_1.20.7       lattice_0.20-29      plyr_1.8.1
[10] reshape2_1.4         rGADEM_2.10.0        seqLogo_1.28.0
[13] stats4_3.1.1         stringr_0.6.2        tools_3.1.1
[16] XVector_0.2.0
```

References

[Chan et al., 2010] Chan, H. P., Zhang, N. R., and Chen, L. H. (2010). Importance Sampling of Word Patterns in DNA and Protein Sequences. *Journal of Computational Biology*, 17(12):1697–1709.

[Chandler Zuo and Sunyoung Shin and Sündüz Keleş, 2014] Chandler Zuo and Sunyoung Shin and Sündüz Keleş (2014). atSNP: affinity test for regulatory SNP detection. *Submitted to Bioinformatics*.

[Grant et al., 2011] Grant, C. E., Bailey, T. L., and Nobel, W. S. (2011). FIMO: Scanning for occurrences of a given motif. *Bioinformatics*, 7:1017.

[Macintyre et al., 2010] Macintyre, G., Bailey, J., Haviv, I., and Kowalczyk, A. (2010). is-rSNP: a novel technique for in silico regulatory SNP detection. *Bioinformatics*, 26(18):524–530.