

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 **S**NP detection) [Zuo et al., 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** avoids computing the p-values analytically. This reduces the execution time drastically because the probability sample space is an 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:

```
> pwms <-
+   LoadMotifLibrary("http://meme.nbcr.net/meme/examples/sample-dna-motif.meme-io")
> pwms <- LoadMotifLibrary(
+     "http://johnsonlab.ucsf.edu/mochi_files/JASPAR_motifs_H_sapiens.txt",
+     tag = "/NAME", skiprows = 1, skipcols = 0, transpose = FALSE,
+     field = 2, sep = "\t")
> pwms <- LoadMotifLibrary(
+ "http://jaspar.genereg.net/html/DOWNLOAD/JASPAR_CORE/pfm/nonredundant/pfm_vertbrates.txt",
+     tag = ">", skiprows = 1, skipcols = 0, transpose = TRUE,
+     field = 1, sep = "\t")
> pwms <- LoadMotifLibrary(
+     "http://gibbs.biomed.ucf.edu/PreDREM/download/nonredundantmotif.transfac",
+     tag = "DE", skiprows = 1, skipcols = 1, transpose = FALSE,
+     field = 2, sep = "\t")
```

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 $(2 \times \text{half.window.size} + 1)$, 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)
> names(motif_library)
[1] "SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic"
[2] "USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic"
[3] "SRF_H1-hESC_encode-Myers_seq_hsa_r1:MDscan#2#Intergenic"
[4] "JUND_K562_encode-Snyder_seq_hsa_r1:MEME#1#Intergenic"
[5] "SIX5_H1-hESC_encode-Myers_seq_hsa_r1:MDscan#1#Intergenic"
[6] "ALX3_jolma_DBD_M449"
[7] "AFP1_transfac_M00616"
> 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  TTGGAGTACTCCTCGTCCAGGCGCCTGTTTCATCTCCTCCAGGATGTAGTCAGGGTGCCCGA
4: rs2843401  TCCTCCACCATTTGTGCCAAACAGCGCCTGGTGGGGCCACCCGATCATCCCACGGGCCCCCA
5: rs2843402  CACCTTCTGGGCTGCAGGACTTCCTGCCCTTTAGGAAAGGGAGGCAGCCCTTCTTCTCTCC
---
1993: rs3003207 CACCAAAACAGCTATGTCAATTTAGAAATGCAAATTTGGACCCTAGAGTTTGATTATCAGCA
1994: rs1173830 ATATAATCTATTCTTTCTTTCCCTTTTCTTCCAGAAACAGCTCAAATTATGAAATAACT
1995: rs654873  GCTTCAGTAAATAAACATTGATGAGTACCCTTATGGAATCTATCATGCATGTTCCAATTT
1996: rs1768071 GGTGTCAGGGAATGCCAATCTCGCTGGTTCCGGTTTATTAGCTCGGGGAATCTCGTTAGAT
1997: rs1538961 CTACCAGGTGCCAGTTGAGGATAGTCTAAACTACATTCTCAGCTTGAAATATTTTGACCA
      snp_seq
1: TGATGCCAGGTGGTCAGTGGGTTTTTGCCACCCGCCAGGAGCTTCACTGGGCCTCCCGTTG
2: ATGGAGAATTCCACAGCTGATTGGAACCTATACGAGAGAACCAAATGGACATCCCAGGGCT
3: TTGGAGTACTCCTCGTCCAGGCGCCTGTTCTGCTCCTCCAGGATGTAGTCAGGGTGCCCGA
4: TCCTCCACCATTTGTGCCAAACAGCGCCTGGCGGGGCCACCCGATCATCCCACGGGCCCCCA
5: CACCTTCTGGGCTGCAGGACTTCCTGCCCTCTAGGAAAGGGAGGCAGCCCTTCTTCTCTCC
---
1993: CACCAAAACAGCTATGTCAATTTAGAAATGTAATTTGGACCCTAGAGTTTGATTATCAGCA
1994: ATATAATCTATTCTTTCTTTCCCTTTTCCAGAAACAGCTCAAATTATGAAATAACT
1995: GCTTCAGTAAATAAACATTGATGAGTACCCTTATGGAATCTATCATGCATGTTCCAATTT
1996: GGTGTCAGGGAATGCCAATCTCGCTGGTTCTGGTTTATTAGCTCGGGGAATCTCGTTAGAT
```

```

1997: CTACCAGGTGCCAGTTGAGGATAGTCTAAATTACATTCTCAGCTTGAAATATTTTGGACCA
                                         ref_seq_rev
1: CAACGGGAGGCCAGTGAAGCTCCTGGCGGATGGCAAAAACCCACTGACCACCTGGCATCA
2: AGCCCTGGGATGTCCATTTGGTTCTCTCGTTAGGTTCCAATCAGCTGTGGAATTCTCCAT
3: TCGGGCACCCCTGACTACATCCTGGAGGAGATGAACAGGCGCCTGGACGAGGAGTACTCCAA
4: TGGGGGCCCCGTGGGATGATCGGGTGGCCCCACCAGGCGCTGTTTGGCACAATGGTGGAGGA
5: GGAGGAAGAAAGGGCTGCCTCCCTTTTCCTAAAGGGCAGGAAGTCCTGCAGCCCAGAAGGTG
---
1993: TGCTGATAATCAAACCTCTAGGGTCCAATTTGCATTTCTAAAATGACATAGCTGTTTTGGTG
1994: AGTTATTTTCATAATTTGAGCTGTTTCTGGAGAAGGAAAGGGAAAGAAAGAATAGATTATAT
1995: AAATTGGAACATGCATGATAGATTCCATAAAGGTTACTCATCAATGTTAATTTTACTGAAGC
1996: ATCTAACGAGATTCCCCGAGCTAATAAACCCGGAACCAGCGAGATTGGCATTCCCTGACACC
1997: TGGTCAAAAATATTTCAAGCTGAGAATGTAGTTTACTATCCTCAACTGGCACCTGGTAG
                                         snp_seq_rev
1: CAACGGGAGGCCAGTGAAGCTCCTGGCGGGTGGCAAAAACCCACTGACCACCTGGCATCA
2: AGCCCTGGGATGTCCATTTGGTTCTCTCGTATAGGTTCCAATCAGCTGTGGAATTCTCCAT
3: TCGGGCACCCCTGACTACATCCTGGAGGAGACGAACAGGCGCCTGGACGAGGAGTACTCCAA
4: TGGGGGCCCCGTGGGATGATCGGGTGGCCCCGCCAGGCGCTGTTTGGCACAATGGTGGAGGA
5: GGAGGAAGAAAGGGCTGCCTCCCTTTTCCTAGAGGGCAGGAAGTCCTGCAGCCCAGAAGGTG
---
1993: TGCTGATAATCAAACCTCTAGGGTCCAATTTACATTTCTAAAATGACATAGCTGTTTTGGTG
1994: AGTTATTTTCATAATTTGAGCTGTTTCTGGAAAAGGAAAGGGAAAGAAAGAATAGATTATAT
1995: AAATTGGAACATGCATGATAGATTCCATAAAGGTTACTCATCAATGTTAATTTTACTGAAGC
1996: ATCTAACGAGATTCCCCGAGCTAATAAACCCAGAACCAGCGAGATTGGCATTCCCTGACACC
1997: TGGTCAAAAATATTTCAAGCTGAGAATGTAAATTTAGACTATCCTCAACTGGCACCTGGTAG
> 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: 0.9776495 0.9626548 0.77254685
2: 0.3767000 0.7685845 0.25680145
3: 0.4267265 0.9081736 0.08460265
4: 0.9911095 0.9982255 0.58550863
5: 0.7636040 0.8077694 0.86817355
---
13975: 0.6791180 0.4550585 0.66532759
13976: 0.4178541 0.8221420 0.37256608
13977: 0.2620478 0.3924319 0.48837719
13978: 0.9164300 0.9749997 0.69863341
13979: 0.7292026 0.2418850 0.19211121
```

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 = c("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 | ref_match_seq | snp_match_seq |
|----|------------|--|------------|---------------|---------------|
| 1: | rs10910078 | SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic | GARWTGTAGT | CTGGCGGATG | GGCGGGTGGC |
| 2: | rs10910078 | USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic | GTCACGTGAC | GGCGGATGGC | GCCACCCGCC |
| 3: | rs4486391 | SIX5_GM12878_encode-Myers_seq_hsa_r1:MEME#1#Intergenic | GARWTGTAGT | CTCGTTTAGG | CTCGTATAGG |
| 4: | rs4486391 | USF2_K562_encode-Snyder_seq_hsa_r1:MDscan#1#Intergenic | GTCACGTGAC | TAAACGAGAG | CTCGTATAGG |

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

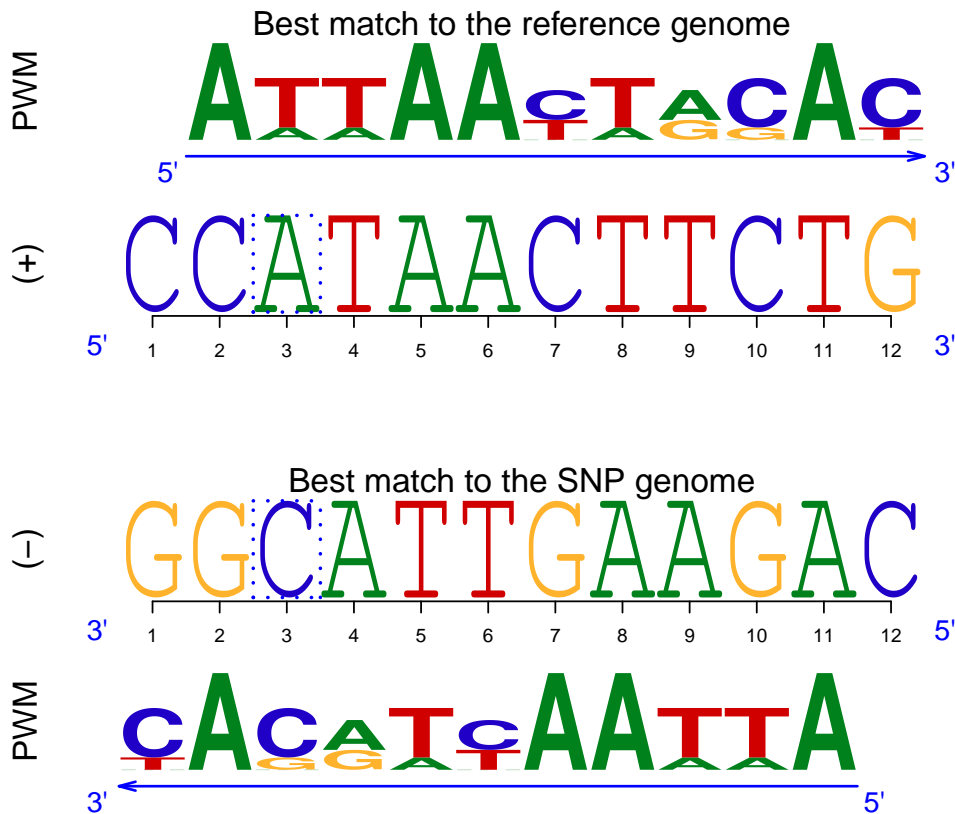
```
> plotMotifMatch(snp.tbl = motif_scores$snp.tbl,
+               motif.scores = motif_scores$motif.scores,
+               snpid = motif_scores$snp.tbl$snpid[50],
```

```

+         motif.lib = motif_library,
+         motif = motif_scores$motif.scores$motif[1])

```

AFP1_transfac_M00616 Motif 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_1.4.1 | 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.
- [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.
- [Zuo et al., 2014] Zuo, C., Shin, S., and Keleş, S. (2014). atsnp: affinity test for regulatory snp detection. *Bioinformatics*, Submitted.