

An Introduction to the *REMP* Package

Yinan Zheng

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1 Introduction

REMP predicts DNA methylation of locus-specific repetitive elements (RE) by learning surrounding genetic and epigenetic information. *REMP* provides genomewide single-base resolution of DNA methylation on RE that are difficult to measure using array-based or sequencing-based platforms, which enables epigenome-wide association study (EWAS) and differentially methylated region (DMR) analysis on RE.

2 Installation

Install *REMP* (release version):

```
> if (!requireNamespace("BiocManager", quietly=TRUE))
+   install.packages("BiocManager")
> BiocManager::install("REMP")
```

To install devel version:

```
> library(devtools)
> install_github("YinanZheng/REMP")
```

Load *REMP* into the workspace:

```
> library(REMP)
```

3 REMP: Repetitive Element Methylation Prediction

Currently *REMP* supports Human (hg19, build 37) Alu and LINE-1 (L1) repetitive element (RE) methylation prediction using Illumina 450k or EPIC array.

3.1 Groom methylation data

Appropriate data preprocessing including quality control and normalization of methylation data are recommended before running *REMP*. Many packages are available to carry out these data preprocessing steps, for example, *minfi*, *wateRmelon*, and *methylumi*.

REMP is trying to minimize the requirement of the methylation data format. User can maintain the methylation data in *RatioSet* or *GenomicRatioSet* object offered by *minfi*, *data.table*, *data.frame*, *DataFrame*, or *matrix*. User can input either beta value or M-value. There are only two basic requirements of the methylation data:

1. Each row should represent CpG probe and each column should represent sample.
2. The row names should indicate Illumina probe ID (i.e. cg00000029).

However, there are some other common data issues that may prevent *REMP* from running correctly. For example, if the methylation data are in beta value and contain zero methylation values, logit transformation (to create M-value) will create negative infinite value; or the methylation data contain NA, Inf, or NaN data. To tackle these potential issues, *REMP* includes a handy function `groomMethy` which can help detect and fix these issues. We highly recommend to take advantage of this function:

```
> # Get GM12878 methylation data (450k array)
> GM12878_450k <- getGM12878('450k')
> GM12878_450k <- groomMethy(GM12878_450k, verbose = TRUE)
> GM12878_450k
```

```
class: RatioSet
dim: 482421 1
metadata(0):
assays(2): Beta M
rownames(482421): cg00000029 cg00000108 ...
  cg27666046 cg27666123
rowData names(0):
colnames(1): GM12878
colData names(0):
Annotation
  array: IlluminaHumanMethylation450k
  annotation: ilmn12.hg19
Preprocessing
  Method: NA
  minfi version: NA
  Manifest version: NA
```

For zero beta values, `groomMethy` will replace them with smallest non-zero beta value. For NA/NaN/Inf values, `groomMethy` will treat them as missing values and then apply KNN-imputation to complete the dataset. If the imputed value is out of the original range (which is possible when `imputebyrow = FALSE`), mean value will be used instead. Warning: imputed values for multimodal distributed CpGs (across samples) may not be correct. Please check package *ENmix* to identify the CpGs with multimodal distribution.

3.2 Prepare annotation data

To run *REMP* for RE methylation prediction, user first needs to prepare some annotation datasets. The function `initREMP` is designed to do the job.

Suppose user will predict Alu methylation using Illumina 450k array data:

```
> data(Alu.demo)
> remparcel <- initREMP(arrayType = "450k", REtype = "Alu",
+                       RE = Alu.demo, ncore = 1)
> remparcel
```

```

REMPParcel object
RE type: Alu
Illumina platform: 450k
Valid (max) Alu-CpG flanking window size: 1200
Number of RE: 500
Number of Alu-CpG: 5039

```

For demonstration, we only use 500 selected Alu sequence dataset which comes along with the package (`Alu.demo`). We specify `RE = Alu.demo`, so that the annotation dataset will be generated for the 500 selected Alu sequences. Most of the time, specifying `RE` is not necessary, as the function will fetch the complete RE sequence dataset from package *AnnotationHub* using `fetchRMSK`. User can also use this argument `RE` to provide customized RE dataset.

All data are stored in the *REMPParcel* object:

```
> saveParcel(remparcel)
```

It is recommended to specify a working directory using argument `work.dir` so that the data generated can be preserved for later use. Without specifying working directory, the annotation dataset will be created under the temporal directory `tempdir()` by default. User can also turn on the `export` parameter in `initREMP` to save the data automatically.

3.3 Run prediction

Once the annotation data are ready, user can pass the annotation data parcel to `remp` for prediction:

```
> remp.res <- remp(GM12878_450k, REtype = 'Alu',
+                 parcel = remparcel, ncore = 1, seed = 777)
```

If `parcel` is missing, `remp` will then try to search the *REMPParcel* data file in the directory indicated by `work.dir`. If `work.dir` is also missing, `remp` will try to search the *REMPParcel* data file in the temporal directory `tempdir()`.

By default, `remp` uses Random Forest (`method = 'rf'`) model (package *randomForest*) for prediction. Random Forest model is recommended because it offers more accurate prediction results and it automatically enables Quantile Regression Forest (Nicolai Meinshausen, 2006) for prediction reliability evaluation. `remp` constructs 19 predictors to carry out the prediction. For Random Forest model, the tuning parameter `param = 6` (i.e. `mtry` in *randomForest*) indicates how many predictors will be randomly selected for building the individual trees. The performance of random forest model is often relatively insensitive to the choice of `mtry`. Therefore, auto-tune will be turned off using random forest and `mtry` will be set to one third of the total number of predictors. It is recommended to specify a seed for reproducible prediction results.

`remp` will return a *REMPset* object, which inherits Bioconductor's *RangedSummarizedExperiment* class:

```
> remp.res

class: REMProduct
dim: 4808 1
metadata(8): REannotation RECpG ... GeneStats Seed
assays(3): rempB rempM rempQC
rownames: NULL
rowData names(1): RE.Index
colnames(1): GM12878
colData names(1): mtry

> # Display more detailed information
> details(remp.res)
```

```

RE type: Alu
Methylation profiling platform: 450k
Flanking window size: 1000

```

Prediction model: Random Forest
QC model: Quantile Regression Forest
Seed: 777
Covered 4808 CpG sites in 500 Alu

Number of Alu-CpGs by chromosome:
chr1 chr2 chr3 chr4 chr5 chr6 chr7 chr8
449 276 293 131 179 397 292 102

chr9 chr10 chr11 chr12 chr13 chr14 chr15 chr16
98 148 254 310 66 127 133 333

chr17 chr18 chr19 chr20 chr21 chr22
295 81 674 66 37 67

Training information:
500 profiled Alu by Illumina array are used for model training.
481 Alu-CpGs that have at least 2 neighboring profiled CpGs are used for model training.

Coverage information:
The data cover 500 Alu (4808 Alu-CpG).
Gene coverage by Alu (out of total refSeq Gene):
491 (1.97%) total genes;
412 (2.15%) protein-coding genes;
117 (1.61%) non-coding RNA genes.

Distribution of methylation value (beta value):
Min. 1st Qu. Median Mean 3rd Qu.
0.02863991 0.47292396 0.66163240 0.59516869 0.75087661
Max.
0.91751710

Distribution of reliability score:
Min. 1st Qu. Median Mean 3rd Qu. Max.
0.7081759 1.4716562 1.7806435 1.8045190 2.0601828 5.5515113

Prediction results can be obtained by accessors:

```
> # Predicted RE-CpG methylation value (Beta value)  
> rempB(remp.res)
```

DataFrame with 4808 rows and 1 column

```
GM12878  
<numeric>  
1 0.762548492185931  
2 0.786434831446939  
3 0.79666176746634  
4 0.798956900836377  
5 0.802273142748572  
... ..  
4804 0.457207371201251  
4805 0.455784429984156  
4806 0.464893976714092  
4807 0.488337254009915  
4808 0.494143836886228
```

```

> # Predicted RE-CpG methylation value (M value)
> rempM(remp.res)

DataFrame with 4808 rows and 1 column
      GM12878
      <numeric>
1      1.68319616740516
2      1.88065085089043
3      1.97008583786597
4      1.9906128638398
5      2.02058465603234
...
4804    -0.247552465688
4805   -0.255826591051544
4806   -0.202923034313283
4807   -0.0673153532644647
4808   -0.0337961753585477

> # Genomic location information of the predicted RE-CpG
> # Function inherit from class 'RangedSummarizedExperiment'
> rowRanges(remp.res)

GRanges object with 4808 ranges and 1 metadata column:
      seqnames      ranges strand | RE.Index
      <Rle>      <IRanges> <Rle> | <Rle>
[1]   chr1      943927-943928   - | Alu_0000527
[2]   chr1      943935-943936   - | Alu_0000527
[3]   chr1      943968-943969   - | Alu_0000527
[4]   chr1      943974-943975   - | Alu_0000527
[5]   chr1      943991-943992   - | Alu_0000527
...
[4804] chr22 42095154-42095155   - | Alu_1170175
[4805] chr22 42095161-42095162   - | Alu_1170175
[4806] chr22 42095170-42095171   - | Alu_1170175
[4807] chr22 42095198-42095199   - | Alu_1170175
[4808] chr22 42095214-42095215   - | Alu_1170175
-----
seqinfo: 93 sequences from an unspecified genome; no seqlengths

> # Standard error-scaled permutation importance of predictors
> rempImp(remp.res)

DataFrame with 19 rows and 1 column
      GM12878
      <numeric>
RE.score      8.36613279966251
RE.Length     6.84053610788701
RE.CpG.density 5.8717675475121
RE.InNM       3.03960195679988
RE.InNR       0.380957538732081
...
distance.min2 13.0322390406927
Methy.min     29.6257004832198
Methy.min2    10.9247996545647
Methy.mean    13.1614780450285
Methy.std     3.84384295430559

```

```
> # Retrieve seed number used for the results
> metadata(remp.res)$Seed
```

```
[1] 777
```

Trim off less reliable predicted results:

```
> # Any predicted CpG values with quality score less than
> # threshold (default = 1.7) will be replaced with NA.
> # CpGs contain more than missingRate * 100% (default = 20%)
> # missing rate across samples will be discarded.
> remp.res <- rempTrim(remp.res, threshold = 1.7, missingRate = 0.2)
> details(remp.res)
```

```
RE type: Alu
Methylation profiling platform: 450k
Flanking window size: 1000
Prediction model: Random Forest - trimmed (1.7)
QC model: Quantile Regression Forest
Seed: 777
Covered 2108 CpG sites in 392 Alu
```

Number of Alu-CpGs by chromosome:

```
chr1 chr2 chr3 chr4 chr5 chr6 chr7 chr8
 215  112  136   73   68  195  135  47

chr9 chr10 chr11 chr12 chr13 chr14 chr15 chr16
  42   80   83  111   22   96   34  182

chr17 chr18 chr19 chr20 chr21 chr22
 141   22  252   34   5   23
```

Coverage information:

```
The data cover 392 Alu (2108 Alu-CpG).
Gene coverage by Alu (out of total refSeq Gene):
 374 (1.5%) total genes;
 309 (1.61%) protein-coding genes;
 87 (1.2%) non-coding RNA genes.
```

Distribution of methylation value (beta value):

```
Min.      1st Qu.      Median      Mean      3rd Qu.
0.06787361 0.67150056 0.74474992 0.70472716 0.79304945
Max.
0.91614817
```

Distribution of reliability score:

```
Min.      1st Qu.      Median      Mean      3rd Qu.      Max.
0.7081759 1.3043792 1.4360032 1.4239904 1.5735525 1.6999412
```

Aggregate the predicted methylation of CpGs in RE by averaging them to obtain the RE-specific methylation level:

```
> remp.res <- rempAggregate(remp.res, NCpG = 2)
> details(remp.res)
```

```

RE type: Alu (aggregated by mean: min # of CpGs: 2)
Methylation profiling platform: 450k
Flanking window size: 1000
Prediction model: Random Forest - trimmed (1.7)
QC model: Quantile Regression Forest
Seed: 777
Covered 294 Alu (aggregated by mean: min # of CpGs: 2)

```

Number of Alu (aggregated by mean: min # of CpGs: 2) by chromosome:

```

chr1 chr2 chr3 chr4 chr5 chr6 chr7 chr8
  28  17  19  11   7  30  20   8

chr9 chr10 chr11 chr12 chr13 chr14 chr15 chr16
   5  13  11  17   3  10   6  22

chr17 chr18 chr19 chr20 chr21 chr22
  16   5  37   5   1   3

```

Coverage information:

```

The data cover 294 Alu (aggregated by mean: min # of CpGs: 2)
Gene coverage by Alu (aggregated by mean: min # of CpGs: 2) (out of total refSeq Gene):
  270 (1.08%) total genes;
  222 (1.16%) protein-coding genes;
   63 (0.87%) non-coding RNA genes.

```

Distribution of methylation value (beta value):

```

      Min.    1st Qu.    Median      Mean    3rd Qu.
0.08808764 0.63681297 0.72739245 0.68464465 0.78314998
      Max.
0.90178841

```

Distribution of reliability score:

```

      Min.    1st Qu.    Median      Mean    3rd Qu.      Max.
0.7106647 1.3567023 1.4457255 1.4374719 1.5440432 1.6962858

```

It is recommended to aggregate the predicted CpG methylation by RE to obtain RE-wise methylation level. This is beneficial because 1) it greatly reduces the data dimension for downstream analysis and 2) it produces more robust RE methylation estimation. Note that by default, RE with 2 or more predicted CpG sites will be aggregated. Therefore, the downside of doing this is the reduced coverage of RE. The assumption of doing this is the CpG methylation level within each RE are similar.

To add genomic regions annotation of the predicted REs:

```

> # By default gene symbol annotation will be added
> remp.res <- decodeAnnot(remp.res)
> rempAnnot(remp.res)

```

GRanges object with 294 ranges and 10 metadata columns:

```

      seqnames      ranges strand |      name
      <Rle>        <IRanges> <Rle> | <character>
[1]    chr1      943896-944203   - |    AluSq2
[2]    chr1     1197026-1197260   - |      AluY
[3]    chr1     6265537-6265810   - |    AluSz
[4]    chr1     7914008-7914123   + |    AluJb
[5]    chr1    12039040-12039314   + |    AluJr
...      ...                ...   ... .      ...

```

[290]	chr20	57413692-57413996	+		AluSz
[291]	chr21	34146037-34146235	-		AluSx
[292]	chr22	22987350-22987681	-		AluY
[293]	chr22	24103787-24104072	+		AluSx1
[294]	chr22	27050687-27050975	-		AluY
	score	Index	InNM.symbol		
	<numeric>	<Rle>	<character>		
[1]	2417	Alu_0000527	<NA>		
[2]	1697	Alu_0000636	UBE2J2		
[3]	2092	Alu_0002477	RNF207		
[4]	1680	Alu_0003481	UTS2		
[5]	1328	Alu_0007823	MFN2		
...		
[290]	2424	Alu_1136815	GNAS		
[291]	1107	Alu_1144838	PAXBP1		
[292]	2378	Alu_1156182	GGTLC2		
[293]	1980	Alu_1156753	C22orf15		
[294]	2468	Alu_1158731	<NA>		
	InNR.symbol	InTSS.symbol	In5UTR.symbol		
	<character>	<character>	<character>		
[1]	<NA>	<NA>	<NA>		
[2]	<NA>	<NA>	<NA>		
[3]	<NA>	RNF207	<NA>		
[4]	<NA>	UTS2	<NA>		
[5]	<NA>	MFN2	<NA>		
...		
[290]	GNAS-AS1	GNAS	<NA>		
[291]	PAXBP1 C21orf62-AS1	PAXBP1	<NA>		
[292]	POM121L1P	POM121L1P GGTLC2	GGTLC2		
[293]	<NA>	C22orf15	<NA>		
[294]	<NA>	<NA>	<NA>		
	InCDS.symbol	InExon.symbol	In3UTR.symbol		
	<character>	<character>	<character>		
[1]	<NA>	<NA>	<NA>		
[2]	UBE2J2	<NA>	<NA>		
[3]	<NA>	<NA>	<NA>		
[4]	<NA>	<NA>	<NA>		
[5]	<NA>	<NA>	<NA>		
...		
[290]	<NA>	<NA>	<NA>		
[291]	<NA>	<NA>	<NA>		
[292]	<NA>	<NA>	<NA>		
[293]	<NA>	<NA>	<NA>		
[294]	<NA>	<NA>	<NA>		

seqinfo: 93 sequences (1 circular) from hg19 genome

Seven genomic region indicators will be added to the annotation data in the input *REMP* object:

- InNM: in protein-coding genes (overlap with refSeq gene's "NM" transcripts + 2000 bp upstream of the transcription start site (TSS))
- InNR: in noncoding RNA genes (overlap with refSeq gene's "NR" transcripts + 2000 bp upstream of the TSS)
- InTSS: in flanking region of 2000 bp upstream of the TSS. Default upstream limit is 2000 bp, which can be modified globally using `remp_options`

- In5UTR: in 5'untranslated regions (UTRs)
- InCDS: in coding DNA sequence regions
- InExon: in exon regions
- In3UTR: in 3'UTRs

Note that intron region and intergenic region information can be derived from the above genomic region indicators: if "InNM" and/or "InNR" is not missing but "InTSS", "In5UTR", "InExon", and "In3UTR" are missing, then the RE is strictly located within intron region; if all indicators are missing, then the RE is strictly located in intergenic region.

3.4 Plot prediction

Make a density plot of the predicted methylation (beta values):

```
> plot(remp.res, main = "Alu methylation (GM12878)", col = "blue")
```

4 Extract RE-CpG methylation profiled by Illumina BeadChip array

REMP offers a handy tool to extract methylation data of CpGs that are located in RE.

```
> # Use Alu.demo for demonstration
> remp.res <- remprofile(GM12878_450k, REtype = "Alu", RE = Alu.demo)
> details(remp.res)
```

```
RE type: Alu
Methylation profiling platform: 450k
Flanking window size: N/A
Prediction model: Profiled
QC model: N/A
Covered 594 CpG sites in 500 Alu
```

Number of Alu-CpGs by chromosome:

```
chr1 chr2 chr3 chr4 chr5 chr6 chr7 chr8
  51  38  39  20  21  61  39  13

chr9 chr10 chr11 chr12 chr13 chr14 chr15 chr16
  11  22  25  31   8  15  21  34

chr17 chr18 chr19 chr20 chr21 chr22
  28  11  82  11   4   9
```

Coverage information:

```
The data cover 500 Alu (594 Alu-CpG).
Gene coverage by Alu (out of total refSeq Gene):
  491 (1.97%) total genes;
  412 (2.15%) protein-coding genes;
  117 (1.61%) non-coding RNA genes.
```

Distribution of methylation value (beta value):

```
Min. 1st Qu. Median Mean 3rd Qu. Max.
0.0010000 0.4232500 0.6695000 0.6052828 0.8280000 0.9710000
```

```
> # All accessors and utilites for REMProduct are applicable
> remp.res <- rempAggregate(remp.res)
> details(remp.res)
```

```
RE type: Alu (aggregated by mean: min # of CpGs: 2)
Methylation profiling platform: 450k
Flanking window size: N/A
Prediction model: Profiled
QC model: N/A
Covered 75 Alu (aggregated by mean: min # of CpGs: 2)
```

Number of Alu (aggregated by mean: min # of CpGs: 2) by chromosome:

```
chr1 chr2 chr3 chr4 chr5 chr6 chr7 chr8
  5   7   6   3   3  11   5   1

chr10 chr11 chr12 chr13 chr14 chr15 chr16 chr17
  1   1   4   1   2   4   3   1

chr18 chr19 chr20 chr22
```

3 11 2 1

Coverage information:

The data cover 75 Alu (aggregated by mean: min # of CpGs: 2)

Gene coverage by Alu (aggregated by mean: min # of CpGs: 2) (out of total refSeq Gene):

86 (0.34%) total genes;
71 (0.37%) protein-coding genes;
17 (0.23%) non-coding RNA genes.

Distribution of methylation value (beta value):

	Min.	1st Qu.	Median	Mean	3rd Qu.
	0.04713393	0.42243309	0.66087749	0.59936950	0.83849455
Max.	0.92886423				

5 Session Information

R version 3.5.2 (2018-12-20)

Platform: x86_64-pc-linux-gnu (64-bit)

Running under: Ubuntu 16.04.5 LTS

Matrix products: default

BLAS: /home/biocbuild/bbs-3.8-bioc/R/lib/libRblas.so

LAPACK: /home/biocbuild/bbs-3.8-bioc/R/lib/libRlapack.so

locale:

[1]	LC_CTYPE=en_US.UTF-8	LC_NUMERIC=C
[3]	LC_TIME=en_US.UTF-8	LC_COLLATE=C
[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]	parallel	stats4	stats	graphics	grDevices
[6]	utils	datasets	methods	base	

other attached packages:

[1]	REMP_1.6.1
[2]	IlluminaHumanMethylationEPICanno.ilm10b2.hg19_0.6.0
[3]	IlluminaHumanMethylation450kanno.ilmn12.hg19_0.6.0
[4]	minfi_1.28.3
[5]	bumphunter_1.24.5
[6]	locfit_1.5-9.1
[7]	iterators_1.0.10
[8]	foreach_1.4.4
[9]	Biostrings_2.50.2
[10]	XVector_0.22.0
[11]	SummarizedExperiment_1.12.0
[12]	DelayedArray_0.8.0
[13]	BiocParallel_1.16.5
[14]	matrixStats_0.54.0
[15]	Biobase_2.42.0

[16] GenomicRanges_1.34.0
[17] GenomeInfoDb_1.18.1
[18] IRanges_2.16.0
[19] S4Vectors_0.20.1
[20] BiocGenerics_0.28.0
[21] knitr_1.21

loaded via a namespace (and not attached):

[1] AnnotationHub_2.14.2
[2] plyr_1.8.4
[3] lazyeval_0.2.1
[4] splines_3.5.2
[5] ggplot2_3.1.0
[6] digest_0.6.18
[7] htmltools_0.3.6
[8] magrittr_1.5
[9] memoise_1.1.0
[10] BSgenome_1.50.0
[11] doParallel_1.0.14
[12] limma_3.38.3
[13] recipes_0.1.4
[14] readr_1.3.1
[15] annotate_1.60.0
[16] gower_0.1.2
[17] siggenes_1.56.0
[18] prettyunits_1.0.2
[19] colorspace_1.3-2
[20] blob_1.1.1
[21] xfun_0.4
[22] dplyr_0.7.8
[23] settings_0.2.4
[24] crayon_1.3.4
[25] RCurl_1.95-4.11
[26] genefilter_1.64.0
[27] impute_1.56.0
[28] bindr_0.1.1
[29] GEOquery_2.50.5
[30] survival_2.43-3
[31] glue_1.3.0
[32] registry_0.5
[33] gtable_0.2.0
[34] ipred_0.9-8
[35] zlibbioc_1.28.0
[36] kernlab_0.9-27
[37] Rhdf5lib_1.4.2
[38] HDF5Array_1.10.1
[39] scales_1.0.0
[40] DBI_1.0.0
[41] rngtools_1.3.1
[42] bibtex_0.4.2
[43] Rcpp_1.0.0
[44] xtable_1.8-3
[45] progress_1.2.0
[46] bit_1.1-14

[47] mclust_5.4.2
[48] preprocessCore_1.44.0
[49] lava_1.6.4
[50] prodlim_2018.04.18
[51] httr_1.4.0
[52] RColorBrewer_1.1-2
[53] pkgconfig_2.0.2
[54] reshape_0.8.8
[55] XML_3.98-1.16
[56] nnet_7.3-12
[57] caret_6.0-81
[58] tidymodels_0.2.5
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