

MotifDb

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Abstract

Many kinds of biological activity are regulated by the binding of proteins to their cognate substrates. Of particular interest is the sequence-specific binding of transcription factors to DNA, often in regulatory regions just upstream of the transcription start site of a gene. These binding events play a pivotal role in regulating gene expression. Sequence specificity among closely related binding sites is nearly always incomplete: some variety in the DNA sequence is routinely observed. For this reason, these inexact binding sequence patterns are commonly described as *motifs* represented numerically as frequency matrices, and visualized as sequence logos. Despite their importance in current research, there has been until now no single, annotated, comprehensive collection of publicly available motifs. The current package provides such a collection, offering more than two thousand annotated matrices from multiple organisms, within the context of the Bioconductor project. The matrices can be filtered and selected on the basis of their metadata, used with other Bioconductor packages (MotIV for motif comparison, seqLogo for visualization) or easily exported for use with standard software and websites such as those provided by the MEME Suite¹.

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1 Introduction and Basic Operations

The first step is to load the necessary packages:

```
> library (MotifDb)
> library (MotIV)
> library (seqLogo)
```

There are more than two thousand matrices, from five sources:

```
> length (MotifDb)
```

[1] 8369

```
> sort (table (values (MotifDb)$dataSource), decreasing=TRUE)
```

¹<http://meme.sdsc.edu/meme/doc/meme.html>

jaspar2016	HOCOMOCOv10	cispb_1.02	jolma2013	SwissRegulon
1209	1066	874	843	684
stamlab	FlyFactorSurvey	JASPAR_2014	JASPAR_CORE	hPDI
683	614	592	459	437
UniPROBE	HOMER	ScerTF		
380	332	196		

And 22 organisms (though the majority of the matrices come from just four):

```
> sort (table (values (MotifDb)$organism), decreasing=TRUE)
```

Hsapiens	Mmusculus	Dmelanogaster	Scerevisiae	Athaliana
4094	1251	1147	876	351
Celegans	Pfalciparum	Rnorvegicus	Zmays	Vertebrata
67	28	28	19	17
Ncrassa	Psativum	Amajus	Ddiscoideum	Anidulans
15	10	9	9	8
Ppatens	Osativa	Xlaevis	Ggallus	Drerio
7	5	5	4	3
Gallus	Hroretzi	Hvulgare	Ocuniculus	Phybrida
3	3	3	3	3
Rrattus	Taestivam	Bdistachyon	Cparvum	Csativa
3	3	2	2	2
Nsylvestris	Otauri	Acarolinensis	Apisum	Aterreus
2	2	1	1	1
Gaculeatus	Hcapsulatum	Mdomestica	Mgallopavo	Mmurinus
1	1	1	1	1
Mtruncatula	Ngruberi	Nhaematococca	Nsp.	Nvectensis
1	1	1	1	1
Pcapensis	Ppygmaeus	Ptetraurelia	Tthermophila	Vvinifera
1	1	1	1	1
Xtropicalis				
1				

With these categories of metadata

```
> colnames (values (MotifDb))
```

```
[1] "providerName" "providerId" "dataSource" "geneSymbol"
[5] "geneId" "geneIdType" "proteinId" "proteinIdType"
[9] "organism" "sequenceCount" "bindingSequence" "bindingDomain"
[13] "tfFamily" "experimentType" "pubmedID"
```

2 Selection

There are three ways to extract subsets of interest from the MotifDb collection. All three operate upon the MotifDb metadata, matching values in one or more of those fifteen attributes (listed just above), and returning the subset of MotifDb which meet the specified criteria. The three techniques: *query*, *subset* and *grep*

2.1 query

This is the simplest technique to use, and will suffice in many circumstances. For example, if you want all of the human matrices:

```
> query (MotifDb, 'hsapiens')
```

```
MotifDb object of length 4094
| Created from downloaded public sources: 2013-Aug-30
| 4094 position frequency matrices from 10 sources:
|   HOCOMOCOv10: 640
|   JASPAR_2014: 117
|   JASPAR_CORE: 66
|   SwissRegulon: 684
|   UniPROBE: 2
|   cispb_1.02: 313
|   hPDI: 437
|   jaspar2016: 442
|   jolma2013: 710
|   stamlab: 683
| 1 organism/s
|   Hsapiens: 4094
```

```

Hsapiens-jolma2013-BCL6B
Hsapiens-jolma2013-CTCF
Hsapiens-jolma2013-EGR1
Hsapiens-jolma2013-EGR1-2
Hsapiens-jolma2013-EGR2
...
Hsapiens-stamlab-UW.Motif.0681
Hsapiens-stamlab-UW.Motif.0682
Hsapiens-stamlab-UW.Motif.0683
Hsapiens-UniPROBE-Sox4.UP00401
Hsapiens-UniPROBE-Oct_1.UP00399

```

If you want all matrices associated with *Sox* transcription factors, regardless of dataSource or organism:

```

> query (MotifDb, 'sox')

MotifDb object of length 157
| Created from downloaded public sources: 2013-Aug-30
| 157 position frequency matrices from 10 sources:
|   FlyFactorSurvey: 2
|   HOCOMOCOv10: 25
|   HOMER: 9
|   JASPAR_2014: 8
|   JASPAR_CORE: 5
|   SwissRegulon: 19
|   UniPROBE: 15
|   ...
|   hPDI: 2
|   jaspar2016: 16
|   jolma2013: 56
| 6 organism/s
|   Hsapiens: 87
|   Mmusculus: 57
|   Dmelanogaster: 2
|   Rnorvegicus: 1
|   Vertebrata: 1
|   other: 9
Hsapiens-SwissRegulon-SOX10.SwissRegulon
Hsapiens-SwissRegulon-SOX11.SwissRegulon
Hsapiens-SwissRegulon-SOX12.SwissRegulon
Hsapiens-SwissRegulon-SOX13.SwissRegulon
Hsapiens-SwissRegulon-SOX14.SwissRegulon
...
Hsapiens-jaspar2016-SOX4-MA0867.1
Hsapiens-jaspar2016-SOX8-MA0868.1
Mmusculus-jaspar2016-Sox11-MA0869.1
Mmusculus-jaspar2016-Sox1-MA0870.1
Hsapiens-jaspar2016-SRY-MA0084.1

```

For all yeast transcription factors with a homeo domain

```

> query (query (MotifDb, 'cerevisiae'), 'homeo')

MotifDb object of length 28
| Created from downloaded public sources: 2013-Aug-30
| 28 position frequency matrices from 4 sources:
|   JASPAR_2014: 10
|   JASPAR_CORE: 10
|   UniPROBE: 4
|   jaspar2016: 4
| 1 organism/s
|   Scerevisiae: 28
Scerevisiae-UniPROBE-Cup9.UP00308
Scerevisiae-UniPROBE-Matalpha2.UP00307
Scerevisiae-UniPROBE-Pho2.UP00268
Scerevisiae-UniPROBE-Yox1.UP00274
Scerevisiae-JASPAR_CORE-CUP9-MA0288.1
...
Scerevisiae-JASPAR_2014-YOX1-MA0433.1
Scerevisiae-jaspar2016-CUP9-MA0288.1
Scerevisiae-jaspar2016-HMRA2-MA0318.1
Scerevisiae-jaspar2016-MATALPHA2-MA0328.1
Scerevisiae-jaspar2016-TOS8-MA0408.1

```

The last example may inspire more confidence in the precision of the result than is justified, and for a couple of reasons. First, the assignment of protein binding domains to specific categories is, as of 2012, an ad hoc and incomplete process. Second, the query commands matches the supplied character string to *all* metadata columns. In this case, 'homeo' appears both in the *bindingDomain* column and the *tfFamily* column, and the above *query* will return matches from both. Searching and filtering should always be accompanied by close scrutiny of the data, such as these commands illustrate:

```
> unique (grep ('homeo', values(MotifDb)$bindingDomain, ignore.case=T, v=T))

[1] "Homeobox"           "Hox9_act;Homeobox"
[3] "LIM;Homeobox"       "PAX;Homeobox"
[5] "OAR;Homeobox"       "Pou;Homeobox"
[7] "Distant similarity to homeodomain" "Homeo"
[9] "Homeo, PAX"         "Homeo, POU"

> unique (grep ('homeo', values(MotifDb)$tfFamily, ignore.case=T, v=T))
```

```
[1] "Homeo"
[2] "Homeo::Nuclear Factor I-CCAAT-binding"
[3] "Homeodomain"
[4] "Paired plus homeo domain"
[5] "TALE-type homeo domain factors"
[6] "homeodomain"
```

2.2 grep

This selection method (and the next, *subset*) require that you address metadata columns explicitly. This is a little more work, but the requisite direct engagement with the metadata is worthwhile. Repeating the 'query' examples from above, you can see how more knowledge of MotifDb metadata is required.

```
> mdb.human <- MotifDb [grep ('Hsapiens', values (MotifDb)$organism)]
> mdb.sox <- MotifDb [grep ('sox', values (MotifDb)$geneSymbol, ignore.case=TRUE)]
> yeast.indices = grepl ('scere', values (MotifDb)$organism, ignore.case=TRUE)
> homeo.indices.domain = grepl ('homeo', values (MotifDb)$bindingDomain, ignore.case=TRUE)
> homeo.indices.family = grepl ('homeo', values (MotifDb)$tfFamily, ignore.case=TRUE)
> yeast.homeo.indices = yeast.indices & (homeo.indices.domain | homeo.indices.family)
> yeast.homeoDb = MotifDb [yeast.homeo.indices]
```

An alternate and somewhat more compact approach:

```
> yeast.homeo.indices <- with(values(MotifDb),
+   grepl('scere', organism, ignore.case=TRUE) &
+   (grepl('homeo', bindingDomain, ignore.case=TRUE) |
+   grepl('homeo', tfFamily, ignore.case=TRUE)))
>
```

2.3 subset

MotifDb::subset emulates the R base data.frame *subset* command, which is not unlike an SQL select function. Unfortunately – and just like the R base subset function – this MotifDb method cannot be used reliably within a script: *It is only reliable when called interactively*. Here, with mixed success (as you will see) , we use MotifDb::subset to reproduce the *query* and *grep* selections shown above.

```
> if (interactive ())
+   subset (MotifDb, organism=='Hsapiens')
```

One can easily find all the 'sox' genes with the subset command, avoiding possible upper/lower case conflicts by passing the metadata's geneSymbol column through the function 'tolower':

```
> if (interactive ())
+   subset (MotifDb, tolower (geneSymbol) == 'sox4')
```

Similarly, subset has limited application for a permissive 'homeo' search. But for the retrieval by explicitly specified search terms, subset works very well:

```
> if (interactive ())
+   subset (MotifDb, organism=='Scerevisiae' & bindingDomain=='Homeo')
```

2.4 The Egr1 Case Study

We now do a simple geneSymbol search, followed by an examination of the sub-MotifDb the search returns. We are looking for all matrices associated with the well-known and highly conserved zinc-finger transcription factor, Egr1. There are two of these in MotifDb, both from mouse, and each from a different data source.

```
> # subset is convenient:
> if (interactive ())
+   as.list (subset (MotifDb, tolower (geneSymbol) == 'egr1'))
> # grep returns indices which allow for more flexibility
> indices = grep ('egr1', values (MotifDb)$geneSymbol, ignore.case=TRUE)
> length (indices)
```

```
[1] 13
```

There are a variety of ways to examine and extract data from this object, a MotifList of length 2.

```
> MotifDb [indices]
```

MotifDb object of length 13
| Created from downloaded public sources: 2013-Aug-30
| 13 position frequency matrices from 8 sources:
|
| HOCOMOCOv10: 3
| HOMER: 1
| JASPAR_2014: 1
| JASPAR_CORE: 1
| SwissRegulon: 1
| UniPROBE: 1
| jasper2016: 2
| jolma2013: 3
| 3 organism/s
|
| Hsapiens: 7
| Mmusculus: 5
| other: 1
Hsapiens-SwissRegulon-EGR1.SwissRegulon
Hsapiens-HOCOMOCOv10-EGR1_HUMAN.H10MO.A
Hsapiens-HOCOMOCOv10-EGR1_HUMAN.H10MO.S
Mmusculus-HOCOMOCOv10-EGR1_MOUSE.H10MO.A
NA-HOMER-Egr1(Zf)/K562-Egr1-ChIP-Seq(GSE32465)/Homer
...
Hsapiens-jasper2016-EGR1-MA0162.2
Hsapiens-jolma2013-EGR1
Hsapiens-jolma2013-EGR1-2
Mmusculus-jolma2013-Egr1
Mmusculus-UniPROBE-Egr1.UP00007

Now view the matrices as a named list:

```
> as.list (MotifDb [indices])
```

\$`Hsapiens-SwissRegulon-EGR1.SwissRegulon`
1 2 3 4 5 6 7 8 9 10
A 0.20000000 0.13333333 0.00000000 0 0.0 0.2 0.06666667 0 0.13333333 0
C 0.26666667 0.06666667 0.86666667 0 0.0 0.0 0.00000000 0 0.66666667 0
G 0.06666667 0.80000000 0.00000000 1 0.2 0.8 0.93333333 1 0.00000000 1
T 0.46666667 0.00000000 0.13333333 0 0.8 0.0 0.00000000 0 0.20000000 0
11
A 0.06666667
C 0.00000000
G 0.46666667
T 0.46666667

\$`Hsapiens-HOCOMOCOv10-EGR1_HUMAN.H10MO.A`
1 2 3 4 5 6 7 8 9 10 11 12 13
A 0.190 0.208 0.212 0.270 0.222 0.116 0.168 0.042 0.034 0.160 0.008 0.032 0.262
C 0.192 0.206 0.144 0.140 0.074 0.082 0.484 0.042 0.008 0.006 0.000 0.038 0.452
G 0.438 0.446 0.452 0.468 0.380 0.756 0.050 0.808 0.452 0.804 0.976 0.914 0.006
T 0.180 0.140 0.192 0.122 0.324 0.046 0.298 0.108 0.506 0.030 0.016 0.016 0.280
14 15 16 17 18
A 0.180 0.072 0.236 0.278 0.218
C 0.012 0.012 0.092 0.098 0.184
G 0.750 0.774 0.534 0.458 0.490
T 0.058 0.142 0.138 0.166 0.108

```
$`Hsapiens-HOCOMOCOv10-EGR1_HUMAN.H10MO.S`  
1 2 3 4 5 6 5
```

```

A 0.1515633 0.04398516 0.05988341 0.003709592 0.009538951 0.07578166
C 0.1886592 0.06041335 0.82829889 0.001059883 0.013248543 0.01907790
G 0.3184950 0.88288288 0.01854796 0.993640700 0.490726020 0.90196078
T 0.3412825 0.01271860 0.09326974 0.001589825 0.486486486 0.00317965
7 8 9 10 11
A 0.025437202 0.01218866 0.089030207 0.021727610 0.09062003
C 0.065712772 0.01006889 0.748277689 0.007419184 0.06518283
G 0.900900901 0.97774245 0.007419184 0.955484897 0.60943296
T 0.007949126 0.00000000 0.155272920 0.015368309 0.23476418

$`Mmusculus-HOCOMOCOv10-EGR1_MOUSE.H10MD.A`
1 2 3 4 5 6
A 0.1515633 0.04398516 0.05988341 0.003709592 0.009538951 0.07578166
C 0.1886592 0.06041335 0.82829889 0.001059883 0.013248543 0.01907790
G 0.3184950 0.88288288 0.01854796 0.993640700 0.490726020 0.90196078
T 0.3412825 0.01271860 0.09326974 0.001589825 0.486486486 0.00317965
7 8 9 10 11
A 0.025437202 0.01218866 0.089030207 0.021727610 0.09062003
C 0.065712772 0.01006889 0.748277689 0.007419184 0.06518283
G 0.900900901 0.97774245 0.007419184 0.955484897 0.60943296
T 0.007949126 0.00000000 0.155272920 0.015368309 0.23476418

$`NA-HOMER-Egr1(Zf)/K562-Egr1-ChIP-Seq(GSE32465)/Homer`
1 2 3 4 5 6 7 8 9 10
A 0.128 0.078 0.154 0.001 0.001 0.027 0.001 0.001 0.153 0.034
C 0.072 0.036 0.523 0.001 0.001 0.001 0.002 0.001 0.415 0.002
G 0.142 0.882 0.023 0.997 0.282 0.971 0.973 0.997 0.010 0.940
T 0.658 0.004 0.300 0.001 0.716 0.001 0.024 0.001 0.422 0.024

$`Mmusculus-JASPAR_CORE-Egr1-MA0162.1`
1 2 3 4 5 6 7 8 9 10
A 0.20000000 0.13333333 0.00000000 0 0 0 0.2 0.06666667 0 0.13333333 0
C 0.26666667 0.06666667 0.86666667 0 0 0 0 0.00000000 0 0.66666667 0
G 0.06666667 0.80000000 0.00000000 1 0.2 0.8 0.93333333 1 0.00000000 1
T 0.46666667 0.00000000 0.13333333 0 0.8 0.0 0.00000000 0 0.20000000 0
11
A 0.06666667
C 0.00000000
G 0.46666667
T 0.46666667

$`Hsapiens-JASPAR_2014-EGR1-MA0162.2`
1 2 3 4 5 6 7 8
A 0.08958877 0.1228786 0.09464752 0.10892624 0.01901110 0.2375163 0 0.00000000
C 0.46736292 0.5586651 0.49355418 0.85109334 0.94435379 0.00000000 1 0.96703655
G 0.25155026 0.1108845 0.18358355 0.00000000 0.00000000 0.5580940 0 0.00000000
T 0.19149804 0.2075718 0.22821475 0.03998042 0.03663512 0.2043897 0 0.03296345
9 10 11 12 13 14
A 0.00000000 0.29797650 0.00000000 0.1932115 0.00000000 0.2468995
C 0.82849217 0.68219648 0.97519582 0.00000000 0.80360640 0.4565111
G 0.04985313 0.00000000 0.00000000 0.5384302 0.11586162 0.1560868
T 0.12165470 0.01982702 0.02480418 0.2683584 0.08053198 0.1405026

$`Mmusculus-jaspar2016-Egr1-MA0162.1`
1 2 3 4 5 6 7 8 9 10
A 0.20000000 0.13333333 0.00000000 0 0 0 0.2 0.06666667 0 0.13333333 0
C 0.26666667 0.06666667 0.86666667 0 0 0 0 0.00000000 0 0.66666667 0
G 0.06666667 0.80000000 0.00000000 1 0.2 0.8 0.93333333 1 0.00000000 1
T 0.46666667 0.00000000 0.13333333 0 0.8 0.0 0.00000000 0 0.20000000 0
11
A 0.06666667
C 0.00000000
G 0.46666667
T 0.46666667

$`Hsapiens-jaspar2016-EGR1-MA0162.2`
1 2 3 4 5 6 7 8
A 0.08958877 0.1228786 0.09464752 0.10892624 0.01901110 0.2375163 0 0.00000000
C 0.46736292 0.5586651 0.49355418 0.85109334 0.94435379 0.00000000 1 0.96703655
G 0.25155026 0.1108845 0.18358355 0.00000000 0.00000000 0.5580940 0 0.00000000
T 0.19149804 0.2075718 0.22821475 0.03998042 0.03663512 0.2043897 0 0.03296345
9 10 11 12 13 14
A 0.00000000 0.29797650 0.00000000 0.1932115 0.00000000 0.2468995
C 0.82849217 0.68219648 0.97519582 0.00000000 0.80360640 0.4565111
G 0.04985313 0.00000000 0.00000000 0.5384302 0.11586162 0.1560868
T 0.12165470 0.01982702 0.02480418 0.2683584 0.08053198 0.1405026

$`Hsapiens-jolma2013-EGR1`
1 2 3 4 5 6
A 0.2494781 0.51390568 0.003223727 0.105202754 0.000000000 0.002604167
C 0.2411273 0.39540508 0.969696970 0.005355777 0.980025773 0.992838542
G 0.1539666 0.03627570 0.007736944 0.854246366 0.007731959 0.000000000
T 0.3554280 0.05441354 0.019342360 0.035195103 0.012242268 0.004557292
7 8 9 10 11 12 13
A 0.000000000 0.652638191 0.003253090 0.01906158 0.010000 0.68089431 0.2790573
C 0.928214732 0.343592965 0.995445673 0.01136364 0.938125 0.06910569 0.2485270
G 0.009363296 0.000000000 0.000000000 0.93181818 0.011875 0.14227642 0.1253348

```

```

T 0.062421973 0.003768844 0.001301236 0.03775660 0.040000 0.10772358 0.3470809
14
A 0.2673936
C 0.1905504
G 0.1396677
T 0.4023884

$`Hsapiens-jolma2013-EGR1-2`
      1      2      3      4 5      6      7
A 0.2722977 0.737507906 0.006723716 0.01834431 0 0.000000000 0.0000000
C 0.2309510 0.249209361 0.987775061 0.00000000 1 0.992159228 0.9797136
G 0.1139988 0.001897533 0.001833741 0.98165569 0 0.000000000 0.0000000
T 0.3827525 0.011385199 0.003667482 0.00000000 0 0.007840772 0.0202864
      8      9      10      11      12      13
A 0.795439739 0.000000000 0.000000000 0.00000000 0.86166008 0.29390244
C 0.200000000 0.9993943065 0.000000000 0.99220156 0.01317523 0.27926829
G 0.004560261 0.000000000 0.9990732159 0.00000000 0.10540184 0.06341463
T 0.000000000 0.0006056935 0.0009267841 0.00779844 0.01976285 0.36341463
14
A 0.3035714
C 0.1255952
G 0.1077381
T 0.4630952

$`Mmusculus-jolma2013-Egr1`
      1      2      3      4      5      6
A 0.3231418 0.32278481 0.618181818 0.000000000 0.075444498 0.000000000
C 0.3241961 0.30907173 0.366753247 0.9968454259 0.004324844 0.9994728519
G 0.1133368 0.03691983 0.003636364 0.0005257624 0.911100432 0.0005271481
T 0.2393253 0.33122363 0.011428571 0.0026288118 0.009130226 0.000000000
      7 8      9      10      11      12      13
A 0.001578117 0 0.517114271 0.003149606 0.00422833 0.001579779 0.89181562
C 0.997369805 1 0.481305951 0.995275591 0.16732105 0.998420221 0.05738476
G 0.001052078 0 0.001579779 0.000000000 0.25581395 0.000000000 0.03621825
T 0.000000000 0 0.000000000 0.001574803 0.57263667 0.000000000 0.01458137
      14      15      16
A 0.44251055 0.31170886 0.26213080
C 0.32278481 0.19778481 0.31012658
G 0.04957806 0.04272152 0.09651899
T 0.18512658 0.44778481 0.33122363

$`Mmusculus-UniPROBE-Egr1.UP00007`
      1      2      3      4      5      6
A 0.2115466 0.14198757 0.03260499 0.11512588 0.003516173 0.004715059
C 0.2827083 0.72243721 0.87717185 0.07060553 0.990021152 0.982482238
G 0.2034722 0.05485440 0.01243161 0.78128969 0.002264928 0.009896878
T 0.3022730 0.08072082 0.07779155 0.03297890 0.004197748 0.002905824
      7      8      9      10      11      12
A 0.001626612 0.262351637 0.005889514 0.02289301 0.02303758 0.56763334
C 0.975937323 0.731731673 0.985755764 0.09046006 0.85994854 0.05739392
G 0.001661635 0.002729558 0.002081402 0.64932246 0.03791264 0.16679165
T 0.020774430 0.003187133 0.006273319 0.23732447 0.07910124 0.20818108
      13      14
A 0.1765973 0.1830489
C 0.3312648 0.1837744
G 0.1253083 0.2267928
T 0.3668295 0.4063840

```

and finally, the metadata associated with these two matrices, transposed, for easy reading and comparison:

```

> noquote (t (as.data.frame (values (MotifDb [indices]))))

providerName      [,1]
providerId        EGR1.SwissRegulon
dataSource        SwissRegulon
geneSymbol        EGR1
geneId            <NA>
geneIdType        <NA>
proteinId         <NA>
proteinIdType     UNIPROT
organism          Hsapiens
sequenceCount     15
bindingSequence   <NA>
bindingDomain     <NA>
tfFamily          <NA>
experimentType    low- and high-throughput methods
pubmedID          19377474
                  [,2]
providerName      EGR1_HUMAN.H10MO.A
providerId        EGR1_HUMAN.H10MO.A
dataSource        HOCOMOCOv10
geneSymbol        EGR1
geneId            <NA>

```

geneIdType	<NA>	
proteinId	P18146	
proteinIdType	UNIPROT	
organism	Hsapiens	
sequenceCount	500	
bindingSequence	<NA>	
bindingDomain	<NA>	
tffamily	<NA>	
experimentType	low- and high-throughput methods	
pubmedID	26586801	
	[,3]	
providerName	EGR1_HUMAN.H10M0.S	
providerId	EGR1_HUMAN.H10M0.S	
dataSource	HOCOMOCOv10	
geneSymbol	EGR1	
geneId	<NA>	
geneIdType	<NA>	
proteinId	P18146	
proteinIdType	UNIPROT	
organism	Hsapiens	
sequenceCount	1887	
bindingSequence	<NA>	
bindingDomain	<NA>	
tffamily	<NA>	
experimentType	low- and high-throughput methods	
pubmedID	26586801	
	[,4]	
providerName	EGR1_MOUSE.H10M0.A	
providerId	EGR1_MOUSE.H10M0.A	
dataSource	HOCOMOCOv10	
geneSymbol	EGR1	
geneId	<NA>	
geneIdType	<NA>	
proteinId	P08046	
proteinIdType	UNIPROT	
organism	Mmusculus	
sequenceCount	1887	
bindingSequence	<NA>	
bindingDomain	<NA>	
tffamily	<NA>	
experimentType	low- and high-throughput methods	
pubmedID	26586801	
	[,5]	
providerName	Egr1(Zf)/K562-Egr1-ChIP-Seq(GSE32465)/Homer	
providerId	Egr1(Zf)/K562-Egr1-ChIP-Seq(GSE32465)/Homer	
dataSource	HOMER	
geneSymbol	Egr1	
geneId	<NA>	
geneIdType	<NA>	
proteinId	?query=Egr1(Zf)_K562-Egr1-ChIP-Seq(GSE32465)	
proteinIdType	UNIPROT	
organism	<NA>	
sequenceCount	1	
bindingSequence	<NA>	
bindingDomain	<NA>	
tffamily	<NA>	
experimentType	low- and high-throughput methods	
pubmedID	26586801	
	[,6]	[,7]
providerName	Egr1	EGR1
providerId	MA0162.1	MA0162.2
dataSource	JASPAR_CORE	JASPAR_2014
geneSymbol	Egr1	EGR1
geneId	13653	1958
geneIdType	ENTREZ	ENTREZ
proteinId	P08046	P18146
proteinIdType	UNIPROT	UNIPROT
organism	Mmusculus	Hsapiens
sequenceCount	15	12256
bindingSequence	<NA>	<NA>
bindingDomain	Zinc-coordinating	Zinc-coordinating
tffamily	BetaBetaAlpha-zinc finger	BetaBetaAlpha-zinc finger
experimentType	bacterial 1-hybrid	ChIP-seq
pubmedID	16041365	16041365
	[,8]	
providerName	MA0162.1	
providerId	MA0162.1	
dataSource	jaspar2016	
geneSymbol	Egr1	
geneId	<NA>	
geneIdType	<NA>	
proteinId	P08046	
proteinIdType	UNIPROT	
organism	Mmusculus	
sequenceCount	15	
bindingSequence	<NA>	
bindingDomain	<NA>	

ttfamily	BetaBetaAlpha-zinc finger	
experimentType	bacterial 1-hybrid	
pubmedID	24194598	
	[,9]	
providerName	MA0162.2	
providerId	MA0162.2	
dataSource	jaspar2016	
geneSymbol	EGR1	
geneId	<NA>	
geneIdType	<NA>	
proteinId	P18146	
proteinIdType	UNIPROT	
organism	Hsapiens	
sequenceCount	12256	
bindingSequence	<NA>	
bindingDomain	<NA>	
ttfamily	Three-zinc finger Krppel-related factors	
experimentType	ChIP-seq	
pubmedID	24194598	
	[,10]	[,11]
providerName	Hsapiens-jolma2013-EGR1	Hsapiens-jolma2013-EGR1-2
providerId	EGR1	EGR1
dataSource	jolma2013	jolma2013
geneSymbol	EGR1	EGR1
geneId	1958	1958
geneIdType	ENTREZ	ENTREZ
proteinId	<NA>	<NA>
proteinIdType	<NA>	<NA>
organism	Hsapiens	Hsapiens
sequenceCount	1831	1703
bindingSequence	NMCGCCCMCGCANN	NACGCCACGCANN
bindingDomain	<NA>	<NA>
ttfamily	C2H2	C2H2
experimentType	SELEX	SELEX
pubmedID	23332764	23332764
	[,12]	[,13]
providerName	Mmusculus-jolma2013-Egr1	SCI09/Egr1_pwm_primary.txt
providerId	Egr1	UP00007
dataSource	jolma2013	UniPROBE
geneSymbol	Egr1	Egr1
geneId	1958	13653
geneIdType	ENTREZ	ENTREZ
proteinId	<NA>	P08046
proteinIdType	<NA>	UNIPROT
organism	Mmusculus	Mmusculus
sequenceCount	2013	<NA>
bindingSequence	NNMCGCCCMCTCANN	<NA>
bindingDomain	<NA>	ZnF_C2H2
ttfamily	C2H2	<NA>
experimentType	SELEX	protein binding microarray
pubmedID	23332764	19443739

We used the *grep* function above to find rows in the metadata table whose *geneSymbol* column includes the string 'Egr1'. If you wish to identify matrices (and/or their attendant metadata) based upon a richer combination of criteria, for instance:

1. organism (*Mmusculus*)
2. gene symbol (*Egr1*)
3. data source (*JASPAR_CORE*)

the *grep* solution, while serviceable, becomes a little awkward:

```
> geneSymbol.rows = grep ('Egr1', values (MotifDb)$geneSymbol, ignore.case=TRUE)
> organism.rows = grep ('Mmusculus', values (MotifDb)$organism, ignore.case=TRUE)
> source.rows = grep ('JASPAR', values (MotifDb)$dataSource, ignore.case=TRUE)
> egr1.mouse.jaspar.rows = intersect (geneSymbol.rows,
+                                     intersect (organism.rows, source.rows))
> print (egr1.mouse.jaspar.rows)
```

[1] 4358 5512

```
> egr1.motif <- MotifDb [egr1.mouse.jaspar.rows]
```

Far more concise, and fully reliable as an interactive command (though *not* if used in a script²):

²See the help page of the base R command *subset* for detail), is the *subset* command

```
> if (interactive ()) {
+   egr1.motif <- subset (MotifDb, organism=='Mmusculus' &
+                         dataSource=='JASPAR_CORE' &
+                         geneSymbol=='Egr1')
+ }
```

Whichever method you use, this next chunk of code displays the matrix, and then the metadata for mouse JASPAR Egr1, the latter textually-transformed for easy reading within the size constraints of this page.

```
> egr1.motif

MotifDb object of length 2
| Created from downloaded public sources: 2013-Aug-30
| 2 position frequency matrices from 2 sources:
|   JASPAR_CORE: 1
|   jasper2016: 1
| 1 organism/s
|   Mmusculus: 2
Mmusculus-JASPAR_CORE-Egr1-MA0162.1
Mmusculus-jasper2016-Egr1-MA0162.1

> as.list (egr1.motif)

$`Mmusculus-JASPAR_CORE-Egr1-MA0162.1`
      1      2      3 4      5      6      7 8      9 10
A 0.20000000 0.13333333 0.0000000 0 0.0 0.2 0.06666667 0 0.1333333 0
C 0.26666667 0.06666667 0.8666667 0 0.0 0.0 0.00000000 0 0.6666667 0
G 0.06666667 0.80000000 0.0000000 1 0.2 0.8 0.93333333 1 0.0000000 1
T 0.46666667 0.00000000 0.1333333 0 0.8 0.0 0.00000000 0 0.2000000 0
      11
A 0.06666667
C 0.00000000
G 0.46666667
T 0.46666667

$`Mmusculus-jasper2016-Egr1-MA0162.1`
      1      2      3 4      5      6      7 8      9 10
A 0.20000000 0.13333333 0.0000000 0 0.0 0.2 0.06666667 0 0.1333333 0
C 0.26666667 0.06666667 0.8666667 0 0.0 0.0 0.00000000 0 0.6666667 0
G 0.06666667 0.80000000 0.0000000 1 0.2 0.8 0.93333333 1 0.0000000 1
T 0.46666667 0.00000000 0.1333333 0 0.8 0.0 0.00000000 0 0.2000000 0
      11
A 0.06666667
C 0.00000000
G 0.46666667
T 0.46666667

> noquote (t (as.data.frame (values (egr1.motif))))

      [,1]      [,2]
providerName Egr1      MA0162.1
providerId   MA0162.1  MA0162.1
dataSource   JASPAR_CORE jasper2016
geneSymbol   Egr1      Egr1
geneId       13653     <NA>
geneIdType   ENTREZ    <NA>
proteinId    P08046     P08046
proteinIdType UNIPROT   UNIPROT
organism      Mmusculus Mmusculus
sequenceCount 15        15
bindingSequence <NA>    <NA>
bindingDomain  Zinc-coordinating <NA>
tfFamily       BetaBetaAlpha-zinc finger BetaBetaAlpha-zinc finger
experimentType bacterial 1-hybrid bacterial 1-hybrid
pubmedID       16041365 24194598
```

Next we use the bioconductor *seqLogo* package to display this motif.

```
> seqLogo (as.list (egr1.motif)[[1]])
```

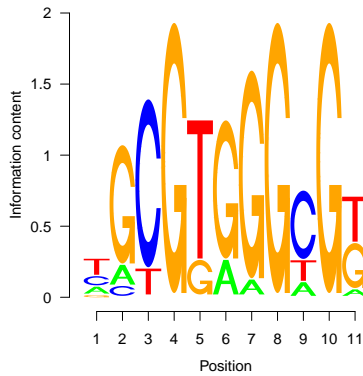


Figure 1: Mmusculus-JASPAR_CORE-Egr1-MA0162.1

3 Motif Matching

We will look for the ten position frequency matrices which are the best match to JASPAR's mouse EGR1, using the MotIV package. We actually request the top eleven hits from the entire MotifDb, since the first hit should be the target matrix itself, since that is of necessity found in the full MotifDb.

```
> egr1.hits <- motifMatch (as.list (egr1.motif) [1], as.list (MotifDb), top=11)
```

```
Ungapped Alignment
Scores read
Database read
Motif matches : 11
```

```
> # 'MotIV.toTable' -- defined above (and hidden) -- will become part of MotIV in the upcoming release
> tbl.hits <- MotIV.toTable (egr1.hits)
> print (tbl.hits)
```

		name	eVal
1		Hsapiens-SwissRegulon-EGR1.SwissRegulon	1.110223e-16
2		Mmusculus-JASPAR_CORE-Egr1-MA0162.1	1.110223e-16
3		Mmusculus-jaspar2016-Egr1-MA0162.1	1.110223e-16
4		Hsapiens-jaspar2016-EGR2-MA0472.2	3.330669e-16
5		Hsapiens-jolma2013-EGR2	3.330669e-16
6		Hsapiens-SwissRegulon-EGR2.SwissRegulon	5.218048e-15
7	NA-HOMER-Egr2(Zf)/Thymocytes-Egr2-ChIP-Seq(GSE34254)/Homer		5.218048e-15
8		Hsapiens-HOCOMOCOv10-EGR2_HUMAN.H10MO.C	9.880985e-15
9		Mmusculus-HOCOMOCOv10-EGR2_MOUSE.H10MO.C	9.880985e-15
10		Hsapiens-HOCOMOCOv10-EGR1_HUMAN.H10MO.S	1.287859e-14
11		Mmusculus-HOCOMOCOv10-EGR1_MOUSE.H10MO.A	1.287859e-14
	sequence	match	strand
1	NGCGTGGGCGK	NGCGTGGGCGK	+
2	NGCGTGGGCGK	NGCGTGGGCGK	+
3	NGCGTGGGCGK	NGCGTGGGCGK	+
4	NGCGTGGGCGK	TGCGTGGGCGK	-
5	NGCGTGGGCGK	TGCGTGGGCGK	-
6	NGCGTGGGCGK-	NGYGTGGGYGKN	+
7	NGCGTGGGCGK-	NGYGTGGGYGKN	+
8	NGCGTGGGCGK	NGNGTGGGCGG	+
9	NGCGTGGGCGK	NGNGTGGGCGG	+
10	NGCGTGGGCGK	NGCGKGGGCGG	+
11	NGCGTGGGCGK	NGCGKGGGCGG	+

The *sequence* column in this table is the *consensus sequence* – with heterogeneity left out – for the matrix it describes.

Puzzling: the strand of the match reported above is opposite of what I expected, and opposite of what seqLogo displays. This is a question for the MotIV developers.

The six logos appear below, beginning with the logo of the query matrix, *Mmusculus-JASPAR_CORE-Egr1-MA0162.1*,

including two other mouse matrices, and two zinc-finger fly matrices. Examining the three mouse matrices and their metadata reveals that all three (geneSymbol differences aside) describe the same protein:

```
> if (interactive ())
+   noquote (t (as.data.frame (subset (values (MotifDb), geneId=='13653'))))
```

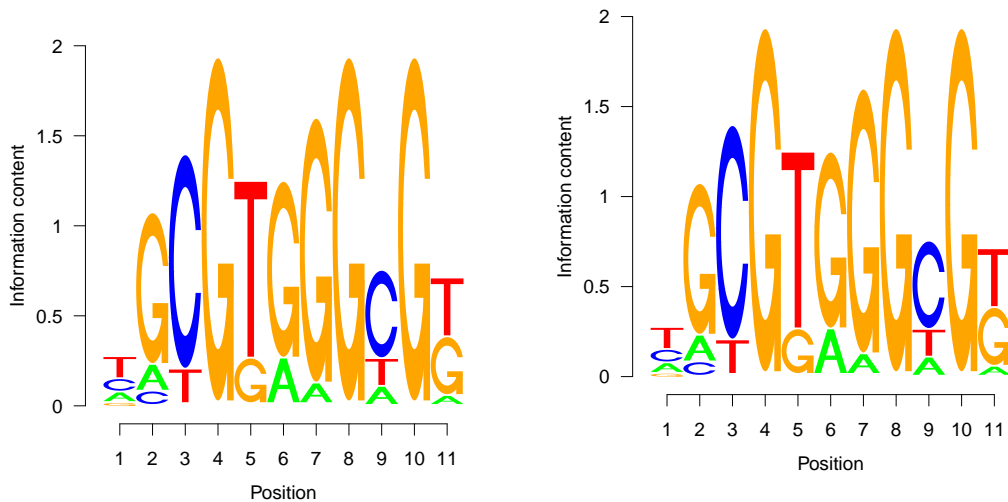
Zinc finger protein domains are classified into many *fold groups*; their respective cognate DNA sequence may classify similarly. That two fly matrices significantly match three reports of the mouse Egr1 motif suggests impressive conservation of this binding pattern, or convergent evolution.

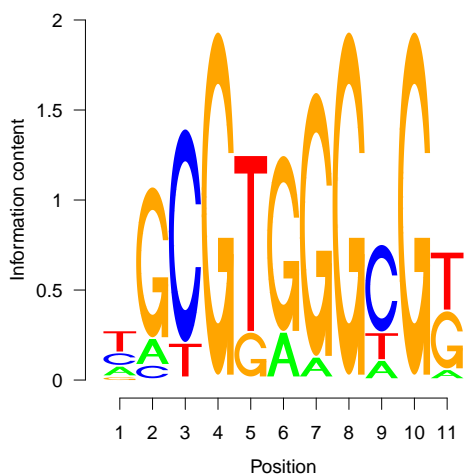
Let us look at the metadata for the first fly match, whose geneId is **FBgn0003499**:

```
> noquote (t (as.data.frame (values (MotifDb)[grep ('FBgn0003499', values (MotifDb)$geneId),])))
```

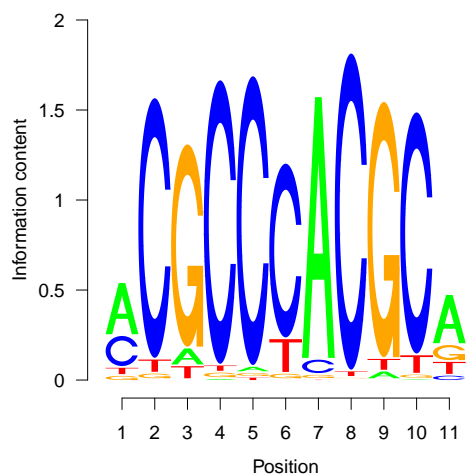
```
providerName
providerId
dataSource
geneSymbol
geneId
geneIdType
proteinId
proteinIdType
organism
sequenceCount
bindingSequence
bindingDomain
tfFamily
experimentType
pubmedID
```

that the SOLEXA motif, based upon 2316 sequences, did not (in work not shown, it appears 22nd in the an expanded motifMatch hit list, with a eval of 10e-5). It is possible that the SOLEXA motif is more accurate, and that a close examination of this case, including sequence logos, position frequency matrices, and the search parameters of motifMatch, will be instructive. Repeating the search with *tomtom* might also be illuminating – either as confirmation of MotIV and the default parameterization we used, or as a correction to it. Here we see the facilities for exploratory data analysis MotifDb provides, and the opportunities for data analysis which result.

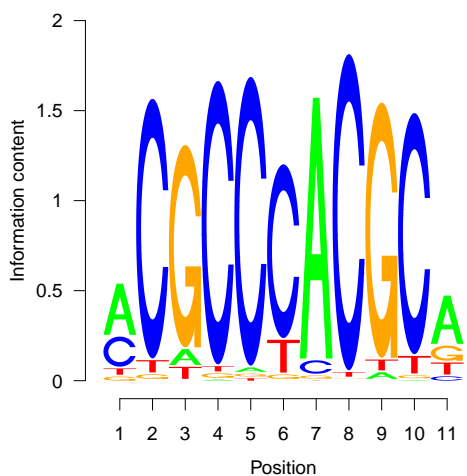




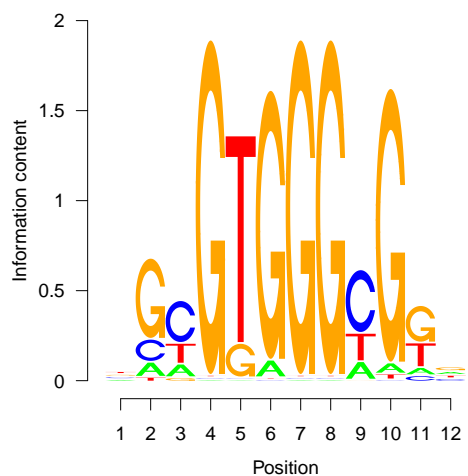
(a) Mmusculus-UniPROBE-Zif268.UP00400



(b) Dme-FFS-klu_SANGER_10.FBgn0013469



(a) Mmusculus-UniPROBE-Egr1.UP00007



(b) Dme-FFS-klu_SOLEXA_5.FBgn0013469

4 Exporting to the MEME Suite

Some users of this package may wish to export the data – both matrices and metadata – so that they may be used in other programs. The MEME suite, among others, is broadly useful, continuously improved and well-regarded throughout the bioinformatics community. The code below exports all of the MotifDb matrices as a text file in the MEME format, and all of the metadata as a tab-delimited text file.

```
> matrix.output.file = tempfile () # substitute your preferred filename here
> meme.text = export (MotifDb, matrix.output.file, 'meme')
> metadata.output.file = tempfile () # substitute your preferred filename here
> write.table (as.data.frame (values (MotifDb)), file=metadata.output.file, sep='\t',
+             row.names=TRUE, col.names=TRUE, quote=FALSE)
```

5 Future Work

This first version of MotifDb collects into one R package all of the best-known public domain protein-DNA binding matrices, with as much metadata as could be gleaned from the five providers. However, not all of these matrices are equally supported by data and by no means are all accompanied by complete metadata.

With the passage of time our knowledge of protein-DNA binding sequence motifs will improve. They will be derived from more binding events, with more precision and specificity, and accompanied by more (and better understood) contextual detail. Cooperative binding, mentioned only in a few times in the current (July 2012) version of this package, will be well-represented. Metadata will improve. Better assignment of binding domains to consensus categories will be especially useful when it is available. Three-dimensional models of specific proteins binding to specific DNA may someday become commonplace.

6 References

- Portales-Casamar E, Thongjuea S, Kwon AT, Arenillas D, Zhao X, Valen E, Yusuf D, Lenhard B, Wasserman WW, Sandelin A. JASPAR 2010: the greatly expanded open-access database of transcription factor binding profiles. *Nucleic Acids Res.* 2010 Jan;38(Database issue):D105-10. Epub 2009 Nov 11.
- Robasky K, Bulyk ML. UniPROBE, update 2011: expanded content and search tools in the online database of protein-binding microarray data on protein-DNA interactions. *Nucleic Acids Res.* 2011 Jan;39(Database issue):D124-8. Epub 2010 Oct 30.
- Spivak AT, Stormo GD. ScerTF: a comprehensive database of benchmarked position weight matrices for *Saccharomyces* species. *Nucleic Acids Res.* 2012 Jan;40(Database issue):D162-8. Epub 2011 Dec 2.
- Xie Z, Hu S, Blackshaw S, Zhu H, Qian J. hPDI: a database of experimental human protein-DNA interactions. *Bioinformatics.* 2010 Jan 15;26(2):287-9. Epub 2009 Nov 9.
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