

EnrichmentBrowser: seamless navigation through combined results of set-based and network-based enrichment analysis

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1 Introduction

The *EnrichmentBrowser* package implements essential functionality for the enrichment analysis of gene expression data. The analysis combines the advantages of set-based and network-based enrichment analysis to derive high-confidence gene sets and biological pathways that are differentially regulated in the expression data under investigation. Besides, the package facilitates the visualization and exploration of such sets and pathways.

The following instructions will guide you through an end-to-end expression data analysis workflow including:

1. Preparing the data
2. Preprocessing of the data
3. Differential expression (DE) analysis
4. Defining gene sets of interest
5. Executing individual enrichment methods
6. Combining the results of different methods
7. Visualize and explore the results

All of these steps are modular, i.e. each step can be executed individually and fine-tuned with several parameters. In case you are interested in a particular step, you can directly move on to the respective section. For example, if you have differential expression already calculated for each gene, and you are now interested whether certain gene

functions are enriched for differential expression, section *Set-based enrichment analysis* would be the one you should go for. The last section *Putting it all together* also demonstrates how to wrap the whole workflow into a single function, making use of suitably chosen defaults.

2 Reading expression data from file

Typically, the expression data is not already available in *R* but rather has to be read in from file. This can be done using the function `read.eset`, which reads the expression data (`exprs`) along with the phenotype data (`pData`) and feature data (`fData`) into an *ExpressionSet*.

```
> library(EnrichmentBrowser)
> data.dir <- system.file("extdata", package="EnrichmentBrowser")
> exprs.file <- file.path(data.dir, "exprs.tab")
> pdat.file <- file.path(data.dir, "pData.tab")
> fdat.file <- file.path(data.dir, "fData.tab")
> eset <- read.eset(exprs.file, pdat.file, fdat.file)
```

The man pages provide details on file format and the *ExpressionSet* data structure.

```
> ?read.eset
> ?ExpressionSet
```

3 Types of expression data

The two major data types processed by the *EnrichmentBrowser* are microarray (intensity measurements) and RNA-seq (read counts) data.

3.1 Microarray data

To demonstrate the functionality of the package for microarray data, we consider expression measurements of patients suffering from acute lymphoblastic leukemia [1]. A frequent chromosomal defect found among these patients is a translocation, in which parts of chromosome 9 and 22 swap places. This results in the oncogenic fusion gene BCR/ABL created by positioning the ABL1 gene on chromosome 9 to a part of the BCR gene on chromosome 22. We load the *ALL* dataset

```
> library(ALL)
> data(ALL)
```

and select B-cell ALL patients with and without the BCR/ABL fusion as it has been described previously [2].

```
> ind.bs <- grep("^B", ALL$BT)
> ind.mut <- which(ALL$mol.biol %in% c("BCR/ABL", "NEG"))
> sset <- intersect(ind.bs, ind.mut)
> all.eset <- ALL[, sset]
```

We can now access the expression values, which are intensity measurements on a log-scale for 12,625 probes (rows) across 79 patients (columns).

```
> dim(all.eset)
```

```
Features  Samples
 12625      79
```

```
> exprs(all.eset)[1:4,1:4]
```

```
           01005    01010    03002    04007
1000_at  7.597323  7.479445  7.567593  7.905312
1001_at  5.046194  4.932537  4.799294  4.844565
1002_f_at 3.900466  4.208155  3.886169  3.416923
1003_s_at 5.903856  6.169024  5.860459  5.687997
```

As we often have more than one probe per gene, we compute gene expression values as the average of the corresponding probe values.

```
> all.eset <- probe.2.gene.eset(all.eset)
> head(featureNames(all.eset))
```

```
[1] "5595" "7075" "1557" "643"  "1843" "4319"
```

Note, that the mapping from probe to gene is done automatically as long as as you have the corresponding annotation package, here the *hgu95av2.db* package, installed. Otherwise, the mapping can be defined in the *fData* slot.

```
> head(fData(eset))
```

```
           PROBEID ENTREZID
1000_at  1000_at    5595
1010_at  1010_at    5600
1011_s_at 1011_s_at    7531
1013_at  1013_at    4090
1018_at  1018_at    7480
1021_at  1021_at    3458
```

3.2 RNA-seq data

To demonstrate the functionality of the package for RNA-seq data, we consider transcriptome profiles of four primary human airway smooth muscle cell lines in two conditions: control and treatment with dexamethasone [3].

We load the [airway](#) dataset

```
> library(airway)
> data(airway)
```

and create the *ExpressionSet*. For further analysis, we remove genes with very low read counts and measurements that are not mapped to an ENSEMBL gene ID.

```
> expr <- assays(airway)[[1]]
> expr <- expr[grepl("^ENSG", rownames(expr)),]
> expr <- expr[rowMeans(expr) > 10,]
> air.eset <- new("ExpressionSet", exprs=expr, annotation="hsa")
> dim(air.eset)
```

```
Features  Samples
  16055         8
```

```
> exprs(air.eset)[1:4,1:4]
```

	SRR1039508	SRR1039509	SRR1039512	SRR1039513
ENSG000000000003	679	448	873	408
ENSG000000000419	467	515	621	365
ENSG000000000457	260	211	263	164
ENSG000000000460	60	55	40	35

4 Normalization

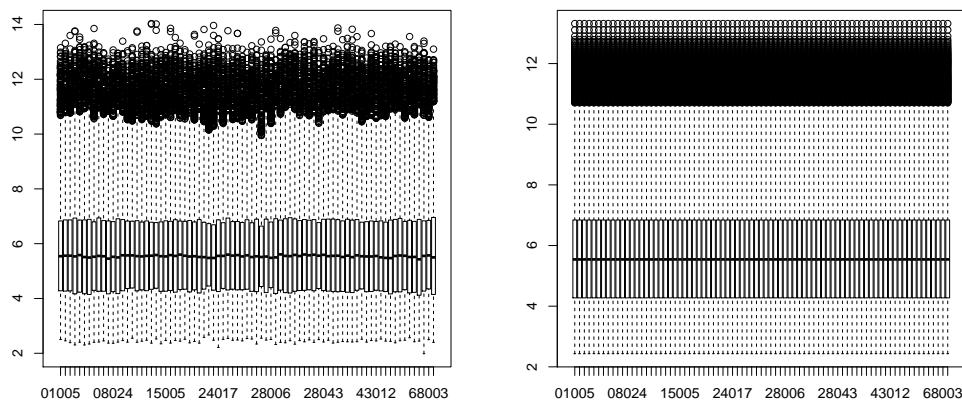
Normalization of high-throughput expression data is essential to make results within and between experiments comparable. Microarray (intensity measurements) and RNA-seq (read counts) data exhibit typically distinct features that need to be normalized for. The function `normalize` wraps commonly used functionality from [limma](#) for microarray normalization and from [EDASeq](#) for RNA-seq normalization. For specific needs that deviate from these standard normalizations, the user should always refer to more specific functions/packages.

Microarray data is expected to be single-channel. For two-color arrays, it is expected that normalization within arrays has been already carried out, e.g. using `normalizeWithinArrays` from [limma](#).

A default quantile normalization based on `normalizeBetweenArrays` from [limma](#) can be carried out via

```
> before.norm <- exprs(all.eset)
> all.eset <- normalize(all.eset, norm.method="quantile")
> after.norm <- exprs(all.eset)

> par(mfrow=c(1,2))
> boxplot(before.norm)
> boxplot(after.norm)
```



Note that this is only done for demonstration, as the ALL data has been already RMA-normalized by the authors of the ALL dataset.

RNA-seq data is expected to be raw read counts. Note that normalization for downstream DE analysis, e.g. with [edgeR](#) and [DESeq2](#), is not ultimately necessary (and in some cases even discouraged) as many of these tools implement specific normalization approaches themselves. See the vignette of [EDASeq](#), [edgeR](#), and [DESeq2](#) for details. In case normalization is desired, between-lane normalization to adjust for sequencing depth can be carried out as demonstrated for microarray data.

```
> norm.air <- normalize(air.eset, norm.method="quantile")
```

Within-lane normalization to adjust for gene-specific effects such as gene length and GC-content requires to retrieve this information first, e.g. from BioMart or specific *Bioconductor* annotation packages. Both modes are implemented in the [EDASeq](#) function `getGeneLengthAndGCCContent`.

```
> ids <- head(featureNames(air.eset))
> lgc <- EDASeq::getGeneLengthAndGCCContent(ids, org="hsa", mode="biomart")
```

Using precomputed information, normalization within and between lanes can be carried out via

```
> lgc.file <- file.path(data.dir, "air_lgc.tab")
> fData(air.eset) <- read.delim(lgc.file)
> norm.air <- normalize(air.eset, within=TRUE)
```

5 Differential expression

Differential expression analysis between sample groups can be performed using the function `de.ana`. As a prerequisite, the phenotype data should contain a binary group assignment for each patient. For the ALL dataset, this indicates whether the BCR-ABL gene fusion is present (1) or not (0).

```
> pData(all.eset)$GROUP <- ifelse(all.eset$mol.biol == "BCR/ABL", 1, 0)
> table(pData(all.eset)$GROUP)

0 1
42 37
```

For the airway dataset, this indicates whether the cell lines have been treated with dexamethasone (1) or not (0).

```
> pData(air.eset)$GROUP <- ifelse(colData(airway)$dex == "trt", 1, 0)
> table(pData(air.eset)$GROUP)

0 1
4 4
```

Paired samples, or in general sample batches/blocks, can be defined via a BLOCK column in the pData slot. For the airway dataset, the sample blocks correspond to the four different cell lines.

```
> pData(air.eset)$BLOCK <- colData(airway)$cell
> table(pData(air.eset)$BLOCK)

N052611 N061011 N080611 N61311
      2      2      2      2
```

For microarray expression data, the `de.ana` function carries out a differential expression analysis between the two groups based on functionality from the [limma](#) package. Resulting fold changes and *t*-test derived *p*-values for each gene are appended to the fData slot.

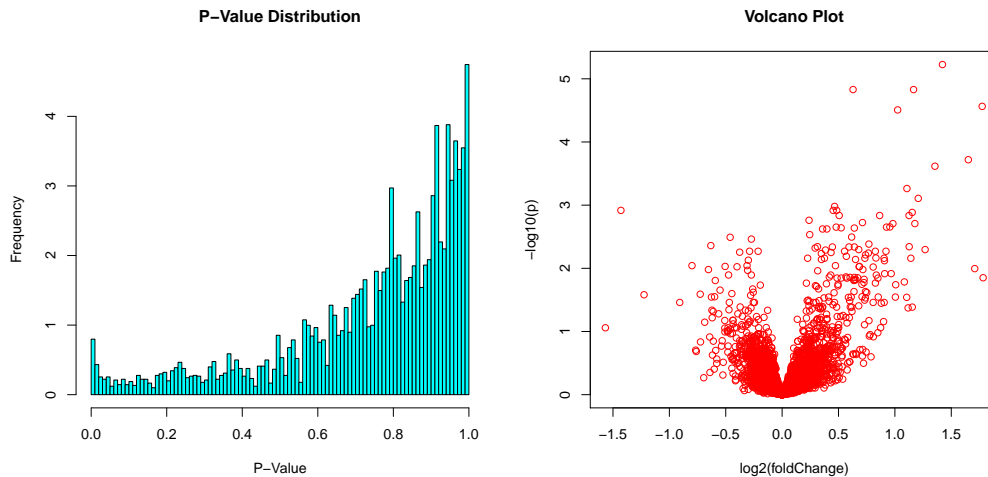
```
> all.eset <- de.ana(all.eset)
> head(fData(all.eset), n=4)

      FC  ADJ.PVAL limma.STAT
5595  0.03875186 0.8617572  0.6581366
7075  0.01731594 0.9589128  0.2456381
1557 -0.05078088 0.6831055 -1.2803378
643  -0.03061907 0.8610136 -0.6643163
```

Raw *p*-values are already corrected for multiple testing (ADJ.PVAL) using the method from Benjamini and Hochberg implemented in the function `p.adjust` from the [stats](#) package.

To get a first overview, we inspect the *p*-value distribution and the volcano plot (fold change against *p*-value).

```
> par(mfrow=c(1,2))
> pdistr(fData(all.eset)$ADJ.PVAL)
> volcano(fData(all.eset)$FC, fData(all.eset)$ADJ.PVAL)
```



The expression change of highest statistical significance is observed for the ENTREZ gene 7525.

```
> fData(all.eset)[ which.min(fData(all.eset)$ADJ.PVAL), ]
```

	FC	ADJ.PVAL	limma.STAT
7525	1.421695	5.944328e-06	7.019066

This turns out to be the YES proto-oncogene 1 ([hsa:7525@KEGG](#)).

For RNA-seq data, the `de.ana` function carries out a differential expression analysis between the two groups either based on functionality from [limma](#) (that includes the `voom` transformation), or alternatively, the popular [edgeR](#) or [DESeq2](#) package. Here, we use the analysis based on [edgeR](#) for demonstration.

```
> air.eset <- de.ana(air.eset, de.method="edgeR")
> head(fData(air.eset), n=4)
```

	length	gc	FC	ADJ.PVAL	edgeR.STAT
ENSG000000000003	8000	0.410	-0.40494563	0.002134583	35.87437100
ENSG000000000419	23656	0.398	0.18298543	0.091569195	5.90960620
ENSG000000000457	40886	0.403	0.01434777	0.922279475	0.02339233
ENSG000000000460	190985	0.392	-0.14117337	0.619013214	0.49292996

6 ID mapping

Using genomic information from different resources often requires mapping between different types of gene identifiers. Although primary analysis steps such as normalization and differential expression analysis can be carried out independent of the gene ID type, downstream exploration functionality of the [EnrichmentBrowser](#) is consistently based on NCBI Entrez Gene IDs. It is thus, in this regard, beneficial to initially map gene IDs of a different type to NCBI Entrez IDs.

The function `id.types` lists the available ID types for the mapping depending on the organism under investigation.

```
> id.types("hsa")

[1] "ACCNUM"      "ALIAS"      "ENSEMBL"    "ENSEMBLPROT" "ENSEMBLTRANS"
[6] "ENTREZID"    "ENZYME"     "EVIDENCE"   "EVIDENCEALL" "GENENAME"
[11] "GO"          "GOALL"      "IPI"        "MAP"          "OMIM"
[16] "ONTOLOGY"    "ONTOLOGYALL" "PATH"       "PFAM"         "PMID"
[21] "PROSITE"     "REFSEQ"     "SYMBOL"     "UCSCKG"       "UNIGENE"
[26] "UNIPROT"
```

ID mapping for the airway dataset (from ENSEMBL to ENTREZ gene ids) can then be carried out using the function `map.ids`.

```
> head(featureNames(air.eset))

[1] "ENSG000000000003" "ENSG000000000419" "ENSG000000000457" "ENSG000000000460"
[5] "ENSG000000000971" "ENSG00000001036"

> air.eset <- map.ids(air.eset, from="ENSEMBL", to="ENTREZID")
> head(featureNames(air.eset))

[1] "7105" "8813" "57147" "55732" "3075" "2519"
```

Now, we subject the ALL and the airway gene expression data to the enrichment analysis.

7 Set-based enrichment analysis

In the following, we introduce how the [EnrichmentBrowser](#) package can be used to perform state-of-the-art enrichment analysis of gene sets. We consider the ALL and the airway gene expression data as processed in the previous sections. We are now interested whether there are not only single genes that are differentially expressed, but also sets of genes known to work together, e.g. as defined in the Gene Ontology or the KEGG pathway annotation.

The function `get.kegg.genesets`, which is based on functionality from the [KEGGREST](#) package, downloads all KEGG pathways for a chosen organism as gene sets.

```
> kegg.gs <- get.kegg.genesets("hsa")
```

Analogously, the function `get.go.genesets` defines GO terms of a selected ontology as gene sets.

```
> go.gs <- get.go.genesets(org="hsa", onto="BP", mode="GO.db")
```

User-defined gene sets can be parsed from the GMT file format

```
> gmt.file <- file.path(data.dir, "hsa_kegg_gs.gmt")
> hsa.gs <- parse.genesets.from.GMT(gmt.file)
> length(hsa.gs)
```

```
[1] 39
```

```
> hsa.gs[1:2]
```

```
$hsa05416_Viral_myocarditis
```

```
[1] "100509457" "101060835" "1525"      "1604"      "1605"      "1756"      "1981"
[8] "1982"      "25"         "2534"      "27"         "3105"      "3106"      "3107"
[15] "3108"      "3109"      "3111"      "3112"      "3113"      "3115"      "3117"
[22] "3118"      "3119"      "3122"      "3123"      "3125"      "3126"      "3127"
[29] "3133"      "3134"      "3135"      "3383"      "3683"      "3689"      "3908"
[36] "4624"      "4625"      "54205"     "5551"      "5879"      "5880"      "5881"
[43] "595"       "60"         "637"       "6442"      "6443"      "6444"      "6445"
[50] "71"        "836"       "841"       "842"       "857"       "8672"      "940"
[57] "941"       "942"       "958"       "959"
```

```
$`hsa04622_RIG-I-like_receptor_signaling_pathway`
```

```
[1] "10010" "1147" "1432" "1540" "1654" "23586" "26007" "29110" "338376"
[10] "340061" "3439" "3440" "3441" "3442" "3443" "3444" "3445" "3446"
[19] "3447" "3448" "3449" "3451" "3452" "3456" "3467" "3551" "3576"
[28] "3592" "3593" "3627" "3661" "3665" "4214" "4790" "4792" "4793"
[37] "5300" "54941" "55593" "5599" "5600" "5601" "5602" "5603" "56832"
[46] "57506" "5970" "6300" "64135" "64343" "6885" "7124" "7186" "7187"
[55] "7189" "7706" "79132" "79671" "80143" "841" "843" "8517" "8717"
[64] "8737" "8772" "9140" "9474" "9636" "9641" "9755"
```

Currently, the following set-based enrichment analysis methods are supported

```
> sbea.methods()
```

```
[1] "ora"      "safe"      "gsea"      "samgs"      "ebm"      "mgsa"
[7] "gsa"      "padog"     "globaltest" "roast"      "camera"    "gsva"
```

- ORA: Overrepresentation Analysis (simple and frequently used test based on the hypergeometric distribution, see [4] for a critical review)
- SAFE: Significance Analysis of Function and Expression (resampling version of ORA, implements additional test statistics, e.g. Wilcoxon's rank sum, and allows to estimate the significance of gene sets by sample permutation; implemented in the [safe](#) package)
- GSEA: Gene Set Enrichment Analysis (frequently used and widely accepted, uses a Kolmogorov–Smirnov statistic to test whether the ranks of the p -values of genes in a gene set resemble a uniform distribution [5])
- PADOG: Pathway Analysis with Down-weighting of Overlapping Genes (incorporates gene weights to favor genes appearing in few pathways versus genes that appear in many pathways; implemented in the [PADOG](#) package)

- ROAST: ROtation gene Set Test (uses rotation instead of permutation for assessment of gene set significance; implemented in the [limma](#) and [edgeR](#) packages for microarray and RNA-seq data, respectively)
- CAMERA: Correlation Adjusted MEan RANk gene set test (accounts for inter-gene correlations as implemented in the [limma](#) and [edgeR](#) packages for microarray and RNA-seq data, respectively)
- GSA: Gene Set Analysis (differs from GSEA by using the maxmean statistic, i.e. the mean of the positive or negative part of gene scores in the gene set; implemented in the [GSA](#) package)
- GSVA: Gene Set Variation Analysis (transforms the data from a gene by sample matrix to a gene set by sample matrix, thereby allowing the evaluation of gene set enrichment for each sample; implemented in the [GSVA](#) package)
- GLOBALTEST: Global testing of groups of genes (general test of groups of genes for association with a response variable; implemented in the [globaltest](#) package)
- SAMGS: Significance Analysis of Microarrays on Gene Sets (extending the SAM method for single genes to gene set analysis [6])
- EBM: Empirical Brown's Method (combines p -values of genes in a gene set using Brown's method to combine p -values from dependent tests; implemented in [EmpiricalBrownsMethod](#))
- MGSA: Model-based Gene Set Analysis (Bayesian modeling approach taking set overlap into account by working on all sets simultaneously, thereby reducing the number of redundant sets; implemented in [mgsa](#))

For demonstration, we perform a basic ORA choosing a significance level α of 0.05.

```
> sbea.res <- sbea(method="ora", eset=all.eset, gs=hsa.gs, perm=0, alpha=0.05)
> gs.ranking(sbea.res)
```

DataFrame with 1 row and 4 columns

	GENE.SET <character>	NR.GENES <numeric>	NR.SIG.GENES <numeric>	P.VALUE <numeric>
1	hsa04622_RIG-I-like_receptor_signaling_pathway	54	5	0.0347

The result of every enrichment analysis is a ranking of gene sets by the corresponding p -value. The `gs.ranking` function displays only those gene sets satisfying the chosen significance level α .

While such a ranked list is the standard output of existing enrichment tools, the [EnrichmentBrowser](#) package provides visualization and interactive exploration of resulting gene sets far beyond that point. Using the `ea.browse` function creates a HTML summary from which each gene set can be inspected in detail (this builds on functionality from the [ReportingTools](#) package). The various options are described in Figure 1.

```
> ea.browse(sbea.res)
```

The goal of the [EnrichmentBrowser](#) package is to provide frequently used enrichment methods. However, it is also possible to exploit its visualization capabilities with user-defined set-based enrichment methods. This requires to implement a function that takes the characteristic arguments `eset` (expression data), `gs` (gene sets), `alpha` (significance level), and `perm` (number of permutations). In addition, it must return a numeric vector `ps` storing the resulting p -value for each gene set in `gs`. The p -value vector must also be named accordingly (i.e. `names(ps) == names(gs)`).

Let us consider the following dummy enrichment method, which randomly renders five gene sets significant and the remaining insignificant.

```
> dummy.sbea <- function(eset, gs, alpha, perm)
+ {
+   sig.ps <- sample(seq(0,0.05, length=1000),5)
+   insig.ps <- sample(seq(0.1,1, length=1000), length(gs)-5)
+   ps <- sample(c(sig.ps, insig.ps), length(gs))
+   names(ps) <- names(gs)
+   return(ps)
+ }
```

ORA - Table of Results

10 records per page

Search all columns:

From to

GENE.SET	TITLE	NR.GENES	P.VALUE	SET.VIEW	PATH.VIEW
hsa04622	RIG-I-like receptor signaling pathway	54	0.00888		
hsa05130	Pathogenic Escherichia coli infection	43	0.01400		
hsa04520	Adherens junction	68	0.02610		
hsa05206	MicroRNAs in cancer	133	0.03310		
hsa05416	Viral myocarditis	55	0.03720		

Showing 1 to 5 of 5 entries

Previous
1
Next

Figure 1: ORA result view. For each significant gene set in the ranking, the user can select to view (1) a gene report, that lists all genes of a set along with fold change and DE p -value, (2) interactive overview plots such as heatmap, p -value distribution, and volcano plot, (3) the pathway in KEGG with differentially expressed genes highlighted in red.

We can plug this method into sbea as before.

```
> sbea.res2 <- sbea(method=dummy.sbea, eset=all.eset, gs=hsa.gs)
> gs.ranking(sbea.res2)
```

DataFrame with 5 rows and 2 columns

	GENE.SET	P.VALUE
	<character>	<numeric>
1	hsa05134_Legionellosis	0.00571
2	hsa04066_HIF-1_signaling_pathway	0.01020
3	hsa05130_Pathogenic_Escherichia_coli_infection	0.03070
4	hsa05144_Malaria	0.03420
5	hsa05218_Melanoma	0.04530

8 Network-based enrichment analysis

Having found sets of genes that are differentially regulated in the ALL data, we are now interested whether these findings can be supported by known regulatory interactions. For example, we want to know whether transcription factors and their target genes are expressed in accordance to the connecting regulations. Such information is usually given in a gene regulatory network derived from specific experiments, e.g. using the [GeneNetworkBuilder](#), or compiled from the literature ([7] for an example). There are well-studied processes and organisms for which comprehensive and well-annotated regulatory networks are available, e.g. the RegulonDB for *E. coli* and Yeastract for *S. cerevisiae*. However, there are also cases where such a network is missing. A first simple workaround is to compile a network from regulations in the KEGG database.

We can download all KEGG pathways of a specified organism via the `download.kegg.pathways` function that exploits functionality from the [KEGGREST](#) package.

```
> pwys <- download.kegg.pathways("hsa")
```

In this case, we have already downloaded a selection of human KEGG pathways. We parse them making use of the [KEGGgraph](#) package and compile the resulting gene regulatory network.

```
> pwys <- file.path(data.dir, "hsa_kegg_pwys.zip")
> hsa.grn <- compile.grn.from.kegg(pwys)
> head(hsa.grn)
```

	FROM	TO	TYPE
[1,]	"3569"	"3570"	"+"
[2,]	"3458"	"3459"	"+"
[3,]	"3458"	"3460"	"+"
[4,]	"1950"	"1956"	"+"
[5,]	"1950"	"2064"	"+"
[6,]	"1950"	"3480"	"+"

Now, we are able to perform enrichment analysis using the compiled network. Currently, the following network-based enrichment analysis methods are supported

```
> nbea.methods()
```

[1]	"ggea"	"spia"	"pathnet"	"degraph"	"topologygsa"	"ganpa"
[7]	"cepa"	"netgsa"	"nea"			

- GGEA: Gene Graph Enrichment Analysis (evaluates consistency of known regulatory interactions with the observed expression data [8])
- SPIA: Signaling Pathway Impact Analysis (combines ORA with the probability that expression changes are propagated across the pathway topology; implemented in the [SPIA](#) package)
- PathNet: Pathway Analysis using Network Information (applies ORA on combined evidence for the observed signal for gene nodes and the signal implied by connected neighbors in the network; implemented in the [PathNet](#) package)
- DEGraph: Differential expression testing for gene graphs (multivariate testing of differences in mean incorporating underlying graph structure; implemented in the [DEGraph](#) package)
- TopologyGSA: Topology-based Gene Set Analysis (uses Gaussian graphical models to incorporate the dependence structure among genes as implied by pathway topology; implemented in the [topologyGSA](#) package)
- GANPA: Gene Association Network-based Pathway Analysis (incorporates network-derived gene weights in the enrichment analysis; implemented in the [GANPA](#) package)
- CePa: Centrality-based Pathway enrichment (incorporates network centralities as node weights mapped from differentially expressed genes in pathways; implemented in the [CePa](#) package)
- NetGSA: Network-based Gene Set Analysis (incorporates external information about interactions among genes as well as novel interactions learned from data; implemented in the [NetGSA](#) package)
- NEA: Network Enrichment Analysis (applies ORA on interactions instead of genes; implemented in the [neaGUI](#) package)

For demonstration, we perform GGEA using the compiled KEGG regulatory network.

```
> nbea.res <- nbea(method="ggea", eset=all.eset, gs=hsa.gs, grn=hsa.grn)
> gs.ranking(nbea.res)
```

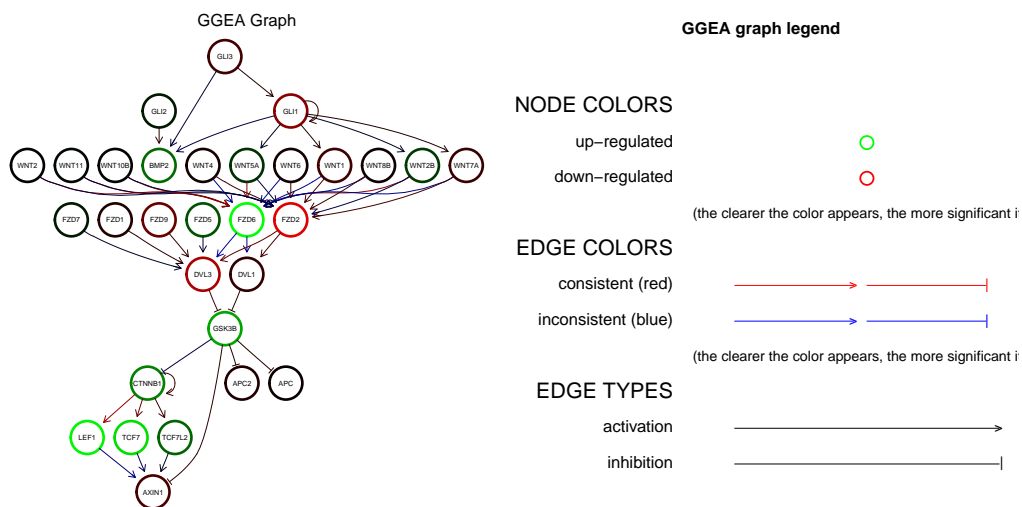
DataFrame with 4 rows and 5 columns

	GENE.SET	NR.RELS	RAW.SCORE	NORM.SCORE	P.VALUE
	<character>	<numeric>	<numeric>	<numeric>	<numeric>
1	hsa05416_Viral_myocarditis	7	3.29	0.470	0.00300
2	hsa04390_Hippo_signaling_pathway	57	20.60	0.361	0.00400
3	hsa04210_Apoptosis	20	7.69	0.385	0.00999
4	hsa04520_Adherens_junction	9	3.66	0.406	0.03300

The resulting ranking lists, for each statistically significant gene set, the number of relations of the network involving a member of the gene set under study (NR.RELS), the sum of consistencies over the relations of the set (RAW.SCORE), the score normalized by induced network size (NORM.SCORE = RAW.SCORE / NR.RELS), and the statistical significance of each gene set based on a permutation approach.

A GGEA graph for a gene set depicts the consistency of each interaction in the set. Nodes (genes) are colored according to expression (up-/down-regulated) and edges (interactions) are colored according to consistency, i.e. how well the interaction type (activation/inhibition) is reflected in the correlation of the observed expression of both interaction partners.

```
> par(mfrow=c(1,2))
> ggea.graph(
+   gs=hsa.gs[["hsa05217_Basal_cell_carcinoma"]],
+   grn=hsa.grn, eset=all.eset)
> ggea.graph.legend()
```



As described in the previous section, it is also possible to plug in user-defined network-based enrichment methods.

9 Combining results

Different enrichment analysis methods usually result in different gene set rankings for the same dataset. To compare results and detect gene sets that are supported by different methods, the *EnrichmentBrowser* package allows to combine results from the different set-based and network-based enrichment analysis methods. The combination of results yields a new ranking of the gene sets under investigation by specified ranking criteria, e.g. the average rank across methods. We consider the ORA result and the GGEA result from the previous sections and use the function `comb.ea.results`.

```
> res.list <- list(sbea.res, nbea.res)
> comb.res <- comb.ea.results(res.list)
```

The combined result can be detailedly inspected as before and interactively ranked as depicted in Figure 2.

```
> ea.browse(comb.res, graph.view=hsa.grn, nr.show=5)
```

COMB - Table of Results

10 records per page

Search all columns:

From to From to From to From to From to

GENE.SET	TITLE	NR.GENES	ORA.RANK	GGEA.RANK	AVG.RANK	ORA.PVAL	GGEA.PVAL	SET.VIEW	PATH.VIEW	GRAPH.VIEW
hsa05416	Viral myocarditis	55	5	2	3	0.0372	0.006			
hsa05130	Pathogenic Escherichia coli infection	43	2	14	8	0.0140	0.243			
hsa04514	Cell adhesion molecules (CAMs)	107	18	4	11	0.3050	0.010			
hsa04520	Adherens junction	68	3	19	11	0.0261	0.498			
hsa05144	Malaria	45	15	7	11	0.1990	0.067			

Showing 1 to 5 of 5 entries

← Previous 1 Next →

Figure 2: Combined result view. By clicking on one of the columns (ORA.RANK, ..., GGEA.PVAL) the result can be interactively ranked according to the selected criterion.

10 Putting it all together

There are cases where it is necessary to perform certain steps of the demonstrated enrichment analysis pipeline individually. However, it is often more convenient to run the complete standardized pipeline. This can be done using the all-in-one wrapper function `ebrowser`. For example, the result page displayed in [Figure 2](#) can also be produced from scratch via

```
> ebrowser(  meth=c("ora", "ggea"),
+           exprs=exprs.file, pdat=pdat.file, fdat=fdat.file,
+           org="hsa", gs=hsa.gs, grn=hsa.grn, comb=TRUE, nr.show=5)
```

11 Frequently asked questions

1. How to cite the [EnrichmentBrowser](#)?

Geistlinger L, Csaba G and Zimmer R. Bioconductor's EnrichmentBrowser: seamless navigation through combined results of set- & network-based enrichment analysis. *BMC Bioinformatics*, **17**:45, 2016.

2. Is it possible to apply the [EnrichmentBrowser](#) to simple gene lists?

Enrichment methods implemented in the [EnrichmentBrowser](#) are, except for ORA, expression-based (and also draw their strength from that). The set-based methods GSEA, SAFE, and SAMGS use sample permutation, involving recomputation of differential expression, for gene set significance estimation, i.e. they require the complete expression matrix. The network-based methods require measures of differential expression such as fold change and *p*-value to score interactions of the network. In addition, visualization of enriched gene sets is explicitly designed for expression data. Thus, for simple gene list enrichment, tools like *DAVID* (<https://david.ncifcrf.gov>) and *GeneAnalytics* (<http://geneanalytics.genecards.org>) are more suitable, and it is recommended to use them for this purpose.

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