Package ‘hilbertSimilarity’

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**Description**
Quantifying similarity between high-dimensional single cell samples is challenging, and usually requires some simplifying hypothesis to be made. By transforming the high dimensional space into a high dimensional grid, the number of cells in each sub-space of the grid is characteristic of a given sample. Using a Hilbert curve each sample can be visualized as a simple density plot, and the distance between samples can be calculated from the distribution of cells using the Jensen-Shannon distance. Bins that correspond to significant differences between samples can be identified using a simple bootstrap procedure.

**LinkingTo** Rcpp

**Imports** Rcpp, entropy

**Suggests** knitr, rmarkdown, ggplot2, dplyr, tidyR, reshape2, bodenmiller, abind

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**LazyData** TRUE

**Encoding** UTF-8

**URL** [http://github.com/yannabraham/hilbertSimilarity](http://github.com/yannabraham/hilbertSimilarity)

**BugReports** [http://github.com/yannabraham/hilbertSimilarity/issues](http://github.com/yannabraham/hilbertSimilarity/issues)

**VignetteBuilder** knitr

**RoxygenNote** 6.1.1

**NeedsCompilation** yes

**Author** Yann Abraham [aut, cre], Marilisa Neri [aut], John Skilling [ctb]
**add.cut**

**Description**

Add new manual cuts to the cuts matrix generated using `make.cut`

**Usage**

```r
add.cut(cuts, new.cuts, cut.id = "manual", update = FALSE)
```

**Arguments**

- `cuts` a list of cuts generated using `make.cut`
- `new.cuts` a list of new cut thresholds to be added to cuts
- `cut.id` string identifying the new cuts
- `update` if FALSE (the default) adding a cut.id that already exists in cuts will return an error

**Details**

The matrix can be cut using either the fixed cuts (type='fixed'), or the combined cuts (type='combined') where the limits have been adjusted to match local minima and maxima.
**Value**

an updated cuts matrix with an extra set of thresholds named cut.id.

**Author(s)**

Yann Abraham

**Examples**

```r
# generate a random 3D matrix with 2 peaks
mat <- rbind(matrix(rnorm(300),ncol=3),
             matrix(rnorm(300,5,1),ncol=3))
dimnames(mat)[[2]] <- LETTERS[1:3]
# estimate the Hilbert order
hilbert.order(mat)
# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat,n=3,count.lim=5)
show.cut(cuts)
# Generate the cuts
cut.mat <- do.cut(mat,cuts,type='fixed')
head(cut.mat)
```

**Description**

Use Andrews plots to visualize the Hilbert curve.

**Usage**

```r
andrewsProjection(x, breaks = 30)
```

**Arguments**

- `x`: a matrix of counts, where rows correspond to samples and columns to Hilbert index
- `breaks`: the number of points used to display the Andrews curve

**Details**

The Andrews curve corresponds to a projection of each item to \((1/2^0.5 \sin(t), \cos(t), \sin(2t), \cos(2t), \ldots)\) where \(t\) (the Andrews index) varies between \(-\pi\) and \(\pi\).
Value

a list with 2 items:

- freq: a matrix with breaks rows and ncol(x) columns containing the Andrews vector for projection
- i: a vector with breaks elements corresponding to the Andrews indices

Author(s)

Yann Abraham

Examples

```r
# generate a random matrix
ncols <- 5
mat <- matrix(rnorm(ncols*1000),ncol=ncols)
dimnames(mat)[[2]] <- LETTERS[seq(ncols)]

# generate categories
conditions <- sample(letters[1:3],nrow(mat),replace = TRUE)
# generate 4 bins with a minimum bin size of 5
horder <- 4
cuts <- make.cut(mat,n=horder+1,count.lim=5)
# Generate the cuts and compute the Hilbert index
cut.mat <- do.cut(mat,cuts,type="fixed")
hc <- do.hilbert(cut.mat,horder)
# compute hilbert index per condition
condition.mat <- table(conditions,hc)
condition.pc <- apply(condition.mat,1,function(x) x/sum(x))
condition.pc <- t(condition.pc)
# project the matrix to the Andrews curve
av <- andrewsProjection(condition.pc)
proj <- condition.pc %*% t(av$freq)

plot(range(av$i),
     range(proj),
     type='n',
     xlab='Andrews index',
     ylab='Projection')
for(i in seq(nrow(proj))) {
   lines(av$i,
         proj[i,],
         col=i)
}
legend('bottomleft',
       legend=letters[1:3],
       col=seq(1,3),
       pch=16,
       bty='n')
```
Apply Cuts to the Reference Matrix

Description
Apply cuts generated using the `make.cut` function to the reference matrix.

Usage
```r
do.cut(mat, cuts, type = "combined")
```

Arguments
- **mat**: the matrix to cut
- **cuts**: a list of cuts generated using `make.cut`
- **type**: the type of cuts to use (use combined by default)

Details
The matrix can be cut using either the fixed cuts (type='fixed'), or the combined cuts (type='combined') where the limits have been adjusted to match local minima and maxima. Returned values correspond to the bin defined between the first and second threshold of the specified cuts, then between the second and third threshold, and so on. The values will range between 0 (the first bin) and n-1 where n is the number of values in the specified cuts.

Value
- a matrix of the same dimensionality as `mat` where values correspond to bins defined by the type thresholds defined `cuts`.

Author(s)
Yann Abraham

Examples
```r
# generate a random 3D matrix with 2 peaks
mat <- rbind(matrix(rnorm(300),ncol=3),
             matrix(rnorm(300,5,1),ncol=3))
dimnames(mat)[[2]] <- LETTERS[1:3]
# estimate the Hilbert order
hilbert.order(mat)
# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat,n=3,count.lim=5)
show.cut(cuts)
# Generate the cuts
cut.mat <- do.cut(mat,cuts,type='fixed')
head(cut.mat)
```
do.hilbert  

Generate the Hilbert Index from a Cut Reference Matrix

Description

Generate the Hilbert Index corresponding to the sub-spaces defined by the coordinates generated via do.cut

Usage

do.hilbert(mat, horder)

Arguments

mat       the cut reference matrix
horder    the Hilbert order, i.e. the number of bins in each dimension

Details

For each line in mat, the function will compute the corresponding Hilbert index. Each index corresponds to a specific sub-cube of the original high-dimensional space, and consecutive hilbert index correspond to adjacent sub-cubes

Value

a vector of indices, one for each line in mat

Author(s)

Marilisa Neri
Yann Abraham
John Skilling (for the original C function)

Examples

# generate a random 3D matrix
mat <- matrix(rnorm(300),ncol=3)
dimnames(mat)[[2]] <- LETTERS[1:3]
# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat,n=3,count.lim=5)
show.cut(cuts)
# Generate the cuts
cut.mat <- do.cut(mat,cuts,type='fixed')
head(cut.mat)
# generate the Hilber index
hc <- do.hilbert(cut.mat,2)
plot(table(hc),type='1')
Estimate the Hilbert order for a given matrix

Description

Estimate the Hilbert order, or the number of bins in each dimension, so that if the matrix was random every row in the matrix would correspond to a single bin.

Usage

hilbert.order(mat)

Arguments

mat
   the matrix for which to estimate the Hilbert order

Details

Assuming the matrix is fully random, there is no need to generate more voxels (the combination of bins over all dimensions) than there are rows in the matrix. The number can be derived from the following formula:

\[ c^d < N \]

where \( c \) is the number of bins, \( d \) is the number of dimensions and \( N \) is the total number of cells in the dataset. \( c \) can be computed easily using the following formula:

\[ c = \lceil \sqrt[d]{N} \rceil \]

The number of cuts for do.cut is the number of bins plus 1.

Value

the suggested number of bins to use for the specified mat.

Author(s)

Yann Abraham

Examples

# generate a random 3D matrix with 2 peaks
mat <- rbind(matrix(rnorm(300),ncol=3),
              matrix(rnorm(300,.5,1),ncol=3))
dimnames(mat)[[2]] <- LETTERS[1:3]
# estimate the Hilbert order
hilbert.order(mat)
# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat,n=3,count.lim=5)
show.cut(cuts)
# Generate the cuts
hilbertMapping <- do.cut(mat,cuts,type='fixed')
head(cut.mat)

hilbertMapping  
Map High Dimensional Coordinates to Hilbert Index and back

Description

hilbertMapping will compute the Hilbert index for each row of a matrix of integer coordinates corresponding to sub-cubes in a high dimensional space.

Arguments

- x: a matrix of a matrix of integer coordinates (see do.hilbert)
- bits: the hilbert order, i.e. the number of cuts in each dimension

Details


The source code includes the correction suggested in the following StackOverflow discussion.

Value

- a vector of hilbert index, one for each line in x

Author(s)

- Marilisa Neri
- Yann Abraham
- John Skilling
hilbertProjection  

**Project a Cut Reference Matrix to a Different Space through an Hilbert Index**

**Description**

Starting from a Hilbert Index generated in a high dimensional space, returns a set of coordinates in a new (lower) dimensional space.

**Usage**

hilbertProjection(hc, target = 2)

**Arguments**

- **hc**
  - the hilbert index returned by do.hilbert
- **target**
  - the number of dimensions in the target space (defaults to 2)

**Details**

Based on the maximum index and the targeted number of dimensions the number of target bins is computed and used to generate a reference matrix and a reference index. The reference matrix is returned, ordered by the reference index.

**Value**

a matrix with target columns, corresponding to the projection of each Hilbert index to target dimensions

**Author(s)**

Marilisa Neri
Yann Abraham
John Skilling (for the original C function)

**Examples**

```r
# generate a random matrix
cols <- 5
mat <- matrix(rnorm(ncols*5000),ncol=cols)
dimnames(mat)[[2]] <- LETTERS[seq(ncols)]

# generate 4 bins with a minimum bin size of 5
horder <- 4
cuts <- make.cut(mat,n=horder+1,count.lim=5)

# Generate the cuts and compute the Hilbert index
cut.mat <- do.cut(mat,cuts,type='fixed')
```
hilbertSimilarity

Hilbert Similarity Index for High Dimensional Data

Description

This package provides a method to compute similarity between single cell samples in high dimensional space. After dividing the space into voxels, each sample is summarized as a number of cells per voxel. Voxels are ordered using a Hilbert curve, so that each sample can be represented as a 1-dimensional density plot. The distance between 2 samples corresponds to the Jensen Shannon distance between the 2 probability vectors.

Examples

# generate 3 samples over 5 dimensions
# sample 1 and 2 are similar, sample 3 has an extra population
# set the seed for reproducible examples
set.seed(1234)
my.samples <- lapply(LETTERS[1:3],function(j) {
  # each sample has a different number of events
  n <- floor(runif(1,0.5,0.8)*10000)
  # matrix is random normal over 5 dimensions
  cur.mat <- matrix(rnorm(5*n),ncol=5)
  # rescale cur.mat to a [0,3] interval
  cur.mat <- 3*(cur.mat-min(cur.mat))/diff(range(cur.mat))
  dimnames(cur.mat)[[2]] <- LETTERS[(length(LETTERS)-4):length(LETTERS)]
  if(j=='C') {
    # select 30% of the points
    cur.rws <- sample(n,round(n*0.3,0))
    # select 2 columns at random
    cur.cls <- sample(ncol(cur.mat),2)
    # create an artificial sub population
    cur.mat[cur.rws,cur.cls] <- 4*cur.mat[cur.rws,cur.cls]
  }
  return(cur.mat)
})

names(my.samples) <- LETTERS[1:3]
# check the population size
lapply(my.samples,nrow)

# assemble a sample matrix
my.samples.mat <- do.call('rbind',my.samples)
my.samples.id <- lapply(names(my.samples),
    function(cur.spl) rep(cur.spl,nrow(my.samples[[cur.spl]])))
my.samples.id <- unlist(my.samples.id)

# Estimate the maximum required Hilbert order
hilbert.order(my.samples.mat)

# Estimate the cut positions
my.cuts <- make.cut(my.samples.mat,n=5,count.lim=5)

# Visualize the cuts
show.cut(my.cuts)

# Cut the matrix & compute the hilbert index
my.samples.cut <- do.cut(my.samples.mat,my.cuts,type='combined')
system.time(my.samples.index <- do.hilbert(my.samples.cut,horder=4))

# Visualize samples as density plots
my.samples.dens <- density(my.samples.index)
my.samples.dens$y <- (my.samples.dens$y-min(my.samples.dens$y))/diff(range(my.samples.dens$y))

plot(my.samples.dens,col='grey3',lty=2)
ksink <- lapply(names(my.samples),function(cur.spl) {
    cat(cur.spl,'\n')
    cur.dens <- density(my.samples.index[my.samples.id==cur.spl],
        bw=my.samples.dens$bw)
    cur.dens$y <- (cur.dens$y-min(cur.dens$y))/diff(range(cur.dens$y))
    lines(cur.dens$x,
        cur.dens$y,
        col=match(cur.spl,names(my.samples))+1)
}
)
legend('topright',
    legend=names(my.samples),
    col=seq(length(my.samples))+1,
    pch=16,
    bty='n' )

# assemble a contingency table
my.samples.table <- table(my.samples.index,my.samples.id)
dim(my.samples.table)

heatmap(log10(my.samples.table+0.00001),
    col=colorRampPalette(c('white',blues9))(24),
    Rowv=NA,Colv=NA,
    scale='none')

# compute the Jensen-Shannon distance
my.samples.dist <- js.dist(t(my.samples.table))
my.samples.clust <- hclust(my.samples.dist)
plot(my.samples.clust)

---

**js.dist**

*Compute the Jensen-Shannon Distance between 2 sets of Hilbert Index*

**Description**

The **Jensen-Shannon distance** is a method to measure the distance between discrete probability distributions. To measure the distance between 2 high-dimensional datasets, we cut the space into sub-cubes, then count the number of events per cube. The resulting probability distributions can be compared using the Jensen-Shannon distance.

**Usage**

```r
js.dist(mat, pc = 1e-04)
```

**Arguments**

- `mat`: a matrix of counts, where rows correspond to samples and columns to Hilbert index
- `pc`: a pseudo-count that is added to all samples to avoid divide-by-zero errors

**Value**

a S3 distance object

**Author(s)**

Yann Abraham

**Examples**

```r
# generate 3 samples over 5 dimensions
# sample 1 and 2 are similar, sample 3 has an extra population
# set the seed for reproducible examples
set.seed(1234)
my.samples <- lapply(LETTERS[1:3],function(j) {
  # each sample has a different number of events
  n <- floor(runif(1,0.5,0.8)*10000)
  # matrix is random normal over 5 dimensions
  cur.mat <- matrix(rnorm(5*n),ncol=5)
  # rescale cur.mat to a [0,3] interval
  cur.mat <- 3*(cur.mat-min(cur.mat))/diff(range(cur.mat))
  dimnames(cur.mat)[[2]] <- LETTERS[length(LETTERS)-4]:length(LETTERS)
  if(j=='C') {
    # select 30% of the points
```
cur.rws <- sample(n,round(n*0.3,0)) # select 2 columns at random
cur.cls <- sample(ncol(cur.mat),2) # create an artificial sub population
cur.mat[cur.rws,cur.cls] <- 4*cur.mat[cur.rws,cur.cls]
}
return(cur.mat)
)
names(my.samples) <- LETTERS[1:3]

# check the population size
lapply(my.samples,nrow)

# assemble a sample matrix
my.samples.mat <- do.call('rbind',my.samples)
my.samples.id <- lapply(names(my.samples),

function(cur.spl) rep(cur.spl,nrow(my.samples[[cur.spl]])))
my.samples.id <- unlist(my.samples.id)

# Estimate the maximum required Hilbert order
hilbert.order(my.samples.mat)

# Estimate the cut positions
my.cuts <- make.cut(my.samples.mat,n=5,count.lim=5)

# Visualize the cuts
show.cut(my.cuts)

# Cut the matrix & compute the hilbert index
my.samples.cut <- do.cut(my.samples.mat,my.cuts,type='combined')
system.time(my.samples.index <- do.hilbert(my.samples.cut,horder=4))

# Visualize samples as density plots
my.samples.dens <- density(my.samples.index)
my.samples.dens$y <- (my.samples.dens$y-min(my.samples.dens$y))/diff(range(my.samples.dens$y))

plot(my.samples.dens,col='grey3',lty=2)
ksink <- lapply(names(my.samples),function(cur.spl) {
  cat(cur.spl,`\n' )
  cur.dens <- density(my.samples.index[my.samples.id==cur.spl],
    bw=my.samples.dens$bw)
  cur.dens$y <- (cur.dens$y-min(cur.dens$y))/diff(range(cur.dens$y))
  lines(cur.dens$x,
    cur.dens$y,
    col=match(cur.spl,names(my.samples))+1)
})
legend('topright',
   legend=names(my.samples),
   col=seq(length(my.samples))+1,
   pch=16,
   bty='n' )
# assemble a contingency table
my.samples.table <- table(my.samples.index,my.samples.id)
dim(my.samples.table)

heatmap(log10(my.samples.table+0.00001),
   col=colorRampPalette(c('white', blues9))(24),
   Rowv=NA, Colv=NA,
   scale='none')

# compute the Jensen-Shannon distance
my.samples.dist <- js.dist(t(my.samples.table))
my.samples.clust <- hclust(my.samples.dist)
plot(my.samples.clust)

localMaxima  

Find Local Maxima in a vector

Description

Given a density object, find the position of local maxima (inflection points)

Usage

localMaxima(x)

Arguments

x  
a vector of density values, as generated through a call to density

Value

a vector of index corresponding to local maxima

Author(s)

Tommy  

Examples

x <- c(rnorm(100), rnorm(100, 3))
dx <- density(x)
plot(dx)
abline(v=dx$x[localMaxima(dx$y)], col=2, lty=2)
localMinima  

Find Local Minima in a vector

Description
Given a density object, find the position of local minima (inflection points)

Usage
localMinima(x)

Arguments
x a vector of density values, as generated through a call to density

Value
a vector of index corresponding to local minima

Author(s)

Examples
x <- c(rnorm(100),rnorm(100,3))
dx <- density(x)
plot(dx)
abline(v=dx$x[localMinima(dx$y)],col=2,lty=2)

make.cut  

Generate Cutting Points for a Multidimensional Matrix

Description
For a given column cur.ch that belongs to a matrix, and a given number of cuts n, compute n-1 bins using either fixed or combined limits

Usage
make.cut(mat, n = 5, count.lim = 40)

Arguments
mat the matrix to cut
n the number of cuts to generate (defaults to 5)
count.lim the minimum number of counts to consider for density (defaults to 40)
Details

The fixed limits correspond to 5 equally spaced values over the range of the column. The combined limits take the local minima and maxima determined using the `localMinima` and `localMaxima` functions, to adjust the limits using the following algorithm:

- define \( d \) as half the distance between 2 fixed limits
- merge local minima and local maxima that are closer than \( d \)
- if any fixed limit is closer to a local minima than \( d \), move the fixed limit to the local minima; move the limits that are not been moved yet, and that are before and after the moved limit so that they are evenly spread; repeat until no fixed limit can be moved
- if some limits have been moved to a local minima, delete limits that are closer than \( d \) to a local maxima; move the limits that are not been moved yet, and that are before and after the deleted limit so that they are evenly spread; repeat until no fixed limit can be moved
- if no limits has been moved to a local minima, move limits that are closer than \( d \) to a local maxima; move the limits that are not been moved yet, and that are before and after the moved limit so that they are evenly spread; repeat until no fixed limit can be moved

The function returns a list of lists, one for each column in `mat`, consisting of

- `cur.dens` the density used to describe the data
- `cur.hist` the histogram used to describe the data
- `fixed` the fixed, evenly spaced cuts
- `minima` the local minima detected in the data
- `maxima` the local maxima detected in the data
- `combined` the cuts defined using a combination of fixed positions, local minima and local maxima

Value

A list of of cuts for each column in `mat`, see details

Author(s)

Yann Abraham

Examples

```r
# generate a random 3D matrix with 2 peaks
mat <- rbind(matrix(rnorm(300),nrow=3),
             matrix(rnorm(300,5,1),nrow=3))
dimnames(mat)[[2]] <- LETTERS[1:3]

# estimate the Hilbert order
hilbert.order(mat)

# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat,n=3,count.lim=5)
show.cut(cuts)

# Generate the cuts
cut.mat <- do.cut(mat,cuts,type='fixed')
head(cut.mat)
```
show.cut

Plot the cuts generated through make.cut

Description

Visualize the cuts in relation with the distribution of the data for each dimension in the original matrix

Usage

show.cut(cuts, type = "all", local = FALSE)

Arguments

cuts the output of the make.cut.

type which cuts to show. This must be one of "all", "fixed" or "combined". Any unambiguous substring can be given.

local defaults to FALSE; if TRUE, shows the local minima and maxima as a rug plot.

Details

"fixed" will show \( n \) equally spaced cuts (see make.cut for the definition of \( n \)). "combined" will show the cuts after adjustment for local minima and maxima. "all" will show both. Setting local to TRUE will enable the visualization of local minima and maxima detected by the algorithm in each dimension.

Value

the function returns an invisible ‘NULL’.

Author(s)

Yann Abraham

Examples

# generate a random 3D matrix with 2 peaks
mat <- rbind(matrix(rnorm(300), ncol=3),
             matrix(rnorm(300, 5, 1), ncol=3))
dimnames(mat)[[2]] <- LETTERS[1:3]
# estimate the Hilbert order
hilbert.order(mat)
# generate 2 bins with a minimum bin size of 5
cuts <- make.cut(mat, n=3, count.lim=5)
show.cut(cuts)
# Generate the cuts
cut.mat <- do.cut(mat, cuts, type='fixed')
head(cut.mat)
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