

Package ‘RScelestial’

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Type Package

Title Scelestial: Steiner Tree Based Single-Cell Lineage Tree Inference

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Maintainer Mohammad Hadi Foroughmand Araabi <foroughmand@gmail.com>

Description Scelestial infers a lineage tree from single-cell DNA mutation matrix. It generates a tree with approximately maximum parsimony through a Steiner tree approximation algorithm.

License GPL (>= 2)

Imports Rcpp (>= 1.0.1)

LinkingTo Rcpp

SystemRequirements C++11

RoxygenNote 7.1.0

Suggests igraph, knitr, rmarkdown

VignetteBuilder knitr

NeedsCompilation yes

Author Mohammad Hadi Foroughmand Araabi [aut, cre],
Sama Goliaei [aut, ctb],
Alice McHardy [ctb]

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R topics documented:

.scelestial	2
.synthesis	2
as.mutation.matrix	4
as.ten.state.matrix	4
as.ten.state.matrix.from.node.seq	5

distance.matrix.scelestial	6
distance.matrix.tree	7
distance.matrix.true.tree	8
Li	9
my.dfs	10
my.general.dfs	11
read.sequence.table	12
RScelestial	12
scelestial	13
synthesis	15
tree.plot	18

Index	19
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.scelestial	<i>Internal function for running scelestial algorithm.</i>
-------------	--

Description

Internal function for running scelestial algorithm.

Usage

```
.scelestial(data, minK = 3L, maxK = 4L)
```

Arguments

data	The data
minK, maxK	Minimum and maximum number of vertices to be considered for k-restricted Steiner tree.

Value

The tree as well as missing value imputation

.synthesis	<i>Internal function for generating synthetic single-cell data through simulation of tumor growth and evolution.</i>
------------	--

Description

Internal function for generating synthetic single-cell data through simulation of tumor growth and evolution.

Usage

```
.synthesis(
  sample,
  site,
  evolutionSteps,
  mutationRate = 0.01,
  advantageIncreaseRatio = 1,
  advantageDecreaseRatio = 10,
  advantageKeepRatio = 100,
  advantageIncreaseStep = 0.01,
  advantageDecreaseStep = 0.01,
  mvRate = 0.5,
  fpRate = 0.2,
  fnRate = 0.1,
  seed = -1L
)
```

Arguments

sample	Number of samples
site	Number of sites
evolutionSteps	Number of non-root nodes in the evolutionary tree to be generated.
mutationRate	The rate of mutation on each evolutionary step in evolutionary tree synthesis.
advantageIncreaseRatio, advantageDecreaseRatio, advantageKeepRatio	A child node in the evolutionary tree is chosen for increase/decrease/keep its parent advantage with probabilities proportional to advantage.increase.ratio/advantage.decrease.ra
advantageIncreaseStep, advantageDecreaseStep	The amount of increasing or decreasing the advantage of a cell relative to its parent.
mvRate	Rate of missing value to be added to the resulting sequences.
fpRate, fnRate	Rate of false positive (0 -> 1) and false negative (1 -> 0) in the sequences.
seed	The seed for randomization.

Value

The function returns a list. The list consists of

- sequence: A data frame representing result of sequencing. The data frame has a row for each locus and a column for each sample.
- true.sequence: The actual sequence for the sample before adding errors and missing values.
- true.clone: A list that stores index of sampled cells for each node in the evolutionary tree.
- true.tree: The evolutionary tree that the samples are sampled from. It is a data frame with src, dest, and len columns representing source, destination and weight of edges of the tree, respectively.

as.mutation.matrix *Conversion of ten-state sequencing matrix to 0/1-mutation matrix.*

Description

Conversion of ten-state sequencing matrix to 0/1-mutation matrix.

Usage

```
as.mutation.matrix(seq)
```

Arguments

seq A dataframe representing the ten-state sequencing matrix. Elements of the matrix are the from "X/Y" for X and Y being nucleotides or "." for missing value. Rows represent loci and columns represent samples.

Value

A data frame with exactly the same size as the input seq matrix. The most abundant state in each loci (row) translated to 0, and the others are translated to 1. Missing values are translated to 3.

Examples

```
## A small 10-state matrix
seq = data.frame("C1" = c("C/C", "C/C"), "C2" = c("A/A", NA),
                "C3" = c("C/C", "A/A"), stringsAsFactors = TRUE)
## Convert it to mutation matrix
as.mutation.matrix(seq)
#   C1 C2 C3
# 1  0  1  0
# 2  1  3  0
```

as.ten.state.matrix *Conversion of 0/1 matrix to 10-state matrix*

Description

It converts 0 to A/A and 1 to C/C. 3 that represents missing values are converted to ".".

Usage

```
as.ten.state.matrix(mut)
```

Arguments

mut A dataframe representing the mutation matrix.

Value

A data frame with the exact size as mut, in which 0, 1 and 3 (or NAs) are replaced with "A/A", "C/C", and "./.", respectively.

Note

Note that following function does not provide inverse of as.mutation.matrix. It could be used to generate input for scestitial.

Examples

```
## A small 0/1/NA mutation matrix
mut = data.frame("C1" = c(0, 0), "C2" = c(0, 3), "C3" = c(1, 0),
  stringsAsFactors = TRUE)
## Convert it to 10-state matrix
as.ten.state.matrix(mut)
#   C1 C2 C3
# 1 A/A A/A C/C
# 2 A/A ././ A/A
```

```
as.ten.state.matrix.from.node.seq
```

Generates 10-state sequence matrix from name/10-char string matrix.

Description

This function is used for conversion of results of internal scestitial result to 10-state sequence matrices.

Usage

```
as.ten.state.matrix.from.node.seq(n.seq)
```

Arguments

n.seq A two column data frame. First column is the name of a node and the second column is a string representation of the sequencing result. Each element of the sequencing result is from a 10-state representation in which each state represented as a character according to the following encoding:

One character representation	10-state representation
"A"	"A/A",
"T"	"T/T",
"C"	"C/C",

"G"	"G/G",
"K"	"A/C",
"L"	"A/G",
"M"	"C/T",
"N"	"C/G",
"O"	"T/G",
"P"	"T/A",
"X"	".."

Value

A 10-state sequence data frame with samples as columns and loci as rows. Elements of `n.seq` are translated to their 10-state representations.

Examples

```
## A node sequence data frame
n.seq = data.frame("node" = c("C1", "C2"), "seq" = c("AKLTCXAAC", "AKKOCXAPC"),
  stringsAsFactors = TRUE)
## Convert it to ten state matrix
as.ten.state.matrix.from.node.seq(n.seq)
#   V1 V2 V3 V4 V5 V6 V7 V8 V9
# C1 A/A A/C A/G T/T C/C ././ A/A A/A C/C
# C2 A/A A/C A/C T/G C/C ././ A/A T/A C/C
```

distance.matrix.scelestial

Calculates distance matrix for result of scelestial

Description

Calculates distance matrix for result of scelestial

Usage

```
distance.matrix.scelestial(SP, normalize = TRUE)
```

Arguments

SP	Output of scelestial function
normalize	If true, sum of all elements of resulting table is added up to one.

Value

The distance matrix

Examples

```
## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Run Scelestial
SC = scelestial(as.ten.state.matrix(S$sequence))
## Calculate the distance matrix
distance.matrix.scelestial(SC)
#           C1           C10           C2           C3           C4
# C1  0.000000000 0.003512891 0.015222451 0.014051472 0.008196692
# C10 0.003512891 0.000000000 0.011709560 0.010538580 0.004683800
# C2  0.015222451 0.011709560 0.000000000 0.010538627 0.007025759
# C3  0.014051472 0.010538580 0.010538627 0.000000000 0.005854780
# C4  0.008196692 0.004683800 0.007025759 0.005854780 0.000000000
# C5  0.011709560 0.008196668 0.003512891 0.007025736 0.003512868
# C6  0.023419213 0.019906322 0.019906368 0.009367741 0.015222521
# C7  0.018735342 0.015222451 0.015222498 0.004683871 0.010538651
# C8  0.015222474 0.011709583 0.014051542 0.012880562 0.007025783
# C9  0.010538627 0.007025736 0.009367695 0.008196715 0.002341935
# C5           C6           C7           C8           C9
# C1  0.011709560 0.023419213 0.018735342 0.015222474 0.010538627
# C10 0.008196668 0.019906322 0.015222451 0.011709583 0.007025736
# C2  0.003512891 0.019906368 0.015222498 0.014051542 0.009367695
# C3  0.007025736 0.009367741 0.004683871 0.012880562 0.008196715
# C4  0.003512868 0.015222521 0.010538651 0.007025783 0.002341935
# C5  0.000000000 0.016393477 0.011709606 0.010538651 0.005854803
# C6  0.016393477 0.000000000 0.004683871 0.022248304 0.017564457
# C7  0.011709606 0.004683871 0.000000000 0.017564433 0.012880586
# C8  0.010538651 0.022248304 0.017564433 0.000000000 0.004683847
# C9  0.005854803 0.017564457 0.012880586 0.004683847 0.000000000
```

distance.matrix.tree *Calculates distance matrix for a nodes on a tree.*

Description

It is used for internal purposes.

Usage

```
distance.matrix.tree(graph, cell.names, tree.nodes, normalize = TRUE)
```

Arguments

graph	The tree
cell.names	Name of the cells to be the row and column name of the resulting matrix
tree.nodes	For each cell.names a tree node is stored in tree.nodes.
normalize	If TRUE the resulting matrix is normalized.

Value

A matrix with equal number of rows and columns, a row/column for each cell. Elements of matrix represent distance between cells on the graph.

Examples

```
## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Run Scelestial
SC = scelestial(as.ten.state.matrix(S$sequence))
## Calculate the distance matrix
vertices <- rownames(SC$input);
distance.matrix.tree(SC$tree, vertices, vertices, normalize = TRUE)
#           C1           C10           C2           C3           C4
# C1  0.000000000 0.003512891 0.015222451 0.014051472 0.008196692
# C10 0.003512891 0.000000000 0.011709560 0.010538580 0.004683800
# C2  0.015222451 0.011709560 0.000000000 0.010538627 0.007025759
# C3  0.014051472 0.010538580 0.010538627 0.000000000 0.005854780
# C4  0.008196692 0.004683800 0.007025759 0.005854780 0.000000000
# C5  0.011709560 0.008196668 0.003512891 0.007025736 0.003512868
# C6  0.023419213 0.019906322 0.019906368 0.009367741 0.015222521
# C7  0.018735342 0.015222451 0.015222498 0.004683871 0.010538651
# C8  0.015222474 0.011709583 0.014051542 0.012880562 0.007025783
# C9  0.010538627 0.007025736 0.009367695 0.008196715 0.002341935
# C5           C6           C7           C8           C9
# C1  0.011709560 0.023419213 0.018735342 0.015222474 0.010538627
# C10 0.008196668 0.019906322 0.015222451 0.011709583 0.007025736
# C2  0.003512891 0.019906368 0.015222498 0.014051542 0.009367695
# C3  0.007025736 0.009367741 0.004683871 0.012880562 0.008196715
# C4  0.003512868 0.015222521 0.010538651 0.007025783 0.002341935
# C5  0.000000000 0.016393477 0.011709606 0.010538651 0.005854803
# C6  0.016393477 0.000000000 0.004683871 0.022248304 0.017564457
# C7  0.011709606 0.004683871 0.000000000 0.017564433 0.012880586
# C8  0.010538651 0.022248304 0.017564433 0.000000000 0.004683847
# C9  0.005854803 0.017564457 0.012880586 0.004683847 0.000000000
```

distance.matrix.true.tree

Calculates distance matrix for a synthesized data

Description

Calculates distance matrix for a synthesized data

Usage

```
distance.matrix.true.tree(D, normalize = TRUE)
```


Arguments

D Output of synthesis function
 normalize If true, sum of all elements of resulting table is added up to one.

Value

The distance matrix of the true tree.

Examples

```
## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Calculating the distance matrix of the true tree.
distance.matrix.true.tree(S)
#           C3           C6           C4           C2           C7
# C3  0.000000000  0.004587156  0.006880734  0.009174312  0.013761468
# C6  0.004587156  0.000000000  0.002293578  0.009174312  0.013761468
# C4  0.006880734  0.002293578  0.000000000  0.011467890  0.016055046
# C2  0.009174312  0.009174312  0.011467890  0.000000000  0.004587156
# C7  0.013761468  0.013761468  0.016055046  0.004587156  0.000000000
# C10 0.006880734  0.006880734  0.009174312  0.011467890  0.016055046
# C8  0.006880734  0.011467890  0.013761468  0.016055046  0.020642202
# C9  0.006880734  0.011467890  0.013761468  0.016055046  0.020642202
# C1  0.011467890  0.011467890  0.013761468  0.002293578  0.006880734
# C5  0.011467890  0.011467890  0.013761468  0.002293578  0.006880734
# C10  C8           C9           C1           C5
# C3  0.006880734  0.006880734  0.006880734  0.011467890  0.011467890
# C6  0.006880734  0.011467890  0.011467890  0.011467890  0.011467890
# C4  0.009174312  0.013761468  0.013761468  0.013761468  0.013761468
# C2  0.011467890  0.016055046  0.016055046  0.002293578  0.002293578
# C7  0.016055046  0.020642202  0.020642202  0.006880734  0.006880734
# C10 0.000000000  0.013761468  0.013761468  0.013761468  0.013761468
# C8  0.013761468  0.000000000  0.000000000  0.018348624  0.018348624
# C9  0.013761468  0.000000000  0.000000000  0.018348624  0.018348624
# C1  0.013761468  0.018348624  0.018348624  0.000000000  0.000000000
# C5  0.013761468  0.018348624  0.018348624  0.000000000  0.000000000
```

 Li

Bladder invasive single cell tumor dataset

Description

Bladder invasive single cell tumor dataset

Usage

data(Li)

Format

Each column represent a cell and each row represent a locus. "/" represent the missing value, "A/A" the normal state and "C/C" the mutated state.

Source

[QTL Archive](#)

References

Gigascience. 2012 Aug 14;1(1):12. doi: 10.1186/2047-217X-1-12. ([PubMed](#))

Examples

```
data(Li)
```

```
my.dfs
```

Runs DFS on tree and calculates parent of each node as well as depth and upper-depth of nodes.

Description

It is used for internal purposes.

Usage

```
my.dfs(graph, root = NULL)
```

Arguments

graph	The tree
root	The starting node of DFS.

Value

a list with father representing the parent node, and balance.depth representing the distance between the node and the farthest node to it, as the elements.

my.general.dfs	<i>Running depth first search on a tree and calling functions on entrance/exit events</i>
----------------	---

Description

It is used for internal purposes.

Usage

```
my.general.dfs(  
  nei,  
  v,  
  f,  
  extra,  
  in.call,  
  mid.call.before,  
  mid.call.after,  
  out.call  
)
```

Arguments

nei	Neighbor list for each vertex
v	Starting node
f	Parent node
extra	the shared object for the whole DFS
in.call	First function to call
mid.call.before	Function to call before calling child DFS
mid.call.after	Function to call after calling child DFS
out.call	Last function to call

Value

the extra parameter modified with in.call, mid.call.before, mid.call.after, and out.call functions

`read.sequence.table` *Read mutation table*

Description

A simple read of a sequencing file.

Usage

```
read.sequence.table(file.name)
```

Arguments

`file.name` Name of the file to be loaded

Value

A table representing the content of the file. First column of the file represents the row names.

Examples

```
# An example input without header could be like following:
# 1 C/C A/A A/A A/A
# 2 ./ A/A C/C C/C
# 3 C/C A/A C/C ./
# 4 A/A ./ ./ ./
# 5 ./ A/A A/A A/A
#
# For this file you can run
read.sequence.table(system.file("extdata/sample1.txt", package="RScelestial"))
```

RScelestial

RScelestial: An R wrapper for scelestial algorithm for single-cell lineage tree reconstruction through an approximation algorithm based on Steiner tree problem

Description

This package provides a wrapper for the scelestial which is implemented in C++. The package contains function `scelestial` for running the algorithm and `synthesis` for tumor simulation for providing synthetic data.

scelestial *Infer the single-cell phylogenetic tree*

Description

Performs the Scelestial algorithm and calculates the phylogenetic tree reconstruction based on an approximation algorithm for Steiner tree problem.

Usage

```
scelestial(
  seq,
  mink = 3,
  maxk = 3,
  root.assign.method = c("none", "balance", "fix"),
  root = NULL,
  return.graph = FALSE
)
```

Arguments

seq	The sequence matrix. Rows represent loci and columns represent samples. Elements of the matrix represent 10-state genome sequencing results, or missing values. I.e each element is in the format "X/Y" where X and Y are from the set A, T, C, G. There is a special case "." that represents the missing value.
mink	The minimum k used in the calculation of k-restricted Steiner trees. It is supposed to be 3.
maxk	The maximum k used in the calculation of k-restricted Steiner trees. When maxk=3, the approximation algorithm produces an 11/6-approximation result. Increasing k increases the running time as well as the approximation ratio of the algorithm. maxk should be not less than mink.
root.assign.method, root	root.assign.method is the method for choosing the root. <ul style="list-style-type: none"> • "none" for undirected tree, • "fix" for a tree with root as its root. • "balance" to let the root to be chosen to produce the most balanced tree.
return.graph	If TRUE, the actual graph through igraph library is generated and produced.

Value

Returns a list containing following elements:

- tree: A data frame representing edges of the tree. tree\$src is the source of the edge, tree\$dest represents the destination of the edge, and tree\$len represents its weight (evolutionary distance).
- input: input sequences.

- `sequence`: inferred or imputed sequences for the tree nodes. If the node is already in the input, `sequence` represents its missing value imputation, in the case of presence of missing values, and if the node is not an input node, the `sequence` represents inferred sequence for the tree node.
- `graph`: `igraph`. If the `return.graph` is `TRUE`, there is an element `G` that represents the graph from the `igraph` library.

Examples

```
## simulates tumor evolution
S = synthesis(10, 10, 2, seed=7)
## convert to 10-state matrix
seq = as.ten.state.matrix(S$sequence)
## runs the scelestial to generate 4-restricted Steiner trees. It represents the tree and graph
SP = scelestial(seq, mink=3, maxk=4, return.graph = TRUE)
SP
## Expected output:
# $input
#   node  sequence
# 1     0 AAXACAAXXA
# 2     1 AXXXAXAAXA
# 3     2 AXAXCAXXAX
# 4     3 AXCCAXAAX
# 5     4 AXCAXXCAX
# 6     5 XXCAXXXXXX
# 7     6 XACXACAAAC
# 8     7 AXAXXAXAXA
# 9     8 AXAAXXAXXX
# 10    9 AAXXXXCXCX
#
# $sequence
#   node  sequence
# 1     0 AAAACAAACA
# 2     1 AACAAAAAAA
# 3     2 AAAACAAAAA
# 4     3 AACCCAAAAA
# 5     4 AACAACACAC
# 6     5 AACAAACAAAC
# 7     6 AACAAACAAAC
# 8     7 AAAACAAACA
# 9     8 AAAACAAACA
# 10    9 AAAACACACA
# 11   10 AAAACAAACA
# 12   16 AACAAAAAAA
# 13   18 AACACAAAAA
#
# $tree
#   src dest  len
# 1   9   10 4.00006
# 2   8   10 3.00006
# 3   7   10 2.50005
# 4   0   10 1.50003
```

```

# 5 6 16 3.00002
# 6 1 16 2.50005
# 7 3 18 2.50003
# 8 0 18 1.50003
# 9 16 18 1.00000
# 10 0 2 3.50008
# 11 4 6 4.00007
# 12 5 6 4.50010
#
# $graph
# IGRAPH 6ba60f3 DNW- 13 12 --
# + attr: name (v/c), weight (e/n)
# + edges from 6ba60f3 (vertex names):
# [1] 9 ->10 8 ->10 7 ->10 0 ->10 6 ->16 1 ->16 3 ->18 0 ->18 16->18 0 ->2
# [11] 4 ->6 5 ->6
#

```

synthesis

Synthesize single-cell data through tumor simulation

Description

This function simulates a evolution in a tumor through two phases: 1) simulation of evolution, 2) sampling.

Usage

```

synthesis(
  sample,
  site,
  evolution.step,
  mutation.rate = 1,
  advantage.increase.ratio = 1,
  advantage.decrease.ratio = 10,
  advantage.keep.ratio = 100,
  advantage.increase.step = 0.01,
  advantage.decrease.step = 0.01,
  mv.rate = 0.5,
  fp.rate = 0.2,
  fn.rate = 0.1,
  seed = -1
)

```

Arguments

sample	Number of samples.
site	number of sites (loci)

<code>evolution.step</code>	Number of evolutionary steps in the process of production of the evolutionary tree.
<code>mutation.rate</code>	The rate of mutation on each evolutionary step in evolutionary tree synthesis.
<code>advantage.increase.ratio</code> , <code>advantage.decrease.ratio</code> , <code>advantage.keep.ratio</code>	A child node in the evolutionary tree is chosen for increase/decrease/keep its parent advantage with probabilities proportional to <code>advantage.increase.ratio/advantage.decrease.ra</code>
<code>advantage.increase.step</code> , <code>advantage.decrease.step</code>	The amount of increasing or decreasing the advantage of a cell relative to its parent.
<code>mv.rate</code>	Rate of missing value to be added to the resulting sequences.
<code>fp.rate</code> , <code>fn.rate</code>	Rate of false positive (0 -> 1) and false negative (1 -> 0) in the sequences.
<code>seed</code>	The seed for randomization.

Details

The simulation of evolution starts with a single cell. Then for `evolution.step` steps, on each step a cell is selected for duplication. A new cell as its child is added to the evolutionary tree. To each node in the evolutionary tree an advantage is assigned representing its relative advantage in replication and in being sampled. Advantage of a node is calculated by increasing (decreasing) its parents advantage by `advantage.increase.step` (`advantage.decrease.step`) with probability proportional to `advantage.increase.ratio` (`advantage.decrease.ratio`). With a probability proportional to `advantage.keep.ratio` the advantage of a node is equal to its parent's advantage.

Sequences for each node is build based on its parent's sequence by adding some mutations. Mutations are added for each locus independently with rate `mutation.rate`.

In the sampling phase, `sample` cells are selected from the evolutionary tree nodes. Result of the sequencing process for a cell is determined by the sequence of the node in the evolutionary tree with addition of some random errors. Errors are result of applying some false positives with rate `fp.rate`, applying some false negatives with rate `fn.rate`, and adding some missing values with rate `mv.rate`.

Value

The function returns a list. The list consists of

- `sequence`: A data frame representing result of sequencing. The data frame has a row for each locus and a column for each sample.
- `true.sequence`: The actual sequence for the sample before adding errors and missing values.
- `true.clone`: A list that stores index of sampled cells for each node in the evolutionary tree.
- `true.tree`: The evolutionary tree that the samples are sampled from. It is a data frame with `src`, `dest`, and `len` columns representing source, destination and weight of edges of the tree, respectively.

Examples

```

## generating a data set with 10 samples and 5 loci through simulation of
## 20-step evolution.
synthesis(10, 5, 20, seed=7)
## The result is
# $sequence
#   C1 C2 C3 C4 C5
# L1  1  1  1  1  1
# L2  3  1  3  3  0
# L3  3  1  3  3  1
# L4  3  0  1  0  0
# L5  1  3  0  3  3
# L6  3  1  3  1  0
# L7  3  3  1  0  3
# L8  3  1  1  3  3
# L9  3  3  1  3  1
# L10 0  3  0  3  0
#
# $true.sequence
#   C1 C2 C3 C4 C5
# L1  0  1  1  1  1
# L2  0  1  0  0  1
# L3  0  1  0  0  1
# L4  0  1  1  1  1
# L5  1  1  0  1  0
# L6  0  1  0  1  0
# L7  0  1  0  0  1
# L8  0  1  1  1  1
# L9  0  1  1  1  1
# L10 0  0  0  0  0
#
# $true.clone
# $true.clone[[1]]
# [1] 4
#
# $true.clone[[2]]
# [1] 1
#
# $true.clone[[3]]
# [1] 6
#
# $true.clone[[4]]
# [1] 10
#
# $true.clone[[5]]
# [1] 2
#
# $true.clone[[6]]
# [1] 3
#
# $true.clone[[7]]
# [1] 8 9

```

```
#
# $true.clone[[8]]
# [1] 7
#
# $true.clone[[9]]
# [1] 5
#
#
# $true.tree
#  src dest len
#  1   1   5   3
#  2   5   7   1
#  3   5  10   2
#  4   1  11   3
#  5   1  12   2
#  6   1  13   3
#  7   7  14   2
#  8  12  19   1
#  9  10  20   1
#
```

tree.plot

Plotting the tree

Description

Plotting the igraph tree created by scelestial.

Usage

```
tree.plot(graph, ...)
```

Arguments

graph	Output of scelestial or the G element of the scelestial output.
...	Parameters passing to the plot function

Index

*Topic **datasets**

- Li, [9](#)
- .scelestial, [2](#)
- .synthesis, [2](#)

- as.mutation.matrix, [4](#)
- as.ten.state.matrix, [4](#)
- as.ten.state.matrix.from.node.seq, [5](#)

- distance.matrix.scelestial, [6](#)
- distance.matrix.tree, [7](#)
- distance.matrix.true.tree, [8](#)

- Li, [9](#)

- my.dfs, [10](#)
- my.general.dfs, [11](#)

- read.sequence.table, [12](#)
- RScelestial, [12](#)

- scelestial, [13](#)
- synthesis, [15](#)

- tree.plot, [18](#)