

Manipulate, Visualize and Compare Dendrograms: The dendextend R Package

Tal Galili
Tel-Aviv University

Yoav Benjamini
Tel-Aviv University

Abstract

A dendrogram is a tree diagram which is often used to visualize an hierarchical clustering of items. Dendrograms are used in many disciplines, ranging from Phylogenetic Trees in computational biology to Lexomic Trees in text analysis.

The **dendextend** package extends the dendrogram objects in the R programming language, allowing for easy manipulation of a dendrogram's shape, color and content. Furthermore, it enables the tools for comparing the similarity of two dendrograms to one another both graphically (using tanglegrams) and statistically (from cophenetic correlations to Bk plots).

The paper gives a detailed exposition of both the internal structure of the package and the provided user interfaces.

Keywords: Dendrogram, hclust, hierarchical clustering, visualization, tanglegram, R.

1. Introduction

1.1. The dendrogram object

The **dendrogram** class provides general functions for handling tree-like structures in R ([R Development Core Team 2013](#)). It is intended as a replacement for similar functions in hierarchical clustering and classification/regression trees, such that all of these can use the same engine for plotting or cutting trees.

A dendrogram object represents a tree as a nested **list** object, with various attributes.

Dendrogram has several useful methods bundled with R:

```
methods(class = "dendrogram")

## [1] [$.dendrogram*      as.hclust.dendrogram*
## [3] as.phylo.dendrogram  cophenetic.dendrogram*
## [5] cut.dendrogram*      cutree.dendrogram
## [7] head.dendrogram*     labels.dendrogram*
## [9] labels<-.dendrogram  merge.dendrogram*
## [11] nleaves.dendrogram*  nnodes.dendrogram*
## [13] plot.dendrogram*     print.dendrogram*
## [15] reorder.dendrogram*  rev.dendrogram*
```

```
## [17] rotate.dendrogram*      sort.dendrogram*
## [19] str.dendrogram*          trim.dendrogram*
## [21] unbranch.dendrogram*
##
##      Non-visible functions are asterisked
```

For example, let's create a dendrogram object based on an hierarchical clustering of 4 states in the U.S.:

```
# our data:
data(USArrests)
US_data <- USArrests[c(2, 5, 32, 35), ]
print(US_data)

##           Murder Assault UrbanPop Rape
## Alaska      10.0      263       48 44.5
## California   9.0      276       91 40.6
## New York     11.1      254       86 26.1
## Ohio         7.3      120       75 21.4

hc <- hclust(dist(US_data), "ave") # create an heirarchical clustering object
dend <- as.dendrogram(hc)
```

Below are examples for some dendrogram methods:

```
print(dend)

## 'dendrogram' with 2 branches and 4 members total, at height 146.7

labels(dend)

## [1] "Ohio"      "Alaska"    "California" "New York"

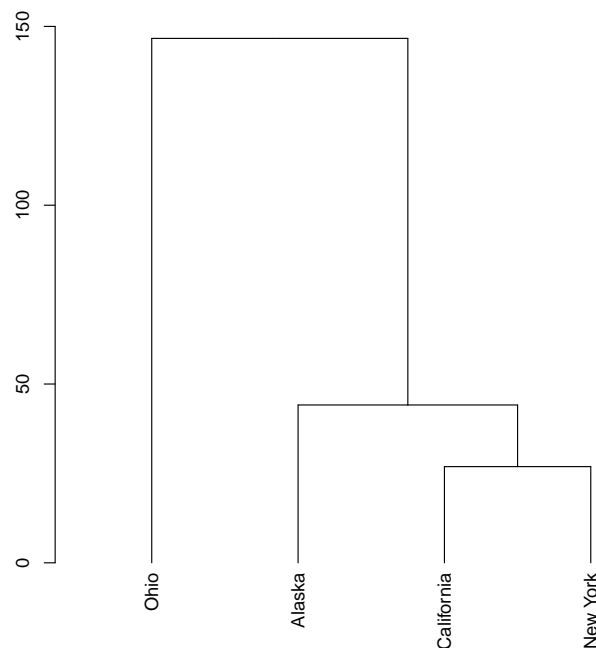
str(dend)

## --[dendrogram w/ 2 branches and 4 members at h = 147]
##   |--leaf "Ohio"
##   `--[dendrogram w/ 2 branches and 3 members at h = 44.1]
##     |--leaf "Alaska"
##     `--[dendrogram w/ 2 branches and 2 members at h = 26.9]
##       |--leaf "California"
##       `--leaf "New York"

str(dend[[2]]) # looking at one branch of the dendrogram
```

```
## --[dendrogram w/ 2 branches and 3 members at h = 44.1]
##   |--leaf "Alaska"
##   `--[dendrogram w/ 2 branches and 2 members at h = 26.9]
##     |--leaf "California"
##     `--leaf "New York"

plot(dend)
```



You might notice how the order of the items (leaves/terminal nodes) of the dendrogram is different than their order in the table. In order to re-order the rows in the data-table to have the same order as the items in the dendrogram, we can use the `order.dendrogram` function:

```
(new_order <- order.dendrogram(dend))

## [1] 4 1 2 3

# the order of the original items to have them be at the
# same order as they assume in the dendrogram
print(US_data[new_order, ])

##           Murder Assault UrbanPop Rape
## Ohio           7.3    120      75 21.4
## Alaska        10.0    263      48 44.5
## California     9.0    276      91 40.6
## New York      11.1    254      86 26.1
```

In order to see what our dendrogram (`list`) object includes, we need to use the `unclass` function, which will strip away the class attribute and will allow us to print the list as is, without going through the `print.dendrogram` method. We can see how each node in the dendrogram/`list` object has the following (self explaining) attributes:

```
str(unclass(dend))

## List of 2
## $ : atomic [1:1] 4
##   ..- attr(*, "members")= int 1
##   ..- attr(*, "height")= num 0
##   ..- attr(*, "label")= chr "Ohio"
##   ..- attr(*, "leaf")= logi TRUE
## $ :List of 2
##   ..$ : atomic [1:1] 1
##   .. ..- attr(*, "members")= int 1
##   .. ..- attr(*, "height")= num 0
##   .. ..- attr(*, "label")= chr "Alaska"
##   .. ..- attr(*, "leaf")= logi TRUE
##   ..$ :List of 2
##   .. ..$ : atomic [1:1] 2
##   .. .. ..- attr(*, "label")= chr "California"
##   .. .. ..- attr(*, "members")= int 1
##   .. .. ..- attr(*, "height")= num 0
##   .. .. ..- attr(*, "leaf")= logi TRUE
##   .. ..$ : atomic [1:1] 3
##   .. .. ..- attr(*, "label")= chr "New York"
##   .. .. ..- attr(*, "members")= int 1
##   .. .. ..- attr(*, "height")= num 0
##   .. .. ..- attr(*, "leaf")= logi TRUE
##   .. ..- attr(*, "members")= int 2
##   .. ..- attr(*, "midpoint")= num 0.5
##   .. ..- attr(*, "height")= num 26.9
##   ..- attr(*, "members")= int 3
##   ..- attr(*, "midpoint")= num 0.75
##   ..- attr(*, "height")= num 44.1
## - attr(*, "members")= int 4
## - attr(*, "midpoint")= num 0.875
## - attr(*, "height")= num 147
```

Notice how terminal nodes uses the "leaf" attribute (set to TRUE).

```
names(attributes(dend)[-4])

## [1] "members" "midpoint" "height"
```

A very important function is `dendrapply`. It applies some function recursively to each node of a dendrogram. It is often used for adjusting attributes of the object, or extracting something from it.

One current "feature" with this function is that just sending a dendrogram through it will return it with each of its nodes becoming of class "dendrogram". Notice the use of the `unclass_dend` function. Example:

```
# dendrapply(dend, unclass) # in case the
  itself <- function(x) x
dend_from_dendrapply <- dendrapply(dend, itself)

# here we must first use unclass since '[[[]]' inherits its
# class to the output:
class(unclass(dend)[[2]])

## [1] "list"

class(unclass(dend_from_dendrapply)[[2]])

## [1] "dendrogram"

class(unclass_dend(dend_from_dendrapply)[[2]]) # the new unclass_dend solves it.

## [1] "list"
```

1.2. Motivation for creating dendextend

The `dendrogram` object has several **advantages**:

1. `dendrogram` objects are list R objects. This makes their structure very familiar and easy to understand by R users. They are also, relatively, simple to manipulate and extend.
2. `dendrogram` objects has various methods and functions for using them within R base.
3. Other tree objects, such as `hclust`, and objects from the **ape** package (Paradis *et al.* 2004), include an `as.dendrogram` method for converting their objects into a dendrogram. And also `as.phylo.dendrogram`, `as.hclust.dendrogram`.
4. `dendrogram` objects are used in various packages as an intermediate step for other purposes (often plotting), such as:
 - (a) The **latticeExtra** package (Sarkar and Andrews 2012), see the `dendrogramGrob` function.
 - (b) The **labeltodendro** package (Nia and Stephens 2011), see the `colorplot` function.
 - (c) The **bclust** package (Nia and Davison 2012), see the `bclust` function.
 - (d) The **ggdendro** package (de Vries and Ripley 2013), see the `dendro_data` function.

- (e) The **Heatplus** package (Ploner 2012), see the `annHeatmap2` function.
- (f) The **sparcl** package (Ploner 2012), see the `ColorDendrogram` function.

However, even with all of its advantages, the `dendrogram` class in R still lacks various basic features.

The **dendextend** package aims at filling some gaps in base R, by extending the available functions for dendrogram manipulation, statistical analysis, and visualization.

This vignettes Provides a step-by-step description of the functionality provided by the **dendextend** package.

1.3. Installing dendextend

To install the stable version from CRAN use:

```
install.packages("dendextend") # not yet available from CRAN
```

To install the **GitHub version** use:

```
if (!require("devtools")) install.packages("devtools")
require("devtools")
install_github("dendextend", "talgalili")
```

2. Tree attributes (extraction, assignment, length)

2.1. labels in base R

In base R, the `labels` function is intended to find/extract a suitable set of labels from an object for use in printing or plotting, for example. By default, it uses the `names` and `dimnames` functions.

What base R `labels` function is missing is assignment. In the next few examples we will go through different examples of what the **dendextend** package offers for various objects.

Credits: These assignment functions were originally written by Gavin Simpson (in a post on [stackoverflow](#)), and adopted/adjusted to this package by Tal Galili. Some modification were inspired by Gregory Jefferis's code from the **dendroextras** package.

2.2. labels for vectors and matrices

In base R, for vectors, `labels` gives the `names` of the object. And if these are missing, then `labels` will give the vector itself as a character vector:

```
x <- 1:3
names(x) # this vector has no names

## NULL
```

```
labels(x) # this vector has no labels

## [1] "1" "2" "3"
```

Assignment to names is available in base R and works as follows:

```
x <- 1:3
names(x) <- letters[1:3] # assignment for names is in base R
# both names and labels will give the same result:
names(x)

## [1] "a" "b" "c"

labels(x)

## [1] "a" "b" "c"
```

The new labels assignment function will allow a user to change the labels of the vector just as if it was "names":

```
x <- 1:3
labels(x) <- letters[1:3]
names(x)

## [1] "a" "b" "c"

labels(x)

## [1] "a" "b" "c"
```

Labels assignment are also available for matrices.

2.3. labels for dendrogram objects

We can get a dendrogram's labels using the `labels` function from base R. However, in order to assign new values to it, we'll need the assignment function from **dendextend**:

```
labels(dend) # from base R

## [1] "Ohio"          "Alaska"        "California" "New York"

set.seed(2354235)
labels(dend) <- sample(labels(dend)) # labels assingment - thanks to dendextend
labels(dend)

## [1] "New York"      "Ohio"          "Alaska"       "California"
```

2.4. labels for hclust objects

dendextend offers a `labels` method for `hclust` objects. It take special care to have the order of the labels be the same as is with dendrogram object, which is the order of the labels in the plotted tree. This can be turned off when using the `order` parameter:

```
# All are from dendextend
labels(hc)

## [1] "Ohio"          "Alaska"        "California" "New York"

labels(hc, order = FALSE) # this is the order of the rows of the original data.

## [1] "Alaska"        "California" "New York"    "Ohio"

set.seed(229835)
labels(hc) <- sample(labels(hc)) # labels assingment - thanks to dendextend
labels(hc)

## [1] "California" "New York"    "Alaska"      "Ohio"
```

2.5. labels assignment and recycling

When the assigned vector has a different length, the **dendextend** assignment functions will recycle the value but also give a warning:

```
x <- 1:3
hc <- hclust(dist(US_data), "ave")
dend <- as.dendrogram(hc)
y <- matrix(1:9, 3, 3)

labels(x) <- "bob"

## Warning: The lengths of the new labels is shorter than the length of the object
- labels are recycled.

labels(x)

## [1] "bob" "bob" "bob"

labels(hc) <- "bob"

## Warning: The lengths of the new labels is shorter than the number of leaves
in the hclust - labels are recycled.

labels(hc)
```



```
## [1] "bob" "bob" "bob" "bob"

labels(dend) <- "bob"

## Warning: The lengths of the new labels is shorter than the number of leaves
in the dendrogram - labels are recycled.

labels(dend)

## [1] "bob" "bob" "bob" "bob"

labels(y) <- "bob"

## Warning: The lengths of the new labels is shorter than the length of the object's
colnames - labels are recycled.

labels(y)

## [1] "bob" "bob" "bob"
```

2.6. Tree size - number of leaves

Getting the size of a tree (e.g: number of leaves/terminal-nodes) is good for validation of functions, and also when we wish to initiate a variable to later fill with data from the leaves. The `labels` function for dendrogram is expensive, since it uses recursion to get all of the tree's elements. If we are only interested in getting the tree size, it is better to use the `nleaves` function. It has an S3 method for `hclust`, `dendrogram` and `phylo` (from the **ape**):

```
nleaves(hc)

## [1] 4

nleaves(dend)

## [1] 4
```

For dendrograms the speed improvement is about 10 times using `labels`, whereas for `hclust`, there is not any gain made by using `nleaves`. Here is a quick benchmark:

```
library(microbenchmark)
microbenchmark(nleaves(dend), length(labels(dend)))

## Unit: microseconds
##          expr      min       lq   median       uq      max
```

```
##          nleaves(dend) 24.08 26.04 27.16 30.8 132.7
## length(labels(dend)) 390.83 394.19 400.35 418.0 535.9
## neval
##      100
##      100

microbenchmark(nleaves(hc), length(labels(hc)))

## Unit: microseconds
##          expr    min      lq median      uq      max neval
##      nleaves(hc) 17.92 18.48  19.04 19.60  31.92   100
## length(labels(hc)) 30.80 31.36  31.92 31.92 131.59   100
```

There are border-line cases where the node above some leaves is of height 0. In such a case, we would consider that node as a "terminal node", and in order to count the number of such terminal nodes we would use `count_terminal_nodes` function. For example:

```
hc <- hclust(dist(USArrests[1:3, ]), "ave")
dend <- as.dendrogram(hc)

par(mfrow = c(1, 2))

### Trivial case
count_terminal_nodes(dend) # 3 terminal nodes

## [1] 3

length(labels(dend)) # 3 - the same number

## [1] 3

plot(dend, main = "This is considered a tree \n with THREE terminal nodes/leaves")

### NON-Trivial case
str(dend)

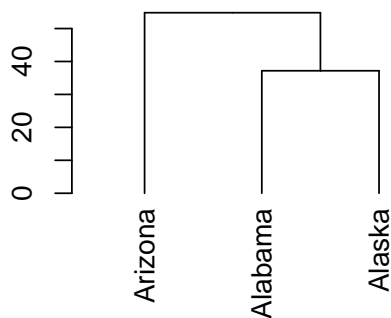
## --[dendrogram w/ 2 branches and 3 members at h = 54.8]
##   |--leaf "Arizona"
##   `--[dendrogram w/ 2 branches and 2 members at h = 37.2]
##     |--leaf "Alabama"
##     `--leaf "Alaska"

attr(dend[[2]], "height") <- 0
count_terminal_nodes(dend) # 2 terminal nodes, why? see this plot:
```

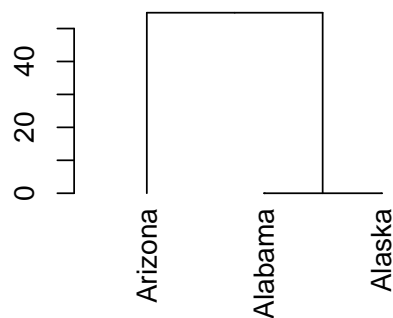
```
## [1] 2

# while we have 3 leaves, in practice we have only 2
# terminal nodes (this is a feature, not a bug.)
plot(dend, main = "This is considered a tree \n with TWO terminal nodes only")
```

**This is considered a tree
with THREE terminal nodes/leaves:**



**This is considered a tree
with TWO terminal nodes only**



2.7. Tree size - number of nodes

Getting the size of a tree, in terms of the number of nodes can easily be done using:

```
hc <- hclust(dist(USArrests[1:3, ]), "ave")
dend <- as.dendrogram(hc)

nnodes(hc)

## [1] 5

nnodes(dend)

## [1] 5
```

2.8. Generally getting tree attributes

Getting tree attributes can more generally be achieved using `get_nodes_attr`, however, the dedicated function are often faster than the general solution. (also, in the future, we might introduce functions based on **Rcpp**, offering even faster times).

Here are some examples:

```
hc <- hclust(dist(USArrests[1:3, ]), "ave")
dend <- as.dendrogram(hc)

# get_leaves_attr(dend) # error :)
get_leaves_attr(dend, "label")

## [1] "Arizona" "Alabama" "Alaska"

labels(dend, "label")

## [1] "Arizona" "Alabama" "Alaska"

get_leaves_attr(dend, "height") # should be 0's

## [1] 0 0 0

get_nodes_attr(dend, "height")

## [1] 54.80 0.00 37.18 0.00 0.00

get_branches_heights(dend, sort = FALSE) # notice the sort=FALSE

## [1] 54.80 37.18

get_leaves_attr(dend, "leaf") # should be TRUE's

## [1] TRUE TRUE TRUE

get_nodes_attr(dend, "leaf") # contains NA's

## [1] NA TRUE NA TRUE TRUE

get_nodes_attr(dend, "leaf", na.rm = TRUE) #

## [1] TRUE TRUE TRUE

get_leaves_attr(dend, "members") # should be 1's

## [1] 1 1 1
```

```

get_nodes_attr(dend, "members", include_branches = FALSE, na.rm = TRUE) #

## [1] 1 1 1

get_nodes_attr(dend, "members") #

## [1] 3 1 2 1 1

get_nodes_attr(dend, "members", include_leaves = FALSE, na.rm = TRUE) #

## [1] 3 2

hang_dend <- hang.dendrogram(dend)
get_leaves_attr(hang_dend, "height") # no longer 0!

## [1] 49.32 31.70 31.70

get_nodes_attr(hang_dend, "height") # does not include any 0s!

## [1] 54.80 49.32 37.18 31.70 31.70

# does not include leaves values:
get_nodes_attr(hang_dend, "height", include_leaves = FALSE)

## [1] 54.80    NA 37.18    NA    NA

# remove leaves values all together:
get_nodes_attr(hang_dend, "height", include_leaves = FALSE, na.rm = TRUE)

## [1] 54.80 37.18

get_branches_heights(hang_dend) # notice the sort

## [1] 37.18 54.80

get_branches_heights(hang_dend, sort = FALSE) # notice the sort

## [1] 54.80 37.18

```

Quick comparison on fetching leaves attributes:

```
require(microbenchmark)
# get_leaves_attr is twice faster than get_nodes_attr
microbenchmark(get_leaves_attr_4members = get_leaves_attr(dend,
  "members"), get_nodes_attr_4members = get_nodes_attr(dend,
  "members", include_branches = FALSE, na.rm = TRUE))

## Unit: microseconds
##           expr      min       lq     median       uq      max
## get_leaves_attr_4members 288.9  296.5   309.1  327.6  3543
## get_nodes_attr_4members 707.8  720.4   745.0  789.2  3127
## neval
##    100
##    100
```

3. Tree manipulation

3.1. unbranching and root height

A tree's nodes has various heights. Sometimes we are interested in changing the height of the entire tree. It is useful when This can be accomplished using **raise.dendrogram**. For example (notice how the entire tree's height is changed):

```
hc <- hclust(dist(USArrests[1:3, ]), "ave")
dend <- as.dendrogram(hc)

taller_dend <- raise.dendrogram(dend, 10)
shorter_dend <- raise.dendrogram(dend, -10)

attr(dend, "height") # 54.80041

## [1] 54.8

attr(taller_dend, "height") # 64.80041

## [1] 64.8

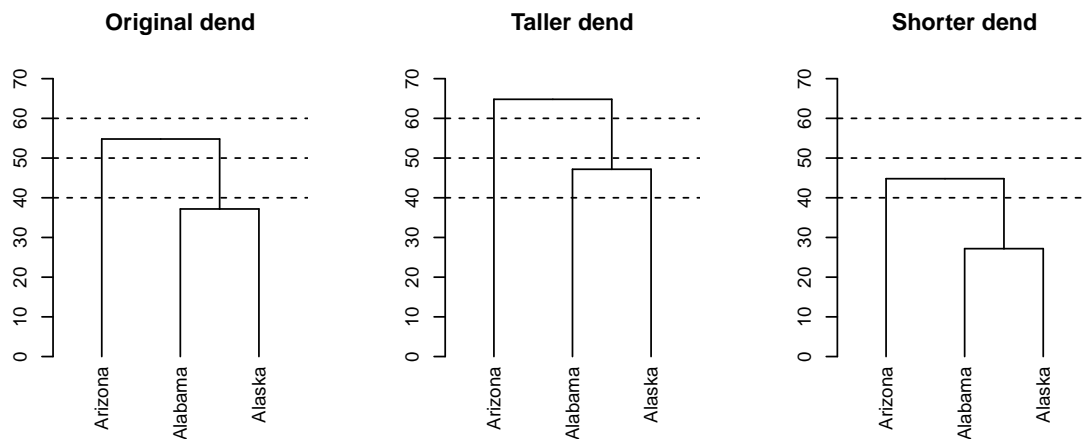
attr(shorter_dend, "height") # 44.80041

## [1] 44.8
```

```

par(mfrow = c(1, 3))
plot(dend, ylim = c(0, 70), main = "Original dend")
abline(h = c(40, 50, 60), lty = 2)
plot(taller_dend, ylim = c(0, 70), main = "Taller dend")
abline(h = c(40, 50, 60), lty = 2)
plot(shorter_dend, ylim = c(0, 70), main = "Shorter dend")
abline(h = c(40, 50, 60), lty = 2)

```



Sometimes we wish to “unbranch” the dendrogram, meaning that we merge one of the tree’s branches with its root. This is useful, for example, when merging phylogenetic trees from several families, and being unwilling to assume a specific root/height to the merged trees. unbranching can be done using the `unbranch` (S3) function (notice the use of the `branch_becoming_root` parameter):

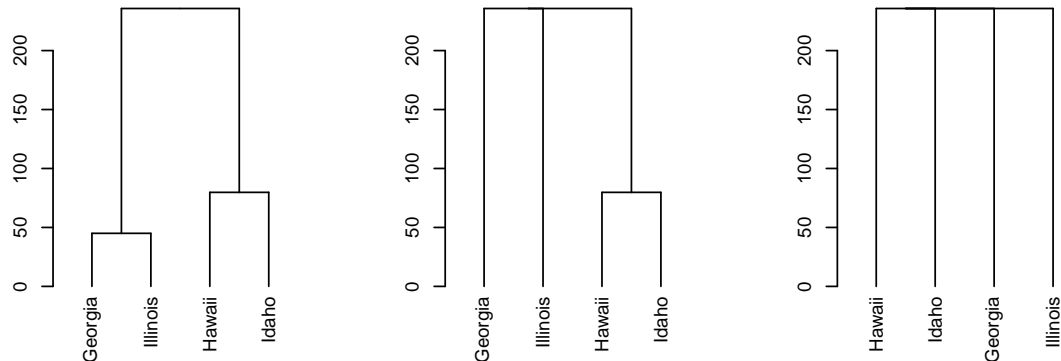
```

hc <- hclust(dist(USArrests[10:13, ]), "ward")
dend <- as.dendrogram(hc)

unbranched_dend <- unbranch(dend, branch_becoming_root = 1)
unbranched_dend_2 <- unbranch(unbranched_dend, branch_becoming_root = 3)

par(mfrow = c(1, 3))
plot(dend)
plot(unbranched_dend)
plot(unbranched_dend_2)

```



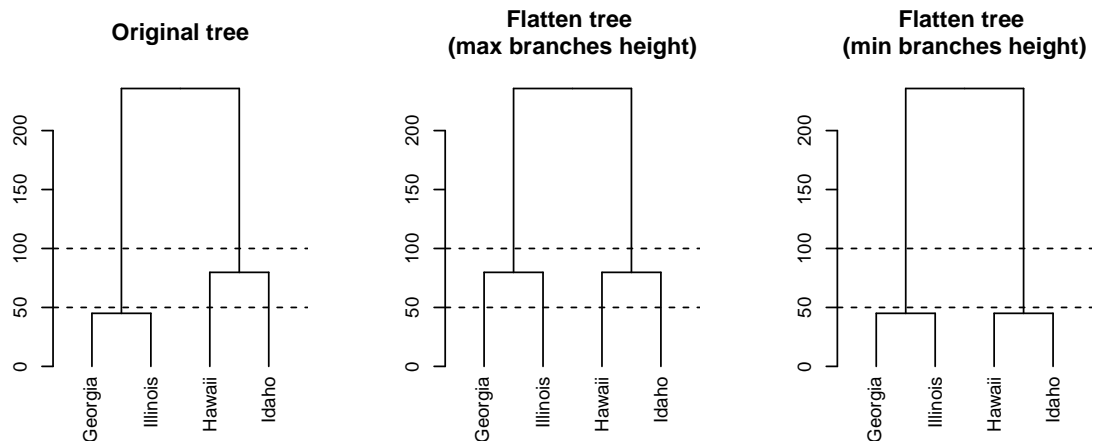
While the `unbranch.hclust` method exists, it is not expected to work since `hclust` objects are not designed to handle non-binary trees (hence the advantage of using `dendrogram` objects). For `phylo` objects (from the **ape** package), there is also a method that would simply use `ape::unbranch(phy = x)`.

In some rare cases, we might wish to equalize the heights of root's branches. For this we can use the `flatten.dendrogram` function:

```
hc <- hclust(dist(USArrests[10:13, ]), "ward")
dend <- as.dendrogram(hc)

flatten_dend_1 <- flatten.dendrogram(dend, FUN = max)
flatten_dend_2 <- flatten.dendrogram(dend, FUN = min)

par(mfrow = c(1, 3))
plot(dend, main = "Original tree")
abline(h = c(50, 100), lty = 2)
plot(flatten_dend_1, main = "Flatten tree \n(max branches height)")
abline(h = c(50, 100), lty = 2)
plot(flatten_dend_2, main = "Flatten tree \n(min branches height)")
abline(h = c(50, 100), lty = 2)
```

3.2. Coloring labels of leaves

Coloring labels can sometimes be useful, it is done through the `labels_colors` function (which also has assignment). Notice the assignment recycling, as well as the difference in the appearance of a dot when labels' color is black, compared to when it is NULL:

```
par(mfrow = c(1, 3))

hc <- hclust(dist(USArrests[1:3, ]), "ave")
dend <- as.dendrogram(hc)

# Defaults:
labels_colors(dend)

## NULL

plot(dend)

# let's add some color:
require(colorspace)

## Loading required package: colorspace

labels_colors(dend) <- rainbow_hcl(3)
labels_colors(dend)

## Arizona Alabama Alaska
## "#E495A5" "#86B875" "#7DB0DD"

plot(dend)

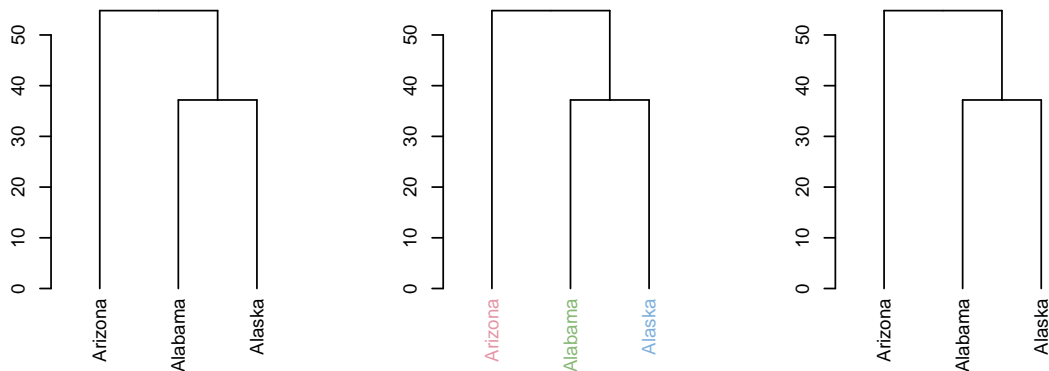
# changing color to black
labels_colors(dend) <- 1
```

```
## Warning: Length of color vector was shorter than the number of leaves - vector
color recycled

labels_colors(dend)

## Arizona Alabama Alaska
##          1         1         1

plot(dend)
```



```
# removing color (and the nodePar completely - if it has no
# other attributed but lab.col)
labels_colors(dend) <- NULL

## Warning: Length of color vector was shorter than the number of leaves - vector
color recycled
## Warning: 'x' is NULL so the result will be NULL

labels_colors(dend)

## NULL
```

3.3. Hanging a dendrogram

Hanging a tree means that we change the height of the leaves to be near their parent node. Hanging helps when examining the topology of the tree. Currently, hanging of a dendrogram was possible by going through the `hclust` object, but now you can simply use the `hang.dendrogram` function. Here is an example:

```

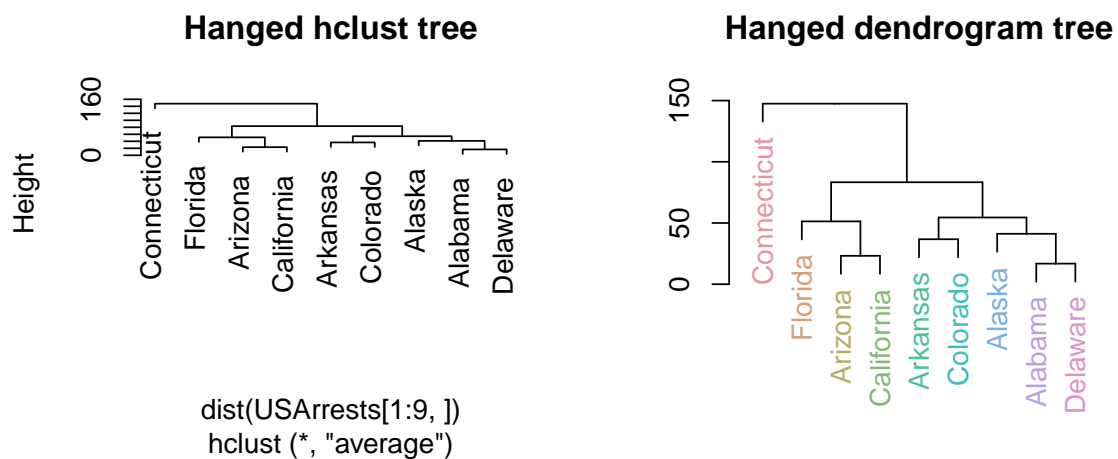
hc <- hclust(dist(USArrests[1:9, ]), "ave")
dend <- as.dendrogram(hc)
hang_dend_1 <- hang.dendrogram(dend, hang = 0.1)
hang_dend_2 <- as.dendrogram(hc, hang = 0.1) # another way of doing it, if
# we could move from/to hclust
identical(hang_dend_1, hang_dend_2) # and they are the same :)

## [1] TRUE

require(colorspace)
labels_colors(hang_dend_1) <- rainbow_hcl(nleaves(hang_dend_1))

par(mfrow = c(1, 2))
plot(hc, main = "Hanged hclust tree")
plot(hang_dend_1, main = "Hanged dendrogram tree")

```



3.4. Trimming leaves

Trimming a tree from some leaves can be done using the `trim` (S3 method) function (notice that the attributes of the trimmed tree are updated):

```

hc <- hclust(dist(USArrests[1:5, ]), "ave")
dend <- as.dendrogram(hc)
library(colorspace)
labels_colors(dend) <- rainbow_hcl(5)

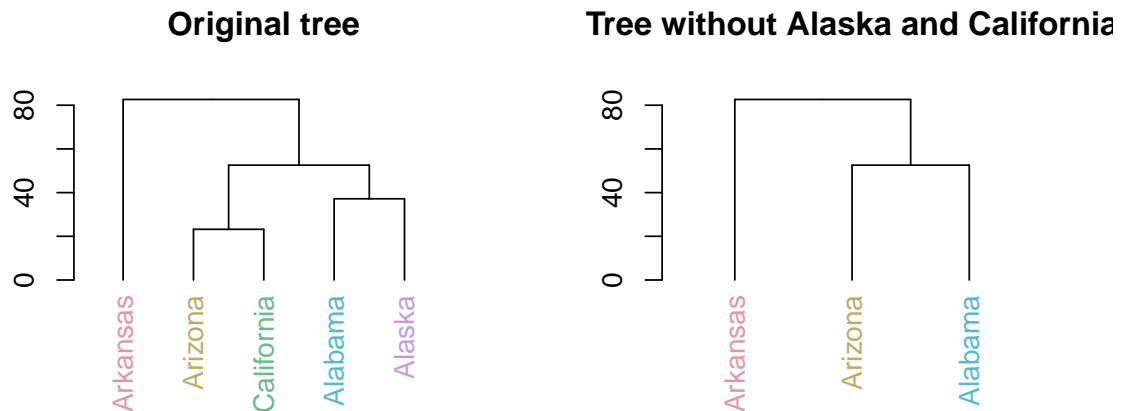
trimmed_dend <- trim(dend, c("Alaska", "California"))

str(unclass(trimmed_dend))

```

```
## List of 2
## $ : atomic [1:1] 4
##   ..- attr(*, "members")= int 1
##   ..- attr(*, "height")= num 0
##   ..- attr(*, "label")= chr "Arkansas"
##   ..- attr(*, "leaf")= logi TRUE
##   ..- attr(*, "nodePar")=List of 2
##     .. ..$ lab.col: chr "#E495A5"
##     .. ..$ pch      : logi NA
## $ :List of 2
##   ..$ : atomic [1:1] 3
##     .. ..- attr(*, "label")= chr "Arizona"
##     .. ..- attr(*, "members")= int 1
##     .. ..- attr(*, "height")= num 0
##     .. ..- attr(*, "leaf")= logi TRUE
##     .. ..- attr(*, "nodePar")=List of 2
##       .. .. ..$ lab.col: chr "#BDAB66"
##       .. .. ..$ pch      : logi NA
##     ..$ : atomic [1:1] 1
##       .. ..- attr(*, "label")= chr "Alabama"
##       .. ..- attr(*, "members")= int 1
##       .. ..- attr(*, "height")= num 0
##       .. ..- attr(*, "leaf")= logi TRUE
##       .. ..- attr(*, "nodePar")=List of 2
##         .. .. ..$ lab.col: chr "#55B8D0"
##         .. .. ..$ pch      : logi NA
##     ..- attr(*, "members")= num 2
##     ..- attr(*, "midpoint")= num 0.5
##     ..- attr(*, "height")= num 52.6
## - attr(*, "members")= num 3
## - attr(*, "midpoint")= num 0.75
## - attr(*, "height")= num 82.6

par(mfrow = c(1, 2))
plot(dend, main = "Original tree")
plot(trimmed_dend, main = "Tree without Alaska and California")
```



If we have two trees, we can use the `intersect_trees` function to reduce both trees to have the same labels (this will be useful later when we'd like to compare the two trees):

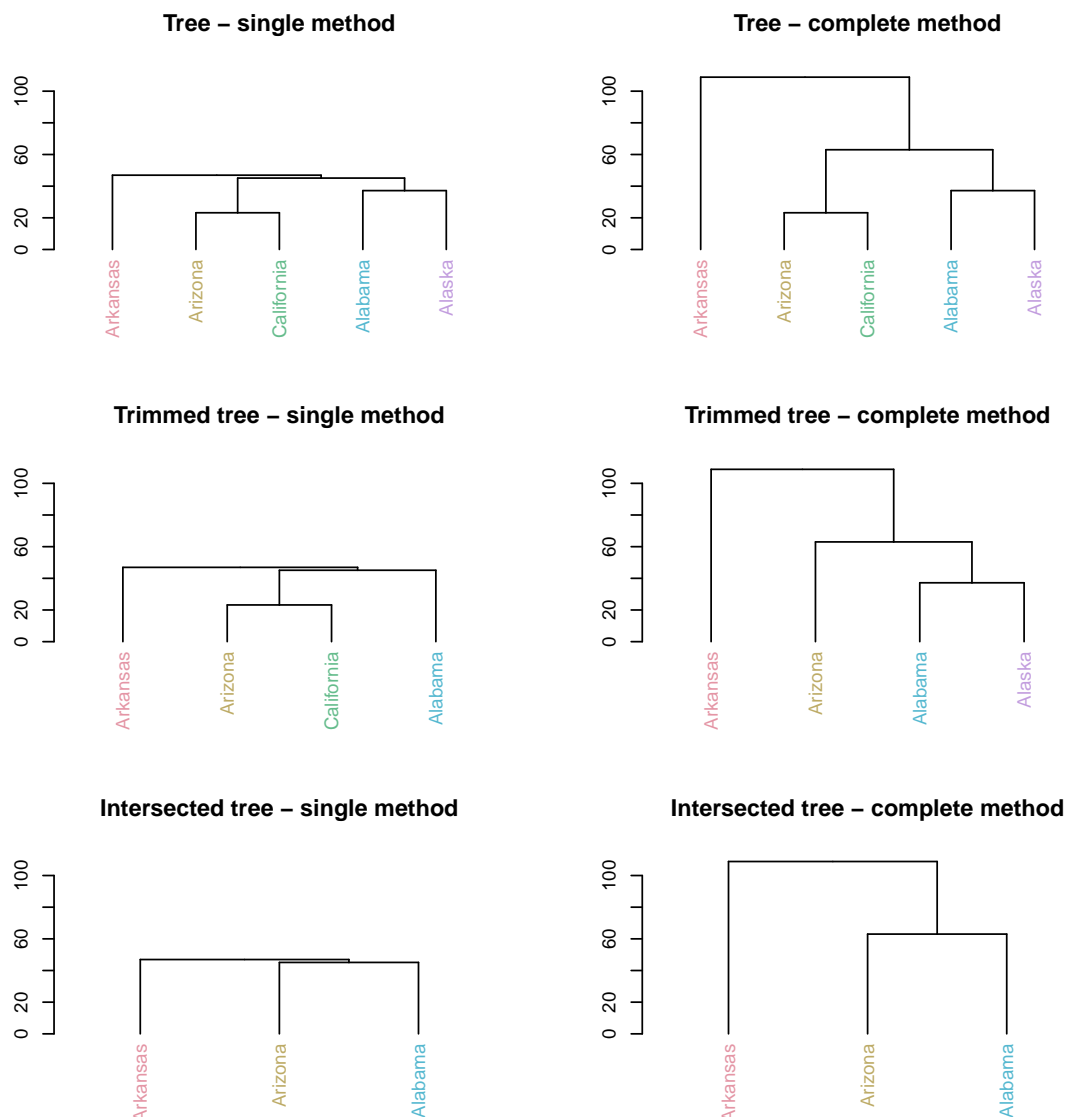
```
hc_1 <- hclust(dist(USArrests[1:5, ]), "single")
hc_2 <- hclust(dist(USArrests[1:5, ]), "complete")
dend_1 <- as.dendrogram(hc_1)
dend_2 <- as.dendrogram(hc_2)

library(colospace)
labels_colors(dend_1) <- rainbow_hcl(5)
labels_colors(dend_2) <- rainbow_hcl(5)

trimmed_dend_1 <- trim(dend_1, c("Alaska"))
trimmed_dend_2 <- trim(dend_2, c("California"))

dends_12 <- intersect_trees(trimmed_dend_1, trimmed_dend_2)

par(mfrow = c(3, 2))
plot(dend_1, main = "Tree - single method", ylim = c(0, 110))
plot(dend_2, main = "Tree - complete method", ylim = c(0, 110))
plot(trimmed_dend_1, main = "Trimmed tree - single method", ylim = c(0, 110))
plot(trimmed_dend_2, main = "Trimmed tree - complete method",
     ylim = c(0, 110))
plot(dends_12[[1]], main = "Intersected tree - single method",
     ylim = c(0, 110))
plot(dends_12[[2]], main = "Intersected tree - complete method",
     ylim = c(0, 110))
```



Sidenote: a similar function, called `plotColoredClusters`, is available in the **ClassDiscovery** package for `hclust` objects.

3.5. Rotating branches

A dendrogram is an object which can be rotated on its hinges without changing its topological. Rotating a dendrogram in base R can be done using the `reorder` function. The problem with this function is that it is not very intuitive. For this reason we wrote the `rotate` function. It has two main arguments: the object, and the order we wish to rotate it by. The order parameter can be either a numeric vector, used in a similar way we would order a simple

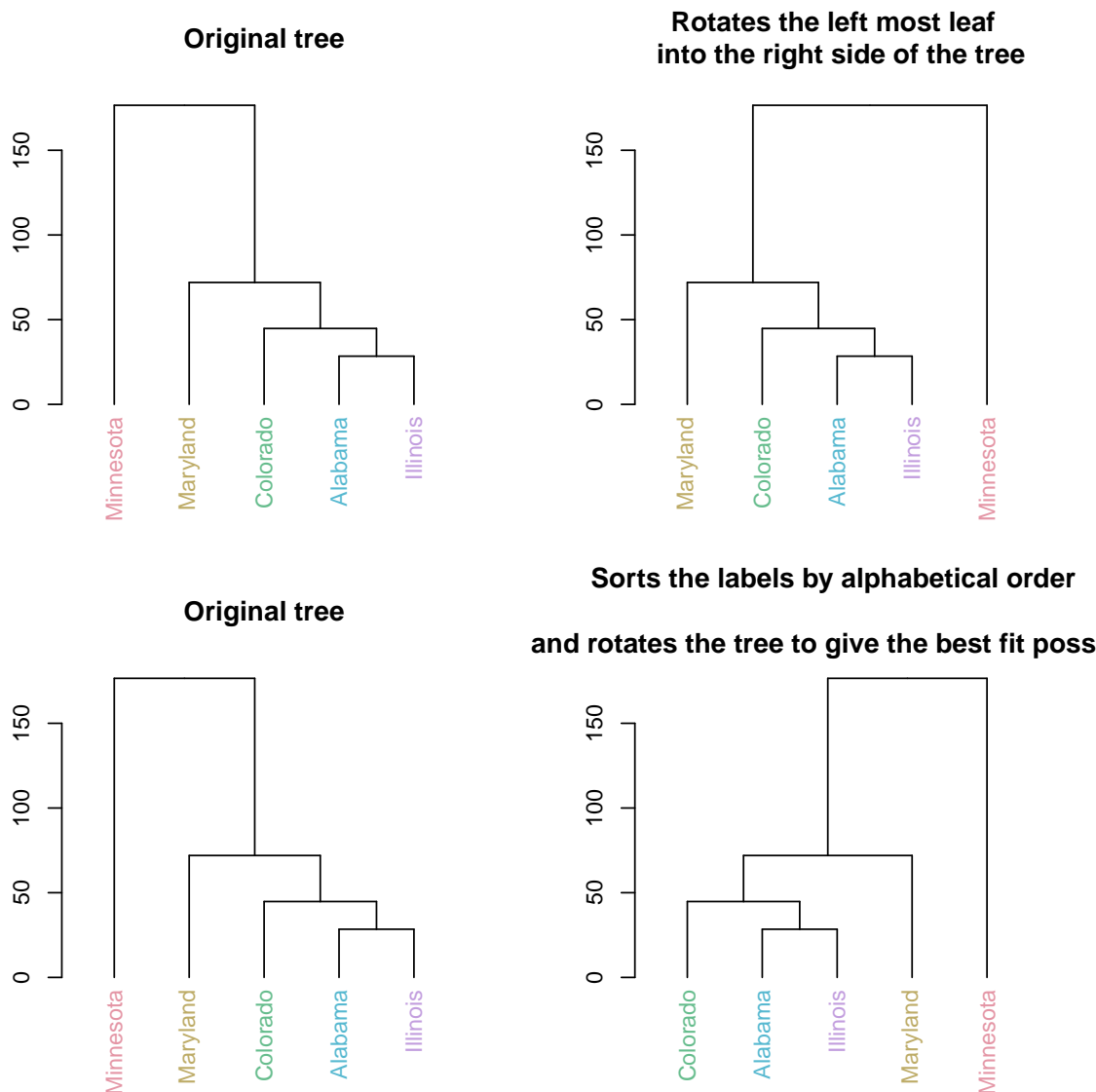
character vector. Or, the order parameter can also be a character vector of the labels of the tree, given in the new desired order of the tree.

It is also worth noting that some order are impossible to achieve for a given tree's topology. In such a case, the function will do its "best" to get as close as possible.

Here are a few examples:

```
hc <- hclust(dist(USArrests[c(1, 6, 13, 20, 23), ]), "ave")
dend <- as.dendrogram(hc)

# For dendrogram objects:
require(colorspace)
labels_colors(dend) <- rainbow_hcl(nleaves(dend))
# let's color the labels to make the followup of the
# rotation easier
par(mfrow = c(2, 2))
plot(dend, main = "Original tree")
plot(rotate(dend, c(2:5, 1)), main = "Rotates the left most leaf \n into the right side of")
plot(dend, main = "Original tree")
plot(sort(dend), main = "Sorts the labels by alphabetical order \n\nand rotates the tree t")
```



3.6. Cutting trees

The `hclust` function comes with a very powerful `cutree` function, for extracting cluster grouping of the original data based on cutting the hierarchical tree at some height (or setting a predefined `k` - number of clusters). The limitation of this function is that it is only available for `hclust` object. Hence, if we are dealing with a tree which is NOT an ultrametric tree (e.g: ultrametric tree = a tree with monotone clustering heights), `cutree` would not be available for us (since `as.hclust` would not work on our dendrogram).

In **dendextend**, we extend `cutree` by turning it into an S3 method, with methods for dendrogram and phylo objects. The phylo method is only turning the phylo object to an `hclust`, and tries to work on it there. However, the dendrogram method (`cutree.dendrogram`) is a complete re-writing of `cutree` based on the `cut.dendrogram` function. `cutree.dendrogram` fully emulates `cutree` by default, but at the same time extends it with the type of trees it

can handle, and with some other options.

Since `cutree.dendrogram` is written in R, it is slower than `cutree` which is implemented in C. If we can turn the dendrogram into `hclust`, we will use `cutree.hclust`, otherwise - `cutree.dendrogram` will be used.

Here are several examples of how these functions are used:

```
hc <- hclust(dist(USArrests[c(1, 6, 13, 20, 23), ]), "ave")
dend <- as.dendrogram(hc)
unbranch_dend <- unbranch(dend, 2)

cutree(hc, k = 2:4) # on hclust

##           2 3 4
## Alabama   1 1 1
## Colorado  1 1 2
## Illinois   1 1 1
## Maryland  1 2 3
## Minnesota 2 3 4

cutree(dend, k = 2:4) # on dendrogram

##           2 3 4
## Alabama   1 1 1
## Colorado  1 1 2
## Illinois   1 1 1
## Maryland  1 2 3
## Minnesota 2 3 4

cutree(hc, k = 2) # on hclust

##   Alabama  Colorado  Illinois  Maryland  Minnesota
##         1         1         1         1         2

cutree(dend, k = 2) # on dendrogram

##   Alabama  Colorado  Illinois  Maryland  Minnesota
##         1         1         1         1         2

cutree(dend, h = c(20, 25.5, 50, 170))

##           20 25.5 50 170
## Alabama   1   1  1  1
## Colorado  2   2  1  1
## Illinois   3   3  1  1
## Maryland  4   4  2  1
## Minnesota 5   5  3  2
```

```

cutree(hc, h = c(20, 25.5, 50, 170))

##           20 25.5 50 170
## Alabama   1   1  1  1
## Colorado  2   2  1  1
## Illinois   3   3  1  1
## Maryland   4   4  2  1
## Minnesota  5   5  3  2

# the default (ordered by original data's order)
cutree(dend, k = 2:3, order_clusters_as_data = FALSE)

## [1] 2 1 1 1 1

labels(dend)

## [1] "Minnesota" "Maryland" "Colorado" "Alabama"
## [5] "Illinois"

# cutree now works for unbranched trees!
# as.hclust(unbranch_dend) # ERROR - can not do this...
cutree(unbranch_dend, k = 2) # all NA's

## Warning: Couldn't cut the tree - returning NA.
## Warning: You (probably) have some branches with equal heights so that there
exist no height(h) that can create 2 clusters

## [1] NA NA NA NA NA

cutree(unbranch_dend, k = 1:4)

## Warning: Couldn't cut the tree - returning NA.
## Warning: You (probably) have some branches with equal heights so that there
exist no height(h) that can create 2 clusters

##           1  2 3 4
## Alabama   1 NA 2 2
## Colorado  1 NA 2 3
## Illinois   1 NA 2 2
## Maryland   1 NA 3 4
## Minnesota 1 NA 1 1

cutree(unbranch_dend, h = c(20, 25.5, 50, 170))

```

```
##          20 25.5 50 170
## Alabama   1   1  2  2
## Colorado  2   2  2  2
## Illinois  3   3  2  2
## Maryland  4   4  3  3
## Minnesota 5   5  1  1

require(microbenchmark)
## this shows how as.hclust is expensive - but still worth
## it if possible
microbenchmark(cutree(hc, k = 2:4), cutree(as.hclust(dend), k = 2:4),
               cutree(dend, k = 2:4), cutree(dend, k = 2:4, try_cutree_hclust = FALSE))

## Unit: microseconds
##                                     expr      min
##                                     cutree(hc, k = 2:4) 134.9
##                                     cutree(as.hclust(dend), k = 2:4) 1738.0
##                                     cutree(dend, k = 2:4) 1865.1
## cutree(dend, k = 2:4, try_cutree_hclust = FALSE) 8250.6
##      lq median      uq      max neval
##  144.5  147.8  199.3   357.2   100
## 1788.1 1851.1 1892.3  4769.5   100
## 1935.4 1991.4 2050.2  4888.2   100
## 8485.5 8676.1 8947.7 99834.4   100

# the dendrogram is MUCH slower...

# and trying to 'hclust' is not expensive (which is
# nice...)
microbenchmark(cutree_unbranch_dend = cutree(unbranch_dend, k = 2:4,
      warn = FALSE), cutree_unbranch_dend_not_trying_to_hclust = cutree(unbranch_dend,
      k = 2:4, try_cutree_hclust = FALSE, warn = FALSE))

## Unit: milliseconds
##                                     expr      min      lq
##                                     cutree_unbranch_dend 6.786 6.924
## cutree_unbranch_dend_not_trying_to_hclust 6.359 6.504
##      median      uq      max neval
##    7.064 7.197 33.35   100
##    6.614 6.916 13.67   100
```

Having `cutree.dendrogram` available to us, we can now gain the ability to color branches for trees which can not be represented as an `hclust` object.

3.7. Coloring branches

Dendrogram plots with colored branches are used to easily distinguishing between different clusters on a tree. They have been available in R for many years in threads on the mailing lists and through various package. However, until recently, all of the functions in packages have always given the user a new `plot` function, without separating the coloring of branches of a dendrogram from its plotting. Often the function for actually plotting the colored branched dendrogram would be hidden from the user. For example, the **labeltodendro** package (Nia and Stephens 2011) gives a colored branch plot through the `colorplot` function, but the work horse for this is available in a hidden function called `dendroplot` or `dendroplotv`, both take care of the plotting by themselves (instead of modifying the dendrogram object, and then letting the base R function do the work). The same story happens in the **Heatplus** (Ploner 2012), where the `plot.annHeatmap2` function actually uses the hidden function `cutplot.dendrogram` for doing the plotting.

This was changed in the beginning of 2013 thanks to Gregory Jefferis's **dendroextras** package (Jefferis 2013), which organized this through the `colour_clusters` function. In the **dendextend** package we imported his code into a new function called `color_branches`, with several useful modifications on the original code. The biggest limitation in the `colour_clusters` function is that it relies on changing the `dendrogram` into `hclust` in order to use `cutree` on it and get the clusters. This has the advantage of being fast, but the **disadvantage** of restricting the function to ultrametric and binary trees (the type of tree `hclust` objects can handle). In our implementation we implemented a new function called `cutree.dendrogram` (available through an S3 method), which can either rely on `hclust` for speed, but in case it is not possible will revert to find the clustering on the dendrogram object itself (the function is completely compatible with the base R `cutree` function). Also, our implementation of the `color_branches` function allows for repeated-multilayered coloring the branches. Another potential bug which is avoided in our implementation is to handle cases where the labels of the tree are of type Integer instead of Character (this happens if the `dendrogram` came from an `hclust`, used on the `dist` of data that has no `rownames`).

Here is an example of using `color_branches` combined with `labels_colors`:

```
require(colorspace)

data(iris)
d_iris <- dist(iris[, -5])
hc_iris <- hclust(d_iris)
labels(hc_iris)

## character(0)

dend_iris <- as.dendrogram(hc_iris)
is.integer(labels(dend_iris)) # this could cause problems...

## [1] TRUE
```

```
iris_species <- rev(levels(iris[, 5]))
dend_iris <- color_branches(dend_iris, k = 3, groupLabels = iris_species)
is.character(labels(dend_iris))

## [1] TRUE

# have the labels match the real classification of the
# flowers:
labels_colors(dend_iris) <- rainbow_hcl(3)[sort_levels_values(as.numeric(iris[,
  5])[order.dendrogram(dend_iris)])]

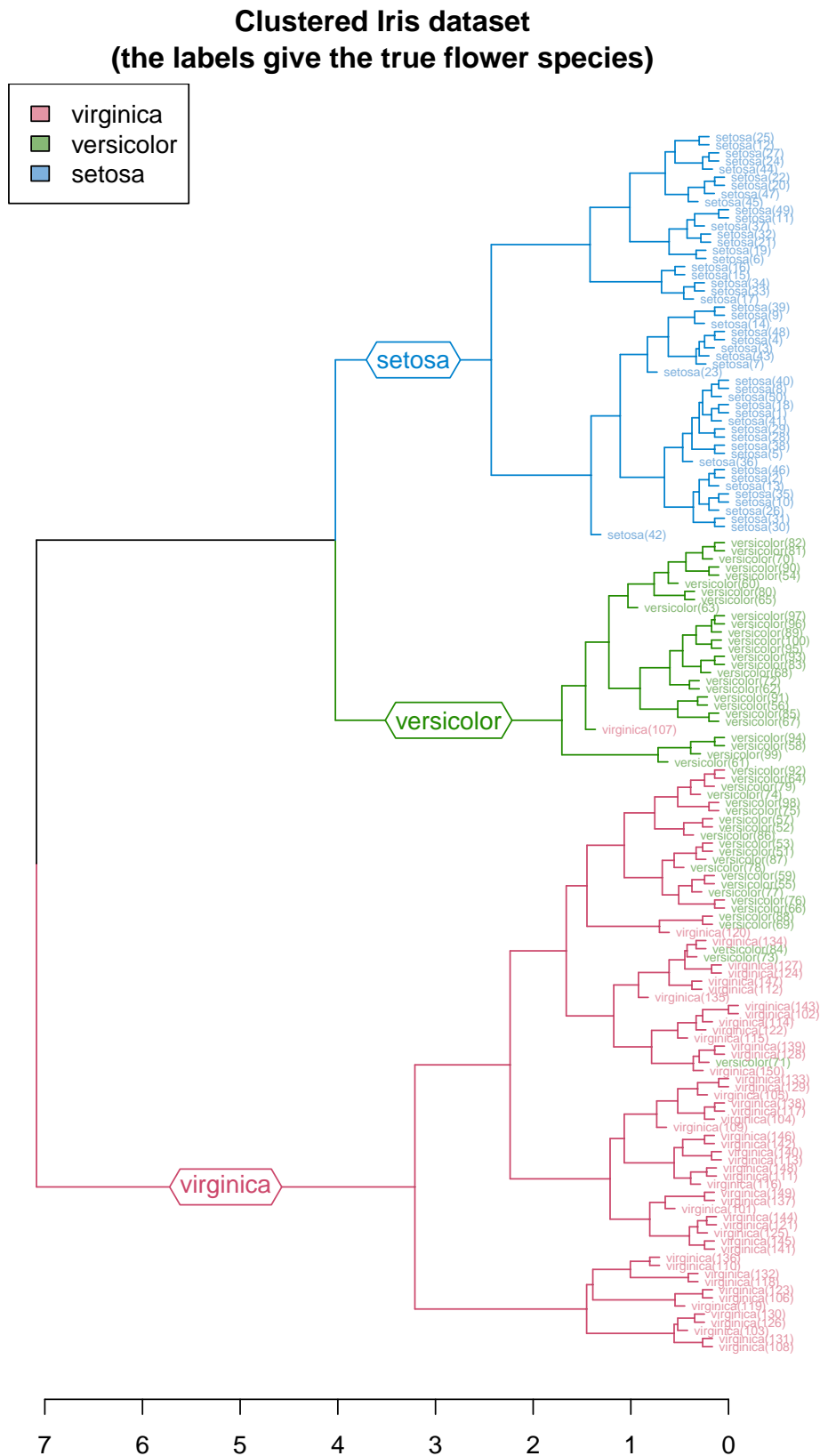
# We'll add the flower type
labels(dend_iris) <- paste(as.character(iris[, 5])[order.dendrogram(dend_iris)],
  "(", labels(dend_iris), ")", sep = "")

dend_iris <- hang.dendrogram(dend_iris, hang_height = 0.1)

# reduce the size of the labels:
dend_iris <- assign_values_to_leaves_nodePar(dend_iris, 0.5,
  "lab.cex")

## Warning: Length of value vector was shorter than the number of leaves - vector
value recycled

par(mar = c(3, 3, 3, 7))
plot(dend_iris, main = "Clustered Iris dataset\n(the labels give the true flower species)",
  horiz = TRUE, nodePar = list(cex = 0.007))
legend("topleft", legend = iris_species, fill = rainbow_hcl(3))
```



This simple visualization easily demonstrates how the separation of the hierarchical clustering is very good with the "setosa" species, but misses in labeling many "versicolor" species as "virginica".

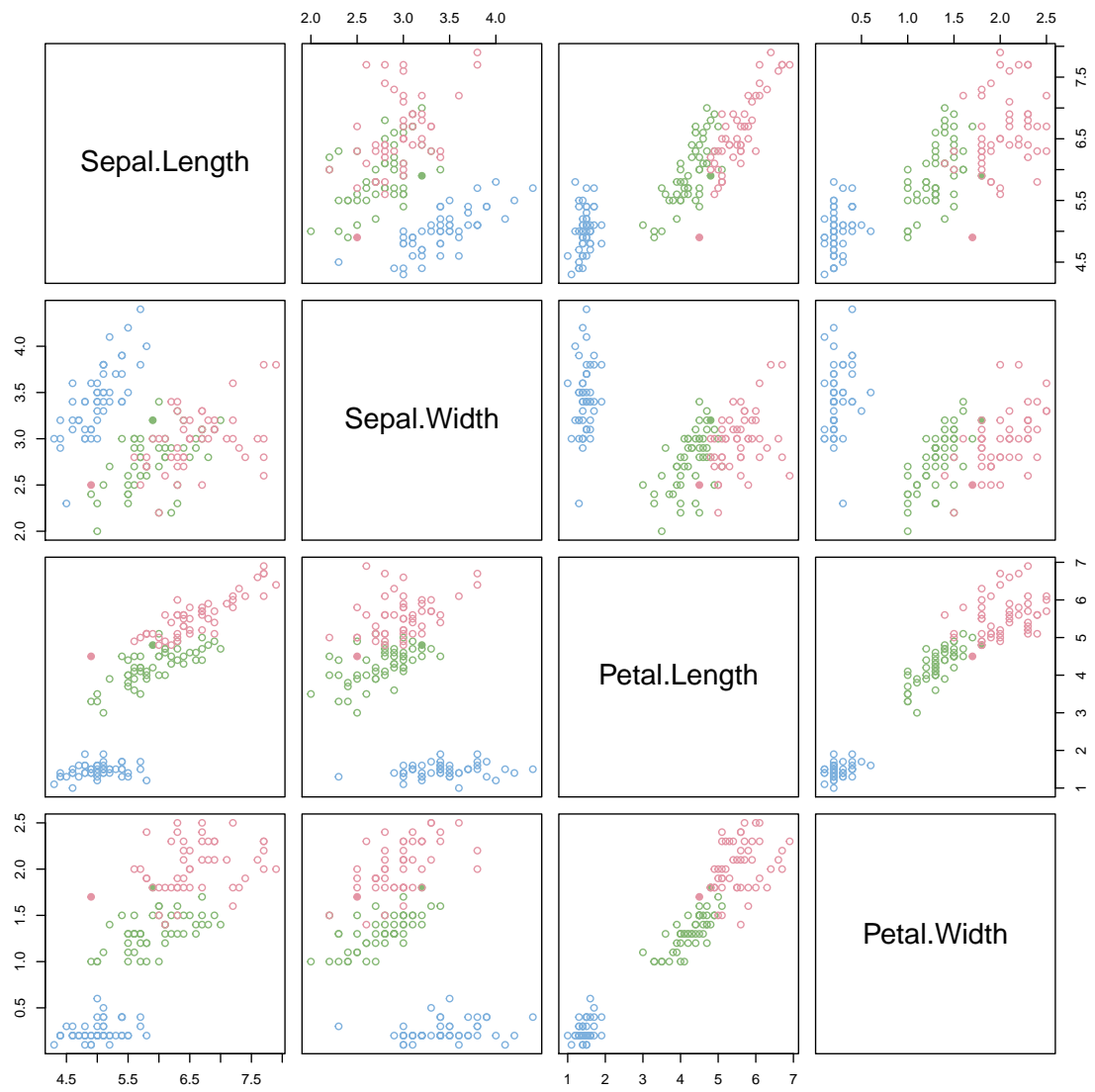
The hanging of the tree also helps to locate extreme observations. For example, we can see that observation "virginica (107)" is not very similar to the Versicolor species, but still, it is among them. Also, "Versicolor (71)" is too much "within" the Virginica bush, and it is a wonder why that is. Of course, the Iris dataset is very well known, and simpler pairs plot often help to locate such problems, yet - dendrogram trees (with all of their limitations) can help gain insights for very high-dimensional data where a simple pairs plot is not possible.

Here is the similar pairs plot. Notice the filled red and green dots, corresponding with the extreme observations we have noticed in the dendrogram. Petal.Length vs Petal.Width gives the best example of why the green dot is an outlier. Whereas most plots show why the red dot is an outlier. There are of course other outliers, and a problem with classification, which we will not go further into.

```
require(colorspace)

species_col <- rev(rainbow_hcl(3))[as.numeric(iris[, 5])]
# species_col[c(107,71)] <- 'red' # highlight the two
# extreme cases we mentioned
species_pch <- rep(1, length(species_col))
species_pch[c(107, 71)] <- 19 # highlight the two extreme cases we mentioned

pairs(iris[, -5], col = species_col, pch = species_pch)
```



4. Tanglegrams - visually comparing two trees side-by-side

4.1. Tanglegram visualization

4.2. Finding an optimal rotation

5. Comparing two trees - statistics and inference

5.1. Baker's gamma

5.2. Bk method

6. Summary

The **dendextend** package presented in this paper greatly extends the available functionality of the dendrogram objects in R.

Acknowledgments

We are very thankful for code contributions and ideas by the R core team (especially Martin Maechler and Brian Ripley, but probably also others without our knowledge), Gavin Simpson, Gregory Jefferis ,

References

- de Vries A, Ripley BD (2013). *ggdendro: Tools for extracting dendrogram and tree diagram plot data for use with ggplot*. R package version 0.1-12, URL <http://CRAN.R-project.org/package=ggdendro>.
- Jefferis G (2013). *dendroextras: Extra functions to cut, label and colour dendrogram clusters*. R package version 0.1-2, URL <http://CRAN.R-project.org/package=dendroextras>.
- Nia VP, Davison AC (2012). "High-Dimensional Bayesian Clustering with Variable Selection: The R Package bclust." *Journal of Statistical Software*, **47**(5), 1–22. URL <http://www.jstatsoft.org/v47/i05/>.
- Nia VP, Stephens DA (2011). *Dendrogram Representation of Stochastic Clustering*, chapter 6, pp. 203–218. Nova Publishers. URL https://www.novapublishers.com/catalog/product_info.php?products_id=28702&osCsid=b.
- Paradis E, Claude J, Strimmer K (2004). "APE: analyses of phylogenetics and evolution in R language." *Bioinformatics*, **20**, 289–290.

Ploner A (2012). *Heatplus: Heatmaps with row and/or column covariates and colored clusters*. R package version 2.6.0.

R Development Core Team (2013). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org/>.

Sarkar D, Andrews F (2012). *latticeExtra: Extra Graphical Utilities Based on Lattice*. R package version 0.6-24, URL <http://CRAN.R-project.org/package=latticeExtra>.

Affiliation:

Tal Galili

Department of Statistics and Operations Research

Tel Aviv University, Israel

E-mail: tal.galili@math.tau.ac.il

URLs: <http://www.r-statistics.com/>, <http://www.r-bloggers.com/>

Yoav Benjamini

The Nathan and Lily Silver

Professor of Applied Statistics

Department of Statistics and Operations Research

Tel Aviv University, Israel

E-mail: ybenja@tau.ac.il

URL: <http://www.tau.ac.il/~ybenja/>