

Network Analysis and Visualization with R and igraph

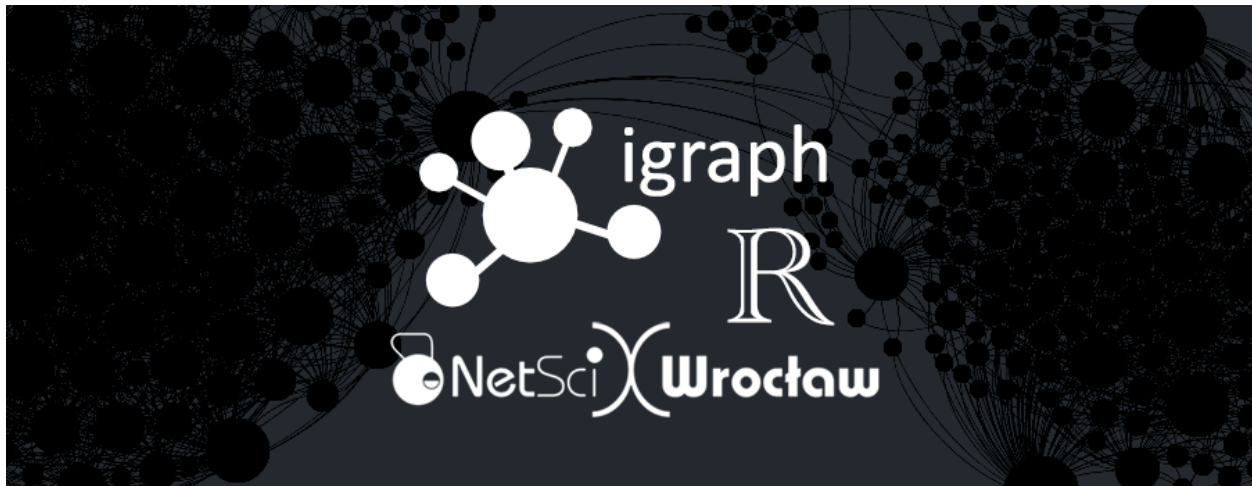
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Note: You can download all workshop materials [here](#), or visit kateto.net/netscix2016.

This tutorial covers basics of network analysis and visualization with the R package `igraph` (maintained by [Gabor Csardi](#) and [Tamas Nepusz](#)). The `igraph` library provides versatile options for descriptive network analysis and visualization in R, Python, and C/C++. This workshop will focus on the R implementation. You will need an [R installation](#), and [RStudio](#). You should also install the latest version of `igraph` for R:

```
install.packages("igraph")
```

1. A quick reminder of R basics

Before we start working with networks, we will go through a quick introduction/reminder of some simple tasks and principles in R.

1.1 Assignment

You can assign a value to an object using `assign()`, `<-`, or `=`.

```
x <- 3          # Assignment
x              # Evaluate the expression and print result

y <- 4          # Assignment
y + 5         # Evaluation, y remains 4

z <- x + 17*y   # Assignment
z             # Evaluation
```

```
rm(z)      # Remove z: deletes the object.
z          # Error!
```

1.2 Value comparisons

We can use the standard operators `<`, `>`, `<=`, `>=`, `==` (equality) and `!=` (inequality). Comparisons return Boolean values: `TRUE` or `FALSE` (often abbreviated to just `T` and `F`).

```
2==2 # Equality
2!=2 # Inequality
x <= y # less than or equal: "<", ">", and ">=" also work
```

1.3 Special constants

Special constants include:

- `NA` for missing or undefined data
- `NULL` for empty object (e.g. null/empty lists)
- `Inf` and `-Inf` for positive and negative infinity
- `NaN` for results that cannot be reasonably defined

```
# NA - missing or undefined data
5 + NA      # When used in an expression, the result is generally NA
is.na(5+NA) # Check if missing

# NULL - an empty object, e.g. a null/empty list
10 + NULL   # use returns an empty object (length zero)
is.null(NULL) # check if NULL
```

`Inf` and `-Inf` represent positive and negative infinity. They can be returned by mathematical operations like division of a number by zero:

```
5/0
is.finite(5/0) # Check if a number is finite (it is not).
```

`NaN` (Not a Number) - the result of an operation that cannot be reasonably defined, such as dividing zero by zero.

```
0/0
is.nan(0/0)
```

1.4 Vectors

Vectors can be constructed by combining their elements with the important R function `c()`.

```
v1 <- c(1, 5, 11, 33)      # Numeric vector, length 4
v2 <- c("hello","world")  # Character vector, length 2 (a vector of strings)
v3 <- c(TRUE, TRUE, FALSE) # Logical vector, same as c(T, T, F)
```

Combining different types of elements in one vector will coerce the elements to the least restrictive type:

```
v4 <- c(v1,v2,v3,"boo")    # All elements turn into strings
```

Other ways to create vectors include:

```
v <- 1:7      # same as c(1,2,3,4,5,6,7)
v <- rep(0, 77) # repeat zero 77 times: v is a vector of 77 zeroes
v <- rep(1:3, times=2) # Repeat 1,2,3 twice
v <- rep(1:10, each=2) # Repeat each element twice
v <- seq(10,20,2) # sequence: numbers between 10 and 20, in jumps of 2

v1 <- 1:5      # 1,2,3,4,5
v2 <- rep(1,5) # 1,1,1,1,1
```

Check the length of a vector:

```
length(v1)
length(v2)
```

Element-wise operations:

```
v1 + v2      # Element-wise addition
v1 + 1       # Add 1 to each element
v1 * 2       # Multiply each element by 2
v1 + c(1,7) # This doesn't work: (1,7) is a vector of different length
```

Mathematical operations:

```
sum(v1)      # The sum of all elements
mean(v1)     # The average of all elements
sd(v1)       # The standard deviation
cor(v1,v1*5) # Correlation between v1 and v1*5
```

Logical operations:

```
v1 > 2      # Each element is compared to 2, returns logical vector
v1==v2     # Are corresponding elements equivalent, returns logical vector.
v1!=v2     # Are corresponding elements *not* equivalent? Same as !(v1==v2)
(v1>2) | (v2>0) # | is the boolean OR, returns a vector.
(v1>2) & (v2>0) # & is the boolean AND, returns a vector.
(v1>2) || (v2>0) # || is the boolean OR, returns a single value
(v1>2) && (v2>0) # && is the boolean AND, ditto
```

Vector elements:

```
v1[3]           # third element of v1
v1[2:4]        # elements 2, 3, 4 of v1
v1[c(1,3)]     # elements 1 and 3 - note that your indexes are a vector
v1[c(T,T,F,F,F)] # elements 1 and 2 - only the ones that are TRUE
v1[v1>3]       # v1>3 is a logical vector TRUE for elements >3
```

Note that the indexing in R starts from 1, a fact known to confuse and upset people used to languages that index from 0.

To add more elements to a vector, simply assign them values.

```
v1[6:10] <- 6:10
```

We can also directly assign the vector a length:

```
length(v1) <- 15 # the last 5 elements are added as missing data: NA
```

1.5 Factors

Factors are used to store categorical data.

```
eye.col.v <- c("brown", "green", "brown", "blue", "blue", "blue") #vector
eye.col.f <- factor(c("brown", "green", "brown", "blue", "blue", "blue")) #factor
eye.col.v
```

```
## [1] "brown" "green" "brown" "blue" "blue" "blue"
```

```
eye.col.f
```

```
## [1] brown green brown blue blue blue
## Levels: blue brown green
```

R will identify the different levels of the factor - e.g. all distinct values. The data is stored internally as integers - each number corresponding to a factor level.

```
levels(eye.col.f) # The levels (distinct values) of the factor (categorical var)
```

```
## [1] "blue" "brown" "green"
```

```
as.numeric(eye.col.f) # As numeric values: 1 is blue, 2 is brown, 3 is green
```

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

```
as.numeric(eye.col.v) # The character vector can not be coerced to numeric
```

```
## Warning: NAs introduced by coercion
```

```
## [1] NA NA NA NA NA NA
```

```
as.character(eye.col.f)
```

```
## [1] "brown" "green" "brown" "blue" "blue" "blue"
```

```
as.character(eye.col.v)
```

```
## [1] "brown" "green" "brown" "blue" "blue" "blue"
```

1.6 Matrices & Arrays

A matrix is a vector with dimensions:

```
m <- rep(1, 20) # A vector of 20 elements, all 1
dim(m) <- c(5,4) # Dimensions set to 5 & 4, so m is now a 5x4 matrix
```

Creating a matrix using `matrix()`:

```
m <- matrix(data=1, nrow=5, ncol=4) # same matrix as above, 5x4, full of 1s
m <- matrix(1,5,4) # same matrix as above
dim(m) # What are the dimensions of m?
```

```
## [1] 5 4
```

Creating a matrix by combining vectors:

```
m <- cbind(1:5, 5:1, 5:9) # Bind 3 vectors as columns, 5x3 matrix
m <- rbind(1:5, 5:1, 5:9) # Bind 3 vectors as rows, 3x5 matrix
```

Selecting matrix elements:

```
m <- matrix(1:10,10,10)

m[2,3] # Matrix m, row 2, column 3 - a single cell
m[2,] # The whole second row of m as a vector
m[,2] # The whole second column of m as a vector
m[1:2,4:6] # submatrix: rows 1 and 2, columns 4, 5 and 6
m[-1,] # all rows *except* the first one
```

Other operations with matrices:

```

# Are elements in row 1 equivalent to corresponding elements from column 1:
m[1,]==m[,1]
# A logical matrix: TRUE for m elements >3, FALSE otherwise:
m>3
# Selects only TRUE elements - that is ones greater than 3:
m[m>3]

```

```

t(m)          # Transpose m
m <- t(m)     # Assign m the transposed m
m %*% t(m)    # %*% does matrix multiplication
m * m        # * does element-wise multiplication

```

Arrays are used when we have more than 2 dimensions. We can create them using the `array()` function:

```

a <- array(data=1:18,dim=c(3,3,2)) # 3d with dimensions 3x3x2
a <- array(1:18,c(3,3,2))          # the same array

```

1.7 Lists

Lists are collections of objects. A single list can contain all kinds of elements - character strings, numeric vectors, matrices, other lists, and so on. The elements of lists are often named for easier access.

```

l1 <- list(boo=v1,foo=v2,moo=v3,zoo="Animals!") # A list with four components
l2 <- list(v1,v2,v3,"Animals!")

```

Create an empty list:

```

l3 <- list()
l4 <- NULL

```

Accessing list elements:

```

l1["boo"]      # Access boo with single brackets: this returns a list.
l1[["boo"]]    # Access boo with double brackets: this returns the numeric vector
l1[[1]]        # Returns the first component of the list, equivalent to above.
l1$boo         # Named elements can be accessed with the $ operator, as with [[]]

```

Adding more elements to a list:

```

l3[[1]] <- 11 # add an element to the empty list l3
l4[[3]] <- c(22, 23) # add a vector as element 3 in the empty list l4.

```

Since we added element 3 to the list 14 above, elements 1 and 2 will be generated and empty (NULL).


```
l1[[5]] <- "More elements!" # The list l1 had 4 elements, we're adding a 5th here.
l1[[8]] <- 1:11
```

We added an 8th element, but not 6th and 7th to the list11 above. Elements number 6 and 7 will be created empty (NULL).

```
l1$Something <- "A thing" # Adds a ninth element - "A thing", named "Something"
```

1.8 Data Frames

The data frame is a special kind of list used for storing dataset tables. Think of rows as cases, columns as variables. Each column is a vector or factor.

Creating a dataframe:

```
dfr1 <- data.frame( ID=1:4,
                   FirstName=c("John","Jim","Jane","Jill"),
                   Female=c(F,F,T,T),
                   Age=c(22,33,44,55) )
```

```
dfr1$FirstName # Access the second column of dfr1.
```

```
## [1] John Jim Jane Jill
## Levels: Jane Jill Jim John
```

Notice that R thinks that `dfr1$FirstName` is a categorical variable and so it's treating it like a factor, not a character vector. Let's get rid of the factor by telling R to treat 'FirstName' as a vector:

```
dfr1$FirstName <- as.vector(dfr1$FirstName)
```

Alternatively, you can tell R you don't like factors from the start using `stringsAsFactors=FALSE`

```
dfr2 <- data.frame(FirstName=c("John","Jim","Jane","Jill"), stringsAsFactors=F)
dfr2$FirstName # Success: not a factor.
```

```
## [1] "John" "Jim" "Jane" "Jill"
```

Access elements of the data frame:

```
dfr1[1,] # First row, all columns
dfr1[,1] # First column, all rows
dfr1$Age # Age column, all rows
dfr1[1:2,3:4] # Rows 1 and 2, columns 3 and 4 - the gender and age of John & Jim
dfr1[c(1,3),] # Rows 1 and 3, all columns
```

Find the names of everyone over the age of 30 in the data:

```
dfr1[dfr1$Age>30,2]
```

```
## [1] "Jim" "Jane" "Jill"
```

Find the average age of all females in the data:

```
mean ( dfr1[dfr1$Female==TRUE,4] )
```

```
## [1] 49.5
```

1.9 Flow Control and loops

The controls and loops in R are fairly straightforward (see below). They determine if a block of code will be executed, and how many times. Blocks of code in R are enclosed in curly brackets {}.

```
# if (condition) expr1 else expr2  
x <- 5; y <- 10  
if (x==0) y <- 0 else y <- y/x #  
y
```

```
## [1] 2
```

```
# for (variable in sequence) expr  
ASum <- 0; AProd <- 1  
for (i in 1:x)  
{  
  ASum <- ASum + i  
  AProd <- AProd * i  
}  
ASum # equivalent to sum(1:x)
```

```
## [1] 15
```

```
AProd # equivalent to prod(1:x)
```

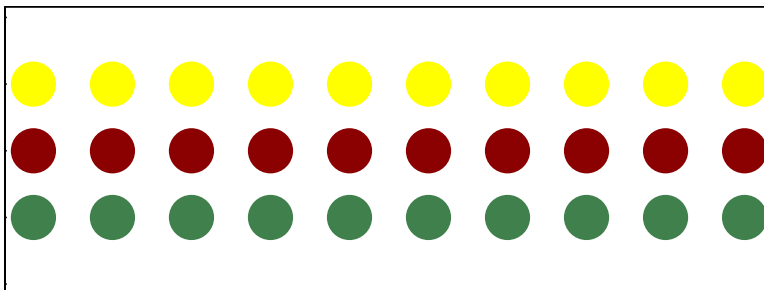
```
## [1] 120
```

```
# while (condition) expr  
while (x > 0) {print(x); x <- x-1;}  
  
# repeat expr, use break to exit the loop  
repeat { print(x); x <- x+1; if (x>10) break}
```

1.10 R plots and colors

In most R functions, you can use *named colors*, *hex*, or *RGB* values. In the simple base R plot chart below, *x* and *y* are the point coordinates, *pch* is the point symbol shape, *cex* is the point size, and *col* is the color. To see the parameters for plotting in base R, check out `?par`

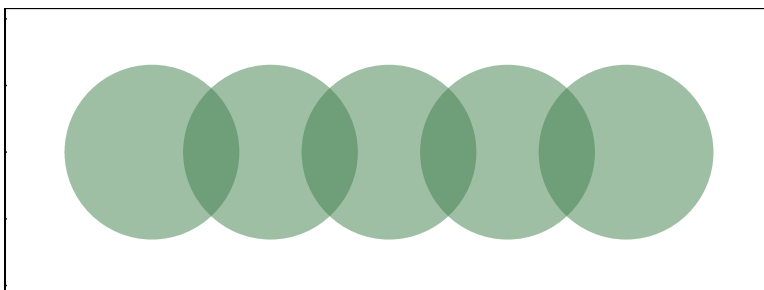
```
plot(x=1:10, y=rep(5,10), pch=19, cex=3, col="dark red")
points(x=1:10, y=rep(6, 10), pch=19, cex=3, col="557799")
points(x=1:10, y=rep(4, 10), pch=19, cex=3, col=rgb(.25, .5, .3))
```



You may notice that RGB here ranges from 0 to 1. While this is the R default, you can also set it for to the 0-255 range using something like `rgb(10, 100, 100, maxColorValue=255)`.

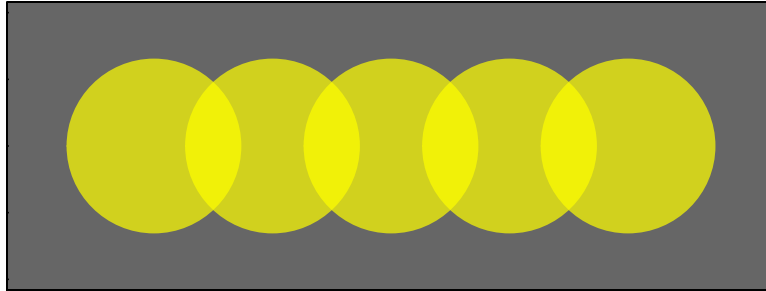
We can set the opacity/transparency of an element using the parameter `alpha` (range 0-1):

```
plot(x=1:5, y=rep(5,5), pch=19, cex=12, col=rgb(.25, .5, .3, alpha=.5), xlim=c(0,6))
```



If we have a hex color representation, we can set the transparency `alpha` using `adjustcolor` from package `grDevices`. For fun, let's also set the plot background to gray using the `par()` function for graphical parameters.

```
par(bg="gray40")
col.tr <- grDevices::adjustcolor("557799", alpha=0.7)
plot(x=1:5, y=rep(5,5), pch=19, cex=12, col=col.tr, xlim=c(0,6))
```

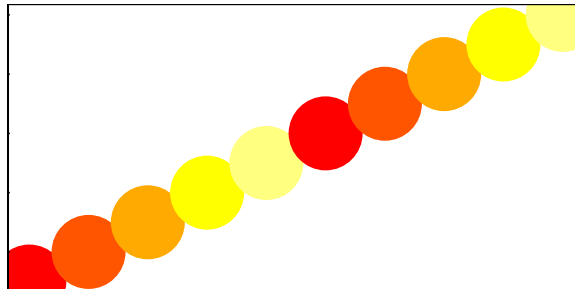


If you plan on using the built-in color names, here's how to list all of them:

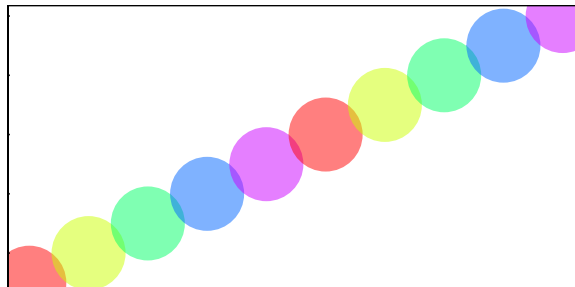
```
colors() # List all named colors
grep("blue", colors(), value=T) # Colors that have "blue" in the name
```

In many cases, we need a number of contrasting colors, or multiple shades of a color. R comes with some predefined palette function that can generate those for us. For example:

```
pal1 <- heat.colors(5, alpha=1) # 5 colors from the heat palette, opaque
pal2 <- rainbow(5, alpha=.5) # 5 colors from the heat palette, transparent
plot(x=1:10, y=1:10, pch=19, cex=5, col=pal1)
```

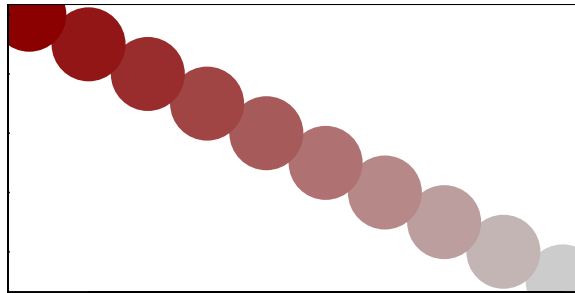


```
plot(x=1:10, y=1:10, pch=19, cex=5, col=pal2)
```



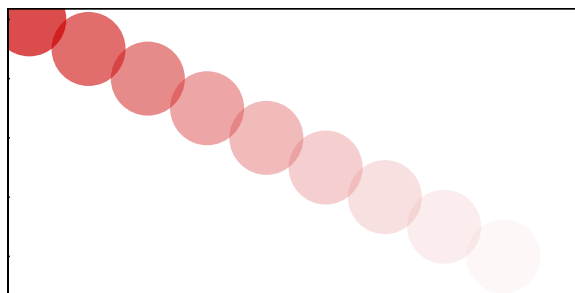
We can also generate our own gradients using `colorRampPalette`. Note that `colorRampPalette` returns a *function* that we can use to generate as many colors from that palette as we need.

```
palf <- colorRampPalette(c("gray80", "dark red"))
plot(x=10:1, y=1:10, pch=19, cex=5, col=palf(10))
```



To add transparency to colorRampPalette, you need to use a parameter alpha=TRUE:

```
palf <- colorRampPalette(c(rgb(1,1,1, .2),rgb(.8,0,0, .7)), alpha=TRUE)
plot(x=10:1, y=1:10, pch=19, cex=5, col=palf(10))
```



1.11 R troubleshooting

While I generate many (and often very creative) errors in R, there are three simple things that will most often go wrong for me. Those include:

- 1) *Capitalization.* R is case sensitive - a graph vertex named “Jack” is not the same as one named “jack”. The function `rowSums` won’t work if spelled as `rowsums` or `RowSums`.
- 2) *Object class.* While many functions are willing to take anything you throw at them, some will still surprisingly require character vector or a factor instead of a numeric vector, or a matrix instead of a data frame. Functions will also occasionally return results in an unexpected formats.
- 3) *Package namespaces.* Occasionally problems will arise when different packages contain functions with the same name. R may warn you about this by saying something like “The following object(s) are masked from ‘package:igraph’ as you load a package. One way to deal with this is to call functions from a package explicitly using `::`. For instance, if function `blah()` is present in packages A and B, you can call `A::blah` and `B::blah`. In other cases the problem is more complicated, and you may have to load packages in certain order, or not use them together at all. For example (and pertinent to this workshop), `igraph` and `Statnet`

packages cause some problems when loaded at the same time. It is best to detach one before loading the other.

```
library(igraph)      # load a package
detach(package:igraph) # detach a package
```

For more advanced troubleshooting, check out `try()`, `tryCatch()`, and `debug()`.

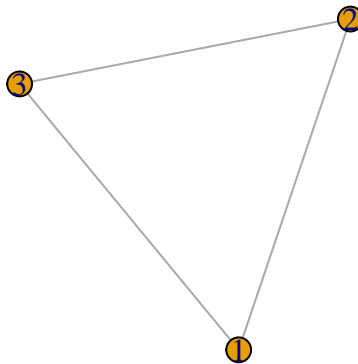
2. Networks in igraph

```
rm(list = ls()) # Remove all the objects we created so far.
library(igraph) # Load the igraph package
```

2.1 Create networks

The code below generates an undirected graph with three edges. The numbers are interpreted as vertex IDs, so the edges are 1→2, 2→3, 3→1.

```
g1 <- graph( edges=c(1,2, 2,3, 3, 1), n=3, directed=F )
plot(g1) # A simple plot of the network - we'll talk more about plots later
```



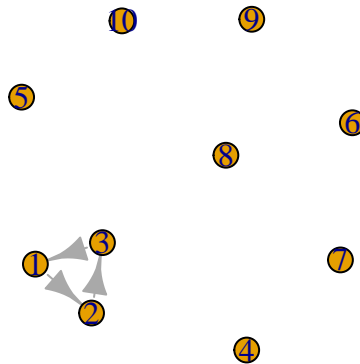
```
class(g1)
```

```
## [1] "igraph"
```

```
g1
```

```
## IGRAPH U--- 3 3 --
## + edges:
## [1] 1--2 2--3 1--3
```

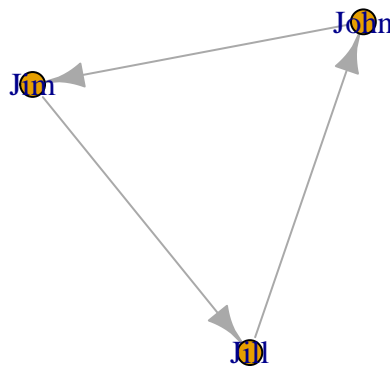
```
# Now with 10 vertices, and directed by default:
g2 <- graph( edges=c(1,2, 2,3, 3, 1), n=10 )
plot(g2)
```



g2

```
## IGRAPH D--- 10 3 --
## + edges:
## [1] 1->2 2->3 3->1
```

```
g3 <- graph( c("John", "Jim", "Jim", "Jill", "Jill", "John")) # named vertices
# When the edge list has vertex names, the number of nodes is not needed
plot(g3)
```

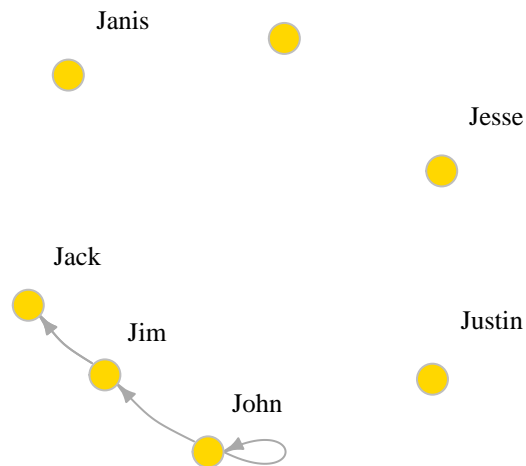


g3

```
## IGRAPH DN-- 3 3 --
## + attr: name (v/c)
## + edges (vertex names):
## [1] John->Jim Jim ->Jill Jill->John
```

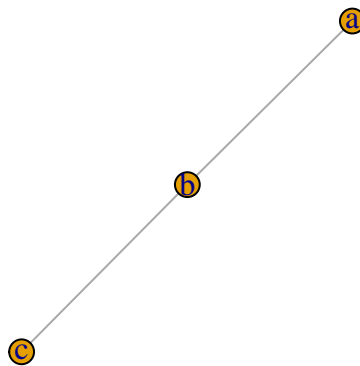
```
g4 <- graph( c("John", "Jim", "Jim", "Jack", "Jim", "Jack", "John", "John"),
             isolates=c("Jesse", "Janis", "Jennifer", "Justin") )
# In named graphs we can specify isolates by providing a list of their names.

plot(g4, edge.arrow.size=.5, vertex.color="gold", vertex.size=15,
     vertex.frame.color="gray", vertex.label.color="black",
     vertex.label.cex=0.8, vertex.label.dist=2, edge.curved=0.2)
```

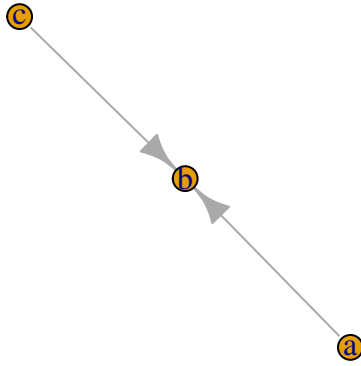


Small graphs can also be generated with a description of this kind: - for undirected tie, +- or -+ for directed ties pointing left & right, ++ for a symmetric tie, and ":" for sets of vertices.

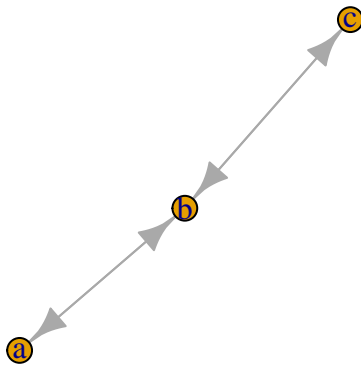
```
plot(graph_from_literal(a---b, b---c)) # the number of dashes doesn't matter
```



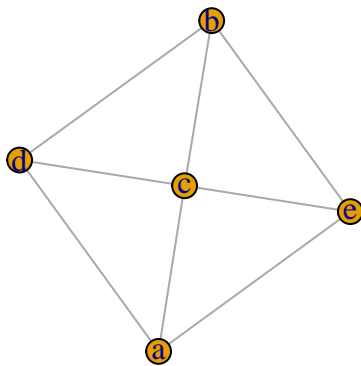
```
plot(graph_from_literal(a--b, b---c))
```

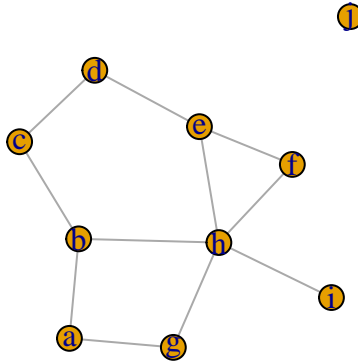
```
plot(graph_from_literal(a-->b, b-->c))
```



```
plot(graph_from_literal(a:b:c---c:d:e))
```



```
g1 <- graph_from_literal(a-b-c-d-e-f, a-g-h-b, h-e:f:i, j)
plot(g1)
```



2.2 Edge, vertex, and network attributes

Access vertices and edges:

```
E(g4) # The edges of the object
```

```
## + 4/4 edges (vertex names):
## [1] John->Jim Jim ->Jack Jim ->Jack John->John
```

```
V(g4) # The vertices of the object
```

```
## + 7/7 vertices, named:
## [1] John      Jim      Jack      Jesse     Janis     Jennifer  Justin
```

You can also examine the network matrix directly:

```
g4[]
```

```
## 7 x 7 sparse Matrix of class "dgCMatrix"
##      John Jim Jack Jesse Janis Jennifer Justin
## John      1  1  .  .  .  .  .
## Jim      .  .  2  .  .  .  .
## Jack     .  .  .  .  .  .  .
## Jesse    .  .  .  .  .  .  .
## Janis    .  .  .  .  .  .  .
## Jennifer .  .  .  .  .  .  .
## Justin   .  .  .  .  .  .  .
```

```
g4[1,]
```

```
##      John      Jim      Jack      Jesse     Janis Jennifer  Justin
##      1         1         0         0         0         0         0
```

Add attributes to the network, vertices, or edges:

```
V(g4)$name # automatically generated when we created the network.
```

```
## [1] "John"      "Jim"      "Jack"      "Jesse"     "Janis"     "Jennifer"
## [7] "Justin"
```

```
V(g4)$gender <- c("male", "male", "male", "male", "female", "female", "male")
E(g4)$type <- "email" # Edge attribute, assign "email" to all edges
E(g4)$weight <- 10    # Edge weight, setting all existing edges to 10
```

Examine attributes:

```
edge_attr(g4)
```

```
## $type
## [1] "email" "email" "email" "email"
##
## $weight
## [1] 10 10 10 10
```

```
vertex_attr(g4)
```

```
## $name
## [1] "John"      "Jim"      "Jack"      "Jesse"     "Janis"     "Jennifer"
## [7] "Justin"
##
## $gender
## [1] "male"     "male"     "male"     "male"     "female"   "female"   "male"
```

```
graph_attr(g4)
```

```
## named list()
```

Another way to set attributes (you can similarly use `set_edge_attr()`, `set_vertex_attr()`, etc.):

```
g4 <- set_graph_attr(g4, "name", "Email Network")
g4 <- set_graph_attr(g4, "something", "A thing")
```

```
graph_attr_names(g4)
```

```
## [1] "name"      "something"
```

```
graph_attr(g4, "name")
```

```
## [1] "Email Network"
```

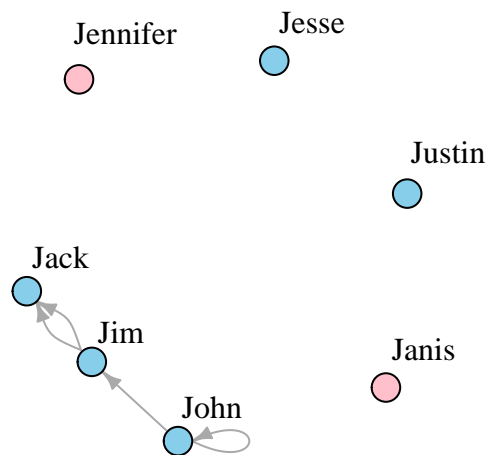
```
graph_attr(g4)
```

```
## $name  
## [1] "Email Network"  
##  
## $something  
## [1] "A thing"
```

```
g4 <- delete_graph_attr(g4, "something")  
graph_attr(g4)
```

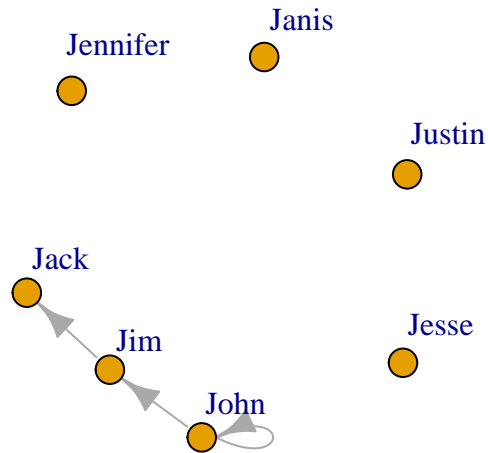
```
## $name  
## [1] "Email Network"
```

```
plot(g4, edge.arrow.size=.5, vertex.label.color="black", vertex.label.dist=1.5,  
      vertex.color=c("pink", "skyblue")[1+(V(g4)$gender=="male")] )
```



The graph `g4` has two edges going from Jim to Jack, and a loop from John to himself. We can simplify our graph to remove loops & multiple edges between the same nodes. Use `edge.attr.comb` to indicate how edge attributes are to be combined - possible options include `sum`, `mean`, `prod` (product), `min`, `max`, `first/last` (selects the first/last edge's attribute). Option "ignore" says the attribute should be disregarded and dropped.

```
g4s <- simplify( g4, remove.multiple = T, remove.loops = F,  
                 edge.attr.comb=c(weight="sum", type="ignore") )  
plot(g4s, vertex.label.dist=1.5)
```



```
g4s
```

```
## IGRAPH DNW- 7 3 -- Email Network
## + attr: name (g/c), name (v/c), gender (v/c), weight (e/n)
## + edges (vertex names):
## [1] John->John John->Jim Jim ->Jack
```

The description of an `igraph` object starts with up to four letters:

1. D or U, for a directed or undirected graph
2. N for a named graph (where nodes have a `name` attribute)
3. W for a weighted graph (where edges have a `weight` attribute)
4. B for a bipartite (two-mode) graph (where nodes have a `type` attribute)

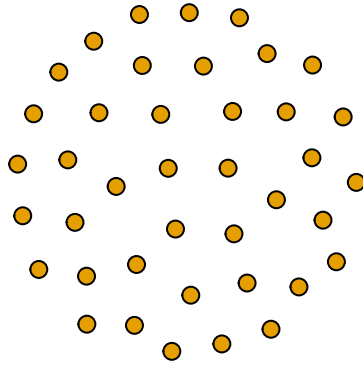
The two numbers that follow (7 5) refer to the number of nodes and edges in the graph. The description also lists node & edge attributes, for example:

- (g/c) - graph-level character attribute
- (v/c) - vertex-level character attribute
- (e/n) - edge-level numeric attribute

2.3 Specific graphs and graph models

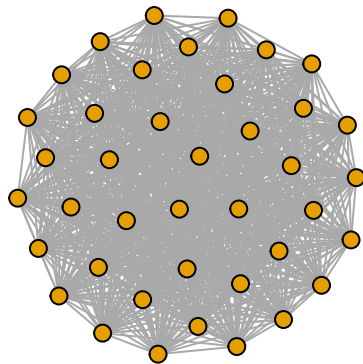
Empty graph

```
eg <- make_empty_graph(40)
plot(eg, vertex.size=10, vertex.label=NA)
```



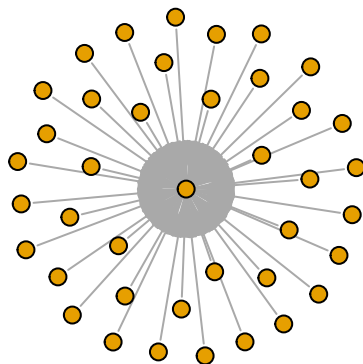
Full graph

```
fg <- make_full_graph(40)  
plot(fg, vertex.size=10, vertex.label=NA)
```



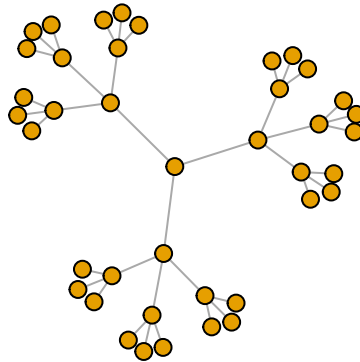
Simple star graph

```
st <- make_star(40)  
plot(st, vertex.size=10, vertex.label=NA)
```



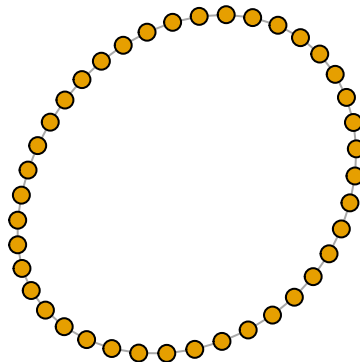
Tree graph

```
tr <- make_tree(40, children = 3, mode = "undirected")
plot(tr, vertex.size=10, vertex.label=NA)
```



Ring graph

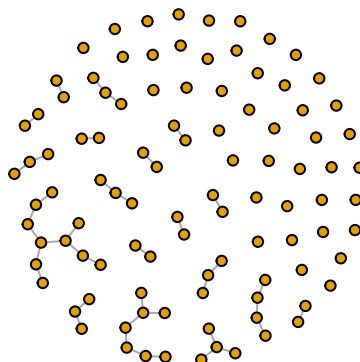
```
rn <- make_ring(40)
plot(rn, vertex.size=10, vertex.label=NA)
```



Erdos-Renyi random graph model

(‘n’ is number of nodes, ‘m’ is the number of edges).

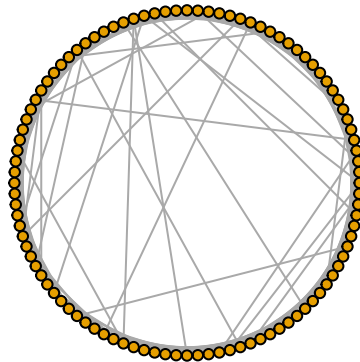
```
er <- sample_gnm(n=100, m=40)
plot(er, vertex.size=6, vertex.label=NA)
```



Watts-Strogatz small-world model

Creates a lattice (with `dim` dimensions and `size` nodes across dimension) and rewires edges randomly with probability `p`. The neighborhood in which edges are connected is `nei`. You can allow loops and multiple edges.

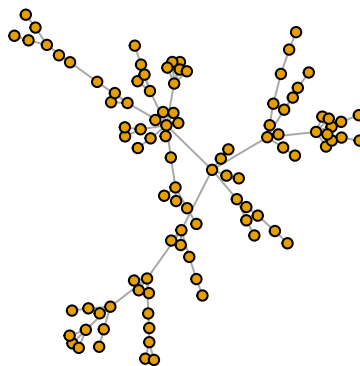
```
sw <- sample_smallworld(dim=2, size=10, nei=1, p=0.1)
plot(sw, vertex.size=6, vertex.label=NA, layout=layout_in_circle)
```



Barabasi-Albert preferential attachment model for scale-free graphs

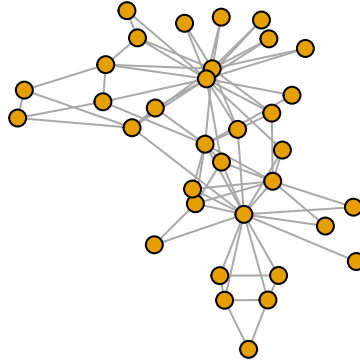
(`n` is number of nodes, `power` is the power of attachment (1 is linear); `m` is the number of edges added on each time step)

```
ba <- sample_pa(n=100, power=1, m=1, directed=F)
plot(ba, vertex.size=6, vertex.label=NA)
```



`igraph` can also give you some notable historical graphs. For instance:

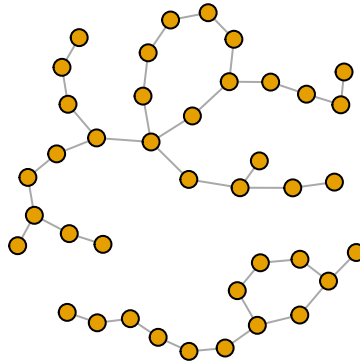
```
zach <- graph("Zachary") # the Zachary carate club
plot(zach, vertex.size=10, vertex.label=NA)
```

Rewiring a graph

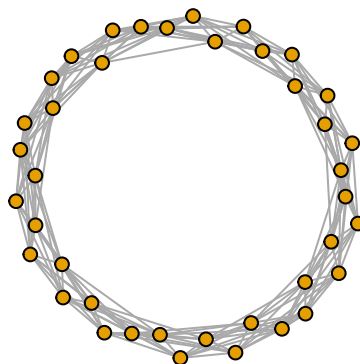
`each_edge()` is a rewiring method that changes the edge endpoints uniformly randomly with a probability `prob`.

```
rn.rewired <- rewire(rn, each_edge(prob=0.1))
plot(rn.rewired, vertex.size=10, vertex.label=NA)
```



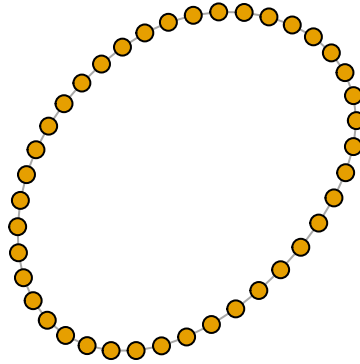
Rewire to connect vertices to other vertices at a certain distance.

```
rn.neigh = connect.neighborhood(rn, 5)
plot(rn.neigh, vertex.size=8, vertex.label=NA)
```

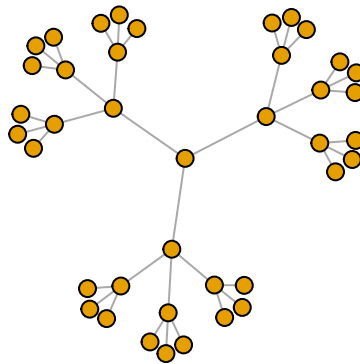


Combine graphs (disjoint union, assuming separate vertex sets): %du%

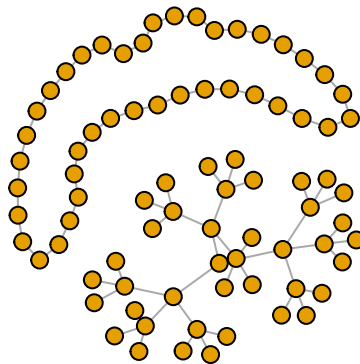
```
plot(rn, vertex.size=10, vertex.label=NA)
```



```
plot(tr, vertex.size=10, vertex.label=NA)
```



```
plot(rn %du% tr, vertex.size=10, vertex.label=NA)
```



3. Reading network data from files

In the following sections of the tutorial, we will work primarily with two small example data sets. Both contain data about media organizations. One involves a network of hyperlinks and mentions among news sources. The second is a network of links between media venues and consumers. While the example data used here is small, many of the ideas behind the analyses and visualizations we will generate apply to medium and large-scale networks.

3.1 DATASET 1: *edgelist*

The first data set we are going to work with consists of two files, “Media-Example-NODES.csv” and “Media-Example-EDGES.csv” ([download here](#)).

```
nodes <- read.csv("Dataset1-Media-Example-NODES.csv", header=T, as.is=T)
links <- read.csv("Dataset1-Media-Example-EDGES.csv", header=T, as.is=T)
```

Examine the data:

```
head(nodes)
head(links)
nrow(nodes); length(unique(nodes$id))
nrow(links); nrow(unique(links[,c("from", "to")]))
```

Notice that there are more links than unique from-to combinations. That means we have cases in the data where there are multiple links between the same two nodes. We will collapse all links of the same type between the same two nodes by summing their weights, using `aggregate()` by “from”, “to”, & “type”. We don’t use `simplify()` here so as not to collapse different link types.

```
links <- aggregate(links[,3], links[,-3], sum)
links <- links[order(links$from, links$to),]
colnames(links)[4] <- "weight"
rownames(links) <- NULL
```

3.2 DATASET 2: *matrix*

Two-mode or bipartite graphs have two different types of actors and links that go across, but not within each type. Our second media example is a network of that kind, examining links between news sources and their consumers.

```
nodes2 <- read.csv("Dataset2-Media-User-Example-NODES.csv", header=T, as.is=T)
links2 <- read.csv("Dataset2-Media-User-Example-EDGES.csv", header=T, row.names=1)
```

Examine the data:

```
head(nodes2)
head(links2)
```

We can see that links2 is an adjacency matrix for a two-mode network:

```
links2 <- as.matrix(links2)
dim(links2)
dim(nodes2)
```

4. Turning networks into igraph objects

We start by converting the raw data to an `igraph` network object. Here we use `igraph`'s `graph.data.frame` function, which takes two data frames: `d` and `vertices`.

- `d` describes the edges of the network. Its first two columns are the IDs of the source and the target node for each edge. The following columns are edge attributes (weight, type, label, or anything else).
- `vertices` starts with a column of node IDs. Any following columns are interpreted as node attributes.

4.1 Dataset 1

```
library(igraph)

net <- graph_from_data_frame(d=links, vertices=nodes, directed=T)
class(net)

## [1] "igraph"

net

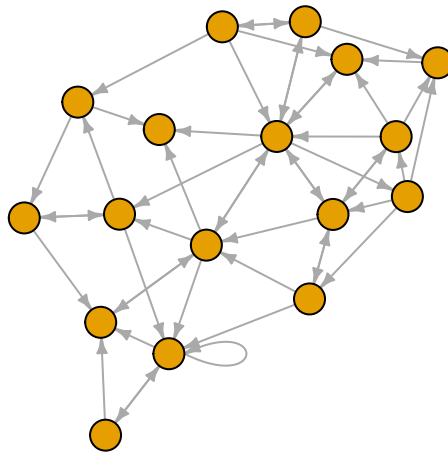
## IGRAPH DNW- 17 49 --
## + attr: name (v/c), media (v/c), media.type (v/n), type.label
## | (v/c), audience.size (v/n), type (e/c), weight (e/n)
## + edges (vertex names):
## [1] s01->s02 s01->s03 s01->s04 s01->s15 s02->s01 s02->s03 s02->s09
## [8] s02->s10 s03->s01 s03->s04 s03->s05 s03->s08 s03->s10 s03->s11
## [15] s03->s12 s04->s03 s04->s06 s04->s11 s04->s12 s04->s17 s05->s01
## [22] s05->s02 s05->s09 s05->s15 s06->s06 s06->s16 s06->s17 s07->s03
## [29] s07->s08 s07->s10 s07->s14 s08->s03 s08->s07 s08->s09 s09->s10
## [36] s10->s03 s12->s06 s12->s13 s12->s14 s13->s12 s13->s17 s14->s11
## [43] s14->s13 s15->s01 s15->s04 s15->s06 s16->s06 s16->s17 s17->s04
```

We also have easy access to nodes, edges, and their attributes with:

```
E(net)      # The edges of the "net" object
V(net)      # The vertices of the "net" object
E(net)$type # Edge attribute "type"
V(net)$media # Vertex attribute "media"
```

Now that we have our igraph network object, let's make a first attempt to plot it.

```
plot(net, edge.arrow.size=.4, vertex.label=NA)
```



That doesn't look very good. Let's start fixing things by removing the loops in the graph.

```
net <- simplify(net, remove.multiple = F, remove.loops = T)
```

You might notice that we could have used `simplify` to combine multiple edges by summing their weights with a command like `simplify(net, edge.attr.comb=list(weight="sum","ignore"))`. The problem is that this would also combine multiple edge types (in our data: “hyperlinks” and “mentions”).

If you need them, you can extract an edge list or a matrix from igraph networks.

```
as_edgelist(net, names=T)
as_adjacency_matrix(net, attr="weight")
```

Or data frames describing nodes and edges:

```
as_data_frame(net, what="edges")
as_data_frame(net, what="vertices")
```

4.2 Dataset 2

As we have seen above, this time the edges of the network are in a matrix format. We can read those into a graph object using `graph_from_incidence_matrix()`. In `igraph`, bipartite networks have a node attribute called `type` that is `FALSE` (or 0) for vertices in one mode and `TRUE` (or 1) for those in the other mode.

```
head(nodes2)
```

```
##   id  media media.type media.name audience.size
## 1 s01   NYT         1 Newspaper         20
## 2 s02  WaPo         1 Newspaper         25
## 3 s03   WSJ         1 Newspaper         30
## 4 s04  USAT         1 Newspaper         32
## 5 s05 LATimes       1 Newspaper         20
## 6 s06   CNN         2          TV         56
```

```
head(links2)
```

```
##      U01 U02 U03 U04 U05 U06 U07 U08 U09 U10 U11 U12 U13 U14 U15 U16 U17
## s01   1   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0
## s02   0   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0
## s03   0   0   0   0   0   1   1   1   1   0   0   0   0   0   0   0
## s04   0   0   0   0   0   0   0   0   1   1   1   0   0   0   0   0
## s05   0   0   0   0   0   0   0   0   0   0   1   1   1   0   0   0
## s06   0   0   0   0   0   0   0   0   0   0   0   0   1   1   0   1
##      U18 U19 U20
## s01   0   0   0
## s02   0   0   1
## s03   0   0   0
## s04   0   0   0
## s05   0   0   0
## s06   0   0   0
```

```
net2 <- graph_from_incidence_matrix(links2)
table(V(net2)$type)
```

```
##
## FALSE  TRUE
##    10    20
```

To transform a one-mode network matrix into an `igraph` object, use instead `graph_from_adjacency_matrix()`.

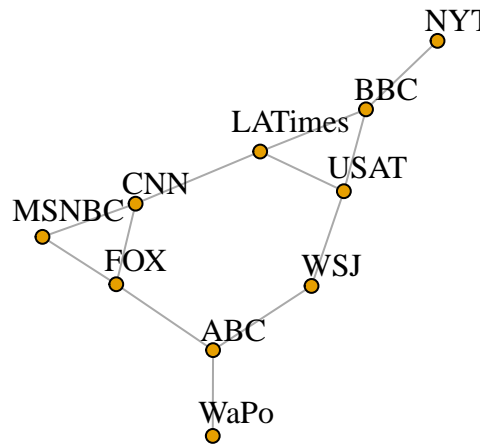
We can also easily generate bipartite projections for the two-mode network: (co-memberships are easy to calculate by multiplying the network matrix by its transposed matrix, or using `igraph`'s `bipartite.projection()` function).

```
net2.bp <- bipartite.projection(net2)
```

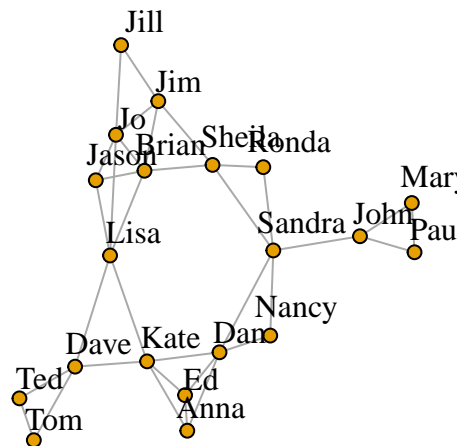
We can calculate the projections manually as well:

```
as_incidence_matrix(net2) %*% t(as_incidence_matrix(net2))  
t(as_incidence_matrix(net2)) %*% as_incidence_matrix(net2)
```

```
plot(net2.bp$proj1, vertex.label.color="black", vertex.label.dist=1,  
     vertex.size=7, vertex.label=nodes2$media[!is.na(nodes2$media.type)])
```



```
plot(net2.bp$proj2, vertex.label.color="black", vertex.label.dist=1,  
     vertex.size=7, vertex.label=nodes2$media[ is.na(nodes2$media.type)])
```



5. Plotting networks with igraph

Plotting with igraph: the network plots have a wide set of parameters you can set. Those include node options (starting with `vertex.`) and edge options (starting with `edge.`). A list of selected options is included below, but you can also check out `?igraph.plotting` for more information.

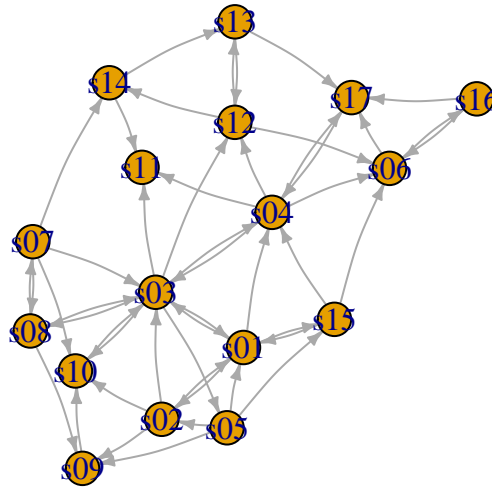
The igraph plotting parameters include (among others):

5.1 Plotting parameters

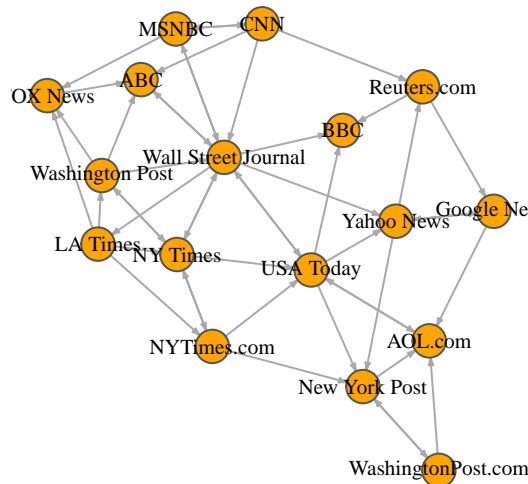
| NODES | |
|----------------------------------|--|
| <code>vertex.color</code> | Node color |
| <code>vertex.frame.color</code> | Node border color |
| <code>vertex.shape</code> | One of “none”, “circle”, “square”, “csquare”, “rectangle” “crectangle”, “vrectangle”, “pie”, “raster”, or “sphere” |
| <code>vertex.size</code> | Size of the node (default is 15) |
| <code>vertex.size2</code> | The second size of the node (e.g. for a rectangle) |
| <code>vertex.label</code> | Character vector used to label the nodes |
| <code>vertex.label.family</code> | Font family of the label (e.g.“Times”, “Helvetica”) |
| <code>vertex.label.font</code> | Font: 1 plain, 2 bold, 3, italic, 4 bold italic, 5 symbol |
| <code>vertex.label.cex</code> | Font size (multiplication factor, device-dependent) |
| <code>vertex.label.dist</code> | Distance between the label and the vertex |
| <code>vertex.label.degree</code> | The position of the label in relation to the vertex, where 0 right, “pi” is left, “pi/2” is below, and “-pi/2” is above |
| EDGES | |
| <code>edge.color</code> | Edge color |
| <code>edge.width</code> | Edge width, defaults to 1 |
| <code>edge.arrow.size</code> | Arrow size, defaults to 1 |
| <code>edge.arrow.width</code> | Arrow width, defaults to 1 |
| <code>edge.lty</code> | Line type, could be 0 or “blank”, 1 or “solid”, 2 or “dashed”, 3 or “dotted”, 4 or “dotdash”, 5 or “longdash”, 6 or “twodash” |
| <code>edge.label</code> | Character vector used to label edges |
| <code>edge.label.family</code> | Font family of the label (e.g.“Times”, “Helvetica”) |
| <code>edge.label.font</code> | Font: 1 plain, 2 bold, 3, italic, 4 bold italic, 5 symbol |
| <code>edge.label.cex</code> | Font size for edge labels |
| <code>edge.curved</code> | Edge curvature, range 0-1 (FALSE sets it to 0, TRUE to 0.5) |
| <code>arrow.mode</code> | Vector specifying whether edges should have arrows, possible values: 0 no arrow, 1 back, 2 forward, 3 both |
| OTHER | |
| <code>margin</code> | Empty space margins around the plot, vector with length 4 |
| <code>frame</code> | if TRUE, the plot will be framed |
| <code>main</code> | If set, adds a title to the plot |
| <code>sub</code> | If set, adds a subtitle to the plot |

We can set the node & edge options in two ways - the first one is to specify them in the `plot()` function, as we are doing below.

```
# Plot with curved edges (edge.curved=.1) and reduce arrow size:
plot(net, edge.arrow.size=.4, edge.curved=.1)
```



```
# Set edge color to gray, and the node color to orange.
# Replace the vertex label with the node names stored in "media"
plot(net, edge.arrow.size=.2, edge.curved=0,
      vertex.color="orange", vertex.frame.color="#555555",
      vertex.label=V(net)$media, vertex.label.color="black",
      vertex.label.cex=.7)
```



The second way to set attributes is to add them to the `igraph` object. Let's say we want to color our network nodes based on type of media, and size them based on audience size (larger audience -> larger node). We will also change the width of the edges based on their weight.

```

# Generate colors based on media type:
colrs <- c("gray50", "tomato", "gold")
V(net)$color <- colrs[V(net)$media.type]

# Set node size based on audience size:
V(net)$size <- V(net)$audience.size*0.7

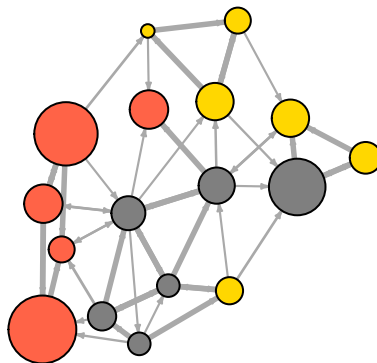
# The labels are currently node IDs.
# Setting them to NA will render no labels:
V(net)$label.color <- "black"
V(net)$label <- NA

# Set edge width based on weight:
E(net)$width <- E(net)$weight/6

#change arrow size and edge color:
E(net)$arrow.size <- .2
E(net)$edge.color <- "gray80"

E(net)$width <- 1+E(net)$weight/12

```

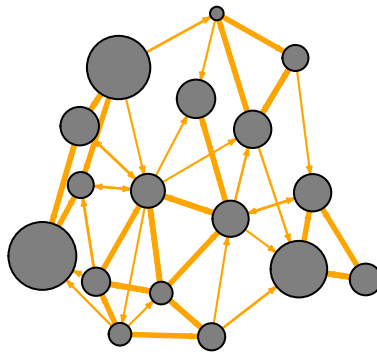


We can also override the attributes explicitly in the plot:

```

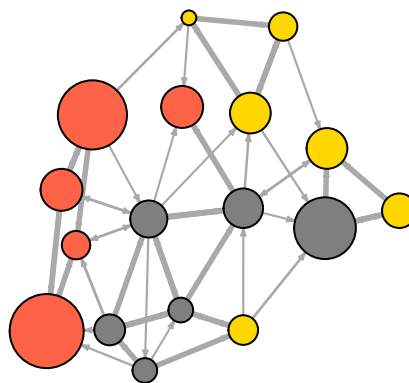
plot(net, edge.color="orange", vertex.color="gray50")

```



It helps to add a legend explaining the meaning of the colors we used:

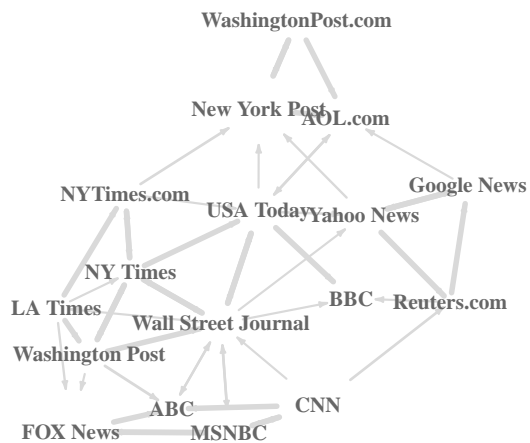
```
plot(net)
legend(x=-1.5, y=-1.1, c("Newspaper", "Television", "Online News"), pch=21,
      col="#777777", pt.bg=colrs, pt.cex=2, cex=.8, bty="n", ncol=1)
```



- Newspaper
- Television
- Online News

Sometimes, especially with semantic networks, we may be interested in plotting only the labels of the nodes:

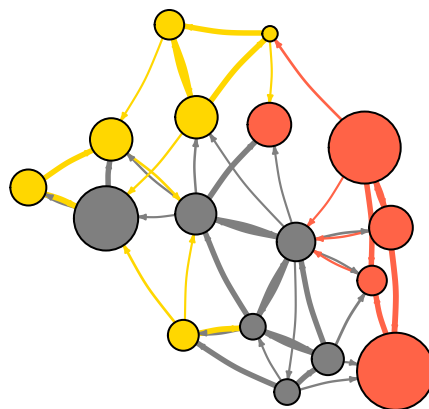
```
plot(net, vertex.shape="none", vertex.label=V(net)$media,
      vertex.label.font=2, vertex.label.color="gray40",
      vertex.label.cex=.7, edge.color="gray85")
```



Let's color the edges of the graph based on their source node color. We can get the starting node for each edge with the `ends()` igraph function.

```
edge.start <- ends(net, es=E(net), names=F)[,1]
edge.col <- V(net)$color[edge.start]

plot(net, edge.color=edge.col, edge.curved=.1)
```

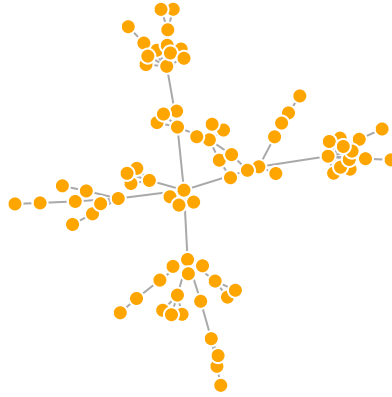


5.2 Network layouts

Network layouts are simply algorithms that return coordinates for each node in a network.

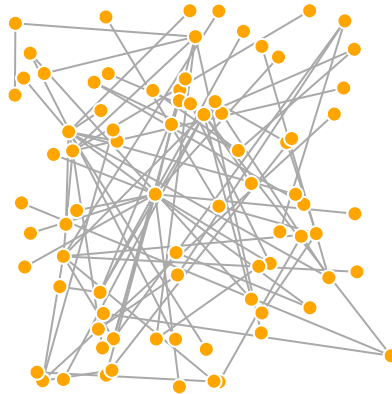
For the purposes of exploring layouts, we will generate a slightly larger 80-node graph. We use the `sample_pa()` function which generates a simple graph starting from one node and adding more nodes and links based on a preset level of preferential attachment (Barabasi-Albert model).

```
net.bg <- sample_pa(80)
V(net.bg)$size <- 8
V(net.bg)$frame.color <- "white"
V(net.bg)$color <- "orange"
V(net.bg)$label <- ""
E(net.bg)$arrow.mode <- 0
plot(net.bg)
```



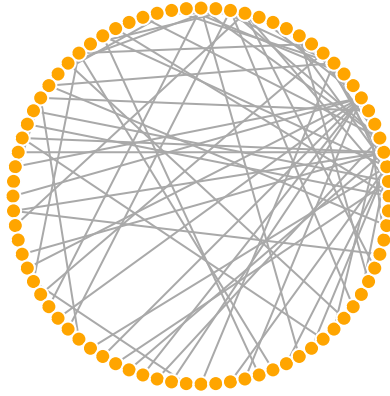
You can set the layout in the plot function:

```
plot(net.bg, layout=layout_randomly)
```



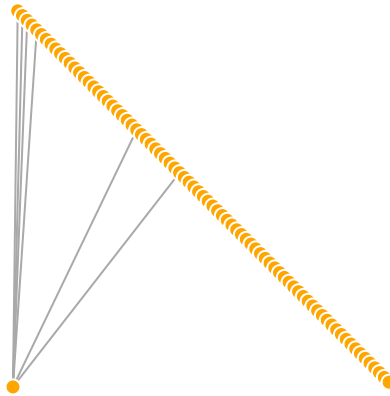
Or you can calculate the vertex coordinates in advance:

```
l <- layout_in_circle(net.bg)
plot(net.bg, layout=l)
```



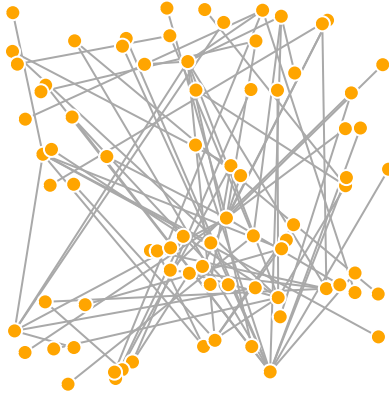
`l` is simply a matrix of `x, y` coordinates ($N \times 2$) for the N nodes in the graph. You can easily generate your own:

```
l <- cbind(1:vcount(net.bg), c(1, vcount(net.bg):2))
plot(net.bg, layout=l)
```

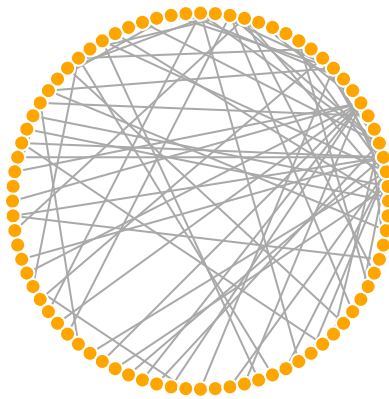


This layout is just an example and not very helpful - thankfully `igraph` has a number of built-in layouts, including:

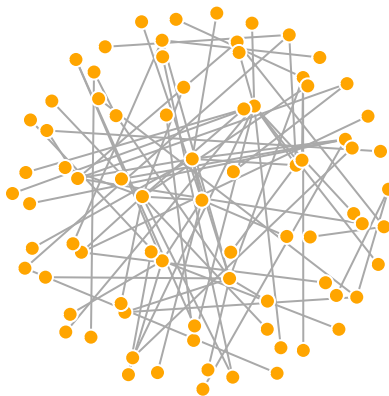
```
# Randomly placed vertices
l <- layout_randomly(net.bg)
plot(net.bg, layout=l)
```



```
# Circle layout  
l <- layout_in_circle(net.bg)  
plot(net.bg, layout=l)
```



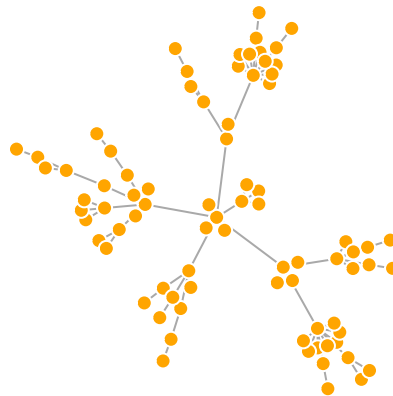
```
# 3D sphere layout  
l <- layout_on_sphere(net.bg)  
plot(net.bg, layout=l)
```



Fruchterman-Reingold is one of the most used force-directed layout algorithms out there.

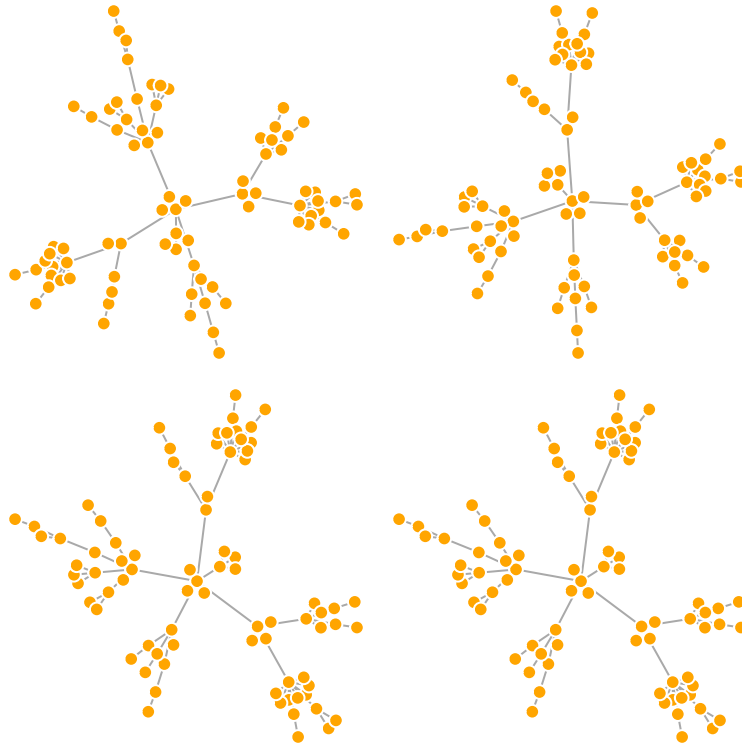
Force-directed layouts try to get a nice-looking graph where edges are similar in length and cross each other as little as possible. They simulate the graph as a physical system. Nodes are electrically charged particles that repulse each other when they get too close. The edges act as springs that attract connected nodes closer together. As a result, nodes are evenly distributed through the chart area, and the layout is intuitive in that nodes which share more connections are closer to each other. The disadvantage of these algorithms is that they are rather slow and therefore less often used in graphs larger than ~1000 vertices. You can set the “weight” parameter which increases the attraction forces among nodes connected by heavier edges.

```
l <- layout_with_fr(net.bg)
plot(net.bg, layout=l)
```



You will notice that the layout is not deterministic - different runs will result in slightly different configurations. Saving the layout in `l` allows us to get the exact same result multiple times, which can be helpful if you want to plot the time evolution of a graph, or different relationships – and want nodes to stay in the same place in multiple plots.

```
par(mfrow=c(2,2), mar=c(0,0,0,0)) # plot four figures - 2 rows, 2 columns
plot(net.bg, layout=layout_with_fr)
plot(net.bg, layout=layout_with_fr)
plot(net.bg, layout=l)
plot(net.bg, layout=l)
```

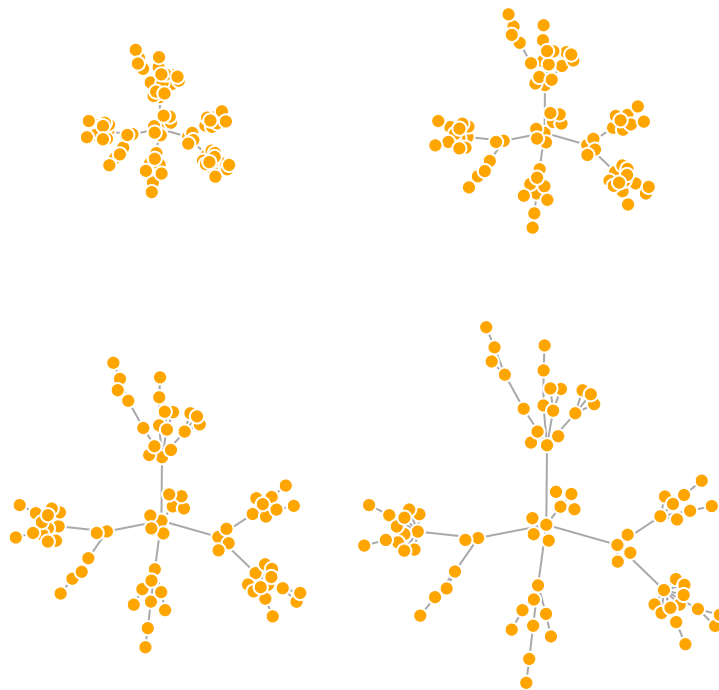



```
dev.off()
```

By default, the coordinates of the plots are rescaled to the $[-1,1]$ interval for both x and y . You can change that with the parameter `rescale=FALSE` and rescale your plot manually by multiplying the coordinates by a scalar. You can use `norm_coords` to normalize the plot with the boundaries you want.

```
l <- layout_with_fr(net.bg)
l <- norm_coords(l, ymin=-1, ymax=1, xmin=-1, xmax=1)

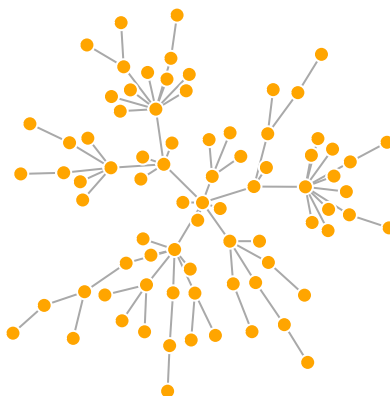
par(mfrow=c(2,2), mar=c(0,0,0,0))
plot(net.bg, rescale=F, layout=l*0.4)
plot(net.bg, rescale=F, layout=l*0.6)
plot(net.bg, rescale=F, layout=l*0.8)
plot(net.bg, rescale=F, layout=l*1.0)
```



```
dev.off()
```

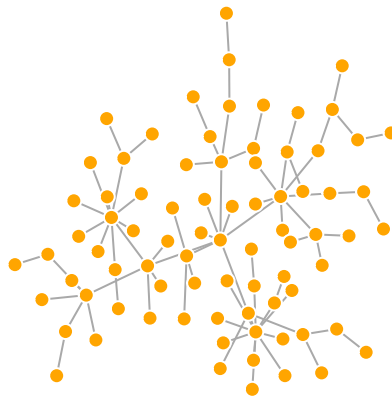
Another popular force-directed algorithm that produces nice results for connected graphs is Kamada Kawai. Like Fruchterman Reingold, it attempts to minimize the energy in a spring system.

```
l <- layout_with_kk(net.bg)  
plot(net.bg, layout=l)
```



The LGL algorithm is meant for large, connected graphs. Here you can also specify a root: a node that will be placed in the middle of the layout.

```
plot(net.bg, layout=layout_with_lgl)
```

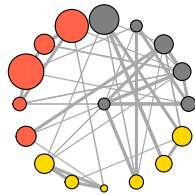


Let's take a look at all available layouts in igraph:

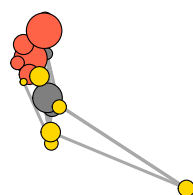
```
layouts <- grep("^layout_", ls("package:igraph"), value=TRUE)[-1]
# Remove layouts that do not apply to our graph.
layouts <- layouts[!grepl("bipartite|merge|norm|sugiyama|tree", layouts)]

par(mfrow=c(3,3), mar=c(1,1,1,1))
for (layout in layouts) {
  print(layout)
  l <- do.call(layout, list(net))
  plot(net, edge.arrow.mode=0, layout=l, main=layout) }
```

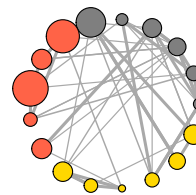
layout_as_star



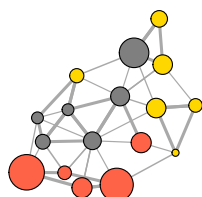
layout_components



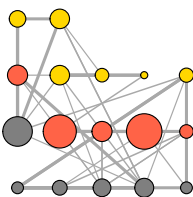
layout_in_circle



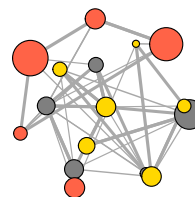
layout_nicely

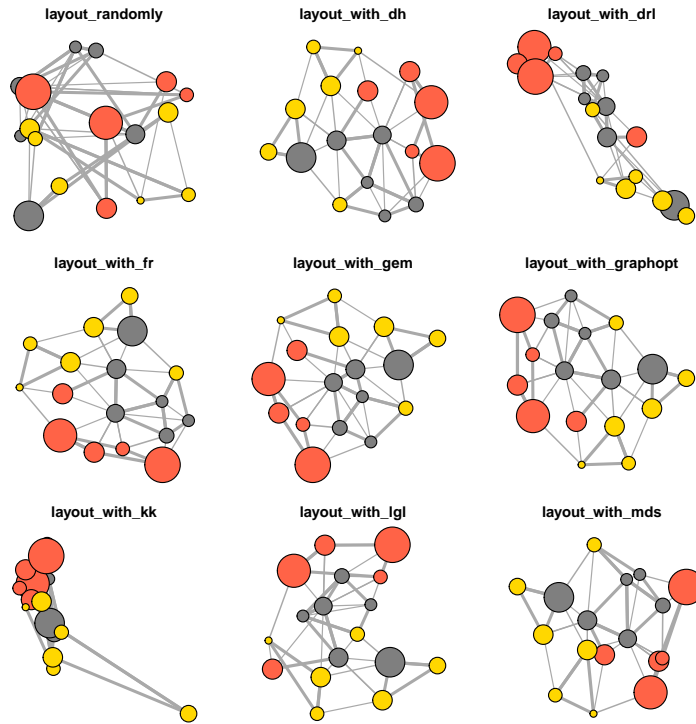


layout_on_grid

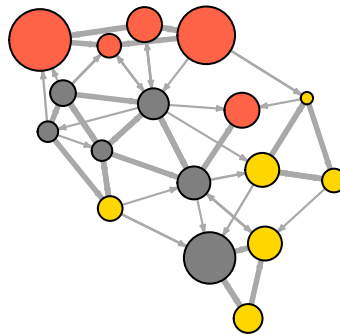


layout_on_sphere





5.3 Improving network plots

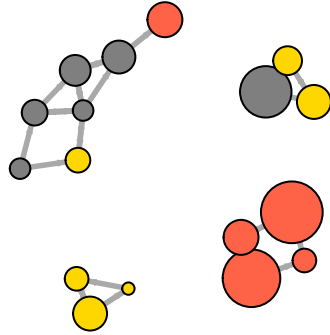


Notice that our network plot is still not too helpful. We can identify the type and size of nodes, but cannot see much about the structure since the links we're examining are so dense. One way to approach this is to see if we can sparsify the network, keeping only the most important ties and discarding the rest.

```
hist(links$weight)
mean(links$weight)
sd(links$weight)
```

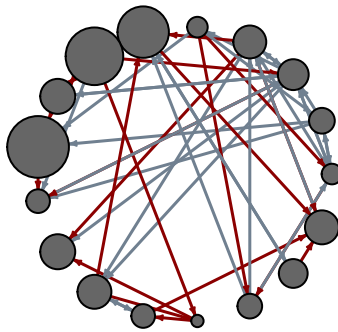
There are more sophisticated ways to extract the key edges, but for the purposes of this exercise we'll only keep ones that have weight higher than the mean for the network. In `igraph`, we can delete edges using `delete_edges(net, edges)`:

```
cut.off <- mean(links$weight)
net.sp <- delete_edges(net, E(net)[weight<cut.off])
plot(net.sp)
```



Another way to think about this is to plot the two tie types (hyperlink & mention) separately.

```
E(net)$width <- 1.5
plot(net, edge.color=c("dark red", "slategrey")[(E(net)$type=="hyperlink")+1],
      vertex.color="gray40", layout=layout.circle)
```

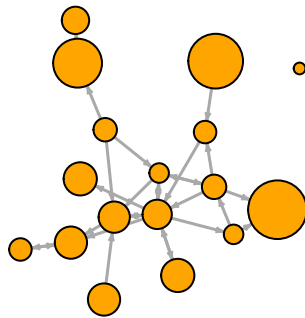


```
net.m <- net - E(net)[E(net)$type=="hyperlink"] # another way to delete edges
net.h <- net - E(net)[E(net)$type=="mention"]
```

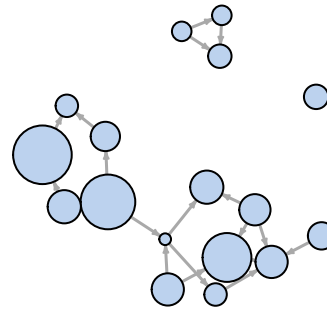
Plot the two links separately:

```
par(mfrow=c(1,2))
plot(net.h, vertex.color="orange", main="Tie: Hyperlink")
plot(net.m, vertex.color="lightsteelblue2", main="Tie: Mention")
```

Tie: Hyperlink

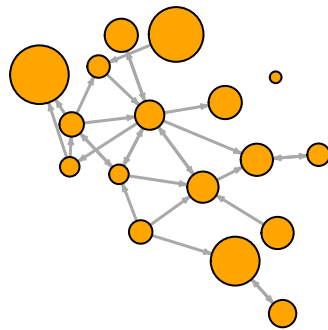


Tie: Mention

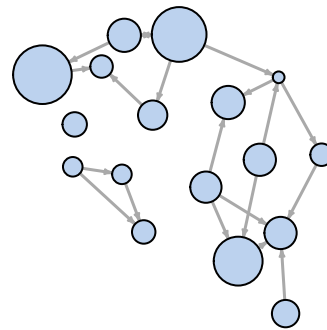


```
# Make sure the nodes stay in place in both plots:  
l <- layout_with_fr(net)  
plot(net.h, vertex.color="orange", layout=l, main="Tie: Hyperlink")  
plot(net.m, vertex.color="lightsteelblue2", layout=l, main="Tie: Mention")
```

Tie: Hyperlink



Tie: Mention

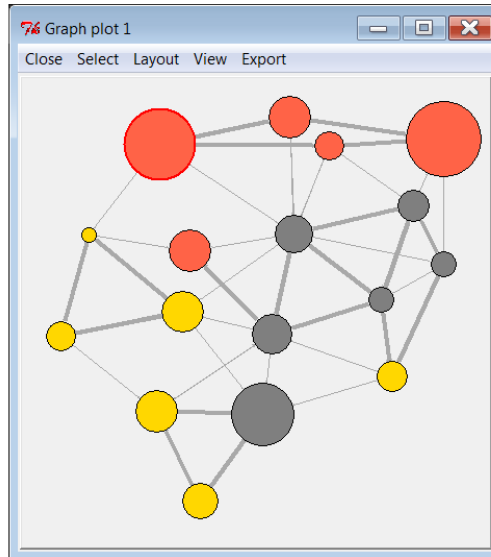


```
dev.off()
```

5.4 Interactive plotting with tkplot

R and igraph allow for interactive plotting of networks. This might be a useful option for you if you want to tweak slightly the layout of a small graph. After adjusting the layout manually, you can get the coordinates of the nodes and use them for other plots.

```
tkid <- tkplot(net) #tkid is the id of the tkplot that will open  
l <- tkplot.getcoords(tkid) # grab the coordinates from tkplot  
tk_close(tkid, window.close = T)  
plot(net, layout=l)
```



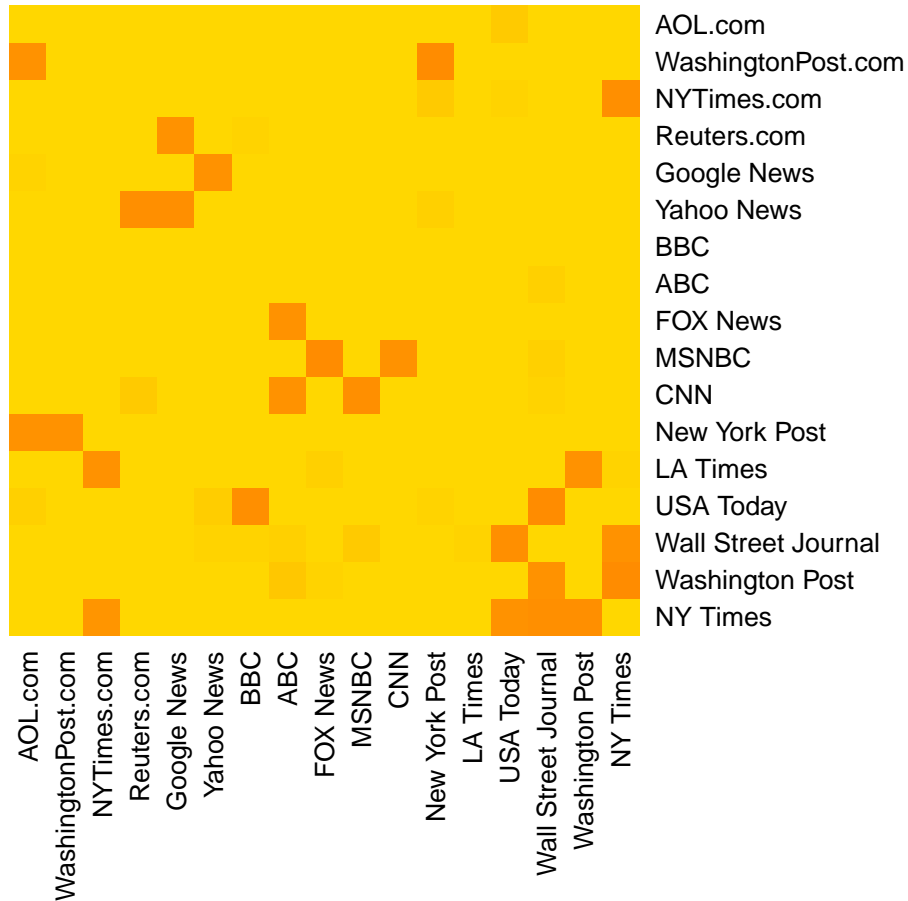
5.5 Other ways to represent a network

At this point it might be useful to provide a quick reminder that there are many ways to represent a network not limited to a hairball plot.

For example, here is a quick heatmap of the network matrix:

```
netm <- get.adjacency(net, attr="weight", sparse=F)
colnames(netm) <- V(net)$media
rownames(netm) <- V(net)$media

palf <- colorRampPalette(c("gold", "dark orange"))
heatmap(netm[,17:1], Rowv = NA, Colv = NA, col = palf(100),
        scale="none", margins=c(10,10) )
```

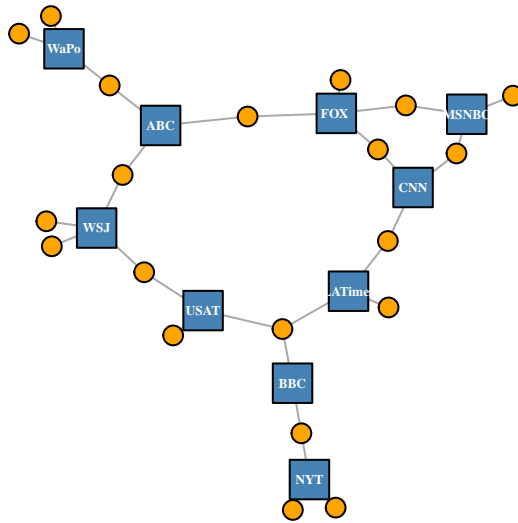


5.6 Plotting two-mode networks with igraph

As with one-mode networks, we can modify the network object to include the visual properties that will be used by default when plotting the network. Notice that this time we will also change the shape of the nodes - media outlets will be squares, and their users will be circles.

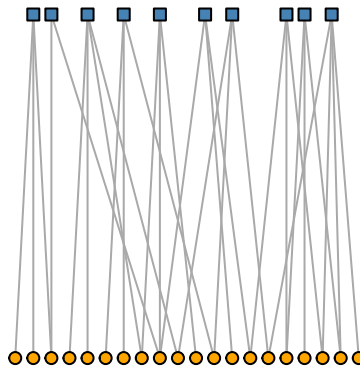
```
V(net2)$color <- c("steel blue", "orange")[V(net2)$type+1]
V(net2)$shape <- c("square", "circle")[V(net2)$type+1]
V(net2)$label <- ""
V(net2)$label[V(net2)$type==F] <- nodes2$media[V(net2)$type==F]
V(net2)$label.cex=.4
V(net2)$label.font=2

plot(net2, vertex.label.color="white", vertex.size=(2-V(net2)$type)*8)
```

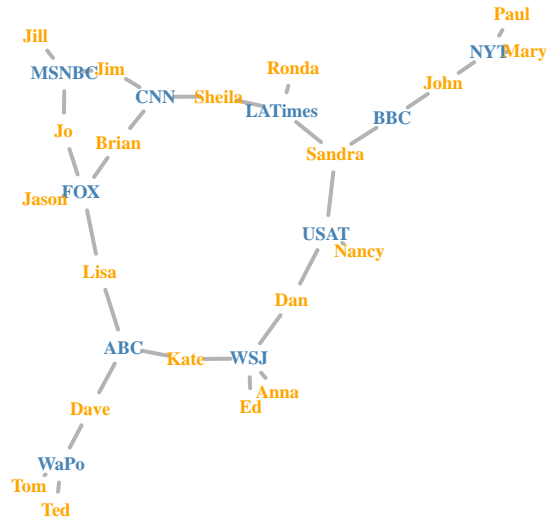
Igraph also has a special layout for bipartite networks (though it doesn't always work great, and you might be better off generating your own two-mode layout).

```
plot(net2, vertex.label=NA, vertex.size=7, layout=layout_as_bipartite)
```



Using text as nodes may be helpful at times:

```
plot(net2, vertex.shape="none", vertex.label=nodes2$media,
      vertex.label.color=V(net2)$color, vertex.label.font=2.5,
      vertex.label.cex=.6, edge.color="gray70", edge.width=2)
```



6. Network and node descriptives

6.1 Density

The proportion of present edges from all possible edges in the network.

```
edge_density(net, loops=F)
```

```
## [1] 0.1764706
```

```
ecount(net)/(vcount(net)*(vcount(net)-1)) #for a directed network
```

```
## [1] 0.1764706
```

6.2 Reciprocity

The proportion of reciprocated ties (for a directed network).

```
reciprocity(net)
dyad_census(net) # Mutual, asymmetric, and null node pairs
2*dyad_census(net)$mut/ecount(net) # Calculating reciprocity
```

6.3 Transitivity

- global - ratio of triangles (direction disregarded) to connected triples.
- local - ratio of triangles to connected triples each vertex is part of.

```
transitivity(net, type="global") # net is treated as an undirected network
transitivity(as.undirected(net, mode="collapse")) # same as above
transitivity(net, type="local")
triad_census(net) # for directed networks
```

Triad types (per Davis & Leinhardt):

- 003 A, B, C, empty triad.
- 012 A->B, C
- 102 A<->B, C
- 021D A<-B->C
- 021U A->B<-C
- 021C A->B->C
- 111D A<->B<-C
- 111U A<->B->C
- 030T A->B<-C, A->C
- 030C A<-B<-C, A->C.
- 201 A<->B<->C.
- 120D A<-B->C, A<->C.
- 120U A->B<-C, A<->C.
- 120C A->B->C, A<->C.
- 210 A->B<->C, A<->C.
- 300 A<->B<->C, A<->C, completely connected.

6.4 Diameter

A network diameter is the longest geodesic distance (length of the shortest path between two nodes) in the network. In `igraph`, `diameter()` returns the distance, while `get_diameter()` returns the nodes along the first found path of that distance.

Note that edge weights are used by default, unless set to NA.

```
diameter(net, directed=F, weights=NA)
```

```
## [1] 4
```

```
diameter(net, directed=F)
```

```
## [1] 28
```

```
diam <- get_diameter(net, directed=T)
diam
```

```
## + 7/17 vertices, named:
## [1] s12 s06 s17 s04 s03 s08 s07
```

Note that `get_diameter()` returns a vertex sequence. Note though that when asked to behave as a vector, a vertex sequence will produce the numeric indexes of the nodes in it. The same applies for edge sequences.

```
class(diam)
```

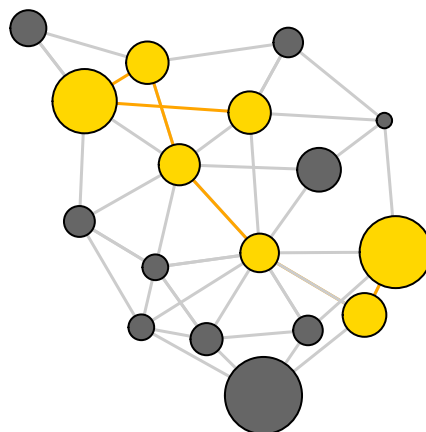
```
## [1] "igraph.vs"
```

```
as.vector(diam)
```

```
## [1] 12 6 17 4 3 8 7
```

Color nodes along the diameter:

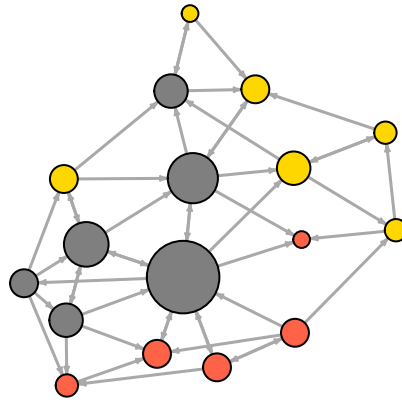
```
vcol <- rep("gray40", vcount(net))
vcol[diam] <- "gold"
ecol <- rep("gray80", ecounet(net))
ecol[E(net, path=diam)] <- "orange"
# E(net, path=diam) finds edges along a path, here 'diam'
plot(net, vertex.color=vcol, edge.color=ecol, edge.arrow.mode=0)
```



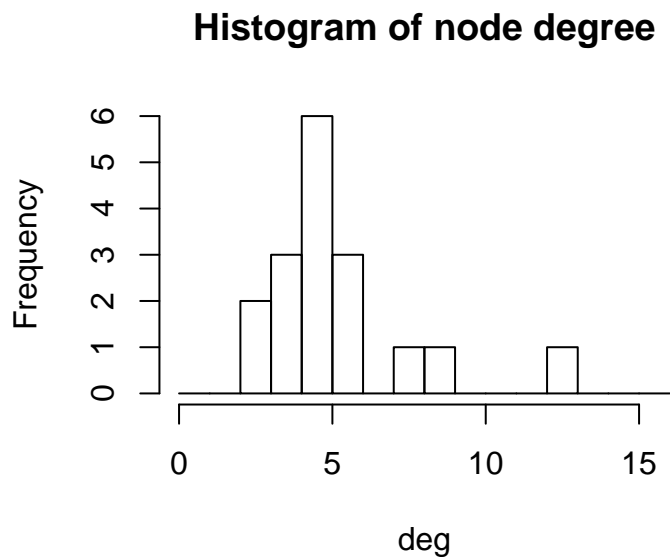
6.5 Node degrees

The function `degree()` has a mode of *in* for in-degree, *out* for out-degree, and *all* or *total* for total degree.

```
deg <- degree(net, mode="all")  
plot(net, vertex.size=deg*3)
```

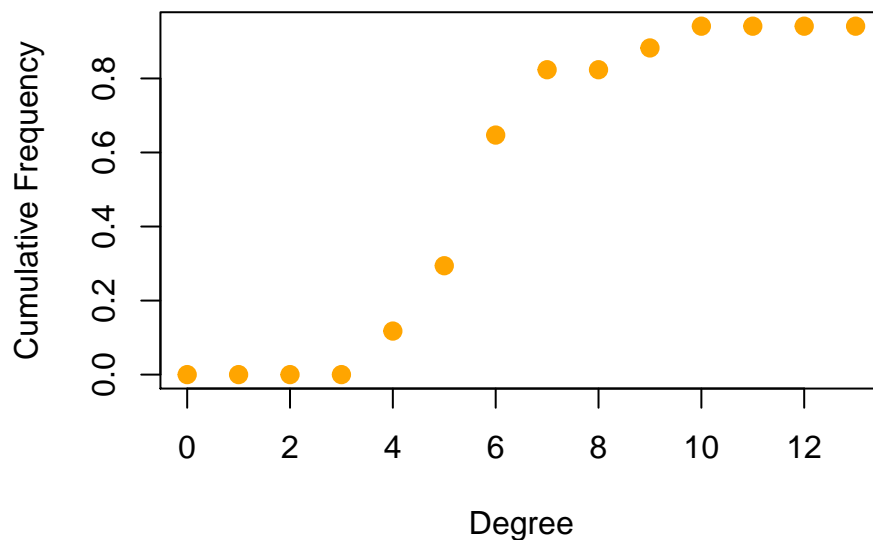


```
hist(deg, breaks=1:vcount(net)-1, main="Histogram of node degree")
```



6.6 Degree distribution

```
deg.dist <- degree_distribution(net, cumulative=T, mode="all")
plot( x=0:max(deg), y=1-deg.dist, pch=19, cex=1.2, col="orange",
      xlab="Degree", ylab="Cumulative Frequency")
```



6.7 Centrality & centralization

Centrality functions (vertex level) and centralization functions (graph level). The centralization functions return `res` - vertex centrality, `centralization`, and `theoretical_max` - maximum centralization score for a graph of that size. The centrality function can run on a subset of nodes (set with the `vids` parameter). This is helpful for large graphs where calculating all centralities may be a resource-intensive and time-consuming task.

Degree (number of ties)

```
degree(net, mode="in")
centr_degree(net, mode="in", normalized=T)
```

Closeness (centrality based on distance to others in the graph)
Inverse of the node's average geodesic distance to others in the network.

```
closeness(net, mode="all", weights=NA)
centr_clo(net, mode="all", normalized=T)
```

Eigenvector (centrality proportional to the sum of connection centralities)
Values of the first eigenvector of the graph matrix.

```
eigen_centrality(net, directed=T, weights=NA)  
centr_eigen(net, directed=T, normalized=T)
```

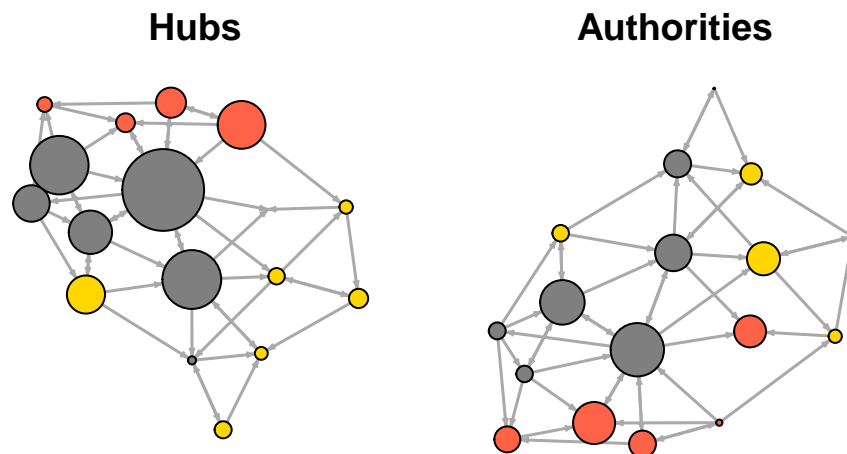
Betweenness (centrality based on a broker position connecting others)
Number of geodesics that pass through the node or the edge.

```
betweenness(net, directed=T, weights=NA)  
edge_betweenness(net, directed=T, weights=NA)  
centr_betw(net, directed=T, normalized=T)
```

6.8 Hubs and authorities

The hubs and authorities algorithm developed by Jon Kleinberg was initially used to examine web pages. Hubs were expected to contain catalogs with a large number of outgoing links; while authorities would get many incoming links from hubs, presumably because of their high-quality relevant information.

```
hs <- hub_score(net, weights=NA)$vector  
as <- authority_score(net, weights=NA)$vector  
  
par(mfrow=c(1,2))  
plot(net, vertex.size=hs*50, main="Hubs")  
plot(net, vertex.size=as*30, main="Authorities")
```



```
dev.off()
```

7. Distances and paths

Average path length: the mean of the shortest distance between each pair of nodes in the network (in both directions for directed graphs).

```
mean_distance(net, directed=F)
```

```
## [1] 2.058824
```

```
mean_distance(net, directed=T)
```

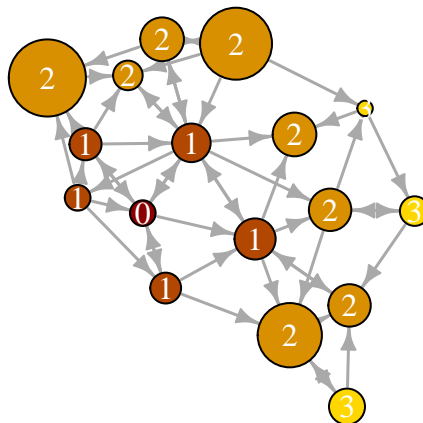
```
## [1] 2.742188
```

We can also find the length of all shortest paths in the graph:

```
distances(net) # with edge weights  
distances(net, weights=NA) # ignore weights
```

We can extract the distances to a node or set of nodes we are interested in. Here we will get the distance of every media from the New York Times.

```
dist.from.NYT <- distances(net, v=V(net)[media=="NY Times"], to=V(net), weights=NA)  
  
# Set colors to plot the distances:  
oranges <- colorRampPalette(c("dark red", "gold"))  
col <- oranges(max(dist.from.NYT)+1)  
col <- col[dist.from.NYT+1]  
  
plot(net, vertex.color=col, vertex.label=dist.from.NYT, edge.arrow.size=.6,  
      vertex.label.color="white")
```

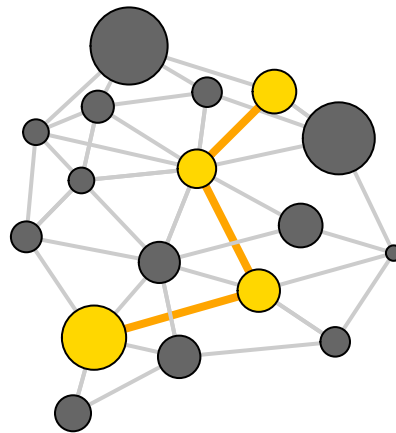


We can also find the shortest path between specific nodes. Say here between MSNBC and the New York Post:

```
news.path <- shortest_paths(net,
                             from = V(net)[media=="MSNBC"],
                             to   = V(net)[media=="New York Post"],
                             output = "both") # both path nodes and edges

# Generate edge color variable to plot the path:
ecol <- rep("gray80", ecount(net))
ecol[unlist(news.path$epath)] <- "orange"
# Generate edge width variable to plot the path:
ew <- rep(2, ecount(net))
ew[unlist(news.path$epath)] <- 4
# Generate node color variable to plot the path:
vcol <- rep("gray40", vcount(net))
vcol[unlist(news.path$vpath)] <- "gold"

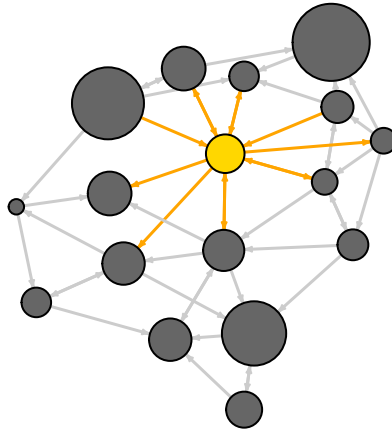
plot(net, vertex.color=vcol, edge.color=ecol,
      edge.width=ew, edge.arrow.mode=0)
```



Identify the edges going into or out of a vertex, for instance the WSJ. For a single node, use `incident()`, for multiple nodes use `incident_edges()`

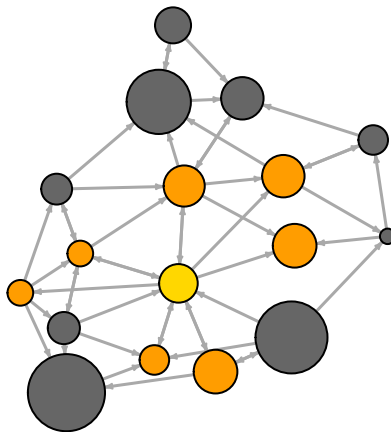
```
inc.edges <- incident(net, V(net)[media=="Wall Street Journal"], mode="all")

# Set colors to plot the selected edges.
ecol <- rep("gray80", ecount(net))
ecol[inc.edges] <- "orange"
vcol <- rep("grey40", vcount(net))
vcol[V(net)$media=="Wall Street Journal"] <- "gold"
plot(net, vertex.color=vcol, edge.color=ecol)
```



We can also easily identify the immediate neighbors of a vertex, say WSJ. The `neighbors` function finds all nodes one step out from the focal actor. To find the neighbors for multiple nodes, use `adjacent_vertices()` instead of `neighbors()`. To find node neighborhoods going more than one step out, use function `ego()` with parameter `order` set to the number of steps out to go from the focal node(s).

```
neigh.nodes <- neighbors(net, V(net)[media=="Wall Street Journal"], mode="out")
# Set colors to plot the neighbors:
vcol[neigh.nodes] <- "#ff9d00"
plot(net, vertex.color=vcol)
```



Special operators for the indexing of edge sequences: `%-%`, `%->%`, `%<-%`
`E(network)[X %-% Y]` selects edges between vertex sets X and Y, ignoring direction
`E(network)[X %->% Y]` selects edges from vertex sets X to vertex set Y
`E(network)[X %<-% Y]` selects edges from vertex sets Y to vertex set X

For example, select edges from newspapers to online sources:

```
E(net)[ V(net)[type.label=="Newspaper"] %->% V(net)[type.label=="Online"] ]
```

```
## + 7/48 edges (vertex names):
```

```
## [1] s01->s15 s03->s12 s04->s12 s04->s17 s05->s15 s06->s16 s06->s17
```

Co-citation (for a couple of nodes, how many shared nominations they have):

```
cocitation(net)
```

```
##      s01 s02 s03 s04 s05 s06 s07 s08 s09 s10 s11 s12 s13 s14 s15 s16 s17
## s01  0   1   1   2   1   1   0   1   2   2   1   1   0   0   1   0   0
## s02  1   0   1   1   0   0   0   0   1   0   0   0   0   0   2   0   0
## s03  1   1   0   1   0   1   1   1   2   2   1   1   0   1   1   0   1
## s04  2   1   1   0   1   1   0   1   0   1   1   1   0   0   1   0   0
## s05  1   0   0   1   0   0   0   1   0   1   1   1   0   0   0   0   0
## s06  1   0   1   1   0   0   0   0   0   0   1   1   1   1   0   0   2
## s07  0   0   1   0   0   0   0   0   1   0   0   0   0   0   0   0   0
## s08  1   0   1   1   1   0   0   0   0   2   1   1   0   1   0   0   0
## s09  2   1   2   0   0   0   1   0   0   1   0   0   0   0   1   0   0
## s10  2   0   2   1   1   0   0   2   1   0   1   1   0   1   0   0   0
## s11  1   0   1   1   1   1   0   1   0   1   0   2   1   0   0   0   1
## s12  1   0   1   1   1   1   0   1   0   1   2   0   0   0   0   0   2
## s13  0   0   0   0   0   1   0   0   0   0   1   0   0   1   0   0   0
## s14  0   0   1   0   0   1   0   1   0   1   0   0   1   0   0   0   0
## s15  1   2   1   1   0   0   0   0   1   0   0   0   0   0   0   0   0
## s16  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
## s17  0   0   1   0   0   2   0   0   0   0   1   2   0   0   0   1   0
```

8. Subgroups and communities

Before we start, we will make our network undirected. There are several ways to do that conversion:

- We can create an undirected link between any pair of connected nodes (*mode="collapse"*)
- Create undirected link for each directed one in the network, potentially ending up with a multiplex graph (*mode="each"*)
- Create undirected link for each symmetric link in the graph (*mode="mutual"*).

In cases when we may have ties $A \rightarrow B$ and $B \rightarrow A$ ties collapsed into a single undirected link, we need to specify what to do with their edge attributes using the parameter 'edge.attr.comb' as we did earlier with `simplify()`. Here we have said that the 'weight' of the links should be summed, and all other edge attributes ignored and dropped.

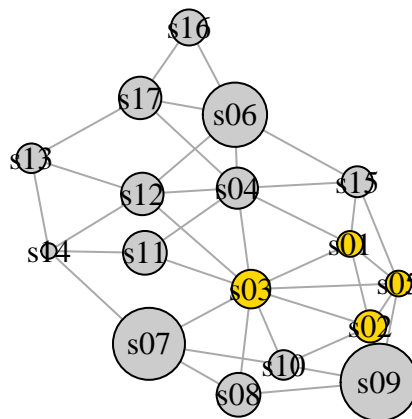
```
net.sym <- as.undirected(net, mode= "collapse",
                        edge.attr.comb=list(weight="sum", "ignore"))
```

8.1 Cliques

Find cliques (complete subgraphs of an undirected graph)

```
cliques(net.sym) # list of cliques
sapply(cliques(net.sym), length) # clique sizes
largest_cliques(net.sym) # cliques with max number of nodes
```

```
vcol <- rep("grey80", vcount(net.sym))
vcol[unlist(largest_cliques(net.sym))] <- "gold"
plot(as.undirected(net.sym), vertex.label=V(net.sym)$name, vertex.color=vcol)
```



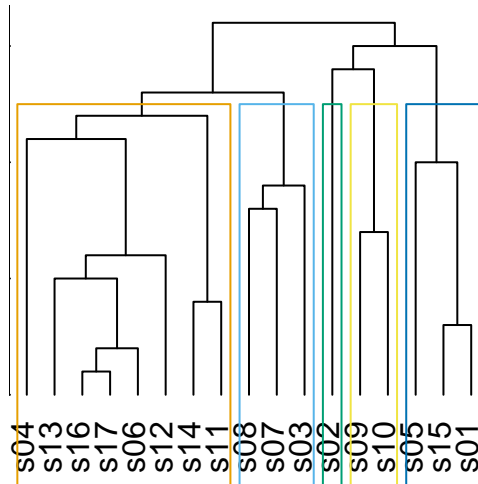
8.2 Community detection

A number of algorithms aim to detect groups that consist of densely connected nodes with fewer connections across groups.

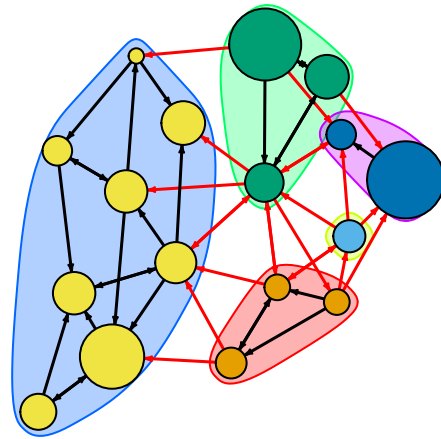
Community detection based on edge betweenness (Newman-Girvan)

High-betweenness edges are removed sequentially (recalculating at each step) and the best partitioning of the network is selected.

```
ceb <- cluster_edge_betweenness(net)
dendPlot(ceb, mode="hclust")
```



```
plot(ceb, net)
```



Let's examine the community detection igraph object:

```
class(ceb)
```

```
## [1] "communities"
```

```
length(ceb) # number of communities
```

```
## [1] 5
```

```
membership(ceb) # community membership for each node
```

```
## s01 s02 s03 s04 s05 s06 s07 s08 s09 s10 s11 s12 s13 s14 s15 s16 s17
## 1 2 3 4 1 4 3 3 5 5 4 4 4 4 1 4 4
```

```
modularity(ceb) # how modular the graph partitioning is
```

```
## [1] 0.292476
```

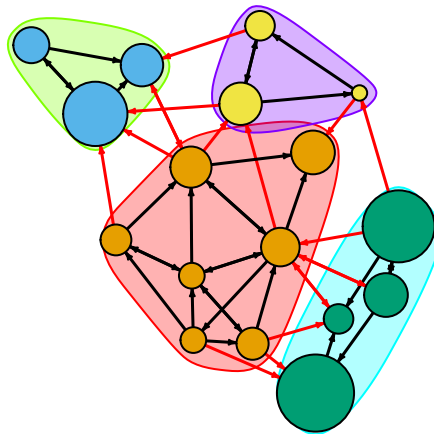
```
crossing(ceb, net) # boolean vector: TRUE for edges across communities
```

High modularity for a partitioning reflects dense connections within communities and sparse connections across communities.

Community detection based on based on propagating labels

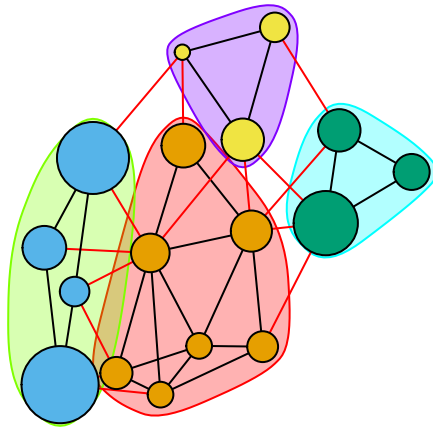
Assigns node labels, randomizes, than replaces each vertex's label with the label that appears most frequently among neighbors. Those steps are repeated until each vertex has the most common label of its neighbors.

```
clp <- cluster_label_prop(net)  
plot(clp, net)
```



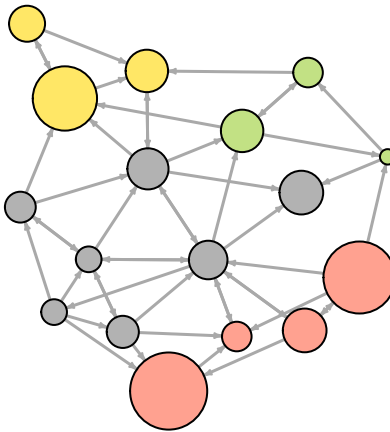
Community detection based on greedy optimization of modularity

```
cfg <- cluster_fast_greedy(as.undirected(net))  
plot(cfg, as.undirected(net))
```



We can also plot the communities without relying on their built-in plot:

```
V(net)$community <- cfg$membership
colrs <- adjustcolor( c("gray50", "tomato", "gold", "yellowgreen"), alpha=.6)
plot(net, vertex.color=colrs[V(net)$community])
```

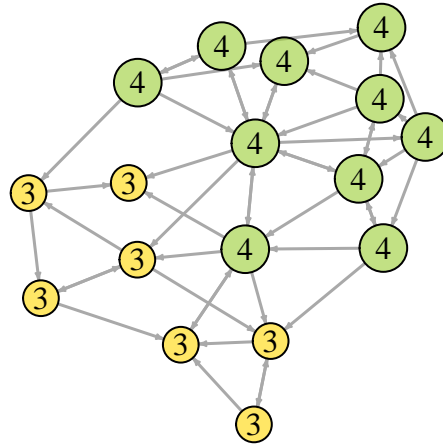


8.3 *K-core decomposition*

The k -core is the maximal subgraph in which every node has degree of at least k . This also means that the $(k+1)$ -core will be a subgraph of the k -core.

The result here gives the coreness of each vertex in the network. A node has coreness D if it belongs to a D -core but not to $(D+1)$ -core.

```
kc <- coreness(net, mode="all")
plot(net, vertex.size=kc*6, vertex.label=kc, vertex.color=colrs[kc])
```



9. Assortativity and Homophily

Homophily: the tendency of nodes to connect to others who are similar on some variable.

- `assortativity_nominal()` is for categorical variables (labels)
- `assortativity()` is for ordinal and above variables
- `assortativity_degree()` checks assortativity in node degrees

```
assortativity_nominal(net, V(net)$media.type, directed=F)
```

```
## [1] 0.1715568
```

```
# Matching of attributes across connected nodes more than expected by chance
```

```
assortativity(net, V(net)$audience.size, directed=F)
```

```
## [1] -0.1102857
```

```
# Correlation of attributes across connected nodes
```

```
assortativity_degree(net, directed=F)
```

```
## [1] -0.009551146
```

```
# As above, with the focal attribute being the node degree D-1
```
