Network Analysis and Visualization

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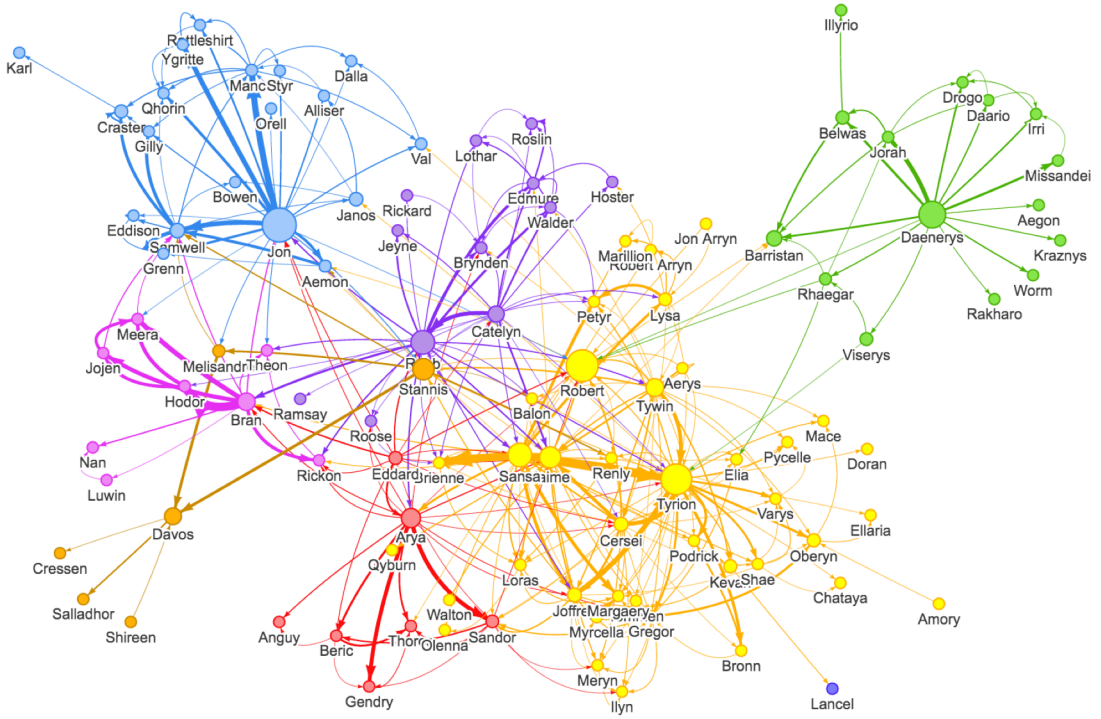
https://github.com/rladiesPHL/workshop_network

Agenda

- Network analysis basics
  - R object IGRAPH ”I/O”
  - object IGRAPH manipulation
- Graph advance
  - Graph measurement
  - Graph cluster
- Network visualization
  - Aesthetics of network elements
  - Network layout
- Network application show case
- Group Exercise – world flight

What is network analysis?

- Network analysis is to study the **inter-relationships** between actors of all sorts and provides an **architectural view** of individual connections. In mathematics, it is part of **graph theory.**
- Network analysis are widely used in
  - Computer science . eg. computational devices connection
  - Linguistics . eg. natural language flow
  - Social sciences. eg. social network
  - Biology. eg. gene regulation network

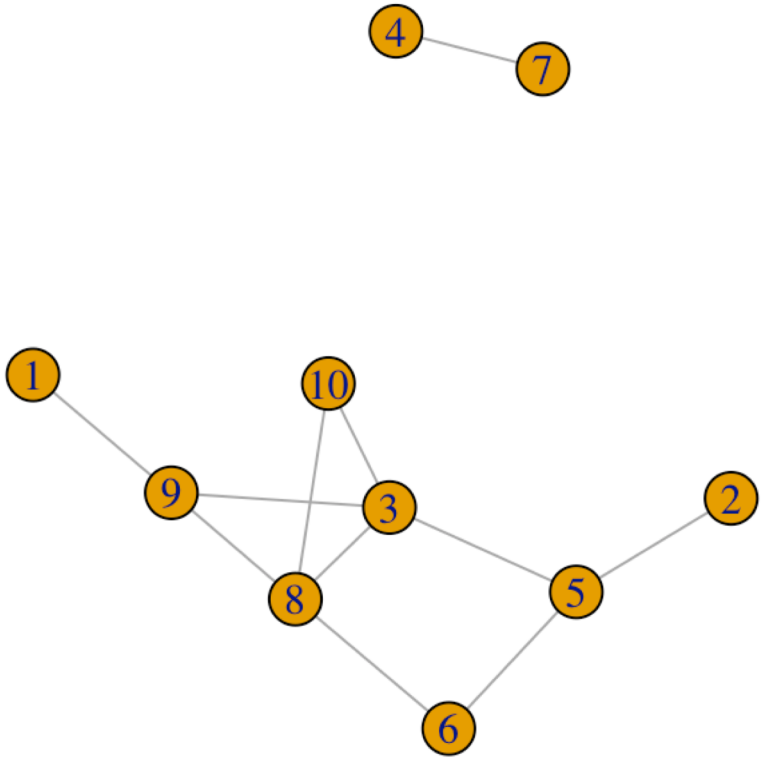


https://www.lyonwj.com/2016/06/26/graph-of-thrones-neo4j-social-network-analysis/

https://en.wikipedia.org/wiki/Graph_theory

Graph elements (Glossaries I)

- **Vertex**: is the node of network
- **Edge**: the connection of notes, sometimes called "link".
  - Directed
  - undirected
- **Graph**: constitute of vertices and edges, which represents the whole inter-relationship of nodes.



IGRAPH object in R

- Package igraph have a class ‘igraph’.

```
g = make_graph(letters[1:10], directed = T)
g
```

```
## IGRAPH 8b3c740 DN-- 10 5 --
## + attr: name (v/c)
## + edges from 8b3c740 (vertex names):
## [1] a->b c->d e->f g->h i->j
```

Named

Edge #

Directed

vertex #

Attribute can be associated with either vertex (v) or edge (e) or both.

Special attributes, name, can be used to select vertices and edges (“from|to”).

Create IGRAPH

- IGRAPH can be created in multiple ways
  - Easy graph:
    - graph_from_literal
    - make_graph
  - Create from user data:
    - graph_from_edgelist
    - graph_from_adjacency_matrix
    - graph_from_data_frame
  - Classic random graphs:
    - sample_gnp
    - sample_gnm
    - sample_pa
    - sample_smallworld

graph_from_adjacency_matrix

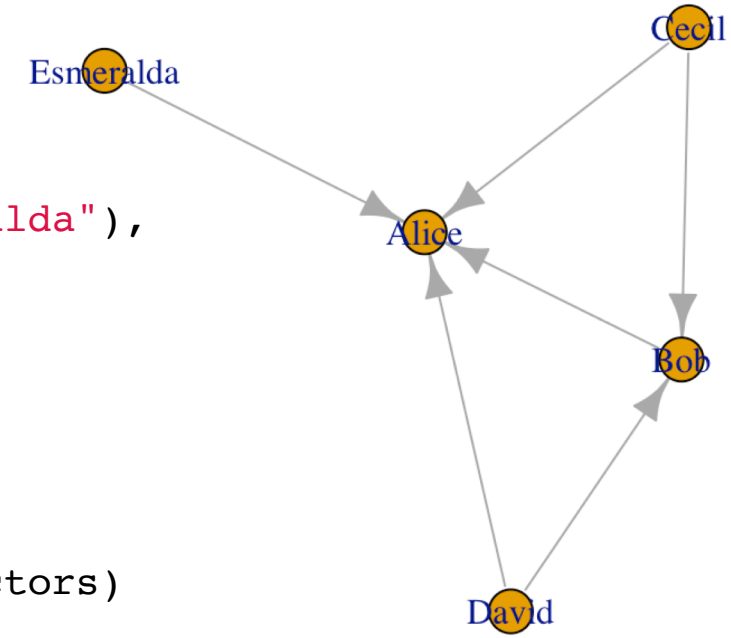
	a	b	c	d	e	f	g	h	i	j
a	0	1	1	1	0	0	0	0	0	0
b	0	0	0	1	0	0	0	0	0	0
c	0	0	0	0	0	0	0	0	0	0
d	0	0	1	0	0	0	0	0	0	0
e	1	0	0	0	0	0	0	0	0	0
f	0	1	0	0	0	0	0	0	0	0
g	0	0	0	0	0	0	0	0	1	0
h	1	0	0	0	0	0	0	0	1	0
i	0	0	0	0	0	1	0	0	0	0
j	0	1	0	0	0	0	0	0	0	0

```
g = graph_from_adjacency_matrix(adj_matrix,
mode = "undirected", weighted = T)
g
```

```
## IGRAPH 48cf731 UNW- 10 12 --
## + attr: name (v/c), weight (e/n)
## + edges from 48cf731 (vertex names):
##  [1] a--b a--c a--d a--e a--h b--d b--f b--j c--d f--i g--i h--i
```

graph_from_data_frame

```
actors <- data.frame(
        name=c("Alice", "Bob", "Cecil", "David","Esmeralda"),
        age=c(48,33,45,34,21),
        gender=c("F","M","F","M","F")
)
relations <- data.frame(
        from=c("Bob", "Cecil", "Cecil", "David","David", "Esmeralda"),
        to=c("Alice", "Bob", "Alice", "Alice", "Bob", "Alice"),
        same.dept=c(FALSE,FALSE,TRUE,FALSE,FALSE,TRUE),
        friendship=c(4,5,5,2,1,1),
        advice=c(4,5,5,4,2,3)
)
g <- graph_from_data_frame(relations, directed=TRUE, vertices=actors)
g
```




```
## IGRAPH 41a8cf9 DN-- 5 6 --
## + attr: name (v/c), age (v/n), gender (v/c), same.dept (e/l),
## | friendship (e/n), advice (e/n)
## + edges from 41a8cf9 (vertex names):
## [1] Bob      ->Alice Cecil    ->Bob   Cecil    ->Alice David    ->Alice
## [5] David    ->Bob   Esmeralda->Alice
```

Retrieve vertex and Edges from IGRAPH

- Vertex and Edges are saved as "`igraph.vs`" and "`igraph.es`" object respectively. Can be retrieved using `V(g)` and `E(g).`

```
V(g)$name
V(g)$age
V(g)$gender
```

```
# [1] "Alice" "Bob" "Cecil" "David" "Esmeralda"
# [1] 48 33 4 5 34 21
# [1] "F" "M" "F" "M" "F"
```

```
E(g)$same.dept
E(g)$friendship
```

```
# [1] FALSE FALSE TRUE FALSE FALSE TRUE
# [1] 4 5 5 2 1 1
```

Retrieve vertex and Edges from IGRAPH

```
as_data_frame(g, what = "vertices")
```

```
##                  name age gender
## Alice           Alice  48      F
## Bob               Bob  33      M
## Cecil           Cecil  45      F
## David           David  34      M
## Esmeralda Esmeralda  21      F
```

```
as_data_frame(g, what = "edges")
```

```
##         from    to same.dept friendship advice
## 1      Alice   Bob     FALSE          4      4
## 2        Bob David     FALSE          5      5
## 3      Cecil Alice      TRUE          5      5
## 4      David Alice     FALSE          2      4
## 5      David   Bob     FALSE          1      2
## 6 Esmeralda Alice      TRUE          1      3
```

Add vertex and edges to IGRAPH

```
# add vertices
g %>% add_vertices(2, name=c("Lisa","Zack")) # the first argument is
number of vertex
g + vertices(c("Lisa","Zack"))

# add connected edges (even number of vertices). The vertices
must be from known vertices already in the graph
g %>% add_edges(c("Alice","Bob"))
g + edge(c("Alice","Bob"))

# add paths. The vertices must be from known vertices already in the graph
g + path("Alice","Bob","Cecil")

# If a new vertex needs to be added to current graph, using add graph method
instead
g + make_graph(c("Alice","Bob","Bob","Melisa"))
```

Delete vertex and edges from IGRAPH

```
### remove the vertices whose age is younger than 30
vertex_df = g %>% as_data_frame(what="vertices") %>% tbl_df %>%
mutate(index=row_number()) %>% filter(age < 30)
# remove vertices by index number
g %>% delete_vertices(vertex_df$index)
# remove vertice by name
g %>% delete_vertices(vertex_df$name)
```

```
### remove the edges with friendship <= 1
edge_df = g %>% as_data_frame(what="edges") %>% tbl_df %>%
mutate(index=row_number()) %>% mutate(name=paste(from,to,sep="|"))
%>% filter(friendship <= 1)
# remove vertice by index
g %>% delete_edges(edge_df$index)
# remove vertice by name
g %>% delete_edges(edge_df$name)
```

Add and delete vertex and edge attributes to IGRAPH

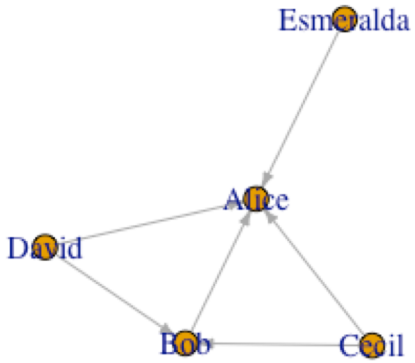
- Add/change new edge attributes using `set_edge_attr()`.
- Add/change new vertice attributes using `set_vertex_attr()`
- Delete edge attributes using `delete_edge_attr(g, attr_name)`.
- Delete vertice attributes using `delete_vertice_attr (g,attr_name,index,attr_value)`

```
# add a new attr "relationship" for people
in the same dept
edge_df = g %>%
as_data_frame(what="edges") %>%
mutate(
       relationship=ifelse(same.dept,"colle
gue",NA)
)
g %>%
   set_edge_attr(
       "relationship",
       which(!is.na(edge_df$relationship)),
       edge_df$relationship[!is.na(edge_df$
relationship)]
   )
```

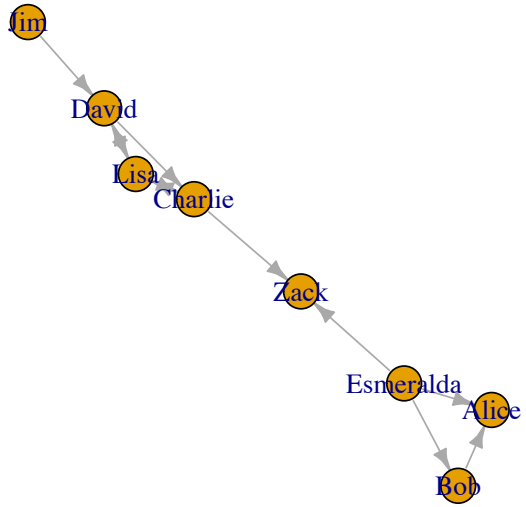
Merge Graph

```
#### create new graph g2
g2 = graph_from_literal(
       "David"-+"Charlie"+-+"Lisa",
       "Lisa"+-+"David"+-"Jim",
       "Zack"+-"Esmeralda"-+"Bob",
       "Zack"+-"Charlie",
       "Lisa"+-"Lisa",
       "Bob"-+"Alice"+-"Esmeralda"
)
#### union graph
g3 = igraph::union(g,g2)
#### graph intersection
g4 = igraph::intersection(g,g2)
```

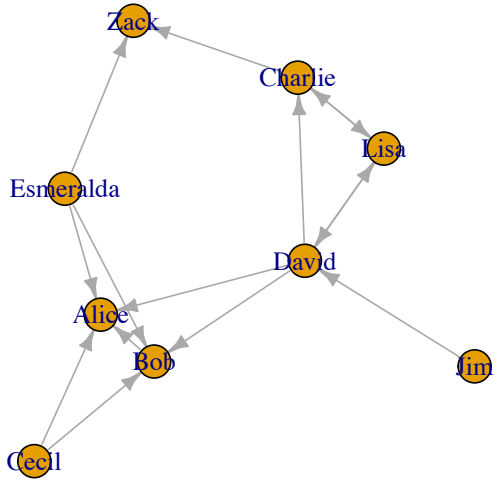
g



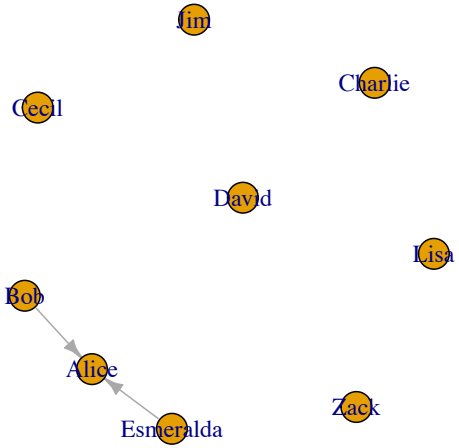
g2



g:g2 union



g:g2 intersect



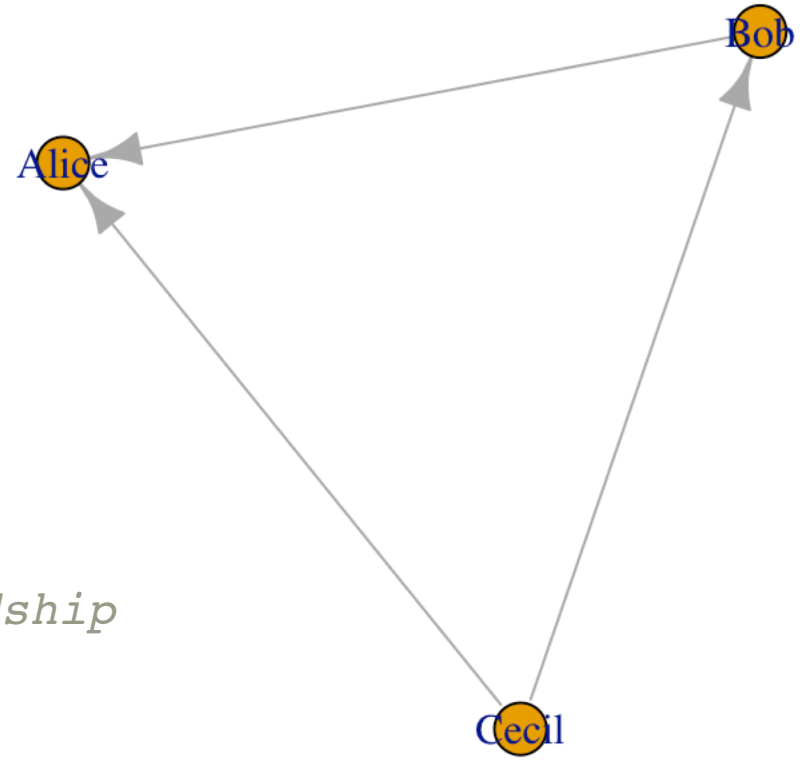
Subgraph

- Subgraph can be induced by vertice and edge names or igraph.es

```
# induce a subgraph using a list of vertice names
induced_subgraph(g, v=c("Alice","Bob","Cecil"))


# induce a subgraph using edges
subgraph.edges(g,
c("Bob|Alice","Cecil|Bob","Cecil|Alice"),
delete.vertices = TRUE)


# induce a subgraph using edges attribute (friendship
score stronger than 3)
e1 = E(g)[E(g)$friendship > 3]
subgraph.edges(g, e1, delete.vertices = TRUE)
```



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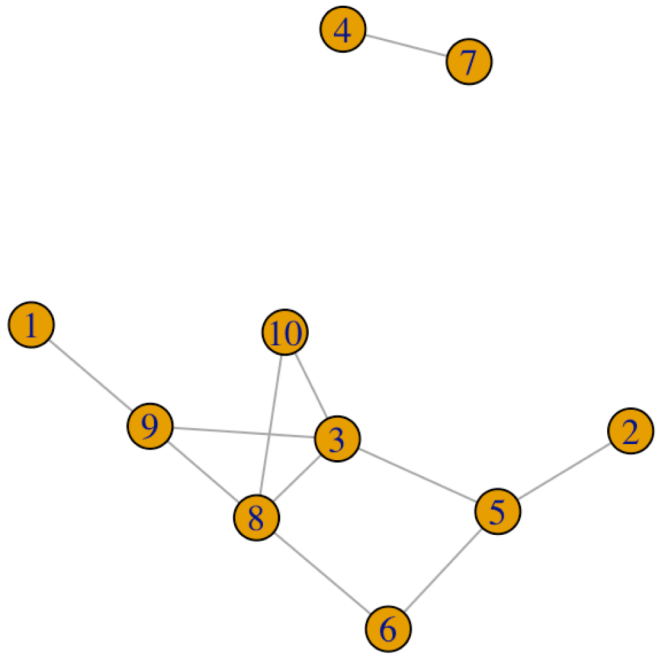
Graph measurement – degree and strength

```
# generate random graph
set.seed(12)
gr <- sample_gnp(10, 0.3)
plot(gr)
```



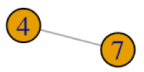
- **Degree**: the number of adjacent vertex.

```
# get degree for each node
degree(gr, v=1:10))
# [1] 1 1 4 1 3 2 1 4 3 2

# probability for degree
degree_distribution(g)
# [1] 0.0 0.4 0.2 0.2 0.2
```

- **Strength:** is weighted version of degree, by summing up the edge weights of the adjacent edges for each vertex

```
# add random weight attribute
set.seed(12)
gr = gr %>% set_edge_attr(
  "weight",index=E(gr),
  value=sample(seq(0,1,0.05),size=length(E(gr)))
)
# calculate strength
strength(gr, weights = E(gr)$weight)
# [1] 0.95 0.05 1.90 0.20 1.70 0.85 0.20 1.75 2.10 1.50
```

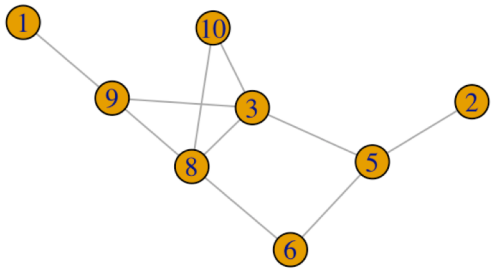
Graph measurement – distance and path



- **Order/Distances** : how far away from one vertex to another.

```
# count all edges from 1 to 10, regardless
of direction
distances(gr, v=1, to=10, mode="all",
weights = NA)
#      [,1]
# [1,]    3
# pairwise distance table
distances(gr, mode="all")
```

	[,1]	[,2]	[,3]	[,4]	[,5]	[,6]	[,7]	[,8]	[,9]	[,10]
[1,]	0	4	2	Inf	3	3	Inf	2	1	3
[2,]	4	0	2	Inf	1	2	Inf	3	3	3
[3,]	2	2	0	Inf	1	2	Inf	1	1	1
[4,]	Inf	Inf	Inf	0	Inf	Inf	1	Inf	Inf	Inf
[5,]	3	1	1	Inf	0	1	Inf	2	2	2
[6,]	3	2	2	Inf	1	0	Inf	1	2	2
[7,]	Inf	Inf	Inf	1	Inf	Inf	0	Inf	Inf	Inf
[8,]	2	3	1	Inf	2	1	Inf	0	1	1
[9,]	1	3	1	Inf	2	2	Inf	1	0	2
[10,]	3	3	1	Inf	2	2	Inf	1	2	0



Path: a route between any two vertices

```
# shortest path to connect
all_shortest_paths(gr, 1,10)$res
# $res[[1]]
# + 4/10 vertices, from 82b58b9:
# [1]  1  9  8 10
# $res[[2]]
# + 4/10 vertices, from 82b58b9:
# [1]  1  9  3 10
```

Both return a list of igraph.vs

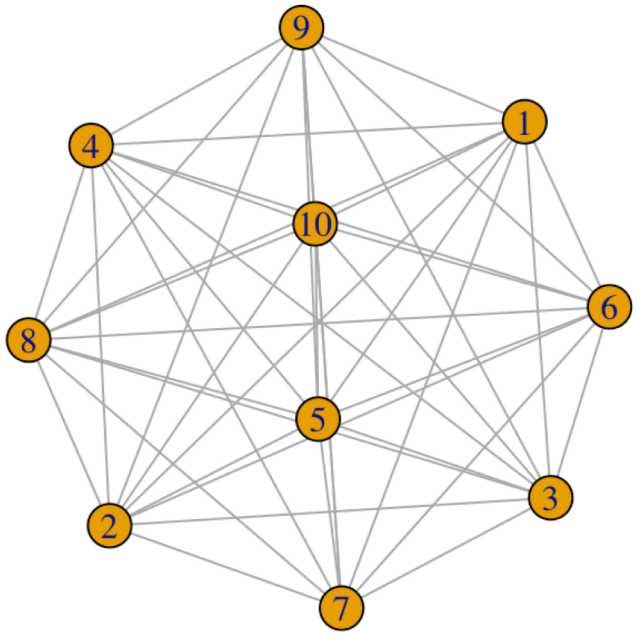
```
# all path to connect
 all_simple_paths(gr, 1,10)
```

Graph measurement – transitivity

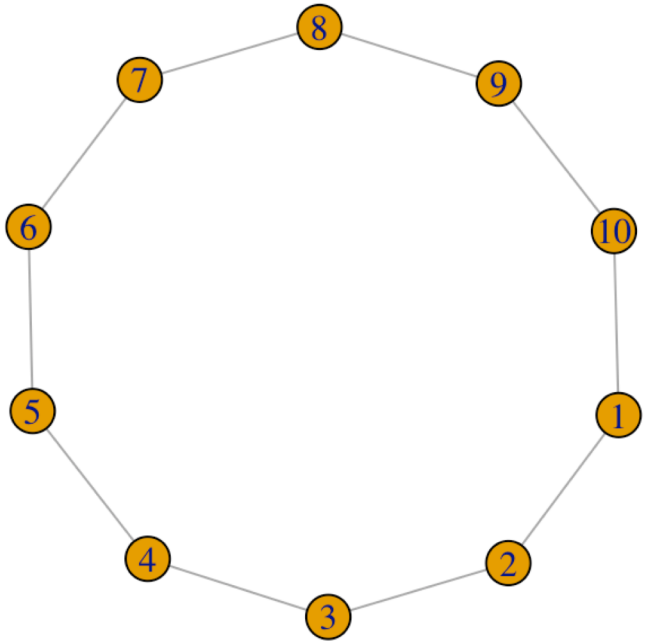
- **Transitivity** measures the probability that the adjacent vertices of a vertex are connected. also called the **clustering coefficient**

```
# two extreme classes -- full graph and
ring graph
g1 = make_full_graph(10)
transitivity(g1)
## [1] 1

g2 = make_ring(10)
transitivity(g2)
## [1] 0
```

A property very important in social networks, and to a lesser degree in other networks



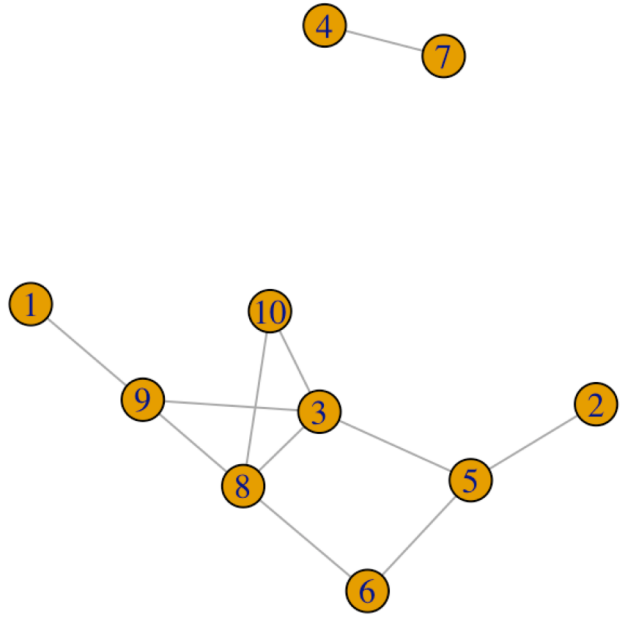
g1



g2

Graph measurement -- centrality

- **Centrality:** measures the importance of a node in a network.
- However, this “importance” can be conceived in two ways:
  - in relation to a type of flow or transfer across the network.
  - involvement in the cohesiveness of the network



- degree centrality (`centr_degree`)
- closeness centrality (`centr_clo`)
- betweenness centrality (`centr_betw`)
- eigenvector centrality (`centr_eigen`)
- …..

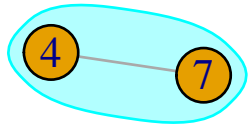
```
centr_betw(gr, directed = FALSE)
## $res
## [1] 0.0 0.0 8.0 0.0 6.5 1.0 0.0 4.5 6.0 0.0

## $centralization
## [1] 0.1666667

## $theoretical_max
## [1] 324
```

Decompose graph to components

- A ***component*** is a subgraph in which all nodes are inter-connected.

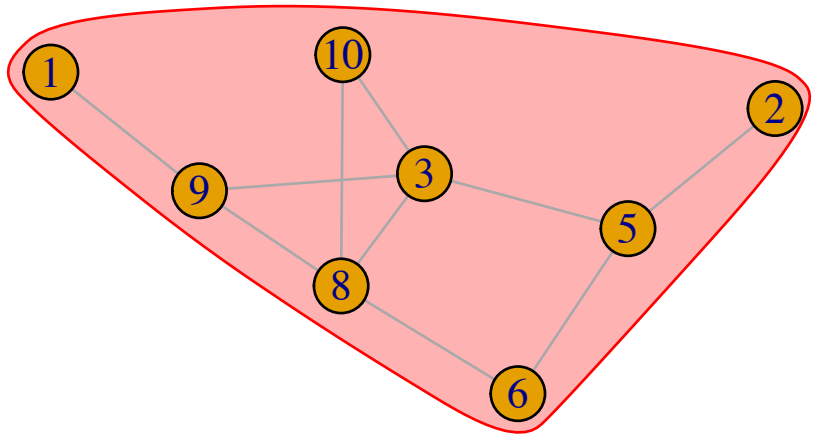
```
# decompose graph to connected components
dg <- decompose.graph(gr)
dg
```

```
## [[1]]
## IGRAPH ec2223e U--- 8 10 -- Erdos renyi (gnp) graph
## + attr: name (g/c), type (g/c), loops (g/l), p (g/n)
## + edges from ec2223e:
##  [1] 2--4 3--4 4--5 3--6 5--6 1--7 3--7 6--7 3--8 6--8
##
## [[2]]
## IGRAPH bef9e40 U--- 2 1 -- Erdos renyi (gnp) graph
## + attr: name (g/c), type (g/c), loops (g/l), p (g/n)
## + edge from bef9e40:
## [1] 1--2
```




```
#summarize components
components(gr)
```

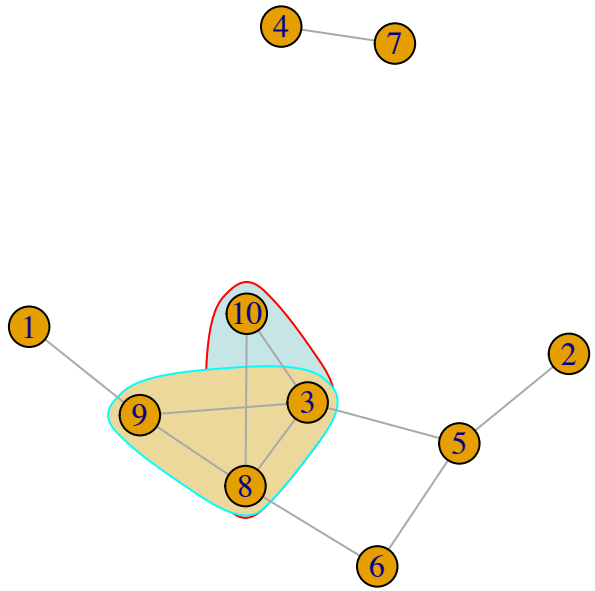
```
## $membership
##  [1] 1 1 1 2 1 1 2 1 1 1
##
## $csize
## [1] 8 2
##
## $no
## [1] 2
```



Graph cluster -- cliques

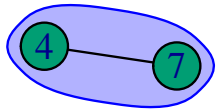
- **Clique**: fully connected subgraph in which the every vertex connects with every other vertex.

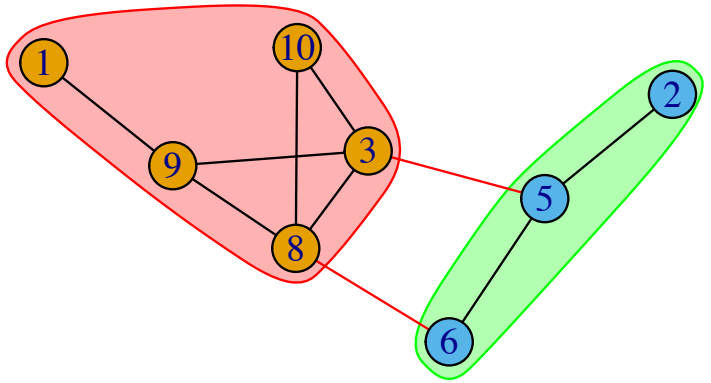
```
# extract cliques that contain more than 3
vertices
cliques(g, min=3)


# get cliques with largest number of vertices
largest_cliques(g)
```



Graph cluster – community/module

- **Communities**: defined if the nodes of the network can be easily grouped into (potentially overlapping) sets of nodes such that each set of nodes is densely connected internally
- **Modularity:** measure the strength of division of a network into community, used in optimization methods for detecting community structure in networks





https://en.wikipedia.org/wiki/Modularity_(networks)#Modularity

Cluster graph – community/module (cont.)

- There are many ways to cluster graph to communities. The functions in igraph packages include
  - `cluster_edge_betweenness` - a hierarchical decomposition process where edges are removed in the decreasing order of their edge betweenness scores
  - `cluster_optimal` - a top-down hierarchical approach that optimizes the modularity function
  - `cluster_walktrap` - an approach based on random walks
  - `cluster_fast_greedy`
  - `cluster_label_prop`
  - `cluster_leading_eigen`
  - `cluster_Louvain`
  - `cluster_spinglass`

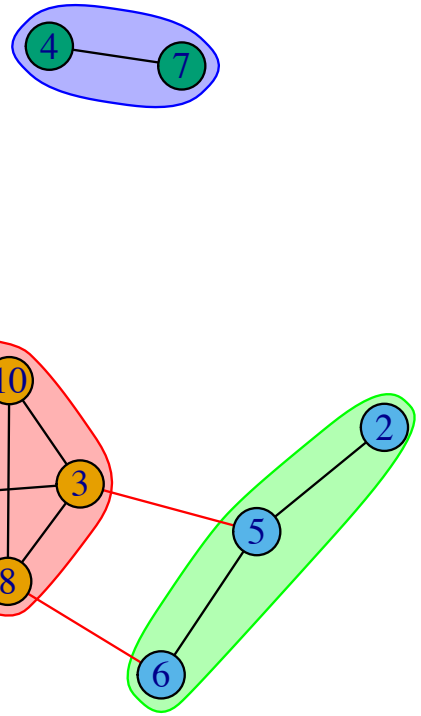
https://stackoverflow.com/questions/9471906/what-are-the-differences-between-community-detection-algorithms-in-igraph

https://en.wikipedia.org/wiki/Community_structure

Cluster graph – community/module (cont.)

```
# cluster graph using walktrap method, turn a "communities" object
wtc <- cluster_walktrap(gr)
wtc
```

```
   IGRAPH clustering walktrap, groups: 3, mod: 0.33
   + groups:
     $`1`
     [1]  1  3  8  9 10

     $`2`
     [1] 2 5 6

     $`3`
     [1] 4 7
```




```
# find membership for each vertice
membership(wtc)
## [1] 1 2 1 3 2 2 3 1 1 1
# calculate modularity for walktrap clustering on this graph
modularity(wtc)
## [1] 0.3305785
```

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- Group Exercise– NYC flight

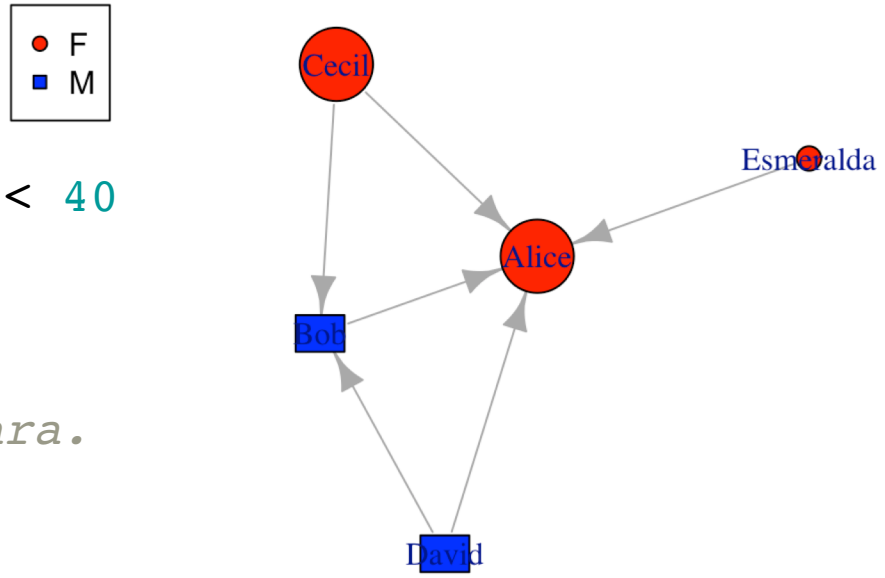
Aesthetics of network elements

- The aesthetics of both vertices and edges can be manipulated at color, transparency.
- Specially for vertices, we can also manipulate its shape, size and fill.
- For edges, we can manipulate its width/thickness, linetype, arrow and so on.

```
actors <- data.frame(
       name=c("Alice", "Bob", "Cecil", "David","Esmeralda"),
       age=c(48,33,45,34,21),
       gender=c("F","M","F","M","F")
)
relations <- data.frame(
       from=c("Bob", "Cecil", "Cecil", "David","David", "Esmeralda"),
       to=c("Alice", "Bob", "Alice", "Alice", "Bob", "Alice"),
       same.dept=c(FALSE,FALSE,TRUE,FALSE,FALSE,TRUE),
       friendship=c(4,5,5,2,1,1),
       advice=c(4,5,5,4,2,3)
)
g <- graph_from_data_frame(relations, directed=TRUE, vertices=actors)
```

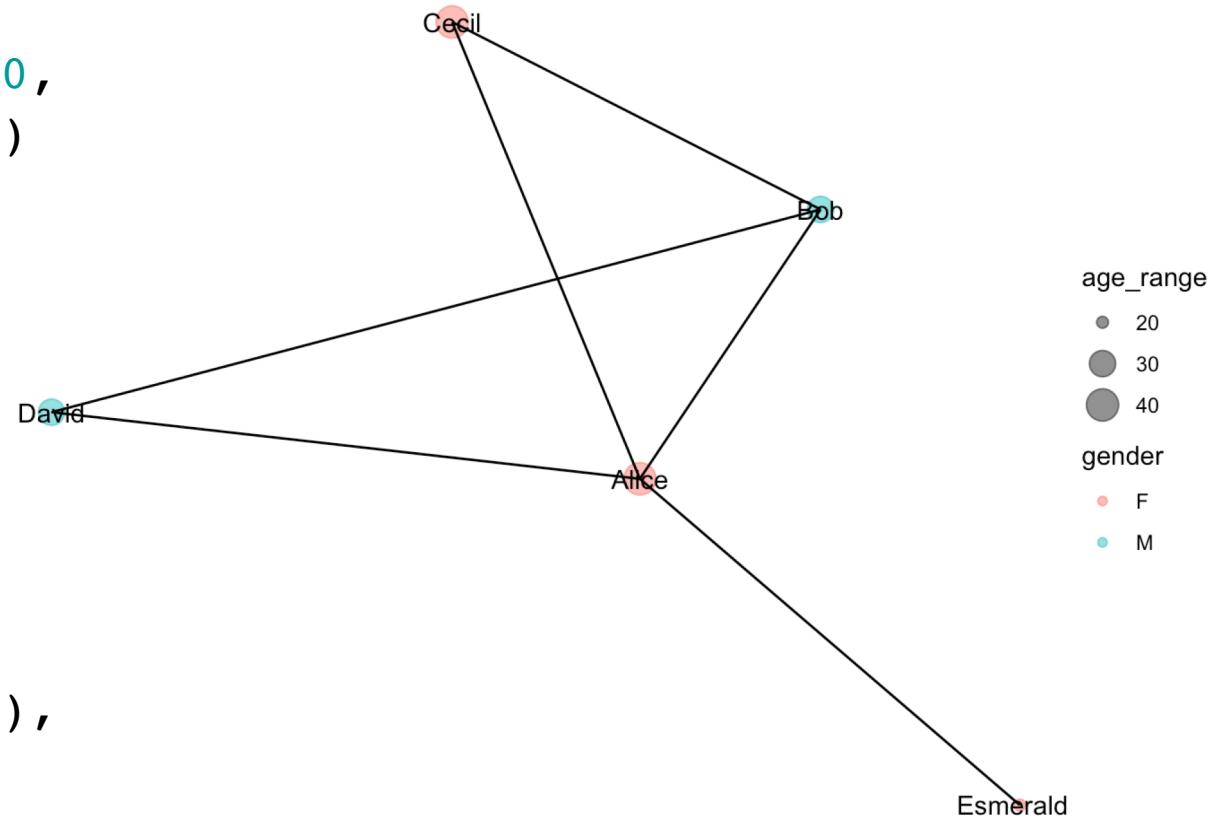
Vertice aesthetics – default igraph.plot

```
# make female and male color different
v = as_data_frame(g, what="vertice") %>% tbl_df %>%
mutate(color=case_when(gender=="F" ~ "red", gender=="M"
~ "blue"))
g = g %>% set_vertex_attr("color", value=v$color)

# make age as size
v = v %>% mutate(size=case_when(age < 30 ~ 10, age < 40
& age >30 ~ 20, age > 40 ~ 30))
g = g %>% set_vertex_attr("size", value=v$size)

# make gender as shape and put into vertex.shape para.
In plot
v = v %>%
mutate(shape=case_when(gender=="F" ~ "circle",
gender=="M" ~ "rectangle"))

# plot
plot(g, vertex.shape=v$shape)
legend('topleft',legend=unique(v$gender),pch=c(21,
22),pt.bg=c("red","blue"))
```



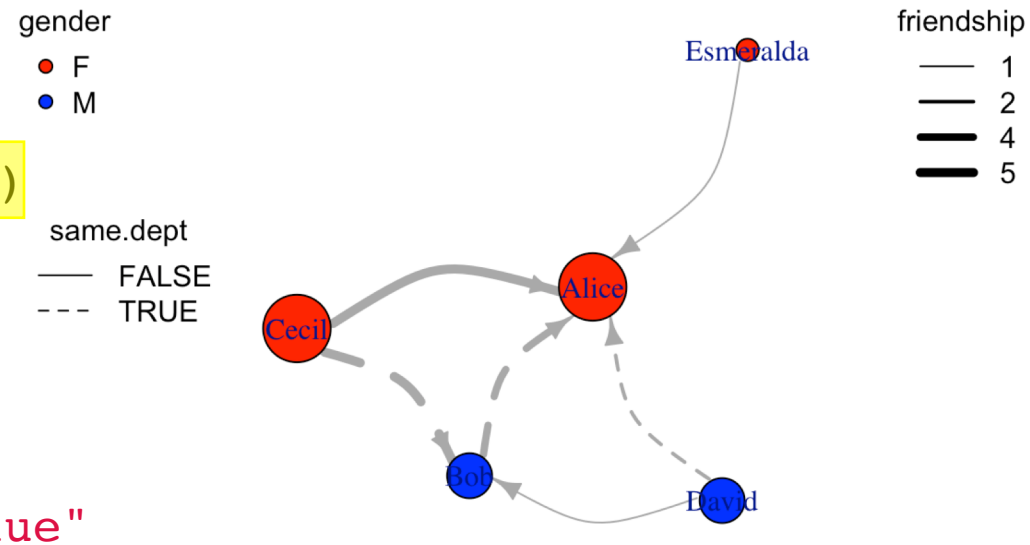
Vertice aesthetics – ggraph

```
# add age_range attr
v = v %>%
mutate(age_range=case_when(age < 30 ~ 20,
age < 40 & age >30 ~ 30, age > 40 ~ 40))
g = g %>% set_vertex_attr("age_range",
value=v$age_range)

# plot in ggraph
ggraph(g, layout = "kk") +
geom_node_point(aes(size=age_range,
color=gender), alpha=0.5) +
geom_node_text(aes(label=name)) +
geom_edge_link() +
scale_size_continuous(breaks=c(20,30,40),
range = c(2, 6)) + theme_void()
```



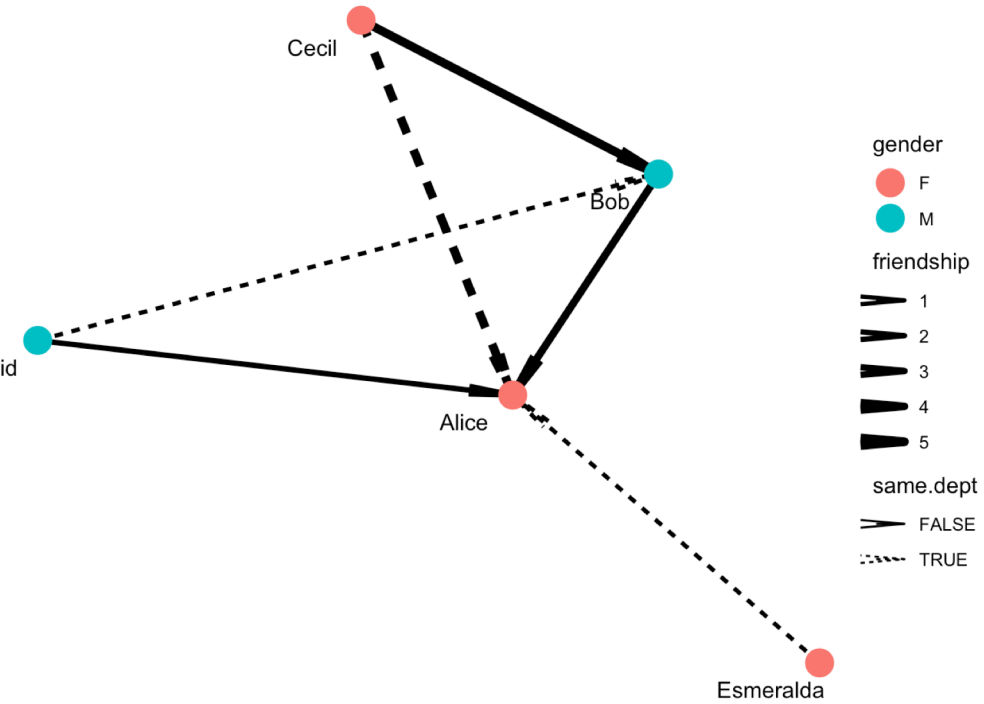
Edge aesthetics -- default igraph.plot

```
# use linetype present whether come from same
department, and line width presents friendship
e = as_data_frame(g, what="edges") %>% tbl_df %>%
mutate(width=friendship) %>%
mutate(lty=ifelse(same.dept,1,2))
# plot
plot(
       g %>% set_edge_attr("width",value=e$width)
%>% set_edge_attr("lty",value=e$lty),
       edge.arrow.size=0.8, edge.curved=T
 )
# legend
legend("topleft",
legend=unique(v$gender),pch=21,pt.bg=c("red","blue"
), title="gender", box.lty=0)
legend("left",legend=unique(e$same.dept),lty=c(1,2)
, title = "same.dept",box.lty=0) legend("topright",
legend=sort(unique(e$friendship)),
lwd=sort(unique(e$friendship)), title="friendship",
box.lty=0)
```



Edge aesthetics -- ggraph

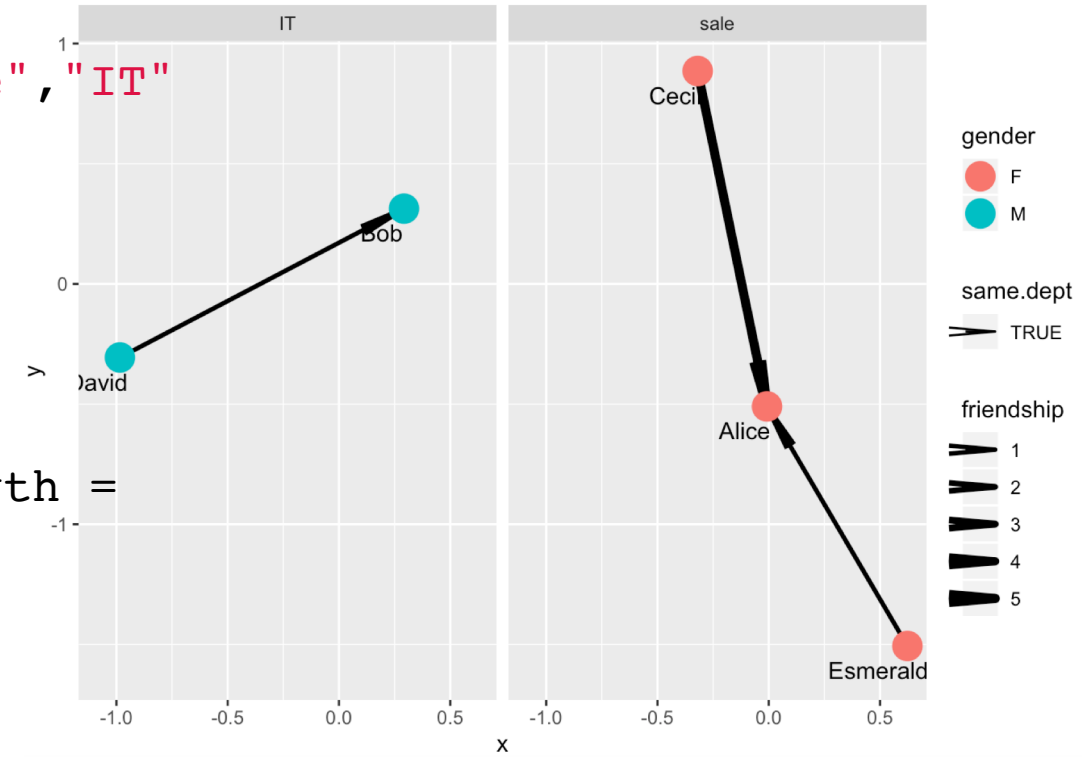
```
ggraph(g, layout="kk") +
geom_edge_link(
        aes(edge_width=friendship,
        edge_linetype=same.dept),
        arrow = arrow(angle=5, length =
unit(0.3, "inches"))
) +
geom_node_point(aes(color=gender), size=6) +
geom_node_text(aes(label=name), nudge_y = -
0.1, nudge_x = -0.1) + scale_edge_width(range
= c(1, 2)) +
theme_void()
```



Facet

- Facet in ggraph can be `facet_edges, facet_nodes` or `facet_graph`.
- The first two are similar to `facet_wrap` while `facet_graphs` is comparable to `facet_grid` in ggplot

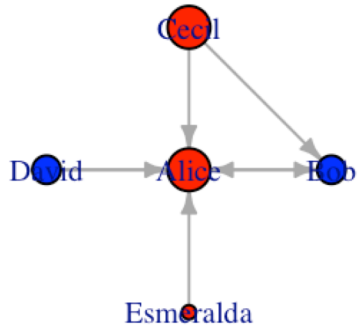
```
# add dept to graph
g = g %>%
set_vertex_attr("dept",value=c("sale","IT","sale","IT"
,"sale")) %>%
set_edge_attr("same.dept",value=c(F,F,T,F,T,T))
# facet based on the dept
ggraph(g, layout="kk") +
facet_nodes(~dept, drop = F) +
geom_edge_link(aes(edge_width=friendship,
linetype=same.dept), arrow = arrow(angle=5, length =
unit(0.3, "inches"))) +
geom_node_point(aes(color=gender), size=6) +
geom_node_text(aes(label=name), nudge_y = -0.1,
nudge_x = -0.1) +
scale_edge_width(range = c(1, 2))
```



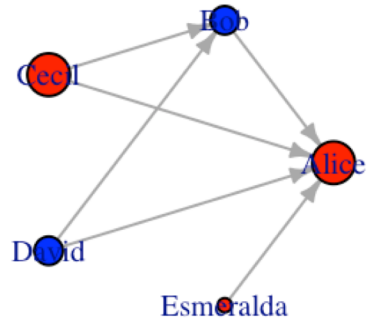
Network layout

- Network visualization layout depends on the coordinates of node at canvas. There are many internal-programed layout in both igraph and ggraph
  - **Standard layouts**
    - **star**: place one node in the center and the rest equidistantly around it. as_star()
    - **circle**: place nodes in a circle in the order of their index. in_circle()
    - **nicely**: default, tries to pick an appropriate layout. nicely
    - **sphere**: place nodes uniformly on a sphere - less relevant for 2D visualizations of networks. with_sphere()
    - **fr**: places nodes according to the force-directed algorithm of Fruchterman and Reingold. with_fr()
    - **kk**: uses the spring-based algorithm by Kamada and Kawai to place nodes. with_kk()
    - …… https://igraph.org/r/doc/layout_.html ….
  - **Hierarchical layouts**
    - **tree**: parent with the parent centered above its children. as_tree()
    - **sugiyama**: user-defined layers

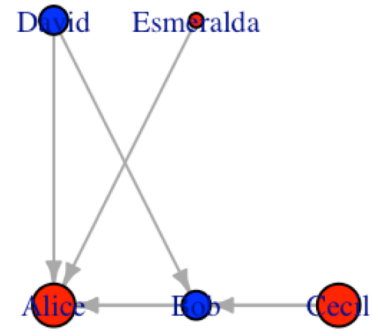
start



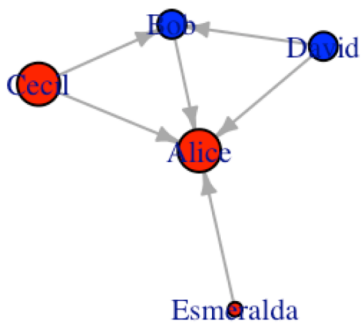
circle



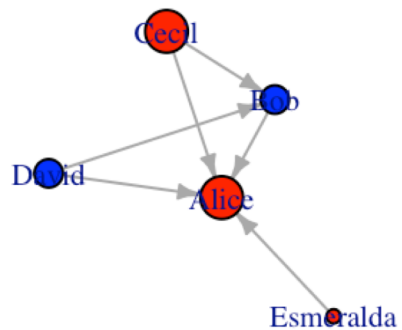
grid



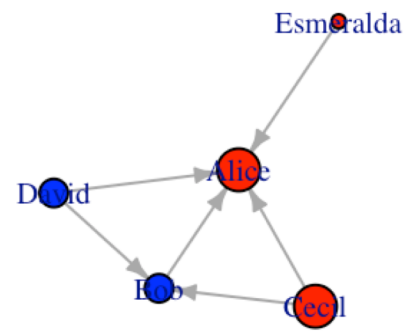
nicely



Kamada and Kawai(kk)

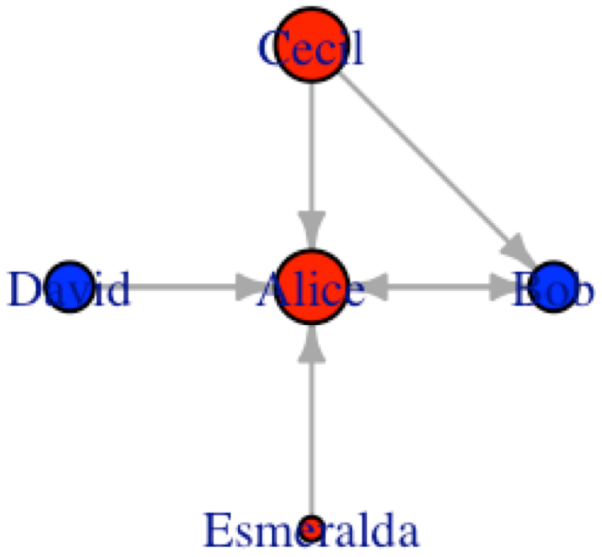


force-directed(fr)



Specify layout in plot

```
# star layout in igraph default plot
coords <- layout_(g, as_star())
plot(g, layout = coords,
edge.arrow.size=0.4)
title("star")
```

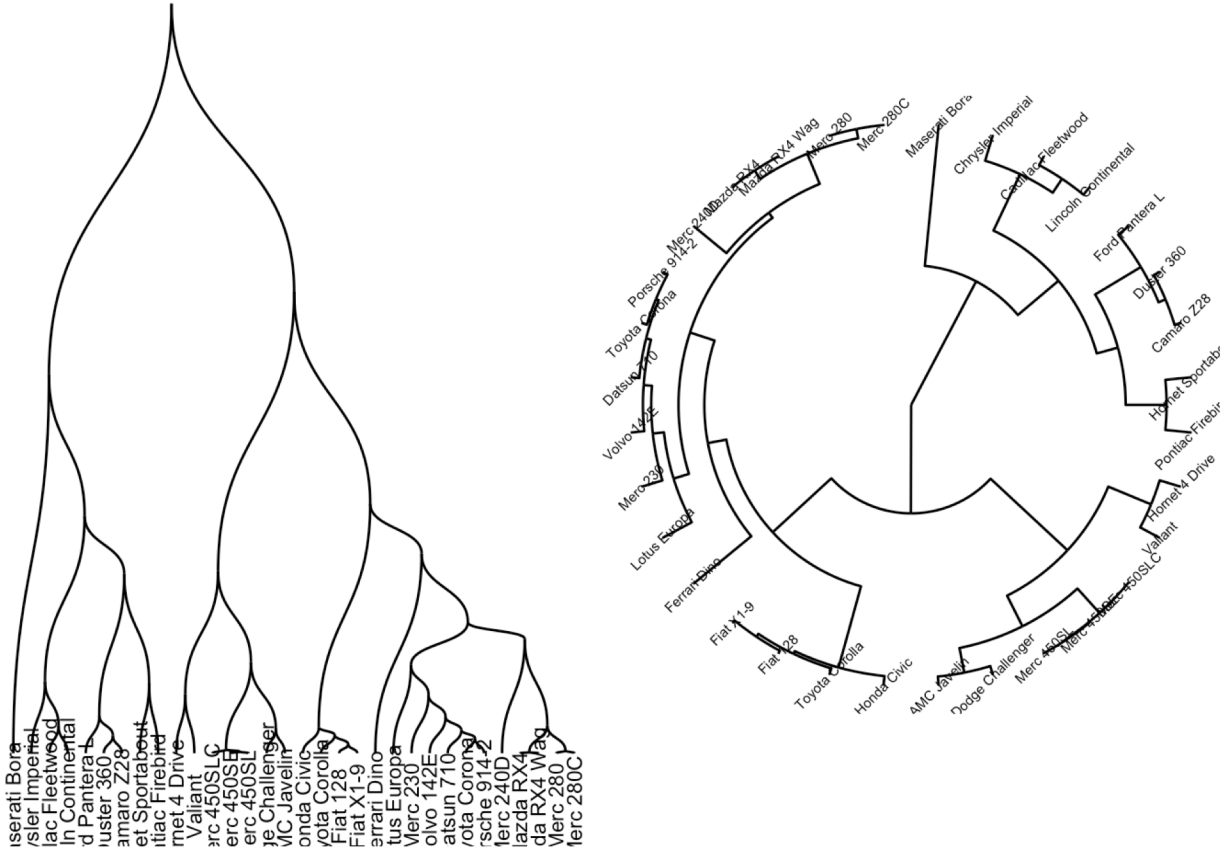



```
# star layout in ggraph
ggraph(g, layout="star") +
geom_edge_link(aes(edge_width=friendship,
edge_linetype=same.dept), arrow =
arrow(angle=5, length = unit(0.3,
"inches"))) +
geom_node_point(aes(color=gender), size=6)
+ geom_node_text(aes(label=name), nudge_y =
-0.1, nudge_x = -0.1) +
scale_edge_width(range = c(1, 2)) +
theme_void()
```

Extra layout in ggraph

- Dendrogram: dendrogram layout not only take in graph object but also dendrogram object.

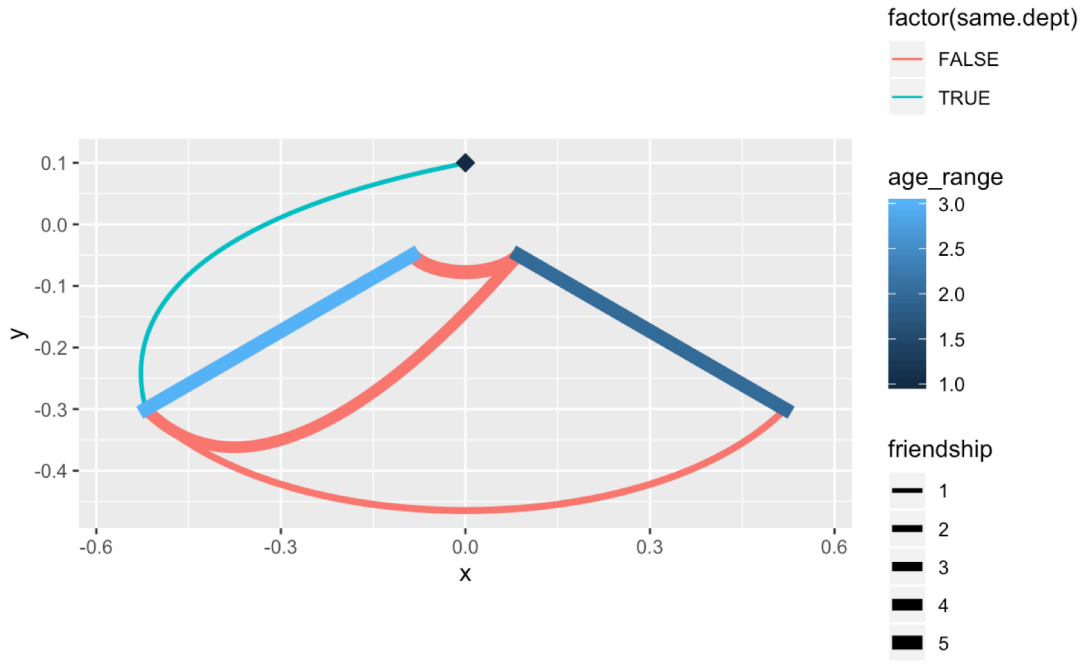
```
den <- as.dendrogram(hclust(dist(mtcars)))
p1 = ggraph(den, 'dendrogram') +
geom_edge_diagonal() +
geom_node_text(aes(label=label), angle=90,
nudge_y=-30, size=3) +
theme_void()

p2 = ggraph(den, 'dendrogram', circular =
TRUE) + geom_edge_elbow() +
geom_node_text(aes(label=label), angle=45,
size=2) + coord_fixed()+
theme_void()

grid.arrange(p1,p2,ncol=2)
```



Extra layout in ggraph

- Hive: make nodes group into a axis and connecting axis instead.

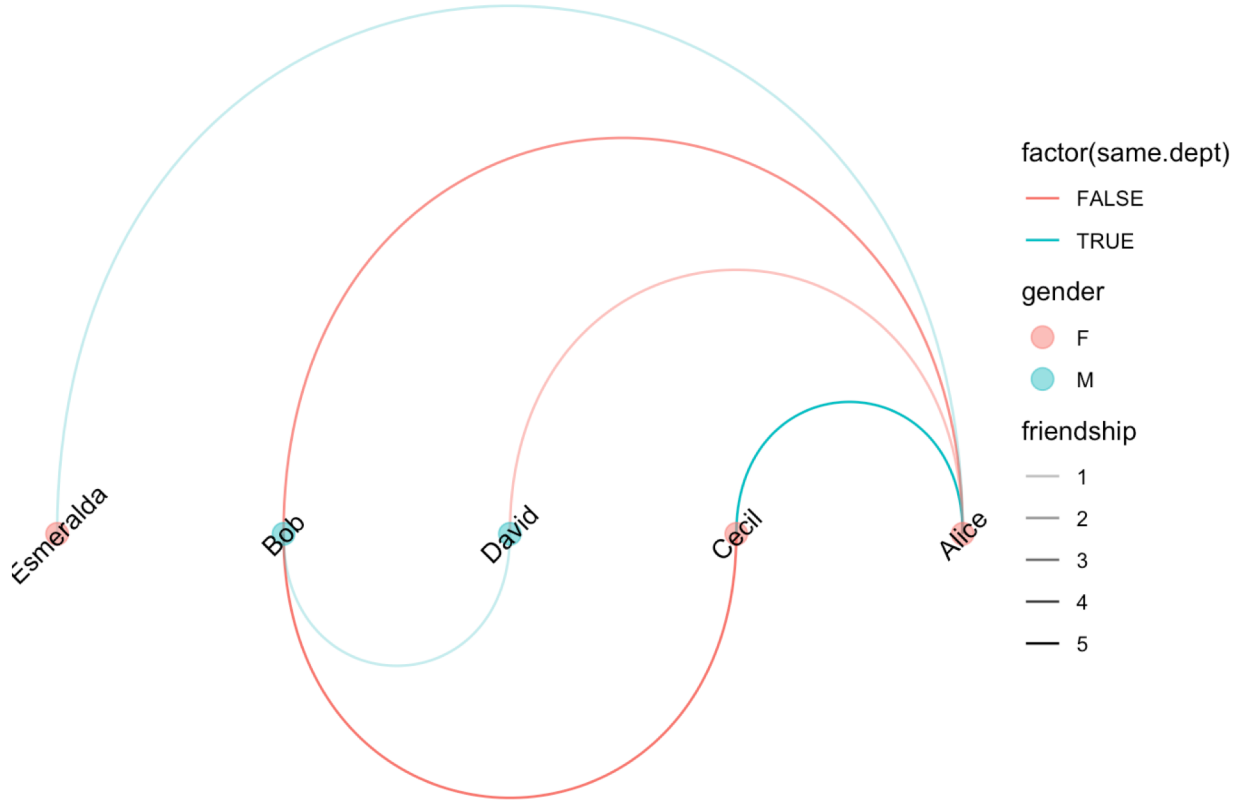
```
# group age_range into axis
V(g)$age_range = factor(V(g)$age_range)

ggraph(g, 'hive', axis = 'age_range',
sort.by = 'age') +
geom_edge_hive(aes(color =
factor(same.dept), edge_width=friendship)) +
geom_axis_hive(aes(color = age_range), size
= 3, label = FALSE) +
coord_fixed() +
scale_edge_width(range=c(1,3))
```



Extra layout in ggraph

- Linear: all nodes at same line

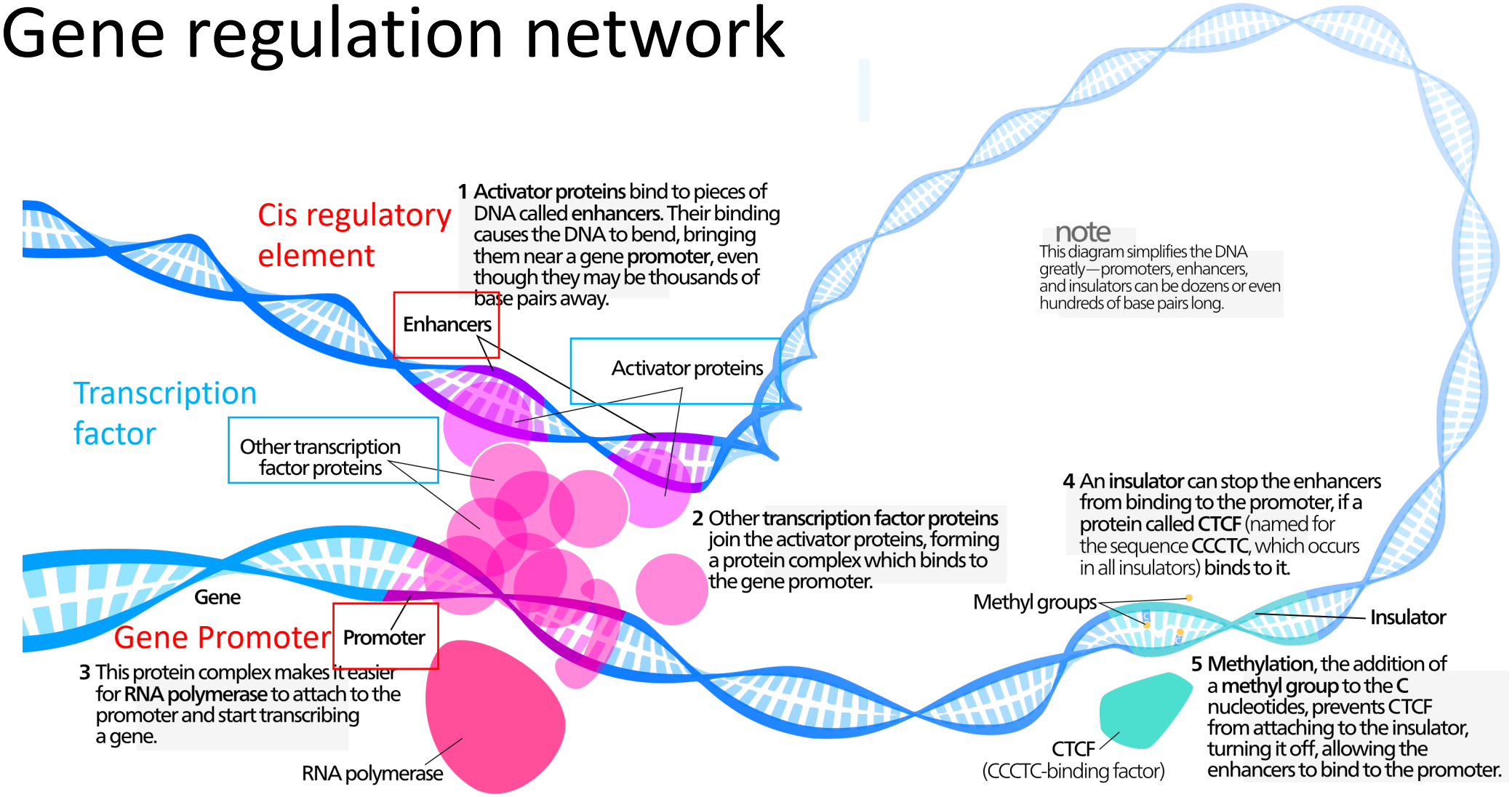
```
ggraph(g, layout = 'linear',
sort.by = 'age') +
geom_edge_arc(aes(color =
factor(same.dept),
edge_alpha=friendship)) +
geom_node_point(aes(color=gender),
size=4, alpha=0.5) +
geom_node_text(aes(label=name),
angle=45) +
theme_void() +
scale_edge_alpha(range=c(0.3,1))
```



Agenda

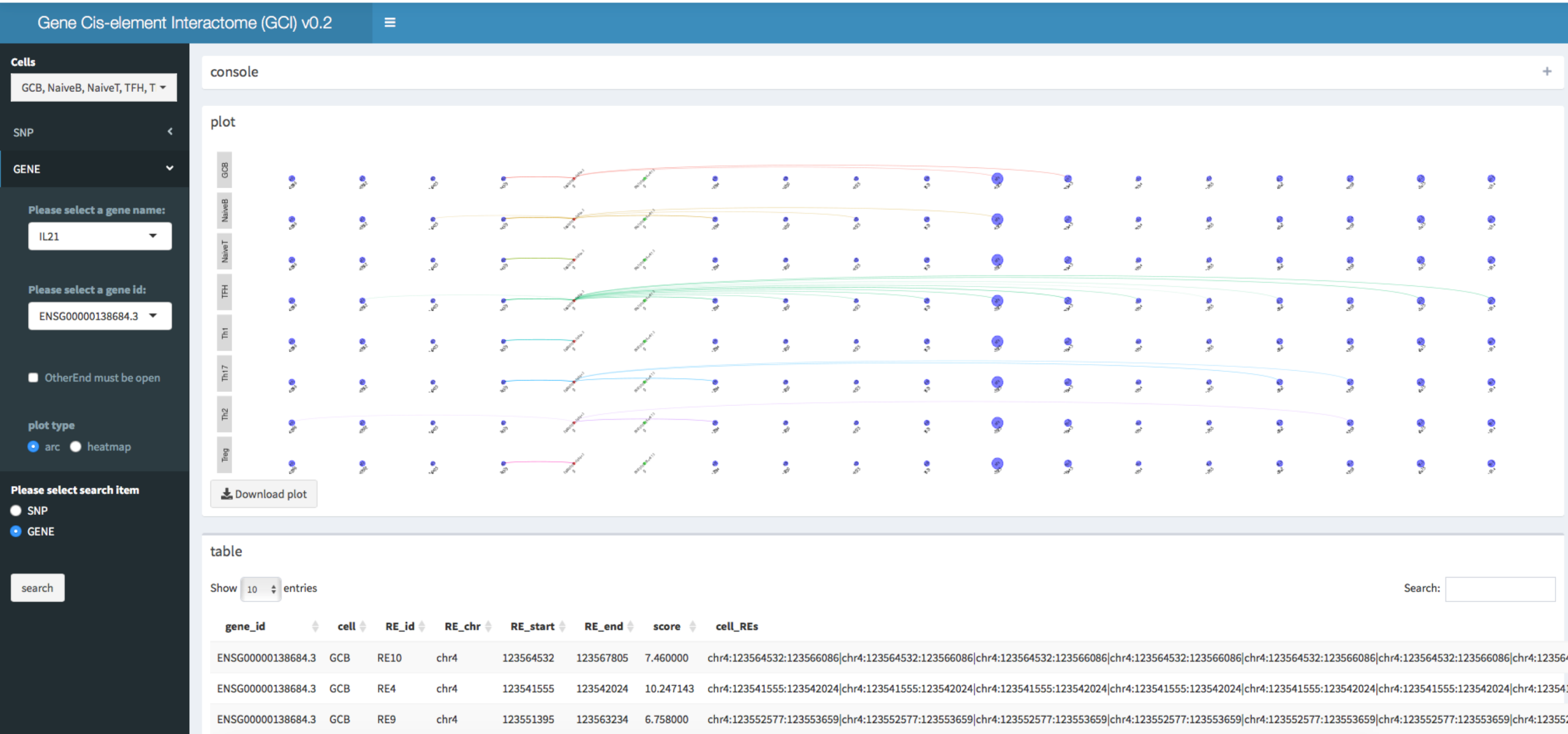
- Network analysis basics
  - R object IGRAPH ”I/O”
  - object IGRAPH manipulation
- Graph advance
  - Graph measurement
  - Graph cluster
- Network visualization
  - Aesthetics of network elements
  - Network layout
- Network application show case in Biology
- Group Exercise – world flight

Gene regulation network



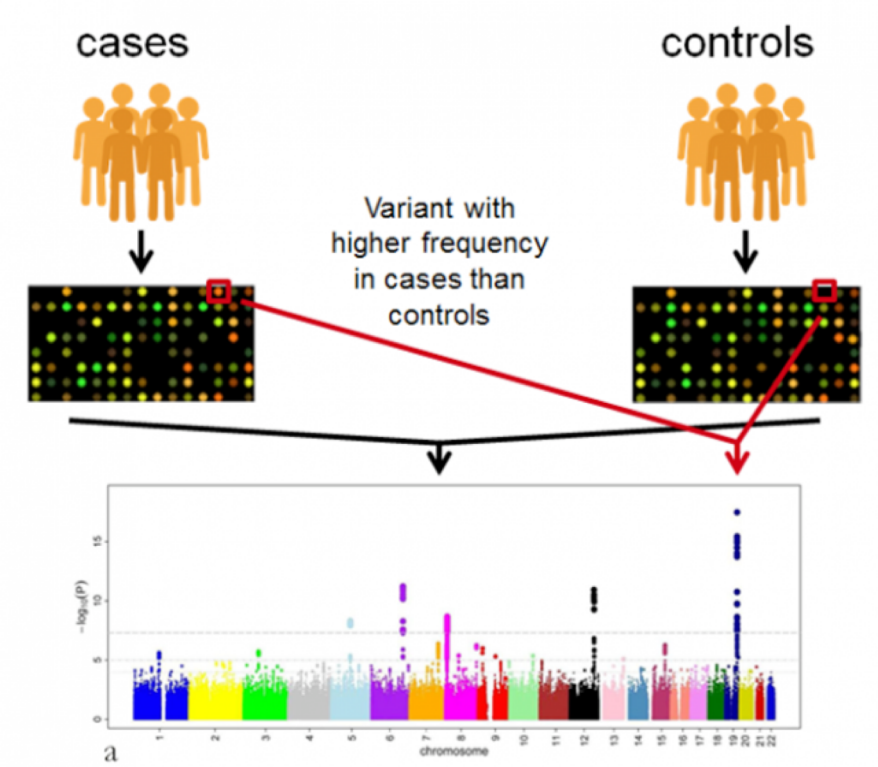
https://upload.wikimedia.org/wikipedia/commons/8/80/Transcription_Factors.svg

Gene promoter-cis regulatory element interactions are cell-specific

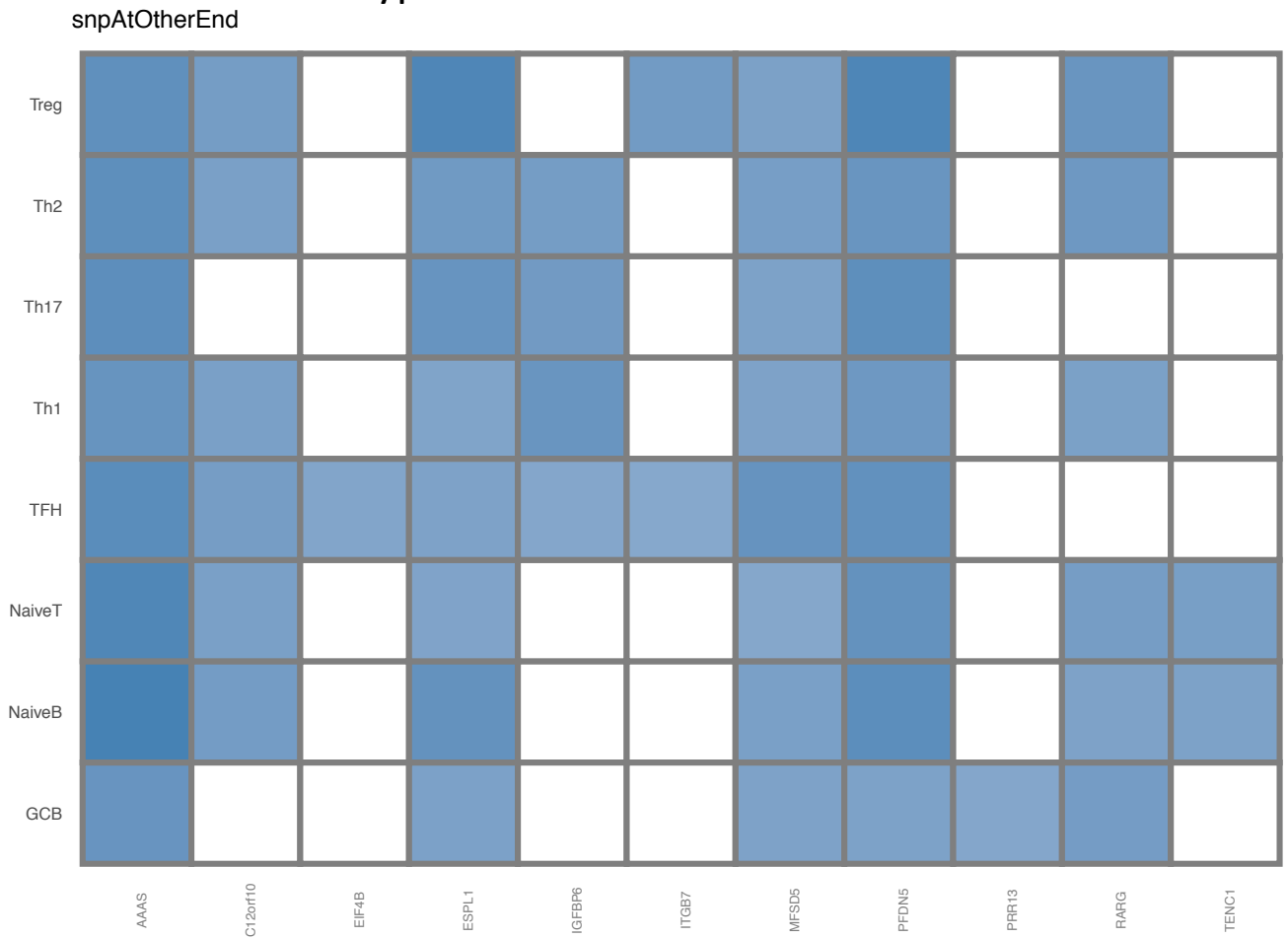


Gene promoter-cis regulatory element interactions predict target genes for disease-associated variants in cell-specific content

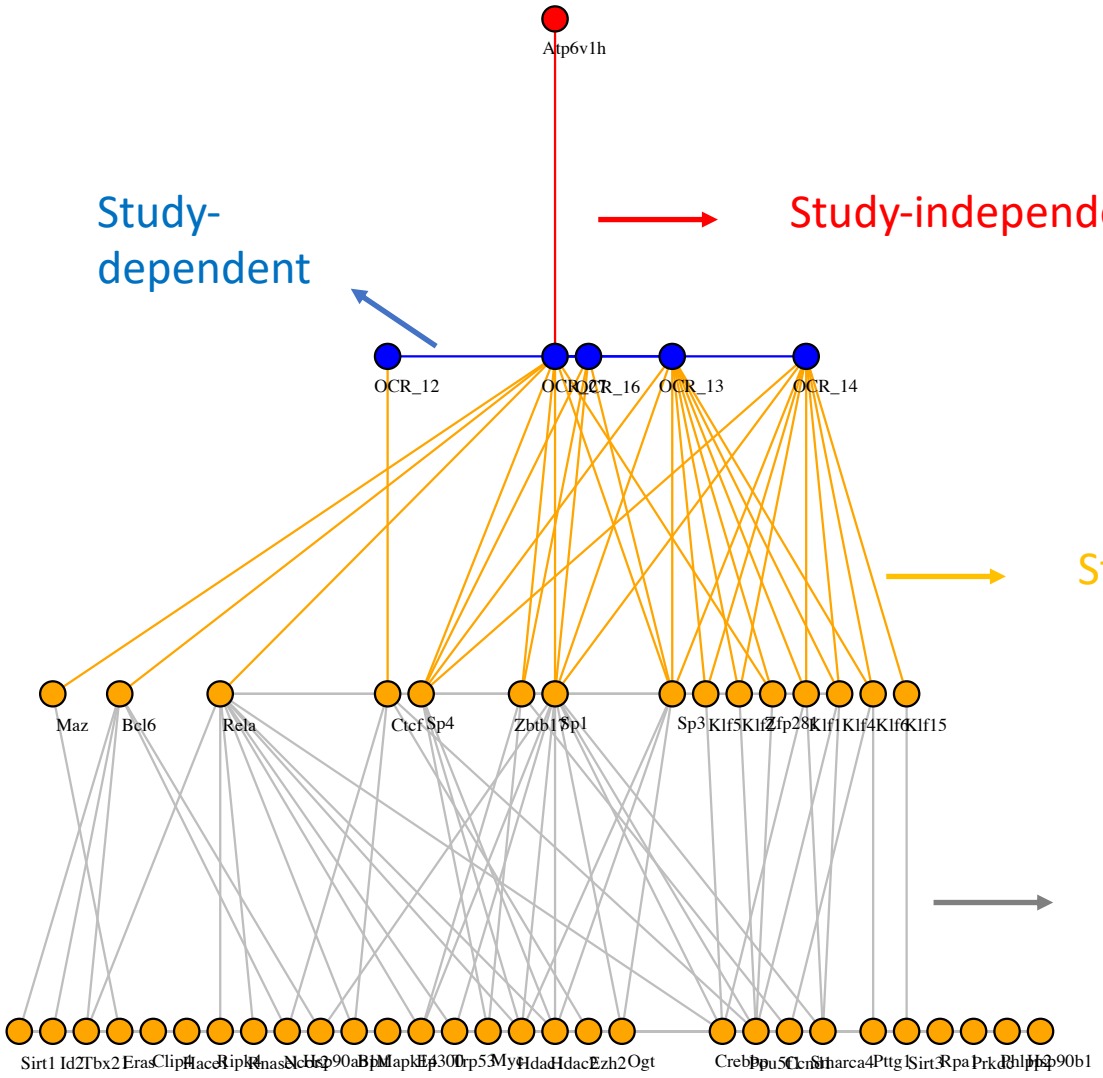
Genome-wide association study (GWAS)



Type 1 Diabetes variant rs11170466



Gene regulation network with transcriptional factors



Layer 1: gene being regulated

Study-dependent

Study-independent

Layer 2: cis-element involved in gene regulation

Study-independent

Layer 3: TF directly binds to cis-element

Study-independent

Layer 4: Scaffold proteins that link TFs to bridge two cis elements

Other network packages

- Network analysis tool:
  - Statnet: https://statnet.org/trac/wiki
- Network visualization:
  - ggnet: https://briatte.github.io/ggnet/
- Interactive network :
  - visNetwork: https://datastorm-open.github.io/visNetwork/
  - jstree: https://bwlewis.github.io/rthreejs/
  - Ndtv: http://statnet.csde.washington.edu/workshops/SUNBELT/current/ndtv/ndtv_workshop.html

Exercise : world flight

- # Exercise 1
- How many different ways with least stops to travel from Philadelphia in US `(city=="Philadelphia", country=="United States")` to Beijing in China `(city=="Beijing", country=="China")`?

- # Exercise 2
- Plot all the possible ways with least stops from Philadelphia to Beijing. Label 1) airports from different countries with different color, 2) edges from the same airline with same color

- # Exercise 3 (optional)
- To limit our options, just choose the paths in which connecting airlines are from the same airline and plot like Exercise 2