

# Network Structure

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In this markdown I will:

1. Create the network structure from the association matrix.
2. Evaluate local and global network metrics.
3. Permutate the link weights using the WalkTrap algorithm.
4. Evaluate modularity.

## PART 1: *Network Structure*

```
## load all necessary packages
require(igraph) # Look at Dai Shizuka/Jordi Bascompte
require(tnet) # For weights
require(sna)
require(statnet)

# Read in social association matrix
setwd("C:/Users/bankh/My_Repos/Dolphins/data")
gbi<- read.csv("gbi.csv")
source("../code/functions.R") # SRI & null permutation
nxn<- SRI.func(gbi)
nxn<-as.matrix(nxn)
## load all necessary packages
require(igraph)

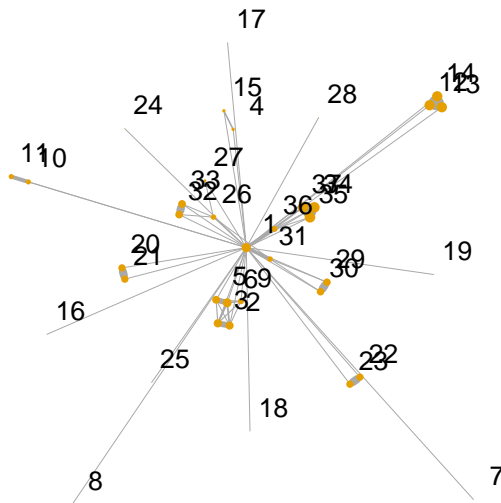
## Create social network
ig <- graph_from_adjacency_matrix(as.matrix(nxn),
                                mode = c("undirected"),
                                weighted = TRUE,
                                diag = F, # No loops
                                add.colnames = T,
                                add.rownames = NA)

# Plot network
plot(ig,
     layout = layout_with_fr(ig),
     # link weight, rescaled for better visualization
     edge.width= E(ig)$weight*4,
```

```

# node size as degree (rescaled)
vertex.size= sqrt(igraph::strength(ig, vids = V(ig), mode = c("all"), loops = TRUE) *10 ),
vertex.frame.color= NA, #"black",
vertex.label.family = "Helvetica",
vertex.label.color="black",
vertex.label.cex=0.8,
vertex.label.dist=2,
# edge.curved=0,
vertex.frame.width=0.01,
)

```



## PART 2: *Network Metrics*

### Local Network Metrics

- Local clustering coefficient: Measure of the prevalence of node clusters in a network.
- Betweenness: A high betweenness means that the individual is in the communication path of other individuals, therefore, the individuals it interacts with, depend on its presence.
- Closeness: The larger the closeness centrality is for an individual, the more rapidly and easily it can influence the behavior of others.
- Degree: # Individual's associates

- Strength: Total strength of an individuals' associations

```
# Source edgelist function
source("../code/functions.R")

# Edgelist: Nodes (i & j) and edge (or link) weight
el <- matrix_to_edgelist(nxn, rawdata = FALSE, idnodes = FALSE)

# Centrality measures
# Weighted clustering coefficients
clustering_local_w(el, measure=c("am", "gm", "mi", "ma", "bi"))
```

```
##      node      am      gm      mi      ma      bi
## [1,]    1 0.08550296 0.09942641 0.1109640 0.08216474 0.04920635
## [2,]    2 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [3,]    3 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [4,]    4 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [5,]    5 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [6,]    6 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [7,]    7      NaN      NaN      NaN      NaN      NaN
## [8,]    8      NaN      NaN      NaN      NaN      NaN
## [9,]    9 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [10,]  10 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [11,]  11 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [12,]  12 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [13,]  13 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [14,]  14 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [15,]  15 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [16,]  16      NaN      NaN      NaN      NaN      NaN
## [17,]  17      NaN      NaN      NaN      NaN      NaN
## [18,]  18      NaN      NaN      NaN      NaN      NaN
## [19,]  19      NaN      NaN      NaN      NaN      NaN
## [20,]  20 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [21,]  21 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [22,]  22 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [23,]  23 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [24,]  24      NaN      NaN      NaN      NaN      NaN
## [25,]  25      NaN      NaN      NaN      NaN      NaN
## [26,]  26 0.55941895 0.57258736 0.60000000 0.53230531 0.50000000
## [27,]  27 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [28,]  28      NaN      NaN      NaN      NaN      NaN
## [29,]  29 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [30,]  30 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [31,]  31 0.90474912 0.85023300 0.7142857 0.93649799 0.66666667
## [32,]  32 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [33,]  33 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [34,]  34 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [35,]  35 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [36,]  36 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
## [37,]  37 1.00000000 1.00000000 1.0000000 1.00000000 1.00000000
```

```
## Betweenness centrality
betweenness_w(el, alpha=1)
```

```
##      node betweenness
## [1,]    1         598
## [2,]    2           0
## [3,]    3           0
## [4,]    4          35
## [5,]    5           0
## [6,]    6          99
## [7,]    7           0
## [8,]    8           0
## [9,]    9           0
## [10,]   10          35
## [11,]   11           0
## [12,]   12           0
## [13,]   13           0
## [14,]   14           0
## [15,]   15           0
## [16,]   16           0
## [17,]   17           0
## [18,]   18           0
## [19,]   19           0
## [20,]   20           0
## [21,]   21           0
## [22,]   22           0
## [23,]   23           0
## [24,]   24           0
## [25,]   25           0
## [26,]   26         101
## [27,]   27           0
## [28,]   28           0
## [29,]   29           0
## [30,]   30           0
## [31,]   31          68
## [32,]   32           0
## [33,]   33           0
## [34,]   34           0
## [35,]   35           0
## [36,]   36          99
## [37,]   37           0
```

```
# Closeness centrality
closeness_w(e1, alpha=1)
```

```
##      node    closeness  n.closeness
## [1,]    1 0.0010627125 2.951979e-05
## [2,]    2 0.0009584334 2.662315e-05
## [3,]    3 0.0009623581 2.673217e-05
## [4,]    4 0.0007143736 1.984371e-05
## [5,]    5 0.0009806138 2.723927e-05
## [6,]    6 0.0009918803 2.755223e-05
## [7,]    7 0.0001569699 4.360275e-06
## [8,]    8 0.0001892842 5.257894e-06
## [9,]    9 0.0009862851 2.739681e-05
## [10,]   10 0.0004346014 1.207226e-05
## [11,]   11 0.0004314982 1.198606e-05
```

```
## [12,] 12 0.0003495630 9.710082e-06
## [13,] 13 0.0003495630 9.710082e-06
## [14,] 14 0.0003495630 9.710082e-06
## [15,] 15 0.0006938678 1.927411e-05
## [16,] 16 0.0004021863 1.117184e-05
## [17,] 17 0.0004196690 1.165747e-05
## [18,] 18 0.0004670400 1.297333e-05
## [19,] 19 0.0004813379 1.337050e-05
## [20,] 20 0.0007032776 1.953549e-05
## [21,] 21 0.0007032776 1.953549e-05
## [22,] 22 0.0005235514 1.454309e-05
## [23,] 23 0.0005235514 1.454309e-05
## [24,] 24 0.0005323560 1.478767e-05
## [25,] 25 0.0005437629 1.510453e-05
## [26,] 26 0.0010123962 2.812212e-05
## [27,] 27 0.0009488154 2.635598e-05
## [28,] 28 0.0005752633 1.597954e-05
## [29,] 29 0.0008918639 2.477400e-05
## [30,] 30 0.0008918639 2.477400e-05
## [31,] 31 0.0010447244 2.902012e-05
## [32,] 32 0.0009520184 2.644496e-05
## [33,] 33 0.0009520184 2.644496e-05
## [34,] 34 0.0009567331 2.657592e-05
## [35,] 35 0.0009567331 2.657592e-05
## [36,] 36 0.0010451369 2.903158e-05
## [37,] 37 0.0009567331 2.657592e-05
```

*# Degree and strength centrality*

```
degree_w(e1, measure=c("degree","output"), type="out", alpha=1)
```

```
##      node degree      output
## [1,]    1     36 1.599068771
## [2,]    2      5 1.232586906
## [3,]    3      5 1.291832833
## [4,]    4      2 0.217001546
## [5,]    5      5 1.160542173
## [6,]    6      5 1.483053921
## [7,]    7      1 0.001523810
## [8,]    8      1 0.001905488
## [9,]    9      5 0.671952895
## [10,]  10      2 0.505736138
## [11,]  11      2 0.503052270
## [12,]  12      3 2.003818251
## [13,]  13      3 2.003818251
## [14,]  14      3 2.003818251
## [15,]  15      2 0.211149558
## [16,]  16      1 0.005353728
## [17,]  17      1 0.005738332
## [18,]  18      1 0.006893910
## [19,]  19      1 0.007279693
## [20,]  20      2 1.016228748
## [21,]  21      2 1.016228748
## [22,]  22      2 1.008052147
## [23,]  23      2 1.008052147
```

```
## [24,] 24      1 0.008825787
## [25,] 25      1 0.009213052
## [26,] 26      5 0.557299758
## [27,] 27      2 0.134600614
## [28,] 28      1 0.010376633
## [29,] 29      3 1.058384138
## [30,] 30      3 1.058384138
## [31,] 31      4 0.583255013
## [32,] 32      3 1.143597443
## [33,] 33      3 1.143597443
## [34,] 34      4 2.107087227
## [35,] 35      4 2.107087227
## [36,] 36      4 0.683224756
## [37,] 37      4 2.107087227
```

## Global Network Metrics

- Size: Number of nodes.
- Density/Connectance: Proportion of realized links (observed/possible links).
- Average Path Length (geodesic): Measures the shortest distance between two random nodes then average shortest pathways between all pairs of nodes. Shows how far apart any pair of individuals will be on average.
- Geodesic path: the shortest path through the network from one node to another (l).
- Diameter: Length of the longest geodesic path (d).
- Clustering coefficient: Tendency of nodes to cluster in the network (Are the friends' friends also friends?).

```
## Size
N = nrow(nxn)
## Number of possible links:
## Nodes*(Nodes-1)/2: (-1 removes the node itself; /2 removes repetitions)
total = N*(N-1)/2
## Number of realized links: all non-zero cells in the association matrix
real = length(which(as.dist(nxn)!=0))
## Connectance: realized/total
real/total
```

```
## [1] 0.1006006
```

```
## Shortest path lengths (geodesics) and diameter
## all binary shortest path lengths between nodes
distances(ig)
```

```
##           [,1]      [,2]      [,3]      [,4]      [,5]      [,6]
## [1,] 0.000000000 0.01036468 0.006118547 0.01700155 0.06728820 0.09654598
## [2,] 0.010364683 0.000000000 0.016483230 0.02736623 0.07765289 0.10691067
## [3,] 0.006118547 0.01648323 0.000000000 0.02312009 0.07340675 0.10266453
## [4,] 0.017001546 0.02736623 0.023120092 0.000000000 0.08428975 0.11354753
```

```

## [5,] 0.067288204 0.07765289 0.073406751 0.08428975 0.00000000 0.16383419
## [6,] 0.096545984 0.10691067 0.102664531 0.11354753 0.16383419 0.00000000
## [7,] 0.001523810 0.01188849 0.007642356 0.01852536 0.06881201 0.09806979
## [8,] 0.001905488 0.01227017 0.008024035 0.01890703 0.06919369 0.09845147
## [9,] 0.092984641 0.10334932 0.099103188 0.10998619 0.11111111 0.18953063
## [10,] 0.005736138 0.01610082 0.011854685 0.02273768 0.07302434 0.10228212
## [11,] 0.003052270 0.01341695 0.009170817 0.02005382 0.07034047 0.09959825
## [12,] 0.003818251 0.01418293 0.009936798 0.02081980 0.07110646 0.10036424
## [13,] 0.003818251 0.01418293 0.009936798 0.02081980 0.07110646 0.10036424
## [14,] 0.003818251 0.01418293 0.009936798 0.02081980 0.07110646 0.10036424
## [15,] 0.011149558 0.02151424 0.017268105 0.02815110 0.07843776 0.10769554
## [16,] 0.005353728 0.01571841 0.011472275 0.02235527 0.07264193 0.10189971
## [17,] 0.005738332 0.01610302 0.011856879 0.02273988 0.07302654 0.10228432
## [18,] 0.006893910 0.01725859 0.013012457 0.02389546 0.07418211 0.10343989
## [19,] 0.007279693 0.01764438 0.013398240 0.02428124 0.07456790 0.10382568
## [20,] 0.016228748 0.02659343 0.022347295 0.03323029 0.08351695 0.11277473
## [21,] 0.016228748 0.02659343 0.022347295 0.03323029 0.08351695 0.11277473
## [22,] 0.008052147 0.01841683 0.014170694 0.02505369 0.07534035 0.10459813
## [23,] 0.008052147 0.01841683 0.014170694 0.02505369 0.07534035 0.10459813
## [24,] 0.008825787 0.01919047 0.014944333 0.02582733 0.07611399 0.10537177
## [25,] 0.009213052 0.01957774 0.015331599 0.02621460 0.07650126 0.10575904
## [26,] 0.094098424 0.10446311 0.100216971 0.11109997 0.16138663 0.19064441
## [27,] 0.009600614 0.01996530 0.015719161 0.02660216 0.07688882 0.10614660
## [28,] 0.010376633 0.02074132 0.016495180 0.02737818 0.07766484 0.10692262
## [29,] 0.010765090 0.02112977 0.016883637 0.02776664 0.07805329 0.10731107
## [30,] 0.010765090 0.02112977 0.016883637 0.02776664 0.07805329 0.10731107
## [31,] 0.058384138 0.06874882 0.064502685 0.07538568 0.12567234 0.15493012
## [32,] 0.018597443 0.02896213 0.024715990 0.03559899 0.08588565 0.11514343
## [33,] 0.018597443 0.02896213 0.024715990 0.03559899 0.08588565 0.11514343
## [34,] 0.023753894 0.03411858 0.029872441 0.04075544 0.09104210 0.12029988
## [35,] 0.023753894 0.03411858 0.029872441 0.04075544 0.09104210 0.12029988
## [36,] 0.107087227 0.11745191 0.113205774 0.12408877 0.17437543 0.20363321
## [37,] 0.023753894 0.03411858 0.029872441 0.04075544 0.09104210 0.12029988
##      [,7]      [,8]      [,9]     [,10]     [,11]     [,12]
## [1,] 0.001523810 0.001905488 0.09298464 0.005736138 0.003052270 0.003818251
## [2,] 0.011888493 0.012270171 0.10334932 0.016100821 0.013416953 0.014182935
## [3,] 0.007642356 0.008024035 0.09910319 0.011854685 0.009170817 0.009936798
## [4,] 0.018525355 0.018907033 0.10998619 0.022737683 0.020053816 0.020819797
## [5,] 0.068812014 0.069193692 0.11111111 0.073024342 0.070340474 0.071106456
## [6,] 0.098069794 0.098451472 0.18953063 0.102282122 0.099598254 0.100364235
## [7,] 0.000000000 0.003429297 0.09450845 0.007259947 0.004576080 0.005342061
## [8,] 0.003429297 0.000000000 0.09489013 0.007641625 0.004957758 0.005723739
## [9,] 0.094508450 0.094890129 0.00000000 0.098720779 0.096036911 0.096802892
## [10,] 0.007259947 0.007641625 0.09872078 0.000000000 0.008788408 0.009554389
## [11,] 0.004576080 0.004957758 0.09603691 0.008788408 0.000000000 0.006870521
## [12,] 0.005342061 0.005723739 0.09680289 0.009554389 0.006870521 0.000000000
## [13,] 0.005342061 0.005723739 0.09680289 0.009554389 0.006870521 0.007636502
## [14,] 0.005342061 0.005723739 0.09680289 0.009554389 0.006870521 0.007636502
## [15,] 0.012673367 0.013055046 0.10413420 0.016885696 0.014201828 0.014967809
## [16,] 0.006877538 0.007259216 0.09833837 0.011089866 0.008405999 0.009171980
## [17,] 0.007262142 0.007643820 0.09872297 0.011474470 0.008790602 0.009556583
## [18,] 0.008417720 0.008799398 0.09987855 0.012630048 0.009946181 0.010712162
## [19,] 0.008803503 0.009185181 0.10026433 0.013015831 0.010331964 0.011097945
## [20,] 0.017752558 0.018134236 0.10921339 0.021964886 0.019281018 0.020046999

```

```

## [21,] 0.017752558 0.018134236 0.10921339 0.021964886 0.019281018 0.020046999
## [22,] 0.009575957 0.009957635 0.10103679 0.013788285 0.011104417 0.011870398
## [23,] 0.009575957 0.009957635 0.10103679 0.013788285 0.011104417 0.011870398
## [24,] 0.010349596 0.010731274 0.10181043 0.014561924 0.011878057 0.012644038
## [25,] 0.010736861 0.011118540 0.10219769 0.014949189 0.012265322 0.013031303
## [26,] 0.095622233 0.096003911 0.18708306 0.099834561 0.097150694 0.097916675
## [27,] 0.011124424 0.011506102 0.10258526 0.015336752 0.012652885 0.013418866
## [28,] 0.011900443 0.012282121 0.10336127 0.016112771 0.013428903 0.014194885
## [29,] 0.012288900 0.012670578 0.10374973 0.016501228 0.013817360 0.014583342
## [30,] 0.012288900 0.012670578 0.10374973 0.016501228 0.013817360 0.014583342
## [31,] 0.059907947 0.060289626 0.15136878 0.064120276 0.061436408 0.062202389
## [32,] 0.020121252 0.020502931 0.11158208 0.024333581 0.021649713 0.022415694
## [33,] 0.020121252 0.020502931 0.11158208 0.024333581 0.021649713 0.022415694
## [34,] 0.025277704 0.025659382 0.11673854 0.029490032 0.026806164 0.027572145
## [35,] 0.025277704 0.025659382 0.11673854 0.029490032 0.026806164 0.027572145
## [36,] 0.108611037 0.108992715 0.20007187 0.112823365 0.110139498 0.110905479
## [37,] 0.025277704 0.025659382 0.11673854 0.029490032 0.026806164 0.027572145
##      [,13]      [,14]      [,15]      [,16]      [,17]      [,18]
## [1,] 0.003818251 0.003818251 0.01114956 0.005353728 0.005738332 0.006893910
## [2,] 0.014182935 0.014182935 0.02151424 0.015718412 0.016103015 0.017258594
## [3,] 0.009936798 0.009936798 0.01726810 0.011472275 0.011856879 0.013012457
## [4,] 0.020819797 0.020819797 0.02815110 0.022355274 0.022739878 0.023895456
## [5,] 0.071106456 0.071106456 0.07843776 0.072641933 0.073026536 0.074182115
## [6,] 0.100364235 0.100364235 0.10769554 0.101899713 0.102284316 0.103439895
## [7,] 0.005342061 0.005342061 0.01267337 0.006877538 0.007262142 0.008417720
## [8,] 0.005723739 0.005723739 0.01305505 0.007259216 0.007643820 0.008799398
## [9,] 0.096802892 0.096802892 0.10413420 0.098338369 0.098722973 0.099878551
## [10,] 0.009554389 0.009554389 0.01688570 0.011089866 0.011474470 0.012630048
## [11,] 0.006870521 0.006870521 0.01420183 0.008405999 0.008790602 0.009946181
## [12,] 0.007636502 0.007636502 0.01496781 0.009171980 0.009556583 0.010712162
## [13,] 0.000000000 0.007636502 0.01496781 0.009171980 0.009556583 0.010712162
## [14,] 0.007636502 0.000000000 0.01496781 0.009171980 0.009556583 0.010712162
## [15,] 0.014967809 0.014967809 0.00000000 0.016503286 0.016887890 0.018043468
## [16,] 0.009171980 0.009171980 0.01650329 0.00000000 0.011092061 0.012247639
## [17,] 0.009556583 0.009556583 0.01688789 0.011092061 0.00000000 0.012632242
## [18,] 0.010712162 0.010712162 0.01804347 0.012247639 0.012632242 0.00000000
## [19,] 0.011097945 0.011097945 0.01842925 0.012633422 0.013018026 0.014173604
## [20,] 0.020046999 0.020046999 0.02737831 0.021582477 0.021967080 0.023122658
## [21,] 0.020046999 0.020046999 0.02737831 0.021582477 0.021967080 0.023122658
## [22,] 0.011870398 0.011870398 0.01920171 0.013405876 0.013790479 0.014946058
## [23,] 0.011870398 0.011870398 0.01920171 0.013405876 0.013790479 0.014946058
## [24,] 0.012644038 0.012644038 0.01997534 0.014179515 0.014564119 0.015719697
## [25,] 0.013031303 0.013031303 0.02036261 0.014566780 0.014951384 0.016106962
## [26,] 0.097916675 0.097916675 0.10524798 0.099452152 0.099836756 0.100992334
## [27,] 0.013418866 0.013418866 0.02075017 0.014954343 0.015338946 0.016494525
## [28,] 0.014194885 0.014194885 0.02152619 0.015730362 0.016114965 0.017270544
## [29,] 0.014583342 0.014583342 0.02191465 0.016118819 0.016503422 0.017659001
## [30,] 0.014583342 0.014583342 0.02191465 0.016118819 0.016503422 0.017659001
## [31,] 0.062202389 0.062202389 0.06953370 0.063737866 0.064122470 0.065278048
## [32,] 0.022415694 0.022415694 0.02974700 0.023951171 0.024335775 0.025491353
## [33,] 0.022415694 0.022415694 0.02974700 0.023951171 0.024335775 0.025491353
## [34,] 0.027572145 0.027572145 0.03490345 0.029107623 0.029492226 0.030647804
## [35,] 0.027572145 0.027572145 0.03490345 0.029107623 0.029492226 0.030647804
## [36,] 0.110905479 0.110905479 0.11823679 0.112440956 0.112825559 0.113981138

```



```

## [37,] 0.027572145 0.027572145 0.03490345 0.029107623 0.029492226 0.030647804
##      [,19]      [,20]      [,21]      [,22]      [,23]      [,24]
## [1,] 0.007279693 0.01622875 0.01622875 0.008052147 0.008052147 0.008825787
## [2,] 0.017644377 0.02659343 0.02659343 0.018416831 0.018416831 0.019190470
## [3,] 0.013398240 0.02234729 0.02234729 0.014170694 0.014170694 0.014944333
## [4,] 0.024281239 0.03323029 0.03323029 0.025053693 0.025053693 0.025827332
## [5,] 0.074567898 0.08351695 0.08351695 0.075340352 0.075340352 0.076113991
## [6,] 0.103825678 0.11277473 0.11277473 0.104598131 0.104598131 0.105371771
## [7,] 0.008803503 0.01775256 0.01775256 0.009575957 0.009575957 0.010349596
## [8,] 0.009185181 0.01813424 0.01813424 0.009957635 0.009957635 0.010731274
## [9,] 0.100264334 0.10921339 0.10921339 0.101036788 0.101036788 0.101810428
## [10,] 0.013015831 0.02196489 0.02196489 0.013788285 0.013788285 0.014561924
## [11,] 0.010331964 0.01928102 0.01928102 0.011104417 0.011104417 0.011878057
## [12,] 0.011097945 0.02004700 0.02004700 0.011870398 0.011870398 0.012644038
## [13,] 0.011097945 0.02004700 0.02004700 0.011870398 0.011870398 0.012644038
## [14,] 0.011097945 0.02004700 0.02004700 0.011870398 0.011870398 0.012644038
## [15,] 0.018429251 0.02737831 0.02737831 0.019201705 0.019201705 0.019975345
## [16,] 0.012633422 0.02158248 0.02158248 0.013405876 0.013405876 0.014179515
## [17,] 0.013018026 0.02196708 0.02196708 0.013790479 0.013790479 0.014564119
## [18,] 0.014173604 0.02312266 0.02312266 0.014946058 0.014946058 0.015719697
## [19,] 0.000000000 0.02350844 0.02350844 0.015331841 0.015331841 0.016105480
## [20,] 0.023508442 0.00000000 0.03245750 0.024280895 0.024280895 0.025054535
## [21,] 0.023508442 0.03245750 0.00000000 0.024280895 0.024280895 0.025054535
## [22,] 0.015331841 0.02428090 0.02428090 0.000000000 0.016104294 0.016877934
## [23,] 0.015331841 0.02428090 0.02428090 0.016104294 0.000000000 0.016877934
## [24,] 0.016105480 0.02505453 0.02505453 0.016877934 0.016877934 0.000000000
## [25,] 0.016492745 0.02544180 0.02544180 0.017265199 0.017265199 0.018038838
## [26,] 0.101378117 0.11032717 0.11032717 0.102150571 0.102150571 0.102924210
## [27,] 0.016880308 0.02582936 0.02582936 0.017652762 0.017652762 0.018426401
## [28,] 0.017656327 0.02660538 0.02660538 0.018428781 0.018428781 0.019202420
## [29,] 0.018044784 0.02699384 0.02699384 0.018817238 0.018817238 0.019590877
## [30,] 0.018044784 0.02699384 0.02699384 0.018817238 0.018817238 0.019590877
## [31,] 0.065663831 0.07461289 0.07461289 0.066436285 0.066436285 0.067209925
## [32,] 0.025877136 0.03482619 0.03482619 0.026649590 0.026649590 0.027423229
## [33,] 0.025877136 0.03482619 0.03482619 0.026649590 0.026649590 0.027423229
## [34,] 0.031033588 0.03998264 0.03998264 0.031806041 0.031806041 0.032579681
## [35,] 0.031033588 0.03998264 0.03998264 0.031806041 0.031806041 0.032579681
## [36,] 0.114366921 0.12331598 0.12331598 0.115139375 0.115139375 0.115913014
## [37,] 0.031033588 0.03998264 0.03998264 0.031806041 0.031806041 0.032579681
##      [,25]      [,26]      [,27]      [,28]      [,29]      [,30]
## [1,] 0.009213052 0.09409842 0.009600614 0.01037663 0.01076509 0.01076509
## [2,] 0.019577735 0.10446311 0.019965298 0.02074132 0.02112977 0.02112977
## [3,] 0.015331599 0.10021697 0.015719161 0.01649518 0.01688364 0.01688364
## [4,] 0.026214597 0.11109997 0.026602160 0.02737818 0.02776664 0.02776664
## [5,] 0.076501256 0.16138663 0.076888819 0.07766484 0.07805329 0.07805329
## [6,] 0.105759036 0.19064441 0.106146599 0.10692262 0.10731107 0.10731107
## [7,] 0.010736861 0.09562223 0.011124424 0.01190044 0.01228890 0.01228890
## [8,] 0.011118540 0.09600391 0.011506102 0.01228212 0.01267058 0.01267058
## [9,] 0.102197693 0.18708306 0.102585255 0.10336127 0.10374973 0.10374973
## [10,] 0.014949189 0.09983456 0.015336752 0.01611277 0.01650123 0.01650123
## [11,] 0.012265322 0.09715069 0.012652885 0.01342890 0.01381736 0.01381736
## [12,] 0.013031303 0.09791667 0.013418866 0.01419488 0.01458334 0.01458334
## [13,] 0.013031303 0.09791667 0.013418866 0.01419488 0.01458334 0.01458334
## [14,] 0.013031303 0.09791667 0.013418866 0.01419488 0.01458334 0.01458334

```

```

## [15,] 0.020362610 0.10524798 0.020750172 0.02152619 0.02191465 0.02191465
## [16,] 0.014566780 0.09945215 0.014954343 0.01573036 0.01611882 0.01611882
## [17,] 0.014951384 0.09983676 0.015338946 0.01611497 0.01650342 0.01650342
## [18,] 0.016106962 0.10099233 0.016494525 0.01727054 0.01765900 0.01765900
## [19,] 0.016492745 0.10137812 0.016880308 0.01765633 0.01804478 0.01804478
## [20,] 0.025441800 0.11032717 0.025829363 0.02660538 0.02699384 0.02699384
## [21,] 0.025441800 0.11032717 0.025829363 0.02660538 0.02699384 0.02699384
## [22,] 0.017265199 0.10215057 0.017652762 0.01842878 0.01881724 0.01881724
## [23,] 0.017265199 0.10215057 0.017652762 0.01842878 0.01881724 0.01881724
## [24,] 0.018038838 0.10292421 0.018426401 0.01920242 0.01959088 0.01959088
## [25,] 0.000000000 0.10331148 0.018813666 0.01958969 0.01997814 0.01997814
## [26,] 0.103311476 0.00000000 0.103699038 0.10447506 0.08333333 0.08333333
## [27,] 0.018813666 0.10369904 0.000000000 0.01997725 0.02036570 0.02036570
## [28,] 0.019589685 0.10447506 0.019977248 0.00000000 0.02114172 0.02114172
## [29,] 0.019978142 0.08333333 0.020365705 0.02114172 0.00000000 0.02153018
## [30,] 0.019978142 0.08333333 0.020365705 0.02114172 0.02153018 0.00000000
## [31,] 0.067597190 0.03571429 0.067984752 0.06876077 0.04761905 0.04761905
## [32,] 0.027810495 0.11269587 0.028198057 0.02897408 0.02936253 0.02936253
## [33,] 0.027810495 0.11269587 0.028198057 0.02897408 0.02936253 0.02936253
## [34,] 0.032966946 0.11785232 0.033354509 0.03413053 0.03451898 0.03451898
## [35,] 0.032966946 0.11785232 0.033354509 0.03413053 0.03451898 0.03451898
## [36,] 0.116300279 0.20118565 0.116687842 0.11746386 0.11785232 0.11785232
## [37,] 0.032966946 0.11785232 0.033354509 0.03413053 0.03451898 0.03451898
##      [,31]      [,32]      [,33]      [,34]      [,35]      [,36]
## [1,] 0.05838414 0.01859744 0.01859744 0.02375389 0.02375389 0.10708723
## [2,] 0.06874882 0.02896213 0.02896213 0.03411858 0.03411858 0.11745191
## [3,] 0.06450268 0.02471599 0.02471599 0.02987244 0.02987244 0.11320577
## [4,] 0.07538568 0.03559899 0.03559899 0.04075544 0.04075544 0.12408877
## [5,] 0.12567234 0.08588565 0.08588565 0.09104210 0.09104210 0.17437543
## [6,] 0.15493012 0.11514343 0.11514343 0.12029988 0.12029988 0.20363321
## [7,] 0.05990795 0.02012125 0.02012125 0.02527770 0.02527770 0.10861104
## [8,] 0.06028963 0.02050293 0.02050293 0.02565938 0.02565938 0.10899272
## [9,] 0.15136878 0.11158208 0.11158208 0.11673854 0.11673854 0.20007187
## [10,] 0.06412028 0.02433358 0.02433358 0.02949003 0.02949003 0.11282337
## [11,] 0.06143641 0.02164971 0.02164971 0.02680616 0.02680616 0.11013950
## [12,] 0.06220239 0.02241569 0.02241569 0.02757215 0.02757215 0.11090548
## [13,] 0.06220239 0.02241569 0.02241569 0.02757215 0.02757215 0.11090548
## [14,] 0.06220239 0.02241569 0.02241569 0.02757215 0.02757215 0.11090548
## [15,] 0.06953370 0.02974700 0.02974700 0.03490345 0.03490345 0.11823679
## [16,] 0.06373787 0.02395117 0.02395117 0.02910762 0.02910762 0.11244096
## [17,] 0.06412247 0.02433577 0.02433577 0.02949223 0.02949223 0.11282556
## [18,] 0.06527805 0.02549135 0.02549135 0.03064780 0.03064780 0.11398114
## [19,] 0.06566383 0.02587714 0.02587714 0.03103359 0.03103359 0.11436692
## [20,] 0.07461289 0.03482619 0.03482619 0.03998264 0.03998264 0.12331598
## [21,] 0.07461289 0.03482619 0.03482619 0.03998264 0.03998264 0.12331598
## [22,] 0.06643629 0.02664959 0.02664959 0.03180604 0.03180604 0.11513937
## [23,] 0.06643629 0.02664959 0.02664959 0.03180604 0.03180604 0.11513937
## [24,] 0.06720992 0.02742323 0.02742323 0.03257968 0.03257968 0.11591301
## [25,] 0.06759719 0.02781049 0.02781049 0.03296695 0.03296695 0.11630028
## [26,] 0.03571429 0.11269587 0.11269587 0.11785232 0.11785232 0.20118565
## [27,] 0.06798475 0.02819806 0.02819806 0.03335451 0.03335451 0.11668784
## [28,] 0.06876077 0.02897408 0.02897408 0.03413053 0.03413053 0.11746386
## [29,] 0.04761905 0.02936253 0.02936253 0.03451898 0.03451898 0.11785232
## [30,] 0.04761905 0.02936253 0.02936253 0.03451898 0.03451898 0.11785232

```

```

## [31,] 0.00000000 0.07698158 0.07698158 0.08213803 0.08213803 0.16547137
## [32,] 0.07698158 0.00000000 0.03719489 0.04235134 0.04235134 0.12568467
## [33,] 0.07698158 0.03719489 0.00000000 0.04235134 0.04235134 0.12568467
## [34,] 0.08213803 0.04235134 0.04235134 0.00000000 0.04750779 0.08333333
## [35,] 0.08213803 0.04235134 0.04235134 0.04750779 0.00000000 0.08333333
## [36,] 0.16547137 0.12568467 0.12568467 0.08333333 0.08333333 0.00000000
## [37,] 0.08213803 0.04235134 0.04235134 0.04750779 0.04750779 0.08333333
##      [,37]
## [1,] 0.02375389
## [2,] 0.03411858
## [3,] 0.02987244
## [4,] 0.04075544
## [5,] 0.09104210
## [6,] 0.12029988
## [7,] 0.02527770
## [8,] 0.02565938
## [9,] 0.11673854
## [10,] 0.02949003
## [11,] 0.02680616
## [12,] 0.02757215
## [13,] 0.02757215
## [14,] 0.02757215
## [15,] 0.03490345
## [16,] 0.02910762
## [17,] 0.02949223
## [18,] 0.03064780
## [19,] 0.03103359
## [20,] 0.03998264
## [21,] 0.03998264
## [22,] 0.03180604
## [23,] 0.03180604
## [24,] 0.03257968
## [25,] 0.03296695
## [26,] 0.11785232
## [27,] 0.03335451
## [28,] 0.03413053
## [29,] 0.03451898
## [30,] 0.03451898
## [31,] 0.08213803
## [32,] 0.04235134
## [33,] 0.04235134
## [34,] 0.04750779
## [35,] 0.04750779
## [36,] 0.08333333
## [37,] 0.00000000

```

```

# mean shortest path
mean_distance(ig)

```

```

## [1] 0.04408461

```

```

# Binary shortest path lengths
distance_table(ig, directed=FALSE)

```

```
## $res
## [1] 67 599
##
## $unconnected
## [1] 0
```

```
# All Weighted Shortest path lenghts (or geodesics)
distance_w(el)
```

```
##           [,1]      [,2]      [,3]      [,4]      [,5]      [,6]
## [1,]          NA    3.5122753    3.3940787    13.904227    2.7794560    2.4485053
## [2,]    3.5122753          NA    0.3151911    17.416502    1.3947208    1.0637701
## [3,]    3.3940787    0.3151911          NA    17.298306    1.2765241    0.9455734
## [4,]    13.904227    17.416502    17.2983057          NA    16.6836830    16.3527323
## [5,]    2.7794560    1.3947208    1.2765241    16.683683          NA    0.3309507
## [6,]    2.4485053    1.0637701    0.9455734    16.352732    0.3309507          NA
## [7,]   155.1331363   158.6454116   158.5272149   169.037363   157.9125922   157.5816415
## [8,]   124.0592304   127.5715057   127.4533090   137.963457   126.8386863   126.5077356
## [9,]    2.5422838    1.8911468    1.6547535    16.446511    1.5129174    1.1819668
## [10,]   41.2112408   44.7235161   44.6053194   55.115468   43.9906967   43.6597460
## [11,]   41.6840275   45.1963028   45.0781061   55.588255   44.4634834   44.1325327
## [12,]   61.9114185   65.4236938   65.3054972   75.815646   64.6908745   64.3599238
## [13,]   61.9114185   65.4236938   65.3054972   75.815646   64.6908745   64.3599238
## [14,]   61.9114185   65.4236938   65.3054972   75.815646   64.6908745   64.3599238
## [15,]   15.0861938   18.5984692   18.4802725    1.181967   17.8656498   17.5346991
## [16,]   44.1549008   47.6671762   47.5489795   58.059128   46.9343568   46.6034061
## [17,]   41.1954812   44.7077566   44.5895599   55.099708   43.9749372   43.6439865
## [18,]   34.2901688   37.8024441   37.6842475   48.194396   37.0696247   36.7386741
## [19,]   32.4729813   35.9852567   35.8670600   46.377208   35.2524373   34.9214866
## [20,]   14.5663331   18.0786085   17.9604118   28.470560   17.3457891   17.0148384
## [21,]   14.5663331   18.0786085   17.9604118   28.470560   17.3457891   17.0148384
## [22,]   29.3578028   32.8700781   32.7518814   43.262030   32.1372587   31.8063080
## [23,]   29.3578028   32.8700781   32.7518814   43.262030   32.1372587   31.8063080
## [24,]   26.7843944   30.2966698   30.1784731   40.688621   29.5638504   29.2328997
## [25,]   25.6585283   29.1708036   29.0526069   39.562755   28.4379842   28.1070335
## [26,]    1.6126656    5.1249410    5.0067443   15.516893    4.3921216    4.0611709
## [27,]    3.5038124    7.0160878    6.8978911   17.408039    6.2832684    5.9523177
## [28,]   22.7813147   26.2935901   26.1753934   36.685542   25.5607707   25.2298200
## [29,]    5.4869046    8.9991799    8.8809832   19.391132    8.2663605    7.9354098
## [30,]    5.4869046    8.9991799    8.8809832   19.391132    8.2663605    7.9354098
## [31,]    0.5226442    4.0349195    3.9167229   14.426871    3.3021002    2.9711495
## [32,]    3.5038124    7.0160878    6.8978911   17.408039    6.2832684    5.9523177
## [33,]    3.5038124    7.0160878    6.8978911   17.408039    6.2832684    5.9523177
## [34,]    3.3823800    6.8946554    6.7764587   17.286607    6.1618360    5.8308853
## [35,]    3.3823800    6.8946554    6.7764587   17.286607    6.1618360    5.8308853
## [36,]    0.5456598    4.0579352    3.9397385   14.449887    3.3251158    2.9941651
## [37,]    3.3823800    6.8946554    6.7764587   17.286607    6.1618360    5.8308853
##           [,7]      [,8]      [,9]      [,10]      [,11]      [,12]
## [1,]   155.1331   124.0592    2.542284   41.2112408   41.6840275   61.9114185
## [2,]   158.6454   127.5715    1.891147   44.7235161   45.1963028   65.4236938
## [3,]   158.5272   127.4533    1.654753   44.6053194   45.0781061   65.3054972
## [4,]   169.0374   137.9635   16.446511   55.1154678   55.5882545   75.8156456
## [5,]   157.9126   126.8387    1.512917   43.9906967   44.4634834   64.6908745
## [6,]   157.5816   126.5077    1.181967   43.6597460   44.1325327   64.3599238
```

```

## [7,]      NA 279.1924 157.675420 196.3443771 196.8171638 217.0445548
## [8,] 279.1924      NA 126.601514 165.2704711 165.7432578 185.9706489
## [9,] 157.6754 126.6015      NA 43.7535246 44.2263113 64.4537023
## [10,] 196.3444 165.2705 43.753525      NA 0.4727867 103.1226593
## [11,] 196.8172 165.7433 44.226311 0.4727867      NA 103.5954460
## [12,] 217.0446 185.9706 64.453702 103.1226593 103.5954460      NA
## [13,] 217.0446 185.9706 64.453702 103.1226593 103.5954460 0.2363934
## [14,] 217.0446 185.9706 64.453702 103.1226593 103.5954460 0.2363934
## [15,] 170.2193 139.1454 17.628478 56.2974346 56.7702213 76.9976123
## [16,] 199.2880 168.2141 46.697185 85.3661416 85.8389283 106.0663193
## [17,] 196.3286 165.2547 43.737765 82.4067220 82.8795087 103.1068997
## [18,] 189.4233 158.3494 36.832453 75.5014096 75.9741963 96.2015873
## [19,] 187.6061 156.5322 35.015265 73.6842221 74.1570088 94.3843998
## [20,] 169.6995 138.6256 17.108617 55.7775739 56.2503606 76.4777516
## [21,] 169.6995 138.6256 17.108617 55.7775739 56.2503606 76.4777516
## [22,] 184.4909 153.4170 31.900087 70.5690435 71.0418302 91.2692213
## [23,] 184.4909 153.4170 31.900087 70.5690435 71.0418302 91.2692213
## [24,] 181.9175 150.8436 29.326678 67.9956352 68.4684219 88.6958129
## [25,] 180.7917 149.7178 28.200812 66.8697690 67.3425557 87.5699468
## [26,] 156.7458 125.6719 4.154949 42.8239064 43.2966931 63.5240841
## [27,] 158.6369 127.5630 6.046096 44.7150532 45.1878399 65.4152309
## [28,] 177.9145 146.8405 25.323599 63.9925555 64.4653422 84.6927332
## [29,] 160.6200 129.5461 8.029188 46.6981453 47.1709320 67.3983231
## [30,] 160.6200 129.5461 8.029188 46.6981453 47.1709320 67.3983231
## [31,] 155.6558 124.5819 3.064928 41.7338850 42.2066717 62.4340627
## [32,] 158.6369 127.5630 6.046096 44.7150532 45.1878399 65.4152309
## [33,] 158.6369 127.5630 6.046096 44.7150532 45.1878399 65.4152309
## [34,] 158.5155 127.4416 5.924664 44.5936208 45.0664075 65.2937985
## [35,] 158.5155 127.4416 5.924664 44.5936208 45.0664075 65.2937985
## [36,] 155.6788 124.6049 3.087944 41.7569006 42.2296873 62.4570783
## [37,] 158.5155 127.4416 5.924664 44.5936208 45.0664075 65.2937985
##      [,13]      [,14]      [,15]      [,16]      [,17]      [,18]
## [1,] 61.9114185 61.9114185 15.086194 44.15490 41.19548 34.29017
## [2,] 65.4236938 65.4236938 18.598469 47.66718 44.70776 37.80244
## [3,] 65.3054972 65.3054972 18.480272 47.54898 44.58956 37.68425
## [4,] 75.8156456 75.8156456 1.181967 58.05913 55.09971 48.19440
## [5,] 64.6908745 64.6908745 17.865650 46.93436 43.97494 37.06962
## [6,] 64.3599238 64.3599238 17.534699 46.60341 43.64399 36.73867
## [7,] 217.0445548 217.0445548 170.219330 199.28804 196.32862 189.42331
## [8,] 185.9706489 185.9706489 139.145424 168.21413 165.25471 158.34940
## [9,] 64.4537023 64.4537023 17.628478 46.69718 43.73777 36.83245
## [10,] 103.1226593 103.1226593 56.297435 85.36614 82.40672 75.50141
## [11,] 103.5954460 103.5954460 56.770221 85.83893 82.87951 75.97420
## [12,] 0.2363934 0.2363934 76.997612 106.06632 103.10690 96.20159
## [13,]      NA 0.2363934 76.997612 106.06632 103.10690 96.20159
## [14,] 0.2363934      NA 76.997612 106.06632 103.10690 96.20159
## [15,] 76.9976123 76.9976123      NA 59.24109 56.28168 49.37636
## [16,] 106.0663193 106.0663193 59.241095      NA 85.35038 78.44507
## [17,] 103.1068997 103.1068997 56.281675 85.35038      NA 75.48565
## [18,] 96.2015873 96.2015873 49.376363 78.44507 75.48565      NA
## [19,] 94.3843998 94.3843998 47.559175 76.62788 73.66846 66.76315
## [20,] 76.4777516 76.4777516 29.652527 58.72123 55.76181 48.85650
## [21,] 76.4777516 76.4777516 29.652527 58.72123 55.76181 48.85650
## [22,] 91.2692213 91.2692213 44.443997 73.51270 70.55328 63.64797

```

##	[23,]	91.2692213	91.2692213	44.443997	73.51270	70.55328	63.64797
##	[24,]	88.6958129	88.6958129	41.870588	70.93930	67.97988	61.07456
##	[25,]	87.5699468	87.5699468	40.744722	69.81343	66.85401	59.94870
##	[26,]	63.5240841	63.5240841	16.698859	45.76757	42.80815	35.90283
##	[27,]	65.4152309	65.4152309	18.590006	47.65871	44.69929	37.79398
##	[28,]	84.6927332	84.6927332	37.867509	66.93622	63.97680	57.07148
##	[29,]	67.3983231	67.3983231	20.573098	49.64181	46.68239	39.77707
##	[30,]	67.3983231	67.3983231	20.573098	49.64181	46.68239	39.77707
##	[31,]	62.4340627	62.4340627	15.608838	44.67755	41.71813	34.81281
##	[32,]	65.4152309	65.4152309	18.590006	47.65871	44.69929	37.79398
##	[33,]	65.4152309	65.4152309	18.590006	47.65871	44.69929	37.79398
##	[34,]	65.2937985	65.2937985	18.468574	47.53728	44.57786	37.67255
##	[35,]	65.2937985	65.2937985	18.468574	47.53728	44.57786	37.67255
##	[36,]	62.4570783	62.4570783	15.631854	44.70056	41.74114	34.83583
##	[37,]	65.2937985	65.2937985	18.468574	47.53728	44.57786	37.67255
##		[,19]	[,20]	[,21]	[,22]	[,23]	[,24]
##	[1,]	32.47298	14.5663331	14.5663331	29.3578028	29.3578028	26.78439
##	[2,]	35.98526	18.0786085	18.0786085	32.8700781	32.8700781	30.29667
##	[3,]	35.86706	17.9604118	17.9604118	32.7518814	32.7518814	30.17847
##	[4,]	46.37721	28.4705602	28.4705602	43.2620298	43.2620298	40.68862
##	[5,]	35.25244	17.3457891	17.3457891	32.1372587	32.1372587	29.56385
##	[6,]	34.92149	17.0148384	17.0148384	31.8063080	31.8063080	29.23290
##	[7,]	187.60612	169.6994694	169.6994694	184.4909391	184.4909391	181.91753
##	[8,]	156.53221	138.6255635	138.6255635	153.4170331	153.4170331	150.84362
##	[9,]	35.01527	17.1086170	17.1086170	31.9000866	31.9000866	29.32668
##	[10,]	73.68422	55.7775739	55.7775739	70.5690435	70.5690435	67.99564
##	[11,]	74.15701	56.2503606	56.2503606	71.0418302	71.0418302	68.46842
##	[12,]	94.38440	76.4777516	76.4777516	91.2692213	91.2692213	88.69581
##	[13,]	94.38440	76.4777516	76.4777516	91.2692213	91.2692213	88.69581
##	[14,]	94.38440	76.4777516	76.4777516	91.2692213	91.2692213	88.69581
##	[15,]	47.55918	29.6525269	29.6525269	44.4439966	44.4439966	41.87059
##	[16,]	76.62788	58.7212340	58.7212340	73.5127036	73.5127036	70.93930
##	[17,]	73.66846	55.7618143	55.7618143	70.5532840	70.5532840	67.97988
##	[18,]	66.76315	48.8565019	48.8565019	63.6479716	63.6479716	61.07456
##	[19,]	NA	47.0393144	47.0393144	61.8307841	61.8307841	59.25738
##	[20,]	47.03931	NA	0.2363934	43.9241359	43.9241359	41.35073
##	[21,]	47.03931	0.2363934	NA	43.9241359	43.9241359	41.35073
##	[22,]	61.83078	43.9241359	43.9241359	NA	0.2363934	56.14220
##	[23,]	61.83078	43.9241359	43.9241359	0.2363934	NA	56.14220
##	[24,]	59.25738	41.3507275	41.3507275	56.1421972	56.1421972	NA
##	[25,]	58.13151	40.2248614	40.2248614	55.0163310	55.0163310	52.44292
##	[26,]	34.08565	16.1789987	16.1789987	30.9704684	30.9704684	28.39706
##	[27,]	35.97679	18.0701455	18.0701455	32.8616152	32.8616152	30.28821
##	[28,]	55.25430	37.3476479	37.3476479	52.1391175	52.1391175	49.56571
##	[29,]	37.95989	20.0532377	20.0532377	34.8447073	34.8447073	32.27130
##	[30,]	37.95989	20.0532377	20.0532377	34.8447073	34.8447073	32.27130
##	[31,]	32.99563	15.0889773	15.0889773	29.8804470	29.8804470	27.30704
##	[32,]	35.97679	18.0701455	18.0701455	32.8616152	32.8616152	30.28821
##	[33,]	35.97679	18.0701455	18.0701455	32.8616152	32.8616152	30.28821
##	[34,]	35.85536	17.9487132	17.9487132	32.7401828	32.7401828	30.16677
##	[35,]	35.85536	17.9487132	17.9487132	32.7401828	32.7401828	30.16677
##	[36,]	33.01864	15.1119930	15.1119930	29.9034626	29.9034626	27.33005
##	[37,]	35.85536	17.9487132	17.9487132	32.7401828	32.7401828	30.16677
##		[,25]	[,26]	[,27]	[,28]	[,29]	[,30]

##	[1,]	25.65853	1.612666	3.503812	22.78131	5.4869046	5.4869046
##	[2,]	29.17080	5.124941	7.016088	26.29359	8.9991799	8.9991799
##	[3,]	29.05261	5.006744	6.897891	26.17539	8.8809832	8.8809832
##	[4,]	39.56276	15.516893	17.408039	36.68554	19.3911316	19.3911316
##	[5,]	28.43798	4.392122	6.283268	25.56077	8.2663605	8.2663605
##	[6,]	28.10703	4.061171	5.952318	25.22982	7.9354098	7.9354098
##	[7,]	180.79166	156.745802	158.636949	177.91445	160.6200409	160.6200409
##	[8,]	149.71776	125.671896	127.563043	146.84055	129.5461349	129.5461349
##	[9,]	28.20081	4.154949	6.046096	25.32360	8.0291884	8.0291884
##	[10,]	66.86977	42.823906	44.715053	63.99256	46.6981453	46.6981453
##	[11,]	67.34256	43.296693	45.187840	64.46534	47.1709320	47.1709320
##	[12,]	87.56995	63.524084	65.415231	84.69273	67.3983231	67.3983231
##	[13,]	87.56995	63.524084	65.415231	84.69273	67.3983231	67.3983231
##	[14,]	87.56995	63.524084	65.415231	84.69273	67.3983231	67.3983231
##	[15,]	40.74472	16.698859	18.590006	37.86751	20.5730984	20.5730984
##	[16,]	69.81343	45.767566	47.658713	66.93622	49.6418054	49.6418054
##	[17,]	66.85401	42.808147	44.699294	63.97680	46.6823858	46.6823858
##	[18,]	59.94870	35.902834	37.793981	57.07148	39.7770734	39.7770734
##	[19,]	58.13151	34.085647	35.976794	55.25430	37.9598859	37.9598859
##	[20,]	40.22486	16.178999	18.070146	37.34765	20.0532377	20.0532377
##	[21,]	40.22486	16.178999	18.070146	37.34765	20.0532377	20.0532377
##	[22,]	55.01633	30.970468	32.861615	52.13912	34.8447073	34.8447073
##	[23,]	55.01633	30.970468	32.861615	52.13912	34.8447073	34.8447073
##	[24,]	52.44292	28.397060	30.288207	49.56571	32.2712990	32.2712990
##	[25,]	NA	27.271194	29.162341	48.43984	31.1454328	31.1454328
##	[26,]	27.27119	NA	1.891147	24.39398	7.0995702	7.0995702
##	[27,]	29.16234	1.891147	NA	26.28513	8.9907170	8.9907170
##	[28,]	48.43984	24.393980	26.285127	NA	28.2682193	28.2682193
##	[29,]	31.14543	7.099570	8.990717	28.26822	NA	0.2363934
##	[30,]	31.14543	7.099570	8.990717	28.26822	0.2363934	NA
##	[31,]	26.18117	2.135310	4.026457	23.30396	4.9642604	4.9642604
##	[32,]	29.16234	1.891147	3.782294	26.28513	8.9907170	8.9907170
##	[33,]	29.16234	1.891147	3.782294	26.28513	8.9907170	8.9907170
##	[34,]	29.04091	4.995046	6.886192	26.16369	8.8692846	8.8692846
##	[35,]	29.04091	4.995046	6.886192	26.16369	8.8692846	8.8692846
##	[36,]	26.20419	2.158325	4.049472	23.32697	6.0325644	6.0325644
##	[37,]	29.04091	4.995046	6.886192	26.16369	8.8692846	8.8692846
##		[,31]	[,32]	[,33]	[,34]	[,35]	[,36]
##	[1,]	0.5226442	3.5038124	3.5038124	3.3823800	3.3823800	0.5456598
##	[2,]	4.0349195	7.0160878	7.0160878	6.8946554	6.8946554	4.0579352
##	[3,]	3.9167229	6.8978911	6.8978911	6.7764587	6.7764587	3.9397385
##	[4,]	14.4268713	17.4080395	17.4080395	17.2866071	17.2866071	14.4498869
##	[5,]	3.3021002	6.2832684	6.2832684	6.1618360	6.1618360	3.3251158
##	[6,]	2.9711495	5.9523177	5.9523177	5.8308853	5.8308853	2.9941651
##	[7,]	155.6557805	158.6369487	158.6369487	158.5155163	158.5155163	155.6787961
##	[8,]	124.5818746	127.5630428	127.5630428	127.4416104	127.4416104	124.6048902
##	[9,]	3.0649281	6.0460963	6.0460963	5.9246639	5.9246639	3.0879437
##	[10,]	41.7338850	44.7150532	44.7150532	44.5936208	44.5936208	41.7569006
##	[11,]	42.2066717	45.1878399	45.1878399	45.0664075	45.0664075	42.2296873
##	[12,]	62.4340627	65.4152309	65.4152309	65.2937985	65.2937985	62.4570783
##	[13,]	62.4340627	65.4152309	65.4152309	65.2937985	65.2937985	62.4570783
##	[14,]	62.4340627	65.4152309	65.4152309	65.2937985	65.2937985	62.4570783
##	[15,]	15.6088380	18.5900062	18.5900062	18.4685739	18.4685739	15.6318537
##	[16,]	44.6775450	47.6587133	47.6587133	47.5372809	47.5372809	44.7005607

##	[17,]	41.7181254	44.6992936	44.6992936	44.5778613	44.5778613	41.7411411
##	[18,]	34.8128130	37.7939812	37.7939812	37.6725488	37.6725488	34.8358286
##	[19,]	32.9956255	35.9767937	35.9767937	35.8553614	35.8553614	33.0186411
##	[20,]	15.0889773	18.0701455	18.0701455	17.9487132	17.9487132	15.1119930
##	[21,]	15.0889773	18.0701455	18.0701455	17.9487132	17.9487132	15.1119930
##	[22,]	29.8804470	32.8616152	32.8616152	32.7401828	32.7401828	29.9034626
##	[23,]	29.8804470	32.8616152	32.8616152	32.7401828	32.7401828	29.9034626
##	[24,]	27.3070386	30.2882068	30.2882068	30.1667745	30.1667745	27.3300543
##	[25,]	26.1811725	29.1623407	29.1623407	29.0409083	29.0409083	26.2041881
##	[26,]	2.1353098	1.8911468	1.8911468	4.9950457	4.9950457	2.1583255
##	[27,]	4.0264566	3.7822936	3.7822936	6.8861925	6.8861925	4.0494723
##	[28,]	23.3039590	26.2851272	26.2851272	26.1636948	26.1636948	23.3269746
##	[29,]	4.9642604	8.9907170	8.9907170	8.8692846	8.8692846	6.0325644
##	[30,]	4.9642604	8.9907170	8.9907170	8.8692846	8.8692846	6.0325644
##	[31,]	NA	4.0264566	4.0264566	3.9050243	3.9050243	1.0683040
##	[32,]	4.0264566	NA	0.2363934	6.8861925	6.8861925	4.0494723
##	[33,]	4.0264566	0.2363934	NA	6.8861925	6.8861925	4.0494723
##	[34,]	3.9050243	6.8861925	6.8861925	NA	0.2363934	2.8367202
##	[35,]	3.9050243	6.8861925	6.8861925	0.2363934	NA	2.8367202
##	[36,]	1.0683040	4.0494723	4.0494723	2.8367202	2.8367202	NA
##	[37,]	3.9050243	6.8861925	6.8861925	0.2363934	0.2363934	2.8367202
##	[,37]						
##	[1,]	3.3823800					
##	[2,]	6.8946554					
##	[3,]	6.7764587					
##	[4,]	17.2866071					
##	[5,]	6.1618360					
##	[6,]	5.8308853					
##	[7,]	158.5155163					
##	[8,]	127.4416104					
##	[9,]	5.9246639					
##	[10,]	44.5936208					
##	[11,]	45.0664075					
##	[12,]	65.2937985					
##	[13,]	65.2937985					
##	[14,]	65.2937985					
##	[15,]	18.4685739					
##	[16,]	47.5372809					
##	[17,]	44.5778613					
##	[18,]	37.6725488					
##	[19,]	35.8553614					
##	[20,]	17.9487132					
##	[21,]	17.9487132					
##	[22,]	32.7401828					
##	[23,]	32.7401828					
##	[24,]	30.1667745					
##	[25,]	29.0409083					
##	[26,]	4.9950457					
##	[27,]	6.8861925					
##	[28,]	26.1636948					
##	[29,]	8.8692846					
##	[30,]	8.8692846					
##	[31,]	3.9050243					
##	[32,]	6.8861925					



```
## [33,] 6.8861925
## [34,] 0.2363934
## [35,] 0.2363934
## [36,] 2.8367202
## [37,] NA
## attr(,"nodes")
## [1] 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
## [26] 26 27 28 29 30 31 32 33 34 35 36 37
```

```
# weighted diameter
max(as.dist(distance_w(el)))
```

```
## [1] 279.1924
```

```
# Clustering coefficients
clustering_w (el, measure=c("am", "gm", "mi", "ma", "bi"))
```

```
##          am          gm          mi          ma          bi
## 0.5998273 0.6424118 0.7060165 0.5794246 0.1920000
```

## PART 3: *Permutate Link Weights*

### Walktrap algorithm breakdown with one iteration

```
# Modularity by the WalkTrap algorithm
dolphin_walk <- cluster_walktrap(dolphin_ig, weights = E(dolphin_ig)$weight,
                                steps = 4, merges = TRUE, modularity = TRUE, membership = TRUE)
## Modularity Q-value
modularity(dolphin_walk)
```

```
## [1] 0.7902111
```

```
## Number of modules
groups(dolphin_walk)
```

```
## $'1'
## [1] "FB56" "V2V2" "DRSN" "FB84"
##
## $'2'
## [1] "X"      "FB94" "FB51"
##
## $'3'
## [1] "F24A" "FB26" "F154" "FB58" "FB60"
##
## $'4'
## [1] "FB82" "FB91"
##
## $'5'
## [1] "FB04" "FB05"
```

```

##
## $'6'
## [1] "C571" "FB57"
##
## $'7'
## [1] "C711" "FB71"
##
## $'8'
## [1] "P3P3" "P6P6"
##
## $'9'
## [1] "C511" "FB13" "FB54"
##
## $'10'
## [1] "R1R1" "R2R2" "R4R4"
##
## $'11'
## [1] "U0U0"
##
## $'12'
## [1] "R3R3"
##
## $'13'
## [1] "FB17"
##
## $'14'
## [1] "FB28"
##
## $'15'
## [1] "SIMO"
##
## $'16'
## [1] "P2P2"
##
## $'17'
## [1] "P9P9"
##
## $'18'
## [1] "W1W1"
##
## $'19'
## [1] "SLIF"

```

```

## Membership of modules
membership(dolphin_walk)

```

```

##      X F24A FB26 FB04 F154 FB58 U0U0 R3R3 FB60 C571 FB57 R1R1 R2R2 R4R4 FB05 FB17
##      2   3   3   5   3   3   11  12   3   6   6   10  10  10   5  13
## FB28 SIMO P2P2 P3P3 P6P6 C711 FB71 P9P9 W1W1 FB56 V2V2 SLIF FB82 FB91 FB94 DRSN
##     14  15  16   8   8   7   7  17  18   1   1  19   4   4   2   1
## FB84 C511 FB13 FB51 FB54
##     1   9   9   2   9

```

```
## Save the edgelist into a new object
auxrand <- as.data.frame(el)
## Link weight distribution
auxrand$vw
```

```
## [1] 0.010364683 0.006118547 0.017001546 0.067288204 0.096545984 0.001523810
## [7] 0.001905488 0.092984641 0.005736138 0.003052270 0.003818251 0.003818251
## [13] 0.003818251 0.011149558 0.005353728 0.005738332 0.006893910 0.007279693
## [19] 0.016228748 0.016228748 0.008052147 0.008052147 0.008825787 0.009213052
## [25] 0.146585472 0.009600614 0.010376633 0.010765090 0.010765090 0.452302632
## [31] 0.018597443 0.018597443 0.023753894 0.023753894 0.433224756 0.023753894
## [37] 0.010364683 0.750000000 0.125000000 0.222222222 0.125000000 0.006118547
## [43] 0.750000000 0.142857143 0.250000000 0.142857143 0.017001546 0.200000000
## [49] 0.067288204 0.125000000 0.142857143 0.714285714 0.111111111 0.096545984
## [55] 0.222222222 0.250000000 0.714285714 0.200000000 0.001523810 0.001905488
## [61] 0.092984641 0.125000000 0.142857143 0.111111111 0.200000000 0.005736138
## [67] 0.500000000 0.003052270 0.500000000 0.003818251 1.000000000 1.000000000
## [73] 0.003818251 1.000000000 1.000000000 0.003818251 1.000000000 1.000000000
## [79] 0.011149558 0.200000000 0.005353728 0.005738332 0.006893910 0.007279693
## [85] 0.016228748 1.000000000 0.016228748 1.000000000 0.008052147 1.000000000
## [91] 0.008052147 1.000000000 0.008825787 0.009213052 0.146585472 0.125000000
## [97] 0.035714286 0.125000000 0.125000000 0.009600614 0.125000000 0.010376633
## [103] 0.010765090 1.000000000 0.047619048 0.010765090 1.000000000 0.047619048
## [109] 0.452302632 0.035714286 0.047619048 0.047619048 0.018597443 0.125000000
## [115] 1.000000000 0.018597443 0.125000000 1.000000000 0.023753894 1.000000000
## [121] 0.083333333 1.000000000 0.023753894 1.000000000 0.083333333 1.000000000
## [127] 0.433224756 0.083333333 0.083333333 0.083333333 0.023753894 1.000000000
## [133] 1.000000000 0.083333333
```

```
# Permutate the link weights
sample(auxrand$vw)
```

```
## [1] 0.011149558 1.000000000 0.018597443 0.125000000 0.016228748 0.001523810
## [7] 0.009600614 0.016228748 0.200000000 0.018597443 0.200000000 0.452302632
## [13] 0.003818251 0.010765090 0.125000000 1.000000000 1.000000000 0.010376633
## [19] 0.125000000 0.125000000 0.146585472 0.035714286 0.003818251 0.200000000
## [25] 1.000000000 0.005738332 0.007279693 0.092984641 0.452302632 0.083333333
## [31] 0.010364683 0.222222222 0.096545984 0.011149558 0.035714286 0.023753894
## [37] 1.000000000 0.003052270 0.092984641 0.023753894 0.018597443 0.003818251
## [43] 0.010765090 0.023753894 0.023753894 0.007279693 0.111111111 0.142857143
## [49] 0.125000000 0.008825787 0.222222222 0.005736138 0.146585472 0.433224756
## [55] 0.083333333 0.125000000 0.006118547 0.433224756 0.010765090 1.000000000
## [61] 1.000000000 0.010765090 0.005738332 1.000000000 0.008052147 0.016228748
## [67] 0.008052147 0.125000000 0.096545984 0.125000000 0.006893910 0.016228748
## [73] 0.714285714 1.000000000 0.142857143 0.047619048 0.010376633 0.750000000
## [79] 0.047619048 0.008052147 0.125000000 0.001905488 0.023753894 0.083333333
## [85] 0.003818251 1.000000000 0.714285714 0.001905488 1.000000000 1.000000000
## [91] 0.003818251 0.017001546 0.003052270 0.750000000 1.000000000 0.500000000
## [97] 0.047619048 0.083333333 0.111111111 0.009600614 0.500000000 0.023753894
## [103] 0.067288204 1.000000000 1.000000000 0.010364683 0.142857143 0.067288204
## [109] 0.083333333 0.005736138 0.006893910 1.000000000 0.009213052 0.008825787
## [115] 0.006118547 0.005353728 0.142857143 1.000000000 0.200000000 0.008052147
## [121] 0.125000000 1.000000000 0.083333333 0.003818251 0.009213052 1.000000000
```

```
## [127] 0.250000000 0.001523810 1.000000000 0.250000000 0.017001546 0.005353728
## [133] 0.047619048 0.018597443
```

```
## Save in the auxrand object
auxrand[,3] <- sample(auxrand$vw)

# Calculate the modularity Q-value for a new permuted edge list
## Create a network from the list of nodes
igrand <- graph.edgelist(el[,1:2])
### Add link weights
E(igrand)$weight <- el[,3]
### Make undirected graph
igrand <- as.undirected(igrand)
## Permute the link weights
E(igrand)$weight <- sample(E(igrand)$weight)
## Calculate modularity Q-value
rmod <- walktrap.community(igrand)
modularity(rmod)
```

```
## [1] 0.4602569
```

```
## Number of modules
groups(rmod)
```

```
## $'1'
## [1] 1 6 9 10 11 12 20 21 22 23 29 30
##
## $'2'
## [1] 34 36
##
## $'3'
## [1] 13 14
##
## $'4'
## [1] 35 37
##
## $'5'
## [1] 26 27 31 32 33
##
## $'6'
## [1] 2 3 5
##
## $'7'
## [1] 4 15
##
## $'8'
## [1] 7
##
## $'9'
## [1] 8
##
## $'10'
## [1] 16
```

```
##
## $'11'
## [1] 17
##
## $'12'
## [1] 18
##
## $'13'
## [1] 19
##
## $'14'
## [1] 24
##
## $'15'
## [1] 25
##
## $'16'
## [1] 28
```

```
## Membership of modules
```

```
membership(rmod)
```

```
## [1] 1 6 6 7 6 1 8 9 1 1 1 1 3 3 7 10 11 12 13 1 1 1 1 14 15
## [26] 5 5 16 1 1 5 5 5 2 4 2 4
```

```
# Difference from our empirical data?
```

```
modularity(dolphin_walk)
```

```
## [1] 0.7902111
```

```
modularity(rmod)
```

```
## [1] 0.4602569
```

## Permutate with multiple iterations

```
# Run modularity permutations 1000 times
iter = 1000
randmod = numeric()
for(i in 1:iter){
  # Save the edgelist into a new object
  auxrand <- el
  # igraph format
  igrand <- graph.edgelist(auxrand[,1:2]) # Create a network from the list of nodes
  E(igrand)$weight <- auxrand[,3] # Add link weights
  igrand <- as.undirected(igrand) # Make undirected graph
  # Permutate the link weights
  E(igrand)$weight <- sample(E(igrand)$weight)
  # calculate the modularity Q-value
  rand_walk <- walktrap.community(igrand)
```

```

  randmod[i] <- modularity(rand_walk) # Save Q-value into a vector
}

```

```

## Distribution with 1000 null Q-values
randmod

```

```

##      [1] 0.5171748 0.4300684 0.7007415 0.4568077 0.3594379 0.5008437 0.4811102
##      [8] 0.4617872 0.5199467 0.5185528 0.5114216 0.5837503 0.4295210 0.5391194
##     [15] 0.4345433 0.4744606 0.4872899 0.5718467 0.4724098 0.5543256 0.5460609
##     [22] 0.5957352 0.4431167 0.6912780 0.5640377 0.3993362 0.5996544 0.4169459
##     [29] 0.3876370 0.6057007 0.5275946 0.2953769 0.5438104 0.5405549 0.4408585
##     [36] 0.5587495 0.4366781 0.4816719 0.4546138 0.6867356 0.4748745 0.6193597
##     [43] 0.5278463 0.5785549 0.6054991 0.4748521 0.4536405 0.4795004 0.5347518
##     [50] 0.4105023 0.3394685 0.5138406 0.4953095 0.4741432 0.4727225 0.6849684
##     [57] 0.4621990 0.6496412 0.5284069 0.4306324 0.5305660 0.3963881 0.5410795
##     [64] 0.6512100 0.5500250 0.5049452 0.4870192 0.5516849 0.3727132 0.4856367
##     [71] 0.5448020 0.4173201 0.3981020 0.6417934 0.4717618 0.6373219 0.3930455
##     [78] 0.4206561 0.5454587 0.4463322 0.3724287 0.5465937 0.4615367 0.5832197
##     [85] 0.6010079 0.4731842 0.4495155 0.4675518 0.4539824 0.6510121 0.4829411
##     [92] 0.5137513 0.3796128 0.4884976 0.3767941 0.6018431 0.4852015 0.5523516
##     [99] 0.5084513 0.6636508 0.4085124 0.5036960 0.5321121 0.5479035 0.4765265
##    [106] 0.4528815 0.6813905 0.5536230 0.5670294 0.4026898 0.5704951 0.6448987
##    [113] 0.3583328 0.4928901 0.5144163 0.3938069 0.6604638 0.5554304 0.4453395
##    [120] 0.4333098 0.4469982 0.3843253 0.4611773 0.5682747 0.5421932 0.5435151
##    [127] 0.5533472 0.4930006 0.4502255 0.6242864 0.4962710 0.6132307 0.5557315
##    [134] 0.4177874 0.5151290 0.5724729 0.4371606 0.4300124 0.4935751 0.3589289
##    [141] 0.4948185 0.4948337 0.3720916 0.2976147 0.3436004 0.3841591 0.4524958
##    [148] 0.6573395 0.4069469 0.4855918 0.4883309 0.5313990 0.3487669 0.5414356
##    [155] 0.5803503 0.4370637 0.4970852 0.5345003 0.5636114 0.4749662 0.4341250
##    [162] 0.5557097 0.4386753 0.6001101 0.6159450 0.3986095 0.3794799 0.6189309
##    [169] 0.5270722 0.4283843 0.5073379 0.4601774 0.5068996 0.5259471 0.4961690
##    [176] 0.5363385 0.5623602 0.4413284 0.4630513 0.6363494 0.5230722 0.5431515
##    [183] 0.5180775 0.5732063 0.6322984 0.3498582 0.5046283 0.3685442 0.4043041
##    [190] 0.3912677 0.3923682 0.4773557 0.4220311 0.4981369 0.4440703 0.3320231
##    [197] 0.4916849 0.3981106 0.5535911 0.3016962 0.4183110 0.5273097 0.4392951
##    [204] 0.5517427 0.4251350 0.5380239 0.3074545 0.3838727 0.4508772 0.5525811
##    [211] 0.3723664 0.5162587 0.5933504 0.5791473 0.5826135 0.4661019 0.4906781
##    [218] 0.6668141 0.4111999 0.5326640 0.3513073 0.4214403 0.5539238 0.4688016
##    [225] 0.3476502 0.6083875 0.3210500 0.5513117 0.5879088 0.5297390 0.4103811
##    [232] 0.1804083 0.5376854 0.5883780 0.5486681 0.4057800 0.5056940 0.4980078
##    [239] 0.3943257 0.3671157 0.4066083 0.5878880 0.6285661 0.3817011 0.5890012
##    [246] 0.4055666 0.5550537 0.6235135 0.4842048 0.4031747 0.5133154 0.5509641
##    [253] 0.5782881 0.4393473 0.3903583 0.4434203 0.5568115 0.4720793 0.4226436
##    [260] 0.4597491 0.4663250 0.5885699 0.4015385 0.5583724 0.5625180 0.5091952
##    [267] 0.4678548 0.3952550 0.4848690 0.5466279 0.4902851 0.6005499 0.5495117
##    [274] 0.6194161 0.4290078 0.4807920 0.4214253 0.5695096 0.3996859 0.2689673
##    [281] 0.6142584 0.3964875 0.2622396 0.4204817 0.5024080 0.3567693 0.6392543
##    [288] 0.5375887 0.5554012 0.6906638 0.5542871 0.5791040 0.5119582 0.5464469
##    [295] 0.4226069 0.5698038 0.6105762 0.4924764 0.4021904 0.4171449 0.4060778
##    [302] 0.5297780 0.3748482 0.3977613 0.5372761 0.3537350 0.4490443 0.3948672
##    [309] 0.6036377 0.3889171 0.6176447 0.4734656 0.4781465 0.4008860 0.4365597
##    [316] 0.4072444 0.6381260 0.3724948 0.4347150 0.4898809 0.5317708 0.6724362
##    [323] 0.4973221 0.7105388 0.4682981 0.4071453 0.6015664 0.5793250 0.5579108

```

```

## [330] 0.5985931 0.5721831 0.4314816 0.4865167 0.4731493 0.6885131 0.6451934
## [337] 0.5637687 0.3888593 0.4992764 0.4990621 0.4412030 0.5906734 0.3934674
## [344] 0.5737323 0.4590556 0.4911738 0.5390002 0.4640791 0.5806856 0.4662958
## [351] 0.5689327 0.6264437 0.4182613 0.5456951 0.4782222 0.5253090 0.5104673
## [358] 0.5006618 0.6362731 0.5045875 0.6670210 0.5418144 0.6100439 0.5344164
## [365] 0.5713542 0.5725448 0.3782379 0.4338450 0.6810528 0.6540162 0.5449103
## [372] 0.5405907 0.5534748 0.1859384 0.6128064 0.5823112 0.3918995 0.4195358
## [379] 0.5569637 0.3217458 0.4543127 0.5365732 0.6106344 0.6316913 0.5868698
## [386] 0.4969098 0.4424123 0.5336808 0.4220306 0.3278326 0.5383559 0.5876524
## [393] 0.4839031 0.4399295 0.6491419 0.6212798 0.4069929 0.4326647 0.4029791
## [400] 0.4569587 0.3790277 0.5561320 0.3979649 0.5636693 0.4916106 0.5445636
## [407] 0.5304912 0.3281549 0.6629969 0.5143063 0.4936781 0.4727131 0.5514092
## [414] 0.5061649 0.4487690 0.4791594 0.3892474 0.3957592 0.6314787 0.4383278
## [421] 0.4699599 0.4554066 0.5918632 0.4883874 0.5199452 0.4698736 0.5261950
## [428] 0.5120138 0.4705939 0.5845312 0.6233801 0.5486104 0.4676546 0.4309582
## [435] 0.6983952 0.4861769 0.6037505 0.4466547 0.5567175 0.5542476 0.3858195
## [442] 0.4408826 0.4330912 0.5886858 0.5044167 0.4539125 0.5681947 0.5506690
## [449] 0.4113821 0.6453682 0.4165469 0.5039452 0.4988991 0.4845920 0.4412371
## [456] 0.6247557 0.5072646 0.3722058 0.4790920 0.4814449 0.5205442 0.5191080
## [463] 0.6241550 0.6005546 0.5218161 0.4504014 0.5561761 0.4437924 0.5372037
## [470] 0.5266027 0.4523139 0.5897390 0.4798707 0.5051609 0.5290783 0.4322095
## [477] 0.4142540 0.5548032 0.5703044 0.5873132 0.5509903 0.5666213 0.4637184
## [484] 0.5437430 0.5529025 0.3168959 0.4043990 0.4142070 0.5495656 0.5175190
## [491] 0.4656030 0.5461458 0.3721592 0.6466184 0.6012905 0.4562405 0.4845991
## [498] 0.4813118 0.3642789 0.4981348 0.5265827 0.5937236 0.5205557 0.5149265
## [505] 0.5925330 0.5208554 0.6400705 0.6270498 0.5477497 0.4609152 0.4419587
## [512] 0.5413461 0.5455017 0.4058522 0.2826351 0.4837435 0.4377544 0.5431218
## [519] 0.5239276 0.4534991 0.4621776 0.4172866 0.4362542 0.5227870 0.5269910
## [526] 0.5409695 0.5064614 0.5385264 0.4623146 0.5751914 0.3031129 0.2857940
## [533] 0.4231796 0.4142595 0.5509847 0.4687889 0.2936027 0.5345390 0.3386157
## [540] 0.5515426 0.4508426 0.5109919 0.4423171 0.5599689 0.5553185 0.5866457
## [547] 0.3855377 0.5438030 0.3538213 0.4898297 0.5255697 0.5323754 0.4051456
## [554] 0.6158916 0.5394522 0.5539919 0.3033841 0.3816750 0.4796873 0.5436823
## [561] 0.5502468 0.3482430 0.4738091 0.4413789 0.5109418 0.5863754 0.5359208
## [568] 0.6801042 0.5054160 0.5209209 0.5368869 0.3625839 0.5354801 0.4558570
## [575] 0.6243145 0.5120615 0.4694113 0.5378753 0.5625774 0.4103640 0.3680722
## [582] 0.6413787 0.5041896 0.4764974 0.3828234 0.6709637 0.4238348 0.4984313
## [589] 0.5069910 0.4588875 0.5847682 0.3436416 0.3326981 0.4007524 0.5325920
## [596] 0.3229135 0.5948630 0.4602843 0.4888298 0.4852900 0.4197266 0.5409814
## [603] 0.3869800 0.5155666 0.6957136 0.4772637 0.5484009 0.6398735 0.4758774
## [610] 0.4607695 0.5431477 0.5745424 0.5614802 0.5996621 0.5858608 0.5956314
## [617] 0.5223898 0.5262163 0.5271073 0.4748636 0.5007091 0.5612714 0.4595860
## [624] 0.5079121 0.5953494 0.4936364 0.5559694 0.3921914 0.4957850 0.5358465
## [631] 0.4860286 0.5912801 0.4172422 0.5174722 0.6461511 0.6064554 0.4717014
## [638] 0.5813227 0.4559540 0.5694371 0.4896681 0.4956207 0.4136350 0.5706993
## [645] 0.4095122 0.6293625 0.5024540 0.4411515 0.6435569 0.4226363 0.4452910
## [652] 0.2698934 0.5754995 0.3763996 0.4312212 0.5336543 0.4433463 0.5927675
## [659] 0.5114881 0.5568622 0.5772539 0.4939134 0.4591021 0.5309229 0.4940065
## [666] 0.4600412 0.5704128 0.6396354 0.4955621 0.4866101 0.5472453 0.3814057
## [673] 0.5046482 0.4747259 0.4310108 0.5614244 0.5466402 0.4306739 0.4884092
## [680] 0.6094145 0.3708572 0.4814287 0.4693390 0.3116095 0.3548756 0.4513365
## [687] 0.5327243 0.4094155 0.6350320 0.4387772 0.5127070 0.4543345 0.4505172
## [694] 0.3551649 0.5229904 0.6338397 0.6184637 0.4677027 0.4920635 0.5350848
## [701] 0.6022445 0.4904556 0.6202459 0.4063207 0.3620939 0.5360857 0.4898026

```

```
## [708] 0.5598030 0.3399617 0.4200575 0.4170795 0.5791826 0.4736026 0.6346201
## [715] 0.4597759 0.5866818 0.4318681 0.5281615 0.4964381 0.4762225 0.4693402
## [722] 0.4547833 0.5009321 0.5370326 0.5210582 0.4529594 0.4661688 0.4699023
## [729] 0.4155461 0.5386193 0.4784289 0.3643688 0.3551602 0.4188272 0.2918869
## [736] 0.4731953 0.4192710 0.4866224 0.5518628 0.5191998 0.5761274 0.5132329
## [743] 0.4272669 0.4469001 0.5227026 0.4263170 0.6563013 0.5633553 0.5619063
## [750] 0.4896936 0.4573854 0.4872704 0.5074121 0.5298680 0.5607347 0.5621367
## [757] 0.5178480 0.6074863 0.3118878 0.4800486 0.5077410 0.4702846 0.5105770
## [764] 0.4940824 0.3465228 0.4133276 0.5321892 0.5142655 0.5294188 0.5352078
## [771] 0.6732431 0.5013402 0.5787380 0.4231277 0.4282222 0.5488461 0.5773522
## [778] 0.4651902 0.4508029 0.5124479 0.4177623 0.5165777 0.5613210 0.4096393
## [785] 0.5690163 0.5415294 0.4785155 0.3476921 0.4585151 0.5097185 0.4914470
## [792] 0.3406015 0.5996366 0.1937846 0.4634374 0.4914455 0.6321558 0.4573958
## [799] 0.3517474 0.5878572 0.4750518 0.4711138 0.4165999 0.6316798 0.5196761
## [806] 0.4957077 0.4485266 0.4556670 0.5605965 0.3839536 0.5626875 0.5318432
## [813] 0.4362564 0.5574563 0.5150806 0.6262784 0.4673672 0.5441616 0.5005616
## [820] 0.4829528 0.5724496 0.5668275 0.3760797 0.4431311 0.5877249 0.5930453
## [827] 0.4915314 0.4146995 0.4789551 0.4803484 0.4918363 0.4773928 0.5087914
## [834] 0.6033128 0.6237936 0.4188783 0.5464341 0.5343596 0.6438422 0.5894191
## [841] 0.4689410 0.5440590 0.6217689 0.4509047 0.3157520 0.5318491 0.6426388
## [848] 0.5329491 0.3942096 0.5726904 0.5610349 0.5023487 0.5916319 0.4371924
## [855] 0.3591050 0.4151571 0.4668607 0.3440780 0.5839940 0.4856585 0.6157600
## [862] 0.5857975 0.4295330 0.3975918 0.5030406 0.3163969 0.5456021 0.5810056
## [869] 0.4300054 0.5269327 0.4151660 0.4839731 0.5443251 0.4762506 0.5398543
## [876] 0.4910778 0.5958808 0.5302737 0.5174922 0.5531103 0.4072726 0.4443482
## [883] 0.5028289 0.6286101 0.4506251 0.3831839 0.4760993 0.5192869 0.3685163
## [890] 0.4193744 0.6684296 0.5628073 0.5295863 0.6238173 0.3974505 0.4245731
## [897] 0.4580544 0.3363141 0.3958931 0.3166240 0.4360262 0.4079046 0.3495396
## [904] 0.5062394 0.4710113 0.5877706 0.5669479 0.6157204 0.5772866 0.4888927
## [911] 0.5374402 0.5673125 0.4921816 0.3676086 0.4242580 0.5897658 0.3497099
## [918] 0.7031758 0.5774336 0.3853944 0.4588874 0.3998021 0.5168547 0.6339814
## [925] 0.3470432 0.5148057 0.5385822 0.5651441 0.3835311 0.4214085 0.4435443
## [932] 0.5287142 0.4596980 0.4233517 0.4271345 0.4179428 0.6307037 0.1949888
## [939] 0.3752681 0.4316173 0.5999312 0.4786174 0.5233916 0.5412773 0.2799346
## [946] 0.6326381 0.5754384 0.5569296 0.4478315 0.5646087 0.5395865 0.4719623
## [953] 0.3895497 0.3939969 0.6292964 0.4802669 0.5308426 0.5436904 0.5026687
## [960] 0.4656180 0.4862672 0.5181090 0.4139906 0.5404852 0.4527812 0.4831085
## [967] 0.3756537 0.5581961 0.4788500 0.5192314 0.3735095 0.5126699 0.5878144
## [974] 0.4581409 0.4067450 0.4318064 0.5868197 0.5578321 0.4789118 0.5408873
## [981] 0.5150666 0.4037180 0.4907246 0.3950211 0.5106959 0.4918319 0.5521395
## [988] 0.5346201 0.3205778 0.4865412 0.5087673 0.5568401 0.5637378 0.4963409
## [995] 0.5880523 0.4049163 0.4755271 0.4878224 0.4681121 0.7051653
```

```
## Calculate the 95% confidence interval (two-tailed test)
```

```
ci = quantile(randmod, probs=c(0.025, 0.975), type=2)
```

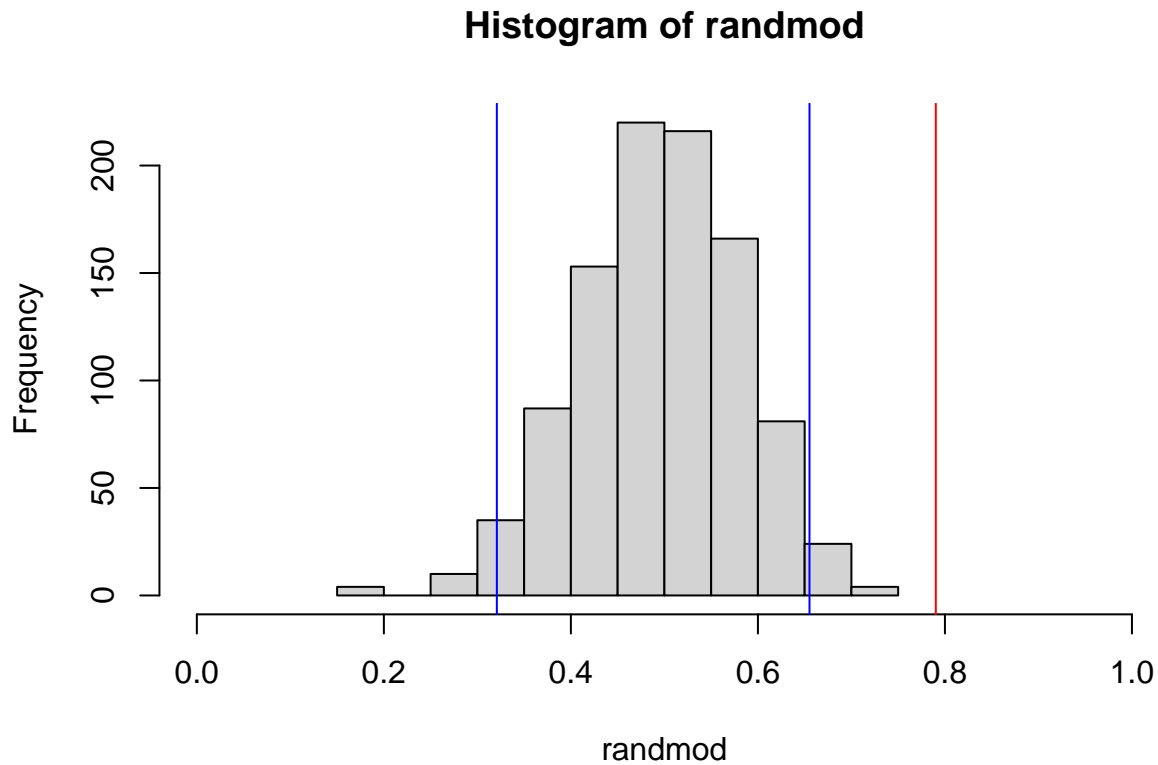
```
## Compare with the empirical Q-value
```

```
data.frame(Q=modularity(dolphin_walk), LowCI=ci[1], HighCI=ci[2])
```

```
##           Q      LowCI    HighCI
## 2.5% 0.7902111 0.3208139 0.6551588
```



```
## Visualization random Q distribution
hist(randmod, xlim=c(0,1))
### Empirical Q-value
abline(v= modularity(dolphin_walk), col="red")
### 2.5% CI
abline(v= ci[1], col="blue")
### 97.5% CI
abline(v= ci[2], col="blue")
```



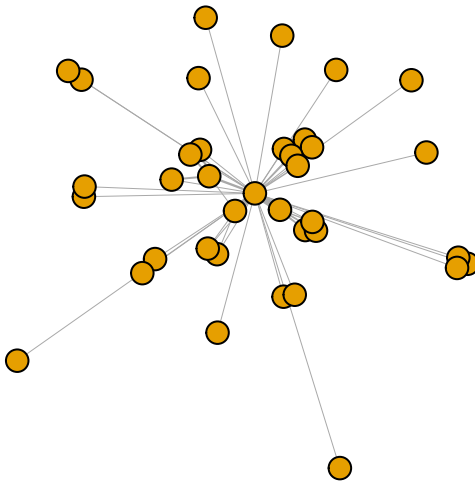
We can reject the null hypothesis that individuals cluster at random and conclude that there is evidence that modularity is higher than what we would expect by chance.

## PART 4: *Modularity*

- Newman's Q modularity: Stopping parameter Q removes links according to the betweenness.

```
# Create a network from the first two columns
dolph_ig <- graph.edgelist(el[,1:2])
# Add the edge weights to this network by assigning an edge attribute called 'weight'.
E(dolph_ig)$weight <- as.numeric(el[,3])
# Create undirect network
dolph_ig <- as.undirected(dolph_ig)
```

```
# Plot
plot(dolp_ig, edge.width=E(dolp_ig)$weight*4, vertex.size=10, vertex.label=NA, edge.curved=F)
```

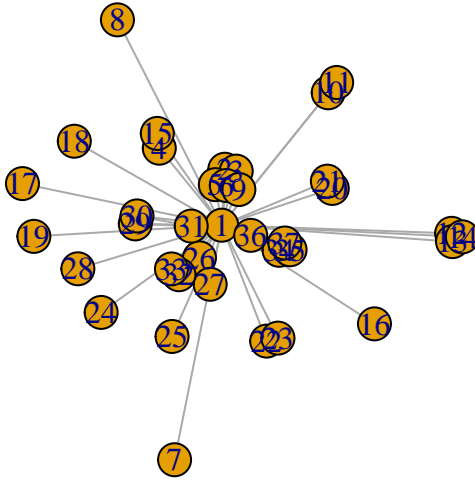


```
# Newman's Q modularity
newman <- cluster_leading_eigen(dolp_ig, steps = -1, weights = E(dolp_ig)$weight,
                                start = NULL, options = arpack_defaults, callback = NULL,
                                extra = NULL, env = parent.frame())

# Assign a random color to individuals of each module ('modules')
col <- rgb(runif(10), runif(10), runif(10))
newman$membership
```

```
## [1] 1 2 2 4 2 2 1 1 1 6 6 5 5 5 4 1 1 1 1 9 9 10 10 1 1
## [26] 1 1 1 8 8 1 7 7 3 3 1 3
```

```
plot(dolp_ig)
```



Since these modules can represent functional units, I need to test which mechanisms drive the modular topology by creating null models.