

# Introduction to Graph Theory

**Proteomes Interactomes and Biological Networks**

**Emidio Capriotti**

<http://biofold.org/>



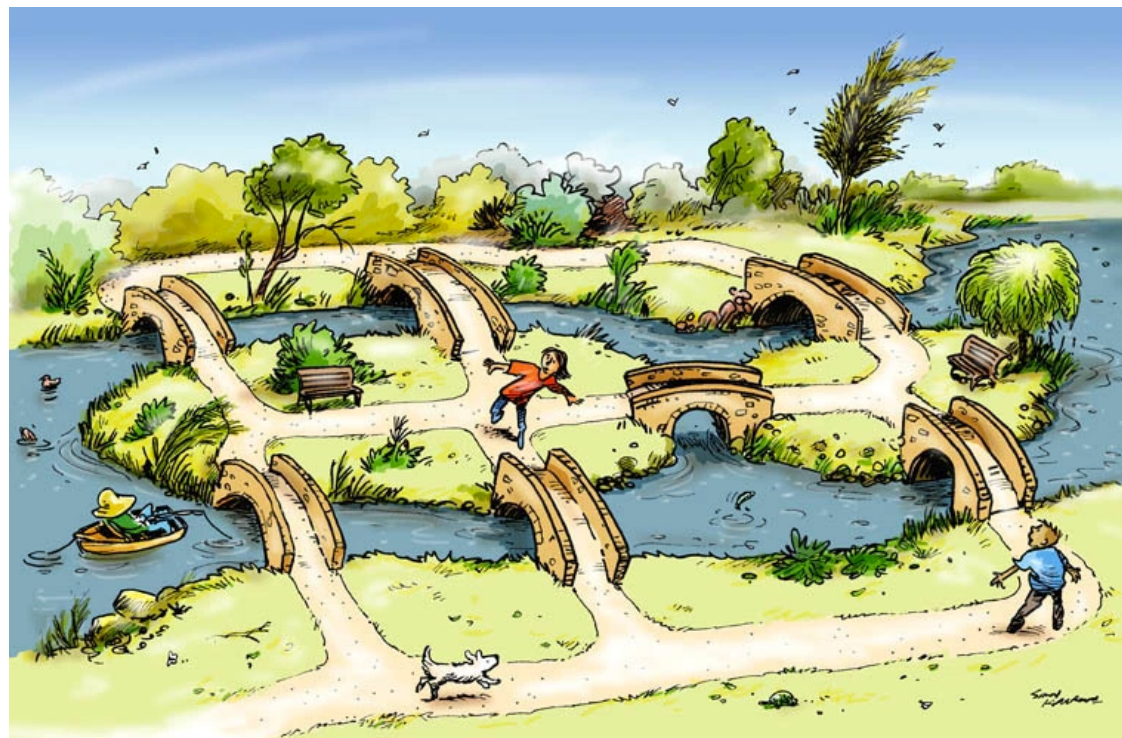
**Biomolecules  
Folding and  
Disease**

Department of Pharmacy and  
Biotechnology (FaBiT)  
University of Bologna



# Historical Perspective

With the **Seven Bridges of Königsberg** problem, Euler in 1737 laid the foundations of the graph theory.

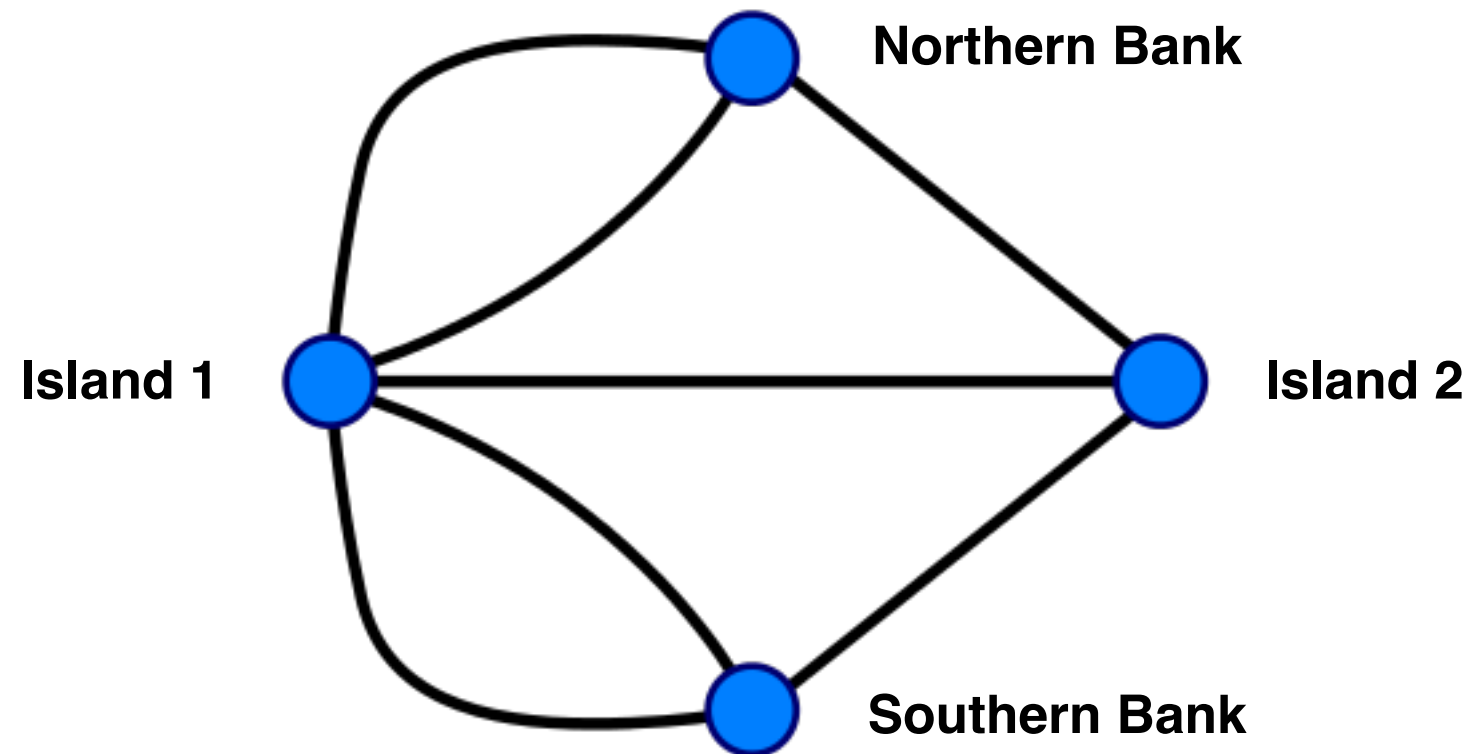


Simon Kneebone – [simonkneebone.com](http://simonkneebone.com)

- Find path (Eulerian Path) that **traverses all the Pregel's bridges**.
- Find walk (Eulerian Circuit) that **traverses all the Pregel's bridges** and has **the same starting and ending point**.

# Solution

Describe the problem as a graph where the **nodes represent the 4 locations** and the **edges correspond to the bridges**



Eulerian path exists only if **zero or 2 nodes** are connected by an **odd number of bridges**.

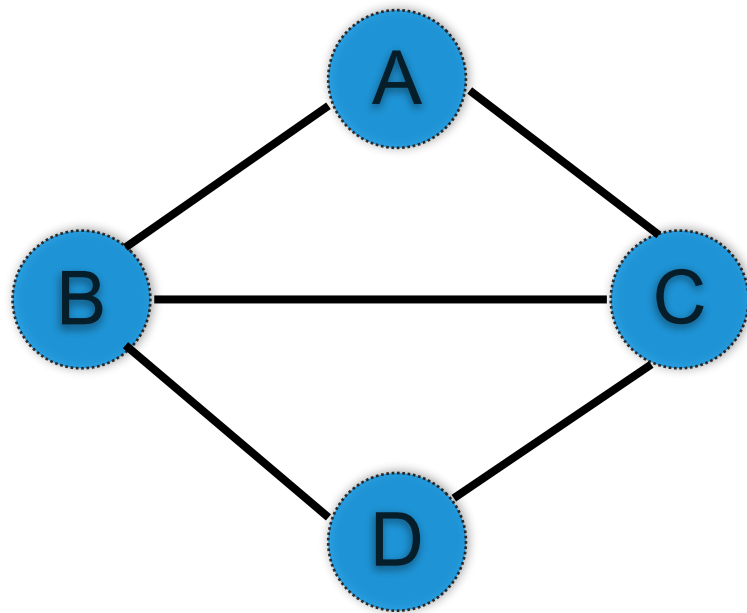
Eulerian circuit exists only if **zero nodes** are connected by an **odd number of bridges**.

# Graph Definition

A graph is a pair  $G=(V,E)$  consisting of two sets:

- $V$  is a set of elements called **Nodes or Vertices**.
- $E$  is a set of pairs  $(v_i, v_j)$  where  $v_i \in V$  and  $v_j \in V$ .

The pairs  $E$  are links between two nodes and are called **Edges**

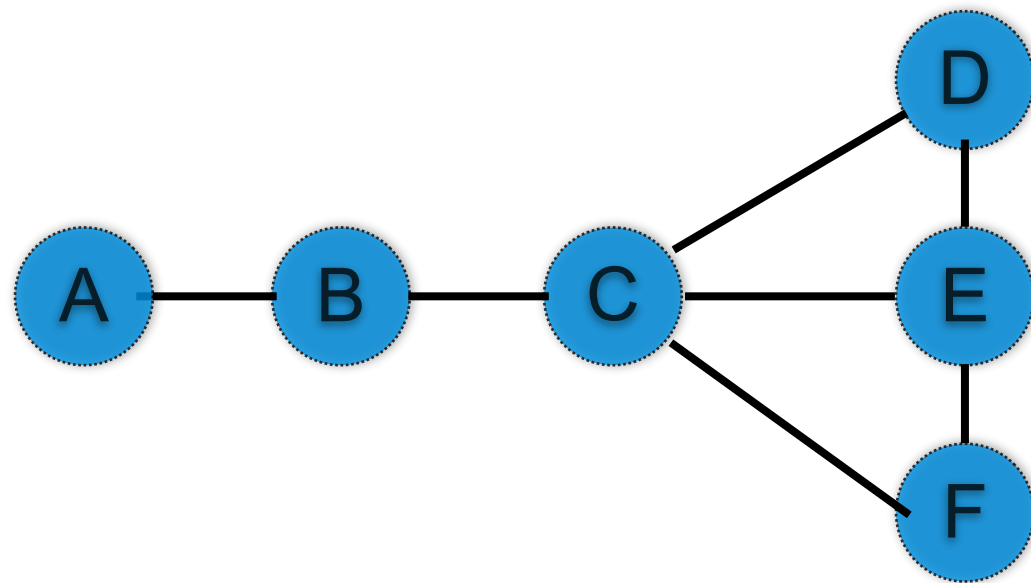


$$V = \{A; B; C; D\}$$

$$E = \{(A,B); (A,C); (B,C); (B,D); (C,D)\}$$

# Undirected Graph

**Undirected graph** is a network where the relationship between nodes are symmetric.

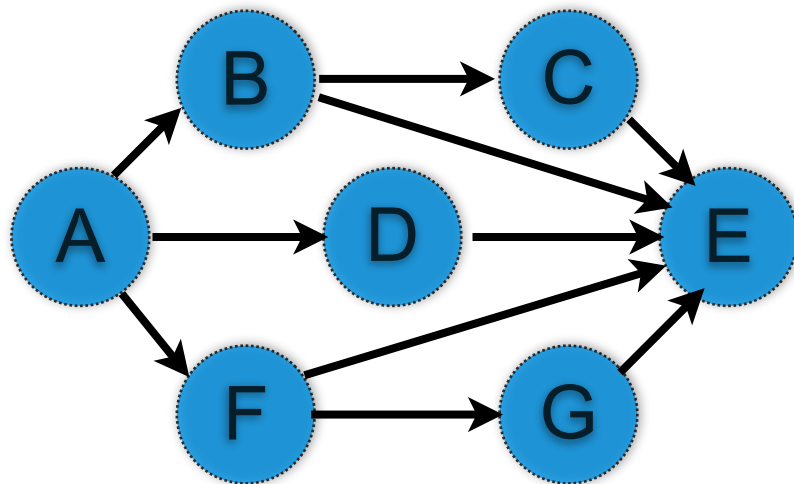
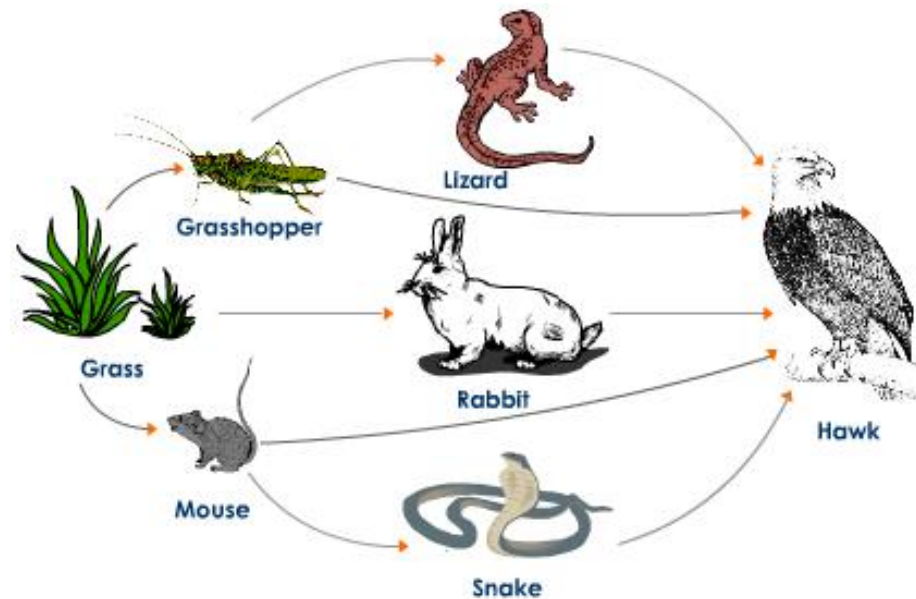


$V = \{\text{Group of People}\}$

$E = \{\text{Pairs of Friends}\}$

# Directed Graph

**Directed graph** is a network where the relationship between nodes are asymmetric. In this case the edges are directed lines.

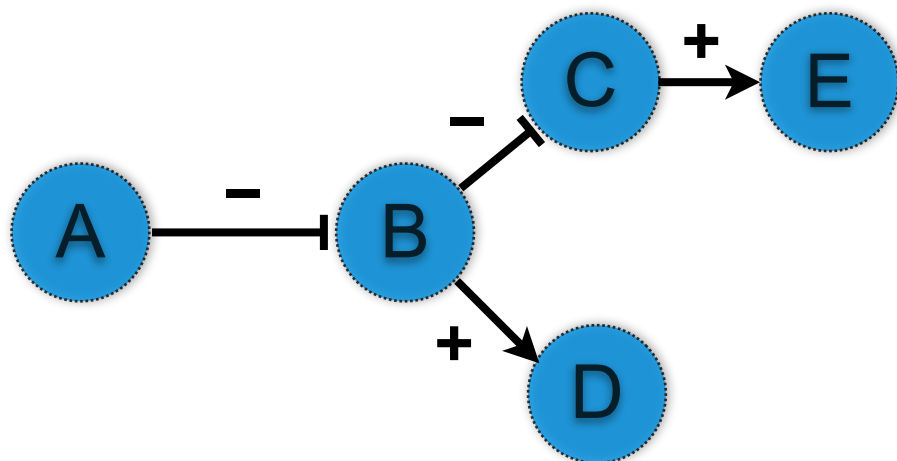
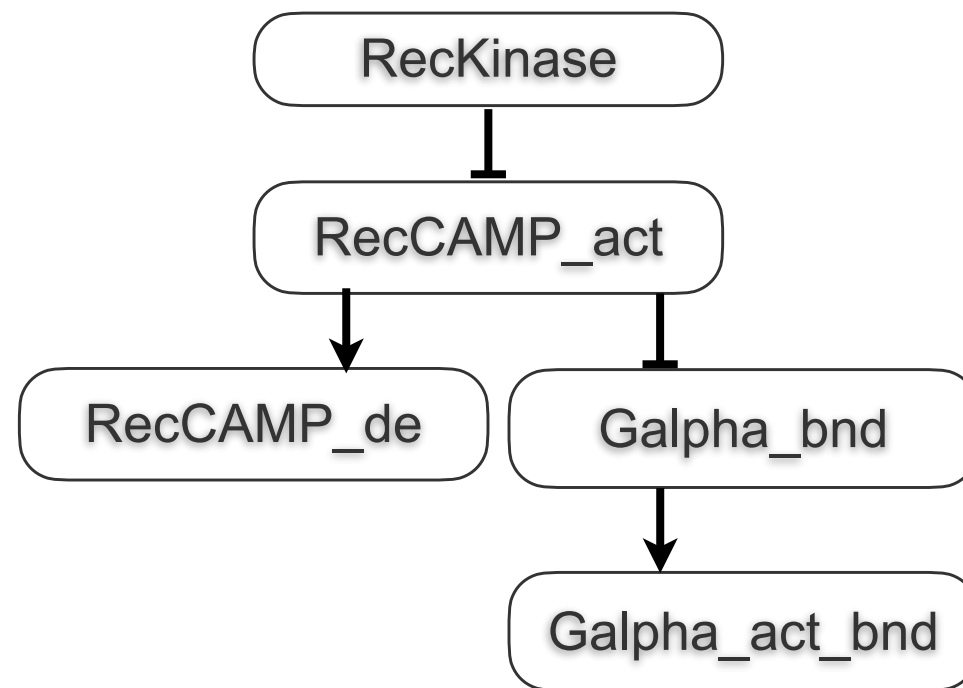


$V = \{\text{Group of Animals}\}$

$E = \{\text{Prey/Predator Relationships}\}$

# Signed Directed Graph

**Signed Directed graph** is a network where the relationship between nodes are asymmetric and have positive or negative associated signs



$V = \{\text{Group of Genes}\}$

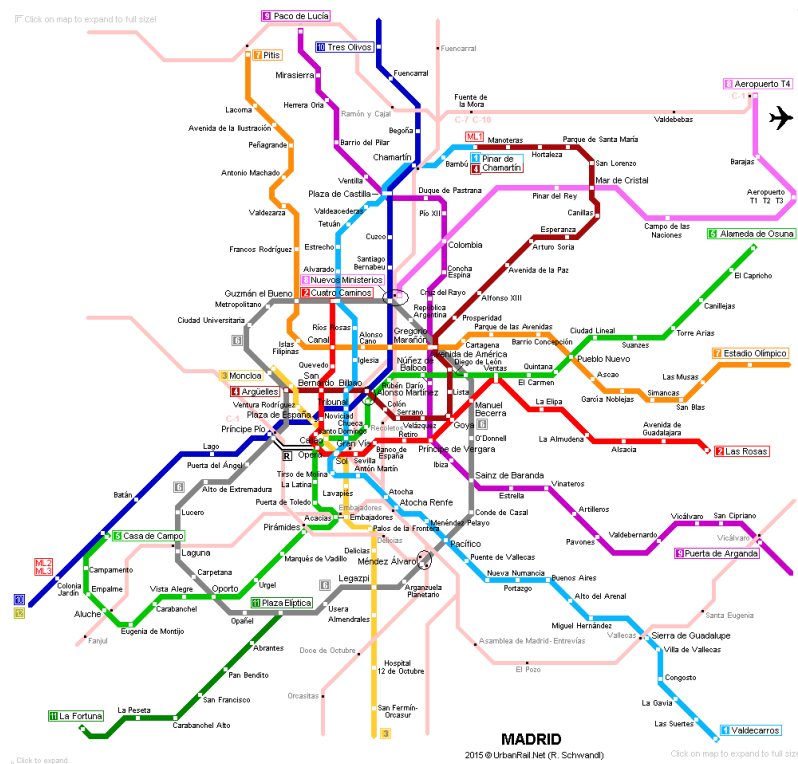
$E = \{\text{Activation/Inhibition Relationships}\}$



# Graph and Networks

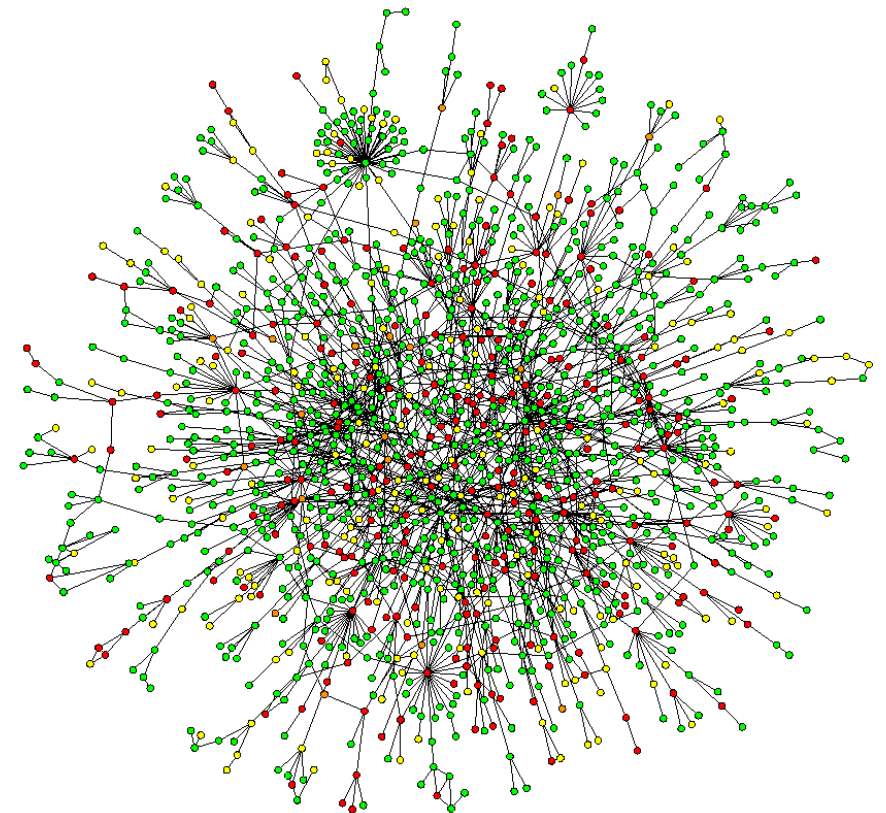
Graphs can be used to represent any observed network.

Networks in nature tend to be highly complex

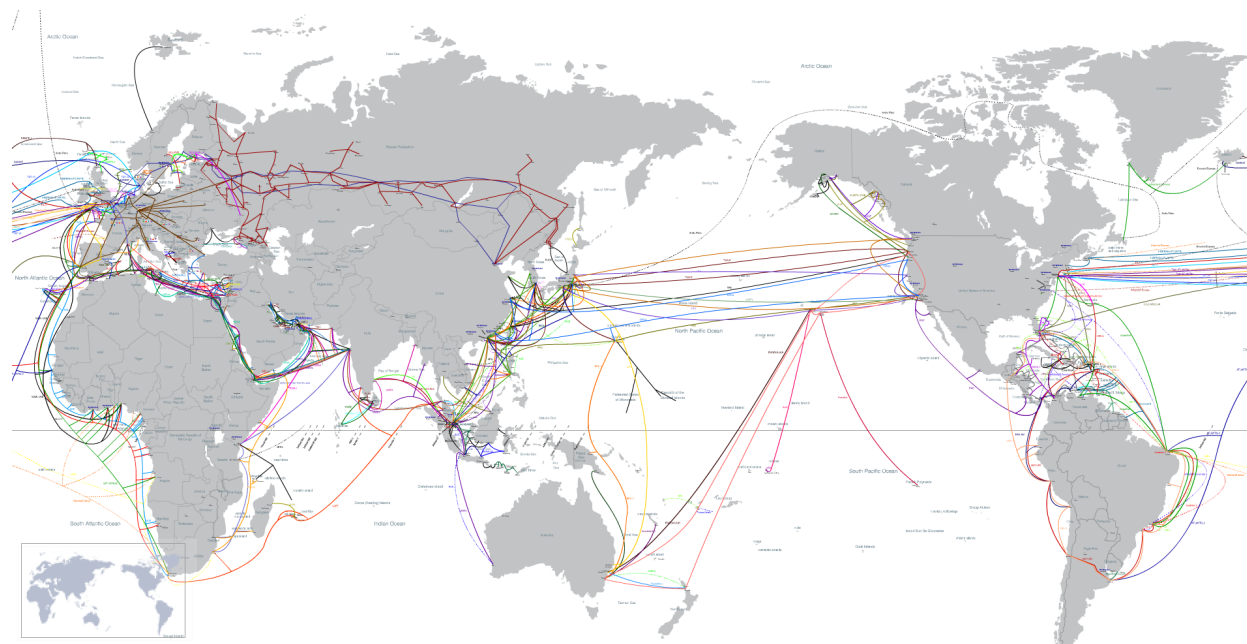


*Madrid Metro*

*Internet connections*



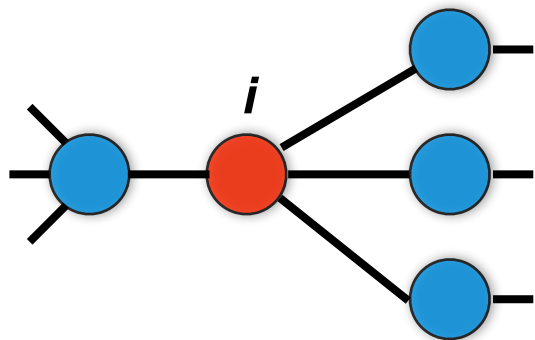
*Yeast interactome*



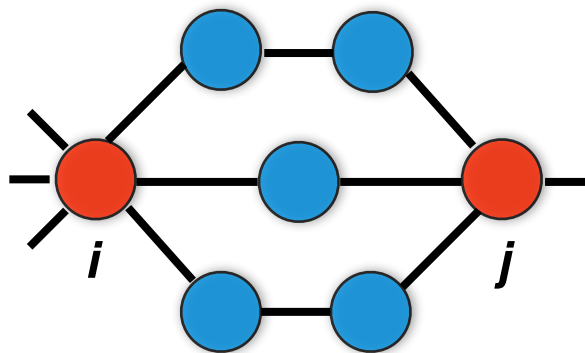


# Network properties (I)

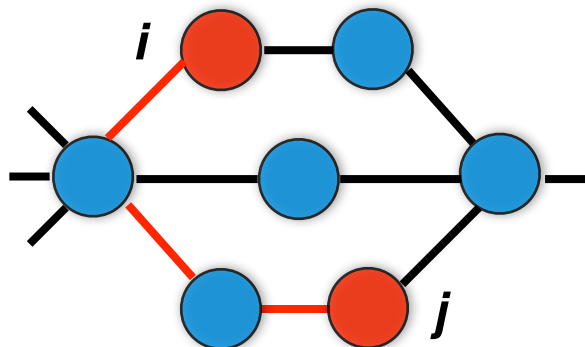
The **topology** of the network **defines its properties**. The level of **connectivity** among the nodes **depends on the number of edges**.



Degree  $k_i$  = number of links connected to node  $i$



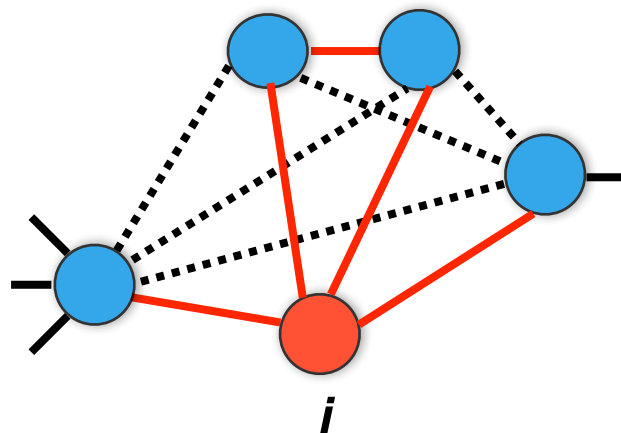
Distance  $d_{ij}$  = shortest path between nodes  $i$  and  $j$



Diameter  $D$  = longest path between all pairs of nodes

# Network properties (II)

The **topology** of the network **defines its properties**. The level of **connectivity** among the nodes **depends on the number of edges**.

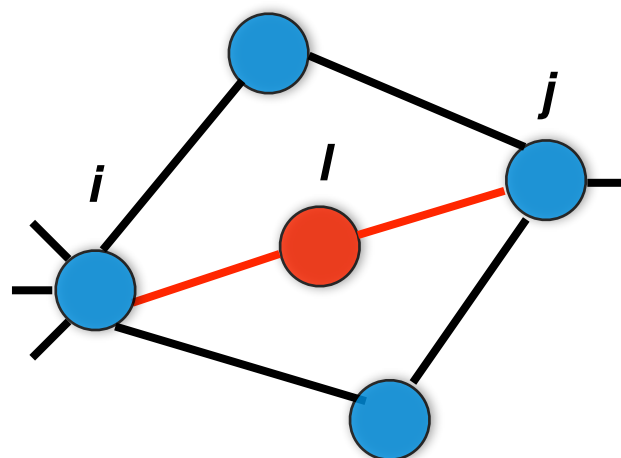


Transitivity  
or  
Clustering  
Coefficient

$$c_i = \frac{2e_i}{k_i(k_i - 1)}$$

$k_i$  = number of nodes connected to  $i$

$e_i$  = number of edges between the  $k_i$  nodes



Betweenness

$$g_l = \sum_{i \neq l \neq j} \frac{\sigma_{ij}(l)}{\sigma_{ij}}$$

$\sigma_{ij}$  = number of shortest path between  $i$  and  $j$

$\sigma_{ij}(l)$  = number of shortest path passing through node  $l$

# Types of Network

The **topology** of the network depends on the **distribution of the degree** for all the nodes.

We can define three types of network:

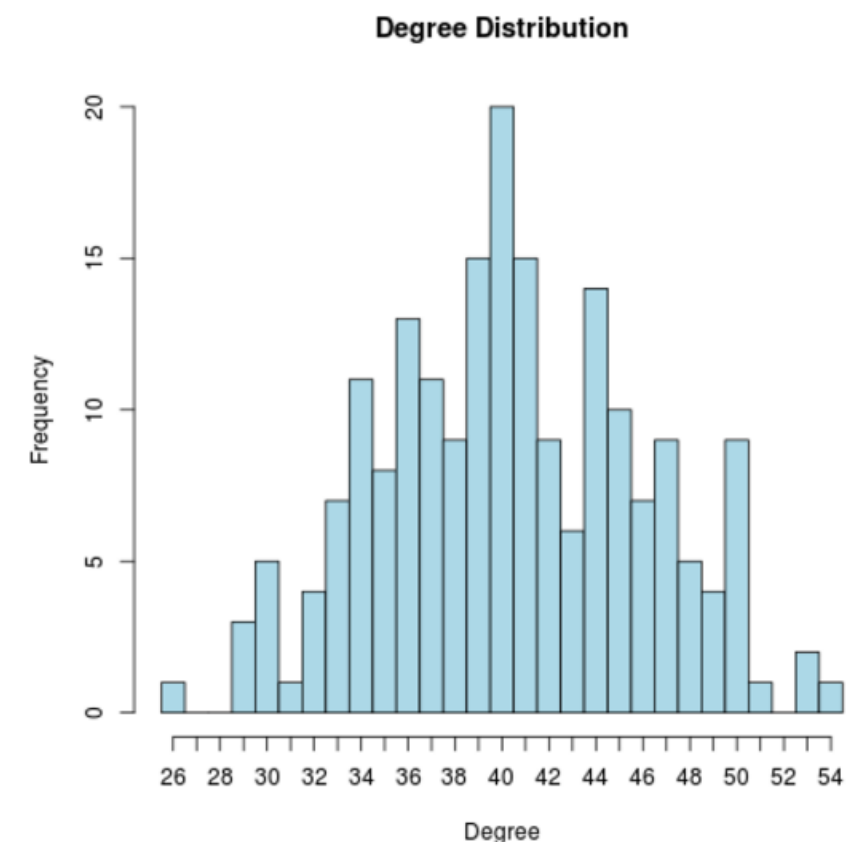
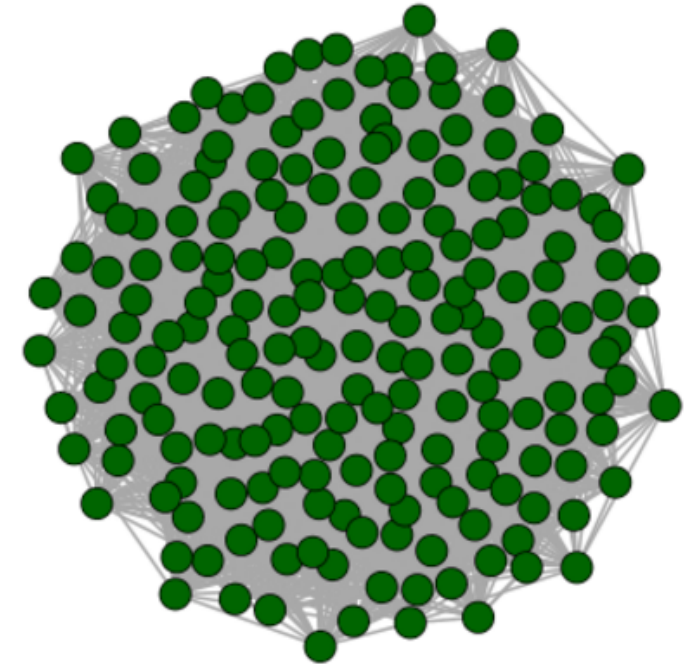
- **Random network**: generated by a constant probability of having an edge between two nodes.
- **Small-world network**: when the degrees follow a Poisson distribution
- **Scale-Free network**: the degrees follow a Power Law distribution

# Random Network

Can be generated by Erdős–Rényi model which assume a **constant probability of generating edges** between nodes.

- High node degree  $\Rightarrow$  **low average path length**
- Degree **distribution tends to be a Gaussian**
- High Transitivity
- Small Betweenness

Degree = 40.3  
Transitivity = 0.2  
Betweenness = 79.3



# Small-World Network

Generated by a Watts–Strogatz model.

- Low node degree  $\Rightarrow$  “Six degrees of separation”
- Degree follow a Poisson distribution
- Low Transitivity than random
- Higher betweenness than random

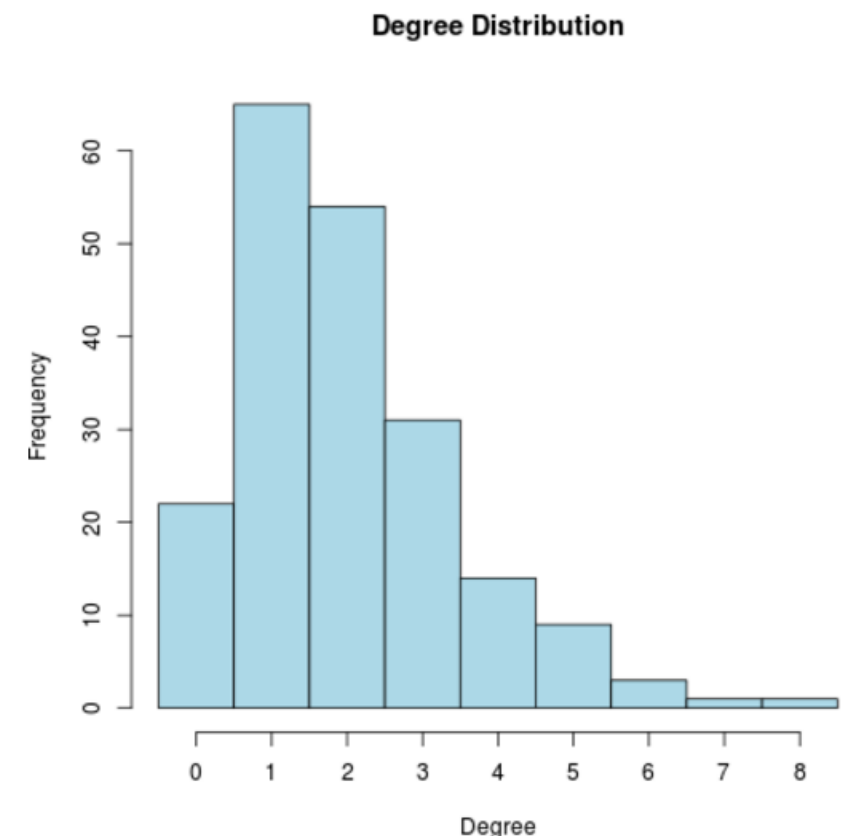
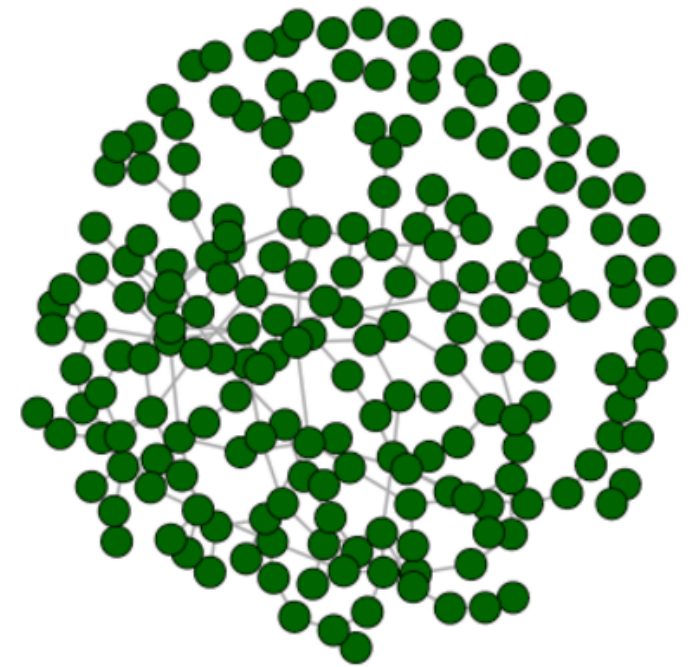
$$p(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

$\lambda$  = the average value of the distribution  
 $k$  = number of observed events

Degree = 2

Transitivity = 0.01

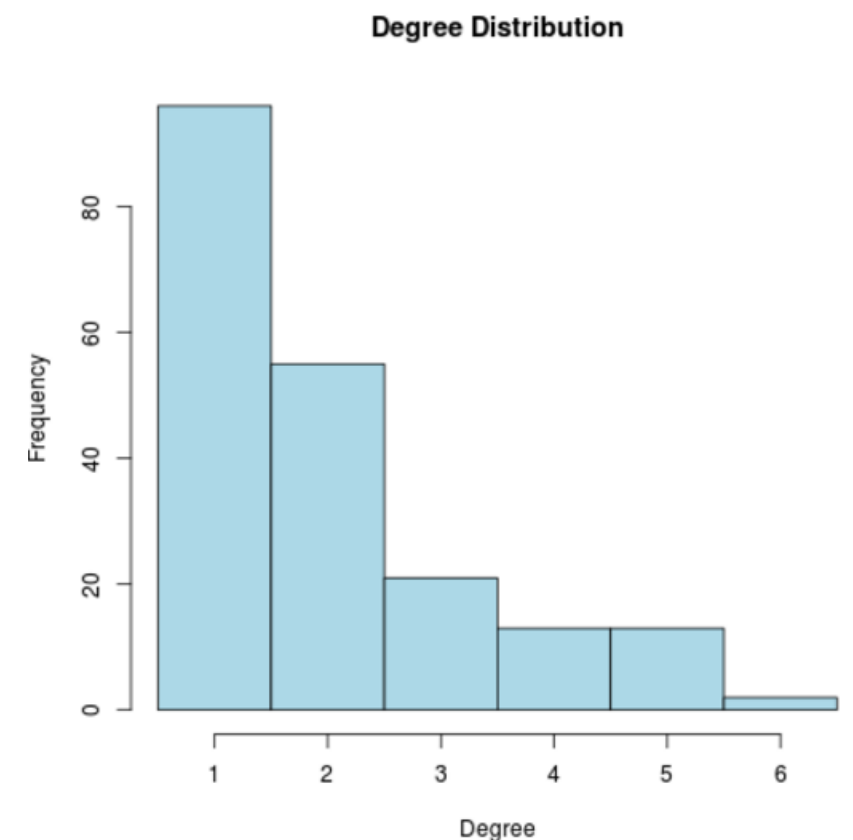
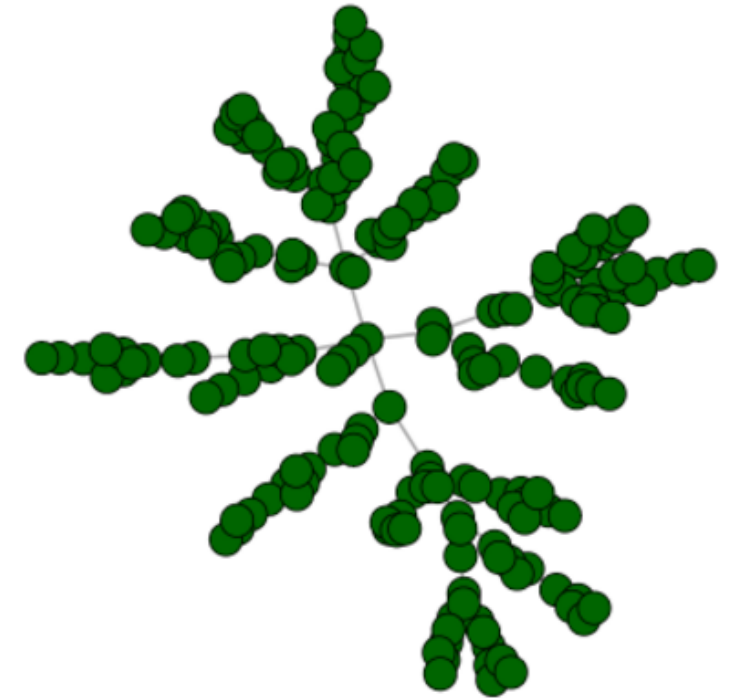
Betweenness = 394.9



# Scale-Free Network

Generated by the Barabasi-Albert model.

- Smallest degree
- Degree follow a Power Law distribution
- Lowest Transitivity
- Highest Betweenness



$$p(k) = Ax^{-k}$$

$x$  = is a constant  
 $k$  = number of observed events

Degree = 2

Transitivity = 0

Betweenness = 753.4



# Biological Network

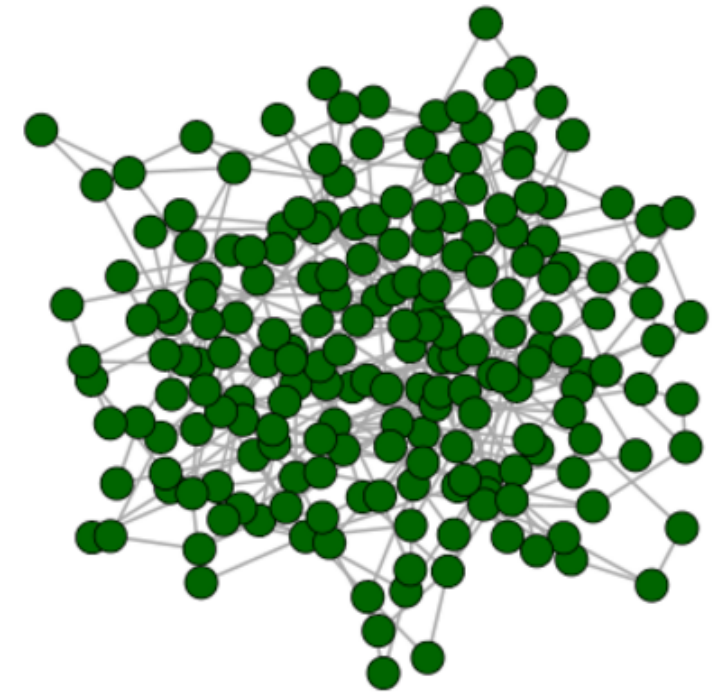
Similar to Small-World and Scale-Free networks

- Small degree
- Average path length proportional to  $\ln(\ln(\#nodes))$
- Transitivity high than Small-World and Scale Free
- Betweenness lower than Small-World and Scale Free

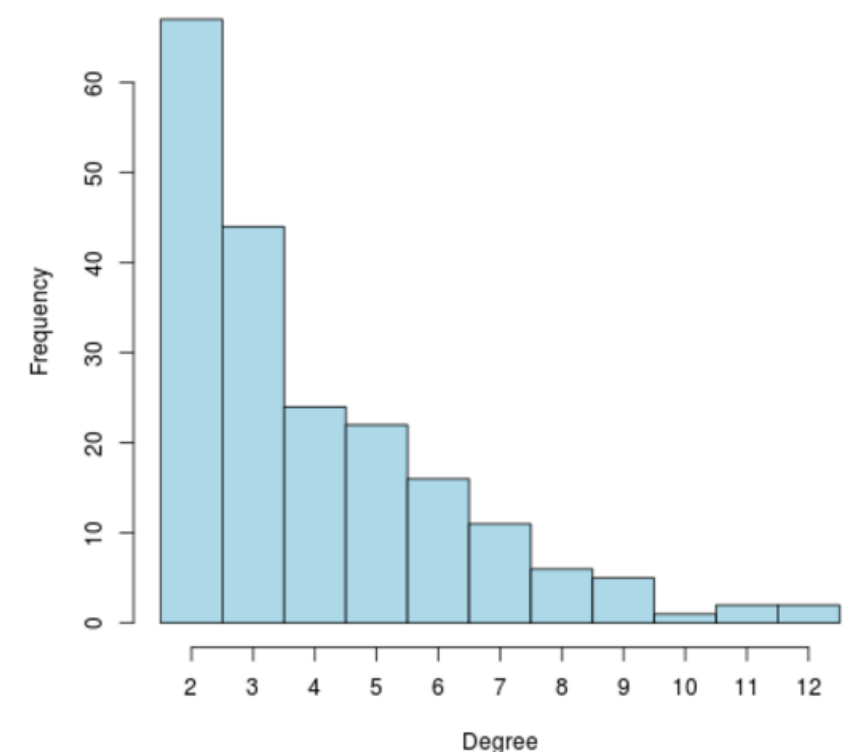
Degree = 4.0

Transitivity = 0.04

Betweenness = 290.4

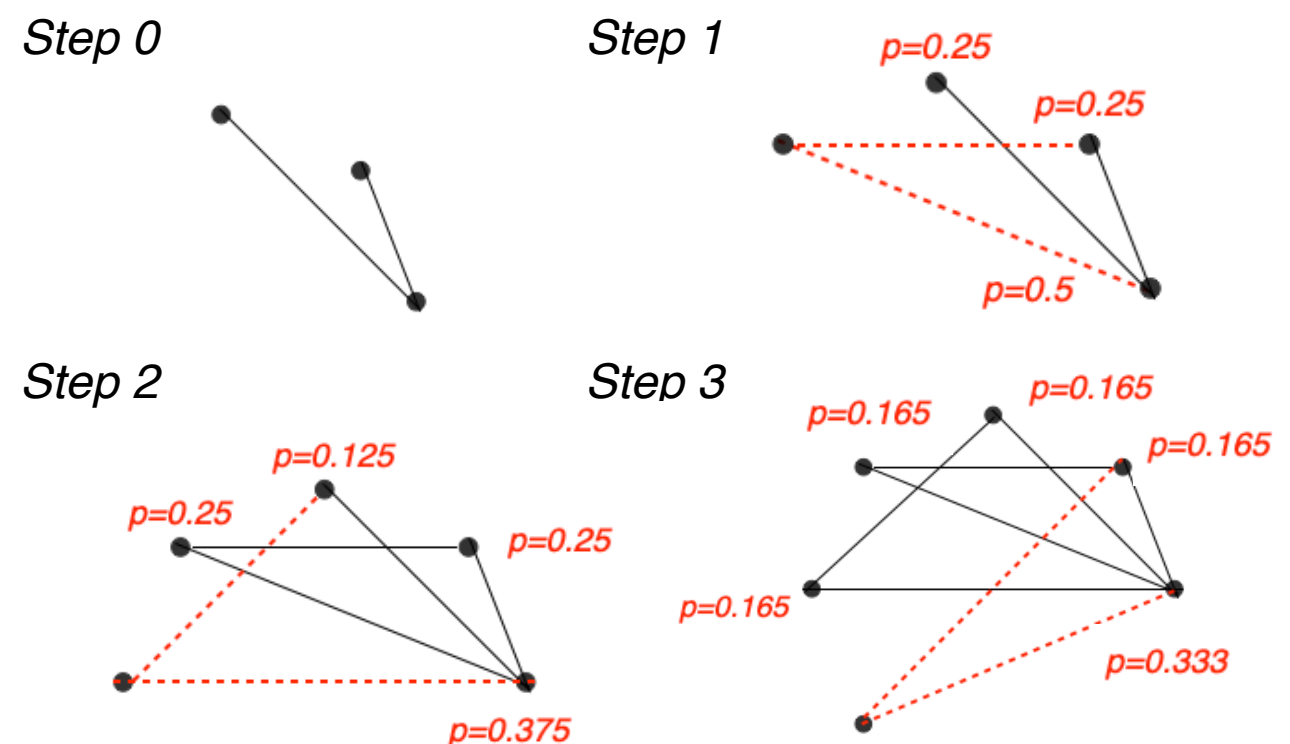


Degree Distribution



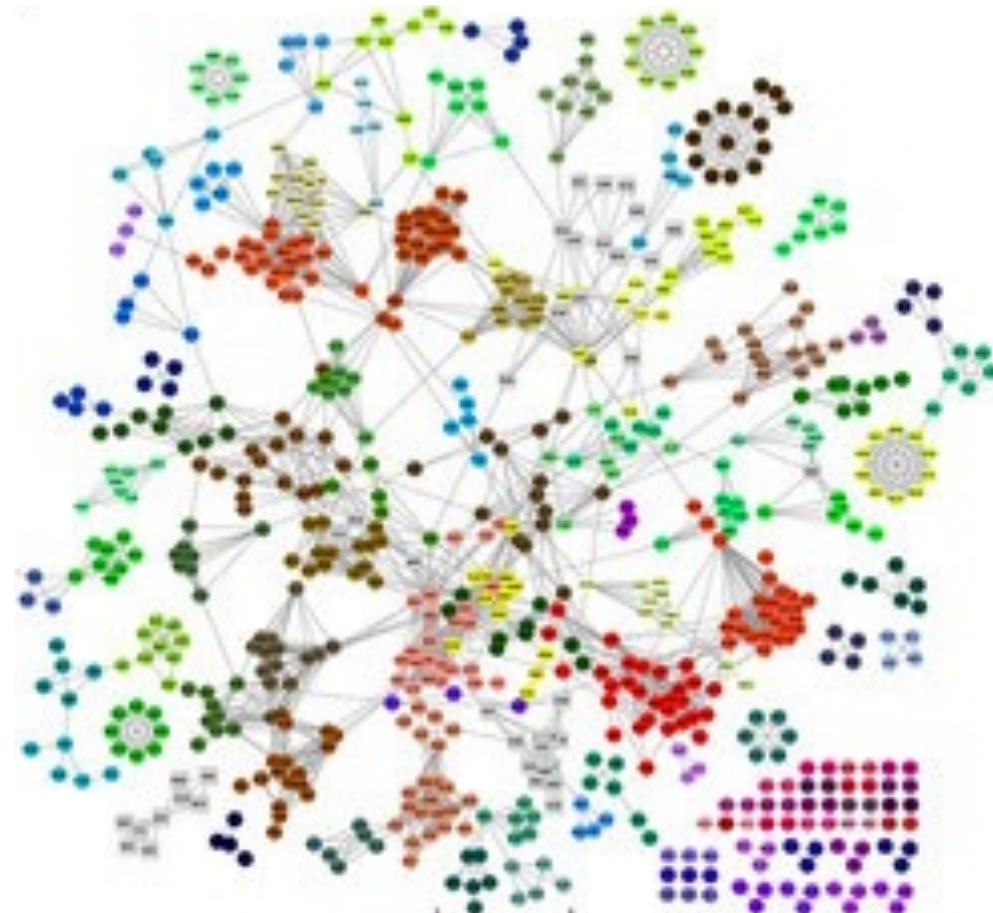
# Random Graph Generation

- **Random Graph:** Given a graph with  $N$  nodes and all the possible  $N \times (N-1)/2$  undirected edges select each of them with an independent probability  $P$
- **Small-World Graph:** Start with a  $N$  nodes, generate a regular graph connect each of them with  $k/2$  neighbors on each side. Rewire each of them with a probability  $P$ .
- **Scale-Free Graph:** Network of  $N$  nodes and  $kN$  edges. Start with  $k+1$  nodes. Add one node at the time connecting  $k$  edges to the previous nodes with probability proportional to the number of edges of each of them (see example with  $k=2$ ).



# Community or Cluster

One of the main feature of the biological network is the presence of subset of nodes densely interconnected (communities or clusters)



*Gaiter, Scientific Reports 2015*

Clusters are important to detect similarity between nodes (genes, diseases, etc) in the same cluster.

# Network Robustness

Robustness, the ability to withstand failures and perturbations. It is a critical attribute of many complex systems including biological networks.

Robustness is tested removing nodes and checking if connections between the remaining nodes are conserved. This is possible because may exist alternative paths between two distinct nodes.

Biological networks persists despite the environmental noise, mutations etc.

Telecommunication networks resist to the attack of hackers and hardware failure

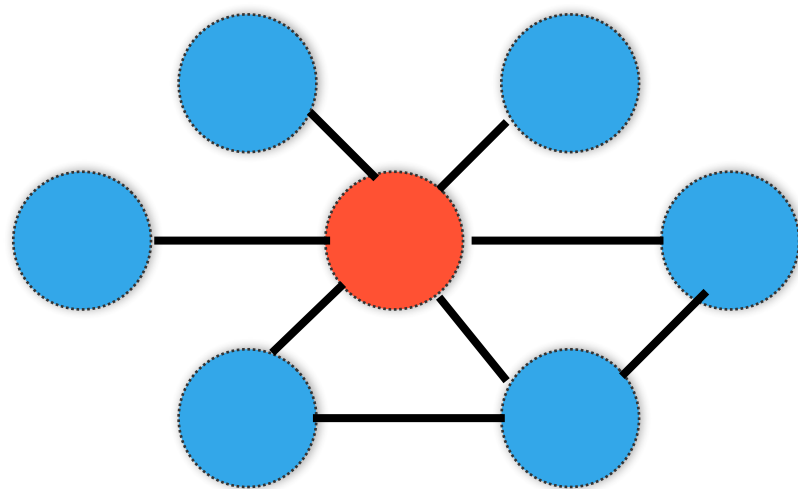
# Network Perturbation

For **random networks the effect** of removing a single node is **on average the same**.

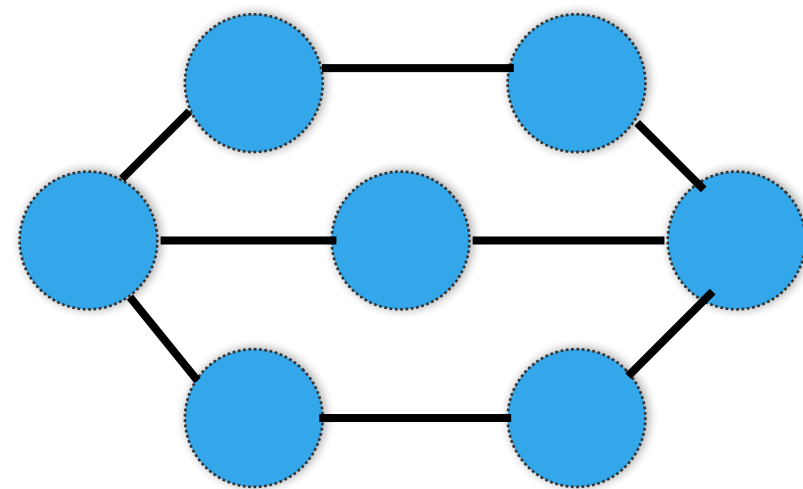
**Biological networks** are characterized by a small fraction of nodes with high degree (**hubs**)

An **attack that aims to a hub has strong effect** on the connectivity of the network.

In normal situation we assume that **attacks are random**. Thus, on average, an attack should have smaller effect on Biological Network.



Biological network

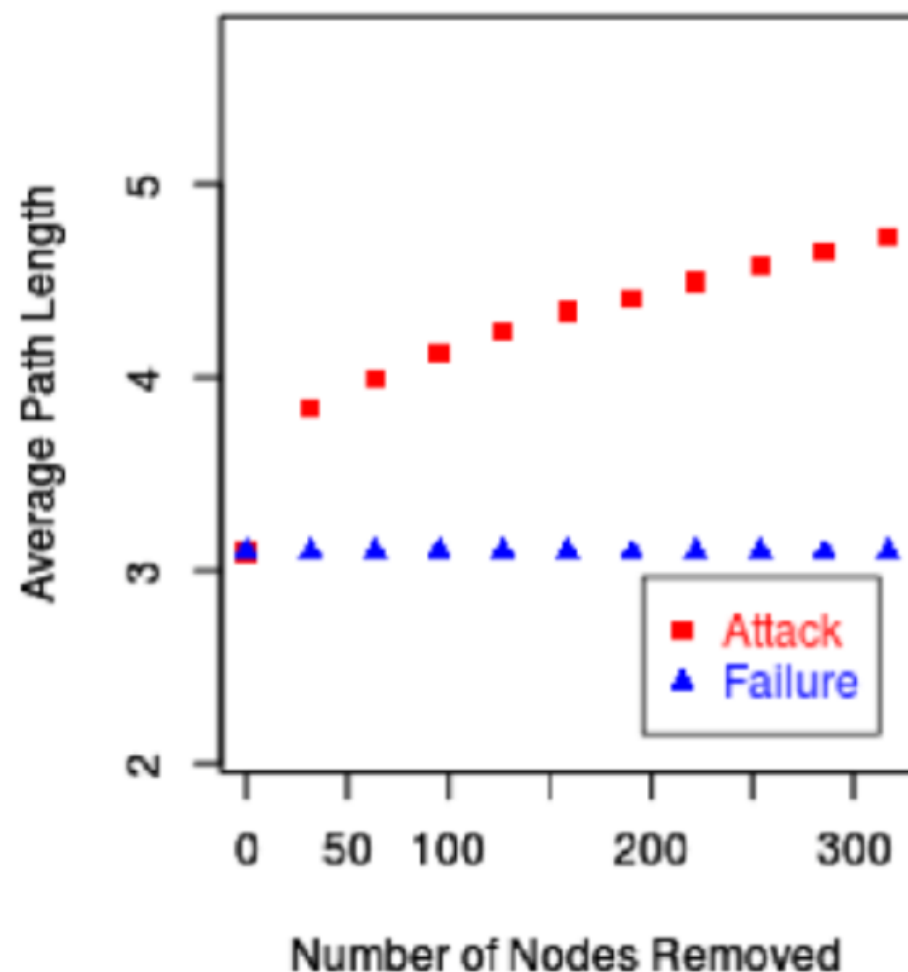


Random network

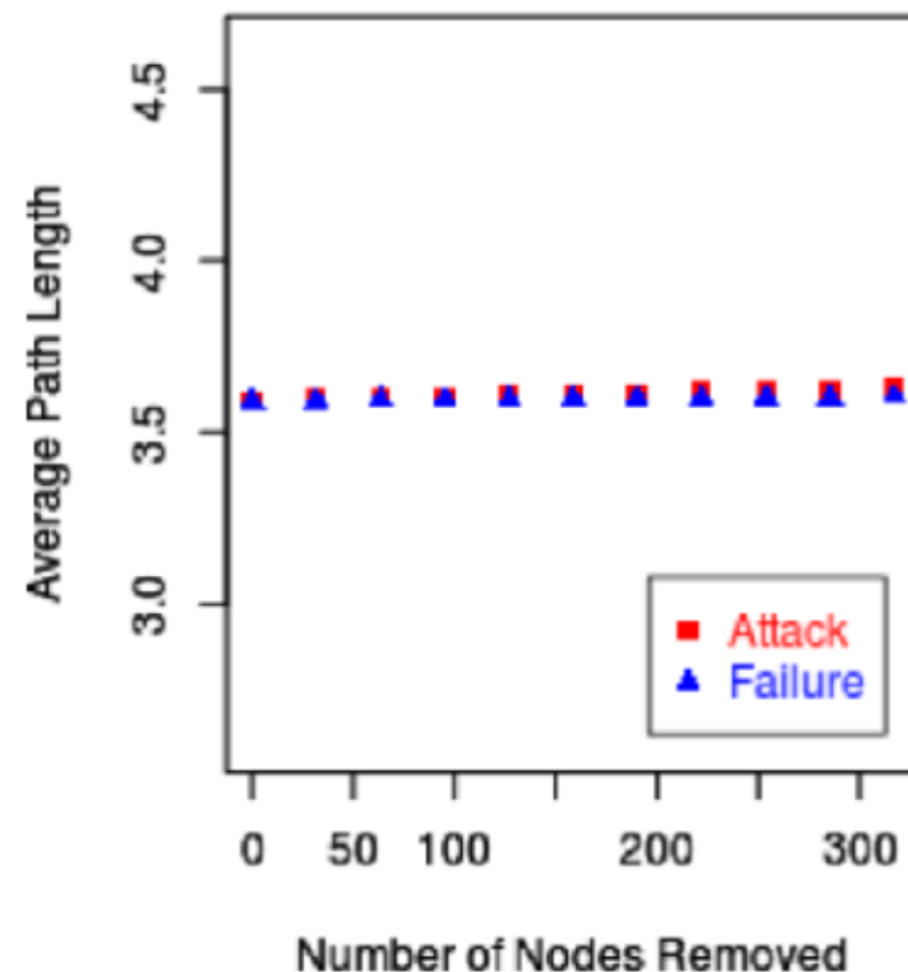
# Failures and Attacks

The **resilience of scale free networks to failures** comes at the price of high **vulnerability to targeted attacks**

## Homo Sapiens



## Random Network





# Python NetworkX

NetworkX is a Python package for the **creation, manipulation, and study** of the structure, dynamics, and functions of **complex networks**.

```
>>> import networkx as nx
```

```
>>> G = nx.Graph()
```

```
>>> G.add_node(1)
```

```
>>> G.add_nodes_from([2, 3]) # add list of nodes
```

```
>>> G.add_edge(1, 2)
```

```
>>> G.add_edges_from([(1, 2), (1, 3)]) # add list of edges
```

```
>>> G.number_of_nodes()
```

```
3
```

```
>>> G.number_of_edges()
```

```
2
```

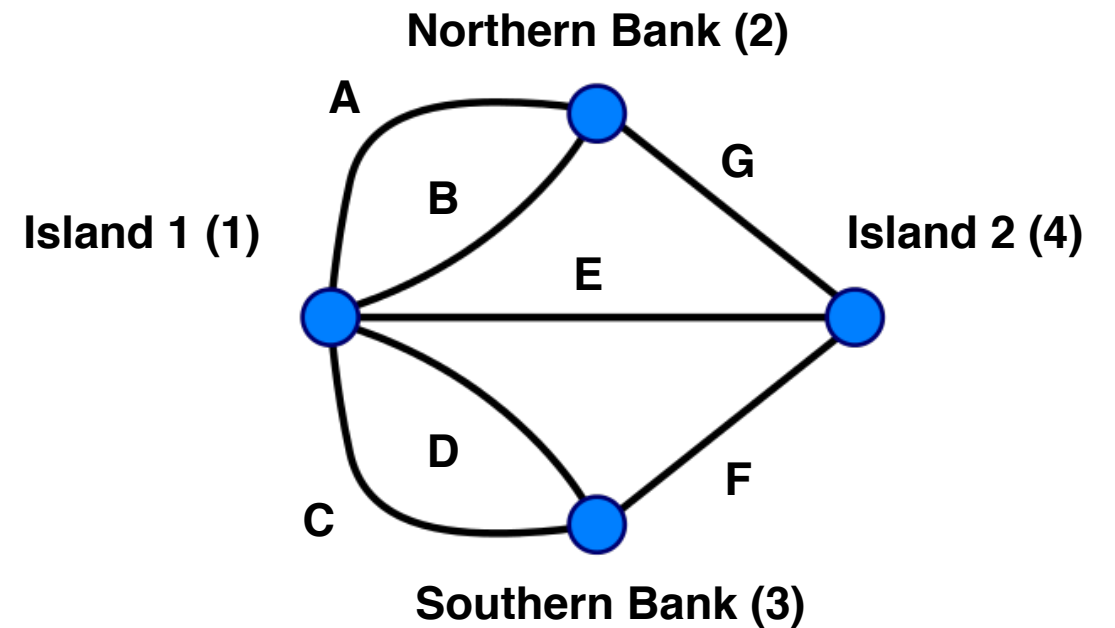
# Königsberg Graph

NetworkX allows to create graphs with **multiple edges connecting the same nodes** using the MultiGraph object.

```
>>> import networkx as nx
>>> M = nx.MultiGraph()

>>> M.add_edges_from([(1, 2, {"name": "A"}),
...                   (1, 2, {"name": "B"}), (1, 3, {"name": "C"}),
...                   (1, 3, {"name": "D"}), (1, 4, {"name": "E"}),
...                   (3, 4, {"name": "F"}), (2, 4, {"name": "G"})])

>>> M = M.degree(1)
```



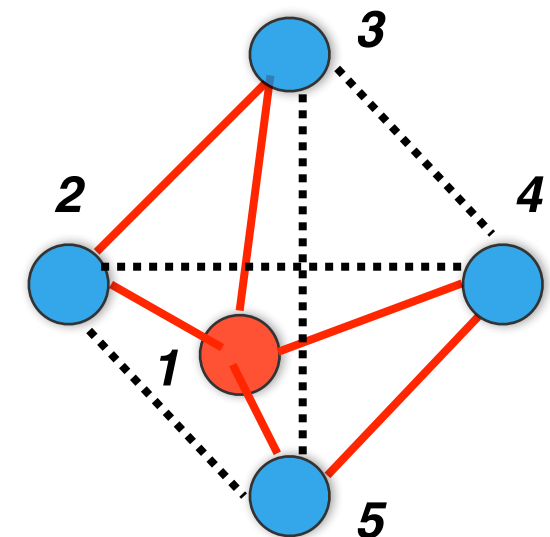
# Exercise

- Calculate the **clustering coefficient of node 1**

$c(1)$  = the number of triangles with fix vertex in node 1 divided by the all possible triangles.

triangles = [(1,2,3),(1,4,5)]

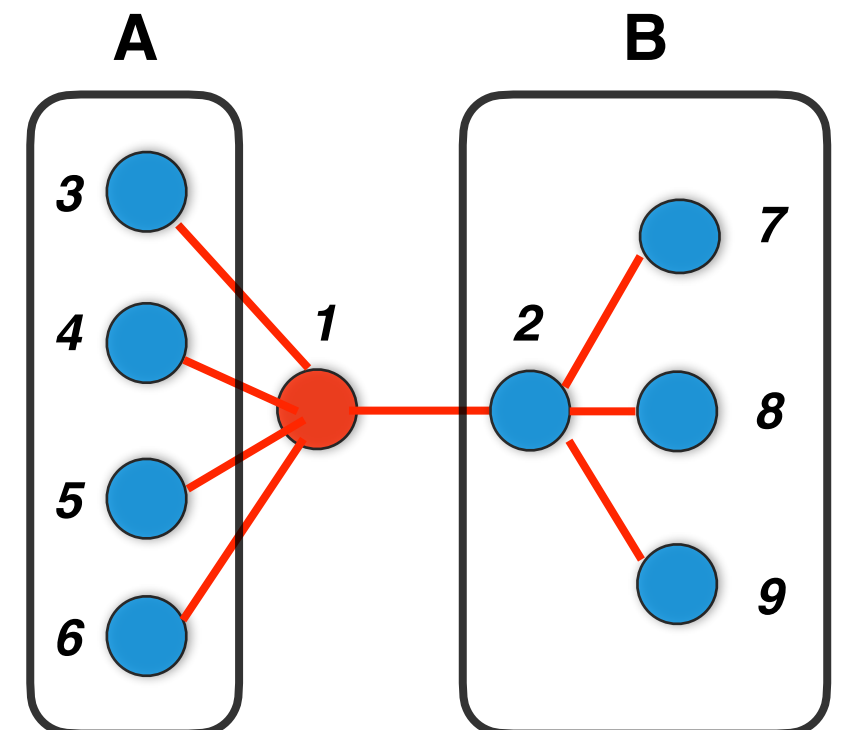
other triangles = [(1,3,4), (1,2,5), (1,2,4), (1,3,5)]



- Calculate the **number of shortest paths passing through node 1**

$\sigma(1)$  = all the paths from block A to block B  
+ all the possible paths between nodes within block A

$3 \rightarrow 2, 7, 8, 9$	$3 \rightarrow 4, 5, 6$
$4 \rightarrow 2, 7, 8, 9$	$4 \rightarrow 5, 6$
$5 \rightarrow 2, 7, 8, 9$	$5 \rightarrow 6$
$6 \rightarrow 2, 7, 8, 9$	



# Network generators

Networkx has function that generate standard network types

```
>>> import networkx as nx
>>> import matplotlib.pyplot as plt

>>> er = nx.erdos_renyi_graph(100, 0.15)
>>> ws = nx.watts_strogatz_graph(30, 3, 0.1)
>>> ba = nx.barabasi_albert_graph(100, 5)

>>> nx.draw(ba)
>>> plt.show()
```

# BioGRID

The **Biological General Repository for Interaction Datasets** (BioGRID) is a curated biological database of protein-protein interactions, genetic interactions, chemical interactions, and post-translational modifications

The screenshot shows the BioGRID 4.2 homepage. At the top is a navigation bar with links: home, help, wiki, projects, tools, contribute, stats, downloads, partners, about us, and a Twitter icon. The main header area has a dark red background with the BioGRID 4.2 logo and a welcome message: "Welcome to our Database of Protein, Genetic and Chemical Interactions". Below this, a paragraph describes the database: "BioGRID is a biomedical interaction repository with data compiled through comprehensive curation efforts. Our current index is version 4.2.191 and searches 75,760 publications for 1,992,321 protein and genetic interactions, 29,093 chemical interactions and 959,750 post translational modifications from major model organism species. All data are freely provided via our search index and available for download in many standardized formats." To the right of the welcome message is a search box titled "Search BioGRID:" with a dropdown menu set to "By Protein/Gene". Below the search box is a text input field "Search by Protein/Gene Identifiers ...", a dropdown menu "All Organisms", and a "Submit Identifier Search Q" button. At the bottom of the search box are three icons: a magnifying glass for "Advanced Search", a flag for "Helpful Search Tips", and a star for "Featured Datasets". Below the search box are two buttons: "BioGRID Statistics" with a bar chart icon and "Latest Downloads" with a download icon. A yellow banner across the middle of the page reads "BioGRID COVID-19 Coronavirus Curation Project" and "Search BioGRID for SARS-CoV-2 Protein Interactions | Download SARS-CoV-2 and Coronavirus-Related Interactions". Below the banner is a section titled "Related Resources" with a sub-section "BioGRID Themed Curation Projects" which describes themed curation projects and includes a "Learn more" link. To the right of the "Related Resources" section is a "Partners" section with logos for NIH, ORIP (Office of Research Infrastructure Programs), CIHR IRSC, Mount Sinai Hospital, Princeton University, and Université de Montréal.

**BioGRID 4.2** home help wiki projects tools contribute stats downloads partners about us

**Welcome to our Database of Protein, Genetic and Chemical Interactions**

BioGRID is a biomedical interaction repository with data compiled through comprehensive curation efforts. Our current index is version **4.2.191** and searches **75,760** publications for **1,992,321** protein and genetic interactions, **29,093** chemical interactions and **959,750** post translational modifications from major model organism species. All data are **freely** provided via our search index and available for download in many standardized formats.

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**Related Resources**

**BioGRID Themed Curation Projects**

BioGRID themed curation projects focus on specific biological processes with disease relevance. Core genes/proteins central to the process are assembled with expert input and relevant publications curated for biological interactions. Themed curation projects are updated monthly and additional projects are generated on a regular basis.

[Learn more](#)

**Partners**

NIH ORIP OFFICE OF RESEARCH INFRASTRUCTURE PROGRAMS CIHR IRSC Mount Sinai Hospital PRINCETON UNIVERSITY Université de Montréal

<https://thebiogrid.org/>

# Exercise

Generate the three types of network (random, "small world" and "scale free" ) and calculate the distribution of the degree, betweenness and clustering.

From BioGRID download the Yeast interactome and analyze it with networkx importing only a list of unique interactions from the BIOGRID repository:

- How many components are present?
- What is the gene with highest degree?
- What is the the average values of degrees, betweenness and clustering?
- Draw the distribution of the degree and fit to a power law distribution