

Graph Theory Basics

Social Networks Analysis and Graph Algorithms

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Contents

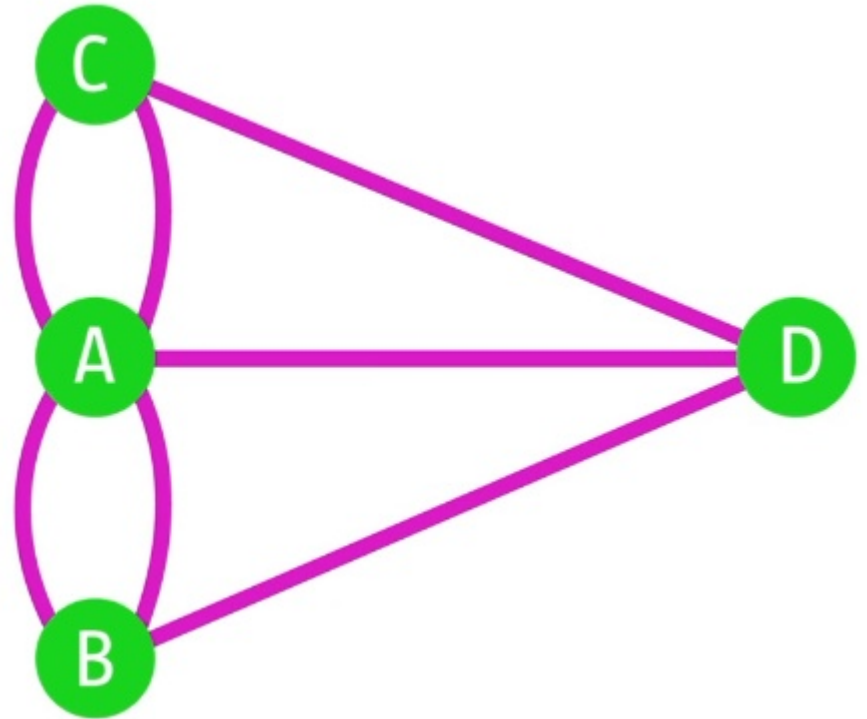
- Notation for graphs
- Degree distributions
- Adjacency matrices

Sources

- A. L. Barabási (2016). Network Science – Chapter 02
- URLs cited in the footer of specific slides

Notation for a graph

- $G = (V, E)$
 - V : nodes or vertices
 - E : links or edges
- $|V| = N$ size of graph
- $|E| = L$ number of links



Subgraph

- Given $G = (V, E)$
- A **subgraph** induced by a nodeset S is the graph $G' = (S, F)$ defined by:
 - nodes in S
 - edges in $F = \{ (u, v) \in E \text{ s.t. } u \in S \text{ and } v \in S \}$

Typical notation variations

- You may find that G is denoted by (N, A) , this is typical of directed graphs, means “*nodes, arcs*”
- You may find that
 - $|V|$ is denoted by n or N
 - $|E|$ is denoted by m , M , or L

Example graphs we will use

Network	$ V $	$ E $
Zachary's Karate Club (karate.gml)	34	78
Game of Thrones (got-relationships.csv)	84	216
US companies ownership	1351	6721
Marvel comics (hero-network.csv)	6K	167K

Directed vs undirected graphs

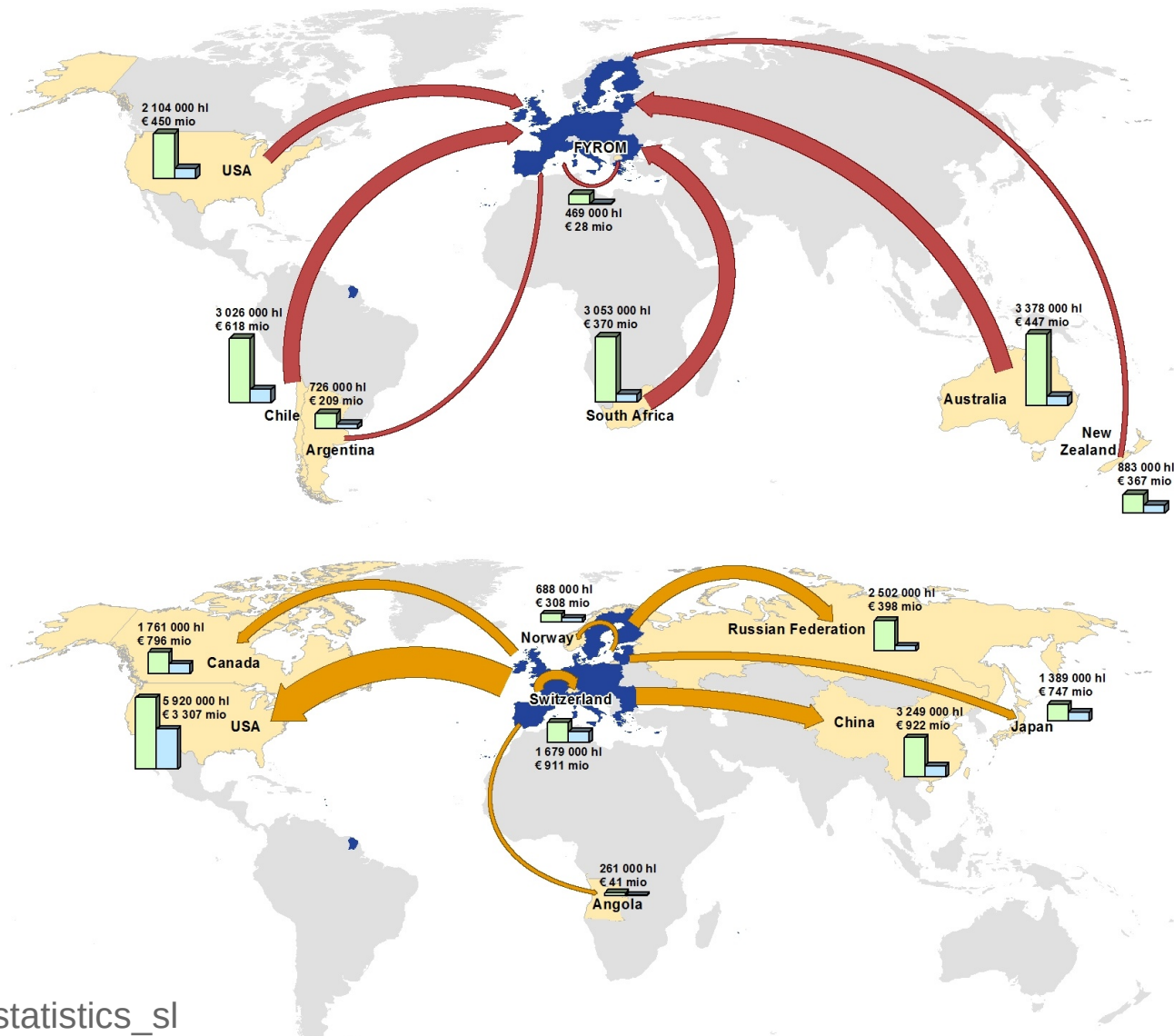
- In an undirected graph
 - E is a symmetric relation
$$(u, v) \in E \Rightarrow (v, u) \in E$$
- In a directed graph, also known as “digraph”
 - E is not a symmetric relation
$$(u, v) \in E \not\Rightarrow (v, u) \in E$$

Weighted vs unweighted graphs

- In a weighted graphs edges have **weights** denoting the strength or importance of a connection
- When drawing, typically larger weights are drawn with ticker lines

Example: weighted networks

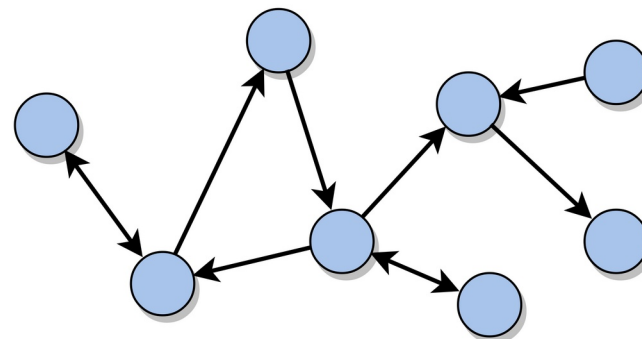
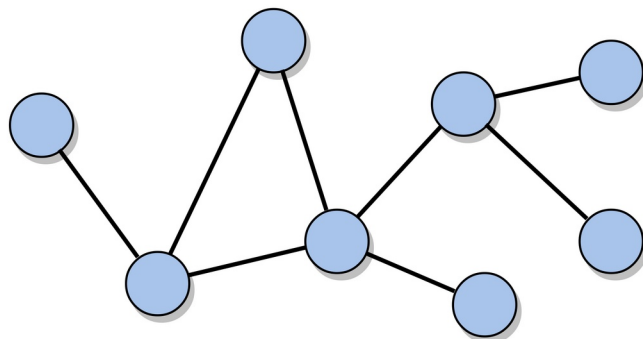
EU imports (top)
and exports (bottom)
of wine



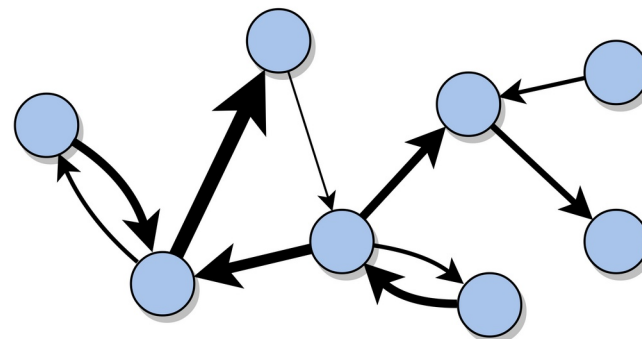
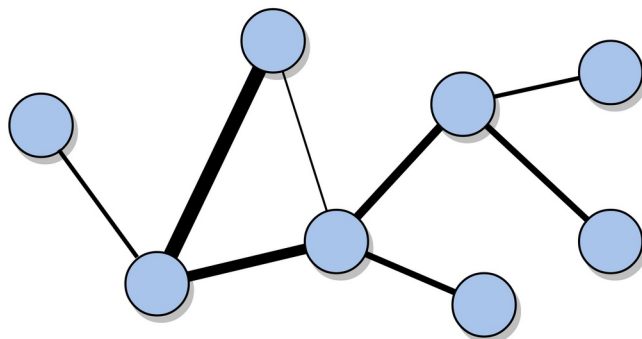
Undirected

Directed

Unweighted



Weighted



Degree

Degree

- Node i has degree k_i
 - This is the number of links incident on this node
 - The total number of links L is given by

$$L = \frac{1}{2} \sum_{i=1}^N k_i$$

- Average degree $\langle k \rangle = \frac{1}{N} \sum_{i=1}^N k_i = \frac{2L}{N}$

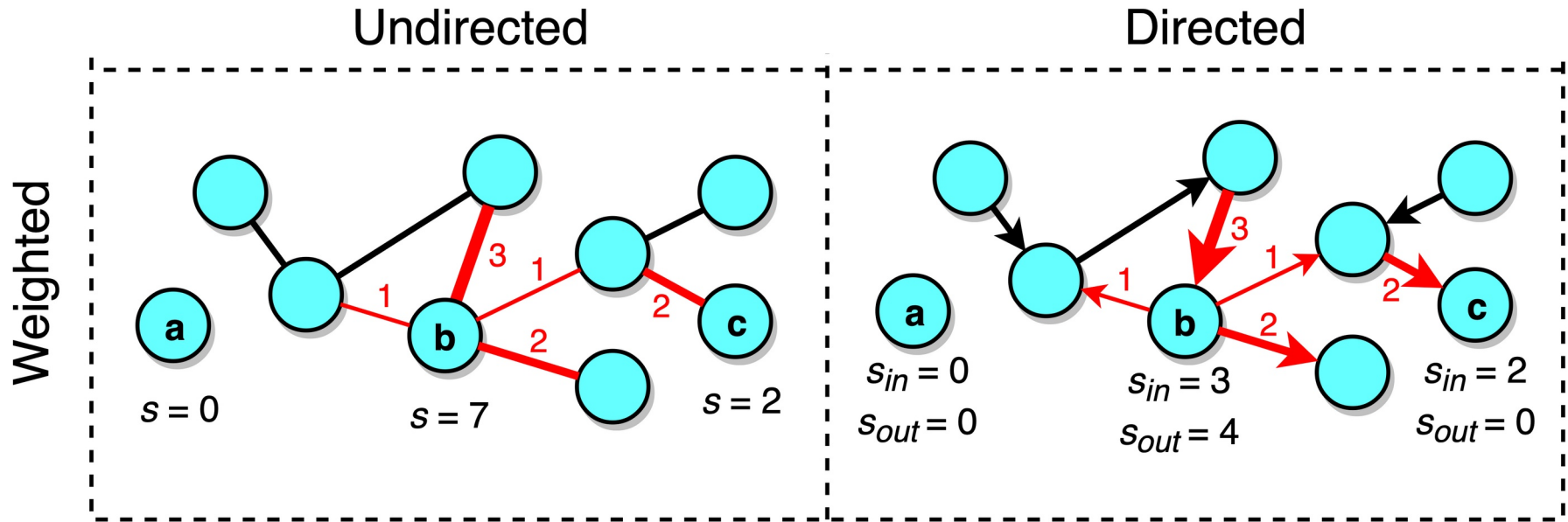
In directed graphs

- We distinguish **in-degree** from **out-degree**
 - Incoming and outgoing links, respectively
- Degree is the sum of both $k_i = k_i^{\text{in}} + k_i^{\text{out}}$
- Counting total number of links:

$$L = \sum_{i=1}^N k_i^{\text{in}} = \sum_{i=1}^N k_i^{\text{out}}$$

In weighted graphs

We speak of “weighted degree” or “strength”



Degree distribution

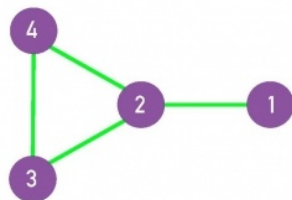
- If there are N_k nodes with degree k

- The degree distribution is given by $p_k = \frac{N_k}{N}$

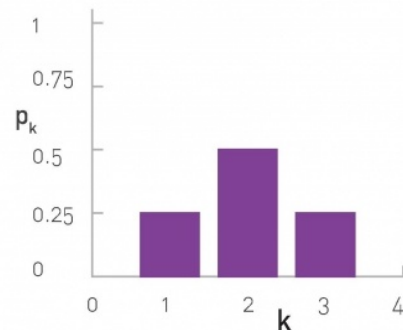
- The average degree is then $\langle k \rangle = \sum_{k=0}^{\infty} k p_k$

Degree distribution; two toy graphs

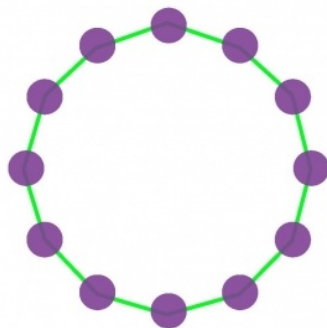
a.



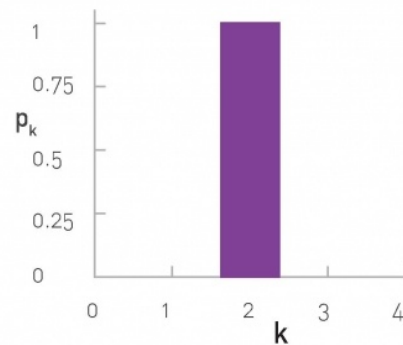
b.



c.

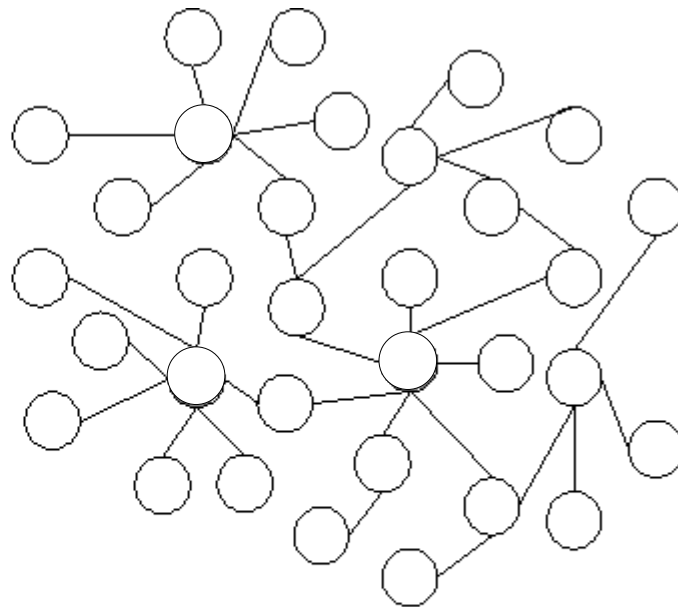
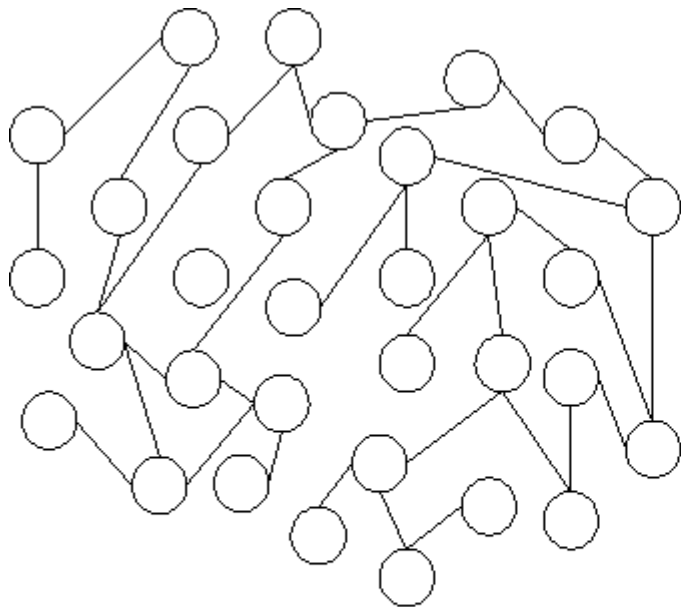


d.



Exercise

Draw the degree distribution of these graphs

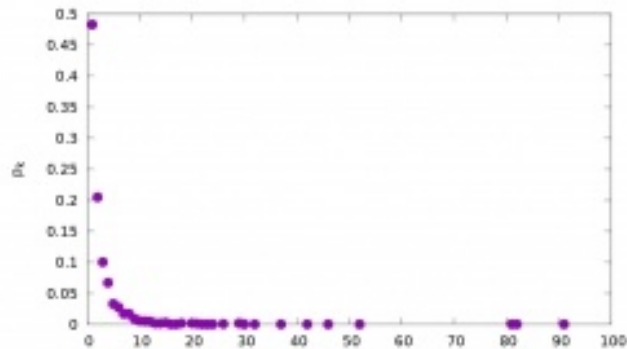
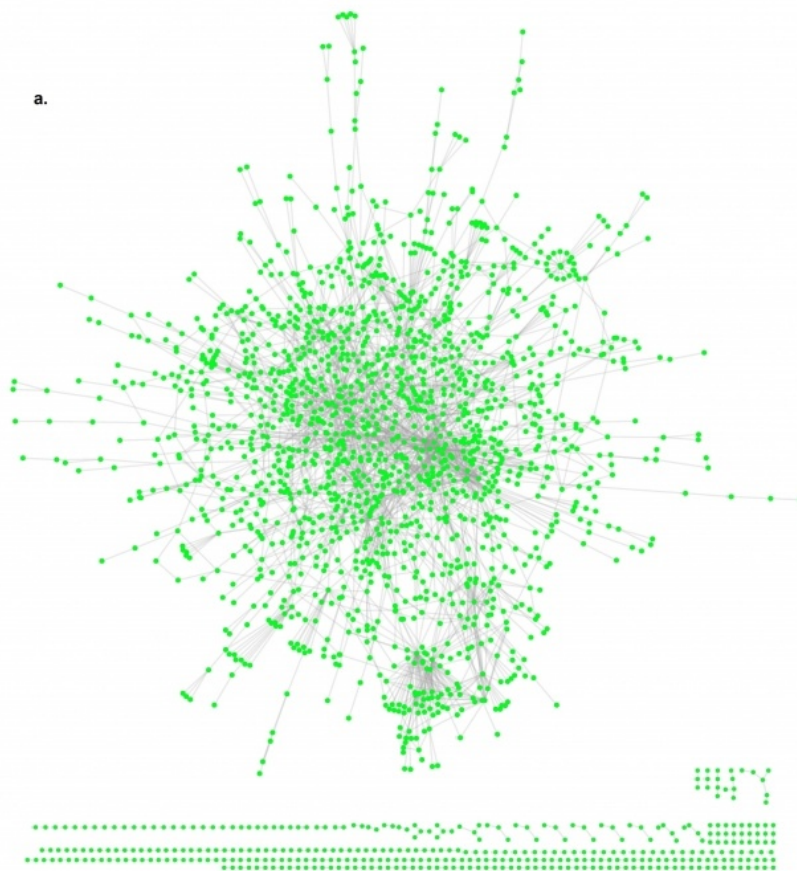


Spreadsheet links: <https://upfbarcelona.padlet.org/chato/shyq9m6f2g2dh1bw>

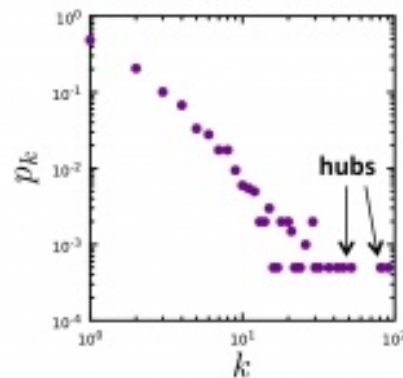


Degree distribution; real graph

a.



Linear
scale



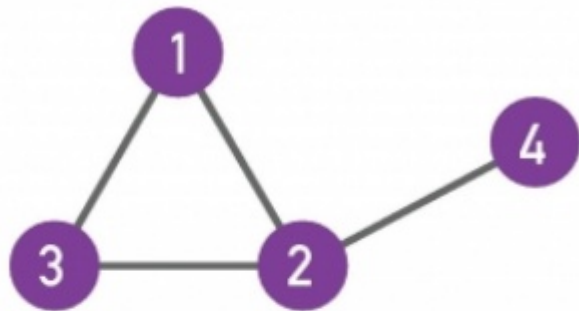
Log-log
scale

Adjacency matrix

What is an adjacency matrix

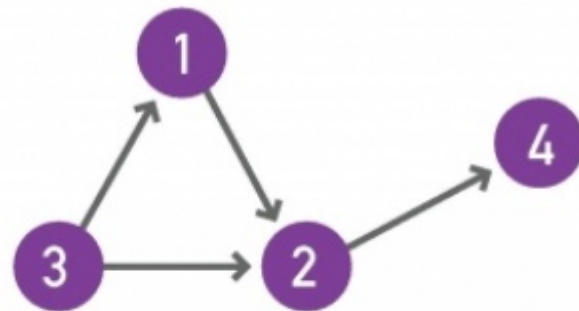
- A is the **adjacency matrix** of $G = (V, E)$ iff:
 - A has $|V|$ rows and $|V|$ columns
 - $A_{ij} = 1$ if $(i,j) \in E$
 - $A_{ij} = 0$ if $(i,j) \notin E$
- **A_{ij} always means row i , column j**
 - Sometimes Barabási's book has this wrong

Examples



Undirected graph

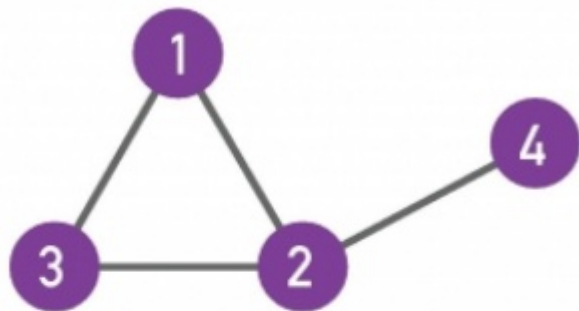
$$A_{ij} = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$



Directed graph

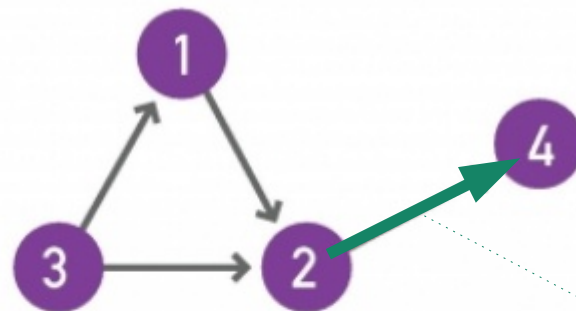
$$A_{ij} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

A_{ij} always means row i , column j



Undirected graph

$$A_{ij} = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$



Directed graph

$$A_{ij} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Row 2
Column 4

Properties of adjacency matrices

- G is undirected $\Leftrightarrow A$ is symmetric
- G has a self-loop
 $\Leftrightarrow A$ has a non-zero element in the diagonal
- G is complete $\Leftrightarrow A_{ij} \neq 0$ (except if $i=j$)

Quick Exercise

- In terms of A , what is the expression for:

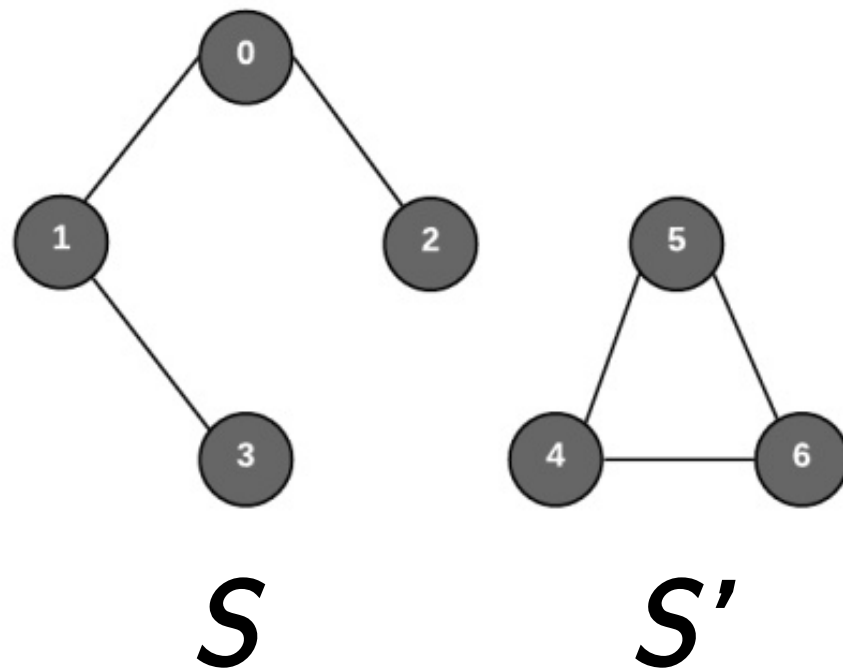
$$k_i^{\text{in}} =$$

$$k_i^{\text{out}} =$$

If a graph is disconnected

Disconnected graphs
have adjacency matrices
with **block structure**

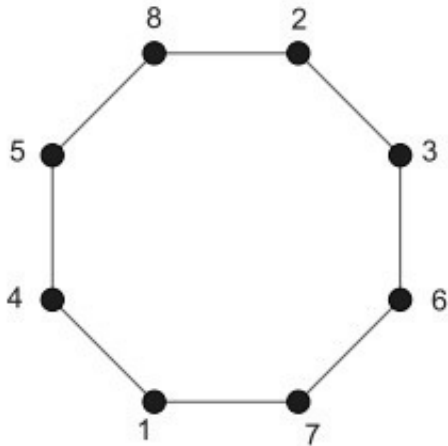
$$A = \begin{bmatrix} S & 0 \\ 0 & S' \end{bmatrix}$$



More concepts

Some graphs have a name

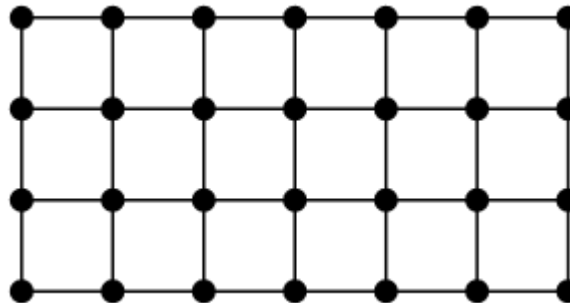
Cycle



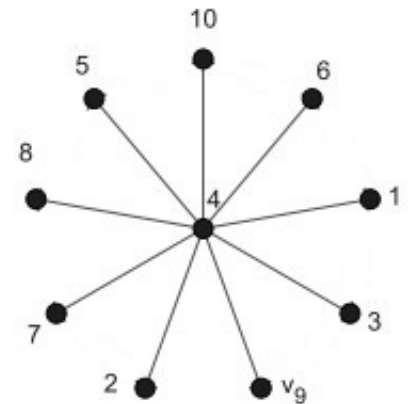
Line



Lattice

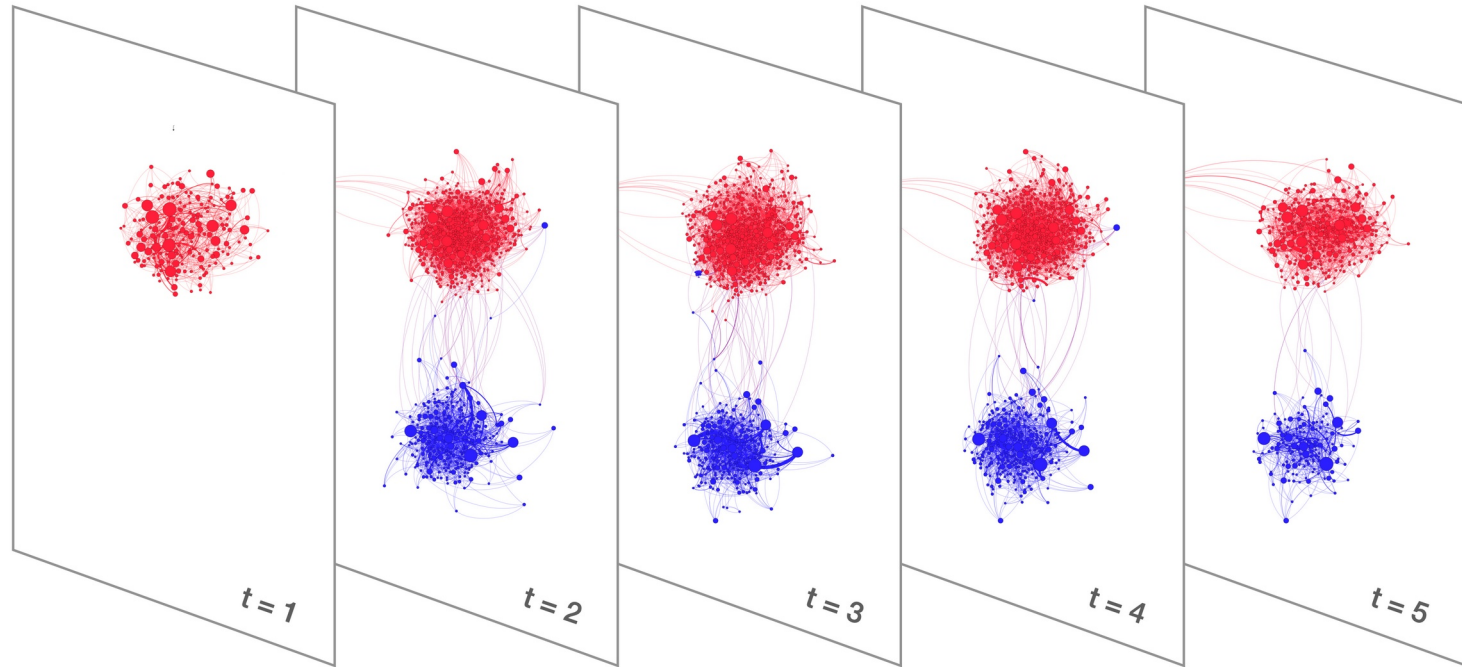


Star



Some graphs change over time

In a **temporal**, or
“time-evolving”
graph, at each
timestep, we
have a snapshot
of the network

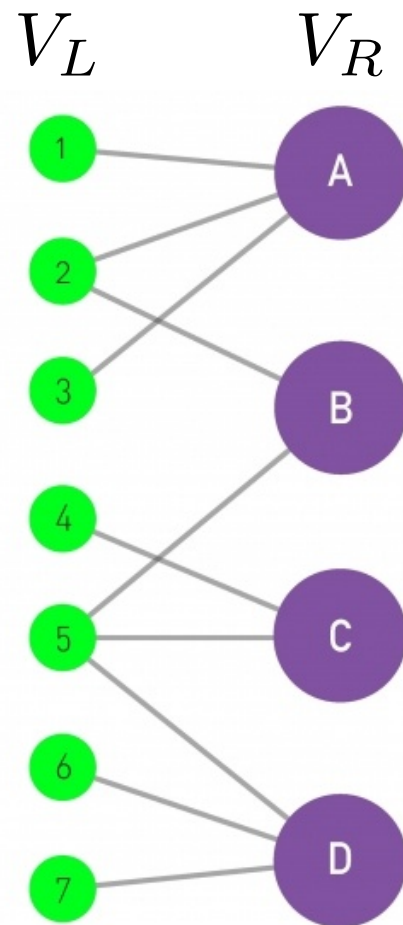


Some graphs are “bi-partite”

- A **bipartite** graph is a graph

$G = (V, E)$ such that

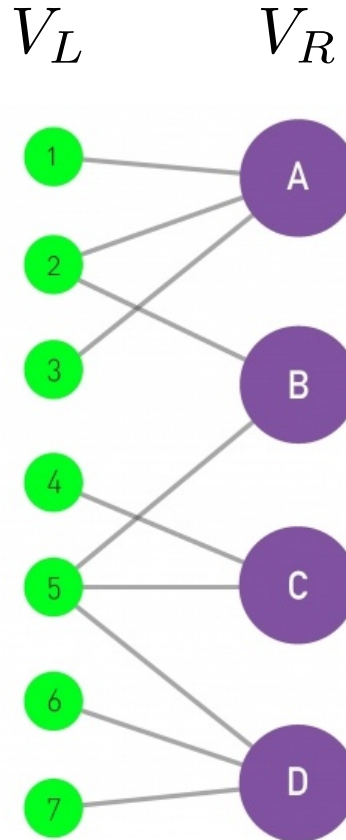
$$V = V_L \cup V_R, V_L \cap V_R = \emptyset, E \subseteq V_L \times V_R$$



Exercise: project a bipartite network

?

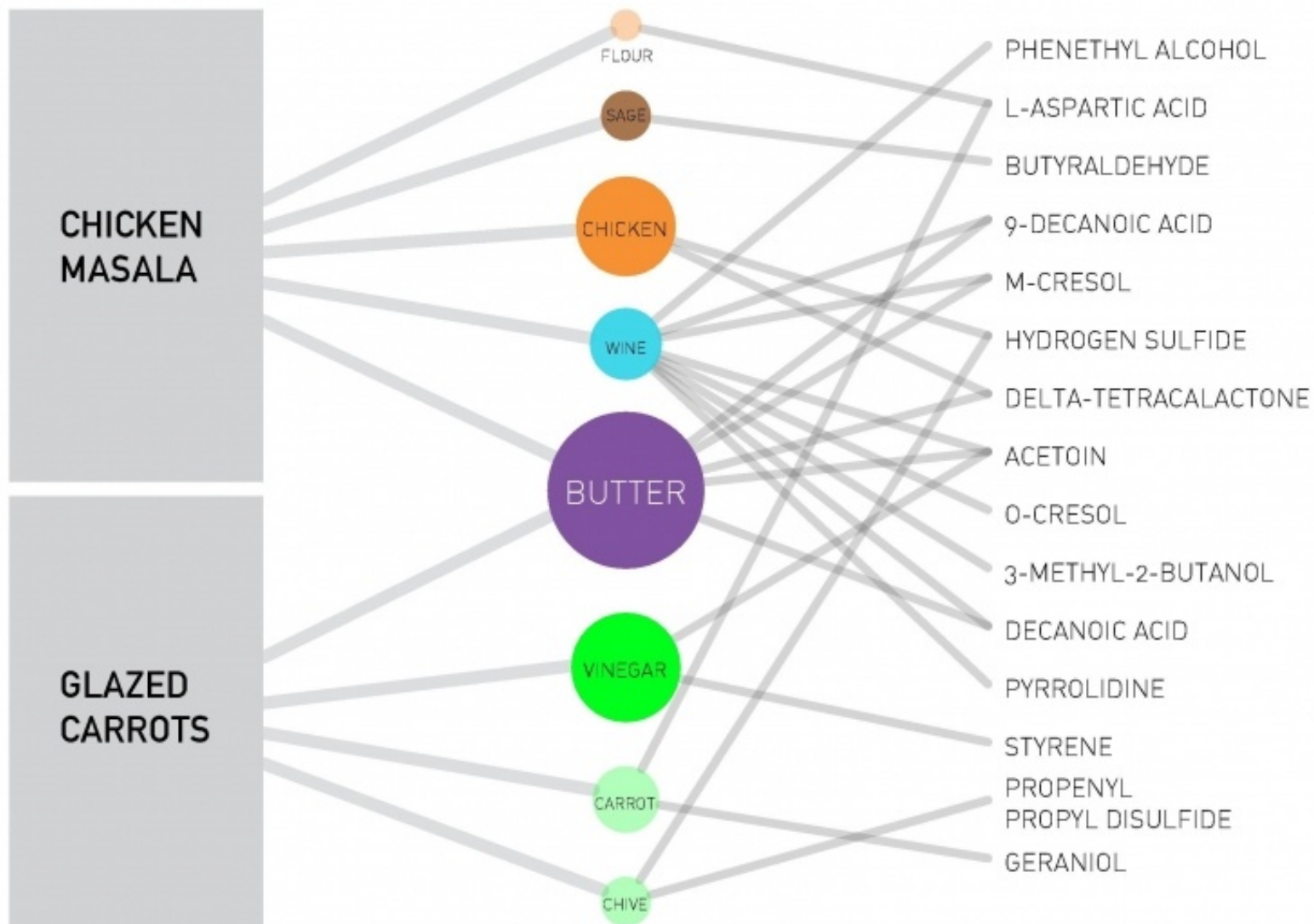
Left projection:
graph where nodes
are 1, 2, ..., 7 and
nodes are connected
if they share a
neighbor



?

Right projection:
graph where nodes
are A, B, ..., D and
nodes are connected
if they share a
neighbor

Tripartite network



Clique and Bi-partite clique

- A **clique** is a complete (sub)graph: $E = (V \times V)$
- An **n-clique** is a complete graph of n nodes
- A **bi-partite clique** is such that

$$V = V_1 \cup V_2, V_1 \cap V_2 = \emptyset, E = (V_1 \times V_2)$$

- A **(n₁, n₂)-clique** is a bipartite clique such that
$$|V_1| = n_1, |V_2| = n_2$$

The word “clique” in popular culture

In some parts of Latin America, a “*clika*” or “*clica*” means a close group of friends, sometimes a gang

Photo credit: @astro_jr



Summary

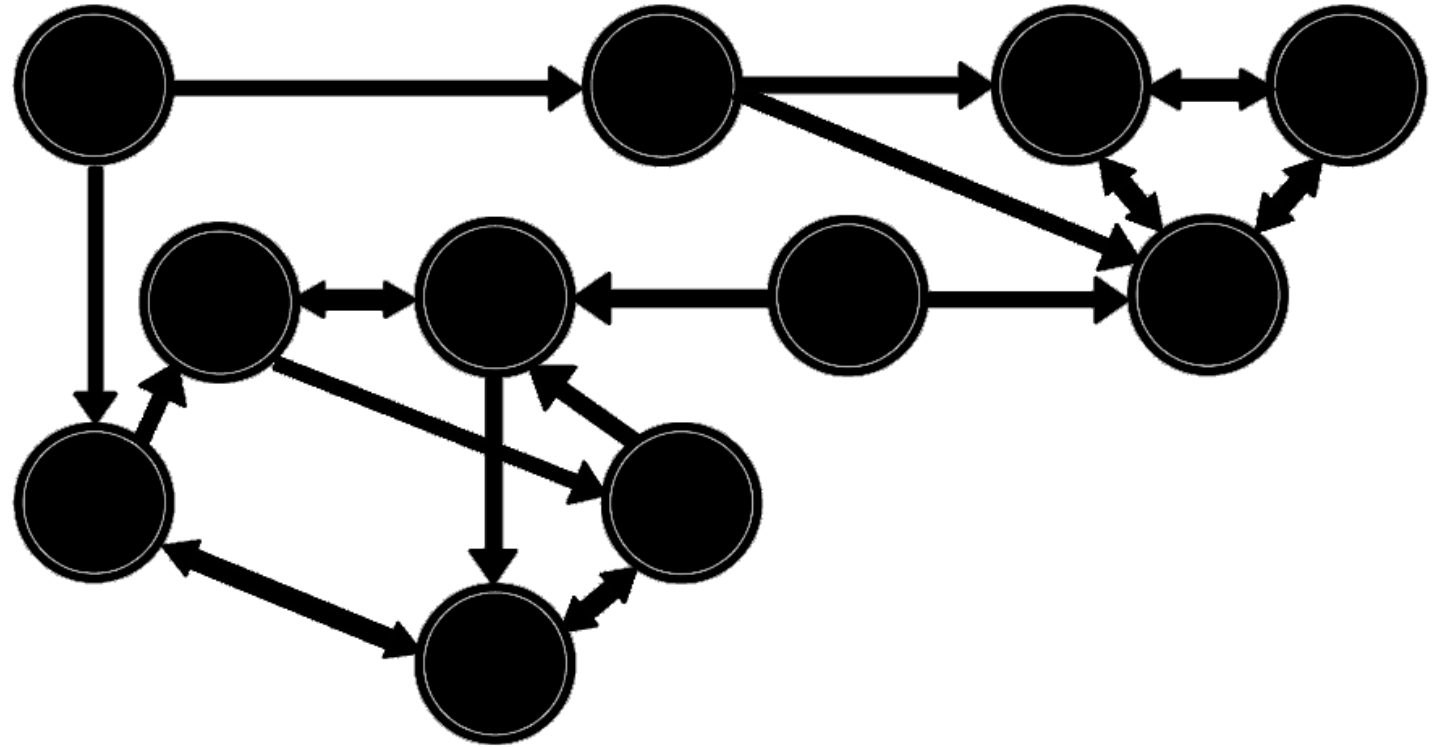
Things to remember

- Definitions: degree, in-degree, out-degree, line graph, cycle graph, star graph, lattice, bi-partite graph
- Writing the adjacency matrix of a graph, and drawing a graph given its adjacency matrix
- Plotting the degree distribution of a graph
- Projecting a bi-partite graph

Practice on your own

Draw the
indegree,
outdegree, degree
distribution

Write the
adjacency matrix



Practice on your own

How do you call the sub-graph induced by nodesets:

- $\{H, A, B\}$
- $\{G, H, D\}$
- $\{B, D, E, G\}$
- $\{A, B, D, E\}$

