CS4423: Networks

# Lecture 7: Permutations and Bipartite Networks


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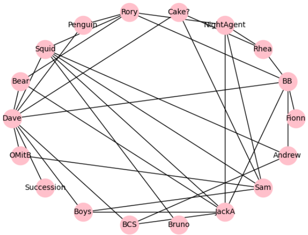
Week 4, Lecture 1 (Wed, 5 Feb 2025)




*These slides are by Niall Madden. Elements are based on "A First Course in Network Theory" by Estrada and Knight. Also AC's notes...*

# Outline

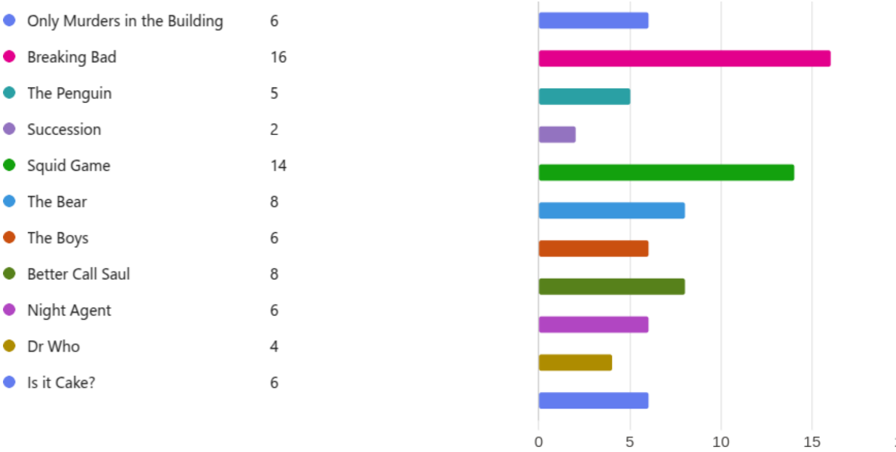


For further reading, see Section 2.4 of A First Course in Network Theory (Knight).

Slides are at:
https://www.niallmadden.ie/2425-CS4423

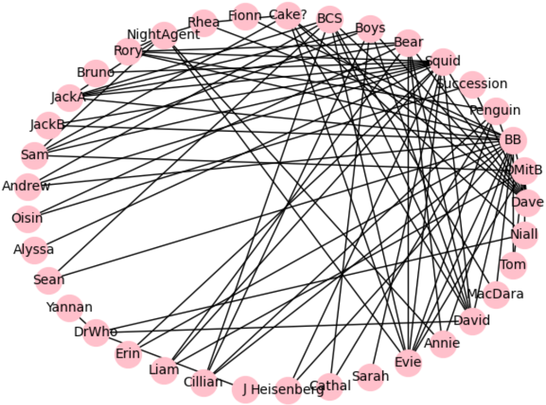
# Thanks for completing the survey!

Here is some of the data we collected:



# Thanks for completing the survey!

Here is what it looks like as a graph:




Its order is 37, and size is 81; we'll return to this later...

# Graph Connectivity

- A graph/network is **connected** if there is a path between every pair of nodes.
- If the graph is *not* connected, we say it is **disconnected**.
- We now know how to check if a graph is connected by looking at powers of its adjacency matrix. However, that is not very practical for large networks.
- However, we can determine if a graph is connected, but just looking at the adjacency matrix, providing we have ordered the nodes properly.

# Permutation matrices

We know that the structure of a network is not changes by relabelling its nodes. Sometimes, it is is useful to relabel them in order to expose certain properties, such as connectivity.

**Example:**

Since we think of the nodes as all being numbered from 1 to $n$, this is the same as **permuting** the numbers of some subset of the nodes.

# Permutation matrices

When working with the adjacency matrix of a graph, such a permutation is expressed in terms of a **permutation matrix**, $P$: this is a $0-1$ matrix (a.k.a. a "Boolean" or "binary" matrix), where there is a single $1$ om every row and column.

If the nodes of a graph $G$ (with adjacency matrix $A$) are listed as entries in a vector, $q$, then

- $Pq$ is a permutation of the nodes, and
- $\boxed{PAP^T}$ is the adjacency matrix of the graph with that node permutation applied.

Permutation matrices are important when studying graph connectivity because...

**FACT!**

A graph with adjacency matrix $A$ is **disconnected** if and only if there is a permutation matrix $P$ such that

$$A = P \begin{pmatrix} X & O \\ O^T & Y \end{pmatrix},$$

where $O$ represents the zero matrix with the same number of rows as $X$ and the same number of columns as $Y$.

**Example:**

# Connected Components

If a network is not connected, then we can divide it into **components** which *are* connected.

The number of connected components is the number of blocks in the permuted adjacency matrix:

# Bipartite Graphs (again)

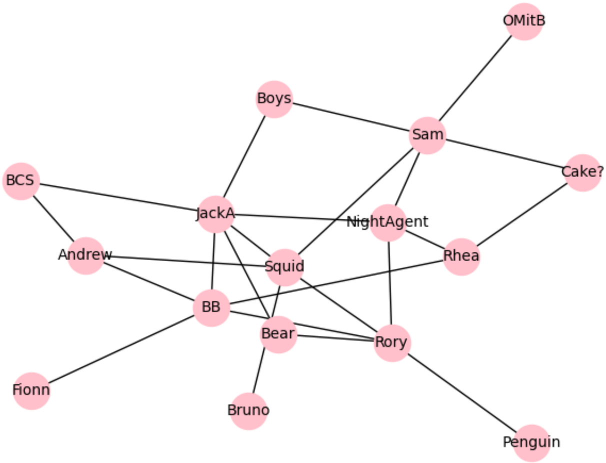
One reason we did the survey is that the resulting data set is a good example of a **bipartite** graph: nodes represent either people or programmes that they watch, with an edge between a person and a programme that they watch.

So the graph must be bipartite.

Such a graph is called an **affiliation** network;

# Bipartite Graphs (again)

Here is a **subgraph** of our survey, of order 16 and size 24, based on 7 randomly chosen people:



# Bipartite Graphs (again)

This is the adjacency matrix:

$$\begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{pmatrix}$$

# Bipartite Graphs (again)

That version of the adjacency matrix is not very insightful. But ordering the nodes so that people are listed first we get the matrix:

$$
A = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

# Bipartite Graphs (again)

Let's consider $B = A^2$:

$$B = \begin{pmatrix}
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 3 & 2 & 0 & 2 & 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 2 & 5 & 1 & 4 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 2 & 4 & 1 & 6 & 3 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 2 & 2 & 1 & 3 & 5 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 2 & 1 & 3 & 1 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 3 & 1 & 1 & 3 & 2 & 1 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 4 & 2 & 1 & 3 & 2 & 2 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 & 2 & 0 & 1 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 3 & 1 & 1 & 5 & 2 & 2 & 2 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 1 & 2 & 2 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 & 1 & 0 & 2 & 1 & 2 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & 0 & 0 & 2 & 1 & 1 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{pmatrix}$$

# Bipartite Graphs (again)

We finished here on Wednesday, but will take up at the same point on Thursday.

# Exercise(s)

1. Let $u$ be a vector with $n$ entries. Let $D = \text{diag}(u)$. That is, $D = (d_{ij})$ is the diagonal matrix with entries

   $$d_{ij} = \begin{cases} u_i & i = j \\ 0 & i \neq j. \end{cases}$$

   Verify that $PDP^T = \text{diag}(Pu)$.

2. In all the examples we looked at, we had a symmetric $P$. Is every permutation matrix symmetric? If so, explain why. If not, give an example.