Networks and Flows on Graphs

Fixing Graph Theoretical Terminology

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What Is a Graph?

Definition

A *directed graph* (or *digraph*) G is given by a set V of *vertices* together with a set A of *arrows*; an arrow being an (ordered) couple $a = (x, y)$ of vertices. The vertex x is called the *source* of a while y is its *target*. We write $G = (V, A)$ for the digraph G.

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Question

What is the most general digraph you can draw? Can you have two loops for a single edge? How many arrows in between two vertices?

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There is a canonical way of attaching a simple graph to a digraph G :

- Delete loops of the set of arrows of G, these are given by couples having two identical entries
- build up the set of edges as the collectiong of pairs $\{x, y\}$ for each arrow (x, y) in G.

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Question

Can you think of others ways of defining a graph? For instance how would you give a definition to allow multiple arrows in a digraph? Or to allow loops and multiple edges in a graph?

Finding Your Way in Graphs

Graph

Chain : A sequence of edges where each edge has a common vertex with the preceding one (except the first), the other being common with the next edge (except the last).

Cycle : A closed chain.

Simple chain : Containing each edge at most once.

Elementary chain : Containing each vertex at most once.

Hamiltonian chain : Passing once by each edge.

Eulerian chain : Passing once by each vertex.

length of chain : The number of edges in the chain.

Digraph

Path : A sequence of arrows where each arrow's target is the source of the next arrow (except the last).

Circuit : A closed path.

Simple path : Containing each arrow at most once.

Elementary path : Containing each vertex at most once.

Hamiltonian path : Passing once by each arrow.

Eulerian path : Passing once by each vertex.

length of chain : The number of arrows in the chain.

Connectedness

Graph

Connectedness : A graph is said to be *connected* if any two distinct vertices are the endpoints of a chain.

Connected components : Maximal subgraphs that are connected.

Digraph

Strong connectedness : A digraph is said to be *strongly connected* if any two distinct vertices are the initial source and target of a path.

Strongly connected components : Maximal subraphs that are strongly connected.

Remark : A digraph is said to be connected if its underlying graph is connected. Connected components of a digraph are defined the same way.

Two extreme cases of connected graphs

Trees

A tree T is a graph where each two vertices are linked by exactly one chain. It is equivalently given by

- T is connected and cycle-free
- T is connected of maximal order
- T is connected and deleting any edge disconnects it
- T is cycle-free and adding any edge creates one.

Complete Graphs

The complete graph $\mathcal{K}_n$ is the graph having n vertices and all possible edges linking them.

It has exactly $\dfrac{n(n-1)}{2}$ edges.

Can you draw $\mathcal{K}_5$ on a paper without having two edges overlapping?

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Adjacency Matrix

Definition

Let G be a graph (resp. digraph) having n vertices. The *adjacency matrix* of G is a square matrix having n columns and n rows, identically indexed by the vertices. Entry (i, j) is 1 iff there is an edge (arrow) from i to j, otherwise it is zero.

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Remark : The adjacency matrix of a graph is symmetric. A digraph having a symmetric adjacency matrix has, for any given arrow (x, y) between distinct vertices, an arrow (y, x) going the other way around.

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Question

Do you know any interesting theoretical results about symmetric matrices?

Adjacency Matrix

Proposition

Let G be either a graph or a digraph and write M for its adjacency matrix. For any given $k \in \mathbb{N}^*$, the matrix M^k has entry (i, j) equal to the number of chains (paths) having source i and target j.

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Proof : This is done by induction. In case $k = 1$, a path of length 1 is just an edge (or an arrow) and this is just the definition of the adjacency matrix.

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Proof : This is done by induction. In case $k = 1$, a path of length 1 is just an edge (or an arrow) and this is just the definition of the adjacency matrix. Assume that entries of the matrix M^k correspond to the number of chains (paths) from the row to the column index. Let $a_k[i, j]$ be the (i, j) coefficient of M^k. Then the entry $a_{k+1}[i, j]$ of M^{k+1} is given by

$$\begin{aligned} a_{k+1}[i,j] &= \sum_{\ell=1}^{n} a_k[i,\ell]\, a_1[\ell,j] \\ &= \sum_{\{\ell \mid \ell \text{ is adjacent to } j\}} a_k[i,\ell] \end{aligned}$$

which is exactly what we are looking for. ■

Generalization and Variant of Adjacency Matrix

Definition

Let G be a graph (resp. digraph) having n vertices and *weighted* edges (resp. arrows). The *adjacency matrix* of G is a square matrix having n columns and n rows, identically indexed by the vertices. If there is an edge from i to j then entry (i, j) gets the weight of that edge, otherwise entry (i, j) is zero.

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Sometimes we are only interested in the fact there is an edge, arrow, chain or path between two given vertices. In that case we look at the adjacency matrix as a *boolean* matrix. This will be worked out in an exercice later on.

It’s all for now!