Discrete Structures
Graph Theory

Nathan Warner

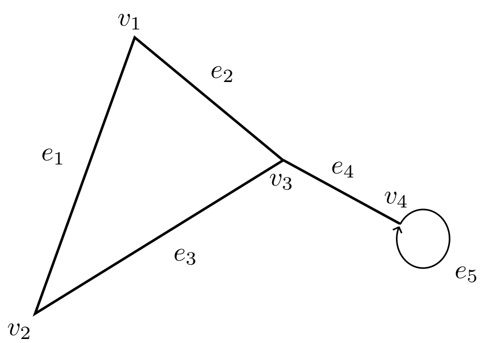
Computer Science
Northern Illinois University
August 31, 2023
United States

Contents

1 Graphs

Definition 1. A graph G consists of two finite sets: a nonempty set $V(G)$ of vertices and a set $E(G)$ of edges, where each edge is associated with a set consisting of either one or two vertices called its endpoints. Formally, a graph is defined as an ordered pair $G = (V, E)$, where V is the set of vertices and E is the set of edges

$$G = (V, E)$$
$$V = \{v_1, v_2, v_3, ..., v_n\}$$
$$E = \{e_1, e_2, e_3, ..., e_m\}.$$



$$V = \{v_1, v_2, v_3, v_4\}$$
$$E = \{e_1, e_2, e_3, e_4, e_5\}.$$

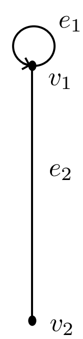
We can also represent the edges by only stating the vertices which connect the edges

Edges	Endpoints
e_1	$\{v_1, v_2\}$
e_2	$\{v_1, v_3\}$
e_3	$\{v_2, v_3\}$
e_4	$\{v_3, v_4\}$
e_5	$\{v_4\}$

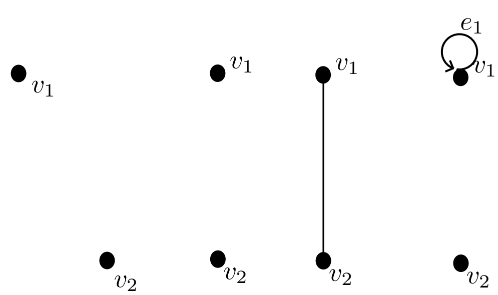
2 Subgraphs

Definition 2. Graph H is said to be a subgraph of a graph H iff every vertex in H is also a vertex in G, every edge in H is also an edge in G, and every edge in H has the same endpoints as it has in G.

Consider the graph:



Then the possible **sub graphs** could be:



Note:-

These graphs are not **all** the possibilites, just a few.

3 Degree

Definition 3. In graph theory, the **degree** of a vertex refers to the number of edges that are connected to that vertex.

Definition 4. **Parallel edges** are two or more edges that have the same pair of end vertices.

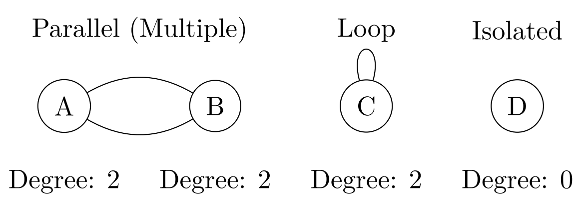
Definition 5. **Multiple Edges** is a term used interchangeably with parallel edges.

Definition 6. An **isolated vertex** is a vertex that has a degree of zero

Definition 7. A **loop** is an edge that connects a vertex to itself.

Definition 8. A **Degree Sequence** is an **n-tuple** of the degrees on vertices, in increasing order and with repetition.

Definition 9. The **overall degree** is the sum of all the degrees.



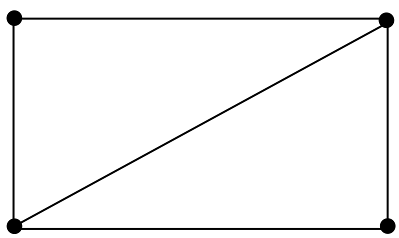
4 Sum of Degrees and Vertices Theorem

Definition 10. To denote the number of vertices in a graph, we say $||V||$, or just $|v|$. To denote the number of edges in a graph, we say $||E||$, or just $|E|$

Definition 11. The number of vertices in a graph is called the **order** of the graph

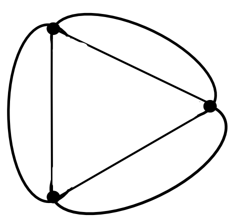
Definition 12. The number of edges in a graph is called the **size** of the graph.

Consider the graphs:



Then we have:

$$\begin{aligned} ||V|| &= 4 \\ ||E|| &= 5 \\ \sum deg &= 10. \end{aligned}$$



$$\begin{aligned} ||V|| &= 3 \\ ||E|| &= 6 \\ \sum deg &= 12. \end{aligned}$$

So you might notice from these two examples that the total degree of the graph ($\sum deg$) is exactly **twice** the number of edges. Thus, we can conclude:

Theorem 1.

$$\sum deg = 2||E||.$$

Proof. Let G be a graph, that has n vertices $v_1, v_2, v_3, v_4, ..., v_n$ and m edges, where n is a positive integer and m is a nonnegative integer.

If e_1 is an edge, then

$$v_i, v_j = \begin{cases} 1\ edge,\ 1V & \rightarrow degree = 2 \\ 1\ edge,\ 2V & \rightarrow degree = 2 \end{cases} \tag{1}$$

Thus, no matter the case, the edge always contributes 2 to the total degree. 😄

Corollary 1. The total degree of a graph is even.

Corollary 2. In any graph, there are an even number of vertices of odd degree.

5 Adjacency and Incidence

Definition 13. vertices that are connected by an edge are adjacent

Definition 14. A vertex with a loop is adjacent to itself

Definition 15. Two edges that share a vertex are adjacent

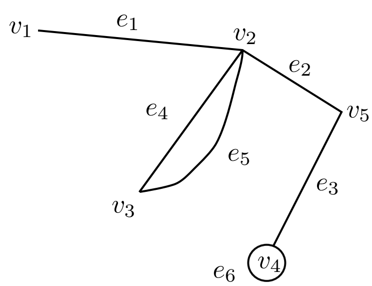
Definition 16. An edge is incident on its endpoints

Definition 17. A vertex on which no edges are incident is an isolated vertex.

6 Adjacency Matrix

Definition 18. Let G be a graph with vertices labeled $\{1, 2, 3, ..., n\}$. Then the **Adjacency Matrix** of G is the $n \times n$ matrix whose ij^{th} term is the number of the edges joining vertex i and vertex j

Consider the graph:



Since we have 5 vertices, then we will have a 5×5 matrix. Thus, our matrix for this graph will be:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 & 1 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \end{bmatrix}.$$

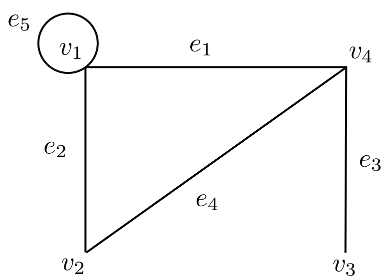
To make things clearer, here is how the rows and columns are labeled:

	v_1	v_2	v_3	v_4	v_5
v_1	0	1	0	0	0
v_2	1	0	2	0	1
v_3	0	2	0	0	0
v_4	0	0	0	1	1
v_5	0	1	0	1	0

7 Incidence Matrix

Definition 19. An **incidence matrix** is a rectangular matrix B where $B[i][j]$ represents the relationship between vertex i and edge j.

Suppose we have the graph:



Then we write the **incidence matrix** as follows:

$$M = \begin{bmatrix} 1 & 1 & 0 & 0 & 2 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \end{bmatrix}.$$

Where the vertices as labeled vertically, and the edges are labeled horizontally, as such:

	e_1	e_2	e_3	e_4	e_5
v_1	1	1	0	0	2
v_2	0	1	0	1	0
v_3	0	0	1	0	0
v_4	1	0	1	1	0

8 Isomorphism

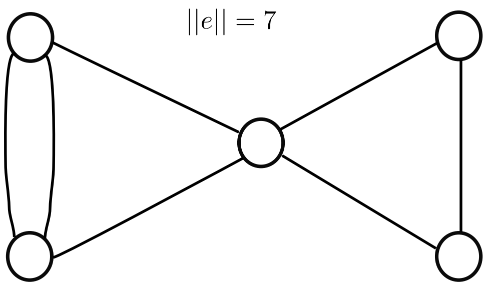
Definition 20. Two graphs G1 and G2 are isomorphic if they have the same number of vertices, edges, and there exists a matching between their vertices so that two vertices are connected by an edge in G1 if and only if corresponding vertices are connected by an edge in G2.

Consider the graphs:

$||v|| = 5$

$||e|| = 7$

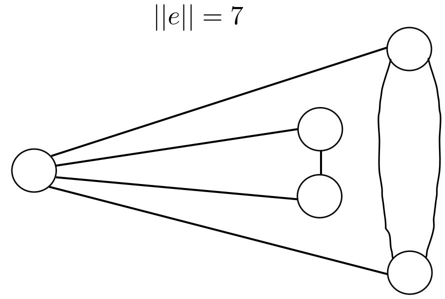
$G1$



$||v|| = 5$

$||e|| = 7$

$G2$



We can then see that these two graphs are **isomorphic**