Overview

• Last Lecture: Completed Algorithms
  – Big-O notation of Growth of Complexity Function
  – Tractable vs Intractable Problems
  – Computability theory
  – Number theory: Division, Primes, GCD, LCM
  – Euclidean Algorithm for GCD
  – Modular Arithmetic: Properties of Congruence

• This Lecture: Graph Theory
  – Introduction of Graphs
  – Graph theory

Chapter 6.1 Theory and Applications of Graphs

Coding

Intuitive

Matrix, Spreadsheet, Visual

Theory

\( G = (V, E) \)
Introduction to Graphs

1. Definition: A **simple graph** \( G = (V, E) \) consists of vertex set \( V \), a nonempty set of vertices/nodes, and edge set \( E \), a set of edges or unordered pairs of vertices. So each edge \( e \in E \) is a set; \( e = \{u, v\} \) where \( u, v \in V \). An edge \( e \) is a self-loop if \( e = \{u, u\} \) for some \( u \in V \).

2. Definition: A **undirected graph** is a simple graph with no self loops and there is at most one edge between two vertices (multipart may have self-loops and multi-edges in between two vertices).

3. Definition: A **directed graph** \( G = (V, E) \) consists of a vertex set \( V \) and an edge set \( E \). Edges are ordered pairs or arrows of elements in \( V \). For each \( e \in E \), \( e = (u, v) \) where \( u, v \in V \).

In this chapter, we assume

“no multi-edges” unless we clearly specify “with multi-edges”

graphs mean undirected graphs

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Graph Models

- Example I: How can we represent a network of (bi-directional) railways connecting a set of cities?

- We should use an undirected graph with an edge \( \{a, b\} \) indicating a direct train connection between cities \( a \) and \( b \).

\[ G=(V,E) \]
\[ V=\{B,T,N,W\} \]
\[ E=\{(T,N), \{B,N\}, \{N,W\}\} \]
- Example II: In a round-robin tournament, each team plays against each other team exactly once. How can we represent the results of the tournament (which team wins over which other team)?

- We should use a directed graph with an edge \((a, b)\) indicating that team \(a\) wins over team \(b\).

\[ G=(V,E) \]

\[ V=\{A,B,C,D\} \]

\[ E=\{(A,C),(B,C),(D,A),\]

\[ (D,B),(D,C)\} \]

**Graph Terminology (undirected graphs)**

- Definition: Two vertices \(u\) and \(v\) in an undirected graph \(G\) are called adjacent or neighbors in \(G\) if \(\{u, v\}\) is an edge in \(G\).

  If \(e = \{u, v\}\), the edge \(e\) is called incident with the vertices \(u\) and \(v\). The edge \(e\) is also said to connect \(u\) and \(v\).

  The vertices \(u\) and \(v\) are called endpoints of the edge \(\{u, v\}\).

- Definition: The degree of a vertex in an undirected graph is the number of edges incident with it, except that a loop at a vertex contributes twice to the degree of that vertex.

  In other words, you can determine the degree of a vertex in a displayed graph by counting the lines that touch it.

- A vertex of degree 0 is called isolated, since it is not adjacent to any vertex.
• **The Handshaking Theorem:** Let $G = (V, E)$ be an undirected graph with $|E|$ edges. Then $2|E| = \sum_{v \in V} \text{deg}(v)$ // sum of degrees

• Example: How many edges are there in a graph with 10 vertices, each of degree 6?

Solution: The sum of the degrees of the vertices is $6 \cdot 10 = 60$. According to the Handshaking Theorem, it follows that $2e = 60$, so there are 30 edges.

• **Theorem:** An undirected graph has an even number of vertices of odd degree.

**Proof:** Let $V_1$ and $V_2$ be the set of vertices of even and odd degrees, respectively. Then by Handshaking theorem

$$2|E| = \sum_{v \in V} \text{deg}(v) = \sum_{v \in V_1} \text{deg}(v) + \sum_{v \in V_2} \text{deg}(v)$$

Since both $2|E|$ and $\sum_{v \in V_1} \text{deg}(v)$ are even, $\sum_{v \in V_2} \text{deg}(v)$ must be even => $|V_2|$ is even.

And for directed graphs:

• Definition: When $(u, v)$ is an edge of the directed graph $G$, $u$ is said to be adjacent to $v$, and $v$ is said to be adjacent from $u$.

• The vertex $u$ is called the **initial vertex** of $(u, v)$, and $v$ is called the **terminal vertex** of $(u, v)$. The initial vertex and terminal vertex of a loop are the same.

• Definition: In a directed graph, the **in-degree** of a vertex $v$ is the number of edges with $v$ as their terminal vertex. The **out-degree** of $v$ is the number of edges with $v$ as their initial vertex.

• Question: How does adding a loop to a vertex change the in-degree and out-degree of that vertex?

Answer: It increases both the in-degree and the out-degree by one.
• **Example:** What are the in-degrees and out-degrees of the vertices \(a, b, c, d\) in this graph:

\[
\begin{align*}
\text{deg}^\text{in}(a) &= 1 \\
\text{deg}^\text{out}(a) &= 2 \\
\text{deg}^\text{in}(b) &= 4 \\
\text{deg}^\text{out}(b) &= 2 \\
\text{deg}^\text{in}(d) &= 2 \\
\text{deg}^\text{out}(d) &= 1 \\
\text{deg}^\text{in}(c) &= 0 \\
\text{deg}^\text{out}(c) &= 2
\end{align*}
\]

• **Theorem:** Let \(G = (V, E)\) be a directed graph. Then:

\[
\sum_{v \in V} \text{deg}^\text{in}(v) = \sum_{v \in V} \text{deg}^\text{out}(v) = |E|
\]

This is easy to see, because every new edge increases both the sum of in-degrees and the sum of out-degrees by one.

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**Special Graphs**

• **Definition:** The **complete graph** on \(n\) vertices, denoted by \(K_n\), is the simple graph that contains exactly one edge between every pair of distinct vertices.
• **Definition:** The n-cube, denoted by $Q_n$, is the graph that has vertices representing the $2^n$ bit strings of length $n$. Two vertices are adjacent if and only if the bit strings that they represent differ in exactly one bit position.

\[ Q_1 \quad Q_2 \quad Q_3 \]

• **Definition:** A graph is called **bipartite** if its vertex set $V$ can be partitioned into two disjoint nonempty sets $V_1$ and $V_2$ such that every edge in the graph connects a vertex in $V_1$ with a vertex in $V_2$ (so that no edge in $G$ connects either two vertices in $V_1$ or two vertices in $V_2$).

• For example, consider a graph that represents mating partners of penguin in a colony. (March of Penguins!)

• This graph is **bipartite**, because the vertex set can be partitioned into female set and male set then each edge connects a vertex between the two sets.

• **Example I:** Is graph $G$ below bipartite?

No, because there is no way to partition the vertices into two sets so that there are no edges with both endpoints in the same set.

• **Example II:** Is graph $G$ below bipartite?

Yes, because we can display $G$ like this:
• **Definition:** The complete bipartite graph \( K_{m,n} \) is the graph that has its vertex set partitioned into two subsets of \( m \) and \( n \) vertices, respectively. Two vertices are connected if and only if they are in different subsets.

![Diagrams of \( K_{3,2} \) and \( K_{3,4} \) graphs]

**Neural Network!**

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**Operations on Graphs**

• **Definition:** A **subgraph** of a graph \( G = (V, E) \) is a graph \( H = (W, F) \) where \( W \subseteq V \) and \( F \subseteq E \).

• **Note:** \( H \) must be a valid graph. i.e. For each \( \{u,v\} \) in \( F \), \( u \) and \( v \) are vertices in \( W \)

• **Example:**

![Diagrams of \( K_5 \), subgraph of \( K_5 \), and a small subgraph]
• **Definition:** The **union** of two graphs \( G_1 = (V_1, E_1) \) and \( G_2 = (V_2, E_2) \) is the simple graph with vertex set \( V_1 \cup V_2 \) and edge set \( E_1 \cup E_2 \).

• The union of \( G_1 \) and \( G_2 \) is denoted by \( G_1 \cup G_2 \).

\[
\begin{align*}
G_1 & \uparrow \quad G_2 \\
\downarrow & \uparrow \quad (V \cup V_2, E \cup E_2) \\
G_1 \cup G_2 &= K_5
\end{align*}
\]

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**Representing Graphs**

• **Definition:** Let \( G = (V, E) \) be a graph with \(|V| = n\). Suppose that the vertices of \( G \) are listed in arbitrary order as \( v_1, v_2, \ldots, v_n \).

• The **adjacency matrix** \( A_G \) of \( G \), with respect to this listing of the vertices, is the \( n \times n \) zero-one-valued matrix with 1 as its \((i, j)\)-th entry when \( v_i \) and \( v_j \) are adjacent, and 0 otherwise.

• In other words, for an adjacency matrix \( A = [a_{ij}] \), \( a_{ij} = 1 \) if \( \{v_i, v_j\} \) is an edge of \( G \), \( a_{ij} = 0 \) otherwise.

• **Example:** What is the adjacency matrix \( A_G \) for the following graph \( G \) based on the order of vertices \( a, b, c, d \)?

\[
A_G = \begin{bmatrix}
0 & 1 & 1 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 1 & 1 & 0
\end{bmatrix}
\]

\[
G = (V, E) \\
V = \{a, b, c, d\} \\
E = \{a, b, c, a, b, c\}
\]
Definition: **Adjacency list** representation consists of a list of its vertices together with a separate list for each vertex that contains all the vertices adjacent to that vertex.

Example: let $1 = a$, $2 = b$, $3 = c$ and $4 = d$

<table>
<thead>
<tr>
<th>Vertex</th>
<th>List of adjacencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>2</td>
<td>1, 4</td>
</tr>
<tr>
<td>3</td>
<td>1, 4</td>
</tr>
<tr>
<td>4</td>
<td>1, 2, 3</td>
</tr>
</tbody>
</table>

Note: Adjacency Matrix and Adjacency Lists can be used to defined directed graphs also.