Graphs

Computer Science & Engineering 235: Discrete Mathematics

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Introduction I

Graph theory was introduced in the 18th century by Leonhard Euler via the Königsberg bridge problem.
In Königsberg (old Prussia), a river ran through town that created an island and then split off into two parts.
Seven bridges were built so that people could easily get around.
Euler wondered, is it possible to walk around Königsberg, crossing every bridge exactly once?

Introduction II

To solve this problem, we need to model it mathematically.
Specifically, we can define a graph whose vertices are the land areas and whose edges are the bridges.

Introduction III

The question now becomes, does there exist a path in the following graph such that every edge is traversed exactly once?

Motivations I

Graph Theory has lots of applications (many problems can be modeled as graphs).
▶ Problems involving geographic/physical relations
▶ Networking
▶ Relations between entities
▶ Workflow applications
▶ Linguistics
▶ Chemistry, Physics, Biology, etc.
Definitions I

Definition

A simple undirected graph \( G = (V, E) \) is a 2-tuple with

\[ V = \{v_1, v_2, \ldots, v_n\} \]  

a finite set of vertices.

\[ E \subseteq V \times V = \{e_1, e_2, \ldots, e_m\} \]  

an unordered set of edges

where each \( e_i = (v, v') \) is an unordered pair of vertices,

\( v, v' \in V \).

Since \( V \) and \( E \) are sets, it makes sense to consider their cardinality. As is standard, \(|V| = n\) denotes the number of vertices in \( G \) and \(|E| = m\) denotes the number of edges in \( G \).

Definitions II

- A multigraph is a graph in which the edge set \( E \) is a multiset. Multiple distinct (or parallel) edges can exist between vertices.
- A pseudograph is a graph in which the edge set \( E \) can have edges of the form \((v, v)\) called loops
- A directed graph is one in which \( E \) contains ordered pairs. The orientation of an edge \((v, v')\) is said to be “from \( v \) to \( v' \).”
- A directed multigraph is a multigraph whose edges set consists of ordered pairs.

Definitions III

If we look at a graph as a relation then, among other things,

- Undirected graphs are symmetric.
- Directed graphs are asymmetric.
- Non-pseudographs are irreflexive.
- Multigraphs have nonnegative integer entries in their matrix; this corresponds to degrees of relatedness.

Other types of graphs can include labeled graphs (each edge has a uniquely identified label or weight), colored graphs (edges are colored) etc.

Terminology

Adjacency

For now, we will concern ourselves with simple, undirected graphs. We now look at some more terminology.

Definition

Two vertices \( u, v \) in an undirected graph \( G = (V, E) \) are called adjacent (or neighbors) if \( e = (u, v) \in E \).

We say that \( e \) is incident with or incident on the vertices \( u \) and \( v \).

Edge \( e \) is said to connect \( u \) and \( v \).

\( u \) and \( v \) are also called the endpoints of \( e \).

Terminology

Degree

Definition

The degree of a vertex in an undirected graph \( G = (V, E) \) is the number of edges incident with it.

The degree of a vertex \( v \in V \) is denoted

\[ \deg(v) \]

In a multigraph, a loop contributes to the degree twice.

A vertex of degree 0 is called isolated.

Handshake Lemma

Lemma

Let \( G = (V, E) \) be an undirected graph. Then

\[ 2|E| = \sum_{v \in V} \deg(v) \]

The handshake lemma applies even in multi and pseudographs.

proof By definition, each \( e = (v, v') \) will contribute 1 to the degree of each vertex, \( \deg(v), \deg(v') \). If \( e = (v, v) \) is a loop then it contributes 2 to \( \deg(v) \). Therefore, the total degree over all vertices will be twice the number of edges. \( \square \)
**Terminology**

**Handshake Lemma**

**Corollary**

An undirected graph has an even number of vertices of odd degree.

**Terminology - Directed Graphs I**

In a directed graph (digraph), $G = (V, E)$, we have analogous definitions.

- Let $e = (u, v) \in E$.
- $u$ is adjacent to or incident on $v$.
- $v$ is adjacent from or incident from $u$.
- $u$ is the initial vertex.
- $v$ is the terminal vertex.
- For a loop in a pseudograph, these are the same.

**Terminology - Directed Graphs II**

We make a distinction between incoming and outgoing edges with respect to degree.

- Let $v \in V$.
- The in-degree of $v$ is the number of edges incident on $v$.
  \[ \deg^- (v) \]
- The out-degree of $v$ is the number of edges incident from $v$.
  \[ \deg^+(v) \]

**Terminology - Directed Graphs III**

Every edge $e = (u, v)$ contributes 1 to the out-degree of $u$ and 1 to the in-degree of $v$. Thus, the sum over all vertices is the same.

**Theorem**

Let $G = (V, E)$ be a directed graph. Then

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

**More Terminology I**

A path in a graph is a sequence of vertices,

\[ v_1 v_2 \cdots v_k \]

such that $(v_i, v_{i+1}) \in E$ for all $i = 1, \ldots, k - 1$.

We can denote such a path by $p : v_1 \rightsquigarrow v_k$.

The length of $p$ is the number of edges in the path,

\[ |p| = k - 1 \]

**More Terminology II**

A cycle in a graph is a path that begins and ends at the same vertex.

\[ v_1 v_2 \cdots v_k v_1 \]

Cycles are also called circuits.

We define paths and cycles for directed graphs analogously.

A path or cycle is called simple if no vertex is traversed more than once. From now on we will only consider simple paths and cycles.
Classes Of Graphs

- Complete Graphs – Denoted $K_n$ are simple graphs with $n$ vertices where every possible edge is present.
- Cycle Graphs – Denoted $C_n$ are simply cycles on $n$ vertices.
- Wheels – Denoted $W_n$ are cycle graphs (on $n$ vertices) with an additional vertex connected to all other vertices.
- $n$-cubes – Denoted $Q_n$ are graphs with $2^n$ vertices corresponding to each bit string of length $n$. Edges connect vertices whose bit strings differ by a single bit.
- Grid Graphs – finite graphs on the $N \times N$ grid.

Bipartite Graphs

Definition
A graph is called bipartite if its vertex set $V$ can be partitioned into two disjoint subsets $L, R$ such that no pair of vertices in $L$ (or $R$) is connected.

We often use $G = (L, R, E)$ to denote a bipartite graph.

A bipartite graph is complete if every $u \in L$ is connected to every $v \in R$. We denote a complete bipartite graph as $K_{n_1,n_2}$ which means that $|L| = n_1$ and $|R| = n_2$.

Examples?

Planar Graphs

- Planar graphs are graphs that can be drawn on the plane (2-space) without any edges crossing.
- Examples: $K_4$ is planar, but $K_5$ is not
- Many efficient algorithms exist for planar graphs

Theorem (Kuratowski’s Theorem)

A graph $G = (V, E)$ is planar if and only if it does not contain any $K_5$ nor $K_{3,3}$ minors.

A minor is a subgraph that can be obtained by expanding/contracting edges to paths and vice versa.

Decomposing & Composing Graphs I

We can (partially) decompose graphs by considering subgraphs.

Definition

A subgraph of a graph $G = (V, E)$ is a graph $H = (V', E')$ where
- $V' \subseteq V$ and
- $E' \subseteq E$.

Subgraphs are simply part(s) of the original graph.
Decomposing & Composing Graphs II

Conversely, we can combine graphs.

<table>
<thead>
<tr>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>The union of two graphs $G_1 = (V_1, E_1)$ and $G_2 = (V_1, E_1)$ is defined to be $G = (V, E)$ where</td>
</tr>
<tr>
<td>▶ $V = V_1 \cup V_2$ and</td>
</tr>
<tr>
<td>▶ $E = E_1 \cup E_2$.</td>
</tr>
</tbody>
</table>

Data Structures I

A graph can be implemented as a data structure using one of two representations. These representations can greatly affect the running time of certain graph algorithms.

**Adjacency List** – An adjacency list representation of a graph $G = (V, E)$ maintains $|V|$ linked lists. For each vertex $v \in V$, the head of the list is $v$ and subsequent entries correspond to adjacent vertices $v' \in V$.

**Adjacency Matrix** – An adjacency matrix representation maintains an $n \times n$ sized matrix with entries

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

for $0 \leq i, j \leq (n - 1)$.

Data Structures II

Example

Consider the following adjacency list.

<table>
<thead>
<tr>
<th>$v_0$</th>
<th>$v_2$</th>
<th>$v_3$</th>
<th>$v_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_1$</td>
<td>$v_0$</td>
<td>$v_2$</td>
<td></td>
</tr>
<tr>
<td>$v_2$</td>
<td>$v_0$</td>
<td>$v_1$</td>
<td>$v_3$</td>
</tr>
<tr>
<td>$v_3$</td>
<td>$v_1$</td>
<td></td>
<td>$v_4$</td>
</tr>
<tr>
<td>$v_4$</td>
<td>$v_1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What is the associated graph?

Data Structures III

- **Advantages**: Less storage
- **Disadvantages**: Adjacency look up is $O(|V|)$, extra work to maintain vertex ordering (lexicographic)

**Adjacency Matrix** – An adjacency matrix representation maintains an $n \times n$ sized matrix with entries

$$
\begin{IEEEc各行
a_{i,j} = \begin{cases}
0 & \text{if } (v_i, v_j) \not\in E \\
1 & \text{if } (v_i, v_j) \in E
\end{cases}
$$

for $0 \leq i, j \leq (n - 1)$.

Data Structures IV

Example

For the same graph in the previous example, we have the following adjacency matrix.

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

- **Advantages**: Adjacency/Weight look up is constant
- **Disadvantages**: Extra storage

Data Structures V

The entry of 1 for edges $e = (v_i, v_j)$ can be changed to a weight function $wt : E \to \mathbb{N}$. Alternatively, entries can be used to represent pseudographs.

Note that either representation is equally useful for directed and undirected graphs.
Sparse vs Dense Graphs

We say that a graph is sparse if $|E| \in O(|V|)$ and dense if $|E| \in O(|V|^2)$.

A complete graph $K_n$ has precisely $|E| = \frac{n(n-1)}{2}$ edges.

Thus, for sparse graphs, Adjacency lists tend to be better while for dense graphs, adjacency matrices are better in general.

Graph Isomorphism I

An isomorphism is a bijection (one-to-one and onto) that preserves the structure of some object.

In some sense, if two objects are isomorphic to each other, they are essentially the same.

Most properties that hold for one object hold for any object that it is isomorphic to.

An isomorphism of graphs preserves adjacency.

Graph Isomorphism II

Definition

Two graphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ are isomorphic if there exists a bijection

$\varphi : V_1 \rightarrow V_2$

such that $(u, v) \in E_1$ if and only if

$(\varphi(u), \varphi(v)) \in E_2$

for all vertices $u, v \in V_1$.

If $G_1$ is isomorphic to $G_2$ we use the notation

$G_1 \cong G_2$

Graph Isomorphism III

Lemma

Isomorphism of graphs is an equivalence relation.

Proof?

Graph Isomorphism I

Computability

Problem

Given: Two graphs, $G_1, G_2$.

Question: Is $G_1 \cong G_2$?

The obvious way of solving this problem is to simply try to find a bijection that preserves adjacency. That is, search through all $n!$ of them.

Wait: Do we really need to search all $n!$ bijections?

There are smarter, but more complicated ways. However, the best known algorithm for general graphs is still only

$O(\exp(\sqrt{n \log n}))$

Graph Isomorphism II

Computability

The graph isomorphism problem is of great theoretical interest because it is believed to be a problem of “intermediate complexity”.

Conversely, it is sometimes easier (though not in general) to show that two graphs are not isomorphic.

In particular, it suffices to show that the pair $(G_1, G_2)$ do not have a property that isomorphic graphs should. Such a property is called invariant wrt isomorphism.
Examples of invariant properties:

- $|V_1| = |V_2|$
- $|E_1| = |E_2|$
- Degrees of vertices must be preserved.
- Lengths of paths & cycles.

Such properties are a necessary condition of being isomorphic, but are not a sufficient condition.

Consider the following bijection.

\[
\begin{align*}
\varphi(u_1) &= v_1 \\
\varphi(u_2) &= v_3 \\
\varphi(u_3) &= v_5 \\
\varphi(u_4) &= v_2 \\
\varphi(u_5) &= v_4
\end{align*}
\]

We still need to verify that $\varphi$ preserves adjacency.

The original edges were

- $(u_1, u_2) \rightarrow (\varphi(u_1), \varphi(u_2)) = (v_1, v_3) \in E_2$?
- $(u_2, u_3) \rightarrow (\varphi(u_2), \varphi(u_3)) = (v_3, v_5) \in E_2$?
- $(u_3, u_4) \rightarrow (\varphi(u_3), \varphi(u_4)) = (v_5, v_2) \in E_2$?
- $(u_4, u_5) \rightarrow (\varphi(u_4), \varphi(u_5)) = (v_2, v_1) \in E_2$?
- $(u_5, u_1) \rightarrow (\varphi(u_5), \varphi(u_1)) = (v_4, v_1) \in E_2$?

Thus, they are isomorphic. Note that there are several bijections that show these graphs are isomorphic.

An undirected graph is called connected if for every pair of vertices, $u, v$ there exists a path connecting $u$ to $v$.

A graph that is not connected is the union of two or more subgraphs called connected components.

We have analogous (but more useful) notions for directed graphs as well.

A directed graph is strongly connected if for every pair of vertices $u,v$

- There exists $p_1: u \leadsto v$ and
- There exists $p_2: v \leadsto u$.
Connectivity II

Even if a graph is not strongly connected, it can still be (graphically) “one piece”.

Definition

A directed graph is weakly connected if there is a path between every two vertices in the underlying undirected graph (i.e. the symmetric closure).

The subgraphs of a directed graph that are strongly connected are called strongly connected components.

Such notions are useful in applications where we want to determine what individuals can communicate in a network (here, the notion of condensation graphs is useful).

Example?

Using Paths & Cycles in Isomorphisms II

If we can find such a path, say

$$u_0 u_1 \cdots u_k$$

it may be a good (partial) candidate for an isomorphic bijection.

Counting Paths I

Often, we are concerned as to how connected two vertices are in a graph.

That is, how many unique, paths (directed or undirected, but not necessarily simple) there are between two vertices, \(u, v\)?

An easy solution is to use matrix multiplication on the adjacency matrix of a graph.

Theorem

Let \(G\) be a graph with adjacency matrix \(A\). The number of distinct paths of length \(r\) from \(v_i \rightsquigarrow v_j\) equals the entry \(a_{ij}\) in the matrix \(A^r\).

The proof is a nice proof by induction.

Euler Paths & Cycles I

Recall the Königsberg Bridge Problem. In graph theory terminology, the question can be translated as follows.

Given a graph \(G\), does there exist a cycle traversing every edge exactly once? Such a cycle is known as an Euler cycle.

Definition

An Euler cycle in a graph \(G\) is a cycle that traverses every edge exactly once. An Euler path is a path in \(G\) that traverses every edge exactly once.
Theorem (Euler)
A graph $G$ contains an Euler cycle if and only if every vertex has even degree.

This theorem also holds more generally for multigraphs.

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Therefore, the answer to the Königsberg Bridge problem is, no, does there does not exist an Euler cycle. In fact, there is not even an Euler path.

Theorem
A graph $G$ contains an Euler path (not a cycle) if and only if it has exactly two vertices of odd degree.

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Constructing Euler paths is simple. Given a (multi)graph $G$, we can start at an arbitrary vertex. We then find any arbitrary cycle $c_1$ in the graph. Once this is done, we can look at the induced subgraph; the graph created by eliminating the cycle $c_1$. We can repeat this step (why?) until we have found a collection of cycles that involves every edge; $c_1, \ldots, c_k$.

The Euler cycle can then be constructed from these cycles as follows. Starting with $c_1$, traverse the cycle until we reach a vertex in common with another cycle, $c_i$; then we continue our tour on this cycle until we reach a vertex in common with another cycle, etc. We are always guaranteed a way to return to the original vertex by completing the tour of each cycle.

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Euler cycles & paths traverse every edge exactly once.

Cycles and paths that traverse every vertex exactly once are Hamiltonian cycles and paths.

Definition
A path $v_0, v_1, \ldots, v_n$ in a graph $G = (V, E)$ is called a Hamiltonian Path if $V = \{v_0, \ldots, v_n\}$ and $v_i \neq v_j$ for $i \neq j$. A Hamiltonian cycle is a Hamiltonian path with $(v_n, v_0) \in E$.

---

Exercise
Show that $K_n$ has a Hamiltonian Cycle for all $n \geq 3$. 
For general graphs, however, there is no known simple necessary and sufficient condition for a Hamiltonian Cycle to exist.

This is a stark contrast with Euler Cycles: we have a simple, efficiently verifiable condition for such a cycle to exist.

There are no known efficient algorithms for determining whether or not a graph $G$ contains a Hamiltonian Cycle.

Similar to the Traveling Salesman Problem, this problem is NP-hard.

Nevertheless, there are sufficient conditions.

**Theorem (Dirac Theorem)**
If $G$ is a graph with $n$ vertices with $n \geq 3$ such that the degree of every vertex in $G$ is at least $n/2$, then $G$ has a Hamiltonian cycle.

**Theorem (Ore’s Theorem)**
If $G$ is a graph with $n$ vertices with $n \geq 3$ such that $\deg(u) + \deg(v) \geq n$ for every pair of nonadjacent vertices $u, v$ in $G$ then $G$ has a Hamiltonian cycle.

Electronic devices often report state by using a series of switches which can be thought of as bit strings of length $n$. (corresponding to $2^n$ states).

If we use the usual binary enumeration, a state change can take a long time—going from 0111 to 10000 for example.

It is much better to use a scheme (a code) such that the change in state can be achieved by flipping a single bit.

A Gray Code does just that.

Recall $Q_n$, the cube graph.

Each edge connects bit strings that differ by a single bit. To define a Gray Code, it suffices to find a Hamiltonian cycle in $Q_n$.

A Hamiltonian Path

So our code is as follows.

000 001
101 111
011 010
110 100