# Principles of Computer Science II

## Introduction to Graph Theory

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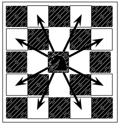
Lecture 17

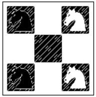
## A little bit of Chess

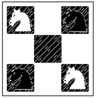
- Knights move using a particular pattern.
- Knights can move two steps in any of four directions (left, right, up, and down) followed by one step in a perpendicular direction,
- Two points are connected by a line if moving from one point to another is a valid knight move.



## A Chess Puzzle

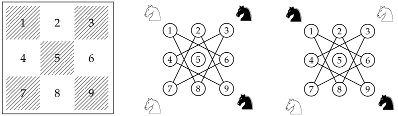
- Two white and two black knights on a $3 \times 3$ chessboard.
- Two Knights cannot occupy the same square.
- Starting from the top configuration,
- Can they move, using the usual chess knight's moves,
- To occupy the bottom configuration?





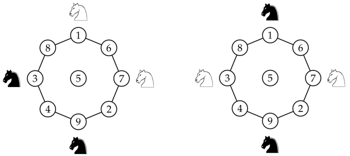
## Chess Diagrams

- A Chess Diagram is used to represent movements of chess pieces on the board.
- Example of a $3 \times 3$ chessboard.
- Two points are connected by a line if moving from one point to another is a valid knight move.



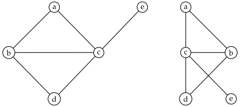
## Chess Diagrams – Equivalent Representations

- An equivalent representation of the resulting diagram.
- Now it is easy to see that knights move around a "cycle".
- Every knight's move corresponds to moving to a neighboring point in the diagram – clockwise or counterclockwise
- white-white-black-black cannot be transformed into white-black-white-black

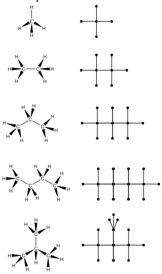



## Chess Diagrams & Graphs

- Chess Diagrams are examples of *graphs*.
- The points are called vertices and lines are called edges.
- A simple graph of five vertices and six edges.
- We denote a graph by $G = G(V, E)$, where
  - $V$ represents the set of vertices
    $V = \{a, b, c, d, e\}$
  - $E$ represents the set of edges
    $E = \{(a, b), (a, c), (b, c), (b, d), (c, d), (c, e)\}$




## Hydrocarbons as Graphs and Structural Isomers



Methane

Ethane

Propane

Butane

Isobutane

## Basic Definitions

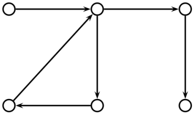
- We denote $|V| = n$ – the number of vertices.
- We denote $|E| = m$ – the number of edges.
- Two vertices $u, v$ are called adjacent or neighboring vertices if there exists an edge $e = (u, v)$.
- We say that edge $e$ is incident to vertices $u$ and $v$.
- We say that vertices $u$ and $v$ are incident to edge $e$.
- A loop is an edge from a node to itself: $(u, u)$.
- Two or more edges that have the same endpoints $(u, v)$ are called multiple edges.
- The graph is called simple if it does not have any loops or multiple edges.

## Degree of the Vertex

- The number of edges incident to a given vertex $v$ is called the degree of the vertex and is denoted $d(v)$.
- For every graph $G = G(V, E)$, $\sum_{u \in V} d(u) = 2 \cdot |m|$.
- Notice that an edge connecting vertices $v$ and $w$ is counted in the sum twice: first in the term $d(v)$ and again in the term $d(w)$.

## Directed & Undirected Graphs

- Many Bioinformatics problems make use of directed graphs.
- An edge can be undirected or directed.
- An undirected edge $e$ is considered an unordered pair, in other words we assume that $(u, v)$ and $(v, u)$ are the same edge.
- A directed edge $e = (u, v)$ and $e' = (v, u)$ are different edges.
- If the edges have a direction, the graph is directed (digraph).
- If a graph has no direction, it is referred as undirected.



## Directed Graphs

- In directed graphs, each vertex $u$ has:
  - *indegree*$(u)$ – the number of incoming edges,
  - *outdegree*$(u)$ – the number of outgoing edges.
- For every directed graph $G = G(V, E)$,

$$\sum_{u \in V} indegree(u) = \sum_{u \in V} outdegree(u)$$

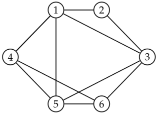
.

## Subgraphs & Complete Graphs

- A subgraph $G'$ of $G$ consists of a subset of $V$ and $E$. That is, $G' = (V', E')$ where $V' \subset V$ and $E' \subset E$.
- A spanning subgraph contains all the nodes of the original graph.
- If all the nodes in a graph are pairwise adjacent, the graph is called complete.

## Triangles, Walks, Trails, Paths & Cycles

- A triangle in an undirected graph is a triplet $(u, v, w)$, where $u, v, w \in V$ such that $(u, v), (v, w), (w, u) \in E$.
- A walk is a sequence of vertices and edges of a graph – Vertex can be repeated. Edges can be repeated.
- Trail is a walk in which no edge is repeated.
- Path is a trail in which no vertex is repeated.
- Paths that start and end at the same vertex are referred to as cycles.

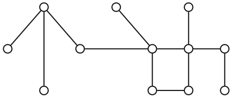



## Paths

- A path of length $k$ is a sequence of nodes $(v_0, v_1, \ldots, v_k)$, where we have $(v_i, v_{i+1}) \in E$.
- If $v_i \neq v_j$ for all $0 \leq i < j \leq k$ we call the path simple.
- If $v_0 = v_k$ for all $0 \leq i < j \leq k$ and $v_0 = v_k$ the path is a cycle.
- A path from node $u$ to node $v$ is a path $(v_0, v_1, \ldots, v_k)$ such that $v_0 = u$ and $v_k = v$.

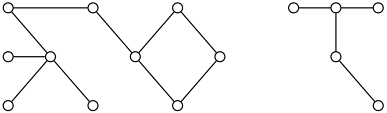
## Graph Connectivity

- Two nodes $u$ and $v$ are connected if there is a path from $u$ to $v$.
- A graph is called connected if all pairs of vertices can be connected by a path, otherwise we say that the graph is disconnected.
- A graph is called complete if there is an edge between every two vertices.



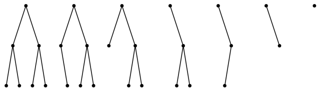
## Graph Connectivity

- Disconnected graphs can be decomposed into a set of one or more connected components.



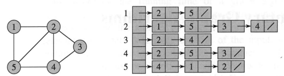
## Forests & Trees

- A simple graph that does not contain any cycles is called a forest.
- A forest that is connected is called a tree.
- A tree has $n-1$ edges.
- Any two of the following three statements imply that a graph is a tree (and thus they also imply the third one):
  1. The graph has $n-1$ edges.
  2. The graph does not contain any cycles.
  3. The graph is connected.



## Representation of Graphs

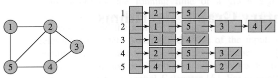
- Two standard ways to represent a graph $G(V,E)$:
  1. A collection of adjacency lists.
     - Usually prefered for sparse graphs.
     - Sparse graph: $|E|$ is much less than $|V|^2$.
  2. An adjacency matrix.
     - Usually prefered for dense graphs.
     - Dense graph: $|E|$ is close to $|V|^2$.



| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 0 | 1 | 0 |
| 4 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 1 | 0 | 1 | 0 |

## Adjacency List

- Adjacency List Representation
- Consists of an array $Adj$ of $|V|$ lists, one for each vertex in V.
- For each $u \in V$, the adjacency list $Adj[u]$ contains all the vertices adjacent to $u$ in G.
- The vertices are stored in arbitrary order.

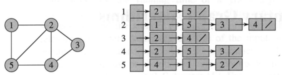


| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 0 | 1 | 0 |
| 4 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 1 | 0 | 1 | 0 |

## Adjacency Matrix

- Adjacency Matrix Representation of $G(V,E)$
- We assume that vertices are numbered $1, 2, \dots |V|$.
- The matrix $|V| \times |V|$ matrix.
- $A = (a_{i,j})$, where

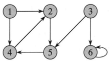
$$a_{i,j} = \begin{cases} 1, & \text{if } (i,j) \in E. \\ 0, & \text{otherwise.} \end{cases}$$

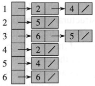


| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 1 |
| 2 | 1 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 0 | 1 | 0 |
| 4 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 1 | 0 | 1 | 0 |

# Adjacency List and Adjacency Matrix Examples

- Adjacency Matrix Representation




| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| 3 | 0 | 0 | 0 | 0 | 1 | 1 |
| 4 | 0 | 1 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 1 |