CSE373: Data Structures and Algorithms

Graphs and Their Representation

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Winter 2016

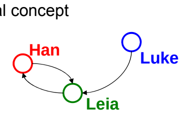
This lecture material represents the work of multiple instructors at the University of Washington. Thank you to all who have contributed!

Midterm, in-class Friday Feb. 12

- In class, closed notes, closed book.
- Covers everything up to and including hashing.
  - Stacks, queues
  - Induction, logs, exponents, geometric series
  - Asymptotic analysis and big-O, Omega, Theta
  - Dictionaries, BSTs, AVL Trees
  - Disjoint sets and the UNION-FIND ADT
  - Hash tables and collisions, primary clustering, lazy deletion, rehashing
- Information, sample past exam and solutions posted online.

Graphs

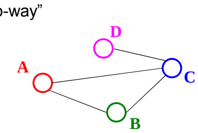
- A graph is a formalism for representing relationships among items
  - Very general definition because very general concept
- A graph is a pair
  `G = (V,E)`
  - A set of vertices, also known as nodes
    $V = \{v_1, v_2, \ldots, v_n\}$
  - A set of edges
    $E = \{e_1, e_2, \ldots, e_m\}$
    - Each edge e_i is a pair of vertices (v_j, v_k)
    - An edge "connects" the vertices
- Graphs can be directed or undirected




```
V = {Han,Leia,Luke}
E = {(Luke,Leia),
     (Han,Leia),
     (Leia,Han)}
```


Undirected Graphs

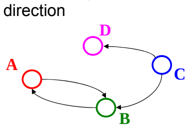
- In undirected graphs, edges have no specific direction
  - Edges are always "two-way"



- Thus, `(u,v)` ∈ `E` implies `(v,u)` ∈ `E`
  - Only one of these edges needs to be in the set
  - The other is implicit, so normalize how you check for it
- Degree of a vertex: number of edges containing that vertex
  - Put another way: the number of adjacent vertices

Directed Graphs

- In directed graphs (sometimes called digraphs), edges have a direction



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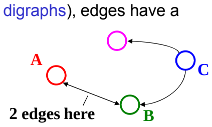
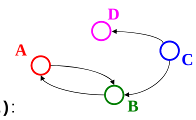


- Thus, `(u,v)` ∈ `E` does *not* imply `(v,u)` ∈ `E`.
  - Let `(u,v)` ∈ `E` mean u → v
  - Call **u** the source and **v** the destination
- In-degree of a vertex: number of in-bound edges, i.e., edges where the vertex is the destination
- Out-degree of a vertex: number of out-bound edges i.e., edges where the vertex is the source

Self-Edges, Connectedness

- A self-edge a.k.a. a loop is an edge of the form `(u,u)`
  - Depending on the use/algorithm, a graph may have:
    - No self edges
    - Some self edges
    - All self edges (often therefore implicit, but we will be explicit)
- A node can have a degree / in-degree / out-degree of zero
- A graph does not have to be connected
  - Even if every node has non-zero degree

More notation



$V = \{A, B, C, D\}$
$E = \{(C, B), (A, B), (B, A), (C, D)\}$

For a graph $G = (V,E)$:

- $|V|$ is the number of vertices
- $|E|$ is the number of edges
  - Minimum? 0
  - Maximum for undirected? $|V||V+1|/2 \in O(|V|^2)$
  - Maximum for directed? $|V|^2 \in O(|V|^2)$

(assuming self-edges allowed, else subtract $|V|$)

- If $(u,v) \in E$
  - Then **v** is a neighbor of **u**, i.e., **v** is adjacent to **u**
  - Order matters for directed edges
    - **u** is not adjacent to **v** unless $(v,u) \in E$

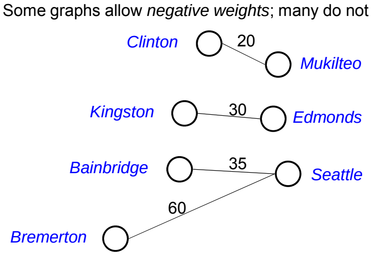
Examples

Which would use directed edges? Which would have self-edges? Which would be connected? Which could have 0-degree nodes?

1. Web pages with links
2. Facebook friends
3. Methods in a program that call each other
4. Road maps (e.g., Google maps)
5. Airline routes
6. Family trees
7. Course pre-requisites

Weighted Graphs

- In a weighed graph, each edge has a weight a.k.a. cost
  - Typically numeric (most examples use ints)
  - *Orthogonal* to whether graph is directed
  - Some graphs allow *negative weights*; many do not



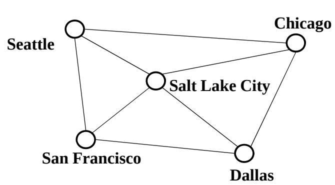
Examples

What, if anything, might weights represent for each of these? Do negative weights make sense?

- Web pages with links
- Facebook friends
- Methods in a program that call each other
- Road maps (e.g., Google maps)
- Airline routes
- Family trees
- Course pre-requisites

Paths and Cycles

- A path is a list of vertices $[v_0, v_1, \ldots, v_n]$ such that $(v_i, v_{i+1}) \in E$ for all $0 \le i < n$. Say *"a path from* v_0 *to* v_n*"*
- A cycle is a path that begins and ends at the same node ($v_0 == v_n$)

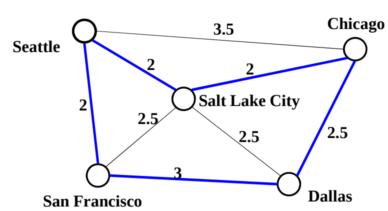


Example: [Seattle, Salt Lake City, Chicago, Dallas, San Francisco, Seattle]

Path Length and Cost

- Path length: Number of *edges* in a path
- Path cost: Sum of *weights* of edges in a path

Example where
P= [Seattle, Salt Lake City, Chicago, Dallas, San Francisco, Seattle]



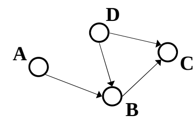
length(P) = 5
cost(P) = 11.5

Simple Paths and Cycles

- A simple path repeats no vertices, except the first might be the last
  [Seattle, Salt Lake City, San Francisco, Dallas]
  [Seattle, Salt Lake City, San Francisco, Dallas, Chicago, Seattle]
- Recall, a cycle is a path that ends where it begins
  [Seattle, Salt Lake City, San Francisco, Dallas, Chicago, Seattle]
  [Seattle, Salt Lake City, Seattle, Salt Lake City, Seattle]
- A simple cycle is a cycle and a simple path
  [Seattle, Salt Lake City, San Francisco, Dallas, Chicago, Seattle]

Paths and Cycles in Directed Graphs

Example:

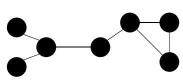


Is there a path from A to D? **No**

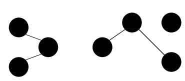
Does the graph contain any cycles? **No**

Undirected-Graph Connectivity

- An undirected graph is connected if for all pairs of vertices **u**, **v**, there exists a *path* from **u** to **v**

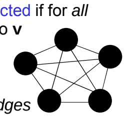


Connected graph



Disconnected graph

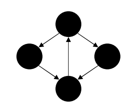
- An undirected graph is complete, a.k.a. fully connected if for *all* pairs of vertices **u**, **v**, there exists an *edge* from **u** to **v**



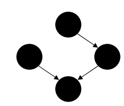
plus self edges

Directed-Graph Connectivity

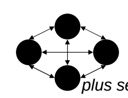
- A directed graph is strongly connected if there is a path from every vertex to every other vertex



- A directed graph is weakly connected if there is a path from every vertex to every other vertex *ignoring direction of edges*



- A complete a.k.a. fully connected directed graph has an edge from every vertex to every other vertex



plus self edges

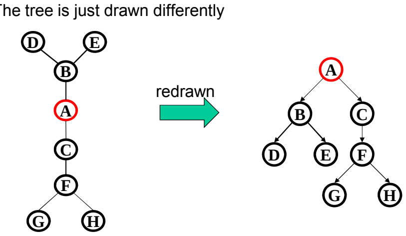
Trees as Graphs

When talking about graphs,
we say a tree is a graph that is:
- Undirected
- Acyclic
- Connected

So all trees are graphs, but not all graphs are trees

Rooted Trees

- We are more accustomed to rooted trees where:
  - We identify a unique root
  - We think of edges as directed: parent to children
- Given a tree, picking a root gives a unique rooted tree
  - The tree is just drawn differently



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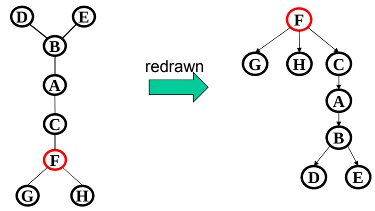
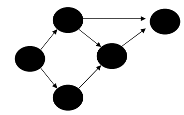
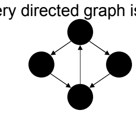


Directed Acyclic Graphs (DAGs)

- A DAG is a directed graph with no (directed) cycles
  - Every rooted directed tree is a DAG
  - But not every DAG is a rooted directed tree



  - Every DAG is a directed graph
  - But not every directed graph is a DAG



Examples

Which of our directed-graph examples do you expect to be a DAG?

- Web pages with links
- Methods in a program that call each other
- Airline routes
- Family trees
- Course pre-requisites

Density / Sparsity

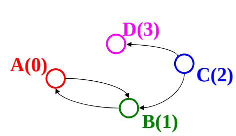
- Recall: In an undirected graph, $0 \leq |E| < |V|^2$
- Recall: In a directed graph: $0 \leq |E| \leq |V|^2$
- So for any graph, $O(|E|+|V|^2)$ is $O(|V|^2)$
- Another fact: If an undirected graph is *connected*, then $|V|-1 \leq |E|$
- Because $|E|$ is often much smaller than its maximum size, we do not always approximate $|E|$ as $O(|V|^2)$
  - This is a correct bound, it just is often not tight
  - If it is tight, i.e., $|E|$ is $\Theta(|V|^2)$ we say the graph is dense
    - More sloppily, dense means "lots of edges"
  - If $|E|$ is $O(|V|)$ we say the graph is sparse
    - More sloppily, sparse means "most possible edges missing"

What is the Data Structure?

- So graphs are really useful for lots of data and questions
  - For example, "what's the lowest-cost path from x to y"
- But we need a data structure that represents graphs
- The "best one" can depend on:
  - Properties of the graph (e.g., dense versus sparse)
  - The common queries (e.g., "is **(u,v)** an edge?" versus "what are the neighbors of node **u**?")
- So we'll discuss the two standard graph representations
  - Adjacency Matrix and Adjacency List
  - Different trade-offs, particularly time versus space

Adjacency Matrix

- Assign each node a number from `0` to `|V|-1`
- A `|V|` x `|V|` matrix (i.e., 2-D array) of Booleans (or 1 vs. 0)
  - If `M` is the matrix, then `M[u][v]` being `true` means there is an edge from `u` to `v`



	0	1	2	3
0	F	T	F	F
1	T	F	F	F
2	F	T	F	T
3	F	F	F	F

Adjacency Matrix Properties

- Running time to:
  - Get a vertex's out-edges: $O(|V|)$
  - Get a vertex's in-edges: $O(|V|)$
  - Decide if some edge exists: $O(1)$
  - Insert an edge: $O(1)$
  - Delete an edge: $O(1)$
- Space requirements:
  - $|V|^2$ bits
- Best for sparse or dense graphs?
  - Best for dense graphs

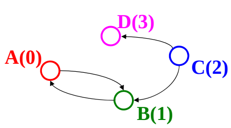
	0	1	2	3
0	F	T	F	F
1	T	F	F	F
2	F	T	F	T
3	F	F	F	F

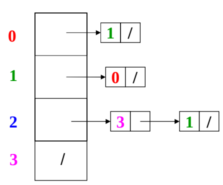
Adjacency Matrix Properties

- How will the adjacency matrix vary for an *undirected graph*?
  - Undirected will be symmetric around the diagonal
- How can we adapt the representation for *weighted graphs*?
  - Instead of a Boolean, store a number in each cell
  - Need some value to represent 'not an edge'
    - In *some* situations, 0 or -1 works

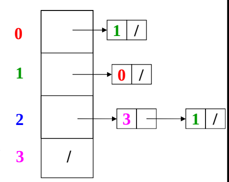
Adjacency List

- Assign each node a number from `0` to `|V|-1`
- An array of length `|V|` in which each entry stores a list of all adjacent vertices (e.g., linked list)





Adjacency List Properties



- Running time to:
  - Get all of a vertex's out-edges:
    O(*d*) where *d* is out-degree of vertex
  - Get all of a vertex's in-edges:
    O(|E|) (but could keep a second adjacency list for this!)
  - Decide if some edge exists:
    O(*d*) where *d* is out-degree of source
  - Insert an edge:
    O(1) (unless you need to check if it's there)
  - Delete an edge:
    O(*d*) where *d* is out-degree of source
- Space requirements:
  - *O*(|V|+|E|)
- Good for sparse graphs

Next…

Okay, we can represent graphs

Next lecture we'll implement some useful and non-trivial algorithms

- Topological sort: Given a DAG, order all the vertices so that every vertex comes before all of its neighbors
- Shortest paths: Find the shortest or lowest-cost path from x to y
  - Related: Determine if there even is such a path