GRAPHS

Lecture 17
CS 2110 — Spring 2019

JavaHyperText Topics

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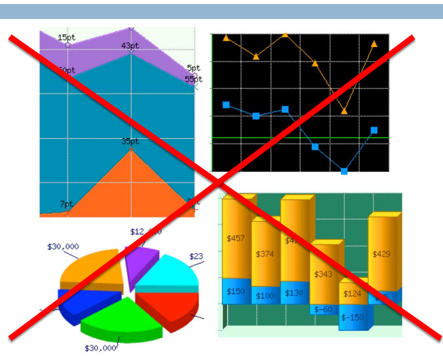
"Graphs", topics 1-3

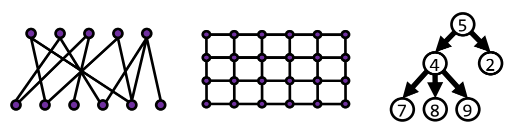
- 1: Graph definitions
- 2: Graph terminology
- 3: Graph representations

Charts (aka graphs)



Graphs

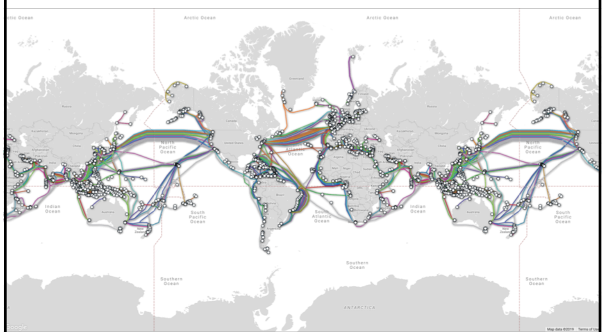
- **Graph:**
  - [charts] **Points** connected by **curves**
  - [in CS] **Vertices** connected by **edges**
- Graphs generalize trees
- Graphs are relevant far beyond CS…examples…



https://medium.com/@johnrobb/facebook-the-complete-social-graph-b58157ee6594

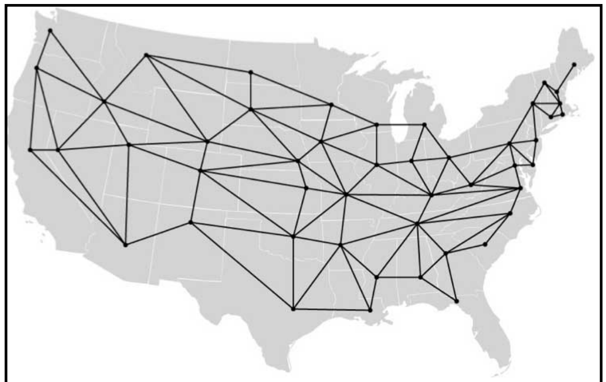
Vertices: people "from"
Edges: friendships

Vertices: subway stops
Edges: railways



https://www.submarinecablemap.com/

Vertices: stations
Edges: cables



http://www.cs.cmu.edu/~bryant/boolean/maps.html

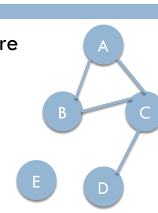
Vertices: State capitals
Edges: “States have shared border”

9 Graphs as mathematical structures

Undirected graphs

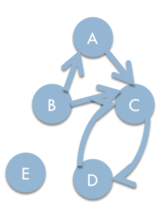
An **undirected** graph is a pair (V, E) where

- V is a set
  - Element of V is called a **vertex** or **node**
  - We’ll consider only finite graphs
  - *Ex:* ***V*** *= {A, B, C, D, E}; |V| = 5*
- E is a set
  - Element of E is called an **edge** or **arc**
  - An edge is itself a two-element set {u, v} where {u, v} ⊆ V
  - Often require u ≠ v (i.e., no **self-loops**)
  - *Ex:* ***E*** *= {{A, B}, {A, C}, {B, C}, {C, D}}, |E| = 4*



Directed graphs

A **directed** graph is similar except the edges are **pairs** (u, v), hence order matters



V *= {A, B, C, D, E}*
E *= {(A, C), (B, A), (B, C), (C, D), (D, C)}*
|V| *= 5*
|E| *= 5*

Convert undirected ←→ directed?

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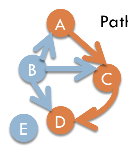
- Right question is: convert and maintain which properties of graph?
- Convert undirected to directed and maintain **paths?**

Paths

- A **path** is a sequence $v_0,v_1,v_2,\ldots,v_p$ of vertices such that for $0 \le i < p$,
  - Directed: $(v_i, v_{i+1}) \in E$
  - Undirected: $\{v_i, v_{i+1}\} \in E$
- The **length** of a path is its number of edges



Convert undirected ←→ directed?

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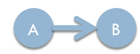
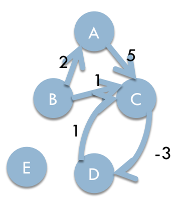
- Right question is: convert and maintain which properties of graph?
- Convert **undirected to directed** and maintain **paths**:
  - Nodes unchanged
  - Replace each edge {u,v} with two edges {(u,v), (v,u)}
- Convert **directed to undirected** and maintain paths: Can't:



Labels

Whether directed or undirected, edges and vertices can be **labeled** with additional data

Nodes already labeled with characters



Edges now labeled with integers

Discuss

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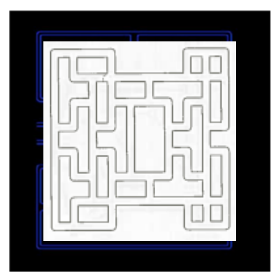
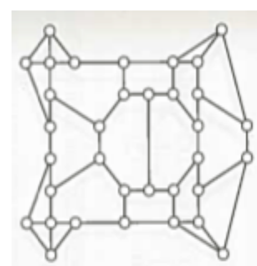
How could you represent a maze as a graph?





Algorithms, 2nd ed., Sedgewick, 1988

Announcement

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A4: See time distribution and comments @735

- Spending >16 hours is a problem; talk to us or a TA about why that might be happening
- Comments on the GUI:
  - "GUI was pretty awesome."
  - "I didn't see the relevance of the GUI."
- Hints:
  - "Hints were extremely useful and I would've been lost without them."
  - "Hints are too helpful. You should leave more for people to figure out on their own."
- Adjectives:
  - "Fun" (x30), "Cool" (x19)
  - "Whack", "Stressful", "Tedious", "Rough"

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Graphs as data structures

Graph ADT

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Operations could include:
- Add a vertex
- Remove a vertex
- Search for a vertex
- Number of vertices
- Add an edge
- Remove an edge
- Search for an edge
- Number of edges

Demo

Graph representations

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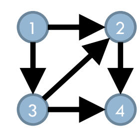
- Two vertices are **adjacent** if they are connected by an edge
- Common graph representations:
  - **Adjacency list**
  - **Adjacency matrix**



running example
(directed, no edge labels)

Adjacency "list"

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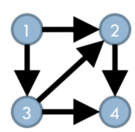
- Maintain a collection of the vertices
- For each vertex, also maintain a collection of its adjacent vertices



- Vertices: 1, 2, 3, 4
- Adjacencies:
  - 1: 2, 3
  - 2: 4
  - 3: 2, 4
  - 4: none

Could implement these "lists" in many ways…

Adjacency list implementation #1

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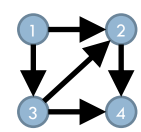
Map from vertex label to sets of vertex labels

1 ↦ {2, 3}
2 ↦ {4}
3 ↦ {2, 4}
4 ↦ {none}



Adjacency list implementation #2

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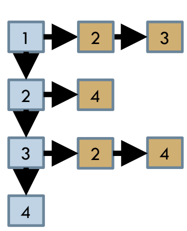
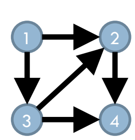
Linked list, where each node contains vertex label and linked list of adjacent vertex labels





Demo

Adjacency list implementation #3

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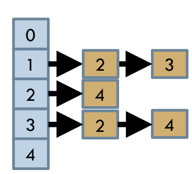
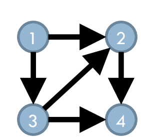
Array, where each element contains linked list of adjacent vertex labels





Requires: labels are integers; dealing with bounded number of vertices

Adjacency "matrix"

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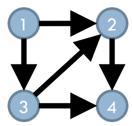
- Given integer labels and bounded # of vertices…
- Maintain a 2D Boolean array **b**
- Invariant: element **b[i][j]** is **true** iff there is an edge from vertex **i** to vertex **j**

	0	1	2	3	4
0	F	F	F	F	F
1	F	F	T	T	F
2	F	F	F	F	T
3	F	F	T	F	T
4	F	F	F	F	F



Adjacency list vs. Adjacency matrix

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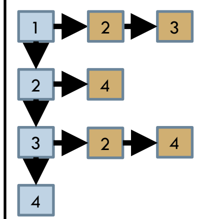

	0	1	2	3	4
0	F	F	F	F	F
1	F	F	T	T	F
2	F	F	F	F	T
3	F	F	T	F	T
4	F	F	F	F	F

Efficiency: Space to store?

O(|V| + |E|) O(|V|²)

Adjacency list vs. Adjacency matrix

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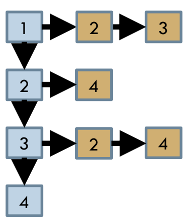

	0	1	2	3	4
0	F	F	F	F	F
1	F	F	T	T	F
2	F	F	F	F	T
3	F	F	T	F	T
4	F	F	F	F	F

Efficiency: Time to visit all edges?

$O(|V| + |E|)$ $O(|V|^2)$

Adjacency list vs. Adjacency matrix

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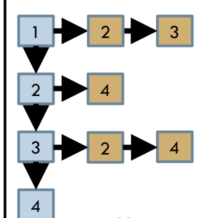

	0	1	2	3	4
0	F	F	F	F	F
1	F	F	T	T	F
2	F	F	F	F	T
3	F	F	T	F	T
4	F	F	F	F	F

Efficiency: Time to determine whether edge from v_1 to v_2 exists?

$O(|V| + |E|)$ $O(1)$

Tighter: $O(|V| + \#$ edges leaving $v_1)$

More graph terminology

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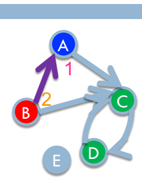
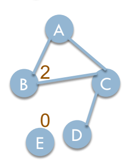
- Vertices u and v are called
  - the source and sink of the directed edge (u, v), respectively
  - the **endpoints** of (u, v) or $\{u, v\}$
- The outdegree of a vertex u in a directed graph is the number of edges for which u is the source
- The indegree of a vertex v in a directed graph is the number of edges for which v is the sink
- The degree of a vertex u in an undirected graph is the number of edges of which u is an endpoint





Adjacency list vs. Adjacency matrix

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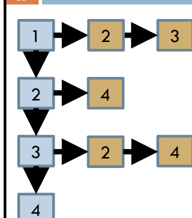

	0	1	2	3	4
0	F	F	F	F	F
1	F	F	T	T	F
2	F	F	F	F	T
3	F	F	T	F	T
4	F	F	F	F	F

Efficiency: Time to determine whether edge from v_1 to v_2 exists?

$O(|V| + |E|)$ $O(1)$

Tighter: $O(|V| +$ outdegree$(v_1))$

Adjacency list vs. Adjacency matrix

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List	Property	Matrix
$O(\|V\| + \|E\|)$	Space	$O(\|V\|^2)$
$O(\|V\| + \|E\|)$	Time to visit all edges	$O(\|V\|^2)$
$O(\|V\| + od(v_1))$	Time to find edge (v_1,v_2)	$O(1)$

Adjacency list vs. Adjacency matrix

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List	Property	Matrix
$O(\|V\| + \|E\|)$	Space	$O(\|V\|^2)$
$O(\|V\| + \|E\|)$	Time to visit all edges	$O(\|V\|^2)$
$O(\|V\| + od(v_1))$	Time to find edge (v_1,v_2)	$O(1)$

Max # edges = $|V|^2$

Sparse Dense

Adjacency list vs. Adjacency matrix

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List	Property	Matrix
$O(\|V\| + \|E\|)$	Space	$O(\|V\|^2)$
$O(\|V\| + \|E\|)$	Time to visit all edges	$O(\|V\|^2)$
$O(\|V\| + od(v_1))$	Time to find edge (v_1,v_2)	$O(1)$

Max # edges = $|V|^2$

Sparse: $|E| \ll |V|^2$ **Dense:** $|E| \approx |V|^2$

Adjacency list vs. Adjacency matrix

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List	Property	Matrix
$O(\|V\| + \|E\|)$	Space	$O(\|V\|^2)$
$O(\|V\| + \|E\|)$	Time to visit all edges	$O(\|V\|^2)$
$O(\|V\| + od(v_1))$	Time to find edge (v_1,v_2)	$O(1)$
Sparse graphs	**Better for**	**Dense graphs**

Max # edges = $|V|^2$

Sparse: $|E| \ll |V|^2$ **Dense:** $|E| \approx |V|^2$