CSE 332: Data Abstractions

Lecture 14: Introduction to Graphs

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Today

- Graphs
  - Intro & Definitions

Where We Are

We have learned about the essential ADTs and data structures:

- Regular and Circular Arrays (dynamic sizing)
- Linked Lists
- Stacks, Queues
- Priority Queues, Heaps
- Unbalanced and Balanced Search Trees, B-Trees
- Hash Tables

We have also learned important algorithms

- Tree traversals
- Floyd's buildheap Method
- Sorting algorithms

Where We Are Going

More on algorithms and related problems that require constructing data structures to make the solutions efficient

Topics will include:

- Graphs
- Parallelism
- Concurrency

Graphs

- A graph is a formalism for representing relationships among items
  - Very general definition because very general concept

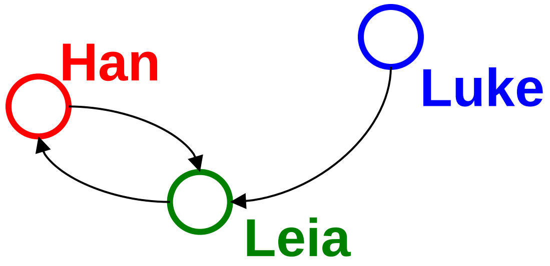
- A graph is a pair

  G = (V,E)
  - A set of vertices, also known as nodes

    $\mathbf{V} = \{v_1, v_2, \dots, v_n\}$
  - A set of edges

    $\mathbf{E} = \{e_1, e_2, \dots, e_m\}$
    - Each edge e_i is a pair of vertices

      (v_j, v_k)
    - An edge "connects" the vertices



V = {Han,Leia,Luke}

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

- Graphs can be directed or undirected

An ADT?

- Can think of graphs as an ADT with operations like **`isEdge((`v_j`,`v_k`))`**
- But it is unclear what the “standard operations” are
- Instead we tend to develop algorithms over graphs and then use data structures that are efficient for those algorithms
- Many important problems can be solved by:
  1. Formulating them in terms of graphs
  2. Applying a standard graph algorithm
- To make the formulation easy and standard, we have a lot of *standard terminology* about graphs

Some graphs

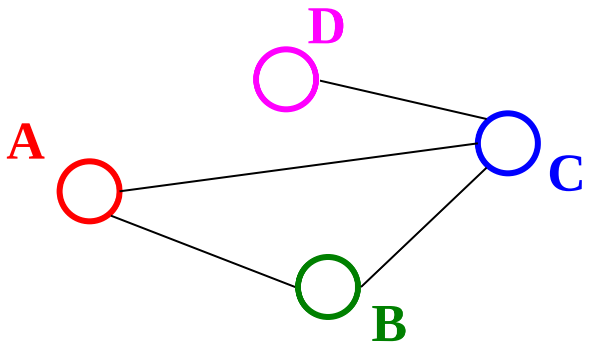
For each, what are the vertices and what are the edges?

- Web pages with links
- Facebook friends
- “Input data” for the Kevin Bacon game
- Methods in a program that call each other
- Road maps (e.g., Google maps)
- Airline routes
- Family trees
- Course pre-requisites
- …

Wow: Using the same algorithms for problems across so many domains sounds like “core computer science and engineering”

Undirected Graphs

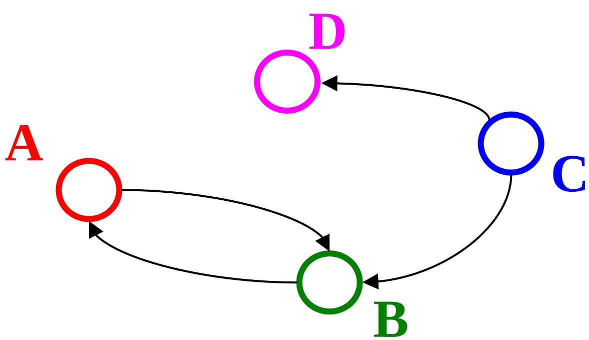
- In undirected graphs, edges have no specific direction
  - Edges are always "two-way"



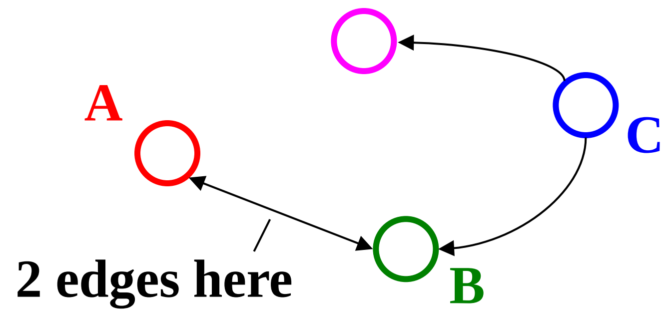
- Thus, **(u,v)** $\in$ **E** implies **(v,u)** $\in$ **E**.
  - Only one of these edges needs to be in the set; the other is implicit
- Degree of a vertex: number of edges containing that vertex
  - Put another way: the number of adjacent vertices

Directed Graphs

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



or

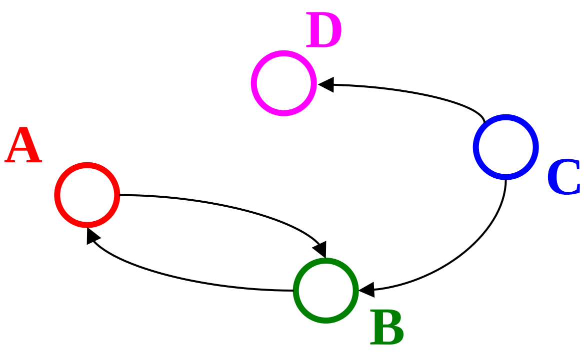


- Thus, **`(u,v)`** $\in$ **`E`** does *not* imply **`(v,u)`** $\in$ **`E`**.
  - Let **`(u,v)`** $\in$ **`E`** mean u → v
  - Call **`u`** the source and **`v`** the destination
- In-Degree of a vertex: number of in-bound edges, i.e., edges where the vertex is the destination
- Out-Degree of a vertex: 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 (In an undirected graph, this means we can follow edges from any node to every other node), even if every node has non-zero degree

More notation



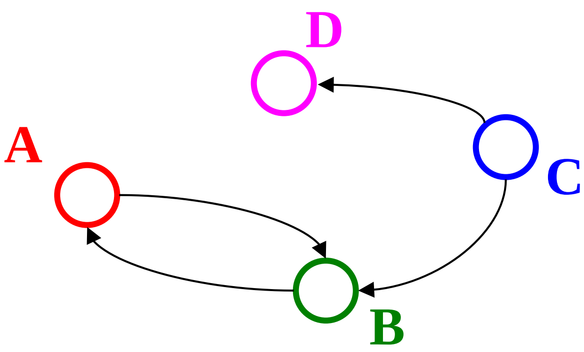
For a graph **G = (V,E)**:

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

- **|V|** is the number of vertices
- **|E|** is the number of edges
  - Minimum?
  - Maximum for undirected?
  - Maximum for directed?

- If **(u,v)** ∈ **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)** ∈ **E**

More notation



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 $(v,u) \in E$

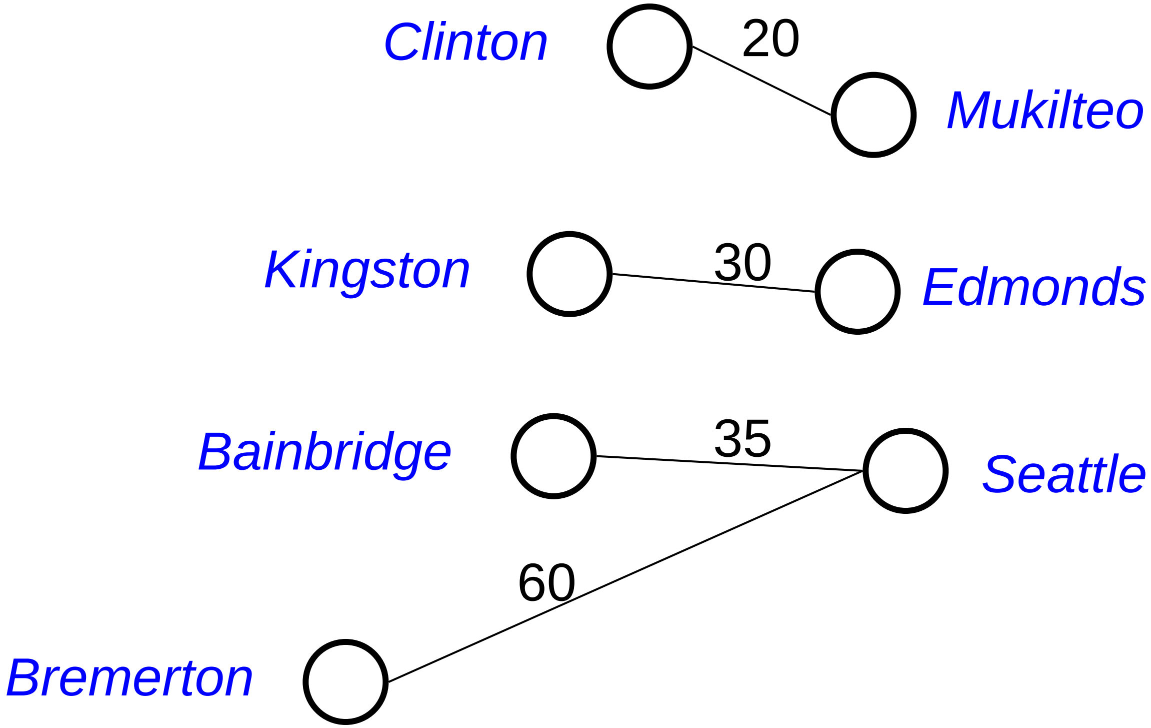
Examples again

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

- Web pages with links
- Facebook friends
- "Input data" for the Kevin Bacon game
- Methods in a program that call each other
- Road maps (e.g., Google maps)
- Airline routes
- Family trees
- Course pre-requisites
- …

Weighted graphs

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



Examples

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

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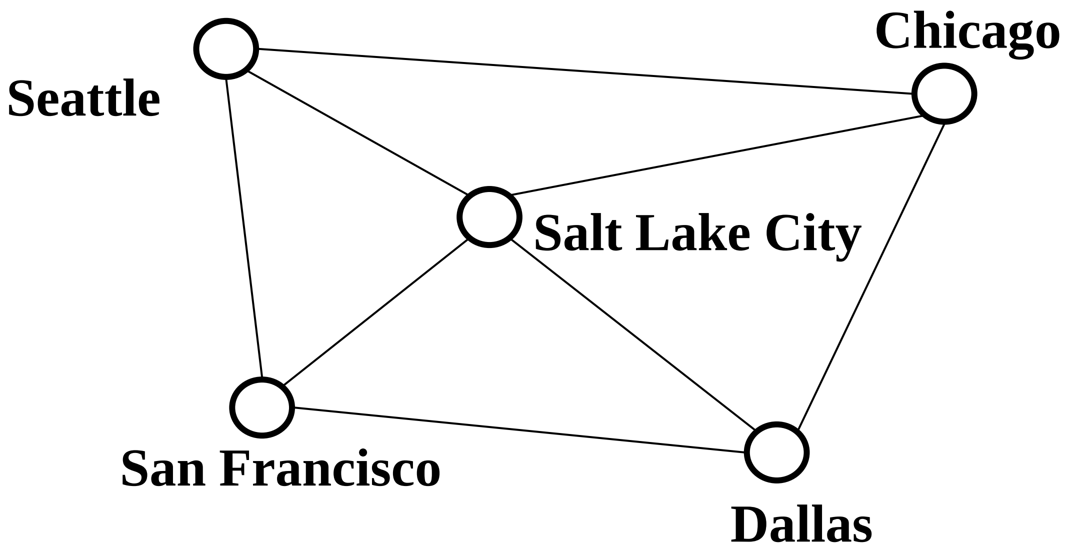
Paths and Cycles

- A path is a list of vertices $[\mathbf{v}_0, \mathbf{v}_1, \dots, \mathbf{v}_n]$ such that $(\mathbf{v}_i, \mathbf{v}_{i+1}) \in \mathbf{E}$ for all $\mathbf{0} \le \mathbf{i} < \mathbf{n}$. Say *"a path from* $\mathbf{v}_0$ *to* $\mathbf{v}_n$*"*

- A cycle is a path that begins and ends at the same node ($\mathbf{v}_0 == \mathbf{v}_n$)



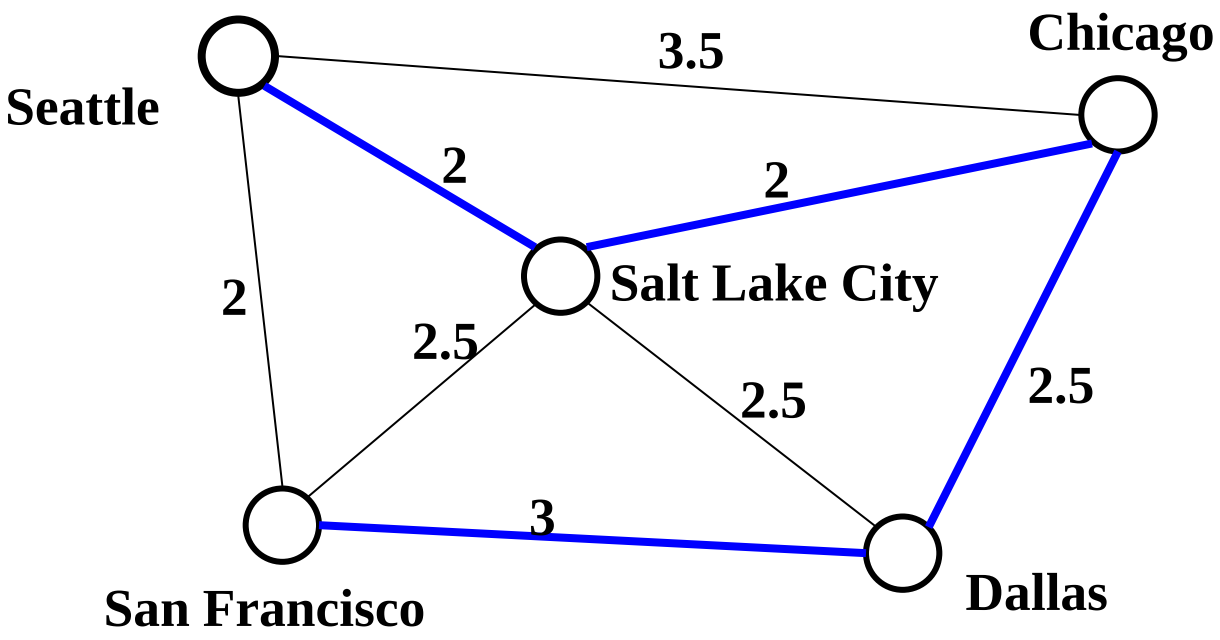
Example path (that also happens to be a cycle):
[Seattle, Salt Lake City, Chicago, Dallas, San Francisco, Seattle]

Path Length and Cost

- Path length: Number of *edges* in a path (also called "unweighted cost")
- Path cost: Sum of the weights of each edge

Example where:

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



length(P) = 4
cost(P) = 9.5

Simple paths and cycles

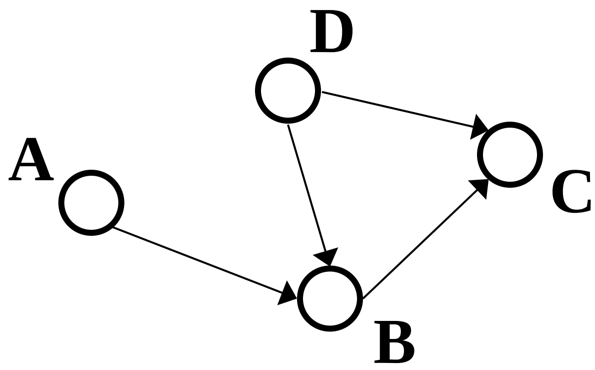
- A simple path repeats no vertices, (except the first might be the last):
  [Seattle, Salt Lake City, San Francisco, Dallas]
  [Seattle, Salt Lake City, San Francisco, Dallas, Seattle]

- Recall, a cycle is a path that ends where it begins:
  [Seattle, Salt Lake City, San Francisco, Dallas, Seattle]
  [Seattle, Salt Lake City, Seattle, Dallas, Seattle]

- A simple cycle is a cycle and a simple path:
  [Seattle, Salt Lake City, San Francisco, Dallas, Seattle]

Paths/cycles in directed graphs

Example:

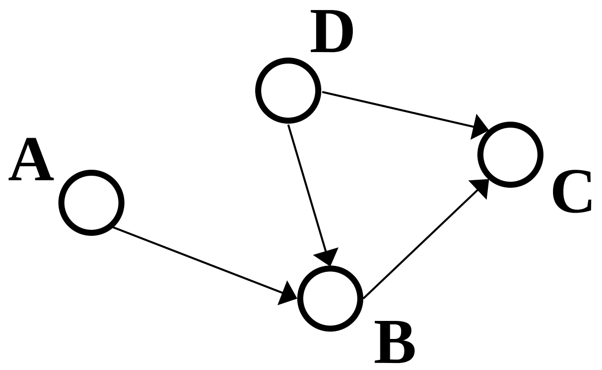


Is there a path from A to D?

Does the graph contain any cycles?

Paths/cycles in directed graphs

Example:

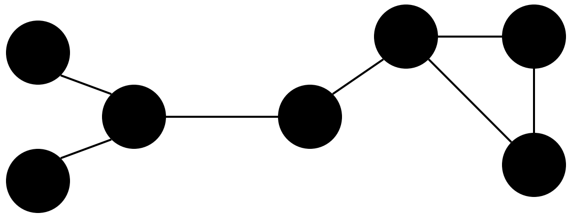


Is there a path from A to D? No

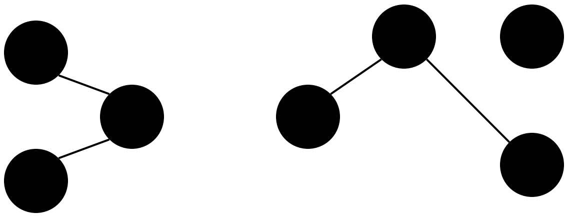
Does the graph contain any cycles? No

<u>Undirected</u> graph connectivity

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



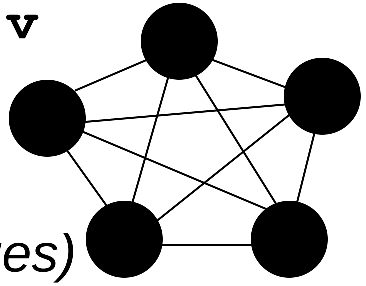
Connected graph



Disconnected graph

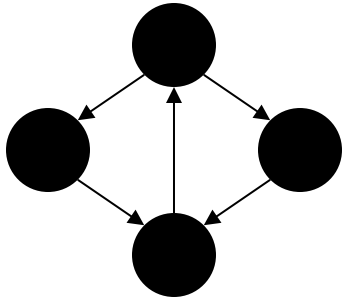
- An undirected graph is complete, a.k.a. fully connected if for all pairs of vertices **`u,v`**, there exists an *<u>edge</u>* from **`u`** to **`v`**

(plus self edges)

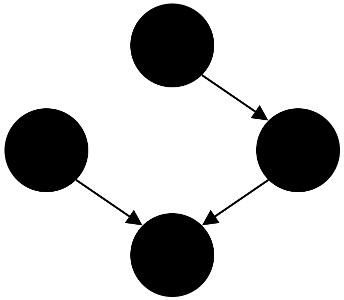


Directed graph connectivity

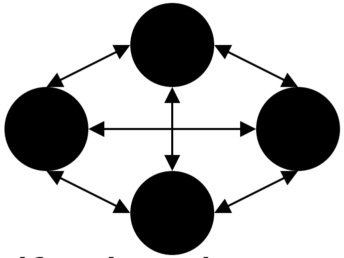
- A directed graph is strongly connected if there is a path from every vertex to every other vertex



- 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)

Examples

For undirected graphs: connected?

For directed graphs: strongly connected? weakly connected?

- Web pages with links
- Facebook friends
- “Input data” for the Kevin Bacon game
- Methods in a program that call each other
- Road maps (e.g., Google maps)
- Airline routes
- Family trees
- Course pre-requisites
- …

Trees as graphs

When talking about graphs,

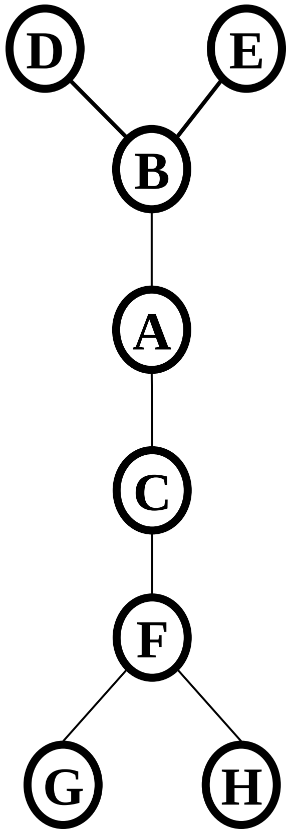
we say a tree is a graph that is:

- undirected
- acyclic
- connected

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

How does this relate to the trees we know and love?...

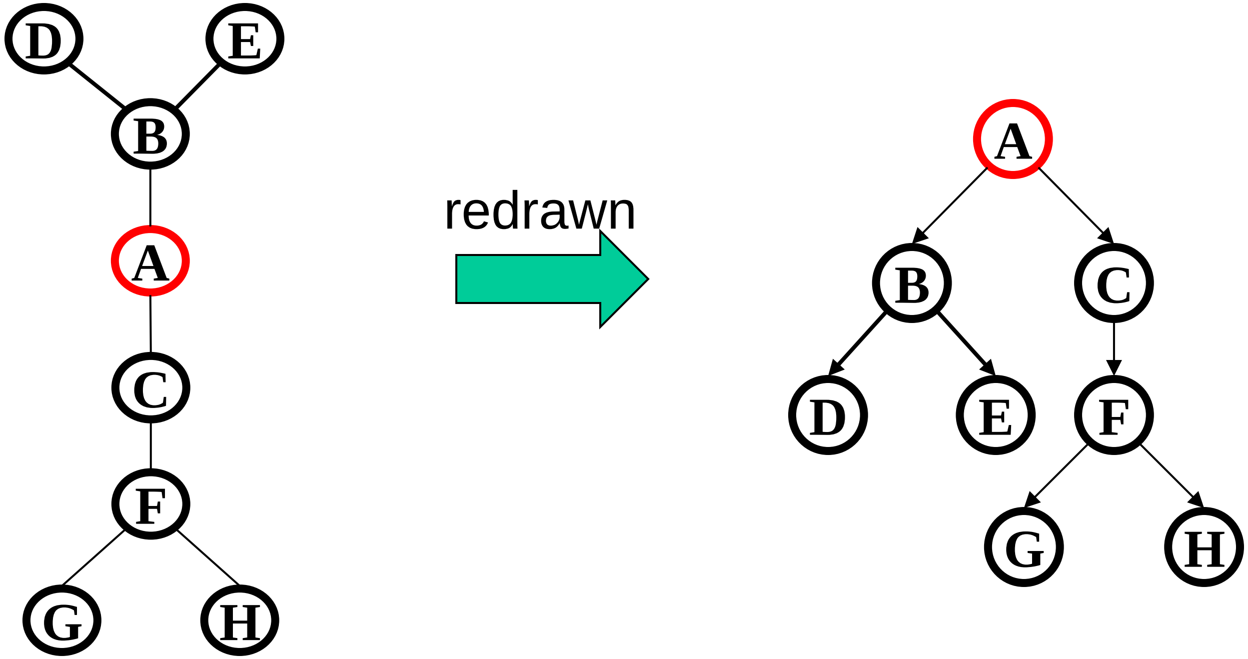
Example:



Rooted Trees

- We are more accustomed to rooted trees where:
  - We identify a unique (“special”) root
  - We think of edges as **directed**: parent to children

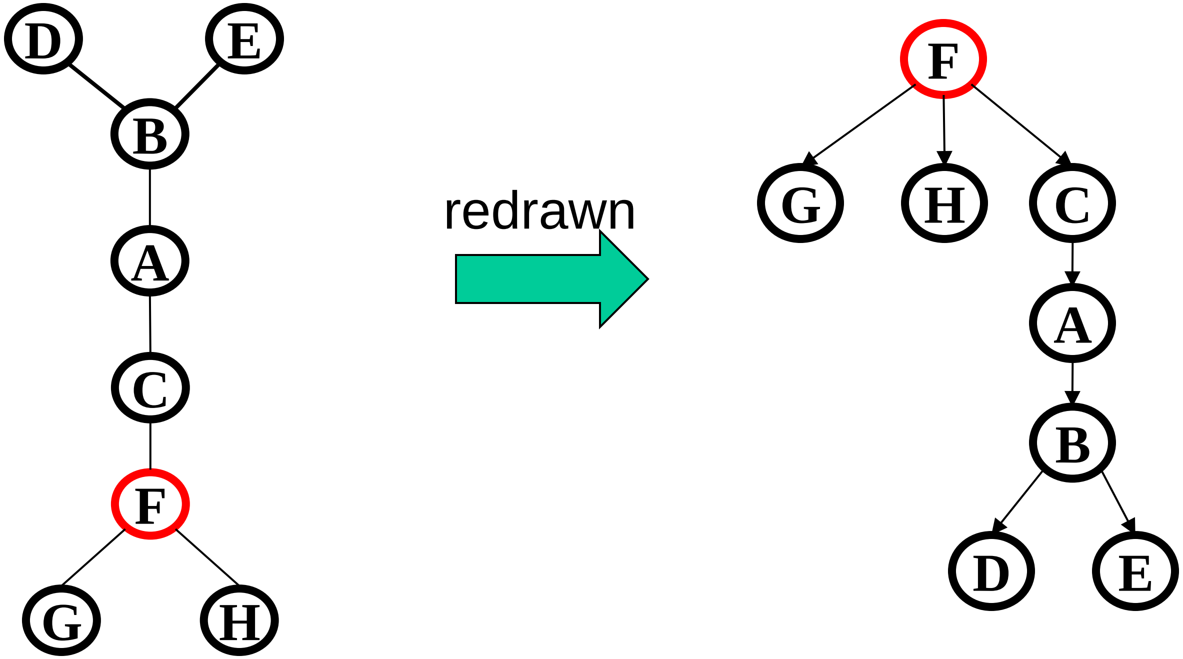
- Given a tree, once you pick a root, you have a unique rooted tree (just drawn differently and with undirected edges)



Rooted Trees (Another example)

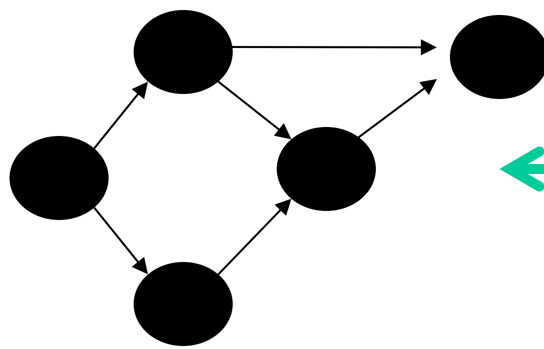
- We are more accustomed to rooted trees where:
  - We identify a unique (“special”) root
  - We think of edges as **directed**: parent to children

- Given a tree, once you pick a root, you have a unique rooted tree (just drawn differently and with undirected edges)



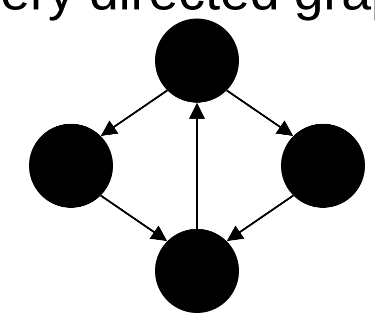
Directed acyclic graphs (DAGs)

- 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:



Not a rooted directed tree,
Has a cycle (in the
undirected sense)

  - 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
- “Input data” for the Kevin Bacon game
- 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, $|E|$ is $O(|V|^2)$
- One more fact: If an undirected graph is *connected*, then $|E| \geq |V|-1$
- Because $|E|$ is often much smaller than its maximum size, we do not always approximate as $|E|$ 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”

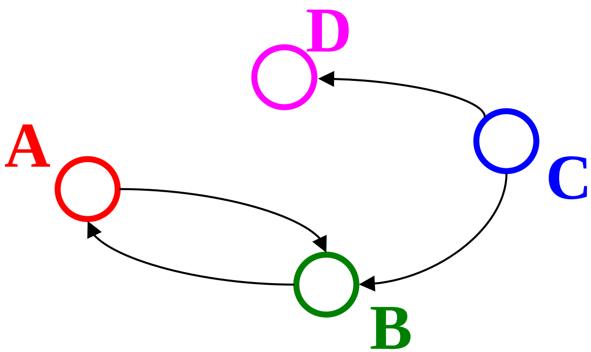
- But we need a data structure that represents graphs

- 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] == true`** means there is an edge from **`u`** to **`v`**



	A	B	C	D
A	F	T	F	F
B	T	F	F	F
C	F	T	F	T
D	F	F	F	F

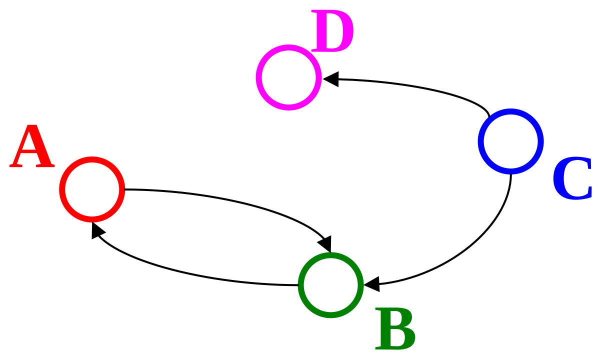
Adjacency Matrix Properties

- Running time to:
  - Get a vertex’s out-edges:
  - Get a vertex’s in-edges:
  - Decide if some edge exists:
  - Insert an edge:
  - Delete an edge:

- Space requirements:

- Best for sparse or dense graphs?

	A	B	C	D
A	F	T	F	F
B	T	F	F	F
C	F	T	F	T
D	F	F	F	F



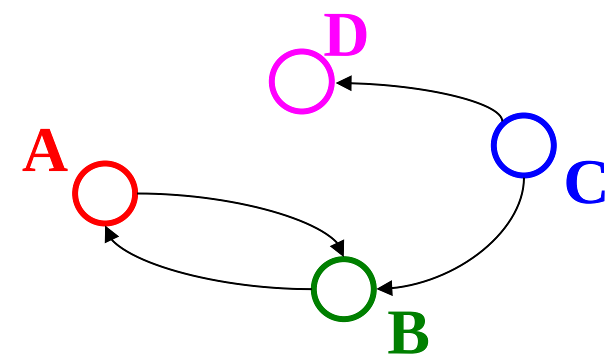
Adjacency Matrix Properties

- 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

	A	B	C	D
A	F	T	F	F
B	T	F	F	F
C	F	T	F	T
D	F	F	F	F



Adjacency Matrix Properties

- How will the adjacency matrix vary for an *undirected graph*?

- How can we adapt the representation for *weighted graphs*?

	A	B	C	D
A	F	T	F	F
B	T	F	F	F
C	F	T	F	T
D	F	F	F	F

Adjacency Matrix Properties

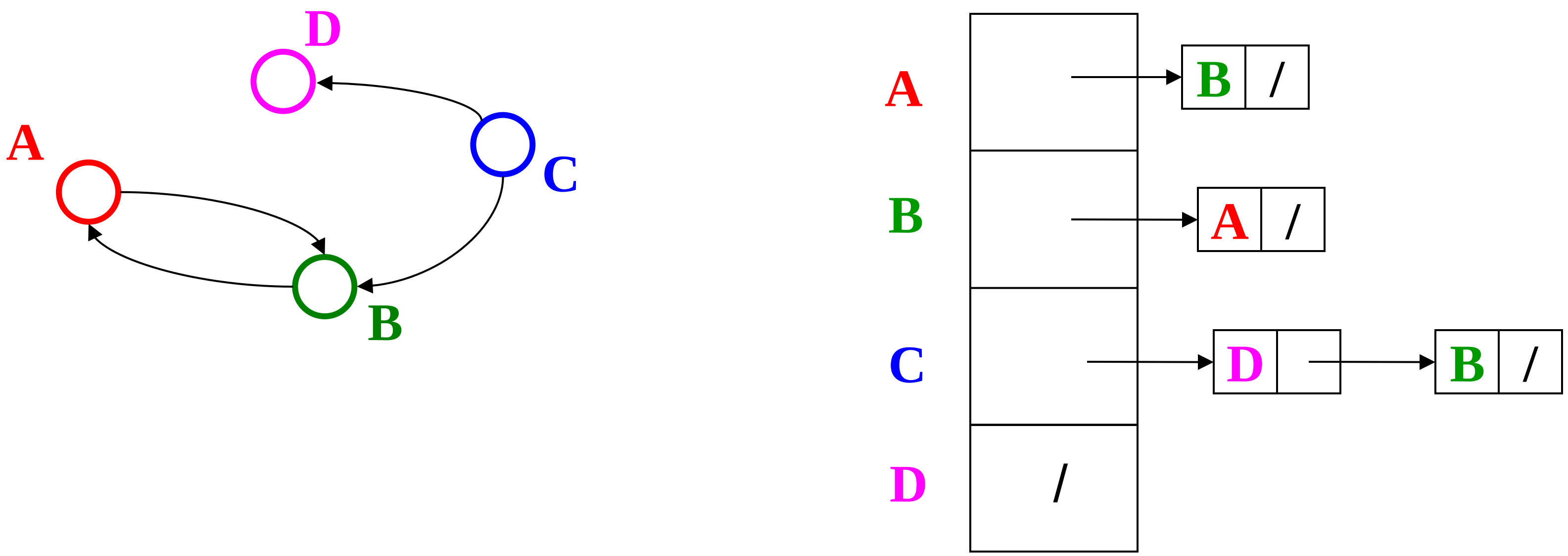
- How will the adjacency matrix vary for an *undirected graph*?
  - Undirected will be symmetric about diagonal axis

- 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

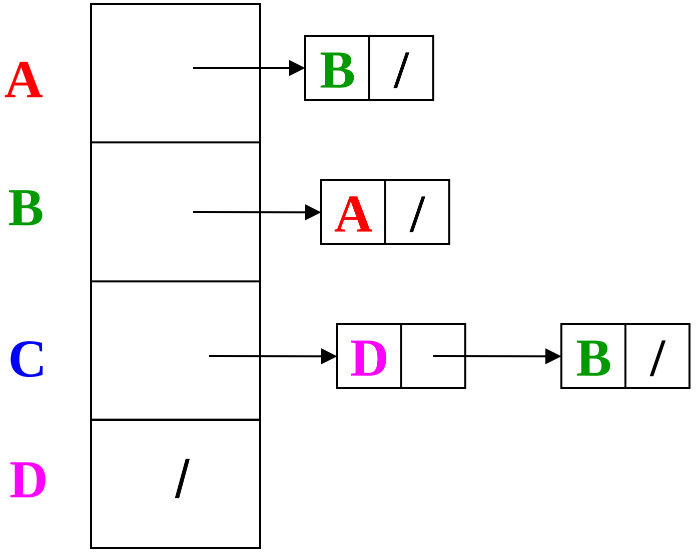
	A	B	C	D
A	F	T	F	F
B	T	F	F	F
C	F	T	F	T
D	F	F	F	F

Adjacency List

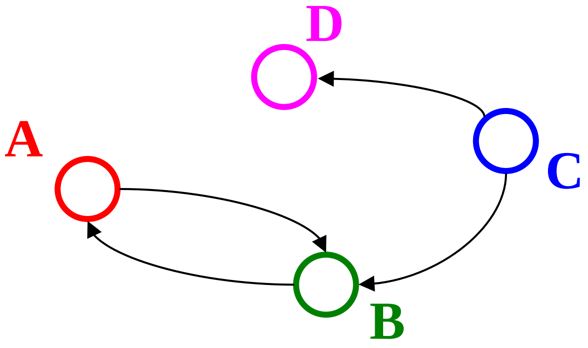
- Assign each node a number from **`0`** to **`|V|-1`**
- An array of length **`|V|`** in which each entry stores a list of all adjacent vertices (e.g., linked list)



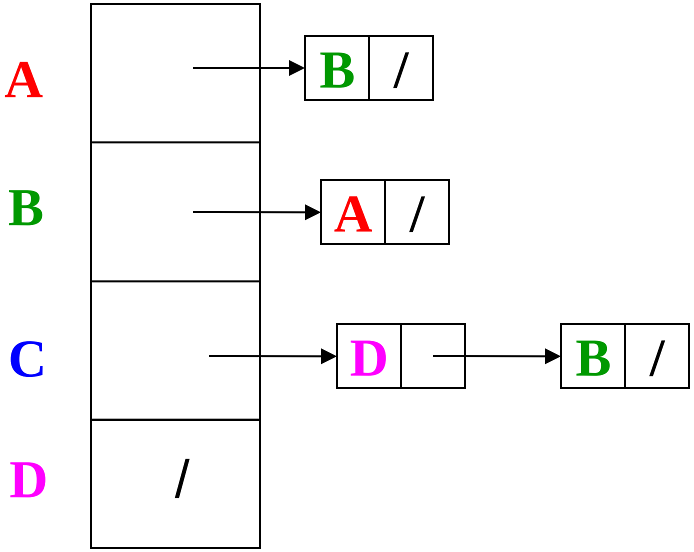
Adjacency List Properties



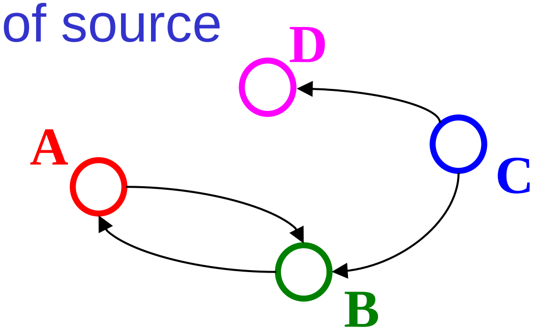
- Running time to:
  - Get all of a vertex's out-edges:
  - Get all of a vertex's in-edges:
  - Decide if some edge exists:
  - Insert an edge:
  - Delete an edge:
- Space requirements:
- Best for dense or sparse graphs?



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



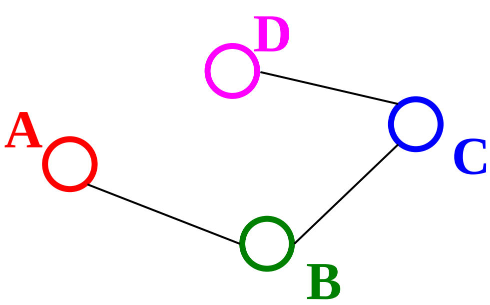
- Space requirements:
  - *O*(|V|+|E|)
- Best for dense or sparse graphs?
  - Best for sparse graphs, so usually just stick with linked lists

Undirected Graphs

Adjacency matrices & adjacency lists both do fine for undirected graphs

- Matrix: Can save roughly ½ the space
  - But may slow down operations in languages with “proper” 2D arrays (not Java, which has only arrays of arrays)
  - How would you “get all neighbors”?
- Lists: Each edge in two lists to support efficient “get all neighbors”

Example:



	A	B	C	D
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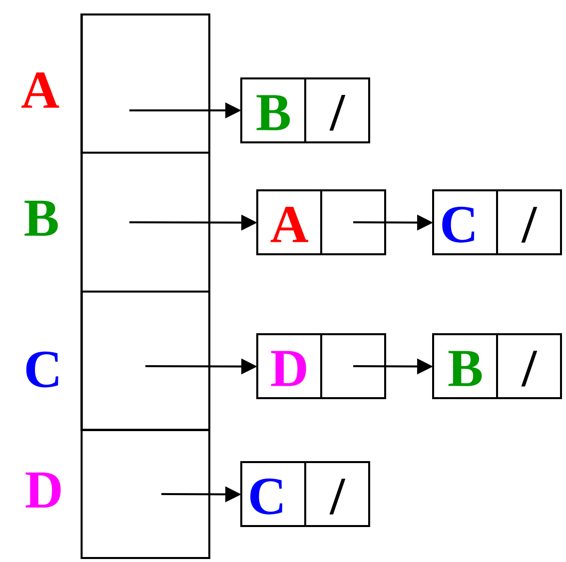
C	F	T	F	T
D	F	F	T	F



Which is better?

Graphs are often sparse:

- Streets form grids
  - every corner is not connected to every other corner
- Airlines rarely fly to all possible cities
  - or if they do it is to/from a hub rather than directly to/from all small cities to other small cities

Adjacency lists should generally be your default choice

- Slower performance compensated by greater space savings

Next…

Okay, we can represent graphs

Now let's 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