CSCI 104
Graph Representation and Traversals

CSCI 104 Teaching Team

Reviewed for Spring 2025

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GRAPH REPRESENTATIONS

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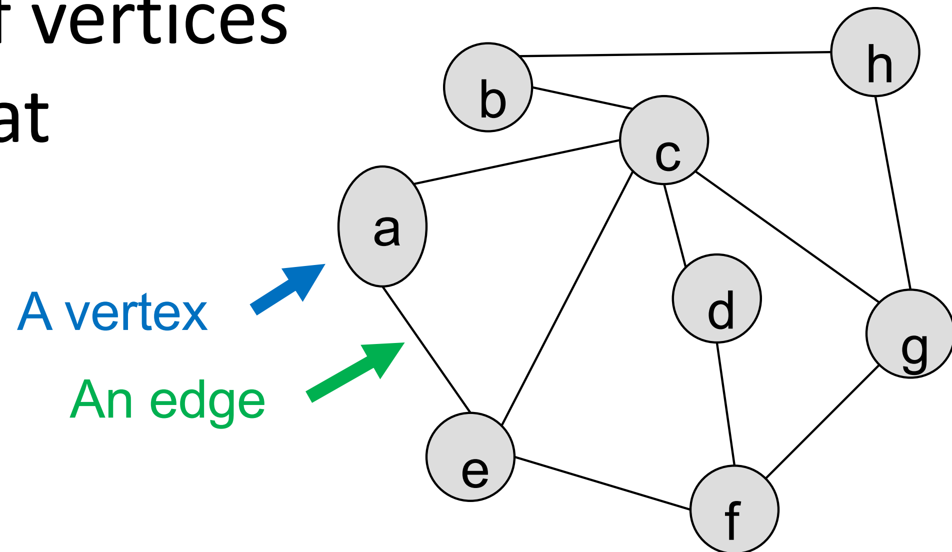
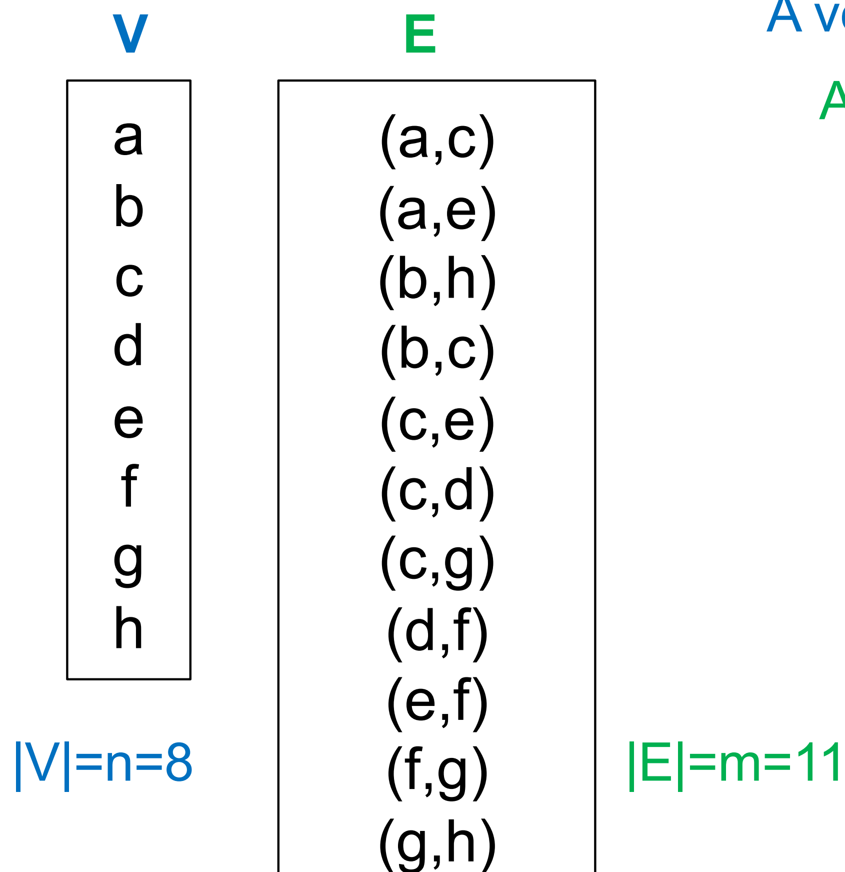
Graph Notation

- A **graph** is a collection of vertices (or nodes) and edges that connect vertices





- Let **V** be the set of vertices
- Let **E** be the set of edges
- Let **|V| or n** refer to the number of vertices
- Let **|E| or m** refer to the number of edges

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Graphs in the Real World

- Social networks
- Computer networks / Internet
- Path planning
- Interaction diagrams
- Bioinformatics

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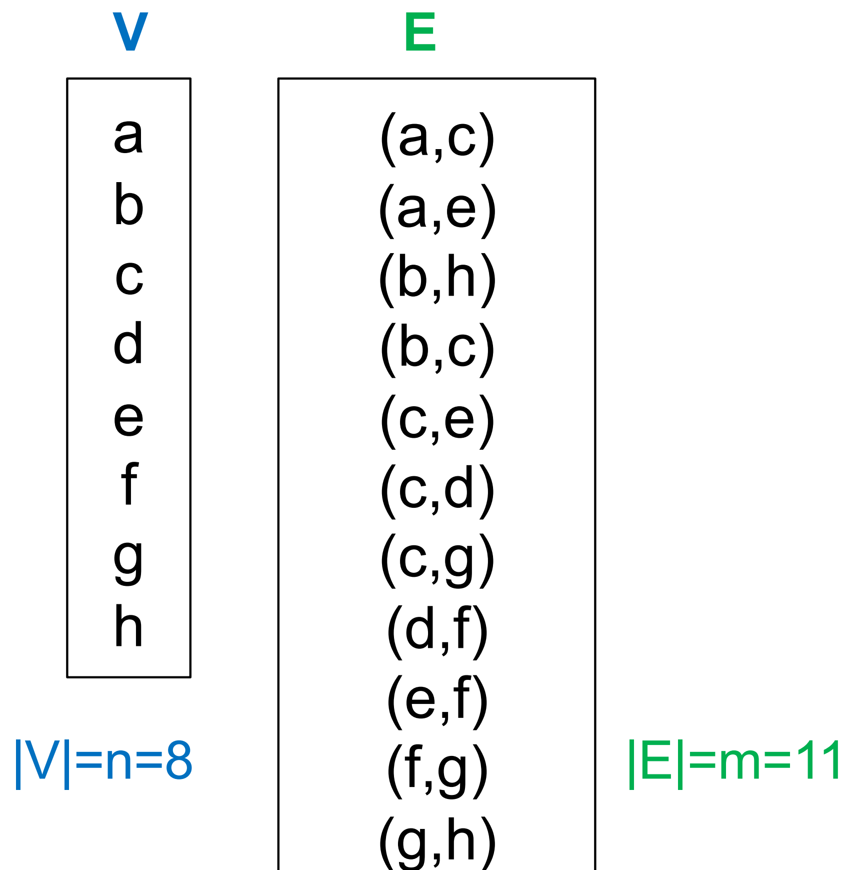
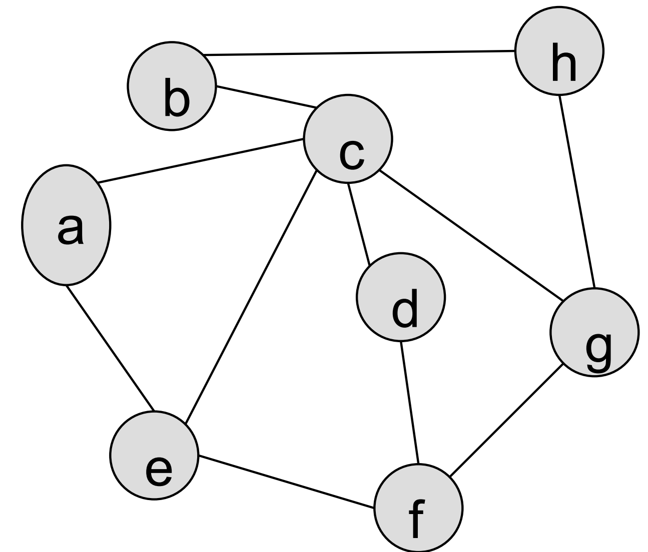
Basic Graph Representation

- Can simply store edges in a list
  - Unsorted
  - Sorted





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Graph ADT

- What operations would you want to perform on a graph?
- `addVertex() : Vertex`
- `addEdge(v1, v2)`
- `getAdjacencies(v1) : List<Vertices>`
  - `Returns any vertex with an edge from v1 to itself`
- `removeVertex(v)`
- `removeEdge(v1, v2)`
- `edgeExists(v1, v2) : bool`

```
#include<iostream>
using namespace std;

template <typename V, typename E>
class Graph{

};
```

Perfect for templating the data associated with a vertex and edge as V and E

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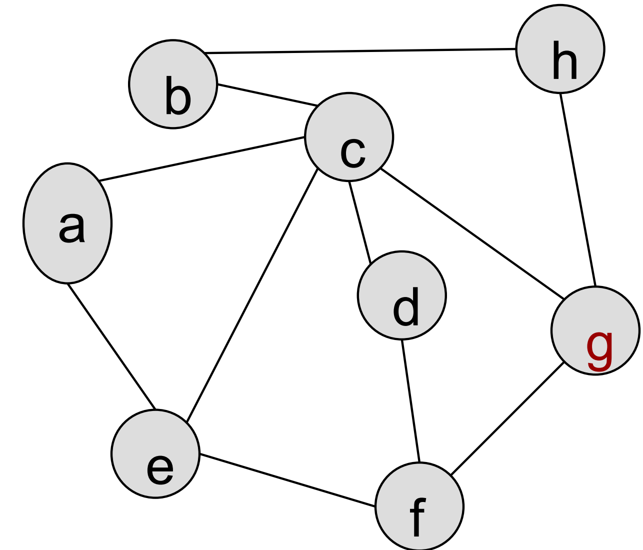
More Common Graph Representations

- Graphs are really just a list of lists
  - List of vertices each having their own list of adjacent vertices
- Alternatively, sometimes graphs are also represented with an adjacency matrix
  - Entry at (`i,j`) = 1 if there is an edge between vertex i and j, 0 otherwise



List of Vertices / Adjacency Lists

List of Vertices	Adjacency Lists
a	c,e
b	c,h
c	a,b,d,e,g
d	c,f
e	a,c,f
f	d,e,g
g	c,f,h
h	b,g

How would you express this using the ADTs you've learned?

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	1	0	0	0	0	1
c	1	1	0	1	1	0	1	0
d	0	0	1	0	0	1	0	0
e	1	0	1	0	0	1	0	0
f	0	0	0	1	1	0	1	0
g	0	0	1	0	0	1	0	1
h	0	1	0	0	0	0	1	0

Adjacency Matrix Representation

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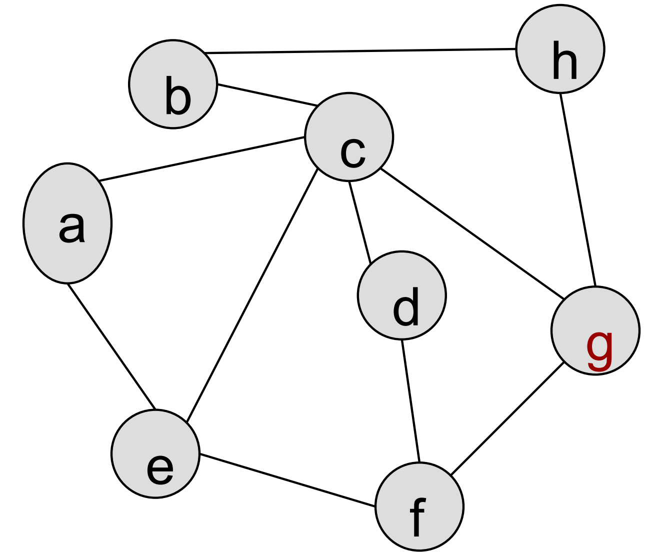
Graph Representations

- Let |V| = n = # of vertices and |E| = m = # of edges
- Adjacency List Representation
  - O(_______________) memory storage
  - Existence of an edge requires O(_____________) time
- Adjacency Matrix Representation
  - O(_______________) storage
  - Existence of an edge requires O(_________) lookup



List of Vertices / Adjacency Lists

List of Vertices	Adjacency Lists
a	c,e
b	c,h
c	a,b,d,e,g
d	c,f
e	a,c,f
f	d,e,g
g	c,f,h
h	b,g

How would you express this using the ADTs you've learned?

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	1	0	0	0	0	1
c	1	1	0	1	1	0	1	0
d	0	0	1	0	0	1	0	0
e	1	0	1	0	0	1	0	0
f	0	0	0	1	1	0	1	0
g	0	0	1	0	0	1	0	1
h	0	1	0	0	0	0	1	0

Adjacency Matrix Representation

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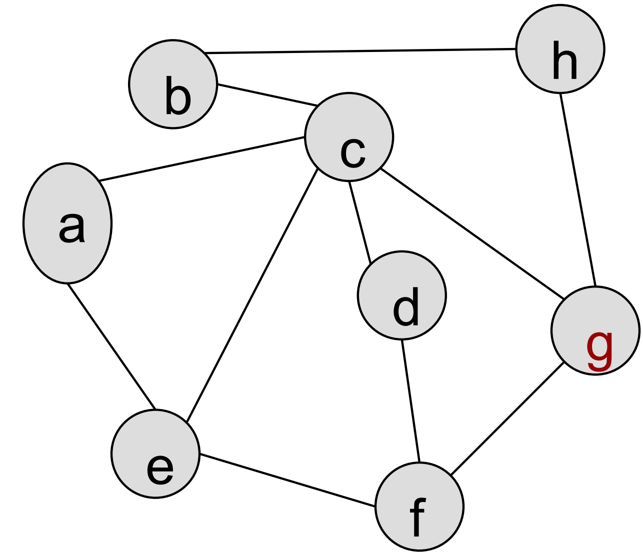
Graph Representations

- Let |V| = n = # of vertices and |E| = m = # of edges
- Adjacency List Representation
  - O(|V| + |E|) memory storage
  - Define **degree** to be the number of edges incident on a vertex (deg(a) = 2, deg(c) = 5, etc.
  - Existence of an edge requires searching the adjacency list in O(deg(v))
- Adjacency Matrix Representation
  - $O(|V|^2)$ storage
  - Existence of an edge requires O(1) lookup (e.g. matrix[i][j] == 1)



List of Vertices | Adjacency Lists

Vertex	Adjacency List
a	c,e
b	c,h
c	a,b,d,e,g
d	c,f
e	a,c,f
f	d,e,g
g	c,f,h
h	b,g

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	1	0	0	0	0	1
c	1	1	0	1	1	0	1	0
d	0	0	1	0	0	1	0	0
e	1	0	1	0	0	1	0	0
f	0	0	0	1	1	0	1	0
g	0	0	1	0	0	1	0	1
h	0	1	0	0	0	0	1	0

Adjacency Matrix Representation

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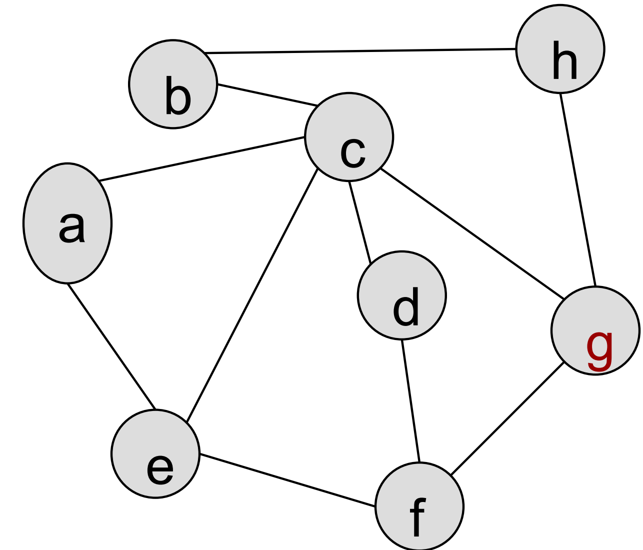
Graph Representations

- Can 'a' get to 'b' in two hops?
- Adjacency List
  - For each neighbor of a…
  - Search that neighbor's list for b
- Adjacency Matrix
  - Take the dot product of row a & column b



a	c,e
b	c,h
c	a,b,d,e,g
d	c,f
e	a,c,f
f	d,e,g
g	c,f,h
h	b,g

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	1	0	0	0	0	1
c	1	1	0	1	1	0	1	0
d	0	0	1	0	0	1	0	0
e	1	0	1	0	0	1	0	0
f	0	0	0	1	1	0	1	0
g	0	0	1	0	0	1	0	1
h	0	1	0	0	0	0	1	0

Adjacency Matrix Representation

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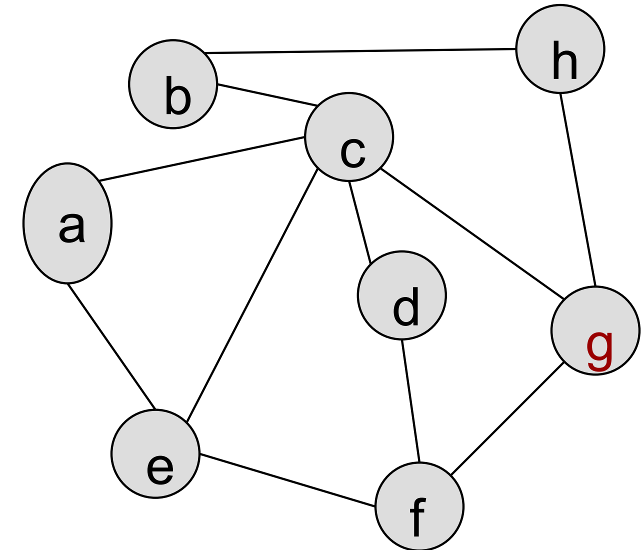
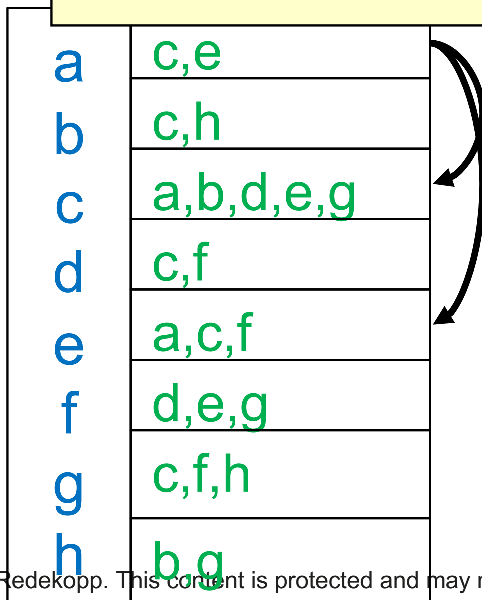
Graph Representations

- Can 'a' get to 'b' in two hops?
- Adjacency List
  - For each neighbor of a…
  - Search that neighbor's list for b
- Adjacency Matrix
  - Take the dot product of row a & column b

```
int sum = 0;
for(int i=0; i < n; i++){
  sum += adj[src][i]*adj[i][dst];
}
if(sum > 0) // two-hop path exists
```





	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	1	0	0	0	0	1
c	1	1	0	1	1	0	1	0
d	0	0	1	0	0	1	0	0
e	1	0	1	0	0	1	0	0
f	0	0	0	1	1	0	1	0
g	0	0	1	0	0	1	0	1
h	0	1	0	0	0	0	1	0

Adjacency Matrix Representation

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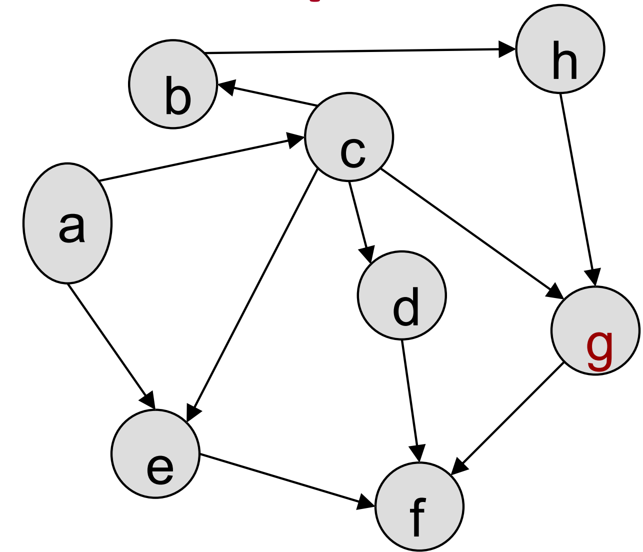
Directed vs. Undirected Graphs

- In the previous graphs, edges were **undirected** (meaning edges are 'bidirectional' or 'reflexive')
  - An edge (u,v) implies (v,u)
- In **directed** graphs, links are unidirectional
  - An edge (u,v) does not imply (v,u)
  - For Edge (u,v): the **source** is u, **target** is v
- For adjacency list form, you may need 2 lists per vertex for both predecessors and successors



List of Vertices / Adjacency Lists

Vertex	Adjacency List
a	c,e
b	h
c	b,d,e,g
d	f
e	f
f	
g	f
h	g

Target (columns) / Source (rows)

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	0	0	0	0	0	1
c	0	1	0	1	1	0	1	0
d	0	0	0	0	0	1	0	0
e	0	0	0	0	0	1	0	0
f	0	0	0	0	0	0	0	0
g	0	0	0	0	0	1	0	0
h	0	0	0	0	0	0	1	0

Adjacency Matrix Representation

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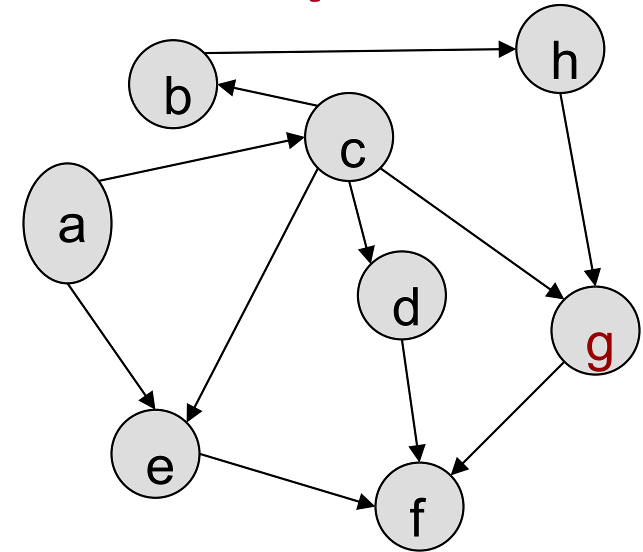
Directed vs. Undirected Graphs

- In directed graph with edge (src,tgt) we define
  - Successor(src) = tgt
  - Predecessor(tgt) = src
- Using an adjacency list representation *may* warrant two lists predecessors and successors



List of Vertices

Vertex	Succs (Outgoing)	Preds (Incoming)
a	c,e	
b	h	c
c	b,d,e,g	a
d	f	c
e	f	a,c
f		d, e, g
g	f	c,h
h	g	b

Adjacency Matrix Representation (rows: Source, columns: Target)

	a	b	c	d	e	f	g	h
a	0	0	1	0	1	0	0	0
b	0	0	0	0	0	0	0	1
c	0	1	0	1	1	0	1	0
d	0	0	0	0	0	1	0	0
e	0	0	0	0	0	1	0	0
f	0	0	0	0	0	0	0	0
g	0	0	0	0	0	1	0	0
h	0	0	0	0	0	0	1	0

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Graph Runtime, |V| = n, |E| =m

Operation vs Implementation for Edges	Add edge	Delete Edge	Test Edge	Enumerate edges for single vertex
Unsorted array or Linked List				
Sorted array				
Adjacency List (Assume use of std::map where key=vertex, value=unsorted list of adjacencies)				
Adjacency Matrix				

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Graph Runtime, |V| = n, |E| =m

Operation vs Implementation for Edges	Add edge	Delete Edge	Test Edge	Enumerate edges for single vertex
Unsorted array or Linked List	Θ(1)	Θ(m)	Θ(m)	Θ(m)
Sorted array	Θ(m)	Θ(m)	Θ(log m) [if binary search used]	Θ(log m) +Θ(deg(v)) [if binary search used]
Adjacency List (Assume use of std::map where key=vertex, value=unsorted list of adjacencies)	log(n) + Θ(1)	log(n)+ Θ(deg(v))	log(n)+ Θ(deg(v))	log(n) + Θ(deg(v))
Adjacency Matrix	Θ(1)	Θ(1)	Θ(1)	Θ(n)

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Graph Algorithms

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PAGERANK ALGORITHM

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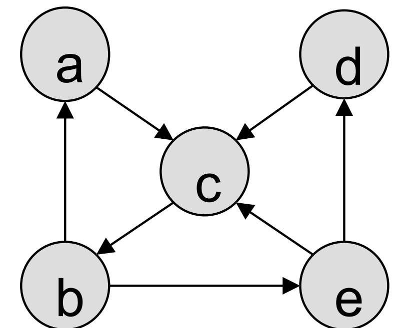
PageRank

- Consider the graph at the right
  - These could be webpages with links shown in the corresponding direction
  - These could be neighboring cities
- PageRank generally tries to answer the question:
  - **If we let a bunch of people randomly "walk" the graph, what is the probability that they end up at a certain location (page, city, etc.) in the "steady-state"**
- We could solve this problem through Monte-Carlo simulation (essentially the CS 103 PA5 or PA1 Coin-flipping or Zombie assignment…depending on semester)
  - Simulate a large number of random walkers and record where each one ends to build up an answer of the probabilities for each vertex
- But there are more efficient ways of doing it



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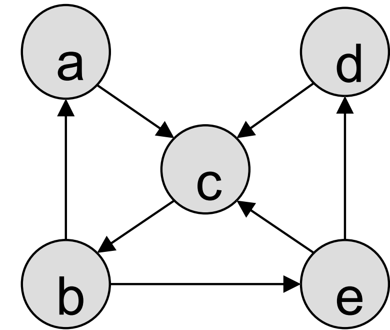
PageRank



- Let us write out the adjacency matrix for this graph
- Now let us make a weighted version by normalizing based on the out-degree of each node
  - Ex. If you're at node B we have a 50-50 chance of going to A or E
- From this you could write a system of linear equations (i.e. what are the chances you end up at vertex I at the next time step, given you are at some vertex J now
  - pA = 0.5*pB
  - pB = pC
  - pC = pA + pD + 0.5*pE
  - pD = 0.5*pE
  - pE = 0.5*pB
  - We also know: pA + pB + pC + pD + pE = 1

Source (columns), Target (rows)

	a	b	c	d	e
a	0	1	0	0	0
b	0	0	1	0	0
c	1	0	0	1	1
d	0	0	0	0	1
e	0	1	0	0	0

Adjacency Matrix

Source=j (columns), Target=i (rows)

	a	b	c	d	e
a	0	0.5	0	0	0
b	0	0	1	0	0
c	1	0	0	1	0.5
d	0	0	0	0	0.5
e	0	0.5	0	0	0

Weighted Adjacency Matrix
[Divide by $(a_{i,j})$/degree(j)]

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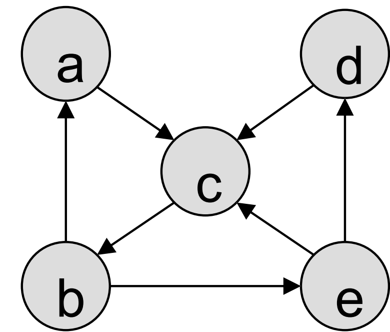
PageRank



- System of Linear Equations
  - pA = 0.5*pB
  - pB = pC
  - pC = pA + pD + 0.5*pE
  - pD = 0.5*pE
  - pE = 0.5*pB
  - We also know: pA + pB + pC + pD + pE = 1
- If you know something about linear algebra, you know we can write these equations in matrix form as a linear system
  - Ax = y

Source=j

Target=i

	a	b	c	d	e
a	0	0.5	0	0	0
b	0	0	1	0	0
c	1	0	0	1	0.5
d	0	0	0	0	0.5
e	0	0.5	0	0	0

Weighted Adjacency Matrix
[Divide by $(a_{i,j})$/degree(j)]

$$\begin{bmatrix} 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} pA \\ pB \\ pC \\ pD \\ pE \end{bmatrix}$$

0	0.5	0	0	0
0	0	1	0	0
1	0	0	1	0.5
0	0	0	0	0.5
0	0.5	0	0	0

*

pA
pB
pC
pD
pE

=

pA = 0.5PB
pB = pC
pC = pA+pD+0.5*pE
pD = 0.5*pE
pE = 0.5*pB

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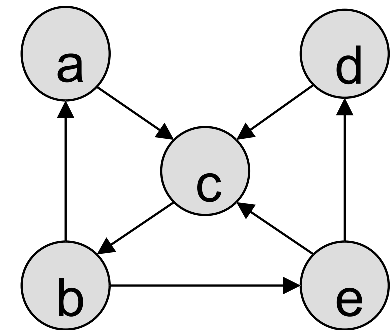
PageRank

- But remember we want the steady state solution
  - The solution where the probabilities don't change from one step to the next
- So we want a solution to: **A**p = p
- We can:
  - Use a linear system solver (Gaussian elimination)
  - Or we can just seed the problem with some probabilities and then just iterate until the solution settles down

$$\begin{vmatrix} 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0 & 0 \end{vmatrix} * \begin{vmatrix} pA \\ pB \\ pC \\ pD \\ pE \end{vmatrix} = \begin{vmatrix} pA \\ pB \\ pC \\ pD \\ pE \end{vmatrix}$$



Source=j

Target=i

	a	b	c	d	e
a	0	0.5	0	0	0
b	0	0	1	0	0
c	1	0	0	1	0.5
d	0	0	0	0	0.5
e	0	0.5	0	0	0

Weighted Adjacency Matrix
[Divide by ($a_{i,j}$)/degree(j)]

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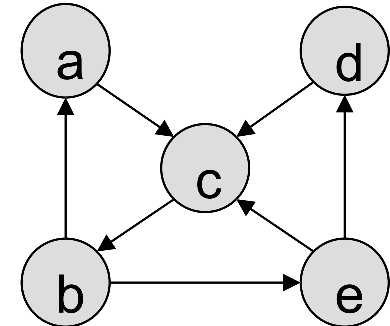
Iterative PageRank



- But remember we want the steady state solution
  - The solution where the probabilities don't change from one step to the next
- So we want a solution to: **A**p = p
- We can:
  - Use a linear system solver (Gaussian elimination)
  - Or we can just seed the problem with some probabilities and then just iterate until the solution settles down

$$\begin{bmatrix} 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0 & 0 \end{bmatrix} * \underbrace{\begin{bmatrix} .2 \\ .2 \\ .2 \\ .2 \\ .2 \end{bmatrix}}_{\text{Step 0 Sol.}} = \underbrace{\begin{bmatrix} .1 \\ .2 \\ .5 \\ .1 \\ .1 \end{bmatrix}}_{\text{Step 1 Sol.}}$$

$$\begin{bmatrix} 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0 & 0 \end{bmatrix} * \underbrace{\begin{bmatrix} .1 \\ .2 \\ .5 \\ .1 \\ .1 \end{bmatrix}}_{\text{Step 1 Sol.}} = \underbrace{\begin{bmatrix} .1 \\ .5 \\ .25 \\ .05 \\ .1 \end{bmatrix}}_{\text{Step 2 Sol.}}$$

$$\begin{bmatrix} 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0 & 0 \end{bmatrix} * \underbrace{\begin{bmatrix} ? \\ ? \\ ? \\ ? \\ ? \end{bmatrix}}_{\text{Step 29 Sol.}} = \underbrace{\begin{bmatrix} .1507 \\ .3078 \\ .3126 \\ .0783 \\ .1507 \end{bmatrix}}_{\text{Step 30 Sol.}}$$

Actual PageRank Solution from solving linear system:

$$\begin{bmatrix} .1538 \\ .3077 \\ .3077 \\ .0769 \\ .1538 \end{bmatrix}$$

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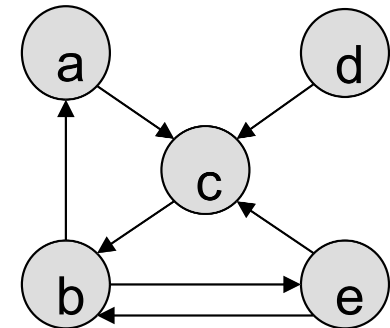
Additional Notes



- What if we change the graph and now D has no incoming links…what is its PageRank?
  - 0
- Most PR algorithms add a probability that someone just enters that URL (i.e. enters the graph at that node)
  - Usually define something called the damping factor, α (often chosen around 0.15)
  - Probability of randomly starting or jumping somewhere = 1-α
- So at each time step the next PR value for node i is given as:
  - $Pr(i) = \frac{\alpha}{N} + (1-\alpha) * \sum_{j \in Pred(i)} \frac{Pr(j)}{OutDeg(j)}$
  - N is the total number of vertices
  - Usually run 30 or so update steps
  - Start each Pr(i) = 1/N

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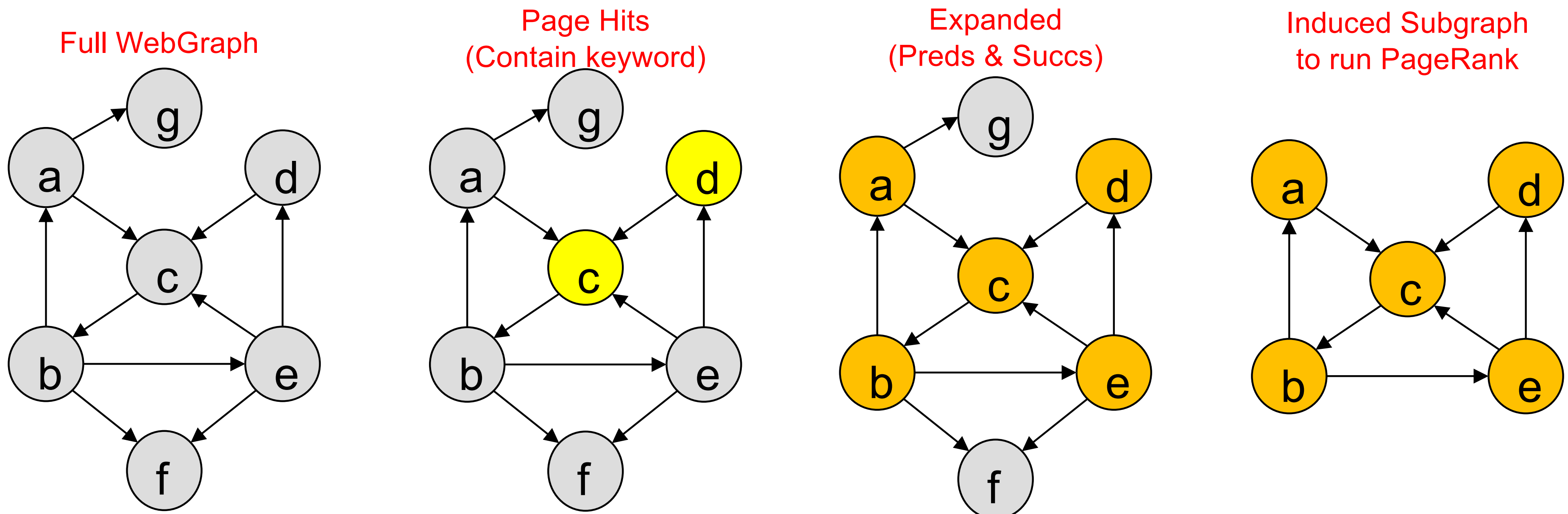
In a Web Search Setting

- Given some search keywords we could find the pages that have that matching keywords
- We often expand that set of pages by including all successors and predecessors of those pages
  - Include all pages that are within a radius of 1 of the pages that actually have the keyword
- Now consider that set of pages and the subgraph that it induces
- Run PageRank on that subgraph



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BREADTH-FIRST SEARCH

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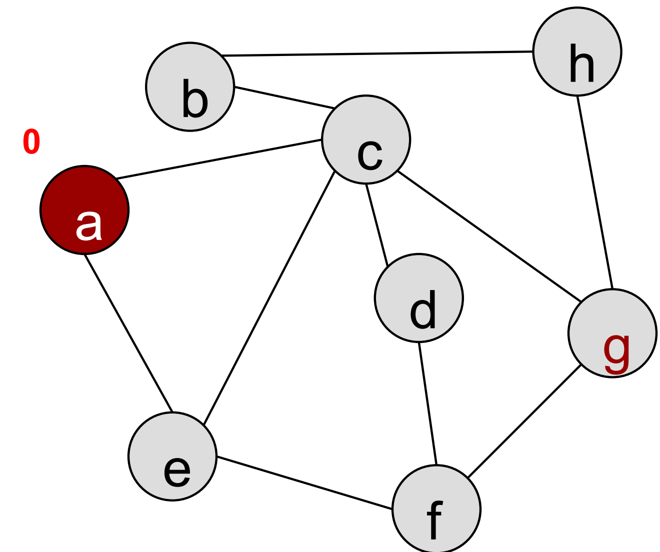
Breadth-First Search

- Given a graph with vertices, V, and edges, E, and a starting vertex that we'll call u
- BFS starts at u ('a' in the diagram to the left) and fans-out along the edges to nearest neighbors, then to their neighbors and so on
- Goal: Find shortest paths (a.k.a. minimum number of hops or depth) from the start vertex to every other vertex



Depth 0: a

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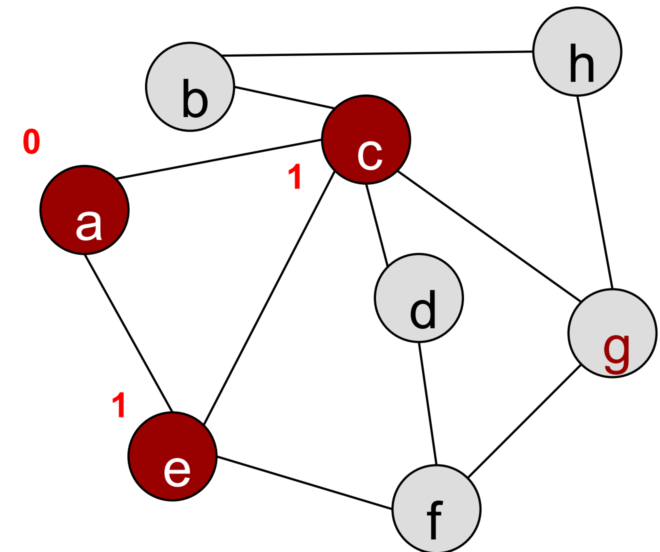

Depth 0: a
Depth 1: c,e

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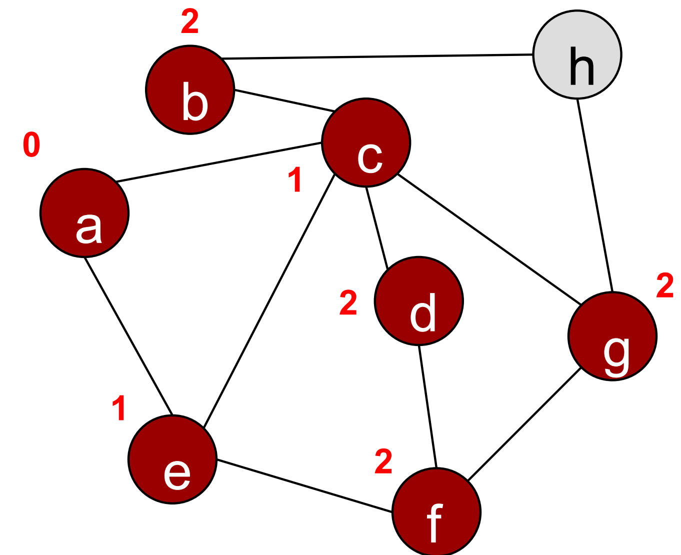

Depth 0: a
Depth 1: c,e
Depth 2: b,d,f,g

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Breadth-First Search

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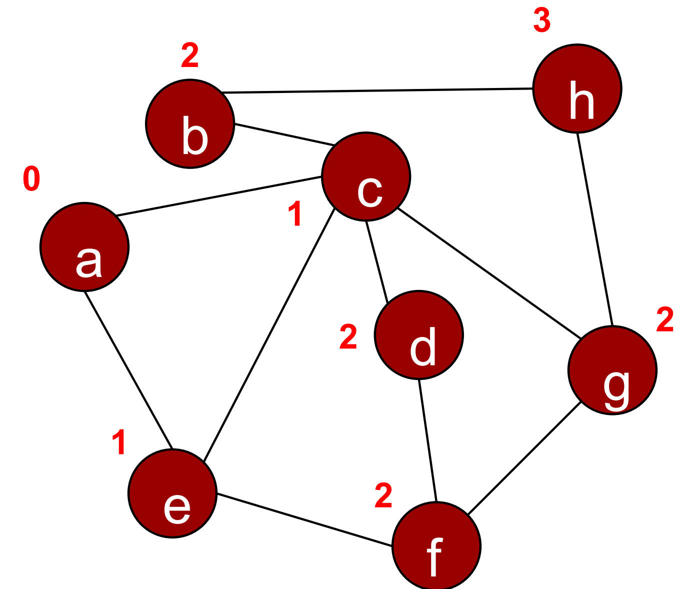

Depth 0: a
Depth 1: c,e
Depth 2: b,d,f,g
Depth 3: h

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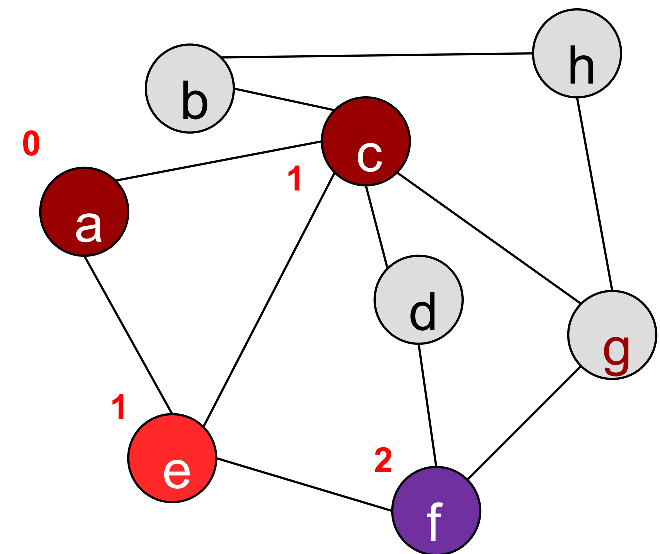
Developing the Algorithm

- Key idea: Must explore all nearer neighbors before exploring further-away neighbors
- From 'a' we find 'e' and 'c'
  - If we explore 'e' next and find 'f' who should we choose to explore from next: 'c' or 'f'?
- Must explore all vertices at depth i before any vertices at depth i+1
  - Essentially, the first vertices we find should be the first ones we explore from
  - What data structure may help us?



Depth 0: a
Depth 1: c,e
Depth 2: b,d,f,g
Depth 3: h

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Developing the Algorithm

- Exploring all vertices in the order they are found implies we will explore vertices in First-In/First-Out order which implies use of a **Queue**
  - Important: BFS implies use of a **queue**
  - Put newly found vertices in the back and pull out a vertex from the front to explore next
- We don't want to put a vertex in the queue more than once...
  - "mark" a vertex the first time we encounter it (only allowing unmarked vertices to be put in the queue)
  - We can "mark" a vertex by **adding them to a set** OR by simply **setting some data member that indicates we've seen this vertex before**
- May also keep a "predecessor" structure or value per vertex that indicates which prior vertex found this vertex
  - Allows us to find a shortest-path back to the start vertex (i.e. retrace our steps)

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Breadth-First Search

Algorithm:

```
BFS(G,u)
1  for each vertex v
2      pred[v] = nil, d[v] = inf.
3  Q = new Queue
4  Q.enqueue(u),  d[u]=0, pred[u] = start
5  while Q is not empty
6     v = Q.front(); Q.dequeue()
7     foreach neighbor, w, of v:
8         if pred[w] == nil // w not found
9             Q.enqueue(w)
10            pred[w] = v,  d[w] = d[v] + 1
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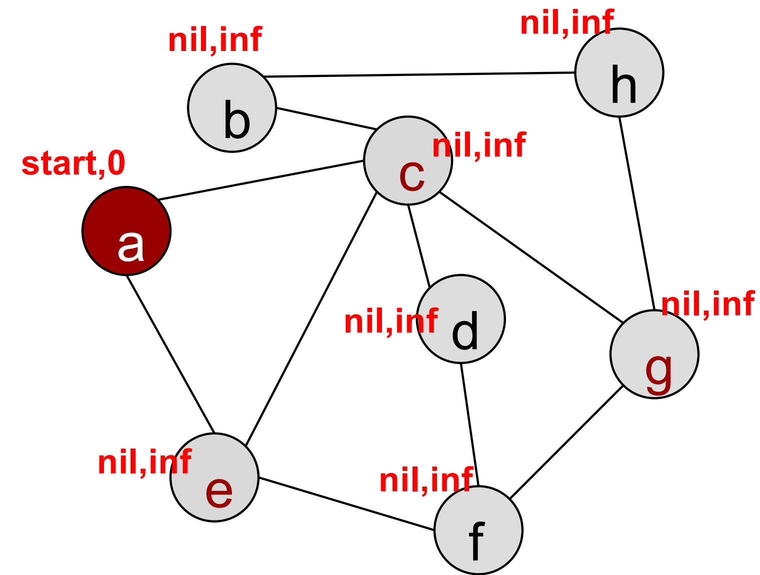
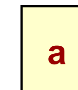


Q:



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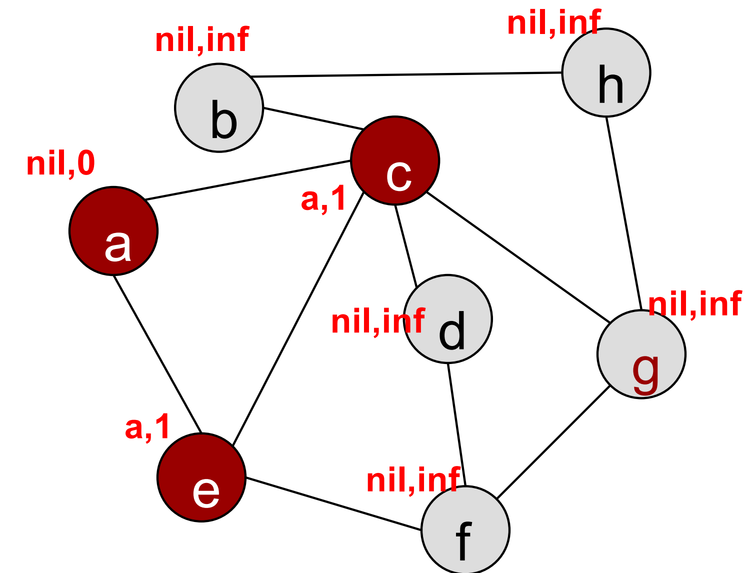
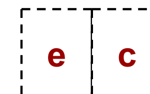


v =


Q:

e	c

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Breadth-First Search

Algorithm:

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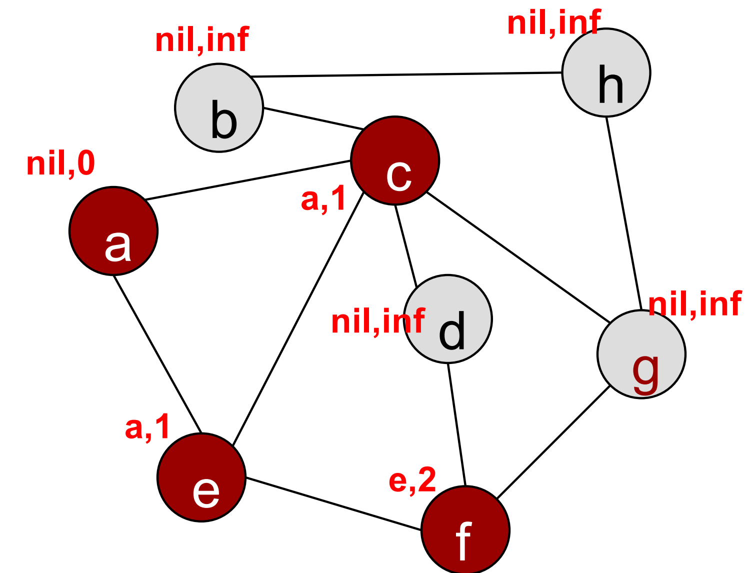
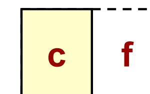


v =



Q:

c	f

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Breadth-First Search

Algorithm:

```
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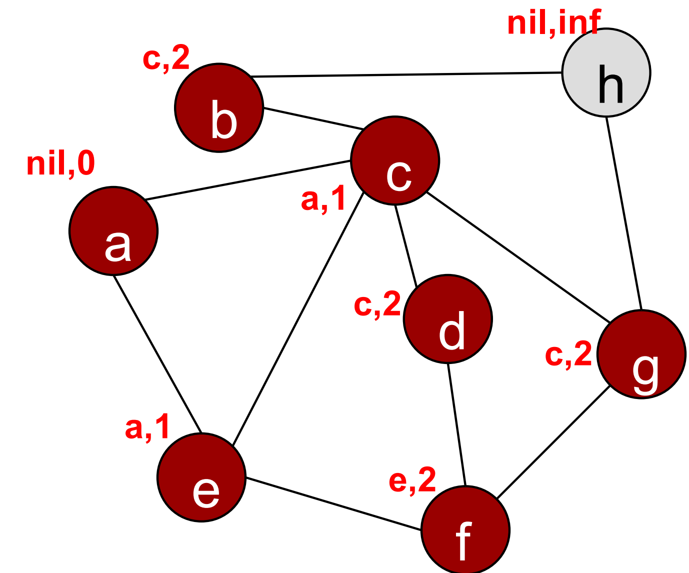

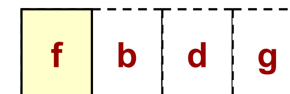

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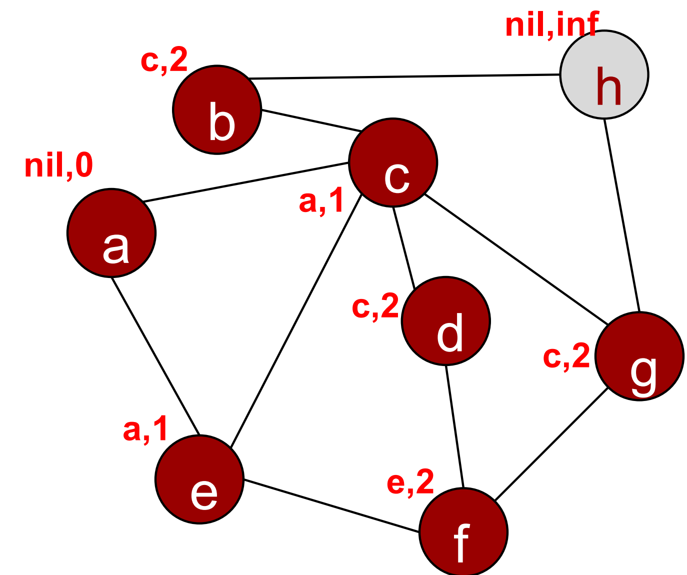

v = f

Q:

b	d	g

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```
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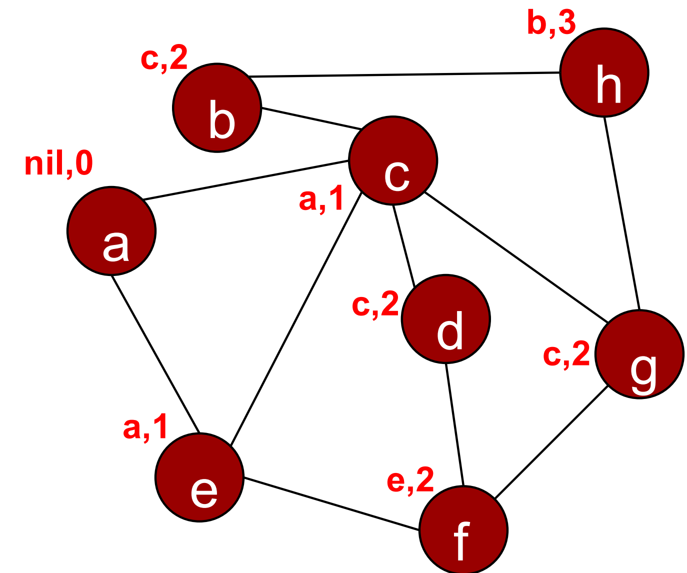
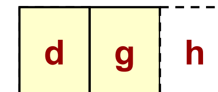


v = b

Q:



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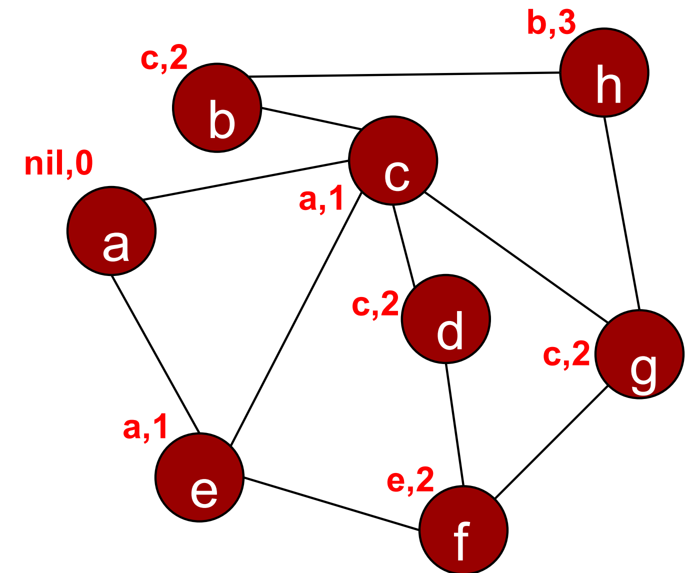

v = d

Q:

g	h

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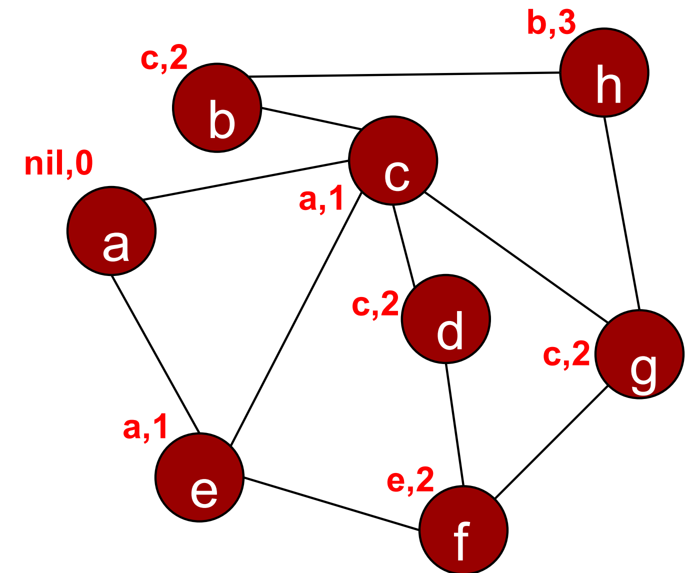

v = g

Q:

h

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Breadth-First Search

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```
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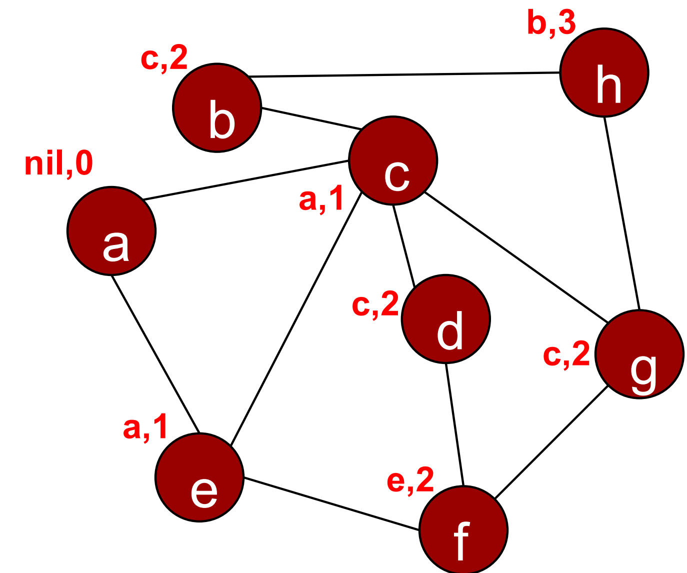

v = h

Q:

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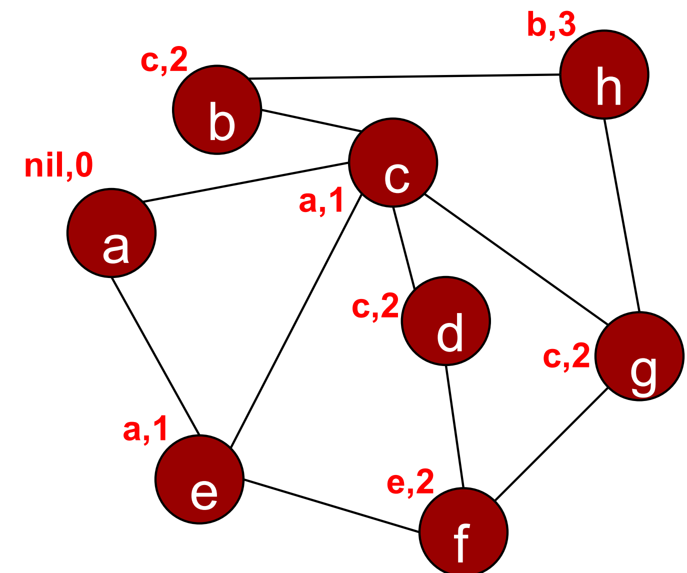
Breadth-First Search

- Shortest paths can be found be walking predecessor value from any node backward
- Example:
  - Shortest path from a to h
  - Start at h
  - Pred[h] = b (so walk back to b)
  - Pred[b] = c (so walk back to c)
  - Pred[c] = a (so walk back to a)
  - Pred[a] = nil … no predecessor, Done!!



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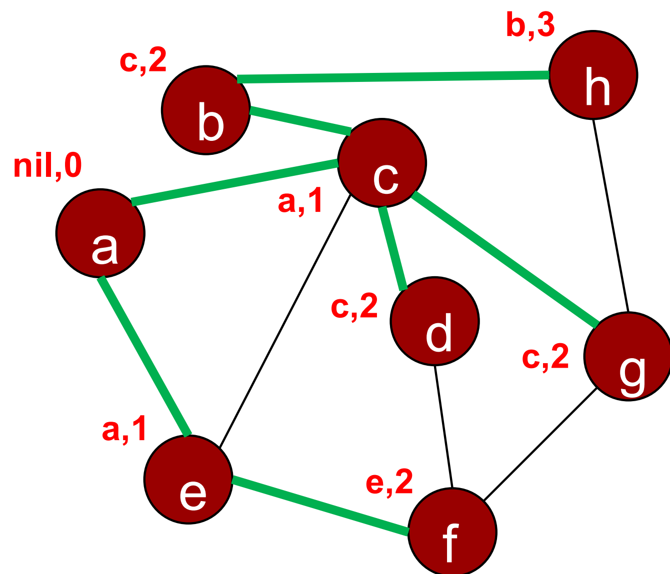
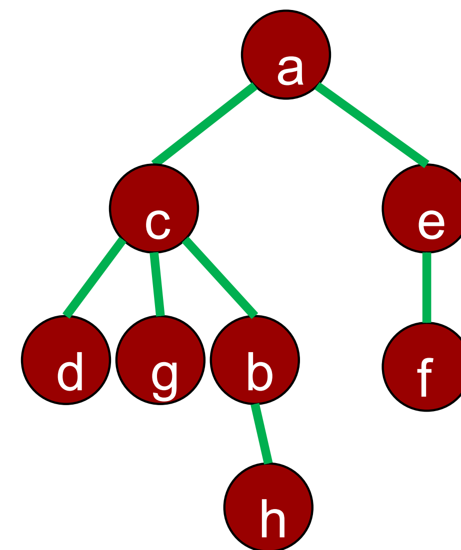
Breadth-First Search Trees

- BFS (and later DFS) will induce a tree subgraph (i.e. acyclic, one parent each) from the original graph
  – BFS is tree of shortest paths from the source to all other vertices (in connected component)



Original graph, G



BFS Induced Tree

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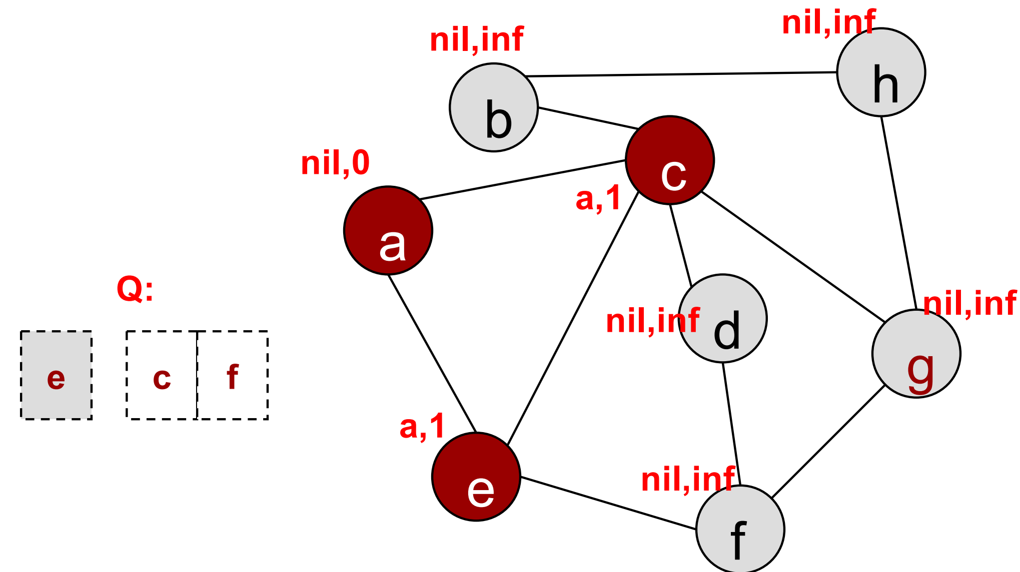
Correctness

- Define
  - dist(s,v) = correct shortest distance
  - d[v] = BFS computed distance
  - p[v] = predecessor of v
- Loop invariant
  - What can we say about the nodes in the queue, their d[v] values, relationship between d[v] and dist[v], etc.?

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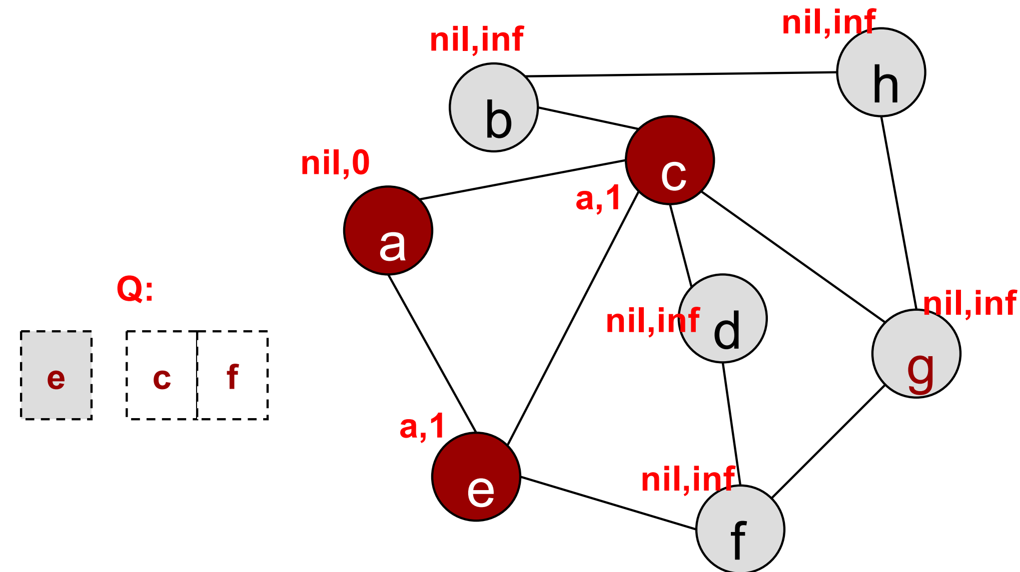
Correctness

- Define
  - dist(s,v) = correct shortest distance
  - d[v] = BFS computed distance
  - p[v] = predecessor of v
- Loop invariant
  - All vertices with p[v] != nil (i.e. already in the queue or popped from queue) have d[v] = dist(s,v)
  - The distance of the nodes in the queue are sorted
    - If Q = {v_1, v_2, …, v_r} then d[v_1] <= d[v_2] <= … <= d[v_r]
  - The nodes in the queue are from 2 adjacent layers/levels
    - i.e. d[v_k] <= d[v_1] + 1
    - Suppose there is a node from a 3rd level (d[v_1] + 2), it must have been found by some, vi, where d[v_i] = d[v_1]+1

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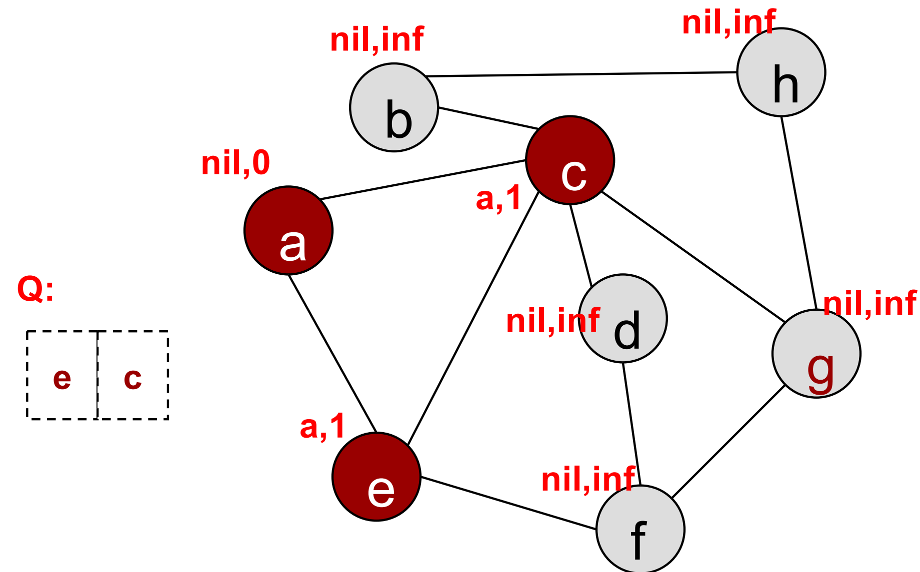
Breadth-First Search

- Analyze the run time of BFS for a graph with n vertices and m edges
  - Find T(n,m)
- How many times does loop on line 5 iterate?
- How many times loop on line 7 iterate?

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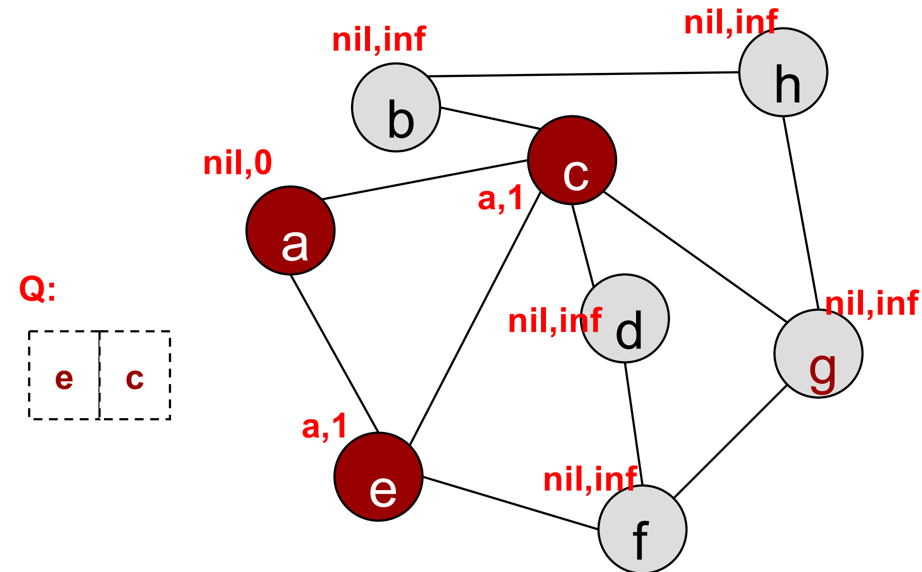
Breadth-First Search

- Analyze the run time of BFS for a graph with n vertices and m edges
  – Find T(n)
- How many times does loop on line 5 iterate?
  – N times (one iteration per vertex)
- How many times loop on line 7 iterate?
  – For each vertex, v, the loop executes deg(v) times
  – $= \sum_{v \in V} \theta[1 + \deg(v)]$
  – $= \theta(\sum_v 1) + \theta(\sum_v \deg(v))$
  – = Θ (n) + Θ (m)
- Total = Θ(n+m)

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Dijkstra's Algorithm

SINGLE-SOURCE SHORTEST PATH (SSSP)

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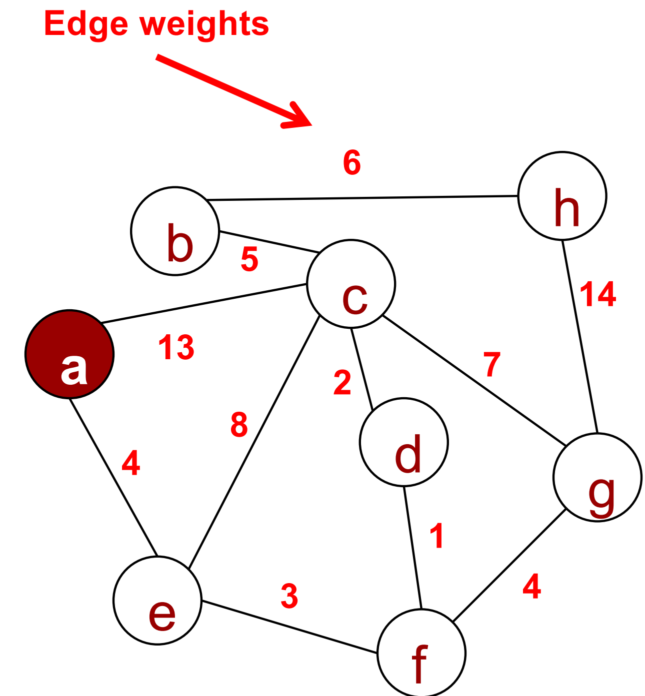
SSSP

- Let us associate a 'weight' with each edge
  - Could be physical distance, cost of using the link, etc.
- Find the shortest path from a source node, 'a' to all other nodes



List of Vertices / Adjacency Lists

a	(c,13),(e,4)
b	(c,5),(h,6)
c	(a,13),(b,5),(d,2),(e,8),(g,7)
d	(c,2),(f,1)
e	(a,4),(c,8),(f,3)
f	(d,1),(e,3),(g,4)
g	(c,7),(f,4),(h,14)
h	(b,6),(g,14)

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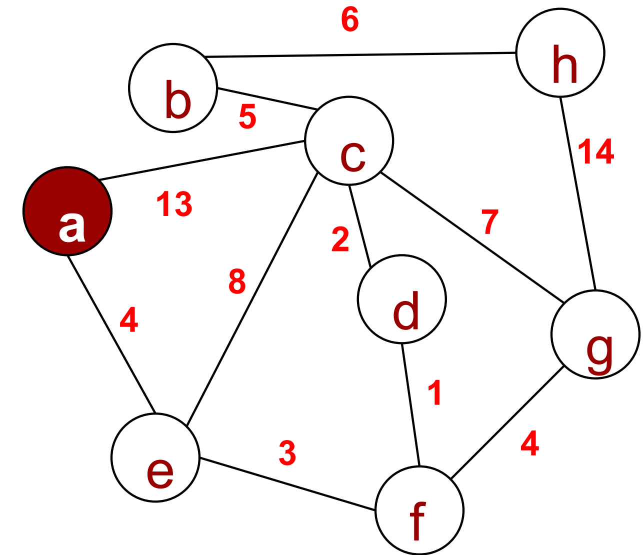
SSSP

- What is the shortest distance from 'a' to all other vertices?
- How would you go about computing those distances?



List of Vertices / Adjacency Lists

Vertex	Adjacency List
a	(c,13),(e,4)
b	(c,5),(h,6)
c	(a,13),(b,5),(d,2),(e,8),(g,7)
d	(c,2),(f,1)
e	(a,4),(c,8),(f,3)
f	(d,1),(e,3),(g,4)
g	(c,7),(f,4),(h,14)
h	(b,6),(g,14)

List of Vertices

Vert	Dist
a	0
b	
c	
d	
e	
f	
g	
h	

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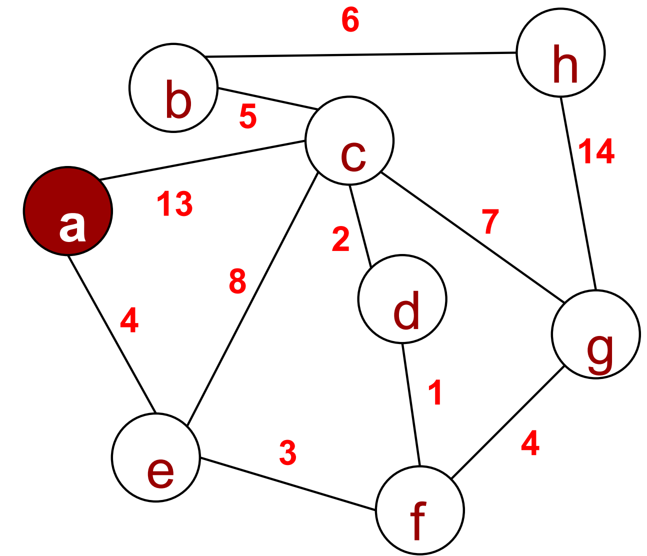
Dijkstra's Algorithm

- Dijkstra's algorithm is similar to a BFS but always chooses the closest (shortest distance) vertex to the source to explore next, rather than exploring vertices in FIFO order (as in BFS)
- We need a structure to store vertices and always be able to give us the smallest ("best") vertex to explore next
  - We'll show it as a table of all vertices with their currently 'known' distance from the source
    - Initially, a has dist=0
    - All others = infinite distance



List of Vertices

Vert	Dist
a	0
b	inf
c	inf
d	inf
e	inf
f	inf
g	inf
h	inf

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Dijkstra's Algorithm

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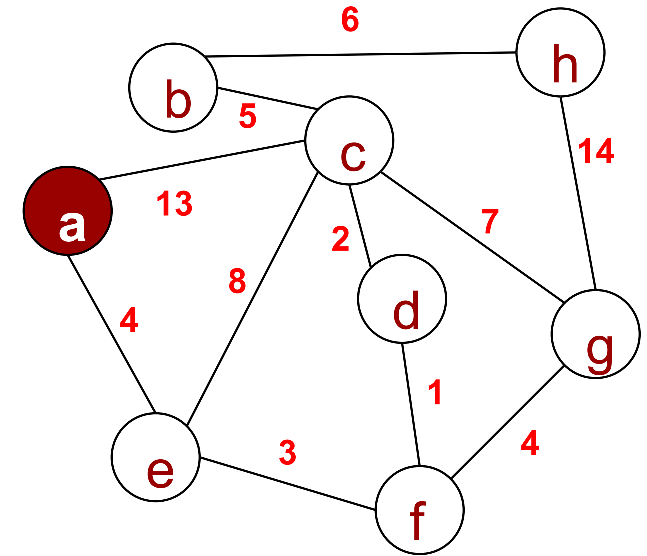
10.             w = weight(v,u)
11.             // is my (v's) distance + edge weight "better" than current path to u
12.             if(v.dist + w < u.dist)
13.                 u.pred = v;     u.dist = v.dist + w;
14.                 PQ.decreaseKey(u, u.dist)
```



List of Vertices

Vert	Dist
a	0
b	inf
c	inf
d	inf
e	inf
f	inf
g	inf
h	inf

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Dijkstra's Algorithm

```
1.   SSSP(G, s)
2.     PQ = empty PQ
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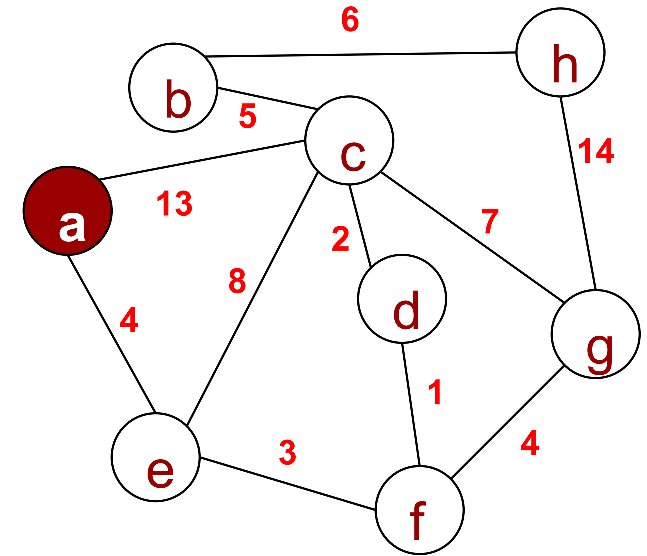

List of Vertices

Vert	Dist	
a	0	
b	inf	
c	inf	13
d	inf	
e	inf	4
f	inf	
g	inf	
h	inf	

v=a

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Dijkstra's Algorithm

```
1.  SSSP(G, s)
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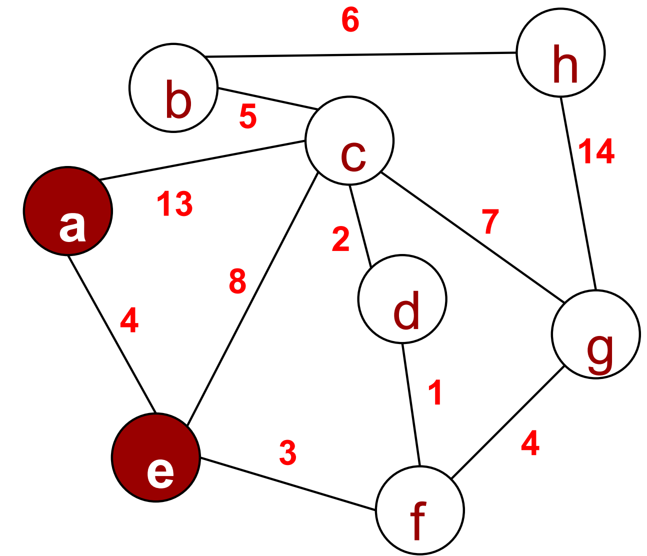

List of Vertices

Vert	Dist	
b	inf	
c	13	12
d	inf	
e	4	
f	inf	7
g	inf	
h	inf	

v=e

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Dijkstra's Algorithm

```
1.    SSSP(G, s)
2.      PQ = empty PQ
3.      s.dist = 0;  s.pred = NULL
4.      PQ.insert(s)
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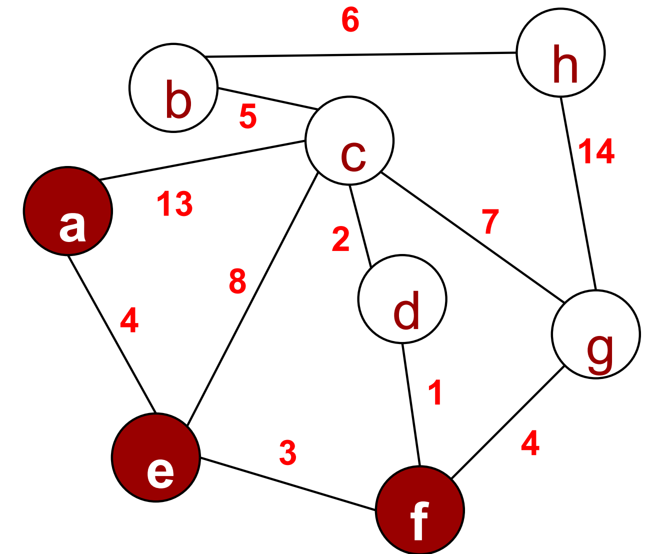
```



List of Vertices

Vert	Dist	
b	inf	
c	12	
d	inf	8
f	7	
g	inf	11
h	inf	

v=f

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Dijkstra's Algorithm

```
1.  SSSP(G, s)
2.    PQ = empty PQ
3.    s.dist = 0;  s.pred = NULL
4.    PQ.insert(s)
5.    For all v in vertices
6.      if v != s then v.dist = inf;  PQ.insert(v)
7.    while PQ is not empty
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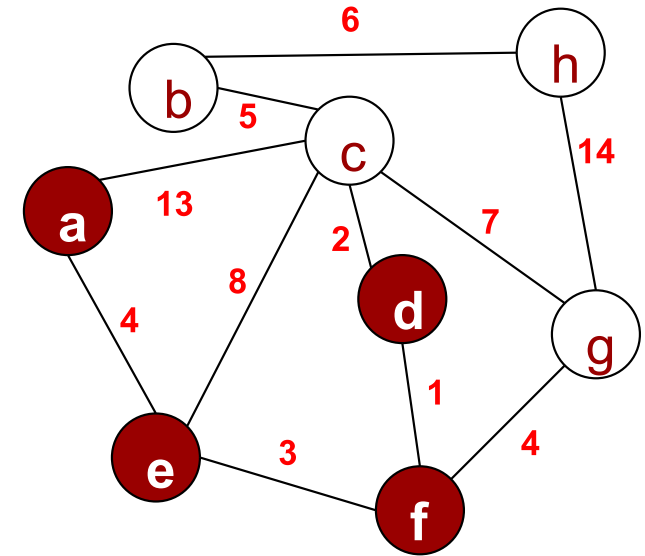

List of Vertices

Vert	Dist
b	inf
c	12
d	8
g	11
h	inf

10

v=d

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Dijkstra's Algorithm

```
1.  SSSP(G, s)
2.    PQ = empty PQ
3.    s.dist = 0;  s.pred = NULL
4.    PQ.insert(s)
5.    For all v in vertices
6.        if v != s then v.dist = inf;  PQ.insert(v)
7.    while PQ is not empty
8.        v = min(); PQ.remove_min()
9.        for u in neighbors(v)  // visit each neighbor
10.           w = weight(v,u)
11.           // is my (v's) distance + edge weight "better" than current path to u
12.           if(v.dist + w < u.dist)
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```

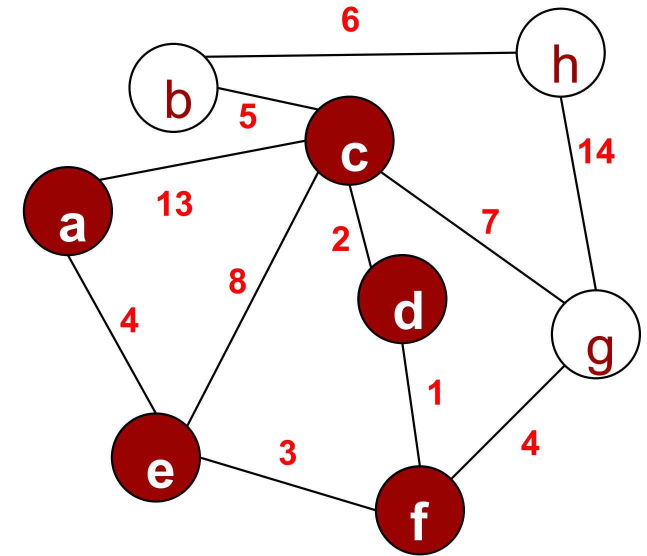

List of Vertices

Vert	Dist
b	inf
c	10
g	11
h	inf

15

v=c

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Dijkstra's Algorithm

```
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5.    For all v in vertices
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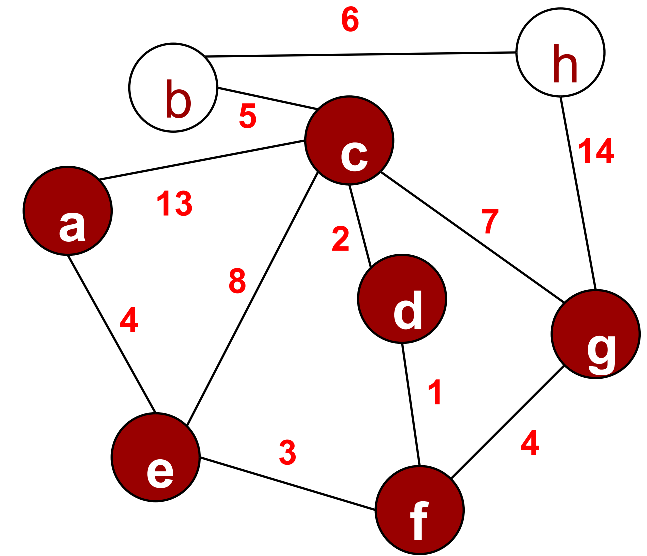

List of Vertices

Vert	Dist
b	15
g	11
h	inf

25

v=g

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Dijkstra's Algorithm

```
1.    SSSP(G, s)
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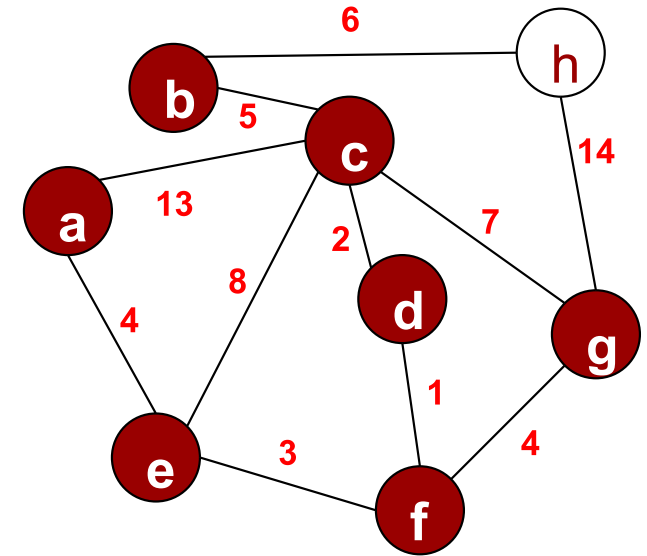

List of Vertices

Vert	Dist
b	15
h	25

21

v=b

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Dijkstra's Algorithm

```
1.   SSSP(G, s)
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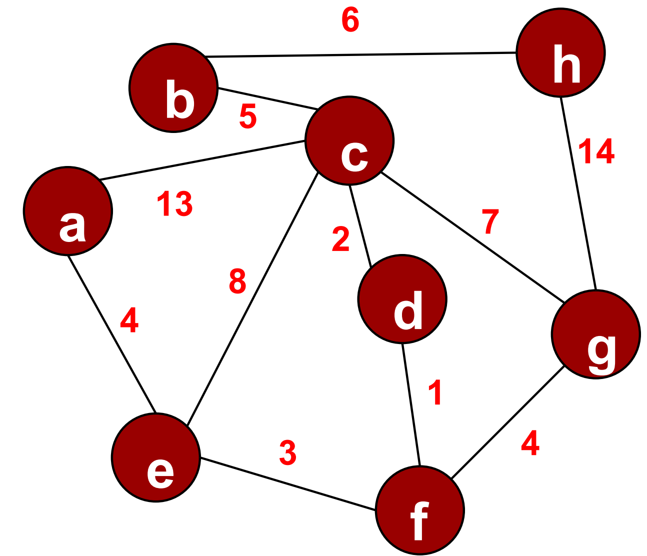

List of Vertices

Vert	Dist
h	21

v=h

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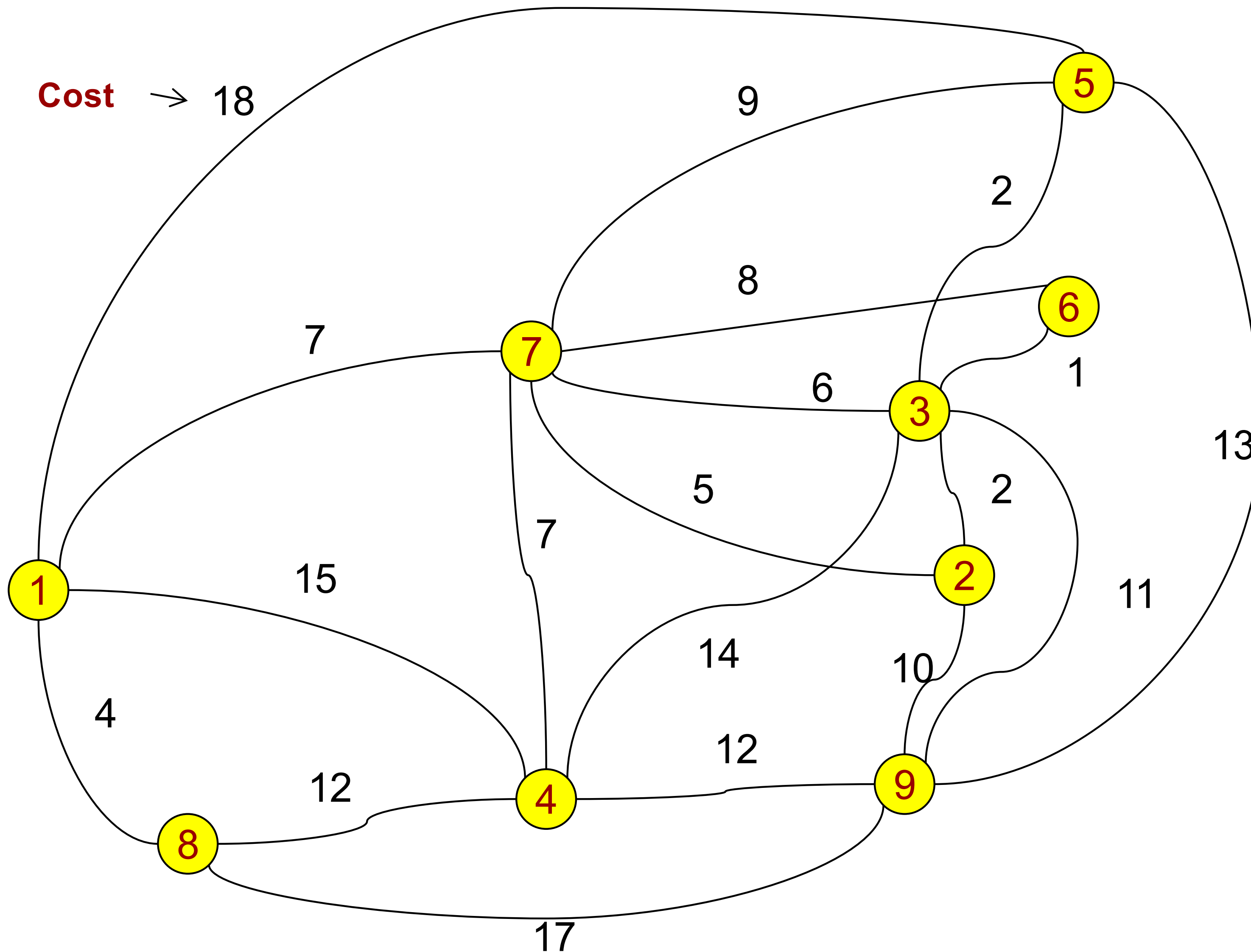
Another Example

- Try another example of Dijkstra's



List of Vertices

Vert	Dist
1	0
2	-
3	-
4	-
5	-
6	-
7	-
8	-
9	-

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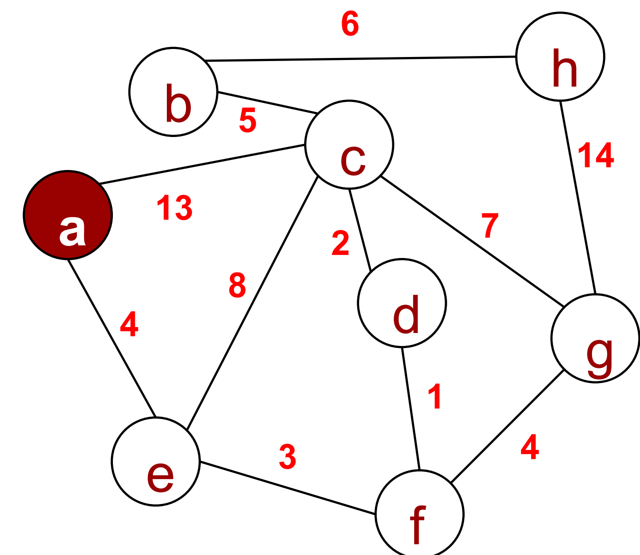
Analysis

- What is the loop invariant? What can I say about the vertex I pull out from the PQ?
  - It is guaranteed that there is no shorter path to that vertex
  - UNLESS: negative edge weights
- Could use induction to prove
  - When I pull the first node out (it is the start node) its weight has to be 0 and that is definitely the shortest path to itself
  - I then "relax" (i.e. decrease) the distance to neighbors it connects to and the next node I pull out would be the neighbor with the shortest distance from the start
    - Could there be shorter path to that node?
  - No, because any other path would use some other edge from the start which would have to have a larger weight



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Dijkstra's Run-time Analysis

- What is the run-time of Dijkstra's algorithm?
- How many times do you execute the while loop on 8?
- How many total times do you execute the for loop on 10?

```
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```

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Dijkstra's Run-time Analysis

- What is the run-time of Dijkstra's algorithm?
- How many times do you execute the while loop on 8?
  - V total times because once you pull a node out each iteration that node's distance is guaranteed to be the shortest distance and will never be put back in the PQ
  - What does each call to remove_min() cost…
  - …log(V) [at most V items in PQ]
- How many total times do you execute the for loop on 10?
  - E total times: Visit each vertex's neighbors
  - Each iteration may call decreaseKey() which is log(V)
- Total runtime = V*log(V) + E*log(V) = (V+E)*log(V)
  - This is usually dominated by E*log(V)

```
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```

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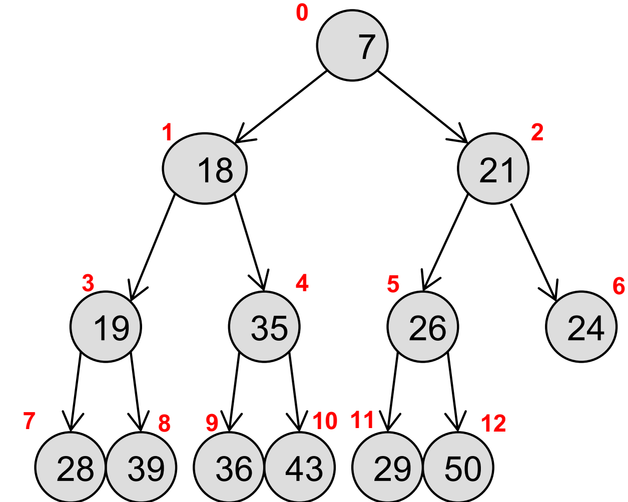
Tangent on Heaps/PQs

- Suppose min-heaps
  - Though everything we're about to say is true for max heaps but for increasing values
- We know insert/remove is log(n) for a heap
- What if we want to decrease a value already in the heap…
  - Example: Decrease 39 to 8
  - Could we find 39 easily?
    - No requires a linear search through the array/heap => O(n)
  - Once we find it could we adjust it easily?
    - Yes, just promote it until it is in the right location => O(log n)
- So currently decrease-key() would cost O(n) + O(log n) = O(n)
- Can we do better?



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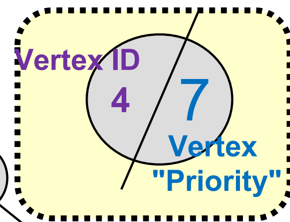
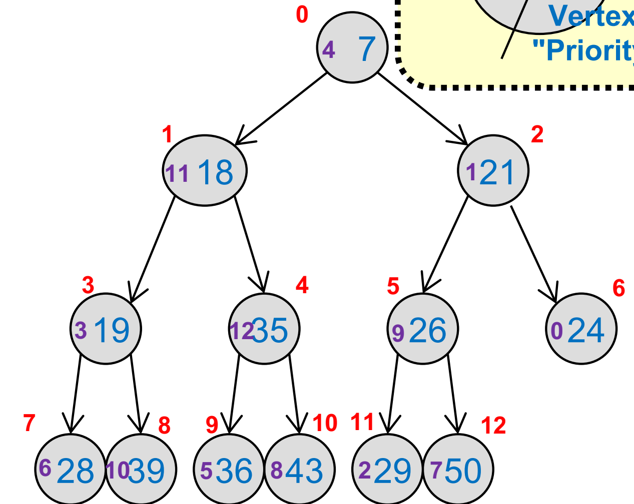
Tangent on Heaps/PQs





- Can we provide a decrease-key() that runs in O(log n) and not O(n)
  - Remember we'd have to first find then promote
- We need to know where items sit in the heap
  - We ***want*** to quickly know the location given the key/priority (that maps **pri** (or id) => **location**)
  - Unfortunately storing the heap as an array does just the opposite. So we have an array that maps **location => pri**)
- What if we assigned each vertex or object in the original graph/problem **a unique index [0 to n-1]** and maintained an alternative map that did provide the reverse indexing
  - Then I could find where the key sits and then promote it
- If I used std::map to maintain the id => heap index map I still cannot achieve O(log n) decreaseKey() time?
  - No! each promotion swap requires update your location and your parents
  - O(log n) swaps each requiring lookup(s) in the location map [O(log n)] yielding $O(\log^2(n))$

Heap Index	0	1	2	3	4	5	6	7	8	9	10	11	12
Heap Array	7	18	21	19	35	26	24	28	39	36	43	29	50

Node ID	Heap Idx
4	0
11	1
1	2
3	3
12	4
8	5
…	…

Map(key=Node ID, val=Heap Index)

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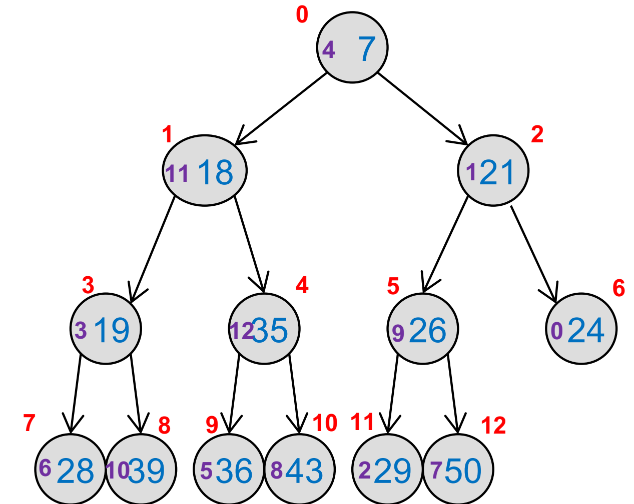
Tangent on Heaps/PQs

- Am I out of luck then?
- No, try an array / hash map
  - O(1) lookup
- Now each swap/promotion up the heap only costs O(1) and thus I have:
  - Find => O(1)
    - Using an array (or hashmap)
  - Promote => O(log n)
    - Bubble up at most log(n) levels with each level incurring O(1) updates of locations in the hashmap
- Decrease-key() is an important operation in the next algorithm we'll look at



Heap Index	0	1	2	3	4	5	6	7	8	9	10	11	12
Heap Array	7	18	21	19	35	26	24	28	39	36	43	29	50

Node ID	0	1	2	3	4	5	6	7	8	9	10	11	12
Heap Idx	6	2	11	3	0	9	7	12	10	5	8	1	4

Map(key=Node ID, val=Heap Index)

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A* Search Algorithm

ALGORITHM HIGHLIGHT

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Search Methods

- Many systems require searching for goal states
  - Path Planning
    - Roomba Vacuum
    - Mapquest/Google Maps
    - Games!!
  - Optimization Problems
    - Find the optimal solution to a problem with many constraints

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Search Applied to 8-Tile Game

- 8-Tile Puzzle
  - 3x3 grid with one blank space
  - With a series of moves, get the tiles in sequential order
  - Goal state:

	1	2
3	4	5
6	7	8

HW6 Goal State

1	2	3
4	5	6
7	8	

Goal State for these slides

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Search Methods

- **Brute-Force Search**: When you don't know where the answer is, just search all possibilities until you find it.
- **Heuristic Search**: A heuristic is a "rule of thumb". An example is in a chess game, to decide which move to make, count the values of the pieces left for your opponent. Use that value to "score" the possible moves you can make.
  - Heuristics are not perfect measures, they are quick computations to give an approximation (e.g. may not take into account "delayed gratification" or "setting up an opponent")

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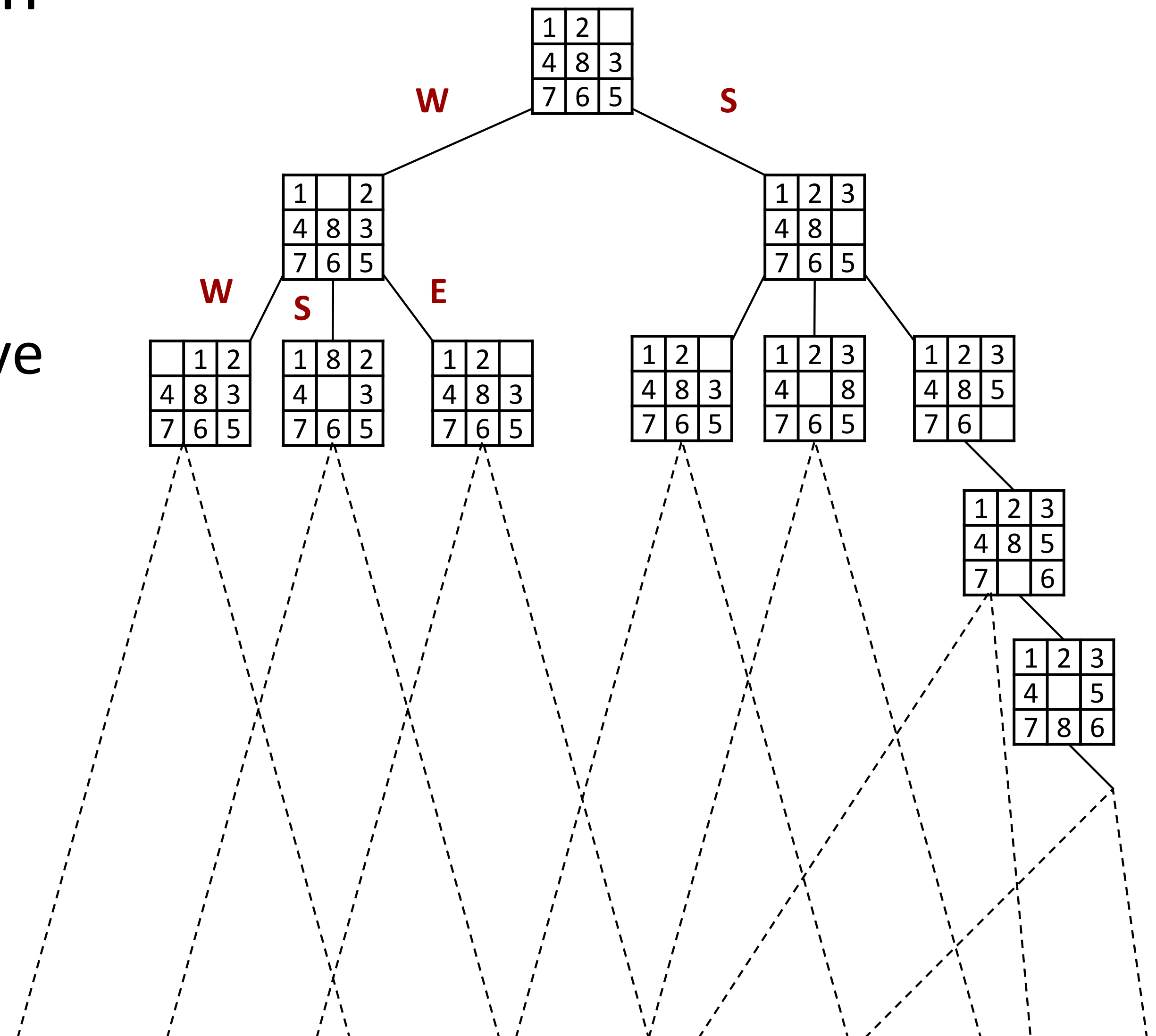
Brute Force Search

- Brute Force Search Tree
  - Generate all possible moves
  - Explore each move despite its proximity to the goal node



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Heuristics

- Heuristics are "scores" of how close a state is to the goal (usually, lower = better)
- These scores must be easy to compute (i.e. simpler than solving the problem)
- Heuristics can usually be developed by simplifying the constraints on a problem
- Heuristics for 8-tile puzzle
  - # of tiles out of place
    - Simplified problem: If we could just pick a tile up and put it in its correct place
  - Total x-, y- distance of each tile from its correct location (Manhattan distance)
    - Simplified problem if tiles could stack on top of each other / hop over each other

1	8	3
4	5	6
2	7	

# of Tiles out of Place = 3

1	8	3
4	5	6
2	7	

Total x-/y- distance = 6

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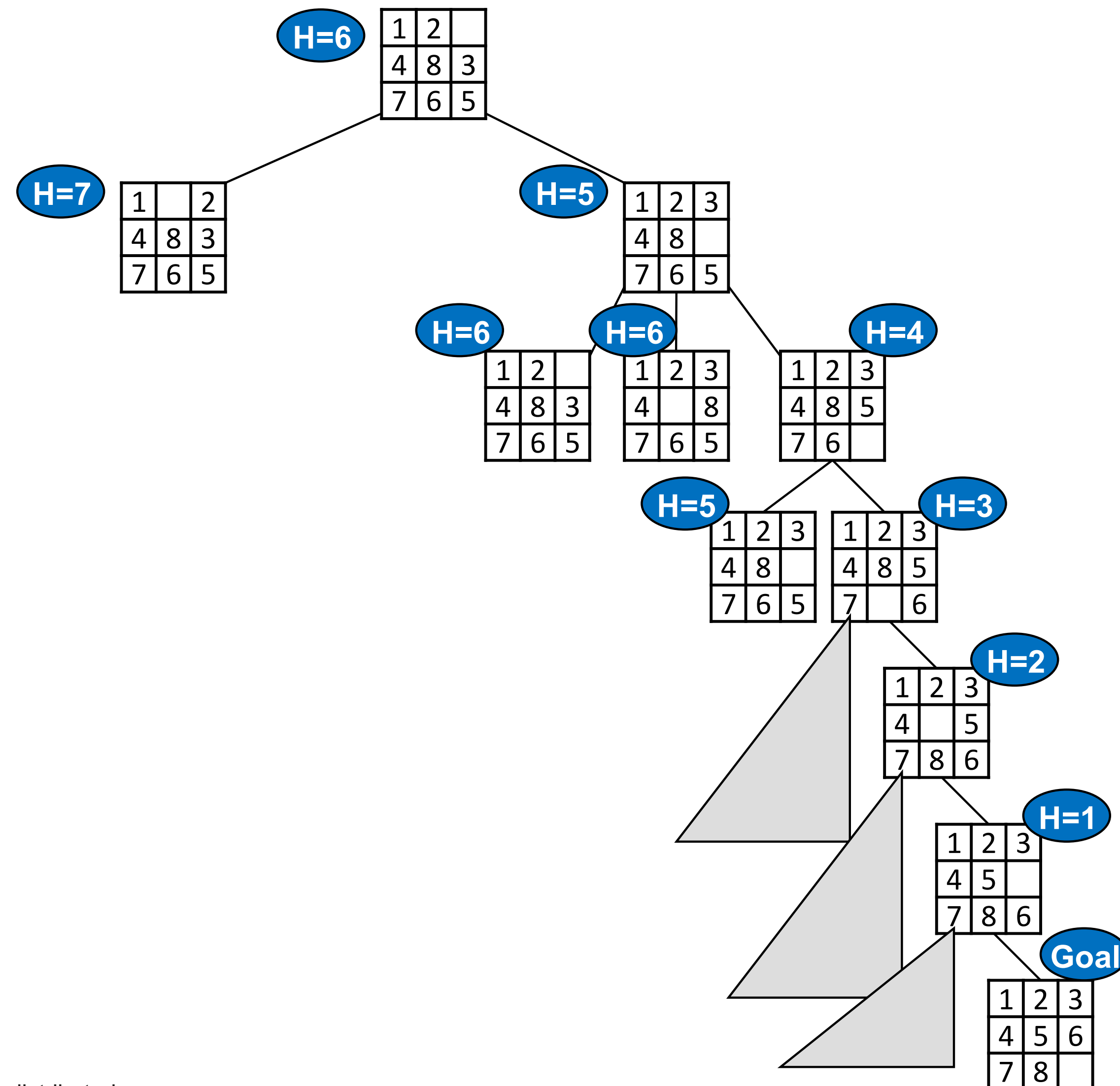
Heuristic Search

- Heuristic Search Tree
  - Use total x-/y-distance (Manhattan distance) heuristic
  - Explore the lowest scored states



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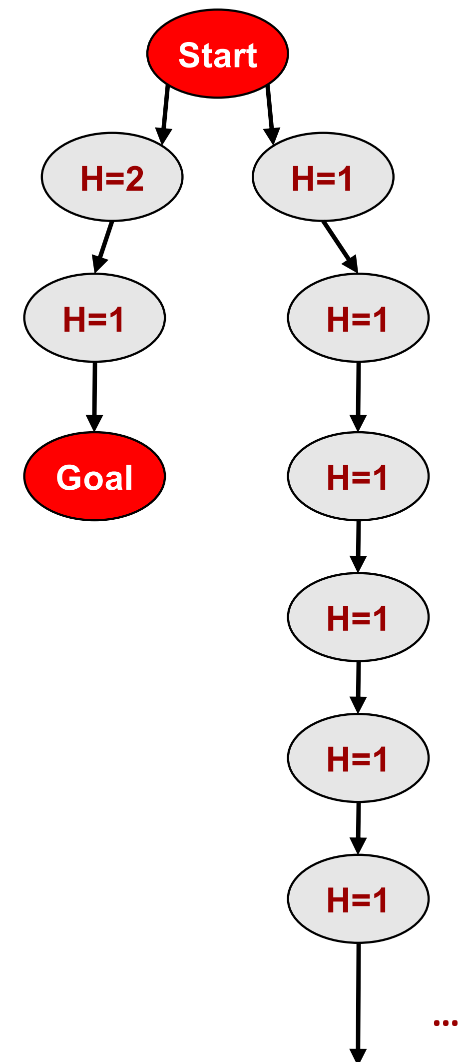
Caution About Heuristics

- Heuristics are just estimates and thus could be wrong
- Sometimes pursuing lowest heuristic score leads to a less-than optimal solution or even no solution
- Solution
  - Take # of moves from start (depth) into account



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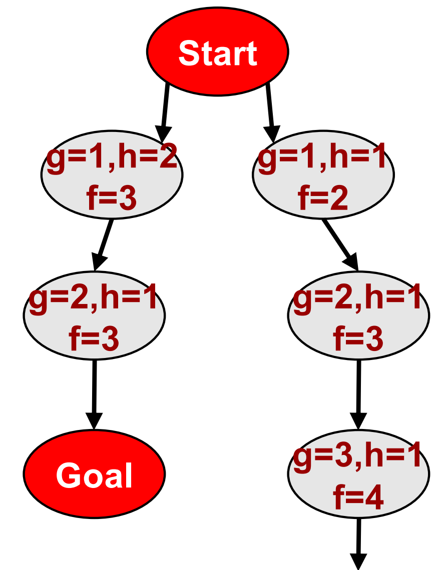
A-Star Algorithm

- Use a new metric to decide which state to explore/expand
- Define
  - h = heuristic score (same as always)
  - g = number of moves from start it took to get to current state
  - f = g + h
- As we explore states and their successors, assign each state its f-score and always explore the state with lowest f-score
- Heuristics should always underestimate the distance to the goal
  - If they do, A* guarantees optimal solutions



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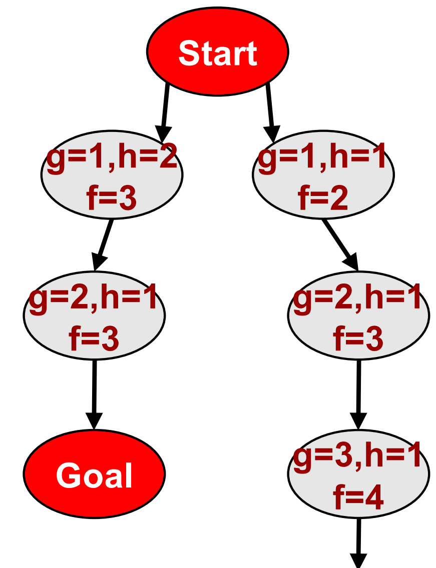
USC Viterbi School of Engineering

A-Star Algorithm

- Maintain 2 lists
  - Open list = Nodes to be explored (chosen from)
  - Closed list = Nodes already explored (already chosen)
- General A* Pseudocode




```
open_list.push(Start State)
while(open_list is not empty)
   1. s ← remove min. f-value state from open_list
         (if tie in f-values, select one w/ larger g-value)
   2. Add s to closed list
   3a. if s = goal node then trace path back to start; STOP!
   3b. Generate successors/neighbors of s, compute their f
        values, and add them to open_list if they are
        not in the closed_list (so we don't re-explore), or
        if they are already in the open list, update them if
        they have a smaller f value
```

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Path-Planning w/ A* Algorithm

- Find optimal path from S to G using A*
  - Use heuristic of Manhattan (x-/y-) distance

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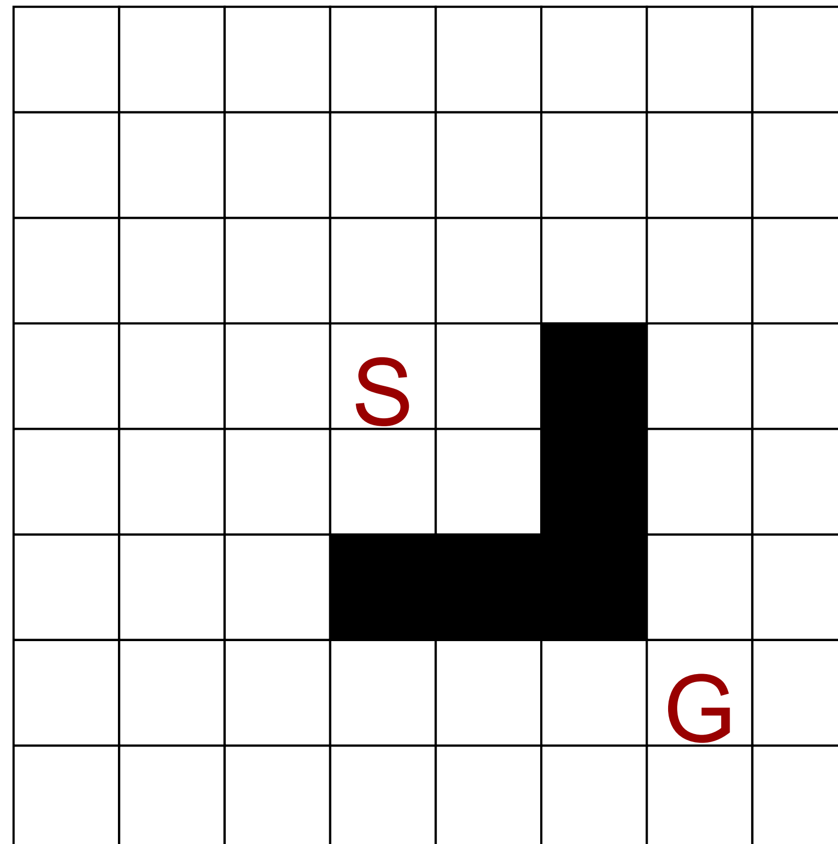

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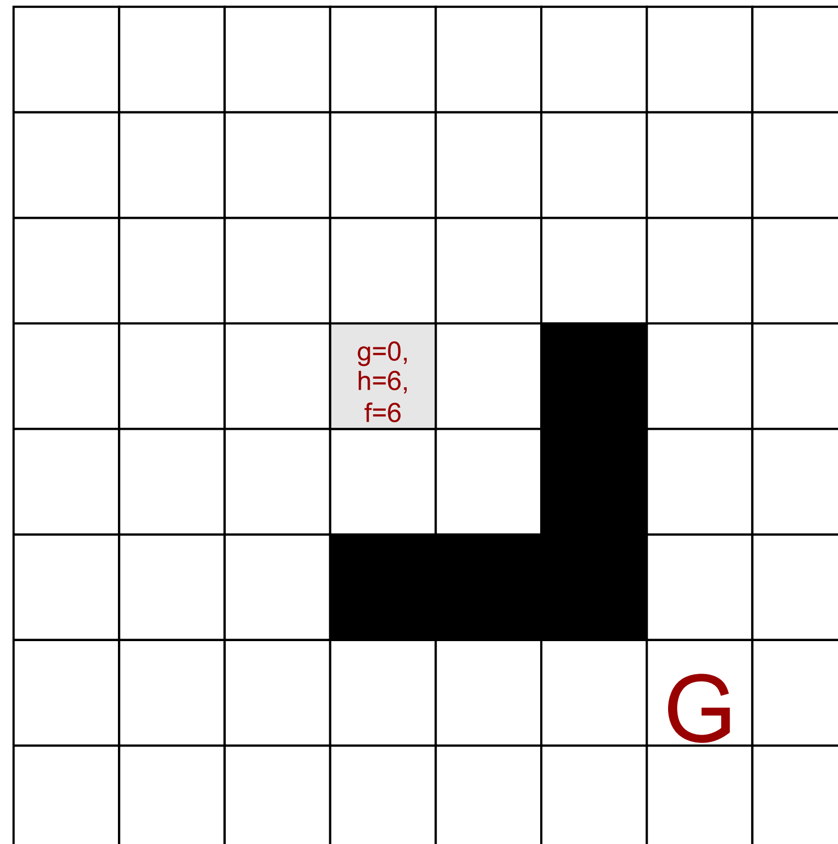

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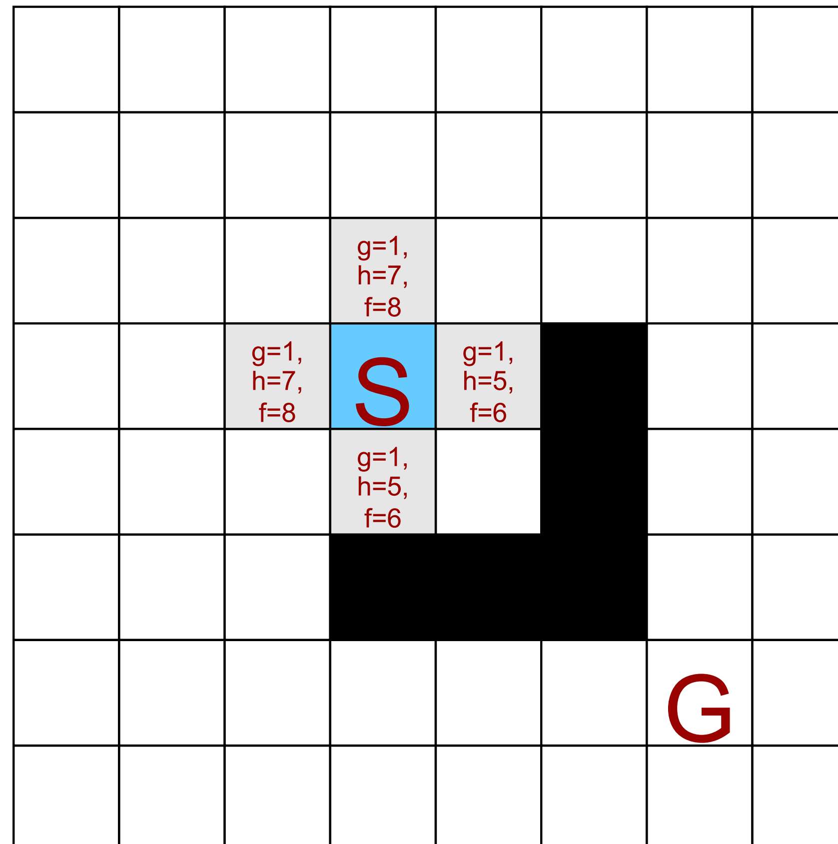

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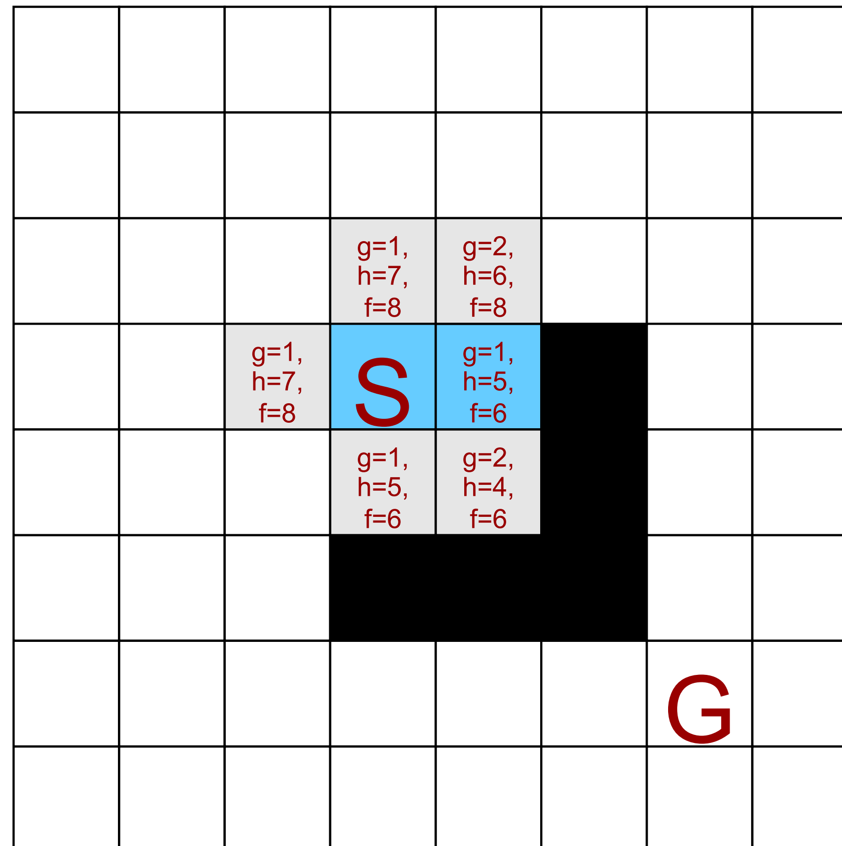

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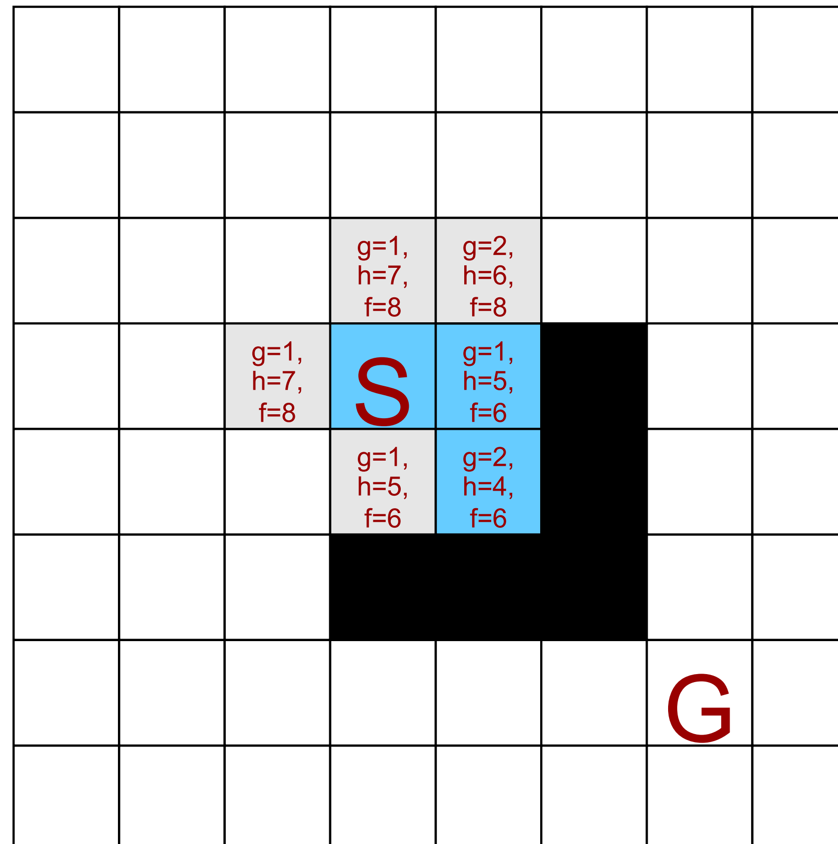

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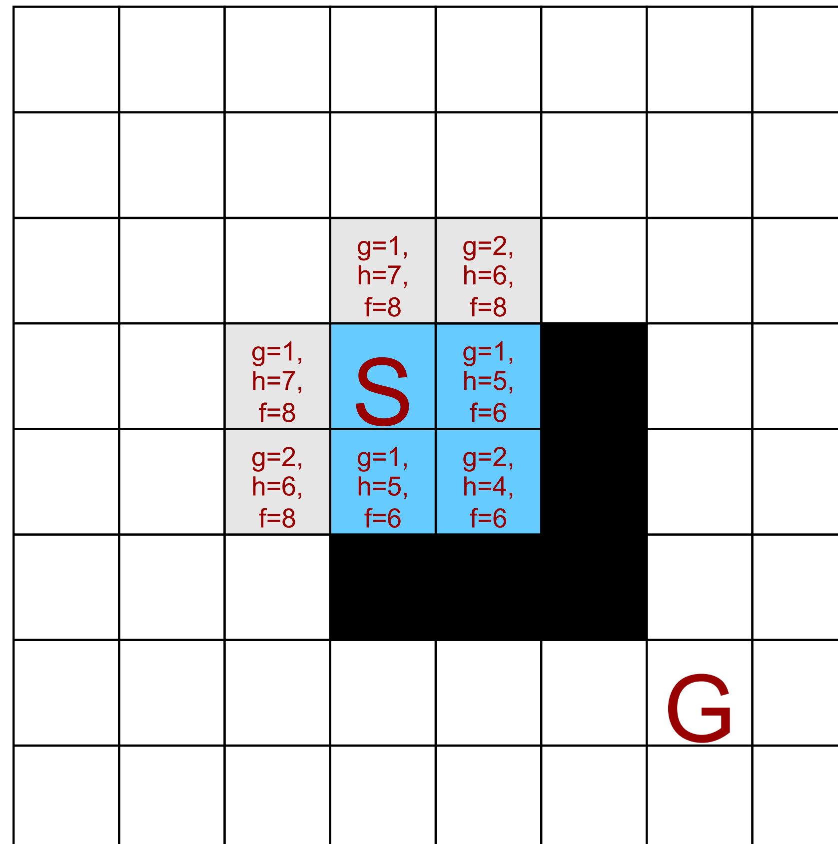

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```

				g=3, h=7, f=10			
			g=1, h=7, f=8	g=2, h=6, f=8	g=3, h=5, f=8		
		g=1, h=7, f=8	S	g=1, h=5, f=6			
		g=2, h=6, f=8	g=1, h=5, f=6	g=2, h=4, f=6			
						G	

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		g=1, h=7, f=8	S	g=1, h=5, f=6		g=5, h=3, f=8	
		g=2, h=6, f=8	g=1, h=5, f=6	g=2, h=4, f=6			
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		g=2, h=6, f=8	g=1, h=5, f=6	g=2, h=4, f=6		g=6, h=2, f=8	g=7, h=3, f=10
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		g=2, h=6, f=8	g=1, h=5, f=6	g=2, h=4, f=6		g=6, h=2, f=8	g=7, h=3, f=10
						g=7, h=1, f=8	g=8, h=2, f=10
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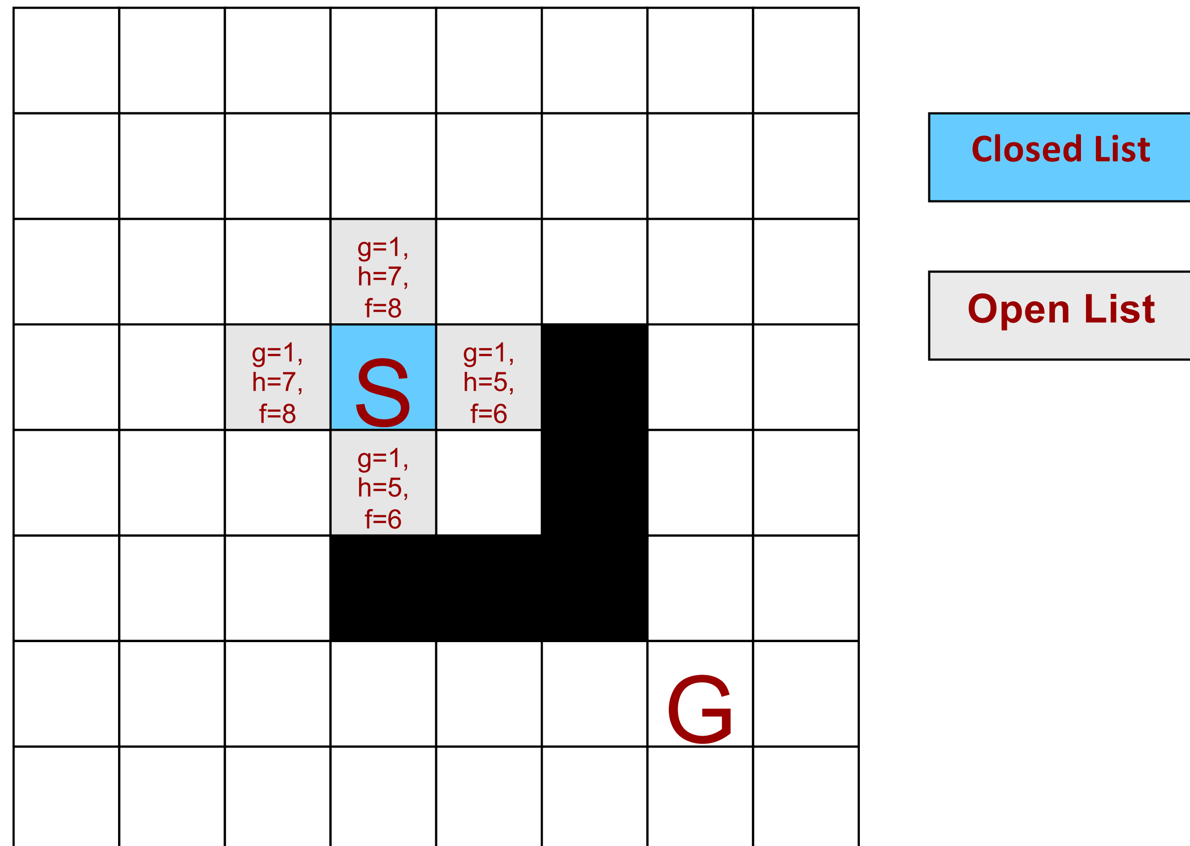
A* and BFS

- BFS explores all nodes at a shorter distance from the start (i.e. g value)



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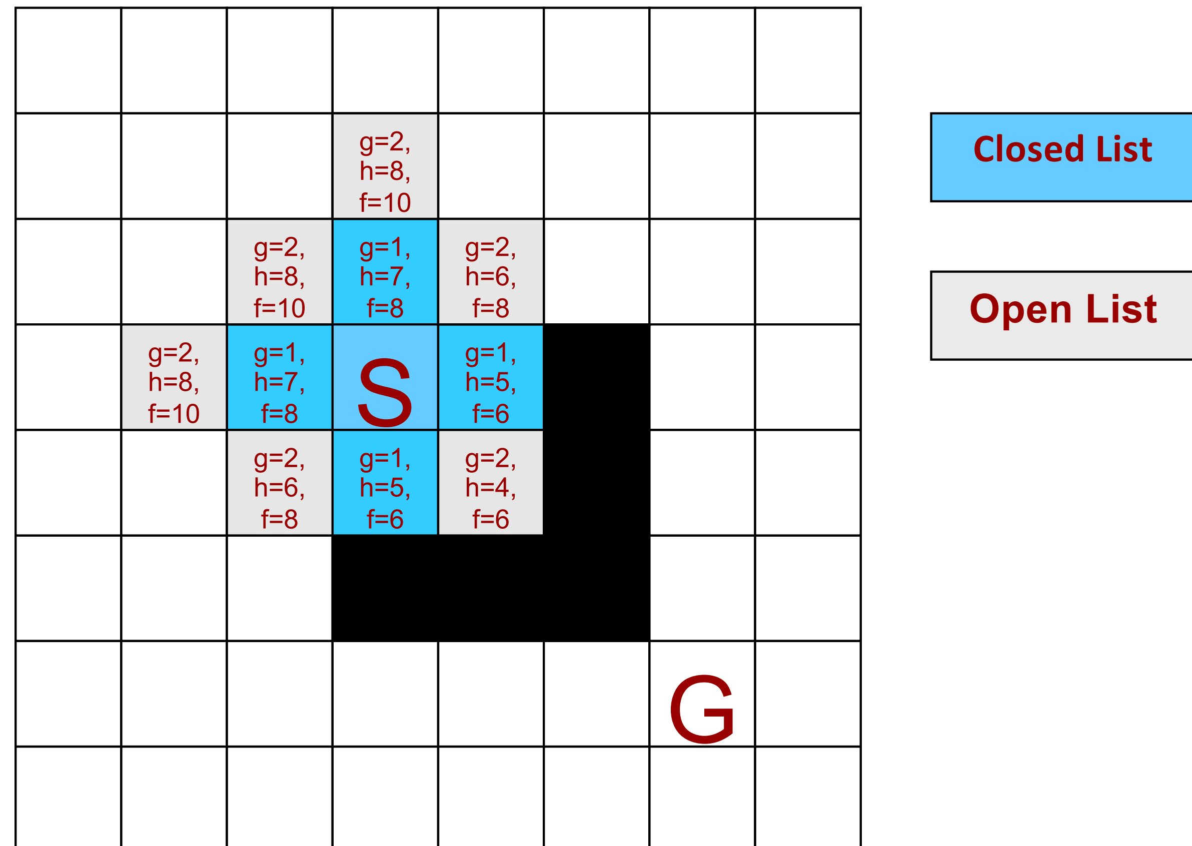

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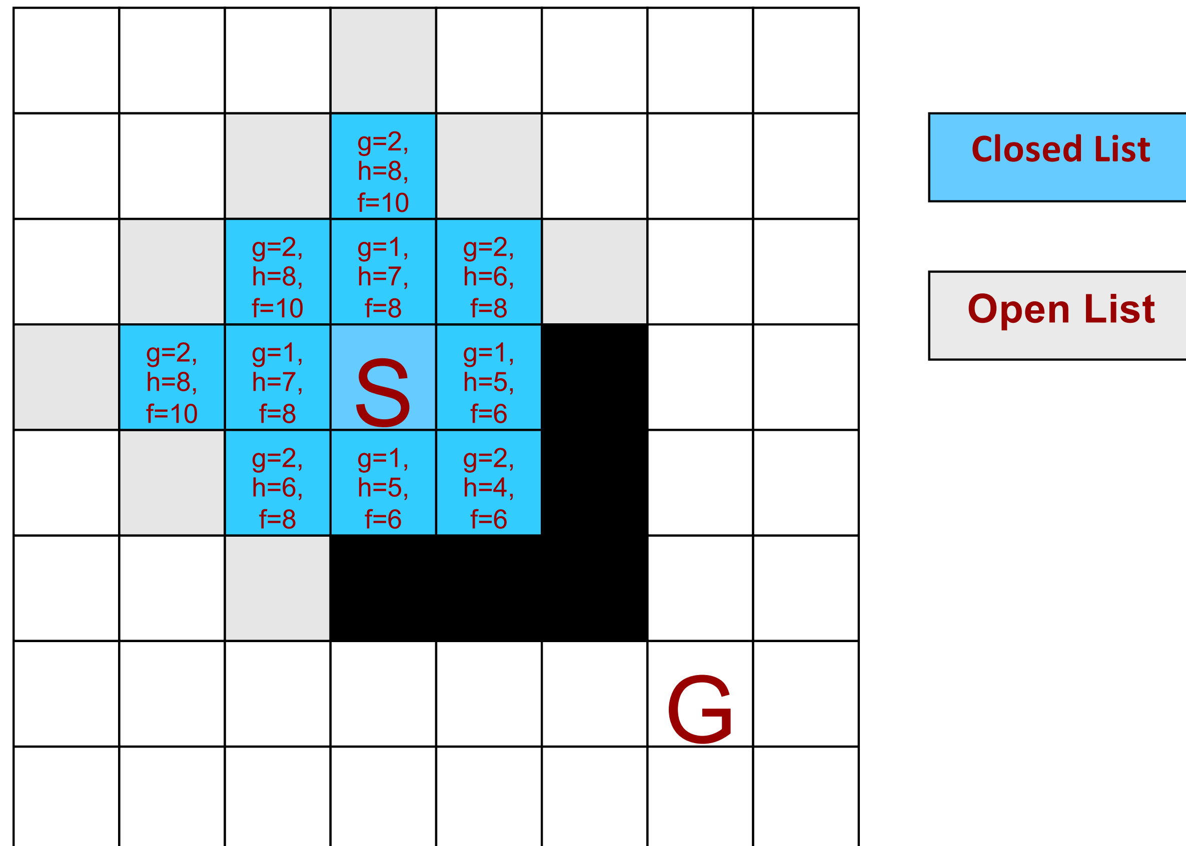
A* and BFS

- BFS is A* using just the g value to choose which item to select and expand



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A* Analysis

- What data structure should we use for the open-list?
- What data structure should we use for the closed-list?
- What is the run time?
- Run time is similar to Dijkstra's algorithm…
  - We pull out each node/state once from the open-list so that incurs N*O(remove-cost)
  - We then visit each successor which is like O(E) and perform an insert or decrease operation which is like E*max(O(insert), O(decrease)
  - E = Number of potential successors and this depends on the problem and the possible solution space
  - For the tile puzzle game, how many potential boards are there?

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Implementation Note

- When the distance to a node/state/successor (i.e. g value) is uniform, we can greedily add a state to the closed-list at the same time as we add it to the open-list

Non-uniform g-values

```
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   2. Add s to closed list
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       values, and add them to open_list if they are
       not in the closed_list (so we don't re-explore), or
       if they are already in the open list, update them if
       they have a smaller f value
```
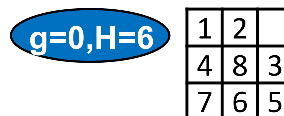
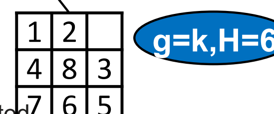

Uniform g-values

```
open_list.push(Start State)
Closed_list.push(Start State)
while(open_list is not empty)
   1. s ← remove min. f-value state from open_list
        (if tie in f-values, select one w/ larger g-value)
   3a. if s = goal node then trace path back to start; STOP!
   3b. Generate successors/neighbors of s, compute their f
       values, and add them to open_list and closed_list
       if they are not in the closed_list
```



...



The first occurrence of a board has to be on the shortest path to the solution

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If time allows…

BETWEENESS CENTRALITY

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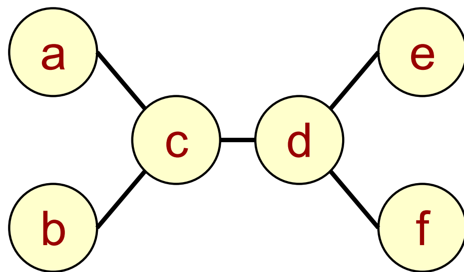
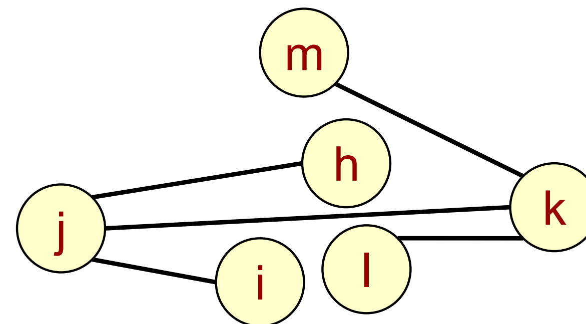
BC Algorithm Overview

- What's the most central vertex(es) in the graph below?
- How do we define "centrality"?
- Betweeness centrality defines "centrality" as the nodes that are between the most other pairs

Sample Graph



Graph 1



Graph 2

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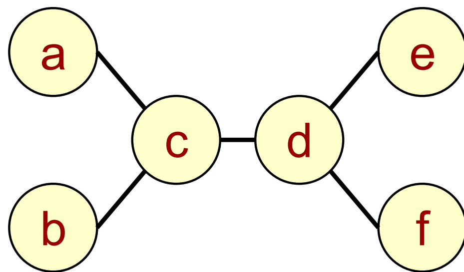
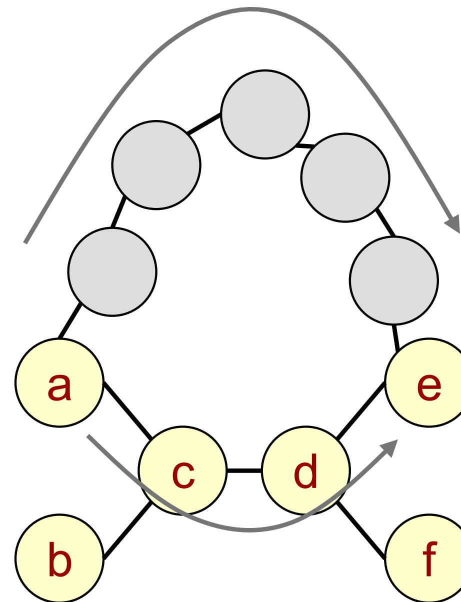
BC Algorithm Overview

- Betweeness centrality (BC) defines "centrality" as the nodes that are between (i.e. on the path between) the most other pairs of vertices
- BC considers betweeness on only "**shortest**" paths!
- To compute centrality score for each vertex we need to find shortest paths between all pairs…
  - Use the Breadth-First Search (BFS) algorithm to do this

Sample Graph



Original 1



Original w/ added path

Are these gray nodes 'between' a and e?

No, a-c-d-e is the shortest path?

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BC Algorithm Overview

- Betweeness-Centrality determines "centrality" as the number of shortest paths from all-pairs upon which a vertex lies
- Consider the sample graph below
  - Each external vertex (a, b, e, f) lies is a member of only the shortest paths between itself and each other vertex
  - Vertices c and d lie on greater number of shortest paths and thus will be scored higher

Sample Graph

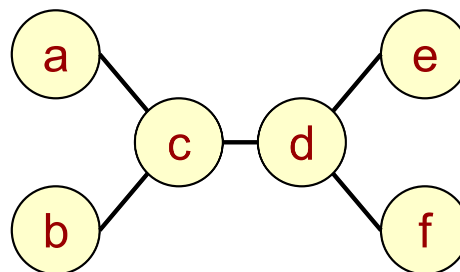

Image each vertex is a ball and each edge is a chain or string. What would this graph look like if you picked it up by vertex c? Vertex a?

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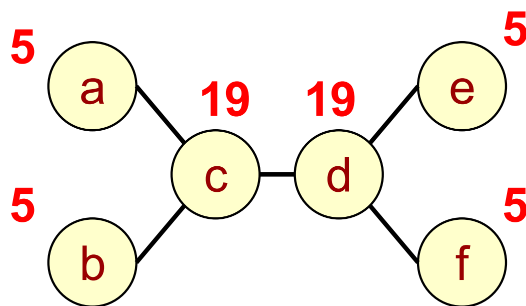
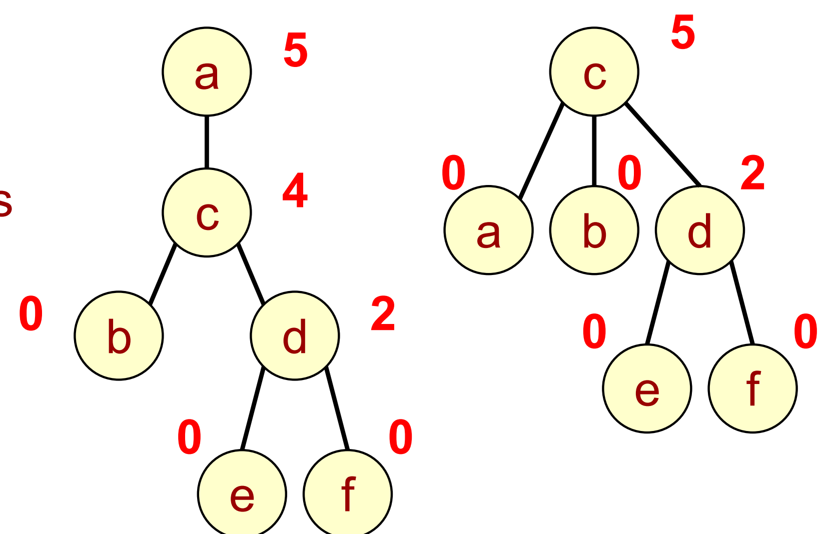
BC Implementation

- Based on Brandes' formulation for unweighted graphs
  - Perform |V| Breadth-first traversals
  - Traversals result in a subgraph consisting of shortest paths from root to all other vertices
  - Messages are then sent back up the subgraph from "leaf" vertices to the root summing the percentage of shortest-paths each vertex is a member of
  - Summing a vertex's score from each traversal yields overall BC result

Sample Graph with final BC scores



Traversals from selected roots and resulting partial BC scores (in this case, the number of descendants)



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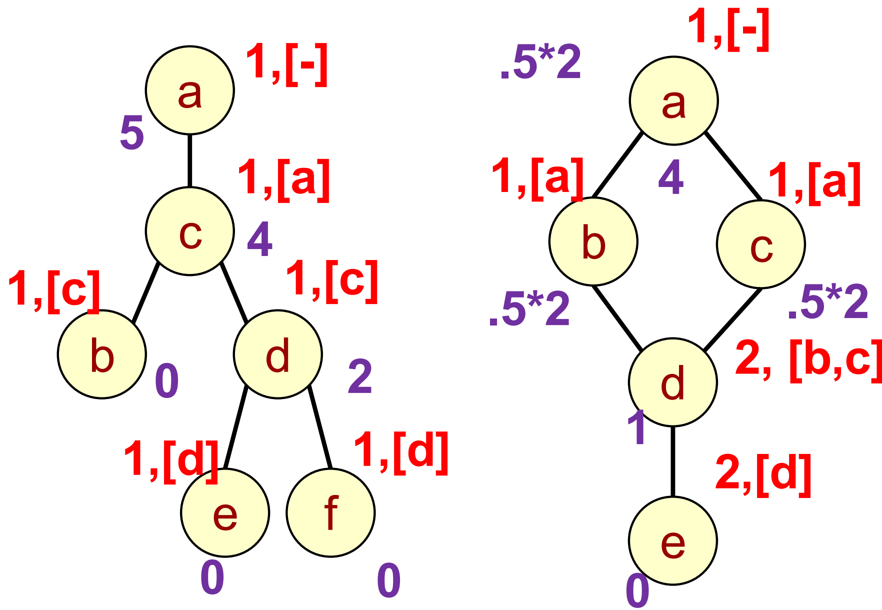
BC Implementation

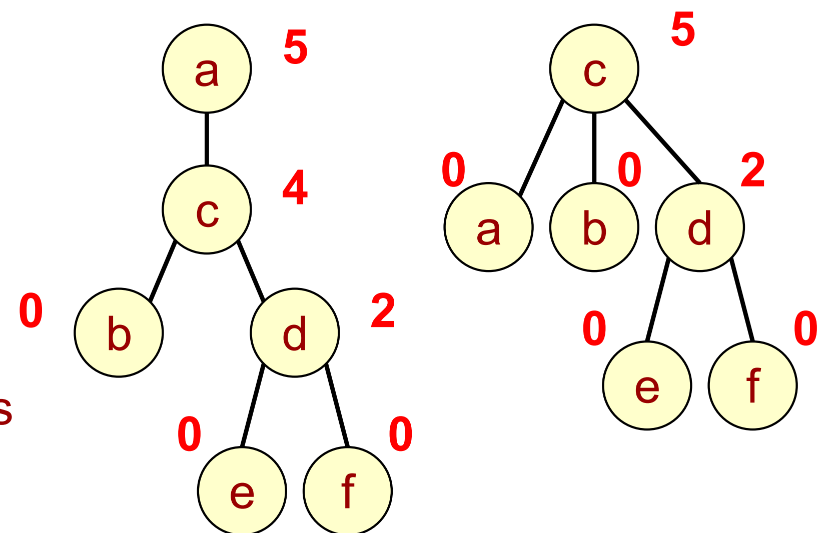
- As you work down, track # of shortest paths running through a vertex and its predecessor(s)
- On your way up, sum the nodes beneath



# of shortest paths thru the vertex, [List of predecessor]

Score on the way back up (if multiple shortest paths, split the score appropriately)

Traversals from selected roots and resulting partial BC scores (in this case, the number of descendants)



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OLD - IGNORE

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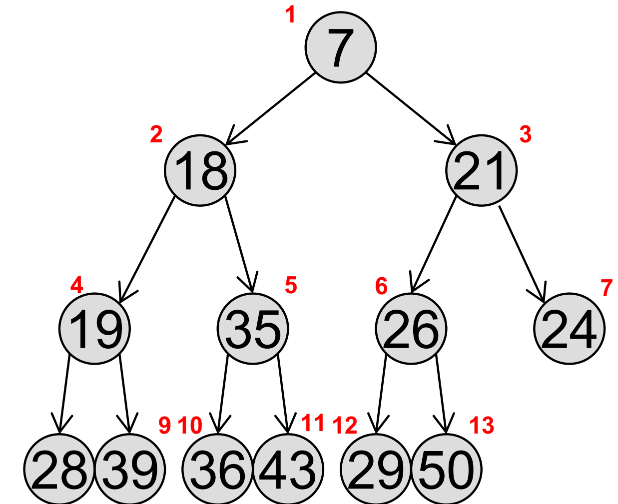
Tangent on Heaps/PQs - old

- Can we provide a decrease-key() that runs in O(log n) and not O(n)
  - Remember we'd have to first find then promote
- We need to know where items sit in the heap
  - Essentially we want to quickly know the location given the key/priority (i.e. Map key => location)
  - Unfortunately storing the heap as an array does just the opposite (maps location => key)
- What if we maintained an alternative map that did provide the reverse indexing
  - Then I could find where the key sits and then promote it
- If I keep that map as a balanced BST can I achieve O(log n) decreaseKey() time?
  - No! each promotion swap requires update your location and your parents
  - O(log n) swaps each requiring lookup(s) in the location map [O(log n)] yielding O($\log^2$(n))



Heap Array

0	1	2	3	4	5	6	7	8	9	10	11	12
7	18	21	19	35	26	24	28	39	36	43	29	50

Map of key to loc.

7	18	21	19	35	26	24	28	39	36	43	29	50
0	1	2	3	4	5	6	7	8	9	10	11	12

Map(key=Node ID, val=Heap Index)

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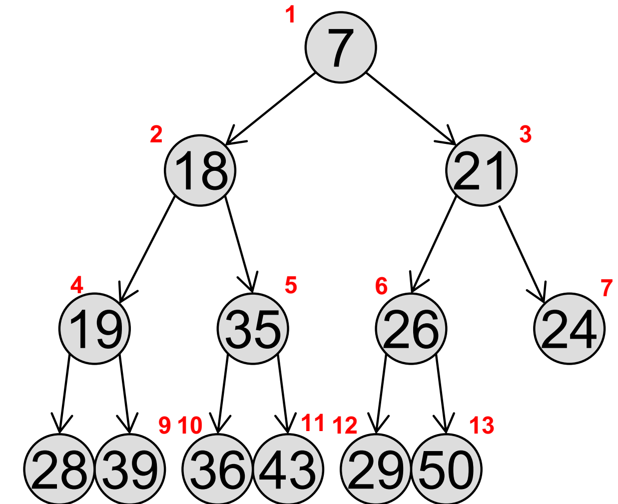
Tangent on Heaps/PQs -old

- Am I out of luck then?
- No, try a hash map
  - O(1) lookup
- Now each swap/promotion up the heap only costs O(1) and thus I have:
  - Find => O(1)
    - Using the hashmap
  - Promote => O(log n)
    - Bubble up at most log(n) levels with each level incurring O(1) updates of locations in the hashmap
- Decrease-key() is an important operation in the next algorithm we'll look at



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