Graphs: Shortest Paths *(Chapter 9)*

CSE 373
Data Structures and Algorithms

Today's Outline

- **Admin**:
  - Homework #4 - due Thurs, Nov 8th at 11pm
  - Midterm 2, Fri Nov 16
- **Graphs**
  - Graph Traversals
  - Shortest Paths

Single source shortest paths

- Done: BFS to find the minimum path length from **v** to **u** in *O*(|E|+(|V|)
- Actually, can find the minimum path length from **v** to *every node*
  - Still *O*(|E|+(|V|)
  - No faster way for a "distinguished" destination in the worst-case
- Now: Weighted graphs

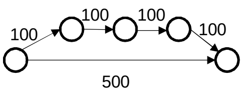
Given a weighted graph and node **v**,
find the minimum-cost path from **v** to every node

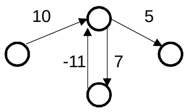
- As before, asymptotically no harder than for one destination
- Unlike before, BFS will not work

Applications

- Network routing
- Driving directions
- Cheap flight tickets
- Critical paths in project management (see textbook)
- …

Not as easy





Why BFS won't work: Shortest path may not have the fewest edges
- Annoying when this happens with costs of flights

We will assume there are no negative weights
- Problem is ill-defined if there are negative-cost *cycles*
- Next algorithm we will learn is wrong if *edges* can be negative

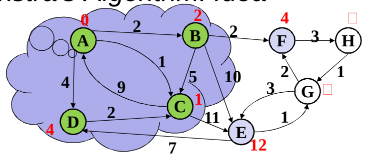
Edsger Wybe Dijkstra
(1930-2002)

- Legendary figure in computer science; was a professor at University of Texas.
- Invented concepts of structured programming, synchronization, and "semaphores" for controlling computer processes.
- Supported teaching programming without computers (pencil and paper)
- 1972 Turing Award
- "computer science is no more about computers than astronomy is about telescopes"

Dijkstra's Algorithm

The idea: reminiscent of BFS, but adapted to handle weights
- A priority queue will prove useful for efficiency (later)
- Will grow the set of nodes whose shortest distance has been computed
- Nodes not in the set will have a "best distance so far"

Dijkstra's Algorithm: Idea



- Initially, start node (A in this case) has "cost" 0 and all other nodes have "cost" ∞
- At each step:
  - Pick closest unknown vertex **v**
  - Add it to the "cloud" of known vertices
  - Update "costs" for nodes with edges from **v**
- That's it! (Have to prove it produces correct answers)

The Algorithm

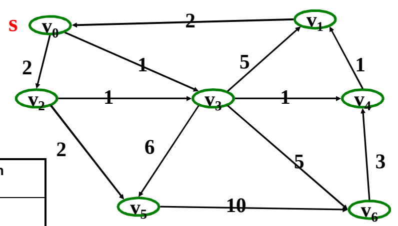
1. For each node **v**, set **`v.cost = ∞`** and **`v.known = false`**
2. Set **`source.cost = 0`**
3. While there are unknown nodes in the graph
   a) Select the unknown node **v** with lowest cost
   b) Mark **v** as known
   c) For each edge **`(v,u)`** with weight **`w`**,

```
c1 = v.cost + w  // cost of best path through v to u
c2 = u.cost      // cost of best path to u previously known
if(c1 < c2){     // if the path through v is better
  u.cost = c1
  u.path = v     // for computing actual paths
}
```


Important features

- Once a vertex is marked known, the cost of the shortest path to that node is known
  - As is the path itself
- While a vertex is still not known, another shorter path to it might still be found

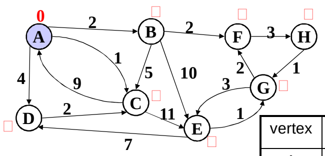
Find the shortest path to each vertex from v_0



V	Known	Dist from s	Path
v0			
v1			
v2			
v3			
v4			
v5			
v6			

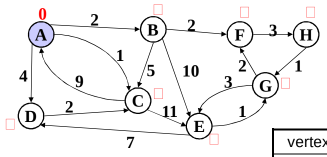
<u>Order declared Known:</u>

Example #1



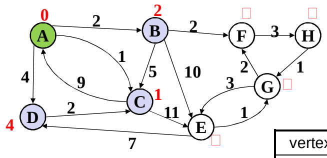
vertex	known?	cost	path
A			
B			
C			
D			
E			
F			
G			
H			

Example #1



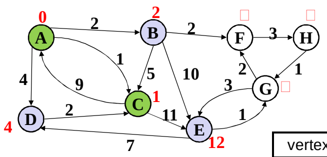
vertex	known?	cost	path
A		0	
B		??	
C		??	
D		??	
E		??	
F		??	
G		??	
H		??	

Example #1



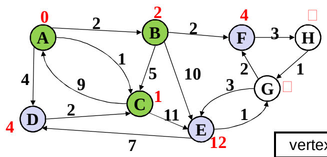
vertex	known?	cost	path
A	Y	0	
B		≤ 2	A
C		≤ 1	A
D		≤ 4	A
E		??	
F		??	
G		??	
H		??	

Example #1



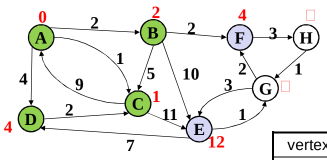
vertex	known?	cost	path
A	Y	0	
B		≤ 2	A
C	Y	1	A
D		≤ 4	A
E		≤ 12	C
F		??	
G		??	
H		??	

Example #1



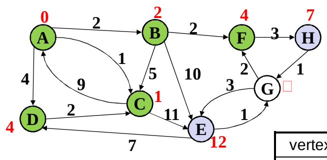
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D		≤ 4	A
E		≤ 12	C
F		≤ 4	B
G		??	
H		??	

Example #1



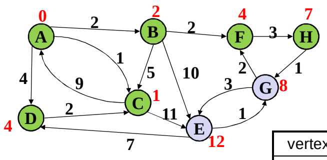
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 12	C
F		≤ 4	B
G		??	
H		??	

Example #1



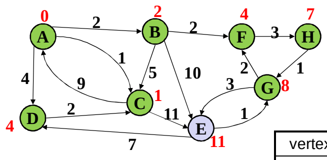
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 12	C
F	Y	4	B
G		??	
H		≤ 7	F

Example #1



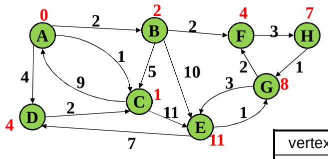
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 12	C
F	Y	4	B
G		≤ 8	H
H	Y	7	F

Example #1



vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

Example #1



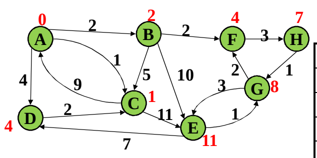
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E	Y	11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

Important features

- Once a vertex is marked ‘known’, the cost of the shortest path to that node is known
  - As is the path itself
- While a vertex is still not known, another shorter path to it might still be found

Interpreting the results

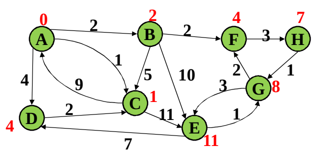
- Now that we’re done, how do we get the path from, say, A to E?



vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E	Y	11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

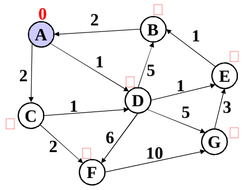
Stopping Short

- How would this have worked differently if we were only interested in the path from A to G?
  - A to E?



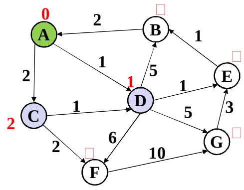
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E	Y	11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

Example #2



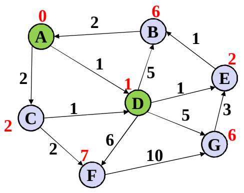
vertex	known?	cost	path
A		0	
B		??	
C		??	
D		??	
E		??	
F		??	
G		??	

Example #2



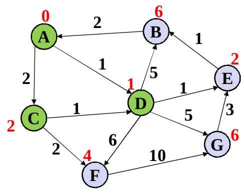
vertex	known?	cost	path
A	Y	0	
B		??	
C		≤ 2	A
D		≤ 1	A
E		??	
F		??	
G		??	

Example #2



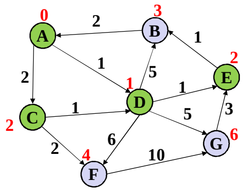
vertex	known?	cost	path
A	Y	0	
B		≤ 6	D
C		≤ 2	A
D	Y	1	A
E		≤ 2	D
F		≤ 7	D
G		≤ 6	D

Example #2



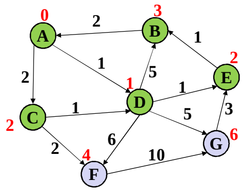
vertex	known?	cost	path
A	Y	0	
B		≤ 6	D
C	Y	2	A
D	Y	1	A
E		≤ 2	D
F		≤ 4	C
G		≤ 6	D

Example #2



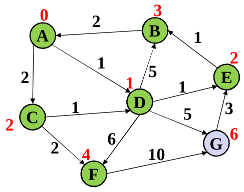
vertex	known?	cost	path
A	Y	0	
B		≤ 3	E
C	Y	2	A
D	Y	1	A
E	Y	2	D
F		≤ 4	C
G		≤ 6	D

Example #2



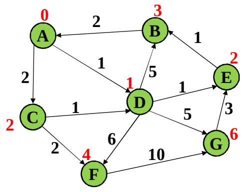
vertex	known?	cost	path
A	Y	0	
B	Y	3	E
C	Y	2	A
D	Y	1	A
E	Y	2	D
F		≤ 4	C
G		≤ 6	D

Example #2



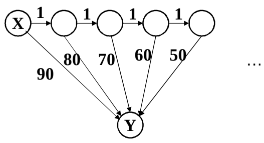
vertex	known?	cost	path
A	Y	0	
B	Y	3	E
C	Y	2	A
D	Y	1	A
E	Y	2	D
F	Y	4	C
G		≤ 6	D

Example #2



vertex	known?	cost	path
A	Y	0	
B	Y	3	E
C	Y	2	A
D	Y	1	A
E	Y	2	D
F	Y	4	C
G	Y	6	D

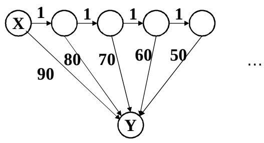
Example #3



How will the best-cost-so-far for Y proceed?

Is this expensive?

Example #3



How will the best-cost-so-far for Y proceed? 90, 81, 72, 63, 54, …

Is this expensive? No, each *edge* is processed only once

A Greedy Algorithm

- Dijkstra's algorithm
  - For single-source shortest paths in a weighted graph (directed or undirected) with no negative-weight edges
  - An example of a *greedy algorithm*:
    - at each step, irrevocably does what seems best at that step (once a vertex is in the known set, does not go back and readjust its decision)
    - Locally optimal – does not always mean globally optimal

Where are we?

- Have described Dijkstra's algorithm
  - For single-source shortest paths in a weighted graph (directed or undirected) with no negative-weight edges
- What should we do after learning an algorithm?
  - Prove it is correct
    - Not obvious!
    - We will sketch the key ideas
  - Analyze its efficiency
    - Will do better by using a data structure we learned earlier!

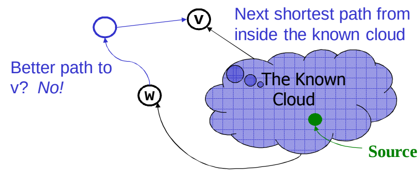
Correctness: Intuition

Rough intuition:

All the "known" vertices have the correct shortest path
- True initially: shortest path to start node has cost 0
- If it stays true every time we mark a node "known", then by induction this holds and eventually everything is "known"

Key fact we need: When we mark a vertex "known" we won't discover a shorter path later!
- This holds only because Dijkstra's algorithm picks the node with the next shortest path-so-far
- The proof is by contradiction…

Correctness: The Cloud (Rough Idea)



Suppose **v** is the next node to be marked known ("added to the cloud")
- The best-known path to **v** must have only nodes "in the cloud"
  - Since we've selected it, and we only know about paths through the cloud to a node right outside the cloud
- Assume the actual shortest path to **v** is different
  - It won't use only cloud nodes, (or we would know about it), so it must use non-cloud nodes
  - Let **w** be the *first* non-cloud node on this path.
  - The part of the path up to **w** is already known and must be shorter than the best-known path to **v**. So **v** would not have been picked. Contradiction.

Efficiency, first approach

Use pseudocode to determine asymptotic run-time
- Notice each edge is processed only once

```
dijkstra(Graph G, Node start) {
  for each node: x.cost=infinity, x.known=false
  start.cost = 0
  while(not all nodes are known) {
    b = find unknown node with smallest cost
    b.known = true
    for each edge (b,a) in G
     if(!a.known)
       if(b.cost + weight((b,a)) < a.cost){
         a.cost = b.cost + weight((b,a))
         a.path = b
       }
}
```


Efficiency, first approach

Use pseudocode to determine asymptotic run-time
- Notice each edge is processed only once

```
dijkstra(Graph G, Node start) {
  for each node: x.cost=infinity, x.known=false     } O(|V|)
  start.cost = 0
  while(not all nodes are known) {
    b = find unknown node with smallest cost        } O(|V|^2)
    b.known = true
    for each edge (b,a) in G
     if(!a.known)
       if(b.cost + weight((b,a)) < a.cost){         } O(|E|)
         a.cost = b.cost + weight((b,a))
         a.path = b
       }
}
                                                      O(|V|^2)
```

Improving asymptotic running time

- So far: $O(|V|^2)$
- We had a similar "problem" with topological sort being $O(|V|^2)$ due to each iteration looking for the node to process next
  - We solved it with a queue of zero-degree nodes
  - But here we need the lowest-cost node and costs can change as we process edges
- Solution?

Improving (?) asymptotic running time

- So far: $O(|V|^2)$
- We had a similar "problem" with topological sort being $O(|V|^2)$ due to each iteration looking for the node to process next
  - We solved it with a queue of zero-degree nodes
  - But here we need the lowest-cost node and costs can change as we process edges
- Solution?
  - A priority queue holding all unknown nodes, sorted by cost
  - But must support **`decreaseKey`** operation
    - Must maintain a reference from each node to its position in the priority queue
    - Conceptually simple, but can be a pain to code up

Efficiency, second approach

Use pseudocode to determine asymptotic run-time

```
dijkstra(Graph G, Node start) {
  for each node: x.cost=infinity, x.known=false
  start.cost = 0
  build-heap with all nodes
  while(heap is not empty) {
    b = deleteMin()
    b.known = true
    for each edge (b,a) in G
     if(!a.known)
      if(b.cost + weight((b,a)) < a.cost){
        decreaseKey(a,"new cost – old cost")
        a.path = b
      }
}
```


Efficiency, second approach

Use pseudocode to determine asymptotic run-time

```
dijkstra(Graph G, Node start) {
  for each node: x.cost=infinity, x.known=false    } O(|V|)
  start.cost = 0
  build-heap with all nodes
  while(heap is not empty) {                        } O(|V|log|V|)
    b = deleteMin()
    b.known = true
    for each edge (b,a) in G                        } O(|E|log|V|)
     if(!a.known)
      if(b.cost + weight((b,a)) < a.cost){
        decreaseKey(a,"new cost – old cost")
        a.path = b
      }
}
                                                    O(|V|log|V|+|E|log|V|)
```

Dense vs. sparse again

- First approach: $O(|V|^2)$
- Second approach: $O(|V|\log|V|+|E|\log|V|)$
- So which is better?
  - Sparse: $O(|V|\log|V|+|E|\log|V|)$ (if $|E| > |V|$, then $O(|E|\log|V|)$)
  - Dense: $O(|V|^2)$
- But, remember these are worst-case and asymptotic
  - Priority queue might have slightly worse constant factors
  - On the other hand, for "normal graphs", we might call **`decreaseKey`** rarely (or not percolate far), making $|E|\log|V|$ more like $|E|$