cse332-16au-lec21-Dijkstra-day2

CSE 332: Data Structures & Parallelism

Lecture 21: Shortest Paths

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Autumn 2016

Today

- Graphs
  - Graph Traversals
  - Shortest Paths

Shortest Path Applications

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

Single source shortest paths

\# of edges

- Done: BFS to find the minimum path length from **v** to **u** in $O(|E|+|V|)$

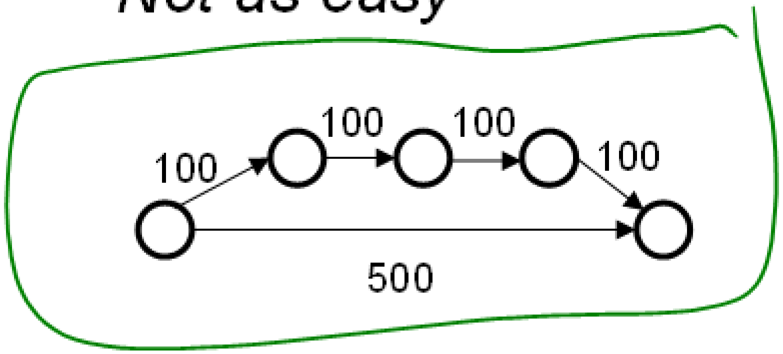
- Actually, can find the minimum path length from **v** to *every node*
  - Still $O(|E|+(|V|)$
  - No faster way for a "distinguished" destination in the worst-case

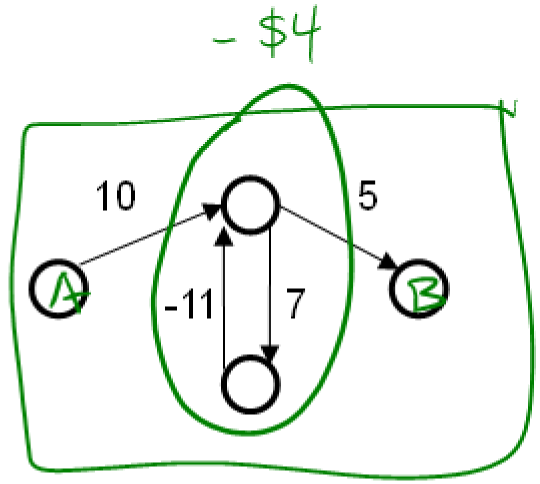
- Now: Weighted graphs

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

Not as easy





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

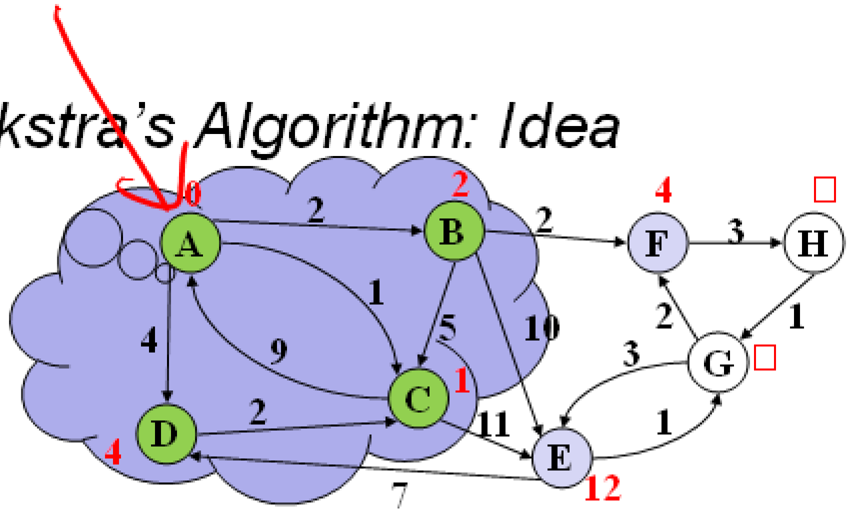
We will assume there are no negative weights
- *Problem* is *ill-defined* if there are negative-cost *cycles*
- *Today's algorithm* is *wrong* if *edges* can be negative

Dijkstra's Algorithm

- Named after its inventor Edsger Dijkstra (1930-2002)
  - Truly one of the "founders" of computer science;
    1972 Turing Award; this is just one of his many contributions
  - Sample quotation: "computer science is no more about computers than astronomy is about telescopes"

- The idea: reminiscent of BFS, but adapted to handle weights
  - Grow the set of nodes whose shortest distance has been computed
  - Nodes not in the set will have a "best distance so far"
  - A priority queue will turn out to be useful for efficiency

Dijkstra's Algorithm: Idea



- Initially, start node 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 distances 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`,

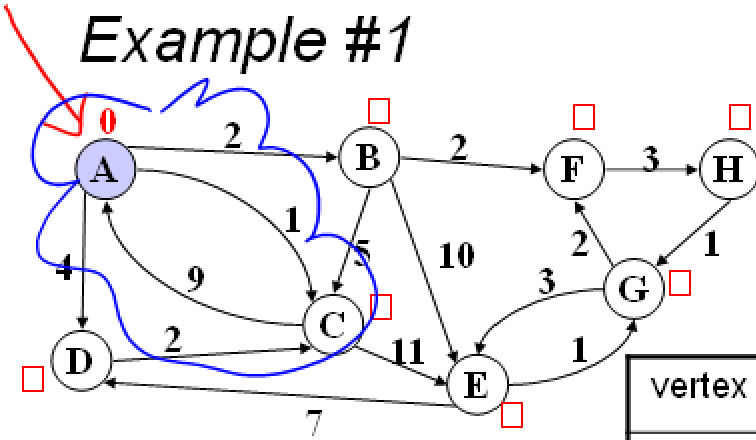
```
c1 = v.cost + w // cost of best path through v to u
c2 = u.cost  // cost of best path to u previously known
if(c1 < c2){ // if the path through v is better
  u.cost = c1
  u.path = v // for computing actual paths
}
```

Important features

- Once a vertex is marked known, the cost of the shortest path to that node is known
  - The path is also known by following back-pointers

- While a vertex is still not known, another shorter path to it might still be found

Example #1



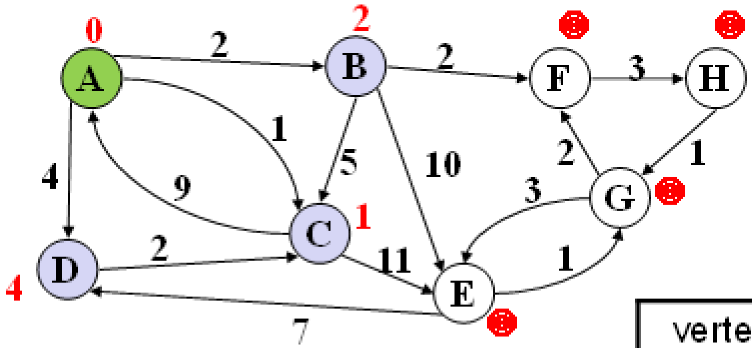
Total cost from A to this vertex

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

Order Added to Known Set:

A C

Example #1

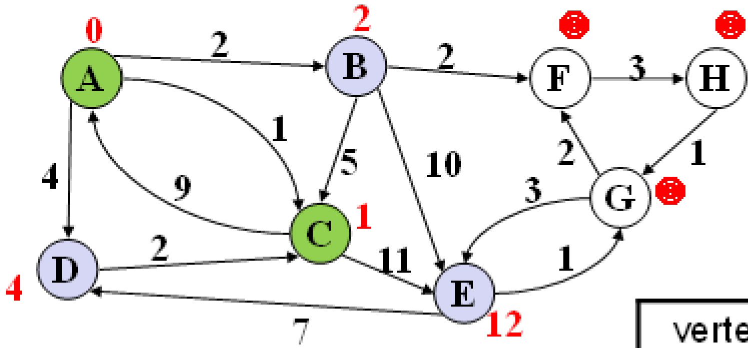


vertex	known?	cost	path
A	Y	0	
B		≤ 2	A
C		≤ 1	A
D		≤ 4	A
E		??	
F		??	
G		??	
H		??	

<u>Order Added to Known Set:</u>

A

Example #1

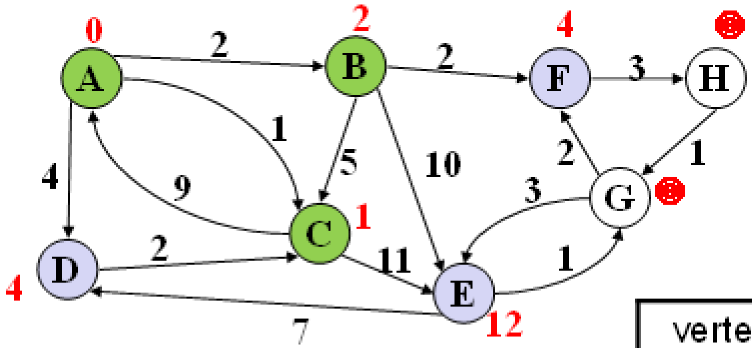


vertex	known?	cost	path
A	Y	0	
B		≤ 2	A
C	Y	1	A
D		≤ 4	A
E		≤ 12	C
F		??	
G		??	
H		??	

<u>Order Added to Known Set:</u>

A, C

Example #1

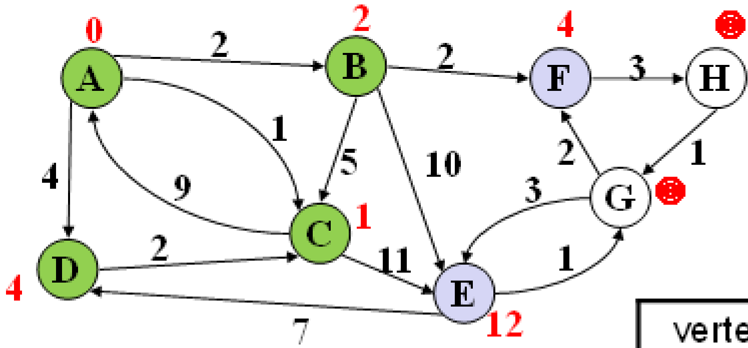


vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D		≤ 4	A
E		≤ 12	C
F		≤ 4	B
G		??	
H		??	

Order Added to Known Set:

A, C, B

Example #1

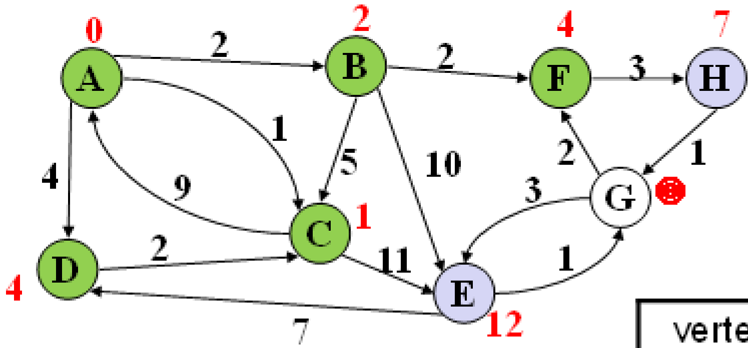


Order Added to Known Set:

A, C, B, D

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

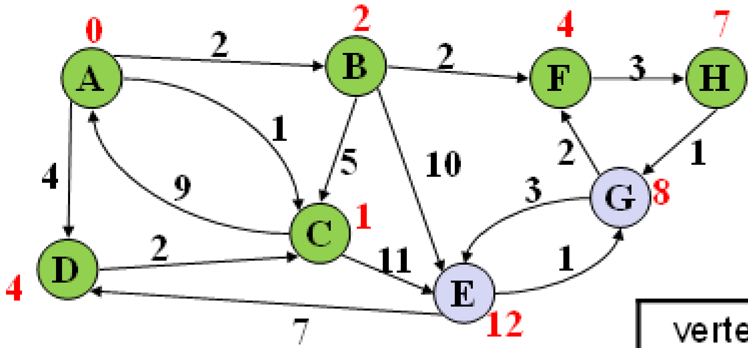


vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		$\leq$ 12	C
F	Y	4	B
G		??	
H		$\leq$ 7	F

<u>Order Added to Known Set:</u>

A, C, B, D, F

Example #1

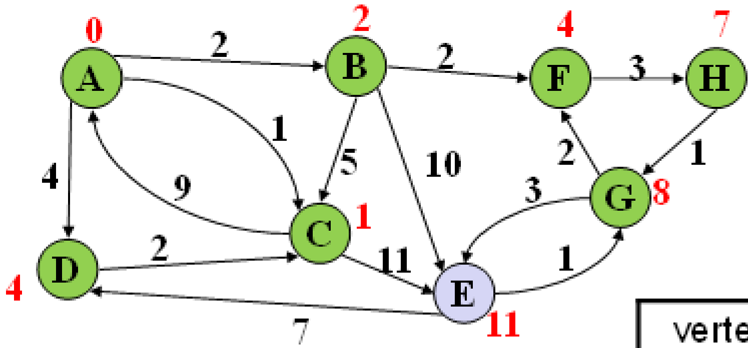


vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 12	C
F	Y	4	B
G		≤ 8	H
H	Y	7	F

<u>Order Added to Known Set:</u>

A, C, B, D, F, H

Example #1

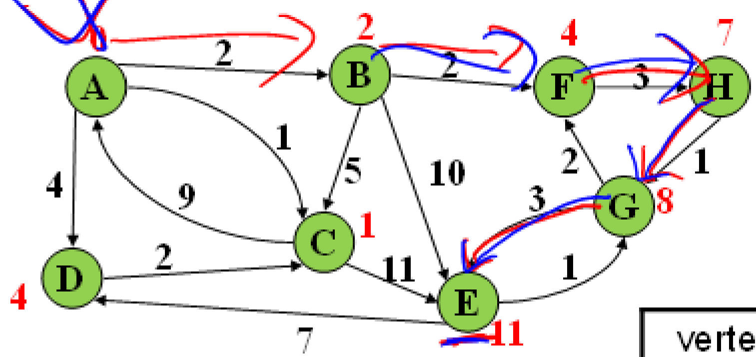


vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E		≤ 11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

Order Added to Known Set:

A, C, B, D, F, H, G

Example #1



Path From A to E:

A B F H G E

Order Added to Known Set:

A, C, B, D, F, H, G, E

from A

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

Features

- When a vertex is marked known,
  the cost of the shortest path to that node is known
  - The path is also known by following back-pointers

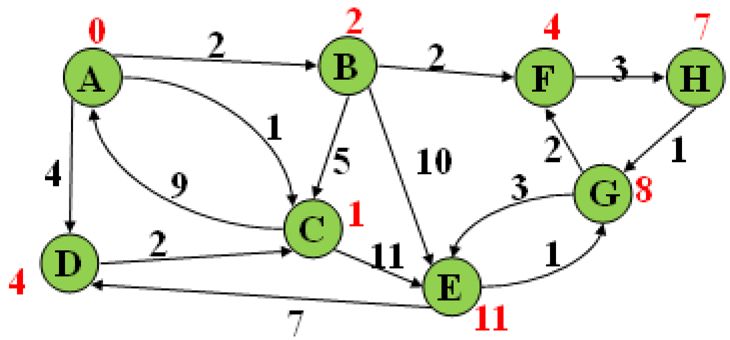
- While a vertex is still not known,
  another shorter path to it might still be found

Note: The "Order Added to Known Set" is not important

- A detail about how the algorithm works (client doesn't care)
- Not used by the algorithm (implementation doesn't care)
- It is sorted by path-cost, resolving ties in some way

Interpreting the Results

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



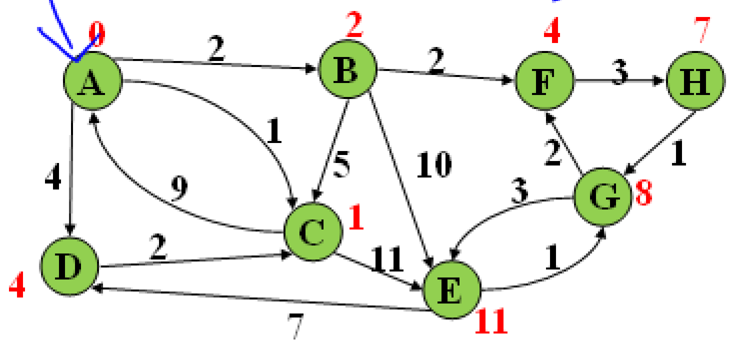
vertex	known?	cost	path
A	Y	0	
B	Y	2	A
C	Y	1	A
D	Y	4	A
E	Y	11	G
F	Y	4	B
G	Y	8	H
H	Y	7	F

Order Added to Known Set:

A, C, B, D, F, H, G, E

Stopping Short

- How would this have worked differently if we were only interested in:
  - The path from A to G?
  - The path from A to D?

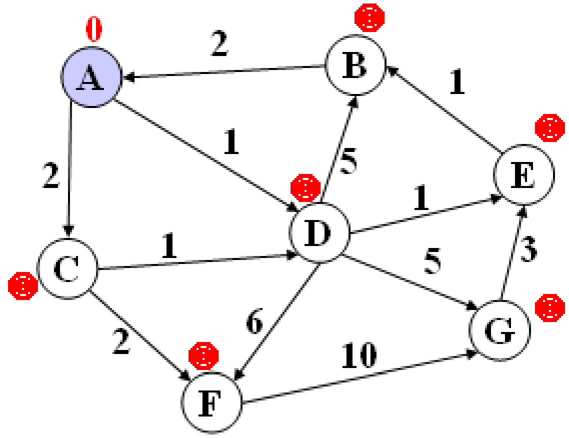


Order Added to Known Set:

A, C, B, D, F, H, G, 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

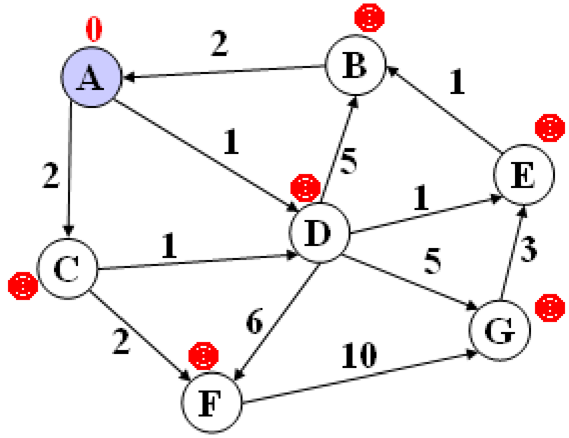
Example #2



Order Added to Known Set:

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

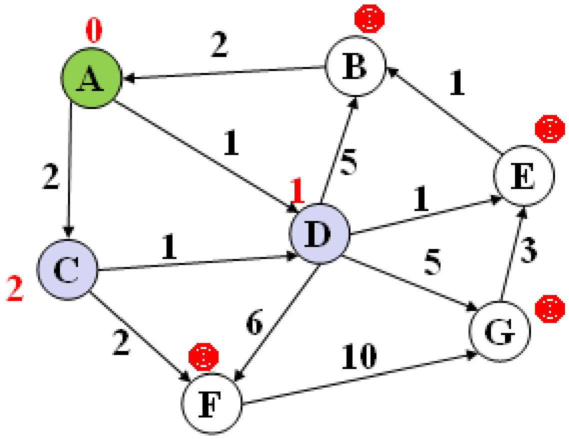
Example #2



Order Added to Known Set:

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

Example #2

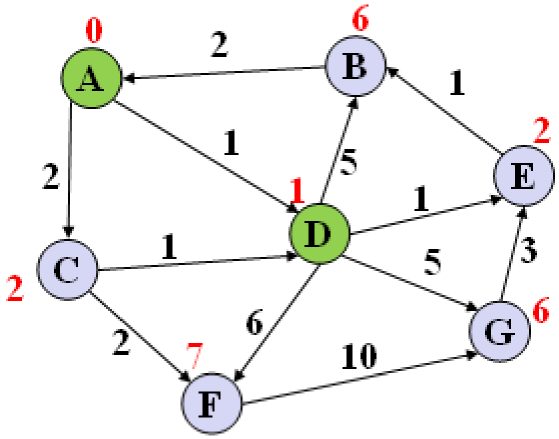


vertex	known?	cost	path
A	Y	0	
B		??	
C		≤ 2	A
D		≤ 1	A
E		??	
F		??	
G		??	

Order Added to Known Set:

A

Example #2

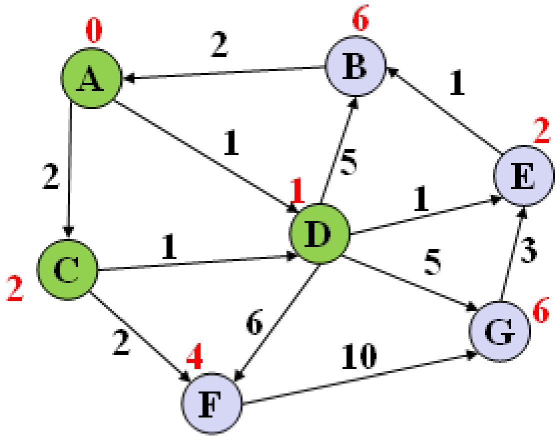


Order Added to Known Set:

A, D

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

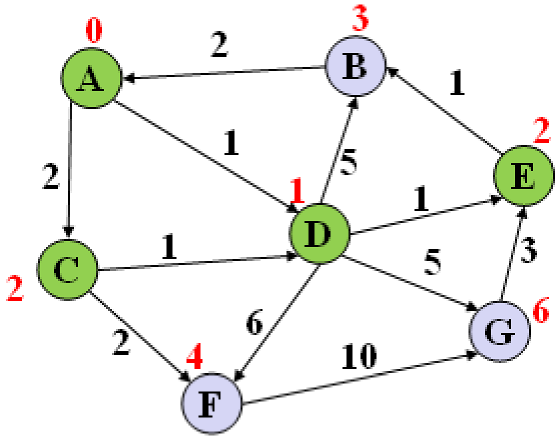


<u>Order Added to Known Set:</u>

A, D, C

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

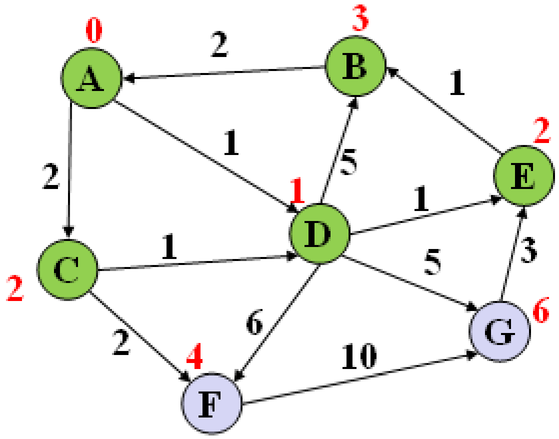


Order Added to Known Set:

A, D, C, E

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

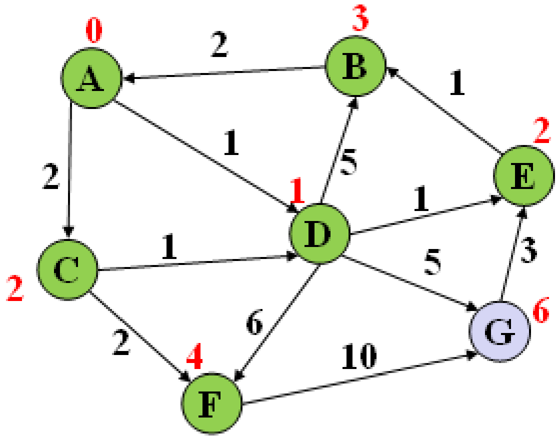


Order Added to Known Set:

A, D, C, E, B

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

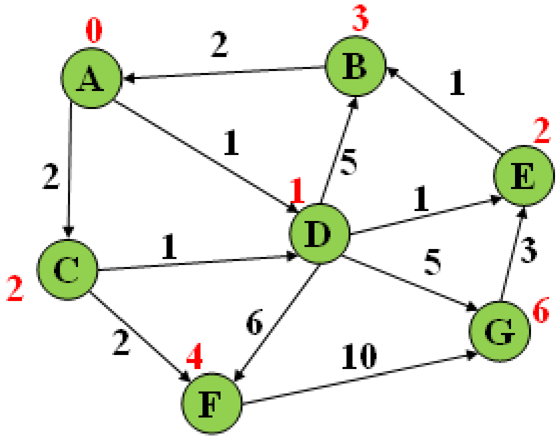


vertex	known?	cost	path
A	Y	0	
B	Y	3	E
C	Y	2	A
D	Y	1	A
E	Y	2	D
F	Y	4	C
G		≤ 6	D

<u>Order Added to Known Set:</u>

A, D, C, E, B, F

Example #2

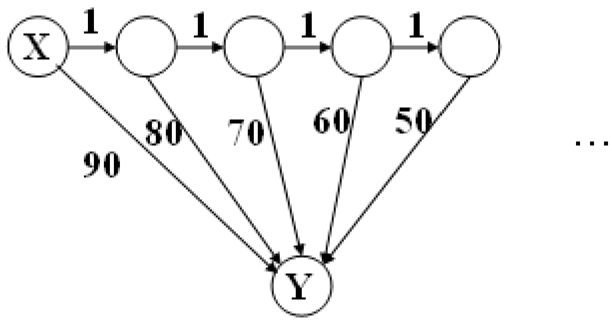


Order Added to Known Set:

A, D, C, E, B, F, G

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

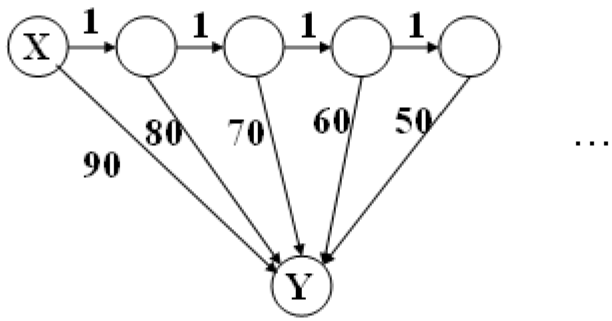
Example #3



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
    - A locally optimal step, not necessarily globally optimal
  - Once a vertex is known, it is not revisited
    - Turns out to be globally optimal

Making Change - use smallest # of coins for 15¢

25, 10, 5, 1 - 10, 5

25, 12, 10, 5, 1 - 12, 1, 1, 1

Greedy algorithm does not work in this case

Where are we?

- 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:

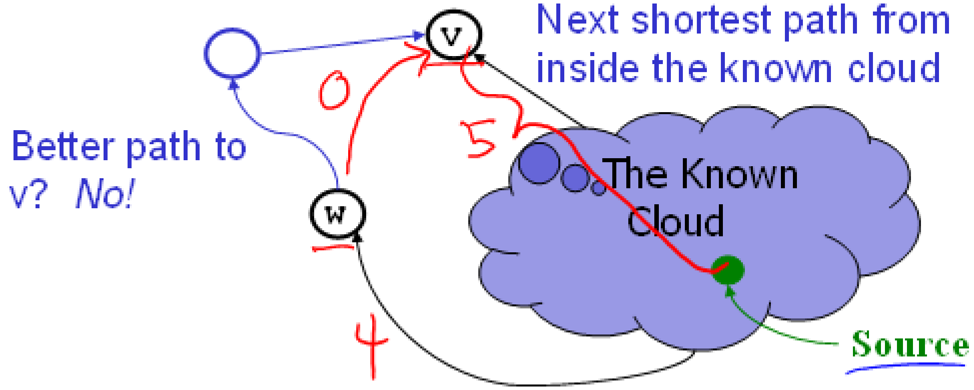
All the "known" vertices have the correct shortest path

- 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.

(w would have been picked) Contradiction!

Assume Adjacency List Representation

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
       }
}
```

$O(V)$

$O(1)$

V times

$O(V)$

$O(V^2)$

$O(1)$

d times, where d is out-degree of node b

$O(1)$

$O(1)$

$O(1)$

$O(1)$

$$O(V + 1 + V \cdot (V + 1 + d(4)))$$

$$O(V + V^2 + \underbrace{V \cdot d}_{E}) \longrightarrow O(V^2 + E)$$

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
       }
}
```

$O(|V|)$

$O(|V|^2)$

$O(|E|)$

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

Improving asymptotic running time

- So far: $O(|V|^2 + |E|)$

- We had a similar "problem" with topological sort being $O(|V|^2 + |E|)$
- 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: $O(|V|^2 + |E|)$

- We had a similar "problem" with topological sort being $O(|V|^2 + |E|)$
- 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   O(V)
  start.cost = 0   O(1)
  build-heap with all nodes  <- O(V)
  while(heap is not empty) {  <- V times
    b = deleteMin()  <- O(log V)
    b.known = true  O(1)
    for each edge (b,a) in G  <- d times, where d is outdegree of node b
     if(!a.known)  O(1)                                  O(1)
      if(b.cost + weight((b,a)) < a.cost){
        decreaseKey(a,"new cost – old cost")  O(log V)
         a.path = b   O(1)
      }
}
```


$$O(V + 1 + V + V(\log V + 1 + d\cdot(1 + 1 + \log V + 1))))$$

$$O(\cancel{V} + V \log V + V \cdot d \cdot \log V)$$

$$O(V \log V + E \log V)$$

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
      }
}
```

O(|V|)

O(|V|log|V|)

O(|E|log|V|)

O(|V|log|V|+|E|log|V|)

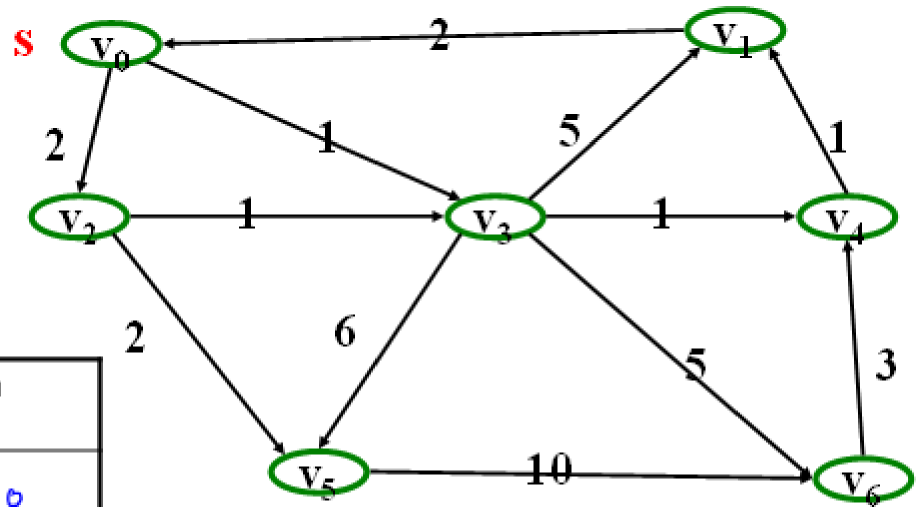
Dense vs. sparse again

- First approach: $O(|V|^2 + |E|)$ or: $O(|V|^2)$
- Second approach: $O(|V|\log|V|+|E|\log|V|)$

$V^2 \log V$

- So which is better?
  - Sparse: $O(|V|\log|V|+|E|\log|V|)$ (if $|E| > |V|$, then $O(|E|\log|V|)$)
  - Dense: $O(|V|^2 + |E|)$, or: $O(|V|^2)$
- 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 $|E|$

Find the shortest path to each vertex from v_0



V	Known	Dist from s	Path
v0	T	0	V_0
v1	T	3	V_4
v2	T	2	V_0
v3	T	1	V_0
v4	T	2	V_3
v5	T	4	V_2
v6	T	6	V_3

Order declared Known:

V_0 V_3 V_2 V_4 V_1 V_5 V_6

order of these two could be reversed