Directed Graphs (Part II)

CSE 373
Data Structures & Algorithms
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Today's Outline

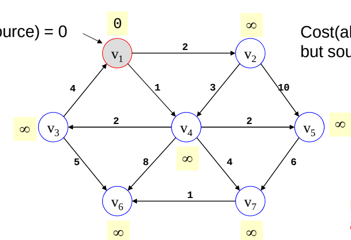
- **Announcements:**
  - › **HW 5 is out.**
- **Today's Topics:**
  - › **Graphs (Weiss 9.2, 9.3, 10.34)**

Dijkstra's Shortest Path Algorithm

- Initialize the cost of s to 0, and all the rest of the nodes to ∞
- Initialize set S to be ∅
  - › S is the set of nodes to which we have a shortest path
- While S is not all vertices
  - › Select the node A with the **lowest cost** that is not in S and identify the node as now being in S
  - › for each node B adjacent to A
    - if cost(A)+cost(A,B) < B's currently known cost
      - set cost(B) = cost(A)+cost(A,B)
      - set previous(B) = A so that we can remember the path

Example: Initialization

Cost(source) = 0



Cost(all vertices but source) = ∞

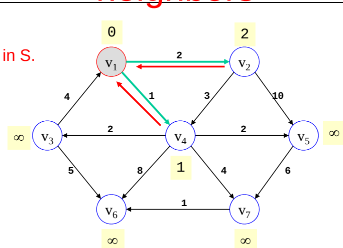
None of them are in S.

Which has the lowest cost?

Pick vertex not in S with lowest cost.

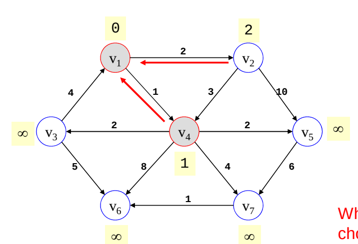
Example: Update Cost neighbors

Now v_1 is in S.



Cost(v_2) = 2
Cost(v_4) = 1

Example: pick vertex with lowest cost and add it to S

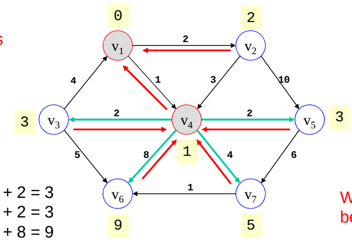


What's the choice?

Pick vertex not in S with lowest cost, i.e., v_4

Example: update neighbors

S contains v_1 and v_4.

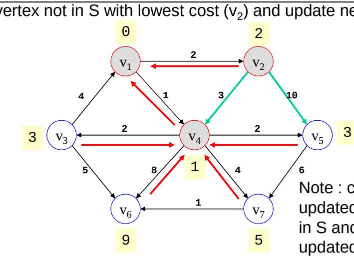


$Cost(v_3) = 1 + 2 = 3$
$Cost(v_5) = 1 + 2 = 3$
$Cost(v_6) = 1 + 8 = 9$
$Cost(v_7) = 1 + 4 = 5$

Who will be next?

Example (Ct'd)

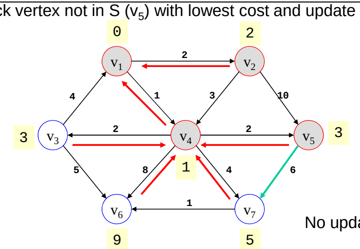
Pick vertex not in S with lowest cost (v_2) and update neighbors



Note : cost(v_4) not updated since already in S and cost(v_5) not updated since it is larger than previously computed

Example: (ct'd)

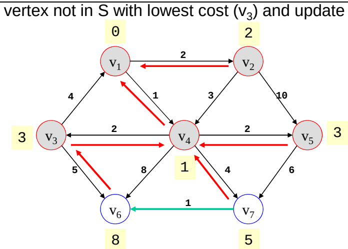
Pick vertex not in S (v_5) with lowest cost and update neighbors



No updating

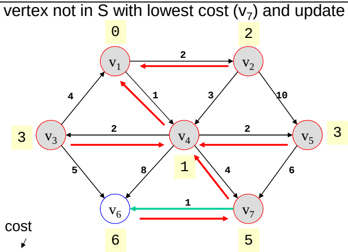
Example: (ct'd)

Pick vertex not in S with lowest cost (v_3) and update neighbors



Example: (ct'd)

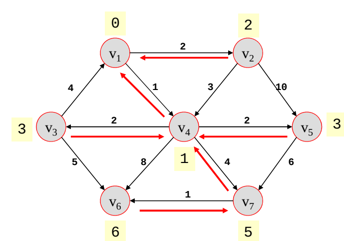
Pick vertex not in S with lowest cost (v_7) and update neighbors



Previous cost

$Cost(v_6) = \min(8, 5+1) = 6$

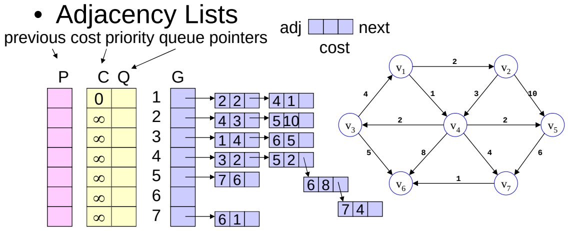
Example (end)



Pick vertex not in S with lowest cost (v_6) and update neighbors

Data Structures

- Adjacency Lists



Priority queue for finding and deleting lowest cost vertex and for decreasing costs (Binary Heap works)

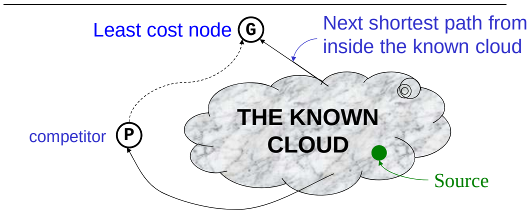
Time Complexity

- n vertices and m edges
- Initialize data structures O(n+m)
- Find min cost vertices O(n log n)
  - n delete mins
- Update costs O(m log n)
  - Potentially m updates
- Update previous pointers O(m)
  - Potentially m updates
- Total time O((n + m) log n) - very fast.

Correctness

- Dijkstra's algorithm is an example of a greedy algorithm
- Greedy algorithms always make choices that currently seem the best
  - Short-sighted – no consideration of long-term or global issues
  - Locally optimal does not always mean globally optimal
- In Dijkstra's case – choose the least cost node, but what if there is another path through other vertices that is cheaper?

"Cloudy" Proof: The Idea

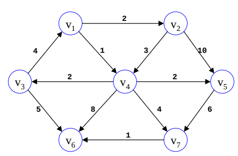


- If the path to G is the next shortest path, the path to P must be at least as long. Therefore, any path through P to G cannot be shorter!

Another Algorithm: All Pairs Shortest Path

- Given a edge weighted directed graph G = (V,E) find for all u,v in V the length of the shortest path from u to v. Use matrix representation.

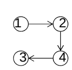
C	1	2	3	4	5	6	7
1	0	2	:	1	:	:	:
2	:	0	:	3	10	:	:
3	4	:	0	:	:	5	:
4	:	:	2	0	2	8	4
5	:	:	:	:	0	:	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0



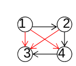
: = infinity

A (simpler) Related Problem: Transitive Closure

- Given a digraph G(V,E) the transitive closure is a digraph G'(V',E') such that
  - V' = V (same set of vertices)
  - If (v_i, v_{i+1},…,v_k) is a path in G, then (v_i, v_k) is an edge of E'



original



closure

In set notation:
E = {(1,2),(2,4),(4,3)}
- (1,2) & (2,4) => (1,4)
- (2,4) & (4,3) => (2,3)
- (1,2) & (2,3) => (1,3)

transi- tivity

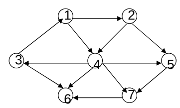
E' = {(1,2),(2,4),(4,3)
(1,4),(2,3),(1,3)}

Unweighted Digraph Boolean Matrix Representation

- C is called the connectivity matrix

1 = connected
0 = not connected

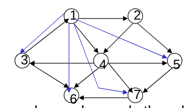
C	1	2	3	4	5	6	7
1	0	1	0	1	0	0	0
2	0	0	0	1	1	0	0
3	1	0	0	0	0	1	0
4	0	0	1	0	1	1	1
5	0	0	0	0	0	0	1
6	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0



Transitive Closure

black 1's were in the original graph
blue 1's were added for the closure

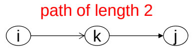
C	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	0	0	0	0	0	1	1
6	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0



On the graph, we show only the edges added with 1 as origin. The matrix represents the full transitive closure.

Idea: Finding Paths of Length 2

path of length 2




```
// First initialize C2 to all zero //
Length2 {
for k = 1 to n
 for i = 1 to n do
  for j = 1 to n do
     C2[i,j] := C2[i,j] ∪ (C[i,k] ∩ C[k,j]);
}
where ∩ is Boolean And (&&) and ∪ is Boolean OR (||)
This means if there is an edge from i to k
AND an edge from k to j, then there is a path
of length 2 between i and j.
Column k (C[i,k]) represents the predecessors of k
Row k (C[k,j]) represents the successors of k
```


Paths of Length 2

C	1	2	3	4	5	6	7
1	0	1	0	1	0	0	0
2	0	0	0	1	1	0	0
3	1	0	0	0	0	1	0
4	0	0	1	0	1	1	1
5	0	0	0	0	0	0	1
6	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0

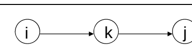
Time $O(n^3)$

C2	1	2	3	4	5	6	7
1	0	0	1	1	1	1	1
2	0	0	1	0	1	1	1
3	0	1	0	1	0	0	0
4	1	0	0	0	0	1	1
5	0	0	0	0	0	1	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0

Transitive Closure

- Union of paths of length 0, length 1, length 2, …, length n-1.
  - Time complexity n * $O(n^3)$ = $O(n^4)$
- There exists a better ($O(n^3)$) algorithm: Warshall's algorithm

Warshall Algorithm




```
TransitiveClosure {
for k = 1 to n do  // k is the step number //
  for i = 1 to n do
    for j = 1 to n do
      C [i,j] := C[i,j] ∪ (C[i,k] ∩ C[k,j]);
}
```

(∪ = or, ∩ = and)

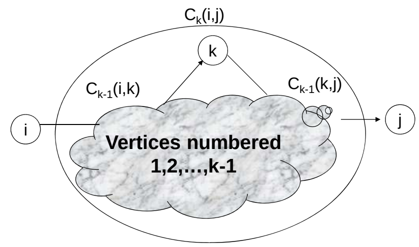
where C[i,j] starts as the original connectivity matrix and **C[i,j] is updated after step k if a new path from i to j through k is found.**

Proof of Correctness

Prove: After the k-th time through the loop, C[i,j] =1 if there is a path from i to j that only passes through vertices numbered 1,2,…,k (except for the initial edges)

- Base case: k = 1. C [i,j] = 1 for the initial connectivity matrix (path of length 0) and C [i,j] = 1 if there is a path (i,1,j)

Cloud Argument



Inductive Step

- Inductive Hypothesis: Suppose after step k-1 that C[i,j] contains a 1 if there is a path **from** i to j through vertices 1,…,k-1.

- Induction: Consider step k, which does

```
C[i,j] := C[i,j] ∪ (C[i,k] ∩ C[k,j]);
                 or              and
```

Either C[i,j] is already 1 or there is a new path through vertex k, which makes it 1.

Back to Weighted Graphs: Matrix Representation

- C[i,j] = the cost of the edge (i,j)
  - C[i,i] = 0 because no cost to stay where you are
  - C[i,j] = infinity (:) if no edge from i to j.

C	1	2	3	4	5	6	7
1	0	2	:	1	:	:	:
2	:	0	:	3	10	:	:
3	4	:	0	:	:	5	:
4	:	:	2	0	2	8	4
5	:	:	:	:	0	:	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0

Floyd – Warshall Algorithm

// Start with the cost matrix C

```
All_Pairs_Shortest_Path {
for k = 1 to n do
  for i = 1 to n do
    for j = 1 to n do
      C[i,j] := min(C[i,j], C[i,k] + C[k,j]);
}
```

old cost updated new cost

`Note x + : = : by definition (: is infinity)`

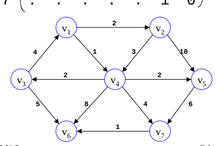
On termination C[i,j] is the length of the shortest path from i to j.

The Computation for k=1 Go from v_i to v_j through v_k

C	1	2	3	4	5	6	7
1	0	2	:	1	:	:	:
2	:	0	:	3	10	:	:
3	4	:	0	:	:	5	:
4	:	:	2	0	2	8	4
5	:	:	:	:	0	:	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0

➡

C	1	2	3	4	5	6	7
1	0	2	:	1	:	:	5
2	:	0	:	3	10	:	:
3	4	**6**	0	**5**	:	5	:
4	:	:	2	0	2	8	4
5	:	:	:	:	0	:	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0

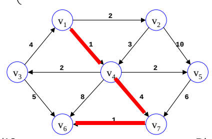


The Result after k=1 through 7

C	1	2	3	4	5	6	7
1	0	2	:	1	:	:	:
2	:	0	:	3	10	:	:
3	4	:	0	:	:	5	:
4	:	:	2	0	2	8	4
5	:	:	:	:	0	:	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0

⇨

C	1	2	3	4	5	6	7
1	0	2	3	1	3	**6**	5
2	9	0	5	3	5	8	7
3	4	6	0	5	4	5	6
4	6	8	2	0	2	5	4
5	:	:	:	:	0	7	6
6	:	:	:	:	:	0	:
7	:	:	:	:	:	1	0



Time Complexity of All Pairs Shortest Path

- n is the number of vertices
- Three nested loops. $O(n^3)$
  - Shortest paths can be found too (see the book).
- Repeated Dijkstra's algorithm
  - $O(n(n + m)\log n)$ (= $O(n^3 \log n)$ for dense graphs).
  - Run Dijkstra starting at each vertex.
  - But, Dijkstra also gives the shortest paths not just their lengths.