CSE 332: Data Structures & Parallelism
Lecture 21: Shortest Paths

Ruth Anderson
Autumn 2017
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**

- 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

11/29/2017
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 $\infty$
- 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 $v.cost = \infty$ 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 $w$,
      \[
      c1 = v.cost + w \quad \text{// cost of best path through } v \ \text{to} \ u
      \]
      \[
      c2 = u.cost \quad \text{// cost of best path to } u \ \text{previously known}
      \]
      \[
      \text{if}(c1 < c2) \{ \quad \text{// if the path through } v \ \text{is better}
      \]
      \[
      u.cost = c1
      \]
      \[
      u.path = v \quad \text{// for computing actual paths}
      \}
\]
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

Order Added to Known Set:

<table>
<thead>
<tr>
<th>vertex</th>
<th>known?</th>
<th>cost</th>
<th>path</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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?

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

<table>
<thead>
<tr>
<th>vertex</th>
<th>known?</th>
<th>cost</th>
<th>path</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Y</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Y</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>Y</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>Y</td>
<td>4</td>
<td>A</td>
</tr>
<tr>
<td>E</td>
<td>Y</td>
<td>11</td>
<td>G</td>
</tr>
<tr>
<td>F</td>
<td>Y</td>
<td>4</td>
<td>B</td>
</tr>
<tr>
<td>G</td>
<td>Y</td>
<td>8</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>Y</td>
<td>7</td>
<td>F</td>
</tr>
</tbody>
</table>
Example #2

Order Added to Known Set:

<table>
<thead>
<tr>
<th>vertex</th>
<th>known?</th>
<th>cost</th>
<th>path</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example #3

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

Is this expensive?
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
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…
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
        }
  }
}
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?
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){
                    a.path = b
                    decreaseKey(a, “new cost – old cost”)
                }
    }
}
Dense vs. sparse again

- First approach: $O(|V|^2 + |E|)$ or: $O(|V|^2)$
- 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: $O(|V|^2 + |E|)$, 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 $v_0$

<table>
<thead>
<tr>
<th>$v$</th>
<th>Known</th>
<th>Dist from s</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$v_6$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Order declared Known: