1 Introduction

Dijkstra’s Algorithm is essentially an extension of the shortest path algorithm in which the graph is weighted. In this case instead of looking for a shortest path we are looking for a path of minimal weight.

What we’ll actually do is better, we’ll find a shortest weight tree which is a tree that is a subgraph of the graph such that, treating the starting vertex as the root, explicitly shows us how to get to every other vertex with minimal weight.

2 Intuition

Example 2.1. Consider the following graph:

Suppose we choose 0 to be our starting vertex.

The intuition is that we grow a minimum tree from the root (the starting vertex) such that each growth step starts from the available vertex whose weight from the starting vertex is minimal.

As with earlier we start by assigning a distance value of \( \infty \) to each vertex except for vertex 0, which we assign a value of 0 since that is the distance from vertex 0 to itself.

In addition we assign a set \( S = \{ \} \) which will contain the visited vertices.
Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in $S = \{\}$. This is of course currently vertex 0 with distance 0. so we look at all vertices connected to vertex 0 and assign their distances as vertex 0’s distance plus the edge weight. We only do this if this value is smaller than their current weight but since their current weight is $\infty$ then of course we replace it. We also set those vertices’ predecessor to be 0.

We put this vertex in $S$, so $S = \{0\}$.

Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in $S = \{0\}$. This is of course vertex 1 with distance 10. Then we look at all vertices connected to vertex 1 and assign their distances as vertex 1’s distance plus the edge weight. We only do this if this value is smaller than their current weight.

We put this vertex in $S$, so $S = \{0, 1\}$.
Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in \( S = \{0, 1\} \). This is of course vertex 3 with distance 20. Then we look at all vertices connected to vertex 3 and assign their distances as vertex 3’s distance plus the edge weight. We only do this if this value is smaller than their current weight. Note that vertex 4 gets its weight reassigned because it was 110 but from vertex 3 it’s 20 + 30 = 50 < 110.

We put this vertex in \( S \), so \( S = \{0, 1, 3\} \).

Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in \( S = \{0, 1, 3\} \). This is of course vertex 2 with distance 30. Then we look at all vertices connected to vertex 2 and assign their distances as vertex 2’s distance plus the edge weight. We only do this if this value is smaller than their current weight.

We put this vertex in \( S \), so \( S = \{0, 1, 3, 2\} \).
Iterate! we look at the graph and choose the vertex with minimum assigned distance which is not already in \( S = \{0, 1, 3, 2\} \). This is of course vertex 4 with distance 50. Then we look at all vertices connected to vertex 4 and assign their distances as vertex 4’s distance plus the edge weight. We only do this if this value is smaller than their current weight.

We put this vertex in \( S \), so \( S = \{0, 1, 3, 2, 4\} \).

Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in \( S = \{0, 1, 3, 2, 4\} \). Both vertices 5 and 7 work so we can pick either. Let’s choose vertex 5 with distance 80. Then we look at all vertices connected to vertex 5 and assign their distances as vertex 5’s distance plus the edge weight. We only do this if this value is smaller than their current weight. Here there are no changes.

We put this vertex in \( S \), so \( S = \{0, 1, 3, 2, 4, 5\} \).
Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in $S = \{0, 1, 3, 2, 4, 5\}$. This is vertex 7 with distance 80. Then we look at all vertices connected to vertex 7 and assign their distances as vertex 7’s distance plus the edge weight. We only do this if this value is smaller than their current weight. Here there are no changes.

We put this vertex in $S$, so $S = \{0, 1, 3, 2, 4, 5, 7\}$.

Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in $S = \{0, 1, 3, 2, 4, 5, 7\}$. This is vertex 6 with distance 90. Then we look at all vertices connected to vertex 6 and assign their distances as vertex 6’s distance plus the edge weight. We only do this if this value is smaller than their current weight. Here there are no changes.

We put this vertex in $S$, so $S = \{0, 1, 3, 2, 4, 5, 7, 6\}$.
Iterate! We look at the graph and choose the vertex with minimum assigned distance which is not already in $S = \{0, 1, 3, 2, 4, 5, 7, 6\}$. This is vertex 8 with distance 100. Then we look at all vertices connected to vertex 8 and assign their distances as vertex 8’s distance plus the edge weight. We only do this if this value is smaller than their current weight. Here there are no changes.

We put this vertex in $S$, so $S = \{0, 1, 3, 2, 4, 5, 7, 6, 8\}$

Now $S$ contains every vertex and we are done.

Our array of predecessors is $P = [NULL, 0, 1, 0, 3, 2, 7, 4, 7]$ and this tells us how to construct our tree in the sense that the predecessor of each vertex is its parent and this tells us the edges. For example $P[0] = NULL$ because there is no predecessor of 0 as it is the root vertex, $P[1] = 0$ and so we need to have the edge $(1, 0)$, and so on.

In other words this array gives us the set of edges:

$$ (1, 0), (2, 1), (3, 0), (4, 3), (5, 2), (6, 7), (7, 4), (8, 7) $$

In the graph we keep only those edges we get the following. The labels show the minimum weight path back to vertex 0 and the brackets show the predecessors still.
3 Rudimentary Pseudocode

Here is the pseudocode for a very rudimentary implementation. This code returns an array \( \text{pred} \) with the property that \( \text{pred}[v] \) gives the predecessor of the vertex \( v \) in the minimal weight tree.

```python
// PRE: G is a graph with n vertices.
// PRE: s is the starting vertex.
def dijkstra(G, s):
    n = len(G)
    dist = [\text{inf}, \ldots, \text{inf}] of length n.
    pred = [\text{NULL}, \ldots, \text{NULL}] of length n.
    S = empty list
    dist[s] = 0
    while len(S) != n
        x = vertex in G-S with smallest assigned distance
        for each edge in the edge set of x:
            y be the connected vertex
            if dist[x] + (Weight of Edge x,y) < dist[y]:
                dist[y] = dist[x] + (Weight of Edge x,y)
                pred[y] = x
            endif
        endfor
        append x to S
    endwhile
    return(pred)
end
```

4 Pseudocode Time Complexity

**Note 4.0.1.** It’s worth noting here that a graph with \( E \) edges cannot possibly have more than \( 2E \) vertices (and will probably have fewer since vertices are generally shared among edges) and so \( V \leq 2E \).

1. If we store the graph as an adjacency matrix then the while loop iterates \( V \) times since it must add all the vertices. Within this loop we execute two things in succession. First, we obtain the vertex in \( G - S \) with minimal assigned distance. Since \( |G - S| \leq V \) this is is \( \Theta(V) \) if done linearly. Second, we iterate through all the edges connected to a particular vertex. This is \( \Theta(V) \). Thus we can say for certain that the time complexity is \( \Theta(V(V + V)) = \Theta(V^2) \). Using the note above this is also \( O(E^2) \).

2. If the graph is stored as an adjacency list then the only change is that iterating through all the edges connected to a particular vertex is at worst \( O(E) \). Thus we can say for certain that the time complexity is \( O(V(V + E)) \). Using the note above this is also \( O(VE) \) and \( O(E^2) \).
5 Elegant Pseudocode

Here is the pseudocode for a more standard implementation. Instead of using simple lists we will manage the vertices using two structures kept in alignment:

- A min-heap $MH$ such that each node contains a vertex number and the corresponding distance from $s$. The distance is the value used for min-heapedness. This is initialized with root node $MH[1]$ storing vertex $s$ with distance 0 and all other nodes the other vertices all with distance $\text{INF}$.

- A management structure $MS$ indexed by vertex which contains the corresponding distance from $s$, the vertex’s predecessor, the heap location of the vertex, and a flag indicating whether the vertex is (still) in the heap. This is initialized with $MS[s]$ storing distance 0 with heap location 0 and predecessor $\text{NULL}$ and all other $MS[i]$ storing distance $\text{INF}$ with corresponding heap location and predecessor $\text{NULL}$.

```python
// PRE: G is a graph with n vertices.
// PRE: s is the starting vertex.
def dijkstra(G,s):
    initialize $MH$
    initialize $MS$
    while $MH$ is not empty
        Extract root node $(u,udist)$ from $MH$
        Update $MS$ to indicate $u$ no longer in heap
        for every edge attached to $u$
            $v = $ vertex at the other end
            $(vdist,vinheap,vpred) = MS[v]$
            if $vinheap$ and $udist + \text{weight}(u,v) < vdist$
                update $MH,MS$ with new distance, pred
        endfor
    endwhile
    return($MS$)
end
```
6 Pseudocode Time Complexity

It’s tempting to say that since the \texttt{while} loop iterates \( V \) times and the \texttt{for} loop iterates at most \( E \) times that there are \( V \) iterations of (B) and \( EV \) iterations of (C).

However we can be a bit more careful here. All together the \texttt{for} loop will follow each edge exactly twice. This is because an edge from \( u_i \) to \( u_j \) is followed once for \( u_i \), directly after \( u_i \) is removed, and once for \( u_j \), directly after \( u_j \) is removed. It is then never visited again. Thus in total (C) will iterate \( 2E \) times. This update of \( \text{MH} \) and \( \text{MS} \) is \( \mathcal{O}(\lg V) \) for a total of \( \mathcal{O}(2E \lg V) \).

In addition (B) will iterate \( V \) times. Extraction and update of \( \text{MH} \) and \( \text{MS} \) is \( \mathcal{O}(\lg V) \) for a total of \( \mathcal{O}(V \lg V) \).

Along with (A), which we presume is \( \mathcal{O}(1) \), we have a total time complexity of:

\[
\mathcal{O}(2E \lg V + V \lg V + 1) = \mathcal{O}((2E + V) \lg V) = \mathcal{O}(E \lg V)
\]

\textbf{Note 6.0.1.} Arguably since we’re allocating structures in (A) one might suggest that they’re both \( \mathcal{O}(V) \) since each has \( V \) items. This does not change the final time complexity calculation.
7 Mathematics

It may (or may not) make intuitive sense that Dijkstra’s Algorithm does what it is claimed to do, but a proof is fairly straightforward.

The key point to understand is that while, in general, assigning a distance to a vertex is not final since that distance may be updated later, when a vertex is added to \( S \) the distance assigned to that vertex is in fact final and will not be updated later. It’s this latter point we need to prove.

By \( d(x) \) we denote the distance as assigned to vertex \( x \) by the algorithm. By \( c(x_1, ..., x_j) \) we mean the total weight along the path \( (x_1, ..., x_j) \).

**Note 7.0.1.** This can also be rephrased in terms of a loop invariant and proven using the Loop Invariant Theorem. In that case the loop invariant is the statement about \( S \) at each iteration and the proof of the maintenance step is essentially what follows.
Theorem 7.0.1. We claim that at each iteration of the algorithm the set $S$ has the property that for each $x \in S$, the minimal path weight back to $u$ is $d(x)$.

Proof. Suppose not. Since vertices are progressively added to $S$ this means that at some earliest iteration we have an $S$ and we choose a vertex $x$ to add but when we do so, $d(x)$ is not minimal. Suppose $S$ is the set right before we add $x$ and put $S' = S \cup \{x\}$.

Since the graph is connected there must of course be a minimal path $P = \langle s = v_1, v_2, ..., v_k = x \rangle$ from $s$ to $x$ and therefore we must have:

$$c(v_1, ..., v_k) < d(v_k = x)$$

The path $P$ starts at $s \in S$ and ends at $x \not\in S$ so there are the first two vertices $v_i, v_{i+1}$ along $P$ and connected by an edge where $v_i \in S$ and $v_{i+1} \not\in S$. However note that since $v_i \in S$ we know that $v_i$ was chosen by the algorithm and hence a finite distance to $v_{i+1}$ has been assigned.

First off note that since $v_i \in S$ and was chosen before $x$ was chosen that we know that $d(v_i)$ is minimal weight and so:

$$d(v_i) \leq c(v_1, ..., v_i)$$

and so then:

$$d(v_i) + c(v_i, v_{i+1}) \leq c(v_1, ..., v_i) + c(v_i, v_{i+1}) \leq c(v_1, ..., v_{i+1})$$

Since $v_{i+1}$ is adjacent to $v_i$ we know that because of how the algorithm processed $v_i$ that:

$$d(v_{i+1}) \leq d(v_i) + c(v_i, v_{i+1})$$

In addition since $S' = S \cup \{x\}$ we know that the algorithm chose $x$ rather than $v_{i+1}$ (perhaps they’re the same) as its minimal weight vertex so that:

$$d(x) \leq d(v_{i+1})$$

All together:

$$d(x) \leq d(v_{i+1}) \leq d(v_i) + c(v_i, v_{i+1}) \leq c(v_1, ..., v_{i+1}) < d(x)$$

This is a contradiction.

Now then since this is true at each iteration is is true at the end of the final iteration at which point $S$ contains all vertices.

$\Box$
8 Thoughts, Problems, Ideas

1. For the graph given in the notes and replicated here, derive the minimal weight tree starting at vertex 7:

![Graph Image]

2. If the algorithm simply needs to find the minimum weight path from $s$ to a specific vertex $t$ at which point can it stop and why? Modify the pseudocode accordingly.

3. Dijkstra’s Algorithm produces a minimal weight tree rooted at a specific vertex $s$. Even though this tree is still a tree when we consider some other vertex $s' \neq s$ as the root this tree need not be a minimal weight tree rooted at $s'$. Show by a four-vertex example that this is the case. Justify your example.

4. A spanning tree for a graph $G$ is a subgraph of $G$ which contains all vertices of $G$ and is also a tree. A minimal spanning tree is a spanning tree that has smallest possible weight. Show by a 3-vertex example that Dijkstra’s Algorithm does not necessarily produce a minimal spanning tree. Justify your example.
9 Python Test and Output

The following code is applied to the graph above. This follows the model of the pseudocode and in addition creates and returns a list of the vertices in the order in which they were visited.

Code:

```python
# Return the minimum value and index in dist but not in S.
def min(G, dist, S):
    n = len(G)
    mdist = float('inf')
    # Find a minimum value.
    for v in range(n):
        if v not in S:
            if dist[v] < mdist:
                mdist = dist[v]
    # Find the first index corresponding to that value.
    mi = None
    for v in range(n):
        if (v not in S) and (dist[v] == mdist):
            mvertex = v
            break
    return(mvertex)

def dijkstra(G, u):
    n = len(G)
    dist = [float('inf')] * n
    pred = [None] * n
    S = []
    dist[u] = 0
    print('S: ' + str(S))
    print(' dist : ' + str(dist))
    while len(S) != n:
        x = min(G, dist, S)
        print(' Vertex not in S with minimum distance : ' + str(x))
        S.append(x)
        print('S = ' + str(S))
        for y in range(n):
            if G[x][y] != 0:
                print(' Vertex : ' + str(y) + ': ', end='')
                if dist[x] + G[x][y] < dist[y]:
                    print('Update from ' + str(dist[y]) + ' to ' + str(dist[x] + G[x][y]))
                    dist[y] = dist[x] + G[x][y]
                    pred[y] = x
                else:
                    print('')
```
Do not update from \'\'+str(dist[y])
, end='\'\')
print(' to ' + str(dist[x]+G[x][y]))
print('dist = ' + str(dist))
return (pred)

G = [[ 0, 10, 0, 20, 0, 0, 0, 0, 0],
     [ 10, 0, 20, 0,100, 0, 0, 0, 0],
     [ 0, 20, 0, 0, 0, 60, 0, 0, 0],
     [ 20, 0, 0, 0, 30, 0,120, 0, 0],
     [ 0,100, 0, 30, 0,70,100, 30, 80],
     [ 0, 0, 60, 0, 70, 0, 0, 0,100],
     [ 0, 0, 0,120,100, 0, 0,10, 0],
     [ 0, 0, 0, 0, 30, 0,10, 0, 20],
     [ 0, 0, 0, 0, 80,100, 0, 20, 0]]

u = 0
pred = dijkstra(G,u)
print(pred)
Output:

S: []
dist: [0, inf, inf, inf, inf, inf, inf, inf, inf]

Vertex not in S with minimum distance: 0
S = [0]
Vertex: 1: Update from inf to 10
Vertex: 3: Update from inf to 20
dist = [0, 10, inf, 20, inf, inf, inf, inf, inf]

Vertex not in S with minimum distance: 1
S = [0, 1]
Vertex: 0: Do not update from 0 to 20
Vertex: 2: Update from inf to 30
Vertex: 4: Update from inf to 110
dist = [0, 10, 30, 20, 110, inf, inf, inf, inf]

Vertex not in S with minimum distance: 3
S = [0, 1, 3]
Vertex: 0: Do not update from 0 to 40
Vertex: 4: Update from 110 to 50
Vertex: 6: Update from inf to 140
dist = [0, 10, 30, 20, 50, 90, 140, inf, inf]

Vertex not in S with minimum distance: 2
S = [0, 1, 3, 2]
Vertex: 1: Do not update from 10 to 50
Vertex: 5: Update from inf to 90
dist = [0, 10, 30, 20, 50, 90, 140, inf, inf]

Vertex not in S with minimum distance: 4
S = [0, 1, 3, 2, 4]
Vertex: 1: Do not update from 10 to 150
Vertex: 3: Do not update from 20 to 80
Vertex: 5: Do not update from 90 to 120
Vertex: 6: Do not update from 140 to 150
Vertex: 7: Update from inf to 80
Vertex: 8: Update from inf to 130
dist = [0, 10, 30, 20, 50, 90, 140, 80, 130]

Vertex not in S with minimum distance: 7
S = [0, 1, 3, 2, 4, 7]
Vertex: 4: Do not update from 50 to 110
Vertex: 6: Update from 140 to 90
Vertex: 8: Update from 130 to 100
dist = [0, 10, 30, 20, 50, 90, 90, 80, 100]

Vertex not in S with minimum distance: 5
S = [0, 1, 3, 2, 4, 7, 5]
Vertex: 2: Do not update from 30 to 150
Vertex: 4: Do not update from 50 to 160
Vertex: 8: Do not update from 100 to 190
\[\text{dist} = [0, 10, 30, 20, 50, 90, 90, 80, 100]\]

Vertex not in S with minimum distance: 6
S = [0, 1, 3, 2, 4, 7, 5, 6]
Vertex: 3: Do not update from 20 to 210
Vertex: 4: Do not update from 50 to 190
Vertex: 7: Do not update from 80 to 100
\[\text{dist} = [0, 10, 30, 20, 50, 90, 90, 80, 100]\]

Vertex not in S with minimum distance: 8
S = [0, 1, 3, 2, 4, 7, 5, 6, 8]
Vertex: 4: Do not update from 50 to 180
Vertex: 5: Do not update from 90 to 200
Vertex: 7: Do not update from 80 to 120
\[\text{dist} = [0, 10, 30, 20, 50, 90, 90, 80, 100]\]
[None, 0, 10, 30, 20, 50, 90, 90, 80, 100]

[None, 0, 1, 0, 3, 2, 7, 4, 7]