Dijkstra’s shortest paths algorithm

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Shown below is pseudocode for Dijkstra’s algorithm. The input is a directed graph \( G = (V, E) \) with non-negative edge weights \( \text{wt}(u, v) \) for every edge \((u, v) \in E\), and a distinguished node \( s \), called the source (or start) node. The algorithm computes, for each node \( u \in V \), the weight of a minimum-weight path from \( s \) to \( u \). (It can be easily modified to compute, for each node \( u \), the predecessor of \( u \) in a minimum-weight path from \( s \) to \( u \), in addition to the weight of such a path.)

\begin{verbatim}
1    R := \emptyset
2    d(s) := 0
3    for each \( v \in V - \{s\} \) do \( d(v) \) := \infty
4    while \( R \neq V \) do
5        let \( u \) be a node not in \( R \) with minimum \( d \)-value (i.e., \( u \in V - R \) and \( \forall u' \in V - R, d(u) \leq d(u') \))
6        \( R := R \cup \{u\} \)
7        for each \( v \in V \) such that \((u, v) \in E\) do
8            if \( d(u) + \text{wt}(u, v) < d(v) \) then \( d(v) := d(u) + \text{wt}(u, v) \)
\end{verbatim}

Intuitively Dijkstra’s algorithm works as follows. It maintains a set \( R \) (the “explored” part of the graph, consisting of nodes to which it has determined the weight of shortest paths). We say that an \( s \rightarrow u \) path is an \( R \)-path (to \( u \)) if every node on the path except (possibly) \( u \) is in the set \( R \). The algorithm also maintains, for every node \( u \), a label \( d(u) \), which is the minimum weight of \( R \)-paths to \( u \). The algorithm starts with an empty \( R \), and it greedily expands the set \( R \) with the node \( u \) that is not presently in \( R \) and has minimum \( d \)-value. The algorithm then updates the \( d \)-values of the nodes adjacent to \( u \) to account for fact that there may now exist shorter \( R \)-paths to these nodes, going through \( u \). When \( R \) contains all nodes, any \( s \rightarrow u \) path is an \( R \)-path to \( u \) and so \( d(u) \) is the minimum weight of \( s \rightarrow u \) paths, which is what we want to compute.

We now prove the correctness of the algorithm. \( X_i \) denotes the value of a variable \( X \) at the end of iteration \( i \) of the while loop. For every node \( u \), we define \( \delta(u) \) to be the minimum weight of \( s \rightarrow u \) paths (\( \infty \) if there is no \( s \rightarrow u \) path). The first claim states that the \( d \)-value of every node does not increase in time.

**Claim 1** For every node \( v \) and iterations \( i, j \), if \( i \leq j \) then \( d_i(v) \geq d_j(v) \).

**Proof.** After being initialized (in line 1 or 2), the value of \( d(v) \) is changed only in line 8, where it is obviously assigned a smaller value than before.

**Claim 2** If node \( u \) is added to \( R \) in iteration \( i \) the value of \( d(u) \) does not change in iteration \( i \).

**Proof.** Suppose for contradiction that \( u \) is added to \( R \) in iteration \( i \) and \( d(u) \) changes in iteration \( i \). Thus, by the algorithm, \((u, u)\) is an edge and \( d_{i-1}(u) + \text{wt}(u, u) < d_{i-1}(u) \) (where \( d_0(u) \) — i.e., if \( i = 1 \) — refers to the initial value of \( d(u) \)). But then \( \text{wt}(u, u) < 0 \), contradicting the assumption that weight of every edge is non-negative.
Claim 3 For every node $v$ and iteration $i$, if $d_i(v) = k \neq \infty$ then there is an $R_i$-path to $v$ of weight $k$.

**Proof.** By induction on the iteration number $i \geq 1$. For the basis $i = 1$, it is easy to see that the node added to $R$ in iteration 1 is $s$, so $R_1 = \{s\}$, $d_1(s) = 0$; and for every node $v \neq s$, $d_1(v) = \text{wt}(s,v)$ if there is an edge $(s,v)$, and $d_1(v) = \infty$ if there is no edge $(s,v)$. So, the claim holds after iteration 1.

For the induction step, let $i > 1$ and suppose the claim holds at the end of iteration $i-1$. Let $u$ be the node added to $R$ in iteration $i$ and consider any node $v$. If $d(v)$ does not change in iteration $i$, the claim holds after iteration $i$ by induction hypothesis. If $d(v)$ changes in iteration $i$ and since (by Claim 2) $d_{i-1}(u) = d_i(u)$, by the algorithm $d_i(v) = d_{i-1}(u) + \text{wt}(u,v)$ and $d_{i-1}(u) \neq \infty$. By the induction hypothesis, there is an $R_{i-1}$-path to $u$ of weight $d_{i-1}(u)$, say path $p$. Since $R_i = R_{i-1} \cup \{u\}$, path $p$ followed by the edge $(u,v)$ is an $R_i$-path to $v$, whose weight is $\text{wt}(p) + \text{wt}(u,v) = d_{i-1}(u) + \text{wt}(u,v)$. So, the claim holds after iteration $i$. \qed

Claim 4 For every node $u$, if $u$ is added to $R$ in iteration $i$ and $d_i(u) = \infty$ then there is no $s \to u$ path.

**Proof.** Suppose $u$ is added to $R$ in iteration $i$ and $d_i(u) = \infty$. Let $j$ be the first iteration such that the node $v$ added to $R$ in iteration $j$ has $d_j(v) = \infty$. Thus $1 < j \leq i$. We claim that there is no edge $(x,y)$ such that $x \in R_{j-1}$ and $y \notin R_{j-1}$. To see this, suppose that such an edge exists. Since $x \in R_{j-1}$, $x$ was added to $R$ in some iteration $j' < j$ and so, by definition of $j$, $d_{j'}(x) \neq \infty$ and so, by Claim 2 and the algorithm, $d_{j'}(y) \neq \infty$. Then by Claim 1, $d_{j-1}(y) \neq \infty$. But since $y \notin R_{j-1}$, $v$ is not the node added to $R$ in iteration $j$ (because there is another node not in $R_{j-1}$, namely $y$, with smaller $d$-value), contradicting the definition of $v$.

Since there is no edge from a node in $R_{j-1}$ to a node not in $R_{j-1}$, and since $s \in R_{j-1}$ while $u \notin R_{j-1}$, it follows that there is no $s \to u$ path. \qed

Claim 5 For every node $u$ and every iteration $i \geq 1$, if $u$ is added to $R$ in iteration $i$, then $d_i(u) = \delta(u)$.

**Proof.** By complete induction on $i$. Suppose $u$ is the node added to $R$ in iteration $i$, and suppose the claim holds for all nodes added to $R$ before iteration $i$.

If $i = 1$, the claim holds since (by the initialization in lines 2–3) the node added to $R$ in iteration 1 is $s$ and $d_1(s) = 0 = \delta(s)$.

If $i > 1$, the claim holds by Claim 4 if $d_i(u) = \infty$. So, suppose $d_i(u) \neq \infty$. Then by Claim 3 there is an $R_i$-path of weight $d_i(u)$ from $s$ to $u$; therefore $d_i(u) \geq \delta(u)$. We will now show that $d_i(u) \leq \delta(u)$, proving that $d_i(u) = \delta(u)$, as wanted.

Since there is and $R_{i-1}$-path to $u$, there is also a minimum weight $s \to u$ path, say $p$ (refer to Figure 1). Since $u$ is added to $R$ in iteration $i$, $u \notin R_{i-1}$ (recall that $i > 1$, so iteration $i-1$ exists, and $R_{i-1}$ is well defined). Since $s \in R_{i-1}$ and $u \notin R_{i-1}$, $p$ contains an edge $(x,y)$ such that $x \in R_{i-1}$ and $y \notin R_{i-1}$. Let $j$ be the iteration in which $x$ was added to $R$, so $j \leq i - 1$. Since $p$ is a minimum-weight $s \to u$ path, the prefix $p_x$ of $p$ up to node $x$ is a minimum-weight $s \to x$ path, i.e., $\text{wt}(p_x) = \delta(x)$. We have:
\[
\begin{align*}
\text{R}_i &= \text{R}_{i-1} \cup \{u\} \\
\text{R}_{i-1}\text{-path to } u \\
\text{min-weight } s \rightarrow u \text{ path } p \\
\end{align*}
\]

\[
\begin{align*}
\delta(u) &= \delta(u) \\
\leq \delta(y) & \quad \text{by definition of } u, \text{ since } u, y \notin \text{R}_{i-1} \\
\leq d_j(y) & \quad \text{by Claim 1, since } j \leq i - 1 \\
\leq d_j(x) + \text{wt}(x, y) & \quad \text{by Claim 2 and line 8, since } x \text{ is added to } \text{R} \text{ in iteration } j \\
= \delta(x) + \text{wt}(x, y) & \quad \text{by the induction hypothesis, since } j < i \\
= \text{wt}(p_x) + \text{wt}(x, y) & \quad \text{since } \text{wt}(p_x) = \delta(x), \text{ as argued above} \\
\leq \text{wt}(p) & \quad \text{since all edges have non-negative weight} \\
= \delta(u) & \quad \text{by definition of } p \\
\end{align*}
\]

So, \(d_i(u) = \delta(u)\), as needed to complete the proof that \(d_i(u) = \delta(u)\). \qed

The algorithm terminates, since one node is added to \(\text{R}\) in each iteration. The next theorem states that when the algorithm terminates, it has computed the weight of a minimum-weight \(s \rightarrow u\) path, for every node \(u\).

**Theorem 6** When the algorithm terminates, for every node \(u\), \(d(u) = \delta(u)\).

**Proof.** By Claim 5, when \(u\) is added to \(R\), \(d(u) = \delta(u)\). By Claim 1, \(d(u)\) cannot later be assigned a larger value, and by Claim 3 it cannot later be assigned a smaller value. So when the algorithm terminates, \(d(u) = \delta(u)\). \qed

**Running time of Dijkstra’s algorithm.** Let \(n\) be the number of nodes and \(m\) be the number of edges in the graph. The running time of Dijkstra’s algorithm depends on the data structure used to store \(d(u)\).

In the simplest implementation, we store \(d\) in an array of \(n\) elements, one per node, in no particular order. The initialization of \(R\) and \(d\) takes \(\Theta(n)\) time. The while loop is executed \(n - 1\) times, because initially \(R\) has one node, we add one node to it in each iteration, and the loop ends when all \(n\) nodes are in \(R\). Each iteration of the loop takes \(O(n)\) time (to find the minimum element in array \(d\) of a node that is not in \(R\), and to update the relevant entries of \(d\)). So the loop in total takes \(O(n^2)\) time. This implementation then takes \(O(n) + O(n^2) = O(n^2)\) time.

We can also use a heap to store the \(d\)-values of the nodes that are not in \(R\). Thus we can find a node not in \(R\) with the minimum \(d\)-value by performing an EXTRACTMIN operation, which takes \(O(\log n)\)
time; and we can update the value of $d$ for a node by performing a \textsc{ChangeKey} operation, which also takes $O(\log n)$ time. We perform $n$ \textsc{ExtractMin} operations, one in each iteration of the while loop. We perform at most $m$ \textsc{ChangeKey} operations: at most once for each edge $(v, u)$, in the iteration of the while loop in which $v$ is added to $R$. In the initialisation we must also perform a \textsc{BuildHeap} operation, to create the initial heap; this takes $O(n)$ time. Thus, the total time required to process all these operations is $O(n) + O(n \log n) + O(m \log n) = O((m + n) \log n)$. If we assume that there is a path from $s$ to each node, then $m \geq n - 1$, and so the above expression simplifies to $O(m \log n)$.

If the graph is “dense”, i.e., it has (roughly) an edge between every two nodes, then $m = \Theta(n^2)$, and in that case the simple array implementation is actually faster! However, in practice often the graph is “sparse” — typically, each node has a constant or perhaps a logarithmic number of neighbours, so $m = \Theta(n)$ or $m = \Theta(n \log n)$. In this case, the heap implementation of Dijkstra’s algorithm is substantially faster.