

Borůvka's Algorithm

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Abstract

[Abstract here.]

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2 Pseudocode

Algorithm 1: Borůvka's Algorithm

Input : A connected, edge-weighted, undirected graph $G = (V, E)$
Output: T (a minimum spanning tree of G) and $totalCost$ (the total cost of T)

- 1 Initialise a minimum spanning tree $T = (V, E')$, where $E' = \{\}$.
- 2 Initialise the total cost of the minimum spanning tree, $totalCost = 0$.
- 3 Initialise a list of components N , where N_k denotes the vertices in component k .
- 4 **for** each vertex v in V **do**
- 5 $N_v = v$.
- 6 **while** $|N| > 1$ **do**
- 7 Initialise an empty list of minimum connecting edges, $L = \{\}$.
- 8 **for** each component c in N **do**
- 9 Initialise the cheapest edge e to ∞ .
- 10 **for** each edge i, j in c **do**
- 11 **if** i, j contains an endpoint that isn't in c and i, j is cheaper than e **then**
- 12 Set e to i, j .
- 13 **if** e is not ∞ **then**
- 14 Add e to L .
- 15 **for** each edge e in L **do**
- 16 **if** e connects two different components **then**
- 17 Merge the components N_i and N_j into a single component, N_k , such that
 $N_k = N_i \cup N_j$.
- 18 Add e to E' in T .
- 19 Add the edge's weight to the total cost: $totalCost = totalCost + e.weight$
- 20 **return** T and $totalCost$.

2.1 Flowchart

3 Time and Space Complexity Analysis

3.1 Time Complexity

Borůvka's algorithm has a time complexity of $O(E \log(V))$, where E is the number of edges and V is the number of vertices in the graph.

The outer loop runs for $\log(V)$ iterations, as each iteration of the algorithm reduces the number of trees to at most half of the previous number of trees. Within each iteration, the algorithm performs a single pass over all the edges to find the minimum weight edge that connects two different components. This is performed in $O(E)$ time, as the algorithm must consider each edge once. The algorithm then performs a single pass over the minimum weight edges to merge two components into one where possible, which is also performed in $O(E)$ time. This gives a total time complexity of $O(E \log(V))$.

It should be noted that the best, average, and worst-case time complexities of Borůvka's algorithm are all the same because the algorithm is not dependent on the input data.

3.2 Space Complexity

The space complexity of Borůvka's algorithm is $O(V)$, as it only stores the component information for each vertex, which contains each vertex's parent and minimum weight edge.

4 Limitations and Constraints

A limitation of Borůvka’s algorithm is that it may not always find the true minimum spanning tree of a graph when the cheapest edge that connects two different components is not part of the true minimum spanning tree. This is because Borůvka’s algorithm only considers the cheapest edge that connects two different components, and does not consider the cheapest edge that connects two components that are already connected. Other algorithms such as Kruskal’s algorithm and Prim’s algorithm do not have this limitation, as they consider all edges in the graph.

Furthermore, Borůvka’s algorithm can be slow to find the minimum spanning tree when the graph has a large number of components or when the components in the graph are large in size. In these cases, the algorithm will have to perform more iterations and contract more edges.

Compared to Prim’s algorithm, which runs in $O(E + V \log(V))$ amortised time when using a Fibonacci heap [4], Borůvka’s algorithm is slightly slower. However, this variation of Prim’s algorithm with the Fibonacci heap is more complicated to implement.

Borůvka’s algorithm only works on undirected graphs as it does not account for the direction of the edges, thus it cannot solve the directed minimum spanning tree problem, which is more complex than the minimum spanning tree problem. Other algorithms such as the Chu-Liu/Edmonds’ algorithm (originally proposed in 1965) can solve the directed minimum spanning tree problem [5].

5 Applications

5.1 Designing Networks in the Real-World

As Borůvka’s algorithm finds a minimum spanning tree, it is most directly used in the design of networks, such as electrical networks, communication networks, and transportation networks [6]. In the original application of an electricity network for Moravia, the vertices represented towns, and edges represented the distances between towns. Borůvka used the assumption that it was not necessary to directly connect every town to the source of electricity – it was sufficient for a town to connect via another town that was already connected to power [1].

5.2 Two-Approximation for the Travelling Salesman Problem

Boruvka’s algorithm satisfies the triangle inequality and finds a minimum spanning tree, so it also acts as a two-approximation algorithm for the travelling salesman problem [7], which is NP-hard and thus not possible to solve in polynomial time [8]. Because it produces a two-approximation, the output is at most twice the cost of the optimal solution. This can be proven as the total cost of a full walk is at most twice the cost of the minimum spanning tree, and the algorithm returns a path with a cost less than the full walk, as our pre-order walk replaces two or more edges of the full walk with a single edge [7].

Algorithm 2: Two-Approximation for the Travelling Salesman Problem with MST-DFS [7]

- 1 Set a vertex as the start.
 - 2 Construct a minimum spanning tree, T .
 - 3 Create a list of vertices, H , that is ordered according to when they are visited in a pre-order tree walk of T , and add the start vertex at the end.
 - 4 Return the path H .
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5.3 Parallel Computation of Minimum Spanning Trees

There are several other algorithms that are more optimal for finding a minimum spanning tree depending on the input graph – Prim’s algorithm is faster for dense graphs, and Kruskal’s algorithm is faster for sparse graphs [9]. However, this only considers sequential implementations of the algorithms – Borůvka’s algorithm has become increasingly popular because it is easy to parallelise and is therefore

well-suited to distributed computing [10]. This contrasts with the aforementioned algorithms, which start with a single component and seek to add edges to it, making it difficult to parallelise them as we must keep and check edges in a strict order. As Borůvka's algorithm starts with multiple components and seeks to connect them with the shortest edge, it can be easily parallelised by distributing the edges between processors to determine the shortest connecting edge for each vertex [11].

5.4 Faster Sequential Algorithms for Minimum Spanning Trees

The concepts behind Borůvka's algorithm have also been used to develop faster sequential algorithms. For example, the expected linear time minimum spanning tree algorithm proposed by Karger, Klein, and Tarjan runs in $O(E)$ time. It involves an adaptation of Borůvka's algorithm, known as the Borůvka step [12, 13], alongside a step to remove F-heavy edges in linear time [14].

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