Universal Optimality of Dijkstra Algorithm

Using Fibonacci-Like Priority Queue with Working Sets

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Introduction

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- Recently Duan, Mao, Shu and Yin in [Dua+23] solved SSSP for undirected graphs with expected time $O(m\sqrt{\log n \log\log n})$
- This year Stefansson, Biggar and Johansson gave a fixed-parameter linear algorithm with running time $O(m + n \log w)$ for the single-source shortest path problem (SSSP) on directed graphs where fixed parameter over nesting width (w).

Universal Optimality

- Let $\mathcal{A}$ is the set of all correct algorithms.
- $\mathcal{G}_{n,m}$ is the set of all graphs with n vertices and m edges.
- $\mathcal{W}_G$ is the set of all possible weights for a graph $G \in \mathcal{G}_{n,m}$.

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A correct algorithm A^* is *existentially optimal* if

$$\forall\ n, m : \sup_{\substack{G \in \mathcal{G}_{n,m} \\ w \in \mathcal{W}_G}} A^*(G, w) \leq \alpha(n, m) \inf_{A \in \mathcal{A}} \sup_{\substack{G \in \mathcal{G}_{n,m} \\ w \in \mathcal{W}_G}} A(G, w)$$

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But this is not good. It is just saying A^* may take as much time as it takes in a star-graph or more complicated one.

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In this work we focus solely on α being a constant i.e. $\alpha(n, m) = O(1)$.

Dijkstra Algorithm

Algorithm 1: $\textsc{Dijkstra}(G, s, w)$

$F \longleftarrow \emptyset$, $\textsc{Insert}(F, s)$, $dist(s) \longleftarrow 0$

while $F \neq \emptyset$ **do**

    $u \longleftarrow \textsc{ExtractMin}(F)$

    for $e = (u, v) \in E$ **do**

        $\textsc{Insert}(F, v)$

        $\textsc{DecreaseKey}(F, v, \min\{dist(v), dist(u) + w(u, v)\})$

Dijkstra Algorithm

Algorithm 2: $\textsc{Dijkstra}(G, s, w)$

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Dijkstra solves three problems:

- Computes Shortest Distances

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Algorithm 3: $\textsc{Dijkstra}(G, s, w)$

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Dijkstra solves three problems:

- Computes Shortest Distances
- Build Shortest Path Tree
- Sorts vertices by Shortest Distance (DO)

Exploration Tree and DO

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- Let T be the exploration tree. Let $\prec$ be the final distance ordering of the vertices.
- Then for every edge $(u, v) \in T$, $u \prec v$.

Order of Vertices by a Tree

- Let T be any tree in G. An order of T is a total order of $V(T)$ such that for every edge $(u, v) \in E(T)$ we have $u \prec v$ in the order.

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Theorem

For any graph G, L is an order of G iff there exists non-negative weights w such that

1. *For every two nodes $u \neq v$, $d_w(s, u) \neq d_w(s, v)$.*
2. *$u \prec_L v$ if and only if $d_w(s, u) < d_w(s, v)$.*

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- $OPT_Q(G)$ is the number of comparison queries of an optimal algorithm for this graph.
- $OPT(G)$ be the number of total steps taken by an optimal correct algorithm for the graph.
- Since $OPT(G) = \Omega(m)$, $OPT_Q(G) + n + m = O(OPT(G))$.

Dijkstra Induced Interval Set

Let an interval of time for any vertex $v \in V(G)$ is the set $[l_v, r_v]$ where l_v is the time when v was first discovered and added to the heap and r_v is the time when v was extracted from the heap.

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A run of Dijkstra induces intervals for each vertex $v \in V$ with the operations $\textsc{Insert}$ and $\textsc{ExtractMin}$.

An interval set $\mathcal{I}$ is collection of intervals for each vertex. It is called Dijkstra Induced when all the intervals for each vertex in $\mathcal{I}$ is induced by a run of Dijkstra on some (G, w).

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$$W_{v,t} = \{[l_u, r_u] \in \mathcal{I} \colon l_v \leq l_u \leq t \leq r_u\}$$

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- Working set of v, $W_v = W_{v,t^*}$ such that $t^* = \arg\max_t |W_{v,t}|$.

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- Working set of v, $W_v = W_{v,t^*}$ such that $t^* = \arg\max_t |W_{v,t}|$.

- The cost of a vertex $v \in V(G)$ is $Cost(x) = \log |W_v|$. And so $Cost(\mathcal{I}) = \sum_{v \in V(G)} \log |W_v|$.

Fibonacci-Like Priority Queue with Working Set Property

A Fibonacci-like priority queue is a priority queue made using a Fibonacci Heap. Fibonacci-Like Priority Queue with Working Set Property is a data structure if it satisfies the amortized time complexity for any sequence of operations as follows:

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Fact

There is a Fibonacci-Like Priority Queue with Working Set Property for Dijkstra. We will use this data structure in every argument from now on by default.

Time Complexity of Dijkstra

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- Hence total time taken by all $\textsc{DecreaseKey}$ calls is $O(m)$.
- Total time taken by all $\textsc{ExtractMin}$ calls is

$$\begin{aligned}\sum_{v \in V(G)} O(1 + \log |W_v|) &= O\left(n + \sum_{v \in V(G)} \log |W_v|\right) \\ &= O(n + Cost(\mathcal{I}))\end{aligned}$$

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- Total time taken by Dijkstra is $O(m + n + Cost(\mathcal{I}))$

We'll show $OPT_Q(G) = \Omega(Cost(\mathcal{I}))$.

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- Let $C_L \in \{-1, 0, 1\}^*$ be the sequence of answers of comparisons made by A on (G, w_L). Then $\mathcal{C} : \mathcal{W} \to \{-1, 0, 1\}^*$, $\mathcal{C}(w_L) = C_L$ is a ternary prefix free code.

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- By Shannon's source coding theorem for symbol codes any such code has expected length $\Omega(\log(|\mathcal{W}|)) = \Omega(\log(\text{Order}(G)))$

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Theorem

A sequence $(B_1, \ldots, B_k)$ of pairwise disjoint vertex sets is barrier sequence if and only if for all $1 \leq i \leq j \leq k$, $v \in B_j$ is not ancestor of any $u \in B_i$ in T.

Barriers Give Lower Bounds

Theorem

Let T be any spanning tree and $(B_1, \ldots, B_k)$ be a barrier sequence of T. Then $\log(\mathrm{Order}(G)) = \Omega\left(\sum_{i=1}^{k} |B_i| \log |B_i|\right)$

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- Delete vertices of B_k to get T'. By induction for the barrier sequence $(B_1, \ldots, B_{k-1})$ for T', $\mathrm{Order}(T') \geq |B_1|!|B_2|! \cdots |B_{k-1}|!$.

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So finally we got the result:

Result

If T is a spanning tree of G and $(B_1, \ldots, B_k)$ is a barrier sequence for T then

$$OPT_Q(G) = \Omega\left(\sum_{i=1}^{k} |B_i| \log |B_i|\right)$$

Construction of Barrier Sequence

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Result

At any time of the algorithm the set of elements in the priority queue forms a barrier

Intersecting Coloring

Definition (Intersecting Coloring)

An intersecting coloring of $\mathcal{I}$ with k colors is a function $C : \mathcal{I} \to [k]$ that assigns a color to every interval and additionally for every color $i \in [k]$, $\bigcap_{I \in \mathcal{I}, C(I)=i} I \neq \emptyset$.

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- Order $\{B_c\}$ by increasing order of $\{t_c\}$. WLOG $t_1 < \cdots < t_k$.
- $(B_1, \ldots, B_k)$ is a barrier sequence.

Intersecting Coloring Gives Lower Bounds

Let C be an intersecting coloring of $\mathcal{I}$ with k colors. Let $(B_1, \ldots, B_k)$ is the barrier sequence induced by C. Then let the energy of C is defined to be

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Result

If $\mathcal{I}$ is the interval set induced by Dijkstra and C be any arbitrary intersecting coloring of $\mathcal{I}$ then

$$OPT_Q(G) = \Omega(E(C))$$

Good Intersecting Coloring gives Optimality

Goal: Find an intersecting coloring of $\mathcal{I}$, C such that $E(C) \geq Cost(\mathcal{I})$

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- We have $OPT_Q(G) = \Omega(E(C))$.

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- Then time complexity of all $\textsc{ExtractMin}$ operations is $O(n + Cost(\mathcal{I})) = O(n + E(C))$.
- We have $OPT_Q(G) = \Omega(E(C))$.
- So overall Cost of $\textsc{ExtractMin}$ in Dijkstra is upper bounded by $O(n + OPT_Q(G))$.

Good Intersecting Coloring gives Optimality

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- Then time complexity of all $\textsc{ExtractMin}$ operations is $O(n + Cost(\mathcal{I})) = O(n + E(C))$.
- We have $OPT_Q(G) = \Omega(E(C))$.
- So overall Cost of $\textsc{ExtractMin}$ in Dijkstra is upper bounded by $O(n + OPT_Q(G))$.
- Dijkstra achieves universal optimality for time complexity.

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We will find such a good intersecting coloring recursively.

Finding Good Intersecting Coloring

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For working set W_x with the largest size

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$Cost(\mathcal{I}) \leq Cost(\mathcal{I}') + 2|W_x| \log |W_x|$. Hence, $E(C) \geq Cost(\mathcal{I})$.

Thank You

Deleting Intervals from $\mathcal{I}$

Theorem

Let $\mathcal{I}$ an interval set and $x \in \mathcal{I}$. $k = \max_t |\{I \in \mathcal{I} \mid t \in I\}|$. Then

$$Cost(\mathcal{I}) \leq Cost(\mathcal{I} \setminus \{x\}) + \log |W_x| + \log k$$

- Let $I_1, \ldots, I_l \in \mathcal{I}$ are the only intervals which had nonempty intersection with x. So $l \leq k - 1$.
- Let t_i is starting point of I_i. WLOG assume $t_l > \cdots > t_1$.
- Let W_i, W_i' are working sets of I_i before and after removing x.

Deleting Intervals from $\mathcal{I}$

- Let t is starting point of x. Then $W_{i,t}$ contains $x, I_1, \ldots, I_i$. So $|W_i| \geq i + 1$.
- $|W_i| \in \{|W_i'|, |W_i'| + 1\}$ for all $i \in [l]$.

$$
\begin{aligned}
& Cost(\mathcal{I}) - Cost(\mathcal{I} \setminus \{x\}) - \log |W_x| \\
= & \sum_{i=1}^{l} \log |W_i| - \log |W_i'| \\
\leq & \sum_{i=1}^{l} \log(i+1) - \log i = \log(l+1) \leq \log k
\end{aligned}
$$

Fact

For any working set $|W_x| = k$ we have

$$Cost(\mathcal{I}) \leq Cost(\mathcal{I} \setminus W_x) + 2|W_x| \log |W_x|$$