Reconstructing Edge-Disjoint Paths Faster

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Abstract

For a simple undirected graph with n vertices and m edges, we consider a data structure that given a query of a pair of vertices u, v and an integer $k \geq 1$, it returns k edge-disjoint uv-paths. The data structure takes $\tilde{O}(n^{3.375})$ time to build, using $O(\sqrt{m}n^{1.5}\log n)$ space, and each query takes $O(\sqrt{k}n)$ time, which is optimal and beats the previous query time of $O(kn\alpha(n))$.

Keywords: ancestor tree, connectivity, edge-disjoint paths

1. Introduction

For a simple undirected graph G with n vertices and m edges, we are interested in building a data structure to return k edge-disjoint paths between two vertices. Conforti, Hassin and Ravi [3] demonstrated a data structure that takes $O(n\,\mathrm{MF}(n,m))$ preprocessing time, uses $O(nm)$ space and queries in $O(kn\alpha(n))$ time, where α is the inverse Ackermann function and $\mathrm{MF}(n,m)$ is the running time for computing a maximum flow in an undirected unit capacity graph with n vertices and m edges.

Our data structure is simple and reaches the optimal query time of $O(\sqrt{k}n)$ while improving the space usage to $O(\sqrt{m}n^{1.5}\log n)$. The query time is optimal as there exist graphs where every k edge-disjoint st-paths uses $\Omega(\sqrt{k}n)$ edges [5].

2. Preliminaries

Throughout the paper, we fix a simple undirected graph $G=(V,E)$ with n vertices and m edges. Denote $\lambda(s,t)$ to be the *local edge-connectivity* between s and t in G, i.e. the maximum number of edge-disjoint paths between s and t. The degree of a vertex is $\deg v$. $\lambda(s,t)$ is bounded above by both $\deg s$ and $\deg t$.

For a rooted tree T with root r, the *lowest common ancestor* of two nodes u and v, denoted α_{uv}, is the node farthest away from the root that is contained in both the ru-path and the rv-path. T_{uv} denotes the subtree of T rooted at α_{uv}. For any internal node v, we abuse the notation and say u is a leaf of v if u is a leaf of the subtree rooted at v. A binary tree is *full* if each internal node has two children.

A rooted full binary tree T with weights on the internal nodes is an *ancestor tree* of $U \subset V$ if the set of leaves coincides with U and $\lambda(u,v)$ equals the weight of α_{uv} for all $u,v \in U$. An immediate consequence of the definition is $\lambda(u,v) \leq \lambda(x,y)$ for all leaves x,y of T_{uv}. An ancestor tree can be found in $O(|U|\,\mathrm{MF}(n,m))$ time [2].

3. Previous data structure

We give a quick sketch of the data structure of Conforti et al. The heart of their data structure exploits that edge-disjoint paths are effectively "composable".

Theorem 1 (Theorem 3.1 [3])**.** *Given k edge-disjoint uw-paths and k edge-disjoint wv-paths with a total of m edges, a set of k edge-disjoint uv-paths can be found in $O(m)$ time.*

Remark 1. For anyone familiar with the original proof would notice it actually obtain the bound $O(m+k^2)$, where k^2 comes from the dummy edges that force a perfect stable matching between the paths. Fortunately, avoiding dummy edges is easy: find any stable matching and match the unmatched paths arbitrarily.

Every k edge-disjoint paths contain $O(kn)$ edges, hence composing k edge-disjoint paths takes $O(kn)$ time. One can construct an auxiliary graph H, such that for each edge uv in H, we precompute the maximum number of edge-disjoint uv-paths in G using any maximum flow algorithm. A query of k edge-disjoint v_1v_l-paths can be answered by a sequence of composition of k edge-disjoint v_1v_2-paths, v_2v_3-paths, $\ldots$ $v_{l-1}v_l$-paths, where $v_1,\ldots,v_l$ is a path in H and $\lambda(v_i,v_{i+1}) \geq k$ for all $i \leq l-1$. The total query time is therefore $O(knl)$. By augment a flow equivalent tree with Chazelle's semigroup product structure for free trees [1], it returns a graph H with $O(n)$ edges and at most $O(\alpha(n))$ composition per query. The preprocessing time is $O(|H|\,\mathrm{MF}(n,m)) = O(n\,\mathrm{MF}(n,m))$ using $O(nm)$ space, and the query time is $O(kn\alpha(n))$.

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4. Data structure

On the high level, our data structure is the same as the previous one: we precompute some edge-disjoint paths, and compose them during query time. The difference is the edge-disjoint paths are short, at most one composition per query and the implementation is a simple binary tree.

4.1. Composition of short edge-disjoint paths

It's easy to find examples where k edge-disjoint paths contain $\Omega(kn)$ edges, even returning the edge-disjoint path itself already exceed our bound. Fortunately, there are always short edge-disjoint paths. A set of k edge-disjoint paths is *short* if it contains at most $2\sqrt{k}n$ edges.

Theorem 2. *There exist short $\lambda(s,t)$ edge-disjoint st-paths P_{st}, and they can be found in $O(\mathrm{MF}(n,m))$ time. Moreover, the k shortest paths in P_{st} have a total of $O(\sqrt{k}n)$ edges for all $k \leq \lambda(s,t)$.*

Proof. Find any maximum 0-1 st-flow from s to t. There is a $O(m)$ time procedure to decycle the flow and then decompose the flow to unit flows along st-paths. Let P_{st} be the paths in the flow decomposition, then P_{st} fits the requirement. Indeed, any acyclic maximum st-flow in a unit capacity simple graph saturates at most $2\sqrt{\lambda(s,t)n}$ edges [5].

The k shortest paths in P_{st} have total length at most

$$k\frac{2\sqrt{\lambda(s,t)}n}{\lambda(s,t)} = k\frac{2n}{\sqrt{\lambda(s,t)}} \leq 2k\frac{n}{\sqrt{k}} = 2\sqrt{k}n.$$

□

Short edge-disjoint paths are closed under our implementation of composition. Let f_{uv} denote some $\lambda(u,v)$ short edge-disjoint uv-paths. Let $\ell = \min(k, \lambda(u,w), \lambda(w,v))$. The previous two theorems imply $\textsc{Compose}(f_{uw}, f_{wv}, k)$ in Figure 1 returns ℓ short edge-disjoint uv-paths. The algorithm runs in $O(\sqrt{\ell}n)$ time.

```
COMPOSE(f_uw, f_wv, k):
  ℓ ← min(k, |f_uw|, |f_wv|)
  p_uw ← ℓ shortest edge-disjoint paths in f_uw
  p_wv ← ℓ shortest edge-disjoint paths in f_wv
  f′ ← compose p_uw and p_wv
  f ← push a unit of flow on all paths of f′
  Decycle f
  return a path decomposition of f
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Figure 1: Compose f_{uw} and f_{wv}.

4.2. Cache paths and queries

The algorithm first finds T, an ancestor tree of V, in $O(n\,\mathrm{MF}(n,m))$ time [2]. If $k \leq \lambda(u,v)$, then there exist k edge-disjoint uw and wv-paths, where w is any leaf of T_{uv}.

For each internal node r of an ancestor tree, we can assign one single leaf w of r called a hub of r, such that for any other leaves u and v, either we have already precomputed edge-disjoint paths for uv, or we can compose edge-disjoint path of uw and wv. It turns out we can assign hubs in a way so we only need to precompute $O(n\log n)$ pairs of edge-disjoint paths.

Let $c(u)$, the *heavier child*, be the child of u in T with larger number of leaves. The heavier child is the root of the larger subtree. If both children have same number of leaves, then c break ties arbitrarily.

Let the *hub* of u be $h(u)$, and defined recursively:

$$h(u) = \begin{cases} u & \text{if } u \text{ is a leaf} \\ h(c(u)) & \text{otherwise.} \end{cases}$$

$h(u)$ is always a leaf of u. For every internal node v and each leaf u of v, the data structure saves maximum edge-disjoint $h(v)u$-paths.

We design a recursive function $\textsc{CacheFlows}$ to satisfy the above requirement. It maintains the invariant that if v is the input, then it saves flow $f_{h(v)u}$ for each u a leaf of v. For an internal node v with children v_1 and v_2, $\textsc{CacheFlows}(v)$ begins by running both $\textsc{CacheFlows}(v_1)$ and $\textsc{CacheFlows}(v_2)$. Assume v_2 is the heavier child, then $h(v_2) = h(v)$, and $f_{h(v)u}$ is cached for all u a leaf of v_2. It remains to compute $f_{h(v)u}$ for all u a leaf of v_1. This can be done by composing $f_{h(v_1)u}$ with $f_{h(v_1)h(v)}$. All $f_{h(v_1)u}$ has been computed due to the last call to $\textsc{CacheFlows}(v_1)$. Finding $f_{h(v_1)h(v)}$ takes a single maximum flow computation. See Figure 2.

```
⟨⟨f_st denote a global variable that stores a max st-flow⟩⟩
CACHEFLOWS(v):
  if v is an internal node
      v1, v2 are children of v, where v2 is the heavier child
      CACHEFLOWS(v1)
      CACHEFLOWS(v2)
      f_h(v1)h(v) ← MAXIMUMFLOW(h(v1), h(v))
      for all leaf u of v1
          f_h(v)u ← COMPOSE(f_h(v1)u, f_h(v1)h(v), ∞)
  else
      do nothing
```

Figure 2: Cache flows.

Let F be the set of pairs $\{s,t\}$ such that we have cached an st-flow at the end of $\textsc{CacheFlow}(r)$, where r is the root of the ancestor tree T. The size of F is an upper bound on the number of times the algorithm applied $\textsc{Compose}$. Let $\ell(v)$ be the number of leaves of the subtree rooted at v. Applying a standard heavy-path decomposition argument [7], $|F|$ is bounded by

$$\sum_{v \text{ an internal node of } T} \ell(v) - \ell(c(v)) = O(n\log n).$$

In each recursive call of the algorithm, the dominating factor of the running time is the maximum flows and compositions. There are $n-1$ maximum flow computations each taking $O(\mathrm{MF}(n,m))$ time, and $O(|F|) = O(n\log n)$

compositions each taking $O(m)$ time. The time spent on CacheFlows is $O(n\,\mathrm{MF}(n,m) + mn\log n)$.

Because we cache $O(n\log n)$ flows and each flow uses at most $O(m)$ edges, the number of edges stored is bounded by $O(mn\log n)$. A more careful analysis can produce a stronger bound. For fixed u and v, the number of edges in the flow is $O(\sqrt{\lambda(u,v)}n) = O(\sqrt{\min\{\deg u, \deg v\}}n)$. The total number of edges is

$$\sum_{\{u,v\}\in F} O(\sqrt{\min\{\deg u, \deg v\}}n)$$

For every cached flow f_{st}, s is called a non-hub for f_{st} if s is not the hub of α_{st}. The main observation is that every leaf can partake as a non-hub for $O(\log n)$ cached flows. Indeed, the number of times s occurs as a non-hub equals to the number of non-heavy child in the root to s path, which is $O(\log n)$ [7]. We can charge the space to the vertex that acts as the non-hub. The total space used is therefore.

$$\sum_{\{u,v\}\in F} O(\sqrt{\min\{\deg u, \deg v\}}) \leq O(\log n) \sum_{v\in V} \sqrt{\deg v}$$

Using the fact that $\sqrt{\cdot}$ is a concave function,

$$\sum_{v\in V} \sqrt{\deg v} \leq \sum_{v\in V} \sqrt{\frac{2m}{n}} = O(\sqrt{mn}).$$

Putting the above together shows the space usage is $O(\sqrt{m}n^{1.5}\log n)$.

When querying vertices u and v for k edge-disjoint paths, the algorithm finds the hub $w = h(\alpha_{uv})$, and return the composition of k shortest edge-disjoint paths of f_{uw} and f_{wv}. The query run time is dominated by the composing procedure. Composing the paths take time proportional to the total number of edges involved, which is $O(\sqrt{k}n)$.

Theorem 3. *There is a data structure that preprocesses an undirected simple graph G of n vertices and m edges in $O(n(\mathrm{MF}(n,m) + m\log n))$ time, use $O(\sqrt{m}n^{1.5}\log n)$ space and answer queries for k edge-disjoint st-paths in $O(\sqrt{k}n)$ time.*

Although there is no known non-trivial lower bound for $\mathrm{MF}(n,m)$, every known maximum flow algorithm dominates $m\log n$ by at least a polynomial factor. It's safe to assume the preprocessing time is n maximum flows. Using the state of art max flow algorithm by Duan [4], the preprocessing time is $\tilde{O}(n^{3.375})$.

Remark 2. Often one is only interested in edge-disjoint paths between a set of n' terminal vertices $U \subset V$. We can find an ancestor tree for U and apply the rest of the algorithm without modification. The preprocessing time becomes $O(n'(\mathrm{MF}(n,m) + m\log n'))$ and the data structure occupies $O(\sqrt{m'n'}n\log n')$ space, where m' is the sum of degree of vertices in U.

If there is an upper bound k_{max} on the query integer k, then all occurrences of m can be replaced by $k_{max}n$ using sparsification [6].

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