

Geometric Partial Matching and Unbalanced Transportation

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November 20, 2018

1 Introduction

Consider the problem of finding a minimum-cost bichromatic matching between a set of red points A and a set of blue points B lying in the plane, where the cost of a matching edge (a, b) is the Euclidean distance $\|a - b\|$; in other words, the minimum-cost bipartite matching problem on the Euclidean complete graph $G = (A \cup B, A \times B)$. Let $r := |A|$ and $n := |B|$. Without loss of generality, assume that $r \leq n$. We consider the problem of *partial matching*, where the task is to find a minimum-cost matching of size $k \leq r$. When $k = r = n$, we say the matching instance is *balanced*. When $k = r < n$ (A and B have different sizes, but the matching is maximal), we say the matching instance is *unbalanced*. We call the geometric problem of finding a size k matching of point sets A and B *geometric partial matching*.

1.1 Contributions

In this paper, we present two algorithms for geometric partial matching that are based on fitting nearest-neighbor (NN) and geometric closest pair (BCP) oracles into primal-dual algorithms for non-geometric bipartite matching and minimum-cost flow. This pattern is not new, see for example (...). Unlike these previous works, we focus on obtaining running time dependencies on k or r instead of n , that is, faster for inputs with small r or k . We begin in Section 2 by introducing notation for matching and minimum-cost flow.

First in Section 3, we show that the Hungarian algorithm [5] combined with a BCP oracle solves geometric partial matching exactly in time $O((n + k^2) \text{polylog } n)$. Mainly, we show that we can separate the $O(n \text{polylog } n)$ preprocessing time for building the BCP data structure from the augmenting paths' search time, and update duals in a lazy fashion such that the number of dual updates per augmenting path is $O(k)$.

Theorem 1.1. *Let A and B be two point sets in the plane with $|A| = r$ and $|B| = n$ satisfying $r \leq n$, and let k be a parameter. A minimum-cost geometric partial matching of size k can be computed between A and B in $O((n + k^2) \text{polylog } n)$ time.*

Next in Section 4, we apply a similar technique to the unit-capacity min-cost circulation algorithm of Goldberg, Hed, Kaplan, and Tarjan [2]. The resulting algorithm finds a $(1 + \epsilon)$ -approximation to the optimal geometric partial matching in $O((n + k\sqrt{k}) \text{polylog } n \log(n/\epsilon))$ time.

Theorem 1.2. *Let A and B be two point sets in the plane with $|A| = r$ and $|B| = n$ satisfying $r \leq n$, and let k be a parameter. A $(1 + \epsilon)$ geometric partial matching of size k can be computed between A and B in $O((n + k\sqrt{k}) \text{polylog } n \log(n/\epsilon))$ time.*

Our third algorithm solves the transportation problem in the unbalanced setting. The transportation problem is a weighted generalization of the matching problem. Each point of A is weighted with an integer *supply* and each point of B is weighted with integer *demand* such that the sum of supply and demand are equal. The goal of the transportation problem is to find a minimum-cost mapping of all supplies to demands, where the cost of moving a unit of supply at $a \in A$ to satisfy a unit of demand at $b \in B$ is $\|a - b\|$. For this, we use the strongly polynomial uncappeditated min-cost flow algorithm by Orlin [6]. The result is an $O(n^{3/2}r \text{ polylog } n)$ time algorithm for unbalanced transportation. This improves over the $O(n^2 \text{ polylog } n)$ time algorithm of Agarwal et al. [1] when $r = o(\sqrt{n})$.

Theorem 1.3. *Let A and B be two point sets in the plane with $|A| = r$ and $|B| = n$ satisfying $r \leq n$, with supplies and demands given by the function $\lambda : (A \cup B) \rightarrow \mathbb{N}$ such that $\sum_{a \in A} \lambda(a) = \sum_{b \in B} \lambda(b)$. An optimal transportation map can be computed in $O(n^{3/2}r \text{ polylog } n)$ time.*

By nature of the BCP/NN oracles we use, these results generalize to when $\|a - b\|$ is any L_p distance, and not just the Euclidean distance between a and b .

2 Preliminaries

2.1 Matching

Let G be a bipartite graph between vertex sets A and B and edge set E , with costs $c(v, w)$ for each edge e in E . We use $C := \max_{e \in E} c(e)$, and assume that the problem is scaled such that $\min_{e \in E} c(e) = 1$. A *matching* $M \subseteq E$ is a set of edges where no two edges share an endpoint. We use $V(M)$ to denote the vertices matched by M . The *size* of a matching is the number of edges in the set, and the *cost* of a matching is the sum of costs of its edges. The *minimum-cost partial matching problem (MPM)* asks to find a size- k matching M^* of minimum cost.

2.2 Minimum-cost flow

Network. For minimum-cost flow, let $G_0 = (V, E_0)$ be a directed graph with nonnegative arc capacities $u(v, w)$ and costs $c(v, w)$ for each arc $(v, w) \in E_0$. We say G_0 is *unit-capacity* if $u(v, w) = 1$ holds for all arc (v, w) . Let $\phi : V \rightarrow \mathbb{N}_{\geq 0}$ be a supply-demand function on V , satisfying $\sum_{v \in V} \phi(v) = 0$. The positive values of $\phi(v)$ are referred to as *supply*, and the negative values of $\phi(v)$ as *demand*.

We augment G_0 to make it *symmetric* and the costs *antisymmetric* by creating an arc (w, v) for each $(v, w) \in E_0$ and define $u(w, v) = 0$ and $c(w, v) = -c(v, w)$. Denote this set of new *reverse arcs* by E^R . Let $E = E_0 \cup E^R$. From here forward, we work with the symmetric multigraph $G = (V, E)$. A *network* $N = (G, c, u, \phi)$ is a graph G augmented with arc costs, capacities, and a supply-demand function on vertices of G .

Pseudoflows. A *pseudoflow* $f : E \rightarrow \mathbb{N}$ is an antisymmetric function on arcs satisfying $f(v, w) \leq u(v, w)$ for all arcs (v, w) . We say that f *saturates* an arc e if $f(v, w) = u(v, w)$. The *support* of f is $E_{>0}(f) := \{(v, w) \mid f(v, w) > 0\}$. All our algorithms will handle integer-valued pseudoflows, so in the unit-capacity setting an arc is either saturated or has zero flow. Given a pseudoflow f , we define the *imbalance* of a vertex to be

$$e_f(v) := \phi(v) + \sum_{(w,v) \in E} f(w, v) - \sum_{(v,w) \in E} f(v, w).$$

We call positive imbalance *excess* and negative imbalance *deficit*; and vertices with positive and negative imbalance *excess vertices* and *deficit vertices*, respectively. A vertex is *balanced* if it has zero imbalance. If all vertices are balanced, the pseudoflow is a *circulation*. The cost of a pseudoflow is

$$\text{cost}(f) := \sum_{(v,w) \in E} c(v,w) \cdot f(v,w).$$

The *minimum-cost flow problem (MCF)* asks to find the circulation f^* of minimum cost.

Residual network. For each arc (v,w) , the *residual capacity* with respect to pseudoflow f is defined to be $u_f(v,w) := u(v,w) - f(v,w)$. The set of *residual arcs* is defined as

$$E_f := \{(v,w) \in E \mid u_f(v,w) > 0\}.$$

We call $G_f = (V, E_f)$ the *residual graph* with respect to pseudoflow f . A pseudoflow f' in G_f can be “added” or “augmented” to f to produce a new pseudoflow (that is, the arc-wise addition $f + f'$ is a valid pseudoflow in G). A pseudoflow f' in G_f is an *improving flow* if

- (1) $0 \leq e_{f'}(v) \leq e_f(v)$ for all excess vertices v ,
- (2) $0 \leq -e_{f'}(v) \leq -e_f(v)$ for all deficit vertices v , and
- (3) $\sum_{v \in V} |e_{f'}(v)| < \sum_{v \in V} |e_f(v)|$ holds.

If improving flow f' is on a simple path (from an excess vertex to a deficit vertex), we call it an *augmenting-path flow* and its underlying support path an *augmenting path*. If f' saturates at least one residual arc in every augmenting path in G_f , we call f' a *blocking flow*. In other words, for blocking flow f' , there is no augmenting-path flow f'' in G_f for which $f + (f' + f'')$ is a feasible pseudoflow in G .

2.3 Primal-dual augmentation algorithms

The Hungarian algorithm begins with an empty matching and gradually increases its size to k using *alternating augmenting paths*. Given a non-maximal matching M , an alternating augmenting path P is a path between an unmatched vertex $a \in A$ and unmatched $b \in B$. Then, $M' = M \oplus P$ is a matching of size 1 greater. By restricting alternating augmenting paths to edges which satisfy a certain cost condition, we can prove that each intermediate matching of size $j \leq k$ is of minimum-cost among matchings of size j .

There is a similar augmentation procedure for flows, which sends improving flows to gradually reduce the imbalance for all vertices to 0, making it a circulation. By restricting augmentations to residual arcs satisfying a certain cost condition (admissibility), one can prove that the resulting circulation is minimum cost.

LP-duality and admissability. Formally, the *potentials* $\pi(v)$ are the variables of the linear program dual to . The *reduced cost* of an arc (v,w) in E_f with respect to π is

$$c_\pi(v,w) := c(v,w) - \pi(v) + \pi(w).$$

Note that reduced costs are antisymmetric: $c_\pi(v,w) = -c_\pi(w,v)$. The *dual feasibility constraint* is that $c_\pi(v,w) \geq 0$ holds for all residual arcs; potentials which satisfy this constraint are said to be *feasible*. The linear programming *optimality conditions* state that, for an optimal circulation f^* ,

Algorithm 1 Hungarian algorithm

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1: function MATCH( $G = (A \cup B, E), k$ )
2:    $M \leftarrow \emptyset$ 
3:    $\pi(v) \leftarrow 0$  for all  $v \in A \cup B$ 
4:   while  $|M| < k$  do
5:      $\Pi \leftarrow \text{HUNGARIAN-SEARCH}(G, M, \pi)$ 
6:      $M \leftarrow M \oplus \Pi$ 
7:   return  $M$ 
```

there are feasible potentials π^* which satisfy $c_{\pi^*}(v, w) = 0$ on all arcs with $f^*(v, w) > 0$. We can similarly define potentials and reduced costs for matchings, using $c_{\pi}(a, b) = c(a, b) - \pi(a) + \pi(b)$ for edges $(a, b) \in A \times B$.

Suppose we relax the dual feasibility constraint to allow for a violation of $\varepsilon > 0$. We say that a pseudoflow f is **ε -optimal** if $c_{\pi}(v, w) \geq -\varepsilon$ for all arcs (v, w) in E_f with $u_f(v, w) > 0$. We say that a residual arc (v, w) satisfying $c_{\pi}(v, w) \leq 0$ is **admissible**. We say that an improving flow f' is **admissible** if $f'(v, w) > 0$ only on admissible arcs (v, w) .

For matchings, we say that matching M is ε -optimal if $c_{\pi}(a, b) \leq \varepsilon$ for $(a, b) \in M$ and $c_{\pi}(a, b) \geq -\varepsilon$ $(a, b) \in E \setminus M$. Matching edges (resp. nonmatching edges) are **admissible** if $c_{\pi}(a, b) \geq 0$ (resp. $c_{\pi}(a, b) \leq 0$); and an alternating augmenting path is **admissible** if all its edges are. For both matching and flows, 0-optimal f implies the admissibility condition is with equality, instead ($c_{\pi}(v, w) = 0$).

Lemma 2.1. *Let f be an ε -optimal pseudoflow in G and let f' be an admissible improving flow in G_f . Then $g = f + f'$ is also ε -optimal.*

Proof. Augmentation by f' will not change the potentials, so any previously ε -optimal arcs remain ε -optimal. However, it may introduce new arcs with $u_g(v, w) > 0$, that previously had $u_f(v, w) = 0$. We will verify that these arcs satisfy the ε -optimality condition.

If an arc is newly introduced this way, then by definition of residual capacities $f(v, w) = u(v, w)$. At the same time, $u_g(v, w) > 0$ implies that $g(v, w) < u(v, w)$. This means that f' augmented flow in the reverse direction of (v, w) ($f'(w, v) > 0$). By assumption, the arcs of $E_{>0}(f')$ are admissible, so (w, v) was an admissible arc ($c_{\pi}(w, v) \leq 0$). By antisymmetry of reduced costs, this implies $c_{\pi}(v, w) \geq 0$. Finally, $c_{\pi}(v, w) \geq 0 \geq -\varepsilon$. Thus, all arcs with $u_g(v, w) > 0$ respect the ε -optimality condition, and g is ε -optimal. \square

In Section 4, we use ε -optimality to prove the approximation quality of an ε -optimal circulation.

3 Matching with the Hungarian algorithm

The Hungarian algorithm maintains a 0-optimal (initially empty) matching M , and repeatedly augments by alternating augmenting paths of admissible edges until $|M| = k$. To this end, the algorithm maintains a set of feasible potentials π and updates them to find augmenting paths of admissible edges. It maintains the invariant that matching edges are admissible. Since there are k augmentations and each alternating path has length at most $2k - 1$, the total time spent on bookkeeping the matching is $O(k^2)$. This leaves the analysis of the subroutine that updates the potentials and finds an admissible augmenting path; we call this subroutine the **Hungarian search**.

Algorithm 2 Hungarian Search (matching)

Require: $c_\pi(a, b) = 0$ for all $(a, b) \in M$

```
1: function HUNGARIAN-SEARCH( $G = (A \cup B, E), M, \pi$ )
2:    $S \leftarrow a \in (A \setminus V(M))$ 
3:   repeat
4:      $(a', b') \leftarrow \arg \min \{c_\pi(a, b) \mid (a, b) \in (S \cap A) \times (B \setminus S)\}$ 
5:      $\gamma \leftarrow c_\pi(a', b')$ 
6:      $\pi(v) \leftarrow \pi(v) + \gamma, \forall v \in S$   $\triangleright$  make  $(a', b')$  admissible
7:      $S \leftarrow S \cup \{b'\}$ 
8:     if  $b' \notin V(M)$  then  $\triangleright b'$  unmatched
9:        $\Pi \leftarrow$  alternating augmenting path from  $a$  to  $b'$ 
10:      return  $\Pi$ 
11:     else  $\triangleright b'$  is matched to some  $a'' \in A \cap V(M)$ 
12:        $S \leftarrow S \cup \{a''\}$ 
13:   until  $S = A \cup B$ 
14:   return failure
```

Theorem 3.1 (Time for Hungarian algorithm). *Let $G = (A \cup B, A \times B)$ be an instance of geometric partial matching with $r := |A|$, $n := |B|$, $r \leq n$, and parameter $k \leq r$. Suppose the Hungarian search finds each augmenting path in $T(n, k)$ time after a one-time $P(n, k)$ preprocessing time. Then, the Hungarian algorithm finds the optimal size k matching in time $O(P(n, k) + kT(n, k) + k^2)$.*

3.1 Hungarian search

Let S be the set of vertices that can be reached from an unmatched $a \in A$ by admissible residual edges, initially the unmatched vertices of A . The Hungarian search updates potentials in a Dijkstra's algorithm-like manner, expanding S until it includes an unmatched $b \in B$ (and thus an admissible alternating augmenting path). The “search frontier” of the Hungarian search is $(S \cap A) \times (B \setminus S)$. We *relax* the minimum-reduced cost edge in the frontier, changing the potentials of vertices S such that the edge becomes admissible, and adding the head of the edge into S .

The potential update uniformly decreases the reduced costs of the frontier edges. Since (a', b') is the minimum reduced cost frontier edge, the potential update in line 6 does not make any reduced cost negative, and thus preserves the dual feasibility constraint for all edges. The algorithm is shown below as Algorithm 2.

By tracking the forest of relaxed edges (e.g. back pointers), it is straightforward to recover the alternating augmenting path Π once we reach an unmatched $b' \in B$. We make the following observation about the Hungarian search:

Lemma 3.2. *There are at most k edge relaxations before the Hungarian search finds an alternating augmenting path.*

Proof. Each edge relaxation either leads to a matched vertex in B (there are at most $k - 1$ such vertices), or finds an unmatched vertex and ends the search. \square

In general graphs, the minimum edge is typically found by pushing all encountered $(S \cap A) \times (B \setminus S)$ edges into a priority queue. However, in the bipartite complete graph, this may take $\Theta(rn \text{ polylog } n)$ time for each Hungarian search — edges are being pushed into the queue even

when they are not relaxed. We avoid this problem by finding an edge with minimum cost using *bichromatic closest pair* (BCP) queries on an additively weighted Euclidean distances, for which there exist fast dynamic data structures. Given two point sets P and Q in the plane, the BCP is the pair of points $p \in P$ and $q \in Q$ minimizing the (adjusted) distance $\|p - q\| - \omega(p) + \omega(q)$, for some real-valued vertex weights $\omega(p)$. In our setting, the vertex weights will mostly be set as the potentials; the adjusted distance is equal to the reduced cost.

The state of the art dynamic BCP data structure from Kaplan, Mulzer, Roditty, Seiferth, and Sharir [4] supports point insertions and deletions in $O(\text{polylog } n)$ time, and answers queries in $O(\log^2 n)$ time. The following lemma, combined with Theorem 3.1, completes the proof of Theorem 1.1.

Lemma 3.3. *Using the dynamic BCP data structure from Kaplan et al., we can implement Hungarian search with $T(n, k) = O(k \text{ polylog } n)$ and $P(n, k) = O(n \text{ polylog } n)$.*

Proof. Recall that we maintain a BCP data structure between $P = (S \cap A)$ and $Q = (B \setminus S)$. Changes to the P and Q are entirely driven by changing S ; that is, updates to S incur BCP insertions/deletions. We first analyze the bookkeeping besides the potential updates, and then show how potential updates can be implemented efficiently.

1. Let S_0^t denote the initial set S at the beginning of the t -th Hungarian search, that is, the set of unmatched points in A after t augmentations. At the very beginning of the Hungarian algorithm, we initialize $S_0^0 \leftarrow A$ (meaning that $P = A$ and $Q = B$), which is a one-time insertion of $O(n)$ points into BCP, attributed to $P(n, k)$. On each successive Hungarian search, S_0^t shrinks as more and more points in A are matched. Assume for now that, at the beginning of the $(t + 1)$ -th Hungarian search, we are able to construct S_0^t from the previous iteration. To construct S_0^{t+1} , we simply remove the point in A that was matched by the t -th augmenting path. Thus, with that assumption, we are able to initialize S using one BCP deletion operation per augmentation.
2. During each Hungarian search, points are added to P (that is, some points in A are added to S) and removed from Q (points in B added to S), which will happen at most once per edge relaxation. By Lemma 3.2 the number of relaxed edges is at most k , so the number of such BCP operations is also at most k .
3. To obtain S_0^t , we keep track of the points added since S_0^{t-1} in the last Hungarian search (i.e. those of (2)). After the augmentation, we use this log to delete the added vertices from S and recover S_0^t . By the argument in (2) there are $O(k)$ of such points to delete, so reconstructing S_0^t takes $O(k)$ BCP operations.

We spend $P(n, k) = O(n \text{ polylog } n)$ time to build the initial BCP. The number of BCP operations associated with each Hungarian search is $O(k)$, so the time spent on BCP operations in each Hungarian search is $O(k \text{ polylog } n)$.

As for the potential updates, we modify a trick from Vaidya [8] to batch potential updates. Potentials have a *stored value*, i.e. the current value of $\pi(v)$, and a *true value*, which may have changed from $\pi(v)$. The algorithm uses the true value when dealing with reduced costs and updates the stored value rarely; we explain the mechanism shortly.

Throughout the course of the algorithm, we maintain a nonnegative value δ (initially 0) which aggregates potential changes. Vertices that are added to S are immediately added to a BCP data structure with weight $\omega(p) \leftarrow \pi(p) - \delta$, for whatever value δ is at the time of insertion. When the points of S have potentials increased by γ in (2), we instead raise $\delta \leftarrow \delta + \gamma$. Thus, true value for

any potential of a point in S is $\omega(p) + \delta$. For points of $(A \cup B) \setminus S$, the true potential is equal to the stored potential.

Since potentials for S points are uniformly offsetted by δ , the minimum edge returned by the BCP oracle does not change. Once a point is removed from S , we update its stored potential to be $\pi(p) \leftarrow \omega(p) + \delta$, for the current value of δ . Importantly, δ is not reset at the end of a Hungarian search, and persists throughout the entire algorithm. This way, the unmatched points in each S_0^t have their true potentials accurately represented by δ and $\omega(p)$.

The number of updates to δ is equal to the number of edge relaxations, which is $O(k)$ per Hungarian search. We update stored potentials when removing a point from S (by the rewind mechanism, or due to an augmentation) which occurs $O(k)$ times per Hungarian search. The time spent on potential updates per Hungarian search is therefore $O(k)$. Overall, the time spent per Hungarian search is $T(n, k) = O(k \text{ polylog } n)$. □

4 Matching with the Goldberg *et al.* algorithm

In this section, we describe a $(1 + \varepsilon)$ -approximation algorithm for geometric partial matching which proves Theorem 1.2. We build atop a *cost-scaling* algorithm for unit-capacity min-cost flow from Goldberg *et al.* [2]. First, we give a cost-preserving near-linear time reduction from geometric partial matching to unit-capacity min-cost flow, which allows us to apply the cost-scaling algorithm to partial matching.

4.1 MPM to unit-capacity MCF reduction

For a partial matching problem on a bipartite graph $G = (A \cup B, E_0)$ with parameter k , we direct each bipartite edge in E_0 from A to B , with cost equal to the original cost $c(a, b)$ and capacity 1. Next, we add a dummy vertex s with arcs (s, a) to every vertex a in A , and a dummy vertex t with arcs (b, t) for every vertex b in B , all with cost 0 and capacity 1. For each of the above arcs (v, w) , we also add a reverse arc (w, v) with cost $c(w, v) = -c(v, w)$ and capacity 0. Let the complete set of arcs be E , and $V = A \cup B \cup \{s, t\}$. Set $\phi(s) = k$, $\phi(t) = -k$, and $\phi(v) = 0$ for all other vertices. Let the resulting graph be $H = (V, E)$, and the network $N_H = ((V, E), c, u, \phi)$. We call H the *reduction graph* of the partial matching instance on A, B with parameter k , and N_H the *reduction network*.

Observation 4.1. *The arcs of H with positive capacity form a directed acyclic graph.*

In other words, there will be no cycles of positive flow in circulations on H . With this, we can show that the number of arcs used by any integer pseudoflow in H is asymptotically bounded by the excess of the pseudoflow.

Lemma 4.2. *Let f be an integer pseudoflow in H with $O(k)$ excess. Then, $|E_{>0}(f)| = O(k)$.*

Proof. By Observation 4.1, the positive-flow edges of f do not contain a cycle. Thus, $E_{>0}(f)$ can be decomposed into a set of inclusion-maximal paths, each of which creates a single unit of excess if it does not terminate at t . A path may also create excess at t if there are at least k other paths terminating at t . By assumption, there are $O(k)$ units of excess to which we can associate paths, and at most k paths that we cannot associate with a unit of excess. The maximum length of any path with positive-flow arcs in H is 3 by construction. We conclude that the number of positive flow arcs in f is $O(k)$. □

It is straightforward to show that any integer circulation on H uses exactly k of the A -to- B arcs, which correspond to the edges of a size- k matching. For a circulation f in H , we use M_f to denote the corresponding matching.

Observation 4.3. *Let f be an integer circulation on H ; f uses exactly k of the A -to- B arcs which correspond to a size k matching on A, B . Call this matching M_f , then $\text{cost}(f) = \text{cost}(M_f)$*

Observe that $\text{cost}(f) = \text{cost}(M_f)$, so an α -approximation to the MCF problem on H is an α -approximation to the matching problem on G . In the next lemma, we show how ε -optimality implies approximation on H .

Lemma 4.4. *Let f an ε -optimal integer circulation in H , and f^* an optimal integer circulation for H . Then, $\text{cost}(f) \leq \text{cost}(f^*) + 6k\varepsilon$.*

Proof. We label the arcs of the residual network H_f as follows:

- **forward arcs:** arcs directed from s -to- A or A -to- B or B -to- t , and
- **reverse arcs:** arcs point in the opposite directions.

Reverse arcs must be induced by positive flow in the opposite direction (forward arc between the same points), since H only has arcs in the forward direction. Since f is a circulation, $E_{>0}(f)$ can be decomposed into k paths from s to t . Each s -to- t path in H is length 3, so the total number of reverse arcs is $3k$.

There exists a residual flow g in H_f such that $f + g = f^*$. Since both f and f^* are both circulations and H is unit-capacity, g is comprised of unit flows on a collection edge-disjoint residual cycles, $\Gamma_1, \dots, \Gamma_\ell$. Observe that each residual cycle Γ_i must have exactly half of its arcs being reverse arcs, thus $\sum_i |\Gamma_i| \leq 6k$.

Let π be a set of potentials which certify that f is ε -optimal. For residual cycles, we have that $c_\pi(\Gamma_i) = c(\Gamma_i)$, since the potential terms telescope. We then see that

$$\text{cost}(f) - \text{cost}(f^*) = \sum_i c(\Gamma_i) = \sum_i c_\pi(\Gamma_i) \geq \sum_i |\Gamma_i|(-\varepsilon) \geq -6k\varepsilon,$$

where the second-to-last inequality follows from the ε -optimality of f with respect to π . Rearranging, we have that $\text{cost}(f) \leq \text{cost}(f^*) + 6k\varepsilon$. \square

Corollary 4.5. *Let f an $(\varepsilon/6k)$ -optimal integer circulation in H , and f^* an optimal integer circulation for H . Then, $\text{cost}(f) \leq \text{cost}(f^*) + \varepsilon$.*

We use a technique from Sharathkumar and Agarwal [7] to transform this additive ε approximation into a relative $(1 + \varepsilon)$ approximation for geometric matching. Let \mathcal{T} be the minimum spanning tree (MST) of $A \cup B$ and order its edges by decreasing length as e_1, \dots, e_{r+n-1} . Let T_i be the connected components of \mathcal{T} induced by $e_{i+1}, \dots, e_{r+n-1}$, i.e. from removing all MST edges of length at least $c(e_i)$. For each component $T \in T_i$, let $A_T = T \cap A$ and $B_T = T \cap B$ respectively.

Let j_1 be minimum index such that there exists a component $T \in T_{j_1}$ with $|A_T| \neq |B_T|$. Choose j_2 to be the maximum index such that $c(e_{j_2}) \geq n^2 c(e_{j_1})$. We partition A, B into the sets A_T, B_T for each $T \in T_{j_2}$. Since $j_2 < j_1$, $|A_T| = |B_T|$ for all $T \in T_{j_2}$.

Lemma 4.6 ([7], Section 3.5). *Consider the partition of A, B into sets A_T, B_T for each $T \in T_{j_2}$. Let M^* be the optimal matching on A, B and M_T^* be the optimal matching on $T \in T_{j_2}$, and let the diameter of a component T be $C_T := \max_{p, q \in A_T \cup B_T} \|p - q\|$. Then,*

- (i) $M^* = \bigcup_{T \in T_{j_2}} M_T^*$,
- (ii) $C_T \leq kn^2 c(e_{j_1})$ for all $T \in T_{j_2}$, and
- (iii) $c(e_{j_1}) \leq \text{cost}(M^*)$.

Furthermore, this partition can be constructed in $O(n \text{ polylog } n)$ time using a dynamic data structure for bichromatic closest pair.

The proof of these properties can be found in the original paper [7, Section 3.5], but we reproduce the rest of their proof below (tailored for ε -optimality). Given this lemma, we can construct the MCF reduction network N_H for each component $T = A_T \cup B_T$, find an $(\varepsilon c(e_{j_1})/6kn)$ -optimal circulation f_T for each, and then $\bigcup_{T \in T_{j_2}} M_{f_T}$ is a $(1 + \varepsilon)$ -approximate partial matching for A, B . Let f_T^* be the optimal flow on H for the component T . By combining Corollary 4.5, Observation 4.3, and Lemma 4.6,

$$\begin{aligned}
\text{cost}\left(\bigcup_{T \in T_{j_2}} M_{f_T}\right) &= \sum_{T \in T_{j_2}} \text{cost}(M_{f_T}) \\
&= \sum_{T \in T_{j_2}} \text{cost}(f_T) \\
&\leq \sum_{T \in T_{j_2}} \text{cost}(f_T^*) + \varepsilon c(e_{j_1})/n \\
&= \sum_{T \in T_{j_2}} \text{cost}(M_T^*) + \varepsilon c(e_{j_1})/n \\
&\leq \text{cost}(M^*) + \varepsilon c(e_{j_1}) \\
&\leq (1 + \varepsilon) \text{cost}(M^*).
\end{aligned}$$

Corollary 4.7. *If an algorithm can compute $(\varepsilon c(e_{j_1})/6kn)$ -optimal circulation for the reduction network N_H of a point set with diameter $C \leq kn^2 \cdot c(e_{j_1})$, then we can find a $(1 + \varepsilon)$ -approximate partial matching of A, B , after $O(n \text{ polylog } n)$ extra preprocessing time.*

4.2 Algorithm description

Pseudocode for the cost-scaling algorithm is given in Algorithm 3. The Goldberg *et al.* [2] algorithm is based on *cost-scaling* or *successive approximation*, originally due to Goldberg and Tarjan [3]. The algorithm finds ε -optimal circulations for geometrically shrinking values of ε . Each iteration of the outer loop (where ε holds single value) is called a *cost scale*. Once ε is sufficiently small, the ε -optimal flow is a suitable approximation (or even an optimal flow itself when costs are integers) [3, 2]. We present this algorithm as an approximation is because costs in the geometric partial matching settings (with respect to Euclidean distances) are generally not integers.

Note that the zero flow is trivially kC -optimal for H . At the beginning of each scale, SCALE-INIT takes the previous circulation (now 2ε -optimal) and transforms it into an ε -optimal pseudoflow with $O(k)$ excess. For the rest of the scale, the procedure REFINE, reduces the excess in the newly constructed pseudoflow to zero, making it an ε -optimal circulation. Thus, the algorithm produces an ε^* -optimal circulation after $O(\log(kC/\varepsilon^*))$ scales.

Lemma 4.8. *For each subproblem in Corollary 4.7, the cost-scaling algorithm requires $O(\log(kn/\varepsilon^*))$ scales.*

Algorithm 3 Cost-Scaling MCF

```

1: function MCF( $H, \varepsilon^*$ )
2:    $\varepsilon \leftarrow kC, f \leftarrow 0, \pi \leftarrow 0$ 
3:   while  $\varepsilon > \varepsilon^*/6$  do
4:      $(f, \pi) \leftarrow \text{SCALE-INIT}(H, f, \pi)$ 
5:      $(f, \pi) \leftarrow \text{REFINE}(H, f, \pi)$ 
6:      $\varepsilon \leftarrow \varepsilon/2$ 
7:   return  $f$ 

```

Proof. Recall that the subproblems in Corollary 4.7 have diameter $C \leq kn^2 \cdot c(e_{j_1})$ and ask for an $(\varepsilon^* c(e_{j_1})/6kn)$ -optimal circulation. The number of cost scales is bounded above by

$$O(\log(kC/\varepsilon^*)) = O\left(\log\left(\frac{kn^2 \cdot c(e_{j_1})}{\varepsilon^* c(e_{j_1})/6kn}\right)\right) = O(\log(kn/\varepsilon^*)).$$

□

4.3 SCALE-INIT

The procedure is described in Algorithm 4.

Algorithm 4 Scale Initialization

```

1: function SCALE-INIT( $H, f, \pi$ )
2:    $\forall a \in A, \pi(a) \leftarrow \pi(a) + \varepsilon$ 
3:    $\forall b \in B, \pi(b) \leftarrow \pi(b) + 2\varepsilon$ 
4:    $\pi(t) \leftarrow \pi(t) + 3\varepsilon$ 
5:   for all  $(v, w) \in E_{>0}(f)$  do
6:     if  $c_\pi(w, v) < -\varepsilon$  then
7:        $f(v, w) \leftarrow 0$ 
8:   return  $(f, \pi)$ 

```

Let the H_f arcs directed from $s \rightarrow A$ or $A \rightarrow B$ or $B \rightarrow t$ be *forward arcs*, and let those in the opposite directions be *reverse arcs*. The first four lines of SCALE-INIT raise the reduced cost of each forward arc by ε , therefore making all forward arcs ε -optimal. In the lines after, we deal with the reduced cost of reverse arcs by simply de-saturating them if they violate ε -optimality. Note that forward arcs will not be de-saturated in this step, since they are now ε -optimal.

Lemma 4.9. SCALE-INIT turns a 2ε -optimal circulation into an ε -optimal pseudoflow with $O(k)$ excess in $O(n)$ time.

Proof. The potential updates affect every vertex except s , so this takes $O(n)$ time. As for the arc de-saturation, every reverse arc is induced by positive flow on a forward arc, and the number of positive flow edges in f is $O(k)$ by Lemma 4.2. The total number of edges examined by the loop is $O(k)$. In total, this takes $O(n)$ time.

Notice that new excess vertex is only created due to the de-saturation of reverse arcs. Because the arcs in the graph has unit capacity, each de-saturation creates one unit of excess. By Lemma 4.2, there are $|E_{>0}(f)| = O(k)$ reverse arcs, so the total excess created must be $O(k)$. □

4.4 REFINE

REFINE is implemented using a primal-dual augmentation algorithm, which sends improving flows on admissible edges like the Hungarian algorithm. Unlike the Hungarian algorithm, it uses blocking flows instead of augmenting paths.

Algorithm 5 Refinement

```

1: function REFINE( $H = (V, E), f, \pi$ )
2:   while  $\sum_{v \in V} |e_f(v)| > 0$  do
3:      $\pi \leftarrow \text{HUNGARIAN-SEARCH2}(H, f, \pi)$ 
4:      $f' \leftarrow \text{DFS}(H, f, \pi)$   $\triangleright f'$  is an admissible blocking flow
5:      $f \leftarrow f + f'$ 
6:   return  $(f, \pi)$ 

```

Using the properties of blocking flows and the unit-capacity input graph, Goldberg *et al.* [2] prove that there are $O(k)$ blocking flows before excess becomes 0, but on a slightly different reduction graph and under a slightly different model of minimum-cost flow. We provide a sketch of their proof technique adapted for the reduction network N_H .

Lemma 4.10 (Goldberg *et al.* [2, Lemma 3.11 and §6]). *Let f be a pseudoflow in H with $O(k)$ excess. There are $O(\sqrt{k})$ blocking flows before excess is 0.*

Proof. □

An *iteration* of REFINE is a complete execution of the main loop in Algorithm 5. Each iteration of REFINE finds an admissible blocking (improving) flow in two stages, and then augments the current pseudoflow by the blocking flow.

1. A *Hungarian search*, which updates duals in a Dijkstra-like manner until there is an excess-deficit path of admissible edges. This is different from the procedure HUNGARIAN-SEARCH used for matching. We call the procedure HUNGARIAN-SEARCH2 to distinguish.
2. A *depth-first search* (DFS) through the set of admissible edges to construct an admissible blocking flow. It suffices to repeatedly extract admissible augmenting paths until no more admissible excess-deficit paths remain. By definition, the union of such paths is a blocking flow.

Both procedures traverse the residual graph using admissible arcs from the set of excess vertices. Each step of these procedures *relaxes* a minimum-reduced cost arc from a visited vertex to an unvisited vertex, until a deficit vertex is visited. We associate each relaxation step with its newly-visited vertex.

Lemma 4.11. *Suppose HUNGARIAN-SEARCH2 can be implemented in $T_1(n, k)$ time after a once-per-REFINE $P_1(n, k)$ time preprocessing, and DFS can be implemented in $T_2(n, k)$ time after $P_2(n, k)$ preprocessing. Then, REFINE can be implemented in time*

$$O(P_1(n, k) + P_2(n, k) + \sqrt{k}T_1(n, k) + \sqrt{k}T_2(n, k) + k\sqrt{k}).$$

As we will show shortly (Lemmas 4.18 and 4.22), the total running time for REFINE is $O((n + k\sqrt{k}) \text{polylog } n)$. Combining with Lemmas 4.8 and 4.9 completes the proof of Theorem 1.2. At a high level, our analysis strategy is to charge relaxation events in the search to arcs of $E_{>0}(f)$. We first extend Lemma 4.2 to bound the size of $E_{>0}(f)$ throughout REFINE, by observing that the amount of excess decreases in each iteration of REFINE.

Corollary 4.12. *Let f be the pseudoflow before or after any iteration of REFINE. Then, $|E_{>0}(f)| = O(k)$.*

We discuss some challenges of our analysis and resolve them, before giving the details of HUNGARIAN-SEARCH2 and DFS.

4.4.1 Empty vertices and the shortcut graph

As it turns out, there are some vertices whose relaxation events we cannot charge to the support size. However, we can replace H_f with an equivalent graph that excludes them, and run HUNGARIAN-SEARCH2 and DFS on the resulting graph.

We say $v \in A \cup B$ is an **empty vertex** if $e_f(v) = 0$ and no edges of $E_{>0}(f)$ adjoin v . We are unable to charge relaxation steps involving empty vertices to $|E_{>0}(f)|$, so the algorithm must deal with them separately. Namely, there is no edge with $f(e) > 0$ adjacent to an empty vertex, reaching an empty vertex does not terminate the search, and there may be $\Omega(n)$ empty vertices at once (consider $H_{f=0}$, the residual graph of the empty flow). We use A_\emptyset and B_\emptyset to denote the empty vertices of A and B respectively. Vertices that are not empty are called **non-empty vertices**.

For an empty vertex v , either residual in-degree ($v \in A_\emptyset$) or residual out-degree ($v \in B_\emptyset$) is 1. Call a length 2 paths through v to/from non-empty vertices an **empty 2-path**. For example, if $v \in A_\emptyset$ (resp. $v \in B_\emptyset$), then its empty 2-paths have the form (s, v, b) (resp. (a, v, t)) for each $b \in B \setminus B_\emptyset$ (resp. $a \in A \setminus A_\emptyset$). We say that (s, v, b) is an empty 2-path **surrounding** empty vertex v . Separately, we define the length 3 s - t paths that pass through two empty vertices to be **empty 3-paths**. As with 2-paths, we say an empty 3-path (s, v_1, v_2, t) surrounds $v_1 \in A_\emptyset$ and $v_2 \in B_\emptyset$.

As for the costs of empty paths, consider an empty 2-path (s, v, b) that surrounds $v \in A_\emptyset$. Because reduced costs telescope for residual paths, the reduced cost of (s, v, b) does not depend on the potential of v .

$$c_\pi((s, v, b)) = c_\pi(s, v) + c_\pi(v, b) = c(v, b) - \pi(s) + \pi(b)$$

Something similar holds for empty 2-paths surrounding B_\emptyset vertices, and empty 3-paths.

We construct the **shortcut graph** \tilde{H}_f from H_f by removing all empty vertices and their adjacent edges, and then inserting a direct arc between the end points of each empty path Π of equal cost. We call this direct edge the **shortcut** $\text{short}(\Pi)$ of empty path Π . For example, the empty 2-path (s, v, b) for $v \in A_\emptyset$ is replaced with a shortcut (s, b) of cost $c(\text{short}(s, v, b)) := c(v, b)$. Similarly, the empty 3-path (s, v_1, v_2, t) would be replaced with a shortcut (s, t) of cost $c(\text{short}((s, v_1, v_2, t))) := c(v_1, v_2)$.

The resulting multigraph \tilde{H}_f contains only the non-empty vertices of V , and has the same connectivity between non-empty vertices as H_f . Consider a path Π from non-empty v to non-empty w in H_f . Any empty vertex in Π is surrounded by an empty 2- or 3-path contained in Π , since the only nontrivial residual paths through an empty vertex are its surrounding empty paths. Thus, there is a corresponding v -to- w path $\tilde{\Pi}$ in \tilde{H}_f by replacing each empty path contained in Π with its shortcut. Furthermore, we have $c(\Pi) = c(\tilde{\Pi})$. We argue now that \tilde{H}_f is fine as a surrogate for H_f , by showing that we can recover ε -optimal potentials for the non-empty vertices.

Lemma 4.13. *Let $\tilde{\pi}$ be a ε -optimal set of potentials for non-empty vertices of H_f . Construct potentials π , extending $\tilde{\pi}$ to empty vertices, by setting $\pi(a) \leftarrow \tilde{\pi}(s)$ for $a \in A_\emptyset$ and $\pi(b) \leftarrow \tilde{\pi}(t)$ for $b \in B_\emptyset$. Then,*

1. π is a set of ε -optimal potentials for H_f , and
2. if a shortcut $\text{short}(\Pi)$ is admissible under $\tilde{\pi}$, then every arc of Π is admissible under π .

Proof. Reduced costs for non-empty to non-empty arcs are unchanged between $\tilde{\pi}$ and π , so ε -optimality are preserved for these. Recall that an empty path is comprised of one A -to- B arc, and 1 or 2 zero-cost arcs (connecting the empty vertex/vertices to s and t). With our choice of empty vertex potentials, we observe that the zero-cost arcs have reduced cost 0: for an empty $a \in A_\emptyset$, $c_\pi(s, a) = 0$, for an empty $b \in B_\emptyset$, $c_\pi(b, t) = 0$. These arcs are both ε -optimal ($\geq -\varepsilon$) and admissible (≤ 0), so it remains to prove ε -optimality and admissibility for arcs (a, b) where either a or b is an empty vertex.

Let $(a, b) \in A \times B$ such that at least one of a or b is empty. There exists an empty path Π that contains (a, b) . Observe that $c_\pi(a, b) = c_\pi(\Pi)$, which we can prove for all varieties of empty paths.

- If $\Pi = (s, a, b)$ for $a \in A_\emptyset$:

$$c_\pi(a, b) = c(a, b) - \pi(a) + \pi(b) = c(a, b) - \pi(s) + \pi(b) = c_\pi(\Pi)$$

- If $\Pi = (a, b, t)$ for $b \in B_\emptyset$:

$$c_\pi(a, b) = c(a, b) - \pi(a) + \pi(b) = c(a, b) - \pi(a) + \pi(t) = c_\pi(\Pi)$$

- If $\Pi = (s, a, b, t)$ for $a \in A_\emptyset$ and $b \in B_\emptyset$:

$$c_\pi(a, b) = c(a, b) - \pi(a) + \pi(b) = c(a, b) - \pi(s) + \pi(t) = c_\pi(\Pi)$$

By construction, $c_\pi(\Pi) = c_{\tilde{\pi}}(\text{short}(\Pi))$, so we have $c_\pi(a, b) = c_{\tilde{\pi}}(\text{short}(\Pi)) \geq -\varepsilon$ and (a, b) is ε -optimal. Additionally, if $\text{short}(\Pi)$ is admissible under $\tilde{\pi}$, then so is (a, b) under π . Empty paths cover all arcs adjoining empty vertices, so we have proved both parts of the lemma for all arcs in H_f . \square

In **REFINE**, we do not explicitly construct \tilde{H}_f for running **HUNGARIAN-SEARCH2** or **DFS**, but query its edges using **BCP/NN** oracles and min/max heaps on elements of H_f . Potentials for empty vertices are only required at the end of **REFINE** (for the next scale), and right before an augmentation sends flow through an empty path, making its surrounded vertices non-empty. During these occasions, we use the procedure in Lemma 4.13 to find feasible, ε -optimal potentials for empty vertices which also preserve the structure of admissibility.

Lemma 4.14. *The number of end-of-REFINE empty vertex potential updates is $O(n)$. The number of augmentation-induced empty vertex potential updates in each invocation of **REFINE** is $O(\sum_i N_i)$ where N_i is the number of positive flow arcs in the i -th blocking flow.*

Proof. The number of end-of-REFINE potential updates is $O(n)$. Each update due to flow augmentation involves a blocking flow sending positive flow through an empty path, causing a potential update on the surrounded empty vertex. We charge this potential update to the edges of that empty path, which are in turn arcs with positive flow in the blocking flow. For each blocking flow, no positive arc is charged more than twice. It follows that the number of augmentation-induced updates is $O(N_i)$ for the i -th blocking flow, and $O(\sum_i N_i)$ over the course of **REFINE**. \square

Ultimately, we prove that $\sum_i N_i = O(k\sqrt{k})$, but this requires that we explain the process creating each blocking flow. We revisit this lemma after analyzing **DFS**.

Algorithm 6 Hungarian Search (cost-scaling)

```

1: function HUNGARIAN-SEARCH2( $H = (V, E), f, \pi$ )
2:    $\tilde{H}_f \leftarrow$  the shortcut graph of  $H_f$ 
3:    $S \leftarrow \{v \in V \mid e_f(v) > 0\}$ 
4:   repeat
5:      $(v', w') \leftarrow \arg \min \{c_\pi(v', w') \mid v' \in S, w' \notin S, (v', w') \in \tilde{H}_f\}$ 
6:      $\gamma \leftarrow c_\pi(v', w')$ 
7:     if  $\gamma > 0$  then  $\triangleright$  make  $(v', w')$  admissible if it isn't
8:        $\pi(v) \leftarrow \pi(v) + \gamma \lceil \frac{\gamma}{\epsilon} \rceil, \forall v \in S$ 
9:        $S \leftarrow S \cup \{w'\}$ 
10:      if  $e_f(w') < 0$  then  $\triangleright$  reached a deficit
11:      return  $\pi$ 
12:   until  $S = (A \setminus A_\emptyset) \cup (B \setminus B_\emptyset)$ 
13:   return failure

```

4.4.2 Hungarian search

Logically, we are executing the Hungarian search (“raise prices”) from [2, Section 3.2] on the shortcut graph \tilde{H}_f . We describe how we can query the minimum-reduced cost arc leaving S in $O(\text{polylog } n)$ time, for the shortcut graph, without constructing \tilde{H}_f explicitly. For this purpose, let S' be a set of “reached” vertices maintained alongside S , identical except whenever a shortcut is relaxed, we add its surrounded empty vertices to S' in addition to its (non-empty) endpoints. Observe that the arcs of \tilde{H}_f leaving S fall into $O(1)$ categories.

1. Non-shortcut reverse arcs (v, w) with $(w, v) \in E_{>0}(f)$. For these, we can maintain a min-heap on $E_{>0}(f)$ arcs as each v arrives in S .
2. Non-shortcut A -to- B forward arcs. For these, we can use a BCP data structure between $(A \setminus A_\emptyset) \cap S$ and $(B \setminus B_\emptyset) \setminus S$, weighted by potential.
3. Non-shortcut forward arcs from s -to- A and from B -to- t . For s , we can maintain a min-heap on the potentials of $B \setminus S$, queried while $s \in S$. For t , we can maintain a max-heap on the potentials of $A \cap S$, queried while $t \notin S$.
4. Shortcut arcs (s, b) corresponding to empty 2-paths from s to $b \in (B \setminus B_\emptyset) \setminus S'$. For these, we maintain a BCP data structure with $P = A_\emptyset$, $Q = (B \setminus B_\emptyset) \setminus S'$ with weights $\omega(p) = \pi(s)$ for all $p \in P$, and $\omega(q) = \pi(q)$ for all $q \in Q$. A response (a, b) corresponds to th empty 2-path (s, a, b) . This is only queried while $s \in S'$.
5. Shortcut arcs (a, t) corresponding to empty 2-paths from $a \in (A \setminus A_\emptyset) \cap S'$ to t . For these, we maintain a BCP data structure with $P = (A \setminus A_\emptyset) \cap S'$, $Q = B_\emptyset \setminus S'$ with weights $\omega(p) = \pi(p)$ for all $p \in P$, and $\omega(q) = \pi(t)$ for all $q \in Q$. A response (a, b) corresponds to th empty 2-path (a, b, t) . This is only queried while $t \notin S'$.
6. Shortcut arcs (s, t) corresponding to empty 3-paths. For these, we maintain in a BCP data structure with $P = A_\emptyset \setminus S'$, $Q = B_\emptyset \setminus S'$ with weights $\omega(p) = \pi(s)$ for all $p \in P$, and $\omega(q) = \pi(t)$ for all $q \in Q$. A response (a, b) corresponds to th empty 3-path (s, a, b, t) . This is only queried while $s \in S'$ and $t \notin S'$.

By construction, the BCP distance of each datastructure in (4-6) is equal to the reduced cost of the shortcut, which is equal to the reduced cost of the corresponding empty path. Each of the above data structures requires one query per relaxation, and an insertion/deletion operation whenever a new vertex moves into S . The data structures above can perform both in $O(\text{polylog } n)$ time each, so the running time of HUNGARIAN-SEARCH2 outside of potential updates can be bounded in the number of relaxation steps.

Lemma 4.15. *There are $O(k)$ non-shortcut relaxations in HUNGARIAN-SEARCH2 before a deficit vertex is reached.*

Proof. Each edge relaxation adds a new vertex to S , and non-shortcut relaxations only add non-empty vertices. The vertices of $V \setminus S$ fall into several categories: (i) s or t , (ii) A or B vertex with 0 imbalance, and (iii) A or B vertex with deficit (S contains all excess vertices). The number of vertices in (i) and (iii) is $O(k)$, leaving us to bound the number of (ii) vertices.

An A or B vertex with 0 imbalance must have an even number of $E_{>0}(f)$ edges. There is either only one positive-capacity incoming edge (for A) or outgoing edge (for B), so this quantity is either 0 or 2. Since the vertex is non-empty, this must be 2. We charge 0.5 to each of the two $E_{>0}(f)$ edges; the edges of $E_{>0}(f)$ have no more than 1 charge each. Thus, the number of (ii) vertex relaxations is $O(|E_{>0}(f)|)$. By Corollary 4.12, $O(|E_{>0}(f)|) = O(k)$. \square

Lemma 4.16. *There are $O(k)$ shortcut relaxations in HUNGARIAN-SEARCH2 before a deficit vertex is reached.*

Proof. Recall the categories of shortcuts from the list of datastructures above. We have shortcuts corresponding to (i) empty 2-paths surrounding $a \in A_\emptyset$, (ii) empty 2-paths surrounding $b \in B_\emptyset$, and (iii) empty 3-paths, which go from s to t .

There is only one relaxation of type (iii), since t can only be added to S once. The same argument holds for type (ii).

Each type (i) relaxation adds some non-empty $b \in B \setminus B_\emptyset$ into S . Since b is non-empty, it must either have deficit or an adjacent edge of $E_{>0}(f)$. We charge this relaxation to b if it is deficit, or the adjacent $E_{>0}(f)$ edge otherwise. No vertex is charged more than once, and no $E_{>0}(f)$ edge is charged more than twice, therefore the total number of type (i) relaxations is $O(|E_{>0}(f)|)$. By Corollary 4.12, $O(|E_{>0}(f)|) = O(k)$. \square

Corollary 4.17. *There are $O(k)$ relaxations in HUNGARIAN-SEARCH2 before a deficit vertex is reached.*

In the following lemma, we complete the time analysis of HUNGARIAN-SEARCH2 by proving that potentials can be maintained in $O(k)$ time over the course of the search.

Lemma 4.18. *Using a dynamic BCP, we can implement HUNGARIAN-SEARCH2 with $T_1(n, k) = O(k \text{ polylog } n)$ and $P_1(n, k) = O(n \text{ polylog } n)$.*

Proof. The initial sets for each data structure can be constructed in $O(n \text{ polylog } n)$ time. For each of the $O(1)$ data structures that are queried during a relaxation, the new vertex moved into S as a result of the relaxation causes $O(1)$ insertion/deletion operations. For each of the data structures mentioned above, insertions and deletions can be performed in $O(\text{polylog } n)$ time. Using Lemma 3.3 as a basis, we first analyze the number of BCP operations over the course of HUNGARIAN-SEARCH2.

1. Let S_0^t denote the initial set S at the beginning of the t -th Hungarian search, i.e. the set of $v \in V$ with $e_f(v) > 0$ after t blocking flows. Assume for now that, at the beginning of the

$(t + 1)$ -th Hungarian search, we have on hand the S_0^t from the previous iteration. To construct S_0^{t+1} , we remove the vertices that had excess decreased to 0 by the t -th blocking flow. Thus, with that assumption, we are able to initialize S at the cost of one BCP deletion per excess vertex, which sums to $O(k)$ over the entire course of REFINE.

2. During each Hungarian search, a vertex entering S may cause P or Q to update and incur one BCP insertion/deletion. Like before, we can charge these to the number of edge relaxations over the course of HUNGARIAN-SEARCH2. The number of these is $O(k)$ by Corollary 4.17.
3. Like before, we can meet the assumption in (1) by rewinding a log of point additions to S , and recover S_0^t .

For potential updates, we use the same trick as in Lemma 3.3 to lazily update potentials after vertices leave S , but only for non-empty vertices. Non-empty vertices are stored in each data structure with weight $\omega(v) = \pi(v) - \delta$, and δ is increased in lieu of increasing the potential of all S vertices. When vertices leave S (through the rewind mechanism above), we restore their potentials as $\pi(v) \leftarrow \omega(v) + \delta$. With lazy updates, the number of potential updates on non-empty vertices is bounded by the number of relaxations in the Hungarian search, which is $O(k)$ by Corollary 4.17. Note that empty vertex potentials are not handled in HUNGARIAN-SEARCH2. \square

4.4.3 Depth-first search

Algorithm 7 Depth-first search

```

1: function DFS( $H = (V, E), f, \pi$ )
2:    $\tilde{H}_f \leftarrow$  the shortcut graph of  $H_f$ 
3:    $f' \leftarrow 0$ .
4:    $S \leftarrow \{v \in V \mid e_f(v) > 0\}$ 
5:    $S_0 \leftarrow \{v \in V \mid e_f(v) > 0\}$  ▷ stack of excess vertices
6:    $P \leftarrow \text{POP}(S_0)$  ▷ current path; stack
7:   repeat
8:      $v' \leftarrow \text{PEEK}(P)$ 
9:     if  $e_f(v') < 0$  then ▷ if we reached a deficit, save the path to  $f'$ 
10:      add to  $f'$  a unit flow on the path  $P$ 
11:       $P \leftarrow \text{POP}(S_0)$ 
12:     else
13:        $w' \leftarrow \arg \min \{c_\pi(v', w') \mid w' \notin S, (v', w') \in \tilde{H}_f\}$ 
14:        $\gamma \leftarrow c_\pi(v', w')$ 
15:       if  $\gamma \leq 0$  then ▷ if  $(v', w')$  is admissible, extend the current path
16:          $S \leftarrow S \cup \{w'\}$ 
17:          $P \leftarrow \text{PUSH}(P, w')$ 
18:       else ▷ No admissible arcs leaving  $v'$ , remove from  $P$ 
19:          $\text{POP}(P)$ 
20:   until  $S_0 = \emptyset$ 
21:   return  $f'$ 

```

The depth-first search is similar to HUNGARIAN-SEARCH2 in that it uses the relaxation of minimum-reduced cost arcs/empty paths, this time to identify admissible arcs/empty paths

in a depth-first manner. This requires some adjustments to the data structures for finding the minimum-reduced cost arc leaving $v' \in S$. Given $v' \in S$, we would like to query:

1. Non-shortcut reverse arcs (v', w') with $(w', v') \in E_{>0}(f)$. For these, we can maintain a min-heap on $(w', v') \in E_{>0}(f)$ arcs for each non-empty $v' \in V$.
2. Non-shortcut A -to- B forward arcs. For these, we maintain a NN data structure over $P = (B \setminus B_\emptyset) \setminus S$, with weights $\omega(p) = \pi(p)$ for each $p \in P$. We subtract $\pi(v')$ from the NN distance to recover the reduced cost of the arc from v' .
3. Non-shortcut forward arcs from s -to- A and from B -to- t . For s , we can maintain a min-heap on the potentials of $B \setminus S$, queried only if $v' = s$. For B -to- t arcs, there is only one arc to check if $v' \in B$, which we can examine manually.
4. Shortcut arcs (s, b) corresponding to empty 2-paths from s to $b \in (B \setminus B_\emptyset) \setminus S'$. For these, we maintain a BCP data structure with $P = A_\emptyset$, $Q = (B \setminus B_\emptyset) \setminus S'$ with weights $\omega(p) = \pi(s)$ for all $p \in P$, and $\omega(q) = \pi(q)$ for all $q \in Q$. A response (a, b) corresponds to the empty 2-path (s, a, b) . This is only queried if $v' = s$.
5. Shortcut arcs (a, t) corresponding to empty 2-paths from $a \in (A \setminus A_\emptyset) \cap S'$ to t . For these, we maintain a NN data structure over $P = B_\emptyset \setminus S'$ with weights $\omega(p) = \pi(t)$ for each $p \in P$. A response (v', b) corresponds to the empty 2-path (v', b, t) . We subtract $\pi(v')$ from the NN distance to recover the reduced cost of the arc from v' . This is not queried if $t \in S$.
6. Shortcut arcs (s, t) corresponding to empty 3-paths. For these, we maintain in a BCP data structure with $P = A_\emptyset \setminus S'$, $Q = B_\emptyset \setminus S'$ with weights $\omega(p) = \pi(s)$ for all $p \in P$, and $\omega(q) = \pi(t)$ for all $q \in Q$. A response (a, b) corresponds to the empty 3-path (s, a, b, t) . This is only queried while $v' = s$ and $t \notin S'$.

Each data structure above performs $O(\text{polylog } n)$ time worth of query and insertion/deletion per relaxation, so the running time is again bounded by $O(\text{polylog } n)$ times the number of relaxations. Since the pseudoflow is not changed within DFS (since the end of HUNGARIAN-SEARCH2), the proofs from Lemmas 4.15 and 4.16 can be recycled for DFS.

Lemma 4.19. *There are $O(k)$ non-shortcut relaxations in DFS before a deficit vertex is reached.*

Lemma 4.20. *There are $O(k)$ shortcut relaxations in DFS before a deficit vertex is reached.*

Corollary 4.21. *There are $O(k)$ relaxations in DFS before a deficit vertex is reached.*

There are no potentials to update within DFS, so the running time of DFS boils down to the time spent to querying and updating the data structures.

Lemma 4.22. *Using a dynamic NN, we can implement DFS with $T_2(n, k) = O(k \text{ polylog } n)$ and $P_2(n, k) = O(n \text{ polylog } n)$.*

Proof. At the beginning of REFINE, we can initialize the $O(1)$ data structures used in DFS in $P_2(n, k) = O(n \text{ polylog } n)$ time. We use the same rewinding mechanism as HUNGARIAN-SEARCH2 (Lemma 4.18) to avoid reconstructing the data structures across iterations of REFINE, so the total time spent is bounded by the $O(\text{polylog } n)$ times the number of relaxations. By Corollary 4.21, we obtain $T_2(n, k) = O(k \text{ polylog } n)$. \square

4.4.4 Size of the blocking flow and completing time analysis

With Lemmas 4.18 and 4.22, we can complete the proof of Lemma 4.11 (time per REFINE) by bounding the total number of arcs whose flow is updated by a blocking flow during REFINE. This bounds both the time spent updating the flow value of these arcs, and also the time spent on empty vertex potential updates (Lemma 4.14).

Lemma 4.23. *Let N_i be the number of positive flow arcs in the i -th blocking flow of REFINE. Then, $\sum_i N_i = O(k\sqrt{k})$.*

Proof. Let i be fixed and consider the invocation of DFS which produces the i -th blocking flow f_i . DFS constructs f_i as a sequence of admissible excess-deficit paths, which appear as path P in Algorithm 7. Every arc in P is an arc relaxed by DFS, so N_i is bounded by the number of relaxations performed in DFS. Using Corollary 4.21, we have $N_i = O(k)$.

By Lemma 4.10, there are $O(\sqrt{k})$ iterations of REFINE before it terminates. Summing, we see that $\sum_i N_i = O(k\sqrt{k})$. \square

We now complete the proof of Lemma 4.11. There $O(\sqrt{k})$ iterations of REFINE, each of which executes HUNGARIAN-SEARCH2 and DFS. By Lemmas 4.18 and 4.22, these calls take $O(T_1(n, k) + T_2(n, k)) = O(k \text{ polylog } n)$ time per iteration. HUNGARIAN-SEARCH2 and DFS require some once-per-REFINE preprocessing to initialize data structures in $P_1(n, k) + P_2(n, k) = O(n \text{ polylog } n)$ time. Outside of these, we need to account for the time spent on flow value updates and augmentation-induced empty vertex potential updates. By Lemma 4.23, the former is $O(k\sqrt{k})$ over the course of REFINE. Combining Lemmas 4.23 and 4.14, the time for the latter is also $O(k\sqrt{k})$.

Filling in the values of $P_1(n, k)$, $P_2(n, k)$, $T_1(n, k)$, and $T_2(n, k)$, the total time for REFINE is $O((n + k\sqrt{k}) \text{ polylog } n)$. Together with Lemmas 4.8 and 4.9, this completes the proof of Theorem 1.2.

5 Unbalanced transportation

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