

Geometric Partial Matchings and Unbalanced Transportation Problem

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Abstract

Let A and B be two point sets in the plane of sizes r and n respectively (assume $r \leq n$), and let k be a parameter. A matching between A and B is a family $M \subseteq A \times B$ of pairs so that any point of $A \cup B$ appears in at most one pair. Given two integers $p, q \geq 1$, we define the cost of M to be $\text{cost}(M) = \sum_{(a,b) \in M} \|a - b\|_p^q$ where $\|\cdot\|_p$ is the L_p -norm. The geometric partial matching problem asks to find the minimum-cost size- k matching between A and B .

We present efficient algorithms for geometric partial matching that work for any powers of L_p -norm matching objective: An exact algorithm that runs in $O((n+k^2) \text{polylog } n)$ time, and a $(1+\varepsilon)$ -approximation algorithm that runs in $O((n+k\sqrt{k}) \text{polylog } n \cdot \log \varepsilon^{-1})$ time. Both algorithms are based on primal-dual flow augmentation scheme; the main improvements are obtained by using dynamic data structures to achieve efficient flow augmentations. Using similar techniques, we give an exact algorithm for the planar transportation problem that runs in $O((r^2\sqrt{n} + rn^{3/2}) \text{polylog } n)$ time. For $r = o(\sqrt{n})$, this algorithm is faster than the state-of-art near-quadratic time algorithm by Agarwal *et al.* [SOCG 2016].

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Lines 558

1 Introduction

Given two point sets A and B in \mathbb{R}^2 , we consider the problem of finding the minimum-cost partial matching between A and B . Formally, suppose A has size r and B has size n where $r \leq n$. Let $G(A, B)$ be the undirected complete bipartite graph between A and B , and let the cost of edge (a, b) be $c(a, b) = \|a - b\|_p$, for some $1 \leq p < \infty$. A *matching* M in $G(A, B)$



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is a set of edges sharing no endpoints. The *size* of M is the number of edges in M . Given $q \geq 1$, the cost of M is defined to be

$$\text{cost}(M) := \sum_{(a,b) \in M} \|a - b\|_p^q.$$

For a parameter $k \leq r$, the problem of finding the minimum-cost size- k matching in $G(A, B)$ is called the *geometric partial matching problem*. We call the corresponding problem in general bipartite graphs (with arbitrary edge costs) the *partial matching problem*.¹

We also consider the following generalization of the bipartite matching problem. Let $\lambda : A \cup B \rightarrow \mathbb{Z}$ be a *supply-demand function* with positive value on points of A and negative value on points of B , satisfying $\sum_{a \in A} \lambda(a) = -\sum_{b \in B} \lambda(b)$. A *transportation map* is a function $\tau : A \times B \rightarrow \mathbb{R}_{\geq 0}$ such that $\sum_{b \in B} \tau(a, b) = \lambda(a)$ for all $a \in A$ and $\sum_{a \in A} \tau(a, b) = -\lambda(b)$ for all $b \in B$. We define the cost of τ to be

$$\text{cost}(\tau) := \sum_{(a,b) \in A \times B} \|a - b\|_p^q \cdot \tau(a, b).$$

The *transportation problem* asks to compute a transportation map of minimum cost.

Both matching and transportation problems arise in a broad range of applications, for example, in computer vision and graphics [30, 34, 39], machine learning [7, 9], economics [19], engineering [28, 35], and medical imaging [22]. More recently, computational/numerical interest has expanded greatly due to the development of fast approximate solvers [5, 6, 13, 15]; see the books by Villani [43, 44], by Cuturi and Peyré [31], and the survey by Solomon [38].

1.1 Related work

Maximum-size bipartite matching is a classical problem in graph algorithms. Upper bounds include the $O(m\sqrt{n})$ time algorithm by Hopcroft and Karp [23] and the $O(m \min\{\sqrt{m}, n^{2/3}\})$ time algorithm by Even and Tarjan [17], where n is the number of vertices and m is the number of edges. The first improvement in over thirty years was made by Mądry [27], which uses an interior-point algorithm and runs in $O(m^{10/7} \text{polylog } n)$ time.

The Hungarian algorithm [25] computes a minimum-cost maximum matching in a bipartite graph in roughly mn time. Faster algorithms have been developed since, such as the $O(m\sqrt{n} \log(nC))$ time algorithms by Gabow and Tarjan [18] and the improved $O(m\sqrt{n} \log C)$ time algorithm by Duan *et al.* [14] assuming that the edge costs are integral; here C is the maximum cost of an edge. Ramshaw and Tarjan [32] showed that the Hungarian algorithm can be extended to compute a minimum-cost partial matching of size k in time $O(km + k^2 \log r)$ time. They also proposed a cost-scaling algorithm for partial matching that runs in time $O(m\sqrt{n} \log(nC))$, again assuming that costs are integral. By reduction to unit-capacity min-cost flow, Goldberg *et al.* [20] developed a cost-scaling algorithm for partial matching with running time $O(m\sqrt{k} \log(kC))$, again only for integral edge costs.

In geometric settings, the Hungarian algorithm can be implemented to compute an optimal perfect matching between A and B (assuming equal size) in time $O(n^2 \text{polylog } n)$ [24] (see also [1, 41]). This algorithm computes an optimal size- k matching in time $O(kn \text{polylog } n)$. Faster approximation algorithms have been developed for computing a perfect matching in geometric settings [4, 36, 41, 42]. The best algorithm to date by Sharathkumar and Agarwal [37] computes a $(1 + \varepsilon)$ -approximation to the optimal perfect matching in $O(n \text{polylog } n \cdot \varepsilon^{-\Omega(1)})$

¹ Partial matching is also called *imperfect matching* or *imperfect assignment* [20, 32].

expected time with high probability, assuming q —the power of the L_p -norm in the matching objective—is equal to one; in other words, when the cost is the sum of L_p -distances between matching pairs. Their algorithm can also compute a $(1 + \varepsilon)$ -approximate optimal partial matching within the same time bound. For $q > 1$, the best known approximation algorithm to compute a perfect matching runs in $O(n^{3/2} \text{polylog } n \cdot \log \varepsilon^{-1})$ time [36]. It is not obvious how to extend it to the partial matching setting.

There is also some work on computing an optimal or near-optimal partial matching when B is fixed but A is allowed to translate and/or rotate [3, 8, 12, 33]. Here, the goal is to (i) compute a (near-)optimal matching over all possible transformations of A , or (ii) to compute a set \mathcal{M} of matchings, such that for any translation/rotation \mathcal{T} of A , a (near-)optimal matching of $\mathcal{T}(A)$ and B in \mathcal{M} .

The transportation problem can also be formulated as a minimum-cost flow problem in a graph. The strongly polynomial uncappeditated min-cost flow algorithm by Orlin [29] solves the transportation problem in $O((m + n \log n)n \log n)$ time. Lee and Sidford [26] give a weakly polynomial algorithm that runs in $O(m\sqrt{n} \text{polylog}(n, U))$ time, where U is the maximum amount of vertex supply-demand. Agarwal *et al.* [2] showed that Orlin’s algorithm can be implemented to solve 2D transportation in time $O(n^2 \text{polylog } n)$. It open whether this algorithm can be implemented to run in $O(rn \text{polylog } n)$ time (recall that r is the size of A). By adapting the Lee-Sidford algorithm, they developed a $(1 + \varepsilon)$ -approximation algorithm that runs in $O(n^{3/2} \varepsilon^{-2} \text{polylog } n)$ time. They also gave a Monte-Carlo algorithm which computes an $O(\log^2(1/\varepsilon))$ -approximate solution in $O(n^{1+\varepsilon})$ time with high probability.

1.2 Our results

There are three main results in this paper. First in Section 2 we present an efficient algorithm for computing an optimal partial matching in \mathbb{R}^2 .

► **Theorem 1.1.** *Given two point sets A and B in \mathbb{R}^2 each of size at most n , a minimum-cost matching of size k between A and B can be computed in $O((n + k^2) \text{polylog } n)$ time.*

We use *bichromatic closest pair (BCP)* data structures to implement the Hungarian algorithm efficiently, similar to Agarwal *et al.* and Kaplan *et al.* [1, 24]. But unlike their algorithms which take $\Omega(n)$ time to find an augmenting path, we show that after $O(n \text{polylog } n)$ preprocessing, an augmenting path can be found in $O(k \text{polylog } n)$ time. The key is to recycle (rather than rebuild) our data structures from one augmentation to the next. We refer to this idea as the *rewinding mechanism*.

Next in Sections 3 and 4, we obtain a $(1 + \varepsilon)$ -approximation algorithm for the planar geometric partial matching problem by providing an efficient implementation of the unit-capacity min-cost flow algorithm by Goldberg *et al.* [20].

► **Theorem 1.2.** *Given two point sets A and B in \mathbb{R}^2 each of size at most n , a $(1 + \varepsilon)$ -approximate min-cost matching of size k between A and B can be computed in $O((n + k\sqrt{k}) \text{polylog } n \cdot \log \varepsilon^{-1})$ time.*

The main challenge here is the set of *null vertices* which do not play any role in the augmentations, but still contribute to the size of the graph. Instead, we run the unit-capacity min-cost flow algorithm on a *shortcut network*, circumventing all null vertices. The shortcut graph itself may have $\Omega(n^2)$ edges, but we can query the min-cost arcs efficiently using BCP oracles without explicitly constructing the graph. Therefore we charge the execution time of each iteration to the size of the *flow support*, which turns out to be of size $O(k)$.

Finally in Section 5 we present a faster algorithm for the planar transportation problem when the two point sets are unbalanced.

► **Theorem 1.3.** *Given two point sets A and B in \mathbb{R}^2 of sizes r and n respectively along with supply-demand function $\lambda : A \cup B \rightarrow \mathbb{Z}$. An optimal transportation map between A and B can be computed in $O((r^2\sqrt{n} + rn^{3/2}) \text{polylog } n)$ time.*

Our result improves over the $O(n^2 \text{polylog } n)$ time algorithm in [2] when $r = o(\sqrt{n})$. The algorithm uses the strongly polynomial uncapacitated minimum-cost flow algorithm by Orlin [29], adapted for geometric costs as in Agarwal *et al.* [2]. Unlike in the case of matchings, the flow support for the transportation problem may have size $\Omega(n)$ even when r is a constant; so naïvely we can no longer charge the execution time to flow support size. However, we show that most of the support arcs are of degree one and thus can be partitioned into *stars* centered at vertices of A . We describe a data structure that processes these stars in amortized $O((r^2/\sqrt{n} + r\sqrt{n}) \text{polylog } n)$ time per augmentation.

We remark that the work by Agarwal *et al.* [3] uses a partial matching algorithm as a black box, and thus can be improved by simply plugging in ours. We omit the details here.

2 Minimum-Cost Partial Matchings using Hungarian Algorithm

In this section, we solve the geometric partial matching problem and prove Theorem 1.1 by implementing the Hungarian algorithm for partial matching in $O((n + k^2) \text{polylog } n)$ time.

The linear program dual to the standard linear program for partial matching has dual variables for each vertex, called *potentials* π . Given potentials π , we can define the *reduced cost* on the edges to be $c_\pi(v, w) := c(v, w) - \pi(v) + \pi(w)$. Potentials π are *feasible* if the reduced costs are nonnegative for all edges in G . We say that an edge (v, w) is *admissible* under potentials π if $c_\pi(v, w) = 0$.

A vertex v is *matched* by M if v is the endpoint of some matching edge in M ; otherwise v is *unmatched*. Given a matching M , an *augmenting path* $\Pi = (a_1, b_1, \dots, a_\ell, b_\ell)$ is an odd-length path with unmatched endpoints $(a_1$ and $b_\ell)$; Π alternates between edges outside and inside of matching M . The symmetric difference $M \oplus \Pi$ creates a new matching of size $|M| + 1$, called the *augmentation* of M by Π .

2.1 The Hungarian Algorithm

The Hungarian algorithm is initialized with $M = \emptyset$ and $\pi = 0$. Each iteration of the Hungarian algorithm augments M with an admissible augmenting path Π , discovered using a procedure called the *Hungarian search*. The algorithm terminates once M has size k ; Ramshaw and Tarjan [32] showed that M is guaranteed to be an optimal partial matching.

The Hungarian search tries grow a set of *reachable vertices* S by augmenting paths consisting of admissible edges. Initially, S is the set of unmatched vertices in A . Let the *frontier* of S be the edges in $(A \cap S) \times (B \setminus S)$. In each iteration, the Hungarian search first *relaxes* the minimum-reduced-cost edge (a, b) in the frontier, raising $\pi(a)$ by $c_\pi(a, b)$ for all $a \in S$ to make (a, b) admissible, and adding b into S . If b is already matched, then we also relax the matching edge (a', b) and add a' into S . The search finishes when b is unmatched, and an admissible augmenting path now can be recovered.

2.2 Fast implementation of Hungarian search

In the geometric setting, we find the min-reduced-cost frontier edge using a dynamic *bichromatic closest pair* (BCP) data structure, as observed in [2, 41]. Given two point sets P and

148 Q in the plane, the bichromatic closest pair are two points $a \in P$ and $b \in Q$ minimizing
 149 the additively weighted distance $c(a, b) - \omega(a) + \omega(b)$ for some real-valued vertex weights ω .
 150 Thus, the minimum reduced-cost among the frontier edges is precisely the cost of the BCP
 151 of point sets $P = A \cap S$ and $Q = B \setminus S$, with $\omega = \pi$.

152 The dynamic BCP data structure by Kaplan *et al.* [24] supports point insertions and
 153 deletions in $O(\text{polylog } n)$ time and answers queries in $O(\log^2 n)$ time for our setting. For
 154 each relaxation, we perform at most $O(1)$ queries and updates.

155 **Rewinding mechanism.** We cannot afford to take $O(n \text{ polylog } n)$ time to initialize the BCP
 156 data structure at the beginning of every Hungarian search beyond the first. To resolve the
 157 issue, observe that exactly one vertex is removed from the set of unmatched vertices in A
 158 after each Hungarian search. Thus we can recover the initial state of the data structure by
 159 keeping track of a list of the points added to S over the course of the Hungarian search.
 160 At the start of the next Hungarian search, *rewind* the data structure by tracing the list in
 161 reverse order, and perform a single deletion to remove the newly matched vertex in A .

162 The number of points in the list is at most $O(k)$ as it is bounded by the number of
 163 relaxations per Hungarian search. Thus, in $O(k \text{ polylog } n)$ time, we can recover the BCP
 164 data structure for each Hungarian search beyond the first. We refer to this procedure as the
 165 *rewinding mechanism*.

166 We adapt a trick from Vaidya [41] to batch potential updates under the rewinding
 167 mechanism, so that the time spent on potential updates per Hungarian search is $O(k)$. See
 168 Appendix A.1 for details. Putting everything together we obtain the following:

169 ► **Lemma 2.1.** *Each Hungarian search can be implemented in $O(k \text{ polylog } n)$ time after a*
 170 *one-time $O(n \text{ polylog } n)$ preprocessing.*

171 Our implementation of the Hungarian algorithm therefore runs in $O((n + k^2) \text{ polylog } n)$
 172 time. This proves Theorem 1.1.

173 3 Approximating Min-Cost Partial Matching through Cost-Scaling

174 The goal of this section and the next is to prove Theorem 1.2; that is, to compute a size- k
 175 geometric partial matching between two point sets A and B in the plane, with cost at most
 176 $(1 + \varepsilon)$ times the optimal matching, in time $O((n + k\sqrt{k}) \text{ polylog } n \log(1/\varepsilon))$.

177 After introducing the necessary terminologies in Section 3.1, we reduce the partial
 178 matching problem to computing an approximate minimum-cost flow on a unit-capacity
 179 reduction network in Section 3.2. In Section 3.3 we prove a high-level overview of the cost-
 180 scaling algorithm, executed on the reduction network. We postpone the fast implementation
 181 using dynamic data structures to Section 4. For lack of space, the proofs for lemmas in this
 182 section have been moved to the appendix.

183 3.1 Preliminaries on Network Flows

184 **Network.** Let $G = (V, E)$ be a directed graph, augmented by edge costs c and capacities u ,
 185 and a supply-demand function ϕ defined on the vertices. One can turn the graph G into
 186 a *network* $N = (V, \vec{E})$: For each directed edge (v, w) in E , insert two *arcs* $v \rightarrow w$ and $w \rightarrow v$
 187 into the arc set \vec{E} ; the *forward arc* $v \rightarrow w$ inherits the capacity and cost from the directed
 188 graph G , while the *backward arc* $w \rightarrow v$ satisfies $u(w \rightarrow v) = 0$ and $c(w \rightarrow v) = -c(v \rightarrow w)$. This
 189 we ensure that the graph (V, \vec{E}) is *symmetric* and the cost function c is *antisymmetric* on
 190 N . The positive values of $\phi(v)$ are referred to as *supply*, and the negative values of $\phi(v)$

as *demand*. We assume that all capacities are nonnegative, all supplies and demands are integers, and the sum of supplies and demands is equal to zero. A *unit-capacity* network has all its edge capacities equal to 1. In this section we assume all networks are of unit-capacity.

Pseudoflows. Given a network $N := (V, \vec{E}, c, u, \phi)$, a *pseudoflow* (or *flow* to be short) $f: \vec{E} \rightarrow \mathbb{Z}^2$ on N is an antisymmetric function on the arcs of N satisfying $f(v \rightarrow w) \leq u(v \rightarrow w)$ for every arc $v \rightarrow w$. We sometimes abuse the terminology by allowing pseudoflow to be defined on a directed graph, in which case we are actually referring to the pseudoflow on the corresponding network by extending the flow values anti-symmetrically to the arcs. We say that f *saturates* an arc $v \rightarrow w$ if $f(v \rightarrow w) = u(v \rightarrow w)$; an arc $v \rightarrow w$ is *residual* if $f(v \rightarrow w) < u(v \rightarrow w)$. The *support* of f in N , denoted as $\text{supp}(f)$, is the set of arcs with positive flows:

$$\text{supp}(f) := \{v \rightarrow w \in \vec{E} \mid f(v \rightarrow w) > 0\}.$$

Given a pseudoflow f , we define the *imbalance* of a vertex (with respect to f) to be

$$\phi_f(v) := \phi(v) + \sum_{w \rightarrow v \in \vec{E}} f(w \rightarrow v) - \sum_{v \rightarrow w \in \vec{E}} f(v \rightarrow w).$$

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 defined to be

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

The *minimum-cost flow problem (MCF)* asks to find a circulation of minimum cost inside a given network.

An alternative objective is the *bottleneck* objective. We define the *bottleneck value* of a flow as

$$\text{bottleneck}(f) := \max_{v \rightarrow w \in \text{supp}(f)} c(v \rightarrow w).$$

The *minimum bottleneck value* for a network is the minimum bottleneck value over all circulations. Bottleneck value will play a part in our analysis, but the primary optimization problem of this section uses the sum-of-costs objective. References to “cost” of a flow only refer to the sum-of-costs objective, and when bottleneck value appears, it will be referred to explicitly.

Residual graph. Given a pseudoflow f , one can define the *residual network* as follows. Recall that the set of *residual arcs* \vec{E}_f under f are those arcs $v \rightarrow w$ satisfying $f(v \rightarrow w) < u(v \rightarrow w)$. In other words, an arc that is not saturated by f is a residual arc; similarly, given an arc $v \rightarrow w$ with positive flow value, the backward arc $w \rightarrow v$ is a residual arc.

Let $N = (V, \vec{E}, c, u, \phi)$ be a network constructed from graph G , with a pseudoflow f on N . The *residual graph* G_f of f has V as its vertex set and \vec{E}_f as its arc set. The *residual capacity* u_f with respect to pseudoflow f is defined to be $u_f(v \rightarrow w) := u(v \rightarrow w) - f(v \rightarrow w)$. Observe

² In general the pseudoflows are allowed to take real-values. Here under the unit-capacity assumption any optimal flows are integer-valued.

that the residual capacity is always nonnegative. We can define residual arcs differently using residual capacities:

$$\vec{E}_f = \{v \rightarrow w \mid u_f(v \rightarrow w) > 0\}.$$

In other words, the set of residual arcs are precisely those arcs in the residual graph, each of which has nonzero residual capacity.

LP-duality and admissibility. The algorithms we use for solving the min-cost flow problem are primal-dual algorithms. Let $G = (V, E)$ be a given directed graph with the corresponding network $N = (V, \vec{E}, c, u, \phi)$. Formally, the *potentials* $\pi(v)$ are the variables of the linear program dual to the standard linear program for the min-cost flow problem with variables $f(v \rightarrow w)$ for each directed edge in E . Assignments to the primal variables satisfying the capacity constraints extend naturally into a pseudoflow on the network N . Let $G_f = (V, \vec{E}_f)$ be the residual graph under pseudoflow f . The *reduced cost* of an arc $v \rightarrow w$ in \vec{E}_f with respect to π is defined as

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

Notice that the cost function c_π is also antisymmetric.

The *dual feasibility constraint* says that $c_\pi(v \rightarrow w) \geq 0$ holds for every directed edge (v, w) in E ; potentials π which satisfy this constraint are said to be *feasible*. Suppose we relax the dual feasibility constraint to allow some small violation in the value of $c_\pi(v \rightarrow w)$. We say that a pair of pseudoflow f and potential π is *θ -optimal*³ [10, 40] if $c_\pi(v \rightarrow w) \geq -\theta$ for every residual arc $v \rightarrow w$ in \vec{E}_f . Pseudoflow f is *θ -optimal* if it is θ -optimal with respect to some potentials π ; potential π is *θ -optimal* if it is θ -optimal with respect to some pseudoflow f . Given a pseudoflow f and potentials π , a residual arc $v \rightarrow w$ in \vec{E}_f is *admissible* if $c_\pi(v \rightarrow w) \leq 0$. We say that a pseudoflow g in G_f is *admissible* if all support arcs of g on G_f are admissible; in other words, $g(v \rightarrow w) > 0$ holds only on admissible arcs $v \rightarrow w$. Throughout the rest of the paper we make use of the property that performing an admissible flow augmentation preserves θ -optimality. To our knowledge this is folklore; we provide a proof in the appendix.

► **Lemma 3.1.** *Let f be a θ -optimal pseudoflow in G and let f' be an admissible flow in G_f . Then $f + f'$ is also θ -optimal.*

3.2 Reduction to Unit-Capacity Min-Cost Flow Problem

Here, we reduce the min-cost partial matching problem to the problem of finding a θ -optimal circulation in a unit-capacity min-cost flow instance. We first give an additive approximation reduction based on θ -optimality, and then convert it into a multiplicative approximation.

Additive approximation. Given a bipartite graph $G = (A, B, E_0)$ for the geometric partial matching problem with cost function c , we construct the *reduction graph* H as follows: Direct the edges in E_0 from A to B , and assign each directed edge with capacity 1. Now add a dummy vertex s with directed edges to all vertices in A , and add a dummy vertex t with directed edges from all vertices in B ; each edge added has cost 0 and capacity 1. Assign vertex s with supply k and vertex t with demand $-k$; the rest of the vertices in H have zero supply-demand. We call the resulting network the *reduction network* N_H . It is straightforward to show that any integer circulation f on N_H uses exactly k of the A -to- B

³ This is commonly written as ϵ -optimality in the min-cost flow literature.

arcs, which correspond to the edges of a size- k matching M_f . Notice that the cost of the circulation f is equal to the cost of the corresponding matching M_f .

First we show that the number of arcs used by any integer pseudoflow in N_H is bounded by three times excess of the pseudoflow.

► **Lemma 3.2.** *The size of $\text{supp}(f)$ is at most $3k$ for any integer circulation f in reduction network N_H . As a corollary, the number of residual backward arcs is at most $3k$.*

Using the bound on the support size, we show that a θ -optimal integral circulation gives an additive $O(k\theta)$ -approximation to the MCF problem.

► **Lemma 3.3.** *Let f be a θ -optimal integer circulation in N_H , and f^* be an optimal integer circulation for N_H . Then, $\text{cost}(f) \leq \text{cost}(f^*) + 6k\theta$.*

Multiplicative approximation. We employ a technique from Sharathkumar and Agarwal [36] to convert the additive approximation into a multiplicative one. The reduction does not work out of the box, as they were tackling a similar but different problem on geometric transportations. See Appendix B.1 for details.

► **Lemma 3.4.** *Computing $(1 + \varepsilon)$ -approximate geometric partial matching reduces to the following problem in $O(n \text{ polylog } n)$ time: For a fixed α , compute an $(\alpha\varepsilon/6k)$ -optimal circulation on a reduction network N with min-bottleneck value at most $n^q\alpha$.*

3.3 High-Level Description of Cost-Scaling Algorithm

The main body of our algorithm is an implementation of the unit-capacity min-cost flow algorithm of Goldberg *et al.* [20]. Their algorithm is based on the *cost-scaling* technique, originally due to originally due to Goldberg and Tarjan [21]. The algorithm finds θ -optimal circulations for geometrically shrinking (halving) values of θ . Each fixed value of θ is called a *cost scale*. Once θ is sufficiently small, the θ -optimal flow is a suitable approximation according to Lemma 3.4.⁴

In what follows, we use θ^* to denote the “target” scale of the cost-scaling (i.e. we seek a θ^* -optimal circulation). The cost-scaling algorithm initializes the flow f and the potential π to be zero. The initial value of the scale parameter, denoted θ_0 , is set to C by the original algorithm [20], but this does not work well with the multiplicative approximation reduction (Lemma 3.4). Instead, we use

$$\theta_0 \in 2 \cdot \{x \in \mathbb{R}_{\geq 0} \mid \text{there exists a circulation supported on edges of cost} \leq x\},$$

or in the terminology of Lemma 3.4, $\theta_0 = 2n^q\alpha$. We show that this is sufficient for correctness in Lemma 3.5. Choosing this type of θ_0 is important for turning the cost-scaling algorithm into a multiplicative approximation — explained in Section B.1 — where we also give the precise method for choosing α . Note that the minimum possible x is the *minimum bottleneck value* of the network.

Within each scale, the algorithm performs the following:

- For scales after the first, SCALE-INIT takes the previous circulation (now 2θ -optimal) and transforms it into an θ -optimal pseudoflow with $O(k)$ excess. On the first scale ($\theta = \theta_0$), it does nothing.

⁴ When the costs are integers, a θ -optimal circulation for a sufficiently small θ (say less than $1/n$) is itself an optimal solution [20, 21]. We present this algorithm without the integral-cost assumption because in the geometric partial matching setting (with respect to L_p norms) the costs are generally not integers.

312 ■ REFINE then reduces the excess to zero while maintaining θ -optimality, turning f into a
 313 θ -optimal circulation.

314 If $\theta \leq \theta^*$, then f is a θ^* -optimal circulation and we are done. Otherwise, θ is halved and
 315 the next scale begins. The algorithm produces a θ^* -optimal circulation after $O(\log(\theta_0/\theta^*))$
 316 scales. Using the reduction in Lemma 3.4, we have an initial scale $\theta_0 = 2n^q\alpha$ and target
 317 scale $\theta^* = \varepsilon\alpha/6k$. Thus, the number of cost scales after the reduction is $O(\log(n/\varepsilon))$.

318 **Scale initialization.** For SCALE-INIT, we use a simple extension to a scale initialization
 319 procedure proposed for partial matching [20, Section 6.1]. Namely, the potential changes are
 320 the same, but we take the additional step to remove arcs violating θ -optimality. The vertex
 321 set of H consists of two point sets A and B , as well as two dummy vertices s and t . The
 322 directed edges in H are pointed from s to A , from A to B , and from B to t . We call those
 323 arcs in N_H whose direction is consistent with their corresponding directed edges as *forward*
 324 *arcs*, and those arcs that points in the opposite direction as *backward arcs*.

325 The procedure SCALE-INIT transforms a 2θ -optimal circulation from the previous cost
 326 scale into a θ -optimal flow with $O(k)$ excess, by raising the potentials π of all vertices in A
 327 by θ , those in B by 2θ , and the potential of t by 3θ . The potential of s remains unchanged.
 328 Now the reduced cost of every forward arc is increased by θ , and thus all the forward arcs
 329 have reduced cost at least $-\theta$.

330 As for backward arcs, the procedure SCALE-INIT continues by setting the flow on $v \rightarrow w$ to
 331 zero for each backward arc $w \rightarrow v$ violating the θ -optimality constraint. In other words, we
 332 set $f(v \rightarrow w) = 0$ whenever $c_\pi(w \rightarrow v) < -\theta$. This ensures that all such backward arcs are no
 333 longer residual, and therefore the flow (now with excess) is θ -optimal.

334 Because the arcs are of unit-capacity in N_H , each arc desaturation creates one unit of
 335 excess. By Lemma 3.2 the number of backward arcs is at most $3k$. Thus the total amount of
 336 excess created is also $O(k)$. In total, the whole procedure SCALE-INIT takes $O(n)$ time.

337 **Refinement.** The procedure REFINE is implemented using a primal-dual augmentation
 338 algorithm, which sends flows on admissible arcs to reduce the total excess. Unlike the
 339 Hungarian algorithm, it uses *blocking flows* instead of augmenting paths. We call a pseudoflow
 340 f on residual network N_g a *blocking flow* if f saturates at least one residual arc in every
 341 augmenting path in N_g . In other words, there is no admissible augmenting path in N_{f+g}
 342 from an excess vertex to a deficit vertex.

343 Each iteration of REFINE finds an admissible blocking flow that is then added to the
 344 current pseudoflow in two stages:

- 345 1. A *Hungarian search*, which increases the dual variables π of vertices that are reachable
 346 from an excess vertex by at least θ , in a Dijkstra-like manner, until there is an excess-deficit
 347 path of admissible edges.
- 348 2. A *depth-first search* through the set of admissible arcs to construct a blocking flow. It
 349 suffices to repeatedly extract admissible augmenting paths until no more admissible
 350 excess-deficit paths remain.

351 The algorithm continues until the total excess becomes zero.

352 First we analyze the number of iterations executed by REFINE. The proof follows the
 353 strategy in Goldberg *et al.* [20, Section 3.2], which proves a $O(\sqrt{n})$ bound on the number of
 354 iterations for general unit-capacity networks. They claimed an analogous $O(\sqrt{k})$ bound for
 355 partial matchings in [20, Section 6.1], which we reproduce for completeness. Due to space
 356 constraint we have moved the proof to Appendix B.2.

In the following lemma, we prove the number of iterations of REFINE required in each cost scale. This is also the place where our assumptions on the initial cost scale θ_0 become important (indeed, the only place). We require that θ_0 is sufficiently high such that N_H there exists a circulation whose bottleneck value is at most $\theta_0/2$.

► **Lemma 3.5.** *Suppose that θ_0 is chosen such that there exists a circulation in N_H with bottleneck value at most $\theta_0/2$. In any scale, let f be a pseudoflow in N_H with $O(k)$ excess. The procedure REFINE runs for $O(\sqrt{k})$ iterations before the excess of f becomes zero.*

4 Fast Implementation of Refinement

The goal of the section is to show that after $O(n \text{ polylog } n)$ time preprocessing, each Hungarian search and depth-first search can be implemented in $O(k \text{ polylog } n)$ time. Combined with Lemma 3.5 the procedure REFINE can be implemented in $O((n + k\sqrt{k}) \text{ polylog } n)$ time. Together with our analysis on scale initialization and the bound on number of cost scales, this concludes the proof to Theorem 1.2.

The Hungarian search and depth-first search are similar, traversing through the residual graph using admissible arcs starting from the excess vertices. Each step of the search procedures *relaxes* a minimum-reduced-cost arc from the set of visited vertices to an unvisited vertex, until a deficit vertex is reached. At a high level, our analysis strategy is to charge the relaxation events to the support arcs of f .

4.1 Null vertices and shortcut graph

As it turns out, there are some vertices visited by a relaxation event which we cannot charge to $\text{supp}(f)$. Unfortunately the number of such vertices can be as large as $\Omega(n)$. To overcome this issue, we replace the residual graph with an equivalent graph that excludes these *null vertices*, and run the Hungarian search and depth-first search on the resulting graph instead.

Null vertices. We say a vertex v in the residual graph N_f is a *null vertex* if $\phi_f(v) = 0$ and no arc of $\text{supp}(f)$ is incident to v . We use A_\emptyset and B_\emptyset to denote the null vertices A and B respectively. Vertices that are not null are called *normal vertices*. A *null 2-path* is a length-2 path in N_f from a normal vertex to another normal vertex, passing through a null vertex. As every vertex in A has in-degree 1 and every vertex in B has out-degree 1 in the residual graph, the null 2-paths must be of the form either (s, v, b) for some vertex b in $B \setminus B_\emptyset$ or (a, v, t) for some vertex a in $A \setminus A_\emptyset$. In either case, we say that the null 2-path *passes through* null vertex v . Similarly, we define the length-3 path from s to t that passes through two null vertices to be a *null 3-path*. Because reduced costs telescope for residual paths, the reduced cost of any null path does not depend on the potentials of the null vertices it passes through.

Shortcut graph. We construct the *shortcut graph* \tilde{H}_f from the reduction graph H by removing all null vertices and their incident edges, followed by inserting an arc from the head of each null path Π to its tail, with cost equals to the sum of costs on the arcs. We call this arc the *shortcut* of null path Π , denoted as $\text{short}(\Pi)$. The resulting multigraph \tilde{H}_f contains only normal vertices of H_f , and the reduced cost of any path between normal vertices are preserved. We argue now that \tilde{H}_f is fine as a surrogate for H_f . Let $\tilde{\pi}$ be a θ -optimal potential on \tilde{H}_f . Construct potentials π on H_f which extends $\tilde{\pi}$ to null vertices, by setting $\pi(a) := \tilde{\pi}(s)$ for $a \in A_\emptyset$ and $\pi(b) := \tilde{\pi}(t)$ for $b \in B_\emptyset$.

398 ► **Lemma 4.1.** *Consider $\tilde{\pi}$ a θ -optimal potential on \tilde{H}_f and π the corresponding potential*
 399 *constructed on H_f . Then, (1) potential π is θ -optimal on H_f , and (2) if $\text{arc short}(\Pi)$ is*
 400 *admissible under $\tilde{\pi}$, then every arc in Π is admissible under π .*

401 4.2 Dynamic data structures for search procedures

402 **Hungarian search.** Conceptually, we execute the Hungarian search on the shortcut graph
 403 \tilde{H}_f . We describe how we can query the minimum-reduced-cost arc leaving \tilde{S} in $O(\text{polylog } n)$
 404 time for \tilde{H}_f , without constructing it explicitly. For this purpose, let S be a set of “reached”
 405 vertices maintained, identical to \tilde{S} except whenever a shortcut is relaxed, we add the null
 406 vertices passed by the corresponding null path to S in addition to its (normal) endpoints.
 407 Observe that the arcs of \tilde{H}_f leaving \tilde{S} fall into $O(1)$ categories:

- 408 ■ non-shortcut backward arcs (v, w) with $(w, v) \in \text{supp}(f)$;
- 409 ■ non-shortcut A -to- B forward arcs;
- 410 ■ non-shortcut forward arcs from s -to- A and from B -to- t ;
- 411 ■ shortcut arcs (s, b) corresponding to null 2-paths from s to $b \in (B \setminus B_\emptyset) \setminus S$;
- 412 ■ shortcut arcs (a, t) corresponding to null 2-paths from $a \in (A \setminus A_\emptyset) \cap S$ to t ; and
- 413 ■ shortcut arcs (s, t) corresponding to null 3-paths.

414 For each category of arcs we maintain a proper data structure (either heap or BCP) to
 415 answer to the min-cost arc query.

416 **Depth-first search.** Depth-first search is similar to Hungarian search in that it uses the
 417 relaxation of minimum-reduced-cost arcs/null paths, this time to identify admissible arcs/null
 418 paths in a depth-first manner. Similar to the Hungarian search, for each category of arcs
 419 in \tilde{H}_f leaving \tilde{S} , we maintain a proper data structure to answer the minimum-reduced cost
 420 arc leaving a *fixed* vertex in \tilde{S} given by the query. Thus unlike Hungarian search which uses
 421 BCP data structures, we use dynamic nearest-neighbor data structures instead [24]. Each
 422 data structure requires $O(1)$ queries and updates per relaxation. So in collaboration each
 423 relaxation can be implemented in $O(\text{polylog } n)$ time [24].

424 **Time analysis.** The complete time analysis can be found in Appendix C.2, C.3, and C.4;
 425 here we sketch the ideas. First we show (in Appendix C.2) that both Hungarian search and
 426 depth-first search performs $O(k)$ relaxations before a deficit vertex is reached, by looking at
 427 shortcut and non-shortcut relaxations separately. Both types of relaxations are eventually
 428 charged to the support size of f . As for the time analysis (see Appendix C.3), using the
 429 same rewinding mechanism as in Section 2.2, the running time of the Hungarian search
 430 and depth-first search, other than the potential updates, can be charged to the number of
 431 relaxations. Again using the trick by Vaidya [41] we can charge the potential updates of
 432 normal vertices to the number of relaxations in the Hungarian search. We never explicitly
 433 maintain the potentials on the null vertices; instead they are reconstructed whenever needed,
 434 either at the end of each iteration of refinement or when an augmentation sends flow through
 435 a null vertex. We show that such updates does not happen often in Appendix C.4. This
 436 completes the time analysis, which we summarize as follows:

437 ► **Lemma 4.2.** *After $O(n \text{ polylog } n)$ -time preprocessing, each Hungarian search and depth-*
 438 *first search can be implemented in $O(k \text{ polylog } n)$ time.*

5 Unbalanced Transportation

In this section, we give an exact algorithm which solves the planar transportation problem in $O((n + k\sqrt{k}) \log(1/\varepsilon) \text{polylog } n)$ time, proving Theorem 1.3. Our strategy is to use the standard reduction to the uncapacitated min-cost flow problem, and provide a fast implementation under the geometric setting for the uncapacitated min-cost flow algorithm by Orlin [29], combined with some of the tools developed in Sections 2 and 3.

For lack of space, we only sketch Orlin’s strongly polynomial-time algorithm for uncapacitated min-cost flow problem [29]. See Appendix D.1 for a brief introduction, as well as the original paper. In short, Orlin’s algorithm follows the *excess-scaling* paradigm under the primal-dual framework: Maintain a *scale parameter* Δ , initially set to U . A vertex v is *active* if $|\phi_f(v)| \geq \alpha\Delta$ for a fixed parameter $\alpha \in (0.5, 1)$. Repeatedly runs a *Hungarian search* that raises potentials (while maintaining dual feasibility) to create an admissible augmenting excess-deficit path between active vertices, on which we perform flow augmentations. Once there are no more active excess or deficit vertices, Δ is halved. Each sequence of augmentations where Δ holds a constant value is called an *excess scale*. On top of that, the algorithm performs contraction on arcs with flow value at least $3n\Delta$ at the beginning of a scale, in which case the flow and potentials are no longer tracked, as well as aggressive Δ -lowering under circumstances.

► **Theorem 5.1 (Orlin [29, Theorems 2 and 3]).** *Orlin’s algorithm finds a set of optimal potentials after $O(n \log n)$ scaling phases and $O(n \log n)$ total augmentations.*

The remainder of the section focuses on showing that each augmentation can be implemented in $O((r^2/\sqrt{n} + r\sqrt{n}) \text{polylog } n)$ time (after preprocessing). A subtle issue is that our geometric data structures must deal with real points in the plane instead of the contracted components. A solution is provided by Agarwal *et al.* [2]; for the sake of completeness, we describe the method for maintaining contractions under dynamic data structures in Appendix D.2.

Recovering optimal flow. Using a strategy from Agarwal *et al.* [2], we can recover the optimal flow in time $O(n \text{polylog } n)$. If furthermore the cost function is just the p -norm (without the q th-power), we show a structural result which is interesting on its own right: the set of admissible arcs under an optimal potential forms a planar graph. Thus, we can extract the admissible network in $O(n \text{polylog } n)$ time thanks to the sparsity of planar graphs, and compute the flow using planar multiple-source multiple-sink maximum-flow algorithm by Borradaile *et al.* [11] which runs in $O(n \log^3 n)$ time. For details see Appendix D.3 and D.4.

5.1 Support stars

To find an augmenting path, we again use a Hungarian search with geometric data structures to perform relaxations quickly. Our strategy is summarized as follows:

- Discard vertices that lead to dead ends in the search (not on a path to a deficit vertex).
- Cluster parts of the flow support, such that the number of support arcs outside clusters is $O(r)$. The number of relaxations we perform is proportional to the number of support arcs outside of clusters.

Querying/updating clusters degrades our amortized time per relaxation from $O(\text{polylog } n)$ to $O(\sqrt{n} \text{polylog } n)$. Thus overall each augmentation takes $O(r\sqrt{n} \text{polylog } n)$ time.

Support stars. The vertices of B with support degree 1 are partitioned into subsets $\Sigma_a \subset B$ by the $a \in A$ lying on the other end of their single support arc. We call Σ_a the *support star* centered at $a \in A$.

Roughly speaking, we would like to handle each support star as a single unit. When the Hungarian search reaches a or any $b \in \Sigma_a$, the entirety of Σ_a (as well as a) is also admissibly-reachable and can be included into S without further potential updates. Additionally, the only outgoing residual arcs of every $b \in \Sigma_a$ lead to a , thus the only way to leave $\Sigma_a \cup \{a\}$ is through an arc leaving a . Once a relaxation step reaches some $b \in \Sigma_a$ or a itself, we would like to quickly update the state such that the rest of $b \in \Sigma_a$ is also reached without performing relaxation steps to each individual $b \in \Sigma_a$.

5.2 Implementation details

Before describing our workaround for support stars, we analyze the number of relaxation steps for arcs outside of support stars. To this end we need to strip of some *dead* vertices—having no incident flow support edges and not an active excess or deficit vertex—that does not affect the search. We use A_ℓ and B_ℓ to denote vertices of points in A and B that are not dead. The details for handling such vertices can be found in Appendix D.5. For a proof of the following lemma, see Appendix D.6.

► **Lemma 5.2.** *Suppose we have stripped the graph of dead vertices. The number of relaxation steps in a Hungarian search outside of support stars is $O(r)$.*

Relaxations outside support stars. For relaxations that don't involve support star vertices, we can once again maintain a BCP data structure to query the minimum A_ℓ -to- B_ℓ arc. To elaborate, this is the BCP between $P = A_\ell \cap S$ and $Q = (B_\ell \setminus (\bigcup_{a \in A_\ell} \Sigma_a)) \setminus S$, weighted by potentials. Since the query is outside the support stars, there is at most one update per relaxation. Backward (support) arcs are kept admissible by the invariant, so we relax them immediately when they arrive at the frontier.

Relaxing support stars. We classify support stars into two categories: *big stars* with $|\Sigma_a| > \sqrt{n}$, and *small stars* with $|\Sigma_a| \leq \sqrt{n}$. Let $A_{big} \subseteq A$ denote the centers of big stars and $A_{small} \subseteq A$ denote the centers of small stars.

■ For each big star Σ_a , we use a data structure $\mathcal{D}_{big}(a)$ to maintain BCP between $P = A_\ell \cap S$ and $Q = \Sigma_a$. We query this until $a \in S$ or any vertex of Σ_a is added to S .

■ All small stars are added to a single BCP data structure \mathcal{D}_{small} between $P = A_\ell \cap S$ and $Q = (\bigcup_{a \in A_{small}} \Sigma_a) \setminus S$. When an $a \in A_{small}$ or any vertex of its support star is added to S , we remove the points of Σ_a from \mathcal{D}_{small} using $|\Sigma_a|$ deletion operations.

We will update these data structures as each support star center is added into S . If a relaxation step adds some $b \in B_\ell$ and b is in a support star Σ_a , then we immediately relax $b \rightarrow a$, as all support arcs are admissible.

Suppose a relaxation step adds $a \in A_\ell$ to S . We must (i) remove a from every \mathcal{D}_{big} , (ii) remove a from \mathcal{D}_{small} . If $a \in A_{big}$, we also (iii) deactivate $\mathcal{D}_{big}(a)$. If $a \in A_{small}$, we also (iv) remove the points of Σ_a from \mathcal{D}_{small} . The operations (i–iii) can be performed in $O(\text{polylog } n)$ time each, but (iv) may take up to $O(\sqrt{n} \text{ polylog } n)$ time. On the other hand, there are now $O(\sqrt{n})$ data structures to query during each relaxation step, which takes $O(\sqrt{n} \log^2 n)$ time in total. Together with Lemma 5.2 we bound the time for each Hungarian search.

► **Lemma 5.3.** *Hungarian search takes $O(r\sqrt{n} \text{ polylog } n)$ time.*

Updating support stars. As the flow support changes, the membership of support stars may shift causing a big star to become small or vice versa. To efficiently support this, we introduce a soft boundary in determining whether a support star is big or small. Standard charging argument shows that the amortized update time per membership change is $O(\text{polylog } n)$ for big-to-small updates, and $O((r/\sqrt{n}) \text{polylog } n)$ for small-to-big ones; see Appendix D.7. The number of star membership changes by adding a single augmenting path is bounded above by twice of its length, so $O(r)$. By Theorem 5.1, the total number of membership changes is $O(rn \log n)$. The total time spent on big-to-small updates is $O(rn \text{polylog } n)$, and the total time spent on small-to-big updates is $O(r^2 \sqrt{n} \text{polylog } n)$. Membership changes themselves can be performed in $O(\text{polylog } n)$ time each.

Preprocessing time. It takes $O(rn \text{polylog } n)$ time to build the very first set of data structures. There are $r \cdot |\Sigma_a|$ points to insert for each $\mathcal{D}_{\text{big}}(a)$, so the number of points to insert is $O(rn)$. At most $O(rn)$ points have to be inserted for $\mathcal{D}_{\text{small}}$. So the total preprocessing time is $O(rn \text{polylog } n)$.

Between searches. After each augmentation, we reset the data structures to their initial state plus the change from augmentation using rewinding mechanism (see Section 2.2). This takes time proportional to the time for Hungarian search, which is $O(r\sqrt{n} \text{polylog } n)$ by Lemma 5.3. The most recent augmentation may have deactivated $O(1)$ active excess and deficit vertices, which takes $O(\sqrt{n} \text{polylog } n)$ time to update. Finally, we note that an augmenting path cannot reduce the support degree of a vertex to zero, and therefore no new dead vertices are created by augmentation.

Between excess scales. When the excess scale changes, vertices that were previously inactive may become active, and vertices that were dead may be revived. If we have the data structures built at the end of the previous scale, then we can add in each new active vertex $a \in A$ and charge the insertion to the (future) augmenting path or contraction which eventually causes the vertex being inactive or absorbed. By Theorem 5.1, there are $O(n \log n)$ such newly active vertices; each of them takes $O(\sqrt{n} \text{polylog } n)$ to update. So the total time spent is $O(n^{3/2} \text{polylog } n)$.

Putting it together. After $O(rn \text{polylog } n)$ preprocessing, we spend $O(r\sqrt{n} \text{polylog } n)$ time on relaxations each Hungarian search by Lemma 5.3, for a total of $O(rn^{3/2} \text{polylog } n)$ time over the course of the algorithm. Rewinding takes the same amount of time. We spend up to $O((r^2 \sqrt{n} + rn) \text{polylog } n)$ time switching stars between big/small. We spend $O(n^{3/2} \text{polylog } n)$ time activating and reviving vertices. Adding, the algorithm takes $O((r^2 \sqrt{n} + rn^{3/2}) \text{polylog } n)$ time to produce optimal potentials π^* , from which we can recover f^* in $O(n \text{polylog } n)$ additional time. This completes the proof of Theorem 1.3.

References

- 1 Pankaj K. Agarwal, Alon Efrat, and Micha Sharir. Vertical decomposition of shallow levels in 3-dimensional arrangements and its applications. *SIAM J. Comput.* 29(3):912–953, 1999. <https://doi.org/10.1137/S0097539795295936>.
- 2 Pankaj K. Agarwal, Kyle Fox, Debmalaya Panigrahi, Kasturi R. Varadarajan, and Allen Xiao. Faster algorithms for the geometric transportation problem. *33rd International Symposium on Computational Geometry, SoCG 2017, July 4-7, 2017, Brisbane, Australia*, 7:1–7:16, 2017. <https://doi.org/10.4230/LIPIcs.SocG.2017.7>.

- 567 **3** Pankaj K. Agarwal, Haim Kaplan, Geva Kipper, Wolfgang Mulzer, Günter Rote, Micha
568 Sharir, and Allen Xiao. Approximate minimum-weight matching with outliers under trans-
569 lation. *CoRR* abs/1810.10466, 2018. (<http://arxiv.org/abs/1810.10466>).
- 570 **4** Pankaj K. Agarwal and Kasturi R. Varadarajan. A near-linear constant-factor approx-
571 imation for euclidean bipartite matching? *Proceedings of the 20th ACM Symposium on*
572 *Computational Geometry, Brooklyn, New York, USA, June 8-11, 2004*, 247–252, 2004.
573 (<https://doi.org/10.1145/997817.997856>).
- 574 **5** Jason Altschuler, Francis Bach, Alessandro Rudi, and Jonathan Weed. Approximating the
575 quadratic transportation metric in near-linear time. *CoRR* abs/1810.10046, 2018. (<http://arxiv.org/abs/1810.10046>).
- 576 **6** Jason Altschuler, Jonathan Weed, and Philippe Rigollet. Near-linear time
577 approximation algorithms for optimal transport via Sinkhorn iteration. *Ad-*
578 *vances in Neural Information Processing Systems 30: Annual Confer-*
579 *ence on Neural Information Processing Systems 2017, 4-9 December 2017,*
580 *Long Beach, CA, USA, 1961–1971*, 2017. ([http://papers.nips.cc/paper/](http://papers.nips.cc/paper/6792-near-linear-time-approximation-algorithms-for-optimal-transport-via-sinkhorn-iteration)
581 [6792-near-linear-time-approximation-algorithms-for-optimal-transport-via-sinkhorn-iteration](http://papers.nips.cc/paper/6792-near-linear-time-approximation-algorithms-for-optimal-transport-via-sinkhorn-iteration)).
- 582 **7** Martín Arjovsky, Soumith Chintala, and Léon Bottou. Wasserstein generative adversarial
583 networks. *Proceedings of the 34th International Conference on Machine Learning, ICML*
584 *2017, Sydney, NSW, Australia, 6-11 August 2017*, 214–223, 2017. ([http://proceedings.](http://proceedings.mlr.press/v70/arjovsky17a.html)
585 [mlr.press/v70/arjovsky17a.html](http://proceedings.mlr.press/v70/arjovsky17a.html)).
- 586 **8** Rinat Ben Avraham, Matthias Henze, Rafel Jaume, Balázs Keszegh, Orit E. Raz, Micha
587 Sharir, and Igor Tubis. Partial-matching RMS distance under translation: Combinator-
588 ics and algorithms. *Algorithmica* 80(8):2400–2421, 2018. ([https://doi.org/10.1007/](https://doi.org/10.1007/s00453-017-0326-0)
589 [s00453-017-0326-0](https://doi.org/10.1007/s00453-017-0326-0)).
- 590 **9** Federico Bassetti, Antonella Bodini, and Eugenio Regazzini. On minimum Kantorovich
591 distance estimators. *Statistics & Probability Letters* 76(12):1298 – 1302, 2006. ([http:](http://www.sciencedirect.com/science/article/pii/S0167715206000381)
592 www.sciencedirect.com/science/article/pii/S0167715206000381).
- 593 **10** D. Bertsekas and D. El Baz. Distributed asynchronous relaxation methods for convex
594 network flow problems. *SIAM Journal on Control and Optimization* 25(1):74–85, 1987.
595 (<https://doi.org/10.1137/0325006>).
- 596 **11** Glencora Borradaile, Philip N. Klein, Shay Mozes, Yahav Nussbaum, and Christian Wulff-
597 Nilsen. Multiple-source multiple-sink maximum flow in directed planar graphs in near-
598 linear time. *SIAM J. Comput.* 46(4):1280–1303, 2017. ([https://doi.org/10.1137/](https://doi.org/10.1137/15M1042929)
599 [15M1042929](https://doi.org/10.1137/15M1042929)).
- 600 **12** Sergio Cabello, Panos Giannopoulos, Christian Knauer, and Günter Rote. Matching point
601 sets with respect to the earth mover’s distance. *Comput. Geom.* 39(2):118–133, 2008.
602 (<https://doi.org/10.1016/j.comgeo.2006.10.001>).
- 603 **13** Marco Cuturi. Sinkhorn distances: Lightspeed computation of optimal transport. *Ad-*
604 *vances in Neural Information Processing Systems 26: 27th Annual Conference on Neural*
605 *Information Processing Systems 2013. Proceedings of a meeting held December 5-8, 2013,*
606 *Lake Tahoe, Nevada, United States.*, 2292–2300, 2013. ([http://papers.nips.cc/paper/](http://papers.nips.cc/paper/4927-sinkhorn-distances-lightspeed-computation-of-optimal-transport)
607 [4927-sinkhorn-distances-lightspeed-computation-of-optimal-transport](http://papers.nips.cc/paper/4927-sinkhorn-distances-lightspeed-computation-of-optimal-transport)).
- 608 **14** Ran Duan, Seth Pettie, and Hsin-Hao Su. Scaling algorithms for approximate and exact
609 maximum weight matching. *CoRR* abs/1112.0790, 2011. ([http://arxiv.org/abs/1112.](http://arxiv.org/abs/1112.0790)
610 [0790](http://arxiv.org/abs/1112.0790)).
- 611 **15** Pavel Dvurechensky, Alexander Gasnikov, and Alexey Kroshnin. Computational op-
612 timal transport: Complexity by accelerated gradient descent is better than by Sink-
613 horn’s algorithm. *Proceedings of the 35th International Conference on Machine Learning,*
614 *ICML 2018, Stockholmsmässan, Stockholm, Sweden, July 10-15, 2018*, 1366–1375, 2018.
615 (<http://proceedings.mlr.press/v80/dvurechensky18a.html>).
- 616

- 617 **16** Jack Edmonds and Richard M. Karp. Theoretical improvements in algorithmic efficiency
618 for network flow problems. *J. ACM* 19(2):248–264, 1972. [⟨https://doi.org/10.1145/
619 321694.321699⟩](https://doi.org/10.1145/321694.321699).
- 620 **17** Shimon Even and Robert E. Tarjan. Network flow and testing graph connectivity. *SIAM*
621 *J. Comput.* 4(4):507–518, 1975. [⟨https://doi.org/10.1137/0204043⟩](https://doi.org/10.1137/0204043).
- 622 **18** Harold N. Gabow and Robert E. Tarjan. Faster scaling algorithms for network problems.
623 *SIAM J. Comput.* 18(5):1013–1036, 1989. [⟨https://doi.org/10.1137/0218069⟩](https://doi.org/10.1137/0218069).
- 624 **19** Alfred Galichon. *Optimal transport methods in economics*. Princeton University Press,
625 2016.
- 626 **20** Andrew V. Goldberg, Sagi Hed, Haim Kaplan, and Robert E. Tarjan. Minimum-cost
627 flows in unit-capacity networks. *Theory Comput. Syst.* 61(4):987–1010, 2017. [⟨https://doi.org/10.1007/s00224-017-9776-7⟩](https://doi.org/10.1007/s00224-017-9776-7).
- 628 **21** Andrew V. Goldberg and Robert E. Tarjan. Finding minimum-cost circulations by success-
629 ive approximation. *Math. Oper. Res.* 15(3):430–466, 1990. [⟨https://doi.org/10.1287/
630 moor.15.3.430⟩](https://doi.org/10.1287/moor.15.3.430).
- 631 **22** Alexandre Gramfort, Gabriel Peyré, and Marco Cuturi. Fast optimal transport averaging of
632 neuroimaging data. *CoRR* abs/1503.08596, 2015. [⟨http://arxiv.org/abs/1503.08596⟩](http://arxiv.org/abs/1503.08596).
- 633 **23** John E. Hopcroft and Richard M. Karp. An $n^{5/2}$ algorithm for maximum matchings in
634 bipartite graphs. *SIAM J. Comput.* 2(4):225–231, 1973. [⟨https://doi.org/10.1137/
635 0202019⟩](https://doi.org/10.1137/0202019).
- 636 **24** Haim Kaplan, Wolfgang Mulzer, Liam Roditty, Paul Seiferth, and Micha Sharir. Dynamic
637 planar Voronoi diagrams for general distance functions and their algorithmic applications.
638 *Proceedings of the Twenty-Eighth Annual ACM-SIAM Symposium on Discrete Algorithms,*
639 *SODA 2017, Barcelona, Spain, Hotel Porta Fira, January 16-19*, 2495–2504, 2017. [⟨https://doi.org/10.1137/1.9781611974782.165⟩](https://doi.org/10.1137/1.9781611974782.165).
- 640 **25** Harold W Kuhn. The Hungarian method for the assignment problem. *Naval Research*
641 *Logistics (NRL)* 2(1-2):83–97. Wiley Online Library, 1955.
- 642 **26** Yin Tat Lee and Aaron Sidford. Following the path of least resistance : An $\tilde{O}(m \sqrt{n})$
643 algorithm for the minimum cost flow problem. *CoRR* abs/1312.6713, 2013. [⟨http://arxiv.
644 org/abs/1312.6713⟩](http://arxiv.org/abs/1312.6713).
- 645 **27** Aleksander Mądry. Navigating central path with electrical flows: From flows to matchings,
646 and back. *54th Annual IEEE Symposium on Foundations of Computer Science, FOCS*
647 *2013, 26-29 October, 2013, Berkeley, CA, USA*, 253–262, 2013. [⟨https://doi.org/10.
648 1109/FOCS.2013.35⟩](https://doi.org/10.1109/FOCS.2013.35).
- 649 **28** VI Olikar. Near radially symmetric solutions of an inverse problem in geometric optics.
650 *Inverse Problems* 3(4):743. IOP Publishing, 1987.
- 651 **29** James B. Orlin. A faster strongly polynomial minimum cost flow algorithm. *Operations*
652 *Research* 41(2):338–350, 1993. [⟨https://doi.org/10.1287/opre.41.2.338⟩](https://doi.org/10.1287/opre.41.2.338).
- 653 **30** Nicolas Papadakis. *Optimal Transport for Image Processing*. Habilitation à diriger des
654 recherches, Université de Bordeaux, Dec. 2015. [⟨https://hal.archives-ouvertes.fr/
655 tel-01246096⟩](https://hal.archives-ouvertes.fr/tel-01246096).
- 656 **31** Gabriel Peyré and Marco Cuturi. Computational Optimal Transport. *ArXiv e-prints* p.
657 arXiv:1803.00567, 2018.
- 658 **32** Lyle Ramshaw and Robert E. Tarjan. A weight-scaling algorithm for min-cost imperfect
659 matchings in bipartite graphs. *53rd Annual IEEE Symposium on Foundations of Com-
660 puter Science, FOCS 2012, New Brunswick, NJ, USA, October 20-23, 2012*, 581–590, 2012.
661 [⟨https://doi.org/10.1109/FOCS.2012.9⟩](https://doi.org/10.1109/FOCS.2012.9).
- 662 **33** Günter Rote. Partial least-squares point matching under translations. *Proc. 26th European*
663 *Workshop Comput. Geom. (EuroCG 2010)* 249–251, 2010.

- 666 34 Yossi Rubner, Carlo Tomasi, and Leonidas J. Guibas. A metric for distributions with
667 applications to image databases. *6th Internat. Conf. on Comp. Vision*, 59–66, 1998. (<http://dx.doi.org/10.1109/ICCV.1998.710701>).
- 668 35 Yuliy Schwartzburg, Romain Testuz, Andrea Tagliasacchi, and Mark Pauly. High-contrast
669 computational caustic design. *ACM Trans. Graph.* 33(4):74:1–74:11, 2014. (<https://doi.org/10.1145/2601097.2601200>).
- 670 36 R. Sharathkumar and Pankaj K. Agarwal. Algorithms for the transportation problem in geo-
671 metric settings. *Proceedings of the Twenty-Third Annual ACM-SIAM Symposium on Dis-
672 crete Algorithms, SODA 2012, Kyoto, Japan, January 17-19, 2012*, 306–317, 2012. (<http://portal.acm.org/citation.cfm?id=2095145&CFID=63838676&CFTOKEN=79617016>).
- 673 37 R. Sharathkumar and Pankaj K. Agarwal. A near-linear time ϵ -approximation algorithm for
674 geometric bipartite matching. *Proceedings of the 44th Symposium on Theory of Computing
675 Conference, STOC 2012, New York, NY, USA, May 19 - 22, 2012*, 385–394, 2012. (<https://doi.org/10.1145/2213977.2214014>).
- 676 38 Justin Solomon. Optimal transport on discrete domains. *CoRR* abs/1801.07745, 2018.
677 (<http://arxiv.org/abs/1801.07745>).
- 678 39 Justin Solomon, Fernando de Goes, Gabriel Peyré, Marco Cuturi, Adrian Butscher, Andy
679 Nguyen, Tao Du, and Leonidas J. Guibas. Convolutional Wasserstein distances: efficient
680 optimal transportation on geometric domains. *ACM Trans. Graph.* 34(4):66:1–66:11, 2015.
681 (<http://doi.acm.org/10.1145/2766963>).
- 682 40 Éva Tardos. A strongly polynomial minimum cost circulation algorithm. *Combinatorica*
683 5(3):247–256, 1985. (<https://doi.org/10.1007/BF02579369>).
- 684 41 Pravin M. Vaidya. Geometry helps in matching. *SIAM J. Comput.* 18(6):1201–1225, 1989.
685 (<https://doi.org/10.1137/0218080>).
- 686 42 Kasturi R. Varadarajan. A divide-and-conquer algorithm for min-cost perfect matching
687 in the plane. *39th Annual Symposium on Foundations of Computer Science, FOCS '98,
688 November 8-11, 1998, Palo Alto, California, USA*, 320–331, 1998. (<https://doi.org/10.1109/SFCS.1998.743466>).
- 689 43 Cédric Villani. *Topics in Optimal Transportation*. vol. 58. American Mathematical Society,
690 2003.
- 691 44 Cédric Villani. *Optimal Transport: Old and New*. vol. 338. Springer Science & Business
692 Media, 2008.

698 **A** Missing Details and Proofs from Section 2

699 **A.1** Potential updates

700 We modify a trick from Vaidya [41] to batch potential updates. Potentials have a *stored*
 701 *value*, i.e. the currently recorded value of $\pi(v)$, and a *true value*, which may have changed
 702 from $\pi(v)$. The resulting algorithm queries the minimum-reduced-cost under the true values
 703 of π and updates the stored value occasionally.

704 Throughout the entire Hungarian algorithm, we maintain a nonnegative scalar δ (initially
 705 set to 0) which aggregates potential changes. Vertices $a \in A$ that are added to S are inserted
 706 into BCP with weight $\omega(a) \leftarrow \pi(a) - \delta$, for whatever value δ is at the time of insertion.
 707 Similarly, vertices $b \in B$ that are added to S have $\omega(b) \leftarrow \pi(b) - \delta$ recorded ($B \cap S$ points
 708 aren't added into a BCP set). When the Hungarian search wants to raise the potentials of
 709 points in S , δ is increased by that amount instead. Thus, true value for any potential of a
 710 point in S is always $\omega(p) + \delta$. For points of $(A \cup B) \setminus S$, the true potential is equal to the
 711 stored potential. Since all the points of $A \cap S$ have weights uniformly offset from their true
 712 potentials, the minimum edge returned by the BCP does not change. *«why?»*

713 Once a point is removed from S (i.e. by an augmentation or the rewinding mechanism),
 714 we update its stored potential $\pi(p) \leftarrow \omega(p) + \delta$, again for the current value of δ . Most
 715 importantly, δ is not reset at the end of a Hungarian search and persists through the entire
 716 algorithm. Thus, the initial BCP sets constructed by the rewinding mechanism have true
 717 potentials accurately represented by δ and $\omega(p)$.

718 We update δ once per edge relaxations; thus $O(k)$ times in total per Hungarian search.
 719 There are $O(k)$ stored values updated per Hungarian search during the rewinding process.
 720 The time spent on potential updates per Hungarian search is therefore $O(k)$.

721 **B** Missing Details and Proofs from Section 3

722 ► **Lemma 3.1.** *Let f be a θ -optimal pseudoflow in G and let f' be an admissible flow in G_f .
 723 Then $f + f'$ is also θ -optimal.*

724 **Proof.** Augmentation by f' will not change the potentials, so any previously θ -optimal arcs
 725 remain θ -optimal. However, it may introduce new arcs $v \rightarrow w$ with $u_{f+f'}(v \rightarrow w) > 0$, that
 726 previously had $u_f(v \rightarrow w) = 0$. We will verify that these arcs satisfy the θ -optimality condition.

727 If an arc $v \rightarrow w$ is newly introduced this way, then by definition of residual capacities
 728 $f(v \rightarrow w) = u(v \rightarrow w)$. At the same time, $u_{f+f'}(v \rightarrow w) > 0$ implies that $(f + f')(v \rightarrow w) < u(v \rightarrow w)$.
 729 This means that f' augmented flow in the reverse direction of $v \rightarrow w$, i.e. $f'(w \rightarrow v) > 0$. By
 730 assumption, the arcs of $\text{supp}(f')$ are admissible, so $w \rightarrow v$ was an admissible arc ($c_\pi(w \rightarrow v) \leq 0$).
 731 By antisymmetry of reduced costs, this implies $c_\pi(v \rightarrow w) \geq 0 \geq -\theta$. Therefore, all arcs with
 732 $u_{f+f'}(v, w) > 0$ respect the θ -optimality condition, and thus $f + f'$ is θ -optimal. ◀

733 ► **Lemma 3.2.** *The size of $\text{supp}(f)$ is at most $3k$ for any integer circulation f in reduction
 734 network N_H . As a corollary, the number of residual backward arcs is at most $3k$.*

735 **Proof.** Because f is a circulation, $\text{supp}(f)$ can be decomposed into k paths from s to t . Each
 736 s -to- t path in N_H is of length three, so the size of $\text{supp}(f)$ is at most $3k$. As every backward
 737 arc in the residual network must be induced by positive flow in the opposite direction, the
 738 total number of residual backward arcs is at most $3k$. ◀

739 ► **Lemma 3.3.** *Let f be a θ -optimal integer circulation in N_H , and f^* be an optimal integer
 740 circulation for N_H . Then, $\text{cost}(f) \leq \text{cost}(f^*) + 6k\theta$.*

Proof. By Lemma 3.2, the total number of backward arcs in the residual network N_f is at most $3k$. Consider the residual flow in N_f defined by the difference between f^* and f . Since both f and f^* are both circulations and N_H has unit-capacity, the flow $f - f^*$ is comprised of unit flows on a collection of edge-disjoint residual cycles $\Gamma_1, \dots, \Gamma_\ell$. Observe that each residual cycle Γ_i must have exactly half of its arcs being backward arcs, and thus we have $\sum_i |\Gamma_i| \leq 6k$.

Let π be some potential certifying that f is θ -optimal. Because Γ_i is a residual cycle, we have $c_\pi(\Gamma_i) = c(\Gamma_i)$ since the potential terms telescope. We then see that

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

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

B.1 Multiplicative approximation

The reduction in Sharathkumar and Agarwal [36] uses a *single-linkage clustering* of G — the clustering induced by a low-cost subgraph of the minimum spanning tree (MST) on G — to transform the instance into a number of bounded-diameter point sets “preserving” M^* . We also perform a single-linkage clustering, but use it to find a good upper bound on the minimum bottleneck value of the reduction network instead.

Let T be the minimum spanning tree on input graph G and order its edges by increasing length as e_1, \dots, e_{r+n-1} ; both T and the sorted edges can be constructed in $O(n \text{ polylog } n)$ time using a dynamic data structure for planar nearest neighbors. Let T_i denote the connected components of T induced by the first i edges (e_1, \dots, e_i) of T . Abusing notation, we also use T_i to denote the clustering of $A \cup B$ induced by the components of T_i . For each cluster $K \in T_i$, we use A_K and B_K to denote the points of $A \cap K$ and $B \cap K$ respectively.

We say a partial matching M is *intra-cluster* with respect to a clustering of $A \cup B$ if no edge of M has endpoints in two different clusters. Otherwise, the matching is *inter-cluster*. Let i^* be the smallest index such that T_{i^*} contains an intra-cluster partial matching. We can compute i^* in $O(n)$ time by traversing the edges e_1, \dots, e_{r+n-1} in ascending order, tracking the number of A and B points in each cluster defined by T_i . Specifically, for each $i \in 1, \dots, (r+n-1)$ let

$$\text{count}(i) := \sum_{K \in T_i} \min(A_K, B_K),$$

which is the size of the largest intra-cluster matching possible under T_i . The first index for which $\text{count}(i) \geq k$ is i^* .

► Lemma B.1.

- (i) $c(e_{i^*}) \leq \text{cost}(M^*)$
- (ii) The minimum bottleneck value for the reduction network on $A \cup B$ is at most $n^q \cdot c(e_{i^*})$.

Proof. First, by definition of i^* , M^* is inter-cluster in T_{i^*-1} . Although M^* need not be intra-cluster in T_{i^*} , this implies that at least one edge $e \in M^*$ has $c(e) \geq c(e_{i^*})$. It follows that $c(e_{i^*}) \leq \text{cost}(M^*)$.

Second, let M be the intra-cluster k -matching purported to exist in T_{i^*} . Each component of T_{i^*} has first-power diameter at most $n\|e_{i^*}\|$, so the longest edge in M has cost at most $n^q \cdot c(e_{i^*})$. In the reduction network N , M corresponds to a circulation where the most expensive arc costs at most $n^q \cdot c(e_{i^*})$; the minimum bottleneck value of N is at most that. \blacktriangleleft

783 With Lemma B.1, we can complete the proof of Lemma 3.4.

784 **Proof of Lemma 3.4.** We can determine i^* and $c(e_{i^*})$ in $O(n \text{ polylog } n)$ time, as described
 785 above. Fix $\alpha = c(e_{i^*})$. By Lemma B.1.ii the minimum bottleneck value of the reduction
 786 network is at most $n^q \alpha$. Computing an $(\alpha\epsilon/6k)$ -optimal circulation produces a partial
 787 matching of cost at most

$$788 \quad \text{cost}(M^*) + 6k(\alpha\epsilon/6k) = \text{cost}(M^*) + \epsilon \cdot c(e_{i^*}) \leq (1 + \epsilon) \text{cost}(M^*)$$

789 where the inequality follows from Lemma B.1.i. ◀

790 B.2 Number of iterations during refinement.

791 To this end we need a bound on the size of the support of f right before and throughout the
 792 execution of REFINE. This bound will also be useful later for bounding the overall running
 793 time.

794 **► Lemma B.2.** *Let f be an integer pseudoflow in N_H with $O(k)$ excess. Then, the size of
 795 the support of f is at most $O(k)$.*

796 **Proof.** Observe that the reduction graph H is a directed acyclic graph, and thus the support
 797 of f does not contain a cycle. Now $\text{supp}(f)$ can be decomposed into a set of inclusion-maximal
 798 paths, each of which contributes a single unit of excess to the flow if the path does not
 799 terminate at t or if more than k paths terminate at t . By assumption, there are $O(k)$ units
 800 of excess to which we can associate to the paths, and at most k paths (those that terminate
 801 at t) that we cannot associate with a unit of excess. The length of any such paths is at most
 802 three by construction of the reduction graph H . Therefore we can conclude that the number
 803 of arcs in the support of f is $O(k)$. ◀

804 **► Corollary B.3.** *The size of $\text{supp}(f)$ is at most $O(k)$ for pseudoflow f right before or during
 805 the execution of REFINE.*

806 **► Lemma 3.5.** *Suppose that θ_0 is chosen such that there exists a circulation in N_H with
 807 bottleneck value at most $\theta_0/2$. In any scale, let f be a pseudoflow in N_H with $O(k)$ excess.
 808 The procedure REFINE runs for $O(\sqrt{k})$ iterations before the excess of f becomes zero.*

809 **Proof.** For cost scales after the first, let f_0 and π_0 be the circulation and potential at the end
 810 of the previous cost scale. For the first cost scale, let $\pi_0 = 0$ and f_0 be any circulation with
 811 bottleneck value $\leq \theta_0/2$. In both cases, f_0 is a 2θ -optimal circulation with respect to π_0 . Let
 812 f and π be the current flow and the potential. Let $d(v)$ defined to be the amount of potential
 813 increase at v since π_0 , measured in units of θ ; in other words, $d(v) := (\pi(v) - \pi_0(v))/\theta$.

814 Now divide the iterations executed by the procedure REFINE into two phases: The
 815 transition from the first phase to the second happens when every excess vertex v has
 816 $d(v) \geq \sqrt{k}$. At most \sqrt{k} iterations belong to the first phase as each Hungarian search
 817 increases the potential π by at least θ for each excess vertex (and thus increases $d(v)$ by at
 818 least one).

819 The number of iterations belonging to the second phase is upper bounded by the amount
 820 of total excess at the end of the first phase, because each subsequent push of a blocking
 821 flow reduces the total excess by at least one. We now show that the amount of such excess
 822 is at most $O(\sqrt{k})$. Consider the set of arcs $E^+ := \{v \rightarrow w \mid f(v \rightarrow w) < f_0(v \rightarrow w)\}$. The total
 823 amount of excess is upper bounded by the number of arcs in E^+ that crosses an arbitrarily
 824 given cut X that separates the excess vertices from the deficit vertices, when the network has

unit-capacity [20, Lemma 3.6]. Consider the set of cuts $X_i := \{v \mid d(v) > i\}$ for $0 \leq i < \sqrt{k}$; every such cut separates the excess vertices from the deficit vertices at the end of first phase. Each arc in E^+ crosses at most 3 cuts of type X_i [20, Lemma 3.1]. So there is one X_i crossed by at most $3|E^+|/\sqrt{k}$ arcs in E^+ . The size of E^+ is bounded by the sum of support sizes of f and f_0 ; by Corollary B.3 the size of E^+ is $O(k)$. This implies an $O(\sqrt{k})$ bound on the total excess after the first phase, which in turn bounds the number of iterations in the second phase. ◀

C Missing Details and Proofs from Section 4

► **Lemma 4.1.** *Consider $\tilde{\pi}$ a θ -optimal potential on \tilde{H}_f and π the corresponding potential constructed on H_f . Then, (1) potential π is θ -optimal on H_f , and (2) if arc $\text{short}(\Pi)$ is admissible under $\tilde{\pi}$, then every arc in Π is admissible under π .*

Proof. Reduced costs for any arc from a normal vertex another is unchanged under either $\tilde{\pi}$ or π . Recall that a null path is comprised of one A -to- B arc, and one or two zero-cost arcs (connecting the null vertex/vertices to s and/or t). With our choice of null vertex potentials, we observe that the zero-cost arcs still have zero reduced cost. It remains to prove that an arbitrary **«residual?»** arc (a, b) **«arc or directed edge?»** satisfies the θ -optimality condition and admissibility when either a or b is a null vertex.

By construction of the shortcut graph, there is always a null path Π that contains (a, b) . Observe that $c_\pi(a, b) = c_\pi(\Pi)$, independent to the type of null path. Again by construction, $c_\pi(\Pi) = c_{\tilde{\pi}}(\text{short}(\Pi))$, so we have $c_\pi(a, b) = c_{\tilde{\pi}}(\text{short}(\Pi)) \geq -\theta$. Additionally, if $\text{short}(\Pi)$ is admissible under $\tilde{\pi}$, then so is (a, b) under π . This proves the lemma. ◀

C.1 Dynamic data structures for search procedures

Here we formally describe in details the set of dynamic data structure we use for the Hungarian search and depth-first search procedures.

For Hungarian search, we maintain the following for each type of outgoing arcs of \tilde{H}_f leaving \tilde{S} :

1. Non-shortcut backward arcs (v, w) with $(w, v) \in \text{supp}(f)$. For these, we can maintain a min-heap on $\text{supp}(f)$ arcs as each v arrives in \tilde{S} .
2. Non-shortcut A -to- B forward arcs. For these, we can use a BCP data structure between $(A \setminus A_\emptyset) \cap \tilde{S}$ and $(B \setminus B_\emptyset) \setminus \tilde{S}$, 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 $B \setminus \tilde{S}$, queried while $s \in \tilde{S}$. For t , we can maintain a max-heap on the potentials of $A \cap \tilde{S}$, queried while $t \notin \tilde{S}$.
4. Shortcut arcs (s, b) corresponding to null 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 null 2-path (s, a, b) . This is only queried while $s \in S$.
5. Shortcut arcs (a, t) corresponding to null 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 null 2-path (a, b, t) . This is only queried while $t \notin S$.
6. Shortcut arcs (s, t) corresponding to null 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

868 $\omega(q) = \pi(t)$ for all $q \in Q$. A response (a, b) corresponds to the null 3-path (s, a, b, t) . This
 869 is only queried while $s \in S$ and $t \notin S$.

870 For depth-first search, we maintain the following for each type of outgoing arcs of \tilde{H}_f
 871 leaving \tilde{S} :

- 872 1. Non-shortcut backward arcs (v', w') with $(w', v') \in \text{supp}(f)$. For these, we can maintain
 873 a min-heap on $(w', v') \in \text{supp}(f)$ arcs for each normal $v' \in V$.
- 874 2. Non-shortcut A -to- B forward arcs. For these, we maintain a NN data structure over
 875 $P = (B \setminus B_\emptyset) \setminus \tilde{S}$, with weights $\omega(p) = \pi(p)$ for each $p \in P$. We subtract $\pi(v')$ from the
 876 NN distance to recover the reduced cost of the arc from v' .
- 877 3. Non-shortcut forward arcs from s -to- A and from B -to- t . For s , we can maintain a
 878 min-heap on the potentials of $B \setminus \tilde{S}$, queried only if $v' = s$. For B -to- t arcs, there is only
 879 one arc to check if $v' \in B$, which we can examine manually.
- 880 4. Shortcut arcs (s, b) corresponding to null 2-paths from s to $b \in (B \setminus B_\emptyset) \setminus S$. For these, we
 881 maintain a NN data structure with $P = A_\emptyset$, $Q = (B \setminus B_\emptyset) \setminus S$ with weights $\omega(p) = \pi(s)$
 882 for all $p \in P$, and $\omega(q) = \pi(q)$ for all $q \in Q$. A response (a, b) corresponds to the null
 883 2-path (s, a, b) . This is only queried if $v' = s$.
- 884 5. Shortcut arcs (a, t) corresponding to null 2-paths from $a \in (A \setminus A_\emptyset) \cap S$ to t . For these,
 885 we maintain a NN data structure over $P = B_\emptyset \setminus S$ with weights $\omega(p) = \pi(t)$ for each
 886 $p \in P$. A response (v', b) corresponds to the null 2-path (v', b, t) . We subtract $\pi(v')$ from
 887 the NN distance to recover the reduced cost of the arc from v' . This is not queried if
 888 $t \in \tilde{S}$.
- 889 6. Shortcut arcs (s, t) corresponding to null 3-paths. For these, we maintain in a NN data
 890 structure with $P = A_\emptyset \setminus S$, $Q = B_\emptyset \setminus S$ with weights $\omega(p) = \pi(s)$ for all $p \in P$, and
 891 $\omega(q) = \pi(t)$ for all $q \in Q$. A response (a, b) corresponds to the null 3-path (s, a, b, t) . This
 892 is only queried while $v' = s$ and $t \notin S$.

893 C.2 Number of relaxations

894 First we bound the number of relaxations performed by both the Hungarian search and the
 895 depth-first search.

896 ► **Lemma C.1.** *Hungarian search performs $O(k)$ relaxations before a deficit vertex is reached.*

897 **Proof.** **«TO BE REWRITTEN.»** First we prove that there are $O(k)$ non-shortcut relaxa-
 898 tions. Each edge relaxation adds a new vertex to S , and non-shortcut relaxations only add
 899 normal vertices. The vertices of $V \setminus S$ fall into several categories: (i) s or t , (ii) vertices of A
 900 or B with 0 imbalance, and (iii) deficit vertices of A or B (S contains all excess vertices).
 901 The number of vertices in (i) and (iii) is $O(k)$, leaving us to bound the number of (ii) vertices.

902 An A or B vertex with 0 imbalance must have an even number of $\text{supp}(f)$ edges. There is
 903 either only one positive-capacity incoming arc (for A) or outgoing arc (for B), so this quantity
 904 is either 0 or 2. Since the vertex is normal, this must be 2. We charge 0.5 to each of the two
 905 $\text{supp}(f)$ arcs; the arcs of $\text{supp}(f)$ have no more than 1 charge each. Thus, the number of
 906 type (ii) vertex relaxations is $O(|\text{supp}(f)|)$. By Corollary B.3, $O(|\text{supp}(f)|) = O(k)$.

907 Next we prove that there are $O(k)$ shortcut relaxations. Recall the categories of shortcuts
 908 from the list of data structures above. We have shortcuts corresponding to (i) null 2-paths
 909 surrounding $a \in A_\emptyset$, (ii) null 2-paths surrounding $b \in B_\emptyset$, and (iii) null 3-paths, which go
 910 from s to t . There is only one relaxation of type (iii), since t can only be added to S once.
 911 The same argument holds for type (ii).

Each type (i) relaxation adds some normal $b \in B \setminus B_\emptyset$ into S . Since b is normal, it must either have deficit or an adjacent arc of $\text{supp}(f)$. We charge this relaxation to b if it is deficit, or the adjacent arc of $\text{supp}(f)$ otherwise. No vertex is charged more than once, and no $\text{supp}(f)$ edge is charged more than twice, therefore the total number of type (i) relaxations is $O(|\text{supp}(f)|)$. By Corollary B.3, $O(|\text{supp}(f)|) = O(k)$. ◀

Similarly we can prove that there are $O(k)$ relaxations during the DFS.

► **Corollary C.2.** *Depth-first search performs $O(k)$ relaxations before a deficit vertex is reached.*

C.3 Time analysis

Now we complete the time analysis by showing that each Hungarian search and depth-first search can be implemented in $O(k \text{ polylog } n)$ time after a one-time $O(n \text{ polylog } n)$ -time preprocessing.

There are only $O(1)$ data structures for both. The rewinding mechanism and potential update scheme of Section 2 to reset for each Hungarian search in time $O(\text{polylog } n)$ times the number of relaxations, giving the following. The main difference is that we are using blocking flows rather than augmenting paths, so the initial S (i.e. excess vertices) may change by more than one element for each REFINES iteration. The total number of such changes throughout REFINES is $O(k)$, however, since REFINES begins with $O(k)$ excess and does not gain more. We obtain the following:

► **Lemma C.3.** *After $O(n \text{ polylog } n)$ -time preprocessing, each Hungarian search can be implemented in $O(k \text{ polylog } n)$ time.*

► **Lemma C.4.** *After $O(n \text{ polylog } n)$ -time preprocessing, each depth-first search can be implemented in $O(k \text{ polylog } n)$ time.*

► **Lemma C.5.** *The rewinding mechanism takes in total $O(k \text{ polylog } n)$ time in REFINES.*

C.4 Number of potential updates on null vertices

In our implementation of REFINES, we do not explicitly construct \tilde{H}_f ; instead we query its edges using BCP/NN oracles and min/max heaps on elements of H_f . Potentials on the null vertices are only required right before an augmentation sends a flow through a null path, making the null vertices it passes normal. We use the construction from Lemma 4.1 to obtain potential π on H_f such that the flow f is both θ -optimal and admissible with respect to π .

Size of blocking flows. Now we bound the total number arcs whose flow is updated by a blocking flow during the course of REFINES. This bounds both the time spent updating the flow on these arcs and also the time spent on null vertex potential updates (Lemma C.7).

► **Lemma C.6.** *The support of each blocking flow found in REFINES is of size $O(k)$.*

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. Let one of these paths be P . 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 C.2, we have $N_i = O(k)$. ◀

► **Lemma C.7.** *The number of end-of-REFINE null vertex potential updates is $O(n)$. The number of augmentation-induced null vertex potential updates in each invocation of REFINE is $O(k \log k)$.*

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 a null path, causing a potential update on the passed null vertex. We charge this potential update to the edges of that null 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 at most the size of support of the blocking flow, which is $O(k)$ by Lemma C.6. According to Lemma 3.5 there are $O(\sqrt{k})$ iterations of REFINE before it terminates. Summing up we have an $O(k\sqrt{k})$ bound over the course of REFINE. ◀

Now combining Lemma 3.4, Lemma 3.5, Lemma C.3, Lemma C.4, and Lemma C.7 completes the proof of Theorem 1.2.

D Missing Details and Proofs from Section 5

D.1 Uncapacitated MCF by excess scaling

We give an outline of the strongly polynomial-time algorithm for uncapacitated min-cost flow problem from Orlin [29]. Orlin's algorithm follows an *excess-scaling* paradigm originally due to Edmonds and Karp [16]. Consider the basic primal-dual framework used in the previous sections: The algorithm begins with both flow f and potentials π set to zero. Repeatedly runs a *Hungarian search* that raises potentials (while maintaining dual feasibility) to create an admissible augmenting excess-deficit path, on which we perform flow augmentations. In terms of cost, f is maintained to be 0-optimal with respect to π and each augmentation over admissible edges preserves 0-optimality (by Lemma 3.1). Thus, the final circulation must be optimal. The excess-scaling paradigm builds on top of this skeleton by specifying (i) between which excess and deficit vertices we send flows, and (ii) how much flow is sent by the augmentation.

The excess-scaling algorithm maintains a *scale parameter* Δ , initially set to U . A vertex v with $|\phi_f(v)| \geq \Delta$ is called *active*. Each augmenting path is chosen between an active excess vertex and an active deficit vertex. Once there are no more active excess or deficit vertices, Δ is halved. Each sequence of augmentations where Δ holds a constant value is called an *excess scale*. There are $O(\log U)$ excess scales before $\Delta < 1$ and, by integrality of supplies/demands, f is a circulation.

With some modifications to the excess-scaling algorithm, Orlin [29] obtains a strongly polynomial bound on the number of augmentations and excess scales. First, an *active* vertex is redefined to be one satisfying $|\phi_f(v)| \geq \alpha\Delta$, for a fixed parameter $\alpha \in (0.5, 1)$. Second, arcs with flow value at least $3n\Delta$ at the beginning of a scale are *contracted* to create a new vertex, whose supply-demand is the sum of those on the two endpoints of the contracted arc. We use $\hat{G} = (\hat{V}, \hat{E})$ to denote the resulting *contracted graph*, where each $\hat{v} \in \hat{V}$ is a contracted component of vertices from V . Intuitively, the flow is so high on contracted arcs that no set of future augmentations can remove the arc from $\text{supp}(f)$. Third, in addition to halving, Δ is aggressively lowered to $\max_{v \in V} \phi_f(v)$ if there are no active excess vertices and $f(v \rightarrow w) = 0$ holds for every arc $v \rightarrow w \in \hat{E}$. Finally, flow values are not tracked within contracted components, but once an optimal circulation is found on \hat{G} , optimal potentials π^* can be *recovered* for G by sequentially undoing the contractions. The algorithm then

performs a post-processing step which finds the optimal circulation f^* on G by solving a max-flow problem on the set of admissible arcs under π^* .

D.2 Implementing contractions

Following Agarwal *et al.* [2], our geometric data structures deals with real points in the plane instead of the contracted components. We will track the contracted components described in \hat{G} (e.g. with a disjoint-set data structure) and mark the arcs of $\text{supp}(f)$ that are contracted. We maintain potentials on the points A and B directly, instead of the contracted components.

When conducting the Hungarian search, we initialize S to be the set of vertices from *active excess contracted components* who (in sum) meet the imbalance criteria. **«unclear»** Upon relaxing any $v \in \hat{v}$, we immediately relax all the contracted support arcs which span \hat{v} . Since the input network is uncapacitated, each contracted component is strongly connected in the residual network by the admissible forward/backward arcs of each contracted arc. **«unparsable»** To relax arcs in \hat{E} , we relax the support arcs before attempting to relax any non-support arcs; this will guarantee that the underlying graph of the support is acyclic (see Lemma D.6). Relaxations of support arcs can be performed without further potential changes, since they are admissible by invariant.

During the augmentations, contracted residual arcs are considered to have infinite capacity, and we do not update the value of flows on these arcs. We allow augmenting paths to begin from any point $a \in \hat{v} \cap A$ in an active excess component \hat{v} , and end at any point $b \in \hat{w} \cap B$ in an active deficit component \hat{w} .

D.3 Recovering the optimal flow

We use the recovery strategy from Agarwal *et al.* [2], which runs in $O(n \text{ polylog } n)$ time. The main idea is that, if \mathcal{T} is an undirected *spanning tree of admissible edges* under optimal potentials π^* , then there exists an optimal flow f^* with support only on arcs corresponding to edges of \mathcal{T} . Intuitively, \mathcal{T} is a maximal set of linearly independent dual LP constraints for the optimal dual (π^*), so there exists an optimal primal solution (f^*) with support only on these arcs. To see this, we can use a perturbation argument: raising the cost of each non-tree edge by a positive amount does not change $\text{cost}(\pi^*)$ or the feasibility of π^* , but does raise the cost of any circulation f using non-tree edges. Strong duality suggests that $\text{cost}(f^*) = \text{cost}(\pi^*)$ is unchanged, therefore f^* must have support only on the tree edges.

Since the arcs corresponding to edges of \mathcal{T} have no cycles, we can solve the maximum flow in linear time using the following greedy algorithm. Let $\text{par}(v)$ be the parent of vertex v in \mathcal{T} . We begin with $f^* = 0$ and process \mathcal{T} from its leaves upwards. For a supply leaf v , we satisfy its supply by choosing $f^*(v \rightarrow \text{par}(v)) \leftarrow \phi(v)$. Otherwise if leaf v is a demand vertex, we choose $f^*(\text{par}(v) \rightarrow v) \leftarrow -\phi(v)$. Once we've solved the supplies/demands for each leaf, then we can *trim* the leaves, removing them from \mathcal{T} and setting the supply/demand of each parent-of-a-leaf to its current imbalance. Then, we can recurse on this smaller tree and its new set of leaves.

► **Lemma D.1.** *Let $G(\mathcal{T})$ be the subnetwork of G corresponding to edges of the undirected spanning tree \mathcal{T} . If there exists a flow in $G(\mathcal{T})$ which satisfies every supply and demand, then the greedy algorithm finds the maximum flow in $G(\mathcal{T})$ in $O(n)$ time.*

Proof. Observe that, for any flow f in G , $\text{supp}(f)$ has no paths of length longer than one. Thus, if a flow f^* satisfying supplies/demands exists within $G(\mathcal{T})$, then each supply vertex has

flow paths that terminate at its parent/children. Similarly, each demand vertex receive all its flow from its parent/children. Since there is only one option for a supply leaf (resp. demand leaf) to send its flow (resp. receive its flow), the greedy algorithm correctly identifies the values of f^* for arcs adjoining \mathcal{T} leaves. Trimming these leaves, we can apply this argument recursively for their parents. The running time of the greedy algorithm is $O(n)$, as leaves can be identified in $O(n)$ time and no vertex becomes a leaf more than once. \blacktriangleleft

It remains to show how we construct \mathcal{T} . We begin with a (spanning) *shortest path tree* (SPT) T in the residual network of f , under reduced costs and rooted at an arbitrary vertex r . For the SPT to span, we need the additional assumption that G is strongly connected. We can make G strongly connected by adding a 0-supply vertex s with arcs $s \rightarrow a$ for all $a \in A$ and $b \rightarrow a$ for all $b \in B$, with some high cost M . Following Orlin [29], these arcs cannot appear in an optimal flow if M is sufficiently high, and we can extend π^* to include s using $\pi^*(s) = 0$ if $M > \max_{b \in B} \pi^*(b)$. This extension to π^* preserves feasibility.

The edges corresponding to arcs of T do not suffice for \mathcal{T} , since some SPT arcs may be inadmissible. Let $d_r(v)$ be the shortest path distance of $v \in A \cup B \cup \{s\}$ from r , and consider potentials $\pi^\# = \pi^* - d_r$.

► **Lemma D.2 Orlin [29] Lemma 3.** *Let f be a flow satisfying the optimality conditions with respect to π^* . Then, (i) f satisfies the optimality conditions with respect to $\pi^\#$, and (ii) all SPT arcs are admissible under $\pi^\#$.*

We can use this lemma to argue that $\pi^\#$ is still optimal. Recall that f has values defined only on the non-contracted residual arcs; we can apply the first part of Lemma D.2 on these arcs. For arcs within contracted components, we use a different argument. Observe that each $\hat{v} \in \hat{V}$ is spanned by a set of $\text{supp}(f)$ arcs, which are admissible by invariant. Thus, all $v \in \hat{v}$ are equidistant from r , and they will have the same value $d_r(v)$. It follows that the reduced costs of arcs with both endpoints in \hat{v} do not change when replacing π^* with $\pi^\#$, so arcs contained in \hat{v} that met the optimality conditions for π^* still meet them for $\pi^\#$.

From the second part of Lemma D.2, the SPT T is a spanning tree of admissible arcs under $\pi^\#$. We set \mathcal{T} to be the set of undirected edges corresponding to T .

Computing the SPT. We conclude by describing the procedure for building the SPT, i.e. by running Dijkstra's algorithm in the residual network. We use a geometric implementation that is very similar to Hungarian search. We begin with $S = \{r\}$ and $d_r(r) = 0$, where r is our arbitrary root. For all other vertices, $d_r(v)$ is initially unknown. In each iteration, we relax the minimum-reduced cost arc $v \rightarrow w$ in the frontier $S \times (A \cup B) \setminus S$, adding w to S , and setting $d_r(w) = d_r(v) + c_{\pi^*}(v, w)$. Once $S = A \cup B$, the SPT T is the set of relaxed arcs.

If an either direction of an arc of $\text{supp}(f)$ enters the frontier, we relax it immediately. To detect support arcs, we build a list for each $v \in A \cup B$ of the support arcs which use v as an endpoint, and once $v \in S$ we check its list. There are $O(n)$ support arcs in total (by acyclicity of $E(\text{supp}(f))$; see Lemma D.6), so the total time spent searching these lists is $O(n)$. Such relaxations are correct for the shortest path tree, since the support edges are admissible and reduced costs are nonnegative.

Other edges appearing in the frontier can be split into three categories:

1. Forward A -to- B arcs. We query these using a BCP with $P = A \cap S$ and $Q = B \setminus S$.
2. B -to- s arcs. These will never have flow support. We can query the minimum with a max-heap on potentials of $B \cap S$. We query these while $s \in S$.
3. s -to- A arcs. These will also never have flow support. We can query the minimum with a min-heap on potentials of $A \setminus S$. We query these while $s \in S$.

1084 We perform $O(n)$ relaxations and takes $O(\text{polylog } n)$ time per relaxation, for non-support
 1085 relaxations. An additional $O(n)$ time is spent relaxing support edges. The total running
 1086 time of Dijkstra's algorithm is $O(n \text{ polylog } n)$. Combining with Lemma D.1, we obtain the
 1087 following.

1088 ► **Lemma D.3.** *Given optimal potentials π^* and an optimal contracted flow f , the optimal*
 1089 *flow f^* can be computed in $O(n \text{ polylog } n)$ time.*

1090 D.4 Recovering the optimal flow for sum-of-distances.

1091 When the matching objective uses the just the p -norms (that is, when $q = 1$), we can prove
 1092 that the subgraph formed by admissible arcs is in fact *planar*. Planarity gives us two things
 1093 for recovery: there are only a linear number of admissible arcs, and the max-flow on them
 1094 can be solved in near-linear time with a planar graph multiple-source multiple-sink max-flow
 1095 algorithm. Note that this recovery algorithm is not asymptotically faster than the other, and
 1096 depending on the planar max-flow algorithm, not necessarily simpler either.

1097 Up until now, we have not placed restrictions on coincidence between A and B , but
 1098 for the next proof it is useful to do so. We can assume that all points within $A \cup B$ are
 1099 distinct, otherwise we can replace all points coincident at $x \in \mathbb{R}^2$ with a single point whose
 1100 supply/demand is $\sum_{v \in A \cup B: v=x} \lambda(v)$. This is roughly equivalent to transporting as much as
 1101 we can between coincident supply and demand, and is optimal by triangle inequality.

1102 Without loss of generality, assume π^* is nonnegative (raising π^* uniformly on all points
 1103 does not change the objective or feasibility). Recall that π^* is feasibility if for all $a \in A$ and
 1104 $b \in B$

$$1105 \quad c_{\pi^*}(a, b) = \|a - b\|_p - \pi^*(a) + \pi^*(b) \geq 0.$$

1106 An arc $a \rightarrow b$ is admissible when

$$1107 \quad c_{\pi^*}(a, b) = \|a - b\|_p - \pi^*(a) + \pi^*(b) = 0.$$

1108 We note that these definitions have a nice visual: Place disks D_q of radius $\pi(q)$ at each
 1109 $q \in A \cup B$. Feasibility states that for all $a \in A$ and $b \in B$, D_a cannot contain D_b with a
 1110 gap between their boundaries. The arc $a \rightarrow b$ is admissible when D_a contains D_b and their
 1111 boundaries are tangent.

1112 ► **Lemma D.4.** *Let π^* be a set of optimal potentials for the point sets A and B , under costs*
 1113 *$c(a, b) = \|a - b\|_p$. Then, the set of admissible arcs under π^* form a planar graph.*

1114 **Proof.** We assume the points of $A \cup B$ are in general position (e.g. by symbolic perturbation)
 1115 such that no three points are collinear. Let $a_1 \rightarrow b_1$ and $a_2 \rightarrow b_2$ be any pair of admissible
 1116 arcs under π^* . We will isolate them from the rest of the points, considering π^* restricted
 1117 to the four points $\{a_1, a_2, b_1, b_2\}$. Clearly, this does not change whether the two arcs cross.
 1118 Observe that we can raise $\pi^*(a_2)$ and $\pi^*(b_2)$ uniformly, until $c_{\pi^*}(a_2, b_1) = 0$, without breaking
 1119 feasibility or changing admissibility of $a_1 \rightarrow b_1$ and $a_2 \rightarrow b_2$. Henceforth, we assume that we have
 1120 modified π^* in this way to make $a_2 \rightarrow b_1$ admissible. Given positions of a_1, a_2 , and b_1 , we now
 1121 try to place b_2 such that $a_1 \rightarrow b_1$ and $a_2 \rightarrow b_2$ cross. Specifically, b_2 must be placed within a
 1122 region \mathcal{F} that lies between the rays $\overrightarrow{a_2 a_1}$ and $\overrightarrow{a_2 b_1}$, and within the halfplane bounded by $\overleftrightarrow{a_1 b_1}$
 1123 that does not contain a_2 .

1124 Let $g_a(q) := \|a - q\| - \pi^*(a)$ for $a \in A$ and $q \in \mathbb{R}^2$. Let the *bisector* between a_1 and a_2
 1125 be $\beta := \{q \in \mathbb{R}^2 \mid g_{a_1}(q) = g_{a_2}(q)\}$. β is a curve subdividing the plane into two open faces,
 1126 one where g_{a_1} is minimized and the other where g_{a_2} is. From these definitions, admissibility
 1127 of $a_1 \rightarrow b_1$ and $a_2 \rightarrow b_1$ imply that b_1 is a point of the bisector.

We show that \mathcal{F} lies entirely on the g_{a_1} side of the bisector. First, we prove that the closed segment $\overline{a_1 b_1}$ lies entirely on the g_{a_1} side, except b_1 which lies on β . Any $q \in \overline{a_1 b_1}$ can be written parametrically as $q(t) = (1-t)b_1 + ta_1$ for $t \in [0, 1]$. Consider the single-variable functions $g_{a_1}(q(t))$ and $g_{a_2}(q(t))$.

$$\begin{aligned} g_{a_1}(q(t)) &= (1-t)\|a_1 - b_1\| - \pi(a_1) \\ g_{a_2}(q(t)) &= \|(a_2 - b_1) - t(a_1 - b_1)\| - \pi(a_2) \end{aligned}$$

At $t = 0$, these expressions are equal. Observe that the derivative with respect to t of $g_{a_1}(q(t))$ is less than $g_{a_2}(q(t))$. Indeed, the value of $\frac{d}{dt}\|(a_2 - b_1) - t(a_1 - b_1)\|$ is at least $-\|a_1 - b_1\| = \frac{d}{dt}g_{a_1}(q(t))$, which is realized if and only if $\frac{(a_2 - b_1)}{\|a_2 - b_1\|} = \frac{(a_1 - b_1)}{\|a_1 - b_1\|}$. This corresponds to $\overrightarrow{a_2 b_1}$ and $\overrightarrow{a_1 b_1}$ being parallel, but this is disallowed since a_1, a_2, b_1 are in general position. Thus, $g_{a_1}(q(t)) \leq g_{a_2}(q(t))$ with equality only at b_1 .

Now, we parameterize each point of \mathcal{F} in terms of points on $\overline{a_1 b_1}$. Every $q \in \mathcal{F}$ can be written as $q(t') = q' + t'(q' - a_2)$ for some $q' \in \overline{a_1 b_1}$ and $t \geq 0$, i.e. $q' = \overline{a_1 b_1} \cap \overrightarrow{a_2 q}$. We call q' the *projection* of q onto $\overline{a_1 b_1}$. We can write g_{a_1} and g_{a_2} in terms of t' and observe that $\frac{d}{dt'}g_{a_1}(q(t')) \leq \frac{d}{dt'}g_{a_2}(q(t'))$, as the derivative of $g_a(q(t'))$ is maximized if $(q(t') - a)$ is parallel to $(q(t') - a_2)$ and lower otherwise. Notably, $q(t')$ with projection b_1 have $\frac{d}{dt'}g_{a_1}(q(t')) < \frac{d}{dt'}g_{a_2}(q(t'))$, since a_1, a_2, b_1 are in general position. Any $q(t')$ with a different projection do not have strict inequality, but the projection itself has $g_{a_1}(q') < g_{a_2}(q')$ for $q' \neq b_1$ since it lies on $\overline{a_1 b_1}$. Therefore, for all $q \in \mathcal{F} \setminus \{b_1\}$, $g_{a_1}(q') < g_{a_2}(q')$, and \mathcal{F} lies on the g_{a_1} side of the bisector except for b_1 which lies on β . We can eliminate b_1 as a candidate position for b_2 , since points of B cannot coincide.

Observe that $g_{a_1}(b) < g_{a_2}(b)$ for $b \in B$ implies that $c_\pi(a_1, b) < c_\pi(a_2, b)$, and $c_\pi(a_1, b) = c_\pi(a_2, b)$ if and only if b lies on β . This holds for all $b \in \mathcal{F}$ including our prospective b_2 , but then $c_\pi(a_1, b_2) < c_\pi(a_2, b_2) = 0$ since $a_2 \rightarrow b_2$ is admissible. This violates feasibility of $a_1 \rightarrow b_2$, so there is no feasible placement of b_2 which also crosses $a_1 \rightarrow b_1$ with $a_2 \rightarrow b_2$. ◀

We can construct the entire set of admissible arcs by repeatedly querying the minimum-reduced-cost outgoing arc for each $a \in A$ until the result is not admissible. By Lemma D.4 the resulting arc set forms a planar graph, so by Euler's formula the number of arcs to query is $O(n)$. We can then find the maximum flow in time $O(n \log^3 n)$ time, using the planar multiple-source multiple-sink maximum-flow algorithm by Borradaile *et al.* [11].

► **Lemma D.5.** *If the transportation objective is sum-of-costs, then given the optimal potentials π^* , we can compute an optimal flow f^* in $O(n \text{ polylog } n)$ time.*

D.5 Dead vertices

Let the *support degree* of a vertex be its degree in the graph induced by the underlying edges of $\text{supp}(f)$. We call a vertex $b \in B$ *dead* if b has support degree 0 and is not an active excess or deficit vertex; call it *living* otherwise. Dead vertices are essentially equivalent to the *null vertices* of Section 3. However, since the reduction in this section does not use a super-source/super-sink, we can simply remove these from consideration during a Hungarian search — they will not terminate the search, and have no outgoing residual arcs. Like the null vertices, we ignore dead vertex potentials and infer feasible potentials when they become live again. We use A_ℓ and B_ℓ to denote the living vertices of points in A and B , respectively. Note that being dead/alive is a notion strictly defined only for vertices, and not for contracted components.

We say a dead vertex is *revived* when it stops meeting either condition of the definition. Dead vertices are only revived after Δ decreases (at the start of a subsequent excess scale) as no augmenting path will cross a dead vertex and they cannot meet the criteria for contractions. When a dead vertex is revived, we must add it back into each of our data structures and give it a feasible potential. For revived $b \in B$, a feasible choice of potential is $\pi(b) \leftarrow \max_{a \in A} (\pi(a) - c(a, b))$ which we can query by maintaining a weighted nearest neighbor data structure on the points of A . The total number of revivals is bounded above by the number of augmentations: since the final flow is a circulation on \hat{G} and a newly revived vertex v has no incident arcs in $\text{supp}(f)$ and cannot be contracted, there is at least one subsequent augmentation which uses v as its beginning or end. Thus, the total number of revivals is $O(n \log n)$.

D.6 Number of relaxations

By prioritizing the relaxation of support arcs, we also have the following lemma.

► **Lemma D.6 (Agarwal et al. [2]).** *If arcs of $\text{supp}(f)$ are relaxed first as they arrive on the frontier, then $E(\text{supp}(f))$ is acyclic.*

Proof. Let f_i be the pseudoflow after the i -th augmentation, and let T_i be the forest of relaxed arcs generated by the Hungarian search for the i -th augmentation. Namely, the i -th augmenting path is an excess-deficit path in T_i , and all arcs of T_i are admissible by the time the augmentation is performed. Let $E(T_i)$ be the undirected edges corresponding to arcs of T_i . Notice that, $E(\text{supp}(f_{i+1})) \subseteq E(\text{supp}(f_i)) \cup E(T_i)$. We prove that $E(\text{supp}(f_i)) \cup E(T_i)$ is acyclic by induction on i ; as $E(\text{supp}(f_{i+1}))$ is a subset of these edges, it must also be acyclic. At the beginning with $f_0 = 0$, $E(\text{supp}(f_0))$ is vacuously acyclic.

Let $E(\text{supp}(f_i))$ be acyclic by induction hypothesis. Since T_i is a forest (thus, acyclic), any hypothetical cycle Γ that forms in $E(\text{supp}(f_i)) \cup E(T_i)$ must contain edges from both $E(\text{supp}(f_i))$ and $E(T_i)$. To give a visual analogy, we will color $e \in \Gamma$ *purple* if $e \in E(\text{supp}(f_i)) \cap E(T_i)$, *red* if $e \in E(\text{supp}(f_i))$ but $e \notin E(T_i)$, and *blue* if $e \in E(T_i)$ but $e \notin E(\text{supp}(f_i))$. Then, Γ is neither entirely red nor entirely blue. We say that red and purple edges are *red-tinted*, and similarly blue and purple edges are *blue-tinted*. Roughly speaking, our implementation of the Hungarian search prioritizes relaxing red-tinted admissible arcs over pure blue arcs.

We can sort the blue-tinted edges of Γ by the order they were relaxed into S during the Hungarian search forming T_i . Let $(v, w) \in \Gamma$ be the last pure blue edge relaxed, of all the blue-tinted edges in Γ — after (v, w) is relaxed, the remaining unrelaxed, blue-tinted edges of Γ are purple.

Let us pause the Hungarian search the moment before (v, w) is relaxed. At this point, $v \in S$ and $w \notin S$, and the Hungarian search must have finished relaxing all frontier support arcs. By our choice of (v, w) , $\Gamma \setminus (v, w)$ is a path of relaxed blue edges and red-tinted edges which connect v and w . Walking around $\Gamma \setminus (v, w)$ from v to w , we see that every vertex of the cycle must be in S already: $v \in S$, relaxed blue edges have both endpoints in S , and any unrelaxed red-tinted edge must have both endpoints in S , since the Hungarian search would have prioritized relaxing the red-tinted edges to grow S before relaxing (v, w) (a blue edge). It follows that $w \in S$ already, a contradiction.

No such cycle Γ can exist, thus $E(\text{supp}(f_i)) \cup E(T_i)$ is acyclic and $E(\text{supp}(f_{i+1})) \subseteq E(\text{supp}(f_i)) \cup E(T_i)$ is acyclic. By induction, $E(\text{supp}(f_i))$ is acyclic for all i . ◀

Let $E(\Sigma_a)$ **◀only used once▶** be the underlying edges of the support star centered at a and $F := E(\text{supp}(f)) \setminus \bigcup_{a \in A} E(\Sigma_a)$. Using Lemma D.6, we can show that the number of

1216 support arcs outside support stars ($|F|$) is small.

1217 ► **Lemma D.7.** $|B_\ell \setminus \bigcup_{a \in A} \Sigma_a| \leq r$.

1218 **Proof.** F is constructed from $E(\text{supp}(f))$ by eliminating edges in support stars, therefore all
 1219 edges in F must adjoin vertices in B of support degree at least 2. By Lemma D.6, $E(\text{supp}(f))$
 1220 is acyclic and therefore forms a spanning forest over $A \cup B_\ell$, so F is also a bipartite forest.
 1221 All leaves of F are therefore vertices of A .

1222 Pick an arbitrary root for each connected component of F to establish parent-child
 1223 relationships for each edge. As no vertex in B is a leaf, each vertex in B has at least one
 1224 child. Charge each vertex in B to one of its children in F , which must belong to A . Each
 1225 vertex in A is charged at most once. Thus, the number of B_ℓ vertices outside of support
 1226 stars is no more than r . ◀

1227 ► **Lemma 5.2.** *Suppose we have stripped the graph of dead vertices. The number of relaxation*
 1228 *steps in a Hungarian search outside of support stars is $O(r)$.*

1229 **Proof.** If there are no dead vertices, then each non-support star relaxation step adds either
 1230 (i) an active deficit vertex, (ii) a non-deficit vertex $a \in A_\ell$, or (iii) a non-deficit vertex $b \in B_\ell$
 1231 of support degree at least 2. There is a single relaxation of type (i), as it terminates the
 1232 search. The number of vertices of type (ii) is r , and the number of vertices of type (iii) is at
 1233 most r by Lemma D.7. The lemma follows. ◀

1234 ► **Lemma 5.3.** *Hungarian search takes $O(r\sqrt{n} \text{polylog } n)$ time.*

1235 **Proof.** The number of relaxation steps outside of support stars is $O(r)$ by Lemma 5.2. The
 1236 time per relaxation outside of support stars is $O(\sqrt{n} \text{polylog } n)$. The time spent processing
 1237 relaxations within a support star is $O(\sqrt{n} \text{polylog } n)$, and at most r are relaxed during the
 1238 search. The total time is therefore $O(r\sqrt{n} \text{polylog } n)$. ◀

1239 D.7 Updating support stars

1240 Initially, we label stars big or small according to the \sqrt{n} threshold. Afterwards, a star that is
 1241 currently big is turned into a small star once $|\Sigma_a| \leq \sqrt{n}/2$, and star that is currently small
 1242 is turned into a big star once $|\Sigma_a| \geq 2\sqrt{n}$. We say a star which crosses one of these size
 1243 thresholds is *changing state* (from small-to-big or big-to-small), and must be represented in
 1244 the opposite type of data structure. Our strategy is to charge the data structure update time
 1245 associated with a state change to the *membership changes* in Σ_a that preceded the state
 1246 change.

1247 A star Σ_a undergoing a big-to-small state change has size $|\Sigma_a| \leq \sqrt{n}/2$. The state change
 1248 deletes $\mathcal{D}_{\text{big}}(a)$ and inserts Σ_a into $\mathcal{D}_{\text{small}}$. Thus, the time spent for a big-to-small state
 1249 change is $O(\sqrt{n} \text{polylog } n)$, and there were at least $\sqrt{n}/2$ points removed from Σ_a since it
 1250 last changed state. The amortized time for a big-to-small state change per star membership
 1251 change is $O(\text{polylog } n)$.

1252 A star Σ_a undergoing a small-to-big state change has size $|\Sigma_a| \geq 2\sqrt{n}$. We can write its
 1253 size as $|\Sigma_a| = \sqrt{n} + x$ for some integer $x \geq \sqrt{n}$, so we also have $|\Sigma_a| \leq 2x$. When switching,
 1254 we delete all $|\Sigma_a|$ points from $\mathcal{D}_{\text{small}}$ and construct a new $\mathcal{D}_{\text{big}}(a)$. Constructing $\mathcal{D}_{\text{big}}(a)$
 1255 requires inserting up to r points of A (into P) and the $|\Sigma_a|$ points of the star (into Q). Thus,
 1256 the time spent for a small-to-big state change is $(r + 2x) \cdot O(\text{polylog } n)$, and there were at
 1257 least x points added to Σ_a since it last changed state. The amortized time for a small-to-big
 1258 state change per star membership change is $O((r/x) \text{polylog } n)$. Since $x \geq \sqrt{n}$, this is at
 1259 most $O((r/\sqrt{n}) \text{polylog } n)$.

1260 Star membership can only be changed by augmenting paths passing through the vertex,
1261 therefore the total number of membership changes is $O(rn \log n)$ by Lemmas 5.1 and 5.2.
1262 Thus, the total time spent on state changes is $O((r^2\sqrt{n} + rn) \text{polylog } n)$.