

# Geodesic Ham-Sandwich Cuts\*

Prosenjit Bose

School of Computer Science  
Carleton University  
jit@cs.carleton.ca

John Iacono

Dep. of Comp. and Inf. Sci.  
Polytechnic University  
jiacono@poly.edu

Erik D. Demaine

MIT Laboratory  
for Computer Science  
edemaine@mit.edu

Stefan Langerman<sup>†</sup>

Département d'Informatique  
Université Libre de Bruxelles  
stefan.langerman@ulb.ac.be

Ferran Hurtado

Depart. de Matem. Aplic. II  
Univ. Polit. de Catalunya  
Ferran.Hurtado@upc.es

Pat Morin

School of Computer Science  
Carleton University  
morin@cs.carleton.ca

## ABSTRACT

Let  $P$  be a simple polygon with  $m$  vertices,  $k$  of which are reflex, and which contains  $r$  red points and  $b$  blue points in its interior. Let  $n = m + r + b$ . A *ham-sandwich geodesic* is a shortest path in  $P$  between any two points on the boundary of  $P$  that simultaneously bisects the red points and the blue points. We present an  $O(n \log k)$ -time algorithm for finding a ham-sandwich geodesic. We also show that this algorithm is optimal in the algebraic computation tree model when parameterizing the running time with respect to  $n$  and  $k$ .

**Categories and Subject Descriptors:** F.2.2 [Numerical Algorithms and Problems]:

**General Terms:** Ham-sandwich theorem

**Keywords:** Ham-sandwich, shortest paths, geodesics, simple polygons

## 1. INTRODUCTION

Let  $R, B \subseteq \mathbb{R}^2$  be two finite point sets of sizes  $r$  and  $b$ , respectively. We call the elements of  $R$  the *red points* and the elements of  $B$  the *blue points*. The (2-dimensional) *ham-sandwich theorem* (for point sets) states that there always exists a line  $L$  such that each of the two open halfplanes defined by  $L$  contains at most  $r/2$  red points and at most  $b/2$  blue points.<sup>1</sup> We call such a line a *ham-sandwich cut*.

\*Partially supported by NSERC, NSF, DURSI 2001SGR00224, Acci Integrada UPC-McGill (DURSI2004) and MCYT BFM2003-0368.

<sup>†</sup>Chargé de recherches du FNRS

<sup>1</sup>The full ham-sandwich theorem is much more general: Let  $S_1, \dots, S_d$  be bounded measurable subsets of  $\mathbb{R}^d$ . The *ham-sandwich theorem* states that there exists a hyperplane  $h$  that divides each  $S_i$  into two subsets of equal measure [18].

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

SCG'04 June 8–11, 2004, Brooklyn, New York, USA  
Copyright 2004 ACM 1-58113-885-7/04/0006 ...\$5.00.

Megiddo [15] showed that, if the sets  $R$  and  $B$  are linearly separable (there exists a line that separates  $R$  from  $B$ ) then a ham-sandwich cut can be found in  $O(n)$  time. Edelsbrunner and Waupotitsch [6] modified Megiddo's method and obtained an  $O(n \log n)$  time algorithm for the general case. Lo and Steiger [13] gave a randomized algorithm with  $O(n)$  expected running time. Since this algorithm is easily derandomized using  $\epsilon$ -nets [12] this result finally settled the problem of finding planar ham-sandwich cuts.

The problem of computing ham-sandwich cuts in  $d$  dimensions,  $d \geq 3$  has been considered by Lo *et al* [12]. Several generalizations of planar ham-sandwich cuts have also been proposed [1, 2, 8, 9]. Particularly relevant to the current paper is the algorithm of Díaz and O'Rourke for computing a ham-sandwich cut of two simple polygons [5].

In this paper we generalize the notion of ham-sandwich cuts to polygonal domains. In particular, we consider the problem of computing ham-sandwich cuts in (rather than of) a polygonal domain. Let  $P$  be a simple polygon with  $m$  vertices and that contains the sets  $R$  and  $B$  in its interior. A *geodesic* is a shortest path in  $P$  that joins two points on the boundary of  $P$ . We show that there always exists a geodesic that has at most  $r/2$  red points to its right and left sides and at most  $b/2$  blue points to its right and left sides. (See Figure 1.) We call such a geodesic a *ham-sandwich geodesic*. We give an  $O(n \log k)$  expected-time randomized algorithm for finding a ham-sandwich geodesic and prove that this is optimal in the algebraic computation tree model. Here, and throughout the remainder of the paper,  $n = m + r + b$  and  $k$  is the number of reflex vertices of  $P$ .

Note that our algorithm is a strict generalization of the algorithm of Lo and Steiger since, in the case of a convex polygon, the polygon plays no role and we are simply looking for a ham-sandwich cut of  $R$  and  $B$ . The main tools used in our algorithm are randomized prune and search [14] and a new duality for points in polygons. We expect that our new duality will find other algorithmic applications. In particular, we believe that it will allow many results on points and lines in the plane to be generalized to points and geodesics in simple polygons.

The remainder of this paper is organized as follows: In Section 2 we describe an  $O(n \log k)$  time algorithm for computing a ham-sandwich geodesic. In Section 3 we prove that this algorithm is optimal in the algebraic computation tree

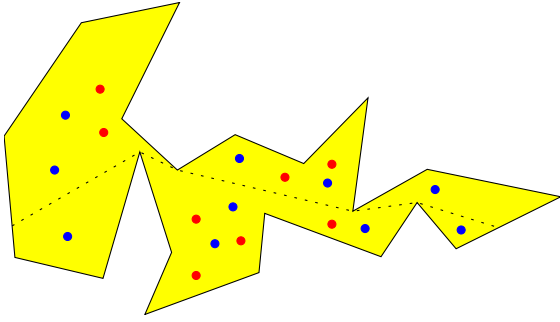


Figure 1. A ham-sandwich geodesic with  $r = 8$  and  $b = 10$ .

model by giving an  $\Omega(n \log k)$  lower bound.

## 2. THE ALGORITHM

We say that a geodesic *bisects* a set of  $n$  points if it has at most  $n/2$  points on each side. A *ham-sandwich geodesic* is a geodesic that has at most  $r/2$  red points on its left or right and at most  $b/2$  blue points on its left or right. That is, a ham-sandwich geodesic simultaneously bisects both the red set  $R$  and the blue set  $B$ . In this section we show how to compute a ham-sandwich geodesic in  $O(n \log k)$  time.

Throughout this section, we use the following notations: For two points  $p$  and  $q$  on the boundary of  $P$ ,  $pq$  denotes the geodesic joining  $p$  to  $q$  and  $[pq]$  denotes the polygonal chain traversed by walking counterclockwise on the boundary of  $P$  beginning at  $p$  and ending at  $q$ . We will also make the following *general position assumption*: No three input points (red points, blue points and vertices of  $P$ ) are collinear. Finally, to save wear and tear on floors and ceilings we will assume that  $r$  and  $b$  are both even.

Our algorithm for computing a ham-sandwich geodesic is quite complex and requires several applications of the prune-and-search paradigm [14]. Some of these applications operate on the reflex vertices of  $P$  while others operate on the point sets  $R$  and  $B$ . The outline of our algorithm is as follows:

1. We preprocess  $P$ ,  $R$  and  $B$  so that, for any geodesic  $pq$ , we can report, in  $O(n)$  time, the points in  $R$  and/or  $B$  to the right of  $pq$ . This preprocessing takes  $O(n \log k)$  time.
2. We find two geodesics  $wy$  and  $xz$  such that
  - (a)  $w, x, y$  and  $z$  appear in that order as we traverse the boundary of  $P$  counterclockwise,
  - (b)  $wy$  and  $xz$  both bisect the blue set  $B$ ,
  - (c)  $wy$  has at least  $r/2$  red points on its right, and
  - (d)  $xz$  has at most  $r/2$  red points on its right.

(Refer to Figure 2.) Lemma 1 (below) shows that there must exist a ham-sandwich geodesic  $pq$  with  $p \in [wx]$  and  $q \in [yz]$ .

3. We perform  $O(\log k)$  rounds of pruning during which we reduce the number of reflex vertices in the two chains  $[wx]$  and  $[yz]$ . During each round, we reduce

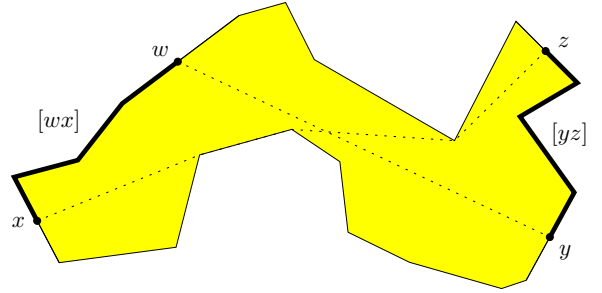


Figure 2. The set of points  $\{w, x, y, z\}$  on the boundary of  $P$ .

the number of reflex vertices in these two chains by a constant factor. This process terminates when  $[wx]$  and  $[yz]$  are both convex chains. Each round runs in  $O(n)$  time and there are  $O(\log k)$  rounds, so this step runs in  $O(n \log k)$  time.

4. We now have a problem of computing a ham-sandwich geodesic  $pq$  where  $p$  and  $q$  are constrained to lie on two convex chains. Using a further prune-and-search step, we reduce this problem, in  $O(n \log k)$  time, to the problem of computing a ham-sandwich geodesic in a 6-sided polygon with two vertical sides and 2 reflex vertices. The points  $p$  and  $q$  are constrained to lie on the two vertical sides.
5. We define a point-geodesic duality that allows us to apply the linear-time planar ham-sandwich algorithm of Lo and Steiger [13] to find a ham-sandwich geodesic of this 6-gon in  $O(n)$  time.

The correctness of this algorithm depends on the following result:

LEMMA 1. *Let  $P$  be a simple polygon containing a set  $R$  of  $r$  red points and a set  $B$  of  $b$  blue points and let  $w, x, y$ , and  $z$  be four points on the boundary of  $P$  that satisfy Conditions 2a-2d above. Then there exists a ham-sandwich geodesic  $pq$  with  $p \in [wx]$  and  $q \in [yz]$ .*

PROOF. The proof is by a continuity argument. Begin by setting  $p = w$  and  $q = y$ . We can move  $p$  and  $q$  continuously and counterclockwise on the boundary of  $P$  while maintaining the invariant that  $pq$  bisects  $B$ . This movement can be accomplished in such a way that we reach a state where  $p = x$  and  $q = z$ . Thus, during this motion the geodesic  $pq$  goes from having at least  $r/2$  red points to its right (when  $p = w$  and  $q = y$ ) to having at most  $r/2$  red points to its right (when  $p = x$  and  $q = z$ ). Since the motion is continuous there must therefore be some point at which the geodesic  $pq$  has at most  $r/2$  red points to its right and at most  $r/2$  red points to its left. This geodesic is a ham-sandwich geodesic with  $w \in [wx]$  and  $y \in [yz]$ , as required.  $\square$

In the next 5 subsections we explain these 5 steps in greater detail.

### 2.1 Preprocessing

Given a polygon  $P$  and a finite point set  $S \subset P$  we would like to preprocess  $P$  and  $S$  so that, for any geodesic  $pq$ , we

can report, in  $O(n)$  time, the subset of  $S$  to the right of  $pq$ . To do this, we partition  $P$  into convex pieces  $P_1, \dots, P_\ell$ ,  $\ell = O(n)$ , to obtain a convex partition. With each piece  $P_i$  we store a list  $L_i$  of the points in  $S$  contained in  $P_i$ . The geodesic  $pq$  defines three types of pieces: (1) The pieces completely to the left of  $pq$ , (2) the pieces completely to the right of  $pq$  and (3) the pieces that intersect  $pq$ . Note that each type 3 piece intersects  $pq$  only in a single line segment (otherwise  $pq$  would not be a shortest path). Therefore, by walking in the convex subdivision along the path  $pq$ , we can classify each  $P_i$  as type 1, 2, or 3. Furthermore, for each type 3 piece  $P_i$  we can compute which points of  $L_i$  are to the right of  $pq$  simply by testing them, one at a time, against the segment  $pq \cap P_i$ . Thus we can count the number of points to the right of  $pq$  in  $O(n)$  time.

What remains is to show how we partition  $P$  into the convex pieces and to determine which piece each element of  $S$  falls into. First we observe that if  $k > \sqrt{n}$  then  $n \log k = \Omega(n \log n)$ . In this case, we can triangulate  $P$  in  $O(n)$  time and use planar point location to determine which triangle contains each point of  $S$  in  $O(n \log n) = O(n \log k)$  time. Therefore, we may assume that  $k \leq \sqrt{n}$ .

To partition  $P$  we shoot upwards and/or downwards vertical rays from each reflex vertex into the interior of  $P$ . These rays partition  $P$  into  $\ell = O(k)$  convex polygons and this convex partition can be computed in  $O(n)$  time using Chazelle’s trapezoidal decomposition algorithm [4]. Next we must determine, for each point in  $S$ , which of the pieces contains it. This presents some difficulty since  $P_1, \dots, P_\ell$  form a planar subdivision that may consist of  $O(n)$  edges so using straightforward data structures for point location would require  $\Omega(n \log n)$  time in the worst case. Instead, we compute a planar subdivision of size  $O(k^2)$  such that locating a point of  $S$  in this subdivision is sufficient to determine which piece  $P_i$  contains that point.

For each piece  $P_i$ , we compute the perpendicular bisector of  $P_i$  with every other piece  $P_j$ , i.e., the perpendicular bisector of the segment joining the two closest points on  $P_i$  and  $P_j$ . Each such bisector can be computed in  $O(\log n)$  time using the binary search procedure of Overmars and van Leeuwen [17]. Clearly a point  $p \in P$  is contained in  $P_i$  if and only if  $p$  is on the same side of each of these  $O(k)$  lines as  $P_i$ . Thus, determining if  $p$  is contained in  $P_i$  involves determining if  $P$  is in a convex polygon with  $O(k)$  vertices.

By doing this for each  $P_i$ , we obtain  $O(k)$  disjoint convex polygons each of size  $O(k)$ . We can, in  $O(k^2 \log k)$  time preprocess this set of polygons for point location so that we can answer point location queries in  $O(\log k)$  time per query. Thus the total preprocessing time is

$$O(n + k^2 \log k + n \log k) = O(n \log k)$$

for  $k \leq \sqrt{n}$ .

To summarize, we partition  $P$  into  $O(k)$  convex pieces. From these pieces we derive a planar subdivision of size  $O(k^2)$  such that, locating a point in this subdivision is sufficient to determine which  $P_i$  the point lies in. We then locate each point of  $S$  in this arrangement in  $O(\log k)$  time per point, for a total running time of  $O(n \log k)$ . Once this is done, we can determine the subset of  $S$  on the right side of a query geodesic in  $O(n)$  time by walking in the subdivision consisting of the  $O(k)$  convex pieces.

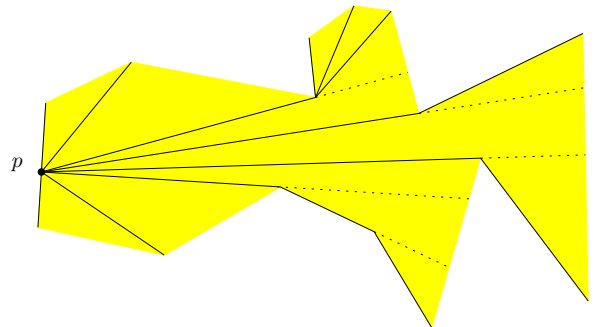
## 2.2 Finding a Blue Bisector

To initialize the iterative phase of our algorithm, we need to partition the boundary of  $P$  into two chains  $[wx]$  and  $[yz]$  such that there exists a ham-sandwich cut with one point on  $[wx]$  and one point on  $[yz]$ . One way to do this is to find a geodesic  $pq$  that bisects  $B$ , i.e., that has exactly  $b/2$  blue points to its right. Suppose  $pq$  has  $r' \geq r/2$  red points on its right side. Then the reverse geodesic  $qp$  has  $r - r' \leq r/2$  red points on its right side. Thus, setting  $w = z = p$  and  $x = y = q$  is sufficient to initialize the algorithm. Therefore, to initialize the algorithm all we need is to show how to compute a geodesic that bisects  $B$ .

We will present an algorithm that, given any point  $p$  on the boundary of  $P$ , finds a point  $q$  such that the geodesic  $pq$  bisects  $B$ . This algorithm will be an oft-used subroutine in subsequent phases of our algorithm, so we require that it has a running time of  $O(n)$ . The algorithm we present is based on the randomized linear-time median finding algorithm of Floyd and Rivest [7] with the simplification presented by Motwani and Raghavan [16, Section 3.3].

Observe that, for each point  $q' \in B$  we can obtain a geodesic by extending the last edge of the shortest path from  $p$  to  $q'$  until it hits the boundary of  $P$ . These kinds of geodesics are totally ordered by the “to the right of” relationship and the bisector  $pq$  that we are looking for is defined by the median  $q'$  in this total order. Thus, we are concerned with finding the point  $q'$ .

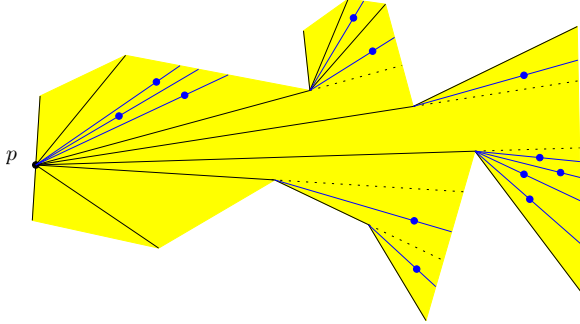
To find this median point  $q'$  we begin by computing the shortest path tree from  $p$  to every vertex of  $P$  in  $O(n)$  time using the *funnel algorithm* of Chazelle [3] and Lee and Preparata [11]. We then *augment* this tree by extending each edge that joins a parent vertex to a child vertex in the direction of the child until it hits the boundary of  $P$  (see Figure 3). The result is a partition of  $P$  into triangles that we call the *augmented shortest path partition*. We then preprocess the augmented shortest-path partition in  $O(n)$  time using Kirkpatrick’s algorithm [10] so that point location queries can be answered in  $O(\log n)$  time.



**Figure 3.** The augmented shortest path tree rooted at  $p$ . Edges added during the augmenting step are dotted.

Next, we choose a random sample  $B'$ , with replacement, of size  $b^{3/4}$  from  $B$ . We then locate, in  $O(n^{3/4} \log n)$  time, each point of  $B'$  in the augmented shortest path partition. Observe that each triangle  $t$  in the augmented shortest path partition has one vertex that is either a reflex vertex of  $P$  or is the point  $p$ . We call this vertex the *parent vertex* of  $t$  and of all points contained in  $t$ . For each point of our sample  $B'$ , we find its parent vertex and draw a line segment from the

parent vertex through the sample point and intersecting the opposite edge of  $t$ . (See Figure 4.) In this way, we obtain a tree that contains, for each point  $y$  in  $B'$ , a geodesic from  $p$  that passes through  $y$ . Note that these  $b^{3/4}$  geodesics (and their defining points) are totally ordered by the “to the right of” relationship and they are easily sorted according to this order in  $O(n + b^{3/4} \log b)$  time by traversing the shortest path tree and sorting the blue points joined to each parent vertex.



**Figure 4.** Computing a tree that contains a geodesic from  $p$  through every point of  $B'$ .

From the set  $B'$  we can select the two points  $a$  and  $b$  that define geodesics  $g_a$  and  $g_b$  with ranks  $b^{3/4}/2 - b^{1/2}$  and  $b^{3/4}/2 + b^{1/2}$ , respectively. That is,  $g_a$  has  $b^{3/4}/2 - b^{1/2}$  points of  $B'$  to its right and  $g_b$  has  $b^{3/4}/2 + b^{1/2}$  points of  $B'$  to its right. Let  $B''$  be the subset of  $B$  that is between  $g_a$  and  $g_b$  i.e., the points of  $B$  that are simultaneously the left of  $g_a$  and to the right of  $g_b$ . With exceedingly high probability, the following two statements are true [16]: (1)  $|B''| \leq 4b^{3/4} + 2$  and (2)  $B''$  contains the median point  $q'$  we are searching for. Furthermore, both these conditions can be checked in  $O(n)$  time by counting the number of points in  $B$  to the right of  $g_a$  and of  $g_b$  and the algorithm can be restarted if either of the conditions is not met.

Thus, we need only search for the point  $q'$  in the set  $B''$ . In  $O(n)$  time, we can compute the number,  $b'$ , of points in  $B$  to the right of  $g_a$ . The element  $q'$  that we are looking for is the element whose rank in  $B''$  is  $b/2 - b'$ . But, since  $|B''| = O(n^{3/4})$  we can easily find the element  $q'$  in  $O(n + b^{3/4} \log b) = O(n)$  time by sorting the elements of  $B''$ .

To summarize, we take a random sample  $B'$  of  $B$  of size  $b^{3/4}$  and sort this sample by the “to the right of relationship.” From this sample we select two points  $a$  and  $b$  that define geodesics  $g_a$  and  $g_b$  such that the set  $B'' \subseteq B$  contained between  $g_a$  and  $g_b$  has size  $O(n^{3/4})$  and one of the points in  $B''$  is the point  $q'$  that defines our bisector. We then sort  $B''$  by the “to the right of relationship” to find the point  $q'$ . Each step takes  $O(n)$  expected time, so the entire cost of finding a bisector of the blue set with one endpoint on  $p$  is  $O(n)$ . Finally, we observe that this algorithm generalizes in a straightforward way to an algorithm for finding a bisector with one endpoint on  $p$ , that has exactly  $i$  points of  $S$  to its right, for any  $1 \leq i \leq |S|$ .

## 2.3 Pruning Reflex Vertices

To reduce the number of reflex vertices on the chains  $[wx]$  and  $[yz]$ , we simply determine which of these two chains contains more reflex vertices by counting them. We then take

$p$  to be the middle reflex vertex on this chain and compute a bisector  $pq$  of  $B$  with one endpoint on  $p$  ( $q$  will be on the other chain). Depending on the number of red points to the right of  $pq$  (which can be counted in  $O(n)$  time) we then either set  $w = p$  and  $z = q$  or  $x = p$  and  $z = q$ , as appropriate. This takes  $O(n)$  time using the algorithm of the previous section and reduces the number of reflex vertices in the two chains  $[wx]$  and  $[yz]$  by a constant factor. Therefore, in  $O(n \log k)$  time we arrive at a state when  $[wx]$  and  $[yz]$  are convex chains, i.e., they contain no reflex vertices of  $P$ .

## 2.4 Fat and Skinny Funnels

At this point, we have reduced the problem of computing a ham-sandwich geodesic to that of finding a ham-sandwich geodesic where the endpoints of the geodesic are constrained to lie on the two convex chains  $[wx]$  and  $[yz]$ . This means that the ham-sandwich geodesic is constrained to lie in the *funnel* to the left of the geodesic  $xy$  and to the right of the geodesic  $wz$ . There are two types of funnels: A *fat funnel* has, as its boundary, two convex chains and two reflex chains (Figure 5.a). A *skinny funnel* consists of a polygonal chain joining two polygons. The boundaries of each of these polygons consist of two reflex chains and one convex chain (Figure 5.b).

First we observe that, in both the skinny and fat cases, the convex vertices of the two chains  $[wx]$  and  $[yz]$  become irrelevant. This is because we are only interested in geodesics with one endpoint on each convex chain and such geodesics can be described simply by listing their interior edges and the slopes of their first and last edges. Using this representation, we can preprocess a funnel using a slight variation on the algorithm of Section 2.1 so that, after  $O(k + r + b)$  preprocessing we can count the number of red and/or blue points on the right side of a query geodesic in  $O(k + r + b)$  time. (Recall that a funnel has at most  $k$  reflex vertices.)

For both skinny and fat funnels we will also be able to ignore any points of  $R \cup B$  that are not contained in the funnel. Note that these points are either to the left of every geodesic contained in the funnel or to the right of every geodesic contained in the funnel, and we can count the number of points of each type in  $O(n)$  time. This leaves us with a generalized ham-sandwich problem of finding a geodesic  $pq$  having exactly  $r'$  points of  $R$  on its right and exactly  $b'$  points of  $B$  on its right. We know such a geodesic exists because  $wy$  has at least  $r'$  red points to its right and  $xz$  has at most  $r'$  red points to its right and both  $wy$  and  $xz$  have exactly  $b'$  blue points to their right.

### 2.4.1 Skinny Funnels

To treat the case of a skinny funnel, we apply prune and search to the sets  $R$  and  $B$ . Note that a skinny funnel consists of two *ends*  $E_1$  and  $E_2$  each of which is a polygon whose boundary is made up of two reflex chains and one convex chain. These ends each have *heads*  $h_1$  and  $h_2$ , respectively, that are the common vertices in the two reflex chains. (See Figure 5.b.) All the geodesics we are interested in must pass through the heads of both ends.

Suppose, without loss of generality, that  $|B| \geq |R|$ . To execute a pruning step we first choose a random point  $p'$  from  $B$ . Suppose, again without loss of generality, that  $p'$  is contained in  $E_1$ . Note that all geodesics that contain  $p'$

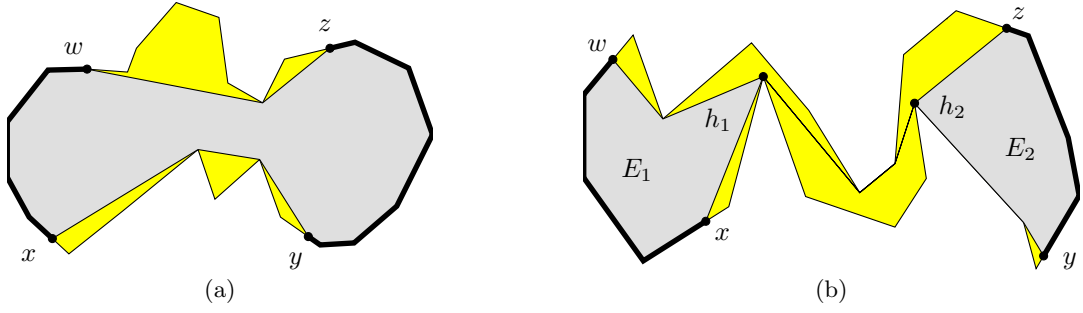


Figure 5. Two funnels: (a) a fat funnel and (b) a skinny funnel.

take the same path through  $E_1$ . Thus, the number of points in  $E_1 \cap B$  to the right of any such geodesic is fixed. Call this number  $b_1$ . We would like to find a geodesic through  $p'$  that has exactly  $b'$  blue points to its right, but such a geodesic is not guaranteed to exist. In particular, such a geodesic will not exist if and only if  $b_1 > b'$  or  $|E_2 \cap B| < b' - b_1$ . However, in these cases we can discard the points of  $E_1 \cap B$  to the left, respectively right, of the geodesic that contains  $h_1$  and  $p'$ . It is an easy exercise to show that, because  $p'$  is chosen at random from  $B$ , either case results in a positive constant fraction of  $B$  being discarded with a positive constant probability.

If a geodesic does exist that contains  $p'$  and has exactly  $b'$  blue points to its right then we compute this geodesic (call it  $pq$ ) and count the number of red points on its right. As in Section 2.3 this count will tell us that we can either remove from consideration the part of  $E_1$  to the left of  $pq$  and the part of  $E_2$  to the right of  $pq$  or vice-versa. In either case, we can discard the elements of  $B$  that lie in these regions. As before, it is an easy exercise to show that either case results in a positive constant fraction of  $B$  being removed with positive constant probability.

The above pruning step runs in  $O(k + r + b)$  time and reduces  $r + b$  by a positive constant fraction with positive constant probability. It follows that the expected time to reduce  $r + b$  to a small constant is  $O(k \log n + n) = O(n \log k)$ , at which point the ham-sandwich cut can be computed in  $O(k)$  time using a brute force method.

#### 2.4.2 Fat Funnels

Next we show how to treat the case of a fat funnel. Note that this case is still far from trivial since it generalizes the linear-time algorithm for computing ham-sandwich cuts with lines in the plane (i.e., the case  $k = 0$ ). This problem was open for many years before it was finally solved by Lo and Steiger [13]. Our strategy, therefore, is to further reduce the number of vertices of  $P$  until we reach a point where we can (almost) apply the algorithm of Lo and Steiger directly. So that we can meaningfully use terms like left, right, above, and below we will assume, without loss of generality, that our fat funnel contains a horizontal line segment with its left endpoint on  $[wx]$  and its right endpoint on  $[yz]$ .

Suppose we have some finite sequence  $(w = p_1), p_2, \dots, (p_d = x)$  of points on the chain  $[wx]$ . Then we can perform binary search to find two points  $p_i$  and  $p_{i+1}$  such that the geodesic  $p_i q_i$  having exactly  $b'$  blue points to its right has at least  $r'$  red points to its right and the geodesic  $p_{i+1} q_{i+1}$  having  $b'$

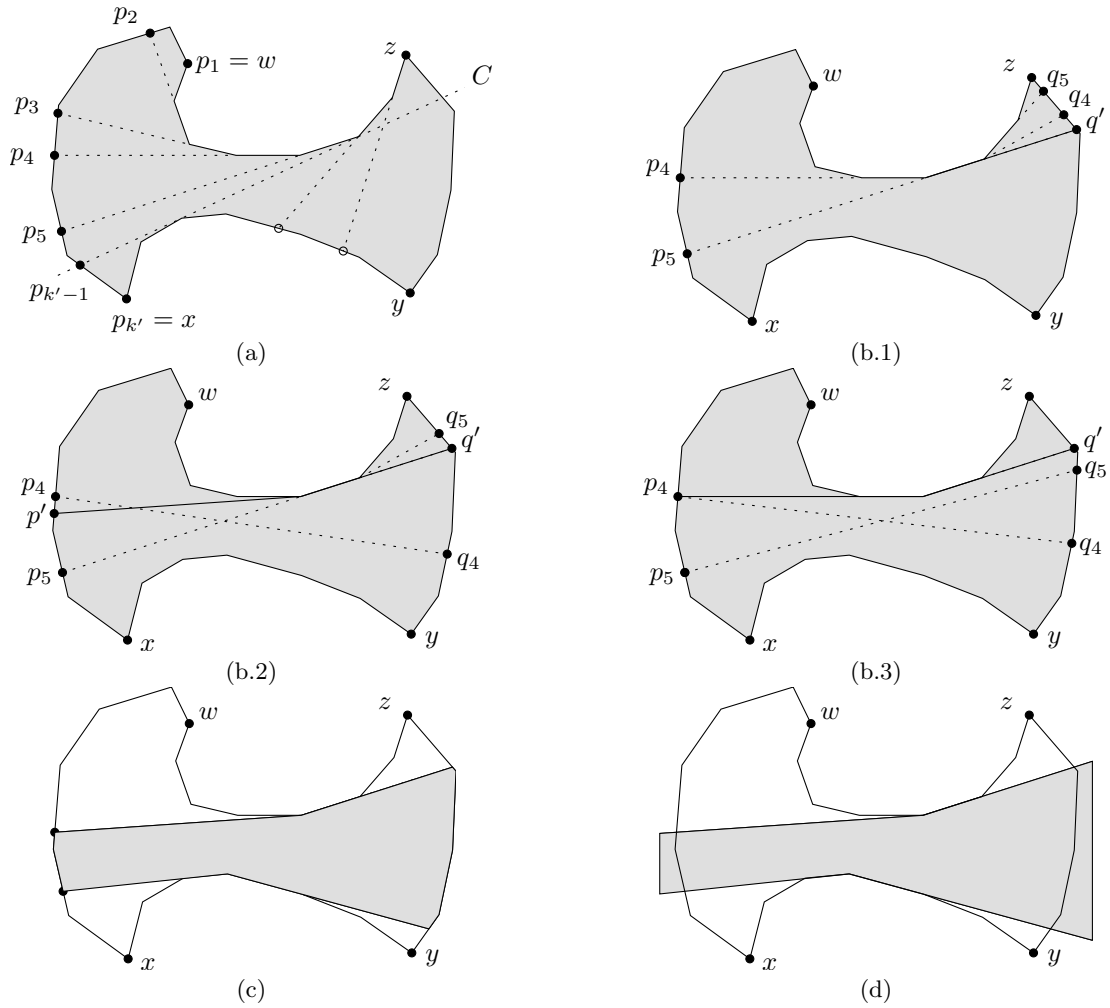
blue points to its right has at most  $r'$  red points to its right. In other words, we can reduce our search for the left endpoint of the ham-sandwich geodesic to the subchain  $[p_i p_{i+1}]$ . Each step of this binary search can be implemented in  $O(n)$  time using the algorithm of Section 2.2 so the total cost of this binary search is  $O(n \log d)$ .

Our goal is to reduce the complexity of the upper and lower reflex chains that make up our fat funnel. In particular, we would like to reach a state where each of these chains has at most two edges. We show how to handle the upper chain. The lower chain is handled symmetrically. Refer to Figure 6.a for what follows. For each edge on the upper chain, we extend it to the left until it hits the chain  $[wx]$  in some point  $p_i$ . If it hits some other part of the funnel first then we ignore it. We also compute the intersection of the cross tangent  $C$  having the upper reflex chain on its left and the lower reflex chain on its right with  $[wx]$ . Call the resulting set of points  $p_1, \dots, p_{k'}$ , where  $p_1 = w$  and  $p_{k'} = x$ . We then apply binary search to locate the pair  $p_i, p_{i+1}$  described in the previous paragraph. There are two distinct cases to consider:

1.  $i = k' - 1$ , In this case we know there exists a ham-sandwich geodesic in the skinny funnel that joins  $[p_{k'-1} p_{k'}]$  to  $[yz]$  and we can find this geodesic in  $O(n \log k)$  time using our algorithm for skinny funnels.
2.  $i < k' - 1$ . Refer to Figure 6.b. In this case, the point  $p_{i+1}$  was generated by the  $(i + 1)$ st edge of the upper chain. Extend this edge to the right until it hits some edge of the funnel. If it does not hit chain  $[yz]$  then we know there exists a ham-sandwich geodesic contained in the funnel that joins  $[p_i p_{i+1}]$  to  $[yz]$  and we can find it in  $O(n \log k)$  time using our algorithm for skinny funnels.

Otherwise, the right-extension of the edge hits the chain  $[yz]$  in some point  $q'$ . There are three subcases to consider depending on the relative locations of  $q'$ ,  $q_i$  and  $q_{i+1}$  on the chain  $[yz]$ :

- (a)  $q_{i+1}$  and  $q_i$  are above  $q'$  (Figure 6.b.1). Then we know there exists a ham-sandwich geodesic contained in the skinny funnel joining  $[p_i p_{i+1}]$  to  $[q_i q_{i+1}]$  and we can find it in  $O(n \log k)$  time using our algorithm for skinny funnels.
- (b)  $q_{i+1}$  is above  $q'$  and  $q_i$  is below  $q'$  (Figure 6.b.1). Then we compute the geodesic  $p' q'$  having exactly  $b'$  blue points below it (which will have its other



**Figure 6.** Reducing a fat funnel to a 6-gon by (a) extending the upper chain edges until they intersect  $[wx]$ , (b.1-b3) using  $p_i$  and  $p_{i+1}$  to eliminate all but one reflex vertex of the upper chain, and (c-d) replacing the two convex chains with vertical edges.

endpoint  $p'$  in  $[p_i p_{i+1}]$ . If  $p'q'$  has at least  $r'$  red points below it then there exists a ham-sandwich geodesic in the skinny funnel that joins  $[p'p_{i+1}]$  and  $[q'q_{i+1}]$  and we can find it in  $O(n \log k)$  time. Otherwise, there exists a ham-sandwich geodesic in the funnel that joins  $[p_i p']$  to  $[q_i q']$ . But this funnel has only one two edges on its upper chain, as required.

- (c)  $q_{i+1}$  and  $q_i$  are both below  $q'$  (Figure 6.b.1).. In this case, the funnel joining  $[p_i p_{i+1}]$  and  $[q_i q_{i+1}]$  has at most one reflex vertex in its upper chain, as required.

By applying the above procedure to both the upper and lower chains we reach a state in which our funnel has at most two reflex vertices, one on the upper chain and one on the lower chain. This funnel can be further simplified since we already argued that the actual convex chains are not relevant, thus they can be replaced with vertical edges as in Figure 6.c-d.

## 2.5 Lo and Steiger Revisited

We are now left with the problem of computing a ham-sandwich geodesic in a 6-gon, in which two edges are vertical and these two vertical edges are joined by reflex chains consisting of at most 2 edges each. Because of the way in which it was constructed, this polygon also has the property that the segment joining the top left corner to the bottom right corner is completely contained in the polygon, as is the segment joining the bottom left corner to the top right corner.

We wish to make use of the algorithm of Lo and Steiger [13] which is most easily described in the dual. In the dual, their algorithm operates on a set of red lines and blue lines and finds an intersection between the median level of the blue lines and the median level of the red lines. More generally, if we provide their algorithm with two vertical lines  $L_1$  and  $L_2$  and two integers  $r'$  and  $b'$  such that

1. the intersection of the  $r'$  level of the red lines with  $L_1$  is *above* the intersection of the  $b'$  level of the blue lines with  $L_1$  and
2. the intersection of the  $r'$  level of the red lines with  $L_2$  is *below* the intersection of the  $b'$  level of the blue lines with  $L_2$

then their algorithm can find an intersection of the  $r'$  level of the red lines with the  $b'$  level of the blue lines in  $O(n)$  time and the intersection found is between the vertical lines  $L_1$  and  $L_2$ . In fact, their algorithm is even more general; a careful inspection of their algorithm reveals that it works even when the input consists of  $x$ -monotone pseudolines.<sup>2</sup>

Our goal, therefore, is to find a dualization of points in the 6-gon to  $x$ -monotone Jordan arcs. It will be easier to first describe the dualization of a geodesic. Recall that we are only interested in the *interesting geodesics* which join one vertical edge of our 6-gon to the other. We can parameterize these two vertical edges linearly so that any point on the edge is represented by a real number in the interval  $(0, 1)$ . (See Figure 7 (left).) Therefore, any interesting geodesic

<sup>2</sup>A set of  $x$ -monotone Jordan arcs are called pseudolines if any two elements of the set intersect in at most one point.

$g$  can be described by a pair of real numbers  $(g_x, g_y)$  that describe the locations of the left and right endpoints of  $g$ , respectively, on the vertical edges. In our dualization, the geodesic  $g$  dualizes to the point  $\varphi(g) = (g_x, g_y)$ .

The dual of a point  $p$  in our polygon is defined as follows: There is an infinite set of interesting geodesics that contain  $p$ . Each of these geodesics  $g$  maps to a dual point  $(g_x, g_y)$  as described above. The locus of all such points is a (weakly)  $x$  and  $y$ -monotone curve that joins two points on the boundary of the unit square. (This latter property depends on the top left corner of the polygon being visible from the bottom right corner and the bottom left corner being visible from the top right corner.) To obtain  $\varphi(p)$  we extend this curve into a Jordan arc by attaching two rays whose slope is 1 ( $45^\circ$ ).

Figure 7 shows an example 6-gon containing three points (left) and the dual of these three points (right). The dashed lines in the left figure show the duals of the polygon's two reflex vertices. This dualization has the following properties:

1. For a point  $p$ ,  $\varphi(p)$  consists of at most five line segments and can be computed in constant time.
2. For a point  $p$ ,  $\varphi(p)$  is an  $x$  and  $y$ -monotone Jordan arc.
3. If a geodesic  $g$  is above a point  $p$  then the point  $\varphi(g)$  is above the Jordan arc  $\varphi(p)$ .
4. For two points  $p$  and  $q$  such that the line through  $p$  and  $q$  is not collinear with either reflex vertex,  $\varphi(p)$  and  $\varphi(q)$  have at most one point in common. I.e., a set of points dualizes to a set of pseudolines.

Property 3 above implies that our problem of finding an interesting geodesic with  $r'$  red points below it and  $b'$  blue points below it is equivalent to finding an intersection of the  $r'$  level in  $\varphi(R)$  with the  $b'$  level in  $\varphi(B)$ . Properties 1, 2 and 4 imply that this intersection can be found in  $O(n)$  time using the algorithm of Lo and Steiger. This completes the proof of:

**THEOREM 1.** *Given a polygon  $P$  with  $m$  vertices,  $k$  of which are reflex, and containing a set  $R$  of  $r$  red points and a set  $B$  of  $b$  blue points, with  $r + b + m = n$ , there exists a randomized algorithm that finds a geodesic  $pq$  that simultaneously bisects  $R$  and  $B$  and runs in  $O(n \log k)$  expected time.*

## 3. AN $\Omega(N \log K)$ LOWER BOUND

In this section we show that the algorithm of the previous section is optimal when parameterizing the running time only in terms of  $n$  and  $k$ . To prove this result, we start with a 1-dimensional problem that has an  $\Omega(n \log k)$  lower bound.

Let  $G$  and  $Y$  be two sets of distinct integers. We call an element  $x \in Y$  *odd* (respectively, *even*) if the number of elements of  $G$  less than or equal to  $x$  is odd (respectively, even). Let  $Y_o$  denote the set of odd elements in  $Y$  and let  $Y_e$  denote the set of even elements in  $Y$ . From the work of Yao, it follows that testing if  $|Y_o| = |Y_e|$  requires  $\Omega(|Y| \log |G|)$  time in the algebraic computation tree model. This is true even if the elements of  $G$  (but not  $Y$ ) are given in sorted order. We refer to the problem of testing if  $|Y_o| = |Y_e|$  as the COLORED-PARITY problem.

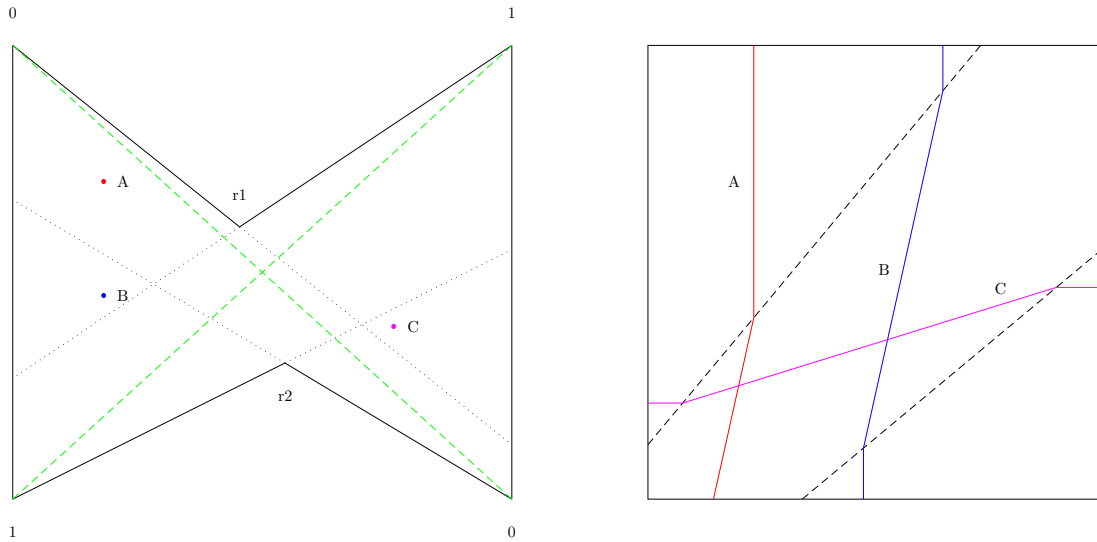


Figure 7. A 6-gon containing three points (left) and the dual of these three points (right).

Given an instance of COLORED-PARITY we construct a ham-sandwich instance as follows (see Figure 8): Our blue point set  $B$  will have  $|Y| + 2$  points. Of these points,  $|Y|$  are on the  $x$  axis and take their  $x$ -coordinate from the elements of  $Y$ . Our polygon  $P$  has a series of  $|G| + 2$  spikes through the  $x$ -axis such that the line segment joining the tip of the  $i$ th spike to the tip of the  $(i + 1)$ st spike intersects the  $x$  axis at the  $i$ th value of  $G$ . These spikes are skinny enough and placed so that they do not intersect any elements of  $G \cup B$ . Such a set of spikes is easy to compute in  $O(|G|)$  time because the elements of  $G \cup B$  are integers and the elements of  $|G|$  are sorted. We then complete our polygon into a series of  $|G| + 2$  chambers as shown in Figure 8.

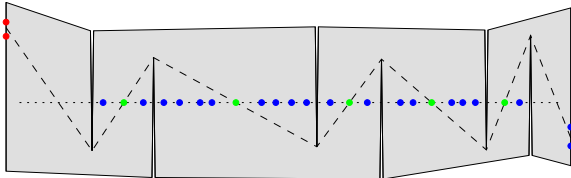


Figure 8. The lower bound input to a ham-sandwich algorithm.

Our two remaining blue points are placed in the  $(|G| + 2)$ nd chamber in such a way that any geodesic that separates them and enters another chamber must pass through the tip of the last spike. Finally, we place two red points in the first chamber so that any geodesic that separates them and enters another chamber must pass through the tip of the first spike.

Observe that, if we take a geodesic  $g$  that separates the two red points in the first chamber and separates the two blue points in the last chamber, then the number of blue points above and below  $G$  is  $|Y_e| + 1$  and  $|Y_o| + 1$ , respectively. Furthermore, of all the geodesics that separate the two red points, only those that separate the two blue points in the final chamber have this property. Therefore, a ham-sandwich geodesic separates the two blue points in the fi-

nal chamber if and only if  $|Y_e| = |Y_o|$ . Thus, computing a ham-sandwich geodesic and testing if it separates the two blue points in the final chamber is sufficient to solve the COLORED-PARITY problem. Since this reduction can be accomplished in  $O(|Y| + |G|)$  time and produces a polygon with  $O(|G|)$  reflex vertices we obtain the following theorem:

**THEOREM 2.** *Given sets  $R$  of red points and  $B$  of blue points in a simple polygon  $P$  with  $k$  reflex vertices, finding a ham-sandwich geodesic requires  $\Omega(n \log k)$  time in the algebraic computation tree model.*

## Acknowledgements

This research was initiated at the McGill Workshop on Instance-Based Learning at Bellairs Marine Biology Institute, Jan. 31–Feb.6, 2003. The authors would like to thank the workshop organizer Godfried Toussaint and the other workshop participants, namely, Greg Aloupis, David Bremner, Vida Dujmović, Jeff Erickson, Danny Krizanc, Henk Meijer, Mark Overmars, Tom Shermer, Sue Whitesides, and David Wood for helpful discussions and for providing a stimulating working environment. Jeff Erickson was particularly helpful with the lower bound argument.

## References

- [1] J. Akiyama, G. Nakamura, E. Rivera-Campo, and J. Urrutia. Perfect divisions of a cake. In *Proc. Canad. Conf. Comput. Geom. (CCCG 98)*, pages 114–115, 1998.
- [2] S. Bespamyatnikh, D. Kirkpatrick, and J. Snoeyink. Generalizing ham sandwich cuts to equitable subdivisions. *Discrete Comput. Geom.*, 24:605–622, 2000.
- [3] B. Chazelle. A theorem on cutting polygons with applications. In *Proc. Symp. Found. Comput. Sci. (FOCS'82)*, pages 339–349, 1982.
- [4] B. Chazelle. Triangulating a Simple Polygon in Linear Time. *Discrete Comput. Geom.*, 6:485–524, 1991.



- [5] M. Díaz and J. O'Rourke. Ham-sandwich sectioning of polygons. In *Proc. Canad. Conf. Comput. Geom. (CCCG 90)*, pages 282–286, 1990.
- [6] H. Edelsbrunner and R. Waupotitsch. Computing a ham sandwich cut in two dimensions. *J. Symbolic Comput.*, 2:171–178, 1986.
- [7] R. W. Floyd and R. L. Rivest. Expected time bounds for selection. *J. ACM*, 18:165–172, 1975.
- [8] H. Ito, H. Uehara, and M. Yokoyama. 2-dimension ham sandwich theorem for partitioning into three convex pieces. In *Proc. Japan. Conf. Discrete Comput. Geom. (JCDCG'98)*, volume 1763 of *Lecture Notes in Computer Science*, pages 129–157. Springer-Verlag, 1998.
- [9] H. Ito, H. Uehara, and M. Yokoyama. A generalization of 2-dimension ham sandwich theorem. *TIEICE: IEICE Trans. Comm./Elec./Inf./Sys.*, 2001.
- [10] D. Kirkpatrick. Optimal search in planar subdivisions. *SIAM J. Comput.*, 12(1):28–35, Feb. 1983.
- [11] D. T. Lee and F. P. Preparata. Euclidean shortest paths in the presence of rectilinear barriers. *Networks*, 14(3):393–410, 1984.
- [12] C.-Y. Lo, J. Matoušek, and W. L. Steiger. Algorithms for ham-sandwich cuts. *Discrete Comput. Geom.*, 11:433–452, 1994.
- [13] C.-Y. Lo and W. L. Steiger. An optimal time algorithm for ham-sandwich cuts in the plane. In *Proc. Canad. Conf. Comput. Geom. (CCCG 90)*, pages 5–9, 1990.
- [14] N. Megiddo. Linear-time algorithms for linear programming in  $\mathbb{R}^3$  and related problems. *SIAM J. Comput.*, 12(4):759–776, 1983.
- [15] N. Megiddo. Partitioning with two lines in the plane. *J. Algorithms*, pages 430–433, 1985.
- [16] R. Motwani and P. Raghavan. *Randomized Algorithms*. Cambridge University Press, 1995.
- [17] M. Overmars and J. van Leeuwen. Maintenance of configurations in the plane. *J. Comput. System Sci.*, 23:166–204, 1981.
- [18] A. H. Stone and J. W. Tukey. Generalized ‘sandwich’ theorems. *Duke Math. J.*, 9:356–359, 1942.