

Drawing Hamiltonian cycles with no large angles*

Adrian Dumitrescu[†]

Department of Computer Science
University of Wisconsin–Milwaukee
Wisconsin, USA

dumitres@uwm.edu

János Pach[‡]

Department of Mathematics
Ecole Polytechnique Fédérale de Lausanne
and City College, New York

pach@cims.nyu.edu

Géza Tóth[§]

Alfred Rényi Institute of Mathematics
Budapest, Hungary

geza@renyi.hu

Submitted: Sep 17, 2010; Accepted: May 9, 2012; Published: Jun 6, 2012

Mathematics Subject Classification: 52C35

Abstract

Let $n \geq 4$ be even. It is shown that every set S of n points in the plane can be connected by a (possibly self-intersecting) spanning tour (Hamiltonian cycle) consisting of n straight-line edges such that the angle between any two consecutive edges is at most $2\pi/3$. For $n = 4$ and 6 , this statement is tight. It is also shown that every even-element point set S can be partitioned into at most two subsets, S_1 and S_2 , each admitting a spanning tour with no angle larger than $\pi/2$. Fekete and Woeginger conjectured that for sufficiently large even n , every n -element set admits such a spanning tour. We confirm this conjecture for point sets in convex position. A much stronger result holds for large point sets *randomly* and uniformly selected from an open region bounded by finitely many rectifiable curves: for any $\varepsilon > 0$, these sets almost surely admit a spanning tour with no angle larger than ε .

Keywords: Hamiltonian cycle, turning angle, geometric graph.

*An extended abstract of this paper appeared in the *Proceedings of the 17th International Symposium on Graph Drawing*, Chicago, Sept. 2009, Volume 5849 of LNCS, Springer Verlag, March 2010, pp. 3–14.

[†]Supported in part by NSF grants CCF-0444188 and DMS-1001667, and by the Discrete and Convex Geometry project, in the framework of the European Community’s “Structuring the European Research Area” program. Part of the research by this author was done at Alfred Rényi Institute of Mathematics in Budapest, and at Ecole Polytechnique Fédérale de Lausanne.

[‡]Research partially supported by NSF grant CCF-08-30272, grants from OTKA, SNF, and PSC-CUNY.

[§]Supported by OTKA K 83767 and NN 102029, and by TÁMOP - 4.2.2.B-10/1–2010-0009, in the framework of the project “Talent care and cultivation in the scientific workshops of BME”.

1 Introduction

In the Euclidean traveling salesman problem (TSP), given a set of points in the plane, one seeks a shortest tour that visits each point. In recent years, there has been an increased interest in studying tours that optimize objective functions related to angles between consecutive edges in the tour, rather than the length. The problem has applications in motion planning, where restrictions on turning angles have to be enforced. For example, an aircraft or a boat moving at high speed, required to pass through a set of given locations, cannot make sharp turns in its motion. This and other applications to planning curvature-constrained paths for auto-vehicles and aircraft are discussed in [2, 7, 13, 14].

Consider a set of $n \geq 2$ points. A *spanning tour* is a directed Hamiltonian cycle, drawn with straight-line edges; if $n = 2$ the tour consists of the two edges, with opposite orientations, connecting the two points. When three points, p_1 , p_2 , and p_3 , are traversed in this order, their *rotation angle* $\angle p_1 p_2 p_3$ is the angle in $[0, \pi]$ determined by segments $p_1 p_2$ and $p_2 p_3$; see Figure 1. If p_3 is on the left (resp. right) side of the oriented line $\overrightarrow{p_1 p_2}$ we say that the tour, or path makes a *left* (resp. *right*) turn at p_2 . If a tour (or path) makes only right turns, we call it *pseudo-convex*. If all of its rotation angles are at most $\pi/2$, we call it an *acute* tour (or path). If all rotation angles are at least $\pi/2$, the tour (or path) is *obtuse*.

Given a set A of angles, the *angle-restricted tour* (ART) problem is to decide whether a set S of n points in the plane allows a (possibly self-intersecting) spanning tour such that all the n angles between consecutive segments belong to the set A ; see [12].

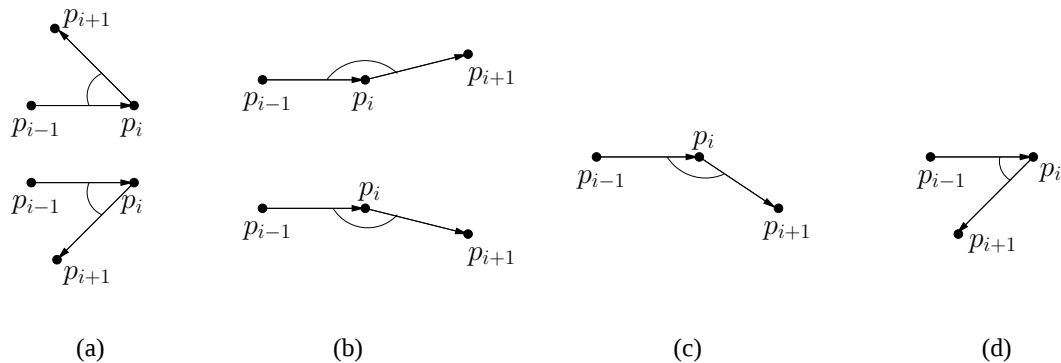


Figure 1: (a) acute (b) obtuse (c) obtuse and pseudo-convex (d) acute and pseudo-convex

Fekete and Woeginger [12] proved that every finite set of at least *five* points admits a pseudo-convex tour and a non-intersecting pseudo-convex spanning path. They also noticed that every n -element point set S admits an acute spanning path. To see this, start at any point $p_1 \in S$. Assuming that the initial portion $p_1 \dots p_i$ of such a path has already been defined and $i < n$, let p_{i+1} be an element of $S \setminus \{p_1, \dots, p_i\}$ farthest away from p_i . It is easy to check that the resulting *path* $p_1 \dots p_n$ is acute. It is also clear that such a path cannot be always completed to an acute *tour*. Indeed, if all points are on a line and n is *odd*, then along any (spanning) tour, one of the rotation angles must be equal to π .

The question arises: Does every *even*-element point set admit a tour with small rotation angles? More precisely, given an n -element point set S in the plane, where n is even, let $\alpha = \alpha(S) \geq 0$ denote the smallest angle such that S admits a (spanning) tour with the property that all of its rotation angles belong to $[0, \alpha]$. Finally, let $\alpha(n)$ be the maximum of $\alpha(S)$ over all n -element point sets in the plane. Trivially, $\alpha(2) = 0$. The 4-element point set formed by the 3 vertices and the center of an equilateral triangle shows that $\alpha(4) \geq 2\pi/3$. The 6-point configuration depicted in Fig. 2 (left) shows that $\alpha(6) \geq 2\pi/3$.

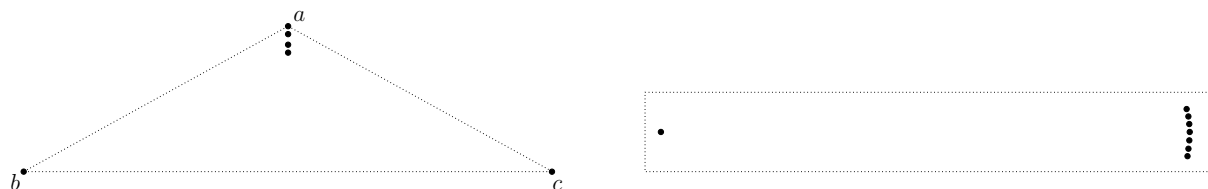


Figure 2: Left: $\triangle abc$ is an isosceles triangle with $\angle bac = 2\pi/3$. Point a and the 3 points below it are placed on the altitude of the triangle, and very closely inter-spaced. Every tour on these 6 points has a rotation angle of at least $2\pi/3 - \varepsilon$. Right: $n - 1$ equidistant points very closely inter-spaced on a small circular arc of a circle, and one point at the center. Every tour on these n points has a rotation angle of at least $\pi/2 - \varepsilon$.

In this note we show that $\alpha(n) \leq 2\pi/3$, for all even $n \geq 4$.

Theorem 1. *Let $n \geq 4$ be even. Every set of n points in the plane admits a spanning tour such that all of its rotation angles are at most $2\pi/3$. This bound is tight for $n = 4, 6$. Such a tour can be computed in $O(n^{4/3} \log^{1+\varepsilon} n)$ time, for every $\varepsilon > 0$.*

It remains open whether the bound $2\pi/3$ can be replaced by $\pi/2$, for every even $n \geq 8$, as was conjectured in [12]. In other words, every n -element set may admit an acute tour, whenever $n \geq 8$ is even. The point set depicted in Fig. 2 (right) demonstrates that this statement, if true, cannot be improved. That is, we have $\alpha(n) \geq \pi/2$, for all even $n \geq 8$.

We confirm three weaker versions of this statement. In Section 4, we show that if we enforce acute rotation angles, *two* tours instead of one will certainly suffice.

Theorem 2. *Let $n \geq 8$ be even.*

(i) *Every set of n points in the plane can be partitioned into two even parts, each of which admits an acute spanning tour. Given the n points, the two tours can be computed in $O(n)$ time.*

(ii) *Every set of n points in the plane can be partitioned into two parts of sizes $2\lfloor \frac{n}{4} \rfloor$ and $2\lceil \frac{n}{4} \rceil$, each of which admits an acute spanning tour. Given the n points, the two tours can be computed in $O(n^{4/3} \log^{1+\varepsilon} n)$ time, for every $\varepsilon > 0$.*

In Section 5, we prove the existence of an acute tour in the special case when the points are in convex position.

Theorem 3. *Every even set S of n points in the plane in convex position, with $n \geq 12$, admits an acute spanning tour. Given the n points, such a tour can be computed in $O(n)$ time.*

A much stronger statement holds for *random* point sets, uniformly selected from a not necessarily connected region.

Theorem 4. *Let B be an open region in the plane bounded by finitely many rectifiable Jordan curves and let S be a set of n points, randomly and uniformly selected from B . Then, for any $\varepsilon > 0$, the point set S almost surely admits a spanning tour with no rotation angle larger than ε , as n tends to infinity.*

The last result easily generalizes to higher dimensions.

Related problems and results. Various angle conditions imposed on *geometric graphs* (graphs with straight-line edges) drawn on a given set of points have been studied in [3, 4, 5, 6, 12]. In particular, Fekete and Woeginger [12] have focused on rotation angles of Hamiltonian cycles and paths and raised many challenging questions. For instance, they conjectured that any point set admits a (possibly self-intersecting) Hamiltonian *path* in which each turning angle is at most $5\pi/6$. Bárány, Pór, and Valtr [6] obtained a first partial result by showing that any point set admits a (possibly self-intersecting) Hamiltonian *path* in which each turning angle is at most $8\pi/9$.

Aichholzer et al. [3] studied similar questions for planar geometric graphs. Among other results, they showed that any point set in general position in the plane admits a non-intersecting Hamiltonian (spanning) path with the property that each rotation angle is at most $3\pi/4$. They also conjectured that this value can be replaced by $\pi/2$. Arkin et al. introduced the notion of *reflexivity* of a point set, as the minimum number of reflex vertices in a polygonalization (i.e., simple polygon) of the set [5]. They gave estimates for the maximum reflexivity of an n -element point set. Recently, Ackerman et al. have made further progress on this problem [1].

2 Balanced partitions

It is well known (see, e.g. [10], Section 6.6) that every region (every continuous probability measure) in the plane can be cut into *four* parts of equal area (measure) by two orthogonal lines. This statement immediately implies:

Lemma 1. *Given a set S of $n \geq 8$ points in the plane (n even), one can always find two orthogonal lines ℓ_1, ℓ_2 and a partition $S = S_1 \cup S_2 \cup S_3 \cup S_4$ with $|S_1| = |S_3| = \lfloor \frac{n}{4} \rfloor$, $|S_2| = |S_4| = \lceil \frac{n}{4} \rceil$ such that S_1 and S_3 belong to two opposite closed quadrants determined by ℓ_1 and ℓ_2 , and S_2 and S_4 belong to the other two opposite quadrants.*

Proof. By a standard compactness argument, it is sufficient to prove this statement for point sets S in general position, in the sense that no 3 points of S are on a line, no 3 determine a right angle, and no two segments spanned by 4 points are orthogonal to each other. Choose a very small $\varepsilon > 0$ and replace each point $p \in S$ by a disk of radius ε around p . Applying the above mentioned result from [10] to the union of these n disks, we obtain two orthogonal lines that meet the requirements of the lemma. $\square$

Lemma 2. *Given a set S of n points in the plane (n even), there exist three concurrent lines such that the angle between any two of them is $\pi/3$, and there is a partition $S = S_1 \cup \dots \cup S_6$ with $|S_1| = |S_4|$, $|S_2| = |S_5|$, and $|S_3| = |S_6|$, such that S_i is contained in the i th closed angular region (wedge) determined by the lines, in counterclockwise order.*

Proof. Just like before, by compactness, it is sufficient to prove the statement for point sets in general position. This time, it is convenient to assume that no 3 points of S determine an angle which is an integer multiple of $\pi/3$, and there are no 2 pairs of points such that the angle between their connecting lines is an integer multiple of $\pi/3$.

Choose again a very small $\varepsilon > 0$ and replace each point $p \in S$ by a disk D_p of radius ε centered at p . Approximate very closely the union of these disks by a continuous measure μ which is strictly positive on every Jordan region in the plane and for which $\mu(\mathbb{R}^2) = n$ and $|\mu(D_p) - 1| < \varepsilon$ for every $p \in S$.

We say that a line ℓ is a *bisecting* line with respect to the continuous measure μ if the measures of both half-planes bounded by ℓ are equal to $n/2$. Clearly, there is a unique bisecting line parallel to every direction, and this line changes continuously as the direction varies. Choose *three* bisecting lines ℓ_1, ℓ_2, ℓ_3 such that the angle between any two of them is $\pi/3$. By changing the direction of ℓ_1 , we can achieve that these lines pass through the same point. Indeed, as we turn ℓ_1 by $\pi/3$, the crossing point of the other two lines moves from one side of ℓ_1 to the other. Therefore, there is an intermediate position in which the three lines pass through the same point.

An easy case analysis shows that if ε was sufficiently small, then either no ℓ_i intersects any disk D_p or there is one ℓ_i that intersects two D_p 's and the others do not intersect any. In the former case, the lines satisfy the conditions in the lemma, in the latter one, they can be slightly perturbed so as to meet the requirements. $\square$

Given a set S of n points in *general position* in the plane (i.e., no three points are collinear), a line passing through two elements of S is called a *halving line* if there are $\lfloor (n-2)/2 \rfloor$ points on one of its sides and $\lceil (n-2)/2 \rceil$ points on the other [15]. The number of halving lines of an n -element point set in the plane is bounded from above by $O(n^{4/3})$, as was established by Dey [11]. It is also known that the set of halving lines can be computed in $O(n^{4/3} \log^{1+\varepsilon} n)$ time [8], for every $\varepsilon > 0$.

Remark. Starting with an arbitrary halving line ℓ and following the rotation scheme described in [15], one can enumerate all halving lines for S . Using this approach, one obtains algorithmic proofs of Lemmas 1 and 2 that run in $O(n^{4/3} \log^{1+\varepsilon} n)$ time, for every $\varepsilon > 0$.

3 Constructing a tour with rotation angles at most $2\pi/3$

In this section, we prove Theorem 1. As we mentioned in the Introduction, for small even values of n , namely for $n = 4$ and $n = 6$, we need to allow rotation angles as large as $2\pi/3$. Here we show that this value suffices for all even n .

Let ℓ_1, ℓ_2, ℓ_3 be three concurrent lines satisfying the conditions of Lemma 2. They divide the plane into six wedges.

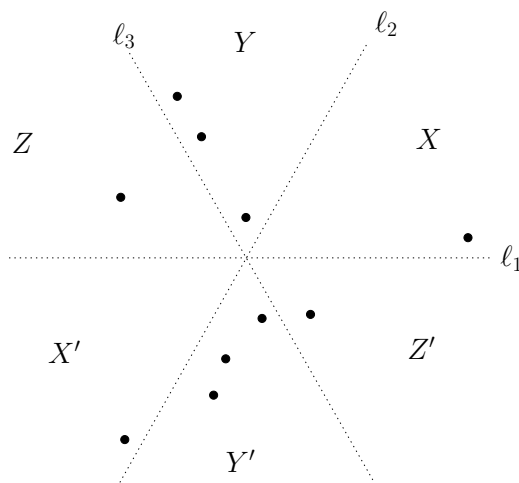


Figure 3: Three concurrent bisecting lines of S : ℓ_1, ℓ_2, ℓ_3 , at angles $0, \pi/3$, and $2\pi/3$.

Let X, Y, Z, X', Y', Z' denote the six wedges in counterclockwise order, labeled as in Fig. 3. Note that the angle between the x -axis and any edge $p_{i-1}p_i$ of a tour with $p_{i-1} \in X$ and $p_i \in X'$, say, belongs to the interval $[0, \pi/3]$. A piece $p_{i-1}p_i p_{i+1}$ of a tour is of the form $XX'X$, say, if $p_{i-1}, p_{i+1} \in X$ and $p_i \in X'$.

Observation 1. *Consider a piece of a tour, which is of the form XQX , where $Q = Y', X'$, or Z . Then the rotation angle at the middle point of this piece, which belongs to Q , is at most $2\pi/3$. The same holds for any other piece consisting of two edges, which starts and ends in the same wedge, and whose middle point belongs to one of the three opposite wedges.*

Observation 2. *Consider a piece of a tour, which is of the form $XX'Y$ or $XX'Z'$. Then the rotation angle at the middle point of this piece, which belongs to X' , is at most $2\pi/3$. The same holds for any other piece of the form $X'XZ, X'XY', YY'X, YY'Z, Y'YX', Y'YZ', ZZ'Y, ZZ'X', Z'ZX, Z'ZY'$.*

Proof of Theorem 1. We distinguish two cases:

Case 1. There are at most two nonempty double wedges. If all points are contained in a unique double wedge, say XX' , then by Observation 1, they can be connected by an acute tour of the form $(XX')^*$. The tour starts in X , ends in X' , and alternates between the wedges X and X' until all points in $X \cup X'$ are exhausted. Assume now that there are exactly two nonempty double wedges, XX' and YY' , say, and refer to Fig. 4. Consider a spanning tour of the form $(XX')^*(YY')^*$, where $(XX')^*$ and $(YY')^*$ are point sequences that alternate between the corresponding opposite wedges until all points in those wedges are exhausted. By Observations 1 and 2, at each vertex of this tour the rotation angle is at most $2\pi/3$.

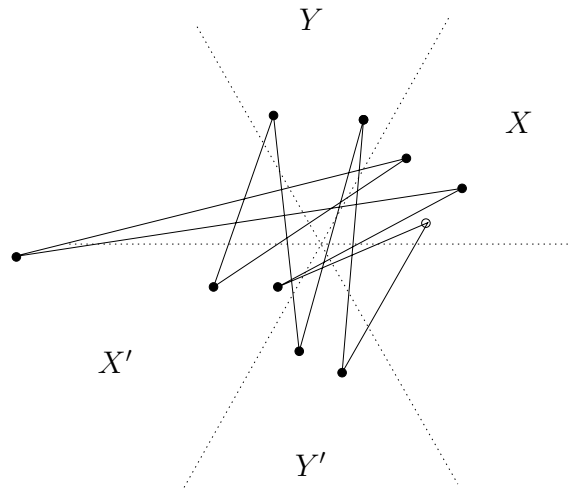


Figure 4: Case 1: points in two double wedges. A tour of the form $XX'XX'XX'YY'YY'$ is shown; its starting vertex in X is drawn as an empty circle.

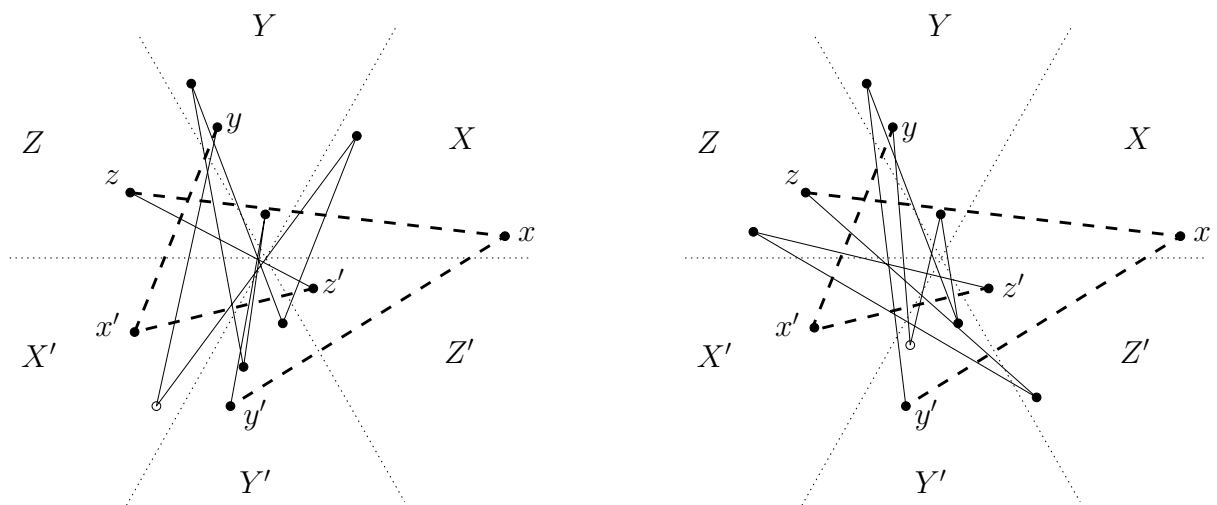


Figure 5: Case 2: points in three double wedges. Left: a tour of the form $X'XY'YY'Yy'xzz'x'y$ is shown; its starting vertex in X' is drawn as an empty circle. Right: a tour of the form $Y'YY'Yy'xzZ'Zz'x'y$ is shown; its starting vertex in Y' is drawn as an empty circle.

Case 2. There are exactly three nonempty double wedges; refer to Fig. 5. Arbitrarily pick one point from each wedge: $x \in X$, $y \in Y$, $z \in Z$, $x' \in X'$, $y' \in Y'$, $z' \in Z'$. Consider the two triangles $\Delta xzy'$ and $\Delta yx'z'$. The sum of the interior angles of the two triangles is obviously 2π . By averaging, there is one pair of points lying in opposite wedges, say x and x' , whose angles sum up to at most $2\pi/3$. Thus, each of these angles is at most $2\pi/3$: $\angle xzy' \leq 2\pi/3$, and $\angle yx'z' \leq 2\pi/3$.

If $|X \cap S| = |X' \cap S| \geq 2$, consider a spanning tour $(X'X)^+(Y'Y)^+y'xz(Z'Z)^+z'x'y$. Here $(X'X)^+$ denotes a nonempty alternating path between the wedges X' and X , that starts in X' , ends in X , and involves all points except x and x' . The notations $(Y'Y)^+$ and $(Z'Z)^+$ are used analogously. An example is depicted in Fig. 5 (left). By Observations 1 and 2, and by our choice of x, y, z, x', y', z' , all rotation angles along this tour are at most $2\pi/3$, as required.

If $|X \cap S| = |X' \cap S| = 1$, consider a spanning tour $(Y'Y)^+y'xz(Z'Z)^+z'x'y$; see Fig. 5 (right). The arguments justifying that all rotation angles are at most $2\pi/3$ are the same as before.

The proof of Theorem 1 is now complete.

4 Covering by two acute tours

Proof of Theorem 2. (i) Take a horizontal line ℓ and a partition of our point set $S = S^+ \cup S^-$ into two subsets, each of size $n/2$, such that S^+ and S^- are in the closed half-planes above and below ℓ , respectively. If some points of S lie on ℓ , we can include them in either of these sets so as to satisfy the condition. Next, take a vertical line ℓ' which gives rise to another equipartition of S . Assume for simplicity that ℓ and ℓ' coincide with the x and y coordinate axes. See Fig. 6, for an illustration.

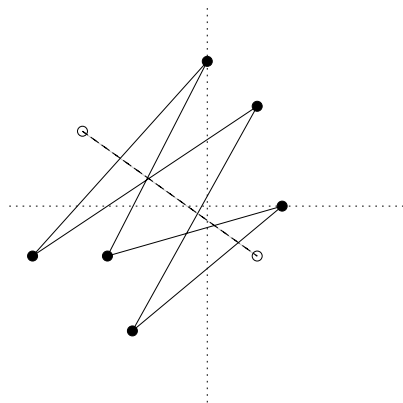


Figure 6: Even set covered by two tours with 6 and 2 points, respectively; $a = 3$, and $b = 1$. (A double-edge counts as a tour.)

Thus, we obtain a partition $S = S_1 \cup S_2 \cup S_3 \cup S_4$ such that all points of S_i belong to the i th closed quadrant determined by the axes (enumerated in the counterclockwise

order), $|S_1| = |S_3| = a$, and $|S_2| = |S_4| = b$ for some integers a and b with $a + b = n/2$. Connect now all elements of $S_1 \cup S_3$ by a tour of length $2a$ alternating between S_1 and S_3 . Similarly, connect the elements of $S_2 \cup S_4$ by an alternating tour of length $2b$. Obviously, both tours are acute. The above procedure can be performed in linear time, using any linear time selection algorithm [9].

(ii) Find two orthogonal lines and a partition $S = S_1 \cup S_2 \cup S_3 \cup S_4$ satisfying the conditions of Lemma 1. Using the notation of the proof of part (i), now we have $a = \lfloor \frac{n}{4} \rfloor$ and $b = \lceil \frac{n}{4} \rceil$. As above, we obtain two acute tours, of lengths $2\lfloor \frac{n}{4} \rfloor$ and $2\lceil \frac{n}{4} \rceil$, respectively. This completes the proof of part (ii) of Theorem 2. $\square$

By keeping only the larger tour, Theorem 2 immediately implies

Corollary 1. *For any even n , every n -element point set in the plane admits an acute even tour covering at least half of its elements.*

5 Acute tours for points in convex position

Throughout this section, let S denote a set of $n \geq 8$ points in the plane, in convex position and let $S = S_1 \cup S_2 \cup S_3 \cup S_4$ be a partition satisfying the conditions in Lemma 1. A 3-edge path (on 4 points) is called a *hook* if the rotation angles at its two intermediate vertices are acute.

Lemma 3. *Let $P = \{p_1, p_2, p_3, p_4\}$ be the vertex set of a convex quadrilateral, with $p_i \in S_i$, $i = 1, 2, 3, 4$. Then at least one of the following two conditions is satisfied.*

- (i) $p_1p_3p_4p_2$ and $p_3p_1p_2p_4$ are hooks, or
- (ii) $p_1p_3p_2p_4$ and $p_3p_1p_4p_2$ are hooks.

Proof. At least one of the two angles defined by the diagonals p_1p_3 and p_2p_4 is larger or equal to $\pi/2$. Let x denote the crossing point of these diagonals. If $\angle p_1xp_2 \geq \pi/2$, then the two 3-edge paths $p_1p_3p_4p_2$ and $p_3p_1p_2p_4$ are hooks, while if $\angle p_2xp_3 \geq \pi/2$, then $p_1p_3p_2p_4$ and $p_3p_1p_4p_2$ are hooks. $\square$

We say that a convex quadrilateral P , as in Lemma 3, is of *type 1* if $\angle p_1xp_2 \geq \pi/2$, and of *type 2*, otherwise (i.e., if $\angle p_2xp_3 > \pi/2$).

Lemma 4. *Let $P = \{p_1, p_2, p_3, p_4\}$, $Q = \{q_1, q_2, q_3, q_4\}$, and $R = \{r_1, r_2, r_3, r_4\}$ be three vertex-disjoint convex quadrilaterals with $p_i, q_i, r_i \in S_i$, for $i = 1, 2, 3, 4$. Then there exist two hooks induced by two of these quadrilaterals such that the two endpoints of the first one and the two endpoints of the second one lie in different parts of the partition $S_1 \cup S_2 \cup S_3 \cup S_4$. Two such hooks are called opposite. (See Fig. 7 (left).)*

Proof. By the pigeonhole principle, two out of the three quadrilaterals, say P and Q , must have the same type. By Lemma 3, one can find a hook in each of them such that their endpoints are all in different parts of the partition, i.e., two opposite hooks. $\square$

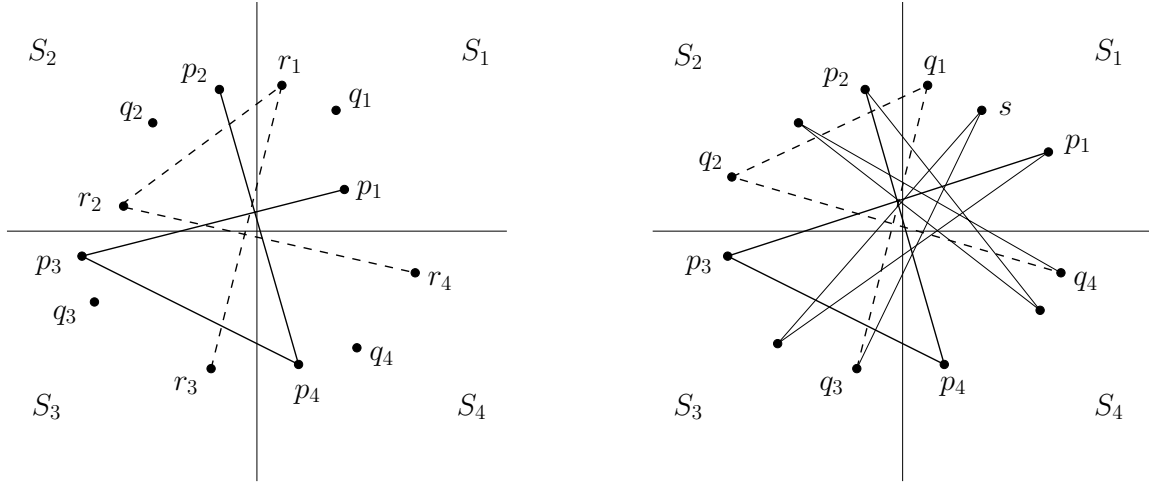


Figure 7: Left: $p_1p_3p_4p_2$ and $r_3r_1r_2r_4$ are two opposite hooks. Right: an acute tour of S of the form $(S_1S_3)^+p_1p_3p_4p_2(S_4S_2)^+q_4q_2q_1q_3$, starting at $s \in S_1$.

Proof of Theorem 3. Consider a partition $S = S_1 \cup S_2 \cup S_3 \cup S_4$ satisfying the conditions in Lemma 1. Since $|S| \geq 12$, we have $|S_i| \geq 3$. Pick 3 points from each S_i , and using these points construct three vertex-disjoint convex quadrilaterals, P , Q , and R . By Lemma 4, two of these quadrilaterals, P and Q , say, determine opposite vertex-disjoint hooks. Suppose without loss of generality that P and Q are of type 1, and these two hooks are $p_1p_3p_4p_2$ and $q_4q_2q_1q_3$, where $p_i, q_i \in S_i$, $i = 1, 2, 3, 4$. See Fig. 7(right).

Let $(S_iS_j)^+$ denote a polygonal path starting in S_i , ending in S_j , alternating between S_i and S_j , and exhausting all points of $S_i \cup S_j$, except for p_i, p_j, q_i, q_j . The following tour is acute: $(S_1S_3)^+p_1p_3p_4p_2(S_4S_2)^+q_4q_2q_1q_3$, and this completes the proof. $\square$

6 Random point sets

We first verify Theorem 4 for centrally symmetric convex bodies, and then in its full generality.

Lemma 5. *Let B be a centrally symmetric convex body in the plane and let S be a set of n points, randomly and uniformly selected from B . Then, for any $\varepsilon > 0$, S almost surely admits a spanning tour with no rotation angle larger than ε , as n tends to infinity.*

Proof. Let ε be fixed, and let o denote the center of B . Assume without loss of generality that $\text{area}(B) = 1$. Any chord through o divides the area of B into two equal parts. Therefore, there is a positive constant $\delta = \delta(B, \varepsilon)$, depending only on B and ε , such that for every wedge W with angle at most $\pi - \frac{\varepsilon}{2}$ and apex at o , we have that $\text{area}(W \cap B) \leq 1/2 - \delta$. Let $m = \lceil n/2 \rceil$.

Let $p_1, p_2, \dots, p_n$ be n random points, independently and uniformly selected from B , listed in their circular order of visibility from o . The indices are taken modulo n , so that $p_{n+1} = p_1$. Note that almost surely all points p_i are distinct and different from o .

If n is odd, consider the spanning tour $C = p_1 p_{m+1} p_2 p_{m+2} \dots p_m p_1$. For every i , almost surely we have

$$\pi - \frac{\varepsilon}{2} \leq \angle p_i o p_{m+i-1} \leq \pi + \frac{\varepsilon}{2},$$

and

$$\pi - \frac{\varepsilon}{2} \leq \angle p_i o p_{m+i} \leq \pi + \frac{\varepsilon}{2}.$$

Therefore, we almost surely have $\angle p_{m+i-1} p_i p_{m+i} \leq \varepsilon$, for every i , and the tour C meets the requirements.

If n is even, we choose two odd numbers n_1, n_2 with $n_1 + n_2 = n$ such that $0 \leq n_1 - n_2 \leq 2$. That is, n_1 is m or $m+1$ while n_2 is m or $m-1$. Connect the points p_i by two disjoint cycles, C_1 and C_2 , of length n_1 and n_2 , with property that (1) in the cyclic order around o , the points $p_1, p_2, \dots$ belong alternately to C_1 and C_2 , as much as possible; and (2) every edge of C_1 and C_2 connects two points, p_i and p_j , with $|j - i - m| \leq 3 \pmod{n}$. We distinguish two cases.

Case 1. $n_1 = n_2 = m$. Let

$$C_1 = p_1 p_{2+m} p_3 p_{4+m} p_5 \dots p_{n-1} p_m,$$

$$C_2 = p_2 p_{3+m} p_4 p_{5+m} p_6 \dots p_n p_{1+m}.$$

Switching between these two cycles at two points, we can combine them into a single spanning tour C , as follows.

$$C = p_1 p_{2+m} p_3 p_{4+m} p_5 \dots p_{n-1} p_m p_2 p_{3+m} p_4 p_{5+m} p_6 \dots p_n p_{1+m}.$$

It remains true that $|j - i - m| \leq 3 \pmod{n}$ for every edge $p_i p_j$ of C , so that almost surely all rotation angles of C will be smaller than ε .

Case 2. $n_1 = m+1, n_2 = m-1$. Let

$$C_1 = p_1 p_{2+m} p_3 p_{4+m} p_5 \dots p_n p_{m+1},$$

$$C_2 = p_2 p_{3+m} p_4 p_{5+m} p_6 \dots p_{n-1} p_m.$$

We can combine them into a single spanning tour C , as follows.

$$C = p_1 p_{2+m} p_3 p_{4+m} p_5 \dots p_n p_{m+1} p_2 p_{3+m} p_4 p_{5+m} p_6 \dots p_{n-1} p_m.$$

It remains true that $|j - i - m| \leq 3 \pmod{n}$ for every edge $p_i p_j$ of C , so that almost surely all rotation angles of C will be smaller than ε . $\square$

To prove Theorem 4 in its full generality, we need the following technical lemma. Its proof is very similar to that of Lemma 5. The minor modifications are left to the reader.

Lemma 6. *Let B be a centrally symmetric convex set in the plane with nonempty interior. Let o denote the center of B , let $\varepsilon > 0$ be fixed, let s and t be two points of B , and let S' be a set of at most $\varepsilon n/4$ points not belonging to B .*

Then, for any set S of n points randomly and uniformly selected from B , the set $S \cup S'$ almost surely admits a spanning path satisfying the following conditions, as $n \rightarrow \infty$:

- (i) all of its turning angles are at most ε ;
- (ii) its first two points are p_1 and p_2 such that $\angle op_1p_2 \leq \varepsilon/3$, and $\angle sop_1 \leq \varepsilon/3$;
- (iii) its last two points are q_2 and q_1 such that $\angle oq_1q_2 \leq \varepsilon/3$, and $\angle toq_1 \leq \varepsilon/3$.

Proof of Theorem 4. Assume without loss of generality that $\text{area}(B) = 1$. Consider a square lattice of minimum distance δ , for some $\delta > 0$ to be specified later. Let $A = A(\delta)$ denote the total area of all cells (lattice squares of side length δ) completely contained in B , and let $A' = A'(\delta)$ denote the total area of all those cells that intersect B , but are not completely contained in it. Obviously, $A + A' \geq 1$. Since the boundary of B is the union of finitely many rectifiable curves, we have

$$\lim_{\delta \rightarrow 0} A = 1, \quad \limsup_{\delta \rightarrow 0} \frac{A'}{\delta} < \infty.$$

Therefore, we can choose $\delta > 0$ so that $A' \leq \varepsilon/6$.

Let $X_1, X_2, \dots, X_m$ denote the cells completely contained in B , in some arbitrary order, and let o_i denote the center of X_i . For any $1 \leq i \leq m$, let s_i be a point on the line $o_i o_{i-1}$ such that o_i belongs to the segment $s_i o_{i-1}$. Analogously, let t_i be a point on the line $o_i o_{i+1}$ such that o_i belongs to the segment $t_i o_{i+1}$. Here the indices are taken modulo m .

Let S be a set of n points in B , selected independently, randomly, and uniformly. Let $S_i = S \cap X_i$, for $1 \leq i \leq m$, and let $S' = S \setminus \cup_{i=1}^m S_i$. Divide S' into m almost equal parts, $S'_1, S'_2, \dots, S'_m$ with $||S'_i| - |S'_j|| \leq 1$, for any $i, j = 1, \dots, m$.

For each $1 \leq i \leq m$, apply Lemma 6 with S_i , S'_i , s_i , and t_i , to obtain a spanning path P_i . The spanning tour $P_1 P_2 \dots P_m$ obtained by the concatenation of these paths now meets the requirements. $\square$

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