

Inscribing an axially symmetric polygon and other approximation algorithms for planar convex sets [☆]

Hee-Kap Ahn ^{a,*}, Peter Brass ^b, Otfried Cheong ^a, Hyeon-Suk Na ^c,
Chan-Su Shin ^d, Antoine Vigneron ^e

^a Division of Computer Science, Korea Advanced Institute of Science and Technology, Daejeon, South Korea

^b Department of Computer Science, City College of New York, USA

^c School of Computing, Soongsil University, Seoul, South Korea

^d School of Electr. and Inform. Engineering, Hankuk University of Foreign Studies, Yongin, South Korea

^e Department of Computer Science, National University of Singapore, Singapore

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Abstract

Given a planar convex set C , we give sublinear approximation algorithms to determine approximations of the largest axially symmetric convex set S contained in C , and the smallest such set S' that contains C . More precisely, for any $\varepsilon > 0$, we find an axially symmetric convex polygon $Q \subset C$ with area $|Q| > (1 - \varepsilon)|S|$ and we find an axially symmetric convex polygon Q' containing C with area $|Q'| < (1 + \varepsilon)|S'|$. We assume that C is given in a data structure that allows to answer the following two types of query in time T_C : given a direction u , find an extreme point of C in direction u , and given a line ℓ , find $C \cap \ell$. For instance, if C is a convex n -gon and its vertices are given in a sorted array, then $T_C = O(\log n)$. Then we can find Q and Q' in time $O(\varepsilon^{-1/2}T_C + \varepsilon^{-3/2})$. Using these techniques, we can also find approximations to the perimeter, area, diameter, width, smallest enclosing rectangle and smallest enclosing circle of C in time $O(\varepsilon^{-1/2}T_C)$.

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1. Introduction

Some problems on convex polygons can be solved in sublinear time when the polygon P is given as an array of the n vertices in sorted order along the boundary of P . For instance, given a line ℓ , the two vertices of P that have tangents parallel to ℓ can be found in $O(\log n)$ time. The shortest line segment connecting two convex polygons can also be

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* Corresponding author.

E-mail addresses: heekap@gmail.com (H.-K. Ahn), peter@cs.ccny.cuny.edu (P. Brass), ofried@cs.kaist.ac.kr (O. Cheong), hsnna@computing.ssu.ac.kr (H.-S. Na), cssin@hufs.ac.kr (C.-S. Shin), antoine@comp.nus.edu.sg (A. Vigneron).

computed in $O(\log n)$ time [10]. Schwarzkopf et al. [19] show how to compute a pair of rectangles approximating a given convex polygon in $O(\log^2 n)$ time. Kirkpatrick and Snoeyink [14] give a general framework that allows to answer several queries on a convex n -gon P in $O(\log n)$ time. Examples are the longest chord (or a chord of given length) parallel to a query line, or the largest homothet of a query triangle that fits inside P . Chazelle et al. [8] recently presented a different framework for obtaining sublinear-time algorithms where the input is not given in sorted arrays, but in linked lists where random nodes can be accessed in constant time. It yields $O(\sqrt{n})$ time randomized algorithms for various problems, for instance for detecting intersections between convex polyhedra.

Other problems on convex polygons cannot be solved in sublinear time. For instance, determining the diameter or area of P takes $\Theta(n)$ time. In this paper we show that some of these problems can be solved in $O(\log n)$ time if an *approximate* solution is sufficient. We can, for instance, compute the diameter or the area of P up to a relative error of ε in time $O((\log n)/\sqrt{\varepsilon})$. In fact, we will give efficient algorithms for arbitrary compact convex sets in the plane. Our only assumption is that a convex set C is given in a data structure that allows to answer the following two types of queries in time T_C :

- given a query line ℓ , find $C \cap \ell$,
- given a query direction u , find an extreme point in direction u .

For instance, if C is a convex n -gon given as an array of its vertices in counter-clockwise order, then we can answer these two types of queries in $O(\log n)$ time by binary search, so $T_C = O(\log n)$.

Our algorithms are based on an approximation of the input convex set C by a convex polygon whose size depends only on ε . This is not a new idea: our approximation is based on a constructive proof by Dudley from 1974 [9]. A paper by Agarwal et al. [1] uses this idea as well, some of these results have been improved recently by Chan [7]. Interestingly, these approximations can be computed in logarithmic time, a striking improvement compared, for instance, to the result by Lopez and Reisner [17]. They proposed an $O(n + (n - k) \log n)$ time algorithm for approximating a convex n -gon by an inscribed polygon with k vertices and relative approximation error $O(1/k^2)$. Our method achieves the same in time $O(k \log n)$ (or in time $O(n)$, independent of k).

In general, if it is possible to compute a certain property of a convex n -gon in time polynomial in n , and this property is “robust” with respect to approximation of the polygon, then our approximation technique immediately results in an approximation algorithm for an arbitrary planar convex set C of running time roughly $O(\varepsilon^{-1/2} T_C + 1/\varepsilon^{O(1)})$. In the case where C is a convex n -gon given in an array, we obtain sublinear $O(\varepsilon^{-1/2} \log n + 1/\varepsilon^{O(1)})$ time algorithms.

We give some rather immediate applications of this technique, and then turn to our main result. We give logarithmic-time approximation algorithms to determine, for a given convex set C , approximations of the largest axially symmetric convex set contained in C , and the smallest such set that contains C .

There are a number of papers that study the best inner approximation of any convex set by a symmetric set; the distance to a symmetric set can be considered a measure of its symmetry [11]. Lower bounds for this distance are given by the Löwner–John ellipsoid [13]: any planar convex body C lies between two homothetic ellipses $E \subset C \subset 2E$ with homothety ratio at most 2. Since any ellipse is axially symmetric, and $\text{area}(E) = \frac{1}{4} \text{area}(2E) \geq \frac{1}{4} \text{area}(C)$, any convex planar set C contains an axially symmetric subset with at least 1/4 of the area of C . The same lower bound of 1/4 follows from the fact that any planar convex body lies between two homothetic rectangles with homothety ratio at most two [16,19]. The lower bound can be raised to 2/3 [15], a bound that is not known to be tight. Bounds are also known for specific axis-symmetric inscribed figures, such as isosceles triangles or kites [21].

The largest centrally symmetric set contained in a convex shape C is the maximum intersection of C and a translate of $-C$. If C is a convex n -gon, this can be computed in $O(n \log n)$ time [5]. Approximation by axially symmetric sets is technically more demanding, as the largest axially symmetric set contained in C is the maximum intersection of C and a *rotated* and translated copy of C' (with C' a fixed axially reflected copy of C). We do not know of any exact algorithm to compute the maximum intersection of two convex polygons under translation and rotation (orientation-preserving rigid motions), indeed it is not clear that such an algorithm can exist within a reasonable model of computation.

Barequet and Rogol [4] propose an algorithm to compute exactly the largest subset of a convex n -gon with an axial symmetry; but it requires to solve $\Theta(n^3)$ optimization problems for which no polynomial time algorithm is known. This is our motivation to give a fast approximation algorithm. We can find a $(1 - \varepsilon)$ -approximation in time $O(\varepsilon^{-1/2} T_C + \varepsilon^{-3/2})$.

The problem of outer approximation of a convex polygon by an axially symmetric polygon seems to have received less interest than inner approximation, perhaps because this is equivalent to the inner approximation problem if one drops the requirement that the axially symmetric polygon has to be convex. The results on approximation by homothetic pairs (ellipses or rectangles) cited above give again simple bounds: for each convex set C there is an axially symmetric set D containing C with $\text{area}(D) \leq 4 \text{area}(C)$. The constant 4 can be reduced to $31/16$ [15], again this is probably not tight. We give an approximation algorithm for this problem with running time $O(\varepsilon^{-1/2} T_C + \varepsilon^{-3/2})$.

Both algorithms are based on three key ideas.

- First, as discussed before, we replace the input figure by a polygon with a number of vertices depending on ε only.
- Second, we discretize the set of directions and sample only directions in a discrete set. This works well as long as the polygon is not long and skinny. Fortunately we can show that for long and skinny polygons, the axis of an optimal symmetry must be very close to the diameter of the polygon, or must be nearly orthogonal to this diameter.
- Finally, we use an algorithm to compute the optimal solution for a given direction of the axis of symmetry. In the inscribed case, this is equivalent to finding the translation of C' that maximizes the area of $C \cap C'$. As mentioned before, this can be done in time $O(n \log n)$ [5]. In our case, it suffices to consider a one-dimensional set of translations, which permits a linear-time solution [3]. We also give a linear-time decimation algorithm for the circumscribed case.

As mentioned before, the inscribed case is a special case of the problem of maximizing the overlap of two convex polygons C and C' under translation and rotation of C' . Surprisingly little is known about this problem. Alt et al. [2] made some initial progress on a similar problem, showing, for instance, how to construct, for a convex polygon P , the axis-parallel rectangle Q minimizing the symmetric difference of P and Q . Our solution does not generalize to this problem. It does not appear to be “robust” under approximation of C and C' . Furthermore, we do not know how to discretize the set of directions when C is fat while C' is long and skinny.

2. Notations

In this paper, all the convex sets we consider are compact and lie in the plane. So we will simply say *convex set* instead of planar compact convex set. We let $|C|$ denote the *area* of a convex set C , while $\text{diam}(C)$ and $\text{peri}(C)$ denote its diameter and perimeter.

We denote by \mathcal{U} the set of unit vectors in the plane. We identify a point M in the plane with the vector OM , where O is the origin. We denote by $\langle a, b \rangle$ the inner product of a and b . The *directional width* of a convex set C in direction $u \in \mathcal{U}$ is the minimum width of a slab that contains C and is orthogonal to u . In other words, the directional width of C in direction u is:

$$\text{dwidth}(u, C) = \max_{x \in C} \langle u, x \rangle - \min_{x \in C} \langle u, x \rangle.$$

The *width* of C is the minimum width along all the directions in \mathcal{U} , that is:

$$\text{width}(C) = \min_{u \in \mathcal{U}} (\text{dwidth}(u, C)).$$

We introduce another notion: for a convex set C , let $\text{breadth}(C) := |C| / \text{diam}(C)$. The name $\text{breadth}(C)$ can be explained as follows: let pq be a diameter of C . There is then a rectangle R circumscribed to C with one side parallel to pq such that C touches all four sides of R . The sides of R have length $\text{diam}(C)$ and w , and we have $\text{diam}(C)w/2 = |R|/2 \leq |C| \leq |R| = \text{diam}(C)w$. This implies $\text{breadth}(C) \leq w \leq 2\text{breadth}(C)$, so $\text{breadth}(C)$ is an estimate for the directional width of C orthogonal to a diameter. (We use the word “breadth” instead of “width” to avoid confusion with the usual notion of width, which is explained in the previous paragraph.)

We assume that a convex set C is given in a data structure that allows to answer the following two types of queries in time T_C :

- given a line ℓ , find the line segment $C \cap \ell$.
- given a direction $u \in \mathcal{U}$, find a point x of C that is extreme along u . In other words,

$$\langle u, x \rangle = \max_{y \in C} \langle u, y \rangle.$$

For instance, if C is a convex n -gon whose vertices are given in a sorted array, we can answer these queries by binary search in time $O(\log n)$, so $T_C = O(\log n)$.

For two sets A and B such that $A \subset B$, the Hausdorff-distance between A and B is

$$d_H(A, B) := \max_{b \in B} \left(\min_{a \in A} d(a, b) \right)$$

where $d(a, b)$ is the Euclidean distance between a and b .

3. Preliminaries

We will make use of the following inequality [22, p. 257, Ex. 7.17a].

Lemma 1. *For a convex set C we have $\text{peri}(C) \leq \pi \text{diam}(C)$.*

The following lemma bounds the increase in area when a convex set is enlarged.

Lemma 2. *Let C be a convex set, let $r > 0$, and let C' be the set of points at distance at most r from C (in other words, C' is the Minkowski sum of C and a disk of radius r). Then $|C'| = |C| + r \text{peri}(C) + \pi r^2$, $\text{peri}(C') = \text{peri}(C) + 2\pi r$, and $\text{diam}(C') = \text{diam}(C) + 2r$.*

Proof. Assume first that C is a convex polygon. Then $C' \setminus C$ can be decomposed into rectangles of width r along each edge of C , and disk sectors at the vertices of C . The union of all the disk sectors is a disk of radius r , which implies the claim. For general C , approximate it by a sequence of polygons and take the limit. \square

An alternate proof is suggested in Exercise 6 on page 47 of do Carmo [6]. A similar bound is the following “volume of tube” formula. Again one could prove this easily for convex polygons, and take the limit. The lemma also follows directly from the general volume-of-tube formula for smooth curves in any dimension by Hotelling [12] and Weyl [23].

Lemma 3. *Let C be a convex set, let $r > 0$, and let C' be the set of points at distance at most r from the boundary of C (in other words, C' is the Minkowski sum of the boundary of C and a disk of radius r). Then $|C'| \leq 2r \text{peri}(C)$.*

Finally, we bound the change in area incurred by a rotation around a point inside a convex polygon.

Lemma 4. *Let C be a convex set, and let C' be a copy of C , rotated by an angle δ around a point p in C . Then*

$$|C \cap C'| \geq |C| - \frac{\pi \delta}{2} \text{diam}(C)^2.$$

Proof. We denote by D the symmetric difference between C and C' , in other words $D = (C \cup C') \setminus (C \cap C')$. We denote by C_m the copy of C rotated by an angle $\delta/2$ around p . Let T_m denote the set of points that are at distance at most $\delta \text{diam}(C)/2$ from the boundary of C_m . Note that any point q in D is obtained from a point on the boundary of C_m by a rotation with center p and angle at most $\delta/2$ in absolute value. Since the distance $d(p, q)$ is at most $\text{diam}(C)$, it follows that $q \in T_m$. Thus $D \subset T_m$. By Lemma 3, the area of T_m is at most $\delta \text{diam}(C) \text{peri}(C_m)$. Since $\text{peri}(C_m) = \text{peri}(C)$ and, by Lemma 1, $\text{peri}(C) \leq \pi \text{diam}(C)$ we obtain that $|T_m| \leq \pi \delta \text{diam}(C)^2$. Since $D \subset T_m$, it implies that $|D| \leq \pi \delta \text{diam}(C)^2$. The result follows from $|D| = |C| - |C \cap C'| + |C'| - |C \cap C'| = 2(|C| - |C \cap C'|)$. \square

4. Approximating a convex set

A key component of our proofs is a polygon approximation whose size depends only on ϵ . In particular, we will show that the framework of Agarwal et al. [1] can be implemented efficiently in the case of planar convex sets. We start with a lemma.

Lemma 5. *Given a convex set C , we can find in $O(T_C)$ time a rectangle R with sides a, b containing C such that C touches all four sides of R and such that $\text{diam}(C)/\sqrt{2} \leq a \leq \text{diam}(C)$, $\text{breadth}(C) \leq b \leq 4\text{breadth}(C)$, and $|R|/(2\sqrt{2}) \leq |C| \leq |R|$.*

Proof. We can determine a point of C that is extreme in a given direction in time T_C . By doing this four times, we can find the axis-parallel bounding box R' of C . Let $a' \geq b' > 0$ be its sides, and pick the vertices p, q of C touching the shorter sides of R' . Then $a' \leq d(p, q) \leq \text{diam}(C) \leq \text{diam}(R) \leq \sqrt{2}a'$. We now compute the smallest rectangle R containing C with a side parallel to pq . The side parallel to pq has length $a \geq d(p, q) \geq a' \geq \text{diam}(C)/\sqrt{2}$. Since C contains two triangles with common base pq and total height b , we have $ab = |R| \geq |C| \geq d(p, q)b/2 \geq ab/(2\sqrt{2}) = |R|/(2\sqrt{2})$. Finally, we have $b \geq |C|/a \geq |C|/\text{diam}(C) = \text{breadth}(C)$, and $b \leq 2\sqrt{2}|C|/a \leq 2\sqrt{2}|C|/(\text{diam}(C)/\sqrt{2}) = 4\text{breadth}(C)$. \square

Following Agarwal et al. [1], we say that a convex set $C' \subset C$ is an ϵ -kernel of C if and only if

$$\forall u \in \mathcal{U}, \quad (1 - \epsilon)\text{dwidth}(u, C) \leq \text{dwidth}(u, C').$$

We give an efficient algorithm to compute a low-complexity ϵ -kernel of a convex set C . It is based on Dudley’s constructive proof [9]. Note that the running time of the linear-time version of the algorithm has no dependence on ϵ at all.

Lemma 6. *Given a planar convex set C and $\epsilon > 0$, one can construct in time $O(T_C/\sqrt{\epsilon})$ two convex polygons C_ϵ and C'_ϵ with $O(1/\sqrt{\epsilon})$ vertices such that $C_\epsilon \subset C \subset C'_\epsilon$ and $|C'_\epsilon \setminus C_\epsilon| \leq \epsilon|C|$. In addition, C_ϵ is an ϵ -kernel of C , and C is an ϵ -kernel of C'_ϵ . If C is a convex n -gon, then we can compute C_ϵ and C'_ϵ in time $O(n)$.*

Proof. We start by computing a rectangle R as in Lemma 5, and apply a transformation that maps R to the unit square. Ratios of area and directional width are invariant under affine transformations. In the following, we will therefore assume that C is inscribed in a unit square R .

First we prove a lower bound on $\text{width}(C)$. By Lemma 5, we have $|C| \geq 1/(2\sqrt{2})$. Let u_0 be a direction such that $\text{width}(C) = \text{dwidth}(u_0, C)$ and u_1 be a direction orthogonal to u_0 . Clearly $\text{dwidth}(u_1, C) \leq \text{diam}(R) = \sqrt{2}$. Therefore

$$\frac{1}{2\sqrt{2}} \leq |C| \leq \text{dwidth}(u_1, C)\text{dwidth}(u_0, C) \leq \sqrt{2}\text{width}(C),$$

so $\text{width}(C) \geq 1/4$.

We now discuss the linear-time algorithm for the case that C is a convex n -gon. We go once around C , starting at an arbitrary vertex, and select edges of C as we go. We always choose the first edge. Let $e = ww'$ be the most recently chosen edge, let $e' = vv'$ be the next candidate edge, and let $e'' = v'v''$ be the edge following e' . We choose e' if

- the distance $d(w', v') > \sqrt{\epsilon}/3$, or
- the outer normals of e and e'' make an angle larger than $\sqrt{\epsilon}/3$.

We observe that the number of edges selected is $O(1/\sqrt{\epsilon})$. Remember that C is inscribed in a unit square, so by Lemma 1, only $O(1/\sqrt{\epsilon})$ edges can be chosen according to the first rule. The total change of the outer normal angles is $2\pi = O(1)$, so only $O(1/\sqrt{\epsilon})$ edges can be chosen according to the second rule.

Let C_ϵ be the convex hull of the selected segments, and let C'_ϵ be the polygon obtained by extending the selected edges until they form a convex polygon. Then $C_\epsilon \subset C \subset C'_\epsilon$.

The difference $C'_\epsilon \setminus C_\epsilon$ consists of $O(1/\sqrt{\epsilon})$ triangles. Each triangle Δ is defined by two consecutive selected edges $e = ww'$ and $e' = vv'$ that are not consecutive in C . If s is the point of intersection of the lines supporting e and e' ,

then $\Delta = \Delta w'vs$. By construction, the supporting lines make an angle of at most $\sqrt{\varepsilon}/3$ and so the angle $\angle w'sv \geq \pi - \sqrt{\varepsilon}/3$. Also by construction, the distance $d(w', v) \leq \sqrt{\varepsilon}/3$. Together this implies that the height of Δ is at most $\varepsilon/9$, and so $d_H(C_\varepsilon, C'_\varepsilon) \leq \varepsilon/9$. In particular, since $C_\varepsilon \subset C \subset C'_\varepsilon$, it follows that $d_H(C_\varepsilon, C) \leq \varepsilon/9$ and $d_H(C, C'_\varepsilon) \leq \varepsilon/9$. So for all directions $u \in \mathcal{U}$, we have $\text{dwidth}(u, C) - 2\varepsilon/9 \leq \text{dwidth}(u, C_\varepsilon)$, and $\text{dwidth}(u, C'_\varepsilon) - 2\varepsilon/9 \leq \text{dwidth}(u, C)$. Remember that $\text{width}(C) > 1/4$, so $\text{dwidth}(u, C) > 1/4$. Therefore $(1 - \varepsilon)\text{dwidth}(u, C) \leq \text{dwidth}(u, C_\varepsilon)$, and C_ε is an ε -kernel for C . Since $\text{dwidth}(u, C'_\varepsilon) \geq \text{dwidth}(u, C) > 1/4$, we also have $(1 - \varepsilon)\text{dwidth}(u, C'_\varepsilon) \leq \text{dwidth}(u, C)$, and C is an ε -kernel for C'_ε .

We have just observed that $C'_\varepsilon \setminus C_\varepsilon$ consists of triangles with height at most $\varepsilon/9$ and such that the sum of the length of their bases is at most $\text{peri}(C_\varepsilon)$. Since C_ε is contained in a unit square, its perimeter is at most 4. So $|C'_\varepsilon \setminus C_\varepsilon| \leq 2\varepsilon/9 < \varepsilon/2\sqrt{2} \leq \varepsilon|C|$.

Let now C be a (not necessarily polygonal) convex set. We will show how to compute C_ε and C'_ε in time $O(T_C/\sqrt{\varepsilon})$. We will select a sequence of points p_1, p_2, \dots, p_s on the boundary of C such that the following holds (let $p_0 := p_s$):

- p_1, p_2, \dots, p_s is sorted in counter-clockwise order along the boundary of C ,
- $s = O(1/\sqrt{\varepsilon})$,
- for $i = 1, \dots, s$, there are tangents to C in p_{i-1} and p_i that make an angle of at most $\sqrt{\varepsilon}/3$, and
- for $i = 1, \dots, s$, the distance between p_{i-1} and p_i is at most $\sqrt{\varepsilon}/3$.

Let C_ε be the convex hull of p_1, \dots, p_s , and let C'_ε be the polygon formed by the at most $2s$ tangents to C in p_1, \dots, p_s . Then $C_\varepsilon \subset C \subset C'_\varepsilon$, and $C'_\varepsilon \setminus C_\varepsilon$ consists of $s = O(1/\sqrt{\varepsilon})$ triangles $p_{i-1}p_iv$. The approximation bounds now follow as in the polygon case.

To compute C_ε , we first select the boundary points of C that are extreme in a set of $6\pi/\sqrt{\varepsilon}$ equally spaced directions. We then consider a set of equally spaced horizontal and vertical lines at distance $\sqrt{\varepsilon}/18$, and select the points of intersection between the boundary of C and these lines. This takes $O(1/\sqrt{\varepsilon})$ queries on the convex set C , and results in a sequence of points as required above. We obtain C_ε as the convex hull of the selected point sequence.

The outer approximation C'_ε takes a little more work: the difficulty is that we do not know the tangents in the boundary points obtained by line intersection queries. We therefore first compute the inner approximation $C_{\varepsilon/4}$ (that is, with $\varepsilon' = \varepsilon/4$). For each edge $p_{i-1}p_i$ of $C_{\varepsilon/4}$, let u_i be the outer normal of $p_{i-1}p_i$. We compute the point $q_i \in C$ extreme in direction u_i . The sequence q_1, q_2, \dots now fulfills the requirements above, and we easily obtain C'_ε given the points and the tangent directions. \square

Following Agarwal et al. [1], we define *faithful measures* for convex sets. A function μ is a faithful measure if $\mu(C) \geq 0$ for any convex set C and if there exists a constant $c > 0$ such that, for any ε -kernel C_ε of C , we have $(1 - c\varepsilon)\mu(C) \leq \mu(C_\varepsilon) \leq \mu(C)$. We list a few measures that were shown to be faithful by Agarwal et al. [1].

Lemma 7 [1, Section 6.1]. *The following measures are faithful: diameter, width, area, perimeter, the radius of the smallest enclosing disk, and the area of the smallest enclosing rectangle.*

5. Simple applications

We give a few simple applications of our approximation technique to optimization problems for convex sets. Following Agarwal et al. [1], we first compute a kernel of the convex input set, and then we apply known algorithms on the kernel. For a number of problems, this provides an approximate solution to the optimization problem on the original convex set.

Theorem 8. *Given a planar convex set C , we can compute a $(1 - \varepsilon)$ -approximation of its area, diameter, perimeter and width in time $O(T_C/\sqrt{\varepsilon})$. In particular, if C is a convex n -gon and its vertices are given in a sorted array or a balanced binary search tree, then we can compute these approximations in time $O(\log n/\sqrt{\varepsilon})$. We can also compute $(1 + \varepsilon)$ -approximations of the smallest area enclosing rectangle and the smallest enclosing disk of C within the same time bounds.*

Proof. The area and perimeter of a convex n -gon can be easily computed in $O(n)$ time. Its diameter, width and smallest area enclosing rectangle can also be computed in $O(n)$ time using, for instance, the rotating callipers technique of Toussaint [20]. The smallest enclosing disk can also be found in $O(n)$ time [18].

By Lemma 7, all these measures are faithful, and so there is a constant $c > 0$ such that an ε/c -kernel $C_{\varepsilon/c}$ for C provides $(1 - \varepsilon)$ -approximations of diameter, width, area, and perimeter of C . We can compute $C_{\varepsilon/c}$ in time $O(T_C/\sqrt{\varepsilon})$. It has $O(1/\sqrt{\varepsilon})$ vertices, and so we can compute its diameter, width, area, and perimeter within the same time bound.

For the smallest enclosing rectangle and disk, we use the outer approximation $C'_{\varepsilon/c}$ for a suitable $c > 0$ instead. Since C is an ε/c -kernel of $C'_{\varepsilon/c}$, the smallest enclosing rectangle and disk of $C'_{\varepsilon/c}$ are $(1 + \varepsilon)$ -approximations of the smallest enclosing rectangle and disk of C . Again, they can be computed in time $O(T_C/\sqrt{\varepsilon})$. \square

6. The largest axially symmetric inscribed set

In the following we denote by $\text{refl}(\cdot, \ell)$ the reflection at line ℓ , so that $\text{refl}(C, \ell)$ is the reflected image of C under reflection at ℓ . Let C be a convex set in the plane and let ℓ be a line. The set $C \cap \text{refl}(C, \ell)$, if it is not empty, is an axially symmetric convex subset of C , the largest axially symmetric subset with reflection axis ℓ . Our goal is to find, for a convex set C , a line $\ell^{\text{opt}}(C)$ that maximizes the area of this set:

$$|C \cap \text{refl}(C, \ell^{\text{opt}}(C))| = \max_{\ell \subset \mathbb{R}^2} |C \cap \text{refl}(C, \ell)|.$$

As we discussed in the introduction, Lassak proved the following lower bound [15]:

Lemma 9.

$$|C \cap \text{refl}(C, \ell^{\text{opt}}(C))| \geq \frac{2}{3}|C|.$$

In this section we show that at least an ε -approximation ℓ_ε with

$$(1 - \varepsilon)|C \cap \text{refl}(C, \ell^{\text{opt}}(C))| < |C \cap \text{refl}(C, \ell_\varepsilon)|$$

can be found fast.

If the direction of ℓ is known, we can compute the optimal line using the following lemma.

Lemma 10. *Given a convex n -gon P and a line ℓ , one can find in $O(n)$ time the line ℓ' parallel to ℓ that maximizes $|P \cap \text{refl}(P, \ell')|$.*

Proof. Let $Q := \text{refl}(P, \ell)$, and let t be a vector orthogonal to ℓ . For any line ℓ' parallel to ℓ , $\text{refl}(P, \ell')$ is a translation of Q by a multiple of t , and so the problem is equivalent to finding $\lambda \in \mathbb{R}$ such that $|P \cap (Q + \lambda t)|$ is maximized. A linear-time algorithm to solve this problem has been given by Avis et al. [3]. \square

We will apply this algorithm to a set of $O(1/\varepsilon)$ directions. The following two lemmas show how to find this set of directions.

Lemma 11. *Let ℓ and ℓ' be two lines intersecting in a point p with an angle δ , and let C be a convex set. If $p \in C \cap \text{refl}(C, \ell)$, then*

$$|C \cap \text{refl}(C, \ell')| \geq |C \cap \text{refl}(C, \ell)| - \pi \delta \text{diam}(C)^2.$$

Proof. The concatenation of the reflection at ℓ and the reflection at ℓ' is a rotation around p by the angle 2δ . Let $Q := C \cap \text{refl}(C, \ell)$. Since Q is symmetric with respect to ℓ , the set $\text{refl}(Q, \ell') = \text{refl}(\text{refl}(Q, \ell), \ell')$ is a copy of Q rotated around p by 2δ . Since $p \in Q$, Lemma 4 implies that

$$|Q \cap \text{refl}(Q, \ell')| \geq |Q| - \pi \delta \text{diam}(Q)^2.$$

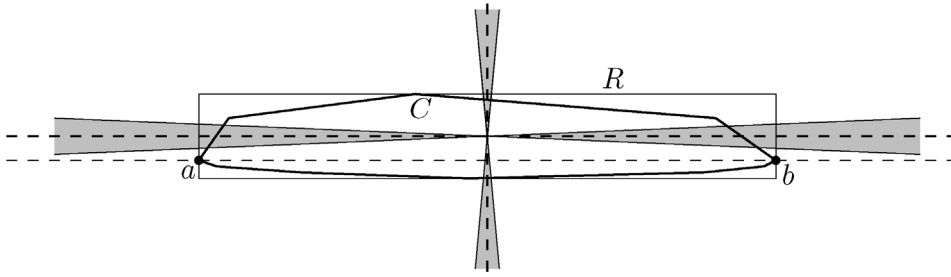


Fig. 1. Case where C is long and skinny. We sample directions from the shaded area.

Since $Q \subset C$, we have

$$C \cap \text{refl}(C, \ell') \supset Q \cap \text{refl}(Q, \ell'),$$

and by the above that implies

$$|C \cap \text{refl}(C, \ell')| \geq |Q| - \pi \delta \text{diam}(Q)^2 \geq |C \cap \text{refl}(C, \ell)| - \pi \delta \text{diam}(C)^2. \quad \square$$

The occurrence of $\text{diam}(C)^2$ instead of $|C|$ is a problem. In the following lemma, we will need to give special consideration to the case where the set C is long and skinny, that is, when $\text{diam}(C)^2$ is much larger than $|C|$. Intuitively, when C is fat we will just sample the space of directions uniformly. When C is long and skinny, we will sample more densely, but we will only sample near the two axes of symmetry of a bounding rectangle R that is parallel to a diametral segment ab (see Fig. 1).

Lemma 12. *Given a convex n -gon P and $\varepsilon > 0$, one can construct in time $O(n + 1/\varepsilon)$ a set D_ε of $O(1/\varepsilon)$ directions such that*

$$\left(1 - \frac{1}{2}\varepsilon\right) |P \cap \text{refl}(P, \ell^{\text{opt}}(P))| \leq \max\{|P \cap \text{refl}(P, \ell)| : \ell \text{ has a direction from } D_\varepsilon\}.$$

Proof. By Lemma 11 and Lemma 9 it is sufficient to choose the set D_ε such that it contains a line that makes an angle δ of at most $\varepsilon|P|/(3\pi \text{diam}(P)^2)$ with ℓ^{opt} .

We start by computing, in time $O(n)$, a diameter pq of P , and the area $|P|$. We then distinguish two cases.

If $\text{diam}(P)^2 \leq 20|P|$, then we generate D_ε by sampling the direction space uniformly, choosing multiples of $\varepsilon/30\pi$. Since $\varepsilon/60\pi \leq \varepsilon|P|/3\pi \text{diam}(P)^2$, this is sufficient.

If, on the other hand, $\text{diam}(P)^2 > 20|P|$, then we sample uniformly the directions within $3\pi|P|/2 \text{diam}(P)^2$ of the direction of the diameter ab , choosing multiples of $2\varepsilon|P|/3\pi \text{diam}(P)^2$. We do the same around the direction that is orthogonal to ab . To show that this is sufficient we have to demonstrate that $\ell^{\text{opt}}(P)$ does not make an angle larger than $3\pi|P|/2 \text{diam}(P)^2$ with the direction of the diameter or with the direction that is orthogonal to the diameter.

As in the argument at the beginning of Section 3, let R be the rectangle circumscribed to P with a side parallel to pq . The longer side of R has length $\text{diam}(P)$, and P touches all four sides of R . This implies that $|R| \leq 2|P|$, and so its width w is at most $2|P|/\text{diam}(P) = 2\text{breadth}(P)$. It follows that P lies in an infinite strip of width at most $2\text{breadth}(P)$. Let $\gamma \in [0, \pi/2]$ be the angle made by the lines $\ell^{\text{opt}}(P)$ and pq . The set $\text{refl}(P, \ell^{\text{opt}})$ is contained in a congruent strip, intersecting the strip of P at an angle 2γ . The set $P \cap \text{refl}(P, \ell^{\text{opt}})$ is contained in the intersection of the two strips, which has area $4\text{breadth}(P)^2/\sin 2\gamma$. By Lemma 9, we know that $|P \cap \text{refl}(P, \ell^{\text{opt}}(P))| \geq 2|P|/3$, so the angle γ must satisfy

$$\frac{4\text{breadth}(P)^2}{\sin 2\gamma} \geq \frac{2}{3}|P|,$$

thus $\sin 2\gamma \leq 6|P|/\text{diam}(P)^2$. It means that we are in one of the following two cases: $\gamma \leq 3\pi|P|/2 \text{diam}(P)^2$ or $\pi/2 - \gamma \leq 3\pi|P|/2 \text{diam}(P)^2$. \square

We can now state the result of this section.

Theorem 13. *Let C be a planar convex set. Given $\varepsilon > 0$, we can find a set $Q \subset C$ with axial symmetry and*

$$\text{area}(Q) \geq (1 - \varepsilon) \max\{\text{area}(Q^*) \mid Q^* \subset C \text{ and } Q^* \text{ axially symmetric}\}$$

in time $O(\varepsilon^{-1/2}T_C + \varepsilon^{-3/2})$.

Proof. We first construct the outer approximating polygon C'_{ε_1} of Lemma 6 with $\varepsilon_1 := \varepsilon/6$, obtain for this polygon a set of $O(1/\varepsilon)$ directions from Lemma 12, and determine for each of them the optimal line by Lemma 10.

It takes time $O(\varepsilon^{-1/2}T_C)$ to construct C'_{ε_1} , time $O(1/\sqrt{\varepsilon} + 1/\varepsilon) = O(1/\varepsilon)$ to construct D_ε , and for each of the $O(1/\varepsilon)$ directions it takes time $O(1/\sqrt{\varepsilon})$ to find the optimal line of that direction. Together this is the claimed complexity of $O(\varepsilon^{-1/2}T_C + \varepsilon^{-3/2})$.

It remains to show that the line ℓ_ε with the largest intersection gives an approximation as claimed.

$$\begin{aligned} \left(1 - \frac{1}{2}\varepsilon\right) |C \cap \text{refl}(C, \ell^{\text{opt}}(C))| &\leq \left(1 - \frac{1}{2}\varepsilon\right) |C'_{\varepsilon_1} \cap \text{refl}(C'_{\varepsilon_1}, \ell^{\text{opt}}(C))| \\ &\leq \left(1 - \frac{1}{2}\varepsilon\right) |C'_{\varepsilon_1} \cap \text{refl}(C'_{\varepsilon_1}, \ell^{\text{opt}}(C'_{\varepsilon_1}))| \\ &\leq |C'_{\varepsilon_1} \cap \text{refl}(C'_{\varepsilon_1}, \ell_\varepsilon)| \\ &\leq |C \cap \text{refl}(C, \ell_\varepsilon)| + 2|C'_{\varepsilon_1} \setminus C| \\ &\leq |C \cap \text{refl}(C, \ell_\varepsilon)| + \frac{1}{3}\varepsilon|C| \\ &\leq |C \cap \text{refl}(C, \ell_\varepsilon)| + \frac{1}{2}\varepsilon|C \cap \text{refl}(C, \ell^{\text{opt}}(C))|. \end{aligned}$$

In the last inequality we used Lemma 9. It follows that

$$(1 - \varepsilon) |C \cap \text{refl}(C, \ell^{\text{opt}}(C))| \leq |C \cap \text{refl}(C, \ell_\varepsilon)|,$$

which completes the proof. \square

7. The smallest axially symmetric circumscribed convex set

Consider again a convex set C in the plane and a line ℓ . Let $\text{conv}(X)$ denotes the convex hull of a planar set X . Then the set $\text{conv}(C \cup \text{refl}(C, \ell))$ is an axially symmetric convex superset of C , the smallest axially symmetric convex superset with reflection axis ℓ . We want to find a line $\ell^{\text{opt}}(C)$ that minimizes the area of this set:

$$|\text{conv}(C \cup \text{refl}(C, \ell^{\text{opt}}(C)))| = \min_{\ell \subset \mathbb{R}^2} |\text{conv}(C \cup \text{refl}(C, \ell))|.$$

As we discussed in the introduction, Lassak proved the following upper bound [15] (in fact, he proved a slightly stronger bound):

Lemma 14.

$$|\text{conv}(C \cup \text{refl}(C, \ell^{\text{opt}}(C)))| \leq 2|C|.$$

The result of this section shows that at least an ε -approximation ℓ_ε with

$$(1 + \varepsilon) |\text{conv}(C \cup \text{refl}(C, \ell^{\text{opt}}(C)))| > |\text{conv}(C \cup \text{refl}(C, \ell_\varepsilon))|$$

can be found fast. As in the previous section, we make use of a subroutine to find the optimal solution for a given direction of ℓ :

Lemma 15. *Given a convex n -gon P and a line ℓ , one can find in $O(n)$ time the line ℓ' parallel to ℓ that minimizes $|\text{conv}(P \cup \text{refl}(P, \ell'))|$.*

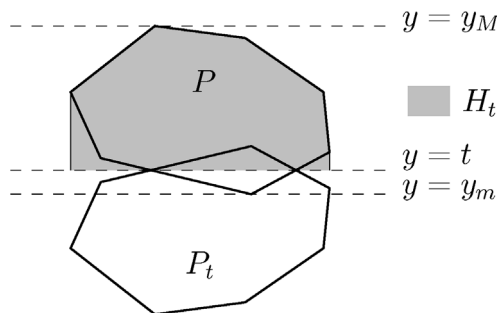


Fig. 2. Proof of Lemma 15.

Proof. We use a coordinate system such that ℓ is the x -axis. For any $t \in \mathbb{R}$, we denote by P_t the polygon obtained from P by a reflexion at the line $y = t$. We denote by H_t the part of $\text{conv}(P \cup P_t)$ that lies on or above the line $y = t$ (see Fig. 2). We want to minimize the area of $\text{conv}(P \cup P_t)$ for $t \in (-\infty, \infty)$. Since exactly half of the area is above the line $y = t$, this reduces to minimizing $|H_t|$. We also note that the minimum necessarily occurs for t in the interval $[y_m, y_M]$, where y_m is the minimum y -coordinate of a vertex of P , and y_M is the maximum.

Imagine moving the line $y = t$ from $t = y_m$ to $t = y_M$. The polygon P_t moves vertically upward. The region of interest, H_t , is (essentially) the upper convex hull of the stationary P and the moving P_t . An edge of the upper hull of H_t (that is, any edge but the vertical left and right edge and the horizontal bottom edge) is either an edge of P (type 0), or an edge of P_t (type 2), or is determined by one vertex from P and one vertex from P_t (type 1). For $t = y_m$ all edges of H_t are type 0 edges, while for $t = y_M$ all edges are type 2 edges.

Consider an edge e of the upper hull of P . This edge appears as a type 0 edge of H_t if and only if no vertex of P_t lies above the supporting line ℓ_e of e . Since P_t moves vertically upwards, there is a unique edge event for e where a vertex of P_t “hits” ℓ_e . This vertex is necessarily a vertex v_e of P_t that is extreme in the direction of the normal of e (it has a tangent parallel to ℓ_e). Let $t(e)$ be the “time” of this event, that is, the value of t such that $v_e \in \ell_e$. Clearly, e appears as a type 0 edge on H_t for $t < t(e)$, and does not appear for $t > t(e)$ (and may or may not appear for $t = t(e)$).

Similarly, consider an edge e' of the upper hull of the moving P_t . If we imagine time running backwards—that is, P_t is moving vertically downwards—there is an edge event for e' where the supporting line of e' touches the first vertex of the stationary P . Again, this is necessarily a vertex extreme in the direction normal to e' . If $t(e')$ is the time of this edge event, then e' appears as a type 2 edge on H_t for $t > t(e')$, and does not appear for $t < t(e')$.

By scanning the upper hulls of P and P_t in parallel, we can compute a list of all edge events in time $O(n)$ (we are basically merging the slopes of edges of the two chains). Note, though, that not every combinatorial change of H_t needs to be an edge event. For instance, a vertex of the moving P_t may hit a moving type 1 edge of H_t from below. We will see below that we can nevertheless restrict our attention to edge events.

Let $L_i(t)$, where $i = 0, 1, 2$, be the summed up length of the projections of edges of H_t of type i onto the x -axis. Clearly, $L_0(t) + L_1(t) + L_2(t) = x_M - x_m$, where x_m is the minimum x -coordinate of a vertex of P , and x_M is the maximum.

Since an edge e of P appears as a type 0 edge if and only if $t < t(e)$ (or $t \leq t(e)$), $L_0(t)$ is a monotonically decreasing function of t . It is piecewise constant, changing value only at edge events. Similarly, $L_2(t)$ is a piecewise constant, monotonically increasing function. It follows that $L(t) := L_2(t) - L_0(t)$ is an increasing function. Since $L_2(y_m) = L_0(y_M) = 0$, we have $L(y_m) < 0$, $L(y_M) > 0$.

Consider now a small movement of the line $y = t$, say from $y = t$ to $y = t + \delta$. If the combinatorial structure of H_t does not change in between, then $|H_t|$ changes as follows: the bottom edge of H_t moves upwards by δ , sweeping over area $\delta(x_M - x_m) = \delta(L_0(t) + L_1(t) + L_2(t))$. An edge of type 0 doesn’t move at all. An edge of type 2 moves upwards a distance 2δ , and so all such edges sweep over area $2\delta L_2(t)$. Finally, the edges of type 1 sweep over area $\delta L_1(t)$ in total. It follows that

$$|H_{t+\delta}| = |H_t| + \delta(2L_2(t) + L_1(t)) - \delta(L_0(t) + L_1(t) + L_2(t)) = |H_t| + \delta L(t).$$

It follows that $|H_t|$ is unimodal: it decreases while $L(t) < 0$, and increases once $L(t) > 0$. Our task is to find a value t^* such that $L(t) \leq 0$ for $t < t^*$ and $L(t) \geq 0$ for $t > t^*$. We know that then $|H_{t^*}|$ has attained the minimum value. Since $L(t)$ changes value at edge events only, we can restrict our search for t^* to edge events.

We avoid having to check whether or not an edge appears on H_t for t the exact time of an edge event by working only with values of $L(t)$ just before and just after such an event. Let us define $L_i^-(t) := \lim_{\varepsilon \rightarrow 0} L_i(t - \varepsilon)$ and $L_i^+(t) := \lim_{\varepsilon \rightarrow 0} L_i(t + \varepsilon)$ (where $\varepsilon > 0$), and similar for $L^-(t) = L_2^-(t) - L_0^-(t)$ and $L^+(t) = L_2^+(t) - L_0^+(t)$. With this notation, our goal is to find a time t^* such that $L^-(t^*) \leq 0$ and $L^+(t^*) \geq 0$.

We now give a recursive decimation algorithm to find t^* . At each stage, we maintain an open interval (t_0, t_1) , the values $L_0^+(t_0)$, $L_0^-(t_1)$, $L_2^+(t_0)$, and $L_2^-(t_1)$, and an unordered list \mathcal{L} of all edge events occurring in the open time interval (t_0, t_1) (that is, occurring strictly after t_0 and strictly before t_1). We maintain the invariant that $L^+(t_0) < 0$ and $L^-(t_1) > 0$. The invariant guarantees that \mathcal{L} contains at least one event, and in particular one with time t^* such that $L^-(t^*) \leq 0$ and $L^+(t^*) \geq 0$.

We initialize the recursion by letting $t_0 = y_m$ and $t_1 = y_M$. We set $L_0^+(t_0) = L_2^-(t_1) = x_M - x_m$ and $L_2^+(t_0) = L_0^-(t_1) = 0$. As we observed above, we can compute the unordered list of all edge events in linear time.

In a recursive step, we first compute a median element of \mathcal{L} in time linear in the size of \mathcal{L} . Let t_2 be the time of this median event. We compute $L_0^-(t_2)$, $L_2^-(t_2)$, $L_0^+(t_2)$, and $L_2^+(t_2)$ by starting with $L_0^+(t_0)$ and $L_2^+(t_0)$ and scanning the list \mathcal{L} for all edge events occurring between t_0 and t_2 . If $L^-(t_2) \leq 0$ and $L^+(t_2) \geq 0$, we return t_2 as t^* . Otherwise, $L^-(t_2)$ and $L^+(t_2)$ are both non-zero and have the same sign. If it is negative, then we scan \mathcal{L} once more to create a list of events occurring strictly between t_2 and t_1 , and recurse on the interval (t_2, t_1) . Otherwise, that is if $L^-(t_2) > 0$, we similarly recurse on the interval (t_0, t_2) .

Since the size of \mathcal{L} decreases to half its previous size in each recursive call, the overall running time of our algorithm is $O(n)$. This completes the proof. \square

Again, we apply the subroutine to a set of directions that we obtain using the following two lemmas.

Lemma 16. *Let ℓ and ℓ' be two lines intersecting in a point p with an angle δ , and let C be a convex set. If $p \in C$, then*

$$|\text{conv}(C \cup \text{refl}(C, \ell'))| \leq |\text{conv}(C \cup \text{refl}(C, \ell))| + 4\pi(1 + \pi/2)\delta \text{diam}(C)^2.$$

Proof. Let $Q := \text{conv}(C \cup \text{refl}(C, \ell))$ and $Q' := \text{conv}(C \cup \text{refl}(C, \ell'))$. As in Lemma 4, we argue that any point of $\text{refl}(C, \ell')$ has distance at most $2\delta \text{diam}(C)$ from some point of $\text{refl}(C, \ell)$. This implies that Q' is contained in the Minkowski-sum of Q with a disk of radius $2\delta \text{diam}(C)$. By Lemma 2, this implies

$$|Q'| \leq |Q| + 2\delta \text{diam}(C) \text{peri}(Q) + \pi(2\delta \text{diam}(C))^2.$$

Since $p \in C$, we have $C \cap \text{refl}(C, \ell) \neq \emptyset$, and so $\text{diam}(Q) \leq 2 \text{diam}(C)$. This implies $\text{peri}(Q) \leq 2\pi \text{diam}(C)$, and we obtain

$$|Q'| \leq |Q| + 4\pi(\delta + \delta^2) \text{diam}(C)^2 \leq |Q| + 4\pi(1 + \pi/2)\delta \text{diam}(C)^2. \quad \square$$

Lemma 17. *Given a convex n -gon P and $\varepsilon > 0$, one can construct in time $O(n + 1/\varepsilon)$ a set D_ε of $O(1/\varepsilon)$ directions such that*

$$\left(1 + \frac{1}{3}\varepsilon\right) |\text{conv}(P \cup \text{refl}(P, \ell^{\text{opt}}(P)))| \geq \min\{|\text{conv}(P \cup \text{refl}(P, \ell))| : \ell \text{ has a direction from } D_\varepsilon\}.$$

Proof. By Lemma 16 it is sufficient to choose the set D_ε such that it contains a line that makes an angle δ of at most $\varepsilon|P|/(12\pi(1 + \pi/2) \text{diam}(P)^2)$ with ℓ^{opt} . Again we distinguish two cases, depending on the ratio $|P|/\text{diam}(P)^2$.

If $\text{diam}(P)^2 \leq 10|P|$, then we generate D_ε by sampling the direction space uniformly, choosing multiples of $\varepsilon/1000$.

If $\text{diam}(P)^2 > 10|P|$, then we generate D_ε as follows. We sample uniformly the directions within $\pi|P|/\text{diam}(P)^2$ of the direction of the diameter pq , choosing multiples of $\varepsilon|P|/100 \text{diam}(P)^2$. We also sample in the same way around the direction orthogonal to pq (see Fig. 1).

To show that this is sufficient, notice that if $\ell^{\text{opt}}(P)$ intersects pq at an angle $\gamma \in [0, \pi/2]$, then $\text{conv}(P \cup \text{refl}(P, \ell^{\text{opt}}(P)))$ contains the diametral pair pq together with its reflected version $p'q'$, and pq makes an angle 2γ with $p'q'$. Therefore

$$2|P| \geq |\text{conv}(P \cup \text{refl}(P, \ell^{\text{opt}}(P)))| \geq |\text{conv}(\{p, q, p', q'\})| \geq \frac{1}{2} \text{diam}(P)^2 \sin 2\gamma.$$

Here we used Lemma 14. It follows that $\sin 2\gamma \leq 4|P|/\text{diam}(P)^2$, and so we are in one of the following two cases: $\gamma \leq \pi|P|/\text{diam}(P)^2$ or $\pi/2 - \gamma \leq \pi|P|/\text{diam}(P)^2$. \square

In order to replace the given input figure by a kernel, we need to show that the area of the smallest axially symmetric convex set containing C is a faithful measure. We use the following lemma.

Lemma 18. *Let ℓ be a line in the plane. Then the following measure is faithful:*

$$\mu(C) := |\text{conv}(C \cup \text{refl}(C, \ell))|.$$

Proof. Let C_ε be an ε -kernel of C . It is not hard to see that then $\text{conv}(C_\varepsilon \cup \text{refl}(C_\varepsilon, \ell))$ is a 2ε -kernel of $\text{conv}(C \cup \text{refl}(C, \ell))$. The claim now follows from Lemma 7. \square

We can now prove the main result of this section.

Theorem 19. *Let C be a convex set in the plane. Given $\varepsilon > 0$, we can find a convex set $Q \supset C$ with axial symmetry and*

$$\text{area}(Q) < (1 + \varepsilon) \min\{\text{area}(Q^*) \mid Q^* \supset C \text{ and } Q^* \text{ convex and axially symmetric}\}$$

in time $O(\varepsilon^{-1/2}T_C + \varepsilon^{-3/2})$.

Proof. We first construct the inner approximating polygon C_{ε_1} of Lemma 6 with $\varepsilon_1 = \varepsilon/c$ for a suitable constant $c > 0$, obtain for this polygon a set of $O(1/\varepsilon)$ directions from Lemma 17, and determine for each of them the optimal line by Lemma 15. The procedure takes time $O(\varepsilon^{-1/2}T_C + \varepsilon^{-3/2})$ in total.

The constant $c > 0$ is chosen such that

$$(1 - \varepsilon/3)|\text{conv}(C \cup \text{refl}(C, \ell))| \leq |\text{conv}(C_{\varepsilon_1} \cup \text{refl}(C_{\varepsilon_1}, \ell))|$$

for any line ℓ . This is possible by Lemma 18.

It remains to show that the line ℓ_ε minimizing $|\text{conv}(C_{\varepsilon_1} \cup \text{refl}(C_{\varepsilon_1}, \ell_\varepsilon))|$ among all lines with directions from D_ε is the required approximation.

$$\begin{aligned} \left(1 + \frac{1}{3}\varepsilon\right)|\text{conv}(C \cup \text{refl}(C, \ell^{\text{opt}}(C)))| &\geq \left(1 + \frac{1}{3}\varepsilon\right)|\text{conv}(C_{\varepsilon_1} \cup \text{refl}(C_{\varepsilon_1}, \ell^{\text{opt}}(C)))| \\ &\geq \left(1 + \frac{1}{3}\varepsilon\right)|\text{conv}(C_{\varepsilon_1} \cup \text{refl}(C_{\varepsilon_1}, \ell^{\text{opt}}(C_{\varepsilon_1})))| \\ &\geq |\text{conv}(C_{\varepsilon_1} \cup \text{refl}(C_{\varepsilon_1}, \ell_\varepsilon))| \\ &\geq \left(1 - \frac{1}{3}\varepsilon\right)|\text{conv}(C \cup \text{refl}(C, \ell_\varepsilon))|. \end{aligned}$$

For ε small enough, it follows that

$$(1 + \varepsilon)|\text{conv}(C \cup \text{refl}(C, \ell^{\text{opt}}(C)))| > |\text{conv}(C \cup \text{refl}(C, \ell_\varepsilon))|. \quad \square$$

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