A Linear-Time Algorithm for the Geodesic Center of a Simple Polygon

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Abstract Let $P$ be a closed simple polygon with $n$ vertices. For any two points in $P$, the geodesic distance between them is the length of the shortest path that connects them among all paths contained in $P$. The geodesic center of $P$ is the unique point in $P$ that minimizes the largest geodesic distance to all other points of $P$. In 1989, Pollack et al. (Discrete Comput Geom 4(1): 611–626, 1989) showed an $O(n \log n)$-time algorithm that computes the geodesic center of $P$. Since then, a longstanding question has been whether this running time can be improved. In this paper we affirmatively answer this question and present a deterministic linear-time algorithm to solve this problem.

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1 Introduction

Let \( P \) be a simple polygon with \( n \) vertices. Given two points \( x, y \) in \( P \) (either on the boundary or in the interior), the geodesic path \( \pi(x, y) \) is the shortest path contained in \( P \) connecting \( x \) with \( y \). If the straight-line segment connecting \( x \) with \( y \) is contained in \( P \), then \( \pi(x, y) \) is a straight-line segment. Otherwise, \( \pi(x, y) \) is a polygonal chain whose vertices (other than its endpoints) are reflex vertices of \( P \). We refer the reader to [21] for more information on geodesic paths.

The geodesic distance between \( x \) and \( y \), denoted by \(|\pi(x, y)|\), is the sum of the Euclidean lengths of each segment in \( \pi(x, y) \). Throughout this paper, when referring to the distance between two points in \( P \), we mean the geodesic distance between them.

Given a point \( x \in P \), a (geodesic) farthest neighbor of \( x \) is a point \( f \in P \) whose geodesic distance to \( x \) is maximized. To ease the description, we assume that each vertex of \( P \) has a unique farthest neighbor. This general position condition was also assumed by Aronov et al. [2] and can be obtained by applying a slight perturbation to the positions of the vertices [11].

Let \( F_P(x) \) be the function that maps each \( x \in P \) to the distance to a farthest neighbor of \( x \) (i.e., \( F_P(x) = |\pi(x, f(x))| \)). A point \( c_P \in P \) that minimizes \( F_P(x) \) is called the geodesic center of \( P \). Similarly, a point \( s \in P \) that maximizes \( F_P(x) \) (together with \( f(s) \)) is called a geodesic diametral pair and their distance is known as the geodesic diameter. Asano and Toussaint [3] showed that the geodesic center is unique whereas it is easy to see that several geodesic diametral pairs may exist.

In this paper we show how to compute the geodesic center of \( P \) in \( O(n) \) time.

1.1 Previous Work

Since the early 80s the problem of computing the geodesic center (and its counterpart, the geodesic diameter) has received a lot of attention from the computational geometry community. Chazelle [8] gave the first algorithm for computing the geodesic diameter (which runs in \( O(n^2) \) time using linear space). Afterwards, Suri [27] reduced it to \( O(n \log n) \)-time without increasing the space constraints. Finally, Hershberger and Suri [14] presented a fast matrix search technique, one application of which is a linear-time algorithm for computing the diameter.

The first algorithm for computing the geodesic center was given by Asano and Toussaint [3], and runs in \( O(n^4 \log n) \)-time. In 1989, Pollack et al. [25] improved it to \( O(n \log n) \) time. Since then, it has been an open problem whether the geodesic center can be computed in linear time (indeed, this problem was explicitly posed by Pollack et al. [25] and later by Mitchell [21, Chap. 27]).

The same problem has been studied under different metrics such as the \( L_1 \) geodesic distance [7], the link distance [10, 15, 26] (where we look for the path with the minimum possible number of bends or links), or even rectilinear link distance [22, 24] (a variation
of the link distance in which only isothetic segments are allowed). The diameter and center of a simple polygon for both the $L_1$ and rectilinear link metrics can be computed in linear time (whereas $O(n \log n)$ time is needed to compute both the center and diameter under the link distance).

Another natural extension is the computation of the diameter and center in polygonal domains (i.e., polygons with one or more holes). Polynomial time algorithms are known for both the diameter [5] and center [6] under the Euclidean metric, although the running times are significantly larger (i.e., $O(n^{7.73})$ and $O(n^{12+\epsilon})$, respectively). Slightly faster algorithms exist to compute both the center and the diameter under the $L_1$ metric in polygonal domains [4].

### 1.2 Outline

In order to compute the geodesic center, $c_P$, Pollack et al. [25] introduced a linear time chord-oracle. Given a chord $C$ that splits $P$ into two sub-polygons, the oracle determines which sub-polygon contains $c_P$. Combining this operation with an efficient search on a triangulation of $P$, Pollack et al. narrow the search for $c_P$ to be within a triangle (and afterwards find the center using optimization techniques). Their approach however, does not allow them to reduce the complexity of the problem in each iteration, and hence it runs in $\Theta(n \log n)$ time.

The general approach of our algorithm described in Sect. 6 is similar: partition $P$ into $O(1)$ cells, use an oracle to determine which cell contains $c_P$, and recurse within the cell. Our approach differs, however, in two important aspects that allow us to speed-up the algorithm. First, we do not use the chords of a triangulation of $P$ to partition the problem into cells. We use instead a cutting of a suitable set of chords. Secondly, we compute a set $\Sigma$ of $O(n)$ functions, each defined in a triangular domain contained in $P$, such that their upper envelope, $\phi(x)$, coincides with $F_P(x)$. Thus, we can “ignore” the polygon $P$ and focus only on finding the minimum of the function $\phi(x)$.

The search itself uses $\epsilon$-nets and cutting techniques, which guarantee that both the size of the cell containing $c_P$ and the number of functions of $\Sigma$ defined in it decrease by a constant fraction (and thus lead to an overall linear time algorithm). However, this search has two stopping conditions, (1) reach a subproblem of constant size, or (2) find a triangle containing $c_P$. In the latter case, we show that $\phi(x)$ is a convex function when restricted to this triangle. Therefore, to find its minimum we can use standard optimization techniques based on cuttings in $\mathbb{R}^3$. This procedure is described in Sect. 7.

The key to this approach lies in the computation of the functions of $\Sigma$ and their triangular domains. Each function $g(x)$ of $\Sigma$ is defined in a triangular domain $\Delta$ contained in $P$ and is associated with a particular vertex $w$ of $P$. Intuitively speaking, $g(x)$ maps points in $\Delta$ to their (geodesic) distance to $w$. We guarantee that, for each point $x \in P$, there is one function $g$ defined in a triangle containing $x$, such that $g(x) = F_P(x)$. To compute these triangles and their corresponding functions, we proceed as follows.

In Sect. 2, we decompose the boundary of $P$, denoted by $\partial P$, into connected edge-disjoint chains. Each chain is defined by either (1) a consecutive list of vertices that
have the same farthest neighbor $v$ (we say that $v$ is marked if it has such a chain associated to it), or (2) an edge whose endpoints have different farthest neighbors (such edge is called a transition edge).

In Sect. 3, we consider each transition edge $ab$ of $\partial P$ independently and compute its hourglass. Intuitively, the hourglass of $ab$, $H_{ab}$, is the region of $P$ between two chains, the edge $ab$ and the chain of $\partial P$ that contains the farthest neighbors of all points in $ab$. Inspired by a result of Suri [27], we show that the sum of the complexities of all hourglasses defined on a transition edge is $O(n)$. (The combinatorial complexity, or simply complexity of a geometric object, is the total number of vertices and edges that define it.) In addition, we provide a new technique to compute all these hourglasses in linear time.

While the hourglasses cover a big part of $P$, to complete the coverage we need to consider funnels from each marked vertex. Intuitively, the funnel of a marked vertex $v$ is the region of $P$ that contains all the paths from $v$ to every point of $\partial P$ that is farther from $v$ than from any other vertex of $P$. In Sect. 4, we prove that the total complexity of all the funnels of all marked vertices is $O(n)$. Moreover, we provide an algorithm to compute all these funnels in linear time.

In Sect. 5 we show how to compute the functions in $\Sigma$ and their respective triangles. We distinguish two cases: (1) Inside each hourglass $H_{ab}$ of a transition edge, we use a technique introduced by Aronov et al. [2] that uses the shortest-path trees of $a$ and $b$ in $H_{ab}$ to construct $O(|H_{ab}|)$ triangles with their respective functions (for more information on shortest-path trees refer to [12]). (2) Inside the funnel of each marked vertex $v$, we compute triangles that encode the distance from $v$. Moreover, we guarantee that these triangles cover every point of $P$ whose farthest neighbor is $v$. Overall, we compute the $O(n)$ functions of $\Sigma$ in linear time.

2 Decomposing the Boundary

In this section, we decompose the boundary of $P$ into chains of consecutive vertices that share the same farthest neighbor and edges of $P$ whose endpoints have distinct farthest neighbors.

Using a result from Hershberger and Suri [14], in $O(n)$ time we can compute the farthest neighbor of each vertex of $P$. Recall that the farthest neighbor of each vertex of $P$ is always a convex vertex of $P$ [3] and is unique by our general position assumption. The (farthest) Voronoi region of a vertex $v$ of $P$ is the set of points $R(v) = \{x \in P : F_P(x) = |\pi(x, v)|\}$ (including boundary points).

We mark the vertices of $P$ that are farthest neighbors of at least one vertex of $P$. Let $M$ denote the set of marked vertices of $P$ (clearly this set can be computed in $O(n)$ time after applying the result of Hershberger and Suri). In other words, $M$ contains all vertices of $P$ whose Voronoi region contains at least one vertex of $P$.

Given a vertex $v$ of $P$, the vertices of $P$ whose farthest neighbor is $v$ appear contiguously along $\partial P$ [2]. Therefore, after computing all these farthest neighbors, we effectively split the boundary into subchains, each associated with a different vertex of $M$; see Fig. 1.
Given two points \( x \) and \( y \) on \( \partial P \), let \( \partial P(x, y) \) be the polygonal chain that starts at \( x \) and follows the boundary of \( P \) clockwise until reaching \( y \). We say that three (non-empty) disjoint sets \( A, B \) and \( C \) contained in \( \partial P \) are in *clockwise order* if \( B \subset \partial P(a, c) \) for any \( a \in A \) and any \( c \in C \). (To ease notation, we say that three points \( x, y, z \in \partial P \) are in clockwise order if \( \{x\}, \{y\} \) and \( \{z\} \) are in clockwise order).

Let \( a \) and \( b \) be the endpoints of an edge of \( \partial P \) such that \( b \) is the clockwise neighbor of \( a \) along \( \partial P \) and \( f(a) \neq f(b) \). Recall that we have computed \( f(a) \) and \( f(b) \) in the previous step and note that \( a, b, f(a), f(b) \) are in clockwise order. For any vertex \( v \in \partial P \) such that \( f(a), v, f(b) \) are in clockwise order, we know that there cannot be a vertex \( u \) of \( P \) such that \( f(u) = v \). As proved by Aronov et al. [2, Cor. 2.7.4], if there is a point \( x \) on \( \partial P \) whose farthest neighbor is \( v \), then \( x \) must lie on the open segment \((a, b)\). In other words, the Voronoi region \( R(v) \) restricted to \( \partial P \) is contained in \((a, b)\).

### 3 Hourglasses

For any polygonal chain \( C = \partial P(p_0, p_k) \), the *hourglass* of \( C \), denoted by \( H_C \), is the simple polygon contained in \( P \) bounded by \( C \), \( \pi(p_k, f(p_0)), \partial P(f(p_0), f(p_k)) \) and \( \pi(f(p_k), p_0) \); see Fig. 2. We call \( C \) and \( \partial P(f(p_0), f(p_k)) \) the *top* and *bottom* chains of \( H_C \), respectively, while \( \pi(p_k, f(p_0)) \) and \( \pi(f(p_k), p_0) \) are referred to as the *walls* of \( H_C \).

We say that the hourglass \( H_C \) is *open* if its walls are vertex-disjoint. We say that \( C \) is a *transition chain* if \( f(p_0) \neq f(p_k) \) and neither \( f(p_0) \) nor \( f(p_k) \) are interior vertices of \( C \). In particular, if an edge \( ab \) of \( \partial P \) is a transition chain, we say that it is a transition edge (see Fig. 2).

**Lemma 3.1** (Restatement of [2, Lem. 3.1.3]) *If \( C \) is a transition chain of \( \partial P \), then the hourglass \( H_C \) is an open hourglass.*

In the remainder of the paper, all the hourglasses considered are defined by a transition chain. In particular, they are open by Lemma 3.1 and their top and bottom chains are edge-disjoint.

The following lemma is depicted in Fig. 2 and is a direct consequence of the Ordering Lemma proved by Aronov et al. [2, Cor. 2.7.4].

**Lemma 3.2** *Let \( C_1, C_2, C_3 \) be three edge-disjoint transition chains of \( \partial P \) in clockwise order. Then, the bottom chains of \( H_{C_1}, H_{C_2}, \) and \( H_{C_3} \) are also edge-disjoint and are in clockwise order.*
Fig. 2 Given two edge-disjoint transition chains, their hourglasses are open and the bottom chains of their hourglasses are also edge-disjoint. Moreover, these bottom chains appear in the same cyclic order as the top chains along \( \partial P \).

Let \( \gamma \) be a geodesic path joining two points on the boundary of \( P \). We say that \( \gamma \) separates two points \( x_1 \) and \( x_2 \) of \( \partial P \) if the points of \( X = \{x_1, x_2\} \) and the endpoints of \( \gamma \) alternate along the boundary of \( P \). We also say that \( \gamma \) separates \( x_1 \) and \( x_2 \) if either of them coincides with an endpoint of \( \gamma \). We say that a geodesic path \( \gamma \) separates an hourglass \( H \) if it separates the points of its top chain from those of its bottom chain.

**Lemma 3.3** Let \( C_1, \ldots, C_r \) be edge-disjoint transition chains of \( \partial P \). Then, there is a set of \( t \leq 10 \) geodesic paths \( \gamma_1, \ldots, \gamma_t \) with endpoints on \( \partial P \) such that for each \( 1 \leq i \leq r \) there exists \( 1 \leq j \leq t \) such that \( \gamma_j \) separates \( H_{C_i} \). Moreover, this set can be computed in \( O(n) \) time.

**Proof** Aronov et al. showed that there exist four vertices \( v_1, \ldots, v_4 \) of \( P \) and geodesic paths \( \pi(v_1, v_2), \pi(v_2, v_3), \pi(v_3, v_4) \) such that for any point \( x \in \partial P \), one of these paths separates \( x \) from \( f(x) \) [2, Lem. 2.7.6]. Moreover, they show how to compute this set in \( O(n) \) time.

Let \( \Gamma = \{\pi(v_i, v_j) : 1 \leq i < j \leq 4\} \) and note that \( v_1, \ldots, v_4 \) split the boundary of \( P \) into at most four connected components. If a chain \( C_i \) is completely contained in one of these components, then one path of \( \Gamma \) separates the top and bottom chain of \( H_{C_i} \). Otherwise, some vertex \( v_j \) is an interior vertex of \( C_i \). However, because the chains \( C_1, \ldots, C_r \) are edge-disjoint, there are at most four chains in this situation. For each chain \( C_i \) containing a vertex \( v_j \), we add the geodesic path connecting the endpoints of \( C_i \) to \( \Gamma \). Therefore, \( \Gamma \) consists of at most 10 geodesic paths and each hourglass \( H_{C_i} \) has its top and bottom chain separated by some path of \( \Gamma \). Since only \( O(1) \) additional paths are computed, this can be done in linear time. \( \square \)

A chord of \( P \) is an edge joining two non-adjacent vertices \( a \) and \( b \) of \( P \) such that \( ab \subseteq P \). Therefore, a chord splits \( P \) into two sub-polygons.

**Lemma 3.4** (Restatement of [2, Lem. 3.4.3]) Let \( C_1, \ldots, C_r \) be a set of edge-disjoint transition chains of \( \partial P \) in clockwise order. Then each chord of \( P \) appears in \( O(1) \) hourglasses among \( H_{C_1}, \ldots, H_{C_r} \).

**Proof** Note that chords can appear only on walls of hourglasses. Because hourglasses are open, any chord must be an edge on exactly one wall of each of these hourglasses. Assume, for the sake of contradiction, that there exist two points \( s, t \in P \) whose chord
$st$ is in three hourglasses $HC_i$, $HC_j$ and $HC_k$ (for some $1 \leq i < j < k \leq r$) such that $s$ is visited before $t$ when going from the top chain to the bottom one along the walls of the three hourglasses. Let $s_i$ and $t_i$ be the points in the in the top and bottom chains of $HC_j$, respectively, such that $\pi(s_i, t_i)$ is the wall of $HC_j$ that contains $st$ (analogously, we define $s_k$ and $t_k$).

Because $C_i$, $C_j$, $C_k$ are in clockwise order, Lemma 3.2 implies that the bottom chains of $C_i$, $C_j$ and $C_k$ are also in clockwise order. Therefore, $C_j$ lies between $s_i$ and $s_k$ and the bottom chain of $HC_j$ lies between $t_i$ and $t_k$. That is, for each $x \in C_j$ and each $y$ in the bottom chain of $HC_j$, the geodesic path $\pi(x, y)$ is “sandwiched” between the paths $\pi(s_i, t_i)$ and $\pi(s_k, t_k)$. In particular, $\pi(x, y)$ contains $st$ for each pair of points in the top and bottom chains of $HC_j$. However, this implies that the hourglass $HC_j$ is not open—a contradiction that comes from assuming that $st$ lies in the wall of three open hourglasses, when this wall is traversed from the top chain to the bottom chain. Analogous arguments can be used to bound the total number of walls that contain the edge $st$ (when traversed in any direction) to $O(1)$.

Given two points $x$ and $y$ in $P$, let $[#x, y]$ denote the number of edges in the path $\pi(x, y)$.

**Lemma 3.5** Let $x, u, y, v$ be four vertices of $P$ in clockwise order. Given the shortest-path trees $T_x$ and $T_y$ of $x$ and $y$ in $P$, respectively, such that $T_x$ and $T_y$ can answer lowest common ancestor (LCA) queries in $O(1)$ time, we can compute the path $\pi(u, v)$ in $O(#[u, v])$ time. Moreover, all edges of $\pi(u, v)$, except perhaps one, belong to $T_x \cup T_y$.

**Proof**

Let $X$ (resp. $Y$) be the set containing the LCA in $T_x$ (resp. $T_y$) of $u$, $y$, and of $v$, $y$ (resp. $u$, $x$ and $y$). Note that the points of $X \cup Y$ lie on the path $\pi(x, y)$ and can be computed in $O(1)$ time by hypothesis; see Fig. 3. Moreover, using LCA queries, we can decide their order along the path $\pi(x, y)$ when traversing it from $x$ to $y$. (Both $X$ and $Y$ could consist of a single vertex in some degenerate situations.) Two cases arise, either (1) there is a vertex $x^* \in X$ lying after a vertex $y^* \in Y$ along $\pi(x, y)$ or (2), all vertices of $X^*$ lie before those of $Y^*$ along $\pi(x, y)$.

**Case I** If there is a vertex $x^* \in X$ lying after a vertex $y^* \in Y$ along $\pi(x, y)$, then the path $\pi(u, v)$ contains the path $\pi(y^*, x^*)$; see Fig. 4 (top). Since $x^* \in \pi(u, v)$, $\pi(u, v)$ can be partitioned into two paths $\pi(u, x^*)$ and $\pi(x^*, v)$. Note that $y^*$ lies either on $\pi(u, x^*)$ or on $\pi(x^*, v)$. Assume without loss of generality that $y^*$ lies on $\pi(u, x^*)$; otherwise swap the roles of $u$ and $v$.

![Fig. 3](image-url) The shortest-path trees $T_x$ and $T_y$ are depicted as well as the set $X$ and $Y$ as defined in the proof of Lemma 3.5
Because $y^*$ lies on $\pi(u, x^*)$, we conclude that $\pi(u, v)$ is the concatenation of the paths $\pi(u, y^*), \pi(y^*, x^*)$ and $\pi(x^*, v)$. Furthermore, these three paths are contained in $T_x \cup T_y$ as $\pi(u, x^*) \subseteq \pi(y, u)$, $\pi(v, y^*) \subseteq \pi(x, v)$, and $\pi(x^*, y^*) \subseteq \pi(x, y)$. Therefore, $\pi(u, v)$ can be computed in time proportional to the number of its edges by traversing the corresponding shortest-path trees.

**Case 2** In this case the vertices of $X$ appear before the vertices of $Y$ along $\pi(x, y)$. Let $x'$ (resp. $y'$) be the vertex of $X$ (resp. $Y$) closest to $x$ (resp. $y$). Notice that $x'$ is in fact the LCA in $T_x$ of $u$ and $v$ as $u$, $y$ and $v$ are in clockwise order. Analogously, $y'$ is the LCA in $T_y$ of $u$ and $v$.

Let $u'$ be the last vertex of $\pi(u, x)$ that is also in $\pi(u, y)$ (maybe $u$ itself). Therefore, $\pi(u', x)$ and $\pi(u', y)$ coincide only at $u'$. Note that $u'$ can be constructed by walking from $u'$ toward $x$ until the path towards $y$ diverges. Thus, $u'$ can be computed in $O(\#[u, u'])$ time. Define $v'$ analogously and compute it in $O(\#[v, v'])$ time.

Because $u' \in \pi(u, x) \cap \pi(u, v)$ by definition and since $y$, $v$ and $x$ are in clockwise order, the path $\pi(u, v)$ contains $u'$. Analogously, we know the path $\pi(u, v)$ contains $v'$. Therefore, the path $\pi(u, v)$ is the union of $\pi(u, u')$, $\pi(u', v')$ and $\pi(v', v)$. Because $\pi(u, u')$ and $\pi(v', v)$ can be computed in time proportional to the number of their edges, it suffices to compute $\pi(u', v')$ in $O(\#[u', v'])$ time.

Let $P'$ be the polygon bounded by the geodesic paths $\pi(x', u'), \pi(u', y'), \pi(y', v')$ and $\pi(v', x')$. By the definitions of $x'$, $y'$, $u'$ and $v'$, and since the vertices of $X$ appear before the vertices of $Y$ along $\pi(x, y)$, we know the four paths bounding $P'$ are pairwise interior disjoint, i.e., $P'$ is a simple polygon; see Fig. 4 (bottom). We claim that $P'$ is a pseudo-quadrilateral with only four convex vertices being $x', u', y'$ and $v'$. To show this, recall that each path bounding $P'$ is a shortest path. Thus, the path $\pi(x', u')$ contains only reflex vertices of $P'$; otherwise, the shortest path from $x'$ to $u'$ restricted to $P'$ would be shorter than $\pi(x', u')$ which is a contradiction as $P' \subseteq P$. Thus, each interior vertex of the path $\pi(x', u')$ is a reflex vertex of $P'$. The same argument holds for each of the other three paths bounding $P'$. Therefore, $P'$ is a simple pseudo-quadrilateral with $x'$, $u'$, $y'$ and $v'$ as its four convex vertices.

![Fig. 4](image-url) (Top) Case 1 of the proof of Lemma 3.5 where the path $\pi(u, v)$ contains a portion of the path $\pi(x, y)$. (Bottom) Case 2 of the proof of Lemma 3.5 where the path $\pi(u, v)$ has exactly one edge being the tangent of the paths $\pi(u', y')$ and $\pi(v', x')$. 
Consequently, the shortest path from \( u' \) to \( v' \) can have at most one diagonal edge connecting distinct reflex chains of \( P' \). Since the rest of the points in \( \pi(u', v') \) lie on the boundary of \( P' \) and because each edge of \( P' \) is an edge of \( T_x \cup T_y \), we conclude all edges of \( \pi(u, v) \), except perhaps one, belong to \( T_x \cup T_y \). In fact, this was already shown by Suri [27, Lem. 4].

We want to find the common tangent from either \( \pi(u', x') \) or \( \pi(u', y') \) to either \( \pi(v', x') \) or \( \pi(v', y') \) that belongs to the shortest path \( \pi(u', v') \). Assume that the desired tangent lies between the paths \( \pi(u', x') \) and \( \pi(v', y') \), we consider the other three possible cases later. Since these paths consist only of reflex vertices, the problem can be reduced to finding the common tangent of two convex polygons. By slightly modifying the linear time algorithm to compute this tangent, we can make it run in \( O(\#[u', v']) \) time.

Since we do not know if the tangent lies between the paths \( \pi(u', x') \) and \( \pi(v', y') \), we process the four pairs of paths in parallel and stop when finding the desired tangent. Therefore, we can compute \( \pi(u', v') \) in \( O(\#[u', v']) \) time and consequently, we can compute \( \pi(u, v) \) in \( O(\#[u, v]) \) time.

\[\square\]

**Lemma 3.6** Let \( P \) be a simple polygon with \( n \) vertices. Given \( k \) disjoint transition chains \( C_1, \ldots, C_k \) of \( \partial P \), it holds that

\[\sum_{i=1}^{k} |H_{C_i}| = O(n).\]

**Proof** Because the given transition chains are disjoint, Lemma 3.2 implies that the bottom chains of their respective hourglasses are also disjoint. Therefore, the sum of the complexities of all the top and bottom chains of these hourglasses is \( O(n) \). To bound the complexity of their walls we use Lemma 3.4. Since no chord is used more than a constant number of times, it suffices to show that the total number of chords used by all these hourglasses is \( O(n) \).

To prove this, we use Lemma 3.3 to construct \( O(1) \) paths \( \gamma_1, \ldots, \gamma_t \) such that for each \( 1 \leq i \leq k \), there is a path \( \gamma_j \) that separates the top and bottom chains of \( H_{C_i} \). For each \( 1 \leq j \leq t \), let

\[\mathcal{H}^j = \{H_{C_j} \text{ : the top and bottom chain of } H_{C_i} \text{ are separated by } \gamma_j \}.\]

Since the complexity of the shortest-path trees of the endpoints of \( \gamma_j \) is \( O(n) \) [12], and from the fact that the chains \( C_1, \ldots, C_k \) are disjoint, Lemma 3.5 implies that the total number of edges in all the hourglasses of \( \mathcal{H}^j \) is \( O(n) \). Moreover, because each of these edges appears in \( O(1) \) hourglasses among \( C_1, \ldots, C_k \), we conclude that

\[\sum_{H \in \mathcal{H}^j} |H| = O(n).\]

Since we have only \( O(1) \) separating paths, our result follows. \[\square\]
3.1 Building Hourglasses

Let $E$ be the set of transition edges of $\partial P$. Given a transition edge $ab \in E$, we say that $H_{ab}$ is a transition hourglass. In order to construct the triangle cover of $P$, we construct the transition hourglass of each transition edge of $E$. By Lemma 3.6, we know that $\sum_{ab \in E} |H_{ab}| = O(n)$. Therefore, our aim is to compute the cover in time proportional to the size of $H_{ab}$.

By Lemma 3.3 we can compute a set $\Gamma$ of $O(1)$ paths such that for any transition edge $ab$, the transition hourglass $H_{ab}$ is separated by one (or more) paths in this set. For each endpoint of the $O(1)$ paths of $\Gamma$, we compute its shortest-path tree in linear time LCA queries [13]. Both computations need linear time per endpoint and use $O(n)$ space. Since we do this process for a constant number of endpoints, overall this preprocessing takes $O(n)$ time.

Let $\gamma \in \Gamma$ be a separating path. Note that $\gamma$ separates the boundary of $P$ into two chains $S_\gamma$ and $S_\gamma'$ such that $S_\gamma \cup S_\gamma' = \partial P$. Let $H(\gamma)$ be the set of transition hourglasses separated by $\gamma$ whose transition edge is contained in $S_\gamma$ (whenever an hourglass is separated by more than one path, we pick one arbitrarily). Note that we can classify all transition hourglasses into their corresponding sets $H(\gamma)$ in $O(n)$ time (since $|\Gamma| = O(1)$).

**Lemma 3.7** Given a separating path $\gamma \in \Gamma$, it holds that $\sum_{H \in H(\gamma)} |H| = O(n)$. Moreover, we can compute all transition hourglasses of $H(\gamma)$ in $O(n)$ time.

**Proof** Since all transition hourglasses in $H$ are defined from disjoint transition edges, Lemma 3.6 implies that $\sum_{H \in H(\gamma)} |H| = O(n)$.

By construction, each wall of these hourglasses consists of a (geodesic) path that connects a point in $S_\gamma$ to a point in $S_\gamma'$. Let $u \in S_\gamma$ and $v \in S_\gamma'$ be two vertices such that $\pi(u, v)$ is the wall of a hourglass in $H(\gamma)$. Because LCA queries can be answered in $O(1)$ time, Lemma 3.5 allows us to compute this path in $O(#\{u, v\})$ time. Therefore, we can compute all hourglasses of $H(\gamma)$ in $O(\sum_{H \in H(\gamma)} |H| + n) = O(n)$ time.

Because $|\Gamma| = O(1)$ and since every transition hourglass is separated by at least one path in $\Gamma$, we obtain the following result.

**Corollary 3.8** The total complexity of the transition hourglasses of all transition edges of $P$ is $O(n)$. Moreover, all these hourglasses can be constructed in $O(n)$ time.

4 Funnels

Let $C = (p_0, \ldots, p_k)$ be a chain of $\partial P$ and let $v$ be a vertex of $P$ not in $C$. The funnel of $v$ to $C$, denoted by $S_v(C)$, is the simple polygon bounded by $C, \pi(p_k, v)$ and $\pi(v, p_0)$; see Fig. 5a. Note that the paths $\pi(v, p_k)$ and $\pi(v, p_0)$ may coincide for a while before splitting into disjoint chains. We call $C$ the main chain of $S_v(C)$ while $\pi(p_k, v)$ and $\pi(v, p_0)$ are referred to as the walls of the funnel. See Lee and Preparata [16] or Guibas et al. [12] for more details on funnels.
A subset $R \subset P$ is geodesically convex if for every $x, y \in R$, the path $\pi(x, y)$ is contained in $R$. This funnel $S_v(C)$ is then the inclusion-wise smallest geodesically convex set that contains $v$ and $C$.

Given two points $x, y \in P$, the (geodesic) bisector of $x$ and $y$ is the set of points contained in $P$ that are equidistant from $x$ and $y$. This bisector is a curve, contained in $P$, that consists of straight-line segments and hyperbolic arcs. Moreover, this curve intersects $\partial P$ only at its endpoints [1, Lem. 3.22].

**Lemma 4.1** Let $v$ be a vertex of $P$ and let $C$ be a transition chain such that $R(v) \cap \partial P \subset C$ and $v \notin C$. Then $R(v)$ is contained in the funnel $S_v(C)$.

**Proof** Let $a$ and $b$ be the endpoints of $C$ such that $a, b, f(a)$ and $f(b)$ are in clockwise order. Because $R(v) \cap \partial P \subset C$, we know that $f(a)$, $v$ and $f(b)$ are in clockwise order by Lemma 3.2. Moreover, we also know that $|\pi(a, v)| < |\pi(a, f(a))|$ and $|\pi(b, v)| < |\pi(b, f(b))|$ as $a, b \notin R(v)$.

Assume for a contradiction that there is a point of $R(v)$ lying outside of $S_v(C)$. Since $R(v) \cap \partial P \subset C$ and by continuity, the boundaries of $R(v)$ and $S_v(C)$ must intersect at a point $w$ not in $\partial P$. Recall that the boundary of $S_v(C)$ is exactly the union of $C$ and the paths $\pi(v, a)$ and $\pi(v, b)$. Therefore, $w$ lies in either $\pi(v, a)$ or $\pi(v, b)$. Assume without loss of generality that $w \in \pi(v, b)$, the case where $w$ lies in $\pi(v, a)$ is analogous. Because $w \in \pi(v, b)$, we know that $|\pi(b, w)| + |\pi(w, v)| = |\pi(b, v)|$.

Moreover, since $w \in R(v)$, we know that $|\pi(w, f(b))| \leq |\pi(w, v)|$.

By the triangle inequality and since $w \notin \partial P$, we get that

$$|\pi(b, f(b))| \leq |\pi(b, w)| + |\pi(w, f(b))| \leq |\pi(b, w)| + |\pi(w, v)| = |\pi(b, v)|.$$

However, we knew that $|\pi(b, v)| < |\pi(b, f(b))|$—a contradiction that comes from assuming that $R(v)$ is not contained in $S_v(C)$. \qed

### 4.1 Funnels of Marked Vertices

Recall that for each marked vertex $v \in M$, we know of at least one vertex on $\partial P$ such that $v$ is its farthest neighbor. Let $u_1, \ldots, u_{k-1}$ be the vertices of $P$ such that $v = f(u_i)$ and assume that $u_1, \ldots, u_{k-1}$ are in clockwise order. Let $u_0$ and $u_k$ be the
neighbors of \( u_1 \) and \( u_{k-1} \) other than \( u_2 \) and \( u_{k-2} \), respectively. Note that both \( u_0u_1 \) and \( u_{k-1}u_k \) are transition edges of \( P \). Let \( C_v = (u_0, \ldots, u_k) \) and consider the funnel \( S_v(C_v) \) defined by \( v \).

**Lemma 4.2** Let \( x \) be a point in \( P \). If \( f(x) = v \) for some marked vertex \( v \in M \), then \( x \in S_v(C_v) \).

**Proof** Since \( f(u_0) \neq f(u_k) \), \( C_v \) is a transition chain. Moreover, \( C_v \) contains \( R(v) \cap \partial P \) by definition. Therefore, Lemma 4.1 implies that \( R(v) \subset S_v(C_v) \). Since \( v = f(x) \), we know that \( x \in R(v) \) and hence that \( x \in S_v(C_v) \). \( \square \)

We focus now on computing the funnels defined by the marked vertices of \( P \).

**Lemma 4.3** Given a marked vertex \( v \) such that \( C_v = (u_0, \ldots, u_k) \), it holds that \( |S_v(C_v)| = O(k + |H_{u_0u_1}| + |H_{u_{k-1}u_k}|) \). Moreover, \( S_v(C_v) \) can be computed in \( O(|S_v(C_v)|) \) time assuming that the transition hourglasses \( H_{u_0u_1} \) and \( H_{u_{k-1}u_k} \) have already been computed.

**Proof** Because \( v = f(u_1) = f(u_{k-1}) \), we know that \( v \) is a vertex of both \( H_{u_0u_1} \) and \( H_{u_{k-1}u_k} \). By definition, we have \( \pi(v, u_0) \subset H_{u_0u_1} \) and \( \pi(v, u_k) \subset H_{u_{k-1}u_k} \). Thus, we can compute both paths \( \pi(v, u_0) \) and \( \pi(v, u_k) \) in \( O(|H_{u_0u_1}| + |H_{u_{k-1}u_k}|) \) time [12] and their complexities are \( O(|H_{u_0u_1}|) \) and \( O(|H_{u_{k-1}u_k}|) \), respectively. So, overall, the funnel \( S_v(C_v) \) has total complexity \( O(k + |H_{u_0u_1}| + |H_{u_{k-1}u_k}|) \) and can be constructed in linear time in its size. \( \square \)

Recall that, by Corollary 3.8, the total sum of the complexities of all transition hourglasses is \( O(n) \). Therefore, Lemma 4.3 implies that

\[
\sum_{v \in M} |S_v(C_v)| = O(n + \sum_{ab \in E} |H_{ab}|) = O(n).
\]

Because the funnel of each marked vertex can be computed in linear time in its size, we obtain the following result.

**Corollary 4.4** The total complexity of the funnels of all marked vertices of \( P \) is \( O(n) \). Moreover, all these funnels can be constructed in \( O(n) \) time.

## 5 Covering the Polygon with Apexed Triangles

An **apexed triangle** \( \Delta = (a, b, c) \) with apex \( a \) is a triangle contained in \( P \) with an associated distance function \( g_\Delta(x) \), called the **apex function** of \( \Delta \), such that (1) \( a \) is a vertex of \( P \), (2) there is an edge of \( \partial P \) containing both \( b \) and \( c \), and (3) there is a vertex \( w \) of \( P \), called the **definer** of \( \Delta \), such that

\[
g_\Delta(x) = \begin{cases} -\infty & \text{if } x \notin \Delta, \\ |xa| + |\pi(a, w)| = |\pi(x, w)| & \text{if } x \in \Delta. \end{cases}
\]

Intuitively, \( \Delta \) bounds a constant complexity region in which the geodesic distance function from \( w \) is explicitly stored by our algorithm.
In this section, we show how to find a set of $O(n)$ apexed triangles of $P$ such that the upper envelope of their apex functions coincides with $F_p(x)$. To this end, we first decompose the transition hourglasses into apexed triangles that encode all the geodesic distance information inside them. For each marked vertex $v \in M$ we construct a funnel that contains the Voronoi region of $v$. We then decompose this funnel into apexed triangles that encode the distance from $v$.

The same approach was already used by Pollack et al. [25, Sect. 3] for a segment contained in the interior of $P$. They show how to compute a linear number of apexed triangles such that $F_p(x)$ coincides with the upper envelope of the corresponding apex functions in the given segment.

While the construction we follow is analogous, we use it in each transition hourglass $H_{ab}$ instead of the full polygon $P$. Therefore, we have to specify what is the relation between the upper envelope of the computed functions and $F_p(x)$. We will show that the upper envelope of the apex functions computed in $H_{ab}$ coincides with $F_p(x)$ inside the Voronoi region $R(v)$ of every vertex $v$ in the bottom chain of $H_{ab}$.

## 5.1 Inside a Transition Hourglass

Let $ab$ be a transition edge of $P$ such that $b$ is the clockwise neighbor of $a$ along $\partial P$. Let $B_{ab}$ denote the open bottom chain of $H_{ab}$. As noticed above, a point on $\partial P$ can be farthest from a vertex in $B_{ab}$ only if it lies in the open segment $ab$. That is, if $v$ is a vertex of $B_{ab}$ such that $R(v) \neq \emptyset$, then $R(v) \cap \partial P \subset ab$.

In fact, not only this Voronoi region is inside $H_{ab}$ when restricted to the boundary of $P$, but we can further bound its location and show that $R(v) \subset H_{ab}$. The next result follows trivially from Lemma 4.1.

**Corollary 5.1** Let $v$ be a vertex of $B_{ab}$. Then $R(v) \subset H_{ab}$.

Our objective is to compute $O(|\partial H_{ab}|)$ apexed triangles contained in $H_{ab}$, each with its distance function, such that the upper envelope of these apex functions coincides with $F_p(x)$ restricted to $H_{ab}$ inside the Voronoi region of every vertex in $B_{ab}$.

Let $T_a$ and $T_b$ be the shortest-path trees in $H_{ab}$ rooted at $a$ and $b$, respectively. We can compute these trees in $O(|\partial H_{ab}|)$ time [12]. For each vertex $v$ such that $f(a), v$ and $f(b)$ are in clockwise order, let $v_a$ and $v_b$ be the neighbors of $v$ in the paths $\pi(v, a)$ and $\pi(v, b)$, respectively. We say that a vertex $v$ is visible from $ab$ if $v_a \neq v_b$. Since $v_a \neq v_b$, the paths $\pi(v, a)$ and $\pi(v, b)$ are interior disjoint. Therefore, the funnel $S_v(ab)$ bounded by these paths and the segment $ab$ is a pseudo-triangle with $a$, $b$ and $v$ as its only convex vertices (if $S_v(ab)$ had any other convex vertex, we could take a shortcut and find a shorter path between $a$ and $v$ or between $b$ and $v$). Since $ab$ is a side of $S_v(ab)$, we infer that $v_a$ and $v_b$ lie in the (straight-line) triangle $\triangle(a, b, v)$.

Thus, if vertex $v$ is visible, then the extension of the segments $vv_a$ and $vv_b$ must intersect the top segment $ab$ at points $x_a$ and $x_b$, respectively. Therefore, for each visible vertex $v$, we obtain a (straight-line) triangle $\triangle_v = \triangle(v, x_a, x_b)$ as shown in Fig. 6.

We further split $\triangle_v$ into a series of triangles with apex at $v$ as follows: Let $u$ be a child of $v$ in either $T_a$ or $T_b$. As noted by Pollack et al. [25], $u$ can be of three types,
either (1) $u$ is not visible from $ab$ (and is hence a child of $v$ in both $T_a$ and $T_b$); or (2) $u$ is visible from $ab$, is a child of $v$ only in $T_b$, and $v_bvu$ is a left turn; or (3) $u$ is visible from $ab$, is a child of $v$ only in $T_a$, and $v_avu$ is a right turn.

Let $u_1, \ldots, u_{k-1}$ be the children of $v$ of type (2) sorted in clockwise order around $v$. Let $c(v)$ be the maximum distance from $v$ to any invisible vertex in the subtrees of $T_a$ and $T_b$ rooted at $v$; if no such vertex exists, then $c(v) = 0$. Define a function $d_l(v)$ on each vertex $v$ of $H_{ab}$ in a recursive fashion as follows: If $v$ is invisible from $ab$, then $d_l(v) = c(v)$. Otherwise, let $d_l(v)$ be the maximum of $c(v)$ and $\max \{d_l(u_i) + |u_iv| : u_i$ is a child of $v$ of type (2)$. Symmetrically, we define a function $d_r(v)$ using the children of type (3) of $v$.

For each $1 \leq i \leq k - 1$, extend the segment $u_iv$ past $v$ until it intersects $ab$ at a point $s_i$. Let $s_0$ and $s_k$ be the intersections of the extensions of $vv_a$ and $vv_b$ with the segment $ab$. We define then $k$ apexed triangles contained in $\triangle_v$ as follows. For each $0 \leq i \leq k - 1$, consider the triangle $\triangle(s_i, v, s_{i+1})$ whose associated apexed (left) function is

$$f_i(x) = \begin{cases} |xv| + \max_{j>i} \{c(v), |vu_j| + d_l(u_j)\} & \text{if } x \in \triangle(s_i, v, s_{i+1}), \\ -\infty & \text{otherwise.} \end{cases}$$

In a symmetric manner, we define a set of apexed triangles induced by the type (3) children of $v$ and their respective apexed (right) functions.

Let $g_1, \ldots, g_r$ and $\triangle_1, \ldots, \triangle_r$ respectively be an enumeration of all the generated apex functions and apexed triangles such that $g_i$ is defined in the triangle $\triangle_i$. Because each function is determined uniquely by a pair of adjacent vertices in $T_a$ or in $T_b$, and since these trees have $O(|H_{ab}|)$ vertices each, we conclude that $r = O(|H_{ab}|)$.

Note that for each $1 \leq i \leq r$, the apexed triangle $\triangle_i$ has two vertices on the segment $ab$ and a third vertex, say $a_i$, being its apex such that for each $x \in \triangle_i$, $g_i(x) = |\pi(x, w_i)|$ for some vertex $w_i$ of $H_{ab}$. Recall that $w_i$ is called the definer of $\triangle_i$.

**Lemma 5.2** Given a transition edge $ab$ of $P$, we can compute a set $A_{ab}$ of $O(|H_{ab}|)$ apexed triangles in $O(|H_{ab}|)$ time with the property that for any point $p \in P$ such that $f(p) \in B_{ab}$, there is an apexed triangle $\triangle \in A_{ab}$ with apex function $g$ and definer equal to $f(p)$ such that
1. \( p \in \triangle \) and
2. \( g(p) = F_p(p) \).

**Proof** Let \( p \in P \) such that \( f(p) \in B_{ab} \) and let \( A_{ab} \) be the set of apexed triangles computed in \( H_{ab} \) by the above procedure. We claim that \( p \) lies inside an apexed triangle of \( A_{ab} \). To show this, note that since \( p \in R(f(p)) \), Corollary 5.1 implies that \( p \in H_{ab} \). Consider the path \( \pi(p, f(p)) \) and let \( v \) be the successor of \( p \) along this path. Because \( p \in R(f(p)) \), the ray shooting from \( v \) towards \( p \) stays within \( R(f(p)) \) until hitting the boundary of \( P \) as shown by [2, Lem. 2.6.6]. Consequently, this ray must intersect the segment \( ab \) which implies that \( v \) is visible from \( ab \). Therefore, \( p \) lies inside \( \triangle \) and hence it is contained in one of the apex triangles defined by \( v \) during the construction of \( A_{ab} \). That is, there is an apexed triangle \( \triangle \in A_{ab} \) with apex \( v \) and definer \( f(p) \) that contains \( p \).

Since the apex function of \( \triangle \) encodes the geodesic distance to a vertex of \( P \) and because \( F_p(x) \) is the upper envelope of all the geodesic functions, we know that \( g(p) \leq F_p(p) \).

To prove the other inequality, note that if \( v = f(p) \), then trivially \( g(p) = |pv| + |\pi(v, w)| \geq |pv| = |\pi(p, f(p))| = F_p(p) \). Otherwise, let \( z \) be the next vertex after \( v \) in the path \( \pi(p, f(p)) \). Three cases arise:

(a) If \( z \) is invisible from \( ab \), then so is \( f(p) \) and hence,

\[
|\pi(p, f(p))| = |pv| + |\pi(v, f(p))| \leq |pv| + c(v) \leq g(p).
\]

(b) If \( z \) is a child of type (2), then \( z \) plays the role of some child \( u_j \) of \( v \) in the notation used during the construction. In this case:

\[
|\pi(p, f(p))| = |pv| + |vz| + |\pi(z, f(p))| \leq |pv| + |vu_j| + d_l(u_j) \leq g(p).
\]

(c) If \( z \) is a child of type (3), then analogous arguments hold using the (right) distance \( d_r \).

Therefore, regardless of the case \( F_p(p) = |\pi(p, f(p))| \leq g(p) \).

To bound the running time, note that the recursive functions \( d_l \), \( d_r \) and \( c \) can be computed in \( O(|T_a| + |T_b|) \) time. Then, for each vertex visible from \( ab \), we can process it in time proportional to its degree in \( T_a \) and \( T_b \). Because the sum of the degrees of all vertices in \( T_a \) and \( T_b \) is \( O(|T_a| + |T_b|) \) and from the fact that both \( |T_a| \) and \( |T_b| \) are \( O(|H_{ab}|) \), we conclude that the total running time to construct \( A_{ab} \) is \( O(|H_{ab}|) \). \( \square \)

In other words, Lemma 5.2 says that no information on farthest neighbors is lost if within \( H_{ab} \) we consider only the functions of \( A_{ab} \). In the next section we use a similar approach to encode distances to marked vertices.

### 5.2 Inside the Funnels of Marked Vertices

We now proceed to split a given funnel into \( O(|S_v(C_v)|) \) apexed triangles that encode the distance function from \( v \). To this end, we use the algorithm described by Guibas et al. [12, Sect. 2] to compute the shortest-path map of \( v \) in \( S_v(C_v) \) in \( O(|S_v(C_v)|) \).
time. This algorithm produces a partition of $S_v(C_v)$ into $O(|S_v(C_v)|)$ interior disjoint triangles with vertices on $\partial P$, such that each triangle consists of all points in $S_v(C_v)$ whose shortest path to $v$ consists of the same sequence of vertices; see Fig. 5b. Let $\Delta$ be a triangle in this partition and let $a$ be its apex, i.e., the first vertex found along each path $\pi(x,v)$, where $x \in \Delta$. We define the apex function $g_\Delta(x)$ of $\Delta$ as follows:

$$g_\Delta(x) = \begin{cases} |xa| + |\pi(a, v)| & \text{if } x \in \Delta, \\ -\infty & \text{otherwise.} \end{cases}$$

Notice that for each $x \in \Delta$, $g_\Delta(x) = |\pi(x, v)|$.

Lemma 5.3 The shortest-path map of $v$ in $S_v(C_v)$ can be computed in $O(|S_v(C_v)|)$ time and produces $O(|S_v(C_v)|)$ interior disjoint apexed triangles such that their union covers $S_v(C_v)$. Moreover, for each point $x \in R(v)$, there is an apexed triangle $\Delta$ with apex function $g(x)$ such that (1) $x \in \Delta$ and (2) $g(x) = |\pi(x, v)| = F_P(x)$. Thus, we obtain properties (1) and (2).

**Proof** The above procedure splits $S_v(C_v)$ into $O(|S_v(C_v)|)$ apexed triangles, such that the apex function in each of them is defined as the geodesic distance to $v$. By Lemma 4.2, if $x \in R(v)$, then $x \in S_v(C_v)$. Therefore, there is an apexed triangle $\Delta$ with apex function $g(x)$ such that $x \in \Delta$ and $g(x) = |\pi(x, v)| = F_P(x)$. Thus, we obtain properties (1) and (2). $\square$

6 Prune and Search

With the tools introduced in the previous sections, we can describe the prune and search algorithm to compute the geodesic center. The idea of the algorithm is to partition $P$ into $O(1)$ cells, determine in which cell of $P$ the center lies and recurse on that cell as a new subproblem with smaller complexity.

Once we find the cell $R$ that contains the center, we can discard all apexed triangles that do not intersect $R$. Using cuttings to produce this partition of $P$, we can show that both the complexity of $R$, and the number of apexed triangles that intersect it decrease by a constant fraction in each iteration of the algorithm. This process is then repeated until either of the two objects has constant descriptive size.

Let $\tau$ be the set of all apexed triangles computed in previous sections. Corollary 3.8 and Lemma 5.2 bound the number of apexed triangles constructed inside the transition hourglasses, while Corollary 4.4 and Lemma 5.3 do so inside the funnels of the marked vertices. We obtain the following.

**Corollary 6.1** The set $\tau$ consists of $O(n)$ apexed triangles.

Let $\phi(x)$ be the upper envelope of the apex functions of the triangles in $\tau$ (i.e., $\phi(x) = \max\{g(x) : \Delta \in \tau$ and $g(x)$ is the apex function of $\Delta\}$). The following result is a direct consequence of Lemmas 5.2 and 5.3, and shows that the $O(n)$ apexed triangles of $\tau$ not only cover $P$, but their apex functions suffice to reconstruct the function $F_P(x)$.

**Corollary 6.2** The functions $\phi(x)$ and $F_P(x)$ coincide in the domain of points of $P$, i.e., for each $p \in P$, $\phi(p) = F_P(p)$.  

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Given a chord \( C \) of \( P \), a half-polygon of \( P \) is one of the two simple polygons in which \( C \) splits \( P \). A \( k \)-cell of \( P \) is a simple polygon obtained as the intersection of at most \( k \) half-polygons. Because a \( k \)-cell is the intersection of geodesically convex sets, it is also geodesically convex.

The recursive algorithm described in this section takes as input a 4-cell (initially equal to \( P \)) containing the geodesic center of \( P \) and the set of apexed triangles of \( \tau \) that intersect it. In each iteration, it produces a new 4-cell of smaller complexity that intersects just a fraction of the apexed triangles and contains the geodesic center of \( P \). By recursing on this new cell, the complexity of the problem is reduced in each iteration.

Let \( R \) be a 4-cell of \( P \) (initially equal to \( P \)) containing the geodesic center of \( P \) and let \( \tau_R \) be the set of apexed triangles of \( \tau \) that intersect \( R \). Let \( m_R = \max\{|R|, |\tau_R|\} \), where \( |R| \) denotes the combinatorial complexity of \( R \).

Let \( C_R \) be the set containing all chords that belong to the boundary of a triangle of \( \tau_R \). Recall that, by construction of the apexed triangles, for each triangle of \( \tau_R \) at least one and at most two of its boundary segments are chords of \( P \). Therefore, \( |C_R| \leq 2|\tau_R| \leq 2m_R \).

To construct \( \varepsilon \)-nets, we need some definitions (for more information on \( \varepsilon \)-nets refer to [17]). Let \( \phi \) be the set of all open 4-cells of \( P \). For each \( t \in \phi \), let \( C_{R}(t) = \{ C \in C_R : C \cap t \neq \emptyset \} \) be the set of chords of \( C_R \) induced by \( t \). Finally, let \( \varphi_{C_R} = \{ C_{R}(t) : t \in \phi \} \) be the family of subsets of \( C_R \) induced by \( \varphi \). Consider the set system \((C_R, \varphi_{C_R})\) (denoted by \((C_R, \varphi)\) for simplicity) defined by \( C_R \) and \( \varphi \). The proof of the next lemma is deferred to the Appendix for ease of readability.

**Lemma 6.3** The set system \((C_R, \varphi)\) has constant VC-dimension.

Let \( \varepsilon > 0 \) be a sufficiently small constant whose exact value will be specified later. Because of Lemma 6.3, we can compute an \( \varepsilon \)-net \( N \) of \((C_R, \varphi)\) in \( O(|C_R|/\varepsilon) = O(m_R) \) time [17]. The size of \( N \) is \( O(\frac{1}{\varepsilon} \log \frac{1}{\varepsilon}) = O(1) \) and its main property is that any 4-cell that does not intersect a chord of \( N \) will intersect at most \( \varepsilon|C_R| \) chords of \( C_R \).

Observe that \( N \) partitions \( R \) into \( O(1) \) sub-polygons (not necessarily 4-cells). We further refine this partition to obtain 4-cells. That is, we shoot vertical rays up and down from each endpoint of \( N \), and from the intersection point of any two segments of \( N \), see Fig. 7. Overall, this partitions \( R \) into \( O(1) \) 4-cells such that each either (i) is a convex polygon contained in \( P \) of at most four vertices, or otherwise (ii) contains some chain of \( \partial P \). Since \( |N| = O(1) \), the whole decomposition can be computed in \( O(m_R) \) time (the intersections between segments of \( N \) are done in constant time, and for the ray shooting operations we walk along the boundary of \( R \) once).

Fig. 7 The \( \varepsilon \)-net \( N \) splits \( R \) into \( O(1) \) sub-polygons that are further refined into a 4-cell decomposition using \( O(1) \) ray-shooting queries from the vertices of the arrangement defined by \( N \)
In order to determine which 4-cell contains the geodesic center of $P$, we extend each edge of a 4-cell to a chord $C$. This can be done with two ray-shooting queries (each of which takes $O(m_R)$ time). We then use the chord-oracle from Pollack et al. [25, Sect. 3] to decide which side of $C$ contains $c_P$. The only requirement of this technique is that the function $F_P(x)$ coincides with the upper envelope of the apex functions when restricted to $C$. This holds by Corollary 6.2 and from the fact that $\tau_R$ consists of all the apexed triangles of $\tau$ that intersect $R$.

Because the chord-oracle described by Pollack et al. [25, Sect. 3] runs in time linear in the number of functions defined on $C$, we can decide in total $O(m_R)$ time in which side of $C$ the geodesic center of $P$ lies. Since our decomposition into 4-cells has constant complexity, we need to perform $O(1)$ calls to the oracle before determining the 4-cell $R'$ that contains the geodesic center of $P$.

Note that the chord-oracle computes the minimum of $F_P(x)$ restricted to the chord before determining the side containing the minimum. In particular, if $c_P$ lies on any chord bounding $R'$, then the chord-oracle will find it. Therefore, we can assume that $c_P$ lies in the interior of $R'$. Moreover, since $N$ is an $\epsilon$-net, we know that at most $\epsilon|C_R|$ chords of $C_R$ intersect $R'$.

In order to proceed with the algorithm on $R'$ recursively, we need to prune the apexed triangles that do not intersect with $R'$. For each apexed triangle $\triangle \in \tau_R$, we can determine in constant time if it intersects $R'$ (either one of the endpoints is in $R' \cap \partial P$ or the two boundaries have non-empty intersection in the interior of $P$). Overall, we need $O(m_R)$ time to compute the at most $\epsilon|C_R|$ triangles of $\tau_R$ that intersect $R'$.

Observe that both the complexity of $R'$ and $\tau_{R'}$ decrease by a constant fraction. Indeed, by construction of the cutting at most $2\epsilon m_R$ apexed triangles can intersect $R'$ (and thus $|\tau_{R'}| \leq 2\epsilon m_R$). In order to bound the complexity of $R'$ we use Corollary 6.2: function $F_P(x)$ is defined in each point of $R'$, and in particular for each vertex $v$ of $R'$ there must exist an apexed triangle $\Delta \in \tau_{R'}$ such that $v \in \Delta$. By definition of apexed triangles, each such triangle can contain at most three vertices of $R'$. Combining this fact with the bound of $|\tau_{R'}|$ we obtain that $R'$ has at most $3|\tau_{R'}| \leq 6\epsilon m_R$ vertices. Thus, if we choose $\epsilon = 1/12$, we guarantee that both the size of the 4-cell $R'$ and the number of apexed triangles in $\tau_{R'}$ are at most $m_R/2$.

By recursing on $R'$, we guarantee that after $O(\log m_R)$ iterations, we reduce the size of either $\tau_R$ or $R'$ to constant. In the former case, the minimum of $F_P(x)$ can be found by explicitly constructing function $\phi$ in $O(1)$ time. In the latter case, we triangulate $R'$ and apply the chord-oracle to determine which triangle will contain $c_P$.

The details needed to find the minimum of $\phi(x)$ inside this triangle are given in the next section.

**Lemma 6.4** In $O(n)$ time we can find either the geodesic center of $P$ or a triangle inside $P$ that contains the geodesic center.

### 7 Finding the Center Within a Triangle

In order to complete the algorithm it remains to show how to find the geodesic center of $P$ for the case in which $R'$ is a triangle inside $P$. If this triangle is in the interior of $P$, it may happen that several apexed triangles of $\tau$ (up to a linear number) fully
contain $R'$. Thus, the pruning technique used in the previous section cannot be further applied. We solve this case with a different approach.

Recall that $\phi(x)$ denotes the upper envelope of the apex functions of the triangles in $\tau$, and the geodesic center is the point that minimizes $\phi$. The key observation is that, as with chords, the function $\phi(x)$ restricted to $R'$ is convex.

Let $\tau_{R'} = \{ \Delta_1, \Delta_2, \ldots, \Delta_m \}$ be the set of $m = O(n)$ apexed triangles of $\tau$ that intersect $R'$. Let $a_i$ and $w_i$ be the apex and the definer of $\Delta_i$, respectively. Let $g_i(x)$ be the apex function of $\Delta_i$ such that

$$g(x) = \begin{cases} |xa_i| + \kappa_i & \text{if } x \in \Delta_i \\ -\infty & \text{otherwise}, \end{cases}$$

where $\kappa_i = |\pi(a_i, w_i)|$ is a constant.

By Corollary 6.2, we have $\phi(x) = F_p(x)$. Therefore, the problem of finding the center is equivalent to the following optimization problem in $\mathbb{R}^3$:

(P1) Find a point $(x, r) \in \mathbb{R}^3$ minimizing $r$ subject to $x \in R'$ and $g_i(x) \leq r$ for $1 \leq i \leq m$.

Thus, we need to find the solution to (P1) to find the geodesic center of $P$. We use some ideas due to Megiddo in order to simplify the description of (P1) [20].

To simplify the formulas, we square the equation $|xa_i| \leq r - \kappa_i$:

$$\|x\|^2 - 2x \cdot a_i + \|a_i\|^2 = |xa_i|^2 \leq (r - \kappa_i)^2 = r^2 - 2r\kappa_i + \kappa_i^2.$$

And finally for each $1 \leq i \leq m$, we define the function $h_i(x, r)$ as follows:

$$h_i(x, r) = \begin{cases} \|x\|^2 - 2x \cdot a_i + \|a_i\|^2 - r^2 + 2r\kappa_i - \kappa_i^2 & \text{if } x \in \Delta_i \\ -\infty & \text{otherwise}. \end{cases}$$

Therefore, our optimization problem can be reformulated as:

(P2) Find a point $(x, r) \in \mathbb{R}^3$ such that $r$ is minimized subject to $x \in R'$ and $h_i(x, r) \leq 0$ and $r > \max\{\kappa_i\}$ for each $i$ such that $x \in \Delta_i$.

Let $h'_i(x, r) = \|x\|^2 - 2x \cdot a_i + \|a_i\|^2 - r^2 + 2r\kappa_i - \kappa_i^2$ be a function defined in the entire plane and let (P2') be an optimization problem equivalent to (P2) in which every instance of $h_i(x, r)$ is replaced by $h'_i(x, r)$. We provide some of the intuition used by Megiddo [20] to solve (P2').

Although the functions $h'_i(x, r)$ are not linear, they all have the same non-linear terms. Therefore, for $i \neq j$, we get that equation $h'_i(x, r) = h'_j(x, r)$ defines a separating plane

$$\gamma_{i,j} = \{ (x, r) \in \mathbb{R}^3 : 2(\kappa_i - \kappa_j)r - 2(a_i - a_j) \cdot x + \|a_i\|^2 - \|a_j\|^2 - \kappa_i^2 + \kappa_j^2 = 0 \}.$$
As noted by Megiddo [20], this separating plane has the following property: If the solution \((x, r)\) to \((P2')\) is known to lie to one side of \(\gamma_{i,j}\), then one of the constraints is redundant.

Thus, to solve \((P2')\) it sufficed to have a side-decision oracle to determine in which side of a plane \(\gamma_{i,j}\) the solution lies. Megiddo showed how to implement this oracle so that the running time is proportional to the number of constraints [20].

Once we have such an oracle, problem \((P2')\) can be solved using a prune and search approach: pair the functions arbitrarily, and consider the set of \(m/2\) separating planes defined by these pairs. For some constant \(t\), compute a \(1/t\)-cutting in \(\mathbb{R}^3\) of the separating planes. A \(1/t\)-cutting is a partition of the space into \(O(t^3) = O(1)\) convex regions each of which is of constant complexity and intersects at most \(m/2t\) separating planes. A cutting of planes can be computed in linear time in \(\mathbb{R}^3\) for any \(t = O(1)\) [18]. After computing the cutting, determine in which of the regions the minimum lies by performing \(O(1)\) calls to the side-decision oracle. Because at least \((t − 1)m/2t\) separating planes do not intersect this constant complexity region, for each of them we can discard one of the constraints as redundant. By repeating this algorithm recursively we obtain a linear running time.

To solve \((P2)\) we follow a similar approach, but our set of separating planes needs to be extended in order to handle apex functions, which are defined only in triangular domains. Note that no vertex of an apexed triangle can lie inside \(R'\).

### 7.1 Optimization Problem in a Convex Domain

In this section we describe our algorithm to solve the optimization problem \((P2)\). We start by pairing the apexed triangles of \(\tau_{R'}\) arbitrarily to obtain \(m/2\) pairs. By identifying the plane where \(P\) lies with the plane \(Z_0 = \{(x, y, z) : z = 0\}\), we can embed each apexed triangle in \(\mathbb{R}^3\). A plane-set is a set consisting of at most five planes in \(\mathbb{R}^3\). For each pair of apexed triangles \((\Delta_i, \Delta_j)\) we define its plane-set as follows: For each chord of \(P\) bounding either \(\Delta_i\) or \(\Delta_j\) (at most two chords on each triangle), consider the line extending this chord and the vertical extrusion of this line in \(\mathbb{R}^3\), i.e., the plane containing this chord orthogonal to \(Z_0\). The set containing these planes, together with the separating plane \(\gamma_{i,j}\), is the plane-set of the pair \((\Delta_i, \Delta_j)\).

Let \(\Gamma\) be the union of all the plane-sets defined by the \(m/2\) pairs of apexed triangles. Because the plane-set of each pair \((\Delta_i, \Delta_j)\) consists of at most five planes, at least one of which is unique to this pair, namely \(\gamma_{i,j}\), we infer that \(m/2 \leq |\Gamma| \leq 5m/2\).

Compute a \(1/t\)-cutting of \(\Gamma\) in \(O(m)\) time for some constant \(t\) to be specified later. Because \(t\) is constant, this \(1/t\)-cutting splits the space into \(O(1)\) convex regions, each bounded by a constant number of planes [18]. Using a side-decision algorithm (to be specified later), we can determine the region \(Q\) of the cutting that contains the solution to \((P2)\). Because \(Q\) is the region of a \(1/t\)-cutting of \(\Gamma\), we know that at most \(|\Gamma|/t\) planes of \(\Gamma\) intersect \(Q\). In particular, at most \(|\Gamma|/t\) plane-sets intersect \(Q\) and hence, at least \((t − 1)|\Gamma|/t \geq (t − 1)m/2t\) plane-sets do not intersect \(Q\).

Let \((\Delta_i, \Delta_j)\) be a pair whose plane-set does not intersect \(Q\). Let \(Q'\) be the projection of \(Q\) on the plane \(Z_0\). Because the plane-set of this pair does not intersect \(Q\), we know that \(Q'\) intersects neither the boundary of \(\Delta_i\) nor that of \(\Delta_j\). Two cases arise:
Case 1 If either $\triangle_i$ or $\triangle_j$ does not intersect $Q'$, then we know that their apex function is redundant and we can drop the constraint associated with this apexed triangle.

Case 2 If $Q' \subset \triangle_i \cap \triangle_j$, then we need to decide which constraint to drop. To this end, we consider the separating plane $\gamma_{i,j}$. Notice that inside the vertical extrusion of $\triangle_i \cap \triangle_j$ (and hence in $Q$), the plane $\gamma_{i,j}$ has the property that if we know its side containing the solution to (P2), then one of the constraints can be dropped.

Regardless of the case, if the plane-set of a pair $(\triangle_i, \triangle_j)$ does not intersect $Q$, then we can drop one of its constraints. Since at least $(t - 1)m/2t$ plane-sets do not intersect $Q$, we can drop at least $(t - 1)m/2t = m/4$ constraints. Consequently, after $O(m)$ time, we are able to drop a constant fraction of the apexed triangles. By repeating this process recursively, we end up with a constant size problem in which we can compute the upper envelope of the functions explicitly and find the solution to (P2) using exhaustive search. Thus, the running time of this algorithm is bounded by the recurrence $T(m) = T(3m/4) + O(m)$ which solves to $O(m)$. Because $m = O(n)$, we can find the solution to (P2) in $O(n)$ time.

The last detail is the implementation of the side-decision algorithm. Given a plane $\gamma$, we need to determine on which side the solution to (P2) lies. To this end, we solve (P2) restricted to $\gamma$, i.e., with the additional constraint of $(x, r) \in \gamma$. This approach was used by Megiddo [20]; the idea is to recurse by reducing the dimension of the problem. Another approach is to use a slight modification of the chord-oracle described by Pollack et al. [25, Sect. 3].

Once the solution to (P2) restricted to $\gamma$ is known, we can follow the same idea used by Megiddo [20] to find the side of $\gamma$ containing the global solution to (P2). Find the apex functions that define the minimum restricted to $\gamma$. Since $\phi(x) = F_P(x)$ is locally defined by these functions, we can decide in which side the minimum lies using convexity. We obtain the following result.

**Lemma 7.1** Let $R'$ be a convex trapezoid contained in $P$ such that $R'$ contains the geodesic center of $P$. Given the set of all apexed triangles of $\tau$ that intersect $R'$, we can compute the geodesic center of $P$ in $O(n)$ time.

The following theorem summarizes the result presented in this paper.

**Theorem 7.2** We can compute the geodesic center of any simple polygon $P$ of $n$ vertices in $O(n)$ time.

### 8 Further Work

Another way to compute the center of a simple polygon is to compute the farthest-point Voronoi diagram of its vertices. While the best known algorithm for this task runs in $O(n \log n)$ time, only a trivial $\Omega(n)$ lower bound is known for this instance of the problem. Therefore, it is natural to ask if the farthest-point Voronoi diagram of the set of vertices of a simple polygon can be computed in $O(n)$ time.

To generalize the result presented in this paper, we ask the following question. Given a set $S$ of $m$ points inside of a simple polygon $P$ with $n$ vertices, how fast can we...
compute the center of $S$ inside $P$? That is, the point in $P$ that minimizes the maximum geodesic distance to a point of $S$. While the (geodesic) farthest-point Voronoi diagram of $S$ provides the answer in $O((n + m) \log(n + m))$ time, we ask whether it is possible to compute this center in $O(n + m)$ time.

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9 Appendix: Bounding the VC Dimension

In this section we provide the proof of Lemma 6.3. That is, we want to prove that the set system $(C_R, \varphi)$ has constant VC-dimension. Recall that $C_R$ is a set of chords of $P$ and $\varphi$ is the set of all open 4-cells of $P$.

Let $A \subseteq C_R$ be a subset of chords. We say that $A$ is shattered by $\varphi$ if each of the subsets of $A$ can be obtained as the intersection of some $Z \in \varphi$ with $A$, i.e., if for each $\sigma \subseteq A$, there exists $Z \in \varphi$ such that $\sigma = Z \cap A$. The VC-dimension of $(C_R, \varphi)$ is the supremum of the sizes of all finite shattered subsets of $C_R$.

Let $H = \{H : H$ is a half-polygon of $P\}$. Because each 4-cell of $P$ is the intersection of at most four half-polygons of $P$, the following result is a direct consequence of Proposition 10.3.3 of [19, Chap. 10].

Lemma 9.1 If $(C_R, H)$ has VC-dimension $d$, then $(C_R, \varphi)$ has VC-dimension $O(d)$.

Let $A$ be an arbitrary subset of $C_R$ such that $|A| = \kappa$ for some constant $\kappa > 6$ to be determined later. Recall that if no subset of $C_R$ of size $\kappa$ is shattered by $H$, then the VC-dimension of $(C_R, H)$ is at most $\kappa - 1$.

By Lemma 9.1, it suffices to show that $A$ is not shattered by $H$ to bound the VC-dimension of $(C_R, H)$ and hence of $(C_R, \varphi)$. We spend the remainder of this section proving that $A$ is not shattered by $H$.

A 6-cell is strict if it is defined as the intersection of six half-polygons, none of them redundant, i.e., the removal of any of them modifies the 6-cell.

Lemma 9.2 If there are six chords of $A$ supporting six half-polygons whose intersection defines a strict 6-cell $\sigma$, then $A$ is not shattered by $H$.

Proof Let $C_1, \ldots, C_6$ be the chords supporting the six half-polygons whose intersection defines $\sigma$. Assume that $C_1, \ldots, C_6$ appear in this order when walking clockwise along the boundary of $\sigma$. Note that any half-polygon that intersects $C_1, C_3$ and $C_5$ must intersect either $C_2, C_4$ or $C_6$. Therefore, the set $\{C_1, C_3, C_5\} \subseteq A$ cannot be obtained as the intersection of some half-polygon $H \in H$ with $A$. Consequently $A$ is not shattered by $H$. $\square$

Given two chords $C_1$ and $C_2$ of $A$, we say that $C_1$ and $C_2$ are separated if there exists a chord $S \in A$ such that $C_1$ and $C_2$ lie on different open half-polygons supported by $S$. In this case, we say that $S$ separates $C_1$ from $C_2$.

Note that if $A$ contains two chords $C_1$ and $C_2$ that are separated by a chord $S$, then any half-polygon that intersects both $C_1$ and $C_2$ must also intersect $S$. In this case,
the subset \( \{ C_1, C_2 \} \) cannot be obtained as the intersection of a half-polygon \( H \in \mathcal{H} \) with \( A \), i.e., \( A \) is not shattered by \( \mathcal{H} \). Therefore, we assume from now on that no two chords of \( A \) are separated.

Let \( G_A \) be the intersection graph of \( A \), i.e., the graph with vertex set \( A \) and an edge between two chords if they intersect. An Erdős-Szekeres type result from Harborth and Möller [23] shows that every arrangement of nine pseudo-lines determines a sub-arrangement with a hexagonal face. Thus, if \( G_A \) has a clique of size nine, then this subset of chords is a set of pseudo-lines. Therefore, it contains a subset of 6 chords that define a strict 6-cell. In this case, Lemma 9.2 implies that \( A \) is not shattered by \( \mathcal{H} \). Consequently, we assume from now on that \( G_A \) has no clique of size nine.

Turán’s Theorem [28] states that if \( G_A \) has no clique of size nine, then it has at most \((7/16) \kappa^2\) edges. Let \( C_1 \) be the chord in \( A \) with the smallest degree in \( G_A \). Notice that \( C_1 \) has degree at most \( 7 \kappa / 8 \). Therefore, there are at least \( \kappa / 8 \) chords of \( A \) that do not intersect \( C_1 \). Consider the two half-polygons supported by \( C_1 \) and note that one of them, say \( P' \), contains at least \( \kappa / 16 \) chords of \( A \) that do not intersect \( C_1 \). Let \( A' \) be the set containing these chords.

Let \( G_A' \) be subgraph of \( G_A \) induced by \( A' \) and let \( C_2 \) be the chord of \( A' \) with smallest degree in \( G_A' \). Because \( G_A' \) has no clique of size nine, we infer that \( C_2 \) has degree at most \( 7 \left| A' \right| / 8 \). Repeating the same argument, there is a set \( A'' \) of at least \( \left| A' \right| / 8 \) chords of \( A' \) that intersect neither \( C_2 \) nor \( C_1 \). Because we assumed that no two chords of \( A \) are separated, all chords in \( A'' \) must be contained in the half-polygon supported by \( C_2 \) that contains \( C_1 \). Otherwise, \( C_1 \) and some of these chords are separated by \( C_2 \).

Let \( G_A'' \) be the subgraph of \( G_A \) induced by \( A'' \). Repeating the above procedure recursively on \( G_A'' \) and \( A'' \) four more times, we obtain a set \( C_1, \ldots, C_6 \) of pairwise disjoint chords such that for each \( 1 \leq i \leq 6 \), \( C_1, \ldots, C_{i-1} \) are contained in the same half-polygon supported by \( C_i \). Consequently, the set \( \{ C_1, \ldots, C_6 \} \) bounds a strict 6-cell.

The above process can be applied as long as

\[
\left( \frac{1}{16} \right) \left( \frac{1}{8} \right)^4 \kappa \geq 1.
\]

That is, as long as \( \left| A \right| \geq 65,536 \) we can always find 6 such chords defining a strict 6-cell. In this case, Lemma 9.2 implies that \( A \) is not shattered by \( \mathcal{H} \). Consequently, no set of 65,536 chord is shattered, i.e., the set system \( (\mathcal{C}_R, \mathcal{H}) \) has VC-dimension at most 65,535. By Lemma 9.1, we obtain the following result.

**Lemma 6.3.** The set system \( (\mathcal{C}_R, \varphi) \) has constant VC-dimension.

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