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On the Complexity of Umbra and Penumbra *

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Abstract

Computing shadow boundaries is a difficult problem in the case of non-point light sources. A point is in the umbra if it does not see any part of any light source; it is in full light if it sees entirely all the light sources; otherwise, it is in the penumbra. While the common boundary of the penumbra and the full light is well understood, less is known about the boundary of the umbra. In this paper we prove various bounds on the complexity of the umbra and the penumbra cast on a fixed plane by a segment or convex polygonal light source in the presence of convex polygonal or polyhedral obstacles in \mathbb{R}^3 .

In particular, we show that a single segment light source may cast on a plane, in the presence of two disjoint triangles, four connected components of umbra and that two fat convex and disjoint obstacles of total complexity n can give rise to as many as $\Omega(n)$ connected components of umbra. In a scene consisting of a segment light source and k disjoint convex polyhedra of total complexity n , we prove an $\Omega(nk^2 + k^4)$ lower bound on the maximum number of connected components of the umbra and a $O(nk^3)$ upper bound on its complexity; if the obstacles may intersect, we only prove an upper bound of $O(n^2k^2)$.

We also prove that, in the presence of k convex polyhedra of total complexity n , some of which are light sources, the umbra cast on a plane may have in the worst case $\Omega(n^2k^3 + nk^5)$ connected components and has complexity $O(n^3k^3)$ (the polyhedra are supposed pairwise disjoint for lower bounds and possibly intersecting for the upper bounds). These are the first bounds on the size of the umbra in terms of both k and n . These results prove that the umbra, which is bounded by arcs of conics, is intrinsically much more intricate than the boundary between full light and penumbra which is bounded by line segments and whose worst-case complexity is, as we show, in $\Omega(nk + k^4)$ and $O(nk\alpha(k) + k^4)$; moreover, if there are only $O(1)$ light sources of total complexity m , then the complexity is in $\Omega(n\alpha(k) + km + k^2)$ and $O(n\alpha(k) + km\alpha(k) + k^2)$.

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1 Introduction

Shadows play a central role in human perception [15, 20]. Unfortunately, computing realistic shadows efficiently is a difficult problem, particularly in the case of non-point light sources. A wide variety of approaches have been considered for rendering shadows (see, for example, the surveys [8, 22]) and many methods make extensive use of graphics hardware (see the survey [13]).

A point is in the *umbra* if it does not see any part of the light source(s); it is in *full light* if it sees entirely all the light source(s); otherwise, it is in the *penumbra*. While the boundary between the penumbra and the full light is reasonably well understood (see Section 3), less is known about the boundary of the umbra. Nevertheless, there is extensive literature concerning the explicit computation of these shadow boundaries; see, for example, [7, 9, 10, 11, 14, 16, 18, 19].

In this paper we prove various bounds, summarized in Tables 1 and 2, on the complexity of the umbra and penumbra cast on a fixed plane by segment or convex polygonal light source(s) in the presence of convex polygonal or polyhedral obstacles in \mathbb{R}^3 . **Unless specified otherwise, the objects in the scene (light sources and obstacles) are supposed pairwise disjoint for lower bounds and possibly intersecting for upper bounds.** We show, in particular, that a single segment light source may cast, in the presence of two triangles, four connected components of umbra. We prove that the umbra defined by one segment light source and two fat convex obstacles of total complexity n can have as many as $\Omega(n)$ connected components. We also prove an $\Omega(nk^2 + k^4)$ lower bound on the maximum number of connected components of the umbra and a $O(n^2k^2)$ (resp., $O(nk^3)$) upper bound on its complexity in a scene consisting of a segment light source and k possibly intersecting (resp., disjoint) convex polyhedra of total complexity n . Finally, we prove that the umbra cast on a plane by a polygonal light source and k convex obstacles can have $\Omega(n^2k^3 + nk^5)$ connected components and has worst-case complexity $O(n^3k^3)$. These are the first bounds on the size of the umbra in terms of both k and n .

These results are related to work on the *aspect graph*, a structure that encodes all topologi-

| Scene type | Lower bound | Upper bound |
|-----------------------------------|-------------------------|----------------------|
| Segment light source: | | |
| 2 disjoint triangles | 4 | $O(1)$ |
| 2 fat disjoint convex polyhedra | $\Omega(n)$ | $O(n)$ |
| k disjoint convex polyhedra | $\Omega(nk^2 + k^4)$ | $O(nk^3)$ |
| k convex polyhedra | $\Omega(nk^2 + k^4)$ | $O(n^2k^2)$ |
| Polygonal light source(s): | | |
| | One light source | $O(k)$ light sources |
| k convex polyhedra | $\Omega(n^2k^3 + nk^5)$ | $O(n^3k^3)$ |

Table 1: Lower bounds on the maximum number of connected components and upper bounds on the complexity of the umbra cast on a plane by one segment light source or polygonal light source(s) in the presence of k convex polyhedra of total complexity $O(n)$.

| Light sources | Lower bound | Upper bound |
|--|---------------------------------|-------------------------------------|
| $O(1)$ convex polyhedra of size m | $\Omega(n\alpha(k) + km + k^2)$ | $O(n\alpha(k) + km\alpha(k) + k^2)$ |
| $O(k)$ convex polyhedra of total size $O(n)$ | $\Omega(nk + k^4)$ | $O(nk\alpha(k) + k^4)$ |

Table 2: Bounds on the complexity of the union of umbra and penumbra cast on a plane by a set of k convex polyhedra of total complexity n , some of which are light sources.

cally distinct views of a scene, where the definition of the view of a scene depends on the choice of a viewpoint space [5]. Two models of viewpoint space are commonly used: the *orthographic* model, where view points are on the plane at infinity and all lines of sight are parallel to a viewing direction, and the *perspective* model, where view points are in \mathbb{R}^3 but not in the objects. In terms of complexity, de Berg *et al.* [6] proved that a scene consisting of k convex polyhedra of total complexity n has at most $O(n^4 k^2)$ distinct orthographic views and at most $O(n^6 k^3)$ perspective views. These bounds are tight as shown by Aronov *et al.* [1]. In our work we limit the viewpoint space to the shadow plane and consider only those views involving the light sources.

Our results are surprising in the sense that they show that the umbra cast by a single segment light source may have many connected components. The fact that the umbra may have four connected components in the case of two triangle obstacles comes as a total surprise. Our lower bounds of $\Omega(nk^2 + k^4)$ and $\Omega(n^2 k^3 + nk^5)$ on the maximum number of connected components, for k convex polyhedra of total complexity n , are rather pathological in the sense that most of the obstacles are very long and thin. However, we also present a lower bound example of $\Omega(n)$ connected components in the case of two fat polygons or convex polyhedra of complexity $O(n)$. Concerning the upper bounds of $O(nk^3)$, $O(n^2 k^2)$ and $O(n^3 k^3)$, even though these bounds are not *a priori* tight, they substantially improve the only previously known bounds for this problem which were the trivial $O(n^4)$ and $O(n^6)$ upper bounds. Finally, it is interesting to point out that even for the simplest case of non-point light sources, obtaining tight bounds on the complexity of the umbra and understanding its structure is a very challenging problem.

These results show that the umbra, which is bounded by arcs of conics, is intrinsically much more intricate than the boundary between full light and penumbra which is bounded by line segments and for which we prove that the worst-case complexity is in $\Omega(nk + k^4)$ and $O(nk\alpha(k) + k^4)$, where $\alpha(k)$ denotes the pseudo-inverse of the Ackermann function; moreover, if there are only $O(1)$ light sources of total complexity m , then the worst-case complexity of the boundary between full light and penumbra is in $\Omega(n\alpha(k) + km + k^2)$ and $O(n\alpha(k) + km\alpha(k) + k^2)$.

The paper is organized as follows. The next section provides notations and definitions. We give in Section 3 lower and almost tight upper bounds on the complexity of the boundary between full light and penumbra cast on a plane by a polygonal light source in the presence of convex polyhedral obstacles. We present, in Section 4, upper bounds on the complexity of the umbra, in Section 5, lower bounds on the maximum number of connected components of umbra and conclude in Section 6.

2 Preliminaries

Let s be a line segment and p a point. We denote by $\langle s, p \rangle$ the set of line transversals to s and p , *i.e.*, the set of lines through p and intersecting s . Similarly, for any triple of segments s_1 , s_2 and s_3 , we denote by $\langle s_1, s_2, s_3 \rangle$ its set of line transversals. It is a well-known fact that $\langle s_1, s_2, s_3 \rangle$ consists of lines belonging to the same regulus of a ruled quadric surface (see *e.g.* [17]). More precisely, the line transversals lie on a hyperboloid of one sheet when the three segments are pairwise skew and not all parallel to the same plane. If the segments are pairwise skew and all parallel to the same plane, then the line transversals lie on a hyperbolic paraboloid. Otherwise, they lie in one or two planes. Hence any set of transversals, whether $\langle s, p \rangle$ or $\langle s_1, s_2, s_3 \rangle$, forms patches of a quadric (possibly degenerating to one or two planes). Moreover, the set of transversals consists of at most three patches, or more formally, at most three connected components in line space [4]. Slightly abusing the notation, we let $\langle s, p \rangle$ and $\langle s_1, s_2, s_3 \rangle$ denote not just sets of lines but also the patches of surfaces in \mathbb{R}^3 .

Let \mathcal{P} be a finite set of convex polygons or convex polyhedra in \mathbb{R}^3 with $\mathcal{L} \subset \mathcal{P}$ identified as

light sources. The elements of \mathcal{P} are called the *objects* of the scenes and the objects in $\mathcal{P} \setminus \mathcal{L}$ are called the *obstacles*. A surface $\sigma = \langle e, v \rangle$ is called an *EV-surface* if there exist two distinct objects $P, Q \in \mathcal{P}$ so that e is an edge of P , v a vertex of Q and σ intersects a light source. A surface $\sigma = \langle e_1, e_2, e_3 \rangle$ is called an *EEE-surface* if there exist three distinct objects $P, Q, R \in \mathcal{P}$ so that e_1, e_2 and e_3 are respective edges of P, Q and R and σ intersects a light source. It is interesting to notice that our definition of EV and EEE surfaces is more restrictive than the common one [5], in the sense that it only considers a surface as a EV or EEE surface if it intersects a light source.

Any plane Π intersects an EV-surface or an EEE-surface in a set of arcs of a conic (each possibly empty or possibly a line segment).

Here we are interested in the arcs of conics that correspond to boundaries between shadow regions on the *shadow plane* Π . In particular, we are interested in arcs in Π , called *shadow boundaries*, resulting from the intersection between Π and maximal free line segments¹ that intersect a light source and are supported by a line which is on an EV or EEE surface. The shadow boundaries define an arrangement on Π which we call the *shadow arrangement*.

A point p is in the umbra if, for every point q on a light source, the segment pq intersects an object from $\mathcal{P} \setminus \mathcal{L}$. Similarly, p is in full light if for any point q on a light source, the segment pq does not intersect any object from $\mathcal{P} \setminus \mathcal{L}$. Otherwise, p is in the penumbra.

We will make extensive use of the fact that the effective boundaries of the umbra and penumbra consist of arcs of the shadow arrangement (see, for example, [14]). Notice that not all arcs of the shadow arrangement are on the umbra or penumbra boundaries; some arcs correspond to other lighting discontinuities.

Throughout this paper, we consider the regions of umbra and penumbra on a plane cast by a segment light source or polygonal light source(s) in the presence of convex polygons or convex polyhedra.

3 The penumbra boundary

We prove here bounds on the complexity of the common boundary of the penumbra and the full light cast on a plane by a set of k convex polyhedra of total complexity n , some of which are light sources. We refer to the union of the umbra and penumbra as the *shadow region*. We can assume without loss of generality that the light sources do not intersect the interior of the obstacles since, otherwise, the shadow region is trivially the whole plane. We first recall some straightforward and well-known properties of the shadow region.

Property 1. The shadow region cast by a light source on a plane in the presence of obstacles is the union of all the shadow regions cast by each obstacle.

Property 2. The shadow region cast on a plane Π by a convex polygonal light source S in the presence of one convex polyhedron P is the intersection of halfplanes in Π . Each halfplane is defined as the intersection of Π with a (closed) halfspace (i) that contains P , (ii) whose interior does not intersect S , and (iii) that is bounded by a plane tangent to P and S and containing an edge of one of them. In other words, each halfspace is bounded by a plane separating P from S and containing an EV-surface which is tangent to P and S .

Note that these two properties imply that the boundary of the shadow region is only composed of line segments induced by EV-surfaces.

¹A line segment e is said to be *free with respect to an object* X if and only if e is an edge of a three-dimensional polyhedron whose interior does not intersect X ; segment e is said to be *free* if it is free with respect with all objects of the scene. A *maximal* free line segment is a free line segment that is maximal under inclusion. As a consequence, each endpoint of a maximal free segment is either at infinity or lies on some object.

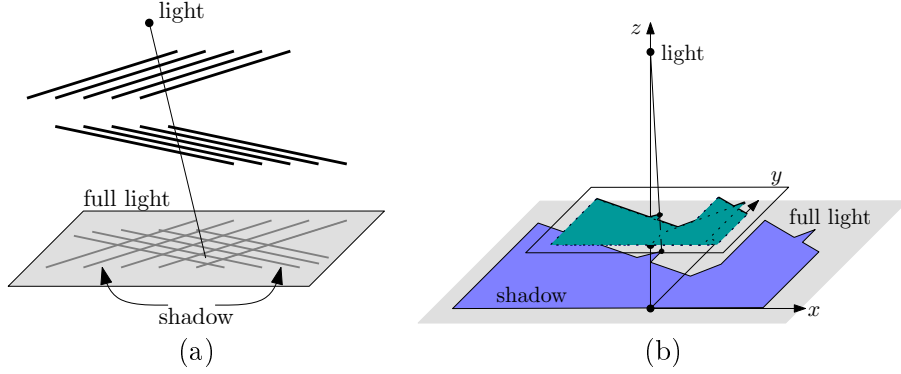


Figure 1: $\Omega(k^2)$ and $\Omega(k\alpha(k))$ lower bounds.

Theorem 1. *The complexity of the shadow region cast on a plane by a set of k convex polyhedra of total complexity n , some of which are light sources, is, in the worst case, in $\Omega(nk + k^4)$ and $O(nk\alpha(k) + k^4)$, where $\alpha(k)$ denotes the pseudo-inverse of the Ackermann function. If there are only $O(1)$ light sources of total complexity m , then the complexity of the shadow region is in $\Omega(n\alpha(k) + km + k^2)$ and $O(n\alpha(k) + km\alpha(k) + k^2)$.*

Proof. By Property 2, the shadow cast on a plane Π by a polygonal light source in the presence of one convex polyhedron is a convex polygon. Furthermore, if the light source has m edges and the polyhedron has n_i edges, the shadow region in Π has $O(n_i + m)$ edges. By Property 1, the shadow region in the presence of k convex polyhedra of total complexity n is thus the union of k convex polygons of total complexity $O(n + km)$, which has complexity $O((n + km)\alpha(k) + k^2)$ [2]. The same bounds hold if there are $O(1)$ light sources of total complexity m . Similarly, if $O(k)$ of the convex polyhedra of the scene are light sources, of total complexity n , the shadow region is the union of $O(k^2)$ convex polygons of total complexity $O(nk)$, which has complexity $O(nk\alpha(k) + k^4)$.

For the proof of the lower bounds, we consider the following collection of examples – which are adapted from lower bounds in [2]. In all constructions the shadow plane Π is the plane $z = 0$.

$\Omega(k^2)$ and $\Omega(k^4)$ examples. Refer to Figure 1. We consider a point light source at a height z (large enough) and a grid consisting of k thin horizontal and parallel rectangles at height $z = 1$ together with k other thin horizontal and parallel rectangles at height $z = 2$. They form a grid of shadow on plane Π which has size $\Omega(k^2)$. Replacing the point light source by k point light sources very close to each other gives, similarly, a shadow region of complexity $\Omega(k^4)$.

$\Omega(k\alpha(k))$ example. Refer to Figure 1. Again, the light source is a point with large positive z -coordinate. We consider a set of k line segments in plane $z = 1$ (with positive y coordinates) having, in that plane, an upper envelope of size $\Omega(k\alpha(k))$ [21]. We transform each line segment into a trapezoid linking it to its projection on the $y = 0$ line (in plane $z = 1$). We get a set of trapezoids whose shadow, in plane $z = 0$, for a point light source at large enough z is basically the upper envelope of the segments. Note that the trapezoids can easily be made disjoint by placing them in different horizontal planes very close to plane $z = 1$.

$\Omega(n\alpha(k))$ example. Refer to Figure 2. First modify the above $\Omega(k\alpha(k))$ example such that the left “vertical” side of each trapezoid has slope γ and the right “vertical” side has slope $-\gamma$, for some γ large enough. Now, by some suitable scaling, we make all slopes of the vertical walls strictly smaller than $\frac{k\pi}{n}$ (in absolute value). Assemble $\frac{n}{k}$ copies of the previous construction into a large regular $\frac{n}{k}$ -gon where each side is, in fact, an upper envelope of complexity $\Omega(k\alpha(k))$.

Finally, this construction can be seen as k convex $3\frac{n}{k}$ -gons by connecting all of the $\frac{n}{k}$ copies of the same trapezoid by extending their walls.

This set of k convex $3\frac{n}{k}$ -gons, embedded in different horizontal planes close to the $z = 1$ plane, engender, in the presence of a point light source at large enough z , shadows of complexity $n\alpha(k)$.

$\Omega(mk)$ example. Refer to Figure 3. We use a horizontal m -gon as light source and a thin rectangle as obstacle. Then the shadow has size $\Omega(m)$. Using multiple copies of the obstacle such that the different shadows are disjoint easily gives an $\Omega(mk)$ example. \square

There is still a small gap between the $\Omega(nk + k^4)$ lower bound and the $O(nk\alpha(k) + k^4)$ upper bound and between the $\Omega(k^2 + mk + n\alpha(k))$ lower bound and the $O(k^2 + mk\alpha(k) + n\alpha(k))$ upper bound.

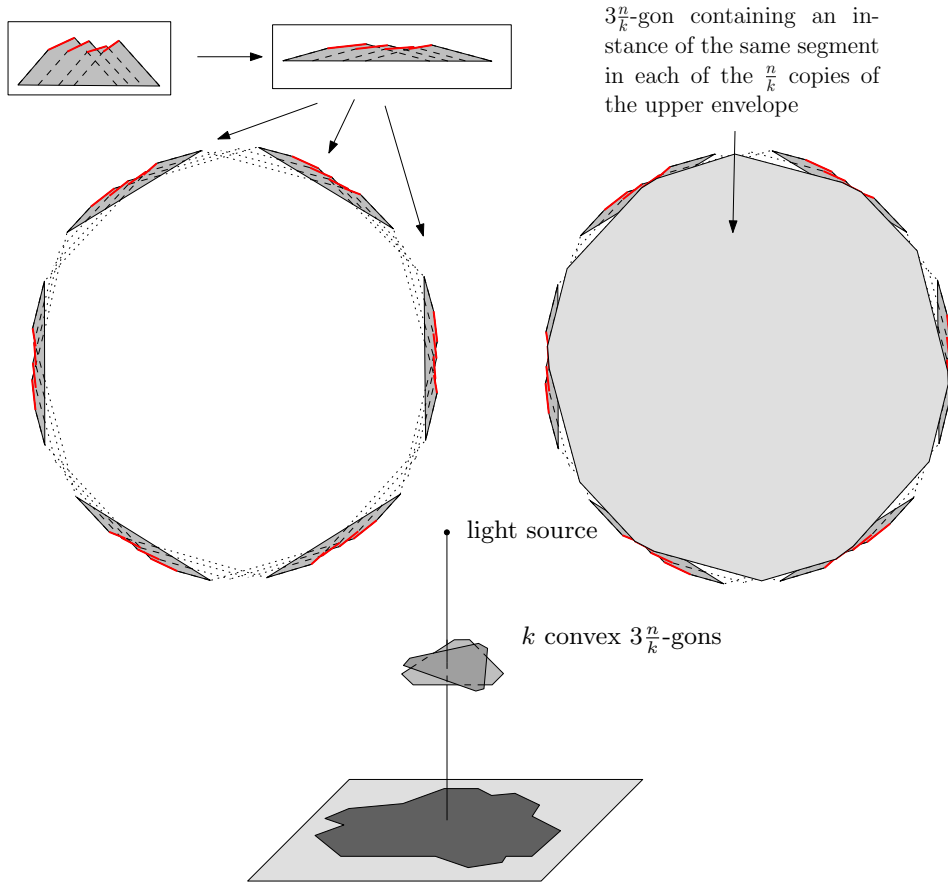


Figure 2: $\Omega(n\alpha(k))$ lower bound.

4 Upper bounds

In this section we prove the following two upper bounds on the complexity of the umbra cast on a plane by a segment light source or polygonal light source(s).

Theorem 2. *The complexity of the umbra cast on a plane by one segment light source in the presence of k convex polyhedra of total complexity n is $O(n^2k^2)$ if the polyhedra may intersect and $O(nk^3)$ otherwise.*

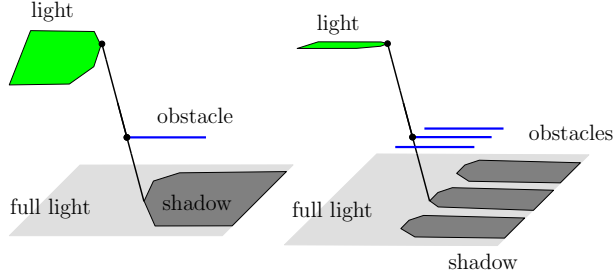


Figure 3: $\Omega(mk)$ lower bound.

Theorem 3. *The complexity of the umbra cast on a plane by a set of k (possibly intersecting) convex polyhedra of total complexity n , some of which are light sources, is $O(n^3k^3)$.*

We first recall a technical lemma from [6].

Lemma 4 ([6, Lemma 2.1]). *Given a collection of p arcs of conics in the plane Π such that any vertical line in Π intersects at most q arcs,² the maximum complexity of the arrangement of the plane induced by these curves is $\Theta(pq)$.*

4.1 The umbra cast by a segment light source

We will actually prove an upper bound on the complexity of the shadow arrangement which yields the same bound for the complexity of the umbra. Notice that, in the case of a single segment light source, the EEE-surfaces $\sigma = \langle e_1, e_2, e_3 \rangle$ that contribute to the shadow arrangement are such that one of e_1, e_2 or e_3 is the segment light source. Similarly, when considering EV-surfaces $\sigma = \langle e, v \rangle$ either e is the segment light source or v is one of its endpoints.

To prove Theorem 2 we consider a plane rotating about the line supporting the segment light source. First, if the segment light source, s , is not parallel to the shadow plane Π , we apply a projective transformation to the scene, sending to infinity the point of intersection between the line containing s and plane Π ; this does not change the complexity of the shadow arrangement. We can thus assume in the rest of this section that the segment light source is parallel to Π . The sweep plane, denoted π , intersects the shadow plane in a line parallel to s ; we will say that, throughout the sweep, this line moves from left to right.

In this proof we consider an arrangement A of arcs of conics in Π which contains the shadow arrangement. We will establish an upper bound of $O(nk^3)$ on the complexity of A which will yield the bound of Theorem 2. The arrangement A is defined as the arrangement of the potential shadow boundaries; a *potential shadow boundary* is an arc of conic defined as the intersection of Π with (i) those lines that are transversal to the light source s , and the edges e_1 and e_2 of two other convex polyhedra and that do not intersect the interior of these convex polyhedra (the connected components of these lines form patches of EEE-surfaces) and (ii) those lines that are transversal to a vertex and an edge of two convex polyhedra, one of which is the segment light source, and that do not intersect the interior of these convex polyhedra (the connected components of these lines form patches of EV-surfaces).

We now count the number of crossings between an instance of the sweep plane π and the potential shadow boundaries.

²Lemma 2.1 in [6] is stated with Jordan arcs that pairwise intersect at most a constant number of times and such that any vertical line intersects the arcs in a total of at most q points. This can trivially be extended to (possibly vertical) conic arcs such that any vertical line intersects at most q arcs.

Lemma 5. *Plane π properly intersects at most $O(nk)$ potential shadow boundaries if the obstacles of the scene may intersect and $O(k^2)$ otherwise.*

Proof. The potential shadow boundaries are defined as the intersection with Π of lines ℓ which are (i) transversal to the segment light source s and tangent to two convex polyhedra, (ii) transversal to an endpoint of s and tangent to another convex polyhedron, or (iii) transversal to s and to a convex polyhedron vertex.

An instance π of the sweep plane never properly intersects an arc of type (iii) (since such an arc is either included in π or does not intersect it). Now, if π intersects an arc of one of the other two types, then π contains the corresponding line ℓ , which is tangent to two polygons of $\mathcal{P} \cap \pi$. If the k convex polygons may intersect (resp., are pairwise disjoint), there are $O(nk)$ (resp., $O(k^2)$) lines in π that are tangent to two polygons of $\mathcal{P} \cap \pi$, hence the result. \square

Proof of Theorem 2. We consider an orthogonal frame in plane Π whose *vertical* axis is parallel to the segment light source s ; the other axis is called *horizontal*.

We bound the number of potential shadow boundaries. Each arc corresponds either to a patch of an EV or EEE surface. Consider first the EV-surfaces. Since either the edge or the vertex is on the light source, there are at most $O(n)$ such surfaces.

Now consider the arcs generated by EEE-surfaces. Let n_i be the number of vertices of convex polyhedron P_i , $1 \leq i \leq k$. The number of EEE-surfaces involving the light source and edges from convex polyhedra P_i and P_j is $O(n_i + n_j)$ [3, Corollary 2.6]. Then, $\sum_{1 \leq i < j \leq k} O(n_i + n_j) = O(nk)$.

There are at most $O(nk)$ potential shadow boundaries and a vertical line intersects at most $O(nk)$ or $O(k^2)$ such arcs depending on whether the obstacles intersect (Lemma 5). Thus Lemma 4 gives an upper bound of $O(n^2k^2)$ or $O(nk^3)$ on the complexity of the arrangement A . The total complexity of the shadow arrangement, and thus of the umbra, is thus $O(n^2k^2)$ if the obstacles may intersect and $O(nk^3)$ otherwise. \square

Note that the upper bound of Theorem 2 is not known to be tight. However, we prove, in Lemma 11, that this is a tight bound on the complexity of the arrangement A .

4.2 The umbra cast by polygonal light sources

To prove Theorem 3 we consider an arrangement B of arcs of conics that, as in the previous section, contains the shadow arrangement. This arrangement B is defined as the arrangement of potential shadow boundaries where, in this section, potential shadow boundaries are the intersections of Π with (i) the lines that are transversal to a vertex and an edge of two convex polyhedra and that do not intersect the interior of these convex polyhedra (the connected components of these lines form patches of EV-surfaces) (ii) the lines that are transversal to edges of three convex polyhedra and that do not intersect the interior of these convex polyhedra (the connected components of these lines form patches of EEE-surfaces). Notice that B may contain arcs generated by surfaces that do not intersect the light sources or possibly by surfaces that intersect the interior of other convex polyhedra in the scene. We will establish a $O(n^3k^3)$ upper bound on the complexity of B which yields the same bound for the complexity of the umbra.

We start with the following lemma (see also [12]).

Lemma 6. *Any line L in Π properly intersects at most $O(nk^2)$ potential shadow boundaries.*

Proof. An intersection point between L and a potential shadow boundary corresponds to a line transversal which belongs to an EV or EEE surface. Consider first EV-surfaces. The line transversal lies in a plane which contains L and a vertex, say v , of one of the convex polyhedra. There exist $O(n)$ such planes and in each of them there are at most $O(k)$ lines through v that

are tangent to a convex polyhedron (since we only consider proper intersections between L and the potential shadow boundaries). Thus there are at most $O(nk)$ points on L and potential shadow boundaries which correspond to lines in EV-surfaces.

Now we consider EEE-surfaces. Let n_i be the number of vertices of convex polyhedron P_i , for $1 \leq i \leq k$. The number of EEE-surfaces generated by three edges of convex polyhedra P_i, P_j and P_l , not intersecting the interior of P_i, P_j and P_l , and that intersect L is $O(n_i + n_j + n_l)$ [3, Main Lemma]. Since $\sum_{1 \leq i < j < l \leq k} O(n_i + n_j + n_l) = O(nk^2)$, there are at most $O(nk + nk^2) = O(nk^2)$ potential shadow boundaries which intersect the line L on Π . \square

Proof of Theorem 3. Here, we introduce an arbitrary coordinate frame Oxy in the plane Π . We call Ox the horizontal axis and Oy the vertical axis. We first break all conic arcs into maximal horizontally monotone pieces. This increases the number of arcs only by a constant factor.

As in the proof of Theorem 2, we bound the number of potential shadow boundaries. Let n_i be the number of vertices of convex polyhedron P_i , $1 \leq i \leq k$ and e an edge. The number of EEE-surfaces pertinent to B and involving e and edges from convex polyhedra P_i and P_j is $O(n_i + n_j)$ [3, Corollary 2.6]. Thus, for each edge e , there are, at most, $\sum_{1 \leq i < j \leq k} O(n_i + n_j) = O(nk)$ EEE-surfaces having e as a generating segment. Furthermore, the number of EV-surfaces involving edge e or one of its vertices is $O(n)$. Since there exist n edges, the total number of potential shadow boundaries is therefore $O(n^2k)$.

In conclusion, there are at most $O(n^2k)$ potential shadow boundaries and a vertical line intersects at most $O(nk^2)$ such arcs (Lemma 6). Thus Lemma 4 gives an upper bound of $O(n^3k^3)$ on the complexity of the arrangement B . The total complexity of the shadow arrangement, and thus of the umbra, is then $O(n^3k^3)$. \square

5 Lower bounds

In this section we present several lower bounds on the complexity of the umbra.

5.1 The umbra cast by a segment light source

Here we concentrate on the umbra cast by a segment light source in the presence of various configurations of obstacles.

Theorem 7. *A segment light source and two triangles may cast, on a plane, four connected components of umbra.*

Proof. Consider the following scene consisting of a segment light source, s , two triangles, T_1 and T_2 , and a shadow plane, Π , the horizontal plane of equation $z = 0$; see Figure 4(a) and (b).

Figure 5(a) shows a superset of the shadow arrangement generated by this configuration (the arrangement A defined in Section 4). Although it can be shown that the four shaded regions in the figure are exactly the umbra, we will simply argue here that there are at least four connected components. We do this by exhibiting four segments in the umbra and then arguing that they are each in different connected components.

The idea is to consider a series of planes rotating about the segment light source and the intersections of those planes with the two triangles and the shadow plane; Figure 6 shows such a sequence. We then examine the umbra in those planes by considering the relevant bitangents.

Let P_+ be one such plane (containing s) and going through the point $(0, 7, 0)$ and L_+ the intersection of P_+ and Π . Figure 6(b) shows the segment s , the intersections between P_+ and the two triangles T_1 and T_2 , L_+ and four bitangents that together define the umbra on L_+ . Consider the two segments R_1^+ and R_2^+ as shown in Figure 6(b). It is easy to see, by examining

the bitangents, that R_1^+ and R_2^+ are in the umbra. Hence there are two segments of umbra on the line L_+ . We obtain two other segments, R_1^- and R_2^- , by taking the symmetric plane P_- with respect to the xz -plane (through point $(0, -7, 0)$ and whose intersections with the scene is shown on Figure 6(d)).

Now, we show that the four segments R_1^+ , R_1^- , R_2^+ and R_2^- lie in different connected components of umbra. In order to prove this result, we exhibit two lines on Π which contain no point in the umbra and separate the four segments as shown in Figure 5(b).

First consider the plane $y = 0$ containing the light segment s and orthogonal to the shadow plane Π . This plane intersects Π in a line, δ_1 , as shown in Figure 5(b), and separates R_1^+ and R_2^+ from R_1^- and R_2^- since P_+ and P_- are symmetric about the plane $y = 0$. To show that δ_1 contains no point of the umbra, consider the intersection of the $y = 0$ plane with the segment s and the two triangles T_1 and T_2 ; see Figure 6(c). A study of the bitangents reveals that no point of δ_1 lies in the umbra.

Now consider the plane orthogonal to Π , parallel to the two triangle hypotenuses and going through the midpoint of s . Let δ_2 be the intersection of this plane with Π ; see Figure 5(b). Elementary computations show that the line δ_2 separates R_1^+ and R_2^- from R_1^- and R_2^+ . There can be no point of the umbra on δ_2 since the plane intersects the light source but not the triangles (see Figure 4(a)). This completes the proof. \square

Note that the line supporting s and the lines supporting the triangle hypotenuses are pairwise skew and not all parallel to a common plane. Thus the corresponding EEE-surface is a hyperboloid of one sheet which intersects Π in a hyperbola. We determine the equation of this hyperbolic curve to be $41y^2 - 52xy + 928 = 0$. This curve admits two asymptotes which contain no point in the umbra and which separate the connected components of umbra. One of these asymptotes is δ_1 and we could have chosen the other to be δ_2 .

Note also that in our example, the light source is parallel to the shadow plane, and there are also many symmetries. None of this is critical; the example can be perturbed and the result still holds.

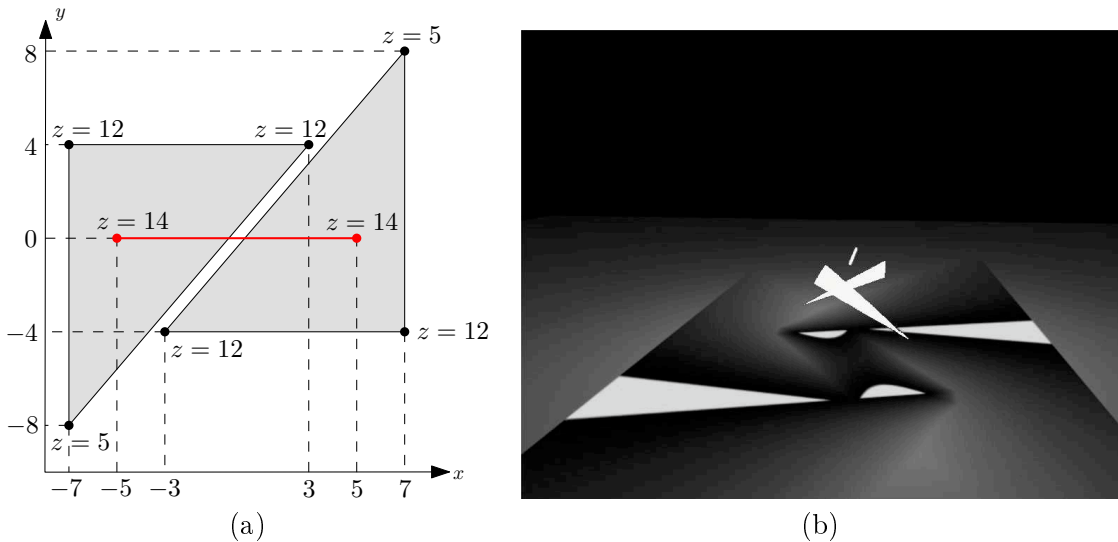


Figure 4: (a) Two triangles and a segment light source (viewed from above) that cast 4 connected components of umbra on the plane $z = 0$. (b) The scene rendered with the ray tracer `OpenRT` (the umbra is in light grey); courtesy of Andreas Dietrich.

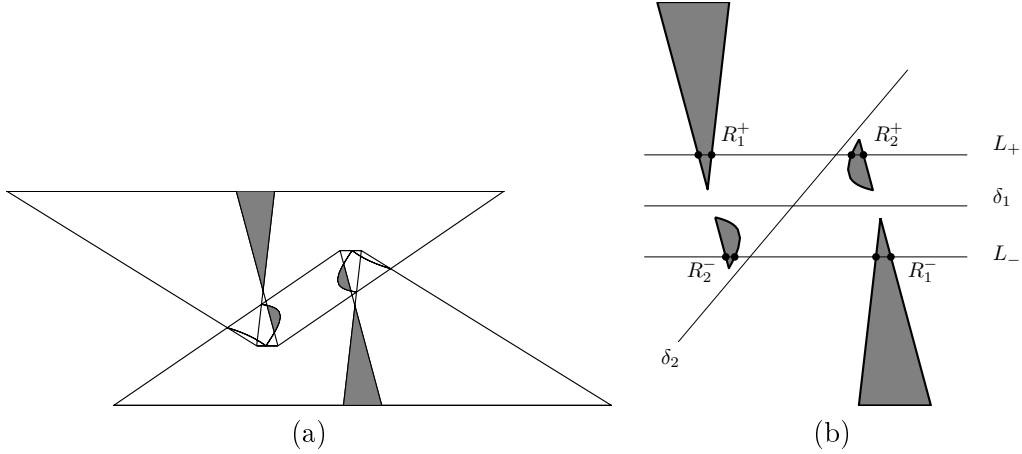


Figure 5: (a) Superset of the shadow arrangement on plane Π . The four shaded regions are the regions of umbra. (b) The four connected components of umbra and the four lines used in the proof of Theorem 7.

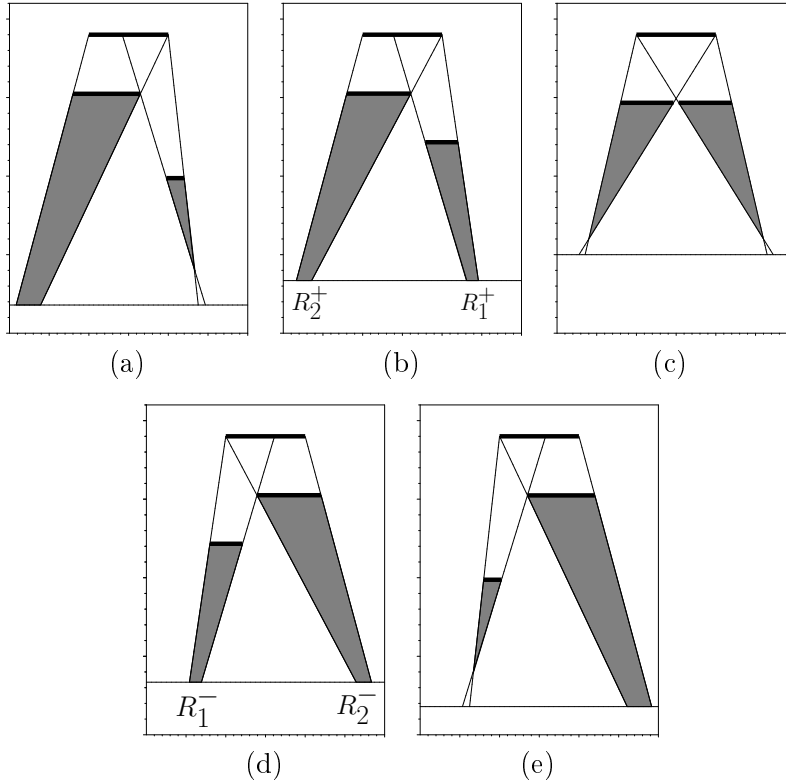


Figure 6: Views in the sweep plane with bitangents that define the umbra. The number of components of umbra in the intersection of the sweep plane and the plane $z = 0$ is: (a) one (sweep plane through $(0, 10, 0)$), (b) two (sweep plane P_+ through $(0, 7, 0)$), (c) zero (sweep plane $y = 0$), (d) two (sweep plane P_- through $(0, -7, 0)$), (e) one (sweep plane through $(0, -10, 0)$).

We now prove a lower bound for fat convex polyhedra, that is, convex polyhedra whose aspect ratios are bounded from below by a positive constant when n goes to infinity.

Theorem 8. *The umbra cast on a plane by one segment light source in the presence of two fat*

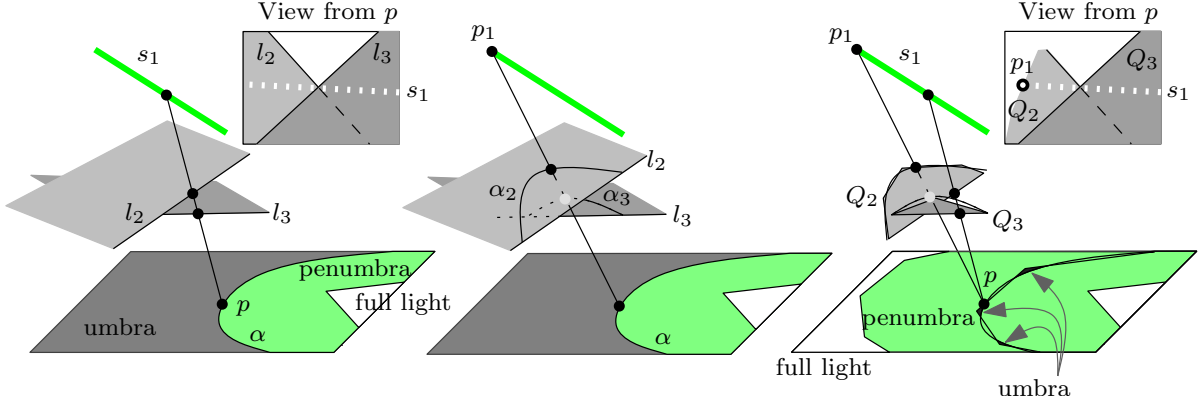


Figure 7: $\Omega(n)$ lower bound.

disjoint convex polyhedra of total complexity n can have $\Omega(n)$ connected components.

Proof. Our lower-bound example consists of one segment light source s_1 , a convex polyhedron Q_2 of size $O(n)$, and another convex polyhedron, Q_3 , of constant size. Refer to Figure 7.

First we consider three non-parallel segments s_1 , l_2 and l_3 all parallel to the shadow plane Π . Let $\sigma = \langle s_1, l_2, l_3 \rangle$ be the quadric patch(es) consisting of the lines stabbing s_1 , l_2 and l_3 . In the shadow plane Π , by adding suitable halfplanes P_2 and P_3 as obstacles limited by the lines supporting l_2 and l_3 , we obtain α , a single conic arc of $\sigma \cap \Pi$, bounding the umbra where the umbra is on the concave side of α (Figure 7-left).

We now consider p_1 , one of the endpoints of s_1 , and curves α_2 , α_3 , the intersections of planes P_2 , P_3 with the cone of apex p_1 and base α (Figure 7-center), respectively.

Next, we reduce the obstacles P_2 and P_3 to convex polygons Q_2 and Q_3 by bounding them by a polygonal approximation of α_2 and α_3 such that Q_3 remains within (*i.e.*, on the convex side of) α_3 and Q_2 intersects α_2 n times (Figure 7-right). The umbra cast by s_1 on Π in the presence of Q_2 and Q_3 then consists of n connected components that are the intersection of the concave region outside α and the convex polygon that is the intersection of the cone of apex p_1 and base Q_2 with the plane Π .

Note that the polygons Q_2 and Q_3 are fat, that is, they have bounded positive aspect ratio when n goes to infinity, since Q_2 consists of a segment and of an approximation of a conic and Q_3 is of constant size. Finally, polygons Q_2 and Q_3 can be trivially transformed into fat convex polyhedra without changing the umbra. \square

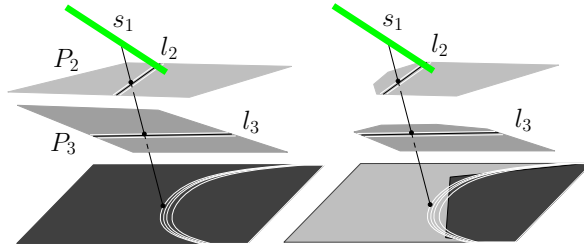


Figure 8: $\Omega(nk^2)$ lower bound.

Theorem 9. *The umbra cast on a plane by one segment light source in the presence of k disjoint convex polyhedra of total complexity n can have $\Omega(nk^2)$ connected components.*

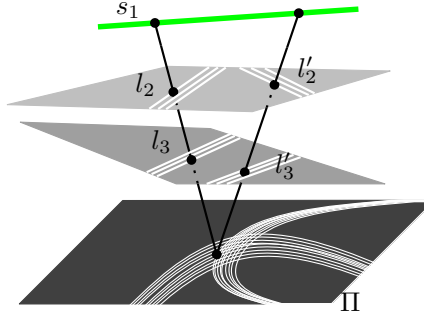


Figure 9: $\Omega(k^4)$ lower bound.

Proof. Consider three non-parallel segments s_1, l_2 , and l_3 all parallel to the shadow plane Π and planes $P_2 \supset l_2$ and $P_3 \supset l_3$ parallel to Π , refer to Figure 8. The surface $\langle s_1, l_2, l_3 \rangle$ intersects Π in a conic arc α .

Now consider the following setup: s_1 is the light source; P_2 has k narrow rectangular holes (or slits) parallel and arbitrary close to l_2 ; similarly P_3 has k slits parallel and arbitrary close to l_3 . (A plane with k such slits can be modelled by $O(k)$ rectangles). Each pair of slits, s_2 from P_2 and s_3 from P_3 , together with the light source s_1 induce a piece of penumbra in Π that is essentially a thickened copy of the conic arc α .

We thus get that the umbra covers the whole plane Π except for k^2 curves of penumbra that are all close to α (see Figure 8-left).

Finally, we trim the two planes P_2 and P_3 , creating an n -sided convex polygon on Π such that the region outside this polygon is in light or penumbra and each edge intersects all the k^2 curves. The umbra then consists of $O(nk^2)$ regions inside the convex polygon and between the k^2 conics (see Figure 8-right). Note that the $O(k)$ convex obstacles can each be transformed into a convex polyhedron by the addition of a single vertex without changing the umbra. \square

Theorem 10. *The umbra cast on a plane by a segment light source in the presence of k disjoint convex polyhedra can have $\Omega(k^4)$ connected components.*

Proof. Refer to Figure 9. As in the previous lower-bound example, we create k^2 curves of penumbra using parallel thin holes. Making a second set of thin holes in each plane, we create a second family of curves of light and penumbra intersecting the first one. The umbra is now the complement of the union of these two sets of curves and it consists of $\Omega(k^4)$ connected components. \square

We now present a lower bound on the maximum complexity of the arrangement A , introduced in Section 4.1, which proves (together with the proof of Theorem 2) that the worst-case complexity of this arrangement is $\Theta(nk^3)$.

Lemma 11. *The arrangement A cast by one segment light source in the presence of k convex obstacles of total complexity n can have an complexity $\Omega(nk^3)$.*

Proof. The proof is obtained by using large obstacles with small holes so that the shadow plane Π is almost completely in umbra with small curves of penumbra drawn by rays going through these holes. Such obstacles with small holes can be created using several convex polygons.

We consider a conic α drawn in Π and a line l_1 (containing the light source) intersecting Π in a point of α .

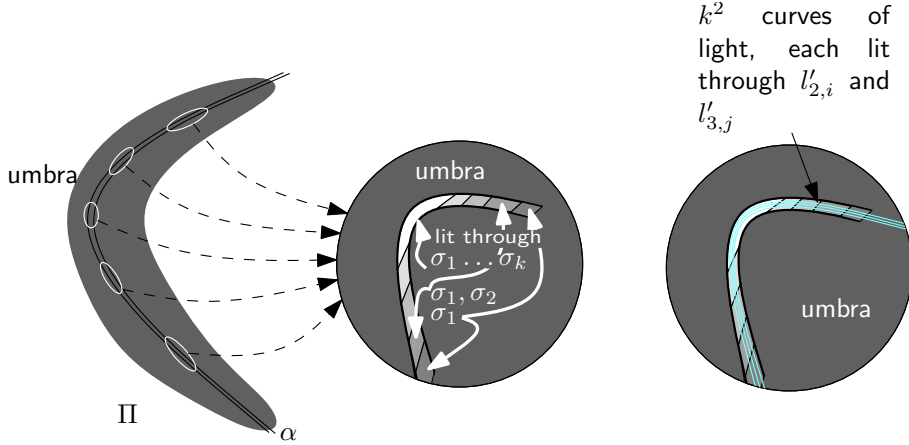


Figure 10: $\Omega(nk^3)$ lower bound on the complexity of arrangement A .

Let $x_1 = \alpha \cap l_1$ (x_1 is at infinity if l_1 is parallel to Π) and x_2, x_3, x_4, x_5 be four other points on α and x_6, x_7 be two other points on l_1 , then any quadric through these seven points contains α and l_1 . Since a quadric is defined by nine points, by choosing the two other points in a different manner we can construct different quadrics containing l_1 and α .

First we construct a set of quadric surfaces, $\sigma_1, \sigma_2 \dots \sigma_k$, close together. On σ_i we choose two lines $l_{2,i}$ and $l_{3,i}$, such that all the lines $l_{h,i}$ for all i and a given h are close together. Then we can construct a (non-convex) polyhedral obstacle of size $O(k)$ with thin holes around lines $l_{h,i}$ for $h = 2, 3; 1 \leq i \leq k$. We consider a plane P above, and parallel to, Π that intersects the quadrics σ_i in a family of conics β_i that are close together. We can construct in plane P a convex n -gon Q that intersects all these conics n times each.

Before the introduction of Q , the picture in Π is a slab of penumbra around α . Adding Q cuts this penumbra into n pieces, and, in each piece, there are k different intensities. Indeed, let p_0 be a point in one of these pieces on α and such that all the k transversals through p_0 and the three line segments $l_1, l_{2,i}$, and $l_{3,i}$, $i = 1, \dots, k$, are non-obstructed. If we move a point p along α and away from p_0 these transversals through p get obstructed one after another by Q until they are all obstructed, *i.e.*, until p is in the umbra (see Figure 10 left and center). This defines $\Omega(nk)$ regions of penumbra of different intensities of light around α .

Now, we choose a completely different quadric σ' far from the σ_i but still containing α and l_1 . Thus, we can choose two lines l'_2 and l'_3 in the same regulus as l_1 and arrange obstacles to light Π through thin holes around l'_2 and l'_3 . The area lit through these holes is also a small area around α . We can arrange things such that this area is much thinner than the previous one, and thus we get a thin curve of penumbra which crosses all the $\Omega(nk)$ regions we have described above. Now, making k holes $l'_{2,i}$ around l'_2 and k holes $l'_{3,j}$ around l'_3 we transform this thin penumbra curve into k^2 "parallel" curves making the size of the arrangement $\Omega(nk^3)$. \square

5.2 The umbra cast by a polygonal light source

Note that the lower bound of $\Omega(nk^2 + k^4)$ of Section 5.1 for a segment light source can easily be modified into a lower bound of $\Omega(nk^3 + k^6)$ in the case of a polygonal light source (by adding a third plane with $O(k)$ slits and a big polygonal light source). We present here a lower bound of $\Omega(n^2k^3 + nk^5)$ on the complexity of the umbra cast by a polygonal light source in the presence of k polygonal obstacles.

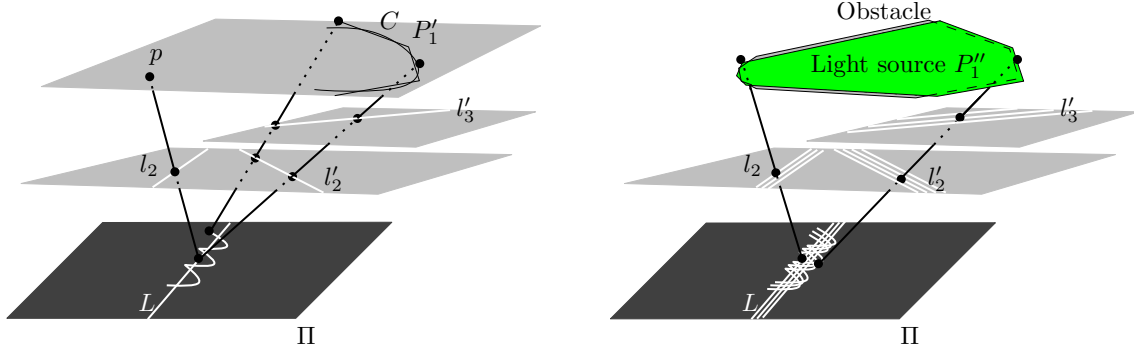


Figure 11: $\Omega(n^2 k^3)$ lower bound.

Theorem 12. *The umbra cast on a plane by one polygonal light source in the presence of k disjoint convex polyhedra of total complexity n can have $\Omega(n^2 k^3)$ connected components.*

Proof. Refer to Figure 11. Let p be a point and P_1 a small n -gon light source very close to p . Add an n -gon obstacle very close to the light source so that the light source behaves like n point light sources (when viewed from the correct side).

Now consider a plane obstacle with k thin holes parallel to a line l_2 . This creates nk parallel thin lines of light on the shadow plane that can be made arbitrarily close to a line L (by having the k thin holes sufficiently close to each other and the n point light sources sufficiently close to each other). Note that by duplicating this construction (and thus with two polygonal light sources which behave as $2n$ point light sources) we get an arrangement of $2nk$ lines of light with $n^2 k^2$ connected components of umbra.

Now consider two lines l'_2 and l'_3 . The set of line transversals to l'_2 , l'_3 and L is a quadric. Cut this quadric by a plane and approximate (a piece C of) the resulting conic by a convex polyline with n vertices, P'_1 . The set of transversals to this polyline with l'_2 and l'_3 defines a curve on the shadow plane that cuts L in $O(n)$ points. We define a light source as the convex hull of P'_1 and put an obstacle very close to it so that the light source behaves as if the polyline P'_1 was the light source (when viewed from the right region). Now, replacing l'_2 and l'_3 by two plane obstacles with $\Omega(k)$ thin holes close and parallel to l'_2 and l'_3 , respectively, we get $\Omega(k^2)$ curves of light, each of which intersects $\Omega(n)$ times each of the nk lines of light close to L . This gives $\Omega(n^2 k^3)$ connected components of umbra.

Note that the two light sources P_1 and P'_1 can be merged into one by considering P''_1 in the same plane as P_1 , by noticing that there are enough degrees of freedom on l'_2 and l'_3 so that the convex hull of P_1 and an arc of the conic contains C on its boundary. \square

Theorem 13. *The umbra cast on a plane by one polygonal light source in the presence of k disjoint convex polyhedra of total complexity n can have $\Omega(nk^5)$ connected components.*

Proof. Refer to Figure 12. Consider three horizontal pairwise skew lines l_1, l_2, l_3 that lie above a horizontal plane Π . Their set of line transversals forms a patch of quadric in \mathbb{R}^3 . Let C be the conic defined as the intersection of this quadric with Π . Replace each of the l_i by a plane obstacle and k thin holes close to l_i and place a large (horizontal) light source S above these plane obstacles.

Consider now an n -gon P that intersects C at $O(n)$ points. Let s_4 and s_5 be two intersecting horizontal segments. Let P' be the n -gon symmetric to P with respect to the point of intersection between s_4 and s_5 . We consider P' as a light source and put an obstacle very close to it so that

it behaves as a one-dimensional polygonal light source when viewed from C . This induces on the shadow plane a polyline of light that intersects C at $O(n)$ points.

Now perturb segments s_4 and s_5 so that they do not intersect and replace them by (horizontal) plane obstacles with k thin holes close and parallel to s_4 and s_5 , respectively. We hence get k^2 curves of light, each of which consists of $O(n)$ conic arcs that each intersects C ; hence each of these k^2 curves of light intersects C at $O(n)$ points. By choosing the holes near l_1 , l_2 and l_3 sufficiently close to each other, respectively, each of the k^2 curves of light close to P intersects $O(n)$ times each of the k^3 curves of light close to C . We hence get $O(nk^5)$ connected components of umbra. \square

We finally present a lower bound on the complexity of the arrangement B , introduced in Section 4.2, which proves (together with the proof of Theorem 3) that the complexity of this arrangement is $\Theta(n^3k^3)$. Recall that arrangement B contains, by construction, all the curves that correspond to limit of umbra and, more generally, all the curves where the derivative of the light intensity is discontinuous. Note, however, that this arrangement also contains arcs that increase its complexity and that are not relevant to light simulation (for instance, the arcs generated by surfaces that do not intersect the light sources or by surfaces that intersect the interior of other polyhedra in the scene).

Lemma 14. *The arrangement B cast by polygonal light sources in the presence of k convex obstacles of total complexity n can have a complexity $\Omega(n^3k^3)$.*

Proof. Suppose, for simplicity, that n and k are such that $\frac{n}{k}$ and $\frac{k}{4}$ are integers. We first consider a construction of two families of $\frac{k}{4}$ polygons each, as introduced in [3]; see Figure 13. Consider a $\frac{n}{k}$ -regular polygon A_1 in the plane $x = 0$. Next we consider a copy, B_0 , of A_1 scaled by a factor of $(1 + \varepsilon)$, and on each edge of B_0 we place $\frac{k}{4}$ points. Polygon B_i , $1 \leq i \leq \frac{k}{4}$, is constructed by taking the i^{th} point on each edge of B_0 . If ε is small enough, the intersection points of A_1 and B_i are outside the other polygons B_j for $1 \leq j \leq \frac{k}{4}$ and $i \neq j$. Now the A_i , for $2 \leq i \leq \frac{k}{4}$, are constructed as copies of A_1 scaled by a factor $1 + \frac{i}{k}\varepsilon$. Finally, we translate slightly all these polygons so that they do not lie in plane $x = 0$. Namely, the A_i are translated by $i\varepsilon$ in the negative x direction and the B_i are translated by $i\varepsilon$ in the positive x direction.

We consider all these polygons as obstacles except for the A_i , i even, which we consider as light sources. Furthermore, we scale down all these polygons so that the scene behaves like

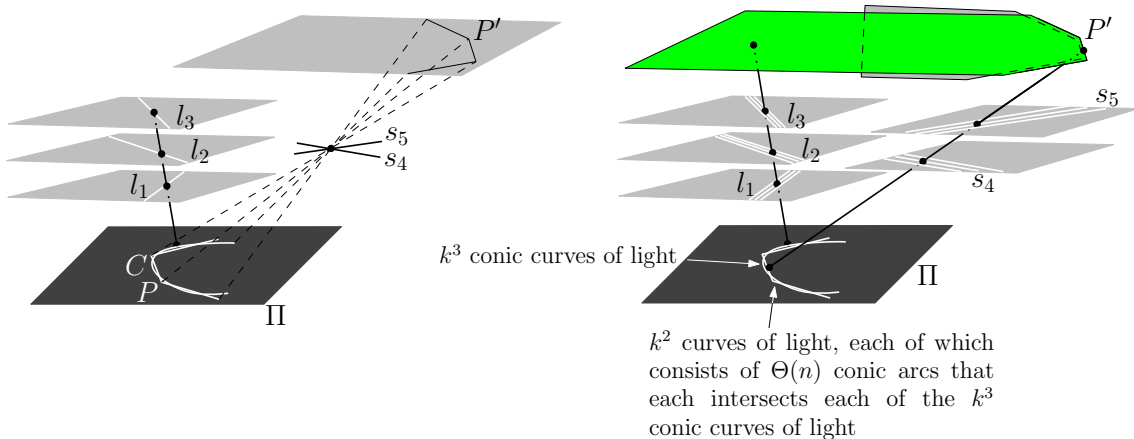


Figure 12: $\Omega(nk^5)$ lower bound.

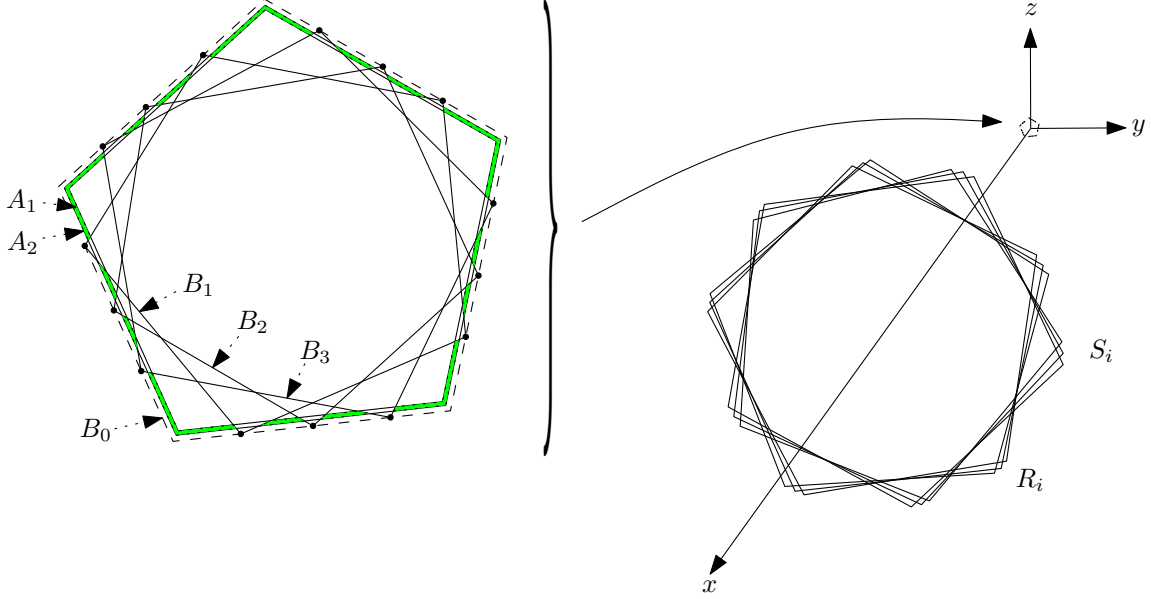


Figure 13: $\Omega(n^3k^3)$ lower bound on the complexity of arrangement B .

$\Theta(nk)$ almost point light sources that are arbitrarily close to each others (viewed from the correct side). On the other hand, consider a translated copy, R_0 , of B_0 in the plane, say $x = 10$. In that plane, let S_0 be a rotated copy of R_0 so that they intersect $2\frac{n}{k}$ times. Consider now two families of polygons R_i and S_i that are $\frac{k}{4}$ arbitrarily close copies of R_0 and of S_0 , respectively, and translate them slightly outside of the plane $x = 10$ so that no two polygons intersect.

We consider the arrangement B on plane, say $x = 20$, induced by these polygons. Let \mathcal{E} be the set of pairs of edges, one from a A_i and one from a B_j that bound one of the almost point light sources (*i.e.*, any two edges that intersect in projection on the plane $x = 0$).

Consider two edges r_k and s_ℓ of R_k and S_ℓ , respectively, that intersect in projection on the plane $x = 10$. Any pair of edges in \mathcal{E} defines with r_k an arc of the arrangement B and, similarly, any (possibly different) pair of edges in \mathcal{E} defines with s_ℓ another arc of B ; furthermore, two such arcs intersect by construction (since the two arcs are, roughly speaking, the umbra of two intersecting segments cast by two arbitrarily close point light sources). There are $\Theta(k^2)$ choices of pairs of R_k and S_ℓ , $\frac{n}{k}$ choices of edge r_k on R_k and 2 choices of segment s_ℓ on S_ℓ ; hence, there are $\Theta(nk)$ choices of pairs of edges r_k and s_ℓ . Since \mathcal{E} consists of $\Theta(nk)$ pairs of edges, the arrangement B contains $\Omega(n^3k^3)$ distinct pairs of intersecting arcs, that is, $\Omega(n^3k^3)$ vertices. Note finally that all the polygons A_i , B_j , R_k and S_ℓ can be easily transformed into pairwise disjoint very thin convex polyhedra. \square

As mentioned above, the arrangement B contains the arrangement, B' , of the curves where the derivative of the light intensity is discontinuous, but it also contains a number of arcs that increase its complexity and that are not relevant to light simulation. The best lower bound we know on the size of B' is $\Omega(n^3k^2 + n^2k^4)$. To prove that it can have size $\Omega(n^2k^4)$, we use the same construction as in Theorem 12 (Figure 11) and simply replace the two polygons that behave like n point light sources by the construction presented in the proof of Lemma 14 (Figure 13) that behaves like nk point light sources. Note that this bound does not apply to the boundary of the umbra because the construction does not perfectly emulate nk point light sources and the thin strips of light (close to line L in Figure 11) on the shadow plane overlap. To prove that B' can have size $\Omega(n^3k^2)$, we consider a point light source and a polygon of size $n/4$. We then duplicate

this construction elsewhere, so that the shadows created by the polygons and their associated point light sources are two polygons in the shadow plane that intersect $n/2$ times (twice per edge). We finally replace each point light source by the construction presented in the proof of Lemma 14 that behaves like nk point light sources.

6 Conclusion

The purpose of this paper is to establish the complexity of the boundaries between the umbra, penumbra and fully-lit regions on a plane in a polyhedral scene consisting of k convex objects of total complexity n .

The results presented here constitute a first step toward understanding the intrinsic structure and complexity of the umbra in this setting. We have proved that if the light is reduced to one line segment, then the umbra may have as many as $\Omega(nk^2 + k^4)$ connected components and has worst-case complexity $O(nk^3)$. We have also shown that a polygonal light source could generate an umbra with as many as $\Omega(n^2k^3 + nk^5)$ connected components and worst-case complexity $O(n^3k^3)$. In both cases these components of umbra are delimited by arcs of conics. These results prove that the umbra is intrinsically much more intricate than the boundary between full light and penumbra which is bounded by line segments and has complexity $O(n\alpha(k) + km\alpha(k) + k^2)$, where m is the complexity of the light source.

Our upper bounds, in fact, apply to the complexity of the arrangement of the curves where the derivative of the light intensity is discontinuous. These arrangements clearly include the boundary of the umbra, but also a lot of curves inside the penumbra that are not relevant to the umbra. Furthermore, our upper bound, $O(nk^3)$, on the complexity of these arrangements is tight for a segment light source. For polygonal light sources, our upper and lower bounds, $O(n^3k^3)$ and $\Omega(n^3k^2 + n^2k^4)$, on the complexity of these arrangements are not tight but they are tighter than for the complexity of the umbra. This perhaps explains why our bounds on the complexity of the umbra are not tight. Notice, however, that we do have tight bounds for small n ($n = O(k)$) and, in the case of segment light source, for small k ($k = O(1)$).

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