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Abstract

Given a collection of n low-degree algebraic surface patches in 3-space with the property that any vertical line stabs at most k of them, we wish to determine the maximum combinatorial complexity, $D(n,k)$, of the entire arrangement that they induce. We show that $D(n,k) = \Theta(n^2k)$. We extend this result to collections of hypersurfaces in 4-space and to collections of $(d-1)$-simplices in d-space. We apply these results to obtain upper bounds on the maximum number of views of a polyhedral terrain consisting of n edges and vertices. Our bounds are $O(n^4\lambda_4(n))$ for views from infinity and $O(n^7\lambda_4(n))$ for perspective views, where $\lambda_4(n)$ is a near-linear function related to Davenport-Schinzel sequences. Furthermore, we show that these bounds are almost tight in the worst case.

In the special case of an arrangement of k convex polyhedra having a total of n faces, we show that the worst case complexity of the arrangement is $\Theta(nk^2)$. For the number of views of a collection of k convex polyhedra with a total of n faces, we show a bound of $O(n^4k^2)$ for views from infinity and $O(n^6k^3)$ for perspective views.

1 Introduction

In this paper we study several instances of the so-called *aspect graph* problem, which has recently attracted much attention, especially in computer vision. Aspect graphs are often studied in the context of three-dimensional scene analysis and object recognition. The complexity of an aspect graph is determined by the number of combinatorially different views of a scene. To bound this number, we investigate arrangements of curves and of surfaces that have a certain sparseness property.

1.1 Background

At a high level, the aspect-graph[1] problem can be formulated as follows: Given a three-dimensional scene consisting of one or more three-dimensional objects, how many qualita-

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[1]The term *aspect graph* is synonymous with *characteristic views, viewing data* and other similar terms.

tively different two-dimensional images can the scene induce and how efficiently can one compute and represent a partitioning of the viewing space into maximal connected portions having the same view each. A concrete instance of the problem is specified by determining (i) the type of objects in the scene; (ii) the viewing space; and (iii) what makes a pair of images of the scene qualitatively different. Koenderink and van Doorn introduced the notion of aspect graphs more than a decade ago [12],[13]. Since then, aspect graphs have attracted a lot of interest, mainly in the computer vision community, e.g., [4], [5], [11], [14], [21], [22]. We also mention the works of Plantinga and Dyer [16] and of Gigus et al. [9] that have a computational geometry flavor.

Here we give the basic terminology needed in the sequel. For a broader introduction and a survey of recent research on aspect graphs see, e.g., [3], from which we borrow most of the subsequent terminology. In this paper, we restrict ourselves to polyhedral scenes, where every face of an object is flat and any induced image of an object is a straight line drawing. We will consider two types of viewing spaces. One is views from infinity which can be modeled by the *viewing sphere* or *sphere of directions* (a view from infinity is also called an *orthographic view*). Conceptually, we place a very large sphere centered at the origin around our scene, and each point on the surface of the sphere represents the direction of view from that point towards the origin. For every direction, the view of the scene is the result of an orthographic (parallel) projection of the visible portions of the objects in the scene onto a plane far from the scene. The other, more general model of viewing space is where we allow the viewing point to be anywhere in the 3D space of the scene, and a view from a point p is the perspective projection of the scene as seen from p. (The perspective view of a scene from a point p can be illustrated by considering an infinitesimally small sphere s centered at p, onto which the scene is projected.)

A fixed view of the scene can be regarded as a planar straight edge arrangement consisting of faces, edges and vertices. We consider two views to be the same if the combinatorial structure of their respective arrangements is the same. We wish to partition the viewing space into maximal connected regions such that inside one region all the views are the same (these will be referred to as *general viewpoints*) and as we cross from one region to the other the view changes. Thus, for views from infinity, we aim to partition the sphere of directions into maximal faces of general viewpoints separated by critical curves, which represent *accidental viewpoints.* For perspective views we aim to partition the entire space of the scene into maximal connected 3D regions having the same view and separated by critical surfaces.

The term *aspect graph* originates from a certain representation of the viewing space as a discrete graph where each node of the graph represents a maximal connected component of the space having the same aspect (or view). Plantinga and Dyer [16] have shown that the maximum number of views of a convex polyhedron with n vertices is $\Theta(n^2)$ for views from infinity and $\Theta(n^3)$ for perspective views. Later, it has been shown that for a general polyhedron, or more generally, for a collection of n non-intersecting triangles in space, the maximum number of views can be as high as $\Theta(n^6)$ for orthographic views and $\Theta(n^9)$ for perspective views [17]. Snoeyink [20] has shown that even if we restrict the objects to be axis-parallel polyhedra, the bound for orthographic views remains $\Theta(n^6)$.

1.2 Summary of Results

In this paper we study two instances of the aspect-graph problem where better bounds can be shown: (i) The case where the scene consists of a *polyhedral terrain* with a total of n edges; and (ii) where the scene consists of k convex polyhedra with a total of n edges. A polyhedral terrain is the graph of a piecewise-linear (polyhedral) continuous function $z = F(x, y)$ defined over the entire xy plane. Cole and Sharir [8] have studied a variety of visibility problems for polyhedral terrains, and showed that the maximum number of distinct views when the viewpoint moves along a fixed vertical line is considerably smaller than the number of distinct views when the viewpoint moves along a line in any other direction. To bound the overall number of views of a polyhedral terrain, we need additional machinery and we consider a special type of *arrangements*. An arrangement of surfaces in d-space is the partitioning of d-space induced by a collection of surfaces. Arrangements play a central role in computational geometry, and the analysis of many geometric algorithms relies on the *complexity* of an arrangement or of portions of an arrangement. The complexity of an arrangement of surfaces in 3-space, for example, is the overall number of faces of dimensions $0, 1, 2$ and 3 in the partitioning of space induced by these surfaces. We obtain the following result which we believe to be of independent interest (Proposition 2.3):

> Given a collection of n low-degree algebraic surface patches in three-dimensional space such that every vertical line stabs at most k of them, $k > 1$, the arrangement induced by these surface patches has complexity $\Theta(n^2 k)$.

This generalizes and improves a result by Sharir [19], who gives an $O(n^2 k\alpha(n/k))$ bound for the case of triangles[2]. We generalize the result even further to collections of hypersurfaces in 4-space and collections of $(d-1)$-simplices in d-space with a low 'vertical stabbing number'.

Using the above result and an analogous result in the plane we show that the maximum number of views of a terrain with n vertices is $O(n^4\lambda_4(n))$ for views from infinity and $O(n^7\lambda_4(n))$ for perspective views, where $\lambda_4(n)$ is a near-linear function related to Davenport-Schinzel sequences, $\lambda_4(n) = \Theta(n2^{\alpha(n)})$ [1]. Furthermore, we show that these bounds are almost tight in the worst case. We also investigate arrangements of k convex polyhedra having a total of n faces—where *any* line stabs only $2k$ faces—and we obtain an improved and tight bound $\Theta(nk^2)$ on the maximum complexity of such an arrangement.

Finally, we study another instance of the aspect-graph problem where the scene consists of k opaque convex polyhedra having a total of n faces. This time we show that the number of curves (or alternatively surfaces) determining the partitioning of the view space is only $O(n^2 k)$ (instead of $\Theta(n^3)$ in the general case) and thus we obtain a bound $O(n^4 k^2)$ on the maximum number of views from infinity and $O(n^6 k^3)$ for perspective views.

The paper is organized as follows: In Section 2 we derive a collection of combinatorial results concerning sparse arrangements in two-, three- and higher dimensions. We then

[2] Here and throughout the paper, $\alpha(n)$ is the extremely slowly growing functional inverse of Ackermann's function.

apply some of these results, in Section 3, to obtain near-tight bounds on the maximum number of views of polyhedral terrains. In Section 4 we consider arrangements of convex polyhedra. In Section 5 we bound the number of views of collections of convex polyhedra. Some concluding remarks and open problems are presented in Section 6.

2 Arrangements of Surfaces with Low Vertical Stabbing Number

This section deals with arrangements of surfaces where any vertical line intersects only a subset of them. In Subsection 2.1 we obtain several combinatorial results for the three-dimensional case that we will be using in the next section. In Subsection 2.2, we extend these results to arrangements of hypersurfaces in 4-space and to arrangements of $(d-1)$-simplices in d-space, for any fixed d.

2.1 Combinatorial Analysis

We start with the easier case of arrangements of curves in the plane and then proceed to handle arrangements of surfaces in 3-space.

Consider an arrangement of n simple curves in the plane, where a pair of curves intersects at most s times for some constant s. The maximum complexity of the entire arrangement in such a case is clearly $\Theta(n^2)$. We are interested in arrangements of curves that have the additional property that every vertical line intersects at most k of the curves. The following result has been previously obtained by several authors (we are aware of a simple and tight bound by Pach, and an almost tight bound by Sharir—both can be found in [19]). We present another simple proof that gives a tight bound. Later we will use a generalization of it for the three-dimensional case.

Lemma 2.1 *Given a collection of n Jordan arcs in the plane, where every pair intersects at most a constant number of times and any vertical line stabs at most k of the arcs, then the maximum complexity, $B(n,k)$, of the partitioning of the plane induced by these curves is $\Theta(nk)$.*

Proof. Partition the plane into n/k vertical slabs such that each slab contains at most $2k$ endpoints of the curves. Inside each slab we have at most $2k$ curves: We consider the intersection of a curve with the vertical boundary of the slab as an endpoint; we thus have at most $4k$ potential endpoints at our disposal—$2k$ inside the slab and $2k$ on its boundaries, therefore we can "pay" for at most $2k$ curves. Hence, there are at most $O(k^2)$ intersection points inside each slab. The total number of intersection points is therefore $n/k \cdot O(k^2) = O(nk)$. The number of intersection points obviously serves as an upper bound on the complexity of the arrangement.

The lower bound follows from the lower bound in Proposition 2.4 with $d = 2$. □

Next, we consider arrangements of algebraic surface patches (2-manifolds with boundary) in three-dimensional space. We assume the surface patches that we deal with to be algebraic of maximum degree b, where b is a small constant. Also we assume that the boundary of each surface patch consists of a small constant number of algebraic curves, all of maximum degree b. There are a few ways to extend the two-dimensional problem to the three-dimensional case. A straightforward extension is the following:

Lemma 2.2 *Given a collection of n low-degree algebraic surface patches in 3-space such that every plane parallel to the yz plane intersects only k of them, then the maximum complexity, $B'(n,k)$, of the entire arrangement induced by these surface patches is $\Theta(nk^2)$.*

But for our purposes (as will be discussed in the next section) we need a different extension whose proof requires the use of a more powerful divide-and-conquer technique.

Proposition 2.3 *Given a collection of n low-degree algebraic surface patches in three-dimensional space such that every vertical line stabs at most k of them, $k > 1$, then the maximum complexity, $D(n,k)$, of the arrangement induced by these surface patches is $\Theta(n^2k)$.*

Proof. First we decompose each surface patch into a constant number of surface patches, with the property that any vertical line intersects any patch in at most one point. We denote the resulting collection of surface patches by S. Then we project the boundaries of the patches onto the xy-plane. This gives a set C of $O(n)$ low-degree algebraic curves.

Next, we use random sampling (see [7]) to control the divide-and-conquer process. We choose a sample of curves $R \subset C$ of size r, and consider the arrangement $\mathcal{A}(R)$, which admits a vertical decomposition into $m = O(r^2)$ faces $f_1, f_2, \ldots, f_m$. Let n_i be the number of curves in C crossing the face f_i. ¿From the analysis of Clarkson and Shor [7], it follows that for any fixed integer $\nu \geq 0$, there is a sample $R \subset C$ of size r for which the following holds:

$$\sum_{i=1}^{m} n_i^{\nu} = O(r^2(n/r)^{\nu}). \tag{1}$$

We choose a sample R of size r for which $\sum_{i=1}^{m} n_i^3 = O(n^3/r)$. Consider one face f_j in the decomposed arrangement and let S_1 be the subset of surfaces of S whose projection onto the xy plane fully contains the face f_j. Let S_2 be the subset of surfaces of S for which the projection of their 1D boundary crosses f_j.

By the assumption of low vertical stabbing number, we know that $|S_1| < O(k)$. By definition $|S_2| = n_j$. Therefore, the complexity of the arrangement above the face f_j is $O((k+n_j)^3)$. Hence

$$D(n,k) = O(\sum_{i=1}^{m}(k+n_i)^3) = O(\sum_{i=1}^{m}(k^3 + k^2n_i + kn_i^2 + n_i^3)).$$

It can be easily verified, that if Equation (1) holds for a certain ν, then it also holds for any μ, $1 \leq \mu < \nu$ (by using Hölder's inequality [10], for example). Therefore, $\sum_{i=1}^{m} n_i^2 = O(n^2)$

and $\sum_{i=1}^{m} n_i = O(nr)$. Choosing $r = \frac{n}{k}$ leads to the desired bound

$$D(n,k) = O(n^2 k).$$

That the bound is tight follows from the lower bound in Proposition 2.4 with $d = 3$. □

Obviously, if $k = 1$, then the surfaces are pairwise disjoint and therefore the complexity of the entire arrangement is $\Theta(n)$. See also Remark 2.5 below.

2.2 Extension to Higher Dimensions

The proof of the previous results relies on "good" partitioning schemes in $(d-1)$-dimensional space. Such partitionings are available for arrangements of simplices in any dimension and for arrangements of low-degree algebraic surfaces in 3-space.

Proposition 2.4 *Given a collection of n $(d-1)$-simplices in E^d for a fixed d, such that any vertical line (i.e., a line parallel to the X_d axis) stabs at most k of them, then the arrangement induced by these simplices has maximum complexity $O(n^{d-1}k)$. Furthermore, this bound is tight for $k > d-2$.*

Proof. Project the simplices onto the hyperplane $X_d = 0$ and construct a $(1/r)$-cutting[3] of size $O(r^{d-1})$ for the projected objects (see [15]). Taking $r = n/k$ we can bound the complexity $D_d(n,k)$ of the entire arrangement as follows:

$$D_d(n,k) = O(r^{d-1}(k + n/r)^d) = O(n^{d-1}k).$$

For the lower bound, construct a "grid" made of n $(d-2)$-simplices on the hyperplane $X_d = 0$ that has complexity $\Omega(n^{d-1})$. Extend each $(d-2)$-simplex in the X_d direction into a "long" $(d-1)$-simplex. Finally, cut the resulting $(d-1)$-simplices by additional $k-d+1$ $(d-1)$-simplices, all parallel to the hyperplane $X_d = 0$. □

Remark 2.5 The reason why the above lower bound holds only for $k > d-2$ is that the grid of the construction has edges parallel to the X_d-axis each of which is the intersection of $d-1$ $(d-1)$-simplices. Consequently, the grid itself requires that the vertical stabbing number be at least $d-1$.

Proposition 2.6 *Given a collection of n low-degree algebraic hypersurfaces in four-dimensional space such that every vertical line (i.e., a line parallel to the X_4 axis) stabs at most k of them, the arrangement induced by these surfaces has complexity $O(n^3 k\, \beta(\frac{n}{k}))$, where $\beta(\cdot)$ is an extremely slowly growing function.[4] Moreover, for $k > 2$, the complexity can be as large as $\Omega(n^3 k)$.*

[3] Given a set S of n $(d-1)$-simplices in E^d, a $(1/r)$-*cutting* for S is a collection Ξ of (possibly unbounded) closed d-simplices which together cover E^d and such that the interior of each simplex in Ξ is intersected by at most $\frac{n}{r}$ $(d-1)$-simplices of S. For more details, see, e.g., [15].

[4] The function $\beta(n)$ is defined in [6]: $\beta(n) = 2^{\alpha(n)^c}$, where c is a constant depending on the degree of the surfaces that are the projection of the original hypersurfaces onto the hyperplane $X_4 = 0$.

Proof. The proof is similar to the proof of Proposition 2.3, and it uses random sampling and the stratification scheme of Chazelle et al. [6]. The lower bound follows from the lower bound of Proposition 2.4 for the case $d = 4$. □

3 The Number of Views of Polyhedral Terrains

In this section we apply the results of the previous section to obtain upper bounds on the number of views of polyhedral terrains when viewed from infinity or from anywhere in 3-space. We also show that our bounds are almost tight in the worst case.

A polyhedral terrain is the graph of a piecewise-linear (polyhedral) continuous function $z = F(x, y)$ defined over the entire xy plane. We assume that the graph has n edges. Since the projection of the terrain onto the xy plane is a planar map, the number of vertices and faces of the polyhedral terrain is $O(n)$. Cole and Sharir [8] study a variety of visibility problems for polyhedral terrains. In particular, they consider the number of views of a terrain when the viewpoint is restricted to move along a given vertical line. We will be using their result, which we now state (in a slightly modified manner):

Theorem 3.1 (Cole and Sharir [8]) *The maximum number of different views of a polyhedral terrain with n vertices when the viewpoint moves along a given vertical line is $O(n\lambda_4(n))$, that is $O(n^2 2^{\alpha(n)})$.*

We extend this result to larger view spaces. In the following subsection we handle the views from infinity and in Subsection 3.2 we deal with perspective views.

3.1 Views from Infinity

To bound the number of views from infinity we partition the *sphere of directions* into maximal connected components such that the view from any two points inside one component is combinatorially the same. Our goal is to obtain a bound the maximum number of these components. The partitioning is induced by certain curves. There are three types of these curves: One type is defined by the plane through a face of the terrain—this curve is a circle on the sphere of directions which is the intersection with the plane through the center of the sphere of directions, that is parallel to the face. Another type is defined by a vertex-edge pair of the terrain. It is also a circle on the sphere of directions resulting from intersecting the sphere of directions with a plane through the center that is parallel to the plane that passes through the vertex and the edge. The third type is a curve describing the union of directions of lines that pass through the same three edges of the terrain. (See [9] for a detailed study of these curves.) By definition, there are $O(n)$ curves of the first type, $O(n^2)$ curves of the second type and $O(n^3)$ curves of the third type. These are all algebraic curves of low degree. An immediate, naive bound on the number of different views is $O(n^6)$ which is the maximum number of faces in a partitioning of a plane (or a sphere) by $O(n^3)$ curves, each pair of which does not intersect more than some constant number of times. But for a polyhedral terrain, we can obtain an improved bound.

We assume, without loss of generality, that the terrain has a minimum z-value $z = z_0$. We fix the center of the sphere of directions to lie on the plane $z = z_0$ and so we are only interested in the upper hemisphere. It is not difficult to see that in terms of views from infinity, Theorem 3.1 can be rephrased to give the same bound on the maximum number of views when letting the viewpoint move along a fixed meridian on the sphere of directions. This implies that as we move the viewpoint along the meridian, although there are $O(n^3)$ curves on the sphere, it does not cross more than $O(n\lambda_4(n))$ curves on its way. Noting that a meridian to the hemisphere is like a vertical line to the plane, we may employ Lemma 2.1 when the total number of curves in this case is $O(n^3)$ and the "vertical" stabbing number is $O(n\lambda_4(n))$. This proves the upper bound in the next theorem. Anticipating the lower bound result that we give below, we have:

Theorem 3.2 *The maximum number of combinatorially distinct views of a polyhedral terrain with a total of n edges, when viewed from infinity, is $O(n^4\lambda_4(n))$. Moreover, the number of views can be as large as $\Omega(n^5\alpha(n))$.*

Our approach to designing lower bound constructions for the number of views consists of building a separate construction for every degree of freedom of the viewpoint such that when fixing one degree of freedom, all the views for the other degree(s) of freedom are attainable. Thus, the number of views of the whole construction is the product of the number of views for each degree of freedom. (This approach will be further exemplified in Section 5.)

For views from infinity, we may regard our viewpoint as moving on the sphere of directions, that is, it has two degrees of freedom. Since our construction will use viewpoints belonging to only a certain portion of the sphere of directions, we may alternatively think of our viewing space as represented by a vertical plane placed far away from the scene. Using this plane as our viewing space model, we can employ terms like *nearer to* or *further away from* the viewpoint space. In this model, the equivalent of a meridian of the sphere of directions is a vertical line on the viewing plane. The equivalent of a *parallel of latitude* (the intersection of a plane parallel to $z = 0$ with the sphere of directions) of the sphere model, is a horizontal line on the viewing plane. We will be using both models alternately.

One construction, for walking up and down a vertical line on the viewing plane, we adapt from [8] (see Figure 1): We take n segments whose upper envelope complexity is $\Omega(n\alpha(n))$ (as in [23]). These segments are put on parallel vertical planes (parallel to our viewing plane) and a thin wedge is drawn downwards from each of them. Further away from the viewing plane we construct a "hill" consisting of parallel horizontal slabs. We take the horizontal edges of the hill to be parallel to the viewing plane. The upper envelope of the thin wedges is constructed such that when moving the viewpoint up a vertical line, the last time a vertex of the upper envelope coincides with an edge e of the hill is before the first time a vertex of the upper envelope coincides with the edge lying immediately below e on the hill. Thus, while moving up a vertical line, we get $\Omega(n^2\alpha(n))$ different views. We call the above construction *the vertical construction.*

The second construction, *the horizontal construction*, is for walking along a horizontal line on the viewing plane. This construction is an adaptation of a part of a construction by

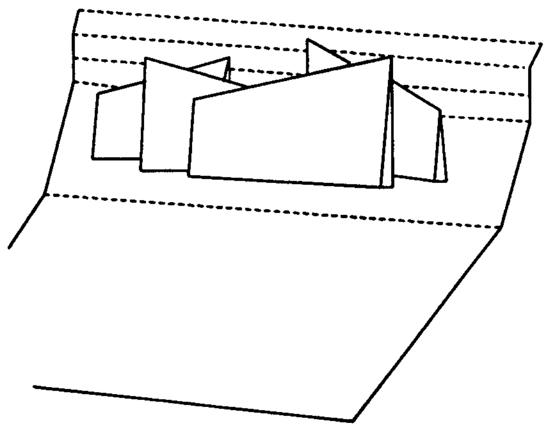

Figure 1: A construction with $\Omega(n^2\alpha(n))$ different views when moving vertically

Canny [17] for the lower bound for the number of views of arbitrary polyhedra. Far from the viewing plane we construct a hill similar to the previous one, only this time the edges defining the hill are slanted. See Figure 2. Before the hill, nearer to the viewing plane, we construct a collection of n pyramids in a row which we denote by S. So far we have created a slanted grid—for a fixed view, a vertex of the grid is created by the intersection (of the projection) of a visible edge of a pyramid and an edge of the hill. Finally, farther from the grid and nearer to the viewing plane we construct a collection of n almost flat prisms which we denote by S'. When viewed from our viewing plane, the prisms of S' resemble wide rectangles, and every edge of a prism that extends from the horizontal plane upwards is very steep, almost vertical. The distance between the adjacent quasi-vertical edges of two neighboring prisms is chosen to be very small. The distances are chosen such that when we move the viewpoint on a horizontal line, we see all the intersection points of the grid through one interval between a pair of prisms of S', before we see any other intersection point of the grid through another interval between another pair of prisms of S'. Consider one such interval between a pair of prisms of S'. The edges that define this viewing "crack" are almost vertical, whereas the edges of the pyramids have a smaller slope. As we move the viewpoint horizontally, each vertex of the grid will coincide with the say, left edge of the interval at a different viewpoint, inducing $\Omega(n^2)$ different views for one interval. Since there are $\Omega(n)$ distinct intervals between adjacent prisms, we get $\Omega(n^3)$ distinct views when moving on a horizontal line.

If we choose the proportions of the two constructions (the horizontal and the vertical) carefully—in particular we make the hill in the vertical construction sufficiently long and the pyramids and prisms in the horizontal construction sufficiently high—then when fixing one degree of freedom of the viewpoint we can achieve all the views for the other degree of freedom. Therefore, in total the number of views of a polyhedral terrain when viewed from infinity can be $\Omega(n^5\alpha(n))$ in the worst case.

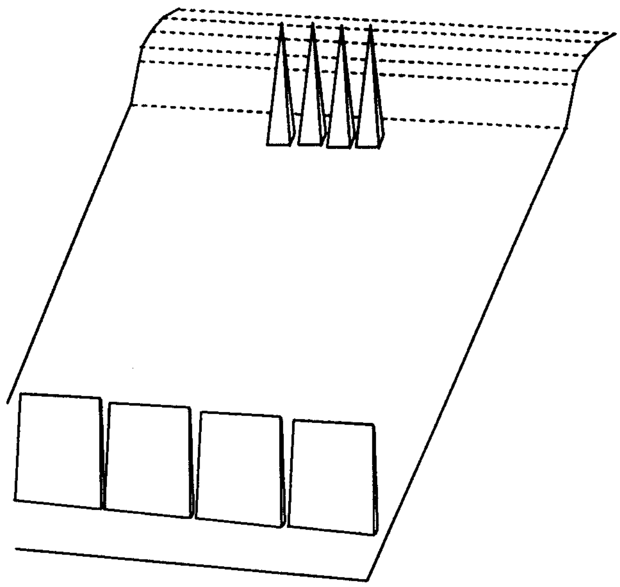

Figure 2: The horizontal construction for a polyhedral terrain, with $\Omega(n^3)$ views

Recall that $\lambda_4(n) = \Theta(n2^{\alpha(n)})$ [1], thus there is only a small gap between the lower and upper bounds that we have shown.

3.2 Perspective Views

For perspective views the viewpoint may be anywhere in 3-space. The surfaces that we have previously used to define curves on the viewing sphere now serve to partition the space into maximal connected (three-dimensional) cells where the perspective view does not change. By the same arguments as for views from infinity we have $O(n^3)$ such surfaces. Theorem 3.1 implies that when we let the viewpoint move along a fixed vertical line, it does not cross more than $O(n\lambda_4(n))$ of these surfaces. This is an upper bound on the vertical stabbing number of the arrangement of $O(n^3)$ surfaces. Plugging these quantities into Proposition 2.3 we get the upper bound in the next theorem.

The lower bound construction is similar to the construction of the previous subsection. In fact, we start with the same construction as for orthographic views, and for the extra degree of freedom that we now have, we use a displaced duplicate of the $\Omega(n^3)$ construction that induces changes in view as the viewpoint moves forwards or backwards. This results in a scene with $\Omega(n^8\alpha(n))$ different views.

Theorem 3.3 *The maximum number of combinatorially distinct perspective views of a polyhedral terrain with a total of n edges, is $O(n^7\lambda_4(n))$. Moreover, the number of views can be as large as $\Omega(n^8\alpha(n))$.*

4 Arrangements of Convex Polyhedra

We next study arrangements defined by a collection of convex polyhedra in 3-space. These arrangements have the special property that a line in any direction stabs only a subset of the surfaces. Note that we consider the interior of each polyhedron as a portion of the arrangement. We prove the following theorem[5]

Theorem 4.1 *The maximum complexity of an arrangement induced by k convex polyhedra with a total of n vertices is $\Theta(nk^2)$.*

Proof. For the upper bound, note that the set S of k convex polyhedra has stabbing number $2k$ in any direction. Consider a segment $f \cap g$ for f, g faces of polyhedra in S. Then, either an edge e_f of f intersects g, or an edge e_g of g intersects f. By the stabbing property, each edge intersects at most $2k$ faces and hence there are at most $2nk$ segments $f \cap g$, over all faces f, g of all the polyhedra in S. Using the stabbing property once more, we see that each segment $f \cap g$ is intersected by at most $2k$ faces, and the upper bound follows.

To see that this bound is tight in the worst case, assume $k \leq n/3$ and take a convex polygon P_1 with n/k vertices lying in the yz-plane. (If $k > n/3$ it is trivial to construct an arrangement with $\Omega(nk^2) = \Omega(n^3)$ vertices.) Denote the number of vertices of P_x by $|P_x|$. Duplicate P_1 $\lfloor k/2 \rfloor - 1$ times to obtain polygons $P_2, \ldots, P_{\lfloor k/2 \rfloor}$ and rotate P_i slightly relative to P_{i-1} (see Figure 3). This results in a planar arrangement (in the yz plane) with complexity $\frac{1}{2}\sum_{i \neq j}(|P_i| + |P_j|) = \Omega(nk)$. Next, extend this arrangement in the x direction, and slice the resulting arrangement of cylinders with additional $\lfloor k/2 \rfloor$ triangles, all parallel to the yz plane to get a subdivision of space with complexity $\Omega(nk^2)$. The overall number of polyhedron vertices in the construction is $n/2 + 3k/2 \leq n$. □

5 The Number of Views of Convex Polyhedra

In this section we study the number of views of a three-dimensional scene consisting of k non-intersecting opaque convex polyhedra having a total of n vertices. Again we consider two types of viewpoint space: The space related to orthographic views (from infinity) and the space related to perspective views. In [16] it was shown that for one convex polyhedron these bounds are $\Theta(n^2)$ and $\Theta(n^3)$. We first derive upper bounds on the maximum number of views of k convex polyhedra and then give lower bounds.

In Subsection 3.1 we have considered three different types of curves (corresponding to accidental viewpoints) that appear on the sphere of directions in the case of a polyhedral terrain. The same types of curves may occur in the case of convex polyhedra. As before, the curves of the third type dominate the complexity of the arrangement, so we restrict our attention to them. Recall that a curve of the third type represents a collection of viewing directions for which the views of a fixed triple of edges of the polyhedra meet at one point.

[5] Independently, Aronov et al. [2] have obtained a similar result, generalized to arrangements of polytopes in d-dimensional space for a fixed d.

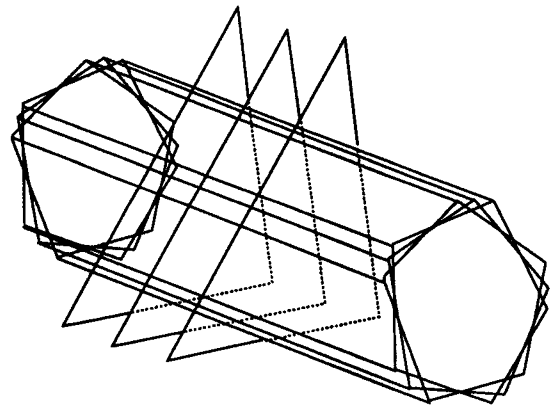

Figure 3: An arrangement of k convex polyhedra having $\Omega(nk^2)$ complexity

Let e_i, e_j and e_l be such a triple of edges. Assume for simplicity that each edge belongs to a distinct polyhedron P_i, P_j and P_l respectively. Each point on the curve represents a line L in the viewing direction that touches the three edges simultaneously. It is easy to verify that each such line L is tangent to at least two of the polyhedra P_i, P_j, P_l. In other words, it may cross the interior of at most one of these polyhedra, as the polyhedra are opaque. Suppose that this is indeed the case and it crosses through P_l. Then, necessarily, the contact between L and P_l lies farther from the viewpoint than the contacts with P_i or P_j.

Next, we fix e_l and bound the possible number of curves of the third type, induced by e_l and pairs of edges—one edge of the polyhedron P_i and one of P_j. Denote the number of vertices of P_x by $|P_x|$.

Lemma 5.1 *The maximum number of pairs of edges, one from P_i and one from P_j, such that together with e_l they define a critical curve on the sphere of directions and such that e_l lies farthest from the viewpoint is $O(|P_i| + |P_j|)$.*

Proof. Suppose first that there is a plane Π_l that contains e_l such that both P_i and P_j lie on one side of Π_l. Take a plane Π parallel to Π_l, far away from the scene and such that e_l is farther from Π than P_i or P_j. Let $q = q(0)$ be an endpoint of e_l and draw on Π the intersection of all the lines through $q(0)$ that are tangent to P_i. The resulting curve on Π is evidently the boundary of a convex polygon, which we denote by $Q_i = Q_i(0)$. The polygon $Q_i(0)$ has at most $O(|P_i|)$ edges. As we let $q(t)$ move along e_l towards the other endpoint $q(1)$, Q_i will change continuously. Still, it will always remain a convex polygon. Furthermore, it will change its (combinatorial) structure only when the line through $q(t)$ coincides with a plane of a facet of P_i. Thus it will not have new edges appearing (or else have edges deleted) more than $|P_i|$ times. The same arguments hold for P_j and its corresponding "shadow" Q_j on Π.

An intersection point of an edge of $Q_i(t)$ and an edge of $Q_j(t)$ along some interval $0 \le t' < t < t'' \le 1$ represents a curve of the third type on the sphere of directions. How many pairs of edges, one from each polygon, intersect on the boundary of the union of the two polygons? At $t = 0$ there are at most $(|Q_i(0)| + |Q_j(0)|) = O(|P_i| + |P_j|)$ such intersection. As t varies, every new pair of edges that intersect must be the result of a critical event that either makes the vertex of one polygon meet the edge of another, or that an edge of a polyhedron inducing a shadow edge is substituted by another edge of the same polyhedron. The first kind of critical event corresponds to the plane through a vertex of one polyhedron and the edge of the other polyhedron crossing e_l. For a fixed vertex of one polyhedron there are at most two edges of the other polyhedron that can participate in such an event, because we take the line through the vertex v and as we move it in contact with e_l it may be tangent to the other polyhedron, not containing v, at most twice. The second kind of critical event occurs when the line through $q(t)$ coincides with a plane of a facet of either polyhedron. This kind as well may incur at most two new intersections with the shadow of the other polyhedron. Therefore only $O(|P_i| + |P_j|)$ critical events occur as $Q_i(t)$ and $Q_j(t)$ move. And thus the overall number of potential curves involving e_l, P_i and P_j is at most $O(|P_i| + |P_j|)$.

To relax the assumption that there is a plane Π_l such that both polyhedra P_i, P_j lie on one side of it we do the following: We arbitrarily choose a plane Π_l containing e_l and cut each polyhedron that intersect Π_l by the plane Π_l into two. We repeat the analysis above for either side of Π_l and the polyhedra portions on that side. The only difference between the new situation and the previous one is that one or both of the corresponding Q_i and Q_j are now unbounded, but the entire analysis holds verbatim. □

Now we can state

Theorem 5.2 *The maximum number of combinatorially distinct views of a scene consisting of k convex non-intersecting polyhedra with a total of n vertices, when viewed from infinity, is $O(n^4k^2)$. The number of distinct views of such a scene where the viewpoint can be anywhere in space is $O(n^6k^3)$.*

Proof. Let $E(k,n)$ be the maximum number of curves of the third type that may appear on the sphere of directions in the current setting. Lemma 5.1 implies that for every edge e_l of a polyhedron P_l the number of critical curves of type three that it may induce due to interaction with a fixed pair of two additional polyhedra P_i and P_j is $O(|P_i| + |P_j|)$. Summing over all edges e_l we get

$$E(k,n) \le \sum_{i \ne j \ne l} |P_l| \cdot O(|P_i| + |P_j|) \le 2 \sum_{i=1}^{k} \sum_{j=1}^{k} \sum_{l=1}^{k} O(|P_j| \cdot |P_l|) = O(n^2 k).$$

The two bounds of the theorem immediately follow. □

Finally, we exhibit lower bound constructions for the number of views of convex polyhedra.

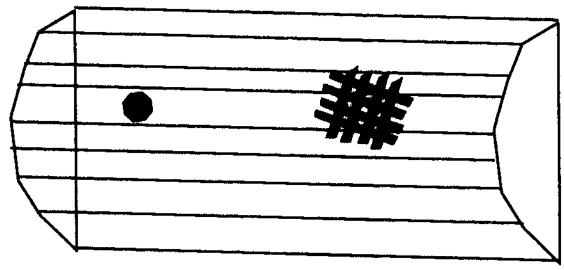

Figure 4: A vertical construction giving $\Omega(n^2 + nk^2)$ different views

Theorem 5.3 *A scene consisting of k convex polyhedra with a total of n vertices may induce $\Omega(n^4 + n^2k^4)$ distinct views from infinity and $\Omega(n^6 + n^3k^6)$ views when the viewpoint can be anywhere in space.*

Proof. Following the idea presented in Section 3 we first present a construction for one degree of freedom of the viewpoint that gives $\Omega(n^2 + nk^2)$ different views when moving along a vertical line. This construction is a superpositioning of two simpler constructions. The first consists of a "hill" with n horizontal edges in front of which there is a very small convex polygon with n edges. As we move the viewpoint up all the vertices of the polygon meet one edge of the hill in the view before they meet another edge (see Figure 4, on the left-hand side of the hill).

For the second construction we place a small slanted grid of roughly $k/2 \times k/2$ segments such that an edge of the hill meets all intersection points of the grid before another edge of the hill does so as the viewpoint moves up (see Figure 4, on the right-hand side of the hill). We position the polygon and the grid such that no two viewing events coincide as we move the viewpoint up or down.

We duplicate this construction and rotate the duplicate by 90° degrees to obtain a similar effect when moving from left to right. To obtain the bounds for perspective views we repeat the basic construction once again. □

6 Conclusion

In this paper we have shown almost-tight combinatorial bounds on the maximum number of qualitatively different views of polyhedral terrains. The bounds are an order-of-magnitude lower than the corresponding bounds for general polyhedra. We obtain these results by investigating arrangements of objects (curves or surfaces) that have the special property that every vertical line stabs only a small number of the objects. We believe that our results for this type of arrangements are of independent interest. We also presented extensions of these results to higher dimensions. Furthermore, we have presented bounds on the number of views of a scene consisting of k convex polyhedra with a total of n vertices.

We suggest the following open problems:

1. Tighten the gap between the lower and upper bounds on the number of views of k convex polyhedra with n vertices in total. A possible approach to improve the upper bound would be to obtain a low stabbing number in the spirit of the result by Cole and Sharir stated as Theorem 3.1 here.

2. What is the complexity of arrangements of surfaces that have a low stabbing number in more than one direction? For example, it would be interesting to have such a bound as a function of n, k_{min} and k_{max}, where k_{min} and k_{max} are the minimum and maximum stabbing number in any direction.

Our paper has concentrated on the combinatorial questions concerning aspect graphs of certain polyhedral scenes. We have not addressed the related algorithmic issues. Efficient computation of a sparse 2D arrangement is straightforward using *plane sweep* (see, e.g., [18]). We believe that computing a sparse 3D arrangement of surfaces in time that is roughly proportional to the maximum combinatorial complexity of the arrangement is fairly simple, imitating the proof of Proposition 2.3, although there are several technical details that still need to be studied. A somewhat more challenging problem is to compute an arrangement of convex polyhedra efficiently.

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