

Shadows and slices of polytopes*

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Abstract

We give a lower bound of $\Omega(f^{\lfloor d/2 \rfloor})$ for the number of vertices of a d -dimensional polytope with f facets which can appear on the outer boundary of a projection to any dimension $2 \leq k < d$. By duality, this implies a lower bound of $\Omega(n^{\lfloor d/2 \rfloor})$ for the number of facets in a k -dimensional slice of a d -dimensional polytope with n vertices. At the same time, the Upper Bound Theorem provides an $O(n^{\lfloor d/2 \rfloor})$ upper bound for this quantity. For cyclic polytopes, however, we show an upper bound of $O(n)$ on this quantity in dimension 4.

1 Introduction

A d -dimensional polytope with f facets may have no more than

$$M(f, d) := \binom{f - \lceil \frac{d}{2} \rceil}{\lfloor \frac{d}{2} \rfloor} + \binom{f - 1 - \lceil \frac{d-1}{2} \rceil}{\lfloor \frac{d-1}{2} \rfloor}$$

vertices, which is $O(f^{\lfloor \frac{d}{2} \rfloor})$; this is the dual statement of the Upper Bound Theorem for polytopes. This bound is achieved by the duals of the cyclic polytopes, defined below. The *shadow* of a d -dimensional polytope P is the set of points (x_1, x_2) such that some point (x_1, x_2, \dots, x_d) belongs to P , or, equivalently, the projection of P to the (x_1, x_2) -plane. The shadow is a convex polygon. How many vertices can the shadow of a d -polytope with f facets have? This question can be generalized in the obvious way, to k -dimensional shadows (k -shadows) for $2 \leq k \leq d-1$, where it also makes sense to ask for the number of i -faces, $0 \leq i \leq k-1$.

It is not inherently unreasonable to hope that the complexity of the shadow of P might be asymptotically less than that of P itself. We show, however, that the k -dimensional shadow of a polytope with f facets in d dimensions might, in the worst

*Much of this work was done while Nina Amenta was employed by the Geometry Center, which is officially the NSF Center for Computation and Visualization of Geometric Structures, supported by NSF/DMS-8920161, and during a visit to the Freie Universität Berlin, supported by the Deutscher Akademischer Austauschdienst.

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case, have complexity $\Omega(f^{\lfloor \frac{d}{2} \rfloor})$. Let $M_2(f, d)$ denote the maximal number of vertices in the shadow (i.e., of any 2-dimensional projection) of a simple d -polytope with f facets. Then $M_2(f, d) \leq M(f, d)$ is immediate. We show that both functions have the same order $\Theta(f^{\lfloor d/2 \rfloor})$ for fixed d . This is somewhat puzzling, since our results on projections of duals of cyclic polytopes suggest that $M_2(f, d)$ may not coincide with $M(f, d)$ even for $d = 4$.

Shadows are natural objects in combinatorial geometry, and they have a number of algorithmic applications. Perhaps most importantly, the shadow vertex algorithm for linear programming chooses a simplex path by following a two-dimensional shadow [GS, Borg]. Lower bounds on the size of the two-dimensional shadow provide lower bounds for this algorithm. Exponential lower bounds in the special case $f = 2d$ were given by Murty [Mu] and Goldfarb [Gol1, Gol2]; our example handles the case where d is fixed and provides worst-case bounds of $\Theta(f^{\lfloor d/2 \rfloor})$. This is in contrast to the results of Borgwardt [Borg], who has established a polynomial bound of at most $O(d^4 f)$ for the expected number of steps of the shadow vertex algorithm on random linear programs. A randomized version of the shadow-vertex rule that may be polynomial on every linear program was suggested by Gärtner & Ziegler [GZ].

The case of fixed dimension is important also for other optimization problems involving shadows. One natural optimization problem is the maximization of a convex function in k variables x_1, \dots, x_k over a polytope P . The maximum is achieved at some vertex of the k -shadow. For example, [AAAS] applies this maximization to finding the largest similar copy of one convex polygon contained in another, a problem with applications in vision and robotics. Sometime the shadow itself is an object of interest. In another robotics application, [PoFa] computes the three-shadow of a five-polytope representing the set of stable three-finger grasps of a polygon, with friction. They give an algorithm for computing k -shadows, and cite some other applications in artificial intelligence. [Chan] remarks that output-sensitive convex hull techniques can be applied to the output-sensitive computation of shadows.

This particular question about shadows is only interesting in dimensions four and higher. In three dimensions, it is not too difficult to construct simple polytopes in which every vertex appears on the shadow. Other questions concerning the shadows of three-dimensional polytopes are considered in [CEG].

2 Results

We relay on the following observation.

Observation 1 *A lower bound on the complexity of the two-dimensional shadow of a polytope also is a lower bound on the complexity of any k -shadow.*

This becomes obvious when we imagine doing the projection to two dimensions by projecting first to dimension k and then to the plane. Any vertex which shows up on the planar shadow has to correspond to at least one vertex on the k -shadow.

To prove the theorem, then, it is sufficient to exhibit a d -dimensional polytope with f facets which has a two-dimensional shadow with $O(f^{\lfloor d/2 \rfloor})$ vertices. Our construction of such a polytope essentially follows an example by Klee and Minty [KlMi] of a polytope with a long monotone path. We do the construction so as to be able to project the whole path to the plane. This gives us our main theorem.

Theorem 2 *For all d , there is a d -dimensional polytope P with f facets, such that the k -shadow of P has $O(f^{\lfloor d/2 \rfloor})$ vertices.*

This result answers an equally natural question in the dual setting. The dual of a polytope P with f facets is a polytope with f vertices. But what is the dual of the k -shadow? The $(d-1)$ -dimensional shadow of P is the intersection of the linear halfspaces parallel to the x_d axis containing P . In the dual, this is the intersection of the dual of P with the hyperplane $x_d = 0$. So the dual of the k -shadow of a polytope is the intersection of the dual polytope with a k -dimensional hyperplane.

Corollary 3 *For all d , there is a d -dimensional polytope P with n vertices, and a k -dimensional plane p in \mathbb{R}^d , such that the intersection $p \cap P$ is a k -polytope with $O(n^{\lfloor d/2 \rfloor})$ facets.*

Recall that the projection of the lower envelope of a polytope to \mathbb{R}^{d-1} is a regular $(d-1)$ -dimensional triangulation of the projected vertices of the lower envelope. If, in the example above, we consider a projection to \mathbb{R}^{d-1} in any direction parallel to p , we get the following configuration.

Corollary 4 *There is a regular triangulation T of a set of n points in \mathbb{R}^{d-1} , and a $(k-1)$ -plane p , which intersects $O(n^{\lfloor d/2 \rfloor})$ of the simplices of T .*

The cyclic polytope duals maximize the number of vertices over all d -dimensional polytopes with f facets, providing the lower bound example matching the Upper Bound Theorem. Somewhat surprisingly, we show the following upper bound on the complexity of the shadow of a cyclic polytope dual.

Theorem 5 *The projection of the dual of a 4-dimensional cyclic polytope with f facets to the plane can have at most $3f$ vertices.*

We also give an example of a projection of a 4-dimensional cyclic polytope dual which achieves $3f - 11$ vertices on the boundary of the projection.

3 The fourth dimension

In this section we develop the 4-dimensional case in detail. In the following section, we give the higher dimensional generalization.

Theorem 6 *There is a 4-dimensional polytope P with $2m$ facets, such that the shadow of P has $m(m+1)/2$ vertices.*

Proof: We construct P in three steps: first, we take the cross-product of two m -gons to get a 4-dimensional polytope P' . Then we deform P' , without changing its combinatorial structure, to make a new polytope P'' . Finally we perform a projective transformation of P'' to get P .

Let A be an m -gon, m divisible by 4, in the (x_1, x_2) coordinate plane, with vertices evenly spaced on a circle, so that vertex $v_i(A) = (\cos(i\alpha), \sin(i\alpha))$ for $\alpha = 2\pi/m$ and $i = 0 \dots m-1$, and edge $e_i(A) = v_i v_{i+1}$ ($i+1$ is taken mod m , here and throughout; that is, the edge $v_i v_{i+1}$ might be $v_m v_1$). Let B be the same m -gon in the x_3, x_4 coordinate plane. The cross-product of A and B (the set of all points with x_1, x_2 in A and x_3, x_4 in B) is a 4-dimensional polytope P' .

A facet of P' is the cross-product either of A with an edge of B (an A -facet), or of B with an edge of A (a B -facet), so P' has $2m$ facets, each a cylinder over an m -gon. There are two kinds of two-faces. The cross-product of an edge of A with an edge of

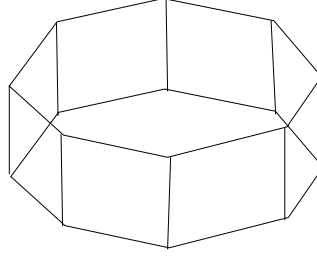


Figure 1: A facet of P'

B is a square, a side of a cylindrical three-face. (The topologically inclined may note that these square faces are a polygonalization of the flat torus.) The cross-product of B with a vertex $v_i(A)$ is a copy of B in the two-flat $(x_1, x_2) = v_i(A)$. We will call these m -gonal faces B -ridges; the A -ridges are defined similarly. There are m B -ridges, each containing m distinct vertices, so P' has m^2 vertices. We write $u_{i,j}$ for the vertex which is the cross product of $v_i(A)$ with $v_j(B)$.

For a fixed i , the orthographic projection to the (x_1, x_2) -plane takes all the vertices in a single B -ridge B_i to a single point (see Figure 3). We now deform P' into P'' , so that these vertices are distributed along a line segment in the projection, without disturbing the combinatorial structure of the polytope.

We do this by tilting each of the B -facets of P' . All the B -facets are parallel to the x_3 and x_4 axes. For i even, we tilt the supporting three-plane of the B -facet containing edge $e_i(B)$ in towards the positive x_3 axis, maintaining the incidence with $e_i(B)$ and keeping it parallel to the x_4 axis. For i odd, we tilt it towards the negative x_3 axis in the same way and by the same amount. We use a gentle enough angle, defined precisely in a moment, so that the combinatorial structure of P'' remains the same as that of P' .

After the tilting, the three-planes supporting the B -facets are defined by linear equations in (x_1, x_2, x_3) . Each B -ridge lies in the intersection of two B -facets. Algebraically, we can use this intersection to eliminate the x_3 variable, which means that a B -ridge lies in a three-plane determined by a linear equation in (x_1, x_2) , so that it does indeed project to a line segment in the x_1, x_2 plane.

In order to verify that we can accomplish this tilting without changing the structure, we consider the motion of the vertices induced by the tilting. A vertex is the intersection of two adjacent A -facets and two adjacent B -facets. The intersection of two adjacent A -facets is a two-plane with constant x_3, x_4 coordinates, so tilting the B -facets will not affect the x_3, x_4 coordinates of the vertices.

Let us consider the extremal two-plane p_{max} in the positive x_3 direction containing A -ridge A_0 . The intersection of p with any plane supporting a B -facet is a line, and the intersections of all of the positive halfspaces of these lines is A_0 , an m -gon. For even i , the tilting causes the line corresponding to the B -facet through $e_i(B)$ to move in its normal direction towards the origin. For odd i , the line moves away from the origin. So the edges of A_0 corresponding to even i get longer, and the edges corresponding to odd i get shorter. The behavior of $A_{m/2}$ on the the extremal two-plane in the negative x_3 direction is just the opposite; even edges get shorter and odd edges get longer. See Figure 2.

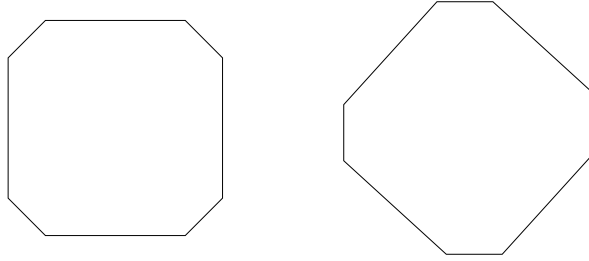


Figure 2: A_0 and $A_{m/2}$ after tilting

In the central two-planes containing ridges $A_{m/4}$ and $A_{3m/4}$, there will be no motion at all, and the intermediate two-planes will exhibit more moderate behavior than the extremal ones.

We claim that so long as we tilt the the three-planes supporting the B -facets by a small enough amount so that none of the shrinking edges of the A -ridges disappear entirely, the combinatorial structure of the resulting polytope P'' remains the same as that of P' .

A combinatorial change would occur if the orientation between a vertex and one of the three-planes supporting a facet changed. This cannot happen in the case of the A -facets, since they are supported by planes defined by a single linear equation in x_3, x_4 , and the x_3, x_4 coordinates of all the vertices do not change. In the case of the B -facets, the orientation of all the vertices in each A -ridge remains the same with respect to each three-plane supporting a B -facet, since each A -ridge remains a convex m -gon. This establishes the claim.

The final step in the construction is simply a projective transformation. For some very small constant ϵ , we multiply every point in the space by the matrix

$$\begin{bmatrix} 1 & 0 & 0 & \epsilon & 0 \\ 0 & 1 & 0 & \epsilon & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The resulting polytope is P . The projection of P'' to the x_1, x_2 plane took every B -ridge B_i to a line segment. This transformation “adds back” some of the x_4 coordinate of each 4-dimensional vertex to its x_1, x_2 coordinates, so that the vertices of B_i lie on an ellipse in the projection, with the arc containing vertices $u_{i,1}, \dots, u_{i,m/2-1}$, where x_4 is positive, curving away from the origin and onto the convex hull. See Figure 3 once again. The constant ϵ can be chosen small enough so that the angle formed,

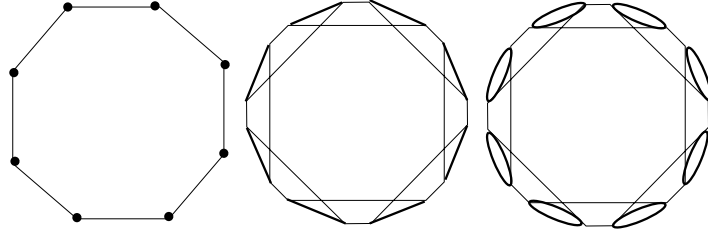


Figure 3: The projections of the ridges B_i in P' , P'' , and P

in the projection, between $u_{i-1,m}, u_{i,0}, u_{i,1}$ remains smaller than π . In that case, the vertices $u_{i,0}, \dots, u_{i,m/2}$ appear on the boundary of the projection, for every B_i , giving the shadow a total of $m(m+1)/2$ vertices. \square

We note that B might be replaced with a roughly semi-circular $(m/2+1)$ -gon, the convex hull of vertices $v_0, \dots, v_{m/2}$, giving a polytope with fewer facets but the same number of vertices on the shadow. This improves the constants in the construction but makes it uglier.

4 Main theorem

We now generalize the 4-dimensional construction to any higher dimension d . Basically, we replace B in the construction above with a $(d-2)$ -dimensional polytope whose shadow has $O(f^{\lfloor d/2-1 \rfloor})$ vertices.

Theorem 7 *For all d , there is a d -dimensional polytope P with f facets, such that the shadow of P has $O(f^{\lfloor d/2 \rfloor})$ vertices.*

Proof: Let A be a planar $f/2$ -gon in x_1, x_2 . We recursively construct a $d-2$ -dimensional polytope \mathcal{B} in x_3, \dots, x_d , with $f/2$ facets, such that the shadow of \mathcal{B} in

the (x_3, x_4) -plane has $O(f^{\lfloor d/2-1 \rfloor})$ vertices. For simplicity, we also stipulate that the shadow is a polygon symmetrical about the x_3 and x_4 axes, with a unique maximal and minimal vertices in x_3 , properties that this construction recursively ensures.

We take the cross-product \mathcal{P}' of A and \mathcal{B} . The A -facets \mathcal{P}' are the cross-products of A with the facets of \mathcal{B} , and the \mathcal{B} -facets are the cross-products of \mathcal{B} with the edges of A , so \mathcal{P}' has f facets. A \mathcal{B} -ridge is again the cross-product of \mathcal{B} with a vertex of A .

We now deform \mathcal{P}' into \mathcal{P}'' . For even edges i of A , we tilt the corresponding \mathcal{B} -facet slightly towards the positive x_3 axis, maintaining its contact with the edge i and keeping it parallel to the x_4, \dots, x_d axes. For odd edges i , we similarly tilt the corresponding \mathcal{B} -facet towards the negative x_3 axis.

We argue again that a small enough tilting leaves the combinatorial structure of \mathcal{P}'' the same as that of \mathcal{P}' . An A -facet is supported by a half-space orthogonal to a facet of \mathcal{B} , a linear equation in x_3, \dots, x_d . The A -facets are unmoved, and the intersection of $d-2$ of them is a two-plane with constant x_3, \dots, x_d coordinates. A vertex is the intersection of $d-2$ A -facets and two \mathcal{B} -facets, so the x_3, \dots, x_d coordinates of each vertex are unchanged by the tilting, and the relationship of each A -facet with the vertices is undisturbed.

Now consider the two-spaces formed by the intersection of the hyperplanes supporting $d-2$ adjacent A -facets (the facets are adjacent if they are the cross-product of a single edge of A with the $d-2$ facets of \mathcal{B} meeting at a vertex). The intersection of the halfspace supporting a \mathcal{B} -facet with such a two-plane is a half-plane. Before the tilting, the intersections of these $f/2$ halfplanes form an $f/2$ -gon identical to A . Consider the minimal and maximal two-faces with respect to x_3 coordinate, p_{min} and p_{max} . In p_{max} , the tilting again moves the even edges of these $f/2$ -gons in towards the origin, and the odd ones outwards, and it does the opposite in p_{min} . Again, if we tilt the \mathcal{B} facets gently enough so that all of these two-faces remain convex $f/2$ -gons, no combinatorial change can occur between a \mathcal{B} -facet and a vertex as a result of the tilting.

Finally, we apply the projective transformation

$$\begin{bmatrix} 1 & 0 & 0 & \epsilon & 0 & \dots & 0 & 0 \\ 0 & 1 & 0 & \epsilon & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & \dots & 0 & 0 \\ & & & \dots & & & & \\ 0 & 0 & 0 & 0 & 0 & \dots & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dots & 0 & 1 \end{bmatrix}$$

to \mathcal{P}'' to produce \mathcal{P} . This “adds back” some of the x_4 coordinate of each vertex to the (x_1, x_2) -coordinates, causing every \mathcal{B} -ridge to project to a convex polygon in the (x_1, x_2) -plane. Again, ϵ can be chosen small enough so that half of the vertices of every \mathcal{B} -ridge end up on the boundary of the shadow. \square

5 The shadow of a cyclic polytope

The dual of a cyclic polytope has the maximum number of faces of all dimensions among polytopes with f facets. We show, however, that the duals of cyclic polytopes do not maximize the complexity of the shadow among all polytopes with f facets. In fact we show that the shadow of a 4-dimensional cyclic polytope dual must have asymptotically fewer vertices than the polytope itself.

Let us review the definition and properties of a cyclic polytope; for more details, see [Z]. Let C be a *curve of order d* in \mathbb{R}^d , meaning that any $(d-1)$ -plane intersects C in at most d points. The convex hull of any set of n points on C is a d -dimensional cyclic polytope P_d . In four and higher dimensions, every pair of vertices in P_d is connected by an edge, in dimension six or higher every triple form a two-face, and so on.

A facet of P_d is supported by a $(d-1)$ -plane which passes through d vertices. Let us index the vertices v_1, \dots, v_n along C . If C passes outside a facet at a vertex v_i , it must come back inside at v_{i+1} , since otherwise v_{i+1} would be outside P_d . So the set of vertices determining a facet is made up of adjacent pairs v_i, v_{i+1} . Every face of smaller dimension is determined by a subset of the set of vertices determining a facet. In four dimensions this means that every two-face of P_4 is the convex hull of three vertices $\{v_i, v_{i+1}, v_j\}$, with v_j distinct from both v_i and v_{i+1} (recall that $i+1$ is taken mod n , as above).

Theorem 8 *Let P_4 be any cyclic polytope in \mathbb{R}^4 with n vertices, and let P'_4 be the dual of P_4 . The shadow of P'_4 in \mathbb{R}^2 may have at most $3n$, and might have as many as $3n - 11$, vertices.*

Proof: Any projection of the dual P'_4 into \mathbb{R}^2 is the dual of the intersection of the cyclic polytope P_4 with some two-plane F_2 . This intersection is a convex polygon P_2 in F_2 . We show that P_2 has at most $3n$, and might have as many as $3n - 11$, vertices.

Consider the 3-polytope P_3 formed by the intersection of P_4 with any three-plane F_3 containing F_2 . A vertex in P_2 is the intersection of F_2 with an edge of P_3 , which in turn is the intersection of a two-face of P_4 with F_3 .

Consider each possible vertex v_j in turn. There are at most $n - 2$ edges of P_3 induced by 2-faces of P_4 involving v_j , one for each possible v_i . Construct a three-plane F_{v_j} through F_2 and v_j ; if the edge of P_3 induced by $\{v_i, v_{i+1}, v_j\}$ is cut by F_2 , then the edge $\{v_i, v_{i+1}\}$ is cut, in P_4 , by the halfspace of F_{v_j} bounded by F_2 and *not* containing v_j . This is easy to see by projecting the situation from \mathbb{R}^4 to \mathbb{R}^2 along F_2 , as in Figure 4.

The vertices v_i and v_{i+1} are connected by a segment of C ; if one of them lies below F_{v_j} and the other lies above it, this segment of C must also cross F_{v_j} at least once. But any three-plane intersects C at most four times; and for F_{v_j} , one of those

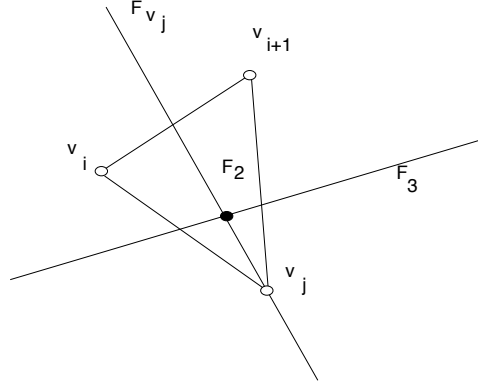


Figure 4: Projection to \mathbb{R}^2 along F_2 . F_2 projects to a point.

intersections is v_j . Hence there are at most three pairs v_i, v_{i+1} separated by F_{v_j} , there are at most three edges of P_3 cut by F_2 , and there are at most three vertices of P_2 for every vertex v_j . This gives the upper bound of $3n$.

Now we construct a cyclic polytope that realizes the lower bound. Select three three-planes F_3 , F_{v_n} and F_{v_5} , all intersecting in a common two-plane F_2 . Figure 5

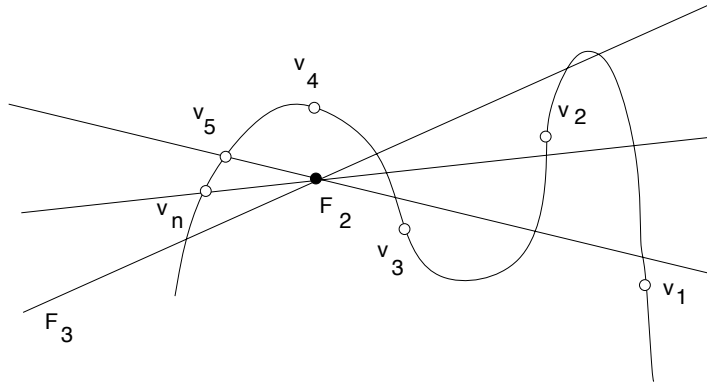


Figure 5: Projection to \mathbb{R}^2 along F_2 .

again represents the projection from \mathbb{R}^4 to \mathbb{R}^2 along F_2 . Select an order four curve C such that intersections of the 3-flats with C occur in the order indicated.

Let v_n be the intersection of F_{v_n} with C , v_5 be the intersection of F_{v_5} with C , and put vertices v_6, \dots, v_{n-1} along C , between v_5 and v_n . Finally, position vertices v_1 through v_4 on C as shown, so that the segments connecting the adjacent pairs $\{v_1, v_2\}$, $\{v_2, v_3\}$ and $\{v_3, v_4\}$ all cross both F_{v_5} and F_{v_n} .

Every 2-face of P_4 formed by $\{v_1, v_2\}$, $\{v_2, v_3\}$ or $\{v_3, v_4\}$, together with any one of the vertices v_5, \dots, v_n , crosses F_2 . This gives $3(n-4)$ vertices in P_2 . In addition, the two-face $\{v_1, v_4, v_5\}$ also crosses F_2 , for a total of $3n-11$. \square

Acknowledgments

We are grateful to Bernd Gärtner for helpful discussions.

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