ON THE STANLEY DEPTH OF THE PATH IDEAL OF A CYCLE GRAPH

MIRCEA CIMPOEAŞ

Abstract. We give tight bounds for the Stanley depth of the quotient ring of the path ideal of a cycle graph. In particular, we prove that it satisfies the Stanley inequality.

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Introduction

Let K be a field and $S = K[x_1,\dots,x_n]$ the polynomial ring over K. Let M be a $\mathbb{Z}^n$-graded S-module. A *Stanley decomposition* of M is a direct sum $\mathcal{D} : M = \bigoplus_{i=1}^r m_iK[Z_i]$ as a $\mathbb{Z}^n$-graded K-vector space, where $m_i \in M$ is homogeneous with respect to $\mathbb{Z}^n$-grading, $Z_i \subset \{x_1,\dots,x_n\}$ such that $m_iK[Z_i] = \{um_i : u \in K[Z_i]\} \subset M$ is a free $K[Z_i]$-submodule of M. We define $\operatorname{sdepth}(\mathcal{D}) = \min_{i=1,\dots,r}|Z_i|$ and $\operatorname{sdepth}(M) = \max\{\operatorname{sdepth}(\mathcal{D})|\ \mathcal{D}$ is a Stanley decomposition of $M\}$. The number $\operatorname{sdepth}(M)$ is called the *Stanley depth* of M.

Herzog, Vladoiu and Zheng show in [10] that $\operatorname{sdepth}(M)$ can be computed in a finite number of steps if $M = I/J$, where $J \subset I \subset S$ are monomial ideals. In [13], Rinaldo give a computer implementation for this algorithm, in the computer algebra system `CoCoA` [6]. In [2], J. Apel restated a conjecture firstly given by Stanley in [14], namely that $\operatorname{sdepth}(M) \geq \operatorname{depth}(M)$ for any $\mathbb{Z}^n$-graded S-module M. This conjecture proves to be false, in general, for $M = S/I$ and $M = J/I$, where $0 \neq I \subset J \subset S$ are monomial ideals, see [7]. For a friendly introduction in the thematic of Stanley depth, we refer the reader [11].

Let $\Delta \subset 2^{[n]}$ be a simplicial complex. A face $F \in \Delta$ is called a *facet*, if F is maximal with respect to inclusion. We denote $\mathcal{F}(\Delta)$ the set of facets of Δ. If $F \in \mathcal{F}(\Delta)$, we denote $x_F = \prod_{j\in F} x_j$. Then the *facet ideal* $I(\Delta)$ associated to Δ is the squarefree monomial ideal $I = (x_F : F \in \mathcal{F}(\Delta))$ of S. The facet ideal was studied by Faridi [8] from the `depth` perspective.

The *line graph* of lenght n, denoted by L_n, is a graph with the vertex set $V = [n]$ and the edge set $E = \{\{1,2\},\{2,3\},\dots,\{n-1,n\}\}$. Let $\Delta_{n,m}$ be the simplicial complex with the set of facets $\mathcal{F}(\Delta_{n,m}) = \{\{1,2,\dots,m\},\{2,3,\dots,m+1\},\dots,\{n-m+1,n-m+2,\dots,n\}\}$, where $1 \leq m \leq n$. We denote $I_{n,m} = (x_1x_2\cdots x_m, x_2x_3\cdots x_{m+1},\dots,x_{n-m+1}x_{n-m+2}\cdots x_n)$, the associated facet ideal. Note that $I_{n,m}$ is the m-path ideal of the graph L_n, provided with the direction given by $1 < 2 < \ldots < n$, see [9] for further details.

According to [9, Theorem 1.2], the projective dimension of $S/I_{n,m}$ is:

$$\operatorname{pd}(S/I_{n,m}) = \begin{cases} \frac{2(n-d)}{m+1},\ n \equiv d(mod\ (m+1))\ with\ 0 \leq d \leq m-1, \\ \frac{2n-m+1}{m+1},\ n \equiv m(mod\ (m+1)). \end{cases}$$

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By Auslander-Buchsbaum formula (see [15]), it follows that $\operatorname{depth}(S/I_{n,m}) = n - \operatorname{pd}(S/I_{n,m})$ and, by a straightforward computation, we can see $\operatorname{depth}(S/I_{n,m}) = n + 1 - \left\lfloor \frac{n+1}{m+1} \right\rfloor - \left\lceil \frac{n+1}{m+1} \right\rceil =: \varphi(n, m)$. We proved in [5] that $\operatorname{sdepth}(S/I_{n,m}) = \varphi(n, m)$.

The *cycle graph* of length n, denoted by C_n, is a graph with the vertex set $V = [n]$ and the edge set $E = \{\{1, 2\}, \{2, 3\}, \ldots, \{n-1, n\}, \{n, 1\}\}$. Let $\bar{\Delta}_{n,m}$ be the simplicial complex with the set of facets $\mathcal{F}(\bar{\Delta}_{n,m}) = \{\{1, 2, \ldots, m\}, \{2, 3, \ldots, m+1\}, \cdots, \{n-m+1, n-m+2, \ldots, n\}, \{n-m+2, \ldots, n, 1\}, \ldots, \{n, 1, \ldots, m-1\}\}$. We denote $J_{n,m} = (x_1x_2 \cdots x_m, x_2x_3 \cdots x_{m+1}, \ldots, x_{n-m+1}x_{n-m+2} \cdots x_n, \ldots, x_nx_1 \cdots x_{m-1})$, the associated facet ideal. Note that $J_{n,m}$ is the m-path ideal of the graph C_n.

Let $p = \left\lfloor \frac{n}{m+1} \right\rfloor$ and $d = n - (m + 1)p$. According to [1, Corollary 5.5],

$$\operatorname{pd}(S/J_{n,m}) = \begin{cases} 2p + 1, & d \neq 0, \\ 2p, & d = 0. \end{cases}$$

By Auslander-Buchsbaum formula, it follows that $\operatorname{depth}(S/J_{n,m}) = n - \operatorname{pd}(S/J_{n,m}) = n - \left\lfloor \frac{n}{m+1} \right\rfloor - \left\lceil \frac{n}{m+1} \right\rceil = \varphi(n-1, m)$. Our main result is Theorem 1.4, in which we prove that $\varphi(n, m) \geq \operatorname{sdepth}(S/J_{n,m}) \geq \varphi(n - 1, m)$. We also prove that, $\operatorname{sdepth}(J_{n,m}/I_{n,m}) = \operatorname{depth}(J_{n,m}/I_{n,m}) = \varphi(n - 1, m) + m - 1$, see Proposition 1.6. These results generalize [4, Theorem 1.9] and [4, Proposition 1.10].

1. Main results

First, we recall the well known Depth Lemma, see for instance [15, Lemma 1.3.9].

Lemma 1.1. *(Depth Lemma) If $0 \to U \to M \to N \to 0$ is a short exact sequence of modules over a local ring S, or a Noetherian graded ring with S_0 local, then*
a) $\operatorname{depth} M \geq \min\{\operatorname{depth} N, \operatorname{depth} U\}$.
b) $\operatorname{depth} U \geq \min\{\operatorname{depth} M, \operatorname{depth} N + 1\}$.
c) $\operatorname{depth} N \geq \min\{\operatorname{depth} U - 1, \operatorname{depth} M\}$.

In [12], Asia Rauf proved the analog of Lemma 1.1(a) for sdepth:

Lemma 1.2. *Let $0 \to U \to M \to N \to 0$ be a short exact sequence of $\mathbb{Z}^n$-graded S-modules. Then:* $\operatorname{sdepth}(M) \geq \min\{\operatorname{sdepth}(U), \operatorname{sdepth}(N)\}$.

The following result is well known. However, we present an original proof.

Lemma 1.3. *Let $I \subset S$ be a nonzero proper monomial ideal. Then, I is principal if and only if* $\operatorname{sdepth}(S/I) = n - 1$.

Proof. Assume $\operatorname{sdepth}(S/I) = n - 1$ and let $S/I = \bigoplus_{i=1}^{r} u_iK[Z_i]$ be a Stanley decomposition with $|Z_i| = n - 1$ for all i, and $u_i \in S$ monomials. Since $1 \notin I$, we may assume that $u_1 = 1$. Let x_{j_1} be the variable which is not in Z_1. If $x_{j_1} \in I$, since $S/(x_{j_1}) = K[Z_1]$ and $K[Z_1] \subset S/I$, then $I = (x_{j_1})$. Otherwise, we may assume that $u_2 = x_{j_1}$.

Let x_{j_2} be the variable which is not in Z_2. If $x_{j_1}x_{j_2} \in I$, then, one can easily see that $I = (x_{j_1}x_{j_2})$. If $x_{j_1}x_{j_2} \notin I$, then we may assume $u_3 = x_{j_1}x_{j_2}$ and so on. Thus, we have $u_i = x_{j_1} \cdots x_{j_{i-1}}$, for all $1 \leq i \leq r + 1$, where x_{j_i} is the variable which is not in Z_i. Moreover, $I = (u_{r+1})$, and therefore I is principal.

In order to prove the other implication, assume that $I = (u)$ and write $u = \prod_{i=1}^{r} x_{j_i}$. We let $u_i = \prod_{k=1}^{i-1} x_{j_k}$ and $Z_i = \{x_1, \ldots, x_n\} \setminus \{x_{j_i}\}$, for all $1 \leq i \leq r$. Then, $S/I = \bigoplus_{i=1}^{r} u_iK[Z_i]$ is a Stanley decomposition with $|Z_i| = n - 1$ for all i. Therefore $\operatorname{sdepth}(S/I) = n - 1$. □

Our main result, is the following theorem.

Theorem 1.4. $\varphi(n,m) \geq \operatorname{sdepth}(S/J_{n,m}) \geq \operatorname{depth}(S/J_{n,m}) = \varphi(n-1,m)$.

Proof. If $n=m$, then $J_{n,n}=(x_1\dots x_n)$ is a principal ideal, and, according to Lemma 1.3 we are done. Also, if $m=1$, then $J_{n,1}=(x_1,\dots,x_n)$ and so there is nothing to prove, since $S/J_{n,1}=K$. The case $m=2$ follows from [4, Proposition 1.8] and [4, Theorem 1.9].

Assume $n>m\geq 3$. If $n=m+1$, then we consider the short exact sequence

$$0 \to S/(J_{n,n-1}:x_n) \to S/J_{n,n-1} \to S/(J_{n,n-1},x_n) \to 0.$$

Note that $(J_{n,n-1}:x_n) = (x_1\cdots x_{n-2}, x_2\cdots x_{n-1}, x_3\cdots x_{n-1}x_1,\cdots, x_{n-1}x_1\cdots x_{n-3}) \cong J_{n-1,n-2}S$. Therefore, by induction hypothesis and [10, Lemma 3.6],

$$\operatorname{sdepth}(S/(J_{n,n-1}:x_n)) = \operatorname{depth}(S/(J_{n,n-1}:x_n)) = 1+\varphi(n-2,n-2) = n-2.$$

Also, $(J_{n,n-1},x_n)=(x_1\cdots x_{n-1},x_n)$ and thus $S/(J_{n,n-1},x_n)\cong K[x_1,\dots,x_{n-1}]/(x_1\cdots x_{n-1})$. Therefore, by Lemma 1.3, we have $\operatorname{sdepth}(S/(J_{n,n-1},x_n)) = n-2 = \operatorname{depth}(S/(J_{n,n-1},x_n))$.

Now, assume $n>m+1>3$. We consider the ideals $L_0=J_{n,m}$, $L_{k+1}=(L_k:x_{n-k})$ and $U_k=(L_k,x_{n-k})$, for $0\leq k\leq m-2$. Note that

$$L_{m-1} = (J_{n,m}:x_{n-m+2}\cdots x_n) = (x_1, x_2\cdots x_{m+1},\dots,x_{n-2m+1}\cdots x_{n-m}, x_{n-m+1}).$$

If $n-2m\leq 2$, then $L_{m-1}=(x_1,x_{n-m+1})$ and thus $\operatorname{sdepth}(S/L_{m-1})=\operatorname{depth}(S/L_{m-1})=n-2=\varphi(n,m)$, since $\left\lfloor\frac{n+1}{m+1}\right\rfloor=1$ and $\left\lceil\frac{n+1}{m+1}\right\rceil=2$.

If $n-2m>2$, then $S/L_{m-1}\cong K[x_2,\dots,x_{n-m},x_{n-m+2},\dots,x_n]/(x_2\cdots x_{m+1},\dots,x_{n-2m+1}\cdots x_{n-m})$ and therefore, by [10, Lemma 3.6] and [5, Theorem 1.3], we have $\operatorname{sdepth}(S/L_{m-1})=\operatorname{depth}(S/L_{m-1}) = n-1-\left\lfloor\frac{n-m}{m+1}\right\rfloor-\left\lceil\frac{n-m}{m+1}\right\rceil=\varphi(n,m)$. On the other hand, for example by [3, Proposition 2.7], $\operatorname{sdepth}(S/L_{m-1})\geq\operatorname{sdepth}(S/J_{n,m})$. Thus, $\operatorname{sdepth}(S/J_{n,m})\leq\varphi(n,m)$.

For any $0<k<m$, we have $L_k=(x_1\cdots x_{m-k}, x_2\cdots x_{m+1},\dots,x_{n-m-k}\cdots x_{n-k-1}, x_{n-m+1}\cdots x_{n-k}, x_{n-m+2}\cdots x_{n-k}x_1,\dots,x_{n-k}x_1\cdots x_{m-k-1})$. Therefore, $U_k=(x_1\cdots x_{m-k}, x_2\cdots x_{m+1},\dots,x_{n-m-k}\cdots x_{n-k-1},x_{n-k})$, for $k\leq m-2$. We consider two cases:

(i) If $n-m-k<2$ and $0\leq k\leq m-2$, then $U_k=(x_1\cdots x_{m-k},x_{n-k})$ and therefore $\operatorname{sdepth}(S/U_k)=\operatorname{depth}(S/U_k)=n-2=\varphi(n,m)$, since $\left\lfloor\frac{n+1}{m+1}\right\rfloor=1$ and $\left\lceil\frac{n+1}{m+1}\right\rceil=2$.

(ii) If $n-m-k\geq 2$, then, for any $0\leq j\leq k\leq m-2$, we consider the ideals $V_{k,j}:=(x_1\cdots x_{m-j},x_2\cdots x_{m+1},\dots,x_{n-m-k}\cdots x_{n-k-1})$ in $S_k:=K[x_1,\dots,n_{n-k-1}]$. Note that $S/U_k\cong(S_k/V_{k,k})[x_{n-k+1},\dots,x_n]$ and thus, by [10, Lemma 3.6], $\operatorname{depth}(S/U_k)=\operatorname{depth}(S_k/V_{k,k})+k$ and $\operatorname{sdepth}(S/U_k)=\operatorname{sdepth}(S_k/V_{k,k})+k$.

For any $0\leq j<k\leq m-2$, we claim that $V_{k,j}/V_{k,j+1}$ is isomorphic to

$$(K[x_{m-j+2},\dots,x_{n-k-1}]/(x_{m-j+2}\cdots x_{2m-j+1},\dots,x_{n-m-k}\cdots x_{n-k-1}))[x_1,\dots,x_{m-j}].$$

Indeed, if $u\in V_{k,j}\setminus V_{k,j+1}$ is a monomial, then $x_1\cdots x_{m-j}|u$ and $x_{m-j+1}\nmid u$. Also, $x_{m-j+2}\cdots x_{2m-j+1}\nmid u$, $\dots$, $x_{n-m-k}\cdots x_{n-k-1}\nmid u$. Denoting $v=u/(x_1\cdots x_{m-j})$, we can write $v=v'v''$, with $v'\in K[x_{m-j+2},\dots,x_{n-k-1}]\setminus(x_{m-j+2}\cdots x_{2m-j+1},\dots,x_{n-m-k}\cdots x_{n-k-1})$ and $v''\in K[x_1,\dots,x_{m-j}]$.

By [10, Lemma 3.6] and [5, Theorem 1.3], $\operatorname{sdepth}(V_{k,j}/V_{k,j+1})=\operatorname{depth}(V_{k,j}/V_{k,j+1})=m-j+\varphi(n-k-m+j-2,m)=n-k-1-\left\lfloor\frac{n-m-1-k+j}{m+1}\right\rfloor-\left\lceil\frac{n-m-1-k+j}{m+1}\right\rceil=n-k+1-\left\lfloor\frac{n-k+j}{m+1}\right\rfloor-\left\lceil\frac{n-k+j}{m+1}\right\rceil\geq\varphi(n,m)-k$. On the other hand, $V_{k,0}=I_{n-k-1,m}$ for any $0\leq k\leq m-2$ and therefore, by [5, Theorem 1.3], $\operatorname{sdepth}(S/V_{k,0})=\operatorname{depth}(S/V_{k,0})=\varphi(n-k-1,m)=n-k-\left\lfloor\frac{n-k}{m+1}\right\rfloor-\left\lceil\frac{n-k}{m+1}\right\rceil\geq\varphi(n,m)-k$, for any $k\geq 1$. From the short exact sequences $0\to V_{k,j}/V_{k,j+1}\to S/V_{k,j+1}\to S/V_{k,j}\to 0$, $0\leq j<k$, Lemma 1.1 and Lemma 1.2, it follows that $\operatorname{sdepth}(S/V_{k,j+1})\geq\operatorname{depth}(S/V_{k,j+1})=\varphi(n,m)-k$, for all $0\leq j<k\leq m-2$. Thus $\operatorname{sdepth}(S/U_k)\geq\operatorname{depth}(S/U_k)\geq\varphi(n,m)$, for all $0<k\leq m-2$.On the other hand, $\operatorname{sdepth}(S/V_{0,0})=\operatorname{depth}(S/V_{0,0})=\varphi(n-1,m)$, and thus $\operatorname{sdepth}(S/U_0)=\operatorname{depth}(S/U_0)=\varphi(n-1,m)$.

Now, we consider short exact sequences

$$0\to S/L_{k+1}\to S/L_k\to S/U_k\to 0, \text{ for } 0\leq k<m.$$

By Lemma 1.1 and Lemma 1.2 we get $\operatorname{sdepth}(S/L_k) \geq \operatorname{depth}(S/L_k) = \varphi(n,m)$, for any $0 < k \leq m-2$, and $\operatorname{sdepth}(S/L_0) \geq \operatorname{depth}(S/L_0) = \varphi(n-1,m)$. □

Corollary 1.5. *If* $\left\lfloor \frac{n+1}{m+1} \right\rfloor = \left\lfloor \frac{n}{m+1} \right\rfloor$ *and* $\left\lceil \frac{n+1}{m+1} \right\rceil = \left\lceil \frac{n}{m+1} \right\rceil$, *then*

$$\operatorname{sdepth}(S/J_{n,m}) = \operatorname{depth}(S/J_{n,m}) = \varphi(n,m).$$

Proposition 1.6. $\operatorname{sdepth}(J_{n,m}/I_{n,m}) \geq \operatorname{depth}(J_{n,m}/I_{n,m}) = \varphi(n-1,m) + m - 1$.

Proof. We claim that $J_{n,m}/I_{n,m}$ is isomorphic to

$$x_{n-m+2}\cdots x_n x_1 \Big(\frac{K[x_2,\ldots,x_{n-m}]}{(x_2\cdots x_m, x_3\cdots x_{m+2}\ldots, x_{n-2m+1}\cdots x_{n-m})}\Big)[x_{n-m+2},\ldots,x_n,x_1]\oplus$$

$$\oplus x_{n-m+3}\cdots x_n x_1 x_2 \Big(\frac{K[x_3,\ldots,x_{n-m+1}]}{(x_3\cdots x_m, x_4\cdots x_{m+3},\ldots, x_{n-2m+2}\cdots x_{n-m+1})}\Big)[x_{n-m+3},\ldots,x_n,x_1,x_2]\oplus$$

$$\cdots \oplus x_n x_1\cdots x_{m-1}\Big(\frac{K[x_m,\ldots,x_{n-2}]}{(x_m, x_{m+1}\cdots x_{2m},\ldots,x_{n-m-1}\cdots x_{n-2})}\Big)[x_n,x_1\ldots,x_{m-1}].$$

Indeed, let $u \in J_{n,m}\setminus I_{n,m}$ be a monomial. If $x_{n-m+2}\cdots x_n x_1 | u$, then $x_{n-m+1} \nmid u$ and $x_2\cdots x_m \nmid u$. It follows that:

$u \in x_{n-m+2}\cdots x_n x_1 (K[x_2,\ldots,x_{n-m}]/(x_2\cdots x_m, x_3\cdots x_{m+2}\ldots, x_{n-2m+1}\cdots x_{n-m}))[x_{n-m+2},\ldots,x_n,x_1]$.

If $x_{n-m+2}\cdots x_n x_1 \nmid u$ and $x_{n-m+3}\cdots x_n x_1 x_2 | u$ then $x_{n-m+2} \nmid u$ and $x_3\cdots x_m \nmid u$. Thus:

$$u \in x_{n-m+3}\cdots x_n x_1 x_2 \Big(\frac{K[x_3,\ldots,x_{n-m+1}]}{(x_3\cdots x_m, x_4\cdots x_{m+3},\ldots, x_{n-2m+2}\cdots x_{n-m+1})}\Big)[x_{n-m+3},\ldots,x_n,x_1,x_2].$$

Finally, if $x_{n-m+2}\cdots x_n x_1 \nmid u$, $\ldots$, $x_{n-1}x_n x_1\cdots x_{m-2} \nmid u$ and $x_n x_1\cdots x_{m-1} | u$, then it follows that $x_{n-1} \nmid u$ and $x_m \nmid u$. Therefore:

$$u \notin x_n x_1\cdots x_{m-1}\Big(\frac{K[x_m,\ldots,x_{n-2}]}{(x_m, x_{m+1}\cdots x_{2m},\ldots,x_{n-m-1}\cdots x_{n-2})}\Big)[x_n,x_1\ldots,x_{m-1}].$$

As in the proof of Theorem 3.1 (see the computations for $V_{k,j}$'s), by applying Lemma 1.1 and Lemma 1.2, it follows that $\operatorname{sdepth}(J_{n,m}/I_{n,m}) \geq \operatorname{depth}(J_{n,m}/I_{n,m}) = \varphi(n-m-2,m)+m = \varphi(n-1,m)+m-1$, as required. □

Inspired by [4, Conjecture 1.12] and computer experiments [6], we propose the following:

Conjecture 1.7. *For any* $n \geq 3(m+1)+1$, *we have* $\operatorname{sdepth}(S/J_{n,m}) = \varphi(n,m)$.

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Simion Stoilow Institute of Mathematics, Research unit 5, P.O.Box 1-764, Bucharest 014700, Romania
E-mail address: mircea.cimpoeas@imar.ro