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# Contracted ideals and the Gröbner fan of the rational normal curve

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The paper has two goals: the study of the associated graded ring of contracted homogeneous ideals in  $K[x, y]$  and the study of the Gröbner fan of the ideal  $P$  of the rational normal curve in  $\mathbb{P}^d$ . These two problems are, quite surprisingly, very tightly related. We completely classify the contracted ideals with Cohen–Macaulay associated graded ring in terms of the numerical invariants arising from Zariski’s factorization. We determine explicitly the initial ideals (monomial or not) of  $P$ , that are Cohen–Macaulay.

## 1. Introduction

The goal of the paper is twofold:

- (1) to describe the Cohen–Macaulay initial ideals of the defining ideal  $P$  of the rational normal curve in  $\mathbb{P}^d$  in its standard coordinate system and for every positive integer  $d$ , and
- (2) to identify the homogeneous contracted ideals in  $K[x, y]$  whose associated graded ring is Cohen–Macaulay.

The two problems are closely related. Indeed they are essentially equivalent, as we proceed to explain. Let  $K$  be a field,  $R = K[x, y]$  and  $I$  be a homogeneous ideal of  $R$  with  $\sqrt{I} = \mathfrak{m} = (x, y)$ . Denote by  $\text{gr}_I(R)$  the associated graded ring

$$\bigoplus_k I^k / I^{k+1}$$

of  $I$ . The ideal  $I$  is said to be contracted if it is contracted from a quadratic extension, that is, if there exists a linear form  $z$  in  $R$  such that

$$I = IR[\mathfrak{m}/z] \cap R.$$

Contracted ideals have been introduced by Zariski in his studies on the factorization property of integrally closed ideals; see [Zariski and Samuel 1960, App. 5]

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or [Huneke and Swanson 2006, Chap. 14]. Every integrally closed ideal  $I$  is contracted and has a Cohen–Macaulay associated graded ring  $\text{gr}_I(R)$ ; see [Lipman and Teissier 1981; Huneke 1989]. On the contrary, the associated graded ring of a contracted ideal does not need to be Cohen–Macaulay. Zariski proved a factorization theorem for contracted ideals, asserting that every contracted ideal  $I$  has a factorization  $I = L_1 \cdots L_s$  where  $L_i$  are themselves contracted but of a very special kind. In the homogeneous case and with  $K$  assumed to be algebraically closed, each  $L_i$  is a lex-segment monomial ideal in a specific coordinate system depending on  $i$ . Recall that a monomial ideal  $L$  in  $R$  is a lex-segment ideal if that  $x^a y^b \in L$  with  $b > 0$  implies that  $x^{a+1} y^{b-1} \in L$  also. In [Conca et al. 2005, Corollary 3.14] it is shown that the Cohen–Macaulayness of  $\text{gr}_I(R)$  is equivalent to the Cohen–Macaulayness of  $\text{gr}_{L_i}(R)$  for every  $i = 1, \dots, s$ . Therefore to answer (2) one has to characterize the lex-segment ideals  $L$  with Cohen–Macaulay associated graded ring. Any lex-segment ideal  $L$  of initial degree  $d$  can be encoded by a vector  $a = (a_0, a_1, \dots, a_d)$  with increasing integral coordinates and  $a_0 = 0$ . Given  $L$  associated to  $a$ , we show that  $\text{gr}_L(R)$  is Cohen–Macaulay if and only if  $\text{in}_a(P)$  defines a Cohen–Macaulay ring. Here  $\text{in}_a(P)$  denotes the ideal of the initial forms of  $P$  with respect to the vector  $a$ . Therefore (1) and (2) are indeed equivalent problems. In Section 4 we solve problem (1) by showing first that  $P$  has exactly  $2^{d-1}$  Cohen–Macaulay initial monomial ideals; see Theorem 4.11. Then we show that every Cohen–Macaulay initial ideal of  $P$  has a Cohen–Macaulay monomial initial ideal; see Theorem 4.13. In terms of the Gröbner fan of  $P$ , Theorem 4.13 can be rephrased as that  $\text{in}_a(P)$  is Cohen–Macaulay if and only if  $a$  belongs to the union of  $2^{d-1}$  maximal closed cones. These cones are explicitly described by linear homogeneous inequalities. The fact that  $P$  has exactly  $2^{d-1}$  Cohen–Macaulay monomial initial ideals can be derived by combining the results of Hoşten and Thomas [2003] and those of O’Shea and Thomas [2005]; see Remark 4.20.

In Section 5 we give an explicit characterization, in terms of the numerical invariants arising from Zariski’s factorization, of the Cohen–Macaulay property of the associated graded ring of a contracted homogeneous ideal in  $K[x, y]$ . In Section 6 we describe the relationship between the Hilbert series of  $\text{gr}_L(R)$  and the multigraded Hilbert series of  $\text{in}_a(P)$ . We discuss also how the formulas for the Hilbert series and the polynomials of  $\text{gr}_L(R)$  change by varying the corresponding cones of the Gröbner fan of  $P$ . This has a conjectural relation with the hypergeometric Gröbner fan introduced by Saito, Sturmfels and Takayama in [Saito et al. 2000]. In Section 7 we show that the union of a certain subfamily of the  $2^{d-1}$  Cohen–Macaulay cones is itself a cone. We call it the big Cohen–Macaulay cone. Indeed, the big Cohen–Macaulay cone is the union of  $f_d$  Cohen–Macaulay cones of the Gröbner fan of  $P$ , where  $f_d$  denotes the  $(d + 1)$ -th Fibonacci number. In Section 8 we present some examples.

## 2. Notation and preliminaries

Let  $S$  be a polynomial ring over a field  $K$  with maximal homogeneous ideal  $\mathbf{m}$ . For a homogeneous ideal  $I$  of  $S$  we denote by  $\text{gr}_I(S)$ ,  $\text{Rees}(I)$  and  $F(I)$  respectively the associated graded ring  $\bigoplus_{k \in \mathbb{N}} I^k / I^{k+1}$ , the Rees algebra  $\bigoplus_{k \in \mathbb{N}} I^k$  and the fiber cone  $\bigoplus_{k \in \mathbb{N}} I^k / \mathbf{m} I^k$  of  $I$ . By the very definition  $F(I)$  is a standard graded  $K$ -algebra. Furthermore  $\text{Rees}(I)$  can be identified with the  $S$ -subalgebra of the polynomial ring  $S[t]$  generated by  $ft$  with  $f \in I$ .

Let  $I \subset S = K[x_1, \dots, x_n]$  be a homogeneous ideal. We may consider the (standard) Hilbert function, Hilbert polynomial and Hilbert series of  $S/I$ . The Hilbert series of  $S/I$  is  $\sum_{i \geq 0} \dim_K(S/I)_i z^i$  and we denote it by  $H_{S/I}(z)$ . The series  $H_{S/I}(z)$  has a rational expression  $h(z)/(1-z)^d$  where  $h(z) \in \mathbb{Z}[z]$  and  $d$  is the Krull dimension of  $S/I$ . The polynomial  $h(z)$  is called the (standard)  $h$ -polynomial of  $S/I$ . In particular,  $h(0) = 1$  and  $h(1)$  is the ordinary multiplicity of  $S/I$ , denoted by  $e(S/I)$ .

If  $I$  is  $\mathbf{m}$ -primary, we may consider also the (local) Hilbert functions, Hilbert polynomials and Hilbert series of  $I$  (or of  $\text{gr}_I(S)$ ). There are two Hilbert functions associated with  $I$  in this context. We denote them by  $H(I, k)$  and  $H^1(I, k)$  and they are defined by

$$H(I, k) = \dim_K(I^k / I^{k+1}) \quad \text{and} \quad H^1(I, k) = \dim_K(S / I^{k+1}).$$

The corresponding Hilbert series are

$$H_I(z) = \sum_{k \geq 0} H(I, k) z^k \quad \text{and} \quad H_I^1(z) = \sum_{k \geq 0} H^1(I, k) z^k.$$

Obviously,  $H_I(z) = (1-z)H_I^1(z)$ . The series  $H_I^1(z)$  has a rational expression

$$H_I^1(z) = \frac{h(z)}{(1-z)^{n+1}}$$

where  $h(z)$  is a polynomial with integral coefficients and is called the (local)  $h$ -polynomial of  $I$  or of  $\text{gr}_I(S)$ . The Hilbert functions  $H(I, k)$  and  $H^1(I, k)$  agree for large  $k$  with polynomials  $P_I(z)$  and  $P_I^1(z)$  at  $z = k$ . The polynomials  $P_I(z)$  and  $P_I^1(z)$  are called the Hilbert polynomials of  $I$ . Their coefficients, with respect to an appropriate binomial basis, are integers and are called Hilbert coefficients of  $I$  and are denoted by  $e_i(I)$ . Precisely,

$$P_I^1(z) = \sum_{i=0}^n (-1)^i e_i(I) \binom{n-i+z}{n-i}.$$

In particular,  $h(0) = \dim_K S/I$  and  $h(1) = e_0(I)$  that is the multiplicity of  $I$ .

**Definition 2.1.** Let  $I \subset S = K[x_1, \dots, x_n]$  be a homogeneous ideal of codimension  $c$  and not containing linear forms. Then

- (1)  $S/I$  has minimal multiplicity if  $e(S/I) = c + 1$ , and
- (2)  $S/I$  has a short  $h$ -vector if its  $h$ -polynomial is  $1 + cz$ , that is, if the Hilbert series of  $S/I$  is  $(1 + cz)/(1 - z)^{n-c}$ .

We denote the Castelnuovo–Mumford regularity of a graded  $S$ -module  $M$  by  $\text{reg}(M)$ . For results on the Castelnuovo–Mumford regularity and the minimal multiplicity we refer the readers to [Eisenbud and Goto 1984]. We just recall that if  $S/I$  has a short  $h$ -vector, then it has minimal multiplicity. On the other hand, if  $S/I$  is Cohen–Macaulay with minimal multiplicity, then it has a short  $h$ -vector. We will need the next lemma whose easy proof follows from the standard facts.

**Lemma 2.2.** *Let  $I \subset S$  be a homogeneous ideal. Assume  $S/I$  has a short  $h$ -vector. Then  $S/I$  is Cohen–Macaulay if and only if  $\text{reg}(I) = 2$ .*

Every vector  $a = (a_0, \dots, a_d) \in \mathbb{Q}_{\geq 0}^{d+1}$  induces a graded structure on the polynomial ring  $K[t_0, \dots, t_d]$  by letting  $\deg t_i = a_i$ . Every monomial  $t^\alpha$  is then homogeneous of degree

$$\deg_a t^\alpha = a\alpha = \sum_{i=0}^d a_i \alpha_i.$$

For every nonzero polynomial  $f = \sum_{i=1}^k \lambda_i t^{\alpha_i}$  we set

$$\deg_a f = \max\{a\alpha_i : \lambda_i \neq 0\} \quad \text{and} \quad \text{in}_a(f) = \sum_{a\alpha_i = \deg_a f} \lambda_i t^{\alpha_i}.$$

Then for every ideal  $I$  one defines the initial ideal  $\text{in}_a(I)$  of  $I$  with respect to  $a$  to be

$$\text{in}_a(I) = (\text{in}_a(f) : f \in I, f \neq 0).$$

Similarly, given a term order  $\tau$ , we denote by  $\text{in}_\tau(I)$  the ideal of the initial monomials of elements of  $I$ . Given  $a \in \mathbb{Q}_{\geq 0}^{d+1}$  the term order defined by

$$t^\alpha \geq t^\beta \text{ if and only if } a\alpha > a\beta \text{ or } (a\alpha = a\beta \text{ and } t^\alpha \geq t^\beta \text{ with respect to } \tau)$$

is denoted by  $\tau_a$ .

One easily shows that  $\text{in}_\tau(\text{in}_a(I)) = \text{in}_{\tau_a}(I)$ . Hence  $\text{in}_a(I)$  and  $I$  have a common monomial initial ideal. This shows (1) of the following lemma.

**Lemma 2.3.** *Let  $I$  be a homogeneous ideal with respect to the ordinary grading  $\deg t_i = 1$  and let  $a \in \mathbb{Q}_{\geq 0}^{d+1}$ . Then*

- (1)  $S/I$  and  $S/\text{in}_a(I)$  have the same Hilbert function, and
- (2)  $\text{depth } S/\text{in}_a(I) \leq \text{depth } S/I$ .

Part (2) follows from the standard one-parameter flat family argument; for details see [Eisenbud 1995, Chap. 15] or [Bruns and Conca 2003].

**Definition 2.4.** Let  $P$  be the ideal of the rational normal curve of  $\mathbb{P}^d$  in its standard embedding. Namely,  $P$  is the kernel of the  $K$ -algebra map

$$S = K[t_0, t_1, \dots, t_d] \rightarrow K[x, y]$$

sending  $t_i$  to  $x^{d-i}y^i$ .

The ideal  $P$  is minimally generated by the 2-minors of the matrix

$$T_d = \begin{pmatrix} t_0 & t_1 & t_2 & \cdots & \cdots & t_{d-1} \\ t_1 & t_2 & \cdots & \cdots & t_{d-1} & t_d \end{pmatrix}$$

and it contains the binomials of the form  $t_{i_1}t_{i_2}\cdots t_{i_k} - t_{j_1}t_{j_2}\cdots t_{j_k}$  with

$$0 \leq i_v, j_v \leq d \quad \text{and} \quad i_1 + i_2 + \cdots + i_k = j_1 + j_2 + \cdots + j_k.$$

The Hilbert series of  $S/P$  is  $(1 + (d-1)z)/(1-z)^2$ .

### 3. Contracted ideals in dimension 2

We briefly recall from [Zariski and Samuel 1960, App. 5], [Huneke and Swanson 2006, Chap. 14] and [Conca et al. 2005] a few facts about contracted ideals. As we deal only with homogeneous ideals, we will state the results in the graded setting.

Assume  $K$  is an algebraically closed field. Let  $R = K[x, y]$  and denote by  $\mathfrak{m}$  its maximal homogeneous ideal. An  $\mathfrak{m}$ -primary homogeneous ideal  $I$  of  $R$  is said to be contracted if it is contracted from a quadratic extension, that is, if there exists a linear form  $z \in R$  such that  $I = IS \cap R$ , where  $S = R[\mathfrak{m}/z]$ . The property of being contracted can be described in several ways; for instance see [Conca et al. 2005, Prop. 3.3]. To a contracted ideal  $I$  one associates a form, the characteristic form of  $I$ , defined as  $\text{GCD}(I_d)$  where  $d$  is the initial degree of  $I$ . For our goals, it is important to recall the following definition and theorem.

**Definition 3.1.** Let  $I$  be a homogeneous  $\mathfrak{m}$ -primary ideal in  $R$  and let  $Q = IR_{\mathfrak{m}}$ . Let  $J \subset R_{\mathfrak{m}}$  be a minimal reduction of  $Q$ . The deviation of  $I$  is the length of  $Q^2/JQ$ . It will be denoted by  $V(I)$ .

**Theorem 3.2.** Let  $I$  be a homogeneous  $\mathfrak{m}$ -primary ideal in  $R$ . One has

- (1)  $\text{gr}_I(R)$  is Cohen–Macaulay if and only if  $V(I) = 0$ , and
- (2)  $V(I) = e_0(I) - \dim_K(R/I^2) + 2 \dim_K(R/I)$ .

See [Huckaba and Marley 1993, Prop. 2.6, Thm. A] for a proof of (1) and [Valla 1979, Lemma 1] for a proof of (2). Similar results are proved also in [Verma 1991].

We recall now Zariski’s factorization theorem for contracted ideals and a related statement, [Conca et al. 2005, Cor. 3.14], concerning associated graded rings. In our setting they can be stated as follows.

**Theorem 3.3.** (1) *Any contracted ideal  $I$  has a factorization  $I = L_1 \cdots L_s$  where  $L_i$  are homogeneous  $\mathfrak{m}$ -primary contracted ideals with characteristic form of type  $\ell_i^{\alpha_i}$  for pairwise linearly independent linear forms  $\ell_1, \dots, \ell_s$ .*  
 (2) *With respect to the factorization in (1) one has*

$$\text{depth gr}_I(R) = \min\{\text{depth gr}_{L_i}(R) : i = 1, \dots, s\}.$$

**Lemma 3.4.** *The fiber cone  $F(I)$  of a contracted ideal  $I$  has a short  $h$ -vector. Its Hilbert series is  $(1 + (d - 1)z)/(1 - z)^2$ , where  $d$  is the initial degree of  $I$ .*

*Proof.* A contracted ideal of initial degree  $d$  is minimally generated by  $d + 1$  elements and products of contracted ideals are contracted. The initial degree of  $I^k$  is  $kd$ . Hence  $I^k$  has  $kd + 1$  minimal generators. It follows that the Hilbert series of  $F(I)$  is  $(1 + (d - 1)z)/(1 - z)^2$ .  $\square$

A monomial  $\mathfrak{m}$ -primary ideal  $I$  of  $R = K[x, y]$  can be encoded in various ways. We use the following. Let  $d \in \mathbb{N}$  be such that  $x^d \in I$  and, for  $i = 0, \dots, d$ , set  $a_i(I) = \min\{j : x^{d-i}y^j \in I\}$ . Then we have  $0 = a_0(I) \leq a_1(I) \leq \dots \leq a_d(I)$ . Obviously, the map

$$I \rightarrow a = (a_0(I), \dots, a_d(I))$$

establishes a bijective correspondence between the set of  $\mathfrak{m}$ -primary monomial ideals containing  $x^d$  and the set of weakly increasing sequences  $a = (a_0, \dots, a_d)$  of nonnegative integers with  $a_0 = 0$ . The inverse map is

$$a = (0 = a_0 \leq a_1 \leq \dots \leq a_d) \rightarrow (x^{d-i}y^{a_i} : i = 0, \dots, d).$$

It is easy to see that if  $a$  corresponds to  $I$ , then  $\dim_K R/I = \sum_{i=0}^d a_i$ . Furthermore, if  $a'$  corresponds to  $J$ , then the sequence associated to the product  $IJ$  is  $(c_0, c_1, c_2, \dots)$  where  $c_i = \min\{a_j + a'_k : j + k = i\}$ . In particular:

**Lemma 3.5.** *Let  $I$  be a monomial ideal and  $a = (a_0, \dots, a_d)$  be the corresponding sequence. Then the Hilbert function of  $I$  is given by*

$$H^1(I, k) = \sum_{i=0}^{(k+1)d} \min\{a_{j_1} + \dots + a_{j_{k+1}} : j_1 + \dots + j_{k+1} = i\}.$$

We set  $b_i(I) = a_i(I) - a_{i-1}(I)$  for  $i = 1, \dots, d$  and observe that the ideal  $I$  can be as well described via the sequence  $b_1(I), \dots, b_d(I)$  of nonnegative integers.

A monomial ideal  $I$  is a lex-segment ideal if  $x^i y^j \in I$  for some  $j > 0$  implies  $x^{i+1} y^{j-1} \in I$ . The  $\mathfrak{m}$ -primary lex-segment ideals are contracted and correspond

exactly to strictly increasing  $a$ -sequences (equivalently, positive  $b$ -sequences) in the above correspondence, provided one takes  $d = \min\{j \in \mathbb{N} : x^j \in I\}$ .

**Remark 3.6.** With respect to suitable coordinate systems the ideals  $L_i$  in [Theorem 3.3](#) are lex-segment ideals.

It follows from [Theorem 3.3](#) and [Remark 3.6](#) that the study of the depth of the associated graded ring of contracted ideals boils down to the study of the depth of  $\text{gr}_L(R)$  for a lex-segment ideal  $L$ . One has  $\text{depth } \text{gr}_L(R) = \text{depth } \text{Rees}(L) - 1$  since  $R$  is regular; see [[Huckaba and Marley 1993](#), Cor. 2.7]. Therefore we can as well study the depth of  $\text{Rees}(L)$  for lex-segment ideals  $L$ . Trung and Hoa gave in [[Trung and Hoa 1986](#)] a characterization of the Cohen–Macaulay property of affine semigroup rings. Since  $\text{Rees}(L)$  is an affine semigroup ring one could hope to use their results to describe the lex-segment ideals  $L$  such that  $\text{Rees}(L)$  is Cohen–Macaulay. In practice, however, we have not been able to follow this idea.

Let  $L$  be the lex-segment ideal with the associated  $a$ -sequence  $a = (a_0, \dots, a_d)$  and  $b$ -sequence  $(b_1, \dots, b_d)$ . We present  $\text{Rees}(L)$  as a quotient of  $R[t_0, \dots, t_d]$  by the  $R$ -algebra map

$$\psi : R[t_0, \dots, t_d] \rightarrow \text{Rees}(L) \subset R[t]$$

obtained by sending  $t_i \mapsto x^{d-i} y^{a_i} t$ . Set

$$\mathbf{1} = (1, 1, \dots, 1) \in \mathbb{N}^{d+1}, \quad \text{and} \quad \mathbf{d} = (d, d-1, d-2, \dots, 0) \in \mathbb{N}^{d+1}.$$

**Lemma 3.7.** *With the above notation,  $\ker \psi$  is generated by the binomials*

- (1)  $x t_i - y^{b_i} t_{i-1}$  with  $i = 1, \dots, d$ , and
- (2)  $t^\alpha - y^u t^\beta$  where  $\alpha, \beta \in \mathbb{N}^{d+1}$  satisfy

$$\mathbf{1}(\alpha - \beta) = 0, \quad \mathbf{d}(\alpha - \beta) = 0, \quad u = a(\alpha - \beta) \geq 0.$$

*Proof.* Let  $J$  be the ideal generated by the binomials of type (1) and (2). Obviously  $J \subseteq \ker \psi$ . Since  $\ker \psi$  is generated by the binomials it contains, it is enough to show that every binomial  $M_1 - M_2 \in \ker \psi$  with  $\text{GCD}(M_1, M_2) = 1$  belongs to  $J$ . Up to multiples of elements of type (1), we may assume that if  $x$  divides one of the  $M_i$ , say  $M_1$ , then  $M_1 = x^i y^j t_0^k$ . But this clearly contradicts the fact that  $M_1 - M_2 \in \ker \psi$ . In other words, every binomial in  $\ker \psi$  is, up to multiples of elements of type (1), a multiple of an element of type (2).  $\square$

**Lemma 3.8.** *Let  $L$  be a lex-segment ideal and  $a = (a_0, \dots, a_d)$  its associated  $a$ -sequence, then we have*

- (1)  $\text{Rees}(L)/(y) \text{Rees}(L) = K[x, t_0, \dots, t_d]/x(t_1, \dots, t_d) + \text{in}_a(P)$ ,
- (2)  $F(L) = K[t_0, \dots, t_d]/\text{in}_a(P)$ , and



$$(3) \text{ depth gr}_L(R) = \text{depth Rees}(L) - 1 = \text{depth } F(L),$$

where  $P$  is the ideal introduced in [Definition 2.4](#).

*Proof.* Set  $F = F(L)$ ,  $G = \text{gr}_L(R)$  and  $\mathcal{R} = \text{Rees}(L)$ . First note that (2) follows from (1) since  $F = \mathcal{R}/(x, y)\mathcal{R}$ . To prove (1) we have to show that

$$\ker \psi + (y) = x(t_1, \dots, t_d) + \text{in}_a(P) + (y).$$

For the inclusion  $\subseteq$  we show that the generators of  $\ker \psi$  of type (1) and (2) in [Lemma 3.7](#) belong to the ideal on the right hand side. This is obvious for those of type (1). For those of type (2), note that for any such  $t^\alpha - y^u t^\beta$  one has  $t^\alpha - t^\beta \in P$  and  $\text{in}_a(t^\alpha - t^\beta) = t^\alpha$  if  $u > 0$  and  $\text{in}_a(t^\alpha - t^\beta) = t^\alpha - t^\beta$  if  $u = 0$ .

The inclusion  $\supseteq$  for the elements of  $x(t_1, \dots, t_d)$  is obvious. Further, since  $P$  is generated by binomials, one knows that  $\text{in}_a(P)$  is generated by  $\text{in}_a(t^\alpha - t^\beta)$  with  $t^\alpha - t^\beta \in P$ ; see [[Sturmfels 1996](#), Chap. 1]. If  $a(\alpha - \beta) = 0$ , then  $\text{in}_a(t^\alpha - t^\beta) = t^\alpha - t^\beta$  and  $t^\alpha - t^\beta \in \ker \psi$ . If instead  $u = a(\alpha - \beta) > 0$ , then  $\text{in}_a(t^\alpha - t^\beta) = t^\alpha$  and  $t^\alpha - y^u t^\beta \in \ker \psi$  so  $t^\alpha \in \ker \psi + (y)$ .

To prove (3) note that  $P \subseteq (t_1, \dots, t_d)$  and hence  $\text{in}_a(P) \subseteq (t_1, \dots, t_d)$ . It follows that

$$(t_1, \dots, t_d) \subseteq (x(t_1, \dots, t_d) + \text{in}_a(P)) : x \subseteq (t_1, \dots, t_d) : x = (t_1, \dots, t_d).$$

Hence

$$(t_1, \dots, t_d) = (x(t_1, \dots, t_d) + \text{in}_a(P)) : x$$

and we get a short exact sequence

$$0 \rightarrow K[x, t_0](-1) \rightarrow \mathcal{R}/(y)\mathcal{R} \rightarrow F \rightarrow 0.$$

By [Lemma 3.4](#) the ring  $F$  is 2-dimensional with short  $h$ -vector. It follows that the same is true for  $\mathcal{R}/(y)\mathcal{R}$  with respect to the standard grading. Using the depth formula for short exact sequences [[Bruns and Herzog 1993](#), Prop. 1.2.9], we have that if  $\text{depth } \mathcal{R}/(y)\mathcal{R}$  is 0 or 1, then  $\text{depth } F = \text{depth } \mathcal{R}/(y)\mathcal{R}$ . Finally, if  $\mathcal{R}/(y)\mathcal{R}$  is Cohen–Macaulay then  $\text{reg}(\mathcal{R}/(y)\mathcal{R}) = 1$  and it follows that  $\text{reg } F = 1$ . Then from [Lemma 2.2](#) we can conclude that  $F$  is Cohen–Macaulay.

We have shown that  $\text{depth } \mathcal{R} - 1 = \text{depth } \mathcal{R}/(y)\mathcal{R} = \text{depth } F$ . Since by [[Huckaba and Marley 1993](#), Cor. 2.7]  $\text{depth } G = \text{depth } \mathcal{R} - 1$ , the proof of (3) is complete.  $\square$

Summing up, we have shown:

**Proposition 3.9.** *Let  $L$  be a lex-segment ideal in  $R = K[x, y]$  with associated  $a$ -sequence  $a = (a_0, \dots, a_d)$ . Then*

$$\text{depth gr}_L(R) = \text{depth } K[t_0, \dots, t_d]/\text{in}_a(P)$$

where  $P$  is the ideal in [Definition 2.4](#).

#### 4. Cohen–Macaulay initial ideals of the ideal of the rational normal curve

The results of the previous sections show that the study of the contracted ideals of  $K[x, y]$  whose associated graded ring is Cohen–Macaulay is equivalent to the study of the initial ideals of  $P$  defining Cohen–Macaulay rings. In this section we describe the initial ideals of  $P$  (with respect to vectors and in the given coordinates) defining Cohen–Macaulay rings. We will say that an ideal  $I$  is Cohen–Macaulay if the quotient ring defined by  $I$  is Cohen–Macaulay. The steps of the classification are

- (1) to classify the 2-dimensional Cohen–Macaulay monomial ideals with minimal multiplicity,
- (2) to identify those of the form  $\text{in}_\tau(P)$  for some term order  $\tau$  among the ideals of (1), and
- (3) to identify the vectors  $a \in \mathbb{Q}_{\geq 0}^{d+1}$  such that  $\text{in}_a(P)$  is Cohen–Macaulay (monomial or not).

We start by classifying the 2-dimensional Cohen–Macaulay square-free monomial ideals with minimal multiplicity. Square-free monomial ideals are in bijective correspondence with simplicial complexes. In particular, square-free monomial ideals defining algebras of Krull dimension 2 are in bijective correspondence with simplicial complexes of dimension 1, that is, graphs. The correspondence goes like this: to any graph with vertex set  $V$  and edge set  $E$  one associates the monomial ideal on variables  $V$ , whose generators are the products  $xy$  such that  $\{x, y\}$  is not in  $E$  and the square-free monomials of degree 3.

Recall that a graph  $G$  with  $n$  vertices and  $e$  edges is a tree if it satisfies the following equivalent conditions:

- (1) For every distinct vertices  $x$  and  $y$ , there exists exactly one path in  $G$  connecting  $x$  and  $y$ ;
- (2)  $G$  is connected and  $n - e = 1$ ;
- (3)  $G$  is connected and if we remove any edge the resulting graph is disconnected.

**Lemma 4.1.** *The 2-dimensional Cohen–Macaulay square-free monomial ideals with minimal multiplicity correspond to trees.*

*Proof.* Let  $G$  be a graph with  $n$  vertices and  $e$  edges. Let  $A$  be the corresponding quotient ring. The Hilbert series of  $A$  is given by

$$1 + \frac{nz}{(1-z)} + \frac{ez^2}{(1-z)^2};$$

see [Bruns and Herzog 1993, 5.1.7]. This implies immediately that  $A$  has minimal multiplicity if and only if  $n - e = 1$ . The Cohen–Macaulay property of  $A$  corresponds to the connectedness of  $G$ ; see [Bruns and Herzog 1993, 5.1.26]. So we are considering connected graphs with  $n - e = 1$ , that is, trees.  $\square$

Next we extend our characterization from the square-free monomial ideals to general monomial ideals. We will make use of the following lemma, whose easy proof belongs to the folklore of the subject.

**Lemma 4.2.** *Let  $I$  be a monomial ideal generated in degree 2 and with linear syzygies. Let  $x, y, z$  be variables. We have*

- (1) *if  $x^2, y^2 \in I$  then  $xy \in I$ , and*
- (2) *if  $x^2, yz \in I$  then either  $xy \in I$  or  $xz \in I$ .*

*Proof.* Say  $I$  is generated by monomials  $m_1 = x^2$ ,  $m_2 = y^2$  and other monomials  $m_3, \dots, m_s$ . Take a free module  $F$  with basis  $e_1, e_2, \dots, e_s$  and map  $e_j$  to  $m_j$ . The syzygy module  $\text{Syz}(I)$  is generated by the reduced Koszul relations  $ae_i - be_j$  with  $a = m_j / \text{GCD}(m_i, m_j)$  and  $b = m_i / \text{GCD}(m_i, m_j)$ . By assumption we know that  $\text{Syz}(I)$  is generated by the elements  $ae_i - be_j$  with  $\deg a = 1$ . Call this set  $G$ . Now  $y^2e_1 - x^2e_2$  is in  $\text{Syz}(I)$  and therefore can be written as  $\sum v_{ij}(ae_i - be_j)$  where the sum is extended to the elements  $ae_i - be_j \in G$ . It follows that there must be in  $G$  an element of the form  $ye_1 - be_i$ . We deduce that  $m_i / \text{GCD}(m_i, x^2) = y$ , forcing  $m_i$  to be  $xy$ . Similarly one proves (2).  $\square$

The crucial inductive step is encoded in the following lemma.

**Lemma 4.3.** *Let  $I \subset S = K[x_1, \dots, x_n]$  be a monomial ideal such that  $S/I$  is Cohen–Macaulay of dimension 2 with minimal multiplicity. Let  $x_i$  be a variable such that  $x_i^2 \in I$ . Set  $S' = K[x_j : 1 \leq j \leq n, j \neq i]$ .*

- (1)  *$I : (x_i)$  is generated by exactly  $n - 2$  variables.*
- (2) *Write  $I + (x_i) = J + (x_i)$  where  $J$  is a monomial ideal of  $S'$ . Then  $S'/J$  is a 2-dimensional Cohen–Macaulay ring with minimal multiplicity.*

*Proof.* First we show that  $I : (x_i)$  is generated by variables. Let  $m$  be one of the generators of  $I$ . We have to show that if  $x_i$  does not divide  $m$  then there exists a variable  $x_j$  such that  $x_j | m$  and  $x_i x_j \in I$ . Let  $V$  be the set of the variables whose square is not in  $I$  and let  $Q$  be the set of the variables whose square is in  $I$ . If  $m$  is divisible by a variable in  $Q$ , then we are done by Lemma 4.2 (1). Otherwise, if  $m$  is not divisible by a variable in  $Q$ , then  $m = x_j x_k$  with  $x_j, x_k \in V$ ,  $j \neq k$ . By Lemma 4.2 (2) we have that either  $x_i x_j$  or  $x_i x_k$  is in  $I$ . Knowing that  $I : (x_i)$  is generated by variables we deduce that  $I : (x)$  is a prime ideal, hence an associated prime of the Cohen–Macaulay ideal  $I$ . Thus the codimension of  $I : (x_i)$  is  $n - 2$ . This proves (1). The standard short exact sequence  $0 \rightarrow S/I : (x_i)(-1) \rightarrow S/I \rightarrow S'/J \rightarrow 0$  shows

that the Hilbert series of  $S'/J$  is  $1 + (n - 3)z/(1 - z)^2$ . Hence  $S'/J$  has a short  $h$ -vector. Furthermore, the exact sequence implies that the regularity of  $S'/J$  is 1, that is,  $\text{reg}(J) = 2$ . By [Lemma 2.2](#) we conclude that  $S'/J$  is Cohen–Macaulay.  $\square$

**Corollary 4.4.** *With the assumptions in [Lemma 4.3](#) and the notation of its proof, there exist  $x_j, x_k \in V$  such that  $I : (x_i) = (x_v : 1 \leq v \leq n \text{ and } v \notin \{j, k\})$  and  $x_j x_k \notin I$ .*

*Proof.* We know by [Lemma 4.3](#) that there are variables  $x_j$  and  $x_k$  so that

$$I : (x_i) = (x_v : 1 \leq v \leq n \text{ and } v \notin \{j, k\}).$$

If  $x_j x_k \in I$ , then  $x_j x_k \in I : (x_i)$ . This is a contradiction.  $\square$

**Definition 4.5.** Let  $V$  and  $Q$  be disjoint sets of variables. Let  $G$  be a tree with vertex set  $V$  and edge set  $E$ . Let  $\phi : Q \rightarrow E$  be a map. Let  $J$  be the square-free monomial ideal associated with  $G$ . Let  $H = (Q)^2 + (xy : x \in Q, y \in V \text{ and } y \notin \phi(x))$ . We define

$$I(G, \phi) = J + H.$$

**Example 4.6.** Let  $V = \{v_1, v_2, v_3, v_4\}$  and  $Q = \{q_1, q_2, q_3, q_4, q_5\}$ . Let  $G$  be the tree on  $V$  with edges  $E = \{e_1, e_2, e_3\}$  where

$$e_1 = \{v_1, v_2\}, e_2 = \{v_1, v_3\}, e_3 = \{v_3, v_4\}.$$

Let  $\phi : Q \rightarrow E$  be the map sending  $q_1, q_2, q_3, q_4, q_5$  to  $e_2, e_1, e_1, e_3, e_2$ , respectively. Then  $J = (v_1 v_4, v_2 v_3, v_2 v_4)$  and

$$H = (q_1, q_2, q_3, q_4, q_5)^2 + q_1(v_2, v_4) + q_2(v_3, v_4) \\ + q_3(v_3, v_4) + q_4(v_1, v_2) + q_5(v_2, v_4).$$

In the next proposition we achieve the first step of the classification.

**Proposition 4.7.** *Let  $I \subset S$  be a monomial ideal. The following conditions are equivalent:*

- (1) *there exist a tree  $G$  and a map  $\phi : Q \rightarrow E$  such that  $I = I(G, \phi)$ ;*
- (2)  *$S/I$  is a 2-dimensional Cohen–Macaulay ring with minimal multiplicity.*

*Proof.* First we show that every ideal of type  $I(G, \phi)$  defines a Cohen–Macaulay, 2-dimensional ring with minimal multiplicity. We proceed by induction on the cardinality of  $Q$ . If  $Q$  is empty, then the ideal  $I$  is 2-dimensional Cohen–Macaulay with minimal multiplicity by [Lemma 4.1](#). Now assume  $Q$  is not empty and pick  $q \in Q$ . By construction  $I(G, \phi) : (q)$  is generated by  $Q \cup V \setminus \phi(q)$  and

$$I(G, \phi) + (q) = I(G, \phi') + (q)$$

where  $\phi'$  is the restriction of  $\phi$  to  $Q' = Q \setminus \{q\}$ . By induction we know that  $I(G, \phi') \subset K[V, Q']$  is 2-dimensional Cohen–Macaulay with minimal multiplicity. The short exact sequence

$$0 \rightarrow K[V, Q]/I(G, \phi) : (q)(-1) \rightarrow K[V, Q]/I(G, \phi) \rightarrow K[V, Q']/I(G, \phi') \rightarrow 0$$

shows that  $I(G, \phi)$  is 2-dimensional with minimal multiplicity and since both  $K[V, Q]/I(G, \phi) : (q)$  and  $K[V, Q']/I(G, \phi')$  are 2-dimensional and Cohen–Macaulay,  $K[V, Q]/I(G, \phi)$  is Cohen–Macaulay.

We show now that every 2-dimensional Cohen–Macaulay monomial ideal  $I$  with minimal multiplicity is of the form  $I(G, \phi)$ . Let  $Q$  be the set of variables whose square is in  $I$  and  $V$  the remaining variables. We argue by induction on the cardinality of  $Q$ . If  $Q$  is empty, then  $I$  is square-free and we know that  $I$  is associated to a tree. If  $Q$  is not empty, let  $q \in Q$ . Write  $I + (q) = J + (q)$  with  $J$  a monomial ideal not involving the variable  $q$ . By [Lemma 4.3](#) we know that  $J \subset K[V, Q \setminus \{q\}]$  is 2-dimensional Cohen–Macaulay with minimal multiplicity. Therefore there exists a tree  $G$  with vertices  $V$  and edges  $E$ , and a map

$$\phi' : Q \setminus \{q\} \rightarrow E$$

so that  $J = I(G, \phi')$ . On the other hand  $I = J + q(I : q)$  and by [Corollary 4.4](#) there are  $x, y \in V$  so that  $I : (q) = (Q \cup V \setminus \{x, y\})$  with  $xy \notin I$ . Hence  $\{x, y\}$  belongs to  $E$  and we extend  $\phi'$  to  $Q$  by sending  $q$  to  $\{x, y\}$ . Call the resulting map  $\phi$ . By construction,  $I(G, \phi) = I$ .  $\square$

Now we come to the second step of our classification: to describe the Cohen–Macaulay monomial initial ideals of  $P$ . Let  $I$  be a monomial Cohen–Macaulay initial ideal of  $P$ . Since  $P$  is 2-dimensional with a short  $h$ -vector, so is  $I$ . By what we have shown above, there exist  $G$  and  $\phi$  so that  $I = I(G, \phi)$ . We want to describe which pairs  $(G, \phi)$  arise in this way.

**Lemma 4.8.** *Let  $I$  be a monomial initial ideal of  $P$  generated in degree 2.*

- (1) *For every  $v$ ,  $0 \leq v \leq 2d$ , there exists exactly one monomial  $t_i t_j$  such that  $i + j = v$  and  $t_i t_j \notin I$ . In particular,  $t_0^2$  and  $t_d^2$  are not in  $I$ .*
- (2) *Let  $0 \leq i < j < k \leq d$ . Assume that  $t_i^2, t_j^2$  and  $t_k^2$  are not in  $I$ . Then  $t_i t_k \in I$ .*
- (3) *Let  $0 \leq i < j < k \leq d$ . Assume that  $t_i^2 \notin I$  and  $t_s t_j \notin I$  for every  $s$  with  $i \leq s \leq j$ . Then  $t_i t_k \in I$ .*

*Proof.* (1) By definition,  $K[t_0, \dots, t_d]/P$  is bigraded by setting  $\deg t_i = (d - i, i)$  and 1-dimensional in each bihomogeneous component. Therefore the ring  $K[t_0, \dots, t_d]/I$  is also bigraded and 1-dimensional in each bihomogeneous component. This proves the assertion. (2) Since  $t_i^{k-j} t_k^{j-i} - t_j^{k-i} \in P$ , we have that either  $t_i^{k-j} t_k^{j-i}$  or  $t_j^{k-i}$  belongs to  $I$ . If  $t_j^{k-i}$  belongs to  $I$ , since  $I$  is generated in

degree 2, then  $t_j^2$  belongs to  $I$ ; a contradiction. So we have  $t_i^{k-j}t_k^{j-i} \in I$ . Since  $t_i^2$  and  $t_k^2$  are not in  $I$  we conclude that  $t_it_k \in I$ . (3) We show that there exist a positive integer  $a$  and  $i \leq s \leq j$  so that  $t_i^a t_k - t_s t_j^a \in P$ . Then since, by assumption, the factors of degree 2 of  $t_s t_j^a$  are not in  $I$ , we have that a factor of degree 2 of  $t_i^a t_k$  is in  $I$ . Since  $t_i^2 \notin I$ , it follows that  $t_it_k \in I$ . To show that  $a$  and  $s$  as above exist, note that the condition  $t_i^a t_k - t_s t_j^a \in P$  translates into  $s = k - a(j - i)$ . So we have to show that there exists a positive integer  $a$  such that

$$i \leq k - a(j - i) \leq j,$$

or equivalently

$$\frac{k - j}{j - i} \leq a \leq \frac{k - i}{j - i}.$$

But this interval has length 1 so it contains an integer which is positive since  $i < j < k$ .  $\square$

The matrix  $T_d$  appearing in the following theorem is defined in [Section 2](#).

**Theorem 4.9.** *Let  $I$  be a monomial ideal of  $K[t_0, \dots, t_d]$ . The following conditions are equivalent.*

- (1) *There exists a sequence  $0 = i_0 < i_1 < i_2 \cdots < i_k = d$  such that  $I(G, \phi) = I$  where  $V = \{t_{i_0}, t_{i_1}, \dots, t_{i_k}\}$ ,  $Q = \{t_0, \dots, t_d\} \setminus V$ ,  $G$  is the tree (a line) with vertex set  $V$  and with edge set  $E = \{\{t_{i_j}, t_{i_{j+1}}\} : 0 \leq j < k - 1\}$  and the map  $\phi : Q \rightarrow E$  sends  $t_s$  to  $\{t_{i_j}, t_{i_{j+1}}\}$  where  $i_j < s < i_{j+1}$ .*
- (2) *There exists a sequence  $0 = i_0 < i_1 < i_2 \cdots < i_k = d$  such that  $I$  is generated by*
  - (a) *the main diagonals  $t_{v-1}t_r$  of the 2-minors of the matrix  $T_d$  with column indices  $v, r$  such that  $v \leq i_j < r$  for some  $j$ , and*
  - (b) *the antidiagonals  $t_v t_{r-1}$  of the 2-minors of the matrix  $T_d$  with column indices  $v, r$  such that  $i_j < v < r \leq i_{j+1}$  for some  $j$ .*
- (3)  *$I$  is a Cohen–Macaulay initial ideal of  $P$ .*

*Proof.* To prove that (1) and (2) are equivalent is just a direct check. To prove that (1) and (2) imply (3), it is enough to describe a term order  $\tau$  such that

$$\text{in}_\tau(P) = I(G, \phi).$$

Indeed, the inclusion  $\text{in}_\tau(P) \supseteq I(G, \phi)$  is enough because the two ideals have the same Hilbert function. To do so, consider a vector  $b = (b_1, b_2, \dots, b_d)$  such that  $b_r > b_v$  if  $v \leq i_j < r$  for some  $j$  and  $b_v > b_r$  if  $i_j < v < r \leq i_{j+1}$  for some  $j$ . In [Remark 4.10](#) we will show a canonical way to construct such a vector. Define  $a = (a_0, a_1, \dots, a_d)$  by setting  $a_0 = 0$  and  $a_i = \sum_{j=1}^i b_j$ . Consider a term order  $\tau$  refining (no matter how) the order defined by the vector  $a$ . We claim that the initial

term with respect to  $\tau$  of the minor with column indices  $v, r$  ( $v < r$ ) of the matrix  $T_d$  is the one prescribed by (2). The minor with those column indices is  $t_{v-1}t_r - t_v t_{r-1}$ . The weights with respect to  $a$  of the two terms are  $a_{v-1} + a_r$  and  $a_v + a_{r-1}$ . Hence  $a_{v-1} + a_r > a_v + a_{r-1}$  if and only if  $b_r > b_v$  and  $a_{v-1} + a_r < a_v + a_{r-1}$  if and only if  $b_r < b_v$ . Therefore, by construction, the initial forms of the minors of  $T_d$  with respect to  $a$  are exactly the monomials prescribed by (2).

We prove now that (3) implies (1). Assume that  $I$  is a Cohen–Macaulay initial ideal of  $P$ . Then  $I$  has regularity 2 and, in particular, is generated by elements of degree 2. Set  $V = \{t_i : t_i^2 \notin I\}$  and  $Q = \{t_i : t_i^2 \in I\}$ . We know by Lemma 4.8 (1) that  $t_0$  and  $t_d$  are in  $V$ . So with  $0 = i_0 < i_1 < i_2 \cdots < i_k = d$  we may write  $V = \{t_{i_0}, t_{i_1}, \dots, t_{i_k}\}$ . Since  $I$  is 2-dimensional Cohen-Macaulay with minimal multiplicity, it has the form  $I = I(G', \phi')$ . We prove that  $G' = G$  and  $\phi' = \phi$  where  $G$  and  $\phi$  are those described in (1). Note that, by Lemma 4.8 (2), we have that  $t_v t_r \in I$  whenever  $r - v > 1$  so that  $\{t_v, t_r\}$  is not an edge of  $G'$ . This implies that the underlying tree  $G'$  is exactly the line  $G$ . It remains to prove that  $\phi = \phi'$ . In other words, we have to prove that for every  $t_j \in Q$ , say  $i_r < j < i_{r+1}$ , one has  $t_j t_r \notin I$  and  $t_j t_{i_{r+1}} \notin I$ . By contradiction, let  $j$  be the smallest element of  $Q$  that does not satisfy the required condition, say  $i_r < j < i_{r+1}$ .

**Claim.** If  $0 \leq v < r$  and  $q \geq j$  then  $t_v t_q \in I$ .

To prove the claim, note that, by the choice of  $j$ , we know that  $t_s t_{i_{v+1}} \notin I$  for every  $i_v \leq s \leq i_{v+1}$  and  $i_{v+1} \leq i_r < j$ . Therefore we may apply Lemma 4.8 (3) to the indices  $i_v, i_{v+1}, q$  and we conclude that  $t_{i_v} t_q \in I$ . In particular, for  $q = j$  the claim says that  $t_{i_v} t_j \in I$  for every  $v < r$ . So  $\phi'(t_j)$  must be an edge of the form  $\{t_{i_u}, t_{i_{u+1}}\}$  with  $u > r$ . It follows that  $t_i t_j \in I$ . But, according to Lemma 4.8 (1), there exists (exactly one but we do not need this) a monomial  $t_a t_b$  (say  $a \leq b$ ) such that  $a + b = i_r + j$  and  $t_a t_b \notin I$ . We distinguish now three cases.

**Case 1.**  $i_r < a$  and  $b < j$ , so that  $a$  and  $b$  are both in  $Q$ . A contradiction (the square of  $Q$  is contained in  $I$ ).

**Case 2.**  $a < i_r, b > j$  and  $a \in V$ . The claim above says that  $t_a t_b \in I$ . A contradiction.

**Case 3.**  $a < i_r, b > j$  and  $a \in Q$ . Say  $i_u < a < i_{u+1}$ . By induction we know that  $\{t_v : t_v t_a \notin I\} = \{t_{i_u}, t_{i_{u+1}}\}$  and therefore  $b > j > i_r \geq i_{u+1}$ . So  $t_a t_b \in I$ . A contradiction.

This concludes the proof. □

**Remark 4.10.** Given  $0 = i_0 < i_1 < i_2 \cdots < i_k = d$ , in the proof of Theorem 4.9 we have used a vector  $b = (b_1, b_2, \dots, b_d) \in \mathbb{Q}_{\geq 0}^d$  with the property that  $b_r > b_v$  if  $v \leq i_j < r$  for some  $j$  and  $b_v > b_r$  if  $i_j < v < r \leq i_{j+1}$  for some  $j$ . Of course there are many vectors with this property. But there is just one “permutation” vector, whose entries are the numbers  $1, \dots, d$  permuted in some way, with this property. It arises

as follows: for  $j = 1, \dots, k$ , consider the vector  $c_j = (i_j, i_j - 1, \dots, i_{j-1} + 1)$  and define the vector  $b$  to be the concatenation of  $c_1, c_2, \dots, c_k$ .

The following theorem summarizes what we have proved so far.

**Theorem 4.11.** (1) *The ideal  $P$  has exactly  $2^{d-1}$  distinct Cohen–Macaulay monomial initial ideals.*

(2) *They are in bijective correspondence with the sequences  $0 = i_0 < i_1 < \dots < i_k = d$ , namely with their radical.*

(3) *Each of them can be obtained with a term order associated to a vector  $a = (a_0, a_1, \dots, a_d) \in \mathbb{N}^{d+1}$  with  $0 = a_0 < a_1 < \dots < a_d$ .*

(4) *Each of them is obtained by taking the appropriate initial terms of the 2-minors of the matrix  $T_d$ .*

(5) *The reduced Gröbner basis of  $P$  giving the Cohen–Macaulay initial ideal corresponding to the sequence  $0 = i_0 < i_1 < i_2 \dots < i_k = d$  is the set of polynomials*

$$\begin{aligned} \underline{t_s t_r} - t_{i_v} t_{s+r-i_v}, & \quad \text{if } 2i_v \leq s+r \leq i_v + i_{v+1}, \\ \underline{t_s t_r} - t_{i_{v+1}} t_{s+r-i_{v+1}}, & \quad \text{if } i_v + i_{v+1} \leq s+r \leq 2i_{v+1}, \end{aligned}$$

where the initial terms are underlined.

**Definition 4.12.** For every sequence  $\mathbf{i} = (i_0, i_1, \dots, i_k)$  with  $0 = i_0 < i_1 < \dots < i_k = d$  we denote by  $C(\mathbf{i})$  the open cone in  $\mathbb{Q}_{\geq 0}^{d+1}$  of the points  $(a_0, \dots, a_d)$  satisfying the inequalities

$$\begin{aligned} a_s + a_r > a_{i_v} + a_{s+r-i_v}, & \quad \text{if } 2i_v \leq s+r \leq i_v + i_{v+1}, \\ a_s + a_r > a_{i_{v+1}} + a_{s+r-i_{v+1}}, & \quad \text{if } i_v + i_{v+1} \leq s+r \leq 2i_{v+1}, \end{aligned}$$

and by  $\overline{C(\mathbf{i})}$  the corresponding closed cone, that is, the subset of  $\mathbb{Q}_{\geq 0}^{d+1}$  described by the inequalities above where  $>$  is replaced throughout by  $\geq$ .

We are ready to state and prove the main theorem of this section.

**Theorem 4.13.** *Let  $a \in \mathbb{Q}_{\geq 0}^{d+1}$ . Then  $\text{in}_a(P)$  is Cohen–Macaulay if and only if  $\text{in}_a(P)$  has a Cohen–Macaulay initial monomial ideal. In other words,*

$$\{a \in \mathbb{Q}_{\geq 0}^{d+1} : \text{in}_a(P) \text{ is Cohen–Macaulay}\} = \bigcup_{\mathbf{i}} \overline{C(\mathbf{i})}$$

where the union is indexed by the  $2^{d-1}$  sequences  $\mathbf{i} = (0 = i_0 < i_1 < \dots < i_k = d)$ .

*Proof.* First we prove the inclusion  $\supseteq$ . Let  $a \in \overline{C(\mathbf{i})}$ . To see that  $\text{in}_a(P)$  is Cohen–Macaulay it is enough to prove that it has a Cohen–Macaulay initial ideal. Just take  $a'$  in the open cone  $C(\mathbf{i})$  and check that  $\text{in}_{a'}(\text{in}_a(P)) = \text{in}_{a'}(P)$ . This is easy since it is enough to check that  $\text{in}_{a'}(\text{in}_a(P)) \supseteq \text{in}_{a'}(P)$ .



In order to prove the opposite inclusion, let  $a \in \overline{\mathbb{Q}_{\geq 0}^{d+1}}$  be such that  $\text{in}_a(P)$  is Cohen–Macaulay. We have to show that  $a \in \overline{C(\mathbf{i})}$  for some  $\mathbf{i}$ . We know already that if  $\text{in}_a(P)$  is monomial then  $a \in C(\mathbf{i})$  where  $\mathbf{i}$  is the sequence of the indices  $i$  such that no power of  $t_i$  belongs to  $\text{in}_a(P)$ . So we are left with the case  $\text{in}_a(P)$  is nonmonomial. To treat this case we first note that, without loss of generality, we may assume that  $a = (a_0, \dots, a_d)$  with  $a_i \in \mathbb{N}$ ,  $a_0 = 0$ , and  $a_i < a_{i+1}$ . This is because cleaning denominators and adding to  $a$  multiples of the vectors  $(1, \dots, 1)$  and  $(0, 1, 2, \dots, d)$  change neither  $\text{in}_a(P)$  nor the membership in the cones. Then we may associate to  $a$  a lex-segment ideal  $L$  in  $R = K[x, y]$  as described in Section 3. We compute the deviation  $V(L)$  of  $L$  in terms of the  $a_i$ 's. It is well-know, see for instance [Delfino et al. 2003], that the multiplicity  $e_0(L)$  of  $L$  is twice the area of the region  $\mathbb{R}_+^2 \setminus \text{New}(L)$  where  $\text{New}(L)$  is the Newton polytope of  $L$ , that is the convex hull of the set of elements  $(a, b) \in \mathbb{N}^2$  such that  $x^a y^b \in L$ . To determine  $e_0(L)$  we describe the vertices of  $\text{New}(L)$ . The generators of  $L$  are the elements  $x^{d-i} y^{a_i}$ . Set  $i_0 = 0$  and assume that  $i_t < d$  is already defined. Then we set

$$m = \min\{(a_j - a_{i_t}) / (j - i_t) : j = i_t + 1, \dots, d\},$$

$$i_{t+1} = \max\{j : i_t + 1 < j \leq d \text{ and } (a_j - a_{i_t}) / (j - i_t) = m\}.$$

The procedure stops when we have reached, say after  $k$  steps,  $i_k = d$ . By construction the points  $(d - c, a_c)$  with  $c \in \{i_0, i_1, \dots, i_k\}$  are the vertices of  $\text{New}(L)$ . Taking into account that twice the area of the triangle with vertices  $(0, 0)$ ,  $(d - i_t, a_{i_t})$ ,  $(d - i_{t+1}, a_{i_{t+1}})$  is  $a_{i_{t+1}}(d - i_t) - a_{i_t}(d - i_{t+1})$  and that  $a_0 = 0$ ,  $i_0 = 0$  we obtain

$$e_0(L) = a_0(i_1 - i_0) + \sum_{t=1}^{k-1} a_{i_t}(i_{t+1} - i_{t-1}) + a_{i_k}(i_k - i_{k-1}).$$

For  $j = 0, \dots, 2d$  set  $\alpha_j = \min\{a_s + a_r : s + r = j\}$  and

$$\beta_j = \begin{cases} a_{i_t} + a_{j-i_t} & \text{if } 2i_t \leq j \leq i_t + i_{t+1}, \\ a_{i_{t+1}} + a_{j-i_{t+1}} & \text{if } i_t + i_{t+1} \leq j \leq 2i_{t+1}. \end{cases}$$

Since  $\dim_K(R/L) = \sum_{i=0}^d a_i$  and  $\dim_K(R/L^2) = \sum_{i=0}^{2d} \alpha_i$  we have

$$\begin{aligned} V(L) &= e_0(L) - \sum_{i=0}^{2d} \alpha_i + 2 \sum_{i=0}^d a_i \\ &= e_0(L) - \sum_{i=0}^{2d} \beta_i + 2 \sum_{i=0}^d a_i + \sum_{i=0}^{2d} (\beta_i - \alpha_i) \\ &= Z + \sum_{i=0}^{2d} (\beta_i - \alpha_i) \end{aligned}$$

where

$$Z = a_0(i_1 - i_0) + \sum_{i=1}^{k-1} a_i(i_{i+1} - i_{i-1}) + a_{i_k}(i_k - i_{k-1}) - \sum_{i=0}^{2d} \beta_i + 2 \sum_{i=0}^d a_i.$$

We claim that  $Z = 0$  identically as a linear form in the  $a_i$ 's. This can be checked directly. That  $Z = 0$  follows also from the fact that  $Z$ , as a linear function in the  $a_i$ 's, computes the deviation  $V(H)$  where  $H$  is any lex-segment with associated vector  $a$  in the cone  $C(\mathbf{i})$ . Since every such lex-segment ideal has a Cohen–Macaulay associated graded ring, we have  $V(H) = 0$ . Therefore  $Z$  vanishes when evaluated at the points of  $C(\mathbf{i}) \cap \{a \in \mathbb{N}^{d+1} : 0 = a_0 < a_1 < \dots < a_d\}$  and so it vanishes identically. Summing up, we have

$$V(L) = \sum_{i=0}^{2d} (\beta_i - \alpha_i).$$

Now, by assumption  $\text{in}_a(P)$  is Cohen–Macaulay, thus by Proposition 3.9  $\text{gr}_L(R)$  is Cohen–Macaulay and by Theorem 3.2  $V(L) = 0$ . Since  $\beta_i \geq \alpha_i$  for every  $i$ , it follows that  $\beta_i = \alpha_i$  for every  $i$ , which in turn implies that  $a \in \overline{C(\mathbf{i})}$ .  $\square$

**Remark 4.14.** Let  $a = (a_0, \dots, a_d)$  be the vector associated to a lex-segment ideal  $L$ . Denote by  $Y$  the convex hull of  $\{(i, j) : x^i y^j \in L\}$ , by  $V$  the set of the vertices of  $Y$  and by  $V'$  the set of the elements  $(d - i, a_i)$  belonging to the lower boundary of  $Y$ . Clearly  $V \subseteq V'$ . Assume that  $\text{gr}_L(R)$  is Cohen–Macaulay. The proof above shows that  $a \in \overline{C(\mathbf{i})}$  where  $\{(d - j, a_j) : j \in \mathbf{i}\} = V$ . The same argument shows also that  $a \in \overline{C(\mathbf{i})}$  for every  $\mathbf{i}$  such that  $V \subseteq \{(d - j, a_j) : j \in \mathbf{i}\} \subseteq V'$ . In particular,  $a$  belongs to  $2^u$  of the cones  $\overline{C(\mathbf{i})}$  where  $u = \#V' - \#V$ .

The next example illustrates the remark above.

**Example 4.15.** Let  $a = (0, 2, 4, a_3, a_4, a_5)$  with

$$4 < a_3 < a_4 < a_5, \quad a_3 > 4 + (a_5 - 4)/3, \quad a_4 > 4 + 2(a_5 - 4)/3.$$

Then  $V = \{(5, 0), (3, 4), (0, a_5)\}$  and  $V' = V \cup \{(4, 2)\}$ . By the remark above we have that if  $\text{in}_a(P)$  is Cohen–Macaulay then  $a \in \overline{C(\mathbf{i})} \cap \overline{C(\mathbf{j})}$  with  $\mathbf{i} = (0, 1, 2, 5)$  and  $\mathbf{j} = (0, 2, 5)$ . In this case the Cohen–Macaulay property is equivalent to the inequalities

$$a_4 \geq a_3 + 2, \quad a_5 \geq a_4 + 2, \quad 2a_3 \geq a_4 + 4, \quad 2a_4 \geq a_3 + a_5.$$

**Definition 4.16.** Let  $\sigma \in S_d$  be a permutation. We may associate to  $\sigma$  a cone

$$C_\sigma = \{a \in \mathbb{Q}_{\geq 0}^{d+1} : b_{\sigma^{-1}(1)} < \dots < b_{\sigma^{-1}(d)}\}$$

where  $b_i = a_i - a_{i-1}$ . We call  $C_\sigma$  the permutation cone associated to  $\sigma$ .

**Remark 4.17.** As shown in the proof of [Theorem 4.9](#) and [Remark 4.10](#) each cone  $C(\mathbf{i})$  contains a specific permutation cone  $C_\sigma$ . The permutations involved in the construction are indeed permutations avoiding the patterns “231” and “312”. More precisely, there is a bijective correspondence between the permutations  $\sigma \in S_d$  avoiding the patterns “231” and “312” and the cones  $C(\mathbf{i})$  so that  $C(\mathbf{i}) \supseteq C_\sigma$ . However, as we will see, the inclusion  $C_\sigma \subseteq C(\mathbf{i})$  can be strict in general. The study of permutation patterns is an important subject in combinatorics; see for instance [[Wilf 2002](#)].

The following example illustrates [Theorem 4.11](#).

**Example 4.18.** Suppose  $d = 6$  and take the sequence  $\mathbf{i}=(i_0=0, i_1=3, i_2=4, i_3=6)$ . The corresponding Cohen–Macaulay initial ideal  $I$  of  $P$  is obtained by dividing the matrix  $T_6$  into blocks (from column  $i_v + 1$  to  $i_{v+1}$ )

$$T_6 = \left( \begin{array}{ccc|cc} t_0 & t_1 & t_2 & t_3 & t_4 & t_5 \\ t_1 & t_2 & t_3 & t_4 & t_5 & t_6 \end{array} \right)$$

and then taking the antidiagonals of minors whose columns belong to the same block:

$$t_1^2, t_1t_2, t_2^2, t_5^2,$$

and the main diagonals from minors whose columns belong to different blocks:

$$t_0t_4, t_0t_5, t_0t_6, t_1t_4, t_1t_5, t_1t_6, t_2t_4, t_2t_5, t_2t_6, t_3t_5, t_3t_6.$$

The ideal  $I$  is the initial ideal of  $P$  with respect to every term order refining the weight  $a = (0, 3, 5, 6, 10, 16, 21)$  obtained from the “permutation” vector

$$\sigma = (3, 2, 1|4|6, 5) \in S_6$$

by setting  $a_0 = 0$  and  $a_i = \sum_{j=1}^i \sigma_j$ . With respect to this term order the 2-minors of  $T_6$  are a Gröbner basis of  $P$  but not the reduced Gröbner basis. The corresponding reduced Gröbner basis is

$$\begin{array}{ccccc} \underline{t_1^2} - t_0t_2, & \underline{t_1t_2} - t_0t_3, & \underline{t_2^2} - t_1t_3, & \underline{t_0t_4} - t_1t_3 & \underline{t_0t_5} - t_2t_3, \\ \underline{t_1t_4} - t_2t_3, & \underline{t_0t_6} - t_3^2, & \underline{t_1t_5} - t_3^2, & \underline{t_2t_4} - t_3^2, & \underline{t_1t_6} - t_3t_4, \\ \underline{t_2t_5} - t_3t_4, & \underline{t_2t_6} - t_4^2, & \underline{t_3t_5} - t_4^2, & \underline{t_3t_6} - t_4t_5, & \underline{t_5^2} - t_4t_6. \end{array}$$

So for every vector  $a = (a_0, a_1, \dots, a_6) \in \mathbb{Q}_{\geq 0}^7$  satisfying the system of linear inequalities

$$\begin{array}{cccc} 2a_1 > a_0 + a_2^*, & a_1 + a_2 > a_0 + a_3, & 2a_2 > a_1 + a_3^*, & a_0 + a_4 > a_1 + a_3^*, \\ a_0 + a_5 > a_2 + a_3, & a_1 + a_4 > a_2 + a_3, & a_0 + a_6 > 2a_3, & a_1 + a_5 > 2a_3, \\ a_2 + a_4 > 2a_3, & a_1 + a_6 > a_3 + a_4, & a_2 + a_5 > a_3 + a_4, & a_2 + a_6 > 2a_4, \\ a_3 + a_5 > 2a_4, & a_3 + a_6 > a_4 + a_5^*, & 2a_5 > a_4 + a_6^*, & \end{array}$$

we have  $\text{in}_a(P) = I$ . The 15 linear homogeneous inequalities above define the open Cohen–Macaulay cone  $C(\mathbf{i})$ . The description is however far from being minimal. The inequalities marked with  $*$  are indeed sufficient to describe  $C(\mathbf{i})$ . In terms of  $b_i = a_i - a_{i-1}$  the inequalities can be described by  $b_3 < b_2 < b_1 < b_4 < b_6 < b_5$ , that is,  $C(\mathbf{i}) = C_\sigma$ .

**Remark 4.19.** (1) There exist Cohen–Macaulay ideals of dimension 2 with minimal multiplicity and without Cohen–Macaulay initial monomial ideals in the given coordinates. For instance, let  $J$  be the ideal of  $K[t_0, \dots, t_4]$  generated by the 2-minors of the matrix

$$\begin{pmatrix} t_0 & t_2 & t_4 - t_0 & 0 \\ t_1 & t_3 & 0 & t_4 + t_0 \end{pmatrix}.$$

Then  $J$  has the expected codimension and hence it is 2-dimensional Cohen–Macaulay with minimal multiplicity. No monomial initial ideal of  $J$  is quadratic since the degree 2 part of every monomial initial ideal has codimension 2. Hence no monomial initial ideal of  $J$  is Cohen–Macaulay. This example shows that [Theorem 4.13](#) does not hold for 2-dimensional binomial Cohen–Macaulay ideals with minimal multiplicity.

(2)  $\text{in}_a(P)$  can be monomial, quadratic and non-Cohen–Macaulay. For example, for  $d = 4$  the ideal  $I = (t_3^2, t_2t_3, t_1t_3, t_0t_4, t_0t_3, t_1^2)$  is a non-Cohen–Macaulay (indeed nonpure) monomial initial ideal of  $P$ . The corresponding cone is described in terms of  $b_i = a_i - a_{i-1}$  by the inequalities  $b_3 > b_1 > b_2 > b_4$  and  $b_3 + b_4 > b_1 + b_2$ .

(3)  $\text{in}_a(P)$  can be quadratic with linear 1-syzygies and not Cohen–Macaulay. For instance, with  $d = 7$  the ideal generated by

$$t_2^2, t_4^2, t_6^2, t_1t_2, t_0t_4, t_0t_5, t_1t_4, t_0t_6, t_1t_5, t_2t_4, t_0t_7, t_1t_6, t_3t_4, \\ t_1t_7, t_2t_6, t_3t_6, t_3t_7, t_4t_6, t_1^2 + t_0t_2, -t_4t_5 + t_2t_7, -t_5t_6 + t_4t_7$$

is an initial ideal of  $P$  with linear 1-syzygies and a nonlinear 2-syzygy.

(4) We do not know any example as the one in (3) if we further assume that  $\text{in}_a(P)$  is a monomial ideal. Note however that 2-dimensional non-Cohen–Macaulay quadratic monomial ideals with a short  $h$ -vector and linear 1-syzygies exist, for example  $(t_1t_3, t_1t_5, t_0t_2, t_2t_5, t_0t_3, t_2^2, t_2t_4, t_2t_3, t_0t_4, t_4t_5)$ .

**Remark 4.20.** As Rekha Thomas pointed out to us, one can deduce from results in [[Hoşten and Thomas 2003](#); [O’Shea and Thomas 2005](#)] that  $P$  has exactly one Cohen–Macaulay monomial initial ideal for each regular triangulation of the underlying point configuration  $A$ . In [[Hoşten and Thomas 2003](#), Theorem 5.5(ii)] it is proved that for every regular triangulation of  $A$  there exists exactly one initial ideal

having no embedded primes (they are called Gomory initial ideals in that paper). In [O’Shea and Thomas 2005] it is proved that every Gomory initial ideal coming from a  $\Delta$ -normal configuration is Cohen–Macaulay. Since every triangulation of  $A$  is  $\Delta$ -normal, one can conclude that the Gomory ideals of  $P$  are indeed Cohen–Macaulay. Hence these results imply that  $P$  has exactly  $2^{d-1}$  Cohen–Macaulay monomial initial ideals.

### 5. Contracted ideals whose associated graded ring is Cohen–Macaulay

In this section we use the results of Section 4 to solve the problem (2) mentioned in Section 1. Since the ideal  $P$  is homogeneous with respect to the vectors  $(1, 1, \dots, 1)$  and  $(0, 1, 2, \dots, d)$  of  $\mathbb{Q}^{d+1}$ , each cone of the Gröbner fan of  $P$  is determined by its intersection with

$$W_d = \{ (a_0, a_1, \dots, a_d) \in \mathbb{N}^{d+1} : 0 = a_0 < a_1 < \dots < a_d \}.$$

As explained in Section 3,  $W_d$  parametrizes the lex-segment ideals of initial degree  $d$ . For a given  $d \in \mathbb{N}$ ,  $d > 0$ , we set

$$CM_d = \{ a \in \mathbb{Q}_{\geq 0}^{d+1} : \text{in}_a(P) \text{ is Cohen–Macaulay} \}$$

the ‘‘Cohen–Macaulay region’’ of the Gröbner fan of  $P$ . According to Theorem 4.13 we have

$$CM_d = \bigcup_{\mathbf{i}} \overline{C(\mathbf{i})}$$

where the union is extended to all of the  $2^{d-1}$  sequences  $\mathbf{i} = (0 = i_0 < i_1 < \dots < i_k = d)$ .

**Theorem 5.1.** *Let  $d_1, \dots, d_s$  be positive integers and  $a_1, \dots, a_s$  be vectors such that  $a_i \in W_{d_i}$ . Let  $\ell_1, \dots, \ell_s, z$  be linear forms in  $R = K[x, y]$  such that each pair of them is linearly independent. For every  $i = 1, \dots, s$ , consider the lex-segment ideals  $L_i$  associated to  $a_i$  with respect to  $\ell_i, z$ , that is,*

$$L_i = (\ell_i^{d_i-j} z^{a_{ij}} : j = 0, \dots, d_i).$$

Set  $I = L_1 \cdots L_s$ . We have

- (1)  $I$  is contracted and every homogeneous contracted ideal in  $R = K[x, y]$  arises in this way, and
- (2)  $\text{gr}_I(R)$  is Cohen–Macaulay if and only if  $a_i \in CM_{d_i}$  for all  $i = 1, \dots, s$ .

*Proof.* (1) is a restatement of Zariski’s factorization theorem for contracted ideals. (2) follows from Theorem 3.3, Proposition 3.9 and Theorem 4.13. □

Theorem 5.1 can be generalized as follows.

**Theorem 5.2.** *Let  $I \subset K[x, y]$  be a monomial ideal (not necessarily contracted) and let  $a = (a_0, \dots, a_d)$  be its associated sequence. Then  $\text{gr}_I(R)$  is Cohen–Macaulay if and only if  $a \in CM_d$ .*

*Proof.* If  $a$  is strictly increasing, then  $I$  is a lex-segment ideal. Hence  $I$  is contracted and the statement is a special case of [Theorem 5.1](#). If  $a$  is not strictly increasing, then we set  $a' = a + (0, 1, \dots, d)$  and let  $L$  be the monomial ideal associated to  $a'$ . Since  $a'$  is strictly increasing,  $L$  is a lex-segment ideal. The cones  $C(\mathbf{i})$  are described by the inequalities that are homogeneous with respect to  $(0, 1, \dots, d)$ . Therefore  $a$  belongs to  $CM_d$  if and only if  $a'$  does. By construction,  $I$  is the quadratic transform of the contracted ideal  $L$  in the sense of [[Conca et al. 2005](#), Sect. 3]. Further we know that  $\text{depth } \text{gr}_I(R) = \text{depth } \text{gr}_L(R)$  according to [[Conca et al. 2005](#), Thm. 3.12]. In summary,  $\text{gr}_I(R)$  is Cohen–Macaulay if and only if  $\text{gr}_L(R)$  is Cohen–Macaulay if and only if  $a' \in CM_d$  if and only if  $a \in CM_d$ .  $\square$

**Remark 5.3.** (1) In  $K[x, y]$  denote by  $C$  the class of contracted ideals, by  $C_1$  the class of the ideals in  $C$  with Cohen–Macaulay associated graded ring and by  $C_2$  the class of integrally closed ideals. We have  $C \supset C_1 \supset C_2$ . One knows that  $C$  and  $C_2$  are closed under product. On the other hand  $C_1$  is not: the lex-segment ideals associated to the sequences  $(0, 4, 6, 7)$  and  $(0, 2)$  belong to  $C_1$  and their product does not. However,  $C_1$  is closed under powers: if  $I \in C_1$  then  $I^k \in C_1$ . This can be seen, for instance, by looking at the Hilbert function of  $I$ . Furthermore we will show in [Section 7](#) that a certain subset of  $C_1$  is closed under product.

(2) For a lex-segment ideal  $L$  in  $K[x, y]$  we have seen that  $\text{gr}_L(R)$  and  $F(L)$  have the same depth. We believe that  $\text{gr}_I(R)$  and  $F(I)$  have the same depth for every contracted ideal  $I$ . In [[D’Cruz et al. 1999](#), Thm. 3.7, Cor. 3.8] D’Cruz, Raghavan and Verma proved that the Cohen–Macaulayness of  $\text{gr}_I(R)$  is equivalent to that of  $F(I)$ . Note however that for a monomial ideal  $I$  the rings  $\text{gr}_I(R)$  and  $F(I)$  might have different depth. For instance, for the ideal  $I$  associated to  $(0, 2, 2, 3)$  one has  $\text{depth } \text{gr}_I(R) = 1$  and  $\text{depth } F(I) = 2$ .

**Remark 5.4.** Two of the cones of the Cohen–Macaulay region  $CM_d$  are special as they correspond to opposite extreme selections.

(1) If  $\mathbf{i} = (0, 1, 2, \dots, d)$ , then the closed cone  $\overline{C(\mathbf{i})}$  is described by the inequality system  $a_i + a_j \geq a_u + a_v$  with  $u = \lfloor (i + j)/2 \rfloor$ ,  $v = \lceil (i + j)/2 \rceil$  for every  $i, j$  or, equivalently, by  $b_{i+1} \geq b_i$  for every  $i = 1, \dots, d - 1$ . In other words,  $C(\mathbf{i})$  equals its permutation cone  $C_{id}$ , where  $id \in S_d$  is the identity permutation. In this case the initial ideal of  $P$  is  $(t_i t_j : j - i > 1)$  and it can be realized by the lex-order  $t_0 < t_1 < \dots < t_d$  or by the lex-order  $t_0 > t_1 > \dots > t_d$ . This is the only radical monomial initial ideal of  $P$ . The points in  $W_d \cap \overline{C(\mathbf{i})}$  correspond

to integrally closed lex-segment ideals. Indeed, they are the products of  $d$  complete intersections of type  $(x, y^u)$ .

(2) If  $\mathbf{i} = (0, d)$  then the closed cone  $\overline{C(\mathbf{i})}$  is described by the inequality system

$$\begin{aligned} a_i + a_j &\geq a_0 + a_{i+j}, & \text{if } i + j \leq d & \text{ and} \\ a_i + a_j &\geq a_d + a_{i+j-d}, & \text{if } i + j \geq d. \end{aligned}$$

It can be realized by the revlex order with  $t_0 < t_1 < \dots < t_d$  or by the revlex order with  $t_0 > t_1 > \dots > t_d$ . The corresponding initial ideal of  $P$  is  $(t_1, \dots, t_{d-1})^2$ . The lex-segment ideals  $L$  belonging to the cone are characterized by the fact that  $L^2 = (x^d, y^{ad})L$ , that is, they are exactly the lex-segment ideals with a monomial minimal reduction and the reduction number 1. It is not difficult to show that the simple homogeneous integrally closed ideals of  $K[x, y]$  are exactly the ideals of the form  $(x^d, y^c)$ , with  $\text{GCD}(d, c) = 1$ . In other words,  $\overline{C(\mathbf{i})}$  contains (the exponent vectors of) all the simple integrally closed ideals of order  $d$ . The associated permutation cone is  $C_\sigma$  with  $\sigma = (d, d - 1, \dots, 1)$ . For  $d \leq 3$  one has  $C(\mathbf{i}) = C_\sigma$ . For  $d = 4$  one has  $C(\mathbf{i}) \supsetneq C_\sigma$  and  $\overline{C(\mathbf{i})} = \overline{C_\sigma} \cup \overline{C_\tau}$  with  $\tau = (4, 2, 3, 1)$ . For  $d > 4$  the cone  $\overline{C(\mathbf{i})}$  is not the union of the closure of the permutation cones it contains. For  $d = 5$ , for example, the cone  $\overline{C(\mathbf{i})}$  is described by the inequalities

$$b_1 + b_2 \geq b_3 + b_4, \quad b_2 + b_3 \geq b_4 + b_5, \quad b_1 \geq b_i \geq b_5 \text{ with } i = 2, 3, 4,$$

and hence it intersects but it does not contain the cone associated with the permutation  $(5, 2, 4, 3, 1)$ .

(3) Apart from the example discussed in (1), the other Cohen–Macaulay monomial initial ideals of  $P$  arising from lex orders are exactly those associated to sequences  $\mathbf{i} = (0, 1, \dots, \widehat{j}, \dots, d)$  for some  $0 < j < d$ . Apart from the example discussed in (2), the other Cohen–Macaulay monomial initial ideals of  $P$  arising from revlex orders are exactly those associated to sequences  $\mathbf{i} = (0, j, d)$  for some  $0 < j < d$ . Therefore, starting from  $d = 5$ , there are Cohen–Macaulay monomial initial ideals of  $P$  not coming from lex or revlex orders. For instance, the initial ideal associated to  $\mathbf{i} = (0, 1, 4, 5)$  is such an example.

### 6. Describing the Hilbert series of $\text{gr}_L(R)$

Let  $L$  be a lex-segment ideal in  $R = K[x, y]$  with associated  $a$ -sequence  $a = (a_0, a_1, \dots, a_d)$ . We have seen in the proof of [Theorem 4.13](#) that the multiplicity  $e_0(L)$  can be expressed as a linear function in  $a_i$ 's. In terms of initial ideals of  $P$ , that assertion can be rephrased as follows. Let  $I$  be a monomial initial ideal of  $P$

and let  $C_I$  be the corresponding closed cone in the Gröbner fan of  $P$ ,

$$C_I = \{ a \in \mathbb{Q}_{\geq 0}^{d+1} : \text{in}_\tau(\text{in}_a(P)) = I \}$$

where  $\tau$  is a given term order such that  $\text{in}_\tau(P) = I$ . Let  $\mathbf{i} = (0 = i_0 < i_1 < \dots < i_k = d)$  and let the set of the integers  $0 \leq j \leq d$  be such that  $t_j \notin \sqrt{I}$ . Then

$$\sqrt{I} = (t_j : j \notin \mathbf{i}) + (t_{i_v} t_{i_r} : r - v > 1).$$

Consider the linear form in  $\mathbb{Z}[A_0, \dots, A_d]$  given by

$$e_0^I = A_0(i_1 - i_0) + \sum_{t=1}^{k-1} A_{i_t}(i_{t+1} - i_{t-1}) + A_{i_k}(i_k - i_{k-1}),$$

where the  $A_i$  are variables. For every lex-segment ideal  $L$  with the associated sequence  $a$  belonging to  $C_I$  one has that  $e_0(L)$  is equal to  $e_0^I$  evaluated at  $A = a$ .

So the “same” formula holds in all the cones of the Gröbner fan associated with the same radical, that is, in all the cones of which the union forms a maximal cone of the secondary fan [Sturmfels 1996, p. 71]. We establish now similar formulas for the Hilbert function  $H^1(L, k)$  and the  $h$ -polynomial of  $\text{gr}_L(R)$ .

To this end, consider  $S = K[t_0, t_1, \dots, t_d]$  equipped with its natural  $\mathbb{Z}^{d+1}$ -graded structure. The quotient  $S/I$  is  $\mathbb{Z}^{d+1}$ -graded and we denote by  $H_{S/I}(t)$  its  $\mathbb{Z}^{d+1}$  graded Hilbert series, namely

$$H_{S/I}(t) = \sum_{\alpha \in \mathbb{N}^{d+1}} \dim[S/I]_\alpha t^\alpha = \sum_{t^\alpha \notin I} t^\alpha$$

where  $t^\alpha = t_0^{\alpha_0} \dots t_d^{\alpha_d}$ . The key observation is contained in the following lemma.

**Lemma 6.1.** *Let  $L$  be a lex-segment ideal with associated vector  $a$  belonging to  $C_I$ . For  $k \in \mathbb{N}$  set  $M_k(I) = \{ \alpha \in \mathbb{N}^{d+1} : t^\alpha \notin I, |\alpha| = k \}$ . Denote by  $\sum M_k(I)$  the sum of the vectors in  $M_k(I)$ . By construction  $\sum M_k(I) \in \mathbb{N}^{d+1}$  and*

$$H^1(L, k - 1) = a \cdot \sum M_k(I)$$

for all  $k$ .

*Proof.* Set  $C_k = a \cdot \sum M_k(I)$ . Writing  $t^\alpha$  as  $t_{j_1} \dots t_{j_k}$ , we may rewrite  $C_k$  as the sum  $a_{j_1} + \dots + a_{j_k}$  over all monomials  $t_{j_1} \dots t_{j_k} \notin I$ . By construction

$$a_{j_1} + \dots + a_{j_k} = \min \{ a_{i_1} + a_{i_2} + \dots + a_{i_k} : i_1 + i_2 + \dots + i_k = j_1 + j_2 + \dots + j_k \}$$

if and only if  $t_{j_1} \dots t_{j_k} \notin I$ . Therefore  $C_k$  is the sum over all  $v$ ,  $0 \leq v \leq kd$  of  $\min \{ a_{i_1} + a_{i_2} + \dots + a_{i_k} : i_1 + i_2 + \dots + i_k = v \}$ . But this is exactly  $H^1(L, k - 1)$ ; see Lemma 3.5. □

In terms of Hilbert series Lemma 6.1 can be rewritten as the follows.



**Lemma 6.2.** *Let  $L$  be a monomial ideal with associated sequence  $a$  belonging to  $C_I$ . Then*

$$H_L^1(z) = a \cdot \nabla H_{S/I}(\underline{t})_{t_i=z}$$

where  $\nabla = (\partial/\partial t_0, \dots, \partial/\partial t_d)$  is the gradient operator.

**Remark 6.3.** (1) The series  $H_{S/I}(\underline{t})$  is rational and it can be described in terms of the multigraded Betti numbers  $\beta_{i,\alpha}(S/I) = \dim_K \text{Tor}_i^S(S/I, K)_\alpha$  as

$$H_{S/I}(\underline{t}) = \frac{\sum_{i,\alpha} (-1)^i t^\alpha \beta_{i,\alpha}(S/I)}{\prod_{i=0}^d (1 - t_i)}.$$

(2) A rational expression of  $H_{S/I}(\underline{t})$  can be computed also from a Stanley decomposition of  $S/I$ . For a monomial ideal  $I$  a Stanley decomposition of  $S/I$  is a finite set  $\Omega$  of pairs  $(\sigma, \tau)$  where  $\sigma \in \mathbb{N}^{d+1}$  and  $\tau \subseteq \{0, \dots, d\}$  which induces a decomposition

$$S/I = \bigoplus_{(\sigma, \tau) \in \Omega} t^\sigma K[t_i : i \in \tau]$$

as a  $K$ -vector space. Stanley decompositions always exist but they are far from being unique. There are algorithms to compute them; see [Maclagan and Smith 2005] for more. For every Stanley decomposition  $\Omega$  of  $S/I$  clearly one has

$$H_{S/I}(\underline{t}) = \sum_{(\sigma, \tau) \in \Omega} \frac{t^\sigma}{\prod_{i \in \tau} (1 - t_i)}.$$

Combining Lemma 6.1, Remark 6.3 with Lemma 6.2 we obtain:

**Corollary 6.4.** *For every cone  $C_I$  and for a monomial ideal  $L$  whose associated sequence  $a$  belongs to  $C_I$  we have*

$$H_L^1(z) = |a| \frac{1 + (d - 1)z}{(1 - z)^3} + a \cdot \sum_{i \geq 1} (-1)^i \sum_{\alpha} \beta_{i,\alpha}(S/I) \frac{z^{|\alpha|-1}}{(1 - z)^{d+1}} \alpha,$$

where  $\beta_{i,\alpha}(S/I)$  are the multigraded Betti numbers of  $S/I$ . Moreover

$$H_L^1(z) = a \cdot \sum_{(\sigma, \tau) \in \Omega} \frac{z^{|\sigma|-1}}{(1 - z)^{|\tau|+1}} (z\tau + (1 - z)\sigma),$$

where  $\Omega$  is a Stanley decomposition of  $S/I$  and we have identified the subset  $\tau$  with the corresponding 0/1-vector.

The next proposition summarizes what we have proved so far concerning formulas for  $h^I$  and related invariants.

**Proposition 6.5.** *Given a cone  $C_I$  of the Gröbner fan of  $P$  there are polynomials  $h^I \in \mathbb{Z}[A, z]$  and  $Q^I, Q_1^I \in \mathbb{Q}[A, z]$  linear in the variables  $A = A_0, \dots, A_d$  and without constant term, such that*

- (1) for every monomial ideal  $L$  with associated sequence  $a$  belonging to  $C_I$ , the polynomial  $h^I$  evaluated at  $A = a$  equals the  $h$ -polynomial of  $L$ ,  $Q^I$  evaluated at  $A = a$  equals the Hilbert polynomial  $P_L$  of  $L$ , and  $Q_1^I$  evaluated at  $A = a$  equals the Hilbert polynomial  $P_L^1$  of  $L$ ;
- (2)  $h^I$ ,  $Q^I$  and  $Q_1^I$  can be expressed in terms of the multigraded Betti numbers of  $I$ ; they can also be expressed in terms of a Stanley decomposition of  $S/I$ ;
- (3) in particular,

$$h^I = |A|(1 + (d - 1)z) + A \sum_{i \geq 1} (-1)^i \sum_{\alpha} \beta_{i,\alpha}(S/I) \frac{z^{|\alpha|-1}}{(1 - z)^{d-2}} \alpha,$$

where  $\beta_{i,\alpha}(S/I)$  are the multigraded Betti numbers of  $S/I$ , and

$$h^I = A \cdot \sum_{(\sigma,\tau) \in \Omega} z^{|\sigma|-1} (1 - z)^{2-|\tau|} (z\tau + (1 - z)\sigma),$$

where  $\Omega$  is a Stanley decomposition of  $S/I$ ; explicit expressions for  $Q^I$  and  $Q_1^I$  can be obtained from that of  $h^I$ .

Similarly one has expressions for the Hilbert coefficients  $e_i^I$  as a linear function in the variables  $A$ . Now we discuss the dependence of the polynomials  $h^I$  and  $Q_1^I$  on  $I$ .

**Proposition 6.6.** *Let  $I, J$  be monomial initial ideals of  $P$ . Then*

- (1)  $e_0^I = e_0^J$  if and only if  $\sqrt{I} = \sqrt{J}$ ,
- (2)  $h^I = h^J$  if and only if  $I = J$ , and
- (3)  $Q_1^I = Q_1^J$  if and only if  $I$  and  $J$  have the same saturation, equivalently, they coincide from a certain degree on.

*Proof.* Denote by  $A$  the vector of variables  $(A_0, \dots, A_d)$ . We have discussed already the fact that the formula for the multiplicity  $e_0^I$  identifies and it is identified by the radical of  $I$ . For statement (2), we have already seen that the coefficient  $C_k$  of  $z^k$  in the series  $h^I/(1 - z)^3$  is exactly  $A \cdot \sum M_{k+1}(I)$ . Hence  $h^I = h^J$  holds if and only if  $A \cdot \sum M_k(I) = A \cdot \sum M_k(J)$  for all  $k$ , that is,  $\sum M_k(I) = \sum M_k(J)$  as vectors for every  $k$ . By virtue of [Sturmfels 1996, Corollary 2.7], we conclude that  $h^I = h^J$  implies  $I = J$ . For (3) one just applies the same argument to all large degrees. □

For an ideal  $I$  of dimension  $v$  we denote by  $I^{top}$  the component of dimension  $v$  of  $I$ , that is, the intersection of the primary components of  $I$  of dimension  $v$ .

**Remark 6.7.** Let  $I, J$  be monomial initial ideals of  $P$ . In terms of  $M_k(I)$  the condition  $Q^I = Q^J$  is equivalent to  $\sum M_k(I) - \sum M_{k-1}(I) = \sum M_k(J) - \sum M_{k-1}(J)$  for all  $k \gg 0$ . There is some computational evidence that  $Q^I = Q^J$  could be

equivalent to  $I^{top} = J^{top}$ . This is related with the hypergeometric Gröbner fan of  $P$ ; see [Saito et al. 2000, Section 3.3]. In particular Example 3.3.7 in [Saito et al. 2000] discusses the secondary fan, the hypergeometric fan and Gröbner fan of  $P$  for  $d = 4$ .

### 7. The big Cohen–Macaulay cone

Starting from  $d = 3$ , the Cohen–Macaulay region  $CM_d$  is not a cone, that is to say it is not convex; see Section 8 for examples. However, a bunch of the cones  $C(\mathbf{i})$  get together to form a big cone.

**Proposition 7.1.** *Let  $B_d = \cup_{\mathbf{i}} \overline{C(\mathbf{i})}$  where the union is extended to all the sequences  $\mathbf{i} = \{0 = i_0 < i_1 < \dots < i_k = d\}$  such that  $i_v - i_{v-1} \leq 2$  for all  $v = 1, \dots, k$ . Then  $B_d$  is the closed cone described in terms of the  $b_i$ 's by the inequalities  $b_j \leq b_{j+2}$  for all  $j = 1, \dots, d - 2$ .*

*Proof.* Let  $B'$  be the cone described by the inequalities  $b_j \leq b_{j+2}$  for all  $j = 1, \dots, d - 2$ . We have to show that  $B_d = B'$ . For the inclusion  $\subseteq$ , let  $a \in B_d$  and  $b_j = a_j - a_{j-1}$ . Then  $a \in \overline{C(\mathbf{i})}$  for a sequence  $\mathbf{i} = \{0 = i_0 < i_1 < \dots < i_k = d\}$  such that  $i_v - i_{v-1} \leq 2$  for all  $v = 1, \dots, k$ . For every  $j, 1 \leq j \leq d - 2$ , at least one among  $j$  and  $j + 1$  is in  $\mathbf{i}$ . We distinguish two cases.

**Case 1.**  $j \in \mathbf{i}$ , say  $j = i_v$ . Then set  $s = j - 1$  and  $r = j + 2$ . We have  $2i_v \leq s + r \leq i_v + i_{v+1}$  and so, by Theorem 4.11 (5),  $a_s + a_r \geq a_{i_v} + a_{s+r-i_v}$  is one of the defining inequalities of  $\overline{C(\mathbf{i})}$ . Explicitly,  $a_{j-1} + a_{j+2} \geq a_j + a_{j+1}$ , that is,  $b_j \leq b_{j+2}$ .

**Case 2.**  $j + 1 \in \mathbf{i}$ , say  $j + 1 = i_{v+1}$ . Then set  $s = j - 1$  and  $r = j + 2$ . We have  $i_v + i_{v+1} \leq s + r \leq 2i_{v+1}$  and so, by Theorem 4.11 (5),  $a_s + a_r \geq a_{i_{v+1}} + a_{s+r-i_{v+1}}$  is one of the defining inequalities of  $\overline{C(\mathbf{i})}$ . Explicitly,  $a_{j-1} + a_{j+2} \geq a_j + a_{j+1}$ , that is,  $b_j \leq b_{j+2}$ .

For the inclusion  $\supseteq$ , let  $a \in B'$  and  $b_i = a_i - a_{i-1}$ . Set

$$U = \{j : 1 \leq j \leq d - 1, b_j > b_{j+1}\}.$$

Since  $b_j \leq b_{j+2}$  for all  $j$ ,  $U$  does not contain pairs of consecutive numbers. Set  $\mathbf{i} = \{0, 1, \dots, d\} \setminus U = (0 = i_0 < \dots < i_k = d)$ . Note that for all  $0 \leq r, s \leq d$  such that  $s - r \geq 2$  one has  $b_s + b_{s-1} \geq b_{r+1} + b_r$  and hence  $a_s + a_r \geq a_{s-2} + a_{r+2}$ . This fact, together with the definition of  $U$ , implies that for all  $0 \leq r, s \leq d$  one has

$$a_s + a_r \geq \begin{cases} a_j + a_{j+1}, & \text{if } s + r = 2j + 1, \\ 2a_j, & \text{if } s + r = 2j \text{ and } j \in \mathbf{i}, \\ a_{j-1} + a_{j+1}, & \text{if } s + r = 2j \text{ and } j \notin \mathbf{i}. \end{cases}$$

Using this information one proves directly that  $a$  satisfies the inequalities in Theorem 4.11 (5) defining  $\overline{C(\mathbf{i})}$ . □

**Remark 7.2.** (1) The number  $f_d$  of the cones  $\overline{C(\mathbf{i})}$  appearing in the description of  $B_d$  satisfies the recursion  $f_d = f_{d-1} + f_{d-2}$  with  $f_1 = 1$  and  $f_2 = 2$ . Hence  $f_d$  is the  $(d + 1)$ -th Fibonacci number.

(2) One also has  $B_d = \cup \overline{C_\sigma}$  where  $\sigma \in S_d$  satisfies  $\sigma(j) < \sigma(j + 2)$  for  $j = 1, \dots, d - 2$ . There are  $\binom{d}{\lfloor d/2 \rfloor}$  such permutations.

(3) Indeed, each cone  $\overline{C(\mathbf{i})}$  appearing in the description of  $B_d$  is the union of permutation cones  $\overline{C_\sigma}$ . Precisely, the permutations involved are those  $\sigma \in S_d$  such that  $\sigma(j) < \sigma(j + 2)$  for all  $j = 1, \dots, d - 2$  and such that  $\sigma(j) > \sigma(j + 1)$  if and only if  $j \notin \mathbf{i}$ . The number of these permutations, say  $n(\mathbf{i})$ , is a product of Catalan numbers. Recall that the  $n$ -th Catalan number is  $c(n) = (n + 1)^{-1} \binom{2n}{n}$ . Decompose  $\{1, \dots, d\} \setminus \mathbf{i}$  as a disjoint union  $\cup_{i=1}^t V_i$  where  $V_i$  are of the form  $\{a, a + 2, \dots\}$  and are maximal. Then  $n(\mathbf{i}) = c(|V_1|) \cdots c(|V_t|)$ . For instance, if  $\mathbf{i} = (0, 2, 3, 5, 7, 9, 10, 12, 14)$  then  $\{1, \dots, 14\} \setminus \mathbf{i} = \{1\} \cup \{4, 6, 8\} \cup \{11, 13\}$  and hence  $\overline{C(\mathbf{i})}$  is the union of  $c(1)c(3)c(2) = 10$  permutation cones.

(4) The family  $B_d$  with  $d \in \mathbb{N}$  is closed under multiplication, that is, if  $a \in B_d$  and  $a' \in B_e$  and  $\mathbf{c} = a \cdot a'$ , then  $\mathbf{c} \in B_{d+e}$ . Set  $\mathbf{c} = (c_0, c_1, \dots, c_{d+e})$ . To show that  $\mathbf{c} \in B_{d+e}$  one has to prove that  $c_{j+2} - c_{j+1} \geq c_j - c_{j-1}$ , that is,

$$c_{j+2} + c_{j-1} \geq c_{j+1} + c_j.$$

By definition,  $c_{j+2} = a_v + a'_u$  with  $v + u = j + 2$  and  $c_{j-1} = a_w + a'_z$  with  $w + z = j - 1$ . Since  $(v - w) + (u - z) = (v + u) - (w + z) = 3$  we may assume that  $v - w \geq 2$ . Then  $a_v + a_w \geq a_{v-2} + a_{w+2}$  and hence

$$c_{j+2} + c_{j-1} = a_v + a'_u + a_w + a'_z \geq a_{v-2} + a'_u + a_{w+2} + a'_z \geq c_j + c_{j+1}.$$

### 8. Examples with small $d$

In this section we describe, for small  $d$ , the Gröbner fan and the Cohen–Macaulay region, and give formulas for the Hilbert series associated to the various cones. For simplicity, the cones will be described in terms of  $b_1, \dots, b_d$  where  $b_i = a_i - a_{i-1}$ .

For  $d = 1$ , there is not much to say. The ideal  $P$  is 0,  $CM_1 = \mathbb{Q}_{\geq 0}^2$  and

$$CM_1 \cap W_1 = \{(0, a) \in \mathbb{N}^2 : a > 0\}.$$

For  $d = 2$  the Gröbner fan has two maximal cones, both Cohen–Macaulay. The lex cone  $C(0, 1, 2)$  is described by  $b_1 \leq b_2$  and the revlex cone  $C(0, 2)$  is described by  $b_1 \geq b_2$ .

For  $d = 3$  the Gröbner fan has 8 maximal cones. 4 of them are Cohen–Macaulay and 4 have depth 1. We show below the cones. Each table shows

(1) an initial ideal  $I$  of  $P$ ,

- (2) the linear inequalities defining the corresponding cone in the Gröbner fan, and
- (3) the coefficients of the  $h$ -vector of  $\text{gr}_L(R)$  for the ideal  $L$  corresponding to points  $(a_0, a_1, a_2, a_3)$  in the cone.

The expressions of the  $h$ -vectors have been computed using Stanley decompositions and the formula in [Corollary 6.4](#). The Stanley decompositions have been computed by the algorithm presented in [[Maclagan and Smith 2005](#)]. Cones (a), (b), (c) and (d) are Cohen–Macaulay cones. In particular (a) is the lex cone and (d) is the revlex cone. The union of (a), (b) and (c) is the big cone  $B_3$  and it is defined by  $b_1 \leq b_3$ . The revlex cone (d) is isolated; it intersects  $B_3$  only at  $b_1 = b_2 = b_3$ . In particular the Cohen–Macaulay region is not a cone.

<p>(a) <math>(t_1t_3, t_0t_3, t_0t_2)</math>,  <math>b_1 \leq b_2 \leq b_3</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) a_1 + a_2</math></p>	<p>(b) <math>(t_1t_3, t_0t_3, t_1^2)</math>  <math>b_2 \leq b_1 \leq b_3</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) a_0 - a_1 + 2a_2</math></p>
<p>(c) <math>(t_2^2, t_0t_3, t_0t_2)</math>,  <math>b_1 \leq b_3 \leq b_2</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) 2a_1 - a_2 + a_3</math></p>	<p>(d) <math>(t_2^2, t_1t_2, t_1^2)</math>,  <math>b_3 \leq b_2 \leq b_1</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) 2a_0 - a_1 - a_2 + 2a_3</math></p>

The non-Cohen–Macaulay cones are

<p>(e) <math>(t_2^2, t_1t_2, t_0t_2, t_0^2t_3)</math>,  <math>b_3 \leq b_1 \leq b_2</math> and <math>b_3 + b_2 \geq 2b_1</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) a_0 + a_1 - 2a_2 + 2a_3</math>  <math>(h_2) -a_0 + a_1 + a_2 - a_3</math></p>	<p>(f) <math>(t_1t_3, t_1t_2, t_1^2, t_0t_3^2)</math>,  <math>b_2 \leq b_3 \leq b_1</math> and <math>b_1 + b_2 \leq 2b_3</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) 2a_0 - 2a_1 + a_2 + a_3</math>  <math>(h_2) -a_0 + a_1 + a_2 - a_3</math></p>
<p>(g) <math>(t_1t_3, t_1t_2, t_1^2, t_2^3)</math>,  <math>b_2 \leq b_3 \leq b_1</math> and <math>b_1 + b_2 \geq 2b_3</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) 2a_0 - 2a_1 + a_2 + a_3</math>  <math>(h_2) a_1 - 2a_2 + a_3</math></p>	<p>(h) <math>(t_2^2, t_1t_2, t_0t_2, t_1^3)</math>,  <math>b_3 \leq b_1 \leq b_2</math> and <math>b_3 + b_2 \leq 2b_1</math>,  <math>(h_0) a_0 + a_1 + a_2 + a_3</math>  <math>(h_1) a_0 + a_1 - 2a_2 + 2a_3</math>  <math>(h_2) a_0 - 2a_1 + a_2</math></p>

For  $d = 4$  there are 42 cones of the Gröbner fan. 10 of them have depth 0, 24 have depth 1 and 8 are Cohen–Macaulay. The big Cohen–Macaulay cone is the union of 5 of the 8 Cohen–Macaulay cones. The remaining 3 are isolated. The following example illustrates [Proposition 6.6](#) and [Remark 6.7](#). The ideals  $I, J$  below are non-Cohen–Macaulay initial ideals of  $P$ . They satisfy  $Q^I = Q^J$  and  $Q_1^I \neq Q_1^J$ . We display the ideals and the formulas for the coefficients  $e_0, e_1, e_2$

that have been computed via Stanley decompositions.

$I \quad (t_1t_3, t_1t_2, t_0t_2, t_3^3, t_1^2t_4, t_1^3, t_2t_4, t_2t_3, t_2^2)$ $(e_0) \quad 4a_0 + 4a_4$ $(e_1) \quad 3a_0 - a_1 - 3a_3 + 4a_4$ $(e_2) \quad -a_0 + 2a_1 - 2a_3 + a_4$	$J \quad (t_1t_3, t_1t_2, t_1^2, t_3^3, t_2t_4, t_2t_3, t_2^2)$ $(e_0) \quad 4a_0 + 4a_4$ $(e_1) \quad 3a_0 - a_1 - 3a_3 + 4a_4$ $(e_2) \quad a_2 - 2a_3 + a_4$
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In this case  $I^{top} = J^{top} = (t_1t_3, t_2, t_3^3, t_1^2)$  as expected by [Remark 6.7](#) and  $J = J^{sat} \neq I^{sat} = (t_2, t_1t_3, t_1^2t_4, t_3^3, t_1^3)$  as proved in [Proposition 6.6](#).

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