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On the Monomial Birational Maps of the Projective Space

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ABSTRACT

We describe the group structure of monomial Cremona transformations. It follows that every element of this group is a product of quadratic monomial transformations, and geometric descriptions in terms of fans.

Key words: monomial birational maps, toric varieties.

1. INTRODUCTION

The best known birational map of \mathbb{P}^r is maybe the *standard Cremona transformation* $S_r : \mathbb{P}^r \dashrightarrow \mathbb{P}^r$ defined by $S_r = (X_0^{-1} : \cdots : X_r^{-1})$. For $r = 2$ there is a geometric description in the classic references on this subject; moreover a Max Noether's famous theorem shows that every birational map of \mathbb{P}^2 is a composition of automorphisms and S_2 , and then that every Cremona transformation is a composition of *quadratic* ones. If $r > 2$ there is no analogous to Noether's theorem (Hudson 1927, Katz 1992, Pan 1999). In this note we consider birational maps generalizing S_r . Our approach is based in a toric point of view and the property that S_r stabilizes the open set $X_0 \cdots X_r \neq 0$. We consider birational maps of \mathbb{P}^r with this property. In the second paragraph of (Russo and Simis 2001) the birationality of these maps is characterized in terms of certain syzygies as an application of a more general criterion; see also (Simis and Villarreal 2002): compare their Proposition 1.1 with our Proposition 3.1.

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2. MONOMIAL CREMONA TRANSFORMATIONS

Let N be a rank r free \mathbb{Z} -module, \mathbb{K} an algebraically closed field, $\mathbb{K}^* := \mathbb{K} \setminus \{0\}$. Let $\mathbb{T} = \mathbb{T}_N := N \otimes_{\mathbb{Z}} \mathbb{K}^*$ be the algebraic torus associated to N over \mathbb{K} . The action of \mathbb{T} on itself induces a natural inclusion ι of the torus in the group $\text{Aut}(\mathbb{T})$ of the algebraic variety's automorphisms of \mathbb{T} ; we consider the subgroup $G_{\mathbb{T}}$ of $\text{Aut}(\mathbb{T})$ given by the algebraic group's automorphisms of \mathbb{T} . Note that, with an appropriate choice of a basis of N , we may identify \mathbb{T} to $(\mathbb{K}^*)^r$. Since \mathbb{K} is algebraically closed an automorphism in $\text{Aut}(\mathbb{T})$ may be written in the form $F = (F_1, \dots, F_r)$ with

$$F_i = \lambda_i x_1^{a_{i1}} \cdots x_r^{a_{ir}} \quad (1)$$

where $\lambda_i \in \mathbb{K}^*$, $a_{ij} \in \mathbb{Z}$, $1 \leq i, j \leq r$.

LEMMA 2.1. *There is a split exact sequence of groups*

$$1 \rightarrow \mathbb{T} \xrightarrow{\iota} \text{Aut}(\mathbb{T}) \xrightarrow{\phi} G_{\mathbb{T}} \rightarrow 1$$

where $\phi(F) := \iota(F(1_{\mathbb{T}})^{-1}) \circ F$, for $F \in \text{Aut}(\mathbb{T})$.

PROOF. One has $\phi(F) \in G_{\mathbb{T}}$, because $\lambda_i^{-1} F_i$ is a character of the torus, $1 \leq i \leq r$; it is easily seen that the sequence is exact. The inclusion of $G_{\mathbb{T}}$ in $\text{Aut}(\mathbb{T})$ is a section of ϕ , hence the sequence splits. \square

In the following we consider the projective space \mathbb{P}^r over \mathbb{K} as a toric variety, *e.g.*, a compactification of the torus $\mathbb{T} = \mathbb{T}_N$ associated to a complete regular fan of $N_{\mathbb{R}} := N \otimes_{\mathbb{Z}} \mathbb{R}$ with $(r+1)$ cones of dimension 1. (One standard reference for toric varieties is (Oda 1988)).

DEFINITION 2.2. *A monomial Cremona transformation is a birational map $F : \mathbb{P}^r \dashrightarrow \mathbb{P}^r$ defined on \mathbb{T} and such that $F(\mathbb{T}) \subset \mathbb{T}$.*

We note $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$ the group of these transformations; there is a natural isomorphism $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r) \xrightarrow{\sim} \text{Aut}(\mathbb{T})$.

PROPOSITION 2.3. *Fixing a basis of the lattice N , there exists an isomorphism*

$$\text{Bir}_{\mathbb{T}}(\mathbb{P}^r) \simeq \mathbb{T} \rtimes \text{GL}_r(\mathbb{Z}).$$

PROOF. It follows from Lemma 2.1. Given $F \in \text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$, we associate $(F(1_{\mathbb{T}}), (a_{ij}))$, where (a_{ij}) is the $r \times r$ -matrix corresponding to $\phi(F) \in G_{\mathbb{T}}$ via the equality (1) and the isomorphism $G_{\mathbb{T}} \xrightarrow{\sim} \text{GL}_r(\mathbb{Z})$ induced by the choice of the basis of N . \square

REMARK 2.4. The action of $\text{GL}_r(\mathbb{Z})$ on \mathbb{T} corresponding to the semidirect product in the proposition is

$$(a_{ij}) \cdot (\lambda_1, \dots, \lambda_r) = \left(\prod_j \lambda_j^{a_{1j}}, \dots, \prod_j \lambda_j^{a_{rj}} \right).$$

COROLLARY 2.5. *The center of $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$ is trivial. The center of the subgroup $\{F : F(1_{\mathbb{T}}) = 1_{\mathbb{T}}\}$ is $\langle S_r \rangle$.*

As a consequence of Proposition 2.3 we obtain an analogous to the M. Noether's theorem (on the generators of the Cremona group of \mathbb{P}^2) in arbitrary dimension for the monomial case.

THEOREM 2.6. *The group $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$ is generated by a quadratic transformation and the linear monomial automorphisms. Consequently, every birational map is a product of quadratic transformations.*

PROOF. It follows from Proposition 2.3 and the fact that $\text{GL}_r(\mathbb{Z})$ is generated by a transvection and two permutations (Coxeter and Moser 1957, Trott 1962) which induce respectively a quadratic transformation and two linear maps in $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$. \square

3. DEGREES AND MATRICES

Let X_0, \dots, X_r be homogeneous coordinates in \mathbb{P}^r , $x_i := X_i/X_0$, $1 \leq i \leq r$, the affine coordinates corresponding to the canonical basis of $N = \mathbb{Z}^r$. Every non-constant monomial *rational* map $F : \mathbb{P}^r \dashrightarrow \mathbb{P}^r$ satisfying $F(1_{\mathbb{T}}) = 1_{\mathbb{T}}$ may be written uniquely in the form

$$F = (X_0^{\alpha_{00}} \dots X_r^{\alpha_{0r}} : \dots : X_0^{\alpha_{r0}} \dots X_r^{\alpha_{rr}}) \quad (2)$$

such that:

- (i) $\alpha(e_j) \in \partial C_+$, $0 \leq j \leq r$,
- (ii) $\alpha(e) = \deg(F)e$, where $\alpha = \alpha_F = (\alpha_{ij})$, e_j , $0 \leq j \leq r$, is the canonical basis of \mathbb{Z}^{r+1} , $e = \sum_j e_j$, C_+ is the cone $\sum_j \mathbb{R}_{\geq 0} e_j$ and ∂C_+ its boundary. The positive integer $\deg(F)$ is the *degree* of F , e.g. $\deg(F) = \sum_j \alpha_{ij}$, $\forall i$.

The map F is *birational* if and only if there exists an integer $(r+1) \times (r+1)$ - matrix β , satisfying (i), (ii), and $v \in \mathbb{Z}^{r+1}$ such that:

- (iii) $\alpha\beta = Id + e \cdot {}^t v$.

In the affine open set $X_0 \cdots X_r \neq 0$ one may write F as

$$F = (1 : x_1^{a_{11}} \cdots x_r^{a_{1r}} : \dots : x_1^{a_{r1}} \cdots x_r^{a_{rr}}). \quad (3)$$

The matrix $A := (a_{ij})$ is the matrix of exponents of (1).

PROPOSITION 3.1. *Let $F \in \text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$ be such that $F(1_{\mathbb{T}}) = 1_{\mathbb{T}}$, $\alpha = \alpha_F$, $d = \deg(F)$. There exists a unique isomorphism $\tilde{\alpha}$ such that the following diagram is commutative and with exact lines.*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{e} & \mathbb{Z}^{r+1} & \longrightarrow & \mathbb{Z}^{r+1}/\mathbb{Z}e \longrightarrow 0 \\ & & \downarrow d & & \downarrow \alpha & & \downarrow \tilde{\alpha} \\ 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{e} & \mathbb{Z}^{r+1} & \longrightarrow & \mathbb{Z}^{r+1}/\mathbb{Z}e \longrightarrow 0. \end{array}$$

One has $d = |\det(\alpha)|$ and A is the matrix of $\bar{\alpha}$ in the basis $\bar{e}_1, \dots, \bar{e}_r$.

PROOF. It follows from properties (ii) and (iii) of α and the form in which α is written in the basis e, e_1, \dots, e_r because (2) and (3) imply $a_{ij} = \alpha_{ij} - \alpha_{0j}$, $1 \leq i, j \leq r$. \square

REMARK 3.2.

(a) $\mathbb{Z}^{r+1}/\alpha(\mathbb{Z}^{r+1})$ is cyclic of order d .

(b) We obtain α from A as follows:

$$\alpha_{0j} = -\min(0, a_{ij}, 1 \leq i \leq r), \text{ for } 1 \leq j \leq r;$$

$$\alpha_{00} = \max(0, \sum_j a_{ij}, 1 \leq i \leq r);$$

$$\alpha_{ij} = a_{ij} + \alpha_{0j}, \text{ for } 1 \leq i, j \leq r;$$

$$\alpha_{i0} = \alpha_{00} - \sum_j a_{ij}, \text{ for } 1 \leq i \leq r.$$

EXAMPLE 3.3. Let A be the matrix whose lines are $(1, 0, 0)$, $(a, 1, 0)$, $(0, a, 1)$, $a \geq 1$. Then

$$F_A = (X_0^{a+1} : X_0^a X_1 : X_1^a X_2 : X_2^a X_3)$$

and

$$F_{A^{-1}} = (X_0^{a^2-a+1} X_1^a X_2^a : X_0^{a^2-a} X_1^{a+1} X_2^a : X_0^{a^2} X_2^{a+1} : X_1^{a^2+a} X_3).$$

EXAMPLE 3.4. Finite subgroup of $\text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$ are obtained by this method. For example the Weyl's group of type $W(D_r)$, $r \geq 3$, and order $2^{r-1}r!$, as a Cremona subgroup may be represented as the subgroup generated by an involution of degree 3

$$F_{\alpha_r} = (X_0 X_{r-1} X_r : X_1 X_{r-1} X_r : \dots : X_{r-2} X_{r-1} X_r : X_0^2 X_{r-1} : X_0^2 X_r)$$

and the linear automorphisms F_{α_i} permuting X_i with X_{i+1} , $1 \leq i < r$. In an analogous form one obtains a representation of the group $W(B_r)$, $r \geq 2$, of order $2^r r!$, generated by an involution of degree 2

$$F_{\beta_r} = (X_0 X_r : X_1 X_r : \dots : X_{r-1} X_r : X_0^2)$$

and the preceding $r - 1$ permutations.

4. GEOMETRIC DESCRIPTION, EXAMPLES

Let $F \in \text{Bir}_{\mathbb{T}}(\mathbb{P}^r)$; we denote by B_F its base-scheme. By composing F with an automorphism induced by an element of the torus we may assume that $F(1_{\mathbb{T}}) = 1_{\mathbb{T}}$. *e.g.* $F = (1_{\mathbb{T}}, A) \in \mathbb{T} \rtimes \text{GL}_r(\mathbb{Z})$, we note $F_A = F$; the base-scheme is not changed.

The union of the fundamental hyperplanes $\mathbb{P}^r \setminus \mathbb{T}$ contains the base-points set.

Let e_1, \dots, e_r the canonical basis for $N = \mathbb{Z}^r$, $e := e_1 + \dots + e_r$, Δ the fan associated to the faces of the simplex $\delta = [e_1, \dots, e_r, -e]$ and $A(\Delta)$ the same with respect to the simplex $A(\delta)$. We consider \mathbb{P}^r defined by Δ ; let Σ be a fan that is a common subdivision for Δ and $A(\Delta)$.

PROPOSITION 4.1. *One has a commutative diagram*

$$\begin{array}{ccc} & X_{\Sigma} & \\ \pi_1 \swarrow & & \searrow \pi_2 \\ \mathbb{P}^r & \xrightarrow{\quad F \quad} & \mathbb{P}^r \end{array}$$

where X_{Σ} is the toric variety associated to Σ , π_1 is equivariant and π_2 is equivariant relatively to the automorphism of the torus induced by A .

PROOF. From (3), it follows that F induce $F^* : \mathbb{K}[\mathbb{T}] \rightarrow \mathbb{K}[\mathbb{T}]$ which corresponds, by duality, to the lattice's automorphism $A : N \rightarrow N$. \square

EXAMPLE 4.2. Let $A = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$ be, $F_A = (X_0^2, X_0X_1, X_1X_2)$. One obtains a (regular) fan Σ that is a subdivision of Δ and $A(\Delta)$ by blowing-up the closed orbits associated to the cones $\langle e_1, e_2 \rangle$ and $\langle e_1, -e \rangle$ and then $\langle -e_2, -e \rangle$.

EXAMPLE 4.3. Let $A = -Id$, then $F_A = S_r$. One obtains a (regular) fan Σ by the elementary subdivisions of Δ (resp. of $-\Delta$), successively, of the cones of decreasing dimensions from r to 2. For example, if $r = 3$, let Σ_0 (resp. Σ'_0) be the fan obtained by the elementary subdivisions of the 4 maximal cones of Δ (resp. $-\Delta$), and Σ_1 (resp. Σ'_1), and the following subdivisions corresponding to the 6 cones of dimension 2 of Δ (resp. $-\Delta$). One has $\Sigma = \Sigma_1 = \Sigma'_1$. The toric variety V_{Σ_0} (resp. $V_{\Sigma'_0}$) is the blowing-up of \mathbb{P}^3 in 4 points and V_{Σ_1} (resp. $V_{\Sigma'_1}$) is the blowing-up of these in the strict transforms of the 6 lines. The induced birational map $V_{\Sigma_0} \dashrightarrow V_{\Sigma'_0}$ is composition of 6 flops, *e.g.*, corresponding to small resolutions of singularities of type an affine cone over a smooth quadric, associated to the 6 faces of the convex polyhedron $P_{\Delta} := \text{Conv}(\Delta \cup (-\Delta))$.

On the other hand, the (normalized) blowing-up of the base-scheme B is the toric variety associated to the fan $\Sigma(B)$ defined by the faces of the polyhedron $P(B) = \text{Conv}(P_{\Delta} \cup C)$, where C is the set of sums of the vertices of a diagonal of each 2-face of P_{Δ} . The toric variety $V_{\Sigma(B)}$ has 12 singular points of type an affine cone over a smooth quadric. Finally, the fan Σ is a regular subdivision of $\Sigma(B)$ and the induced morphism $V_{\Sigma} \rightarrow V_{\Sigma(B)}$ is a minimal resolution of $V_{\Sigma(B)}$.

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RESUMO

Descrevemos a estrutura do grupo das transformações de Cremona monomiais. Concluimos que todo elemento deste grupo é um produto de aplicações monomiais quadráticas e damos descrições geométricas em termos de leques.

Palavras-chave: aplicações biracionais monomiais, variedades tóricas.

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