$D_n(A)$ for a class of polynomial automorphisms and stably tameness

Arno van den Essen and Engelbert Hubbers

Abstract

In this paper we introduce a set, denoted by $D_n(A)$, for every commutative ring $A$ and every positive integer $n$. It is shown that the elements of this set can be used to give an explicit description of the class $H_n(A)$ introduced in [5]. We deduce that each polynomial map of the form $F = X + H$ with $H \in H_n(A)$ can be written as a finite product of automorphisms of the form $\exp(D)$, where each $D$ is a locally nilpotent derivation satisfying $D^2(X_i) = 0$ for all $i$. Furthermore we deduce that all such $F$’s are stably tame.

1 Notations, definitions and an explicit description of the class $H_n(A)$

1.1 Notations

Throughout this paper $A$ denotes an arbitrary commutative ring and $A[X] := A[X_1, \ldots, X_n]$ denotes the polynomial ring in $n$ variables over $A$. Furthermore if $G = (G_1, \ldots, G_n) \in A[X]^n$ and $S = (S_{ij}(X)) \in M_{p,q}(A[X])$ then $S(G)$ or $S|_G$ denotes the $p \times q$ matrix $(S_{ij}(G_1, \ldots, G_n))_{i,j}$. In particular if $F \in A[X]^n$ ($= M_{n,1}(A[X])$) then the composition of the polynomial maps $F$ and $G$, denoted $F \circ G$, is equal to $F(G)$.

Matrix multiplication will be denoted by the symbol ‘*’. So if $S, T \in M_n(A[X])$ then the matrix product of $S$ and $T$ is denoted by $S \ast T$. By $X$ we denote the column vector $(X_1, \ldots, X_n)'$. In the sequel we also need another multiplication in $M_n(A[X])$, which we denote by ‘$\triangle$’. This multiplication is defined as follows:

$$S \triangle T := S(T \ast X) \ast T$$

for all $S, T \in M_n(A[X])$.

One easily verifies that this multiplication is associative, so it makes sense to write

$$S_1 \triangle S_2 \triangle \cdots \triangle S_n$$
for each \( n \)-tuple \( S_1, \ldots, S_n \) in \( M_n(A[X]) \). Sometimes we need to extend a vector of length \( 1 \leq p \leq n - 1 \) or a \( p \times p \) matrix to a vector of length \( n \) respectively an \( n \times n \) matrix. This is done as follows: let \( 1 \leq p \leq n - 1 \), \( c \in A[X]^p \) and \( T \in M_p(A[X]) \). Then \( \tilde{c}^n \) denotes the vector

\[
\tilde{c}^n = \begin{pmatrix} c \\ 0 \\ \vdots \\ 0 \end{pmatrix} \in A[X]^n,
\]

given by extending \( c \) by \( n - p \) zeros and \( \tilde{T}^n \) denotes the matrix

\[
\tilde{T}^n = \begin{pmatrix} T \\ 0 \\ I_{n-p} \end{pmatrix} \in M_n(A[X]),
\]

obtained by extending \( T \) with the \( n - p \times n - p \) identity matrix. To simplify the notations we drop the superscript ‘\( n \)’ and write \( \tilde{c} \) and \( \tilde{T} \), even sometimes when it is clear from the context that we mean \( \tilde{c}^{n-1} \) respectively \( \tilde{T}^{n-1} \) instead of \( \tilde{c}^n \) respectively \( \tilde{T}^n \).

Finally the adjoint of a matrix \( T \) is denoted by \( \text{Adj}(T) \) and if \( a_1, \ldots, a_p \) are elements of a (non-necessary commutative) ring then \( \prod_{i=1}^p a_i \) denotes the element \( a_1 \cdots a_p \).

### 1.2 \( \mathcal{D}_n(A) \) and the class \( \mathcal{H}_n(A) \)

In [5] we introduced a new class of polynomial maps, denoted by \( \mathcal{H}_n(A) \), and showed that for each \( H \in \mathcal{H}_n(A) \) the Jacobian matrix \( JH \) is nilpotent and that the polynomial map \( F = X + H \) is invertible over \( A \) with \( \det(JF) = 1 \).

Let us recall the definition of \( \mathcal{H}_n(A) \).

**Definition 1.1** First if \( n = 1 \) we define \( \mathcal{H}_1(A) = A \). If \( n \geq 2 \) we define \( \mathcal{H}_n(A) \) inductively as follows: let \( H \in A[X]^n \), then \( H \in \mathcal{H}_n(A) \) if and only if there exist \( T \in M_n(A), c \in A^n \) and \( H_* \in \mathcal{H}_{n-1}(A[X^n]) \) such that

\[
H = \text{Adj}(T) \ast \begin{pmatrix} H_* \\ 0 \end{pmatrix} + c.
\]

The main aim of this section is to give an explicit description of the elements of \( \mathcal{H}_n(A) \). Therefore we introduce some useful objects.

**Definition 1.2** Let \( n \geq 2 \). Then \( \mathcal{D}_n(A) \) is the set of \((2n - 1)\)-tuples

\[
(T, c) := (T_2, \ldots, T_n, c_1, \ldots, c_n)
\]

where \( T_n \in M_n(A), T_i \in M_i(A[X_{i+1}, \ldots, X_n]) \) for all \( 2 \leq i \leq n - 1 \), \( c_n \in A^n(= M_{n,1}(A)) \) and \( c_i \in M_{i,1}(A[X_{i+1}, \ldots, X_n]) \) for all \( 1 \leq i \leq n - 1 \).
If $n \geq 3$ we get a natural map $\pi : D_n(A) \to D_{n-1}(A[X_n])$ defined by

$$\pi((T_2, \ldots, T_n, c_1, \ldots, c_n)) = (T_2, \ldots, T_{n-1}, c_1, \ldots, c_{n-1}).$$

Instead of $\pi((T, c))$ we often write $(T', c')$.

**Definition 1.3** Let $n \geq 2$ and $0 \leq p \leq n - 2$. Then

$$E_{n,p} : D_n(A) \to A[X]^n$$

is given by

1. $E_{n,0}((T, c)) := \text{Adj}(T_n) \cdot c_{n-1} |_{T_n \ast X}$ for all $(T, c) \in D_n(A)$.

2. If $n \geq 3$ and $1 \leq p \leq n - 2$, then inductively (with respect to $n$)

$$E_{n,p}((T, c)) := \text{Adj}(T_n) \cdot \begin{pmatrix}
E_{n-1,p-1}((T', c')) \\
0
\end{pmatrix} |_{T_n \ast X}$$

Instead of $E_{n,p}((T, c))$ we simply write $E_{n,p}(T, c)$.

Now we are able to give the main result of this section.

**Proposition 1.4** Let $n \geq 2$ and $H \in A[X]^n$. Then $H \in \mathcal{H}_n(A)$ if and only if there exists $(T, c) \in D_n(A)$ such that

$$H = \sum_{p=0}^{n-2} E_{n,p}(T, c) + c_n.$$

**Proof.** By induction on $n$. The case $n = 2$ is obvious, so let $n \geq 3$. Then

$$H = \text{Adj}(T_n) \cdot \begin{pmatrix}
H_* \\
0
\end{pmatrix} |_{T_n \ast X} + c_n$$

where $T_n \in M_n(A)$, $c_n \in A^n$ and $H_* \in \mathcal{H}_{n-1}(A[X_n])$. So by the induction hypothesis we have

$$H_* = \sum_{p=0}^{n-3} E_{n-1,p}(T^*, c^*) + c^*_{n-1}$$

for some $(T^*, c^*) \in D_{n-1}(A[X_n])$. Put $(T, c) := (T^*, T_n, C^*, c_n)$ and observe that $(T, c) \in D_n(A)$ and $(T', c') = (T^*, c^*)$. So

$$H = \sum_{p=0}^{n-3} \text{Adj}(T_n) \cdot E_{n-1,p}(T', c'|_{T_n \ast X}) + \text{Adj}(T_n) \cdot \begin{pmatrix}
c_n^{n-1} \\
0
\end{pmatrix} |_{T_n \ast X} + c_n
= \sum_{p=1}^{n-2} E_{n,p}(T, c) + E_{n,0}(T, c) + c_n
= \sum_{p=0}^{n-2} E_{n,p}(T, c) + c_n.$$
Proposition 1.5 Let $n \geq 2$, $0 \leq p \leq n - 2$ and $(T, c) \in \mathcal{D}_n(A)$. Then

$$E_{n,p}(T, c) = \text{Adj}(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) \ast \tilde{c}_{n-p-1} |(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) * X$$

**Proof.** By induction on $p$. The case $p = 0$ is obvious. So let $p \geq 1$. Then

$$E_{n,p}(T, c) = \text{Adj}(T_n) \ast \left( \begin{array}{c} E_{n-1,p-1}(T', c') \\ 0 \end{array} \right)_{|T_n * X}$$

(by the induction hypothesis)

$$= \text{Adj}(T_n) \ast \text{Adj}(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1})_{|T_n * X} \ast \left( \begin{array}{c} \tilde{c}_{n-p-1} |(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1}) * X \\ 0 \end{array} \right)_{|T_n * X}$$

$$= \text{Adj}(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) \ast \tilde{c}_{n-p-1} |(\tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) * X$$

Example 1.6 Consider the polynomial map $F := X + H : \mathbb{C}^4 \to \mathbb{C}^4$ where $H$ equals

$$\begin{pmatrix} -X_2X_4^2 - c_4X_3^2X_4 - 2\frac{m_4}{g_4}X_2X_3X_4 - g_4X_1X_3X_4 - k_4X_3^3 - \frac{m_2}{g_4^2}X_2X_3^2 - m_4X_1X_3^2 \\ -X_3X_4^2 - c_3X_3^2X_4 + g_4X_2X_3X_4 - k_3X_3^3 + m_4X_2X_3^2 + g_4^2X_1X_3^2 \\ -\frac{k_3}{3}X_3^4 \\ 0 \end{pmatrix}$$

and $c_3, k_3, c_4, g_4, k_4, m_4 \in \mathbb{C}$ and $g_4 \neq 0$. This $F$ is invertible. In fact if we take $P = P^{-1} = (X_4, X_3, X_2, X_1)$, we have that $PF\bar{P}$ is one of the eight representatives of the cubic homogeneous maps in dimension four as given by the second author in [6], also published in [4, Theorem 2.10].

Now consider the following element $(T, c)$ of $\mathcal{D}_4(\mathbb{C})$ where

$$T = \begin{pmatrix} 1 \\ g_4^2X_3 \\ g_4X_4 + m_4X_3 \\ 0 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

and

$$c = \begin{pmatrix} \frac{g_4}{2}X_2 \\ -\frac{k_3}{3}X_3^2 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ -X_3^2(\epsilon_4X_4 + k_4X_3) \\ -X_3X_4^2 - \epsilon_4X_4X_3^2 - k_3X_3^3 \\ -\frac{2}{3}X_3^4 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Our claim is that

$$H = \sum_{p=0}^{2} E_{4,p}(T, c) + c_4.$$
To prove this we will compute $E_{4,0}$, $E_{4,1}$ and $E_{4,2}$ by the method of proposition 1.5. Note that $c_4 = 0$. Since $T_4 = T_3 = I_4$, $E_{4,0}$ and $E_{4,1}$ are easy:

$$E_{4,0} = \text{Adj}(T_4) \ast \tilde{c}_3 |_{T_4 \ast X} = \tilde{c}_3 = \begin{pmatrix} 0 & 0 & -\frac{1}{3}X_3^3 \\ 0 & 0 & 0 \end{pmatrix}$$

$$E_{4,1} = \text{Adj}(\tilde{T}_3 \triangle T_4) \ast \tilde{c}_2 |_{T_3 \triangle T_4 \ast X} = \tilde{c}_2 = \begin{pmatrix} -X_3^2(e_4 X_4 + k_4 X_3) \\ -X_3 X_4^2 - e_3 X_4 X_3^2 - k_3 X_3^4 \\ 0 \\ 0 \end{pmatrix}$$

Before we compute $E_{4,2}$ we present the following identities:

$$\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4 = \tilde{T}_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ g_4^2 X_3 & g_4 X_4 + m_4 X_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\text{Adj}(\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4) = \begin{pmatrix} g_4 X_4 + m_4 X_3 & 0 & 0 & 0 \\ -g_4^2 X_3 & 1 & 0 & 0 \\ 0 & 0 & g_4 X_4 + m_4 X_3 & 0 \\ 0 & 0 & 0 & g_4 X_4 + m_4 X_3 \end{pmatrix}$$

$$(\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4) \ast X = \begin{pmatrix} X_1 \\ g_4^2 X_1 X_3 + g_4 X_1 X_4 + m_4 X_1 X_3 \\ X_3 \\ X_4 \end{pmatrix}$$

$$\tilde{c}_1 |_{(\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4) \ast X} = \begin{pmatrix} -X_1 X_3 - \frac{1}{g_4} X_2 X_4 - \frac{m_4}{g_4} X_2 X_3 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

and finally

$$E_{4,2} = \text{Adj}(\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4) \ast \tilde{c}_1 |_{(\tilde{T}_2 \triangle \tilde{T}_3 \triangle T_4) \ast X} = \begin{pmatrix} -X_4 + \frac{m_4}{g_4} X_3 & \left(g_4 X_1 X_3 + X_2 X_4 + \frac{m_4}{g_4} X_2 X_3 \right) \\ X_3 \left(g_4^2 X_1 X_3 + g_4 X_1 X_4 + m_4 X_2 X_3 \right) & 0 \\ 0 & 0 \end{pmatrix}$$

It is easy to verify that $H = E_{4,0} + E_{4,1} + E_{4,2} + c_4$, which was our claim.

### 2 Nice derivations

Let $B := A[x_1, \ldots, x_n]$ be a finitely generated $A$-algebra and $D$ a subset of $\text{Der}_A(B)$. By $B^D$ we denote the set of all $b \in B$ such that $d(b) = 0$ for all $d \in D$. 
Definition 2.1 Let $D \subseteq \text{Der}_A(B)$ a finite subset and $\tau \in \text{Der}_A(B)$.

1. We say that $\tau$ is derived from $D$ in at most one step if $\tau$ is of the form $\tau = \sum_{d \in D} b_d d$, where $b_d \in B^D$ for all $d \in D$.

2. Let $m \geq 2$. We say that $\tau$ is derived from $D$ in at most $m$ steps if there exists a sequence of finite subsets

$$D = D_0, D_1, D_2, \ldots, D_m$$

of $\text{Der}_A(B)$ such that $\tau \in D_m$ and all elements of $D_i$ are derived from $D_{i-1}$ in at most one step, for all $1 \leq i \leq m$. If furthermore the elements of $D$ satisfy $d_1 d_2 (x_i) = 0$ for all $d_1, d_2 \in D$ and all $i$, then $\tau$ is called nice of order $\leq m$, with respect to $x_1, \ldots, x_n$ and $D$.

Proposition 2.2 Notations as in definition 2.1. If $d_1 d_2 (x_i) = 0$ for all $d_1, d_2 \in D$ and all $i$, then $d_1 d_2 (x_i) = 0$ for all $d_1, d_2 \in D_m$ and all $i$. In particular $d^2 (x_i) = 0$ for every nice derivation.

Proof. We use induction on $m$. The case $m = 0$ is obvious since $D_0 = D$. Now let $m \geq 1$. Then $d_1 = \sum_{d' \in D_{m-1}} b_{d'} d$, $d_2 = \sum_{d'' \in D_{m-1}} b'_{d''} d''$ with $b_{d'}, b'_{d''} \in B^{D_{m-1}}$. Then

$$d_1 d_2 (x_i) = \sum_{d, d'} b(d'(d'_i)) d(x_i) + \sum_{d, d''} b(d''(d_i)) d''(d_i).$$

(2)

Now observe that $d(d'_i) = 0$ since $b'_{d''} \in B^{D_{m-1}}$ and $d \in D_{m-1}$. Finally the induction hypothesis gives $d''(x_i) = 0$ for all $d, d' \in D_{m-1}$ and all $i$, so (2) implies $d_1 d_2 (x_i) = 0$. \qed

We demonstrate these aspects by the so-called Winkelmann derivation. See [10].

Example 2.3 Let $\tau = (1 + X_4 X_2 - X_5 X_3) \partial X_1 + X_5 \partial X_2 + X_4 \partial X_3$, a derivation on $B := A[X_1, X_2, X_3, X_4, X_5]$. Let $D = \{ \partial X_1, \partial X_2, \partial X_3 \}$. Then $\tau$ is nice of order two with respect to $X_1, X_2, X_3, X_4, X_5$ and $D$. To show that this is true, we present a sequence of finite subsets of $\text{Der}_A(B)$,

$$D = D_0, D_1, D_2$$

Take $D_1 := \{ \partial X_1, X_5 \partial X_2 + X_4 \partial X_3 \}$ and $D_2 := \{ \tau \}$. Note that in definition 2.1 it is not demanded that the set $D_i$ of this sequence is a subset of $D_{i+1}$. The only demand is that each $D_i$ is a finite subset of $\text{Der}_A(B)$. Since $X_4, X_5 \in B^D$ it follows immediately that $\partial X_1$ and $X_5 \partial X_2 + X_4 \partial X_3$ are derived from $D$ in one step. And from $1 + X_4 X_2 - X_5 X_3 \in B^{D_1}$ it follows that $\tau$ is derived from $D_1$ in one step. Obviously we have $d_1 d_2 (x_i) = 0$ for all $d_1, d_2 \in D$ and hence with proposition 2.2 also $\tau^2 (x_i) = 0$. 


3 Derivations associated to polynomial maps

The main aim of this section is to show that for each $0 \leq p \leq n-2$ the polynomial map $X + E_{n,p}(T, c)$ (where $(T, c) \in D_n(A)$) is of the form $\exp(d)$, for some nice $A$-derivation $d$ of $A[X]$. Observe that $d$ is locally nilpotent if $d$ is nice with respect to $X_1, \ldots, X_n$ since $d^2(X_i) = 0$ for all $i$, by proposition 2.2.

In order to prove this result (see theorem 3.3), we need to generalise some of the notions of section 1 to arbitrary finitely generated $A$-algebras. So let $B := A[x_1, \ldots, x_n]$ be a finitely generated $A$-algebra and $\varphi : A[X_1, \ldots, X_n] \to B$ the $A$-ringhomomorphism defined by $\varphi(X_i) = x_i$ for all $i$. For each $p, q \geq 1$ consider the natural extension

$$\varphi : M_{p,q}(A[X_1, \ldots, X_n]) \to M_{p,q}(B).$$

Then for each $(T, c) \in D_n(A)$ we define

$$E_{n,p}(T, c)(x) := \varphi(E_{n,p}(T, c)) \in B^n.$$

Now let $(\partial_1, \ldots, \partial_n)$ be an $n$-tuple of $A$-derivations of $B$. To each vector $b = (b_1, \ldots, b_n)^T \in B^n$ we associate the following $A$-derivation of $B$:

$$D(b; \partial_1, \ldots, \partial_n) := b_1 \partial_1 + \cdots + b_n \partial_n \quad (= b^T \cdot \begin{pmatrix} \partial_1 \\ \vdots \\ \partial_n \end{pmatrix}).$$

To formulate the next lemma we need some more notations: let $(T, c) \in D_n(A)$. Put

$$(x'_1, \ldots, x'_n)^T := T_n \ast (x_1, \ldots, x_n)^T$$

$$(\partial'_1, \ldots, \partial'_n) := (\text{Adj}(T_n))^T \ast (\partial_1, \ldots, \partial_n)^T$$

$$x''^T := (x'_1, \ldots, x'_{n-1})$$

$$(T'', c'') := (T'(X_n = x'_n), c'(X_n = x'_n)) \in D_{n-1}(A[x'_n])$$

**Lemma 3.1** Let $n \geq 3$ and $1 \leq p \leq n-2$. Then

$$D(E_{n,p}(T, c)(x); \partial_1, \ldots, \partial_n) = D(E_{n-1,p-1}(T'', c'')(x''); \partial'_1, \ldots, \partial'_{n-1}).$$

**Proof.**

$$D(E_{n,p}(T, c)(x); \partial_1, \ldots, \partial_n) = (E_{n,p}(T, c)(x))^T \cdot \begin{pmatrix} \partial_1 \\ \vdots \\ \partial_n \end{pmatrix}$$

$$= \left( (E_{n-1,p-1}(T', c')|_{T_n \ast c^T})^T \ast \text{Adj}(T_n))^T \ast \begin{pmatrix} \partial_1 \\ \vdots \\ \partial_n \end{pmatrix} \right)$$
Derivations associated to polynomial maps

\[
\begin{align*}
\text{Lemma 3.2} & \quad \text{Notations as above. Let } a \in A \text{ and let } \partial_1, \ldots, \partial_n \text{ be } A\text{-derivations of } B \text{ such that } \partial_i(x_j) = a \delta_{ij} \text{ for all } i, j. \text{ Then } \\
\partial_i'(x_j) &= a \det(T_n) \delta_{ij}
\end{align*}
\]

for all \(i, j\).

\textbf{Proof.} Denote the \(i\)-th column of \(\text{Adj}(T_n)\) by \((t^*_{i1}, \ldots, t^*_{in})^t\) and the \(j\)-th row of \(T_n\) by \((t_{j1}, \ldots, t_{jn})\). Then

\[
\partial_i'(x_j) = \left( \sum_{s=1}^{n} t^*_{is} \partial_s \right) \left( \sum_{s=1}^{n} t_{js} x_s \right)
= \sum_{s=1}^{n} a t^*_{is} t_{js}
= a (T_n * \text{Adj}(T_n))_{ji}
= a \det(T_n) \delta_{ij}
\]

Now we are able to prove:

\textbf{Theorem 3.3} Let \(\partial_1, \ldots, \partial_n\) be \(A\)-derivations on \(A[x_1, \ldots, x_n]\) such that there exists an element \(a \in A\) such that \(\partial_i(x_j) = a \delta_{ij}\) for all \(i, j\). Let \((T, c) \in \mathcal{D}_n(A)\). Then the \(A\)-derivation \(d := D(E_{n,p-1}(T, c)(x); \partial_1, \ldots, \partial_n)\) is nice with respect to \(x_1, \ldots, x_n\) and \(D_0 := \{\partial_1, \ldots, \partial_n\}\), for all \(n \geq 2\) and all \(0 \leq p \leq n - 2\).

\textbf{Proof.}

1. The hypothesis on the \(\partial_i\) imply that \(dd'(x_i) = 0\) for all \(d, d' \in D_0\) and all \(i\).

2. First we consider the case \(p = 0\). Then

\[E_{n,0}(T, c) = \text{Adj}(T_n) * \bar{c}_{n-1} |T_{n} \times X|.
\]

So

\[
d = (\bar{c}_{n-1} |T_{n} \times X|)^t * (\text{Adj}(T_n))^t * \begin{pmatrix}
\partial_1 \\
\vdots \\
\partial_n
\end{pmatrix}.
\]
Write \( \gamma_n(x_n, \ldots, x_{n-1}, 0) \). Then the definition of \( x'_n \) and the \( \partial'_j \) imply that

\[
d = (\gamma_1(x'_n, \ldots, x'_{n-1}, 0) \ast (\partial'_1, \ldots, \partial'_{n-1})) = \sum_{i=1}^{n-1} \gamma_i(x'_n) \partial'_{i+1}
\]  

(3)

Put \( D_1 := \{ \partial'_1, \ldots, \partial'_{n-1} \} \) and observe that \( D_1 \subset \text{Der}_A(B) \) and that each element of \( D_1 \) is derived from \( D_0 \) in at most one step. Finally since \( \partial'_i(x'_n) = 0 \) for all \( 1 \leq i \leq n-1 \) (by lemma 3.2) we get that \( \gamma_i(x'_n) \in B^{D_1} \) for all \( 1 \leq i \leq n-1 \). So (3) implies that \( d \) is derived from \( D_1 \) in at most one step. Consequently \( d \) is derived from \( D_0 \) in at most two steps. So \( d \) is nice with respect to \( x_1, \ldots, x_n \) and \( D_0 \) by case 1.

3. Now we prove the theorem by induction on \( n \). If \( n = 2 \), then \( p = 0 \) and we are in case 2. So let \( n \geq 3 \). By case 2 we may assume that \( p \geq 1 \). Then by lemma 3.1 we have

\[
d = D(E_{n-1,0-1}(T', \nu')(x''; \partial'_1, \ldots, \partial'_{n-1})
\]

with \( (T'', \nu'') \in D_{n-1}(A[x'_n]) \). By lemma 3.2 we can apply the induction hypothesis to the ring \( A[x'_n] \) and the \( (n-1) \)-tuple of \( A[x'_n] \)-derivations \( \partial'_1, \ldots, \partial'_{n-1} \) on the \( A[x'_n] \)-algebra \( B' := A[x'_n][x'_1, \ldots, x'_{n-1}] \). So the \( A[x'_n] \)-derivation \( d \) is nice with respect to \( D_0' := \{ \partial'_1, \ldots, \partial'_{n-1} \} \) and \( x'_1, \ldots, x'_{n-1} \). So there exists a sequence

\[ D'_0, D'_1, \ldots, D'_m \]

of finite subsets of \( \text{Der}_A(A[x'_n]) \) such that \( d \in D'_m \) and \( D'_i \) is derived from \( D'_{i-1} \) in at most one step for all \( 1 \leq i \leq m \). Now observe that \( D'_0 \subset \text{Der}_A(B) \) and that \( B' \subset B \) since by definition obviously \( x'_i \in B \) for all \( i \). Consequently if \( d' \) is an \( A[x'_n] \)-derivation of \( B' \) derived from \( D'_0 \) in at most one step, then \( d' \in \text{Der}_A(B) \). Hence \( D'_i \subset \text{Der}_A(B) \). Arguing in a similar way we conclude by induction on \( i \) that \( D'_i \subset \text{Der}_A(B) \) for all \( 0 \leq i \leq m \). Since as remarked in case 2 above, all elements of \( D'_0 (= D_1 \) in case 2) are derived from \( D_0 \) in at most one step we deduce that \( d \) is derived from \( D_0 \) in at most \( m+1 \) steps. Just define \( D_i := D'_{i-1} \) for all \( 1 \leq i \leq m+1 \). Hence \( d \) is nice with respect to \( x_1, \ldots, x_n \) and \( D_0 \) by 1.

\[ \square \]

**Corollary 3.4** Let \((T, c) \in D_n(A)\) and \( 0 \leq p \leq n-2 \). Put

\[
D := D(E_{n,p}(T, c); \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n})
\]

Then \( D \) is nice with respect to \( X_1, \ldots, X_n \) and \( \{ \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n} \} \). Furthermore we have \( \exp(D) = X + E_{n,p}(T, c) \) and the inverse map is given by \( \exp(-D) = X - E_{n,p}(T, c) \).

**Proof.** The first part is an immediate consequence of theorem 3.3. Furthermore \( D^2(X_i) = 0 \) by proposition 2.2. So \( \exp(D)(X) = X + E_{n,p}(T, c) \) and the inverse map is given by \( \exp(-D)(X) = X - E_{n,p}(T, c). \) \[ \square \]
4 The main theorem

In this section we show that for every $H \in \mathcal{H}_n(A)$ the polynomial map $F = X + H$ is a product of $n$ polynomial automorphisms of the form $\exp(D)$, where each $D$ is a nice derivation on $A[X]$. More precisely

**Theorem 4.1** Let $F = X + H$, where $H = \sum_{p=0}^{n-2} E_{n,p}(T, c) + c_n$, for some $(T, c) \in \mathcal{D}_n(A)$. Then

$$F = \exp(D\left(c_n; \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n}\right)) \prod_{p=0}^{n-2} \exp(D\left(E_{n,p}(T, c); \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n}\right)).$$

**Proof.** Observe that

$$\exp(-D\left(c_n; \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n}\right)) \circ F = \sum_{p=0}^{n-2} E_{n,p}(T, c).$$

So the case $n = 2$ follows from corollary 3.4. Hence we may assume that $n \geq 3$. Now theorem 4.1 follows directly from proposition 4.2 below and corollary 3.4. □

**Proposition 4.2** Let $n \geq 3$, $0 \leq p \leq n - 3$ and $(T, c) \in \mathcal{D}_n(A)$. Then

$$\exp(-D(E_{n,p}(T, c))) \circ (X + \sum_{q=p}^{n-2} E_{n,q}(T, c)) = X + \sum_{q=p+1}^{n-2} E_{n,q}(T, c).$$

**Proof.** Put $G := \exp(-D(E_{n,p}(T, c)))$. So $G = X - E_{n,p}(T, c)$ (by corollary 3.4). Hence if we put

$$U := \tilde{T}_{n-p} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n$$

then by proposition 1.4 we get

$$G = X - \Adj(U) \ast \tilde{c}_{n-p-1} |_{U*X}.$$

So if we put

$$f := X + \sum_{q=p+1}^{n-2} E_{n,q}(T, c)$$

then

$$G \circ f = f - \Adj(U(f)) \ast \tilde{c}_{n-p-1} |_{U(f)*f}.$$

Since $U(f) = f$ (by corollary 4.4 below, with $j = 0$) we get

$$G \circ f = f - \Adj(U) \ast \tilde{c}_{n-p-1} |_{U*}.$$

Now observe that each component of $\tilde{c}_{n-p-1}$ belongs to $A[X_{n-p}, \ldots, X_n]$ and that for each $i \geq n - p$ $(U * f)_i = (U * X)_i$ (by lemma 4.3 below). So $\tilde{c}_{n-p-1} |_{U*} = \tilde{c}_{n-p-1} |_{U*X}$ and hence

$$G \circ f = f - \Adj(U) \ast \tilde{c}_{n-p-1} |_{U*X}$$

(by proposition 1.4). □
Lemma 4.3 Let \( n \geq 3, 0 \leq p \leq n - 2, 0 \leq j \leq p \) and \( (T, c) \in \mathcal{D}_n(A) \). Put 
\[
 f := X + \sum_{i=p}^{n-2} E_{n, i}(T, c).
\]
Then
\[
 [(\tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) * f]_i = [(\tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n) * X]_i
\]
for all \( i \geq n - p + j \).

Proof. Put \( U := \tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n \). It suffices to show that for each \( q \geq p \)
\[
[U * E_{n, q}(T, c)]_i = 0
\]
for all \( i \geq n - p + j \). So let \( q \geq p \), then \( q \geq p - j \).

1. We first treat the case that \( q = p - j \). Then \( j = 0 \) and \( q = p \). Consequently \( U = T_{n-p} \Delta \cdots \Delta T_{n-1} \Delta T_n \), \( E_{n, q}(T, c) = E_{n, p}(T, c) \) and hence by proposition 1.4
\[
 U * E_{n, q}(T, c) = U * \text{Adj}(U) * \tilde{c}_{n-p-1} |_{U \times X} = \text{det}(U) * \tilde{c}_{n-p-1} |_{U \times X}
\]
Since the last \( p + 1 \) coordinates of \( \tilde{c}_{n-p-1} \) are zero, we obtain that
\[
[U * E_{n, q}(T, c)]_i = 0
\]
for all \( i \geq n - p \), which proves the case that \( q = p - j \).

2. Now assume that \( q \geq p - j + 1 \). So \( n - q \leq n - p + j - 1 \). Put \( V := \tilde{T}_{n-q} \Delta \cdots \Delta \tilde{T}_{n-p+j-1} \). Then by proposition 1.4 we can write
\[
 E_{n, q}(T, c) = \text{Adj}(V \Delta U) * \tilde{c}_{n-q-1} |_{(V \Delta U) \times X} = \text{Adj}(V |_{U \times X} * U) * \tilde{c}_{n-q-1} |_{(V \Delta U) \times X} = \text{Adj}(U) * \text{Adj}(V |_{U \times X} * \tilde{c}_{n-q-1} |_{(V \Delta U) \times X})
\]
Consequently
\[
 U * E_{n, q}(T, c) = \text{det}(U) * \text{Adj}(V |_{U \times X} * \tilde{c}_{n-q-1} |_{(V \Delta U) \times X})
\]
Note that \( V \), and hence \( V |_{U \times X} \), is of the form \( \tilde{B} \) for some \( B \in \mathcal{M}_{n-p+j-1}(A[X]) \). Furthermore \( (\tilde{c}_{n-q-1})_i = 0 \) if \( i \geq n - q \) which implies that \( (\tilde{c}_{n-q-1} |_{(V \Delta U) \times X})_i = 0 \) if \( i \geq n - p + j \) (since \( n - p + j > n - q \)). Now the desired result (4) follows from (5).

\[
 \square
\]

Corollary 4.4 Notations as in lemma 4.3. Then
\[
(\tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)(f) = \tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n.
\]
Proof. By induction on $N := p - j$. If $N = 0$ the result is obvious. So let $N \geq 1$. Then

$$
(\tilde{T}_{n-p+j} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)(f)
$$

$$
= \tilde{T}_{n-p+j} |(\tilde{T}_{n-p+j+1} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)(f)| f * (\tilde{T}_{n-p+j+1} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)(f)
$$

$$
= \tilde{T}_{n-p+j} |(\tilde{T}_{n-p+j+1} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)| f * (\tilde{T}_{n-p+j+1} \Delta \cdots \Delta \tilde{T}_{n-1} \Delta T_n)(f)
$$

by the induction hypothesis. Finally observe that the matrix elements of $\tilde{T}_{n-p+j}$ depend only on $X_{n-p+j+1}, \ldots, X_n$. The result follows immediately from lemma 4.3 (with $j + 1$ instead of $j$).

5 Stably tameness

With theorem 4.1 we are now able to prove the stably tame generators conjecture for all maps in our class $\mathcal{H}(A)$. And will also show that this result is ‘sharp’: we give an example of an element of our class which is not tame, so in general we cannot get a better result than this stable tameness.

First let us recall the conjecture (it was already mentioned in [1], [2], [3], [4] and [7]):

Conjecture 5.1 For every invertible polynomial map $F : k^n \rightarrow k^n$ over a field $k$ there exist $t_1, \ldots, t_m$ such that

$$
F[m] = (F, t_1, \ldots, t_m) : k^{n+m} \rightarrow k^{n+m}
$$

is tame, i.e. $F$ is stably tame.

Theorem 5.2 Let $F = X + H$ with $H \in \mathcal{H}(A)$. Then $F$ is stably tame.

To do this we use the following result due to Martha Smith in [9]:

Proposition 5.3 Let $D$ be a locally nilpotent derivation of $A[X]$. Let $a \in \ker(D)$. Extend $D$ to $A[X][t]$ by setting $D(t) = 0$. Note that $tD$ is locally nilpotent. Define $\rho \in \text{Aut}_A A[X][t]$ by $\rho(X_i) = X_i, i = 1, \ldots, n$ and $\rho(t) = t + a$. Then

$$
(\exp(aD), t) = \rho^{-1} \exp(-tD) \rho \exp(tD).
$$

Corollary 5.4 Let $D, a$ be as in proposition 5.3. If $D$ is conjugate by a tame automorphism to a triangular derivation, then $(\exp(aD), t)$ is tame.

Lemma 5.5 Let $\tau$ be a nice derivation of order $m$ with respect to $X_1, \ldots, X_n$ and $D := \{ \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n} \}$ on $A[X]$. Then $\exp(a\tau)$ is stably tame for all $a \in \ker(\tau)$.  

\textbf{Stably tameness}
Proof. We use induction on \( m \). Consider the case that \( m = 1 \). Then \( \tau = \sum_{d \in D} b_d d \) with \( b_d \in A[X]^D = \cap_{d \in D} \ker(d) = A \). And hence \( \tau(X_i) \in A \) and clearly \( \tau \) is on triangular form. So now we can apply corollary 5.4 and find that \( \exp(a\tau) \) is stably tame.

Now consider the case \( m > 1 \). We may assume that for all nice derivations \( \sigma \in \text{Der}_A(A[X]) \) of order \( m - 1 \) with respect to \( D \) and \( X_1, \ldots, X_n \) and for any commutative ring \( A \) we have that \( \exp(a\sigma) \) is stably tame for all \( a \in \ker(\sigma) \). Let \( \tau \) be nice of order \( m \). Define \( \rho \) and extend \( \tau \) to \( A[X][t] \) as in proposition 5.3 (in fact we extend all derivations of \( D \) to \( A[X][t] \) in this way). Now from

\[
(\exp(a\tau), t) = \rho^{-1} \exp(-t \tau) \rho \exp(t \tau)
\]

it follows that it suffices to see that \( \exp(t \tau) \) is stably tame. Now we see that

\[
t\tau = \sum_{d \in D_{m-1}} t \, b_d \, d \quad \text{with} \quad b_d \in A[X][t] D_{m-1}.
\]

But from this it follows that

\[
\exp(t \tau) = \exp\left( \sum_{d \in D_{m-1}} t \, b_d \, d \right)
\]

\[
= \prod_{d \in D_{m-1}} \exp(t \, b_d \, d)
\]

This last equation follows from proposition 1.5. Obviously it suffices to prove that each \( \exp(t \, b_d \, d) \) is stably tame to conclude that \( \exp(t \tau) \) is stably tame. But \( d \) is a nice derivation of order \( m - 1 \), \( t \, b_d \in \ker(d) \) and hence we can apply the induction hypothesis to the ring \( A[t] \) and find that \( \exp(t \tau) \) is stably tame and hence \( \exp(a\tau) \) is stably tame. \( \Box \)

Proof of theorem 5.2. Now if we look at theorem 4.1 we see that each \( F = X + H \) with \( H \in \mathcal{H}_n(A) \) can be written as the product of a finite number of \( \exp(a_i D_i) \)'s where each \( D_i \) is a nice derivation with respect to \( X_1, \ldots, X_n \) and \( \{ \frac{\partial}{\partial X_1}, \ldots, \frac{\partial}{\partial X_n} \} \) and \( a_i \in \ker(D_i) \). Applying lemma 5.5 \( n \) times gives us the desired result: \( F \) is stably tame. \( \Box \)

Remark 5.6 Note that we don’t give an indication of the value of \( m \) in conjecture 5.1. As can be seen from the proof above, this \( m \) can be very high. At the highest level we have \( n \ \exp(a_i D_i) \)'s, but each of these factors can give rise to a great number of extra variables, depending on the ‘order of niceness’ of each \( D_i \).

To conclude this paper we show that in general the automorphisms \( F = X + H \) with \( H \in \mathcal{H}_2(A) \) need not be tame. Actually, this idea was already presented by Nagata in [8].

Example 5.7 Let \( A \) be a domain, but not a principal ideal domain. Let \( a, b \in A \) such that \( Aa + Ab \) is not a principal ideal. Let \( f(T) \in A[T] \) with \( \deg(f) \geq 2 \) and let \( F = X + H \) with

\[
H = \begin{pmatrix}
bf(aX_1 + bX_2) \\
-af(aX_1 + bX_2)
\end{pmatrix}
\]

Since \( H \in \mathcal{H}_2(A) \) \( F \) is an automorphism of \( A[X_1, X_2] \). However, it is shown in [8] that \( F \) is not tame.
References


