THE CANCELLATION PROBLEM
IN DIMENSION FOUR

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Abstract
This paper proves that the Cancellation Problem has an affirmative answer over a Dedekind containing the rational numbers in dimension three. As a consequence, the Cancellation Problem turns out to have an affirmative answer for a large class of locally nilpotent derivations in dimension four, including the triangular ones.

1 Introduction
Let $k$ be a field of characteristic zero and let $V$ be an algebraic variety over $k$. The Cancellation Problem asks if $V \times k \cong k^n$ implies that $V \cong k^{n-1}$. This problem was first posed by Zariski in 1942. See [Kra89] for an overview of the Cancellation Problem.

Algebraically, the Cancellation Problem amounts to asking if $A[T] \cong k[X_1, \ldots, X_n]$ implies that $A \cong k[X_1, \ldots, X_{n-1}]$ for an affine $k$-domain $A$. One can also phrase this in terms of locally nilpotent derivations. The question is whether the kernel of a locally nilpotent derivation on $k[X_1, \ldots, X_n]$ with a slice is isomorphic to $k[X_1, \ldots, X_{n-1}]$. For more information on locally nilpotent derivations and their application to problems related to the Cancellation Problem, such as the Embedding Conjecture, Hilbert’s Fourteenth Problem, and the Jacobian Conjecture, see [Ren68], [AM75], [Ess93], [Now94], [DF99], [Fre00] and [Ess00].

The structure of this paper is as follows. Section 2 contains an overview of locally nilpotent derivations and their relationship to the Cancellation Problem. Section 3 uses a technique from Quillen to show that local coordinates (and partial local coordinate systems) over a Hermite domain are coordinates (and partial coordinate systems). Together with a result from Sathaye on the recognition of a polynomial ring in two variables over a discrete valuation ring containing $\mathbb{Q}$, this result is used to prove that the Cancellation Problem has an affirmative answer over a Dedekind domain containing $\mathbb{Q}$ for $n = 3$. As a consequence, the Cancellation Problem turns out to have an affirmative answer for a large class of derivations (or varieties) for $n = 4$ over a field, including the triangular derivations.

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2 Preliminaries

In this paper all rings will be commutative and have a unit element.

Let $A$ be a ring. A derivation on $A$ is a map $D: A \to A$ satisfying $D(a + b) = D(a) + D(b)$ and $D(ab) = aD(b) + D(a)b$ for all $a, b \in A$. If $R$ is a ring and $A$ is an $R$-algebra via $f: R \to A$, then $A$ is called an $R$-derivation if $D(f(r)) = 0$ for all $r \in R$. A derivation $D$ is called locally nilpotent if for all $a \in A$ there is an $n \in \mathbb{N}$ such that $D^n(a) = 0$. The kernel of $D$ is denoted by $A^D$. If $s \in A$ is such that $D(s) = 1$, then $s$ is called a slice of $D$.

The following proposition (see [Wri81]) is well-known.

**Proposition 2.1.** Let $A$ be a $\mathbb{Q}$-algebra and let $D$ be a locally nilpotent derivation on $A$. Assume that $s \in A$ is a slice of $D$. Then $A = A^D[s]$ and $s$ is algebraically independent over $A^D$. Furthermore, $D = d/ds$. □

In the applications, $A$ will invariably be a polynomial ring $R[X] := R[X_1, \ldots, X_n]$ over a ring $R$. An $R$-derivation $D$ on such a ring is called triangular if $D(X_i) \in R[X_{i+1}, \ldots, X_n]$ for all $i$. Such a derivation is automatically locally nilpotent. An element $s \in R[X]$ is called a coordinate if there is a polynomial automorphism $F$ of $R[X]$ with $s$ as one of its components. More generally, a sequence $(s_1, \ldots, s_k)$ of elements of $R[X]$ with $1 \leq k \leq n$ is called a partial coordinate system if there are polynomials $f_{k+1}, \ldots, f_n \in R[X]$ such that $(s_1, \ldots, s_k, f_{k+1}, \ldots, f_n)$ is a polynomial automorphism of $R[X]$.

Proposition 2.1 implies the following.

**Corollary 2.2.** Let $R$ be a ring and let $n \geq 2$. Let $D$ be a locally nilpotent $R$-derivation on $R[X] := R[X_1, \ldots, X_n]$ and let $s \in R[X]$ be a slice of $D$. Then $s$ is a coordinate if and only if $R[X]^D \cong R^{[n-1]}$. □

This gives the following reformulation of the Cancellation Problem in terms of locally nilpotent derivations.

**Problem 2.3 (Cancellation Problem).** Let $k$ be a field of characteristic zero and let $n \geq 2$. Let $D$ be a locally nilpotent $k$-derivation on $k[X] := k[X_1, \ldots, X_n]$ and assume that $D$ has a slice $s \in k[X]$. Is then $k[X]^D \cong k^{[n-1]}$, i.e., is $s$ a coordinate in $k[X]$?

More generally, one can ask the following question.

**Problem 2.4 (Generalized Cancellation Problem).** Let $k$ be a field of characteristic zero, let $R$ be an affine $k$-domain, and let $n \geq 2$. Let $D$ be a locally nilpotent $R$-derivation on $R[X] := R[X_1, \ldots, X_n]$ and assume that $D$ has a slice $s \in R[X]$. Is then $R[X]^D \cong R^{[n-1]}$, i.e., is $s$ a coordinate in $R[X]$?

In dimension two, matters were settled for the field case by Rentschler in [Ren68], who proved the following.

**Theorem 2.5.** Let $k$ be a field of characteristic zero. Let $D$ be a locally nilpotent $k$-derivation on $k[X] := k[X_1, X_2]$. Then $k[X]^D \cong k^{[1]}$. □
Nowadays even stronger results have been obtained by Bhadwadekar and Dutta ([BD97]) and Berson, Van den Essen, and Maubach ([BEM99]). The field $k$ in the theorem can in fact be replaced by an arbitrary $\mathbb{Q}$-algebra $R$.

In dimension three, theCancellation Problem was proved by Fujita (see [Fuj79]) for an algebraically closed field. See also [MS80] and [Miy85]. It was remarked by Daigle in [Dai97] that a straightforward use of [Kam75] then proves the general case.

**Theorem 2.6.** Let $k$ be a field of characteristic zero and let $D$ be a locally nilpotent $k$-derivation on $k[X] := k[X_1, X_2, X_3]$. Assume that $D$ has a slice. Then $k[X] \cong k[2]$.

This paper now proves the Generalized Cancellation Problem for $n = 3$ in case $R$ is a Dedekind domain over $\mathbb{Q}$. As a consequence, the Cancellation Problem turns out to have an affirmative answer for locally nilpotent derivations of the form

$$D := a(X_1, X_2, X_3, X_4)\partial_1 + b(X_1, X_2, X_3, X_4)\partial_2 + c(X_1, X_2, X_3, X_4)\partial_3 + d(X_4)\partial_4$$

for $n = 4$, where $\partial_i$ denotes $\partial/\partial X_i$. In particular, the Cancellation Problem turns out to have an affirmative answer for triangular derivations for $n = 4$. This is especially interesting since [Asa99] (implicitly) and [ER00] (explicitly) give a candidate counterexample to the Cancellation Problem for $n = 5$ which is triangular, namely $D := (2X_2^2 - 3)\partial_1 + (4X_4^2 - 8X_4)\partial_2 + (5X_4^4 - 10)\partial_3 + X_5\partial_4$.

### 3 Local Coordinates

Let $R$ be a domain, $n \in \mathbb{N}$, and $R[X] := R[X_1, \ldots, X_n]$ the polynomial ring in $n$ variables over $R$. This section shows that a polynomial in $R[X]$ is a coordinate if and only if it is a coordinate when considered as an element of $R_m[X]$, for all maximal ideals $m$ of $R$, provided that $R$ is Hermite, and similarly for partial coordinate systems. Recall that $R$ is called Hermite if every unimodular row $(r_1, \ldots, r_k)$ can be extended to an invertible square matrix over $R$.

The ideas present in this section can in fact already be found in [Qui76]. The abstract notion of Quillen Induction is essentially taken from [BCW77] and the results from that paper can also be used to derive the main result of this section.

**Definition 3.1.** Define $\text{Loc}(R) := \{ R_r \mid r \in R \setminus \{0\} \}$.

**Proposition 3.2 (Quillen Induction).** Let $P \subseteq \text{Loc}(R)$. Write $P(L)$ instead of $L \in P$ for $L \in \text{Loc}(R)$. In that case, $L$ is said to have property $P$. Assume that

(a) for all $m \in \text{Max}(R)$: there exists an $r \in R \setminus m$ such that $P(R_r)$;

(b) for all $r, s, t \in R \setminus \{0\}$: if $rR_t + sR_t = R_t$, $P(R_r)$, and $P(R_s)$, then $P(R_t)$.

Then $P(L)$ for all $L \in \text{Loc}(R)$. In particular $P(R)$.
Proof. Let $S$ be the collection of all $r \in R \setminus \{0\}$ such that $P(R_r)$ together with 0. This is an ideal of $R$. It is not empty because 0 is in $S$, closed under addition because of (b) (for $r, s \in S$ take $t := r + s$), and closed under multiplication with elements of $R$ also because of (b) (for $r \in R$ and $s \in S$, take $r := s, s := r, s, t := r s$).

Suppose that $S \neq R$. Then $S$ is contained in some maximal ideal of $R$, say $m$. By (a) there is an $r \in R \setminus m$ such that $P(R_r)$. But then $r \in S \subseteq m$, which contradicts $r \not\in m$. So $S = R$ and therefore $P(L)$ for all $L \in \text{Loc}(R)$. \hfill $\square$

Definition 3.3. An element $H$ of $\text{End}_R(R[X])$ is called nice if it is of the form $H = (X_1 + \text{h.o.t.}, \ldots, X_n + \text{h.o.t.})$. Here h.o.t. stands for higher order terms, i.e., terms of degree 2 or greater, and $\text{End}_R(R[X])$ has been identified with $R[X]^n$. A coordinate $h \in R[X]$ is called nice if there is a nice $H \in \text{Aut}_R(R[X])$ which has $h$ as its first component. Similarly, a partial coordinate system $(h_1, \ldots, h_k) \in R[X]^k$ is called nice if there is a nice $H \in \text{Aut}_R(R[X])$ which has $(h_1, \ldots, h_k)$ as its first $k$ components.

Lemma 3.4. A partial coordinate system $(h_1, \ldots, h_k) \in R[X]^k$ is nice if and only if it is of the form $(X_1 + \text{h.o.t.}, \ldots, X_k + \text{h.o.t.})$. In particular, a coordinate $h \in R[X]$ is nice if and only if it is of the form $X_1 + \text{h.o.t.}$.

Proof. By linear algebra, looking at the linear part of a polynomial automorphism without constant parts with $h_1, \ldots, h_k$ as its first $k$ components. \hfill $\square$

Definition 3.5. Let $H \in \text{End}_R(R[X])$ be nice. Then $T H \in \text{End}_R([R[T]][X])$ is defined by

$$T H := T^{-1} H[X_1 := TX_1, \ldots, X_n := TX_n].$$

(This is defined over $R[T]$ and not just over $R[T, T^{-1}]$ because $H$ is nice.) If $r \in R$, then $T H[T := r] \in \text{End}_R(R[X])$ is denoted by $T^r H$.

One can easily see that $(\det J H)[X := TX] = \det J T H$ and that $H$ is invertible if and only if $T^r H$ is. Here $J H$ denotes the Jacobian matrix $(\partial H_i/\partial X_j)_{ij}$ of $H$. Even better, if $r \in R \setminus \{0\}$, then $\det J^r H \in R^*$ if and only if $\det J H \in R^*$ and $T^r H$ is invertible if and only if $H$ is.

The map $T H$ is called the clearing map because of the following: if $K$ is the quotient field of $R$ and $H \in \text{End}_K(K[X])$ is of the form $H = X + \text{h.o.t.}$, then there is an $r \in R \setminus \{0\}$ such that $T H \in \text{End}_R(R[X])$. So, the denominators of $H$ are cleared. See Chapter 1 of [Ess00].

Lemma 3.6. Let $r, s \in R \setminus \{0\}$ be such that $r R + s R = R$ and let $H \in \text{Aut}_{R_s}(R_{r s}[X])$ be nice. Then there are nice $H_1 \in \text{Aut}_{R_s}(R_r[X])$ and $H_2 \in \text{Aut}_{R_s}(R_s[X])$ such that $H = H_1 H_2$.

Proof. Note that

$$T^d H = H(1) + T H(2) + T^2 H(3) + \cdots + T^{d-1} H(d)$$

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where each $H_{(i)}$ is the homogeneous part of degree $i$ of $H$ and $d$ is the degree of $H$. Hence

$$1^{-TH} = H_{(1)} + (1 - T)H_{(2)} + (1 - T)^2H_{(3)} + \cdots + (1 - T)^{d-1}H_{(d)}$$

$$= H_{(1)} + H_{(2)} + H_{(3)} + \cdots + H_{(d)} + T(h.o.t.)$$

$$= H + T(h.o.t.),$$

where, as before, h.o.t. stands for some terms of $X$-degree at least two. As a consequence

$$H^{-1} \circ 1^{-TH} = H^{-1} \circ (H + T(h.o.t.))$$

$$= X + T(h.o.t.).$$

Now let $k \in \mathbb{N}$ be sufficiently large. From $rR + sR = R$ it follows that $r^kR + s^kR = R$. Take $v, w \in R$ with $r^kv + s^kw = 1$. If $k$ is sufficiently large, then $s^kwH$ and $s^w(H^{-1})$ are elements of $\text{End}_{R_e}(R_e[X])$. They are also each others inverse and hence they are in fact elements of $\text{Aut}_{R_e}(R_e[X])$.

Take $H_1 := s^kwH$ and compute $H^{-1}H_1$. This gives

$$H^{-1}H_1 = H^{-1} \circ TH \ [T := s^kw]$$

$$= H^{-1} \circ 1^{-TH} \ [T := r^kv]$$

$$= (X + T(h.o.t.))[T := r^kv])$$

$$= X + r^k v(h.o.t.)$$

and similarly

$$H^{-1}_1H = X + r^k v(h.o.t.).$$

For $k$ sufficiently large, $H_2 := H^{-1}_1H$ and its inverse apparently are elements of $\text{Aut}_{R_e}(R_e[X])$. So now $H = H_1H_2$ with $H_1$ and $H_2$ are both of the required form. \boxed{\small{$\square$}}

**Lemma 3.7.** Let $r, s \in R$ be such that $rR + sR = R$. Take $t \in R_{rs}$ such that $t \in R_r \cap R_s$. Then $t \in R$.

**Proof.** Write $t = v/r^k = w/s^l$ with $v, w \in R$ and $k, l \in \mathbb{N}$. Because $rR + sR = R$, also $r^kR + s^lR = R$. Write $r^kx + s^ly = 1$ for some $x, y \in R$. Then $t = (r^kx + s^ly)t = vx + wy \in R$. \boxed{\small{$\square$}}

**Lemma 3.8 (Patching Lemma).** Let $r, s \in R$ with $rR + sR = R$. Let $k \in \{1, \ldots, n\}$ and let $h_1, \ldots, h_k \in R[X]$ be polynomials of the form $h_i = X_i + \text{h.o.t.}$. Assume that there is a nice $F \in \text{Aut}_R(R_r[X])$ with first $k$ components equal to $h_1, \ldots, h_k$ and that there is a nice $G \in \text{Aut}_{R_r}(R_r[X])$ with first $k$ components equal to $h_1, \ldots, h_k$. Then there is a nice $H \in \text{Aut}_R(R[X])$ with first $k$ components equal to $h_1, \ldots, h_k$. 

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Proof. Consider the polynomial map $F^{-1}G \in \text{Aut}_{R_\alpha}(R_\alpha[X])$ and note that it is fact an $R_\alpha[X_1, \ldots, X_k]$-automorphism of $R_\alpha[X] = R_\alpha[X_1, \ldots, X_k][X_{k+1}, \ldots, X_n]$. Now apply Lemma 3.6 to the ring $R[X_1, \ldots, X_k]$ and write $F^{-1}G = H_1H_2$ with $H_1 \in \text{Aut}_{R_\alpha[X_1, \ldots, X_k]}(R_\alpha[X])$ and $H_2 \in \text{Aut}_{R_\alpha[X_1, \ldots, X_k]}(R_\alpha[X])$, where both $H_i$ are of the form $X + \text{h.o.t.}$. Considered as automorphisms over respectively $R_\alpha$ and $R_\alpha$, the first $k$ components of $H_1$ and $H_2$ of course equal $X_1, \ldots, X_k$. Hence $H := FH_1 = GH_2^{-1}$ is a nice polynomial automorphism (over $R_\alpha$, a priori) whose first $k$ components equal $h_1, \ldots, h_k$. It is defined over $R_\alpha$ (because $H = FH_1$ and $F$ and $H_1$ are defined over $R_\alpha$) and it is defined over $R_\alpha$ (because $H = GH_2^{-1}$ and $G$ and $H_2$ are defined over $R_\alpha$). Hence, applying Lemma 3.7 to every one of its coefficients, it is in fact defined over $R$. \hfill \square

Theorem 3.9. Let $k \in \{1, \ldots, n\}$ and let $h_1, \ldots, h_k \in R[X]$ be polynomials of the form $h_i = X_i + \text{h.o.t.}$. Assume that for every maximal ideal $\mathfrak{m}$ of $R$, $(h_1, \ldots, h_k)$ is a nice partial coordinate system when considered as an element of $R_\mathfrak{m}[X]^k$. Then $(h_1, \ldots, h_k)$ is a nice partial coordinate system.

Proof. Let $P \subseteq \text{Loc}(R)$ be the collection of all $R_r, r \in R \setminus \{0\}$, such that $(h_1, \ldots, h_k)$ is a nice partial coordinate system over $R_r$. Now check the two conditions for Quillen Induction.

(a) Let $\mathfrak{m}$ be a maximal ideal of $R$. It is assumed that $(h_1, \ldots, h_k)$ is a nice partial coordinate system over $R_\mathfrak{m}$. Using Lemma 3.4, choose $F \in \text{Aut}_{R_\mathfrak{m}}(R_\mathfrak{m}[X])$ nice with first $k$ components equal to $h_1, \ldots, h_k$. There are only finitely many elements of $R$ appearing in the denominator of a coefficient of a component of $F$ and its inverse. Denote the product of these denominators by $r$. None of these denominators is an element of $\mathfrak{m}$ and, because $\mathfrak{m}$ is prime, $r$ is not an element of $\mathfrak{m}$ either. Furthermore, obviously, $P(R_r)$.

(b) Let $r, s, t \in R \setminus \{0\}$ be such that $rR_t + sR_t = R_t$ and assume $P(R_r)$ and $P(R_s)$. Then $P(R_t)$ follows by applying the Patching Lemma (Lemma 3.8) to the ring $R_t$.

So, using Quillen Induction (Proposition 3.2), $P(R)$, which means that $(h_1, \ldots, h_k)$ is a nice partial coordinate system over $R$. \hfill \square

Corollary 3.10. Assume that $R$ is Hermite. Let $k \in \{1, \ldots, n\}$ and $h_1, \ldots, h_k \in R[X]$. Assume that $(h_1, \ldots, h_k)$ is a partial coordinate system when considered as an element of $R_\mathfrak{m}[X]^k$, for every maximal ideal $\mathfrak{m}$ of $R$. Then $(h_1, \ldots, h_k)$ is a partial coordinate system.

Proof. First of all note that it is possible to assume that the $h_i$ have no constant part. Write $h_i = r_{i1}X_1 + \cdots + r_{in}X_n + \text{h.o.t.}$ for all $i$, with $r_{ij} \in R$.

Consider a maximal ideal $\mathfrak{m}$ of $R$. Then $(h_1, \ldots, h_k)$ is a partial coordinate system over $R_\mathfrak{m}$, which means that there are $f_{k+1}, \ldots, f_n \in R_\mathfrak{m}[X]$ such that $F := (h_1, \ldots, h_k, f_{k+1}, \ldots, f_n) \in \text{Aut}_{R_\mathfrak{m}}(R_\mathfrak{m}[X])$. The $f_i$ can be chosen in such a way
that they have no constant part. Then \(\det JF \in R_m[X]^n\) and hence substituting \(X_1 := 0, \ldots, X_n := 0\) gives

\[
\begin{vmatrix}
11 & \cdots & 1n \\
\vdots & \ddots & \vdots \\
1k & \cdots & 1n \\
\ast & \cdots & \ast \\
\vdots & & \vdots \\
\ast & \cdots & \ast
\end{vmatrix} = \det J(F[X := 0]) = (\det JF)[X := 0] \in R_m^n.
\]

In particular, the matrix \((r_{ij})_{ij}\) represents a surjective \(R_m\)-module homomorphism from \(R^n_m\) to \(R^k_m\).

Because this holds for every maximal ideal of \(R\), it follows that the matrix \((r_{ij})_{ij}\) represents a surjective \(R\)-module homomorphism from \(R^n\) to \(R^k\). Now \(R\) is Hermite, which implies that the matrix \((r_{ij})_{ij}\) can be extended to an invertible square matrix \(M\) over \(R\) (see [Lam78], Corollary 4.5). Viewing this matrix \(M\) as a polynomial automorphism of \(R[[X]]\) and applying its inverse to the polynomials \(h_i\), it follows that one can assume that \((h_1, \ldots, h_k)\) is of the form \((X_1 + \text{h.o.t.}, \ldots, X_k + \text{h.o.t.})\).

By Lemma 3.4, \((h_1, \ldots, h_k)\) then is a nice coordinate system in \(R_m[[X]]\), for every \(m \in \text{Max}(R)\). Now apply Theorem 3.9.

The condition that \(R\) be Hermite in the previous corollary is necessary. For let \(R\) be any non-Hermite ring; say \((a_1, \ldots, a_n)\) is a unimodular row over \(R\) that cannot be extended to an invertible square matrix. Then \(h := a_1X_1 + \cdots + a_nX_n \in R[X_1, \ldots, X_n]\) is not a coordinate (if it were, the coefficients of the linear part of an automorphism with \(h\) as its first component would form an invertible square matrix over \(R\) extending \((a_1, \ldots, a_n)\)). However, localising in a maximal ideal \(m\) of \(R\), \((a_1, \ldots, a_n)\) is extendible to an invertible square matrix over \(R_m\) (since \(R_m\) is local) and so \(h\) is a coordinate over \(R_m\).

**4 Main Result**

In [Sat83], Sathaye proved the following characterization of a polynomial ring in two variables over an discrete valuation ring containing \(\mathbb{Q}\).

**Theorem 4.1.** Let \(R\) be a discrete valuation ring containing \(\mathbb{Q}\). Denote the unique maximal ideal of \(R\) by \(m\), write \(K\) for the quotient field \(Q(R)\) of \(R\), and write \(k\) for the residue field \(R/m\) of \(R\). Let \(A\) be a finitely generated affine \(R\)-domain and assume that \(K \otimes_R A \cong K[2]\) and that \(k \otimes_R A \cong k[2]\). Then \(A \cong R[2]\).

In order to use this result, a lemma is needed on the behaviour of the kernel of a locally nilpotent derivation with a slice under tensoring.

**Lemma 4.2.** Let \(s \in R[X] := R[X_1, \ldots, X_n]\) and let \(A\) be an \(R\)-algebra via the map \(\varphi: R \to A\). Denote the induced map \(R[X] \to A[X]\) by \(\varphi_#\). Then

\[
A \otimes_R R[X] / (sR[X]) \cong A[X]/(\varphi_#(s)A[X])
\]
In particular, if \( D \) is a locally nilpotent \( R \)-derivation on \( R[X] \) and \( s \) is a slice of \( D \), then

\[
A \otimes_R R[X]^D \cong A[X]^\tilde{D},
\]

where \( \tilde{D} \) denotes the extension of \( D \) to \( A[X] \).

**Proof.** The following diagram is a commutative diagram of \( R \)-modules and \( R \)-module homomorphism in which the horizontal sequences are exact.

\[
\begin{array}{cccccc}
\text{s}R[X] & \rightarrow & R[X] & \rightarrow & R[X]/sR[X] & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \\
A \otimes_R sR[X] & \rightarrow & A \otimes_R A[X] & \rightarrow & A \otimes_R R[X]/sR[X] & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \\
\varphi_#(s)A[X] & \rightarrow & A[X] & \rightarrow & A[X]/(\varphi_#(s)A[X]) & \rightarrow & 0 \\
\end{array}
\]

The map \( A \otimes_R sR[X] \rightarrow \varphi_#(s)A[X] \) is surjective: take an element \( \varphi_#(s)f \in A[X] \) with \( f \in A[X] \). Write \( f = \sum c_s X_1^{a_1} \cdots X_n^{a_n} \) with each \( c_s \in A \). Then \( \varphi_#(s)f \) is the image of \( \sum c_s \otimes sX_1^{a_1} \cdots X_n^{a_n} \). Also, the map \( A \otimes_R R[X] \rightarrow A[X] \) is an isomorphism. Hence, by the Five Lemma, the map \( A \otimes_R R[X]/sR[X] \rightarrow A[X]/(\varphi_#(s)A[X]) \) is an isomorphism. A priori this is an isomorphism of \( R \)-modules. However, since it is an \( A \)-module homomorphism, it is even an isomorphism of \( A \)-modules.

The second claim follows from the first one using Theorem 2.1.

Note that this lemma is false if \( D \) does not have slice. For instance, let \( K \) be some field, \( R := K[Y] \), and consider \( A := K \) as an \( R \)-module by sending elements of \( K \) to themselves and \( Y \) to \( 0 \). Let \( D \) be the locally nilpotent derivation \( Y \partial_Y \) on \( R[X] \). Then \( R[X]^D = R \), so \( A \otimes_R R[X]^D = A = K \). However, the extension \( \tilde{D} \) of \( D \) to \( A[X] \) is 0 and hence \( A[X]^\tilde{D} = A[X] \).

**Lemma 4.3.** Let \( R \) be a discrete valuation ring containing \( \mathbb{Q} \) and let \( D \) be a locally nilpotent \( R \)-derivation on \( R[X,Y,Z] \) with a slice \( s \in R[X,Y,Z] \). Then \( R[X,Y,Z]^D \cong R^{[2]} \).

**Proof.** Let \( k \) be the residue field of \( R \) and let \( K \) be the quotient field of \( R \). Denote the extension of \( D \) to \( K \otimes_R R[X,Y,Z] \cong K[X,Y,Z] \) by \( \tilde{D} \). By Lemma 4.2 and Theorem 2.6 it follows that

\[
K \otimes_R R[X,Y,Z]^D \cong K[X,Y,Z]^\tilde{D} \cong K^{[2]}.
\]

In exactly the same way it follows that

\[
k \otimes_R R[X,Y,Z]^D \cong k^{[2]}.
\]

Hence, by Theorem 4.1, \( R[X,Y,Z]^D \cong R^{[2]} \).
Theorem 4.4. Let $R$ be a Dedekind domain containing $\mathbb{Q}$ and let $D$ be a locally nilpotent $R$-derivation on $R[X, Y, Z]$ with a slice. Then $R[X, Y, Z]^D \cong R^{[2]}$.

Proof. Let $s \in R[X, Y, Z]$ be a slice of $D$. Note that a unimodular row of length 2 is always extendible to an invertible square matrix and by Bass’ Cancellation Theorem for Stably Free Modules ([Bas68], Theorem V.3.2; see also [Wei00], Theorem 1.3) every unimodular row of length at least 3 over a Noetherian ring of dimension one is extendible. In particular, $R$ is Hermite. By Corollary 3.10 it is enough to show that $s$ is a coordinate in $R_m[X, Y, Z]$ for every maximal ideal $m$ of $R$.

So let $m$ be a maximal ideal of $R$. Then $R_m$ is a discrete valuation ring. Because $R$ contains $\mathbb{Q}$, $R_m$ contains $\mathbb{Q}$ as well. Now Lemma 4.3 implies that $R_m[X, Y, Z]^D \cong R_m^{[2]}$. In other words, $s$ is a coordinate in $R_m[X, Y, Z]$.

Corollary 4.5. Let $k$ be a field of characteristic zero and let $D$ be a locally nilpotent $k$-derivation on $k[X, Y, Z, W]$ of the form

$$D := a(X, Y, Z, W)\partial_X + b(X, Y, Z, W)\partial_Y + c(X, Y, Z, W)\partial_Z + d(W)\partial_W.$$  

Assume that $D$ has a slice. Then $k[X, Y, Z, W]^D \cong k^{[3]}$.

Proof. If $d(W) \neq 0$, then $d(W) \in k^*$, since $D$ is locally nilpotent. So $d^{-1}W$ is a slice of $D$. This slice is also a coordinate and hence $k[X]^D \cong k^{[3]}$. Otherwise, if $d(W) = 0$, apply Theorem 4.4 with $R = k[W]$.

References


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