A SIMPLE SOLUTION OF HILBERT’S FOURTEENTH PROBLEM IN DIMENSION FIVE

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Abstract. We give a short proof of a counterexample (due to Daigle and Freudenburg) to Hilbert’s fourteenth problem in dimension five.

Introduction. In 1900 at the International Congress of Mathematicians in Paris David Hilbert presented a list of 23 problems, intended to challenge the mathematicians of the new century. The fourteenth problem of this list can be stated as follows: let $k$ be a field, $k[x] := k[x_1, \ldots, x_n]$ the polynomial ring, $k(x)$ its quotient field and $L$ a subfield containing $k$.

Is $L \cap k[x]$ a finitely generated $k$-algebra?

A positive answer was given by Zariski ([7]) in case $\text{trdeg}_k L \leq 2$. However in 1958 Nagata ([5]) constructed a counterexample in dimension 32. Then in 1988 Roberts ([6]) found a new counterexample in dimension 7. Recently, in 1998 Freudenburg ([2]), studying Robert’s example, found a 6-dimensional counterexample, from which a 5-dimensional example was obtained in 1999 by Daigle and Freudenburg in [1]: they consider on $B := k[X, S, T, U, V]$ the derivation $D := X^3 \partial_S + S \partial_T + T \partial_U + X^2 \partial_V$ and show that $B^D := \ker D : B \to B$ is not finitely generated over $k$ (then the quotient field $L$ of $B^D$ is a counterexample to Hilbert fourteen, since $L \cap B = B^D$).

The main aim of this note is to give a short proof of this result, by substantially simplifying the arguments given in [1] and [2].

Finally, I would like to mention that recently S. Kuroda has constructed new counterexamples to Hilbert fourteen in the missing dimensions 4 and 3 ([3], [4]).

1. The main result. Throughout this paper we use the following notations: $k$ is a field of characteristic zero,

$$B := k[X, S, T, U, V], \quad D_0 := X^3 \partial_S + S \partial_T + T \partial_U, \quad D := D_0 + X^2 \partial_V.$$
Furthermore,
\[ A := k[S, T, U], \quad D_1 := \partial_S + S \partial_T + T \partial_U. \]

Finally, for any \( 0 \neq f \in B \), \( \deg f \) denotes the usual degree of \( f \). We also use another grading on \( A \) given by a vector \( w \in \mathbb{N}^3 \) and we write \( w \)-deg to denote the degree with respect to this grading. The main aim of this note is to give a short proof of

**Theorem 1.1** (Daigle–Freudenburg). \( B^D \) is not a finitely generated \( k \)-algebra.

The proof is based on the following result which will be proved in the next section.

**Proposition 1.2.** Let \( e : \mathbb{N} \to \mathbb{N} \) be defined by \( e(3l) = 2l \), \( e(3l + 1) = e(3l + 2) = 2l + 1 \) for all \( l \geq 0 \). There exist \( c_0 = 1, c_1, c_2, \ldots \) in \( A \) with \( D_1 c_i = c_{i - 1} \) and \( \deg c_i \leq e(i) \) for all \( i \geq 1 \).

**Proof of Theorem 1.1.** (i) Define
\[ a_i := X^{2i+1} c_i \left( \frac{S}{X^3}, \frac{T}{X^3}, \frac{U}{X^3} \right) \quad \text{for} \ i \geq 0. \]

Then one easily verifies that \( D_0 a_i = X^2 a_{i-1} \) for all \( i \geq 1 \) and that
\[ F_n := \sum_{i=0}^{n} (-1)^i \frac{n!}{(n-i)!} a_i V^{n-i} \in B^D \quad \text{for all} \ n \geq 1. \]

Suppose now that \( B^D \) is finitely generated by \( g_1, \ldots, g_s \) over \( k \). We may assume that \( g_i(0) = 0 \) for all \( i \). Write \( g_i = \sum g_{ij} V^j \) with \( g_{ij} \in k[X, S, T, U] \).

By (ii) below we find that \( g_{ij} \in (X, S, T, U) \) for all \( i, j \). Let \( d \) denote the maximum of the \( V \)-degrees of all \( g_i \). Consider \( F_{d+1} = X V^{d+1} + \text{lower degree} \ V \)-terms as above. So \( F_{d+1} \in B^D = k[g_1, \ldots, g_s] \). Looking at the coefficient of \( V^{d+1} \), we deduce that \( X \in (X, S, T, U)^2 \), a contradiction.

(ii) To prove that \( g_{ij} \in (X, S, T, U) \) for all \( i, j \) it suffices to show that if \( g = \sum g_{ij} V^j \in B^D \) satisfies \( g(0) = 0 \) then each \( g_j \in (X, S, T, U) \). First, clearly \( g_0 \in (X, S, T, U) \). So let \( j \geq 1 \). From \( D g = 0 \) we get \( j g_j X^2 = D_0 (-g_{j-1}) \in D_0 (k[X, S, T, U]) \subset (X^3, S, T) \) for all \( j \geq 1 \). If \( g_j(0) \in k^* \), then \( X^2 \in (X^3, S, T, UX^2) \), contradiction. So \( g_j(0) = 0 \), i.e. \( g_j \in (X, S, T, U) \).

**2. The proof of Proposition 1.2.** Put
\[ T_1 := T - \frac{1}{2} S^2, \quad U_1 := U - ST + \frac{1}{3} S^3. \]

Then \( A = k[T_1, U_1][S] \). Since \( D_1 T_1 = D_1 U_1 = 0 \) and \( D_1 S = 1 \) we get \( A_1^D = k[T_1, U_1] \). Consider on \( A \) the grading defined by \( w(S) = 1, w(T) = 2 \) and \( w(U) = 3 \). Then \( D_1 (A_n) \subset A_{n-1} \) for all \( n \geq 1 \), where \( A_n \) is the \( k \)-span of all monomials of \( A \) of \( w \)-degree \( n \). By induction on \( n \) we construct \( c_n \in A \).
So assume that \( c_n \) is already constructed. Write \( c_n = \sum_{i=0}^{n} H_{n-i} S^i \) with 
\( H_{n-i} \in A_{n-i} \cap A^{D_1} \) (this is possible since \( A = A^{D_1} [S] \) and \( c_n \in A_n \)). Then

\[ \tilde{c}_{n+1} := \sum_{i=0}^{n} \frac{1}{i+1} H_{n-i} S^{i+1} \in A_{n+1} \]

and \( D_1(\tilde{c}_{n+1}) = c_n \). Finally, by Lemma 2.1 below, there exists \( h \in A_{n+1} \cap A^{D_1} \) such that \( \tilde{c}_{n+1} := c_{n+1} - h \) satisfies \( \deg(c_{n+1}) \leq e(n+1) \).

**Lemma 2.1.** If \( f \in A_{n+1} \) is such that \( \deg D_1 f \leq e(n) \), then there exists \( h \in A_{n+1} \cap A^{D_1} \) such that \( \deg(f - h) \leq e(n+1) \).

**Proof.** (i) Let \( n = 3l \) (the cases \( n = 3l + 1 \) and \( n = 3l + 2 \) are treated similarly) and let \( M \) be the \( k \)-span of all \( f \in A_{n+1} \) such that \( \deg D_1 f \leq 2l \) (= \( e(3l) \)). Write \( f = \sum \alpha_{ijk} S^i T^j U^k \) with \( i + 2j + 3k = 3l + 1 \) and \( \alpha_{ijk} \in k \). Then

\[ D_1 f = \sum_{i+2j+3k=3l+1} (i\alpha_{ijk} + (j+1)\alpha_{i-2,j+1,k} + (k+1)\alpha_{i-1,j-1,k+1}) S^{i-1} T^j U^k. \]

So

\[(*) \quad \deg D_1 f \leq 2l \quad \text{iff} \quad i\alpha_{ijk} + (j+1)\alpha_{i-1,j-1,k+1} + (k+1)\alpha_{i-2,j+1,k} = 0 \]

for all \( i, j, k \) satisfying \( i + 2j + 3k = 3l + 1 \) and \( (i - 1) + j + k \geq 2l + 1 \), i.e. \( i + j + k \geq 2l + 2 \). For such a triple we have \( i > 0 \). Hence by (\( *) \) each \( \alpha_{ijk} \) is a linear combination of certain \( \alpha_{pqr} \)’s with \( p + q + r < i + j + k \). Consequently, each \( \alpha_{ijk} \) is a linear combination of the \( \alpha_{pqr} \)’s satisfying \( p + q + r = 2l + 2 \). Since there are \( [(l - 1)/2] + 1 \) of them (just solve the equations \( p + 2q + 3r = 0 \) and \( p + q + r = 2l + 2 \)) it follows that \( \dim \pi(M) \leq [(l - 1)/2] + 1 \), where for any \( g \in A, \pi(g) \) denotes the sum of all monomials of \( g \) of degree \( \geq 2l + 2 \).

(ii) Put \( N := A^{D_1} \cap A_{n+1} \). Then \( N \) is the \( k \)-span of all “monomials”

\[ n_p := T_1^{3p+2} U_1^{l-(2p+1)}, \quad \text{where} \ 0 \leq p \leq [(l - 1)/2]. \]

**Claim.** The \( \pi(n_p) \) are linearly independent over \( k \).

It then follows from (i) and the inclusion \( \pi(N) \subset \pi(M) \) that \( \pi(N) = \pi(M) \), which proves the lemma.

(iii) To see the claim put

\[ w_p := (-2)^{3p+2} S^{l-(2p+1)} \pi(n_p)|_{T=0, U=\frac{1}{2} S} = \pi((S^2)^{3p+2}(S + S^3)^{l-(2p+1)}). \]

Observe that

\[ (S^2)^{3p+2}(S + S^3)^{l-(2p+1)} = \sum_{j=0}^{l-(2p+1)} \binom{l -(2p + 1)}{j} S^{3l+1-2j}. \]
Since $3l + 1 - 2j \geq 2l + 2$ iff $0 \leq j \leq [(l - 1)/2]$ we get

$$w_p = \sum_{j=0}^{[(l-1)/2]} \binom{l - (2p + 1)}{j} S^{3l+1-2j}.$$ 

Then the linear independence of the $w_p$ (and hence of the $\pi(n_p)$) follows since

$$\det \left( \binom{l - (2p + 1)}{j} \right)_{0 \leq p, j \leq [(l-1)/2]} \neq 0.$$ 

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