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A commuting derivations theorem on UFD’s

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Abstract

Let $A$ be the polynomial ring over $k$ (a field of characteristic zero) in $n + 1$ variables. The commuting derivations conjecture states that $n$ commuting locally nilpotent derivations on $A$, linearly independent over $A$, must satisfy $AD_1,...,D_m = k[f]$ where $f$ is a coordinate. The conjecture can be formulated as stating that a $(G_m)^n$-action on $k^{n+1}$ must have invariant ring $k[f]$ where $f$ is a coordinate. In this paper we prove a statement (theorem 2.1) where we assume less on $A$ ($A$ is a UFD over $k$ of transcendence degree $n + 1$ satisfying $A^* = k$) and prove less ($A/(f - a)$ is a polynomial ring for all but finitely many $a$). Under certain additional conditions (the $D_i$ are linearly independent modulo $(f - a)$ for each $a \in k$) we prove that $A$ is a polynomial ring itself and $f$ is a coordinate. This statement is proven even more generally by replacing “free unipotent action of dimension $n$” for “$G_a^n$-action”.

We make links with the (Abhyankar-)Sataye conjecture and give a new equivalent formulation of the Sataye conjecture.

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1 Preliminaries and introduction

Notations: \( k \) will denote a field of characteristic zero. For a \( k \)-algebra \( A \) we define \( \text{LND}(A) \) as the set of all locally nilpotent derivations, and \( \text{DER}(A) \) as the set of derivations. We will denote by \( A^{D_1,\ldots,D_m} := \{ a \in A; D_1(a) = \ldots = D_m(a) = 0 \} \).

In the paper [7], the following conjecture is posed:

**Commuting Derivations Conjecture:** Let \( A := k[X_1,\ldots,X_{n+1}] \), and let \( D_1,\ldots,D_n \in \text{LND}(A) \) be commuting, linearly independent over \( A \), locally nilpotent derivations. Then \( A^{D_1,\ldots,D_n} = k[f] \) and \( f \) is a coordinate.

**Geometric version:** Suppose we have a \( G := (G_a)^n \)-action on \( k^{n+1} \). Then \( k[X_1,\ldots,X_{n+1}]^G = k[f] \) and \( f \) is a coordinate.

In the elegant paper [1], it is shown that this conjecture is equivalent to the following:

**Weak Abhyankar-Sataye Conjecture:** Let \( A := k[X_1,\ldots,X_{n+1}] \), and let \( f \in A \) be such that \( k(f)[X_1,\ldots,X_n] \cong k(f)[Y_1,\ldots,Y_{n-1}] \). Then \( f \) is a coordinate in \( A \).

For completeness sake, let us state

**Abhyankar-Sataye Conjecture:** Let \( A := k[X_1,\ldots,X_{n+1}] \), and let \( f \in A \) be such that \( A/(f) \cong k[Y_1,\ldots,Y_n] \). Then \( f \) is a coordinate.

**Sataye Conjecture:** Let \( A := k[X_1,\ldots,X_{n+1}] \), and let \( f \in A \) be such that \( A/(f-\alpha) \cong k[Y_1,\ldots,Y_n] \) for all \( \alpha \in \mathbb{C} \). Then \( f \) is a coordinate.

In [7], the Commuting Derivations Conjecture is proven for \( n = 3 \). But there is no indication that it might be true in higher dimensions. Even more, the Vénéreux polynomials (see [8]) (or similar objects), which are candidate counterexamples to the Abhyankar-Sataye conjecture, could very well spoil things for the Commuting Derivations Conjecture in higher dimensions. In any case, it seems like a proof is far away.

Therefore, it seems a good idea to be a little less ambitious. In this paper, we consider the weaker statement that \( A \) is a UFD (instead of a polynomial ring). It turns out that the situation can be quite different and interesting. Let us consider a famous example:

**Example 1.1.** Let \( A := \mathbb{C}[x,y,z,t] = \mathbb{C}[X,Y,Z,T]/(X^2Y + X + Z^2 + T^3) \) and let \( D_1 := 2z \frac{\partial}{\partial y} - x^2 \frac{\partial}{\partial z} \) and \( D_2 := 3t^2 \frac{\partial}{\partial y} - x^2 \frac{\partial}{\partial t} \). \( A \) is a UFD of transcendence degree 3 which is not a polynomial ring (see [6], or use the fact that the commuting derivations conjecture in dimension 3 holds). \( D_1 \) and \( D_2 \) commute, and \( A^{D_1,D_2} = \mathbb{C}[x] \). Now \( A/(x-\alpha) \cong \mathbb{C}[Y_1,Y_2] \) except in the case that \( \alpha = 0 \).
Also, $D_1 \mod (x - \alpha), D_2 \mod (x - \alpha)$ are independent over $A/(x - \alpha)$ if
and only if $\alpha \neq 0$.

# 2 The UFD Commuting derivations theorem

The following theorem is the main result of this paper.

**Theorem 2.1.** Let $A$ be a UFD over $k$ with $\text{trdeg}_k Q(A) = n + 1 (\geq 1)$, $A^* = k^*$, and let $D_1, \ldots, D_n$ be commuting locally nilpotent derivations (linearly independent over $A$). Now $A D_1, \ldots, D_n = k[f]$ for some $f \in A\setminus k$, and

1. If $D_1 \mod (f - \alpha), \ldots, D_n \mod (f - \alpha)$ are independent over $A/(f - \alpha)$, then $A/(f - \alpha) \cong \mathbb{C}[\alpha]$. There are only finitely many $\alpha \in \mathbb{C}$ for which $D_1 \mod (f - \alpha), \ldots, D_n \mod (f - \alpha)$ are dependent over $A/(f - \alpha)$.

2. In the case that $D_1 \mod (f - \alpha), \ldots, D_n \mod (f - \alpha)$ are independent over $A/(f - \alpha)$ for each $\alpha \in k$, then $A = k[s_1, \ldots, s_n, f]$, a polynomial ring in $n + 1$ variables.

**Geometric Version:** Let $V$ be a factorial affine surface over $k$ of dimension $n + 1$ such that $\mathcal{O}(V)^* = k^*$. Suppose there exists a $G := (G_\alpha)^n$-action on $V$. Then $\mathcal{O}(V)^G = k[f]$ and

1. Suppose that the fiber $f = \alpha$ has a point with trivial stabilizer. Then the fiber $f = \alpha$ is isomorphic to $\mathbb{C}^n$. There are only finitely many $\alpha$ for which $f = \alpha$ has no point with trivial stabilizer.

2. Suppose that all fibers $f = \alpha$ have a point with trivial stabilizer. (Then, all points have trivial stabilizers.) Then $V \cong \mathbb{C}^n+1$ and the action $G \times V \rightarrow V$ is a translation on the first $n$ coordinates.

In the last section we will prove a more general geometric statement of part 2 for unipotent groups in stead of $G_\alpha^n$-actions, but we will stick with this description for the moment, as this is the most interesting case for us, and has a simpler, direct, algebraic proof.

Before we give a proof of the above theorem, let us meditate on this a bit. The example 1.1 is a typical case of part 1 of the above theorem. But there is a connection with the Sataye Conjecture. Let us consider the following conjecture:

**Modified Sataye Conjecture:** Let $A := k[X_1, \ldots, X_{n+1}]$, and let $f \in A$ be such that $A/(f - \alpha) \cong k[Y_1, \ldots, Y_n]$ for all $\alpha \in \mathbb{C}$. Then there exist $n$ commuting locally nilpotent derivations $D_1, \ldots, D_n$ on $A$ such that $A D_1, \ldots, D_n = \mathbb{C}[f]$ and the $D_i$ are linearly independent modulo $(f - \alpha)$ for each $\alpha \in \mathbb{C}$.

**Proposition 2.2.** The Modified Sataye Conjecture is equivalent to the Sataye Conjecture.
Proof. Let us abbreviate the conjectures by SC and MSC. Suppose we have proven the MSC. Then for any \( f \) satisfying \( A/(f - \alpha) \cong k[Y_1, \ldots, Y_n] \) for all \( \alpha \in \mathbb{C} \) we can find commuting derivations as stated in the MSC. But using theorem 2.1 part 2 we get that \( f \) is a coordinate in \( A \). So the SC is true in that case.

Now suppose we have proven the SC. Let \( f \) satisfy the requirements of the MSC, that is, \( A/(f - \alpha) \cong k[Y_1, \ldots, Y_n] \) for all \( \alpha \in \mathbb{C} \). Since \( f \) satisfies the requirements of the SC, \( f \) then must be a coordinate. So it has \( n \) so-called mates: \( \mathbb{C}[f, f_1, \ldots, f_n] = \mathbb{C}[X_1, \ldots, X_{n+1}] \). But then each of these \( n + 1 \) polynomials \( f, f_1, \ldots, f_n \) defines a locally nilpotent derivation, all of them commute, and the intersection of the last \( n \) derivations is \( \mathbb{C}[f] \); so the MSC holds.

But now it is time to stop daydreaming about big conjectures, and start doing some hard-core proofs. Since the following proof uses the tools of the next section, the reader is encouraged to read section 3 before reading the following proof in detail.

Proof. (of theorem 2.1) Using lemma 3.4 we have \( p_i \in A \) such that \( D_j(p_i) = 0 \) if \( i \neq j \), and \( D_i(p_j) = q_j(\alpha) \in \mathbb{C}[\alpha] \) of lowest possible degree.

Part 1: \( D_1, \ldots, D_n \) are independent over \( A \), but they may become dependent modulo \( (f - \alpha) \). Let us first consider the case where they are independent modulo \( (f - \alpha) \): then \( D_1, \ldots, D_n \) are linearly independent over \( A/(f - \alpha) \). Then, by proposition 3.1 we have that \( A/(f - \alpha) \cong k[n] \).

So, left to prove is that \( D_1, \ldots, D_n \) can only be linearly dependent modulo finitely many \( (f - \alpha) \). But this follows directly from lemma 3.5, as there are only finitely many zeroes in \( q_1q_2 \cdots q_n \).

Part 2: Lemma 3.5 tells us directly that for each \( 1 \leq i \leq n \) and \( \alpha \in k \), we have \( q_i(\alpha) \neq 0 \). But this means that the \( q_i \in k^* \), so the \( p_i \) are in fact slices, and using 3.3 we are done. \( \square \)

3 Tools

The tools proven in this section focus on the situation of theorem 2.1 part 1, and are interesting in their own respect.

In this section, \( A \) is a \( k \)-domain, and \( trdeg(A) = n + 1 (\geq 1) \).

The following two propositions are proposition 3.2 and 3.4 in [7].

Proposition 3.1. Let \( D_1, \ldots, D_{n+1} \) be commuting locally nilpotent \( k \)-derivations on \( A \) which are linearly independent over \( A \). Then

(i). There exist \( s_i \) in \( A \) such that \( D_is_i = \delta_{ij} \) for all \( i, j \)

(ii). \( A = k[s_1, \ldots, s_{n+1}] \) a polynomial ring in \( n + 1 \) variables over \( k \).

Proposition 3.2. Let \( A \) be a UFD and let \( A^* = k^* \). Let \( D_1, \ldots, D_n \) be commuting locally nilpotent derivations, linearly independent over \( A \). Then \( AD_1, \ldots, D_n = k[f] \) for some \( f \in A\backslash k \), and \( f - \alpha \) is irreducible for each \( \alpha \in \mathbb{C} \).
Proposition 3.3. Let $A$, $D_i$, $f$ as in proposition 3.2. Suppose there exist $s_1, \ldots, s_n$ such that $D_i(s_i) = 1$. Then $A = k[s_1, \ldots, s_n, f]$, a polynomial ring in $n + 1$ variables.

Proof. This is an easy consequence of the fact that, if $D \in \text{LND}(A)$ having an $s \in A$ such that $D(s) = 1$, then $A^D[s] = A$. 

Define the following abbreviation:

(S1:) Let $A$ be a UFD and let $A^* = k^*$. Let $D_1, \ldots, D_n$ be commuting locally nilpotent derivations, linearly independent over $A$.

Lemma 3.4. Assume (S1).

(1) Then there exist $p_i \in A$ such that $D_i(p_i) = 0$ if $j \neq i$, and $D_i(p_i) \in k[f]\{0\}$. Furthermore, $k[p_1, \ldots, p_n, f] \subseteq A$ is algebraic.

(2) Define $P_i := \{p_i \in A \mid D_j(p_i) = 0 \text{ if } i \neq j \text{ and } D_i(p_i) \in k[f]\}$. then $D_i(P_i) = q_i(f)k[f]$ for some nonzero polynomial $q_i$. Taking $p_i$ such that $D_i(p_i)$ is of lowest possible degree yields $D_i(p_i) \in kq_i(f)$.

Proof. (1) We assume that all $n$ derivations commute, so $D_i (A^{D_j}) \subseteq A^{D_j}$, and therefore $D_i$ sends $A_i := A^{D_1, \ldots, D_{i-1}, D_{i+1}, \ldots, D_n}$ to itself. Taking some $a \in A_i \setminus C[f]$ nonzero, we use the fact that $D_i$ is locally nilpotent to find the lowest $m \in \mathbb{N}$ such that $D^m(a) = 0$. Now define $p_i := D^m(a)$ (indeed $m \geq 2$). The rest is easy.

(2) Take $p_i$ such that $D_i(p_i) = q_i(f) \neq 0$ has lowest possible degree. Let $\tilde{p}_i \in P_i$. then $D_i(\tilde{p}_i) = h_i(f)q_i(f) + r_i(f)$ where $\deg(r_i) < \deg(q_i)$. Now $D_i(\tilde{p}_i - h_i(f)p_i) = r_i(f)$ so $r_i = 0$. So $D_i(\tilde{p}_i) \in q_i(f)C[f]$. 

Lemma 3.5. Assume (S1). Choose $p_i$ such that $D_i(p_i) = q_i(f)$ as in lemma 3.4, where $q_i$ is of lowest possible degree. The $D_i$ are linearly dependent modulo $f - \alpha$ if and only if $q_i(\alpha) = 0$ for some $i$.

Proof. ($\Rightarrow$): Write “bars” for “modulo $f - \alpha$”. Suppose that $0 \neq D := g_1 D_1 + \ldots + g_n D_n$ satisfies $D = 0$ where $g_i \in A$, and not all $\overline{g}_i \neq 0$. Now $\overline{g}_i D_i(\overline{p}_i) = \overline{D}(\overline{p}_i) = 0$ for each $i$, so for each $i$, either $\overline{g}_i = 0$ or $q_i(\overline{f}) = 0$ (as $f - \alpha$ is irreducible by proposition 3.2). Since not all $\overline{g}_i = 0$, at least one $q_i(\overline{f}) = 0$. Since $f - \alpha$ is irreducible for each $\alpha$, we not only have $(f - \alpha)|q_i(\overline{f})$, but even $(X - \alpha)|q_i(X)$, so $q_i(\alpha) = 0$.

($\Leftarrow$): Assume $f - \alpha$ divides $q_i(\overline{f})$. We need to show that the $D_i \mod (f - \alpha)$ are linearly dependent over $A/\langle f - \alpha \rangle$. Suppose the $\overline{D}_i$ are linearly independent over $A$. Then we have $n$ commuting, linearly independent LNDs on a domain of transcendence degree $n$, so we can use proposition 3.1 and conclude that $\overline{A}^{\overline{D}_1, \ldots, \overline{D}_n} = k$. This means, since $\overline{q}_i(\overline{f}) = 0$, that $\overline{p}_i \in k$. So, $p_i = (f - \alpha)a + \lambda$ where $a \in A, \lambda \in k$. Now taking $a \in A$ we still have $D_j(a) = 0$ for all $j \neq i$, and $D_i(a) = q_i(\overline{f})(f - \alpha)^{-1} \in \mathbb{C}[f]$. This contradicts the assumption that $q_i$ was minimal, so our assumption that the $\overline{D}_i$ are linearly independent was incorrect. 

\[ \square \]
Now we want to point out the following phenomenon:

**Example 3.6.** Let $D_1 = Z \partial_X + \partial_Y, D_2 = \partial_Y$ on $A = \mathbb{C}[X,Y,Z]$. Now $A^{D_1,D_2} = \mathbb{C}[Z]$. The $D_1,D_2$ are linearly independent modulo $Z - \alpha$ as long as $\alpha \neq 0$. But it is clear that a different set of derivations, namely $E_1 = \partial_X, E_2 = \partial_Y$ commute, their $\mathbb{C}[Z]$-span contains $D_1, D_2$ and the $E_i$ are linearly independent for more fibers $f - \alpha$.

The $E_i$ of the example are an improvement over the $D_i$: all the same properties, but they are linearly independent for more $f - \alpha$. Perhaps for your given space $A$ and derivations $D_i$ it is impossible to find $E_i$ such that the $E_i$ are independent modulo every $f - \alpha$, giving more information on your ring $A$. Before we elaborate on this, let us give a lemma that enables construction of the $E_i$:

**Lemma 3.7.** Assume (S1). Define
\[ M := k(f)D_1 + \ldots + k(f)D_n \implies \text{DER}(A). \]
Then $M = k[f]E_1 \oplus \ldots \oplus k[f]E_n$ for some $E_i \in M$, and the $E_i$ have all the properties that the $D_i$ have (i.e. commuting locally nilpotent, linearly independent over $A$). Furthermore, if the $D_i$ are linearly independent modulo $(f - \alpha)$, then the $E_i$ are too (but not necessary the other way around).

**Proof.** Use lemma 3.4 we find preslices $p_i$ and $D(p_i) = q_i(f)$ as stated there.

If $D \in M$ then $D = g_1(f)D_1 + \ldots + g_n(f)D_n$ where $g_i(f) \in k(f)$. Now since $D \in \text{DER}(A)$ we have $D(p_i) \in A$. Also $D(p_i) = g_1(f)D_1(p_i) = g_i(f)q_i(f) \in k(f)$ thus $D(p_i) \in A \cap k(f)$, which equals $k[f]$ since $A^* = k^*$.

Therefore the map $\varphi : M \longrightarrow k[f]^n$ sending $D \longrightarrow (D(p_1), \ldots, D(p_n))$ is well-defined. If $0 = \varphi(g_1(f)D_1 + \ldots + g_n(f)D_n)$ then $g_i(f)D_i(p_i) = 0$ and therefore $g_i(f) = 0$; thus $\varphi$ is injective.

Since $\varphi$ is an injective map, $M$ must be a free $k[f]$-module. Note that $M$ can only have dimension $n$. Therefore we can find $E_1, \ldots, E_n$ as required.

Any derivation in $M$ is locally nilpotent. Even more, any two derivations of $M$ commute! Next to that, the $E_i$ are clearly independent over $A$. □

Note that the $E_i$ can be constructively made, given the injective map $\varphi$ in the above proof. This actually gives an interesting concept. Given the situation (S1), one can improve the derivations $D_i$ (by replacing them by the $E_i$) and then they are linearly independent modulo as much as possible $f - \alpha$. For every such $\alpha$ we have that $A/(f - \alpha)$ is a polynomial ring. The question is if the converse holds:

**Question:** Assume (S1). Additionally, assume $k[f]D_1 + \ldots + k[f]D_n = (k(f)D_1 + \ldots + k(f)D_n) \cap \text{DER}(A)$. Is the set $\{ \alpha \in \mathbb{C} \mid D_1, \ldots, D_n \text{ linearly dependent modulo } (f - \alpha) \}$ equal to the set $\{ \alpha \in \mathbb{C} \mid A/(f - \alpha) \text{ is not a polynomial ring} \}$? (One always has $\geq$.) Or, if this equality does not hold, what type of rings $A$ do have equality?

Note that the requirement “$A$ UFD” is absolutely necessary, as for a simple Danielewski surface $\mathbb{C}[X,Y,Z]/(X^2Y - Z^2)$ we find a LND $2Z \partial_Y + X^2 \partial_Z$ which
is nonzero modulo each $X - \alpha$. (But $A/(f - \alpha)$ is not always a domain in this case, even.)

## 4 Unipotent actions

The authors would like to thank prof. Kraft for pointing out the generalization of theorem 2.1 part 2, which has become the below theorem 4.2.

**Proposition 4.1.** If $U \times V \longrightarrow V$ is an action of a unipotent group $U$ on an affine variety $V$, then for each $u \in U$, the map $u^*: O(V) \longrightarrow O(V)$ is an exponent of a locally nilpotent derivation.

For the proof we can refer to proposition 2.1.3 in [2], or ask the reader to verify that $u^* - \text{Id}$ is a locally nilpotent endomorphism, and that thus “log($u^*$)” can be defined, and is a derivation.

This proposition has some immediate consequences, like that the invariants of a unipotent group action are the intersection of kernels of locally nilpotent derivations. Since kernels of locally nilpotent derivations are factorially closed, their intersection is too, so the invariants of a unipotent group is factorially closed.

In the below theorem, $\mathbb{C}$ is a field of characteristic zero, which is algebraically closed.

**Theorem 4.2.** Let $U$ be a unipotent algebraic group of dimension $n$, acting freely on $X$, a factorial variety of dimension $n + 1$ satisfying $O(X)^* = \mathbb{C}^*$. Then $X$ is $U$-isomorphic to $U \times \mathbb{C}$. In particular, $X \simeq \mathbb{C}^{n+1}$.

**Proof.** The fact that $U$ acts free means that each $x \in X$ has trivial stabilizer: $U_x = \{ u \in U; ux = x \} = \{ \text{id} \}$. So, each orbit $Ux$ is of dimension $n$. This means that $X/U$ is of dimension 1. Also, as remarked above, $X^U$ is factorial. But then it is also normal, and smooth. So $X/U$ is a smooth, rational, affine curve, in other words, an open subvariety of $\mathbb{C}$. Now suppose that $X/U \not\subseteq \mathbb{C}$, so $X/U = \mathbb{C} - \{ p_1, \ldots, p_n \}$, then $O(X)^U = O(\mathbb{C} - \{ p_1, \ldots, p_n \}) = \mathbb{C}[t, (t - p_1)^{-1}, \ldots, (t - p_n)^{-1}]$. This means that $O(X)$ contains invertible elements $(t - p_1)^{-1}$, giving a contradiction with the assumption $O(X)^* = \mathbb{C}^*$. Hence, $X/U \simeq \mathbb{C}$, so $O(X)^U = O(X/U) = O(\mathbb{C}) \simeq \mathbb{C}[f]$ for some $f$. Now every $f - \lambda$ ($\lambda \in \mathbb{C}$) is irreducible, as otherwise any irreducible factor of $f - \lambda$ would be in $O(X)^U$ too.

Now consider the map $f: X \longrightarrow \mathbb{C}$. This is in fact the map $X \longrightarrow X/U$ (as it corresponds to the map $O(X) \longleftarrow O(X)^U = \mathbb{C}[f]$) and thus surjective. Also note that the fibers $f^{-1}(\lambda)$ are invariant under $U$: they correspond to the function space $O(X)/(f - \lambda)$. By assumption, $U$ acts free on each fiber of $X \longrightarrow X/U$, which means exactly that $U$ acts free on $f^{-1}(\lambda)$ for each $\lambda$. Let $x \in f^{-1}(\lambda)$. Then $Ux$ is of dimension $n$ (it is just a copy of $U$). Also, each orbit of a unipotent group is closed (see Satz 4 from [3]), and therefore the inclusion $Ux \subseteq f^{-1}(\lambda)$ is an equality. So orbits of $U$ are the same as fibers of $f$, i.e. we have an orbit fibration (or $U$-fibration).
$X_{\text{sing}}$ is closed and $U$-stable, hence a union of $U$-orbits, and so $\text{codim} X_{\text{sing}} = 1$ or $X_{\text{sing}}$ is empty. But $X$ is factorial, so in particular normal, which implies $\text{codim}(X_{\text{sing}}) \geq 2$. So $X_{\text{sing}}$ is empty, in other words: $X$ is smooth.

Now we claim that $f : X \rightarrow \mathbb{C}$ is smooth. To see this, first note that $\mathcal{O}(f^{-1}(\lambda)) = \mathcal{O}(X)/(f - \lambda)$ is reduced as $f - \lambda$ is irreducible, as seen before. And, as we already implied, the set of functions vanishing on $f^{-1}(\lambda)$ is the ideal $(f - \lambda)$. Now consider the tangent map $df_x : T_x X \rightarrow T_x \mathbb{C} = \mathbb{C}$ where $x \in f^{-1}(\lambda)$. Using “Satz 2”, page 269 in [3] we see that, $\ker df \supseteq T_x f^{-1}(\lambda)$, but since $f^{-1}(\lambda)$ is reduced, we even have equality $\ker df = T_x f^{-1}(\lambda)$. Now remember that the fiber $f^{-1}(\lambda)$ is an orbit, hence smooth (as any orbit is smooth!). This implies $\dim T_x f^{-1}(\lambda) = n$ and thus $\dim \ker df = n$. Since $\dim T_x X = n + 1$ we have $\dim \operatorname{Im}(df_x) = 1$, hence $df_x$ is surjective. A morphism between smooth varieties is smooth if and only if the differential is surjective. So we have shown that $f$ is smooth.

So: $f : X \rightarrow \mathbb{C}$ is surjective, and smooth. Let $K := \ker df|_x \subset T_x X$. Take some linear subspace $C$ such that $K \oplus C = T_x X$. Note that $C$ has dimension 1. Seeing $X$ as a subset of some $\mathbb{C}^N$, we can find hyperplanes $H$ that contains $C$. We even want $H \cap T_x X = C$, so this means that $H \oplus T_x \subseteq \mathbb{C}^N$, so let us take a hyperplane $H$ of codimension $n$ such that $H \cap T_x X = C$. Now let $Z$ be an irreducible component of $H \cap X$ which contains $x$. Also, $\dim_x H \cap X \geq 1$, thus $\dim_x Z = 1$ and $Z$ is smooth at $x$. Now $Z$ and $\mathbb{C}$ are smooth, and the differential of $f|_Z : Z \rightarrow \mathbb{C}$ is an isomorphism at $x$ (implying surjective), thus we have that $f|_Z$ is smooth at $x$. Replacing $Z$, if necessary, by a (special) open subset $Z' \subset Z$, we have $f|_Z$ is étale.

Now look at the following diagram

\[
\begin{array}{ccc}
Z \times_{\mathbb{C}} X & \xrightarrow{p} & X \\
\downarrow f & & \downarrow f \\
Z & \xrightarrow{f|_Z} & \mathbb{C}
\end{array}
\]

where $Z \times_{\mathbb{C}} X = \{(x, z) \in X \times Z \mid f(x) = f|_Z(z)\}$ is the (schematic) fiber product. Since $f$ is smooth, the same holds for $f$ and so $Z \times_{\mathbb{C}} X$ is smooth. Moreover, $U$ acts on $Z \times_{\mathbb{C}} X$ by $u(z, x) = (z, ux)$ and $p(u(x, z)) = ux$ ($p$ is $U$-equivariant) and $f(u(x, z)) = z = f(x, z)$ ($f$ is $U$-invariant). The fibers of $\tilde{f}$ are $\tilde{f}^{-1}(z) = \{(x, z) \mid f(x) = f|_Z(z)\} = \{x \mid f(x) = \alpha\} = f^{-1}(\alpha)$ where $\alpha = f_Z(z)$. Now $\tilde{f}$ has a section $\sigma : Z \rightarrow Z \times_{\mathbb{C}} X$ given by $z \mapsto (z, z)$, i.e. $\tilde{f} \circ \sigma = \text{id}_Z$. Therefore, we can extend the diagram above

\[
\begin{array}{ccc}
U \times Z & \xrightarrow{q} & Z \times_{\mathbb{C}} X \xrightarrow{p} & X \\
\downarrow \text{pr}_Z & & \downarrow \tilde{f} & \downarrow f \\
Z & \xrightarrow{f|_Z} & \mathbb{C}
\end{array}
\]

where $q : U \times Z \rightarrow Z \times_{\mathbb{C}} X$ is given by $(u, z) \mapsto (z, uz)$. By construction, $q$ is bijective, hence an isomorphism, since the second variety is normal (see [4])
proposition 5.7). Note that the role of $x$ was arbitrary: for each $x$ we find a neighborhood $Z$ where $Z \times_{\mathbb{C}} X = Z \times_{\mathbb{C}} U$. This last statement exactly means that the map $f : X \to \mathbb{C}$ is a locally trivial principal $U$-bundle with respect to the étale topology: for every point $\lambda \in \mathbb{C}$ there is an étale map $Z \to \mathbb{C}$ such that $\lambda$ is in the image and the fiber product $Z \times_{\mathbb{C}} X$ is a trivial $U$-bundle, i.e. isomorphic to $U \times_{\mathbb{C}} Z$.

In the paper [5] we now find a result that tells us that a principal $G$-bundle where $G$ is a unipotent group is trivial over any affine variety, and then we are done.

□

References


[6] L. Makar-Limanov, *On the hypersurface $x + x^2y + z^2 + t^3 = 0$ in $\mathbb{C}^4$ or a $\mathbb{C}^3$-like threefold which is not $\mathbb{C}^3$*, Israel J. Math., 96(1996), 419-429
