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ON AUTOMORPHISMS OF WEYL ALGEBRA

BY

L. MAKAR-LIMANOV (*)

RéSUMÉ. — Le but de cette note est de généraliser un théorème de Jacques Dixmier qui décrit le groupe des automorphismes de l’algèbre de Weyl dans le cas de caractéristique positive et de donner une nouvelle démonstration dans le cas de caractéristique zéro.

ABSTRACT. — In this note I am going to generalize a theorem of J. Dixmier [1] describing the group of automorphisms of the Weyl algebra to the case of non-zero characteristic and give a new proof of it in the case of zero characteristic.

Let $A$ be the Weyl algebra with generators $p$ and $q ([p, q] = pq - qp = 1)$ over a field $K$. Let the characteristic of $K$ be $\chi$.

LEMMA 1. — If $\chi \neq 0$ then $p^2$ and $q^2$ generate (over $K$) the center $C$ of $A$.

Proof. — It is clear that $p^2$ and $q^2 \in C ([p^2, q] = \chi p^2 - 1 = 0)$. Let $r = \sum_i j k_i j p^i q^j$ belong to $C$, where $k_i j \in K$ (as is well known every element of $A$ can be represented in such a form). Then

$$[p, r] = \sum j k_i j p^i q^j - 1 = 0$$

which means that $jk_i j = 0$, i.e. $j \equiv 0 \pmod{\chi}$ if $k_i j \neq 0$. Analogously from $[r, q] = 0$ it follows that $i \equiv 0 \pmod{\chi}$ if $k_i j \neq 0$. So $r \in K[p^2, q^2]$.

The group $H$ of automorphisms of the polynomial ring $K[x, y]$ is generated by linear automorphisms

$$x \rightarrow ax + by, \quad y \rightarrow cx + dy \left( \begin{array}{cc} a & c \\ b & d \end{array} \right) \neq 0$$

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and triangular automorphisms \( x \mapsto x, y \mapsto y + f(x) \) where \( f(x) \in k[x] \) (this is proven by H. W. E. Jung in case \( \text{char } K = 0 \) [2] and by W. van der Kulk for arbitrary \( \text{char } K \) [3]). So the images \( X = \tau(x) \) and \( Y = \tau(y) \) of \( x \) and \( y (\tau \in H) \) have the following property.

Let \( X = \sum_{i=0}^n X_i \) and \( Y = \sum_{j=0}^n Y_j \) where \( X_i \) and \( Y_j \) are homogeneous polynomials of \( x \) and \( y \) of degree \( i \) (\( j \) correspondingly) with respect to the degree given by \( \deg x = 1, \deg y = 1 (X_m \neq 0, Y_n \neq 0) \). Let us denote \( X_m \) by \( X \) and \( Y_n \) by \( Y \).

**Lemma 2.** — Either \( X = c(\mathbf{Y})^\mathbf{Y} \), or \( Y = d(\mathbf{X})^\mathbf{X} \) where \( c, d \in K \) and \( r \) is a natural number, or \( \deg X = \deg Y = 1 \).

**Proof.** — This is a rather well known statement and more or less every description of \( H \) is based on something like this (see: [2], [3], [4]). I’ll outline how it can be deduced from the above description of \( H \). Let us represent \( \tau \in H \) as a shortest possible product of the linear and triangular automorphisms: \( \tau = \Delta_1 \ldots L_1 \Delta_1 L_0 \). It is easy to see that if \( L \) is an upper triangular matrix then \( L \Delta = \Delta L \). So we can assume that each \( L_i \) with \( i \neq 0 \) has one of the forms \( \begin{pmatrix} 1 & 0 \\ b & 1 \end{pmatrix} \) or \( \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \). Also we can assume that \( \deg \Delta_i(y) > 1 \) if \( i \neq 1 \) because \( L \Delta L' = \Delta L \) if \( \deg \Delta(y) = 1 \). Now if \( t = 1 \), then \( \deg X = \deg Y = 1 \) if \( \deg \Delta_1(y) = 1 \), and \( Y = d(\mathbf{X})^\mathbf{X} \) if \( \deg \Delta_1(y) = r > 1 \). If \( r > 1 \) then \( \deg \Delta_r(y) > 1 \) for \( i < t \) and it is easy to show by induction (using of course the special form of the linear transformations \( L_i \)) that \( Y = d(\mathbf{X})^\mathbf{X} \) where \( X' = \Delta_1 \ldots L_0(x), Y' = \Delta_1 \ldots L_0(y), \) and \( r = \prod_{i=1}^{t-1} \deg \Delta_i(y) \). If \( \deg \Delta_i(y) > 1 \) then it is sufficient to make one more induction step. If, however, \( \deg \Delta_1(y) = 1 \) then \( \Delta_1 L_{t-1} = \Delta L' \) where \( \Delta L' = y + e (e \in K) \), and depending on \( L' \) we can have either \( Y = d'(\mathbf{X})^\mathbf{X} \) or \( X = d(\mathbf{Y})^\mathbf{Y} \) or \( Y = d(\mathbf{X})^\mathbf{X} \).

Let us call the automorphism \( \tau \) of \( K[x, y] \) normalized if the determinant of the Jacoby matrix of \( \tau(x), \tau(y) \) is equal to \( 1 \). Let us denote the group of all such automorphisms by \( \text{Aut}_n(K[x, y]) \). One more denotation. Any element \( R = \sum_{ij} p^i q^j \in \mathcal{A} \) also can be rewritten as \( \sum_{i=0}^n R_i \) where the total degree of \( R_j \) is \( i \). Let us denote \( R_n \) by \( \mathcal{R} \). It is easy to see from the definition of multiplication in \( \mathcal{A} \) that \( \mathcal{R} \) is well defined and that \( R \mapsto \mathcal{R} \) gives a multiplicative homomorphism of \( \mathcal{A} \) into the ring of commuting polynomials.

**Theorem 1.** — If \( \chi \neq 0 \) then \( \text{Aut}(\mathcal{A}) \cong \text{Aut}_n(K[x, y]) \).

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Proof. — Let σ be an automorphism of A and \( P = \sigma(p) \), \( Q = \sigma(q) \). Let us denote \( p^2 \) by \( x^2 \), \( q^2 \) by \( y^2 \), \( P^2 \) by \( X^2 \), and \( Q^2 \) by \( Y^2 \) where \( x, y, X, \) and \( Y \) are commuting. Then (Lemma 1) \( C = K[x^2, y^2] \). On the other hand \( X^2 \) and \( Y^2 \) also generate the center \( C \) of \( A \). Thus the mapping \( x^2 \mapsto X^2, \ y^2 \mapsto Y^2 \) gives an automorphism of \( K[x^2, y^2] \). So we can apply Lemma 2 to \((X^2) = (P)^2 \) and \((Y^2) = (Q)^2 \) and obtain that if \( \deg P < \deg Q \) then \( Y^2 = c(X^2)^r \). Therefore \( Y = c'(X)^r \) (where \( c' \in K \) because \( c' \) is the element of \( K(x, y) \) such that \( (c')^2 = c \)). Thus the degree of \( Q_1 = Q - c'P^r \) is smaller than \( \deg Q \). But \( p \mapsto P_1 = P, \ q \mapsto Q_1 \) also generates an automorphism. We can repeat such a transformation of \( P \) and \( Q \) only a finite number of times because \( \deg P + \deg Q \) drops with every step. If after some step, e.g. in the very beginning, \( \deg Q_1 < \deg P_1 \), then we'll consider the automorphism \( p \mapsto Q_1, \ q \mapsto -P_1 \). So after a finite number of triangular automorphisms and linear automorphisms \( P \mapsto q, \ q \mapsto -p \) we reduce \( P \) and \( Q \) to elements \( P' \) and \( Q' \) of degree 1. Then \( P' = a_1p + a_2q + a_3, \ Q' = b_1p + b_2q + b_3 \) where \( \begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = 1 \). So both groups \( \text{Aut}(A) \) and \( \text{Aut}_n(K[x, y]) \) are spanned by triangular automorphisms and linear automorphisms with determinant equal to 1. Let us consider now the free algebra \( K\langle a, b \rangle \). Triangular automorphisms and “normalized” linear automorphisms span a subgroup \( \text{Aut}_n(K\langle a, b \rangle) \) of the group of automorphisms of \( K\langle a, b \rangle \). It is clear that

\[ \text{Aut}_n(K\langle a, b \rangle) \cong \text{Aut}_n(K[x, y]), \]

and that \( \text{Aut}_n(K\langle a, b \rangle) \cong \text{Aut}(A) \) because there exist natural surjective homomorphisms from the left sides to the right sides in both cases. For checking that the kernels are trivial, it is sufficient to investigate the homogeneous forms of the images of biggest degrees, which can be done along the same lines as in lemma 2. So \( \text{Aut}_n(k[x, y]) \cong \text{Aut}(A) \).

Now the Dixmier theorem.

Theorem 2. — If \( \text{char} \ K = 0 \) then \( \text{Aut}(A) \cong \text{Aut}_n(K[x, y]) \).

Proof. — Let \( R \) be the field of rational numbers and \( Z \) be the ring of integers; the field \( K \) contains \( R \). Let us fix \( \tau \in \text{Aut}(A) \). Let us consider the subfield \( k \) of \( K \) generated by all coefficients of \( P = \tau(p) \) and \( Q = \tau(q) \) and \( \tau^{-1}(p), \ \tau^{-1}(q) \). (Here one can have in mind a “polynomiallike” representation of \( P \) and \( Q \) as in lemma 1 though it is not essential because the commutator relation involves only rational numbers.) Let \( u_1, \ldots, u_n \) be a transcendence basis of \( k \) over \( R \).- Then \( k \) is algebraic over the field
There exists an element \( \theta \in k \) which is integral over the ring \( \mathcal{O}_k \), and there exists an element \( \pi_k \) from \( k \) onto some field \( k' \) with \( \text{char } k' = \chi \), \( \pi_k \) is defined on the subring of \( \mathcal{R} \) consisting of all elements \( \not\equiv \infty \pmod{\chi} \) and maps this subring naturally onto \( Z_\chi \) (field of residues modulo \( \chi \)). Then \( \pi_k \) can be extended to the corresponding subring of \( k \) by the formulas \( \pi_k(u_i) = u_i' \) where \( u_i' \) are transcendental over \( Z_\chi \) and \( \pi_k(\theta) = \theta' \), where \( \theta' \) is a root of the polynomial obtained from \( \text{irr}_\chi(\theta) \) by applying \( \pi_k \) to its coefficients.

Let us consider the Weyl algebra \( A' \) over \( k' \). The mapping \( \pi_k \) can be extended to some subring of \( A \) (which depends on \( \chi \)) by \( \pi_k(p) = p' \), \( \pi_k(q) = q' \); and \( \pi_k(A) = A' \). Now if \( \pi_k \) is defined on \( \tau(p) \) and \( \tau(q) \) and \( \tau^{-1}(p) \), \( \tau^{-1}(q) \) then \( P' = \pi_k \tau(p) \) and \( Q' = \pi_k \tau(q) \) are the images of \( p' \) and \( q' \) under some automorphism of \( A' \). So from Theorem 1 \( \pi_k(\mathcal{O}_k) \pi_k(k) \) when defined. The image of a nonconstant rational function under \( \pi_k \) may be a constant only for finite number of \( \chi \). So \( R = \mathcal{O}_k \mathcal{F}^{-r} \) itself must belong to \( k \) because \( \pi_k(R) \) is defined and constant for all but finite number of \( \chi \). Therefore the analog of Lemma 2 is proved and the proof of Theorem 1 can be repeated word by word in this case.

Remarks. — The "place" technique which was used here may be used for proving that the skew field \( D \) of fractions of \( A \) has a nonabelian free subgroup in every noncentral normal subgroup of \( D^* \). This may be done by reducing the problem to the finite dimensional situation and then applying the finite dimensional result (see [5]; the statement on free subgroups of \( D^* \) is proved among other things in [6]). It seems rather natural that reduction of the infinite dimensional situation to the finite dimensional can be very helpful. So any answer to the following question would be of considerable importance. Is it true that for any infinite dimensional (over its center) skew field \( B \) there exists a sufficient number of partial homomorphisms to finite dimensional (over their centers which need not be the images of the center of \( B \)) skew fields?

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