

On group operations other than xy or yx

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1. Introduction. Professor E. MARCZEWSKI suggested recently a notion of *weak isomorphism* of algebraic systems (see „Definition” below). In this paper we solve a problem raised by him, concerning the weak isomorphism of groups.

In the course of the solution we show the existence of groups G which have the following

Property (*): There is a binary operation $x \circ y$ in G , other than xy or yx , i. e. a word

$$x \circ y = x^{k_1} y^{l_1} x^{k_2} y^{l_2} \dots x^{k_r} y^{l_r} \quad (k_i, l_i \text{ integers})$$

not identically equal in G to xy or to yx , such that

- (i) the elements of G form a group $G_\circ$ under the operation $x \circ y$,
- (ii) the operation xy is a word in $G_\circ$, i. e. there are integers $m_1, \dots, m_s$ and $n_1, \dots, n_s$ such that

$$xy = [x]_\circ^{m_1} \circ [y]_\circ^{n_1} \circ \dots \circ [x]_\circ^{m_s} \circ [y]_\circ^{n_s}$$

holds identically for all x, y in G ($[x]_\circ^m$ denotes the m -th power of x with respect to the multiplication $\circ$ in $G_\circ$).

G. HIGMAN and B. H. NEUMANN [1] have proposed the following problem: "Is there any binary operation in a group G , other than xy^{-1} or yx^{-1} and their transposes, in terms of which all group operations can be expressed?" Our examples of groups with Property (*) answer this question. For, it is clear that if G has Property (*), then $x \circ y^{(-1)}$ where by $y^{(-1)}$ we mean the inverse element of y with respect to the $\circ$ multiplication is an operation required by G. HIGMAN and B. H. NEUMANN.

As has been recently shown by HANNA NEUMANN [3], if G is a free group, then any binary operation in G which is associative is of one of the following types: a, x, y, xay, yax where a is any constant element of G . This covers an unpublished result of K. URBANIK that a free group does not possess Property (*). It follows from our Theorem 1 (see the Remark) that a free nilpotent group of class 2 does not possess Property (*) either.

We prove below that if G is a periodic nilpotent group of class 2 and G has Property (*), then the groups G and $G_\circ$ are isomorphic (Theorem 2). We do not know whether our assumptions are essential and we would like to suggest the following

PROBLEM. If G has Property $(*)$, are G and G_o isomorphic?

We now proceed to define the notion of weak isomorphism of two algebraic systems. By an *algebraic system*, or shortly *algebra*, we mean a pair (A, F) composed of a set A and a family F of operations (functions) of finitely many variables defined on A and taking values in A . For every positive integer n we define the class $\mathbf{A}^{(n)}$ of *algebraic operations of n variables* as the smallest class of operations such that

(j) the identity operations $e_j^n(x_1, \dots, x_n)$ defined by

$$e_j^n(x_1, \dots, x_n) = x_j \text{ for all } x_1, \dots, x_n,$$

belong to $\mathbf{A}^{(n)}$,

(jj) if $f \in F$ is an operation of m variables and $g_i(x_1, \dots, x_n)$, $i = 1, \dots, m$, are operations belonging to $\mathbf{A}^{(n)}$, then the operation

$$f(g_1(x_1, \dots, x_n), \dots, g_m(x_1, \dots, x_n))$$

belongs to $\mathbf{A}^{(n)}$.

We call $\mathbf{A} = \bigcup_{n=1}^{\infty} \mathbf{A}^{(n)}$ the class of algebraic operations of the algebra (A, F) (cf. [2]).

We shall identify a group G with the algebra (A, F) where A is the set of elements of G and F is the class composed of the unary operation x^{-1} and the binary operation xy , i. e. $F = \{x^{-1}, xy\}$. Then it is easily seen that $\mathbf{A}$ is the class of all operations $f(x_1, \dots, x_n)$ which are given by words in G , i. e. which are of the form

$$(1) \quad f(x_1, \dots, x_n) = x_{i_1}^{m_1} x_{i_2}^{m_2} \dots x_{i_l}^{m_l}$$

where $m_1, \dots, m_l$ are arbitrary integers, $i_1, \dots, i_l \in \{1, \dots, n\}$, and $n = 1, 2, \dots$.

Definition. Let $\mathcal{A}_1 = (A_1, F_1)$ and $\mathcal{A}_2 = (A_2, F_2)$ be two algebras and let $\mathbf{A}_1, \mathbf{A}_2$ be the corresponding classes of algebraic operations. We say, following E. MARCZEWSKI, that a one-to-one mapping τ of the set $A_1 \cup \mathbf{A}_1$ onto the set $A_2 \cup \mathbf{A}_2$ is a *weak isomorphism* of $\mathcal{A}_1$ onto $\mathcal{A}_2$ if

$$(k) \quad A_1 \tau = A_2, \mathbf{A}_1^{(n)} \tau = \mathbf{A}_2^{(n)} \text{ for every } n,$$

$$(kk) \quad \text{if } f \in \mathbf{A}_1^{(n)}, \text{ then } [f(a_1, \dots, a_n)] \tau = (f\tau)(a_1 \tau, \dots, a_n \tau) \\ \text{for every } a_1, \dots, a_n \text{ in } A_1.$$

If the algebras $\mathcal{A}_1$ and $\mathcal{A}_2$ coincide, then we call τ a *weak automorphism* of $\mathcal{A} [= \mathcal{A}_1 = \mathcal{A}_2]$.

A weak isomorphism τ of the algebras $\mathcal{A}_1$ and $\mathcal{A}_2$ is an isomorphism in the usual sense if $F_1 \tau = F_2$. A weak automorphism of $\mathcal{A}$ is an automorphism in the usual sense if it is the identity mapping on F .

EXAMPLE. Let $G = (A, \{x^{-1}, xy\})$ be a group. We define a weak automorphism τ of G by

$$(k_1) \quad x\tau = x^{-1} \text{ for every } x \text{ in } A,$$

$$(k_2) \quad \text{if } f \in \mathbf{A}^{(n)} \text{ is of the form (1),}$$

$$(f\tau)(x_1, \dots, x_n) = x_{i_l}^{m_l} x_{i_{l-1}}^{m_{l-1}} \dots x_{i_1}^{m_1}.$$

We call this weak automorphism *natural*.

PROBLEM (E. MARCZEWSKI): Do there exist two groups G and H such that there is a weak isomorphism of G onto H which is neither an isomorphism (in the usual sense) nor a combination of an isomorphism with the natural weak automorphism of one of the groups?

We give in the sequel a positive answer to this question. In fact, we prove that there is a finite group G which admits a weak automorphism τ such that τ is neither an automorphism nor a combination of an automorphism with the natural weak automorphism.

2. Results. In the sequel we deal only with nilpotent groups of class 2. It is well known that if G is nilpotent of class 2, then every word

$$x^{k_1}y^{l_1}x^{k_2}\dots x^{k_r}y^{l_r} \quad (k_i, l_i \text{ integers})$$

is identically equal to a word of the form $x^ay^b[x, y]^k$ where the integers a, b and k depend only on $k_1, l_1, \dots, k_r, l_r$. Thus in particular the operation $x \circ y$ considered in Property (*) must be of the form $x^ay^b[x, y]^k$. We shall prove the following two theorems.

Theorem 1. *If G is a nilpotent group of class 2, then a binary operation $x \circ y$ in G has properties (i) and (ii) (cf. (*)) if and only if*

$$(2) \quad x \circ y = xy[x, y]^k$$

where k is any integer such that $2k+1$ is prime to the exponent n of the derived subgroup G' of G .

Then, if and only if m is an integer such that $k+m(2k+1)$ is divisible by n^* , we have that

$$(3) \quad xy = x \circ y \circ [x, y]_{\circ}^m$$

where $[x, y]_{\circ}^m$ is the m -th power of the commutator of the elements x, y with respect to the multiplication $\circ$ in $G_{\circ}$.

REMARK. This theorem answers the problem of HIGMAN and NEUMANN (quoted above) in the affirmative. Another consequence of Theorem 1 is that a free nilpotent group of class 2 does not possess Property (*). For if Γ is free nilpotent of class 2 and an operation $x \circ y = xy[x, y]^k$ in Γ has properties (i) and (ii), then clearly this operation will have these properties in any homomorphic image G of Γ . But in the solution of MARCZEWSKI's problem below we define, for every $n > 1$, a group G with two generators which is nilpotent of class 2 and such that the exponent of its derived subgroup is n . We conclude, by Theorem 1, that $2k+1$ is prime to every $n > 1$, i. e. $k=0$ or -1 . Therefore $x \circ y = xy$ or yx , and these are the only two operations in Γ which have the properties (i) and (ii).

Theorem 2. *If G is a periodic nilpotent group of class 2 which has Property (*), then the groups G and $G_{\circ}$ are isomorphic.*

Postponing the proofs of these theorems to the next section we give now the solution of MARCZEWSKI's problem.

*) The existence of such an integer m follows from the fact that $2k+1$ is prime to n .

We observe first that, for every integer $n > 1$, there is a finite group G which is nilpotent of class 2 and such that the exponent of the derived subgroup G' is n . In fact, let C be the cyclic group of order n and let the group G be defined as the splitting extension of the direct product $C \times C = \{(a, b) | a, b \in C\}$ by the automorphism α

$$(a, b)^{\alpha} = (a, ab) \quad \text{for all } a, b \text{ in } C.$$

Then it is easily checked that $G' = \{(1, a) | a \in C\}$. Hence G' is in the centre of G , and G' has exponent n . (For our previous application note that the two elements $\alpha, (a, 1)$ generate G whenever a is a generator of C).

Now let k be any integer such that $k \not\equiv 0, -1 \pmod{n}$ and $(2k+1, n) = 1$ (e. g. $k = 1$ if $n = 4$). Then the operation $x \circ y = xy[x, y]^k$ is different from the operations xy and yx , and, by Theorem 1, $x \circ y$ has the properties (i) and (ii). Hence G has Property (*). By Theorem 2, there is an isomorphism φ of G onto $G_{\circ}$, i. e. a mapping φ such that

$$(4) \quad (xy)\varphi = x\varphi \circ y\varphi \quad \text{for all } x, y \text{ in } G.$$

To define a weak automorphism of G , we consider G as the algebra $(A, \{x^{-1}, xy\})$ where A is the set of elements of G . Denoting by $\mathbf{A}^{(n)}$ the class of algebraic operations of n variables and by $\mathbf{A}$ the class of algebraic operations, we define the mapping τ of $A \cup \mathbf{A}$ onto itself as follows

$$(k'_1) \quad x\tau = x\varphi \quad \text{for all } x \text{ in } A,$$

$$(k'_2) \quad \text{if } f \in \mathbf{A}^{(n)} \text{ is of the form (1), then}$$

$$(f\tau)(x_1, \dots, x_n) = [x_{i_1}]_{\circ}^{m_1} \circ [x_{i_2}]_{\circ}^{m_2} \circ \dots \circ [x_{i_t}]_{\circ}^{m_t}$$

where, as in (ii), $[x]_{\circ}^m$ denotes the m -th power of x in $G_{\circ}$. Then τ is a weak automorphism of G . The mapping τ is well defined, for if $f, g \in \mathbf{A}^{(n)}$ are such that $f = g$ holds identically in G , then $f\tau = g\tau$ holds identically in $G_{\circ}$, because G and $G_{\circ}$ are isomorphic. Hence $f = g$ implies $f\tau = g\tau$. By the same argument, $f\tau = g\tau$ implies $f = g$, and thus τ is one-to-one on $\mathbf{A}$. We also have that τ is one-to-one on A , because τ is an isomorphism of G onto $G_{\circ}$. From (3) it follows that τ maps $\mathbf{A}$ onto $\mathbf{A}$ and thus, by (4), τ is a weak automorphism. But τ is not an automorphism nor a combination of an automorphism with the natural weak automorphism, because the τ -image of the operation xy , i. e. the operation $x \circ y = xy[x, y]^k$, is different from both xy and yx .

3. Proofs of the Theorems. Before proving the theorems we wish to recall some well known identities valid in any nilpotent group of class 2. If G is a nilpotent group of class 2, then for any x, y, z in G and any integer n the following identities hold:

$$(5) \quad (xy)^n = x^n y^n [y, x]^{\frac{n(n-1)}{2}}$$

$$(6) \quad [xy, z] = [x, z][y, z], \quad [x, yz] = [x, y][x, z],$$

hence

$$(7) \quad [x^n, y] = [x, y^n] = [x, y]^n.$$

PROOF OF THEOREM 1. Let G be a nilpotent group of class 2 and let $x \circ y$ be an operation in G which has the properties (i) and (ii) (cf. (*)). Then, as we observed at the beginning of the previous section

$$x \circ y = x^a y^b [x, y]^k$$

for all x, y in G and some integers a, b, k . Let 1 be the unit element of G . By the above equality, $1 \circ 1 = 1$, hence 1 is also the unit element of $G_\circ$. Therefore

$$x = x \circ 1 = x^a, \quad y = 1 \circ y = y^b$$

hold identically in G , and we have (2). It follows immediately from (2) that, for every integer n , the n -th power of any element x with respect to the operation $\circ$ is just x^n . Also, the commutator $[x, y]_\circ$ in $G_\circ$ can be easily expressed in terms of the commutator $[x, y]$. In fact, a simple application of (2), (6), and (7) shows that

$$(8) \quad [x, y]_\circ = [x, y]^{2k+1}.$$

Hence $[[x, y]_\circ, z]_\circ = [[x, y]^{2k+1}, z]^{2k+1} = 1$, i. e. $G_\circ$ is nilpotent of class 2. From this and from (ii) we infer that for some integers a, b, m

$$xy = x^a \circ y^b \circ [x, y]_\circ^m.$$

The argument used to prove (2) will also serve now to prove that (3) holds identically for all x, y in G .

We note that, by (8), $[x, y]_\circ^m = [x, y]^{m(2k+1)}$. Substituting this in (3) and using (2) we get

$$xy = xy[x, y]^{k+m(2k+1)}$$

valid for all x, y in G . Hence the order of each commutator $[x, y]$ must divide $k + m(2k + 1)$ and so, as G is nilpotent of class 2, the exponent n of the derived subgroup G' of G must also divide $k + m(2k + 1)$. It follows that $2k + 1$ is prime to n . This completes the proof of the necessity of the conditions.

To prove the sufficiency, we suppose that G is a nilpotent group of class 2 and that k is an integer such that $2k + 1$ is prime to the exponent n of the derived subgroup G' . In this case there is an integer m such that $k + m(2k + 1)$ is divisible by n .

To prove (i), we observe first that the operation (2) is associative. In fact, by (7),

$$(x \circ y) \circ z = xyz[x, y]^k [x, z]^k [y, z]^k = x \circ (y \circ z).$$

We also have $1 \circ x = x \circ 1 = x$ and $x^{-1} \circ x = x \circ x^{-1} = 1$, so that the elements of G form a group $G_\circ$ under the multiplication $x \circ y$.

To prove (ii) we note that, as before, we have (8); whence, applying (2), we deduce that

$$x \circ y \circ [x, y]_\circ^m = xy[x, y]^{k+m(2k+1)}.$$

Using the fact that the exponent of G' divides $k + m(2k + 1)$, we obtain (3). This completes the proof of the theorem.

PROOF OF THEOREM 2. The following well known lemma will be applied in the proof.

Lemma. *If G is a periodic nilpotent group, then G is the direct product of its Sylow p -groups.*

We now assume that G is a periodic nilpotent group of class 2 which has Property (*). Then, by Theorem 1, the operation $x \circ y$ is of the form (2) and there is an integer m such that (3) holds. Moreover, the exponent of the derived subgroup G' of G divides the number $t = k + m(2k + 1)$.

Let $t = p_1^{z_1} \dots p_r^{z_r}$ be the factorization of t into primes and let

$$P = P_1 \times \dots \times P_r$$

be the direct product of the Sylow p_i -subgroups ($i = 1, \dots, r$) of the group G . Then, by the lemma,

$$G = P \times Q.$$

Of course each element of Q has order prime to t . Moreover, the group Q is Abelian. For if x, y are in Q , then, since the exponent of G' divides t , $[x, y]$ must belong to P , so $[x, y] \in P \cap Q = \{1\}$. We note that also

$$G_\circ = P_\circ \times Q_\circ,$$

where $P_\circ$ and $Q_\circ$ are the groups formed from the elements of P and Q respectively under the multiplication $x \circ y$.

Let $s = 2m + 1$. We have that s is (prime to t , for $2m + 1, m + (2m + 1)k = d$ implies $d | 2m + 1$, whence $d | m$, and so $d | 1$). We define now a mapping φ of G onto $G_\circ$ by

$$a\varphi = a^s \quad \text{if } a \text{ is in } P,$$

$$b\varphi = b \quad \text{if } b \text{ is in } Q,$$

$$(ab)\varphi = a\varphi \circ b\varphi \quad \text{for any } a \text{ in } P \text{ and } b \text{ in } Q.$$

It is clear that, by $(s, t) = 1$, s is prime to the orders of the elements of P , hence φ is one-to-one and onto. We prove that φ is an isomorphism of G onto $G_\circ$. To this purpose it is sufficient to prove that φ is a homomorphism on P . If x, y are in P , we have, by (5),

$$(xy)\varphi = (xy)^s = x^s y^s [y, x]^{\frac{s(s-1)}{2}} = x^s y^s [x, y]^{\frac{s(1-s)}{2}}.$$

On the other hand, by (2) and (7),

$$x\varphi \circ y\varphi = x^s \circ y^s = x^s y^s [x^s, y^s]^k = x^s y^s [x, y]^{s^2 k}.$$

Thus all that remains to prove is that

$$\frac{s(1-s)}{2} \equiv s^2 k \pmod{n}$$

where n is the exponent of G' . But this is immediate, for we have $n | t$ and

$$s^2 k - \frac{s(1-s)}{2} = s \left(sk - \frac{1-s}{2} \right) = s((2m+1)k + m) = st.$$

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