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ON THE NUMBER OF NORMAL SUBGROUPS OF A GIVEN PRIME INDEX

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Our aim in this short note is to give an optimum upper bound to the number of normal subgroups of index p, p a prime, in groups of order n. Our result is divided into two theorems: Theorem 1 gives the estimate, Theorem 2 states its optimality.

Remark on notation and terminology. By $|X|$ we mean the cardinality of a set X (or its order if it is a group). If A, B are two complexes in a group G, then AB means, as usual, the complex in G consisting of all ab where $a \in A$, $b \in B$. The sign $\otimes$ denotes the direct product of groups. A normal subgroup of index p (in a group G) will also be briefly called an Np-subgroup (of G). The word "group" means "finite group" throughout the paper.

Lemma. *Let N_1, N_2 be two distinct Np-subgroups of a group G. Then $N_1 \cap N_2$ is an Np-subgroup of N_1.*

Proof. The second (or the first as it is sometimes called) theorem on isomorphism states, if applied to our subgroups N_1, N_2, that $N_1/N_1 \cap N_2$ is isomorphic to N_1N_2/N_2. As both N_1, N_2 are of a prime index, we have $N_1N_2 = G$, and the proof follows immediately.

Theorem 1. *For the number $s_p(G)$ of normal subgroups of index p, p a prime, in a group G of order n, the following inequality holds:*

$$s_p(G) \leqq \frac{p^r - 1}{p - 1}, \tag{1}$$

where r is the greatest integer such that $p^r \mid n$.

Proof. For an arbitrary group X, let $r_p(X)$ denote the greatest integer such that $p^{r_p(X)} \mid |X|$. We shall prove (1) by induction with respect to $r_p(G)$. The case $r_p(G) = 0$ is obvious, the case $r_p(G) = 1$ follows immediately from the lemma since if N_1, N_2

are two distinct Np-subgroups of G, then $|G| = p|N_1| = p^2|N_1 \cap N_2|$ so that $r_p(G) \geqq 2$. Hence, let r be an integer, $r \geqq 2$, and suppose that (1) holds for all groups X for which $r_p(X) \leqq r - 1$. Let G be a group of order n with $r_p(G) = r$. Suppose that G has exactly q Np-subgroups $N_1, N_2, \ldots, N_q$. We clearly may assume $q \geqq 2$. Let us now take the set $\mathscr{B} = \{N_2, N_3, \ldots, N_q\}$ and partition it into β disjoint nonempty subsets $\mathscr{A}_i$ such that N_j and N_k $(2 \leqq j, k \leqq q)$ belong to the same class if and only if $N_1 \cap N_j = N_1 \cap N_k$. Thus, among the groups $N_1 \cap N_2, N_1 \cap N_3, \ldots$ $\ldots, N_1 \cap N_q$, there are exactly β distinct ones. Since all these groups are Np-subgroups of N_1 (as follows from the lemma) and since $r_p(N_1) = r - 1$, we have by hypothesis

$$(2) \qquad \beta \leqq \frac{p^{r-1} - 1}{p - 1}.$$

Further, we shall prove

$$(3) \qquad \alpha_i \leqq p \quad \text{for} \quad i = 1, \ldots, \beta$$

where $\alpha_i = |\mathscr{A}_i|$. Without any loss of generality, let $\mathscr{A}_i$ (i arbitrary) consist of the first α_i elements of $\mathscr{B}$. Thus, let $N_1 \cap N_2 = N_1 \cap N_3 = \ldots = N_1 \cap N_{\alpha_i+1} = Q$. By an easy argument we find that

$$(4) \qquad N_j \cap N_k = Q \quad \text{for any} \quad 1 \leqq j \leqq \alpha_i + 1 \quad \text{and} \quad 2 \leqq k \leqq \alpha_i + 1.$$

Indeed, we have $N_j \cap N_k \supset (N_1 \cap N_j) \cap (N_1 \cap N_k) = Q$ and $|N_j \cap N_k| = |Q|$ by the lemma. According to (4), the sets $Q, N_1 - Q, \ldots, N_{\alpha_i+1} - Q$ must be disjoint. Hence, in view of the relations $|Q| = n/p^2$, $|N_l - Q| = n/p - n/p^2$ $(1 \leqq l \leqq$ $\leqq \alpha_i + 1)$ following from the lemma, we get the condition

$$\left(\frac{n}{p} - \frac{n}{p^2}\right)(\alpha_i + 1) + \frac{n}{p^2} \leqq n$$

implying (3). By (3) and (2), we have

$$q - 1 = \sum_{i=1}^{\beta} \alpha_i \leqq \beta p \leqq p \frac{p^{r-1} - 1}{p - 1}$$

whence

$$q \leqq \frac{p^r - 1}{p - 1}.$$

This completes our proof.

Theorem 2. *The estimate (1) of Theorem 1 is best possible since for any pair p, n, p a prime, of positive integers, at least one group G of order n exists for which the equality sign takes place in (1).*

Our proof is based on a certain well-known assertion of the theory of abelian groups, see e.g. [1], p. 53, Satz 51.

Proof of Theorem 2. For given n, p, let r, m be those integers for which $n = p^r m$, $p \nmid m$. Let H be an arbitrary group of order m and let A denote the (elementary) abelian group of order p^r and of type $(p, \ldots, p)$. Put $G = A \otimes H$. (For $m = 1$ or $r = 0$, this reduces to $G = A$ and $G = H$, respectively.) To prove Theorem 2, it evidently suffices to show that A possesses $(p^r - 1)/(p - 1)$ distinct subgroups of index p (that is just a special case of the assertion mentioned above; we shall, however, give its proof for the sake of completeness). Indeed, if B_1, B_2 are two distinct subgroups of index p in A, then $B_1 \otimes H$, $B_2 \otimes H$ are two distinct Np-subgroups of G. – To determine the number of Np-subgroups in A (we retain our short notation though the normality is trivial in this case), let us first note that each Np-subgroup of A is of type $(p, \ldots, p)$ since its invariants must be divisors of those of A. The basis of each Np-subgroup therefore consists of $r - 1$ elements. Any independent $(r - 1)$-tuple of elements of A may evidently be chosen in the following manner: In the first step, we choose an arbitrary element $a_1 \in A$, $a_1 \neq 1$; the elements $a_1, \ldots, a_{i-1}$ being already chosen, in the i-th step $(2 \leqq i \leqq r - 1)$ we choose an arbitrary element $a_i \in A$ not belonging to the group generated by the elements $a_1, \ldots, a_{i-1}$. In this way, just $n_1 = (p^r - 1)(p^r - p)\ldots(p^r - p^{r-2})$ distinct independent $(r - 1)$-tuples may be chosen. Analogously, we find that for each Np-subgroup of A, exactly $n_2 = (p^{r-1} - 1)(p^{r-1} - p)\ldots(p^{r-1} - p^{r-2})$ distinct independent $(r - 1)$-tuples may be chosen out of its elements. Thus, among the total of n_1 distinct independent $(r - 1)$-tuples made up of the elements of A, every n_2 of them generate the same Np-subgroup. The number of distinct Np-subgroups in A is therefore given by $n_1/n_2 = (p^r - 1)/(p - 1)$. The same number of (distinct) Np-subgroups will, as remarked above, exist in the group $G = A \otimes H$. The proof is hereby completed.

In the end of our note, let us mention two special cases of Theorem 1 which perhaps are of certain importance since they are concerned with the class of all, not explicitly normal, subgroups.

Corollary 1. *For the number $s_p(G)$ of subgroups of a given prime index, p, in an abelian group G of order n, the estimate (1) of Theorem 1 holds and is best possible.*

Corollary 2. *For the number $s_2(G)$ of subgroups of index 2 in a group G of order n, the inequality*

$$s_2(G) \leqq 2^r - 1$$

holds where r is the greatest integer such that $2^r \mid n$. This estimate is best possible.

Proof of Corollary 1 is obvious (the optimality is secured by Theorem 2 – just taking H abelian), proof of Corollary 2 follows from the well-known fact that in a group G, any subgroup A of index 2 is normal since (in usual notation) $G = A + x_1 A = A + A x_2 \Rightarrow x_1^{-1} A x_2 = A$.

References

[1] A. *Speiser:* Theorie der Gruppen von endlicher Ordnung, 2nd ed., Julius Springer Verlag, Berlin, 1927.

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