

Bounds for the Number of Generators of a Finite Group

Morris Newman

Institute for Basic Standards, National Bureau of Standards, Washington, D.C. 20234
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It is proved that if G is a finite group of order n , then the generator rank of G does not exceed the total number of primes dividing n and is equal to this number for infinitely many groups G .

Key Words: Bounds, elementary abelian groups, generator rank, Sylow subgroups.

Let G be a finite group of order n . By the *generator rank* of G (denoted by $r(G)$) we shall mean the smallest number of elements of G which generate G . In this note we shall give bounds for $r(G)$ in terms of the group order n , and also some relevant facts about p -groups.

Let the canonical decomposition of n into its prime power factors be

$$n = p_1^{e_1} p_2^{e_2} \cdots p_s^{e_s},$$

and define

$$\Omega(n) = \sum_{i=1}^s e_i,$$

so that $\Omega(n)$ is the total number of primes dividing n . Let G_i be any Sylow subgroup of G of order $p_i^{e_i}$, and suppose that C_i is a cyclic group of largest order $p_i^{f_i}$ contained in G_i , $1 \leq i \leq s$. Then we shall prove

THEOREM 1. *The function $r(G)$ satisfies*

$$r(G) \leq \sum_{i=1}^s (e_i - f_i + 1). \quad (1)$$

If G is the elementary abelian group of order p^e (p prime), then (1) becomes an equality.

A corollary of Theorem 1 is

COROLLARY 1. *The function $r(G)$ satisfies*

$$r(G) \leq \Omega(n). \quad (2)$$

If G contains an element of prime power order p^f with $f > 1$, then the inequality (2) is strict.

We note first that if N is a normal subgroup of G , then

$$r(G) \leq r(G/N) + r(N); \quad (3)$$

and if $H = \{H_1, H_2, \dots, H_t\}$ (the group generated by the subgroups H_1, H_2, \dots, H_t of G) then

$$r(G) \leq \sum_{i=1}^t r(H_i). \quad (4)$$

We first prove
LEMMA 1. *We have*

$$G = \{G_1, G_2, \dots, G_s\}, \quad (5)$$

where G_i is any Sylow subgroup of G of order $p_i^{e_i}$, $1 \leq i \leq s$.

PROOF. Put

$$H = \{G_1, G_2, \dots, G_s\}, \quad o(H) = m.$$

Since $H \supseteq G_i$, m must be divisible by $p_i^{e_i}$, $1 \leq i \leq s$. Since these are pairwise relatively prime, m must be divisible by their product. Hence m is divisible by n , which implies that $m = n$, $H = G$. This completes the proof.

Lemma 1 and (4) imply that

$$r(G) \leq \sum_{i=1}^s r(G_i). \quad (6)$$

We now prove
LEMMA 2. *We have*

$$r(G_i) \leq e_i - f_i + 1, \quad 1 \leq i \leq s, \quad (7)$$

where C_i is a cyclic group of largest order $p_i^{f_i}$ contained in G_i .

PROOF. By one of the Sylow theorems there is a chain of groups

$$G_i \supset H_1 \supset H_2 \supset \dots \supset H_{e_i-f_i-1} \supset C_i, \quad (8)$$

where H_k is of order $p_i^{e_i-k}$ ($1 \leq k \leq e_i - f_i - 1$), and each member of the chain is a normal subgroup of the one preceding it. Using (3) and noting that all the quotient groups in (8) are cyclic of order p_i , we find in succession that

$$\begin{aligned} r(G_i) &\leq 1 + r(H_1) \\ &\leq 2 + r(H_2) \\ &\quad \dots \\ &\leq e_i - f_i - 1 + r(H_{e_i-f_i-1}) \\ &\leq e_i - f_i + r(C_i) \\ &= e_i - f_i + 1. \end{aligned}$$

This completes the proof.

The first part of Theorem 1 now follows from Lemmas 1 and 2. The second part of Theorem 1 is clear, and Corollary 1 is an immediate consequence of Theorem 1.

We note that the weaker inequality

$$r(G) \leq \log n / \log 2$$

is immediate. For if g_1, g_2, \dots, g_r ($r = r(G)$) are generators of G , then the 2^r elements

$$g_1^{e_1} g_2^{e_2} \dots g_r^{e_r}$$

where each exponent is either 0 or 1, are distinct.

Notice that Corollary 1 implies that if G is of prime power order p^e , then

$$r(G) \leq e, \quad (9)$$

and the inequality (9) is strict unless every element of G is of order p .

On the other hand, if every element of G is of order p it does not necessarily mean that $r(G) = e$. For example the Burnside group

$$B(3, 2) = F_2 / F_2^3,$$

where F_2 is the free group on 2 generators and F_2^3 the fully invariant subgroup generated by the cubes of the elements of F_2 , is known to have order 3^3 (see [1],¹ p. 324). Thus $B(3, 2)$ is of generator rank 2, every element of $B(3, 2)$ is of order 3, but the order of $B(3, 2)$ is not 3^2 .

¹ Marshall Hall, Jr., The Theory of Groups (Macmillan, New York, 1959).

As was previously noted, the elementary abelian group of order p^e makes (9) an equality. In this connection we prove

THEOREM 2. *The only groups of prime power order p^e and generator rank e are the elementary abelian ones.*

PROOF. We proceed by induction on the exponent e . The result is certainly correct for $e=1$ and $e=2$. Assume the result correct for all exponents $< e$, and let G be any group of order p^e and generator rank e . As was previously noted, every element of G is of order p . Let g_1, g_2, \dots, g_e be a basis for G ;

$$G = \{g_1, g_2, \dots, g_e\}.$$

Then every element of G occurs precisely once among the p^e elements

$$g_1^{r_1} g_2^{r_2} \dots g_e^{r_e}, \quad 0 \leq r_i \leq p-1, \quad 1 \leq i \leq e.$$

For if two such elements are equal, say

$$g_1^{r_1} g_2^{r_2} \dots g_e^{r_e} = g_1^{s_1} g_2^{s_2} \dots g_e^{s_e},$$

then

$$g_1^{r_1-s_1} \in \{g_2, g_3, \dots, g_e\};$$

which is impossible unless $r_1=s_1$, since otherwise $(r_1-s_1, p)=1$ and it would follow that

$$g_1 \in \{g_2, g_3, \dots, g_e\}.$$

Repeating the argument we find in succession that $r_2=s_2, \dots, r_e=s_e$.

Now let G_i be the subgroup of G generated by $g_1, g_2, \dots, g_{i-1}, g_{i+1}, \dots, g_e$ ($1 \leq i \leq e$). Then the previous argument shows that $o(G_i) = p^{e-1}$, and furthermore $r(G_i) = e-1$. By the induction hypothesis, G_i is elementary abelian ($1 \leq i \leq e$). This certainly implies that G is abelian, since $e > 2$. But the only abelian group of order p^e in which every element is of order p is the elementary abelian group of that order. Hence the result follows for the exponent e , and the proof is concluded.

It is of course perfectly possible for $r(G)$ to remain bounded as $o(G)$ goes to infinity. For example the symmetric group S_m ($m \geq 3$), and any metacyclic group have generator rank 2.

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Publications of the National Bureau of Standards*

Selected Abstracts

Classification of normal subgroups of the modular group, M. Newman, *Trans. Am. Math. Soc.* **126**, No. 2, 267–277 (Feb. 1967). The normal subgroups of the classical modular group are studied, and theorems such as the following are proved:

(1) There are no normal subgroups of index $12q$, where q is a prime > 11 .

(2) There are exactly $1 + \binom{q}{3}$ normal subgroups of index $6q$, where q is a prime > 3 and $\binom{q}{3}$ is the Legendre symbol.

(3) If there is no normal subgroup of index μ and q is a prime $> \mu$, then there is no normal subgroup of index $q^k\mu$ for all $k \geq 0$.

Key Words: Modular group, normal subgroups, congruence groups, parabolic classes.

Note on normal subgroups of the modular group, L. Greenberg, *Proc. Am. Math. Soc.* **17**, No. 5 1195–1198 (Oct. 1966).

Let N be a normal subgroup of the modular group Γ , of index μ and parabolic class number t . It is shown that $\mu \leq 6t^4$. It follows immediately from this that there are only a finite number of normal subgroups with given parabolic class number. This is in sharp contrast to the case of non-normal subgroups. For it is known that for any integer $t \geq 1$, there are infinitely many subgroups of finite index with t parabolic classes. It is also shown that if p is a prime such that $p \equiv -1 \pmod{3}$, then there are no normal subgroups with p parabolic classes.

Key Words: Modular group, quotient surface, factor set, group extension, split extension, parabolic class number, level.

Comparison of three spin algebras employed in SU(6) theories, R. C. Casella, *Phys. Rev.* **147**, No. 4, 962–964 (July 29, 1966).

The Lipkin Meshkov W spin, Foldy Wouthuysen mean spin, and an algebra constructed from the four generators of the Wigner little group provide SU(2) algebras which can be imbedded in an SU(6) description of moving hadrons. It is shown that when acting on particle states obeying the Dirac equation, all three are identical. Differences occur with regard to behavior under charge conjugation. In particular, the FW spin acts on particles and anti-particles alike and, in the quark model does not lead to the LM spin flip between the vector and pseudoscalar mesons.

Key Words: Hadrons, little group, spin algebras, SU(6), W spin.

Fundamental polygons for Fuchsian groups, L. Greenberg, *J. Anal. Math.* **18**, 99–105 (1967).

It is proved that a certain class of fundamental polygons for finitely generated Fuchsian groups are finite-sided. This is already known for convex polygons. However, this paper gives a much shorter proof for a wider class of polygons.

Key Words: Fuchsian group, fundamental polygon, simple fundamental polygon, F -regular region, horocyclic region, hypercyclic region.

Fundamental polyhedra for Kleinian groups, L. Greenberg, *Ann. Math.* **84**, No. 3, 433–441 (Nov. 1966).

The following theorem is proved: Let Γ be a Kleinian group whose limit set contains at least two points. If Γ has a fundamental polyhedron (in hyperbolic 3-space) with a finite number of sides, then

the region of discontinuity in the complex plane cannot be connected and simply connected. From this, it follows that there exist finitely generated Kleinian groups which have no finite-sided fundamental polyhedron. This is in surprising contrast to the case of Fuchsian groups.

Key Words: Kleinian group, hyperbolic space, region of discontinuity, limit set, fundamental polyhedron, Euler characteristic.

On a theorem of Ahlfors and conjugate subgroups of Kleinian groups, L. Greenberg, *Am. J. Math.* **LXXXIX**, No. 1, 56–68 (Jan. 1967).

A gap in a theorem of L. Ahlfors is filled and a generalization of the problem is studied.

Key Words: Kleinian group, region of discontinuity, parabolic triangle group, Hilbert nullstellensatz, prime ideal, Fuchsian group, conjugate subgroups.

Representations of discrete groups, J. Lehner, *Proc. Symp. Pure Mathematics, California Institute of Technology, Pasadena, Calif., Nov. 21–22, 1963, Chapt. VIII, Theory of Numbers, pp. 203–208 (American Mathematical Society, Providence, Rhode Island, 1965).*

It is shown that certain properties of a class of finitely generated abstract groups known as F -groups are preserved when the F -group is imbedded in $SL(2, \text{reals})$ as a discrete matrix subgroup. Thus the abstract structure of the F -group determines to a certain extent the topological properties of the matrix group.

Key Words: Abstract groups, finitely generated abstract groups, F -groups, discrete matrix group, representations of discrete groups.

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Kinetics of crystallization in multicomponent systems: I. Binary mixtures of n -paraffins. J. I. Lauritzen, Jr., E. Passaglia, and E. A. DiMarzio.

Kinetics of crystallization in multicomponent systems: II. Chain-folded polymer crystals. J. I. Lauritzen, Jr., and E. Passaglia.

Infrared absorption spectra of 2-oxo-1,3-bis(phenylhydrazone) derivatives and related bis- and tris-phenylhydrazones. A. J. Fatiadi.

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