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ASYMPTOTIC PROPERTIES OF GROUP GENERATION

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Let G be a finite group, A and B two elements of G, which generate a subgroup L of order λ. We call an expression of the form $A^{\alpha_1}B^{\beta_1}A^{\alpha_2}\cdots B^{\beta_2}$ with $\alpha_i, \beta_i \geqq 0$ a word in A and B and $\sum_i(\alpha_i+\beta_i)$ the weight of the word. For any $g \in G$ define $f_m(g)$ as the number of words of weight m which are equal to g. Our purpose in this paper is to investigate the asymptotic dependence of $f_m(g)$ on m. Subject to some simple side conditions, it turns out that the elements of L all occur with relative equal frequency as m approaches infinity. We also have an estimate of the smallest weight for which all elements of L can be realized.

Now define the matrix F_m, whose rows and columns are indexed by the elements of G, for which the entry in the gth row and hth column is $f_m(g^{-1}h)$. By virtue of the obvious identity:

$$f_{m+n}(g) = \sum_{h \in G} f_m(h) f_n(h^{-1}g)$$

we have $F_{m+n} = F_m, F_n$, more particularly $F_m = F_1^m$. Note that F_1 is the sum of the permutation matrices of A and B in the regular representation in G.

The matrix $P = (1/2)F_1$ is doubly stochastic, and may be thought of as the matrix of transition probabilities of a Markov chain. In its study then, we take over the language of Markov chains as found in [1]. The irreducible sets of states are now easily described; they are the left cosets of L in G. A state is periodic if and only if the weights of all words equal to the identity have a greatest common divisor other than one. It is possible to have periodicity; if the symmetric group is generated by two odd permutations then all representations of the identity will have even weight.

Let us agree to call two generators A and B periodic of period d if the weights of all words in A and B equal to the identity have greatest common divisor $d > 1$. If $d = 1$, we will say A and B are aperiodic. (A simple way to insure aperiodicity is to have the periods of A and B relatively prime.)

THEOREM. *Let A and B be periodic of period d. Then the group*

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generated by A and B has a normal subgroup for which the factor group is cyclic of order d. Moreover, A and B both belong to a coset of the normal subgroup which generates the cyclic factor group.

Proof. Imagine the group generated by A and B presented in terms of the generators A and B and relations. Without loss of generality we may suppose that the exponents in all these relations are positive. Since the weight of every relation is a multiple of d, the mapping $A \to w, B \to w$, where w is a primitive dth root of unity is a homomorphism of the group onto a cyclic group of order d. The theorem follows.

The following converse is also clearly true; i.e., if A and B are both selected from the same coset of a proper normal subgroup for which the factor group is cyclic, then A and B are periodic.

As immediate consequences we have the following facts. A and B generating the symmetric group are periodic if and only if both odd, and then the period is 2. A and B generating a noncyclic simple group are aperiodic. Hence A and B generating an alternating group are aperiodic except for the alternating group on 4 letters. In that case (123) and (134) give a periodic generation of period 3.

We are now in a position to invoke the familiar statements about the limiting behavior of finite irreducible aperiodic doubly stochastic matrices.

Let M be the λ by λ matrix all of whose entries are $1/\lambda$. Then we have:

THEOREM. *Let aperiodic A and B belonging to G generate a subgroup L of order λ. Construct the matrix P as before, but ordering the indices sequentially within the left cosets of L in G. Then we have:*

$$\lim_{m\to\infty} P^m = \begin{bmatrix} M & & 0 \\ & M & \\ 0 & & M \end{bmatrix}$$

where the number of M blocks on the diagonal is the index of L in G. In particular if $L = G$, we have:

$$\lim P^m = M$$

An alternative statement is that the elements of the group generated *by aperiodic A and B are asymptotically equidistributed over the words of weight m.*

COROLLARY. *For some weight m (and all larger weights) the elements of the group generated by aperiodic A and B are all realized by words of weight m. (There are corresponding statements for periodic generation.)*

It is some interest to know the first m for which the above conclusion is true. Subsequently, we give a direct proof of the above corollary, which supplies us with an upper bound for the first such m.

It is known [2] that an irreducible doubly stochastic matrix has but a single real eigenvalue of absolute magnitude one, this clearly belonging to the eigenvector all of whose entries are one. So we have:

THEOREM. *A necessary and sufficient condition that A and B belonging to a group G shall generate all of G is that the associated matrix P shall have but a single eigenvalue one, and this with eigenvector* $[1, 1, \cdots, 1]$.

This last results admits a simple restatement in the group algebra of G over the complex numbers. For if $[v_g]$ is an eigenvector of eigenvalue one of the matrix P, we simply read in the group algebra:

$$\left(\sum_g v_g g\right)(A + B - 2I) = 0 .$$

Our conclusion above then says that essentially the only element R of the group algebra for which $R(A + B - 2I) = 0$ is $R \equiv \sum_g g$. For a semi-simple ring, if the right ideal J_1 is properly contained in the right ideal J_2 then the left annihilator of J_1 properly contains the left annihilator of J_2. We conclude:

THEOREM. *A necessary and sufficient condition that A and B belonging to a group G shall generate all of G is that the right ideal generated by* $A + B - 2I$ *in the group algebra of G over the complex numbers consists of all elements of the group algebra whose coefficient sum is zero.*

Let now aperiodic A and B generate a group G of order λ. Let the minimum of the periods of A and B be p. We now prove directly that every element of g is realized by a word of weight $(\lambda - 2)p + 1$. To this end, note first that the number of distinct group elements realized by words of weight m is a nondecreasing function of m. Let $g_1, g_2, \cdots, g_k$ be the distinct group elements of weight m. To say that the number of distinct group elements of weight $m+1$ is still k means that the sets $\{g_iA\}$ and $\{g_jB\}$ are the same, or put another way that the set $\{g_i\}$ and $\{g_jBA^{-1}\}$ are the same. To say that the number of distinct group elements of weight $m+v$ is still k means more generally that the sets $\{g_i\}, \{g_iBA^{-1}\}, \{g_iB^2A^{-2}\}, \cdots, \{g_iB^vA^{-v}\}$ are all the same, or put another way, that the set $\{g_i\}$ is invariant under multiplication on the right by any element of the group H generated by $\alpha_1 = BA^{-1}, \alpha_2 = B^2A^{-2}, \cdots,$ and $\alpha_v = B^vA^{-v}$. Put $v =$ period of A. Then $\alpha_v = B^v$ and $\alpha_{v+b} = \alpha_v\alpha_b$ so that the group H generated by $\alpha_1, \alpha_2, \cdots, \alpha_v$ includes all elements of the form B^uA^{-u}. Furthermore:

$$A\alpha_u A^{-1} = \alpha_1^{-1}\alpha_{u+1}$$
$$B\alpha_u B^{-1} = \alpha_{u+1}\alpha_1^{-1}$$

so that the group H is normal in G.

Again, since $\alpha_1 = BA^{-1} \in H$, we have that A and B belong to the same coset of H in G. And finally any element of G, written in terms of A and B, may be reduced modulo H to a power of A. Thus the factor group of G by H is cyclic. Since A and B are aperiodic we are forced to conclude that $H = G$. All of which implies of course that either $k = \lambda$ or there are more distinct group elements of weight $m+v$ than of weight m. Since the situation is symmetric in A and B we may assume that $v =$ period of $A = P =$ minimum of the periods of A and B. Starting then with the two distinct group elements of weight one, there are at least 3 distinct group elements of weight $P+1$, 4 of weight $2P+1$, and finally at least λ of weight $(\lambda-2)P+1$. We have proved:

THEOREM. *Every element in the group G of order λ generated by aperiodic A and B is realized by a word of weight $(\lambda-2)P+1$, where P is the minimum of the periods of A and B.*

REFERENCES

1. W. Feller, *Probability Theory and its Applications*, Wiley, 1957.
2. F. R. Gantmacher, *Applications of the Theory of Matrices*, Interscience, 1959.

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