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Donald W. Miller
University of Nebraska - Lincoln

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ON A THEOREM OF HÖLDER

DONALD W. MILLER, University of Wisconsin and University of Nebraska

1. Introduction. A well-known result, due to Hölder [1], is the following: The symmetric group S_n has outer automorphisms if and only if $n=6$. The classical proof of the existence of a class of outer automorphisms of S_6, as formulated by Burnside [2], rests in part on the theory of primitive groups and entails extensive computation. In this note we offer a direct method for constructing such automorphisms.

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2. Construction of an outer automorphism of S_6. Let S_6 be defined on the set $M=\{1, 2, 3, 4, 5, 6\}$; let I denote the identity of S_6. Call two elements of S_6 *disjoint* if no element of M is displaced by both of them.

Define the mapping ψ by: $(1\ 2)\psi=(1\ 2)(3\ 6)(4\ 5)=P_2$, $(1\ 3)\psi=(1\ 3)(2\ 4)(5\ 6)=P_3$, $(1\ 4)\psi=(1\ 4)(2\ 6)(3\ 5)=P_4$, $(1\ 5)\psi=(1\ 5)(2\ 3)(4\ 6)=P_5$, $(1\ 6)\psi=(1\ 6)(2\ 5)(3\ 4)=P_6$. Write $N=\{2, 3, 4, 5, 6\}$, $\mathcal{P}=\{P_i \mid i\in N\}$. Note that the elements of $\mathcal{P}$ include as factors the 15 distinct transpositions of S_6; consequently $\mathcal{P}$ is transitive on M. Moreover, for $i, j, k\in M$, $i\neq j$,

$$P_i^2 = I, \qquad kP_i \neq kP_j, \qquad iP_j \neq i.$$

Note that $iP_j=jP_i$ implies $i=j$. For if $iP_j=jP_i=k$ then $P_i=(1\ i)(j\ k)(r\ s)$, $P_j=(1\ j)(i\ k)(r\ s)$, so $i=j$. Also, $P_iP_j=(i\ \ j\ \ jP_iP_j \cdots (1\ \ iP_j\ \ iP_jP_iP_j \cdots$. Hence $(jP_iP_j)P_iP_j$ equals i or 1. But in the latter case $jP_iP_j=1P_jP_i=jP_i$, whereas P_j fixes no element of M. Thus P_iP_j has order three, so $P_iP_jP_i=P_jP_iP_j$, all $i, j\in N$.

If i, j, k are distinct elements of N, then

$$iP_j = jP_k = kP_i \tag{1}$$

cannot hold. For, if so, write $iP_j=q$ and $N=\{i, j, k, q, r\}$. Now $q=fP_r$ for some f in M. Certainly f is not one of i, j, k, or q. But if $f=r$ then $q=rP_r=1$, contradicting $i\neq j$.

If P_i, P_j, P_k are distinct elements of $\mathcal{P}$, then

$$(P_iP_kP_j)P_i = P_j(P_iP_kP_j). \tag{2}$$

It is sufficient to prove that P_k commutes with $P_iP_jP_i$, for then $P_kP_iP_jP_i = P_iP_jP_iP_k$, $P_iP_kP_iP_jP_i = P_jP_iP_k$, $P_iP_kP_jP_iP_j = P_jP_iP_kP_jP_j$, $P_iP_kP_jP_i = P_jP_iP_kP_j$. Now

$$Q = P_iP_jP_i = P_jP_iP_j = (1\ \ iP_jP_i)(i\ \ jP_i)(j\ \ iP_j).$$

Each of the three transpositions of Q is a factor of some P_k, $k\neq i, j$. If Q should have two cycles in common with some P_t then $Q=P_t$. But in that case the displayed representation of Q would yield $iP_j=jP_t$, $iP_jP_i=t$ (so $iP_j=tP_i$), whence $tP_t=iP_j=jP_t$, contradicting (1). (Thus we can write $Q=(a\ b)(c\ d)(e\ f)$, $P_k=(a\ b)(c\ f)(d\ e)$. But then $QP_k=(c\ e)(d\ f)=P_kQ$.

If $A_1, \cdots, A_n, B, C$ are distinct elements of $\mathcal{P}$, then

$$B(CA_1 \cdots A_nB) = (CA_1 \cdots A_nB)C. \tag{3}$$

If $n=1$, (3) follows from (2). Assume inductively that (3) holds for n; then

$$\begin{aligned} &B(CA_1 \cdots A_nA_{n+1}B) \\ &= B(CA_1 \cdots A_nB)(BA_{n+1}B) \quad = \quad (CA_1 \cdots A_nBC)(A_{n+1}BA_{n+1}) \\ &= (CA_1 \cdots A_nA_{n+1})(A_{n+1}BCA_{n+1})BA_{n+1} = (CA_1 \cdots A_nA_{n+1})(BCA_{n+1}B)BA_{n+1} \\ &= (CA_1 \cdots A_nA_{n+1}B)C. \end{aligned}$$

Further, if $A_1, \cdots, A_n, B, C$ are distinct elements of $\mathcal{P}$, then

$$CB(A_1 \cdots A_n)B = B(A_1 \cdots A_n)BC. \tag{4}$$

For by (3), $CBA_1 \cdots A_nB = BC(BCA_1 \cdots A_nB) = BC(CA_1 \cdots A_nBC) = B(A_1 \cdots A_nBC)$.

Define the mapping θ as follows. Let $a_1, \cdots, a_n$ be distinct elements of N and write $(1\ a_i)\psi=A_i$. Then set

$$\begin{aligned} I\theta = I, \qquad (1a_1 \cdots a_n)\theta = A_1 \cdots A_n, \\ (a_1a_2 \cdots a_n)\theta = A_nA_1A_2 \cdots A_n, \qquad (QR)\theta = (Q\theta)(R\theta), \end{aligned} \tag{5}$$

where Q, R are arbitrary disjoint cycles of S_6. By (3),

$$(a_1a_2 \cdots a_n)\theta = A_1A_2 \cdots A_nA_1.$$

Clearly θ maps S_6 into itself.

To show that θ is single-valued it will be sufficient to establish that if $Q=(a_1 \cdots a_m)$, $R=(b_1 \cdots b_n)$ are arbitrary disjoint cycles in S_6, then

(i) $(QR)\theta=(RQ)\theta$;
(ii) $(a_1a_2 \cdots a_m)\theta=(a_2a_3 \cdots a_ma_1)\theta$.

If Q displaces 1 then $Q\theta$ is uniquely defined; if not, (ii) follows from (3). As to (i), suppose without loss of generality that R does not displace 1; then $R\theta$ is of the form $BA_1 \cdots A_nB$, so by successive applications of (4), $(QR)\theta=(Q\theta)(R\theta)=(R\theta)(Q\theta)=(RQ)\theta$.

For arbitrary elements Q, R of S_6, $(QR)\theta=(Q\theta)(R\theta)$. To prove this it is sufficient to consider the case where R is a transposition (since every element of S_6 is a product of transpositions). If Q and R are disjoint the asserted relation is trivial. Hence we write Q as a product of disjoint cycles and let Q' denote the product of those factors of Q which are not disjoint from R. We need to show that $(Q'R)\theta=(Q'\theta)(R\theta)$.

Let $1, e, f, a_1, \cdots, a_m, b_1, \cdots, b_n$ denote distinct elements of M.

(i) If $Q' = (1\ a_1 \cdots a_m)$, $R = (1\ b_1)$, then $(Q'\theta)(R\theta) = A_1 \cdots A_m B_1 = (1\ a_1 \cdots a_m\ b_1)\theta = (Q'R)\theta$.

(ii) If $Q' = (e\ a_1 \cdots a_m)$, $V = (e\ b_1 \cdots b_n)$, then $(Q'\theta)(V\theta) = (EA_1 \cdots A_m E) \cdot (EB_1 \cdots B_n E) = EA_1 \cdots A_m B_1 \cdots B_n E = (e\ a_1 \cdots a_m\ b_1 \cdots b_n)\theta = (Q'V)\theta$.

(iii) If $Q' = (1\ a_1 \cdots a_m\ e\ b_1 \cdots b_n)$, $R = (1\ e)$, with $m, n \geqq 0$, then $(Q'\theta)(R\theta) = A_1 \cdots A_m(EB_1 \cdots B_n E) = A_1 \cdots A_m B_n E B_1 \cdots B_n = [(1\ a_1 \cdots a_m) \cdot (e\ b_1 \cdots b_n)]\theta = (Q'R)\theta$.

(iv) If $Q' = (1\ a_1 \cdots a_m)(e\ b_1 \cdots b_n)$, $R = (1\ e)$, then $(Q'\theta)(R\theta) = A_1 \cdots A_m E B_1 \cdots B_n E E = A_1 \cdots A_m E B_1 \cdots B_n = (1\ a_1 \cdots a_m\ e\ b_1 \cdots b_n)\theta = (Q'R)\theta$.

(v) If $Q' = (e\ a_1 \cdots a_m\ f\ b_1 \cdots b_n)$, $R = (e\ f)$, with $m, n \geqq 0$, then by (4), $(Q'\theta)(R\theta) = (EA_1 \cdots A_m F B_1 \cdots B_n E)(EFE) = (EA_1 \cdots A_m)(FB_1 \cdots B_n F E) = (EA_1 \cdots A_m)(EFB_1 \cdots B_n F) = [(e\ a_1 \cdots a_m)(f\ b_1 \cdots b_n)]\theta = (Q'R)\theta$.

(vi) If $Q' = (e\ a_1 \cdots a_m)(f\ b_1 \cdots b_n) = Q_1' Q_2'$, $R = (e\ f)$, then, by (ii), $(Q'\theta)(R\theta) = (Q_1'\theta)(Q_2'\theta)(R\theta) = (Q_1' Q_2' R)\theta = (Q'R)\theta$.

θ is an automorphism of S_6. Indeed, the kernel, K, of θ is a normal subgroup of S_6, so K is one of S_6, A_6, $\{I\}$, where A_6 denotes the alternating group of degree 6. But $[(3\ 6)(4\ 5)]\theta = (3\ 6)(4\ 5)$, so $K \neq S_6$, $K \neq A_6$. Therefore $K = \{I\}$ so θ is 1-1 and hence an automorphism.

Finally, θ is outer since $(1\ 3\ 5)\theta = (1\ 2\ 6)(3\ 5\ 4)$, whereas if θ were inner it would map every conjugate class of S_6 onto itself. This completes the proof.

We observe in conclusion that *all* outer automorphisms of S_6 are obtainable with the aid of the above construction. Indeed, as shown by Hölder [1], the automorphism group of S_6 has order $1440 = 2(6!)$; thus the group, $\mathfrak{J}$, of inner automorphisms is of index 2 in the full automorphism group. Hence if θ is any outer automorphism of S_6 then the right coset $\mathfrak{J}\theta$ includes all outer automorphisms of S_6.

References

1. O. Hölder, Bildung zusammengesetzter Gruppen, Math. Ann., vol. 46, 1895, pp. 321–422.
2. W. Burnside, Theory of Groups of Finite Order, Cambridge, 1911.