SYLOW \( p \)-SUBGROUPS OF THE CLASSICAL GROUPS OVER FINITE FIELDS WITH CHARACTERISTIC PRIME TO \( p \)

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If \( S_n \) is a Sylow \( p \)-subgroup of the symmetric group of degree \( p^n \), then any group of order \( p^n \) may be imbedded in \( S_n \). We may express \( S_n \) as the complete product \( C \circ C \circ \cdots \circ C \) of \( n \) cyclic groups of order \( p \) and the purpose of this paper is to show that any Sylow \( p \)-subgroup of a classical group (see §1) over the finite field GF\( (q) \) with \( q \) elements, where \( (q, p) = 1 \), is expressible as a direct product of basic subgroups \( S_n \cong C \circ C \circ \cdots \circ C \) (\( n \) factors), where \( C \) is cyclic of order \( p^r \). (We assume always that \( p \neq 2 \).) Since \( C \) may be imbedded in \( S_r \), we see that \( S_n \) is imbedded in \( S_{n+r-1} \) in a particularly simple way. The above \( r \) is defined by the equation \( q^{*} - 1 = p^r \cdot \) where \( q^{*} \) is the first power of \( q \) which is congruent to 1 mod \( p \) and \( * \) denotes some unspecified number prime to \( p \). The case \( r = 1 \) is therefore of frequent occurrence, and then clearly \( S_n \cong S_n \).

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1. We shall refer to the following groups as the Classical Groups:

I. The general linear group \( GL(n, q) \) is the group of all nonsingular \( (n \times n) \) matrices with coefficients in \( GF(q) \). The order of \( GL(n, q) \) is

\[
q^{n(n-1)/2}(q - 1)(q^2 - 1) \cdots (q^n - 1).
\]

II. The symplectic group (Komplexgruppe) \( C(2m, q) \) is the group of all \( (2m \times 2m) \) matrices with coefficients in \( GF(q) \) which leave invariant a given nonsingular skew-symmetric form. For different choices of skew-symmetric form all the symplectic groups are isomorphic and their order is

\[
q^{m^2}(q^2 - 1)(q^4 - 1) \cdots (q^{2m} - 1).
\]

III. The unitary group \( U(n, q^2) \) is the group of all \( (n \times n) \) matrices with coefficients in \( GF(q^2) \) which leave invariant a given nonsingular Hermitian form. (Hermitian has its usual meaning if we write \( \bar{a} = a^q \))

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1 The notion of complete product is carefully discussed in [1] and a summary given in [2]. A discussion of the groups \( S_n \) in these terms will be found in [3].

2 See [4] and [5]. We use here the notation of [5].
in \( GF(q^2) \). Again there is essentially only one \( U(n, q^2) \). The order is

\[
q^n(a_n-1/2)(q + 1)(q^2 - 1)(q^3 + 1) \cdots (q^n - (-1)^n).
\]

IV. The orthogonal groups \( O_D(n, q) \) are the groups of all \( (n \times n) \) matrices with coefficients in \( GF(q) \) which leave invariant a given nonsingular quadratic form with discriminant \( D \). For \( n = 2m + 1 \) there is essentially only one \( O_D(n, q) \). The order is \( q^{m^2}(q^m - 1)(q^4 - 1) \cdots (q^{2m} - 1) \).

For \( n = 2m \), there are two types, \( O_1(n, q) \) and \( O_2(n, q) \), depending on whether or not \( D \) is a square in \( GF(q) \). The symbol \( \nu \) denotes a nonsquare in \( GF(q) \). Their orders are

\[
q^m(a_m-1/2)(q^2 - 1)(q^4 - 1) \cdots (q^{2m-2} - 1)(q^m - \sigma^m)
\]

where \( \epsilon = (-1)^{a-1/2} \) and \( \sigma = 1 \) for \( O_1 \), \( \sigma = -1 \) for \( O_2 \).

2. The general linear group. Let \( e \) be the least positive integer for which \( p \) divides \( q^e-1 \) and suppose that \( q^e = 1 + p^e \ast \) where \( \ast \) denotes some unspecified number prime to \( p \). It follows that

\[
q^{te} = 1 + t p^e \ast + C_t,2 p^{2e} \ast + \cdots \quad (t \text{ integer }>1).
\]

If \( t = p^e \ast \) where \( s \) is an integer \( >0 \),

\[
q^{te} = 1 + p^{e+s} \ast + C_t,2 p^{2e} \ast + \cdots.
\]

Now \( p \not= 2 \), so that \( C_t,2 \) is divisible by \( p^s \) and the subsequent terms are divisible by \( p^{e+s+1} \). Hence,

\[(1) \quad q^{te} = 1 + p^{e+s} \ast \quad \text{where} \quad t = p^s \ast. \quad \text{[True even if } s = 0].\]

Suppose \( n = e + ea \) \((0 \leq c < e)\) and \( a = a_0 + a_1 p + \cdots + a_e p^e \) \((0 \leq a_i < p)\). The factors of the order of \( GL(n, q) \) which are divisible by \( p \) are \( q^e-1, q^{2e}-1, \cdots, q^{ae}-1 \). The number of these factors which are divisible by \( p^{e+s} \) is \([a/p^s]\). (See (1).) Hence \( p \) divides the order of \( GL(n, q) \) \( N \) times where \( N = r a + [a/p] + [a/p^2] + \cdots \) i.e. \( N = r a + \sum_i a_i \mu_i(p) \) where \( \mu_i(p) = 1 + p + \cdots + p^{i-1} \).

In particular when \( n = e, e p, \cdots, e p^i \) we obtain \( N_0 = r, N_1 = r p + 1, \cdots, N_i = r p^i + \mu_i(p) \). If \( G_0, G_1, \cdots \) are the corresponding Sylow \( p \)-subgroups, \( N = \sum_i a_i N_i \) so the direct product \( \Pi = \prod_0^i G_i^a \) is a group of order \( n \) and degree \( \sum a_i e p^{i+1} = ea \). By introducing a diagonal block \( 1_e \) we imbed \( \Pi \) in a Sylow \( p \)-subgroup of \( GL(n, q) \).

Consider the Sylow \( p \)-subgroup \( G_0 \) of \( GL(e, q) \). We may regard \( GF(q^e) \) as a vector space of dimension \( e \) over the field \( GF(q) \) and so we can find a basis \( a_1, \cdots, a_e \). Given \( x \in GF(q^e) \) we define the matrix
(x_{ij}) by the equation \( x = \sum_j x_{ij}a_j \) and then the mapping \( x \rightarrow (x_{ij}) \) is an isomorphism of the multiplicative group of \( GF(q^e) \) into \( GL(e, q) \). Hence \( GL(e, q) \) contains a cyclic subgroup of order \( q^e - 1 = p^r \) and \( G_0 \) is therefore cyclic of order \( p^r \). We write \( \overline{C} = G_0 \).

If \( A, B \) are groups of permutation matrices of degrees \( m, n \) respectively and orders \( a, b \) respectively, then \( A \circ B \) is a group of permutation matrices of degree \( mn \) and order \( a^n b^b \).

We may define \( G_i \) inductively: \( G_0 = \overline{C}, G_1 = G_{i-1} \circ C \) for then \( G_i \) has order \( p^{N_i} \) and degree \( e^i \). In the special case \( r = 1 \), \( G_i \cong S_{e+1} \) and so we rename \( G_i = S_{e+1} \). In other words \( S_n \cong \overline{C} \circ C \circ \cdots \circ C \) (\( n \) factors).

3. The symplectic group. If \( e \) is even, the factors of the order of \( C(2m, q) \) which are divisible by \( p \) are again \( q^e - 1, q^{2e} - 1, \ldots \) and so a Sylow \( p \)-subgroup of \( C(2m, q) \) is already a Sylow \( p \)-subgroup of \( GL(2m, q) \).

If \( e \) is odd, the factors which are divisible by \( p \) are \( q^{2e} - 1, q^{4e} - 1, \ldots, q^{2be} - 1 \) where \( 2m = d + 2eb \) (\( 0 \leq d < 2e \)). Since \( p \neq 2 \), the number of these factors which are divisible by \( p^{r+1} \) is \( \lfloor b/p^r \rfloor \) and if \( b = b_0 + b_1 p + \cdots + b_r p^r \) (\( 0 \leq b_i < p \)) the order of a Sylow \( p \)-subgroup is \( p^M \) where \( M = rb + \sum b_i \mu_i(p) \). The particular values \( 2m = 2e, 2ep, \ldots \) again give Sylow \( p \)-subgroups \( G_0, G_1, \ldots \) of orders \( N_0, N_1, \ldots \) and a Sylow \( p \)-subgroup of \( C(2m, q) \) is of the form \( \Pi = \prod G_i^b \). [The matrix of the skew-symmetric form left invariant by \( \Pi \) is a diagonal sum of constituent blocks \( J_i \) belonging to the \( G_i \).]

We may again define the \( G_i \) inductively: \( G_i = G_{i-1} \circ C \). (The matrix \( J_i \) of \( G_i \) is the diagonal sum of \( p \) matrices \( J_{i-1} \).)

It remains to show that \( G_0 \) is cyclic. Consider the subgroup \( R \) of \( GL_{2e}(q) \) of all

\[
T = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}
\]

satisfying \( T^tJT = J \) where \( A, B \subseteq \overline{S}_1 \subseteq GL_e(q) \) and

\[
J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.
\]

The condition on \( A, B \) is \( A^tB = 1 \) so that \( R \) is isomorphic to \( \overline{S}_1 \) and is cyclic of order \( p^r \). Hence \( G_0 \) is cyclic of order \( p^r \).

If we write \( G_0 = \overline{C} \) (now of degree \( 2e \)), the Sylow \( p \)-subgroups of \( C(2m, q) \) may be expressed as direct products of \( \overline{S}_n \cong \overline{C} \circ C \circ \cdots \circ C \).

4. The unitary group. Suppose \( e \) is odd. If \( f \) is odd then \( q^f + 1 \) is

\[\text{[3, §2]. It is shown there that the operation } \circ \text{ is associative.}\]
prime to \( p \) (otherwise \( q^{t*} \equiv -1 \pmod{p} \) \( (p \neq 2) \)). The factors of the order of \( U(n, q^2) \) which are divisible by \( p \) are

\[
q^{2t} - 1, q^{4t} - 1, \ldots, q^{2te} - 1
\]

where \( n = d + 2eb \) \( (0 \leq d < 2e) \), and so in this case we are reduced to the same type of construction as in §3. \( G_0 \) is again of degree \( 2e \) and by using the matrix

\[
J = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}
\]

as above we verify that \( G_0 \) is cyclic of order \( p^r \).

Suppose \( e = 2e \). Now \( q^e = 1 + p^{2e} \) and \( q^e - 1 \) is prime to \( p \) (by the definition of \( e \)); hence \( q^e = -1 + p^{2e} \). If \( t \) is an integer greater than 1 then

\[
q^{te} = (-1)^t \left[ 1 - t^2 p^{2e} \right. + C_{1,2,3} p^{2e} \cdots ].
\]

There are two cases to consider:

(i) If \( e \) is odd, \( q^{t*} = (-1)^t = p^{t*} \) where \( t = p^{t*} \), and also \( q^{2te} - 1 = p^{t*} \) so that a Sylow \( p \)-subgroup of \( U(n, q^2) \) is already a Sylow \( p \)-subgroup of \( GL(n, q^2) \).

(ii) If \( e \) is even, the factors of the order of \( U(n, q^2) \) which are divisible by \( p \) are \( q^e - 1, q^{2e} - 1, \ldots, q^{ae} - 1 \) where \( n = c + ea \) \( (0 \leq c < e) \), and we may use the construction of §2.

With

\[
J = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}
\]

(of degree \( e \)),

we may verify that \( G_0 \) is cyclic of order \( p^r \).

5. The orthogonal groups. If \( e \) is even, a Sylow \( p \)-subgroup of \( O(2m+1, q) \) is already a Sylow \( p \)-subgroup of \( GL(2m+1, q) \).

If \( e \) is odd, we may use the construction of §3 and verify that \( G_0 \) is cyclic of order \( p^r \) using

\[
J = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

(of degree \( 2e + 1 \)).

If \( L \in O_D(n, q) \) then

\[
\begin{pmatrix} 1 & 0 \\ 0 & L \end{pmatrix} \in O_D(n + 1, q)
\]
and so we may imbed $O_D(n, q)$ in $O_D(n+1, q)$ in a natural way.

Consider $q^m+1, q^m-1$. One at least is prime to $p$, and their product is $q^{2m}-1$. In terms of the above imbedding a Sylow $p$-subgroup of $O_D(2m, q)$ is already a Sylow $p$-subgroup of $O_D(2m+1, q)$ or of $O_D(2m-1, q)$.

Finally we may sum up the results of §2—§5: The Sylow $p$-subgroups of the classical groups over $GF(q)$ ($q$ prime to $p$) are all expressible as direct products of the basic subgroups $S_n$$\cong C \circ C \circ \cdots \circ C$.

Bibliography

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