SOLVABILITY OF CERTAIN $p$-SOLVABLE LINEAR GROUPS
OF FINITE ORDER

DAVID LAWRENCE WINTER
SOLVABILITY OF CERTAIN $p$-SOLVABLE LINEAR GROUPS OF FINITE ORDER

DAVID L. WINTER

Let $p$ be an odd prime. Let $G$ be a finite $p$-solvable group which does not have a normal $p$-Sylow subgroup. Let $G$ have a faithful, irreducible representation of degree $n$ over the complex number field. It is proved that if $n = p - 1$, $p$ or $p + 1$, $G$ is solvable.

Until now most of the general structure theorems on finite linear groups of degree $n$ over the complex field have been limited to the case $n < p - 1$ where $p$ is a prime divisor of the group order (for example, [5], [8], [3], [4]). In order to obtain suitable results for $n \geq p - 1$, it is necessary (as it was for $n < p - 1$) to first have results for the class of $p$-solvable linear groups. Such results are obtained here for $n = p - 1$, $p$ and $p + 1$ in §'s 3, 4 and 5, respectively.

2. Notation and preliminary results. All groups considered are of finite order. All group representations occurring are representations by linear transformations over the complex numbers and all characters mentioned are characters of such representations. $p$ will always denote a fixed odd prime. A group is called $p$-closed if it has a normal $p$-Sylow subgroup and $p$-nilpotent if it has a normal $p$-complement. $Z(H)$ denotes the center of the group $H$. $Z$ will sometimes be used in place of $Z(G)$.

The following easily verified result is referred to as the Frattini argument.

2.1. If $H$ is a normal subgroup of $G$ and $P$ is a Sylow $p$-subgroup of $H$, then $G = N(P)H$.

2.2. ([7], p. 253) If the Sylow $p$-subgroup $P$ of $G$ is abelian, then the maximal $p$-factor group of $G$ is isomorphic to $P \cap Z(N(P))$.

2.3. Let $G$ be a $p$-solvable group which has a Sylow $p$-subgroup $P$ of order $p$. If $P$ is self-centralizing, then $G$ is solvable.

Indeed, by $p$-solvability $PO_p(G) \triangleleft G$ and by the Frattini argument $G = N(P)O_p(G)$. Because $P$ acts fixed-point-free on $O_p(G)$, the latter group is nilpotent by a result of Thompson and (2.3) follows.
The following statement is an immediate consequence of Schur's lemma.

2.4. Let $X$ be a faithful representation over the field of complex numbers of the finite group $G$. If $H$ is a subgroup of $G$ such that $X|H$ is irreducible, then $C(H) \subseteq Z(G)$.

2.5. ([10], (2.1)) Let $p$ be an odd prime and let $G$ be a finite $p$-solvable group. Suppose $G$ has a faithful representation $X$ over the complex number field all of whose irreducible constituents have degree not exceeding $p - 1$. Then $G$ is $p$-closed unless $p$ is a Fermat prime and $X$ has an irreducible constituent of degree $p - 1$.

We omit the proof of the following elementary result.

2.6. Let $H$ be a normal subgroup of $G$ of prime index $p$. Let $\chi$ be an ordinary irreducible character of $G$ such that $\chi|H$ is reducible. Then $\chi|H$ is a sum of $p$ distinct irreducible characters of $H$ which are conjugate in $G$.

It will be convenient to have (*) denote the following set of conditions.

(*) Let $p$ be an odd prime and let $G$ be a finite $p$-solvable group with $p$-Sylow subgroup $P$ which is not normal in $G$. Let $G$ have a faithful, irreducible representation $X$ of degree $n$ over the complex number field with character $\chi$.

3. In this section we prove

**Theorem 1.** If $G$ satisfies (*) and $n = p - 1$, then $p$ is a Fermat prime and $G/Z$ has order $2^s p$ for some $s$. In particular, $G$ is solvable.

A preliminary step is needed.

3.1. The conclusions of Theorem 1 hold if it is also assumed that $G = PN$ where $|P| = p$ and $N$ is a normal $p$-complement of $G$.

**Proof.** Let $B = C(P) \cap N$. We may assume $(\det \chi)(w) = 1$ for $w \in P$, multiplying $\chi$ by a suitable linear character of $G/N$ if necessary ([6], Th. 2). Then by ([10], (2.3)) $\chi|P \times B = \rho \Psi + \lambda$ or $\chi|P \times B = \rho \Psi - \lambda$ where $\Psi, \lambda$ are characters of $PB/P$ and $\rho$ is the character of the regular representation of $PB/B$. Since $\chi(1) = p - 1$, it is easily verified that the second case must occur and $\Psi = \lambda$ is a linear char-
Let $q$ be an odd prime divisor of $|N|$. Since $G$ is $p$-nilpotent, there is a $q$-Sylow subgroup $Q$ of $N$ normalized by $P$. Applying (2.5) to the odd order group $PQ$, we get that $Q \leq B = Z$. Thus $G/Z$ has order $2^s p$ for some $s$. Finally, $p$ is a Fermat prime by (2.5).

Now let $G$ be a counterexample to Theorem 1 of minimal order. Because $n < p$, $\chi|P$ is a sum of linear characters and $P$ is therefore abelian. Hence $P \leq C(O_p(G)) \lhd G$. If $C(O_p(G)) \neq G$, then $\chi|C(O_p(G))$ is reducible by (2.4). By (2.5) $C(O_p(G))$ is $p$-closed which implies $G$ is $p$-closed. This is a contradiction and therefore $O_p(G) \leq Z$. By [10], $|P: O_p(G)| = p$. Suppose $O_p(G) \neq \langle 1 \rangle$. From (2.2) it follows that $G$ has a normal subgroup $H$ of index $p$. If $H$ is not $p$-closed, then $\chi|H$ is irreducible by (2.5). Therefore $Z(H) \leq Z$ and we get a contradiction by applying the induction hypothesis to $H$. Therefore $H$ is $p$-closed and it follows that $H = O_p(G) \times N$ where $N$ is a normal $p$-complement of $G$. Since $O_p(G) \leq Z$, $\chi|O_p(G) = (p - 1)\lambda$ for some linear character $\lambda$ of $O_p(G)$. Let $\mu$ be a linear constituent of $\chi|p$. Then $\mu|O_p(G) = \lambda$. Consider $\mu$ as a linear character of $G/N$. Then $\mu \chi$ is a faithful irreducible character of $G/O_p(G)$ of degree $p - 1$. The induction hypothesis now yields a contradiction because $|\mu \chi| = |\chi|$ implies $Z(G/O_p(G)) = Z(G)/O_p(G)$. This proves that $O_p(G) = \langle 1 \rangle$ and $|P| = p$.

By $p$-solvability, $PO_p(G) \lhd G$ and by the Frattini argument $G = N(P)PO_p(G) = N(P)O_p(G)$. $N(P)$ normalizes the normal $p$-complement $V$ of $C(P)$ and therefore $V \leq O_p(G)$. Furthermore, $G/PO_p(G) \cong N(P)/C(P)$ is cyclic of order dividing $p - 1$. Since $p$ is a Fermat prime by (2.5), $|G: PO_p(G)|$ is a power of 2. Because $PO_p(G)$ is not $p$-closed, $\chi|PO_p(G)$ is irreducible by (2.5) and this implies $Z(PO_p(G)) \leq Z$. The proof of Theorem 1 is now completed by applying (3.1) to $PO_p(G)$.

4. The purpose of this section is to prove the following result.

**Theorem 2.** If $G$ satisfies (*) and $n = p$, then $G$ is solvable.

For the proof, assume Theorem 2 is false and let $G$ denote a counterexample of minimal order.

4.1. $G$ has a normal series $O_p(G) < N_1 < P_1 \leq G$ where $N_1/O_p(G) = O_p(G/O_p(G)), P_1/N_1 = O_p(G/N_1)$ has order $p$ and $|G: P_1|$ is relatively prime to $p$.

This is clear from the definitions and the fact that $|P: O_p(G)| = p$ by [10].
4.2. \( O_p(G) \not\leq Z \). In particular, \( O_p(G) \neq \langle 1 \rangle \).

Proof. Suppose \( \langle 1 \rangle \neq O_p(G) \leq Z \). Then \( P \) is abelian and by (2.2), \( G \) has a normal subgroup \( H \) of index \( p \). If \( H \) is not \( p \)-closed, \( \chi|H \) is irreducible by Clifford's theorem and (2.5) and then minimality of \( |G| \) yields a contradiction. Therefore \( H \) is \( p \)-closed and we must have \( H = O_p(G) \times N \) where \( N \) is a normal \( p \)-complement of \( G \). A contradiction can now be obtained by applying the induction hypothesis to \( G/O_p(G) \) as in the proof of Theorem 1.

Therefore if (4.2) is false, \( O_p(G) = \langle 1 \rangle \) and \( |P| = p \). In this case consider \( PO_p(G) \vartriangleleft G \). \( PO_p(G) \) cannot be \( p \)-closed and therefore, \( \chi|PO_p(G) \) is irreducible. This implies that \( \chi|O_p(G) \) is a sum of \( p \) distinct conjugate linear characters. Hence \( O_p(G) \) must be abelian. By the Frattini argument, \( G = N(P)PO_p(G) = N(P)O_p(G) \). Since \( |P| = p \), \( C(P) = P \times V \) for some group \( V \leq O_p(G) \). It follows that \( N(P) \) is solvable and hence \( G \) is solvable, proving (4.2).

4.3. \( X \) is primitive and \( O_p(G) \) is nonabelian.

Proof. If \( X \) is imprimitive, the underlying vector space is a direct sum of \( p \) subspaces of dimension 1 which are permuted transitively by the action of \( G \). If \( K \) is the normal subgroup of \( G \) stabilizing all the subspaces, then \( K \) is abelian and \( G/K \) is isomorphic to a subgroup of the symmetric group \( S_p \). Since \( P \) is not contained in \( K \), it follows from (2.3) that \( G/K \) is solvable. This implies that \( G \) is solvable, a contradiction. Therefore \( X \) is primitive.

If \( O_p(G) \) were abelian, primitivity of \( X \) would force \( O_p(G) \leq Z \), contrary to (4.2).

Since we are interested only in the solvability of \( G \), it may be assumed, by a method of Blichfeldt ([1], p. 14), that \( X \) is unimodular. Now a result of Brauer ([2], (5C)) yields that \( G/O_p(G) \cong SL(2, p) \). If \( p > 3 \), \( G \) is not \( p \)-solvable and if \( p = 3 \), \( G \) is solvable. These are contradictions and the proof of Theorem 2 is complete.

5. In this section the following theorem is proved.

Theorem 3. If \( G \) satisfies (*) and \( n = p + 1 \), then \( p \) is a Mersenne prime and \( G \) is solvable.

In the first step a special case is treated.

5.1. Let \( G \) be a finite 3-solvable group which has a faithful irreducible representation of degree \( n = 4 \) over the complex number
field. If $G$ is not 3-closed, then $G$ is solvable.

Proof. Let $q$ be a prime with $q \geq 11$. Then $(q - 1)/2 \geq 5 > n$ and so $G$ has a normal abelian $q$-Sylow subgroup by [5]. Suppose $G$ does not have a normal abelian 7-Sylow subgroup. Then by [8], $G/Z$ is isomorphic to $\text{PSL}(2, 7)$ or $A_7$ and so $G$ is not 3-solvable. Hence if $F$ is the maximal normal nilpotent subgroup of $G$, the only possible prime divisors of $|G:F|$ are 2, 3 and 5. Since $G/F$ is 3-solvable, it must be solvable and therefore $G$ is solvable.

Suppose Theorem 3 is false and let $G$ be a counterexample of minimal order. A contradiction is obtained after a series of steps. By [9] it is sufficient to prove that $G$ is solvable.

5.2. $X$ is a primitive representation of $G$.

Proof. Suppose $X$ is imprimitive. Let $V$ be the underlying vector space and let $V_1, \ldots, V_r$ be the subspaces which form a system of imprimitivity for $G$. Let $K$ be the normal subgroup of $G$ stabilizing all $V_i$. Then $G/K$ is isomorphic to a subgroup of $S_r$.

$\chi|K$ is a sum of $r$ constituents all of the same degree $(p + 1)/r$ which is less than $p - 1$ unless $p = 3$ and $r = 2$. By (5.1) the latter case does not occur. Therefore by (2.5), $K$ is $p$-closed and consequently $p|G:K|$ and $r > p$. It follows that $r = p + 1$. Therefore the dimension of each $V_i$ is 1, $\chi|K$ is a sum of linear characters and $K$ is abelian. $G/K$ is solvable by (2.3) and therefore $G$ is solvable.

5.3. It may be assumed that the following does not hold: $G = PN$ where $N$ is a normal $p$-complement of $G$ and $|P| = p$.

Assume on the contrary that $G = PN$ as in (5.3). A contradiction proving (5.3) is obtained after a number of steps. By a method of Blichfeldt ([1], p. 14) we may assume $\chi$ is unimodular for this proof.

5.3.1. Let $B = C(P) \cap N$. Then $\chi|P \times B = \rho \Psi + \lambda$ where $\Psi$ and $\lambda$ are linear characters of $PB/P$ and $\rho$ is the character of the regular representation of $PB/B$. $B$ is abelian.

Proof. By ([10], (2.3)), $\chi|P \times B = \rho \Psi + \lambda$ or $\chi|P \times B = \rho \Psi - \lambda$ where $\Psi$ and $\lambda$ are characters of $PB/P$ with $\lambda$ irreducible and $\rho$ is the character of the regular representation of $PB/B$. It is easily verified that the first case must occur and $\Psi$ and $\lambda$ are linear characters. Here we use the fact that $\chi|P \times B$ is a linear combination of irreducible characters of $P \times B$ with nonnegative coefficients and
p > 3 by (5.1). B is abelian because $\chi|B = p(\psi|B) + (\lambda|B)$ is a sum of linear characters.

5.3.2. G contains no proper normal subgroup of index prime to p.

Proof. Let $H$ be such a subgroup. Then $H$ cannot be $p$-closed. Therefore by Clifford’s theorem, (2.5) and (5.1), $\chi|H$ is irreducible. By minimality of $|G|$, $H$ is solvable and $p$ is a Mersenne prime. By the Frattini argument $G = N(P)H = (P \times B)H = BH$, $B$ being abelian implies that $G$ is solvable and (5.3.2) is proved.

5.3.3. Let $H$ be a subgroup of $G$ such that $\chi|H$ contains an irreducible constituent of degree $p$. Then $H \cap N$ is abelian.

Proof. By assumption $\chi|H = \chi_1 + \chi_2$ where $\chi_1$ is irreducible and $\chi_2$ is linear. Because $p \nmid |H \cap N|$, $\chi_i|H \cap N$ must be reducible and by (2.6), $\chi_i|H \cap N$ is a sum of linear characters. Therefore $\chi|H \cap N$ is a sum of linear characters implying $H \cap N$ is abelian.

5.3.4. Let $Q$ be a Sylow $q$-subgroup of $G$ for some prime $q \neq p$. Then $Q$ is not contained in $B$.

Proof. Suppose on the contrary that $Q \subseteq B$. Then $P \subseteq C(Q) \triangleleft N(Q)$. If $P \triangleleft N(Q)$, then $N(Q) \leq N(P) = P \times B$. This implies that $N(Q)$ is abelian and that $G$ has a normal $q$-complement by Burnside’s transfer theorem. This contradicts (5.3.2) and therefore $N(Q)$ and, consequently, $C(Q)$ are not $p$-closed.

By (2.5), $\chi|N(Q)$ contains an irreducible constituent $\chi_1$ of degree at least $p - 1$. If $\chi_1(1) = p$, $N(Q) \cap N$ is abelian by (5.3.3). By Burnside’s theorem, $N$ has a normal $q$-complement $N_1$ which is a characteristic subgroup of $N$. Therefore $N_1 \triangleleft G$ and $PN_1$ is a group. If $P \triangleleft PN_1$, then $N_1 \leq B$ and $N_1$ is therefore abelian. This yields that $G$ is solvable. Therefore $PN_1$ is not $p$-closed and $\chi|PN_1$ contains an irreducible constituent $\varphi$ of degree at least $p - 1$. If $\varphi(1) = p - 1$, then $\varphi|N_1$ is irreducible. This implies by Clifford’s theorem that $\chi|N_1$ is a sum of irreducible characters of degree $p - 1$. $\chi(1) = p + 1$ implies $p = 3$, a contradiction. If $\varphi(1) = p$, then $N_1$ is abelian by (5.3.3) and $G$ is solvable.

Suppose now that $\chi_1(1) = p - 1$ and at first that $\chi|N(Q) = \chi_1 + \chi_2$ where $\chi_2$ is irreducible. $N(Q) \neq C(Q)$ because $G$ does not have a normal $q$-complement. $\chi_1|C(Q)$ must be irreducible by (2.5) and (5.1), and therefore $\chi_2|C(Q) = \lambda_1 + \lambda_2$ where $\lambda_1$ and $\lambda_2$ are linear characters conjugate in $N(Q)$ which do not agree on $Q$. Indeed, otherwise we would
have \(|\chi_i(x)| = \chi_i(1), i = 1, 2\) for \(x \in Q\) and this would imply \(Q \leq Z(N(Q))\). However, by (5.3.1) \(\chi|Q\) contains at most two distinct characters. \(\chi_1|Q\) contains exactly one linear character because \(\chi_1|C(Q)\) is irreducible. Therefore \(\chi_1|Q = (p - 1)\lambda_i, i = 1\) or \(i = 2\). But this contradicts Clifford's theorem which states that \(\chi_1|Q\) must contain both \(\lambda_1\) and \(\lambda_2\).

Suppose now that \(\chi|N(Q) = \chi_1 + \chi_2 + \chi_3\) where \(\chi_1\) is irreducible of degree \(p - 1\) and \(\chi_2(1) = \chi_3(1) = 1\). By the complete reducibility of \(X|N(Q), Z(N(Q)) = \{x \in N(Q)|\chi_i(x) = p - 1\}\). By Theorem 1, \(P\) normalizes but does not centralize some Sylow 2-subgroup \(S\) of \(N(Q)\). Therefore by (2.5) \(\chi_1|S\) is irreducible. This yields that \(Z(S) \leq Z(PS) \leq B\). Let \(\mu\) be the linear character of \(Z(S)\) such that \(\chi_1|Z(S) = (p - 1)\mu\). By (5.3.1), \(\mu\) must have multiplicity at least \(p\) as a constituent of \(\chi|Z(S)\). Therefore \(\chi_i|Z(S) = \mu\) for \(i = 2\) or \(3\). It follows that \(S' \cap Z(S) = 1\) because \(S' \leq \ker \chi_2 \cap \ker \chi_3\) and \(\chi\) is faithful. This is possible only if \(S\) is abelian and \(\chi_1(1) = p - 1 = 1\), which is a contradiction.

The only remaining case is \(\chi|N(Q)\) irreducible. If this holds, \(\chi|Q\) is a sum of distinct (since \(N(Q) \neq C(Q)\)) linear characters each occurring with the same multiplicity. This is contradictory to (5.3.1) and (5.3.4) is proved.

5.3.5. \(p\) is a Mersenne prime and not a Fermat prime. Let \(q\) be any odd prime divisor of \(|N|\) and let \(Q\) be a Sylow \(q\)-subgroup of \(N\) normalized by \(P\). Then \(Q\) is abelian and \(\chi|N(Q)\) is irreducible.

Proof. By (5.3.4) \(PQ\) is not \(p\)-closed and by (2.5), \(\chi|PQ\) contains an irreducible constituent of degree at least \(p - 1\). \(PQ\) having odd order implies \(\chi|PQ\) must have an irreducible constituent of degree \(p\). By (5.3.3), \(Q\) is abelian and \(\chi|N(Q)\) must contain an irreducible constituent \(\chi_1\) of degree at least \(p\). If \(\chi_1(1) = p, N(Q) \cap N\) is abelian and we obtain a contradiction (as in the second paragraph of the proof of (5.3.4)). Therefore \(\chi|N(Q)\) is irreducible and \(\chi|Q\) is a sum of distinct (by (5.3.4)) linear characters. \(N(Q) \neq G\) for otherwise the primitivity of \(X\) would be contradicted. Minimality of \(|G|\) yields that \(p\) is a Mersenne prime. \(p\) is not also a Fermat prime since \(p \neq 3\).

5.3.6. Let \(q\) be an odd prime divisor of \(|N|\). Then \(q\) divides \(|B|\).

Proof. Let \(Q\) be a Sylow \(q\)-subgroup of \(G\) normalized by \(P\). By (5.3.4), \(PQ\) is not \(p\)-closed. Because \(PQ\) has odd order \(\chi|PQ = \chi_1 + \chi_2\) where the \(\chi_i\) are irreducible of degree \(p\) and \(1\), respectively. Let \(K\) be the kernel of \(\chi_2\). Then \(Q \not\leq K\) because by (5.3.5) and Clifford's theorem \(\chi|Q\) is the sum of conjugate characters and \(\chi\) is faithful.
Multiplying $\chi_2$ by a nonprincipal linear character of $PQ/Q$ if necessary, we may assume $P \cap K = \langle 1 \rangle$. Then $\chi_2$ is a faithful linear character of $PQ/K \cap Q$ and therefore this group is cyclic and $P$ centralizes $Q/K \cap Q$. It follows that $Q = (B \cap Q)(K \cap Q)$ ([6], Lemma 3 (c)), proving (5.3.6).

5.3.7. $B - Z$ is nonempty.

Proof. If $B = Z$, then $P$ acts fixed-point-free on $N/Z$ whence $N/Z$ is nilpotent by a result of Thompson. It follows that $G$ is solvable.

5.3.8. There exists $b \in B - Z$ such that $C(b)$ is not $p$-closed.

Proof. Suppose on the contrary that $C(b)$ is $p$-closed for all $b \in B - Z$. We shall show that $N/Z$ is a Frobenius group with complement $B/Z$. Let $\bar{G} = G/Z$ and let $\bar{H}, \bar{x}$ denote, respectively, the subgroup $HZ/Z$ and the element $Zx$ of $\bar{G}$ where $H \leq G$ and $x \in G$.

Let $\bar{y} \in \bar{B} \cap \bar{B}^x$, $y \in Z$, $x \in N$. Then $y$ and $y^{x^{-1}}$ are in $B$. Therefore $P$ and $P^x$ are in $C(y)$. By assumption, $P = P^x$, so $x \in N(P) \cap N = B$ and therefore $x \in \bar{B}$. Therefore $\bar{N}$ is a Frobenius group with abelian complement $\bar{B}$. Consequently, $\bar{N}$ is solvable and it follows that $G$ is solvable.

5.3.9. For all $b \in B - Z$, $C(b) \cap N = C(B) \cap N$ and this group is abelian.

Proof. By the preceding step there exists $b_1 \in B - Z$ such that $C(b_1)$ is not $p$-closed. $\chi | C(b_1)$ is reducible because $b_1 \notin Z$ and $\chi | C(b_1)$ contains an irreducible constituent $\chi_1$ of degree $p - 1$ or $p$ because $C(b_1)$ is not $p$-closed. By (2.5), $\chi_1(1) = p$ because $p$ is not a Fermat prime. By (5.3.3), $C(b_1) \cap N$ is abelian. Because $B \leq C(b_1) \cap N$, $C(b_1) \cap N \leq C(B) \cap N$ and therefore $C(b_1) \cap N = C(B) \cap N$ and $C(b_1) = C(B)$. Thus $C(B)$ is not $p$-closed. If $b \in B - Z$, $C(B) \leq C(b)$ and $C(b)$ cannot be $p$-closed. Repeating the argument, we have $C(b) \cap N = C(B) \cap N$ as desired.

From (5.3.5), (5.3.6) and (5.3.9), we get

5.3.10. $|N : C(B) \cap N|$ is a power of $2$.

Let $q$ be an odd prime divisor of $|N|$. Because $C(B)$ is $p$-nilpotent, there is a $q$-Sylow subgroup $Q$ of $C(B)$ normalized by $P$. By (5.3.4),
PQ is not $p$-closed. Since $PQ$ has odd order, it follows from (2.5) that $\chi|PQ$ contains an irreducible constituent $\chi_1$ of degree $p$. By (2.6), $\chi_1|Q$ is a sum of distinct linear characters. Therefore $\chi|Q$ is a sum of $p + 1$ distinct linear characters because $\chi|N(Q)$ is an irreducible by (5.3.5) and Clifford’s theorem may be applied. By a result of Brauer ([2], (3F)) $C(Q)/Z$ is a $(2, q)$-group. By unimodularity of $X$, $|Z||(p + 1)$. Since $p$ is a Mersenne prime $Z$ is a 2-group and therefore $C(Q)$ is a $(2, q)$-group. $C(B) \cap N \leq C(Q)$ because $C(B) \cap N$ is abelian. Therefore by (5.3.10), 2 and $q$ are the only prime divisors of $|N|$. It follows that $N$ and therefore $G$ are solvable. This completes the proof of (5.3).

5.4. $O_p(G) \leq Z(G)$.

Proof. By [10], $|P: O_p(G)| = p$. Assume (5.4) does not hold. As in the proof of (4.2), it can be shown that $|P| = p, O_p(G) = \langle 1 \rangle$. Because $PO_p(G) \not< G, PO_p(G)$ is not $p$-closed and $\chi|PO_p(G)$ is irreducible by (2.5) and (5.1). Let $C(P) = P \times V$. Then $\chi|PVO_p(G)$ is also irreducible. Therefore $PVO_p(G)$ is solvable by either (5.3) or minimality of $|G|$. Because $N(P)/PV$ is cyclic, $N(P)$ is solvable. But by the Frattini argument $G = N(P)PO_p(G)$ and therefore $G$ is solvable, proving (5.4).

Now a final contradiction can be obtained. $\chi|O_p(G)$ must be a sum of $p + 1$ linear characters. If they are all equal, (5.4) is contradicted. If they are not all equal, $X$ is imprimitive contradicting (5.2).

REFERENCES

1. H. F. Blichfeldt, Finite collineation groups, Univ. of Chicago, Chicago, Ill., 1917.
5. W. Feit and J. G. Thompson, On groups which have a faithful representation of degree less than $(p - 1)/2$, Pacific J. Math. 11 (1961), 1257–1262.
10. ———, p-solvable linear groups of finite order (to appear)

Received January 7, 1970.

MICHIGAN STATE UNIVERSITY
PACIFIC JOURNAL OF MATHEMATICS

EDITORS

H. SAMELSON
Stanford University
Stanford, California 94305

RICHARD PIERCE
University of Washington
Seattle, Washington 98105

J. DUGUNDJI
Department of Mathematics
University of Southern California
Los Angeles, California 90007

RICHARD ARENS
University of California
Los Angeles, California 90024

ASSOCIATE EDITORS

E. F. BECKENBACH
B. H. NEUMANN
F. WOLE
K. YOSHIDA

SUPPORTING INSTITUTIONS

UNIVERSITY OF BRITISH COLUMBIA
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA
MONTANA STATE UNIVERSITY
UNIVERSITY OF NEVADA
NEW MEXICO STATE UNIVERSITY
OREGON STATE UNIVERSITY
UNIVERSITY OF OREGON
OSAKA UNIVERSITY
UNIVERSITY OF SOUTHERN CALIFORNIA

STANFORD UNIVERSITY
UNIVERSITY OF TOKYO
UNIVERSITY OF UTAH
WASHINGTON STATE UNIVERSITY
UNIVERSITY OF WASHINGTON
AMERICAN MATHEMATICAL SOCIETY
CHEVRON RESEARCH CORPORATION
TRW SYSTEMS
NAVAL WEAPONS CENTER

The Supporting Institutions listed above contribute to the cost of publication of this Journal, but they are not owners or publishers and have no responsibility for its content or policies.

Mathematical papers intended for publication in the Pacific Journal of Mathematics should be in typed form or offset-reproduced, (not dittoed), double spaced with large margins. Underline Greek letters in red, German in green, and script in blue. The first paragraph or two must be capable of being used separately as a synopsis of the entire paper. The editorial "we" must not be used in the synopsis, and items of the bibliography should not be cited there unless absolutely necessary, in which case they must be identified by author and Journal, rather than by item number. Manuscripts, in duplicate if possible, may be sent to any one of the four editors. Please classify according to the scheme of Math. Rev. Index to Vol. 39. All other communications to the editors should be addressed to the managing editor, Richard Arens, University of California, Los Angeles, California, 90024.

50 reprints are provided free for each article; additional copies may be obtained at cost in multiples of 50.

The Pacific Journal of Mathematics is published monthly. Effective with Volume 16 the price per volume (3 numbers) is $8.00; single issues, $3.00. Special price for current issues to individual faculty members of supporting institutions and to individual members of the American Mathematical Society: $4.00 per volume; single issues $1.50. Back numbers are available.

Subscriptions, orders for back numbers, and changes of address should be sent to Pacific Journal of Mathematics, 108 Highland Boulevard, Berkeley, California, 94708.

PUBLISHED BY PACIFIC JOURNAL OF MATHEMATICS, A NON-PROFIT CORPORATION

Printed at Kokusai Bunken Insatsusha (International Academic Printing Co., Ltd.), 7-17, Fujimi 2-chome, Chiyoda-ku, Tokyo, Japan.
Richard Hindman Bouldin, *The perturbation of the singular spectrum* ........... 569
Hugh D. Brunk and Søren Glud Johansen, *A generalized Radon-Nikodym derivative* ............................................................... 585
Esmond Ernest Devun, *Special semigroups on the two-cell* ..................... 639
Murray Eisenberg and James Howard Hedlund, *Expansive automorphisms of Banach spaces* .................................................. 647
Frances F. Gulick, *Actions of functions in Banach algebras* ...................... 657
Douglas Harris, *Regular-closed spaces and proximities* ......................... 675
Norman Lloyd Johnson, *Derivable semi-translation planes* ...................... 687
Donald E. Knuth, *Permutations, matrices, and generalized Young tableaux* ..................................................................................... 709
Herbert Frederick Kreimer, Jr., *On the Galois theory of separable algebras* ................................................................................. 729
You-Feng Lin and David Alon Rose, *Ascoli’s theorem for spaces of multifunctions* ................................................................. 741
David London, *Rearrangement inequalities involving convex functions* .... 749
Louis Pigno, *A multiplier theorem* ........................................................ 755
Helga Schirmer, *Coincidences and fixed points of multifunctions into trees* ...................................................................................... 759
Richard A. Scoville, *Some measure algebras on the integers* ................. 769
Ralph Edwin Showalter, *Local regularity of solutions of Sobolev-Galpern partial differential equations* ..................................... 781
Allan John Sieradski, *Twisted self-homotopy equivalences* ...................... 789
John H. Smith, *On S-units almost generated by S-units of subfields* ....... 803
Masamichi Takesaki, *Algebraic equivalence of locally normal representations* ....................................................................................... 807
Joseph Earl Valentine, *An analogue of Ptolemy’s theorem and its converse in hyperbolic geometry* ............................................. 817
David Lawrence Winter, *Solvability of certain p-solvable linear groups of finite order* ................................................................. 827