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Finite Groups with Few Conjugacy Classes of Subgroups.

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Introduction.

Let (X, \leq) be a finite partially ordered set (poset). A subset A of X is called an *antichain* if no two distinct elements of A are comparable with respect to the order of X . Thus if $x, y \in A$ and $x \leq y$ then $x = y$. Such a subset intersects every chain of X in one element at most. The Dilworth number $D(X)$ is a nonnegative integer defined to be the maximum taken over all cardinalities of antichains in X . As we will consider finite posets, $D(X)$ is a positive integer.

In this note we consider the poset $C(G)$ of all conjugacy classes of subgroups of a finite group G . If H is a subgroup of G , the set $\{H^g \mid g \in G\}$ will be denoted by $[H]$. Thus $C(G) = \{[H] \mid H \leq G\}$. The ordering in $C(G)$ is defined by setting $[H] \leq [K]$ if H is contained in some conjugate of K . It is clear that $C(G)$ is a poset; however, in general, $C(G)$ need not be a lattice.

DEFINITION. The Dilworth number $D(C(G))$ of the poset $C(G)$ will be denoted by $w_C(G)$. If it is clear which poset is meant, we shall write $w_C(G)$.

It is easy to see that $w_C(G) = 1$ implies that G is a cyclic p -group for some prime p , and, in general, groups G with $w_C(G) \leq n$ for a fixed n , seem to have a rather restricted structure. For example, in [1] it was shown that although all 2-groups G of maximal class satisfy $w_C(G) = 3$, for every $n \geq 4$ there are only finitely many p -groups G with $w_C(G) =$

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$= n$. This may be compared with a similar result of Landau (see [6]) on groups with a given number of conjugacy classes of elements.

Here, we are interested in arbitrary finite groups G . Clearly, the set of conjugacy classes of Sylow subgroups for all primes forms an antichain in $C(G)$, and hence we have $w_C(G) \geq |\Pi(G)|$, where $\Pi(G)$ denotes the set of all primes dividing the order of G . In this paper we give a characterization of groups for which the aforementioned inequality becomes an equality.

During the proofs, we frequently need to consider the poset of the conjugacy classes of subgroups of G contained in a fixed subgroup H of G . The corresponding Dilworth number will be denoted by $w_{C(G)}(H)$. Thus $w_{C(G)}(G) = w_C(G)$. The case when H is a Sylow p -subgroup is crucial and we determine the possibilities when $w_{C(G)}(H) = 1$ (see Theorem 3). This may be of interest in the theory of defect groups in modular representation theory.

Results.

First we give some simple upper bounds for $w_C(G)$. Let \mathfrak{a} be any antichain in $C(G)$, let $\nu(\mathfrak{a})$ be the maximal number of subgroups of G such that no one of them is isomorphic to a subgroup of any other and whose conjugacy classes are belonging to \mathfrak{a} . Let then $\nu(G) = \max\{\nu(\mathfrak{a}) \mid \mathfrak{a} \text{ antichain of } C(G)\}$. The following is obvious:

LEMMA 1. Let G be a finite group. We have:

- a) $w_C(G) \geq |\Pi(G)|$.
- b) If $H \triangleleft G$ then $w_C(G) \geq w_{C(G/H)}(G/H)$.
- c) If H is a nontrivial complemented normal subgroup of G , then $w_C(G) \geq w_{C(G/H)}(G/H) + w_{C(G)}(H)$.
- d) For every subgroup M and for every quotient G/H of G we have $w_C(G) \geq \nu(M)$ and $w_C(G) \geq \nu(G/H)$.

COROLLARY 2. Let G be a finite soluble group and let $f(G)$ be the Fitting length of G . Then $f(G) \leq w_C(G)$.

PROOF. By induction on $f(G)$. The result is true if G is nilpotent. Since $F(G)/\Phi(G)$ is complemented in $G/\Phi(G)$, we have:

$$\begin{aligned} w_C(G) &\geq w_{C(G/\Phi(G))}(G/\Phi(G)) \geq \\ &\geq w_{C(G/F(G))}(G/F(G)) + w_{C(G/\Phi(G))}(F(G)/\Phi(G)) \geq f(G/F(G)) + 1 = f(G). \end{aligned}$$

Our aim is now the classification of groups G such that $w_C(G) = |\Pi(G)|$. Before answering this question, we examine the case of a group G containing a Sylow subgroup P such that $w_{C(G)}(P) = 1$, by classifying these subgroups P and showing their existence by examples.

THEOREM 3. Let G be a finite group and P a Sylow p -subgroup of G such that $w_{C(G)}(P) = 1$. Then one of the following holds:

- 1) P is cyclic.
- 2) P is a quaternion group of order 8.
- 3) P is elementary abelian of order $p^2, p^3, 2^5$.
- 4) G is not p -soluble and P is extraspecial of order p^3 and exponent p .

PROOF. Certainly the subgroups of P of the same order must be isomorphic. If $\exp P \geq p^2$ then the subgroups of order p^2 are cyclic, therefore by [5], p. 311, we have that P is cyclic or generalized quaternion. But in the last case, if $|P| > 8$ then P would have two nonisomorphic subgroups of order 8, the first one being cyclic and the other one isomorphic to Q_8 , so $|P| = 8$.

If $\exp P = p$ and if P is elementary abelian of order p^n , then two subgroups of P are conjugate in G if and only if they are conjugate in $N_G(P)$ ([5], pag. 418, Lemma 2.5 (a theorem of Burnside)), so we may assume that P is normal in G . Then for every k , our group G acts transitively on the subgroups of order p^k of P . Therefore if $n > 3$, a theorem of Cameron & Kantor (see [2]) yields that, if p is odd, G/P contains $SL(n, p)$ and, if $p = 2$, then $|P| = 2^4$ and G/P is isomorphic to A_7 , or $|P| = 2^5$ and G/P is isomorphic to $\Gamma L(1, 2^5)$. But p divides $|SL(n, p)|$ and 2 divides $|A_7|$, so that in these two cases, P is not a Sylow p -subgroup of G . Thus $|P| = p^2, p^3$ or 2^5 .

Finally, if P is nonabelian of exponent p , then P contains a subgroup, which is extraspecial of order p^3 (to see this, let $x \in Z_2(P) \setminus Z(P)$ and $y \in P$ such that $[x, y] \neq 1$. Then $\langle x, y \rangle$ has the property, since $[[x, y], x] = [[x, y], y] = x^p = y^p = [x, y]^p = 1$). It follows that the maximal order of an abelian normal subgroup of P is p^2 . Let A be one of them. Then $|\text{Aut}(A)| = p(p-1)^2(p+1)$ and $A = C_P(A)$ and hence it follows that P/A has order p at most, therefore $|P| = p^3$. But in this case there cannot exist a normal subgroup H in G whose Sylow p -subgroup is nontrivial and has order $< p^3$, because otherwise P would contain at least two conjugacy classes of subgroups of order p . Thus G is not p -soluble.

EXAMPLES. In Case 2) we have for example $G = SL(2, 3)$.

In Case 3), when $|P| = p^k$, $k = 2, 3$, we can choose the semi-direct product of the additive group by the multiplicative group of the field $GF(p^k)$; if $|P| = 2^5$ we can take the relative holomorph of P by $\Gamma L(1, 2^5)$.

Finally, in Case 4), for $p = 5$, there is the Thompson simple group G , whose Sylow 5-subgroups are of the required type (see [7]). Moreover, we show that all subgroups of order 5 (respectively 25) are conjugate. Using the notation of [7], let z be an involution of G , $H = C_G(z)$, $b \in H$, $|b| = 5$, $B = \langle b \rangle$. Then by [7], (5.2), $P = O_5(C_G(b))$ is a Sylow 5-subgroup of G , $B = Z(P)$, and P is normal in $N_G(B)$. Moreover, G contains one class of elements of order 5 and an element $b_1 \in P \setminus B$ has 120 conjugates in P under the action of $N_G(B)$. Thus all subgroups of order 5 and 25 of P are conjugate in G and we have $w_{C(G)}(P) = 1$.

Returning to our classification, we observe that if $w_C(G) = |\Pi(G)|$, $p \in \Pi(G)$ and P is a Sylow p -subgroup of G then $w_{C(G)}(P) = 1$, so P is as in Theorem 3. Moreover, we have:

LEMMA 4. If G is a finite group such that $w_C(G) = |\Pi(G)|$ then:

a) if $M \leq G$ then $\nu(M) \leq |\Pi(M)|$.

b) If H is a proper normal soluble subgroup of G , then $w_{C(G/H)}(G/H) = |\Pi(G/H)|$.

c) If $1 \neq H \triangleleft G$ and p is a prime divisor of both $|H|$ and $[G:H]$, then the Sylow p -subgroups of G are cyclic or quaternion groups.

PROOF. a) If $\nu(M) > |\Pi(M)|$, then

$$w_C(G) \geq \nu(M) + |\Pi(G) \setminus \Pi(M)| > |\Pi(G)|.$$

b) Let $H \triangleleft G$. First assume that H has a complement M in G : if \mathcal{C} is any antichain of G/H with $m = w_{C(G/H)}(G/H)$ elements and K_1, \dots, K_m are subgroups of M such that $[HK_i/H] \in \mathcal{C}$, then these subgroups are not conjugate in G . Let Π' be the set of all prime divisors of $|G|$ that are not divisors of $|G/H|$ and let $n = |\Pi'|$. For every $p_i \in \Pi'$ we consider a Sylow p_i -subgroup S_i of G . Then the set $\{[K_1], \dots, [K_m], [S_1], \dots, [S_n]\}$ is an antichain of $C(G)$, therefore in this case the assertion follows from:

$$w_C(G) \geq m + n = w_{C(G/H)}(G/H) + n \geq |\Pi(G/H)| + n = |\Pi(G)| = w_C(G).$$

Now assume that H is contained in $\Phi(G)$. Then:

$$|\Pi(G)| = |\Pi(G/H)| \leq w_{C(G/H)}(G/H) \leq w_C(G) = |\Pi(G)|,$$

and the assertion follows also in this case. Finally, let H be soluble and let P be a minimal normal subgroup of G contained in H . Then $P \leq \Phi(G)$ or P has a complement in G , therefore in every case $w_{C(G/P)} = |\Pi(G/P)|$. So the assertion follows by induction.

c) Let P be a Sylow p -subgroup of G . From $w_{C(G)}(P) = 1$ it follows that $P \cap H$ is the only subgroup of P of its order. Thus P is cyclic or a quaternion group.

Now we distinguish two subcases: G soluble and G non-soluble. Let $O(G)$ and $O'(G)$ be respectively the maximal normal subgroup of odd order and the minimal normal subgroup with odd quotient. For the non-soluble case, we need the following:

LEMMA 5. Let G be a finite group such that $w_C(G) = |\Pi(G)|$. Then:

a) If $G/O(G)$ is isomorphic to $PSL(2, 5)$ or to $SL(2, 5)$ then $O(G) = 1$.

b) If G contains a normal subgroup K isomorphic to $PSL(2, 5)$ then $K = G$.

PROOF. a) Let $G/O(G) \cong PSL(2, 5)$. As $O(G)$ is soluble, it has a subgroup H normal in G whose index in $O(G)$ is a power of an odd prime p . First let $p = 3$ or $p = 5$. The Sylow p -subgroups of G/H are cyclic, by Lemma 4c) so $C_{G/H}(O(G)/H)$ contains the Sylow p -subgroups of G/H , therefore it is equal to G/H . Thus $O(G)/H$ is in the center of G/H , but then for $p = 3$ and $p = 5$ respectively, G/H contains subgroups of order 4, 9, 5 and 6 and of order 4, 3, 25, 10, against Lemma 4. If $p > 5$ then p does not divide $|PSL(2, 5)|$. So $O(G)/H$ is the Sylow p -subgroup of G/H , and it must have order p , p^2 or p^3 . Trivially we do not have $PSL(2, 5)H/H \triangleleft G/H$, because otherwise G would contain subgroups of order $2p$, $3p$, $5p$, 4, 10, 6; a contradiction. It is well known that, in characteristic $p > 5$, $PSL(2, 5)$ has no faithful representations of degree < 3 , therefore $|O(G)/H| = p^3$. Then there are $p^2 + p + 1$ subgroups of order p , so if $x \in G/H$, $x^2 = 1$, then x must fix at least one of them. Thus in G/H there is also a subgroup of order $2p$, so $w_{C(G/H)}(G/H) \geq 5$, while $|\Pi(G/H)| = 4$, against Lemma 4. Thus $O(G) = 1$. We can use the same argument if $G/O(G)$ is isomorphic to $SL(2, 5)$.

b) Recall that $\text{Aut}(PSL(2, 5)) \cong \text{Aut}(A_5) \cong S_5$. Let p be a prime divisor of $|G/K|$. If $p = 2$ then G would contain the dihedral group of

order 8, against Lemma 2, or there would be an involution out of K , so in every case $w_C(G) \geq |\Pi(G)| + 1$. If p were odd, let $M \leq G$ such that $|M/K| = p$. If $p = 3$ then M would contain subgroups of order 4, 6, 10, 9, so in every case $\nu(M) > 3 = |\Pi(M)|$, against Lemma 4a). The same argument works if $p = 5$. Finally, if $p > 5$, we would have $M = PSL(2, 5) \times P$, with $|P| = p$ and $\nu(M) = 6 > 4 = |\Pi(M)|$, against Lemma 4a) again. Thus $K = G$.

THEOREM 6. Let G be a non-soluble group. Then $w_C(G) = |\Pi(G)|$ if and only if G is isomorphic to $PSL(2, 5)$ or to $SL(2, 5)$.

PROOF. If G is isomorphic to $PSL(2, 5)$ or $SL(2, 5)$, the direct examination of the poset of conjugacy classes of subgroups shows that $w_C(G) = 3 = |\Pi(G)|$. We prove that these two groups are the only non-soluble groups with this property. So let G be a non-soluble group such that $w_C(G) = |\Pi(G)|$. Then $|G|$ is even, so let P be a Sylow 2-subgroup of G . We know that $w_{C_G}(P) = 1$. As P is not cyclic, we have the following two cases:

1) P is elementary abelian. Here Walter's theorem (see [8]) tell us that the group $R = O'(G/O(G))$ is isomorphic to the direct product $A \times S_1 \times \dots \times S_t$, where A is abelian and the S_i are isomorphic to the first Janko group J_1 , or to a group $PSL(2, 2^k)$, or to $PSL(2, q)$, q an odd prime, or to a Ree group. But the Sylow 3-subgroups of the Ree groups are nilpotent of class three (see [9]), against Theorem 3. Moreover, there are 7 isomorphism classes of maximal subgroups in J_1 ([3], p. 36), so $w_C(J_1) \geq 7 > 6 = |\Pi(J_1)|$ eliminates J_1 . Since the involutions of G must be all conjugate, $A \triangleleft G/O(G)$ implies $A = 1$. The direct product $K = S_1 \times \dots \times S_t$ contains t classes of involutions that are not conjugate because their centralizers form a chain: let $x_i \in S_i$, $o(x_i) = 2$ and let $e_i = x_1 x_2 \dots x_i$; if $C_i = C_{S_i}(x_i)$, we have $C_K(e_i) = C_1 \times C_2 \times \dots \times C_i \times S_{i+1} \times \dots \times S_t$. Thus if $t > 1$ the subgroups $\langle e_1 \rangle, \dots, \langle e_t \rangle$ cannot be conjugate in $G/O(G)$, so $t = 1$ and therefore R is isomorphic to $PSL(2, 2^k)$ or to $PSL(2, q)$, where q is an odd prime. In the first case, we have $|P| = 2^k$, then $|N_G(P)/C_G(P)| = 2^k - 1$ (see [5], p. 191). Now, P is elementary abelian of order 2^k , so it has $((2^k - 1)(2^k - 2))/6$ subgroups of order 2^2 , that must be conjugate in G , so in $N_G(P)$. This implies $((2^k - 1)(2^k - 2))/6 \leq 2^k - 1$, i.e. $k \leq 3$. Then R is isomorphic to $PSL(2, 4)$ ($\cong PSL(2, 5)$) or to $PSL(2, 8)$. The last group however contains subgroups of order 9, 4, 6, 7, so $\nu(PSL(2, 8)) > |\Pi(PSL(2, 8))|$, against Lemma 4. Now let R be isomorphic to $PSL(2, q)$. Then it contains cyclic subgroups of order $(q + 1)/2$ and $(q - 1)/2$, dihedral subgroups of order $2r$ for every odd prime $r \in \Pi(R)$ and the Sylow 2-subgroups, which contain elementary abelian subgroups of order 4. Thus $\nu(R) > |\Pi(R)|$ un-

less one of the numbers $(q + 1)/2$ and $(q - 1)/2$ is odd and the other one is 2. This is possible only for $q = 3$ or $q = 5$, but $PSL(2, 3)$ is soluble, so $R \cong PSL(2, 5)$. By Lemma 5 we have $G \cong PSL(2, 5)$.

II) $P \cong Q_8$. In this case, Glauberman's Z^* -theorem (see [4]) implies that the centre of the group $G/O(G)$ has even order. Let $T \leq G$ be such that $Z(G/O(G)) = T/O(G)$. Then $w_{C(G/T)}(G/T) = |\Pi(G/T)|$, by Lemma 4. As the Sylow 2-subgroup of G/T is elementary abelian, by I) we have $O'((G/T)/O(G/T)) \cong PSL(2, 5)$. By Lemma 5, we have $G/T \cong PSL(2, 5)$, and then $G/O(G) \cong SL(2, 5)$. Again by Lemma 5 we must have $O(G) = 1$. This concludes the proof.

Now we examine the case when G is soluble. Certainly, we have $m = w_C(G) = |\Pi(G)| \leq 3$, because the conjugacy classes of Hall subgroups whose order is a multiple of two distinct prime powers form an antichain of $\binom{m}{2}$ elements.

The case $m = 1$ is trivially that of cyclic p -groups. We examine now the case $m = 2$. Let G be a soluble group such that $w_C(G) = 2$. Then G is not a p -group, since a non-cyclic p -group has three maximal normal subgroups at least. Therefore $|G| = p^a q^b$ and G is soluble, $f(G) \leq 2$ by Lemma 2 and its Sylow subgroups must be as in Theorem 3, (except for the case 4). Moreover, we have:

LEMMA 7. Let $w_C(G) = 2$. Then:

- a) If G is nilpotent then it is cyclic of order $p^a q$.
- b) $G/F(G)$ is cyclic.

PROOF. a) In this case the maximal subgroups of a Sylow subgroup P of G are normal in G , therefore P must contain just one maximal subgroup and hence it is cyclic. Thus G is cyclic too. If $|G| = p^a q^b$ with $a, b > 1$ then G would have subgroups of order p^2 , q^2 and pq , therefore $w_C(G) \geq 3$. Now b) follows from a) and Corollary 2.

The Fitting subgroup of G can be a p -group or not. We first examine the case when $F(G)$ is not a p -group. We have:

PROPOSITION 8. Let $w_C(G) = 2$, and assume that G is non-nilpotent and $F(G)$ is not a p -group. Then $|G| = p^n q$ where $q \equiv 1 \pmod{p}$ and the Sylow p -subgroups are cyclic. Moreover $|G'| = q$ and G has the following presentation:

$$G = \langle a, b \mid a^q = b^{p^n} = 1, b^{-1}ab = a^r \rangle, \quad 1 < r < q, \quad r^{p^k} \equiv 1 \pmod{q}$$

for some k .

If h is the minimal integer such that $r^{p^h} \equiv 1 \pmod{q}$ then $Z(G) = \Phi(G)$ is a p -subgroup of order p^{n-h} . Also, $F(G) = \Phi(G) \times G'$.

PROOF. Since $F(G)$ is not a p -group, we have $F(G) = P \times Q$, where P and Q are normal in G . One of them must have prime order, because otherwise G would have subgroups of order p^2 , q^2 , pq and then $w_c(G) \geq 3$. Let us assume that $|Q| = q$. The same argument shows that G must have order $p^n q$, Q is the Sylow q -subgroup and is normal in G . Thus Q is not contained in $\Phi(G)$. Therefore $\Phi(G) \leq P$. Let S be a Sylow p -subgroup of G . Since G is non-nilpotent then $P \neq S$; being $P \triangleleft G$, P is unique in its order in G and being $G/F(G)$ cyclic, then S/P is cyclic and S is cyclic too, by Theorem 3. This implies that G is supersoluble. Clearly, G is noncyclic, and so we must have $q > p$ and $q \equiv 1 \pmod{p}$. Certainly $P = Z(G) = \Phi(G)$ and moreover $G' = Q$. This concludes the proof.

When $F(G)$ is a p -group there are some more cases. We have in fact:

PROPOSITION 9. Let $w_c(G) = 2$ and assume that G is non-nilpotent and $F(G)$ is a p -subgroup. Then $F(G)$ is the Sylow p -subgroup of G . Moreover:

a) If $F(G)$ is a quaternion group, then G is isomorphic to $SL(2, 3)$.

b) If $F(G)$ is cyclic then $|G| = p^a q$ with $p \equiv 1 \pmod{q}$ or $|G| = pq^b$, where q^b is a divisor of $p - 1$.

c) If $F(G)$ is elementary abelian, its order must be 4 (and then G is isomorphic to A_4) or p^3 and in this case $|G| = p^3 q^b$, with $q^b = p^2 + p + 1$.

PROOF. Since $F(G)$ is a normal p -subgroup and $G/F(G)$ is cyclic, we have $G' \leq F(G)$, so the Sylow p -subgroup of G is normal in G and therefore coincides with $F(G)$. Let Q be a Sylow q -subgroup of G . Then Q is isomorphic to $G/F(G)$, it is cyclic and it acts transitively on the subgroups of the same order in $F(G)$. So:

a) If $F(G)$ is a quaternion group, $\text{Aut } F(G) \cong S_4$ implies that we must have $q = 3$ and $|Q| = 3$, therefore G is isomorphic to $SL(2, 3)$.

b) If $F(G)$ is cyclic and $|F(G)| = p^a$ with $a > 1$ then $|Q| = q$, because otherwise G would have subgroups of order p^2 , pq , q^2 . If $|F(G)| = p$ then q^b must divide $p - 1$, since no q -element can centralize $F(G)$.

c) Let $F(G)$ be elementary abelian. First of all $|F(G)| \neq 2^5$, since in this case the order of $G/F(G)$ would be a multiple of $31 \cdot 5$, as $G/F(G)$ must act transitively on subgroups of order 2 and 4 respectively. If $|G| = p^2$ then $F(G)$ contains $p + 1$ subgroups of order p , on which Q must act transitively. Then $p + 1 = q^n$. If $p > 2$, we must have $q = 2$, so $n \geq 2$ but since every element of order 2 of $GL(2, p)$ fixes at least one subgroup of order p , G contains one subgroup of order p^2 , one of order 4 and a dihedral one of order $2p$, a contradiction. Thus $p = 2$ and then G is isomorphic to A_4 . Instead if $|F(G)| = p^3$ then Q must have order q^b and must act transitively on $p^2 + p + 1$ subgroups of order p . Thus $q^b = p^2 + p + 1$. This is possible for example, for $b = 1$, if $p = 2$ and $q = 7$, or $p = 3$ and $q = 13$.

Concerning the last case of the previous proposition, we have:

PROPOSITION 10. Let $G = [V]C$, with $|V| = p^3$, $|C| = q^n$, V elementary abelian, C cyclic, and $1 + p + p^2 = q^n$. If $Z(G) = 1$ then $w_C(G) = 2$.

PROOF. Let us consider the equation $1 + p + p^2 = q^n$, with p, q primes. If $n = 1$, as known, there are some solutions: $(p, q) = (2, 7), (3, 13), (5, 31), \dots$ We have:

a) n is odd. In fact the equation $x^2 + x + (1 - q^n) = 0$ has discriminant $4q^n - 3$ and it must be a square d^2 in \mathbb{Z} , therefore if $n = 2m$ then $(2q^m)^2 - d^2 = 3$, so $d = 1$ and $q = 1$, a contradiction.

b) $q \neq 3$. In fact if $q = 3$ then $p^2 + p + 1 \equiv 0 \pmod{3}$, so $p \equiv 1 \pmod{3}$, i.e. $p = 3r + 1$. But then $9r^2 + 6r + 1 + 3r + 1 + 1 = 3(3r^2 + 3r + 1) = 3^{2m+1}$ and 3 would divide $3r^2 + 3r + 1$.

c) If an element y of order q fixes a subgroup P of order p of V then $Z(G) \neq 1$. In fact let's suppose first that y does not centralize P . Then q divides $p - 1$, so q divides also $3p = 1 + p + p^2 - (p - 1)^2$. Thus $q = 3$, a contradiction by b). Therefore y centralizes P . Moreover by Maschke's theorem there is a complement W in V which is fixed by y . Since W contains $p + 1$ subgroups of order p , the same argument shows that W is centralized by y . Then $[y, V] = 1$ and $y \in Z(G)$.

d) If G is as before and $Z(G) = 1$ then $w_C(G) = 2$. In fact an element u of order q^n must permute cyclically the subgroups of order p of V : otherwise $N_G(P)$, where $|P| = p$, would be greater than V , so at least one element y of order q would fix P and belong to $Z(G)$. Likewise u permutes cyclically the subgroups of order p^2 . So we have that in $C(G)$ there are only two maximal chains: $[G], [\langle u \rangle], [\langle u^q \rangle], \dots, [1]$ and $[G], [V, \langle u^q \rangle], \dots, [V], [W], [P], [1]$, where $|W| = p^2$; thus $w_C(G) = 2$.

REMARK. If $n > 1$ then $q \equiv 1 \pmod{3}$ and $p \equiv 2 \pmod{3}$. In fact from $4q^{2m+1} - 3 = d^2$ it follows $q^{2m+1} \equiv 1 \pmod{3}$, as $q \neq 3$, so $q \equiv 1 \pmod{3}$. Next, from $1 + p + p^2 = q^{2m+1}$ it follows $p(p+1) \equiv 0 \pmod{3}$, thus if $p = 3$ then $q = 13$ and $n = 1$: otherwise $p \equiv 3 \pmod{3}$.

Now let $w_C(G) = |\Pi(G)| = 3$, let G be soluble and $|G| = p^a q^b r^c$. We distinguish three cases depending on $|\Pi(F(G))|$. First of all, we need the following lemma:

LEMMA 11. Let $w_C(G) = |\Pi(G)| = 3$ and let G be soluble. Then:

- a) G contains no proper subgroup H such that $|\Pi(H)| = 3$.
- b) All the minimal normal subgroups of G are Sylow subgroups, and just one of them can have order not a prime.
- c) If the Sylow p -subgroup is normal in G , $a > 1$ and there is a subgroup of order pq then there is none of order $p^h r$, $0 < h < a$.

PROOF. a) Let $0 < h < a$ and let $|H| = p^h q^k r^m$: then G contains subgroups of order p^a , $p^h q^k$, $p^h r^m$, $q^k r^m$, a contradiction.

b) If P is a minimal normal subgroup, $|P| = p^h$ with $0 < h < a$, then G would contain subgroups of order p^a , $p^h q$, $p^h r$, $q^b r^c$, a contradiction. If the Sylow q -subgroup Q also is normal in G and $a, b > 1$ then G would contain subgroups of order $p^a q$, $p^a r$, $q^b r$, pq^b , another contradiction. Likewise we can prove the last assertion.

COROLLARY 12. Let G be soluble. Then $w_C(G) = |\Pi(G)| = 3$ and $|\Pi(F(G))| = 3$ if and only if $|G| = pqr$ and G is cyclic.

PROPOSITION 13. Let G be soluble. Then $w_C(G) = |\Pi(G)| = 3$ and $|\Pi(F(G))| = 2$ if and only if G is one of the following types:

- a) $G = [\mathbb{Z}_p \times \mathbb{Z}_q] \mathbb{Z}_r$.
- b) $G = [(\mathbb{Z}_2)^2 \times \mathbb{Z}_q] \mathbb{Z}_3$ and the 2-Sylow subgroup is a minimal normal subgroup of G . (Thus G has a subgroup isomorphic to A_4).
- c) $G = [(\mathbb{Z}_p)^3 \times \mathbb{Z}_q] \mathbb{Z}_r$ and the Sylow p -subgroup is a minimal normal subgroup. (Thus $p^2 + p + 1 = r$ and G has no subgroups of order pr or $p^2 r$).

PROOF. Let $w_C(G) = |\Pi(G)| = 3$ and let $|F(G)| = p^h q^k$, where $h, k > 0$. By Lemma 11 we have $h = a$, $k = b = c = 1$, the Sylow p -subgroup P of G is a minimal normal subgroup of G and hence elementary abelian. If $a = 1$ we are in Case a). If $a = 2$ then the subgroups of order p must be all conjugate. Therefore $p + 1 = r$, which implies $p = 2$,

$r = 3$, and we are in Case *b*). Notice that there are no subgroups of order 6, therefore G contains a subgroup isomorphic to A_4 . If $a = 3$, we are in Case *c*). Also we must have $p^2 + p + 1 = r$ and there are no subgroups of order pr or p^2r . It is impossible that $p^a = 2^5$ because, as observed in Theorem 3, in this case $|G| = 32 \cdot 31 \cdot 5$, but $|F(G)| = 32$.

Conversely, a straightforward inspection of the poset $C(G)$ shows that if G is as in *a*), *b*), *c*) then $w_C(G) = |\Pi(G)| = 3$. Case *a*) is obvious. In Case *b*), since the Sylow 2-subgroup is a minimal normal subgroup, G cannot have subgroups of order 6. It has subgroups of orders 1, 2, 3, 4, 12, q , $2q$, $4q$, $3q$, $12q$, and for each of these orders the subgroups are conjugate in both cases of $A_4 \times \mathbb{Z}_q$ and when the q -Sylow subgroup is not central. In Case *c*), likewise, G cannot have subgroups of order pr or p^2r . It has subgroup of orders 1, p , p^2 , p^3 , q , pq , p^2q , p^3q , r , p^3r , qr ; subgroups of the same order are conjugate. Indeed, as G does not contain subgroups of order pr , an element of order r permutes cyclically the $r = p^2 + p + 1$ subgroups of order p and p^2 respectively, so it also acts transitively on the set of the (abelian) subgroups of order pq and p^2q respectively. The remaining subgroups are Hall subgroups.

We say that a group A acts fixed point freely (f.p.f.) on a vector space V if for every $1 \neq a \in A$ and $0 \neq v \in V$ we have $v^a \neq v$.

PROPOSITION 14. Let G be soluble. If $w_C(G) = |\Pi(G)| = 3$ and $|\Pi(F(G))| = 1$ then:

- i) $F(G)$ is the Sylow p -subgroup of G and it is a minimal normal subgroup.
- ii) $G/F(G)$ is cyclic and it acts. f.p.f. on $F(G)$.
- iii) $|G| = p^a qr$, with $a = 1$ or $a = 3$.
- iv) If $a = 3$ then $p^2 + p + 1 = qr$, $(qr, 6) = 1$, or $p^2 + p + 1 = q$, $r|p - 1$, $r \neq 1$, and an element of order r induces a power automorphism on $F(G)$.

PROOF. Let $|G| = p^a q^b r^c$ and let Q be a Hall subgroup of order $q^b r^c$ of G .

i) Lemma 11 implies that $F(G)$ is a minimal normal subgroup of G , so it is elementary abelian, and $|F(G)| = p^a$.

ii) Since $F(G)$ is abelian, we have $C_G(F(G)) = F(G)$. We show that Q acts f.p.f. on $F(G)$. Let $x \in Q$ be of order q . If x would centralize an element y of order p then $a > 1$ (because otherwise $x \in F(G)$) and $C = C_{F(G)}(\langle x \rangle)$ is a proper subgroup of $F(G)$ and the subgroup $M\langle x \rangle$ would have no elements of order pq . Therefore G would have sub-

groups of order p^a , pq (cyclic), $|M|q$, $q^b r^c$, a contradiction. Likewise if x has order r or pq . Thus, Q acts f.p.f. on $F(G)$.

iii) First we show that $|Q| = qr$ and Q is cyclic. By [5], p. 502 and Theorem 3, for each odd prime dividing $|Q|$ the Sylow subgroup must be cyclic, while the Sylow 2-subgroup must be also cyclic or quaternion. In the first case Q is supersoluble and, if $q > r$, all of its q -subgroups are normal in Q . If $b > 1$ then G would have subgroups of order $p^a q$, $p^a r$, q^b , qr , a contradiction. Thus $b = 1$. A similar argument shows that $c = 1$. Therefore $|Q| = qr$ and by [5], p. 502, Q is cyclic. When $q = 2$ the same argument shows that the Sylow 2-subgroup of Q cannot be isomorphic to the quaternion group Q_8 .

Next, we cannot have $p^a = 2^5$, otherwise $|G| = 2^5 \cdot 31 \cdot 5$ and $F(G)$ would have 31 elements of order 2, so G would have an element of order 10.

By Theorem 3, $|F(G)| \leq p^3$. The subgroups of order p must form just one conjugacy class of G , so $G/F(G)$ must act transitively on them. Let $2 \leq a \leq 3$ and let g be of order qr , $x = g^q$ and $y = g^r$. First of all we need to consider the case when x fixes a nontrivial subgroup of $F(G)$. Then x fixes a subgroup of order p and has an eigenvalue $k \neq 0$ in $GF(p)$. Being $xy = yx$, the eigenspace P of k is also fixed by y . Therefore $P^g = P$, and because $P \triangleleft F(G)$, we have $P \triangleleft G$, so i) implies $P = F(G)$ and x must act as a power automorphism on $F(G)$. In this case the number of subgroups of order p must be q .

If $a = 2$, p must be odd (otherwise $\text{Aut}(F(G))$ would be noncyclic); then $p + 1$ is even, so we can assume $r = 2$ and $p + 1 = 2q$. But since an element of order 2 has always eigenvalues, by the previous argument we would also have $p + 1 = q$, a contradiction. Thus $a \neq 2$.

iv) If $a = 3$ then either $p^2 + p + 1 = qr$ or $p^2 + p + 1 = q$ and r divides $p - 1$. In the first case we have $r \neq 2, 3$. In fact, if $r = 3$ and $x = g^q$, as a basis of $F(G)$ one could choose three vectors u, v, w such that $u^x = v$, $v^x = w$, $w^x = u$, but then $(uvw)^x = (uvw)$, a contradiction, because x cannot fix any subgroup of order p . Similar arguments can be used for $r = 2$. So $(qr, 6) = 1$. In the second case, when $p^2 + p + 1 = q$ and r divides $p - 1$, we must have $r \neq 3$; in fact if $r = 3$ then $p = 3t + 1$, so $9t^2 + 9t + 3 = q$ and $3|q$, a contradiction.

PROPOSITION 15. Let G be a soluble group. Then $w_C(G) = 3 = |\Pi(G)|$ and $F(G)$ is a p -group if and only if:

- i) $|G| = p^a qr$, with $a = 1$ or $a = 3$;
- ii) $|F(G)| = p^a$ and $F(G)$ is elementary abelian;

iii) in the case $a = 3$ we have:

iiia) $p^2 + p + 1 = qr$, $(qr, 6) = 1$, $G/F(G)$ cyclic, or

iiib) $p^2 + p + 1 = q$, $r|p - 1$, and an element of order r acts on $F(G)$ as a power automorphism.

PROOF. The necessity follows by Proposition 14. If G satisfies i), ii), iii), the case $a = 1$ is obvious. Let $a = 3$, let x be of order q and let y be of order r . If $p^2 + p + 1 = q$, no p -subgroup P or order p can be fixed by x . In fact otherwise, since q does not divide $p - 1$, we would have $[P, x] = 1$, and on the other hand x would fix a complement W of P in $F(G)$ and permute its $p + 1$ onedimensional subspaces. But q neither divides $p + 1$ nor p , therefore x must fix at least two of them, so it would fix them pointwise. Therefore $[x, F(G)] = 1$, a contradiction. Thus $F(G)$ is a minimal normal subgroup, the subgroups of order p are all conjugate and also those of order p^2 . Moreover there are no subgroups of order $p^h q$, with $0 < h < a$. Since y induces a power automorphism on $F(G)$, then $xy = yx$, so $G/F(G)$ is cyclic. Thus the subgroups of order pr are all conjugate and also these of order $p^2 r$. Then $w_C(G) = 3$. In the case $p^2 + p + 1 = qr$, let g be of order qr and let $x = g^r$ and $y = g^q$. If x should fix some subgroup P of order p , then q would divide $p - 1$, so $q = 3$, a contradiction, or $[x, P] = 1$, so $[x, F(G)] = 1$ as before, another contradiction. Likewise, y fixes no subgroup of order p . Thus there are no subgroups of order $p^h q$ or $p^h r$, with $0 < h < 3$, $F(G)$ is a minimal normal subgroup, the subgroups of order p are all conjugate and also those of order p^2 . This implies $w_C(G) = 3$.

EXAMPLES. Let $p = 41$, let V be the elementary abelian p -group of order p^3 and let x and y be the automorphisms of V whose matrices are

$$\begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

respectively. They commute and we have $x^5 = 1$, $y^{1723} = 1$. If G is the split extension of V with respect to $\langle xy \rangle$, it satisfies i), ii), iiib) of Proposition 15 and we have $w_C(G) = 3$.

One can construct a similar example, of even order, if $p = 3$, $q = 13$, $r = 2$.

We have an example of the other type, that satisfies iiia) of Proposition 15, if $p = 11$, $q = 29$, $r = 7$.

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