

Problem Set 7

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1 Problem 1

Note that if either $p = 1$ or $q = 1$, G is a p -group, which is a nontrivial center that is always normal. So assume $p \neq 1$ and $q \neq 1$.

We want to show that G has a non-trivial normal subgroup. Noting that $\#G = p^2q$, we will proceed by showing that either n_p or n_q must be 1.

We immediately note that

$$\begin{array}{ll} n_p \equiv 1 \pmod{p} & n_q \equiv 1 \pmod{q} \\ n_p \mid q & n_q \mid p^2, \end{array}$$

which forces

$$n_p \in \{1, q\}, \quad n_1 \in \{1, p, p^2\}.$$

If either $n_p = 1$ or $n_q = 1$, we are done, so suppose $n_p \neq 1$ and $n_1 \neq 1$. This forces $n_p = q$, and we proceed by cases:

1.1 Case 1: $p = q$.

Then $\#G = p^3$ and G is a p -group. But every p -group has a non-trivial center $Z(G) \leq G$, and the center is always a normal subgroup.

1.2 Case 2: $p > q$.

Here, since $n_p \mid q$, we must have $n_p < q$. But if $n_p < q < p$ and $n_p \equiv 1 \pmod{p}$, then $n_p = 1$.

1.3 Case 3: $q > p$.

Since $n_p \neq 1$ by assumption, we must have $n_p = q$. Now consider sub-cases for n_q :

- $n_q = p$: If $n_q = p \equiv 1 \pmod{q}$ and $p < q$, this forces $p = 1$.
- $n_q = p^2$: We will reach a contradiction by showing that this forces

$$\left| P := \bigcup_{S_p \in \text{Syl}(p, G)} S_p \setminus \{e\} \right| + \left| Q := \bigcup_{S_q \in \text{Syl}(q, G)} S_q \setminus \{e\} \right| + |\{e\}| > |G|.$$

We have

$$\begin{aligned} |P| + |Q| + |\{e\}| &= n_p(q-1) + n_q(p^2-1) + 1 \\ &= p^2(q-1) + q(p^2-1) + 1 \\ &= p^2(q-1) + 1(p^2-1) + (q-1)(p^2-1) + 1 \quad (\text{since } q > 1) \\ &= (p^2q - p^2) + (p^2-1) + (q-1)(p^2-1) + 1 \\ &= p^2q + (q-1)(p^2-1) \\ &\geq p^2q + (2-1)(2^2-1) \quad (\text{since } p, q \geq 2) \\ &= p^2q + 3 \\ &> p^2q = |G|, \end{aligned}$$

which is a contradiction. \square

2 Problem 2

We'll use the fact that $H \trianglelefteq N(H)$ for any subgroup H (following directly from the closure axioms for a subgroup), and thus

$$P \trianglelefteq N(P) \quad \text{and} \quad N(P) \trianglelefteq N^2(P).$$

Since it is then clear that $N(P) \subseteq N^2(P)$, it remains to show that $N^2(P) \subseteq N(P)$.

So if we let $x \in N^2(P)$, so x normalizes $N(P)$, we need to show that x normalizes P as well, i.e. $xPx^{-1} = P$.

However, supposing that $|G| = p^k m$ where $(p, m) = 1$, we have

$$P \leq N(P) \leq G \implies p^k \mid |N(P)| \mid p^k m,$$

so in fact $P \in \text{Syl}(p, N(P))$ since it is a maximal p -subgroup.

Then $P' := xPx^{-1} \in \text{Syl}(p, N(P))$ as well, since all conjugates of Sylow p -subgroups are also Sylow p -subgroups.

But since $P \trianglelefteq N(P)$, there is only *one* Sylow p -subgroup of $N(P)$, namely P . This forces $P = P'$, i.e. $P = xPx^{-1}$, which says that $x \in N(P)$ as desired. \square

3 Problem 3

By definition, G is simple iff it has no non-trivial subgroups, so we will show that if $|G| = 148$ then it must contain a normal subgroup.

Noting that $248 = p^2 q$ where $p = 2, q = 37$, we find that (for example) $n_2 \mid 37$ but $n_2 \equiv 1 \pmod{2}$; but the only odd divisor of 37 is 1, forcing $n_2 = 1$. So G has a normal Sylow 2-subgroup and we are done.

4 Problem 4

Let $\tau := (t_1, t_2)$ denote the transposition and $\sigma = (s_1, s_2, \dots, s_p)$ denote the p -cycle, and let $S = \langle \sigma, \tau \rangle$. We would like to show that $S = S_p$, and since $S \subseteq S_p$ is clear, we just need to show that $S_p \subseteq S$.

We first note that because p is prime, σ^k is a p -cycle for every $1 \leq k \leq p$, and $\langle \sigma \rangle = \langle \sigma^k \rangle$ for any such k .

Then note that $t_1 = s_i$ for some i and $t_2 = s_j$ for some j , so we can take $k = j - i$ to get a cycle σ^k that sends t_1 to t_2 . So without loss of generality, we can replace σ with

$$\sigma = (t_1, t_2, \dots)$$

But now, we can relabel all of the elements of S_p simultaneously (i.e. replace $\langle \sigma, \tau \rangle$ with another subgroup in the same conjugacy class) in such a way that t_1 becomes 1 and t_2 becomes 2. We can

then assume wlog that

$$\tau = (1, 2), \quad \sigma = (1, 2, \dots, p)$$

We can then get all adjacent transpositions: noting that

$$\begin{aligned} \sigma^{-1}\tau\sigma &= (2, 3) \\ \sigma^{-2}\tau\sigma^2 &= (3, 4) \\ &\dots \\ \sigma^{-k}\tau\sigma^k &= (k+1 \bmod p, k+2 \bmod p) \quad \forall 1 \leq k \leq p, \end{aligned}$$

where we use the fact that for any $\gamma \in S_p$, we have $\gamma\tau\gamma = (\gamma(1), \gamma(2))$.

But this also gives us all transpositions of the form $(1, j)$ for each $2 \leq j \leq p$:

$$\begin{aligned} (2, 3)^{-1}(1, 2)(2, 3) &= (1, 3) \\ (3, 4)^{-1}(1, 3)(3, 4) &= (1, 4) \\ &\dots \\ (j-1, j)^{-1}(1, j-1)(j-1, j) &= (1, j) \quad \forall 1 \leq j \leq p. \end{aligned}$$

Thus we have $J := \langle \{(1, j) \mid 2 \leq j \leq p\} \rangle \subseteq S$.

But now if $\gamma = (g_1, g_2, \dots, g_k) \in S_p$ is an arbitrary cycle, we can write

$$\gamma = (g_1, g_2, \dots, g_k) = (1, g_1)(1, g_2), \dots, (1, g_k),$$

so $\gamma \in J$. Then writing any arbitrary permutation as a product of disjoint cycles, we find that $S_p \subseteq J \subseteq S$, and so $S_p \subseteq S$ as desired. \square

5 Problem 5

Since G is a p -group, it has a nontrivial center. Since p is prime and $Z(G)$ is a subgroup, this forces $\#Z(G) \in \{p, p^2\}$, where p^3 is ruled out because this would make G abelian.

Supposing that $\#Z(G) = p^2$, we would have $[G : Z(G)] = p$, and since $Z(G) \trianglelefteq G$, we can take the quotient and $\#(G/Z(G)) = p$. But this means $G/Z(G)$ is cyclic, which implies that G is abelian, a contradiction.

So we must have $\#Z(G) = p$, and $\#(G/Z(G)) = p^2$.

But any group of p^2 is abelian, and we can characterize $G' := [G, G]$ in the following way:

$G' \leq G$ is the unique subgroup of G such that if $N \trianglelefteq G$ and G/N is abelian, then $N \subseteq G'$.

5.1 Case 2: $\#Z(G) = p$:

6 Problem 6

7 Problem 7}

8 Problem 8

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9 Problem 9

10 Problem 10