

# Midterm

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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,  $\sigma^k$  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  $\sigma^k$  that sends  $t_1$  to  $t_2$ . So without loss of generality, we can replace  $\sigma$  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  $N \leq G'$ .

We can thus conclude that  $G' \leq Z(G)$ . It can not be the case that  $G' = \{e\}$ , since this would make  $G$  abelian. This forces  $G' = Z(G)$  as desired.  $\square$

## 6 Problem 6

Writing  $f(x) = x^3 - 3x - 3 = \sum a_i x_i \in \mathbb{Q}[x]$ , we can conclude that  $f$  is irreducible over  $\mathbb{Q}$  by Eisenstein with the prime  $p = 3$ , since  $p \mid a_0 = -3, a_1 = 3, a_2 = 0$ , but  $p^2 \nmid a_3 = 1$ .

We can check that  $f(0) < 0$  and  $f(10) > 0$ , so  $f$  has at least one real root. By the 1st derivative test, we can find that  $f$  is increasing on  $(-\infty, -1)$  and less than zero, decreasing on  $(-1, 1)$  and less than zero, and increasing on  $(1, \infty)$ , where it attains its root. This root has multiplicity one, since  $\gcd(f, f') = 1$ , which means that  $f$  has *exactly* one real root  $r_0$ , and thus a complex conjugate pair of roots  $r_1, \bar{r}_1$  as well.

This means that complex conjugation is a nontrivial element  $\tau$  of the Galois group  $G \leq S_3$ , and thus  $G$  contains a 2-cycle.

The Galois group must be a transitive subgroup of  $S_3$ , which restricts the possibilities to  $S_3, A_3$ .

Since  $A_3$  only contains 3-cycles, this possibility is ruled out. Thus the Galois group must be  $S_3$ .  $\square$

## 7 Problem 7

Definition: A field  $F$  is *perfect* if every irreducible polynomial  $f(x) \in F[x]$  is separable in  $\bar{F}[x]$ .

Note that since  $F$  is a finite field,  $p$  must be a prime.

**7.1**  $\implies$  :

Suppose all irreducible polynomials in  $F[x]$  are separable. Then let  $a \in K$  be arbitrary, we will show that there exists some  $\beta \in K$  such that  $\beta^p = a$ .

Given such an  $a$ , define the polynomial

$$f(x) = x^p - a \in F[x].$$

Note that  $f$  is *not* separable, since  $f'(x) = px^{p-1} = 0$  since  $\text{char}(F) = p$ , which means (by assumption) that  $f$  must be *reducible*.

Thus we can write  $f(x) = g(x)h(x)$  where  $g \in F[x]$  is some irreducible factor that divides  $f$ .

Noting that if  $\beta \in \bar{F}$  is a any root of  $f$ , then

$$f(\beta) = 0 \implies \beta^p = a \implies f(x) = x^p - a = x^p - \beta^p = (x - \beta)^p,$$

and so  $\beta$  is necessarily a multiple root.

Moreover, since  $g \mid f$ , we must have  $g(x) = (x - \beta)^\ell$  for some  $1 \leq \ell \leq p$ .

But then we can expand  $g$  using the binomial formula:

$$g(x) = (x - \beta)^\ell = \sum_{k=1}^{\ell} \binom{\ell}{k} x^{\ell-k} (-\beta)^k = x^\ell + \cdots + (-\beta)^\ell \in F[x].$$

But since every coefficient must be in  $F$ , we must have  $\beta^\ell \in F$ . We know that  $\beta^p = a \in F$  as well, but since  $p$  is prime,  $\gcd(p, \ell) = 1$ .

We can thus find  $s, t \in \mathbb{Z}$  such that  $ps + t\ell = 1$ . But then

$$\beta = \beta^1 = \beta^{ps+t\ell} = \beta^{st}\beta^{t\ell} = (\beta^\ell)^s(\beta^p)^t,$$

where since  $\beta^\ell, \beta^p \in F$ , the entire RHS is in  $F$ , and thus the LHS  $\beta \in F$  as well.

But then  $\alpha = \beta^p$  where  $\beta \in F$ , which is exactly what we wanted to show.

## 7.2 $\Leftarrow$ :

Suppose every element in  $F$  admits a  $p$ th root in  $F$ , and suppose  $f \in F[x]$  is an irreducible polynomial which is *not* separable, so it has a repeated root in  $\overline{F}$ .

Supposing that  $\gcd(f, f') = g(x)$  for any polynomial  $g(x)$ , this would imply that  $g \mid f$ . But  $f$  was assumed irreducible, so the only possibility is that in fact  $g = f$ .

But if  $\gcd(f, f') = f$ , since  $\deg f' < \deg f$ , we can not have  $f \mid f'$  unless  $f'$  is identically zero.

If we thus write

$$\begin{aligned} f(x) &= \sum_{k=0}^n c_k x^k, \\ f'(x) &= \sum_{k=1}^n k c_k x^{k-1} \\ &\equiv 0, \end{aligned}$$

then for each  $k$  we must have  $c_k = 0$  or  $k = 0$  in  $F$ , i.e.  $c_k = 0$  or  $p \mid k$ .

Thus the only possible nonzero terms in  $f$  must come from coefficients of  $x^{kp}$  for each  $k$  such that  $1 \leq kp \leq n$ , i.e.

$$f(x) = c_0 + c_p x^p + c_{2p} x^{2p} + \dots$$

But this says we can write  $f(x) := g(x^p)$ , where

$$g(x) = c_0 + c_p x + c_{2p} x^2 + \dots$$

and furthermore, we can now use the assumption that  $F$  is perfect to write  $c_i = b_i^p$  for each  $i$ , yielding

$$g(x) = b_0^p + b_p^p x + b_{2p}^p x^2 + \dots$$

and thus

$$\begin{aligned}
f(x) &= g(x^p) \\
&= b_0^p + b_p^p x^p + b_{2p}^p x^{2p} + \dots \\
&= (b_0 + b_p x + b_{2p} x^2)^p \\
&:= (j(x))^p,
\end{aligned}$$

from which it follows that  $j \mid f$  in  $F[x]$ . But since  $f$  was irreducible, this is a contradiction, and so  $f$  could not have had a repeated root. Thus every irreducible polynomial is separable, which is what we wanted to show.  $\square$

## 8 Problem 8

Let  $f(x) \in F[x]$  be irreducible, then since  $p(x) := \gcd(f, f')$  must divide  $f$  and  $f$  is irreducible, the only possibilities are  $p(x) = 1$  or  $p(x) = f(x)$ .

If  $p(x) = 1$ , then  $f$  is separable, so every root is distinct and  $f$  itself is of the form  $f(x^{p^e})$  where each  $e = 0$ .

Otherwise,  $p(x) = f(x)$ , which forces  $f'(x) = 0$  in  $K[x]$ . If we write

$$\begin{aligned}
f(x) &= \sum_{k=0}^n a_k x^k \\
f'(x) &= \sum_{k=1}^n k a_k x^{k-1}
\end{aligned}
,$$

then  $f'(x) \equiv 0$  forces either  $a_k = 0$ , or  $k = 0$  in  $F$  (so  $p \mid k$ ).

We can thus rewrite  $f$  by leaving out all terms where  $a_k = 0$  to obtain

$$f(x) = a_p x^p + a_{2p} x^{2p} + \dots$$

and we thus define

$$g(x) := a_p x + a_{2p} x^2 + \dots$$

and we recover  $f(x) = g(x^p)$ . Moreover,  $g$  is irreducible; otherwise if  $h(x) \mid g(x)$  then  $h(x^p) \mid g(x^p) = f$ , where  $f$  was assumed irreducible. If  $g$  is separable we are done; otherwise  $g$  fulfills the same hypotheses of that applied to  $f$ , so we can inductively continue this process to write  $g(x) = g_1(x^p)$ , and thus  $f(x) = g(x^p)g_1(x^{p^2})$ , and so on.

To see that every root of  $f$  has multiplicity  $p^e$ , note that if  $f(\alpha) = 0$  then  $g(\alpha^{p^k}) = 0$ . But  $g$  is separable, so  $(x - \alpha^{p^k}) \mid g$ .

## 9 Problem 9

Let  $x = [\mathbb{Q}(\zeta + \zeta^{-1}) : \mathbb{Q}]$ .

Noting that

$$\zeta(\zeta + \zeta^{-1}) = \zeta^2 + 1,$$

if we let

$$f(x) = x^2 - (\zeta + \zeta^{-1})x + 1 \in \mathbb{Q}(\zeta + \zeta^{-1})[x],$$

then  $f(\zeta) = 0$ .

Since  $\mathbb{Q}(\zeta + \zeta^{-1}) \subset \mathbb{R}$ ,  $\mathbb{Q}(\zeta)$  is a proper extension over this field, so if  $d := [\mathbb{Q}(\zeta) : \mathbb{Q}(\zeta + \zeta^{-1})]$  then  $d > 1$ . The fact that  $\zeta$  is a root of  $f$  shows that  $d \leq 2$ , so  $d = 2$ . We also know that  $[\mathbb{Q}(\zeta) : \mathbb{Q}] = \phi(n)$ .

We thus have

$$[\mathbb{Q}(\zeta) : \mathbb{Q}] = [\mathbb{Q}(\zeta) : \mathbb{Q}(\zeta + \zeta^{-1})][\mathbb{Q}(\zeta + \zeta^{-1}) : \mathbb{Q}] \implies \phi(n) = 2x,$$

and so  $x = \frac{\phi(n)}{2}$  as desired.  $\square$

## 10 Problem 10

Suppose  $K/F$  is a finite, normal, Galois extension.

### 10.1 Part 1

We have  $F \leq E \leq K$ . Suppose that

- $K/F$  is cyclic, so  $\text{Gal}(K/F)$  is a cyclic group,
- $E/F$  is normal

We then want to show that

1.  $E/F$  is cyclic, i.e.  $\text{Gal}(E/F)$  is cyclic, and
2.  $K/E$  is cyclic, i.e.  $\text{Gal}(K/E)$  is cyclic.

By the fundamental theorem of Galois theory,  $E/F$  is normal if and only if

- a.  $\text{Gal}(K/E) \trianglelefteq \text{Gal}(K/F)$ , and
- b.  $\text{Gal}(E/F) \cong \text{Gal}(K/F)/\text{Gal}(K/E)$ .

Since  $\text{Gal}(K/F)$  is a cyclic group and every subgroup of a cyclic group is itself cyclic, (a) lets us conclude that (1) holds.

Similarly, since  $\text{Gal}(K/F)$  is a cyclic group and every *quotient* of a cyclic group is cyclic, (b) lets us conclude (2).



## 10.2 Part 2

By the Galois correspondence, all intermediate fields will correspond to subgroups of  $\text{Gal}(K/F)$ . Since this group is cyclic, we are reduced to analyzing the subgroup lattice of a generic cyclic group.

But if  $G = \langle x \mid x^n = e \rangle$  where  $\#G = n$ , then there is one and *only* one subgroup of index  $d$  and order  $\frac{n}{d}$  for every  $d$  dividing  $n$ , given by  $H_d := \langle x^d \rangle$ .

So we have  $[G : H_d] = d$ , so  $H_d$  corresponds to a field  $E_d/F$  of degree  $d$  where  $F \leq E_d \leq K$ . This can be done for every  $d$  dividing  $n$ , and since  $K/F$  is a Galois extension,  $n = |\text{Gal}(K/F)| = [K : F]$ , and this can be done for every divisor of  $[K : F]$  as desired.  $\square$