

MA553: Spring 2016 Homework

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Course Notes

These notes roughly correspond to the three sections (by the same name) on groups, rings and fields from Dummit and Foote's *Abstract Algebra* [1]. I also make nominal use of Herstein's *Topics in Abstract Algebra* [2]

1.1 Group Theory

1.2 Rings

1.3 Field Theory

Homework (Spring 2016)

2.1 Homework 1

Problem 2.1. Let G be a group, $a \in G$ an element of finite order m , and n a positive integer. Prove that

$$|a^n| = \frac{m}{\gcd(m, n)}.$$

Proof. Without loss of generality, we may assume $n < m$; otherwise, by the fundamental theorem of arithmetic, there exist q and r with $r < m$ such that $n = qm + r$ so $a^n = a^{qm+r} = a^{qm}a^r = a^r$. ■

Problem 2.2. Let G be a group, and let a, b be elements of finite order m, n respectively. Show that if $ba = ab$ and $\langle a \rangle \cap \langle b \rangle = \{e\}$, then $|ab| = \text{lcm}(m, n)$.

Proof. ■

Problem 2.3. Let G be a group and H, K normal subgroups with $H \cap K = \{e\}$. Show that

- (a) $hk = kh$ for every $h \in H, k \in K$.
- (b) HK is a subgroup of G with $HK \simeq H \times K$.

Proof. ■

Problem 2.4. Show that A_4 has no subgroup of order 6 (although $6 \mid 12 = |A_4|$).

Proof. ■

2.2 Homework 2

Problem 2.5. Let G be the group of order $2^3 \cdot 3$, $n \geq 2$. Show that G has a normal 2-subgroup $\neq \{e\}$.

Proof. ■

Problem 2.6. Let G be a group of order p^2q , p and q primes. Show that the Sylow p -Sylow subgroup or the q -Sylow subgroup of G is normal in G .

Proof. ■

Problem 2.7. Let G be a subgroup of order pqr , $p < q < r$ primes. Show that the r -Sylow subgroup of G is normal in G .

Proof. ■

Problem 2.8. Let G be a group of order n and let $\varphi: G \rightarrow S_n$ be given by the action of G on G via translation.

- (a) For $a \in G$ determine the number and the lengths of the disjoint cycles of the permutation $\varphi(a)$.
- (b) Show that $\varphi(G) \not\subset A_n$ if and only if n is even and G has a cyclic 2-Sylow subgroup.
- (c) If $n = 2m$, m odd, show that G has a subgroup of index 2.

Proof. ■

Problem 2.9. Show that the only simple groups $\neq \{e\}$ of order < 60 are the groups of prime order.

Proof. ■

2.3 Homework 3

Problem 2.10. Let G be a finite group, p a prime number, N the intersection of all p -Sylow subgroups of G . Show that N is a normal p -subgroup of G and that every normal p -subgroup of G is contained in N .

Proof. ■

Problem 2.11. Let G be a group of order 231 and let H be an 11-Sylow subgroup of G . Show that $H \subset Z(G)$.

Proof. ■

Problem 2.12. Let $G = \{e, a_1, a_2, a_3\}$ be a non-cyclic group of order 4 and define $\varphi: S_3 \rightarrow \text{Aut}(G)$ by $\varphi(\sigma)(e) = e$ and $\varphi(\sigma)(a_i) = a_{\sigma(i)}$. Show that φ is well-defined and an isomorphism of groups.

Proof. ■

Problem 2.13. Determine all groups of order 18.

Proof. ■

2.4 Homework 4

Problem 2.14. Let p be a prime and let G be a nonAbelian group of order p^3 . Show that $G' = Z(G)$.

Proof. ■

Problem 2.15. Let p be an odd prime and let G be a nonAbelian group of order p^3 having an element of order p^2 . Show that there exists an element $b \notin \langle a \rangle$ of order p .

Proof. ■

Problem 2.16. Let p be an odd prime. Determine all groups of order p^3 .

Proof. ■

Problem 2.17. Show that $(S_n)' = A_n$.

Proof. ■

Problem 2.18. Show that every group of order < 60 is solvable.

Proof. ■

Problem 2.19. Show that every group of order 60 that is simple (or not solvable) is isomorphic to A_5 .

Proof. ■

2.5 Homework 5

Problem 2.20. Find all composition series and the composition factors of D_6 .

Proof. ■

Problem 2.21. Let T be the subgroup of $\mathrm{GL}(n, \mathbb{R})$ consisting of all upper triangular invertible matrices. Show that T is solvable.

Proof. ■

Problem 2.22. Let $p \in \mathbb{Z}$ be a prime number. Show:

- (a) $(p-1)! \equiv -1 \pmod{p}$.
- (b) If $p \equiv 1 \pmod{4}$ then $x^2 \equiv -1 \pmod{p}$ for some $x \in \mathbb{Z}$.

Proof. ■

Problem 2.23. (a) Show that the following are equivalent for an odd prime number $p \in \mathbb{Z}$:

- (i) $p \equiv 1 \pmod{4}$.
- (ii) $p = a^2 + b^2$ for some a, b in \mathbb{Z} .
- (iii) p is not prime in $\mathbb{Z}[i]$.

- (b) Determine all prime ideals of $\mathbb{Z}[i]$.

Proof. ■

2.6 Homework 6

Problem 2.24. Let R be a domain. Show that R is a UFD if and only if every nonzero nonunit in R is a product of irreducible elements and the intersection of any two principal ideals is again principal.

Proof. ■

Problem 2.25. Let R be a PID and p a prime ideal of $R[X]$. Show that p is principal or $p = (a, f)$ for some $a \in R$ and some monic $f \in R[X]$.

Proof. ■

Problem 2.26. Let k be a field and $n \geq 1$. Show that $Z^n + Y^3 + X^2 \in k(X, Y)[Z]$ is irreducible.

Proof. ■

Problem 2.27. Let k be a field of characteristic zero and $n \geq 1$, $m \geq 2$. Show that $X_1^n + \cdots + X_m^n - 1 \in k[X_1, \dots, X_m]$ is irreducible.

Proof. ■

Problem 2.28. Show that $X^{3^n} + 2 \in \mathbb{Q}(i)[X]$ is irreducible.

Proof. ■

2.7 Homework 7

Problem 2.29. Let $k \subset K$ and $k \subset L$ be finite field extensions contained in some field. Show that:

- (a) $[KL : L] \leq [K : k]$.
- (b) $[KL : k] \leq [K : k][L : k]$.
- (c) $K \cap L = k$ if equality holds in (b).

Proof. ■

Problem 2.30. Let k be a field of characteristic $\neq 2$ and a, b elements of k so that a, b, ab are not squares in k . Show that $[k(\sqrt{a}, \sqrt{b}) : k] = 4$.

Proof. ■

Problem 2.31. Let R be a UFD, but not a field, and write $K := \text{Quot}(R)$. Show that $[\bar{K} : k] = \infty$.

Proof. ■

Problem 2.32. Let $k \in K$ be an algebraic field extension. Show that every k -homomorphism $\delta : K \rightarrow K$ is an isomorphism.

Proof. ■

Problem 2.33. Let K be the splitting field of $X^6 - 4$ over \mathbb{Q} . Determine K and $[K : \mathbb{Q}]$.

Proof. ■

2.8 Homework 8

Problem 2.34. Let k be a field, $f \in k[X]$ a polynomial of degree $n \geq 1$, and K the splitting field of f over k . Show that $[K : k] \mid n!$.

Proof. ■

Problem 2.35. Let k be a field and $n \geq 0$. Define a map $\Delta_n : k[X] \rightarrow k[X]$ by $\Delta_n(\sum a_i X^i) := \sum a_i \binom{i}{n} X^{i-n}$. Show that

- (a) Δ_n is k -linear, and for $f, g \in k[X]$, $\Delta_n(fg) = \sum_{j=0}^n \Delta_j(f) \Delta_{n-j}(g)$.
- (b) $f^{(n)} = n! \Delta_n(f)$.
- (c) $f(x+a) = \sum \Delta_n(f)(a) X^n$.
- (d) $a \in k$ is a root of f of multiplicity n if and only if $\Delta_i(f)(a) = 0$ for $0 \leq i \leq n-1$ and $\Delta_n(f)(a) \neq 0$.

Proof. ■

Problem 2.36. Let $k \subset K$ be a finite field extension. Show that k is perfect if and only if K is perfect.

Proof. ■

Problem 2.37. Let K be the splitting field of $X^p - X - 1$ over $k = \mathbb{Z}/p\mathbb{Z}$. Show that $k \subset K$ is normal, separable, of degree p .

Proof. ■

Problem 2.38. Let k be a field of characteristic $p > 0$, and $k(X, Y)$ the field of rational functions in two variables.

- (a) Show that $[k(X, Y) : k(X^p, Y^p)] = p^2$.
- (b) Show that the extension $k(X^p, Y^p) \subset k(X, Y)$ is not simple.
- (c) Find infinitely many distinct fields L with $k(X^p, Y^p) \subset L \subset k(X, Y)$.

Proof. ■

2.9 Homework 9

Problem 2.39. Let $k \subset K$ be a finite extension of fields of characteristic $p > 0$. Show that if $p \nmid [K : k]$, then $k \subset K$ is separable.

Proof. ■

Problem 2.40. Let $k \subset K$ be an algebraic extension of fields of characteristic $p > 0$, let L be an algebraically closed field containing K , and let $\delta: k \rightarrow L$ be an embedding. Show that $k \subset K$ is purely inseparable if and only if there exists exactly one embedding $\tau: K \rightarrow L$ extending δ .

Proof. ■

Problem 2.41. Let $k \subset K = k(\alpha, \beta)$ be an algebraic extension of fields of characteristic $p > 0$, where α is separable over k and β is purely inseparable over k . Show that $K = k(\alpha + \beta)$.

Proof. ■

Problem 2.42. Let $f(x) \in \mathbb{F}_q[X]$ be irreducible. Show that $f(X) \mid X^{q^n} - X$ if and only if $\deg f(X) \mid n$.

Proof. ■

Problem 2.43. Show that $\text{Aut}_{\mathbb{F}_q}(\overline{\mathbb{F}_q})$ is an infinite Abelian group which is torsionfree (i.e., $\delta^n = \text{id}$ implies $\delta = \text{id}$ or $n = 0$).

Proof. ■

Problem 2.44. Show that in a finite field, every element can be written as a sum of two perfect squares.

Proof. ■

Bibliography

- [1] D.S. Dummit and R.M. Foote. *Abstract Algebra*. Wiley, 2004. ISBN 9780471433347. URL <https://books.google.com/books?id=KIGbCgAAQBAJ>.
- [2] I.N. Herstein. *Topics in algebra*. Xerox College Pub., 1975. URL <https://books.google.com/books?id=lgfvAAAAAAAJ>.