MATH 601 (DUE 11/6)

HIDENORI SHINOHARA

Contents

1. Galois Theory II (P.2)

Exercise. (Problem 1) Let $f(x) \in F[x]$ be an irreducible polynomial of degree d. Let $F \subset K$ be a field extension such that $f(x)$ factors as a product of linear polynomials in $K[x]$. Show that $f(x)$ is separable if and only if there exist d distinct F-algebra homomorphisms, $F[x]/(f(x)) \to K$.

Proof. Without loss of generality, assume $f(x)$ is monic and $f(x) = \prod_{i=1}^{d}(x - a_i)$ for some $a_i \in K$.

Suppose $f(x)$ is separable. Then $a_i \neq a_j$ for all $i \neq j$. For each i, let $\phi_i : F[x]/(f(x)) \to K$ be an F-algebra homomorphism such that $x \mapsto a_i$ and $a \mapsto a$ for all $a \in F$. Then each ϕ_i is distinct because $\phi_i(x) \neq \phi_j(x)$ whenever $i \neq j$. Thus we showed the existence of d distinct F-algebra homomorphisms.

Suppose there exist d distinct homomorphisms ϕ_i for $i = 1, \cdots, d$. For any j, $\prod_{i=1}^{d}(\phi_j(x) - a_i) = \phi_j(\prod_{i=1}^{d}(x - a_i)) = \phi_j(f(x)) = 0$, so $\phi_j(x) \in K$ is a root of $f(x)$. Thus $x - \phi_i(x)$ divides $f(x)$ for each i. Since ϕ_i is uniquely determined by the value $\phi_i(x)$, $\phi_i(x) \neq \phi_j(x)$ whenever $i \neq j$. Thus $f(x) = \prod_{i=1}^{d}(x - \phi_i(x))$, and $f(x)$ is separable. $\square$

Exercise. (Problem 2) Let $F \subset F[v_1, \cdots, v_r] = K$ be an algebraic field extension such that the irreducible monic polynomial, $f_i(x) \in F[x]$, for v_i is separable for each i. Let $F \subset L$ be a splitting field of $f(x) := \prod_{i=1}^{r} f_i(x) \in F[x]$. Let $w \in K$ and let $g(x) \in F[x]$ be the minimal manic polynomial of w. Set $d = \deg(g(x))$. Show that there are exactly d distinct F-algebra homomorphisms, $F[w] \to L$.

Proof.

Because of Problem 3, I don't think I'm supposed to show that g is separable.

$\square$

Exercise. (Problem 3) Let $F \subset F[v_1, \cdots, v_r] = K$ be as in the previous problem. Let $w \in K$. Show that the monic irreducible polynomial of w is separable.

Proof. By Problem 1 and 2, this is trivial because $F[w]$ is isomorphic to $F[x]/(f(x))$ by Lemma 2.1 (Field Extension handout). $\square$

2. Galois Theory II (P.8)

Exercise. (Problem 1) Recall that p is prime and q is a power of p. Define $F_q : \mathbb{F}_{q^r} \to \mathbb{F}_{q^r}$ by $F_q(a) = a^q$. Show that $F_q \in \mathrm{Aut}(\mathbb{F}_{q^r}/\mathbb{F}_q)$.

Proof. $F_q(a+b) = (a+b)^q = a^q + b^q$ since $p \mid \binom{q}{i}$ for $1 \le i \le q-1$. Thus F_q preserves addition, and it is clear that F_q preserves multiplication, so F_q is a homomorphism. Moreover, any element in $\mathbb{F}_q$ satisfies $x^q - x = 0$, so $F_q(a) = a^q = a$ for any $a \in \mathbb{F}_q$. $\square$

Exercise. (Problem 2) Show that $F_p : \mathbb{F}_{q^r} \to \mathbb{F}_{q^r}$, $F_p(a) = a^p$ is not an element of $\mathrm{Aut}(\mathbb{F}_{q^r}/\mathbb{F}_q)$ unless $q = p$.

Proof. If $q = p$, we are done. Suppose $q > p$. Let $\langle \alpha \rangle = (\mathbb{F}_q)^*$. Then the order of α is $q-1$, so $F_p(\alpha) = \alpha^p \neq \alpha$. $\square$

Exercise. (Problem 3) Let $f(x) \in \mathbb{F}_q[x]$ be a monic irreducible polynomial of degree r. Explain why $f(x)$ has a root $\alpha \in \mathbb{F}_{q^r}$.

Proof. Let $f(x) = \sum_{i=0}^{r} a_i x^i$. Since $\langle f(x) \rangle$ is a maximal ideal, $\mathbb{F}_q[x]/\langle f(x) \rangle$ is a field with an $\mathbb{F}_q$-basis $\{1, x, \cdots, x^{d-1}\}$. Thus the field contains q^r elements. By the uniqueness of a finite field, there exists an isomorphism $\phi : \mathbb{F}_{q^r} \to \mathbb{F}_q[x]/\langle f(x) \rangle$. Let $\alpha = \phi^{-1}(x)$. Then $\phi(\sum_{i=0}^{r} a_i \alpha^i) = \sum_{i=0}^{r} a_i x^i = 0$. Thus $\mathbb{F}_{q^r}$ contains a root of $f(x)$. $\square$

Exercise. (Problem 4) With $f(x)$ as in the previous problem, show that $f(x) = \prod_{i=0}^{r-1}(x - \alpha^{q^i}) \in \mathbb{F}_{q^r}[x]$. Conclude that $\mathbb{F}_{q^r}$ is a splitting field for $f(x)$ over $\mathbb{F}_q$. In other words, α^{q^i} is a root of $f(x)$ for any $i \in \mathbb{N}$.

How do I show that $\alpha^{q^i} \neq \alpha^{q^j}$ if $0 \le i < j \le r-1$?

Proof. Let $f(x) = \sum_{i=0}^{r} a_i x^i$. Then $(f(x))^q = (\sum_{i=0}^{r} a_i x^i)^q = \sum_{i=0}^{r} a_i^q (x^q)^i = \sum_{i=0}^{r} a_i (x^q)^i$. Thus the qth power of any root β of $f(x)$ is a root of $f(x)$. $\square$

3. Factoring Polynomials with Coefficients in Finite Fields

Exercise. (Problem 9) Let $\mathbb{F}_q$ be a field with $q = p^m$ elements. Let $f(x) \in \mathbb{F}_q[x]$ be square free. Describe $\gcd(x^q - x, f(x))$ in terms of the linear factors of $f(x)$.

Proof. Since $(x^q - x)' = -1$, $\gcd(x^q - x, (x^q - x)') = 1$. Thus $x^q - x$ is square free by Problem 7 from last week. Thus $x^q - x = \prod_{i=1}^{q}(x - a_i)$ where $\mathbb{F}_q = \{a_1, \cdots, a_q\}$. Each linear factor (if any) of $f(x)$ is associate to $x - a_i$ for some i. Since $f(x)$ is square free, $\gcd(x^q - x, f(x))$ is the product of all the linear factors of $f(x)$. $\square$

Exercise. (Problem 10) Let $f(x) \in \mathbb{F}_q[x]$ be square free. Describe, $h(x) = \gcd(x^{q^2} - x, f(x))$, in terms of the irreducible quadratic polynomials which divide $f(x)$ and whatever other information is necessary.

Proof. Since every element in $\mathbb{F}_q$ is a root of $x^{q^2} - x$, $h(x)$ is divisible by all the linear polynomials that divide $f(x)$.

Let $g(x) \in \mathbb{F}_q[x]$ be an irreducible monic quadratic polynomial. Then $\mathbb{F}_q[x]/(g(x)) \cong \mathbb{F}_{q^2}$ with an isomorphism ϕ. Then $\phi(x)$ is a root of $g(x)$. Thus $g = (x - \alpha)(x - \beta)$ in $\mathbb{F}_{q^2}[x]$.

Moreover, every element in $\mathbb{F}_{q^2}$ is a root of $x^{q^2} - x$. Thus $g = (x - \alpha)(x - \beta) \mid x^{q^2} - x$. Therefore, $h(x)$ is divisible by all the irreducible monic quadratic polynomials that divide $f(x)$.

Finally, the set of roots of $x^{q^2} - x$ is exactly $\mathbb{F}_{q^2}$. Since $[\mathbb{F}_{q^2} : \mathbb{F}_q] = 2$, the degree of the minimal polynomial of each element must be either 1 or 2. In other words, $x^{q^2} - x$ is a product of some linear and quadratic polynomials in $\mathbb{F}_q[x]$.

Therefore, $h(x)$ is exactly the product of all the irreducible monic polynomials of degree 1 or 2 that divide $f(x)$. ($x^{q^2} - x$ may or may not be square free, but $f(x)$ is square free, so $h(x)$ must be square free.) $\square$

Lemma 3.1. *Suppose $f \in \mathbb{F}_q[x]$ is irreducible. Let $d \in \mathbb{N}$. Then $f \mid (x^{q^d} - x)$ if and only if $\deg(f) \mid d$.*

Proof. Let $d \in \mathbb{N}$ be given. Let $n = \deg(f)$. Then $\mathbb{F}_q[x]/(f(x)) = \mathbb{F}_{q^n}$ contains a root α of $f(x)$.

Suppose $n \mid d$. $\alpha^{q^n} - \alpha = 0$ implies $0 = (\alpha^{q^n} - \alpha)^{q^n} = \alpha^{q^{2n}} - \alpha^{q^n} = \alpha^{q^{2n}} - \alpha$. By repeating this process, we get $\alpha^{q^d} - \alpha = 0$ since $n \mid d$. Thus α satisfies $f(x)$ and $x^{q^d} - x$, and $f(x)$ is irreducible. Thus $f \mid x^{q^d} - x$.

Suppose $f(x) \mid (x^{q^d} - x)$. Since $f(x)$ is an irreducible polynomial with a root α, it must be the minimal polynomial of α. Thus $[\mathbb{F}_q(\alpha) : \mathbb{F}_q] = n$. $f(x) \mid (x^{q^d} - x)$ implies that α satisfies $x^{q^d} - x$. Thus $\alpha \in \mathbb{F}_{q^d}$. Then $d = [\mathbb{F}_{q^d} : \mathbb{F}_q(\alpha)][\mathbb{F}_q(\alpha) : \mathbb{F}_q]$, so $n \mid d$. $\square$

Exercise. (Problem 11) Given a square free polynomial $f(x) \in \mathbb{F}_q[x]$, describe how to use repeated gcd calculations to factor $f(x)$ as $f = f_1 f_2 \cdots f_r$, where each f_i is a product of distinct irreducible factors of degree i.

Proof. We will use Lemma 3.1 above. We will start with $n = 1$.

- If $f(x)$ is a unit, terminate.
- Calculate $h(x) = \gcd(x^{q^n} - x, f(x))$. This is the product of all irreducible polynomials of $f(x)$ of degree n by Lemma 3.1.
- Record $h(x)$. Set $f(x) = f(x)/h(x)$ and $n = n + 1$. Repeat.

Then the h's that we record are the products of distinct irreducible of factors of degree i for each i. $\square$

Exercise. (Problem 12) Prove the following criterion for a degree n polynomial $f(x) \in \mathbb{F}_q[x]$ to be irreducible: $f(x)$ is irreducible if and only if

- $\gcd(f(x), x^{q^n} - x) = f(x)$, and
- For each proper divisor d of n, $\gcd(f(x), x^{q^d} - x) = 1$.

Proof. Suppose $f(x)$ is irreducible. By Lemma 3.1, $\gcd(f(x), x^{q^n} - x) = f(x)$. Since the same lemma implies that $x^{q^d} - x$ cannot be divided by any irreducible polynomial of degree $> d$, $\gcd(f(x), x^{q^d} - x) = 1$.

Suppose the two conditions are met. We will show that $f(x)$ is irreducible. Let $g(x)$ be an irreducible polynomial that divides $f(x)$. Since $\gcd(f(x), x^{q^d} - x) = 1$ for each proper divisor d of n, $\gcd(g(x), x^{q^d} - x) = 1$ as well. By the lemma, $\deg(g(x)) \nmid d$. Since $\gcd(f, x^{q^n} - x) = f$, $\gcd(g, x^{q^n} - x) = g$. By the lemma, $\deg(g) \mid n$. Therefore, $\deg(g)$ is a divisor of n that is not a proper divisor of n. In other words, $\deg(g) = n$, so f is irreducible. $\square$

Exercise. (Problem 13) Suppose $f(x) \in \mathbb{F}_q[x]$ is a product of m distinct monic irreducible polynomials of degree r. To what ring is $\mathbb{F}_q[x]/(f(x))$ isomorphic?

Proof. By the Chinese remainder theorem, $\mathbb{F}_q[x]/(f(x)) = \mathbb{F}_q[x]/(f_1) \times \cdots \times \mathbb{F}_q[x]/(f_m)$. Thus $\mathbb{F}_q[x]/(f(x)) = \mathbb{F}_{q^r} \times \cdots \times \mathbb{F}_{q^r}$ (m times) $\square$