

Math 111C HW2

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1

Question 1 *Let $F \subseteq K \subseteq L$ be fields and let $\alpha \in L$ be algebraic over F . Prove that $[K(\alpha) : K] \leq [F(\alpha) : F]$.*

Pf:

Given that $\alpha \in L$ is algebraic over F , there exists minimal polynomial $f_{\alpha,F}(x) \in F[x]$, such that $f_{\alpha,F}(\alpha) = 0$. On the other hand, since $F[x] \subseteq K[x]$, then $f_{\alpha,F}(x)$ as a polynomial over K has α being a root, implies that α is also algebraic over K , hence its minimal polynomial $p_{\alpha,K}(x) \in K[x]$ exists, with $p_{\alpha,K}(\alpha) = 0$.

Now, since $f_{\alpha,F}(x) \in K[x]$ has α being a root, then it implies that $p_{\alpha,K}(x) \mid f_{\alpha,F}(x)$ (since minimal polynomial of α divides all polynomials having α being a root), hence $\deg(p_{\alpha,K}) \leq \deg(f_{\alpha,F})$.

Lastly, since α is algebraic over both F and K , then $F(\alpha) \cong F[x]/(f_{\alpha,F}(x))$ (which the extension has degree being $\deg(f_{\alpha,F})$) and $K(\alpha) \cong K[x]/(p_{\alpha,K}(x))$ (which the extension has degree being $\deg(p_{\alpha,K})$), then:

$$[K(\alpha) : K] = [K[x]/(p_{\alpha,K}(x)) : K] = \deg(p_{\alpha,K}) \leq \deg(f_{\alpha,F}) = [F[x]/(f_{\alpha,F}(x)) : F] = [F(\alpha) : F]$$

Hence, $[K(\alpha) : K] \leq [F(\alpha) : F]$.

2

Question 2 Let K/F be a field extension and $\alpha_1, \dots, \alpha_n \in K$ be algebraic over F . Prove that $F(\alpha_1, \dots, \alpha_n) = F[\alpha_1, \dots, \alpha_n]$.

Pf:

We'll prove this statement by induction on the number of elements n .

First, given arbitrary field F , for $n = 1$, if $\alpha_1 \in K/F$ is algebraic over F , if we consider its minimal polynomial $m_{\alpha, F}(x) \in F[x]$, since it is irreducible while $F[x]$ is a PID, then $F[x]/(m_{\alpha, F}(x))$ is a field.

Now, consider the following ring homomorphism $\phi : F[x]/(m_{\alpha, F}(x)) \rightarrow F[\alpha_1]$ by $\phi(\bar{x}) = \alpha_1$. Then, since it is a nonzero map, while $F[x]/(m_{\alpha, F}(x))$ is a field, then ϕ is injective; also, for all $a_k \alpha^k + \dots + a_0 \in F[\alpha]$, let $f(x) = a_k x^k + \dots + a_0 \in F[x]$, then $\overline{f(x)} = a_k \bar{x}^k + \dots + a_0 \in F[x]/(m_{\alpha, F}(x))$, it satisfies:

$$\phi(\overline{f(x)}) = \phi(a_k \bar{x}^k + \dots + a_0) = a_k \phi(\bar{x})^k + \dots + a_0 = a_k \alpha_1^k + \dots + a_0$$

This shows that ϕ is also surjective.

Then, because ϕ is bijective, $F[x]/(m_{\alpha, F}(x)) \cong F[\alpha_1]$, hence $F[\alpha_1]$ is a field.

Given that $F(\alpha_1)$ is a field containing all operations of F and α_1 , we know $F[\alpha_1] \subseteq F(\alpha_1)$; on the other hand, since $F(\alpha_1)$ is defined to be the smallest field containing both α_1 and F , because $F[\alpha_1]$ also satisfies this property, then $F(\alpha_1) \subseteq F[\alpha_1]$. This shows that $F(\alpha_1) = F[\alpha_1]$.

Now, suppose for given $n \in \mathbb{N}$, given arbitrary field F , any $\alpha_1, \dots, \alpha_n \in K/F$ that are algebraic over F satisfy $F(\alpha_1, \dots, \alpha_n) = F[\alpha_1, \dots, \alpha_n]$. Then, for the case $(n + 1)$, given arbitrary $\alpha_1, \dots, \alpha_n, \alpha_{n+1} \in K$ that are algebraic over F , we know $F(\alpha_1, \dots, \alpha_n, \alpha_{n+1}) = F(\alpha_1, \dots, \alpha_n)(\alpha_{n+1})$, which by induction hypothesis, $F(\alpha_1, \dots, \alpha_n) = F[\alpha_1, \dots, \alpha_n] = K''$. Then, since $F \subseteq K''$, while α_{n+1} is algebraic over F , then α_{n+1} is also algebraic over K'' , so its minimal polynomial $m(x) \in K''[x]$ exists (with respect to field K'').

Then, using the same logic for the case $n = 1$ (since initially we're using arbitrary field, then let $F = K''$ for the case $n = 1$), we know $K''[x]/(m(x)) \cong K''[\alpha_{n+1}] = K''(\alpha_{n+1})$.

Hence, we have the following:

$$\begin{aligned} F(\alpha_1, \dots, \alpha_n, \alpha_{n+1}) &= F(\alpha_1, \dots, \alpha_n)(\alpha_{n+1}) = K''(\alpha_{n+1}) = K''[\alpha_{n+1}] = F(\alpha_1, \dots, \alpha_n)[\alpha_{n+1}] \\ &= F[\alpha_1, \dots, \alpha_n][\alpha_{n+1}] = F[\alpha_1, \dots, \alpha_n, \alpha_{n+1}] \end{aligned}$$

This proves that $F(\alpha_1, \dots, \alpha_n, \alpha_{n+1}) = F[\alpha_1, \dots, \alpha_n, \alpha_{n+1}]$ for the case $(n + 1)$.

Finally, by the principle of mathematical induction, given arbitrary field F and field extension K/F , given any $\alpha_1, \dots, \alpha_n \in K$ that are algebraic over F , we have $F(\alpha_1, \dots, \alpha_n) = F[\alpha_1, \dots, \alpha_n]$.

Question 3 Let F be a field of characteristic p , where p is a prime number. Suppose that $x^p - a$ where $a \in F$, does not have a root in F . Show that $x^p - a$ is irreducible in $F[x]$.

Pf:

We'll prove by contradiction, that if $x^p - a$ has no roots in F , then $x^p - a \in F[x]$ is irreducible. Suppose it is reducible, then there exists nonconstant polynomials $q(x), r(x) \in F[x]$, with $x^p - a = q(x)r(x)$. (Note: it also implies $p = \deg(x^p - a) > \deg(q), \deg(r)$).

First, given $x^p - a \in F[x]$, we know there exists a field extension K/F , such that $x^p - a$ splits completely over K . In particular, there exists $b \in K$, such that $(x - b)$ is a linear factor of $x^p - a$. This implies that $b^p - a = 0$, or $b^p = a$ (since $(x - b)$ is a factor of the polynomial iff b is a root of the polynomial).

Now, since $F \subseteq K$, while K is an integral domain, then they share the same unity element 1; also, because $\text{char}(K)$ is dependent on the order of 1 under addition, while $\text{char}(F) = p$ is the order of 1, then $\text{char}(K) = \text{char}(F) = p$. Similar argument applies to $K[x]$, where $\text{char}(K[x]) = \text{char}(K) = p$. Hence, we can apply freshman's dream to the element $(x - b) \in K[x]$, and get that $(x - b)^p = x^p - b^p = x^p - a$.

This demonstrates that $(x - b)^p$ is a factorization of $x^p - a$, while $x^p - a = q(x)r(x)$. Then, since $q(x), r(x)$ divides $x^p - a$ while $x^p - a$ splits completely over K , then $q(x), r(x)$ must also split completely over K ; also, for the factorization to be unique, we must have $q(x) = (x - b)^k$ and $r(x) = (x - b)^l$, where $\deg(q) = k$ and $\deg(r) = l$.

Now, if we focus on $q(x) = (x - b)^l \in K[x]$, since $q(x) \in F[x]$, all of its coefficients should be in F , then the constant term of $q(x)$ (represented as $(-b)^l \in K$) should also be in F . But, here is a contradiction:

Since $b^p = a \in F$, there exists a minimum positive integer $n \leq p$, where $b^n \in F$, but if $n < p$, since p is a prime, then $n \nmid p$, hence $p = qn + r$, for $q, r \in \mathbb{N}$, and $0 < r < n$. Which, we get the following:

$$b^p = b^{nq+r} = (b^n)^q \cdot b^r \in F$$

Also, since $b^p = a$, while the equation $x^p - a$ has no roots in F , then $a \neq 0$, hence $b \neq 0$. This implies that $b^n \neq 0$, which is invertible in F . Hence:

$$((b^n)^{-1})^q \cdot (b^n)^q \cdot b^r = b^r \in F$$

However, since $b^r \in F$ and $0 < r < n$, while n is assumed to be the smallest positive integer satisfying $b^n \in F$, we reach a contradiction.

Therefore, our initial assumption must be false, $x^p - a \in F[x]$ must be irreducible.

Question 4

- (a) Find all ring homomorphisms $\Psi : \mathbb{Q}[x] \rightarrow \mathbb{C}$.
- (b) Find all ring homomorphisms $\Psi_1 : \mathbb{Q}[x]/(x^3 - 2) \rightarrow \mathbb{C}$ and $\Psi_2 : \mathbb{Q}[x]/(x^3 - 2) \rightarrow \mathbb{R}$.

Pf:

- (a) First, the zero map $\Psi = 0$ is an answer.

Now, suppose $\Psi \neq 0$, then because $\Psi(\mathbb{Q}[x]) \subset \mathbb{C}$ is a nontrivial subring, while \mathbb{C} is an integral domain, then all its nontrivial subring must have the same identity. Hence, $\Psi(1) = 1 \in \mathbb{C}$.

This also implies that for all $q \in \mathbb{Q}$, $\Psi(q) = q$: Since $\Psi(1) = 1$, then for all $a \in \mathbb{Z}$, $\Psi(a) = a$; now, if represent $q = \frac{a}{b}$ for $a, b \in \mathbb{Z}$, $b \neq 0$, then we get:

$$\Psi(q) = \Psi(a \cdot b^{-1}) = \Psi(a) \cdot \Psi(b)^{-1} = a \cdot b^{-1} = q$$

Hence, all the rationals are fixed by the homomorphism.

Now, we can simply define $\Psi(x) = a$ for arbitrary $a \in \mathbb{C}$. Then, for all $f(x) = \sum_{k=0}^n f_k x^k \in \mathbb{Q}[x]$, we get:

$$\Psi(f(x)) = \Psi\left(\sum_{k=0}^n f_k x^k\right) = \sum_{k=0}^n \Psi(f_k) \cdot \Psi(x)^k = \sum_{k=0}^n f_k a^k$$

So, all the nonzero possibilities are characterized by $\Psi(1) = 1$, and $\Psi(x) = a$ for arbitrary $a \in \mathbb{C}$.

- (b) Notice that since $x^3 - 2$ has no roots over \mathbb{Q} , then it must be irreducible. Hence, $\mathbb{Q}[x]/(x^3 - 2)$ is in fact a field (since the ideal $(x^3 - 2) \subset \mathbb{Q}[x]$ is maximal).

Possibility of Ψ_1 :

First, the zero map $\Psi_1 = 0$ is always an answer.

For other possibilities, suppose $\Psi_1 \neq 0$, because $\mathbb{Q}[x]/(x^3 - 2)$ is a field, then Ψ_1 must be injective, hence $\mathbb{Q}[x]/(x^3 - 2) \cong \Psi_1(\mathbb{Q}[x]/(x^3 - 2)) \subseteq \mathbb{C}$. In this case, since the image is nontrivial, while \mathbb{C} in particular is an integral domain, then all its subring (including the image of Ψ_1) must have the same identity as \mathbb{C} , so $\Psi_1(1) = 1 \in \mathbb{C}$.

Then, since $\bar{x} \in \mathbb{Q}[x]/(x^3 - 2)$ satisfies $\bar{x}^3 - 2 = \overline{x^3 - 2} = 0$, hence $\Psi_1(\bar{x}) \in \mathbb{C}$ must also satisfy this relationship, namely:

$$0 = \Psi_1(\bar{x}^3 - 2) = \Psi_1(\bar{x})^3 - \Psi_1(2) = \Psi_1(\bar{x})^3 - 2$$

(Note: since $\Psi_1(1) = 1$, then $\Psi_1(2) = \Psi_1(1 + 1) = \Psi_1(1) + \Psi_1(1) = 2$).

So, $\alpha = \Psi_1(\bar{x}) \in \mathbb{C}$ must satisfy $\alpha^3 - 2 = 0$, which is a root of $x^3 - 2 \in \mathbb{C}[x]$. Then, the only possibilities of $\alpha \in \mathbb{C}$ is $\alpha = \sqrt[3]{2}$, $\sqrt[3]{2}e^{i \cdot 2\pi/3}$, $\sqrt[3]{2}e^{i \cdot 4\pi/3}$.

Therefore, if $\Psi_1 \neq 0$, then it must satisfy $\Psi_1(1) = 1$, and $\Psi_1(\bar{x}) = \sqrt[3]{2}$, $\sqrt[3]{2}e^{i \cdot 2\pi/3}$, or $\sqrt[3]{2}e^{i \cdot 4\pi/3}$.

Possibility of Ψ_2 :

Again, the zero map $\Psi_2 = 0$ is an answer.

Now, suppose $\Psi_2 \neq 0$, again because $\mathbb{Q}[x]/(x^3 - 2)$ is a field, Ψ_2 must be injective, and $\Psi_2(1) = 1 \in \mathbb{R}$ (based on the same reason as described in Ψ_1).

Then, since $\bar{x} \in \mathbb{Q}[x]/(x^3 - 2)$ satisfies $\bar{x}^3 - 2 = 0$, hence $0 = \Psi_2(\bar{x}^3 - 2) = \Psi_2(\bar{x})^3 - \Psi_2(2) = \Psi_2(\bar{x})^3 - 2$. So, $\beta = \Psi_2(\bar{x}) \in \mathbb{R}$ satisfies $\beta^3 - 2 = 0$, which is a root of $x^3 - 2 \in \mathbb{R}[x]$. Then, the only possibility of $\beta \in \mathbb{R}$ is $\beta = \sqrt[3]{2}$.

Therefore, if $\Psi_2 \neq 0$, then it must satisfy $\Psi_2(1) = 1$, and $\Psi_2(\bar{x}) = \sqrt[3]{2}$.

5

Question 5 Let p be prime number and F be a finite field with $q = p^k$ elements. Prove that

$$x^{q-1} - 1 = \prod_{\alpha \in F^\times} (x - \alpha)$$

in $F(x)$. By comparing coefficients of suitable powers of x , conclude that

(a)

$$\sum_{\alpha \in F^\times} \alpha = 0$$

(b)

$$\prod_{\alpha \in F^\times} \alpha = -1$$

Pf:

Since F is a finite field with order $|F| = q$, then F^\times is a group under multiplication with $|F^\times| = q - 1$ (without 0). Hence, for all $\alpha \in F^\times$, $\alpha^{q-1} = 1$ (since 1 is the identity of F^\times , and all element's order in a finite group divides the order of the group itself).

So, given $x^{q-1} - 1 \in F[x]$, since F is a field, and the polynomial has degree $q - 1$, it has at most $q - 1$ roots counting multiplicity; on the other hand, all $\alpha \in F^\times$ satisfies $\alpha^{q-1} - 1 = 1 - 1 = 0$, hence α is a root of $x^{q-1} - 1$. And, since there are $q - 1$ distinct elements in F^\times , then F^\times in fact contains (and only contains) all the roots of $x^{q-1} - 1$.

Now, because each $\alpha \in F^\times$ is a root of $x^{q-1} - 1$, then $(x - \alpha) \mid (x^{q-1} - 1)$, $x^{q-1} - 1 = (x - \alpha)q_1(x)$. Then, for a distinct $\beta \in F^\times$, since $0 = \beta^{q-1} - 1 = (\beta - \alpha)q_1(\beta)$, while $\beta \neq \alpha$, then $q_1(\beta) = 0$, showing that $(x - \beta) \mid q_1(x)$. So, inductively, we can factor out all $(x - \alpha)$ (with $\alpha \in F^\times$) as a linear factor of $x^{q-1} - 1$, showing the following:

$$x^{q-1} - 1 = f(x) \prod_{\alpha \in F^\times} (x - \alpha), \quad f(x) \in F[x], \quad f(x) \neq 0$$

On the other hand, the left hand side above has degree $q - 1$, while the right hand side has degree $\deg(f) + \deg(\prod_{\alpha \in F^\times} (x - \alpha)) \geq \deg(\prod_{\alpha \in F^\times} (x - \alpha)) = q - 1$ (Note: since there are $q - 1$ elements in F^\times , then $\prod_{\alpha \in F^\times} (x - \alpha)$ is a product of $q - 1$ linear factors, hence has degree $q - 1$). So, this enforces $\deg(f) = 0$, which the nonzero $f(x) \in F$ must be an invertible element.

Lastly, if we consider the leading coefficient, the left hand side has coefficient 1, while the right side has coefficient $f(x)$, hence $f(x) = 1$, showing the following:

$$x^{q-1} - 1 = \prod_{\alpha \in F^\times} (x - \alpha)$$

- (a) Given the above statement, if we consider the coefficient of degree $q-2$, we get 0 for $x^{q-1} - 1$; on the right side, since x^{q-2} can only be obtained by choosing 1 linear factor to multiply with its constant, while the other factors are x , then the x^{q-2} has the coefficient $\sum_{\alpha \in F^\times} -\alpha$. Hence, $\sum_{\alpha \in F^\times} \alpha = 0$.
- (b) Again, if we consider the constant term, we get -1 for $x^{q-1} - 1$; on the right side, since constant term can only be obtained by the product of all constant terms, then it has constant term $\prod_{\alpha \in F^\times} \alpha$. Hence, $\prod_{\alpha \in F^\times} \alpha = -1$.