MATH 370 (Sp. 2025): ULA Midterm I Review Session (with Lực Ta and Adam Wesley)

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Problem 1. Let F be a subfield of $\mathbb{C}$, and let K/F be a degree 2 extension. Is K/F necessarily Galois?

Solution. Yes. Since $F \subset \mathbb{C}$, HW2 problem 4 (Stewart 5.5) implies that $K = F(\sqrt{\lambda})$ for some $\lambda \in F$ (and $\sqrt{\lambda} \notin F$ by hypothesis). Thus, K is the splitting field of $x^2 - \lambda \in F[x]$. □

Problem 2. Let $F \subset M \subset K$ be fields.

(a) Suppose K/F is Galois. Is K/M necessarily Galois?

Solution. Yes, by the fundamental theorem of Galois theory. □

(b) Suppose K/F is Galois. Is M/F necessarily Galois?

Solution. No. Take $F = \mathbb{Q}$ and $M = \mathbb{Q}({}^3\sqrt{2})$, and let K be the splitting field of $x^3 - 2$ (so that $K = \mathbb{Q}(\sqrt[3]{2}, \zeta_3)$, where $\zeta_3 = \exp(2\pi i/3)$ is a third root of unity). Since K is the splitting field of an irreducible (by Eisenstein with $p = 2$) polynomial over $\mathbb{C}$, we know K/F is Galois. But M/F isn't Galois because $[M : F] = 3 \neq 1 = |\operatorname{Gal}(M/F)|$. □

(c) Suppose M/F and K/M are both Galois. Is K/F necessarily Galois?

Solution. No. Take $F = \mathbb{Q}$, $M = \mathbb{Q}(\sqrt{2})$, and $K = \mathbb{Q}(\sqrt[4]{2})$. □

Problem 3. Classify the Galois groups of the following polynomials.

(a) $f(x) := x^3 - 3x + 1$ over $\mathbb{Q}$.

Solution. It's irreducible by reduction modulo 2 (it's cubic, so it's reducible if and only if it has a root, which it doesn't in $\mathbb{F}_2$). So, a theorem from class says that the Galois group is $A_3 \cong Z_3$ if the discriminant is a square in $\mathbb{Q}$ and S_3 otherwise. Indeed, the discriminant is 81, so the Galois group is Z_3. □

(b) The minimal polynomial of $\sqrt{2+i}$ over $\mathbb{Q}$.

Solution. Call this thing α. The minimal polynomial is $f(x) := x^4 - 4x^2 + 5$, which is irreducible over $\mathbb{Q}$; $f(x+1) = x^4 + 4x^3 + 2x^2 - 4x + 2$ is irreducible by Eisenstein with $p = 2$. (Alternatively, you could reduce modulo 2, check that $\overline{f}$ has no roots in $\mathbb{F}_2$, and then conclude that it also doesn't factor into irreducible quadratics since the only such quadratic over $\mathbb{F}_2$ is $x^2 + x + 1$, which doesn't square to $\overline{f}$.)

Thus, $\mathbb{Q}(\alpha)$ has degree 4, but is it the splitting field? Well, using the quadratic formula on $f(\sqrt{x})$, we find that the roots of f are $\pm\alpha$ and $\pm\beta$, where $\beta = \sqrt{2-i}$. In particular, the roots are all distinct, so by a problem from HW4, the form of f tells us that the Galois group is contained in D_4.

On the other hand, $\alpha\beta = \sqrt{5} \notin \mathbb{Q}(\alpha)$, so $\beta \notin \mathbb{Q}(\alpha)$, so the splitting field—which is $\mathbb{Q}(\alpha, \beta)$—isn't $\mathbb{Q}(\alpha)$. It follows that the Galois group has order greater than 4, but it's contained in D_4, so it has to be D_4. (Indeed, we have $i \in \mathbb{Q}(\alpha)$, so the minimal polynomial of β over $\mathbb{Q}(\alpha)$ is $x^2 - 2 + i$.) □

(c) The minimal polynomial of $\sqrt{2+\sqrt{2}}$ over $\mathbb{Q}$.

Solution. Call this thing α, and call the splitting field K. To find $[K:\mathbb{Q}] = |\operatorname{Gal}(K/\mathbb{Q})|$, one can compute that α is a root of $x^4 - 4x^2 + 2$, which is irreducible over $\mathbb{Q}$ by Eisenstein with $p = 2$. So, $\mathbb{Q}(\alpha)$ has degree order 4.

But does K also have order 4? Well, let's find out what the roots are by using the quadratic formula on $x^2 - 4x + 2$. We get that the roots are $\pm\alpha$ and $\pm\beta$, where $\beta = \sqrt{2-\sqrt{2}}$, so $K = \mathbb{Q}(\alpha, \beta)$. By squaring α, we observe that $\mathbb{Q}(\alpha)$ contains $\sqrt{2}$. Does it also contain β? One litmus test is to see what $\alpha\beta$ is. It's actually $\sqrt{2}$, which, sure enough, is in $\mathbb{Q}(\alpha)$. Therefore, $\mathbb{Q}(\alpha) \ni \sqrt{2}/\alpha = \beta$. Hence, $\mathbb{Q}(\alpha) = K$, so the Galois group has order 4.

So, is it $Z_2 \times Z_2$ or Z_4? Well, if α is sent to $-\alpha$, then $-\alpha$ is sent to α. Similarly, if β is sent to $-\beta$, then $-\beta$ is sent to β. This gives us two distinct elements of order 2 in the Galois group, so it's $Z_2 \times Z_2$ since Z_4 only has one element of order 2. □

(d) $f(x) := x^4 - 2$ over F, where F is the splitting field of $x^2 - 2$ over $\mathbb{Q}$.

Solution. Write $F = \mathbb{Q}(\sqrt{2})$. The splitting field of f over $\mathbb{Q}$ is $K := \mathbb{Q}(\sqrt[4]{2}, i) = F(\sqrt[4]{2}, i)$, and $\operatorname{Gal}(K/\mathbb{Q}) \leq D_4$ by a problem from HW4 (look at the form of f). It follows from the Tower Law that

$$|\operatorname{Gal}(K/F)| = [K:F] = \frac{[K:\mathbb{Q}]}{[F:\mathbb{Q}]} = \frac{|\operatorname{Gal}(K/\mathbb{Q})|}{2} \leq \frac{|D_4|}{2} = 4,$$

so $\operatorname{Gal}(K/F)$ is either 1, Z_2, Z_4, or $Z_2 \times Z_2$.

We claim that $\operatorname{Gal}(K/F) \cong Z_2 \times Z_2$. By the bound from above, it will suffice to just find two distinct elements of order 2, since that will imply that $Z_2 \times Z_2 \leq \operatorname{Gal}(K/F)$. Indeed, consider the maps $[\sqrt[4]{2} \mapsto -\sqrt[4]{2}, i \mapsto i]$ and $[\sqrt[4]{2} \mapsto \sqrt[4]{2}, i \mapsto -i]$. These are two valid automorphisms of order 2 that fix F, so we're done. (Note that $\sqrt[4]{2}$ can't be sent to $\pm i\sqrt[4]{2}$ since then $\sqrt{2} = (\sqrt[4]{2})^2$ would get sent to $(\pm i\sqrt[4]{2})^2 = -\sqrt{2}$, meaning that F wouldn't be fixed.)

Or, we can deduce that it's $Z_2 \times Z_2$ (as opposed to Z_4) by the fundamental theorem of Galois theory, since K has two distinct subextensions of degree 2 over F (which, by the fundamental theorem, correspond to two distinct subgroups of order 2 in $\operatorname{Gal}(K/F)$). □

(e) The same polynomial as in the last part, but now over $\mathbb{Q}$.

Solution. It's D_4. The previous part and the Tower Law imply that $[K:\mathbb{Q}] = 8$. The only subgroup of order 8 in S_4, thanks to Sylow II. □

Problem 4. Let K be a subfield of $\mathbb{R}$, and let $f \in K[x]$ be an irreducible polynomial. Show that if the Galois group of f has odd order, then the discriminant of f is positive.

Solution. Let's prove the contrapositive. Note that the discriminant of f can't be 0, since then f would have a repeated root, making it inseparable and thus (by virtue of the fact that $K \subset \mathbb{C}$) reducible.

So, suppose that the discriminant of f is negative. Then, by the definition of the discriminant in terms of the roots, at least one of the roots α is nonreal; since $K \subset \mathbb{R}$, it follows that $\overline{\alpha}$ is also a (distinct) root of f. Therefore, complex conjugation is an order 2 element of f (rather than an order 1 element), so by Lagrange's theorem, the Galois group has even order.

(Note that complex conjugation is always in the Galois group of a polynomial over a real ground field—sometimes as an order 1 element/the identity map, other times as an order 2 element—because complex conjugation fixes $\mathbb{R}$ and is a field automorphism of $\mathbb{C}$.) □

Problem 5. Let K/F be a Galois extension such that $\mathrm{Gal}(K/F) \cong Z_3 \times Z_{18}$. How many intermediate fields M are there such that

(a) $[M : F] = 18$

Solution. Four Z_3's, one generated by $(1, 0)$ and the others generated by $(n, 6)$ for $n = 0, 1, 2$. □

(b) $[M : F] = 27$

Solution. There's a unique Z_2, generated by $(0, 9)$. To see that this is the unique one, note that in $Z_3 \times Z_{18} \cong Z_3 \times Z_9 \times Z_2$, there can't be any nonidentity elements of order dividing 2 inside the Z_3 or the Z_9. □

(c) $[M : F] = 3$

Solution. Four. There's one $Z_3 \times Z_6 \cong Z_3 \times Z_3 \times Z_2$, which we can see by writing $Z_3 \times Z_{18} \cong Z_3 \times Z_9 \times Z_2$. There are also three Z_{18}'s, namely those generated by $(n, 1)$ for $n = 0, 1, 2$. □

(d) $[M : F] = 6$

Solution. Four. There's one $Z_3 \times Z_3$, namely $\langle (1, 0), (0, 6) \rangle$, and three Z_9's, namely those generated by $(n, 2)$ for $n = 0, 1, 2$. □

(e) $\mathrm{Gal}(K/M) \cong Z_2$

Solution. This is the same as part (b). □

(f) $|\,\mathrm{Gal}(K/M)| = 6$

Solution. Four. Note that such a subgroup is an abelian group, so it must be isomorphic to $Z_6 \cong Z_3 \times Z_2$. So, you can reason through this one by decomposing $Z_3 \times Z_{18} \cong Z_3 \times Z_9 \times Z_2$ and using the previous parts. Or, you could note first that $(1, 0)$ and $(0, 9)$ generate a $Z_3 \times Z_2 \cong Z_6$. We also have three other copies of Z_6, each generated by $(n, 3)$ for $n = 0, 1, 2$. □

(g) $\mathrm{Gal}(K/M) \cong Z_{27}$

Solution. None. □

(h) $|\,\mathrm{Gal}(K/M)| = 27$

Solution. Just one, generated by $(1, 0)$ and $(0, 2)$. □

Problem 6. True or false? Justify your answer.

(a) If $\alpha \neq \beta$ are both irrational, then $\mathbb{Q}(\alpha, \beta)$ is not a simple extension of $\mathbb{Q}$.

(b) Every algebraic extension is finite.

(c) Two extensions of the same degree are isomorphic.

(d) Suppose there exist α and β such that the extensions $\mathbb{Q}(\alpha)/\mathbb{Q}$ and $\mathbb{Q}(\beta)/\mathbb{Q}$ are isomorphic. Then α and β have the same minimal polynomial over $\mathbb{Q}$.

Problem 7. Let $K/\mathbb{Q}$ be a Galois extension of degree 4 and suppose that $i \in K$. Prove that $\mathrm{Gal}(K/\mathbb{Q}) \simeq Z_2 \times Z_2$. *Hint: what can you say about the extension $K/\mathbb{Q}(i)$?*

Problem 8. Show that there are infinitely many irreducible polynomials over any field. *Hint: think about Euclid's proof that there are infinitely many primes in $\mathbb{Z}$.*

You're doing great! :)