Solutions to David A.Cox "Galois Theory"

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6 Chapter 6 : THE GALOIS GROUP

6.1 DEFINITION OF THE GALOIS GROUP

Ex. 6.1.1 *Let $L = F(\alpha_1, \ldots, \alpha_n)$, and let $p_i \in F[x]$ be a nonzero polynomial vanishing at α_i. Explain why the proof of Corollary 6.1.5 implies that $|\mathrm{Gal}(L/F)| \le \deg(p_1)\cdots\deg(p_n)$.*

Proof. $L = F(\alpha_1, \cdots, \alpha_n)$, where α_i is algebraic over F. α_i is the root of a polynomial $p_i \in F(x)$.

By Proposition 6.1.4, every $\sigma \in \mathrm{Gal}(L/F)$ is uniquely determined by the images of $\alpha_i, i = 1, \cdots, n$. α_i being a root of $p_i \in F[x]$, $\sigma(\alpha_i)$ is also a root of p_i. So there exist only $\deg(p_i)$ possibilities for the choice of $\sigma(\alpha_i)$.

More formally, write R_i the set of the roots of p_i in L, then $\sigma(\alpha_i) \in R_i$, with $|R_i| \le \deg(p_i)$, and the map

$$\left\{ \begin{array}{ccc} \mathrm{Gal}(L/F) & \to & R_1 \times \cdots \times R_n \\ \sigma & \mapsto & (\sigma(\alpha_1), \cdots, \sigma(\alpha_n)) \end{array} \right.$$

is injective (one-to-one), since $\sigma \in \mathrm{Gal}(L/F)$ is uniquely determined by the images of $\alpha_i,\ i = 1, \cdots, n$.

Therefore

$$|\mathrm{Gal}(L/F)| \le |R_1| \times \cdots \times |R_n| \le \deg(p_1)\cdots\deg(p_n).$$

□

Ex. 6.1.2 *Consider the extension $\mathbb{Q} \subset L = \mathbb{Q}(\sqrt{2}, \sqrt{3})$. In Exercise 13 of Section 5.1, you used Proposition 5.1.8 to construct an automorphism of L that takes $\sqrt{3}$ to $-\sqrt{3}$ and is the identity on $\mathbb{Q}(\sqrt{2})$. By interchanging the roles of 2 and 3 in this construction, explain why all possible signs in (6.1) can occur. This shows that $|\mathrm{Gal}(L/\mathbb{Q})| = 4$.*

Proof. As $L = \mathbb{Q}(\sqrt{2}, \sqrt{3})$ is the splitting field of $x^2 - 3$ over $\mathbb{Q}(\sqrt{2})$, and as $x^2 - 3$ is irreducible over $\mathbb{Q}(\sqrt{2})$ (see Exercise 5.1.13), there exists by Proposition 5.1.8 a field isomorphism $\sigma : L \to L$ which is identity on $\mathbb{Q}(\sqrt{2})$ and which takes $\sqrt{3}$ on $-\sqrt{3}$. As σ is identity on $\mathbb{Q}(\sqrt{2})$, we have also $\sigma(\sqrt{2}) = \sqrt{2}$. As the restriction of σ to $\mathbb{Q}(\sqrt{2})$ is identity, the restriction of σ to $\mathbb{Q}$ is the identity on $\mathbb{Q}$, so $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$.

Similarly $\mathbb{Q}(\sqrt{2}, \sqrt{3})$ is the splitting field of x^2-2 over $\mathbb{Q}(\sqrt{3})$, and x^2-2 is irreducible over $\mathbb{Q}(\sqrt{3})$ by the Reciprocity Theorem (see Exercise 4.3.6), so there exists by Proposition 5.1.8 a field isomorphism $\tau : L \to L$ which is identity on $\mathbb{Q}(\sqrt{3})$ and which takes $\sqrt{2}$ on $-\sqrt{2}$. As τ is identity on $\mathbb{Q}(\sqrt{3})$, we have also $\sigma(\sqrt{3}) = \sqrt{3}$, and $\tau \in \mathrm{Gal}(L/\mathbb{Q})$.

Moreover $1_L(\sqrt{2}) = \sqrt{2}, 1_L(\sqrt{3}) = \sqrt{3}$, avec $1_L \in \mathrm{Gal}(L/\mathbb{Q})$.

Finally $\sigma\tau = \sigma \circ \tau \in \mathrm{Gal}(L/\mathbb{Q})$ satisfies $(\sigma\tau)(\sqrt{2}) = -\sqrt{2}, (\sigma\tau)(\sqrt{3}) = -\sqrt{3}$.

All possibilities in Example 6.1.10 can occur. Consequently $|\mathrm{Gal}(L/\mathbb{Q})| \geq 4$. As it is proved in Example 6.1.10 that $|\mathrm{Gal}(L/\mathbb{Q})| \leq 4$, then $|\mathrm{Gal}(L/\mathbb{Q})| = 4$, and

$$\mathrm{Gal}(\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}) = \{1_L, \sigma, \tau, \sigma\tau\}.$$

□

Ex. 6.1.3 *This exercise will prove a generalizes form of Proposition 6.1.11.*

(a) Let $\varphi : L_1 \to L_2$ be an isomorphism of fields. Given a subfield $F_1 \subset L_1$, set $F_2 = \varphi(F_1)$, which is a subfield of L_2. Prove that the map sending $\sigma \in \mathrm{Gal}(L_1/F_1)$ to $\varphi \circ \sigma \circ \varphi^{-1}$ induces an isomorphism $\mathrm{Gal}(L_1/F_1) \simeq \mathrm{Gal}(L_1/F_2)$.

(b) Explain why Proposition 6.1.11 follows from part (a).

Proof. (a) If $\varphi : L_1 \to L_2$ is a field isomorphism, and $\sigma \in \mathrm{Gal}(L_1/F_1)$, then $\sigma : L_1 \to L_1$, and so $\varphi \circ \sigma \circ \varphi^{-1}$ is a map from L_2 to L_2, composed of three field isomorphisms, is an automorphism of L_2.

Moreover, if $\alpha \in F_2$, then $\varphi^{-1}(\alpha) \in F_1$, since $F_2 = \varphi(F_1)$. As $\sigma \in \mathrm{Gal}(L_1/F_1)$, σ is identity on F_1, thus $\sigma(\varphi^{-1})(\alpha)) = \varphi^{-1}(\alpha)$, and $(\varphi \circ \sigma \circ \varphi^{-1})(\alpha) = \alpha$. Consequently

$$\varphi \circ \sigma \circ \varphi^{-1} \in \mathrm{Gal}(L_2/F_2).$$

Let

$$\chi : \left\{ \begin{array}{ccc} \mathrm{Gal}(L_1/F_1) & \to & \mathrm{Gal}(L_2/F_2) \\ \sigma & \mapsto & \varphi \circ \sigma \circ \varphi^{-1} \end{array} \right.$$

If $\sigma, \tau \in \mathrm{Gal}(L_1/F_1)$,

$$\chi(\sigma)\chi(\tau) = \varphi \circ \sigma \circ \varphi^{-1} \circ \varphi \circ \tau \circ \varphi^{-1} = \varphi \circ \sigma \circ \tau \circ \varphi^{-1} = \chi(\sigma \circ \tau).$$

χ is so a group homomorphism.

Moreover, if $\chi(\sigma) = \mathrm{id}$, alors $\varphi \circ \sigma \circ \varphi^{-1} = \mathrm{id}$, then $\sigma = \varphi^{-1} \circ \varphi = \mathrm{id}$: $\ker(\chi) = \{\mathrm{id}\}$, so χ is injective.

If $\tau \in \mathrm{Gal}(L_2/F_2)$, let $\sigma = \varphi^{-1} \circ \tau \circ \varphi$, then $\sigma \in \mathrm{Gal}(L_1/F_1)$ with the same arguments, and $\chi(\sigma) = \tau$, thus χ is surjective.

Conclusion : $\chi : \mathrm{Gal}(L_1/F_1) \to \mathrm{Gal}(L_2/F_2)$ is a group isomorphism.

(b) Suppose as in Proposition 6.1.11 that the restriction of φ to F is identity, and let $F_1 = F$. Then $F_2 = \varphi(F_1) = F_1 = F$, and part (a) shows that

$\chi : \mathrm{Gal}(L_1/F) \to \mathrm{Gal}(L_2/F), \sigma \mapsto \varphi \circ \sigma \circ \varphi^{-1}$ is a group isomorphism : this is Proposition 6.1.11.

□

Ex. 6.1.4 *In the Historical Notes, we saw that Dedekind defined a "permutation" $\alpha \to \alpha'$ to be a map $\Omega \to \omega'$ satisfying $(\alpha+\beta)' = \alpha' + \beta'$ and $(\alpha\beta)' = \alpha'\beta'$ for all $\alpha\beta \in \Omega$. Dedekind also assumes that $\Omega' = \{\alpha' \mid \alpha \in \Omega]$ and that the α' are not all zero.*

(a) Show that $1 \in \Omega$ maps to $1 \in \Omega'$. Once this is proved, it follows that $\alpha \mapsto \alpha'$ is a ring homomorphism (Recall that sending 1 to 1 is part of the definition of ring homomorphism given in Appendix A.)

(b) Show that the map $\alpha \to \alpha'$ is one-to-one. This shows that Dedekind's definition of field is equivalent to ours.

Proof. Let $\varphi : \alpha \to \alpha'$. By hypothesis, for all $\alpha, \beta \in \Omega$,

$$\varphi(\alpha + \beta) = \varphi(\alpha) + \varphi(\beta), \varphi(\alpha\beta) = \varphi(\alpha)\varphi(\beta).$$

(a) By hypothesis, there exists $\alpha \in \Omega$ such that $\alpha' = \varphi(\alpha) \neq 0$. Then $\varphi(\alpha) = \varphi(\alpha.1) = \varphi(\alpha)\varphi(1)$, and since $\varphi(\alpha) \neq 0$, $\alpha' = \varphi(\alpha)$ has a inverse in Ω, thus

$$\varphi(1) = 1.$$

φ is so a ring homomorphism between two fields.

(b) We show that φ is injective:

If $a \neq 0$, there exists an iverse b of a : $ab = 1$, thus $\varphi(a)\varphi(b) = \varphi(ab) = \varphi(1) = 1$, therefore $\varphi(a) \neq 0$. The kernel of φ is null, thus φ is injective.

As $\Omega' = \{\varphi(\alpha), \alpha \in \Omega\}$, φ is surjective. So $\varphi : \Omega \to \Omega'$ is a field isomorphism.

$\square$

Ex. 6.1.5 *Prove the following inequalities:*

(a) $|\mathrm{Gal}(\mathbb{Q}(\sqrt{2}, \sqrt{3}, \sqrt{5})/\mathbb{Q})| \leq 8$

(b) $|\mathrm{Gal}(\mathbb{Q}(\sqrt{p_1}, \ldots, \sqrt{p_n})/\mathbb{Q})| \leq 2^n$*, where $p_1, \ldots, p_n$ are the first n primes. In each case, one can show that these are actually equalities.*

Proof. (a) As $\sqrt{2}$ is a root of $f_1 = x^2 - 2$, $\sqrt{3}$ a root of $f_2 = x^2 - 3$, and $\sqrt{5}$ a root of$f_3 = x^2 - 5$, Exercise 1 shows that

$$|\mathrm{Gal}(F(\sqrt{2}, \sqrt{3}, \sqrt{5})/F)| \leq \deg(f_1)\deg(f_2)\deg(f_3) = 8.$$

(b) As $\sqrt{p_i}$ is a root of $f_i = x^2 - p_i$, the same Exercise 1 shows that

$$|\mathrm{Gal}(F(\sqrt{p_1}, \cdots, \sqrt{p_n})/F)| \leq \deg(f_1)\cdots\deg(f_n) = 2^n.$$

$\square$

Ex. 6.1.6 *If we apply Exercise 1 to the extension* $\mathbb{Q} \subset L = \mathbb{Q}(\sqrt{6}, \sqrt{10}, \sqrt{15})$, *we get the inequality* $|\mathrm{Gal}(L/\mathbb{Q})| \leq 8$. *Show that* $|\mathrm{Gal}(L/\mathbb{Q})| \leq 4$.

Proof. $L = \mathbb{Q}(\sqrt{6}, \sqrt{10}, \sqrt{15})$.

$\sqrt{15} = \sqrt{3 \cdot 5} = 3\frac{\sqrt{10}}{\sqrt{6}} \in \mathbb{Q}(\sqrt{6}, \sqrt{10})$, therefore

$$L = \mathbb{Q}(\sqrt{6}, \sqrt{10}, \sqrt{15}) = \mathbb{Q}(\sqrt{6}, \sqrt{10}).$$

Then Exercise 1 shows that

$$|\mathrm{Gal}(L/\mathbb{Q})| \leq 4$$

.

Note : moreover, $x^2 - 10$ is irreducible over $\mathbb{Q}(\sqrt{6})$, otherwise the roots $\pm\sqrt{10}$ of f would be in $\mathbb{Q}(\sqrt{6})$, and then

$$\sqrt{10} = a + b\sqrt{6},\ a, b \in \mathbb{Q}(\sqrt{6}).$$

By squaring, we obtain $10 = a^2 + 6b^2 + 2ab\sqrt{6}$. The irrationality of$\sqrt{6}$ shows that $ab = 0, a^2 + 6b^2 = 10$. Since $\sqrt{10}$ and $\sqrt{\frac{5}{3}}$ are irrational, this system has no solution in $\mathbb{Q} \times \mathbb{Q}$.

$x^2 - 10$ is irreducible over $\mathbb{Q}(\sqrt{6})$, thus

$$[\mathbb{Q}(\sqrt{6}, \sqrt{10}) : \mathbb{Q}] = [\mathbb{Q}(\sqrt{6}, \sqrt{10}) : \mathbb{Q}(\sqrt{6}] \cdot [\mathbb{Q}(\sqrt{6}) : \mathbb{Q}] = 4.$$

Using section 6.2, as L is the splitting field of the separable polynomial $(x^2 - 6)(x^2 - 10)$ over $\mathbb{Q}$, we obtain

$$|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}] = 4.$$

$\square$

Ex. 6.1.7 *Let* $F \subset L$ *be a finite extension, and let* $\sigma : L \to L$ *be a ring homomorphism that is the identity on* F. *This exercise will show that* σ *is an automorphism.*

(a) *Show that* σ *is one-to-one.*

(b) *Show that* σ *is onto.*

Proof. (a) Let $a \in L, a \neq 0$. Then a has an inverse b in the field L, so $ab = 1$, $\sigma(a)\sigma(b) = \sigma(1) = 1$, $\sigma(a) \neq 0$. Therefore $\ker(\sigma) = \{0\}$, thus σ is injective.

$\sigma : L \to L$ is an injective field homomorphism.

(b) As $K \subset L$ is a finite extension, L is a finite dimensional vector space over F. As σ ris identity on F, $\sigma : L \to L$ is an injective linear application on a finite dimensional vector space, thus σ is also surjective :

$$\sigma \in \mathrm{Gal}(L/F).$$

$\square$

6.2 GALOIS GROUPS OF SPLITTING FIELDS

Ex. 6.2.1 *Complete Example 6.2.2 by showing that* $\mathrm{Gal}(L/\mathbb{Q}) = \{1_L, \sigma, \tau, \sigma\tau\}$ *and that* $\mathrm{Gal}(L/\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.

Proof. We proved in Exercise 6.1.2 that

$$G := \mathrm{Gal}(\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}) = \{1_L, \sigma, \tau, \sigma\tau\}.$$

Every group of order 4 is abelian, and isomorphic to $\mathbb{Z}/4\mathbb{Z}$ or $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.

As G as at least 2 elements of order d'ordre 2, since $\sigma^2 = \tau^2 = 1_L$. This is not the case in $\mathbb{Z}/4\mathbb{Z}$. Thus

$$\mathrm{Gal}(\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}.$$

□

Ex. 6.2.2 *Consider* $\mathbb{Q} \subset L = \mathbb{Q}(\omega, \sqrt[3]{2})$*, where* $\omega = e^{2\pi i/3}$.

(a) Explain why $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ *is uniquely determined by* $\sigma(\omega) \in \{\omega, \omega^2\}$ *and* $\sigma(\sqrt[3]{2}) \in \{\sqrt[3]{2}, \omega\sqrt[3]{2}, \omega^2\sqrt[3]{2}\}$.

(b) Explain why all possible combinations for $\sigma(\omega)$ *and* $\sigma(\sqrt[3]{2})$ *actually occur.*

In the next section we will show that $\mathrm{Gal}(L/Q) \simeq S_3$.

Proof. (a) As $L = \mathbb{Q}(\omega, \sqrt[3]{2})$, Proposition 6.1.4(b) shows that $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ is uniquely determined by $\sigma(\omega), \sigma(\sqrt[3]{2})$.

Moreover, by theorem 6.1.4 (a), $\sigma(\omega)$ is a root of $f = x^2 + x + 1$, whose roots are ω, ω^2, and $\sigma(\sqrt[3]{2})$ is a root of $g = x^3 - 2$ whose roots are $\sqrt[3]{2}, \omega\sqrt[3]{2}, \omega^2\sqrt[3]{2}$.

Then Exercise 6.1.1 shows that

$$|\mathrm{Gal}(L/\mathbb{Q})| \le \deg(f)\deg(g) = 6.$$

(b) L is the splitting field of the separable irreducible polynomial $g = x^3 - 2 \in \mathbb{Q}[x]$. Indeed, g is irreducible over $\mathbb{Q}$ since $\deg(g) = 3$ and g has no root in $\mathbb{Q}$,and separable since its roots in $\mathbb{C}$ are $\sqrt[3]{2}, \omega\sqrt[3]{2}, \omega^2\sqrt[3]{2}$ which are distinct.

By theorem 6.2.1, $|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}]$, and by Exercise 5.1.8, $[L : \mathbb{Q}] = 2 \times 3 = 6$, therefore

$$|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}] = 6.$$

If all possible combinations for $\sigma(\omega)$ and $\sigma(\sqrt[3]{2})$ don't actually occur, then $|\mathrm{Gal}(L/\mathbb{Q})| < 6$, which is false, so all possible combinations occur.

□

Ex. 6.2.3 *Consider $\mathbb{Q} \subset L = \mathbb{Q}(\zeta_5, \sqrt[5]{2})$, where $\zeta_5 = e^{2\pi i/5}$. By proposition 4.2.5, the minimal polynomial of ζ_5 over $\mathbb{Q}$ is $x^4 + x^3 + x^2 + x + 1$.*

(a) Show that $[L : \mathbb{Q}] = 20$.

(b) Show that L is the splitting field of $x^5 - 2$ over $\mathbb{Q}$, and conclude that $\mathrm{Gal}(L/\mathbb{Q})$ is a group of order 20.

We will describe the structure of this Galois group in section 6.4.

Proof. Write $\zeta = \zeta_5$.

(a) as $L = \mathbb{Q}(\zeta, \sqrt[5]{2})$, Proposition 6.1.4(b) shows that $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ is uniquely determined by $\sigma(\zeta), \sigma(\sqrt[3]{2})$.

Moreover by Proposition 6.4.1(a), $\sigma(\zeta)$ is a root of $f = x^4 + x^3 + x^2 + x + 1$, whose roots are $\zeta^i,\ 1 \le i \le 4$, and $\sigma(\sqrt[5]{2})$ is a root of $g = x^5 - 2$, whose roots are $\zeta^j \sqrt[5]{2},\ 0 \le j \le 4$.

Then Exercice 6.1.1 shows that

$$|\mathrm{Gal}(L/\mathbb{Q})| \le \deg(f) \deg(g) = 20.$$

(b) L is the splitting field of the separable irreducible polynomial $g = x^5 - 2 \in \mathbb{Q}[x]$ over $\mathbb{Q}$. Indeed, g is irreducible over $\mathbb{Q}$ by Schönemann-Eisenstein Criterion with $p = 2$, and separable since its roots in $\mathbb{C}$ are $\sqrt[5]{2}, \zeta\sqrt[5]{2}, \zeta^2\sqrt[5]{2}, \zeta^3\sqrt[5]{2}, \zeta^4\sqrt[5]{2}$ which are distinct.

By theorem 6.2.1, $|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}]$, and by Exercise 5.1.8, $[L : \mathbb{Q}] = 4 \times 5 = 20$, therefore

$$|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}] = 20.$$

$\square$

Ex. 6.2.4 *Consider the nth root of unity $\zeta_n = e^{2\pi i/n}$. We call $\mathbb{Q} \subset \mathbb{Q}(\zeta_n)$ a cyclotomic extension of $\mathbb{Q}$.*

(a) Show that $\mathbb{Q} \subset \mathbb{Q}(\zeta_n)$ is a splitting field of a separable polynomial.

(b) Given $\sigma \in \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q})$, show that $\sigma(\zeta_n) = \zeta_n^i$ for some integer i.

(c) Show that the integer i in part (b) is relatively prime to n.

(d) The set of congruence classes modulo n relatively prime to n form a group under multiplication, denoted $(\mathbb{Z}/n\mathbb{Z})^*$. Show that the map $\sigma \mapsto [i]$, where $\sigma(\zeta_n) = \zeta_n^i$, define a one-to-one group homomorphism $\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \to (\mathbb{Z}/n\mathbb{Z})^*$.

(e) The order of $(\mathbb{Z}/n\mathbb{Z})^*$ is $|(\mathbb{Z}/n\mathbb{Z})^*| = \phi(n)$, where $\phi(n)$ is the Euler ϕ-function from number theory. Prove that the homomorphism of part (d) is an isomorphism if and only if $[\mathbb{Q}(\zeta_n) : \mathbb{Q}] = \phi(n)$.

(f) Let p be prime. Use part (e) and Proposition 4.2.5 to show that $\mathrm{Gal}(\mathbb{Q}(\zeta_p)/\mathbb{Q}) \simeq (\mathbb{Z}/p\mathbb{Z})^*$.

In chapter 9 we will prove that $[Q(\zeta_n) : \mathbb{Q}] = \phi(n)$. *By part (e), this will imply that there is an isomorphism* $\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \simeq (\mathbb{Z}/n\mathbb{Z})^*$ *for all* n.

Proof. (a) ζ_n is a root of $x^n - 1 \in \mathbb{Q}[x]$. Write $\mathbb{U}_n$ the set of nth roots of unity in $\mathbb{C}$:

$$\mathbb{U}_n = \{\zeta_n^k,\ 0 \le k \le n-1\}$$

and $|\mathbb{U}_n| = n$.

As $x^n - 1 = \prod_{\zeta \in \mathbb{U}_n} (x - \zeta)$, $x^n - 1$ is separable, and the splitting field of $x^n - 1$ over $\mathbb{Q}$ is $\mathbb{Q}(\zeta, \ldots, \zeta^{n-1}) = \mathbb{Q}(\zeta)$

Conclusion : $\mathbb{Q}(\zeta_n)$ is the splitting field of the separable polynomial $x^n - 1 \in \mathbb{Q}[x]$ over $\mathbb{Q}$.

(b) Soit $\sigma \in \mathrm{Gal}(\mathbb{Q}(\zeta_n) : \mathbb{Q})$.

As ζ_n is a root of $x^n - 1 \in \mathbb{Q}[x]$, by Proposition 6.1.4(a) $\sigma(\zeta_n)$ is a root of $x^n - 1$, thus $\sigma(\zeta_n) \in \mathbb{U}_n$, so

$$\sigma(\zeta_n) = \zeta_n^i,\ i \in \mathbb{N}.$$

(c) Note that $\zeta_n = e^{2i\pi/n}$ is an element of order n in the group $\mathbb{U}_n$. Indeed, for all $k \in Z$,

$$\zeta_n^k = 1 \iff e^{2i\pi k/n} = 1 \iff k/n \in \mathbb{Z} \iff n \mid k.$$

σ being a field isomorphism, $\sigma(\zeta_n) \in \mathbb{U}_n$ is also of order n. Indeed, for all $k \in Z$,

$$\sigma(\zeta_n)^k = 1 \iff \sigma(\zeta_n^k) = 1 \iff \zeta_n^k = 1 \iff n \mid k.$$

If the order of an element ζ is $|\zeta| = n$, then for all integer j, the order of ζ^j in $\mathbb{U}_n$ is

$$|\zeta^j| = \frac{n}{n \wedge j}.$$

Indeed for all $k \in \mathbb{Z}$,

$(\zeta^j)^k = 1 \iff n \mid jk \iff \frac{n}{n\wedge j} \mid \frac{j}{n\wedge j} k \iff \frac{n}{n\wedge j} \mid k$ (since $\frac{n}{n\wedge j} \wedge \frac{j}{n\wedge j} = 1$).

If we apply this result to $\zeta_n^i = \sigma(\zeta_n)$, on obtient

$$\frac{n}{n \wedge i} = |\zeta_n^i| = |\sigma(\zeta_n| = n,$$

thus

$$n \wedge i = 1.$$

(d) Let

$$\varphi : \left\{ \begin{array}{ccc} \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) & \to & (\mathbb{Z}/n\mathbb{Z})^* \\ \sigma & \mapsto & [i] :\ \sigma(\zeta_n) = \zeta_n^i \end{array} \right.$$

We show that φ is a group homomorphism.

If $\sigma, \tau \in \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q})$, and $\varphi(\sigma) = [i], \varphi(\tau) = [j]$, then $\sigma(\zeta_n) = \zeta_n^i, \tau(\zeta_n) = \zeta_n^j$, thus

$$(\sigma \circ \tau)(\zeta_n) = \sigma((\zeta_n)^j) = (\sigma(\zeta_n))^j = (\zeta_n^i)^j = \zeta_n^{ij},$$

therefore

$$\varphi(\sigma \circ \tau) = [ij] = [i][j] = \varphi(\sigma)\varphi(\tau).$$

φ is injective :

if $\varphi(\sigma) = [1]$, then $\sigma(\zeta_n) = \zeta_n$. Since $\sigma \in \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q})$, σ is uniquely determined by the image of ζ_n, thus $\sigma = 1_{\mathbb{Q}(\zeta_n)}$. The kernel of φ is trivial, thus φ is injective.

Conclusion : there exist an injective group homomorphism

$$\varphi : \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \to (\mathbb{Z}/n\mathbb{Z})^*.$$

(e) As $\mathbb{Q}(\zeta_n)$ is the splitting field of a separabel polynomial over $\mathbb{Q}$,

$$|\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q})| = [\mathbb{Q}(\zeta_n) : \mathbb{Q}].$$

If we suppose that $[\mathbb{Q}(\zeta_n) : \mathbb{Q}] = \phi(n)$, $\varphi$is an injection between two set of same cardinality, thus φ is a bijection, and soφ is a group isomorphism. Reciprocally, if φ is a group isomorphism, then $[\mathbb{Q}(\zeta_n) : \mathbb{Q}] = \mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q})| = \phi(n)$

Conclusion : $[\mathbb{Q}(\zeta_n) : \mathbb{Q}] = \phi(n)$ if and only if $\mathrm{Gal}(\mathbb{Q}(\zeta_n)/\mathbb{Q}) \simeq (\mathbb{Z}/n\mathbb{Z})^*$.

(f) If p is prime, we know that $f = 1 + x + \cdots + x^{p-1}$ is irreducible over $\mathbb{Q}$, so f is the minimal polynomial of ζ_p over Q. This implies that $[\mathbb{Q}(\zeta_p) : \mathbb{Q}] = p - 1 = \phi(p)$.

By part (e), we know then that $\mathrm{Gal}(\mathbb{Q}(\zeta_p)/\mathbb{Q}) \simeq (\mathbb{Z}/p\mathbb{Z})^*$ (and so this group is cyclic).

□

Ex. 6.2.5 *Let F have characteristic p, and assume that $f = x^p - x + a \in F[x]$ is irreducible over F. Then let $L = F(\alpha)$, where α is a root of f in some splitting field. In Exercise 16 of Section 5.3, you showed that $F \subset L$ is a normal extension.*

(a) Show that $|\mathrm{Gal}(L/F)| = p$, and use this to prove that $|\mathrm{Gal}(L/F) \simeq \mathbb{Z}/p\mathbb{Z}$.

(b) Exercise 15 of Section 5.3 showed that $\alpha + 1$ is a root of f. For $i = 0, \ldots, p-1$, show that there is a unique element of $\mathrm{Gal}(L/F)$ that takes α to $\alpha + i$.

(c) Use part (b) to describe an explicit isomorphism $\mathrm{Gal}(L/F) \simeq \mathbb{Z}/p\mathbb{Z}$.

Proof. (a) $L = F(\alpha)$ and α has for minimal polynomial $f = x^p - x + a$, thus $[L : F] = p$.

By Exercice 5.3.16, we know that $L = F(\alpha) = F(\alpha, \alpha + 1, \ldots, \alpha + p - 1)$ is the splitting field of

$$f = x^p - x - a = (x - \alpha)(x - \alpha - 1) \cdots (x - \alpha - p + 1).$$

Therefore $F(\alpha)$ is the splitting field of a separable polynomial $f \in F[x]$, and by theorem 6.2.1

$$|\mathrm{Gal}(L/F)| = [L : F] = p.$$

Every group of order p, where p is prime, is cyclic and isomorphic to $\mathbb{Z}/p\mathbb{Z}$:

$$\mathrm{Gal}(L/F) \simeq \mathbb{Z}/p\mathbb{Z}.$$

(b) $F \subset L$ is by part (a) a normal extension, and $f \in F[x]$ is irreducible over F by hypothesis. The roots of f in L are $\alpha, \alpha+1, \ldots, \alpha+p-1$. By Proposition 5.1.8 , there exists a field isomorphism $\sigma_i : L \to L$ which is identity on F and which takes α on $\alpha + i, i \in \mathbb{F}_p$. Then $\sigma_i \in \mathrm{Gal}(L/F), \sigma(\alpha) = \alpha + i$. As $L = F(\alpha)$, σ is uniquely determined by the image of α.

Conclusion: α being a fixed root of f, and $i \in \mathbb{F}_p$, there exist a unique $\sigma_i \in \mathrm{Gal}(L/F)$ such that $\sigma_i(\alpha) = \alpha + i$.

(c) Let

$$\varphi \left\{ \begin{array}{ccc} \mathrm{Gal}(L/F) & \to & \mathbb{F}_p \\ \sigma & \mapsto & \sigma(\alpha) - \alpha \end{array} \right.$$

• For all $\sigma \in \mathrm{Gal}(L/F)$, $\varphi(\sigma) \in \mathbb{F}_p$ since $\sigma(\alpha)$ is a root of f, so $\sigma(\alpha) - \alpha = i \in \mathbb{F}_p$.

• φ is bijective by part(b), since for all $i \in \mathbb{F}_p$, there exists a unique $\sigma \in \mathrm{Gal}(L/F)$ such that $\varphi(\sigma) = \sigma(\alpha) - \alpha = i$.

• φ is a group homomorphism : if $\sigma, \tau \in \mathrm{Gal}(L/F)$, and $\varphi(\sigma) = i, \varphi(\tau) = j$, then $\sigma(\alpha) = \alpha + i, \tau(\alpha) = \alpha + j(\ i, j \in \mathbb{F}_p)$.

$(\sigma \circ \tau)(\alpha) = \sigma(\alpha + j) = \sigma(\alpha) + \sigma(j) = (\alpha + i) + j = \alpha + (i + j)$ ($\sigma(j) = j$ since σ is identity on F, a fortiori on $\mathbb{F}_p \subset F$).

As $(\sigma \circ \tau)(\alpha) = \alpha + (i + j)$, $\varphi(\sigma \circ \tau) = i + j = \varphi(\sigma) + \varphi(\tau)$.

$\varphi : \mathrm{Gal}(L/F) \to \mathbb{F}_p$ is so a group isomorphism.

□

Ex. 6.2.6 *Let $f \in F[x]$ be irreducible and separable of degree n, and let $F \subset L$ be a splitting field of f. Prove that n divides $|\mathrm{Gal}(L/F)|$.*

Proof. Let L a splitting field of f over F, where f is a separable irreducible polynomial.

By Proposition 6.2.1 (using the separability of f) :

$$|\mathrm{Gal}(L/F)| = [L : F].$$

Let α a root of f in L. As f is irreducible, f is the minimal polynomial of α over F, thus $[F(\alpha) : F] = \deg(f) = n$, and

$$[L : F] = [L : F(\alpha)]\,[F(\alpha) : F] = n[L : F(\alpha)] :$$

So n divides $|\mathrm{Gal}(L/F)|$.

□

6.3 PERMUTATION OF THE ROOTS

Ex. 6.3.1 *Consider $\mathrm{Gal}(L/\mathbb{Q})$, where $L = \mathbb{Q}(\omega, \sqrt[3]{2}), \omega = e^{2\pi i/3}$. By Exercise 2 of section 6.2, there are $\sigma, \tau \in \mathrm{Gal}(L/\mathbb{Q})$ such that*

$$\sigma(\sqrt[3]{2}) = \omega\sqrt[3]{2}, \sigma(\omega) = \omega \quad \text{and} \quad \tau(\sqrt[3]{2}) = \sqrt[3]{2}, \tau(\omega) = \omega^2.$$

Find the permutations in S_3 corresponding to σ and τ.

Proof. $L = \mathbb{Q}(\omega, \sqrt[3]{2})$ is the splitting field over $\mathbb{Q}$ of $f = x^3 - 2$.

By Exercise 6.2.2, there exist $\sigma, \tau \in \mathrm{Gal}(L/\mathbb{Q})$ such that

$$\sigma(\sqrt[3]{2}) = \omega\sqrt[3]{2}, \sigma(\omega) = \omega \quad \text{and} \quad \tau(\sqrt[3]{2}) = \sqrt[3]{2}, \tau(\omega) = \omega^2.$$

Number the roots of f by $\alpha_1 = \sqrt[3]{2}, \alpha_2 = \omega\sqrt[3]{2}, \alpha_3 = \omega^2\sqrt[3]{2}$.

Then $\sigma(\alpha_1) = \alpha_2, \sigma(\alpha_2) = \alpha_3, \sigma(\alpha_3) = \alpha_1$. If we write $\tilde{\sigma} = (1,2,3)$, then for $i = 1,2,3, \sigma(\alpha_i) = \sigma(\alpha_{\tilde{\sigma}(i)})$, so the 3-cycle $\tilde{\sigma} = (1,2,3)$ corresponds to σ.

$\tau(\alpha_1) = \alpha_1, \tau(\alpha_2) = \alpha_3, \tau(\alpha_3) = \alpha_2$, so $\tilde{\tau} = (2,3)$ corresponds to τ.

As S_3 is generated by $\tilde{\sigma}, \tilde{\tau}$, $\mathrm{Gal}(L/\mathbb{Q})$ is generated by σ, τ. □

Ex. 6.3.2 *For each of the following Galois groups, find an explicit subgroup of S_4 that is isomorphic to the group. Also, the Galois group is isomorphic to which known group?*

(a) $\mathrm{Gal}(\mathbb{Q}(i, \sqrt{2})/\mathbb{Q})$.

(b) $\mathrm{Gal}(\mathbb{Q}(i, \sqrt[4]{2}/\mathbb{Q})$.

Proof. (a) $\mathrm{Gal}(\mathbb{Q}(i, \sqrt{2})/\mathbb{Q}) = \{1_{\mathbb{Q}}, \sigma, \tau, \sigma\tau\}$, where

$$\sigma(i) = -i, \sigma(\sqrt{2}) = \sqrt{2},$$

$$\tau(i) = i, \tau(\sqrt{2}) = -\sqrt{(}2).$$

As every $g \in \mathrm{Gal}(\mathbb{Q}(i, \sqrt{2})/\mathbb{Q})$ satisfies $g^2 = 1_{\mathbb{Q}}$,

$$\mathrm{Gal}(\mathbb{Q}(i, \sqrt{2})/\mathbb{Q}) \simeq \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$$

(ViertelGruppe de Klein : cf Exercise 6.2.1 and example 6.2.2 for more details).

If we number the roots by $\alpha_1 = i, \alpha_2 = -i, \alpha_3 = \sqrt{2}, \alpha_4 = -\sqrt{2}$, then $(1,2)$ corresponds to σ, and $(3,4)$ to τ.

As subgroup of S_4, $\mathrm{Gal}(Q(i, \sqrt{2})/\mathbb{Q})$ is represented by

$$\{(), (1,2), (3,4), (1,2)(3,4)\} = \langle (1,2), (3,4) \rangle \simeq \mathrm{Gal}(\mathbb{Q}(i, \sqrt{2})/\mathbb{Q}).$$

(b)

$$\begin{aligned} f &= x^4 - 2 \\ &= (x^2 - \sqrt{2})(x^2 + \sqrt{2}) \\ &= (x - \sqrt[4]{2})(x + \sqrt[4]{2})(x + i\sqrt[4]{2})(x - i\sqrt[4]{2}) \end{aligned}$$

The splitting root of f over $\mathbb{Q}$ is so $L = \mathbb{Q}(i, i\sqrt[4]{2}) = \mathbb{Q}(i, \sqrt[4]{2})$. f is separable, since f has simple roots in its splitting field. L is so the splitting field over $\mathbb{Q}$ of a separable polynomial, therefore by Theorem 6.2.1,

$$|\mathrm{Gal}(L : \mathbb{Q})| = [L : \mathbb{Q}].$$

f is irreducible over $\mathbb{Q}$ by the Schönemann-Eisenstein Criterion with $p = 2$. As f is irreducible over $\mathbb{Q}$,

$$[\mathbb{Q}(\sqrt[4]{2}) : \mathbb{Q}] = \deg(f) = 4,$$

and x^2+1 is irreducible over $\mathbb{Q}(\sqrt[4]{2})$, since it is of degree 2 , without root in $\mathbb{Q}(\sqrt[4]{2}) \subset \mathbb{R}$, thus

$$[\mathbb{Q}(i, \sqrt[4]{2}) : \mathbb{Q}(\sqrt[4]{2})] = 2.$$

Consequently,

$$[\mathbb{Q}(i, \sqrt[4]{2}) : \mathbb{Q}] = [\mathbb{Q}(i, \sqrt[4]{2}) : \mathbb{Q}(\sqrt[4]{2})]\ [\mathbb{Q}(\sqrt[4]{2}) : \mathbb{Q}] = 8,$$

and so

$$|\mathrm{Gal}(L : \mathbb{Q})| = 8.$$

If $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$, as i is a root of $x^2+1 \in \mathbb{Q}[x]$, and $\sqrt[4]{2}$ a root of $x^4-2 \in \mathbb{Q}[x]$, then $\sigma(i) = \pm i$, et $\sigma(\sqrt[4]{2}) = i^k \sqrt[4]{2}, k = 0,1,2,3$. as σ is uniquely determined by the images of $i, \sqrt[4]{2}$, and as $|\mathrm{Gal}(L : \mathbb{Q})| = 8$, these 8 possibilities occur, thus $G = \mathrm{Gal}(L/\mathbb{Q}) = \{\sigma_{j,k} \mid 0 \le j \le 1, 0 \le k \le 3\}$, where $\sigma_{j,k}$, which is identity on $\mathbb{Q}$, is determined by

$$\sigma_{j,k}(i) = (-1)^j i, \sigma_{j,k}(\sqrt[4]{2}) = i^k \sqrt[4]{2}.$$

Write $\tau : L \to L, z \mapsto \overline{z}$ the complex conjugation restricted to L. τ is a ring homomorphism and an involution, thus τ is a field automorphism of L,which is identity on $\mathbb{Q}$, so $\tau \in G$. Moreover

$$\tau(i) = -i, \tau(\sqrt[4]{2}) = \sqrt[4]{2},$$

Let $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ defined by

$$\sigma(i) = i, \sigma(\sqrt[4]{2}) = i\sqrt[4]{2}.$$

Then $\tau = \sigma_{1,0}, \sigma = \sigma_{0,1}$.

As $\tau^2 = 1_L$ and $\tau \neq e$, the order of τ is 2.

$\sigma^4(i) = i$ and $\sigma^4(\sqrt[4]{2}) = \sqrt[4]{2}$, thus $\sigma^4 = e$. As $\sigma^2(\sqrt[4]{2}) = i^2\sqrt[4]{2} = -\sqrt[4]{2}, \sigma_2 \neq e$, thus the order of σ is 4.

$$|\tau| = 2, \qquad |\sigma| = 4|.$$

As $\tau(i) = -i, \tau \notin \langle \sigma \rangle$.Thus the subgroup $\langle \sigma, \tau \rangle$ of G contains at least 5 elements, so is equal to G by Lagrange's Theorem :

$$G = \langle \sigma, \tau \rangle.$$

As the index of $H = \langle \sigma \rangle$ in G is 2, and $\tau \notin H$, $G = H \cup \tau H$:

$$G = \mathrm{Gal}(L/\mathbb{Q}) = \{1_L, \sigma, \sigma^2, \sigma^3, \tau, \tau\sigma, \tau\sigma^2, \tau\sigma^3\}.$$

If we number the roots of f by $\alpha_k = i^{k-1}\sqrt[4]{2}$, for $k = 1,2,3,4$, then τ corresponds to the transposition $(2,4)$, and σ to the cycle $(1,2,3,4)$:

$$G \simeq \langle (1,2,3,4), (2,4) \rangle \subset S_4.$$

If we number the 4 summits of a square by 1,2,3,4 in the direct orientation, then σ corresponds to a rotation of angle $\pi/2$, and τ to a symmetry with respect to the diagonal $[1,3]$. They generate the group of isometry of the square, which is the dihedral group D_8, defined also by generators and relations :

$$G = \langle \sigma, \tau \rangle, \sigma^4 = \tau^2 = e, \tau\sigma = \sigma^{-1}\tau.$$

(En effet, $\tilde{\sigma}^{-1}\tilde{\tau} = (1,4,3,2)(2,4) = (4,3,2,1) = (2,4)(1,2,3,4) = \tilde{\tau}\tilde{\sigma}$.)

As a verification, the following GAP instruction confirm the result D_8 :

```
G:= Group((1,2,3,4),(2,4));
StructureDescription(G);
  "D8"
```

□

Ex. 6.3.3 *In the terminology of Exercise 2,* $\mathrm{Gal}(\mathbb{Q}(i,\sqrt{2},\sqrt{3})/\mathbb{Q})$ *is isomorphic to which known group? Explain your reasoning in detail.*

Proof. We have already proved (Ex. 5.1.13) that $f = x^2 - 3$ is irreducible over $\mathbb{Q}[\sqrt{2}]$. f is so the minimal polynomial of $\sqrt{3}$ over $\mathbb{Q}(\sqrt{2})$, thus $[\mathbb{Q}(\sqrt{2},\sqrt{3}) : \mathbb{Q}(\sqrt{2})] = \deg(f) = 2$.

As $g = x^2 - 2$ is irreducible over $\mathbb{Q}$, $[\mathbb{Q}(\sqrt{2}) : \mathbb{Q}] = \deg(g) = 2$, therefore

$$[\mathbb{Q}(\sqrt{2},\sqrt{3}) : \mathbb{Q}] = [\mathbb{Q}(\sqrt{2},\sqrt{3}) : \mathbb{Q}(\sqrt{2})]\ [\mathbb{Q}(\sqrt{2}) : \mathbb{Q}] = 4.$$

Moreover, $h = x^2+1$ has no real root, a fortiori h has no root in $\mathbb{Q}(\sqrt{2},\sqrt{3})$. As $\deg(h) = 2$, h is irreducible over $\mathbb{Q}(\sqrt{2},\sqrt{3})$, h is the minimal polynomial of $i$over $\mathbb{Q}(\sqrt{2},\sqrt{3})$, thus $[\mathbb{Q}(\sqrt{2},\sqrt{3},i) : \mathbb{Q}(\sqrt{2},\sqrt{3})] = 2$, and by the Tower Theorem, and the equality $\mathbb{Q}(\sqrt{2},\sqrt{3},i) = \mathbb{Q}(i,\sqrt{2},\sqrt{3})$,

$$[\mathbb{Q}(i,\sqrt{2},\sqrt{3}) : \mathbb{Q}] = 8.$$

$L = \mathbb{Q}(i,\sqrt{2},\sqrt{3})$ is the splitting field of $p = (x^2+1)(x^2-2)(x^2-3)$ over $\mathbb{Q}$, and $p = (x-i)(x+i)(x-\sqrt{2})(x+\sqrt{2})(x-\sqrt{3})(x+\sqrt{3})$ is separable. By theorem 6.2.1, we obtain

$$|\mathrm{Gal}(L : \mathbb{Q})| = [L : \mathbb{Q}] = 8.$$

If $\sigma \in \mathrm{Gal}(L : \mathbb{Q})$, $\sigma(i) = \pm i, \sigma(\sqrt{2}) = \pm\sqrt{2}, \sigma(\sqrt{3}) = \pm\sqrt{3}$. As $|\mathrm{Gal}(L : \mathbb{Q})| = 8$, all of these possibilities occur: there exist 8 $\mathbb{Q}$-automorphisms of L satisfying thes equalities. As $L = \mathbb{Q}(i,\sqrt{2},\sqrt{3})$, $\sigma \in \mathrm{Gal}(L : \mathbb{Q})$ is uniquely determined by the images of these 3 elements.

In particular, there exist $\sigma_1, \sigma_2, \sigma_3 \in \mathrm{Gal}(L : \mathbb{Q})$ defined by

$$\begin{array}{lll} \sigma_1(i) = -i, & \sigma_1(\sqrt{2}) = \sqrt{2}, & \sigma_1(\sqrt{3}) = \sqrt{3} \\ \sigma_2(i) = i, & \sigma_2(\sqrt{2}) = -\sqrt{2}, & \sigma_2(\sqrt{3}) = \sqrt{3} \\ \sigma_3(i) = i, & \sigma_3(\sqrt{2}) = \sqrt{2}, & \sigma_3(\sqrt{3}) = -\sqrt{3} \end{array}$$

and $1_L, \sigma_1, \sigma_2, \sigma_3, \sigma_1\sigma_2, \sigma_1\sigma_3, \sigma_2\sigma_3, \sigma_1\sigma_2\sigma_3$ give distinct images to $i, \sqrt{2}, \sqrt{3}$, thus

$$G := \mathrm{Gal}(L : \mathbb{Q}) = \{1_L, \sigma_1, \sigma_2, \sigma_3, \sigma_1\sigma_2, \sigma_1\sigma_3, \sigma_2\sigma_3, \sigma_1\sigma_2\sigma_3\}.$$

Therefore

$$G = \langle \sigma_1, \sigma_2, \sigma_3 \rangle.$$

Note that $\sigma_1\sigma_2 = \sigma_2\sigma_1$ since they give the same images to $i, \sqrt{2}, \sqrt{3}$. Similarly $\sigma_1\sigma_3 = \sigma_3\sigma_1$ and $\sigma_2\sigma_3 = \sigma_3\sigma_2$. Thus G is abelian, generated by 3 elements of order 2, with $\sigma_2 \notin \langle\sigma_1\rangle, \sigma_3 \notin \langle\sigma_1, \sigma_2\rangle$. Therefore G is the direct sum of the 3 subgroups $\{e, \sigma_i\},\ i = 1, 2, 3$, d'ordre 2 :

$$\mathrm{Gal}(L : \mathbb{Q}) \simeq (\mathbb{Z}/2\mathbb{Z})^3.$$

Some instructions Sage and Gap to verify these results :

```
f=(x-i-sqrt(2)-sqrt(3))*(x-i-sqrt(2)+sqrt(3))*(x-i+sqrt(2)-sqrt(3))
*(x-i+sqrt(2)+sqrt(3))*(x+i-sqrt(2)-sqrt(3))*(x+i-sqrt(2)+sqrt(3))
*(x+i+sqrt(2)-sqrt(3))*(x+i+sqrt(2)+sqrt(3));f
```

$$\left(x+\sqrt{3}+\sqrt{2}+i\right)\left(x+\sqrt{3}+\sqrt{2}-i\right)\left(x+\sqrt{3}-\sqrt{2}+i\right)\left(x+\sqrt{3}-\sqrt{2}-i\right)$$
$$\left(x-\sqrt{3}+\sqrt{2}+i\right)\left(x-\sqrt{3}+\sqrt{2}-i\right)\left(x-\sqrt{3}-\sqrt{2}+i\right)\left(x-\sqrt{3}-\sqrt{2}-i\right)$$

```
g=f.expand();g
```

$x^8 - 16\,x^6 + 88\,x^4 + 192\,x^2 + 144$

```
g.factor()
```

$x^8 - 16\,x^6 + 88\,x^4 + 192\,x^2 + 144$

```
x=polygen(QQ,'x')
K.<z> = NumberField(x^8-16*x^6+88*x^4+192*x^2+144)
G = K.galois_group();G
```

$\langle(1,2)(3,4)(5,6)(7,8),(1,3)(2,4)(5,7)(6,8),(1,5)(2,6)(3,7)(4,8)\rangle$

With Gap :

```
G:=Group((1,2)(3,4)(5,6)(7,8),(1,3)(2,4)(5,7)(6,8),(1,5)(2,6)(3,7)(4,8));
StructureDescription(G);
```

$C_2 \times C_2 \times C_2$

As $x^8 - 16\,x^6 + 88\,x^4 + 192\,x^2 + 144$ is irreductible over $\mathbb{Q}$, $[\mathbb{Q}(i+\sqrt{2}+\sqrt{3}) : \mathbb{Q}] = 8 = [L : \mathbb{Q}]$, and since $\mathbb{Q}(i+\sqrt{2}+\sqrt{3}) \subset L$, $L = \mathbb{Q}(i+\sqrt{2}+\sqrt{3})$.

These results imply that $L = \mathbb{Q}(i, \sqrt{2}, \sqrt{3})$ is the splitting field of the irreducible polynomial $x^8 - 16\,x^6 + 88\,x^4 + 192\,x^2 + 144$, that $i + \sqrt{2} + \sqrt{3}$ is a primitive element of $\mathbb{Q} \subset L$, and that $\mathrm{Gal}(L : \mathbb{Q}) \simeq C_2 \times C_2 \times C_2$. $\square$

Ex. 6.3.4 *Consider the extension $\mathbb{Q} \subset L = \mathbb{Q}(\alpha)$, where $\alpha = \sqrt{2+\sqrt{2}}$. In Exercise 6 of Section 5.1, you showed that $f = x^4 - 4x^2 + 2$ is the minimal polynomial of α over $\mathbb{Q}$ and that L is the splitting field of f over $\mathbb{Q}$. Show that* $\mathrm{Gal}(L/\mathbb{Q}) \simeq \mathbb{Z}/4\mathbb{Z}$.

Proof. $L = \mathbb{Q}(\alpha), \alpha = \sqrt{2+\sqrt{2}}$. We have already proved (Ex. 5.1.6) that

$$\begin{aligned} f &= x^4 - 4x^2 + 2 \\ &= \left(x - \sqrt{2+\sqrt{2}}\right)\left(x + \sqrt{2+\sqrt{2}}\right)\left(x - \sqrt{2-\sqrt{2}}\right)\left(x + \sqrt{2-\sqrt{2}}\right) \end{aligned}$$

is the minimal polynomial of α over $\mathbb{Q}$, and that $L = \mathbb{Q}(\alpha)$ is the splitting field of f over $\mathbb{Q}$.

$L = \mathbb{Q}(\alpha)$ is so the splitting field of the irreducible separable polynomial f. By theorem 6.2.1,

$$|\mathrm{Gal}(L/\mathbb{Q})| = [L : \mathbb{Q}] = 4.$$

Write $\beta = \sqrt{2-\sqrt{2}}$.If $\sigma \in \mathrm{Gal}(L/\mathbb{Q}), \sigma(\alpha)$ is a root of f, thus

$$\sigma(\alpha) \in \{\alpha, \beta, -\alpha, -\beta\}.$$

Moreover, since $L = \mathbb{Q}(\alpha)$, an automorphism of $\mathrm{Gal}(L/\mathbb{Q})$ is uniquely determined by the image of α, and since $|\mathrm{Gal}(L/\mathbb{Q})| = 4$, all of these possibilities occur, so there exist one and only one $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ such that $\sigma(\alpha) = \gamma$, where $\gamma \in \{\alpha, \beta, -\alpha, -\beta\}$ (alternatively, since f is irreducible over $\mathbb{Q}$, we can use Theorem 5.1.8).

$$\mathrm{Gal}(L/\mathbb{Q}) = \{\sigma_0 = e, \sigma_1, \sigma_2, \sigma_3\}, \sigma_1(\alpha) = \beta, \sigma_2(\alpha) = -\alpha, \sigma_3(\alpha) = -\beta.$$

In particular, there exists so $\sigma(= \sigma_1) \in \mathrm{Gal}(L/\mathbb{Q})$ defined by $\sigma(\alpha) = \beta$.

Recall that $\alpha\beta = \sqrt{2}, \alpha^2 = 2 + \sqrt{2}, \beta^2 = 2 - \sqrt{2}$ (see Ex. 5.1.6), thus

$$\alpha^2 - \beta^2 = 2\alpha\beta.$$

From this equality we obtain

$$\alpha^2 - \frac{2}{\alpha^2} = 2\alpha\beta, \ \frac{2}{\beta^2} - \beta^2 = 2\alpha\beta,$$

therefore

$$\beta = \frac{1}{2}\left(\alpha - \frac{2}{\alpha^3}\right), \ \alpha = -\frac{1}{2}\left(\beta - \frac{2}{\beta^3}\right).$$

As $\sigma(\alpha) = \beta$,

$$\begin{aligned} \sigma(\beta) &= \frac{1}{2}\left(\sigma(\alpha) - \frac{2}{\sigma(\alpha)^3}\right) \\ &= \frac{1}{2}\left(\beta - \frac{2}{\beta^3}\right) \\ &= -\alpha \end{aligned}$$

Finally $\sigma(-\alpha) = \sigma(-1)\sigma(\alpha) = -\sigma(\alpha) = -\beta$, so

$$\sigma(\alpha) = \beta, \sigma^2(\alpha) = -\alpha, \sigma^3(\alpha) = -\beta.$$

As every element in $\mathrm{Gal}(L/\mathbb{Q})$ is uniquely determined by the image of α,

$$\sigma^0 = e = \sigma_0, \sigma^1 = \sigma_1, \sigma^2 = \sigma_2, \sigma^3 = \sigma_3,$$

and

$$\mathrm{Gal}(L/\mathbb{Q}) = \{e, \sigma, \sigma^2, \sigma^3\} = \langle\sigma\rangle.$$

$\mathrm{Gal}(L/\mathbb{Q})$ is so cyclic, generated by σ :

$$\mathrm{Gal}(L/\mathbb{Q}) \simeq \mathbb{Z}/4\mathbb{Z}.$$

$\square$

Ex. 6.3.5 *Let $f \in F[x]$ be separable, where $f = g_1 \cdots g_s$ for $g_i \in F[x]$ of degree $d_i > 0$, and let L be the splitting field of f over F. Show that $\mathrm{Gal}(L/F)$ is isomorphic to a subgroup of the product group $S_{d_1} \times \cdots \times S_{d_s}$.*

Proof. We show the proposition for $s = 2$ to have lighter notations.

Suppose that $f = gh \in F[x]$ is separable, with $g, h \in F[x]$, $\deg(g) = r, \deg(h) = s$. Then g, h are separable.

Write $\alpha_1, \cdots, \alpha_r$ the roots of g in M, and $\beta_1, \cdots, \beta_s$ the roots of h in N.

Let $M = F(\alpha_1, \cdots, \alpha_r), N = F(\beta_1, \cdots, \beta_s)$, then M is a splitting field of g over F, N a splitting field of h over F, and $L = F(\alpha_1, \cdots, \alpha_r, \beta_1, \cdots, \beta_s)$ is a splitting field of f over F. As f is separable, the $d = r + s$ roots of f, $\alpha_1, \cdots, \alpha_r, \beta_1, \cdots, \beta_s$ are distinct.

Write A the set of the roots of g in L, B the set of roots of h in L : $|A| = r, |B| = s$, and write $S(A)$ the set of bijections of A (and the same for B) : $S(A) \simeq S_r, S(B) \simeq S_s$.

Let $\sigma \in \mathrm{Gal}(L/F)$. As $g, h \in F[x]$, σ induce a permutation of the roots of g and of the roots of h, so the maps

$$\sigma_1 : \left\{ \begin{array}{ccc} A & \to & A \\ \alpha & \mapsto & \sigma(\alpha) \end{array} \right. \text{ and } \sigma_2 : \left\{ \begin{array}{ccc} B & \to & B \\ \beta & \mapsto & \sigma(\beta) \end{array} \right.$$

restrictions of σ à A, B, satisfy $\sigma_1 \in S(A), \sigma_2 \in S(B)$.

The map

$$\varphi : \left\{ \begin{array}{ccc} \mathrm{Gal}(L/F) & \to & S(A) \times S(B) \\ \sigma & \mapsto & (\sigma_1, \sigma_2) \end{array} \right.$$

is a group homomorphism : if $\varphi(\sigma) = (\sigma_1, \sigma_2)$ and $\varphi(\tau) = (\tau_1, \tau_2)$ (with $\sigma, \tau \in \mathrm{Gal}(L/F)$), and also $\eta = \sigma \circ \tau, \varphi(\eta) = (\eta_1, \eta_2)$, then for all α in A and $\beta \in B$,

$$\eta_1(\alpha) = \eta(\alpha) = (\sigma\tau)(\alpha) = (\sigma_1\tau_1)(\alpha), \eta_2(\beta) = \eta(\beta) = (\sigma\tau)(\beta) = (\sigma_2\tau_2)(\beta),$$

thus $\eta_1 = \sigma_1\tau_1, \eta_2 = \sigma_2\tau_2$. Consequently

$\varphi(\sigma \circ \tau) = \varphi(\eta) = (\eta_1, \eta_2) = (\sigma_1\tau_1, \sigma_2\tau_2) = (\sigma_1, \sigma_2)(\tau_1, \tau_2) = \varphi(\sigma)\varphi(\tau)$.

φ is injective : if $\varphi(\sigma) = (\sigma_1, \sigma_2) = (1_A, 1_B)$, then

$$\sigma(\alpha_i) = \alpha_i, \ i = 1, \cdots r \text{ et } \sigma(\beta_j) = \beta_j, \ j = 1, \cdots s.$$

Comme $L = F(\alpha_1, \cdots, \alpha_r, \beta_1, \cdots, \beta_s)$, $\sigma = 1_L$.

$\mathrm{Gal}(L/F)$ is isomorphic to a subgroup of $S(A) \times S(B)$, and as $S(A) \times S(B) \simeq S_r \times S_s$, $\mathrm{Gal}(L/F)$ is isomorphic to a subgroup of $S_r \times S_s$.

We can generalize to s polynomials similarly, or by induction. □

Ex. 6.3.6 *Let H be a transitive subgroup of S_n. Prove that $|H|$ is a multiple of n.*

Proof. A subgroup H of S_n defines an action on $[1, n]$ by $h \cdot x = h(x), h \in H, x \in [1, n]$. By definition H is a transitive subgroup of S_n if this action is transitive, i.e. if the only orbit is $\mathcal{O}_i = [1, n], \ i = 1, \cdots, n$. If we write $H_i = \mathrm{Stab}_H(i)$ the stabilizer in H of a fixed element i, then $(H : H_i) = |\mathcal{O}_i| = n$, thus $|H| = |H_i| \times n$:

$$n \text{ divides } |H|.$$

□

Ex. 6.3.7 *Let $f \in F[x]$ be irreducible and separable of degree n and let $F \subset L$ be a splitting field of f over F. Use Exercise 6 and Proposition 6.3.7 to prove that n divides $|\mathrm{Gal}(L/F)|$. This gives an alternate proof of Exercise 6 of Section 6.2.*

Proof. We define a left action of the Galois group $G = \mathrm{Gal}(L/F)$ on the set S of the roots of f by $\sigma \cdot \alpha = \sigma(\alpha)$, where $\sigma \in G, \alpha \in S$ (we know that $\sigma(\alpha) \in S$).

For a fixed $\alpha \in S$, define $G_\alpha = \mathrm{Stab}_G(\alpha) = \{\sigma \in G \mid \sigma(\alpha) = \alpha\}$ the stabilizer of α in G, and $\mathcal{O}_\alpha = \{\sigma \cdot \alpha \mid \sigma \in G\}$ its orbit.

As f is irreducible, by proposition 5.8.1, if α, β are two roots of f, there exists a field isomorphism $\sigma : L \to L$, which is identity on F (so $\sigma \in \mathrm{Gal}(L/F)$, and such that $\sigma(\alpha) = \beta$.

Therefore the action of G on S is transitive, so there exists a unique orbit : for all $\alpha \in S$, $\mathcal{O}_\alpha = \mathcal{S}$, thus
$$|\mathcal{O}_\alpha| = |S| = n.$$
Indeed the separability of f implies that f has $n = \deg(f)$ distinct roots in L.

As $(G : G_\alpha) = |\mathcal{O}_\alpha|$, we obtain
$$|G| = |\mathrm{Gal}(L/F)| = n \times |G_\alpha|.$$
So $n = \deg(f)$ divides $|\mathrm{Gal}(L/F)|$. $\square$

6.4 EXAMPLES OF GALOIS GROUPS

Ex. 6.4.1 *Given $a, b \in \mathbb{F}_p$, define $\gamma_{a,b} : \mathbb{F}_p \to \mathbb{F}_p$ by $\gamma_{a,b}(u) = au + b$.*

(a) Prove that $\gamma_{a,b}$ is one-to-one and onto if and only if $a \neq 0$.

(b) Suppose that $a \neq 0$. Prove that the inverse function of $\gamma_{a,b}$ is $\gamma_{a^{-1},-a^{-1}b}$.

(c) Show that
$$\mathrm{AGL}(1, \mathbb{F}_p) = \{\gamma_{a,b} \mid (a, b) \in \mathbb{F}_p^* \times \mathbb{F}_p\}$$
is a group under composition.

Proof. Let $a, b \in \mathbb{F}_p$, and $\gamma_{a,b} : \mathbb{F}_p \to \mathbb{F}_p, u \mapsto \gamma_{a,b}(u) = au + b$.

(a) If $a = 0$, $\gamma_{a,b}$ is the constant function b, thus $\gamma_{0,b}$ is not a bijection.

Suppose that $a \neq 0$. Then , for all $u, v \in \mathbb{F}_p$,
$$v = au + b \iff u = a^{-1}v - a^{-1}b.$$
So every $v \in \mathbb{F}_p$ has a unique antecedent, therefore $\gamma_{a,b}$ est bijective.

(b) If $a \neq 0$, by part (a),$\gamma_{a,b}$ is bijective, and the unique antecedent u of any $v \in \mathbb{F}_p$ is given by $u = a^{-1}v - a^{-1}b = \gamma_{a^{-1},-a^{-1}b}(v)$. Consequently
$$\gamma_{a,b}^{-1} = \gamma_{a^{-1},-a^{-1}b}.$$

(c) We show that $\mathrm{AGL}(1, \mathbb{F}_p)$ is a subgroup of $(S(\mathbb{F}_p), \circ)$.

• By part (a), if $f \in \mathrm{AGL}(1, \mathbb{F}_p)$, then $f = \gamma_{a,b}$, where $a \neq 0$, thus f est bijective : $\mathrm{AGL}(1, \mathbb{F}_p) \subset S(\mathbb{F}_p)$, and $1_{\mathbb{F}_p} = \gamma_{1,0} \in \mathrm{AGL}(1, \mathbb{F}_p)$, so $\mathrm{AGL}(1, \mathbb{F}_p) \neq \emptyset$.

• If $f, g \in \mathrm{AGL}(1, \mathbb{F}_p)$, then $f = \gamma_{a,b}, g = \gamma_{c,d},\ a, b, c, d \in \mathbb{F}_p, a \neq 0, c \neq 0$.

For all $u \in \mathbb{F}_p$,

$(g \circ f)(u) = \gamma_{c,d}(\gamma_{a,b}(u) = \gamma_{c,d}(au + b) = c(au + b) + d = acu + (bc + d) = \gamma_{ac,bc+d}$.

Therefore $g \circ f = \gamma_{c,d} \circ \gamma_{a,b} = \gamma_{ac,bc+d}$ and $ac \neq 0$, so $g \circ f \in \mathrm{AGL}(1, \mathbb{F}_p)$.

• If $f \in \mathrm{AGL}(1, \mathbb{F}_p)$, $f = \gamma_{a,b}, a \neq 0$, then $f^{-1} = \gamma_{a^{-1},-a^{-1}b} \in \mathrm{AGL}(1, \mathbb{F}_p)$.

$\mathrm{AGL}(1, \mathbb{F}_p)$ is a group under composition.

□

Ex. 6.4.2 *Consider the map* $\mathrm{AGL}(1, \mathbb{F}_p) \to \mathbb{F}_p^*$ *defined by* $\gamma_{a,b} \mapsto a$.

(a) *Show that this map is an onto group homomorphism with kernel* $T = \{\gamma_{1,b} \mid b \in \mathbb{F}_p\}$. *Then use this to prove (6.6).*

(b) *Show that* $T \simeq \mathbb{F}_p$.

Proof. Let $\varphi : \mathrm{AGL}(1, \mathbb{F}_p) \to \mathbb{F}_p^*, \gamma_{a,b} \mapsto \varphi(\gamma_{a,b}) = a$.

(a) This map is well defined, since

$$f = \gamma_{a,b} = \gamma_{c,d} \in \mathrm{AGL}(1, \mathbb{F}_p) \Rightarrow \forall u \in \mathbb{F}_p, au + b = cu + d \Rightarrow a = c.$$

φ is a group homomorphism: if $f = \gamma_{a,b}, g = \gamma_{c,d} \in \mathrm{AGL}(1, \mathbb{F}_p)$, then

$$\varphi(g \circ f) = \varphi(\gamma_{c,d} \circ \gamma_{a,b}) = \varphi(\gamma_{ac,bc+d}) = ac = \varphi(g)\varphi(f).$$

This homomorphism is surjective, since every $a \in \mathbb{F}_p^*$ satisfies $a = \varphi(\gamma_{a,0})$, with $\gamma_{a,0} \in \mathrm{AGL}(1, \mathbb{F}_p)$.

$\gamma_{a,b} \in \ker(\varphi) \iff a = 1$: the kernel of φ is $T = \{\gamma_{1,b} \mid b \in \mathbb{F}_p\}$, so T is a normal subgroup.

As the image of the group homorphism φ is $\mathbb{F}_p^*$, and its kernel T, the Isomorphism Theorem shows that

$$\mathrm{AGL}(1, \mathbb{F}_p)/T \simeq \mathbb{F}_p^*.$$

(b) The map $\psi : T \to \mathbb{F}_p, \gamma_{1,b} \mapsto b$ is bijective, and satisfies

$$\psi(\gamma_{1,b} \circ \gamma_{1,d}) = \psi(\gamma_{1,b+d}) = b + d = \psi(\gamma_{1,b})\psi(\gamma_{1,d}),$$

So ψ is a group homomorphism: $T \simeq \mathbb{F}_p$.

□

Ex. 6.4.3 *This exercise is concerned with the proof of (6.7). Given* $\tau \in S_n$, *observe that* $f \mapsto \tau \cdot f$ *can be regarded as the evaluation map from* $F[x_1, \ldots, x_n]$ *to itself that evaluates* $f(x_1, \ldots, x_n)$ *at* $(x_{\tau(1)}, \ldots, x_{\tau(n)})$.

(a) *Explain why Theorem 2.1.2 implies that* $f \mapsto \tau \cdot f$ *is a ring homomorphism. This proves the first two bullets of (6.7).*

(b) *Prove the third bullet of (6.7).*

Proof. (a) Let $\tau \in S_n$. As $f \mapsto \tau.f$ is the evaluation map that evaluates $f(x_1,\dots,x_n)$ at $(x_{\tau(1)},\dots,x_{\tau(n)})$, Theorem 2.1.2 shows that this application is a ring homomorphism, thus

$$\tau.(f+g) = \tau.f + \tau.g$$
$$\tau.(fg) = (\tau.f)(\tau.g)$$

(b) Let $f = f(x_1,\cdots,x_n) \in F(x_1,\cdots,x_n)$, and $\tau,\gamma \in S_n$. Define g by

$$g(x_1,\cdots,x_n) = \gamma.f = f(x_{\gamma(1)},\cdots,x_{\gamma(n)}).$$

Then $\tau\cdot(\gamma\cdot f) = \tau\cdot g = g(x_{\tau(1)},\dots,x_{\tau(n)})$ is obtained by substituting each x_i in the expression of g by $x_{\tau(i)}$, thus $x_{\gamma(j)}$ becomes $x_{\tau(\gamma(j))} = x_{(\tau\gamma)(j)}$:

$$\tau\cdot(\gamma\cdot f) = f(x_{(\tau\gamma)(1)},\cdots,x_{(\tau\gamma)(n)}) = (\tau\gamma)\cdot f.$$

Conclusion :

$$\tau\cdot(\gamma\cdot f) = (\tau\gamma)\cdot f.$$

□

Ex. 6.4.4 *Let $\tau \in S_n$. Prove that $f \mapsto \tau\cdot f$ is a ring isomorphism from $F[x_1,\dots,x_n]$ to itself.*

Proof. We know (Exercise 6.4.3 (a)) that $\varphi : f \mapsto \tau\cdot f$ is a ring isomorphism. As $\tau \in S_n$, τ is bijective and so τ^{-1} exists. Let $\psi : f \mapsto \tau^{-1}\cdot f$. Then for all $f \in F[x_1,\dots,x_n]$, by Exercise 6.4.3 (b)

$$(\psi\circ\varphi)(f) = \tau^{-1}\cdot(\tau\cdot f) = (\tau^{-1}\tau)\cdot f = 1_{[1,n]}\cdot f = f$$
$$(\varphi\circ\psi)(f) = \tau\cdot(\tau^{-1}\cdot f) = (\tau\tau^{-1})\cdot f = 1_{[1,n]}\cdot f = f$$

Therefore $\psi\circ\varphi = \varphi\circ\psi = 1_{F[x_1,\dots,x_n}$, so φ is a bijection.

Conclusion : φ is a ring isomorphism. □

Ex. 6.4.5 *Let R be an integral domain, and let K be its field of fractions. Prove that every ring isomorphism $\phi : R \to R$ extends uniquely to an automorphism $\tilde{\phi} : K \to K$.*

Proof. If $f = p/q \in K$, then the fraction $\phi(p)/\phi(q)$ doesn't depends of the choice of the representent (p,q) rof the fraction: if $f = p/q = r/s$, then $ps = qr$, thus $\phi(p)\phi(s) = \phi(ps) = \phi(qr) = \phi(q)\phi(r)$, and so $\phi(p)/\phi(q) = \phi(r)/\phi(s)$. Therefore there exists a map $\tilde{\phi} : K \to K$ defined for all $p/q \in K$ by

$$\tilde{\phi}(p/q) = \phi(p)/\phi(q).$$

In particular, if $p \in R$, $\tilde{\phi}(p) = \tilde{\phi}(p/1) = \phi(p)/\phi(1) = \phi(p)$: $\tilde{\phi}$ extends ϕ.

$\tilde{\phi}$ is a ring homomorphism: $\tilde{\phi}(1) = 1$ since $1 \in R$ and $\phi(1) = 1$.

$$\begin{aligned}
\tilde{\phi}\left(\frac{p}{q}\frac{r}{s}\right) &= \tilde{\phi}\left(\frac{pr}{qs}\right) = \frac{\phi(pr)}{\phi(qs)} = \frac{\phi(p)\phi(r)}{\phi(q)\phi(s)}\\
&= \tilde{\phi}\left(\frac{p}{q}\right)\tilde{\phi}\left(\frac{r}{s}\right).\\
\tilde{\phi}\left(\frac{p}{q}+\frac{r}{s}\right) &= \tilde{\phi}\left(\frac{ps+qr}{qs}\right) = \frac{\phi(ps+qr)}{\phi(qs)}\\
&= \frac{\phi(p)\phi(s)+\phi(q)\phi(r)}{\phi(q)\phi(s)} = \frac{\phi(p)}{\phi(q)} + \frac{\phi(r)}{\phi(s)}\\
&= \tilde{\phi}\left(\frac{p}{q}\right)+\tilde{\phi}\left(\frac{r}{s}\right)
\end{aligned}$$

If $\tilde{\phi}(p/q) = 0$, then $\phi(p)/\phi(q) = 0$, thus $\phi(p) = 0$, $p = 0$, $p/q = 0$: $\tilde{\phi}$ is injective.

If $g = u/v \in K$, as ϕ is surjective, $u = \phi(p), v = \phi(q),\ p, q \in R$. Then $g = \phi(p)/\phi(q) = \tilde{\phi}(p/q),\ p/q \in K$: $\tilde{\phi}$ est surjective.

$\tilde{\phi} : K \to K$ is a field automorphism.

If $\psi : K \to K$ is any field automorphism which extends ϕ, then for any fraction $p/q \in K$,

$$\psi\left(\frac{p}{q}\right) = \frac{\psi(p)}{\psi(q)} = \frac{\phi(p)}{\phi(q)} = \tilde{\phi}\left(\frac{p}{q}\right),$$

so $\psi = \tilde{\phi}$:

every ring isomorphism $\phi : R \to R$ extends uniquely to an automorphism of K. □

Ex. 6.4.6 *As in the text, let $f = x^5 - 6x + 3$.*

(a) Use the hints given in the text to show that every element of S_5 of order 5 is a 5-cycle.

(b) Use curve graphing from calculus to show that f has exactly three real roots.

Proof. Let $f = x^5 - 6x + 3$.

(a) Let $\sigma \in S_5$ a permutation of order 5. Write $\sigma = \sigma_1 \cdots \sigma_r$ ($\sigma_i \neq e$) the cycle decomposition of σ. Let $d_i = |\sigma_i|$ the order of σ_i in S_n. As the cycles are disjoint, for all integer k, $\sigma^k = \sigma_1^k \cdots \sigma_r^k$ and

$$\begin{aligned}
\sigma^k = e &\iff \sigma_1^k = \cdots = \sigma_r^k = e\\
&\iff d_1 \mid k,\ d_2 \mid k, \ldots,\ d_r \mid k\\
&\iff \mathrm{lcm}(d_1, \ldots, d_r) \mid k
\end{aligned}$$

So the order of σ is the lcm of the orders d_i.

$$5 = \mathrm{lcm}(d_1, \cdots, d_r).$$

As $d_i \mid 5,\ i = 1, \ldots, r$, and $d_i \neq 1$, where 5 is prime, $d_i = 5$. The cycles σ_i being disjoint, as $d_i = |\sigma_i| = \mathrm{length}(\sigma_i)$, $d_1 + \cdots + d_r \leq 5$, thus $rd_1 = 5r \leq 5$, so $r = 1$.

Conclusion : $\sigma = \sigma_1$ is a 5-cycle.

(b) Let $f : \mathbb{R} \to \mathbb{R}, x \mapsto f(x) = x^5 - 6x + 3$.

If $x \in \mathbb{R}$, $f'(x) = 5x^4 - 6 < 0 \iff x^4 < \frac{6}{5} \iff -x_0 < x < x_0, \quad$ where $x_0 = \sqrt[4]{\frac{6}{5}}$.

f is so strictly increasing on $]-\infty, -x_0]$, strictly decreasing on $[-x_0, x_0]$, and strictly increasing on $[x_0, +\infty[$.

$f(x_0) = x_0(x_0^4 - 6) + 3 = x_0(\frac{6}{5} - 6) + 3 = -\frac{24}{5}x_0 + 3 = \frac{3}{5}(5 - 8x_0) < 0$: indeed $x_0 = \sqrt[4]{\frac{6}{5}} > 1 > \frac{5}{8}$, so $5 - 8x_0 < 0$.

$f(-x_0) = -x_0(x_0^4 - 6) + 3 = \frac{24}{5}x_0 + 3 > 0$.

As f is continuous, $\lim\limits_{x \to -\infty} f(x) = -\infty, f(-x_0) > 0$, and f is strictly increasing on $]-\infty, -x_0]$, the Intermediate Values Theorem shows that f has a unique root in $]-\infty, -x_0]$.

With a similar reasoning on $[-x_0, x_0]$ and and on $[x_0, +\infty[$, with $f(-x_0) < 0, f(x_0) > 0$, $\lim\limits_{x \to +\infty} f(x) = +\infty$, we prove that f has a unique root in $[-x_0, x_0]$, and also in $[x_0, +\infty[$.

Conclusion : f has exactly three real roots.

$\square$

Ex. 6.4.7 *Show that S_n is generated by the transposition $(1\,2)$ and the n-cycle $(1\,2\dots\,n)$.*

Proof. Let G_n lthe subgroup of S_n generated by the transpositions $(1,2), (2,3), \cdots, (n-1, n)$:

$$G_n = \langle (1,2), (2,3), \cdots, (n-1,n) \rangle$$

For all $i \in \{1, \cdots, n\}$, there exists $g \in G_n$ such that $g(n) = i$.

Indeedt, if $g = (i, i+1) \circ (i+1, i+2) \circ \cdots \circ (n-1, n) = (i, i+1)(i+1, i+2) \cdots (n-1, n)$ (with the convention $g = e$ if $i = n$).

Then $g \in G_n$ and $g(n) = i$ (as $\mathcal{O}_n = [1, n]$, G_n is a transitive subgroup of S_n).

Conclusion :for all $i \in \{1, \cdots, n\}$, there exists $g \in G_n$ tel que $g(n) = i$.

We show that $G_n = S_n$.

$S_2 = \{e, (1,2)\}$ is equal to $G_2 = \langle (1,2) \rangle$.

By induction, we suppose that $S_{n-1} = G_{n-1}$ $(n \geq 3)$.

The subgroup of S_n of the permutations fixing n is identified with S_{n-1}, so

$$\mathrm{Stab}_{S_n}(n) = S_{n-1}.$$

Let $\sigma \in S_n$ and $i = \sigma(n)$. By part (a), there exist $g \in G_n$ such that $g(n) = i$. Then

$$(g^{-1} \circ \sigma)(n) = n : g' = g^{-1} \circ \sigma \in S_{n-1}.$$

Thus $\sigma = g \circ g'$, where $g \in G_n, g' \in G_{n-1} \subset G_n$, therefore $\sigma \in G_n$. So $S_n \subset G_n$, and by definition $G_n \subset S_n$, thus $G_n = S_n$.

Conclusion : for all $n \geq 2$, $S_n = \langle (1,2), (2,3), \cdots, (n-1,n) \rangle$

We recall the following lemma :

Lemma : *If $g = (a_1, \cdots, a_k)$ is a cycle in S_n, and $\sigma \in S_n$, then*

$$\sigma \circ g \circ \sigma^{-1} = (\sigma(a_1), \cdots, \sigma(a_k)).$$

Indeed,
• If $1 \leq i < k$, $(\sigma \circ g \circ \sigma^{-1})(\sigma(a_i)) = \sigma(g(a_i)) = \sigma(a_{i+1}))$.
• If $i = k$, $(\sigma \circ g \circ \sigma^{-1})(\sigma(a_k)) = \sigma(g(a_k)) = \sigma(a_1))$.
• if $x \not\in \{\sigma(a_1), \cdots, \sigma(a_k)\}$, then $\sigma^{-1}(x) \not\in \{a_1, \cdots, a_k\}$,
therefore $g(\sigma^{-1}(x)) = \sigma^{-1}(x)$, $(\sigma \circ g \circ \sigma^{-1})(x) = x$. □

Let $\tau = (1,2), \sigma = (1, 2, \cdots, n)$.
We apply the Lemma to τ and $\sigma^{k-1}, 1 \leq k < n$:

$$\sigma^{k-1} \circ \tau \circ \sigma^{-(k-1)} = (\sigma^{k-1}(1), \sigma^{k-1}(2)) = (k, k+1).$$

Thus $\langle \sigma, \tau \rangle \supset G_n = S_n$.
Conclusion : S_n is generated by the transposition $(1,2)$ and the n-cycle $(1, 2 \ldots, n)$.
□

Ex. 6.4.8 *Let G and H be groups where G acts on H by group homomorphisms. As in the text, we let $H \rtimes G$ denote the set $H \times G$ with the binary operation given by (6.9).*

(a) Prove that $H \rtimes G$ is a group.

(b) Prove that the map $H \rtimes G \to G$ defined by $(h, g) \mapsto g$ is an onto homomorphism with kernel $H \times \{e\}$.

(c) Prove that $h \mapsto (h, e)$ defines an isomorphism $H \simeq H \times \{e\}$ (where the group structure on $H \times \{e\}$ comes from $H \rtimes G$).

Proof. By definition of an action by group homomorphisms, there exists a group homomorphism $\varphi : G \to \mathrm{Aut}(H)$ such that for all $(g, h) \in G \times H$,

$$g \cdot h = \varphi(g)(h),$$

so $h \mapsto g \cdot h$ is a group automorphism of H for all $g \in G$.

(a) $\boxed{I}$ If $h, h' \in H, g, g' \in G$, then $g \cdot h' \in H$, thus $(h(g \cdot h'), gg') \in H \times G$, so this law defines a binary operation on $H \times G$.

$\boxed{A}$ Let $(h, g), (h', g'), (h'', g'') \in H \times G$. Then

$$\begin{aligned}((h, g).(h', g')).(h'', g'') &= (h(g \cdot h'), gg').(h'', g'') \\ &= (h(g \cdot h')((gg') \cdot h''), gg'g'') \\ &= (h(g \cdot h')(g \cdot (g' \cdot h'')), gg'g'').\end{aligned}$$

The last equality is true because G acts on H.

$$\begin{aligned}(h, g).((h', g').(h'', g'')) &= (h, g)((h'(g' \cdot h''), g'g'') \\ &= (h(g \cdot (h'(g' \cdot h''))), gg'g'') \\ &= (h(g \cdot h')(g \cdot (g' \cdot h'')), gg'g'').\end{aligned}$$

The last equality is true because G acts on H by group homomorphism.

Therefore $((h,g).(h',g')).(h'',g'') = (h,g).((h',g').(h'',g''))$: the law is associative.

$\boxed{N}$ Write e_H, e_G the identity of H and the identity of G.

$$\begin{aligned}(f,g).(e_H,e_G) &= (f(g\cdot e_H), ge_G) = (fe_H, ge_G) = (f,g),\\ (e_H,e_G).(f,g) &= (e_H(e_G\cdot f), e_G g) = (e_H f, e_G g) = (f,g).\end{aligned}$$

So (e_H, e_G) is the identity of $H \rtimes G$, which we will write now $(1,1)$.

$\boxed{S}$

Analysis : if (h',g') is the inverse of (h,g), then $(h(g\cdot h'), gg') = (1,1)$. Thus $g' = g^{-1}$, and $g\cdot h' = h^{-1}$, therefore $h' = g^{-1}\cdot(h^{-1})$.

Synthesis : we show that $(g^{-1}\cdot(h^{-1}), g^{-1})$ is the inverse of (h,g) :

$$\begin{aligned}(h,g).(g^{-1}\cdot(h^{-1}), g^{-1}) &= (h(g.(g^{-1}\cdot(h^{-1}))), gg^{-1})\\ &= (h(gg^{-1}\cdot(h^{-1})), 1)\\ &= (hh^{-1}, 1) = (1,1)\\ (g^{-1}\cdot(h^{-1}), g^{-1})(h,g) &= ((g^{-1}\cdot(h^{-1}))(g^{-1}.h), g^{-1}g)\\ &= (g^{-1}\cdot(h^{-1}h), 1)\\ &= (g^{-1}\cdot 1, 1) = (1,1)\end{aligned}$$

Every element of $H \rtimes G$ has an inverse.

$$H \rtimes G \text{ is a group.}$$

(b) Let $\psi : \left\{\begin{array}{ccc} H\rtimes G & \to & G\\ (h,g) & \mapsto & g\end{array}\right.$.

$\psi((h,g).(h',g')) = \psi(h(g\cdot h'), gg') = gg' = \psi(h,g)\psi(h',g')$. ψ is so a group homomorphism.

As every g in G is the image of $(1,g) \in H\rtimes G$ by ψ, ψ is surjective.

$\ker(\psi) = \{(h,g)\in H\rtimes G \mid g = e\} = H\times\{e\}$.

(c) Let $\chi : \left\{\begin{array}{ccc} H & \to & H\times\{e\}\\ h & \mapsto & (h,e)\end{array}\right.$.

$\chi(h)\chi(h') = (h,e)(h',e) = (h(e\cdot h'), e) = (hh', e) = \chi(hh')$: χ is a group homorphisme from H on the subgroup $H\times\{e\}$ of $H\rtimes G$.

$\chi(h) = (e,e) \iff h = e$, thus χ est injective, and surjective since every element of $H\times\{e\}$ is of the form $(h,e) = \chi(h)$: $H \simeq H\times\{e\}$.

Therefore the sequence $\{e\}\to H \to H\rtimes G \to G \to \{e\}$ is a short exact sequence, so $H\rtimes G$ is an extension of H by G.

$\square$

Ex. 6.4.9 *Explain how (6.6) and (6.10) relate to the last paragraph of the discussion of semidirect products in the Mathematical Notes.*

Proof. The group homomorphism ψ of Exercise 8 shows that $(H \rtimes G)/(H \times \{e\}) \simeq G$.
Moreover the isomorphism (6.10) $\phi : \left\{ \begin{array}{ccc} \mathrm{AGL}(1,\mathbb{F}_p) & \to & \mathbb{F}_p \rtimes \mathbb{F}_p^* \\ \gamma_{a,b} & \mapsto & (b,a) \end{array} \right.$
maps $T = \{\gamma_{1,b} \mid b \in \mathbb{F}_p\}$ on $\mathbb{F}_p \times \{1\}$.
Therefore $\mathrm{AGL}(1,\mathbb{F}_p)/T \simeq (\mathbb{F}_p \rtimes \mathbb{F}_p^*)/(\mathbb{F}_p \times \{1\}) \simeq \mathbb{F}_p^*$: we obtain so (6.6) :

$$\mathrm{AGL}(1,\mathbb{F}_p)/T \simeq \mathbb{F}_p^*.$$

□

Ex. 6.4.10 *Let $p \geq 3$ be prime, and let $\mathbb{F}_p \rtimes \mathbb{F}_p^*$ be the semidirect product described in the Mathematical Notes.*

(a) Show that $\mathbb{F}_p \rtimes \mathbb{F}_p^*$ is not Abelian.

(b) Show that the product group $\mathbb{F}_p \times \mathbb{F}_p^*$ is Abelian.

(c) Show that $\mathbb{F}_p \times \mathbb{F}_p^*$ is an extension of $\mathbb{F}_p$ by $\mathbb{F}_p^*$.

Since we already know that $\mathbb{F}_p \rtimes \mathbb{F}_p^*$ is an extension of $\mathbb{F}_p$ by $\mathbb{F}_p^*$, we see that (a) and (b) give nonisomorphic extensions.

Proof. (a) As $p \geq 3$, there exist in $\mathbb{F}_p$ an element 2 with $2 \neq 0, 2 \neq 1$, so $(0,2) \in \mathbb{F}_p \rtimes \mathbb{F}_p^*$, and also $(1,1) \in \mathbb{F}_p \rtimes \mathbb{F}_p^*$.

$$\begin{aligned} (0,2).(1,1) &= (0 + 2 \times 1, 2 \times 1) = (2,2) \\ (1,1).(0,2) &= (1 + 1 \times 0, 1 \times 2) = (1,2) \end{aligned}$$

Since $2 \neq 1$, $(0,2).(1,1) \neq (1,1).(0,2)$. So if $p \geq 3$, then $\mathbb{F}_p \rtimes F_p^*$ is not Abelian.

(b) By definition of the product in $\mathbb{F}_p \times \mathbb{F}_p^*$, $(a,b)(c,d) = (ac,bd) = (ca,db) = (c,d)(a,b)$: $\mathbb{F}_p \times \mathbb{F}_p^*$ is Abelian.

(c) The sequence

$$\{0\} \to \mathbb{F}_p \to \mathbb{F}_p \times \mathbb{F}_p^* \to \mathbb{F}_p^* \to \{1\}$$

is a short exact sequence (the first arrow is the injective map $x \mapsto (x,1)$, and the second one is the surjective map $(x,y) \mapsto y$). Actually, a direct product is a special case of semidirect product, where $\varphi : G \to \mathrm{Aut}(h)$ is the trivial action defined by $\phi(g) = 1_H$ for all $g \in G$, so $\varphi(g)(h) = g \cdot h = h$ for all $h \in H$. By part (a) and (b), these two extensions are not isomorphic.

□

Ex. 6.4.11 *The goal of this exercise is to show that the group G of permutations (6.11) is metacyclic in the sense that G has a normal subgroup H such that H and G/H are cyclic. Show that this follows from $G \simeq AGL(1,\mathbb{F}_p)$ together with (6.6) and proposition A.5.3.*

Proof. If $L = \mathbb{Q}(\zeta_p, \sqrt[p]{2})$, and $G = \mathrm{Gal}(L/\mathbb{Q})$, then by (6.4), $G \simeq \mathrm{AGL}(1,\mathbb{F}_p)$. By (6.6) and Exercise 9, $\mathrm{AGL}(1,\mathbb{F}_p)/T \simeq \mathbb{F}_p^*$, and $T \simeq \mathbb{F}_p$. As $\mathbb{F}_p$ is a cyclic (additive) group, and $\mathbb{F}_p^*$ a cyclic (multiplicative) group by Proposition A.5.3, $G = \mathrm{Gal}(L/\mathbb{Q})$ is metacyclic. □

Ex. 6.4.12 *Let p be prime. Generalize part (a) of Exercise 6 by showing that every element of S_p of order p is a p-cycle.*

Proof. Let $\sigma \in S_p$ a permutation of order p. Write $\sigma = \sigma_1 \cdots \sigma_r$ $(\sigma_i \neq e)$ the cycle decomposition of σ. Let $d_i = |\sigma_i|$ the order of σ_i in S_n. The order of σ is the lcm of the orders d_i (see Ex. 6).

$$p = \mathrm{lcm}(d_1, \cdots, d_r).$$

As $d_i \mid p$, $i = 1, \ldots, r$, and $d_i \neq 1$, where p is prime, $d_i = p$. The cycles σ_i being disjoint, as $d_i = |\sigma_i| = \mathrm{length}(\sigma_i)$, $d_1 + \cdots + d_r \leq p$, thus $rd_1 = pr \leq p$, so $r = 1$.

Conclusion : $\sigma = \sigma_1$ is a 5-cycle. $\square$

Ex. 6.4.13 *Let L be the splitting field of $2x^5 - 10x + 5$ over $\mathbb{Q}$. Prove that* $\mathrm{Gal}(L/\mathbb{Q}) \simeq S_5$.

Lemma : *Let p be a prime number. Let $\alpha = (i, j) \in S_p$ a transposition, and $\beta \in S_p$ a p-cycle. Then $S_p = \langle \alpha, \beta \rangle$.*

Proof of lemma. $\beta \in S_p$ is a p-cycle, so $\beta = (a_1, a_2, \cdots, a_p) = (a, \beta(a), \cdots, \beta^{p-1}(a))$, where $1 \leq a = a_1 \leq p$ is fixed.

The $\beta^i(a)$ are distinct, otherwise $\beta^i(a) = \beta^j(a), i < j$ implies $\beta^{j-i}(a) = a$, so the cycle would have an order at most equal to $j - i < p$, thus not equal to p.

The support of β, $\mathrm{Supp}(\beta) = \{a_1, \cdots, a_p\}$ has so p elements, therefore

$$\mathrm{Supp}(\beta) = \{1, 2, \cdots, p\}.$$

So there exists $r < p, s < p$ such that $i = \beta^r(a), j = \beta^s(a)$, thus $j = \beta^{s-r}(i)$.

Let k the remainder of the division of $s - r$ by p. Then $\beta^k(i) = j, 0 \leq k \leq p - 1$, and as $i \neq j$ since $\alpha = (ij)$ is a transposition, $k \neq 0$, so

$$\beta^k(i) = j, 1 \leq k \leq p - 1.$$

As p is prime, and $1 \leq k \leq p - 1$, β^k is also a p-cycle.

Indeed, $H = \{n \in \mathbb{Z} \mid (\beta^k)^n(a) = a\}$ is a subgroup of $\mathbb{Z}$, therefore it is of the form $H = d\mathbb{Z}, d > 0$.

As $p \in H$, d divides p, and $d \neq 1$ (otherwise $\beta^k(a) = a, k < p$), thus $d = p$.

Consequently $\beta^k = (a, \beta^k(a), \beta^{2k}(a), \cdots, \beta^{(p-1)k}(a))$ is a p-cycle, thus i is in the support of β^k.

$\alpha = (i, j), \beta^k = (i, j = \beta^k(i), \cdots, \beta^{(p-1)k}(i))$ generate S_n as in Exercice 7 where we have proved that $\sigma = (1, 2, \cdots, p)$ and $\tau = (1, 2)$ generate Sp.

There is a simple relabeling of the roots. More formally, let

$$\gamma = \begin{pmatrix} 1 & 2 & \cdots & p \\ i & j = \beta^k(i) & \cdots & \beta^{k(p-1)}(i) \end{pmatrix}.$$

Let g be any permutation in S_n. Then $\gamma^{-1} g \gamma \in S_n = \langle \sigma, \tau \rangle$.

So $\gamma^{-1} g \gamma = \sigma_1 \sigma_2 \cdots \sigma_l$, where $\sigma_i = \tau$, or $\sigma_i = \sigma$ (we can avoid negative powers since each element is of finite order).

Then $g = (\gamma \sigma_1 \gamma^{-1})(\gamma \sigma_2 \gamma^{-1}) \cdots (\gamma \sigma_l \gamma^{-1})$, and $\gamma \sigma_i \gamma^{-1} \in \{\alpha, \beta^k\}$, since by the Lemma of Exercise 6.4.1: $\gamma \tau \gamma^{-1} = \alpha, \gamma \sigma \gamma^{-1} = \beta^k$.

S_n is generated by α, β^k, a fortiori by α, β.

Conclusion: if p is prime, a p-cycle β, and any transposition (i, j) generate S_n. $\square$

Proof. Let $f = 2x^5 - 10x + 5 \in \mathbb{Q}[x]$, and L the splitting field of f, $G = \mathrm{Gal}(L, \mathbb{Q})$, and $G' \subset S_5$ the corresponding subgroup of S_5 isomorphic to G.

The Schönemann-Eisenstein Criterion with $p = 5$ shows that f is irreducible over $\mathbb{Q}$ (if $f = \sum_{k=0}^{5} a_i x^i$, $5 \nmid a_5 = 2, 5 \mid a_i, i = 0, \cdots 4, 5^2 \nmid a_0 = 5$).

Thus G acts transitively on the roots of f (Proposition 6.3.7). By Exercise 6.3.6, 5 divides $|G|$.

By Cauchy's Theorem, there exists an element σ of order 5 in G, thus an element $\tilde{\sigma}$ of order 5 in $G' \subset S_5$. Exercice 6.4.6(a) shows that $\tilde{\sigma}$ is a 5-cycle.

For all $t \in \mathbb{R}, f'(t) < 0 \iff |t| < 1$, f is strictly decreasing on $[-1, 1]$, strictly increasing on $]-\infty, -1]$ and on $[1, +\infty[$. As f is continuous, $f(1) = -3 < 0, f(-1) = 13 > 0$, and $\lim_{+\infty} f = +\infty, \lim_{-\infty} f = -\infty$, the Intermediate Values Theorem shows that the polynomial f has exactly 3 real roots, thus 2 non real conjugate complex roots. The restriction τ of complex conjugation to L is a $\mathbb{Q}$-automorphism of L (thus $\tau \in G$) who fixes three roots and exchanges the two others. The corresponding element $\tilde{\tau}$ in $G' \subset S_5$ is so a transposition. By the above Lemma, $G' = S_5$, and so

$$G = \mathrm{Gal}(L/\mathbb{Q}) \simeq S_5.$$

$\square$

Ex. 6.4.14 *Let $L = \mathbb{Q}(\zeta_p, \sqrt[p]{2})$. Prove that $L = \mathbb{Q}(\sqrt[p]{2}, \zeta_p \sqrt[p]{2})$, i.e. the splitting field of $x^p - 2$ over Q can be generated by two of its roots.*

Proof. Let $L = \mathbb{Q}(\zeta_p, \sqrt[p]{2})$.

$\sqrt[p]{2} \in L$, and $\zeta_p \sqrt[p]{2} \in L$, thus $\mathbb{Q}(\sqrt[p]{2}, \zeta_p \sqrt[p]{2}) \subset L$.

$\zeta_p = \zeta_p \sqrt[p]{2} / \sqrt[p]{2} \in \mathbb{Q}(\sqrt[p]{2}, \zeta_p \sqrt[p]{2})$, and $\sqrt[p]{2} \in \mathbb{Q}(\sqrt[p]{2}, \zeta_p \sqrt[p]{2})$. As L is the smallest subfield of $\mathbb{C}$ containing $\mathbb{Q}$, ζ_p, $\sqrt[p]{2}$, then $L \subset \mathbb{Q}(\sqrt[p]{2}, \zeta_p \sqrt[p]{2})$.

Conclusion :

$$\mathbb{Q}(\zeta_p, \sqrt[p]{2}) = \mathbb{Q}(\zeta_p, \zeta_p \sqrt[p]{2}).$$

The splitting field of $x^p - 2$ over $\mathbb{Q}$ is generated by two of its roots. $\square$

Ex. 6.4.15 *Let $L = \mathbb{Q}(\zeta_p, \sqrt[p]{2})$. The description of $\mathrm{Gal}(L/\mathbb{Q})$ given in the text enables one to construct some elements of $\mathrm{Gal}(L/\mathbb{Q}(\zeta_p))$. Use these automorphisms and Proposition 6.3.7 to prove that $x^p - 2$ is irreducible over $\mathbb{Q}(\zeta_p)$.*

Proof. Let $L = \mathbb{Q}(\zeta_p, \sqrt[p]{2})$, the splitting field of $f = x^p - 2$ over $\mathbb{Q}$. Then $\mathrm{Gal}(L/\mathbb{Q}) \simeq \mathrm{AGL}(1, \mathbb{F}_p)$.

We show that $x^p - 2$ is irreducible over $\mathbb{Q}(\zeta_p)$.

- First proof (without Galois groups).

  $\Phi_p = 1 + x + \cdots + x^{p-1}$ is irreducible over $\mathbb{Q}$, thus $[\mathbb{Q}(\zeta_p) : \mathbb{Q}] = p - 1$.

  $[L : Q] = p(p-1)$ by Section 6.4. We deduce of $[L : \mathbb{Q}] = [L : \mathbb{Q}(\zeta_p)]\ [(\mathbb{Q}(\zeta_p) : \mathbb{Q}]$ that

  $$[\mathbb{Q}(\zeta_p, \sqrt[p]{2}) : \mathbb{Q}(\zeta_p)] = p.$$

  If g is the minimal polynomial of $\sqrt[p]{2}$ over $\mathbb{Q}(\zeta_p)$, then $\deg(g) = [\mathbb{Q}(\zeta_p, \sqrt[p]{2}) : \mathbb{Q}(\zeta_p)] = p$. Moreover $\sqrt[p]{2}$ is a root of $f = x^p - 2 \in \mathbb{Q}[x] \subset \mathbb{Q}(\zeta_p)[x]$, thus $g \mid f$ in $\mathbb{Q}(\zeta_p)[x]$, where f, g are of the same degree p and monic, thus $g = f = x^p - 2$.

  Conclusion : $x^p - 2$ is irreducible over $\mathbb{Q}(\zeta_p)$.

- Second proof (with Galois groups).

  In L, f splits entirely under the form $x^p - 2 = \prod_{k=1}^{p} (x - \alpha_k)$, where $\alpha_k = \zeta_p^{k-1} \sqrt[p]{2}$.

  Let g the minimal polynomial of $\sqrt[p]{2}$ over $\mathbb{Q}(\zeta_p)$. As g divides $x^p - 2$, the set of its roots is a subset of $\{\alpha_1, \cdots, \alpha_p\}$.

  By Section 6.4, there exists $\sigma \in \mathrm{Gal}(L/\mathbb{Q})$ such that $\sigma(\zeta_p) = \zeta_p, \sigma(\sqrt[p]{2}) = \zeta_p \sqrt[p]{2}$.

  $\sigma = \sigma_{1,1}$ maps to $\mathrm{AGL}(1, \mathbb{F}_p)$ on the translation $u \mapsto u + 1$, which generates the subgroup T with p elements.

  Since $\sigma(\zeta_p) = \zeta_p, \sigma \in \mathrm{Gal}(L : \mathbb{Q}(\zeta))$ fixes the polynomial g, thus sends the roots of g on the roots of g. This remains true for the powers $\sigma_{1,k} = \sigma^k$ of σ.Therefore, $\alpha_1 = \sqrt[p]{2}$ being a root of g, its successive images by σ are $\alpha_2, \cdots, \alpha_{p-1}$, which are so roots of g, and so $f \mid g, f = g$. Therefore $x^p - 2$ is irreducible over $\mathbb{Q}(\zeta_p)$.

  Note : $\mathrm{Gal}(L/\mathbb{Q}(\zeta)) \simeq T \subset \mathrm{AGL}(1, \mathbb{F}_p)$, thus $\mathrm{Gal}(L/\mathbb{Q}(\zeta)) \simeq \mathbb{Z}/p\mathbb{Z}$.

$\square$

6.5 ABELIAN EQUATION (OPTIONAL)

Ex. 6.5.1 *Assume that $f \in F[x]$ is nonconstant and has roots $\alpha_1 = \alpha, \alpha_2, \dots, \alpha_n$ in a splitting field L. Prove that $L = F(\alpha)$ if and only if there are rational functions $\theta_i \in F(x)$ such that $\alpha_i = \theta_i(\alpha)$.. Can we assume that the θ_i are polynomials?*

Proof. • Suppose that $L = F(\alpha)$. As $\alpha_i \in L$, $\alpha_i \in F(\alpha)$. By definition of $F(\alpha)$, there exist $\theta_i \in F(x)$ such that $\alpha_i = \theta_i(\alpha)$.

• Reciprocally, suppose that for all i, $1 \le i \le n$, $\alpha_i = \theta_i(\alpha), \theta_i \in F(x)$. Thus $\alpha_i \in F(\alpha)$. Consequently $L = F(\alpha_1, \cdots, \alpha_n) \subset F(\alpha)$.

As $F(\alpha) = F(\alpha_1) \subset F(\alpha_1, \cdots, \alpha_n)$, $L = F(\alpha_1, \cdots, \alpha_n) = F(\alpha)$.

Conclusion : $L = F(\alpha) \iff \alpha_i = \theta_i(\alpha), \theta_i \in F(x)$ $(1 \le i \le n)$.

Moreover, as α is algebraic over F, $F(\alpha) = F[\alpha]$, therefore every $\alpha_i \in F(\alpha) = F[\alpha]$ is of the form $\alpha_i = \theta_i(\alpha)$, where the $\theta_i \in F[x]$ are polynomials. $\square$

Ex. 6.5.2 *Show that the equation $x^4 - 10x^2 + 1 = 0$ discussed in Example 6.5.1 is Abelian.*

Proof. As in Example 6.5.1, let $\theta_1(x) = x, \theta_2(x) = -x, \theta_3(x) = 10x - x^3, \theta_4(x) = -10x + x^3$, so the solutions of the equations are $\alpha_i = \theta_i(\alpha),\ i = 1, 2, 3, 4$.

The roots of f being polynomials in α, the splitting field of f is $F(\alpha)$ (See Exercise 1).

Moreover, as $\theta_1 = x, \theta_2 = -x, \theta_4 = -\theta_3$ and θ_3, θ_4 are odd functions,
$\theta_1(\theta_i(\alpha)) = \theta_i(\alpha) = \theta_i(\theta(\alpha)),\ i = 2, 3, 4.$
$\theta_2(\theta_i(\alpha)) = -\theta_i(\alpha) = \theta_i(-\alpha) = \theta_i(\theta_2(\alpha)),\ i = 3, 4.$
$\theta_3(\theta_4(\alpha)) = \theta_3(-\theta_3(\alpha)) = -\theta_3^2(\alpha) = -\theta_4^2(\alpha) = \theta_4(-\theta_4(\alpha)) = \theta_4(\theta_3(\alpha)).$
Thus $\theta_i(\theta_j(\alpha)) = \theta_j(\theta_i(\alpha))$, for $1 \le i < j \le 4$, thus also for $1 \le i, j \le 4$.

$$x^4 - 10x^2 + 1 = 0 \text{ is an Abelian equation.}$$

$\square$

Ex. 6.5.3 *Complete the proof of theorem 6.5.3.*

Proof. We show that the Galois group G of an Abelian equation is Abelian.

Let $L = F(\alpha_1, \cdots, \alpha_n)$ a splitting field of $f \in F[x]$, et $\alpha = \alpha_1$.

By definition of an Abelian equation, there exists $\theta_i \in F(x)$ tels que $\alpha_i = \theta_i(\alpha)$ ($i = 1, \cdots, n$), so $L = F(\alpha)$ (see Exercise 1).

• $\sigma \in \mathrm{Gal}(L/F)$, et $f \in F[x]$, thus $\sigma(\alpha)$ is also a root $\alpha_i, 1 \le i \le n$ of f:
$\sigma(\alpha) = \alpha_i = \theta_i(\alpha)$. Similarly $\tau(\alpha) = \theta_j(\alpha), 1 \le j \le n$.

• if $\sigma\tau = \tau\sigma$, then $\sigma(\tau(\alpha)) = (\sigma\tau)(\alpha) = (\tau\sigma)(\alpha) = \tau(\sigma(\alpha))$.

Réciproquement, si $\sigma(\tau(\alpha)) = \tau(\sigma(\alpha))$, then $(\sigma\tau)(\alpha) = (\tau\sigma)(\alpha)$.

As $L = F(\alpha)$, and as $\sigma\tau$ and $\tau\sigma$ are identity over f F and send α on the same element, $\sigma\tau = \tau\sigma$.

$$\sigma\tau = \tau\sigma \iff \sigma(\tau(\alpha)) = \tau(\sigma(\alpha)).$$

• $\sigma(\tau(\alpha)) = \sigma(\theta_j(\alpha))$. Moreover σ is a F-automorphism of fields, et $\theta_j \in F(x)$ a polynomial, thus $\sigma(\theta_j(\alpha)) = \theta_j(\sigma(\alpha)) = \theta_j(\theta_i(\alpha)$. Therefore $\sigma(\tau(\alpha)) = \theta_j(\theta_i(\alpha))$. Similarly $\tau(\sigma(\alpha)) = \theta_i(\theta_j(\alpha))$.

The equation $f = 0$ being Abelian, $\theta_j(\theta_i(\alpha)) = \theta_i(\theta_j(\alpha))$, thus $\sigma(\tau(\alpha)) = \tau(\sigma(\alpha))$, so $\sigma\tau = \tau\sigma$, and this is true for all $\sigma, \tau \in \mathrm{Gal}(L/F)$: $\mathrm{Gal}(L/F)$ is Abelian.

Conclusion: the Galois group of an Abelian equation is Abelian. □

Ex. 6.5.4 *Show that $x^n - 1$ is an Abelian equation over $\mathbb{Q}$.*

Proof. The roots of $f = x^n - 1$ in $\mathbb{C}$ are $\zeta^k, 0 \le k < n$, where $\zeta = e^{2i\pi/n}$.

The splitting field of f over $\mathbb{Q}$ is $Q(1, \zeta, \cdots, \zeta^{n-1}) = \mathbb{Q}(\zeta)$. Moreover, every root ζ^k is of the form $\zeta^k = \theta_k(\zeta)$, where $\theta_k = x^k, 0 \le k \le n-1$.

$$\theta_i(\theta_j(\zeta)) = (\zeta^j)^i = \zeta^{ji} = (\zeta^i)^j = \theta_j(\theta_i(\zeta)),\ 0 \le i, j \le n-1,$$

so by definition $x^n - 1 = 0$ is an Abelian equation. □

Ex. 6.5.5 *Let f the minimal polynomial of $\sqrt{2+\sqrt{2}}$ over $\mathbb{Q}$. Show that $f = 0$ is an Abelian equation.*

Proof. By Exercises 5.1.6 and 6.3.4,

$$\begin{aligned} f &= x^4 - 4x^2 + 2 \\ &= \left(x - \sqrt{2+\sqrt{2}}\right)\left(x + \sqrt{2+\sqrt{2}}\right)\left(x - \sqrt{2-\sqrt{2}}\right)\left(x + \sqrt{2-\sqrt{2}}\right) \\ &= (x-\alpha)(x+\alpha)(x-\beta)(x+\beta) \end{aligned}$$

where $\beta = \frac{1}{2}\left(\alpha - \frac{2}{\alpha^3}\right) = \alpha^3 - 3\alpha$.

The 4 roots of f are of the form $\alpha = \theta_1(\alpha), -\alpha = \theta_2(\alpha), \beta = \theta_3(\alpha), -\beta = \theta_4(\alpha)$, where

$$\theta_1(x) = x, \theta_2(x) = -x, \theta_3(x) = x^3 - 3x, \theta_4(x) = -x^3 + 3x.$$

As $\theta_1 = x, \theta_2 = -x, \theta_4 = -\theta_3$ and θ_3, θ_4 are odd functions, as in Exercise 2,
$\theta_1(\theta_i(\alpha)) = \theta_i(\alpha) = \theta_i(\theta_1(\alpha)),\ i = 2, 3, 4.$
$\theta_2(\theta_i(\alpha)) = -\theta_i(\alpha) = \theta_i(-\alpha) = \theta_i(\theta_2(\alpha)),\ i = 3, 4.$
$\theta_3(\theta_4(\alpha)) = \theta_3(-\theta_3(\alpha)) = -\theta_3^2(\alpha) = -\theta_4^2(\alpha) = \theta_4(-\theta_4(\alpha)) = \theta_4(\theta_3(\alpha)).$

Thus $\theta_i(\theta_j(\alpha)) = \theta_j(\theta_i(\alpha))$, for $1 \le i < j \le 4$, thus also for $1 \le i, j \le 4$.
$\theta_i(\theta_j(\alpha)) = \theta_j(\theta_i(\alpha)),\ 1 \le i, j \le 4.$

$$x^4 - 4x^2 + 2 = 0 \text{ is an Abelian equation.}$$

□

Ex. 6.5.6 *In this exercise, you will prove a partial converse to Theorem 6.5.3. Suppose that a finite extension $F \subset L$ is normal ans separable and has an Abelian Galois group.*

(a) Explain why $F \subset L$ has a primitive element.

(b) By part (a), we can find $\alpha \in L$ such that $L = F(\alpha)$. Let f be the minimal polynomial of α. Prove that $f = 0$ is an Abelian equation over f.

Proof. Suppose that $F \subset L$ is normal and separable and that $G = \mathrm{Gal}(L/F)$ is an Abelian group.

(a) As $F \subset L$ is separable, the Theorem of the Primitive Element shows that there exists a separable element $\alpha \in L$ such that $L = F(\alpha)$.

(b) Let f the minimal polynomial of α over F. Then f is irreducible and separable. As $F \subset L$ is normal, the roots $\alpha_1 = \alpha, \cdots, \alpha_n$ of f are all in L, so $L = F(\alpha) = F(\alpha_1, \ldots, \alpha_n)$ is the splitting field of f. By Exercise 1, there exist polynomials $\theta_i \in F[x]$ such that $\alpha_i = \theta_i(\alpha),\ i = 1, \cdots, n$.

Let $1 \le i, j \le n$. As f is separable and irreducible, by Proposition 6.3.7, the Galois group G acts transitively on the set of the roots of f : so there exists $\sigma, \tau \in G$ such that $\theta_i(\alpha) = \sigma(\alpha)$ and $\theta_j(\alpha) = \tau(\alpha)$.

Exercise 3 shows that $(\sigma\tau)(\alpha) = \theta_j(\theta_i(\alpha))$ and $(\tau\sigma)(\alpha) = \theta_i(\theta_j(\alpha))$. As G is Abelian by hypothesis, $\sigma\tau = \tau\sigma$, so

$$\theta_j(\theta_i(\alpha)) = \theta_i(\theta_j(\alpha)), 1 \le i, j \le n.$$

The equation $f = 0$ is Abelian.

Conclusion: if the finite extension $F \subset L$ is normal and separable and has an Abelian Galois group, and if f is the minimal polynomial of a primitive element α, then $f = 0$ is an Abelian equation.

□

Ex. 6.5.7 *Show that the implication (a) $\Rightarrow$ (b) of Theorem 6.5.5 is equivalent to Kronecker's assertion that the roots of an Abelian equation over $\mathbb{Q}$ can be expressed rationally in terms of a root of unity.*

Proof. Suppose that the implication (a)$\Rightarrow$(b) of Theorem 6.5.5 is true.

Let $f \in \mathbb{Q}[x]$ such that the equation $f = 0$ is Abelian. Then f has a root α such that $L = F(\alpha)$ is the splitting field of F, so the extension $F \subset L$ is normal. By Theorem 6.5.3 (and Exercise 3), as the equation $f = 0$ is Abelian, $\mathrm{Gal}(L/\mathbb{Q})$ is an Abelian group. The hypothesis (a) is so satisfied, and (b) follows : $L \subset \mathbb{Q}(\zeta_n)$, where $\zeta_n = e^{2i\pi/n}$. As the roots of f are in L, these roots can be expressed rationally in terms of a root of unity.

Conversely, suppose that the roots $\alpha_1, \cdots, \alpha_n$ of any Abelian equation $f = 0$ in the splitting field of f can be expressed rationally in terms of a root of unity ζ_n, and suppose also (a) : $\mathbb{Q} \subset L \subset \mathbb{C}$, the extension $\mathbb{Q} \subset L$ is normal, and $\mathrm{Gal}(L/\mathbb{Q})$ is an Abellan group.

As the characteristic of $\mathbb{Q}$ is 0, $\mathbb{Q} \subset L$ is also separable, and there exists a primitive element α for the extension $\mathbb{Q} \subset L$. Let f the minimal polynomial of α over $\mathbb{Q}$. By Exercise 6, since $\mathbb{Q} \subset L$ is normal and separable, the equation $f = 0$ is Abelian. By hypothesis, the roots $\alpha_1 = \alpha, \cdots, \alpha_n$ of f can be expressed rationally in terms of a root of unity ζ_n, therefore $\alpha_i \in \mathbb{Q}(\zeta_n), 1 \leq i \leq n$. In particular $\alpha \in \mathbb{Q}(\zeta_n)$, thus $L = \mathbb{Q}(\alpha) \subset \mathbb{Q}(\zeta_n)$. (b) is so proved under the hypothesis (a).

Conclusion : (a)$\Rightarrow$(b) is equivalent to the assertion of Kronecker : the roots of an Abelian equation over $\mathbb{Q}$ can be expressed rationally in terms of a root of unity. $\square$