Leandro Vendramin

Galois theory

Notes

Thursday 21st April, 2022

Preface

The notes correspond to the bachelor course *Galois theory* of the Vrije Universiteit Brussel, Faculty of Sciences, Department of Mathematics and Data Sciences. The course is divided into thirteen two-hours lectures.

The material is somewhat standard. Basic texts on fields and Galois theory are for example [1]. . .

As usual, we also mention a set of great expository papers by Keith Conrad available at `https://kconrad.math.uconn.edu/blurbs/`. The notes are extremely well-written and are useful at at every stage of a mathematical career.

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Leandro Vendramin
Brussels, Belgium

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Lecture 1

§1. Fields

Recall that a **field** is a commutative ring such that $1 \neq 0$ and that every non-zero element is invertible. Examples of (infinite) fields are $\mathbb{Q}$, $\mathbb{R}$ and $\mathbb{C}$. If p is a prime number, then $\mathbb{Z}/p$ is a field.

Example 1.1. The abelian group $\mathbb{Z}/2\times\mathbb{Z}/2$ is a field with multiplication

$$(a,b)(c,d) = (ac+bd, ad+bc+bd).$$

Example 1.2. $\mathbb{Q}(i) = \{a+bi : a,b \in \mathbb{Q}\}$ and $\mathbb{Q}(\sqrt{2})$ are fields.

xca:Q(i)

Exercise 1.3. Prove that $\mathbb{Q}(i)$ and $\mathbb{Q}(\sqrt{2})$ are not isomorphic as fields.

If R is a ring, there exists a unique ring homomorphism $\mathbb{Z} \to R$, $m \mapsto m1$. The image $\{m1 : m \in \mathbb{Z}\}$ of this homomorphism is a subring of R and it is known as the **ring of integers** of R. The kernel is a subgroup of $\mathbb{Z}$ and hence it is generated by some $t \geq 0$. The integer t is the **characteristic** of the ring R.

Exercise 1.4. The characteristic of a field is either zero or a prime number.

Recall that a commutative ring R is an **integral domain** if $xy = 0 \implies x = 0$ or $y = 0$. Fields are integral domains.

Exercise 1.5. Let K be a field. Prove that the following statements are equivalent:

1) K is of characteristic zero.
2) The additive order of 1 is infinite.
3) The additive order of each $x \neq 0$ is infinite.
4) The ring of integers of K is isomorphic to $\mathbb{Z}$.

Exercise 1.6. Let K be a field. Prove that the following statements are equivalent:

1) K is of characteristic p.

2) The additive order of 1 is p.
3) The additive order of each $x \neq 0$ is p.
4) The ring of integers of K is isomorphic to $\mathbb{Z}/p$.

Definition 1.7. A **subfield** of a ring R is a subring of R that is also a field.

Note that if K is a subfield of E, then the characteristic of K coincides with the chacteristic of E. Moreover, if $K \to L$ is a field homomorphis, then K and L have the same characteristic.

Exercise 1.8. Let K be a field of characteristic p. Prove that $K \to K$, $x \mapsto x^{p^n}$, is a field homomorphism for all $n \in \mathbb{Z}_{\geq 0}$.

Note that finite fields are of characteristic p.

Let K be a subfield of a field E. Then E is a K-vector space with the usual scalar multiplication $K \times E \to E$, $(\lambda, x) \mapsto \lambda x$.

Definition 1.9. A field K is **prime** if there are no proper subfields of K.

Examples of prime fields are $\mathbb{Q}$ and $\mathbb{Z}/p$ for p a prime number.

Proposition 1.10. *Let K be a field. The following statements hold:*

*1) K contains a unique prime field, it is known as the **prime subfield** of K.*
2) The prime subfield of K is either isomorphic to $\mathbb{Q}$ if the characteristic of K is zero, or it is isomorphic to $\mathbb{Z}/p$ for some prime number p if the characteristic of K is p.

Proof. To prove the first claim let L be the intersection of all the subfields of K. Then L is a subfield of K. If F is a subfield of L, then F is a subfield of K. Thus $L \subseteq F$ and hence $F = L$, which proves that L is prime. If L_1 is a subfield of K and L_1 is prime, then $L \subseteq L_1$ and hence $L = L_1$.

Let K_0 be the prime field of K. Suppose that K is of characteristic $p > 0$. Then the ring $K_{\mathbb{Z}}$ of integers of K is a field isomorphic to $\mathbb{Z}/p$ and hence $K_0 \simeq K_{\mathbb{Z}}$. Suppose now that the characteristic of K is zero. Let $E = \{m1/n1 : m, n \in \mathbb{Z}, n \neq 0\}$. We claim that $K_0 = E$. Since $K_{\mathbb{Z}} \subseteq K_0$, it follows that $E \subseteq K_0$. Hence $E = K_0$, as E is a subfield of K. $\square$

Definition 1.11. Let E be a field and K be a subfield of E. Then E is an **extension** of K. We will use the notation E/K.

If E is an extension of K, then E is a K-vector space.

Definition 1.12. The degree of an extension E of K is the integer $\dim_K E$. It will be denoted by $[E : K]$.

We say that E is a finite extension of K if $[E : K]$ is finite.

Example 1.13. Let K be a field. Then $[K : K] = 1$. Conversely, if E is an extension of K and $[E : K] = 1$, then $K = E$. If not, let $x \in E \setminus K$. We claim that $\{1, x\}$ is linearly independent over K. Indeed, if $a1 + bx = 0$ for some $a, b \in K$, then $bx = -a$. If $b \neq 0$, then $x = -a/b \in K$, a contradiction. If $b = 0$, then $a = 0$.

We know that $[\mathbb{C} : \mathbb{R}] = 2$.

Example 1.14. A basis of $\mathbb{Q}(\sqrt{2})$ over $\mathbb{Q}$ is given by $\{1, \sqrt{2}\}$. Then $[\mathbb{Q}(\sqrt{2}) : \mathbb{Q}] = 2$.

Example 1.15. Since $\mathbb{Q}$ is numerable and $\mathbb{R}$ is not, $[\mathbb{R} : \mathbb{Q}] > \aleph_0$. If $\{x_i : i \in \mathbb{Z}_{>0}\}$ is a numerable basis of $\mathbb{R}$ over $\mathbb{Q}$, for each n consider the $\mathbb{Q}$-vector space V_n generated by $\{x_1, \dots, x_n\}$. Then

$$\mathbb{R} = \bigcup_{n \geq 1} V_n,$$

is numerable, as each V_n is numerable, a contradiction.

If E is an extension of K and E is finite, then $[E : K]$ is finite.

Proposition 1.16. *Let K be a finite field. Then $|K| = p^m$ for some prime number p and some $m \geq 1$.*

Proof. We know that the prime subfield of K is isomorphic to $\mathbb{Z}/p$. In particular, $|K_0| = p$. Since K is finite, $[K : K_0] = m$ for some m. If $\{x_1, \dots, x_m\}$ is a basis of K over K_0, then each element of K can be written uniquely as $\sum_{i=1}^m a_i x_i$ for some $a_1, \dots, a_m \in K_0$. Then $K \simeq K_0^m$ and hence $|K| = |K_0^m| = p^m$. $\square$

Definition 1.17. Let E be an extension of K. A **subextension** F of K is a subfield F of E that contains K, that is $K \subseteq F \subseteq E$.

Definition 1.18. Let E and E_1 be extensions over K. An extension **homomorphism** $E \to E_1$ is a field homomorphism $\sigma \colon E \to E_1$ such that $\sigma(x) = x$ for all $x \in K$.

To describe the homomorphism $\sigma \colon E \to E_1$ of the extensions over K one typically writes the commutative diagram

$$\begin{tikzcd} K \arrow[r, equal] \arrow[d, hook] & K \arrow[d, hook] \\ E \arrow[r, "\sigma"] & E_1 \end{tikzcd}$$

We write $\mathrm{Hom}(E/K, E_1/K)$ to denote the set of homomorphism $E \to E_1$ of extensions of K. Note that if $\sigma \in \mathrm{Hom}(E/K, E_1/K)$, then σ is a K-linear map, as

$$\sigma(\lambda x) = \sigma(\lambda)\sigma(x) = \lambda\sigma(x)$$

for all $\lambda \in K$ and $x \in E$.

Example 1.19. The conjugation map $\mathbb{C} \to \mathbb{C}$, $z \mapsto \overline{z}$, is an endomorphism of $\mathbb{C}$ as an extension over $\mathbb{R}$. Let $\varphi \in \operatorname{Hom}(\mathbb{C}/\mathbb{R}, \mathbb{C}/\mathbb{R})$. Then

$$\varphi(x+iy) = \varphi(x) + \varphi(i)\varphi(y) = x + \varphi(i)y$$

for all $x, y \in \mathbb{R}$. Since $\varphi(i)^2 = \varphi(i^2) = \varphi(-1) = -1$, it follows that $\varphi(i) \in \{-i, i\}$. Thus either $\varphi(x+iy) = x+iy$ or $\varphi(x+iy) = x-iy$.

Exercise 1.20. Prove that if K is a field and $\sigma\colon K \to K$ is a field homomorphism, then $\sigma \in \operatorname{Hom}(K/K_0, K/K_0)$.

If E/K is an extension, then

$$\operatorname{Aut}(E/K) = \{\sigma : \sigma\colon E \to E \text{ is a bijective extension homomorphism}\}$$

is a group with composition.

Definition 1.21. Let E/K be an extension. The **Galois group** of E/K is the group $\operatorname{Aut}(E/K)$ and it will be denoted by $\operatorname{Gal}(E/K)$.

A typicall example: $\operatorname{Gal}(\mathbb{C}/\mathbb{R}) \simeq \mathbb{Z}/2$.

Example 1.22. Let $\theta = \sqrt[3]{2}$ and let $E = \{a + b\theta + c\theta^2 : a, b, c \in \mathbb{Q}\}$. Note that

$$a + b\theta + c\theta^2 = 0 \Longleftrightarrow a = b = c = 0.$$

Then E is an extension of $\mathbb{Q}$ such that $[E : \mathbb{Q}] = 3$. We claim that $\operatorname{Gal}(E/\mathbb{Q})$ is trivial. If $\sigma \in \operatorname{Gal}(E/\mathbb{Q})$ and $z = a + b\theta + c\theta^2$, then $\sigma(z) = a + b\sigma(\theta) + c\sigma^2(\theta)$. Since $\sigma(\theta)^3 = \sigma(\theta^3) = \sigma(2) = 2$, it follows that $\sigma(\theta) = \theta$ and therefore $\sigma = \mathrm{id}$.

Exercise 1.23. Prove that the polynomial $X^3 - 2$ is irreducible in $\mathbb{Q}[X]$.

Lecture 2

If E/K is an extension and S is a subset of E, then there exists a unique smallest subextension F/K of E/K such that $S \subseteq F$. In fact,

$$F = \bigcap \{T : T \text{ is a subfield of } E \text{ that contains } K \cup S\}$$

If L/K is a subextension of E/K such that $S \subseteq L$, then $F \subseteq L$ by definition. The extension F is known as the **subextension generated by** S and it will be denoted by $K(S)$. If $S = \{x_1, \dots, x_n\}$ is finite, then $K(S) = K(x_1, \dots, x_n)$ is said to be of **finite type**.

Example 1.24. If $\{e_1, \dots, e_n\}$ is a basis of E over K, then $E = K(e_1, \dots, e_n)$.

Example 1.25. The field $\mathbb{Q}(\sqrt{2})$ is precisely the extension of $\mathbb{R}/\mathbb{Q}$ generated by $\sqrt{2}$.

Let E/K be an extension and S and T be subsets of E. Then

$$K(S \cup T) = K(S)(T) = K(T)(S).$$

If, moreover, $S \subseteq T$, then $K(S) \subseteq K(T)$.

§2. Algebraic extensions

Definition 2.1. Let E/K be an extension. An element $x \in E$ is **algebraic** over K if there exists a non-zero polynomial $f(X) \in K[X]$ such that $f(x) = 0$. If x is not algebraic over K, then it is called **trascendent** over K.

If E/K is an extension, let

$$\overline{K}_E = \{x \in E : x \text{ is algebraic over } K\}.$$

Definition 2.2. An extension E/K is **algebraic** if every $x \in E$ is algebraic over K.

If K is a field, every $x \in K$ is algebraic over K, as x is a root of $X - x \in K[X]$. In particular, K/K is an algebraic extension.

Example 2.3. $\mathbb{C}/\mathbb{R}$ is an algebraic extension. If $z \in \mathbb{C} \setminus \mathbb{R}$, then z is a root of the polynomial $X^2 + (z + \overline{z})X + |z|^2 \in \mathbb{R}[X]$.

If F/K is an algebraic extension and $x \in E$ is algebraic over K, then x is algebraic over E.

Example 2.4. $\mathbb{Q}(\sqrt{2})/\mathbb{Q}$ is algebraic, as the number $a + b\sqrt{2}$ is a root of the polynomial $X^2 - 2aX + (a^2 - 2b^2) \in \mathbb{Q}[X]$.

The extension $\mathbb{C}/\mathbb{Q}$ is not algebraic.

If E/K is an extension and $x \in E$ is algebraic over K, then the evaluation homomorphism $K[X] \to E$, $f \mapsto f(x)$, is not injective. In particular, its kernel is a non-zero ideal and hence it is generated by a monic polynomial f.

Definition 2.5. Let E/K be an extension and $x \in E$ be an algebraic element. The monic polynomial that generates the kernel of $K[X] \to E$, $f \mapsto f(x)$, is known as the **minimal polynomial** of x over K and it will be denoted by $f(x, K)$. The **degree** of x over K is then $\deg f(x, K)$.

Some basic properties of the minimal polynomial of an algebraic element:

Proposition 2.6. *Let E/K be an extension and $x \in E$.*

1) *If $g \in K[X] \setminus \{0\}$ is such that $g(x) = 0$, then $f(x, K)$ divides g. In particular, $\deg f(x, K) \leq \deg g$.*
2) *$f(x, K)$ is irreducible in $K[X]$.*
3) *If F/K is a subextension of E/K, then $f(x, F)$ divides $f(x, K)$.*

Proof. Write $f = f(x, K)$ to denote the minimal polynomial of x. To prove 1) note that $g(x) = 0$ implies that g belongs to the kernel of the evaluation map, so g is a multiple of f. To prove 2) note that if $f = pq$ for some $p, q \in K[X]$ such that $0 < \deg p, \deg q < \deg f$, then $f(x) = 0$ implies that either $p(x) = 0$ or $q(x) = 0$, a contradiction. Finally we prove 3). Since $f \in K[X] \subseteq F[X]$ and $f(x) = 0$, it follows from 1) that $f(x, F)$ divides f. $\square$

Some easy examples: $f(i, \mathbb{R}) = X^2 + 1$ and $f(\sqrt[3]{2}, \mathbb{Q}) = X^3 - 2$.

Example 2.7. Let us compute $f(\sqrt{2} + \sqrt{3}, \mathbb{Q})$. Let $\alpha = \sqrt{2} + \sqrt{3}$. Then

$$\begin{aligned} \alpha - \sqrt{2} = \sqrt{3} &\implies (\alpha - \sqrt{2})^2 = 3 \implies \alpha^2 - 2\sqrt{2}\alpha + 2 = 3 \\ &\implies \alpha^2 - 1 = 2\sqrt{2}\alpha \implies (\alpha^2 - 1)^2 = 8\alpha^2 \implies \alpha^4 - 10\alpha^2 + 1 = 0. \end{aligned}$$

Thus α is a root of $g = X^4 - 10X^2 + 1$. To prove that $g = f(\alpha, \mathbb{Q})$ it is enough to prove that g is irreducible in $\mathbb{Q}[X]$. First note that the roots of g are $\sqrt{2} + \sqrt{3}$, $\sqrt{2} - \sqrt{3}$, $-\sqrt{2} + \sqrt{3}$ and $-\sqrt{2} - \sqrt{3}$. This means that if g is not irreducible, then $g = hh_1$ for some polynomials $h, h_1 \in \mathbb{Q}[X]$ such that $\deg h = \deg h_1 = 2$. This is not possible, as $(\sqrt{2} + \sqrt{3}) + (\sqrt{2} - \sqrt{3}) = 2\sqrt{2} \notin \mathbb{Q}$, $(\sqrt{2} + \sqrt{3}) + (-\sqrt{2} + \sqrt{3}) = 2\sqrt{3} \notin \mathbb{Q}$ and $(\sqrt{2} + \sqrt{3})(-\sqrt{2} - \sqrt{3}) = -5 - 2\sqrt{6} \notin \mathbb{Q}$.

Proposition 2.8. *Let F/K be a subextension and E/K. Then*

$$[E:K]=[E:F][F:K].$$

Proof. Let $\{e_i : i\in I\}$ be a basis of E over F and $\{f_j : j\in J\}$ be a basis of F over K. If $x\in E$, then $x=\sum_i \lambda_i e_i$ (finite sum) for some $\lambda_i\in F$. For each i, $\lambda_i=\sum_j a_{ij}f_j$ (finite sum) for some $a_{ij}\in K$. Then $x=\sum_i\sum_j a_{ij}(f_je_i)$. This means that $\{f_je_i : i\in I, j\in J\}$ generates E as a K-vector space. Let us prove that $\{f_je_i : i\in I, j\in J\}$ is linearly independent. If $\sum_i\sum_j a_{ij}(f_je_i)=0$ (finite sum) for some $a_{ij}\in K$, then

$$\begin{aligned} 0=\sum_i\left(\sum_j a_{ij}f_j\right)e_i &\implies \sum_j a_{ij}f_j=0 \text{ for all } i\in I\\ &\implies a_{ij}=0 \text{ for all } i\in I \text{ and } j\in J. \end{aligned}$$

□

We state a lemma:

Lemma 2.9. *If A is a finite-dimensional commutative algebra over K and A is an integral domain, then A is a field.*

Proof. Let $a\in A\setminus\{0\}$. We need to prove that there exists $b\in A$ such that $ab=1$. Let $\theta\colon A\to A$, $x\mapsto ax$. Clearly θ is an algebra homomorphism. It is injective, since A is an integral domain. Since $\dim_K A<\infty$, it follows that θ is an isomorphism. In particular, $\theta(A)=A$, which means that there exists $b\in A$ such that $1=ab$. □

Let E/K be an extension and $x\in E\setminus K$. Then

$$K[x]=\{y=f(x):\ \text{for some } f\in K[X]\}$$

is a subring of E that contains K. More generally, if $x_1,\dots,x_n\in E$, then

$$K[x_1,\dots,x_n]=\{f(x_1,\dots,x_n): f\in K[X_1,\dots,X_n]\}$$

is a subring of E. Clearly, $K[x_1,\dots,x_n]$ is a domain and

$$K(x_1,\dots,x_n)=\left\{\frac{f(x_1,\dots,x_n)}{g(x_1,\dots,x_n)} : f,g\in K[X_1,\dots,X_m] \text{ with } g(x_1,\dots,x_n)\neq 0\right\}$$

is the extension of K generated by $x_1,\dots,x_n$. Note that

$$K(x_1,\dots,x_n)=(K(x_1,\dots,x_{n-1})(x_n).$$

The previous construction can be generalized. Let I be a non-empty set. For each $i\in I$ let X_i be an indeterminate. Consider the polynomial ring $K[\{X_i : i\in I\}]$ and let $S=\{x_i : i\in I\}$ be a subset of E. There exists a unique algebras homomorphism $K[\{X_i : i\in I\}]\to E$ such that $X_i\mapsto x_i$ for all $i\in I$. The image is denoted by $K[S]$.

Exercise 2.10. Prove that $\mathbb{Q}[\sqrt{2}]=\mathbb{Q}(\sqrt{2})$.

Theorem 2.11. *Let E/K be an extension and $x \in E \setminus K$. The following statements are equivalent:*

1) *x is algebraic over K.*
2) $\dim_K K[x] < \infty$.
3) *$K[x]$ is a field.*
4) *$K[x] = K(x)$.*

Proof. We first prove 1) $\implies$ 2). Let $z \in K[x]$, say $z = h(x)$ for some $h \in K[X]$. There exists $g \in K[X]$ such that $g \neq 0$ and $g(x) = 0$. Divide h by g to obtain polynomials $q, r \in K[X]$ such that $h = gq + r$, where $r = 0$ or $\deg r < \deg g$. This implies that

$$z = h(x) = g(x)q(x) + r(x) = r(x).$$

If $\deg g = m$, then $r = \sum_{i=0}^{m-1} a_i X^i$ for some $a_0, \dots, a_{m-1} \in K$. Thus $z = \sum_{i=0}^{m-1} a_i x^i$, so $K[x] \subseteq \langle 1, x, \dots, x^{m-1} \rangle$.

The previous lemma proves that 2) $\implies$ 3).

It is trivial that 3) $\implies$ 4).

It remains to prove that 4) $\implies$ 1). Since $x \neq 0$, $1/x \in K[x]$. There exists $a_0, \dots, a_n \in K$ such that $1/x = a_0 + a_1 x + \cdots + a_n x^n$. Thus

$$a_n x^{n+1} + \cdots + a_1 x^2 + a_0 x - 1 - 0$$

so x is a root of $a_n X^{n+1} + \cdots + a_0 X - 1 \in K[X] \setminus \{0\}$. □

Note that if x is algebraic over K, then $K[x] \simeq K[X]/(f(x,K))$.

Corollary 2.12. *If E/K is finite, then E/K is algebraic.*

Proof. Let $n = [E:K]$ and $x \in E$. The set $\{1, x, \dots, x^n\}$ is linearly dependent, so there exist $a_0, \dots, a_n \in K$ not all zero such that $a_0 + a_1 x + \cdots + a_n x^n = 0$. Thus x is a root of the non-zero polynomial $a_0 + a_1 X + \cdots + a_n X^n \in K[X]$. □

We note that the converse of the previous corollary does not hold.

Corollary 2.13. *If E/K is an extension and $x_1, \dots, x_n \in E$ are algebraic over K, then $K(x_1, \dots, x_n)/K$ is finite and $K(x_1, \dots, x_m) = K[x_1, \dots, x_n]$.*

Proof. We proceed by induction on n. The case $n = 1$ follows immediately from the theorem. So assume the result holds for some $n \geq 1$. Since the extensions $K(x_1, \dots, x_n)/K(x_1, \dots, x_{n-1})$ and $K(x_1, \dots, x_{n-1})/K$ are both finite, it follows that $K(x_1, \dots, x_n)/K$ is finite. Moreover,

$$\begin{aligned} K(x_1, \dots, x_n) &= K(x_1, \dots, x_{n-1})(x_n) \\ &= K(x_1, \dots, x_{n-1})[x_n] = K[x_1, \dots, x_{n-1}][x_n] = K[x_1, \dots, x_n]. \end{aligned}$$ □

Corollary 2.14. *Let $E = K(S)$. Then E/K is algebraic if and only if x is algebraic over K for all $x \in S$.*

Proof. Let us prove the non-trivial implication. Let $z \in K(S)$. In particular, there exists a finite subset $T \subseteq S$ such that $z \in K(T)$. The previous corollary implies that $K(T)/K$ is algebraic and hence z is algebraic. □

Corollary 2.15. *If E/K is an extension, then $\overline{K}_E$ is a subfield of E that contains K. Moreover, $K(\overline{K}_E)/K$ is algebraic.*

Proof. By definition, $K(\overline{K}_E)/K$ is algebraic. Thus $K(\overline{K}_E) \subseteq \overline{K}_E$. From this it follows that $K(\overline{K}_E) = \overline{K}_E$. □

The following exercise is now almost trivial:

Exercise 2.16. Let E/K be an extension of finite type. Prove that E/K is algebraic if and only if E/K is finite.

Let $\overline{\mathbb{Q}} = \{\alpha \in \mathbb{C} : \alpha \text{ is algebraic over } \mathbb{Q}\}$. Then $\overline{\mathbb{Q}}$ is the field of algebraic numbers. Can you compute $[\overline{\mathbb{Q}} : \mathbb{Q}]$?

Lecture 3

Algebraic field extensions form a nice class of extensions. The same happens with finite field extensions.

Proposition 2.17. *Let F/K is a subextension of E/K. Then E/K is algebraic if and only if E/F and F/K are algebraic.*

Proof. We know that if E/K is algebraic, then E/F and F/K are both algebraic. Let us assume that E/F and F/K are both algebraic. Let $x \in E$ and let L be the subextension over K generated by the coefficients of $f(x, F)$, the minimal polynomial of x over F. Then L/K is finite, since it is generated by finitely many algebraic elements. Moreover, x is algebraic over L. Since

$$[L(x) : K] = [L(x) : L][L : K] < \infty,$$

$L(x)/K$ is algebraic. In particular, x is algebraic over K. □

Exercise 2.18. Let F/K is a subextension of E/K. Prove that E/K is finite if and only if E/F and F/K are finite.

Let $F \subseteq E$ and $L \subseteq E$. The composite of F and L is defined as

$$FL = K(F \cup L) = F(L) = L(F)$$

and it is equal to the smallest field that contains F and L.

Exercise 2.19. If $F = \mathbb{Q}(\sqrt{2})$ and $L = \mathbb{Q}(\sqrt{3})$, then $FL = \mathbb{Q}(\sqrt{2}, \sqrt{3})$. Compute $[\mathbb{Q}(\sqrt{2}, \sqrt{3}) : \mathbb{Q}]$ and $\mathbb{Q}(\sqrt{2}) \cap \mathbb{Q}(\sqrt{3})$.

Exercise 2.20. Let $\xi \in \mathbb{C}$ be a primitive cubic root of one. If $F = \mathbb{Q}(\sqrt[3]{2})$ and $L = \mathbb{Q}(\xi)$, then $FL = \mathbb{Q}(\sqrt[3]{2}, \xi)$. Compute $[\mathbb{Q}(\sqrt[3]{2}, \xi) : \mathbb{Q}]$ and $\mathbb{Q}(\sqrt[3]{2}) \cap \mathbb{Q}(\xi)$.

Exercise 2.21. Let E/K and F/K be extensions, where both E and F are subfields of a field L. If F/K is algebraic, then EF/E is algebraic.

Exercise 2.22. Let E/K and F/K be extensions, where both E and F are subfields of a field L. If F/K is finite, then EF/E is finite.

The solution to the previous exercise shows, in particular, that $[EF:E] \leq [F:K]$.

Lemma 2.23. *Let $\sigma\colon K \to L$ be a field homomorphism. Then there exists an extension E/K and a field isomorphism $\varphi\colon E \to L$ such that $\varphi|_K = \sigma$.*

Proof. Let A be a set in bijection with $L \setminus \sigma(K)$ and disjoint with K. Let $E = K \cup A$. If $\theta\colon A \to L \setminus \sigma(K)$ is bijective, then let

$$\varphi\colon E \to L, \quad \varphi(x) = \begin{cases} \sigma(x) & \text{if } x \in K, \\ \theta(x) & \text{if } x \in A. \end{cases}$$

Then φ is a bijective map such that $\varphi|_K = \sigma$. Transport the operations of L onto E, that is to define binary operations on E as follows:

$$(x,y) \mapsto x \oplus y = \varphi^{-1}(\varphi(x) + \varphi(y)), \qquad (x,y) \mapsto x \odot y = \varphi^{-1}(\varphi(x)\varphi(y)).$$

Then, for example,

$$x \oplus y = \varphi^{-1}(\varphi(x)+\varphi(y)) = \varphi^{-1}(\sigma(x)+\sigma(y)) = \varphi^{-1}(\sigma(x+y)) = \varphi^{-1}(\varphi(x+y)) = x+y$$

for all $x, y \in K$. □

If $\sigma\colon A \to B$ is a ring homomorphism, then σ induces a ring homomorphism $\overline{\sigma}\colon A[X] \to B[X]$, $\sum_i a_i X^i \mapsto \sum \sigma(a_i) X^i$.

Theorem 2.24. *Let K be a field and $f \in K[X]$ be such that* $\deg f > 0$*. Then there exists an extension E/K such that f admits a root in E.*

Proof. We may assume that f is irreducible over K. Let $L = K[X]/(f)$ and $\pi\colon K[X] \to L$ be the canonical map. Then L is a field (the reader should explain why). The field homomorphism $\sigma\colon K \to L$, $a \mapsto \pi(aX^0)$. Let $g = \overline{\sigma}(f) \in L[X]$.

We claim that $\pi(X)$ is a root of g in L. Suppose that $f = \sum_i a_i X^i$. Then

$$\begin{aligned} g(\pi(X)) &= \overline{\sigma}(f)(\pi(X)) \\ &= \sum_i \sigma(a_i)\pi(X)^i = \sum_i \pi(a_i X^0)\pi(X^i) = \pi\left(\sum a_i X^i\right) = \pi(f) = 0. \end{aligned}$$

The previous lemma states that there exists an extension E/K and an isomorphism $\varphi\colon E \to L$ such that $\varphi|_K = \sigma$. Note that $\varphi(x) = 0$ if and only if $x = 0$. If $u = \pi(X)$, then $\varphi^{-1}(u)$ is a root of f in E, as

$$\begin{aligned} \varphi(f(\varphi^{-1}(u))) &= \varphi\left(\sum_i a_i \varphi^{-1}(u)^i\right) = \varphi\left(\sum_i a_i \varphi^{-1}(u^i)\right) \\ &= \sum_i \varphi(a_i) u^i = \sum_i \sigma(a_i) u^i = g(u) = 0. \end{aligned}$$ □

As a corollary, if K is a field and $f_1, \dots, f_n \in K[X]$ are polynomials of positive degree, then there exists an extension E/K such that each f_i admits a root in E. This is proved by induction on n.

Definition 2.25. A field K is **algebraically closed** if each $f \in K[X]$ of positive degree admits a root in K.

The *fundamental theorem of algebra* states that $\mathbb{C}$ is algebraically closed. A typical proof uses complex analysis. Later we will give a proof of this result using Galois theory.

Proposition 2.26. *The following statements are equivalent:*

1) *K is algebraically closed.*
2) *If $f \in K[X]$ is irreducible, then* $\deg f = 1$.
3) *If $f \in K[X]$ is non-zero, then f decomposes linearly in $K[X]$, that is*

$$f = a \prod_{i=1}^{n} (X - \alpha_i)^{m_i}$$

for some $a \in K$ and $\alpha_1, \dots, \alpha_n \in K$.
4) *If E/K is algebraic, then $E = K$.*

Proof. 1) $\implies$ 2 $\implies$ 3) are exercises.

Let us prove that 3) $\implies$ 4). Let $x \in E$. Decompose $f(x, K)$ linearly in $K[X]$ as $f(x, K) = a \prod_{i=1}^{n} (X - \alpha_i)^{m_i}$ and evaluate on x to obtain that $x = \alpha_j$ for some j.

To prove that 4) $\implies$ 1) let $f \in K[X]$ be such that $\deg f > 0$. There exists an extension E/K such that f has a root x in E. The extension $K(x)/K$ is algebraic and hence $K(x) = K$, so $x \in K$. □

§3. Artin's theorem

Definition 3.1. The **algebraic closure** of a field K is an algebraic extension C/K such that C is algebraically closed.

For example, $\mathbb{C}/\mathbb{R}$ is an algebraic closure but $\mathbb{C}/\mathbb{Q}$ it is not.

pro:Artin

Proposition 3.2. *Let C be algebraically closed and $\sigma\colon K \to C$ be a field homomorphism. If E/K is algebraic, then there exists a field homomorphism $\varphi\colon E \to C$ such that $\varphi|_K = \sigma$.*

Proof. Suppose first that $E = K(x)$ and let $f = f(x, K)$. Let $\overline{\sigma}(f) \in C[X]$ and let $y \in C$ be a root of $\overline{\sigma}(f)$. If $z \in E$, then $z = g(x)$ for some $g \in K[X]$. Let $\varphi\colon E \to C$, $z \mapsto \overline{\sigma}(g)(y)$.

The map φ is well-defined. If $z = h(x)$ for some $h \in K[X]$, then

$$0 = g(x) - h(x) = (g-h)(x)$$

and thus f divides $g-h$. In particular, $\overline{\sigma}(f)$ divides $\overline{\sigma}(g-h) = \overline{\sigma}(g) - \overline{\sigma}(h)$ and hence $(\overline{\sigma}(g) - \overline{\sigma}(h))(y) = 0$.

It is an exercise to show that the map φ is a ring homomorphism.

Let $a \in K$. It follows that $\varphi|_K = \sigma$, as

$$\varphi(a) = \overline{\sigma}(aX^0)(y) = \sigma(a)$$

Let us now prove the proposition in full generality. Let X be the set of pairs (F, τ), where F is a subfield of E that contains K and $\tau \colon F \to C$ is a field homomorphism such that $\tau|_K = \sigma$. Note that $(K, \sigma) \in X$, so X is non-empty. Moreover, X is partially ordered by

$$(F, \tau) \leq (F_1, \tau_1) \iff F \subseteq F_1 \text{ and } \tau_1|_F = \tau.$$

If $\{(F_i, \tau_i) : i \in I\}$ is a chain in X, then $F = \cup_{i \in I} F_i$ is a subfield of E that contains K. Moreover, if $z \in F$, then $z \in F_i$ for some $i \in I$ and then one defines $\tau(z) = \tau_i(z)$. It is an exercise to prove that τ is well-defined. Since $(F, \tau) \in X$ is an upper bound, Zorn's lemma implies that there exists a maximal element $(E_1, \theta) \in X$. We claim that $E = E_1$. If not, let $z \in E \setminus E_1$. Since we know the proposition is true for the extension $E_1(z)/K$, let $\rho \colon E_1(z) \to C$ be a field homomorphism such that $\rho|_{E_1} = \sigma$. Then, in particular, $\rho|_K = \sigma$. This implies that $(E_1(z), \rho) \in X$ and hence $(E_1, \theta) < (E_1(z), \rho)$, a contradiction to the maximality of (E_1, θ). $\square$

Lecture 4

The previous proposition will be used to prove that the algebraic closure always exists.

Theorem 3.3 (Artin). *Let K be a field. Then K admits an algebraic closure C/K. If C_1/K is an algebraic closure, then the extensions C/K and C_1/K are isomorphic.*

Proof. Let us first prove the uniqueness. The previous proposition implies the existence of an extensions homomorphism $\varphi\colon C \to C_1$. Let $y \in C_1$ and $f = f(y, K)$ be the minimal polynomial of y in K. Since f admits a factorization

$$f = \lambda \prod (X - \alpha_i)^{m_i}$$

in $C[X]$, it follows that

$$f = \overline{\varphi}(f) = \prod (X - \varphi(\alpha_i))^{m_i}$$

Since $0 = f(y)$, we conclude that $y = \varphi(\alpha_j)$ for some j. In particular, φ is surjective and hence φ is bijective.

We now prove the existence. Let us assume that K admits an extension E/K with E algebraically closed. We will prove later that this extension indeed exists, at the moment we only want to get an algebraic extension from this setting. Let

$$F = \{x \in E : x \text{ is algebraic over } K\}.$$

Then F/K is algebraic. Let $g \in F[X]$ be such that $\deg g > 0$. Since E is algebraically closed, g admits a root α in E. In particular, α is algebraic over F and hence α is algebraic over K. This implies that $\alpha \in F$, thus F is algebraically closed. This proves that F/K is an algebraic closure.

Let us prove that there exists an extension E_1/K such that every polynomial $f \in K[X]$ with $\deg f > 0$ has a root in E_1. Let $\{f_i : i \in I\}$ be the family of monic irreducible polynomials with coefficients in K. We may think that $f_i = f_i(X_i)$. Let $R = K[\{X_i : i \in I\}]$ and let J be the ideal of R generated by the $f_i(X_i)$. We claim that $J \neq R$. If not, $1 \in J$, so

$$1 = \sum_{j=1}^{m} g_j f_{i_j}(X_j)$$

for some $g_1, \dots, g_m \in R$. There exists an extension F/K such that f_{i_j} has a root α_j in F for all j. Let

$$\sigma \colon R \to F, \quad \sigma(X_k) = \begin{cases} \alpha_j & \text{if } k = i_j, \\ 0 & \text{if } k \notin \{i_1, \dots, i_m\}. \end{cases}$$

Then $1 = \sigma(1) = \sum_{j=1}^{m} \sigma(g_j) f_{i_j}(\alpha_j) = 0$, a contradiction.

Since J is a proper ideal, it is contained in a maximal ideal M. Let $L = R/M$ and let $\sigma \colon K \to L$ be the composition $K \hookrightarrow R \to R/M = L$, where $\pi \colon R \to R/M$ is the canonical map. As we did before, $\pi(X_i)$ is a root of $\overline{\sigma}(f_i)$ for all in and there exists an extension E_1/K such that every f_i has a root in E_1. Proceeding in this way, we construct a sequence

$$E_1 \subseteq E_2 \subseteq \cdots$$

of fields such that every polynomial of positive degree and coefficients in E_k admits a root in E_{k+1}. Let $E = \cup E_k$. We claim that E is algebraically closed. In fact, let $g \in E[X]$ be such that $\deg g > 0$. Then, since $g \in E_r[X]$ for some r, it follows that g has a root in $E_{r+1} \subseteq E$. □

§4. Decomposition fields

Definition 4.1. Let K be a field and $f \in K[X]$ be such that $\deg f > 0$. A **decomposition field** of f over K is field E that contains K and that satisfies the following properties:

1) f factorizes linearly in $E[X]$.
2) if F is a field such that $K \subseteq F \subseteq E$ and f factorizes linearly in $F[X]$, then $F = E$.

Easy examples:

Example 4.2. $\mathbb{C}$ is a decomposition field of $X^2 + 1 \in \mathbb{R}[X]$.

Example 4.3. $\mathbb{Q}[\sqrt{2}]$ is a decomposition field of $X^2 - 2 \in \mathbb{Q}[X]$.

Example 4.4. $\mathbb{Q}(\sqrt[3]{2})$ is not a decomposition field of $X^3 - 2 \in \mathbb{Q}[X]$. However, if ω ia a primitive cubic root of one, then $\mathbb{Q}(\sqrt[3]{2}, \omega)$ is is a decomposition field of $X^3 - 2 \in \mathbb{Q}[X]$.

Proposition 4.5. *E is a decomposition field of $f \in K[X]$ if and only if f factorizes linearly in $E[X]$ and $E = K(x_1, \dots, x_n)$, where $x_1, \dots, x_n$ are the roots of f.*

Proof. Let $f = a \prod_{i=1}^{r} (X - x_i)^{n_i}$ and $F = K(x_1, \dots, x_r)$ with $x_1, \dots, x_r \in E$. Since f factorizes linearly in $F[X]$, it follows that $F = E$. Conversely, let $E = K(x_1, \dots, x_r)$ and assume that f factorizes linearly in $F[X]$. Then, in particular, $x_1, \dots, x_r \in F$. Hence $E \subseteq F$ and $F = E$. □

One immediately obtains the following consequence: If E is a decomposition field of $f \in K[X]$, then E/K is finite.

Theorem 4.6. *Let $f \in K[X]$ be such that* $\deg f > 0$. *There exists a (unique up to extension isomorphism) decomposition field of f over K.*

Proof. Let C/K be an algebraic closure. Write $f = a\prod_{i=1}^{r}(X - x_i)^{n_i}$ in $C[X]$. Then $E = K(x_1, \dots, x_r)$ is a decomposition field of f over K. Let us prove uniqueness: if E_1/K is a decomposition field of f over K, then E_1/K is algebraic and thus Proposition 3.2 implies that there exists $\varphi \in \mathrm{Hom}(E_1/K, C/K)$, that is $\varphi\colon E_1 \to C$ is a field homomorphism such that $\varphi|_K$ is the identity. Factorize f linearly in $E_1[X]$ and apply $\overline{\varphi}$:

$$f = a\prod_{j=1}^{s}(X - y_j)^{m_j} \implies f = \overline{\varphi}(f) = \varphi(a)\prod_{j=1}^{s}(X - \varphi(y_j))^{m_j}$$

so f factorizes linearly in $\varphi(E_1)$. Moreover, $E_1 = K(y_1, \dots, y_s)$ and it follows that $\varphi(E_1) = K(\varphi(y_1), \dots, \varphi(y_s))$. Thus $\varphi(E_1)$ is a decomposition field of f. Since $\varphi(E_1) \subseteq C$, it follows that $\varphi(E_1) = E$. □

Exercise 4.7. If E/K is finite and $\varphi \in \mathrm{Hom}(E/K, E/K)$, then φ is an isomorphism.

Let C be an algebraic closure of K and $G = \mathrm{Gal}(C/K)$. The group G acts on C

$$\sigma \cdot x = \sigma(x), \quad \sigma \in G, x \in C.$$

The orbits are of the form

$$O_G(x) = \{\sigma(x) : \sigma \in G\} = \{y \in C : y = \sigma(x) \text{ for some } \sigma \in G\}$$

The elements $x, y \in C$ are **conjugate** if $y = \sigma(x)$ for some $\sigma \in G$.

Proposition 4.8. *Let C be an algebraic closure of K and $x, y \in C$. Then x and y are conjugate if and only if $f(x,K) = f(y,K)$. In particular, $O_G(x)$ is finite.*

Proof. Let $G = \mathrm{Gal}(C/K)$. If x and y are conjugate, say $y = \sigma(x)$ for some $\sigma \in G$, let us write $g = f(x,K)$ as

$$g = X^n + \sum_{i=0}^{n-1} a_i X^i.$$

Then $0 = g(x) = x^n + \sum_{i=0}^{n-1} a_i x^i$ and hence y is a root of g, as

$$\begin{aligned} 0 = \sigma\left(x^n + \sum_{i=0}^{n-1} a_i x^i\right) &= \sigma(x)^n + \sum_{i=0}^{n-1} \sigma(a_i)\sigma(x)^i \\ &= \sigma(x)^n + \sum_{i=0}^{n-1} a_i \sigma(x)^i = y^n + \sum_{i=0}^{n-1} a_i y^i. \end{aligned}$$

Thus $f(y,K) = g$.

Conversely, assume that $f(x,K) = f(y,K)$. Let $g = f(x,K) = f(y,K)$ and let

$$\varphi\colon K[x] \to K[y], \quad h(x) \mapsto h(y).$$

Let us show that the map φ is well-defined: we need to show that if $h_1(x) = h_2(x)$, then $h_1(y) = \varphi(h_1(x)) = \varphi(h_2(x)) = h_2(y)$. If $h_1(x) = h_2(x)$, then

$$(h_1 - h_2)(x) = h_1(x) - h_2(x) = 0.$$

Thus implies that g divides $h_1 - h_2$. In particular, $h_1(y) = h_2(y)$.

A straightforward calculation shows that φ is a field homomorphism such that $\varphi|_K = \mathrm{id}$, so φ is an extension homomorphism such that $\varphi(x) = y$. There exists $\sigma \in \mathrm{Hom}(C/K, C/K)$ such that $\sigma|_{K[x]} = \varphi$. Since σ is a bijective, $\sigma(x) = \varphi(x) = y$ and hence $O_G(x) = O_G(y)$. □

Proposition 4.9. *Let C be an algebraic closure of K and x. Then*

$$f(x,K) = \prod_{y \in O_G(x)} (X - y)^m$$

for some m.

Proof. For each $y \in O_G(x)$ let m_y be the multiplicity of y in $f(x,K)$. Then, for example, $f(x,K) = (X - x)^{m_x} g$ for some g. If $y \in O_G(x)$, then $y = \sigma(x)$ for some $\sigma \in \mathrm{Gal}(C/K)$. Since

$$\overline{\sigma}(f(x,K)) = f(x,K) = (X - y)^{m_x} \overline{\sigma}(g),$$

it follows that $m_y \geq m_x$. By symmetry, we conclude that $m_x = m_y$. □

The previous proposition shows, in particular, that all the roots of an irreducible polynomial $f \in K[X]$ in an algebraic closure C of K have the same multiplicity. This is clearly not true if f is not irreducible. Find an example.

Definition 4.10. Let K be a field and $\{f_i : i \in I\}$ be a non-empty family of polynomials of positive degree with coefficients in K. A **decomposition field** of $\{f_i : i \in I\}$ is an extension E/K such that every f_i factorizes linearly in $E[X]$ and if F/K is a subextension of E/K such that every f_i factorizes linearly in $F[X]$, then $F = E$.

Exercise 4.11. Prove that E/K is a decomposition field of $\{f_i : i \in I\}$ if and only if every f_i factorizes linearly in $E[X]$ and $E = K(S)$ where $S = \{\text{roots of } f_i \text{ for all } i\}$.

Exercise 4.12. Prove that if E/K is a decomposition field of $\{f_i : i \in I\}$, then E/K is algebraic. If, moreover, I is finite, then E/K is a decomposition field of $\prod_{i \in I} f_i$.

Exercise 4.13. Prove that there exists a decomposition field of $\{f_i : i \in I\}$ and it is unique up to extension isomorphism.

§5. Normal extensions

Proposition 5.1. *Let E/K be an algebraic extension and $\sigma \in \mathrm{Hom}(E/K, E/K)$. Then σ is bijective.*

Proof. Let $x \in E$ and C be an algebraic closure of K that contains E. There exists $\varphi\colon C \to C$ such that $\varphi|_E = \sigma$. Thus $\varphi|_K = \sigma|_K = \mathrm{id}_K$. Let $G = \mathrm{Gal}(C/K)$. Then $\varphi \in G$. If $z \in O_G(x)$, then $z = \tau(x)$ for some $\tau \in G$ and hence

$$\varphi(z) = \varphi(\tau(x)) = (\varphi\tau)(x).$$

This implies that $\varphi(z) \in O_G(x)$ and $\varphi(O_G(x)) = O_G(x)$. Thus $\sigma|_{(E \cap O_G(x)}$ is injective, as

$$\begin{aligned}\sigma(E \cap O_G(x)) &= \varphi(E \cap O_G(x)) \\ &= \varphi(E) \cap \varphi(O_G(x)) = \sigma(E) \cap O_G(x) \subseteq E \cap O_G(x).\end{aligned}$$

Since $|E \cap O_G(x)| < \infty$, it follows that $E \cap O_G(x) = \sigma(E \cap O_G(x))$ and hence x belongs to the image of σ. $\square$

Lecture 5

Definition 5.2. Let E/K be an algebraic extensions and C be an algebraic closure of K. Then E/K is **normal** if $\sigma(E) \subseteq E$ for all $\sigma \in \operatorname{Hom}(E/K, C/K)$.

Note that $\sigma(E) \subseteq E$ in the previous definition is equivalent to $\sigma(E) = E$.

Example 5.3. The extension $\mathbb{Q}(\sqrt[3]{2})/\mathbb{Q}$ is not normal. Why?

Some trivial examples of normal extensions: K/K is normal and if C is an algebraic closure of K, then C/K is normal.

Example 5.4. The extension $\mathbb{Q}(\sqrt{2})/\mathbb{Q}$ is normal. In fact, every extension generated by algebraic elements of degree two is normal.

Exercise 5.5. Let ξ be a primitive cubic root of one. Then $\mathbb{Q}(\sqrt[3]{2}, \xi)/\mathbb{Q}$ is normal.

The following result is useful but technical, that is why we leave the proof as an exercise.

Exercise 5.6. Prove that the previous definition depends on E and not on the algebraic closure C.

Some properties:

Proposition 5.7. *Let E/K be a normal extension and $f \in K[X]$ be an irreducible polynomial that admits a root x in E. Then f factorizes linearly in E.*

Proof. We may assume that f is monic. Let C/K be an algebraic closure of K containing E. Let y be a root of f in C. Since $f = f(x, K) = f(y, K)$, it follows that $y = \sigma(x)$ for some $\sigma \in \operatorname{Gal}(C/K)$. Since E/K is normal, $\sigma|_E : E \to C$ is an automorphism of E/K, that is $\sigma(E) \subseteq E$. In particular, $y \in E$. $\square$

Let $K \subseteq F \subseteq E$ be a tower of fields. If E/K is normal, then E/F is normal. However, Note that E/K normal does not imply F/K normal, as this would imply that every extension is normal. Moreover, E/F normal and F/K normal do not imply E/K normal.

Example 5.8. The extensions $\mathbb{Q}(\sqrt[4]{2})/\mathbb{Q}(\sqrt{2})$ and $\mathbb{Q}(\sqrt{2})/\mathbb{Q}$ are both normal, but $\mathbb{Q}(\sqrt[4]{2})/\mathbb{Q}$ is not normal, as the roots of X^4-2 are $\sqrt{2}$, $-\sqrt{2}$, $\sqrt{2}i$ and $-\sqrt{2}i$.

Recall that if C is an algebraic closure of K and $x \in C$, then

$$f(x,K) = \prod (X-y)^m,$$

where the product is taken over all $y \in O_{\mathrm{Gal}(C/K)}(x)$. If E/K is normal and $x \in E$, then there exists m such that

$$f(x,K) = \prod (X-y)^m,$$

where the product is taken over all $y \in O_{\mathrm{Gal}(E/K)}(x)$.

Proposition 5.9. *Let E/K and F/K be extensions. If F/K is normal, then EF/E is normal.*

Proof. Let C be an algebraic closure of E containing EF. Let $\sigma \in \mathrm{Hom}(EF/E, C/E)$. We claim that $\sigma(EF) = EF$. Let

$$\overline{K} = \{x \in C : x \text{ is algebraic over } K\}.$$

Then $\overline{K}$ is an algebraic closure over K and $F \subseteq \overline{K}$. Since F/K is normal and $\sigma|_F \in \mathrm{Hom}(F/K, \overline{K}/K)$, it follows that $\sigma(F) = F$. If $z \in EF$, then $z = \sum_{i=1}^m e_i f_i$ for some $e_1, \dots, e_m \in E$ and $f_1, \dots, f_m \in F$. Since $\sigma(e_i) = e_i$ for all i,

$$\sigma(z) = \sum_{i=1}^m \sigma(e_i)\sigma(f_i) = \sum_{i=1}^m e_i \sigma(f_i) \in EF. \qquad \square$$

Proposition 5.10. *Let E/K be an algebraic extension. Then E/K is normal if and only if E/K is the decomposition field of a family of polynomials of $K[X]$ of positive degree.*

Proof. Let $G = \mathrm{Gal}(E/K)$. If $x \in E$ and $f(x,K) = \prod_{y \in O_G(x)} (X-y)^m$, then $f(x,K)$ factorizes linearly in $E[X]$. Thus E/K is a decomposition field of the family $\{f(x,K) : x \in E\}$. Conversely, assume that E/K is a decomposition field of the family $\{f_i : i \in I\}$. Then $E = K(S)$ where S is the set of roots of the polynomials f_i. Let C/K be an algebraic closure of K that contains E and let $\sigma \in \mathrm{Hom}(E/K, C/K)$. Let $x \in S$. Then x is a root of some $f_j = \sum a_k X^k$. Since $f_j(x) = 0$, it follows that $\sigma(x)$ is a root of f_j, as

$$f_j(\sigma(x)) = \sum a_k \sigma(x)^k = \sum \sigma(a_k)\sigma(x^k) = \sigma\left(\sum a_k x^k\right) = \sigma(0) = 0.$$

Hence $\sigma(E) \subseteq E$. $\square$

§6. Dedekind's theorem

Note that every extension homomorphism $E/K \to F/K$ is, in particular, a K-linear map $E \to F$, that is

$$\mathrm{Hom}(E/K, F/K) \subseteq \mathrm{Hom}_K(E, F).$$

If F/K is an extension and V is a K-vector space, the set $\mathrm{Hom}_K(E, F)$ of K-linear maps is a vector space over F with $(a \cdot f)(v) = af(v)$ for $a \in F$, $f \in \mathrm{Hom}_K(E, F)$ and $v \in V$.

xca:dim **Exercise 6.1.** Prove that $\dim_F \mathrm{Hom}_K(V, F) \geq \dim_K V$. Moreover, if $\dim_K V < \infty$, then $\dim_F \mathrm{Hom}_K(V, F) = \dim_K V$.

If V is a vector space and S is a (possibly infinite) subset of V, then S is linearly independent if every finite subset of S is linearly independent.

Theorem 6.2 (Dedekind). *Let E/K and F/K be extensions and let $\{\varphi_i : i \in I\}$ be a subset of* $\mathrm{Hom}(E/K, F/K)$*, i.e. a family of extension homomorphisms. Assume that $\varphi_i \neq \varphi_j$ if $i \neq j$. Then the subset $\{\varphi_i : i \in I\} \subseteq \mathrm{Hom}_K(E, F)$ is linearly independent over F.*

Proof. Assume it is not. Let $\{\varphi_1, \dots, \varphi_n\}$ be linearly dependent over F with n minimal. Clearly, $n > 1$. We may assume that

$$\sum_{i=1}^{n} a_i \varphi_i = 0 \tag{5.1}$$ eq:Dedekind1

for some $a_1, \dots, a_n \in F$ all different from zero. Let $z \in E \setminus \{0\}$ be such that $\varphi_1(z) \neq \varphi_2(z)$. If $x \in E$, then

$$0 = \left(\sum_{i=1}^{n} a_i \varphi_i\right)(xz) = \sum_{i=1}^{n} a_i \varphi_i(xz) = \sum_{i=1}^{n} a_i \varphi_i(x) \varphi_i(z) = \left(\sum_{i=1}^{n} (a_i \varphi_i(z)) \varphi_i\right)(x).$$

Thus

$$\sum_{i=1}^{n} (a_i \varphi_i(z)) \varphi_i = 0. \tag{5.2}$$ eq:Dedekind2

Since $\sum_{i=1}^{n} a_i \varphi_i = 0$ and $\varphi_1(z) \neq 0$, subtracting (5.1) and (5.2) we obtain that

$$a_1 \varphi_1 + a_2 \frac{\varphi_2(z)}{\varphi_1(z)} \varphi_2 + \cdots + a_n \frac{\varphi_n(z)}{\varphi_1(z)} \varphi_n = 0.$$

Thus

$$\left(a_2 - a_2 \frac{\varphi_2(z)}{\varphi_1(z)}\right) \varphi_2 + \cdots + \left(a_n - a_n \frac{\varphi_n(z)}{\varphi_1(z)}\right) \varphi_n = 0.$$

Since $a_n \neq 0$ and $\varphi_2(z) \neq \varphi_1(z)$, the scalar $a_2 - a_2 \frac{\varphi_2(z)}{\varphi_1(z)} \neq 0$ and hence $\{\varphi_2, \dots, \varphi_n\}$ is linearly dependent, a contradiction. □

If E/K and F/K are extensions, let $\gamma(E/K, F/K) = |\operatorname{Hom}(E/K, F/K)|$.

Exercise 6.3. Prove the following statements:

1) $\gamma(E/K, F/K) \leq \dim_F \operatorname{Hom}_K(E, F)$.
2) If $[E : K] < \infty$, then $\gamma(E/K, F/K) \leq [E : K]$.
3) If x is algebraic over K, then $\gamma(K(x)/K, F/K) \leq \deg(x, K)$.

If C is an algebraic closure of K, then we define $\gamma(E/K) = \gamma(E/K, C/K)$. This definition does not depend on the algebraic closure.

xca:gamma_C **Exercise 6.4.** If C and C_1 are algebraic closures of K, then

$$|\operatorname{Hom}(E/K, C/K)| = |\operatorname{Hom}(E/K, C_1/K)|.$$

pro:gamma_orbit **Proposition 6.5.** *Let C be an algebraic closure of K and $G = \operatorname{Gal}(C/K)$. If $x \in C$, then $\gamma(K(x)/K) = |O_G(x)|$.*

Proof. If $\sigma \in \operatorname{Hom}(K(x)/K, C/K)$, then there exists $\phi \in G$ such that $\phi|_{K(x)} = \sigma$. Thus $\sigma(x) = \phi(x) \in O_G(x)$. Conversely, if $y \in O_G(x)$, then there exists $\tau \in G$ such that $y = \tau(x)$. Hence $\tau|_{K(x)} \in \operatorname{Hom}(K(x)/K, C/K)$ and $\tau|_{K(x)}(x) = y$. In particular, $\gamma(K(x)/K)$ divides $\deg(x, K)$. □

Exercise 6.6. If E/K is finite, then $|\operatorname{Gal}(E/K)| \leq [E : K]$. Moreover, E/K is normal if and only if $|\operatorname{Gal}(E/K)| = \gamma(E/K)$.

Lecture 6

If $t\colon A \to B$ is a surjective map, then $a \sim a_1 \iff t(a) = t(a_1)$ defines an equivalence relation on A. The set $\overline{A}$ of equivalence classes is in bijective correspondence with B, $\overline{A} \to B$, $\overline{a} \mapsto t(a)$. Moreover, if $|t^{-1}(\{b\})| = m$ for all $b \in B$, then $|A| = m|\overline{A}| = m|B|$.

Proposition 6.7. *Let E/K be algebraic and F/K be a subextension such that E/F is finite. Then $\gamma(E/K) = \gamma(E/F)\gamma(F/K)$.*

Proof. Assume that $E = F(x)$. Let $f = f(x, F) = \sum b_i X^i$ and let $G = \mathrm{Gal}(E/F)$. Let C be an algebraic closure of K containing E. The map

$$\lambda\colon \mathrm{Hom}(E/K, C/K) \to \mathrm{Hom}(F/K, C/K), \quad \sigma \mapsto \sigma|_F,$$

is well-defined. It is surjective: if $\varphi \in \mathrm{Hom}(F/K, C/K)$, then $\varphi\colon F \to C$ is, in particular, a field homomorphism. Since E/F is algebraic, by Proposition 3.2 there exists a field homomorphism $\sigma\colon E \to C$ such that $\sigma|_F = \varphi$. Since $\sigma|_K = \varphi|_K = \mathrm{id}$, in particular $\sigma \in \mathrm{Hom}(E/K, C/K)$.

For $\varphi \in \mathrm{Hom}(F/K, C/K)$,

$$\lambda^{-1}(\{\varphi\}) = \{\sigma \in \mathrm{Hom}(E/K, C/K) : \sigma|_F = \varphi\}$$

and let R_φ be the set of roots (in C) of the polynomial $\overline{\varphi}(f) = \sum \varphi(b_i) X^i$.

Claim. The map $\alpha\colon \lambda^{-1}(\{\varphi\}) \to R_\varphi$, $\sigma \mapsto \sigma(x)$, is well-defined.

We need to show that $\sigma(x)$ is a root of $\overline{\varphi}(f)$:

$$\begin{aligned}
\overline{\varphi}(f)(\sigma(x)) &= \sum \varphi(b_i)\sigma(x)^i = \sum \sigma(b_i)\sigma(x^i) \\
&= \sum \sigma(b_i x^i) = \sigma\left(\sum b_i x^i\right) = \sigma(f(x)) = \sigma(0) = 0.
\end{aligned}$$

Claim. The map $\beta\colon R_\varphi \to \lambda^{-1}(\{\varphi\})$, $y \mapsto \sigma_y$, where $\sigma_y(z) = \overline{\varphi}(h)(y)$ if $z = h(x)$, is well-defined.

We need to show that if $z = h(x)$ and $z = h_1(x)$ for some $h, h_1 \in F[X]$, then $\overline{\varphi}(h)(y) = \overline{\varphi}(h_1)(y)$. The assumptions imply that $(h-h_1)(x) = 0$ and hence f divides $h - h_1$. Since $\overline{\varphi}$ is a ring homomorphism, $\overline{\varphi}(f)$ divides $\overline{\varphi}(h) - \overline{\varphi}(h_1)$. This implies $(\overline{\varphi}(h) - \overline{\varphi}(h_1))(y) = 0$. We also need to show that $\sigma_y|F = \varphi$: if $f \in F$, then write $f = fX^0 \in F[X]$. Thus $\sigma_y(f) = \overline{\varphi}(fX^0)(y) = \varphi(f) \in C$. We now left as an exercise to prove that $\sigma_y \in \mathrm{Hom}(E/K, C/K)$.

Claim. $|\lambda^{-1}(\{\varphi\})| = |R_\varphi|$.

For this we need to show that β is the inverse of α, that is $\alpha \circ \beta = \mathrm{id}$ and $\beta \circ \alpha = \mathrm{id}$. To prove that $\beta \circ \alpha = \mathrm{id}$ let σ be such that $\sigma|_F = \varphi$. Then $y = \sigma(x) \in R_\varphi$. Let $z = h(x) = \sum a_i x^i \in F[x] = E$. Then

$$\overline{\varphi}(h)(y) = \sum \varphi(a_i) y^i = \sum \sigma(a_i) y^i = \sigma\left(\sum a_i x^i\right) = \sigma(y).$$

Conversely, if $y \in R_\varphi$, then

$$\alpha(\sigma_y) = \sigma_y(x) = y,$$

as $\sigma_y(x) = \overline{\varphi}(X)(y) = y$.

Claim. If $\phi \in \mathrm{Gal}(C/K)$ is such that $\phi|_F = \varphi$, then $O_{\mathrm{Gal}(C/K)}(x) = \phi^{-1}(R_\varphi)$.

Let us first prove $O_{\mathrm{Gal}(C/K)}(x) \supseteq \phi^{-1}(R_\varphi)$. If $y \in R_\varphi$, then

$$\begin{aligned} f(\phi^{-1}(y)) &= \sum b_i \phi^{-1}(y^i) = \phi^{-1}\left(\sum \phi(b_i) y^i\right) \\ &= \phi^{-1}\left(\sum \varphi(b_i) y^i\right) = \phi^{-1}\overline{\varphi}(f)(y)) = \phi^{-1}(0) = 0. \end{aligned}$$

Now we prove $O_{\mathrm{Gal}(C/K)}(x) \subseteq \phi^{-1}(R_\varphi)$. Let $z \in O_{\mathrm{Gal}(C/K)}(x)$ and $y \in C$ be such that $\phi^{-1}(y) = z$. Then $\overline{\varphi}(f)(y) = 0$, as

$$\begin{aligned} \overline{\varphi}(f)(y) &= \sum \varphi(b_i) y^i \\ &= \sum \varphi(b_i)\phi(z^i) = \sum \phi(b_i)\phi(z^i) = \phi\left(\sum b_i z^i\right) = \phi(f(z)) = \phi(0) = 0. \end{aligned}$$

It follows that $|\lambda^{-1}(\varphi)| = |O_{\mathrm{Gal}(C/K)}(x)|$ for all φ. By using the argument before the proposition,

$$\begin{aligned} \gamma(E/K) &= |\mathrm{Hom}(E/K, C/K)| \\ &= |O_{\mathrm{Gal}(C/K)}(x)||\mathrm{Hom}(F/K, C/K)| \\ &= |O_{\mathrm{Gal}(C/K)}(x)|\gamma(F/K). \end{aligned}$$

Since $\gamma(K(x)/K) = |O_{\mathrm{Gal}(C/K)}(x)|$ by Proposition 6.5, the claim follows.

For the general case we assume that $E = F(x_1, \dots, x_n)$. We proceed by induction on n. If $n = 0$, then $E = F$ and the result is trivial. If $n > 0$, let $L = F[x_1, \dots, x_{n-1}]$

and $E = L(x_n)$. The case proved implies that $\gamma(E/F) = \gamma(E/L)\gamma(L/F)$. By the inductive hypothesis, $\gamma(L/K) = \gamma(L/F)\gamma(F/K)$. Thus

$$\gamma(E/F)\gamma(F/K) = \gamma(E/L)\gamma(L/F)\gamma(F/K) = \gamma(E/L)\gamma(L/K) = \gamma(E/K),$$

again using the previous case. □

§7. Separable extensions

Definition 7.1. Let E/K be an algebraic extension and $x \in E$. Then x is **separable** over K if x is a simple root of $f(x,K)$.

An algebraic extension E/K is **separable** if every $x \in E$ is separable over K. Clearly, K/K is separable.

Exercise 7.2. Prove that an element x is separable over K if and only if x is a simple root of a polynomial with coefficients in K.

If F/K is a subextension of E/K and $x \in E$ is separable over K, then x is separable over F.

Exercise 7.3. If C is an algebraic closure of K, $x \in C$ and $G = \mathrm{Gal}(C/K)$ Prove that the following statements are equivalent:

1) x is separable over K.
2) Every $y \in O_G(x)$ is separable over K.
3) $\gamma(K(x)/K) = [K(x) : K] = \deg f(x,K)$.

Let K be any field and $g \in K[X]$. Let z be a root of g. Then z is a multiple root of g if and only if z is a root of g'.

Exercise 7.4. Prove that if K has characteristic zero or K is finite, then every algebraic extension of K is separable.

A consequence: Let E/K be a finite extension. Then E/K is separable if and only if $\gamma(E/K) = [E : K]$.

Example 7.5. Let $E = \mathbb{Q}(\sqrt{2}, \sqrt{3})$. Then $[E : \mathbb{Q}] = 4$ and $\mathrm{Gal}(E/Q) \simeq C_2 \times C_2$. The extension E/Q is normal, as it is the decomposition field of $(X^2-2)(X^2-3)$ and it is separable as $\mathbb{Q}$ has characteristic zero.

Example 7.6. Let E be a decomposition field of $X^4 - 2$ over $\mathbb{Q}$. Then $E/\mathbb{Q}$ is normal and separable. Note that $E = \mathbb{Q}(\sqrt[4]{2}, i)$, so $[E : \mathbb{Q}] = 8 = |\mathrm{Gal}(E/\mathbb{Q})|$.

Let us compute $\mathrm{Gal}(E/\mathbb{Q})$. If $\sigma \in \mathrm{Gal}(E/\mathbb{Q})$, then $\sigma(\sqrt[4]{2}) \in \{\sqrt[4]{2}, -\sqrt[4]{2}, \sqrt[4]{2}i, -\sqrt[4]{2}i\}$ and $\sigma(i) \in \{-i, i\}$. Two examples are

$$\alpha\colon \begin{cases} \sqrt[4]{2} \mapsto \sqrt[4]{2}i, \\ i \mapsto i, \end{cases} \qquad \beta\colon \begin{cases} \sqrt[4]{2} \mapsto \sqrt[4]{2}, \\ i \mapsto -i. \end{cases}$$

It follows that $\mathrm{Gal}(E/\mathbb{Q})$ is isomorphic to the group $\langle \alpha, \beta \rangle$, which turns out to be isomorphic to the dihedral group of eight elements.

Another consequence: If $E = K(S)$, then E/K is separable if and only if every $x \in S$ is separable over K. One first does the case $E = K(x)$ and then proceed by induction.

xca:separable1

Exercise 7.7. Let $K \subseteq F \subseteq E$ be a tower of fields. Prove that if E/K is separable, then F/K and E/F are separable.

xca:separable2

Exercise 7.8. Let E/K and F/K be extensions. Prove that if E/K is separable, then EF/E is separable.

Lecture 7

separable

If E/K is algebraic, then

$$F = \{x \in E : x \text{ is separable over } K\}$$

is a subfield of E that contains K. It is known as the **separable closure** of K with respect to E. Note that $F = K(F)$, as $K(F)$ is separable because it is generated by separable elements. Moreover, F/K is separable and E/F is a **purely inseparable** extension, meaning that for every $x \in E \setminus F$, the polynomial $f(x,F)$ is not separable.

pro:monogenic

Proposition 7.9. *If E/K is separable and finite, then $E = K(x)$ for some $x \in E$.*

Proof. Let us assume that K is finite. Then E is finite and hence the multiplicative group $E^\times = E \setminus \{0\}$ is cyclic, say $E^\times = \langle x \rangle$. It follows that $E = K(x)$.

Let us now assume that K is infinite. We first consider the case $E = K(x,y)$. The general case $E = K(x_1,\dots,x_n)$ is left as an exercise, one needs to proceed by induction. Let $n = [E:K]$ and C be an algebraic closure of K containing E. Write $\mathrm{Hom}(E/K, C/K) = \{\sigma_1,\dots,\sigma_n\}$. Let

$$f = \prod_{1 \le i < j \le n} \big((\sigma_i(y) - \sigma_j(y)) + X(\sigma_i(x) - \sigma_j(x))\big) \in C[X].$$

Then $f \neq 0$, as f is a product of non-zero polynomials. Since K is infinite, there exists $c \in K$ such that $f(c) \neq 0$. For any $r,s \in \{1,\dots,n\}$ with $r \neq s$,

$$\sigma_r(y) - \sigma_s(y) + c(\sigma_r(x) - \sigma_s(x)) \neq 0,$$

as $c \in K$. It follows that $\sigma_r(y+cx) \neq \sigma_s(y+cx)$. Thus $\gamma(K(y+cx)/K) \ge n$. Now

$$n \ge [K(y+cx):K] = \gamma(K(y+cx)/K) \ge n,$$

so $[K(y+cx):K] = n$ and hence $K(y+cx) = E$. $\square$

For example, $\mathbb{Q}(\sqrt{2}, i) = \mathbb{Q}(\sqrt{2}+i)$.

Proposition 7.10. *Let E/K be a finite extension. Then $E = K(x)$ for some $x \in E$ if and only if E/K admits finitely many subextensions.*

Proof. We first prove $\implies$. We may assume that K is infinite, otherwise the result is trivial. Let us assume that $E = K(x)$. We claim that the map

$$\Psi\colon \{F : K \subseteq F \subseteq E\} \to \{\text{monic divisors of } f(x,K)\}, \quad F \mapsto f(x,F),$$

is injective. Let $\Psi(F) = g \in F[X]$ and write $g = \sum_{i=0}^{m} a_i X^i$, where $m = \deg g$. Thus $a_m = 1$. Let $F_0 = K(a_0,\dots,a_m)$. Then $F_0 \subseteq F$. Since $g = f(x,F)$, the polynomial g is irreducible in $F[X]$ and hence it is irreducible in $F_0[X]$. Now

$$[E : F_0] = [F_0(x) : F_0] = \deg f(x,F_0) = m = [F(x) : F] = [E : F]$$

and hence $F = F_0$. It follows that Ψ is injective and therefore there are finitely many fields between K and E.

Let us prove $\impliedby$. As before let us assume that $E = K(x,y)$. For each $a \in K$ we consider the extension $K(ay+x)/K$. By assumption, there exist $a,b \in K$ such that $a \neq b$ and $K(x+ay) = K(x+by) = L$. We claim that $L = E$. Note that $x+ay \in L$ and $x+by \in L$, so $(a-b)y \in L$ and hence, since $K \subseteq L$, it follows that $y \in L$. Thus $x \in L$ and therefore $L = E$. □

As a consequence, if E/K is finite and separable, then E/K admits finitely many subextensions.

§8. Galois extensions

Let E/K be an algebraic extension. Assume that $E = K(S)$ and let C be an algebraic closure of K containing E. Let

$$T = \{y \in C : y \text{ is a root of } f(x,K) \text{ for some } x \in S\}$$

and let $L = K(T)$. Then $E \subseteq L$, as $S \subseteq T$. The extension L/K is normal, as L/K is a decomposition field of the family $\{f(x,K) : x \in S\}$. Moreover, L is the smallest normal extension of K containing E. The field L is the **normal closure** of E (with respect to C).

Exercise 8.1. If E/K is finite, then L/K is finite

Exercise 8.2. If E/K is separable, then L/K is separable.

Let E/K be an extension and $S \subseteq \operatorname{Gal}(E/K)$ be a subset. the set

$$^{S}E = \{x \in E : \sigma(x) = x \text{ for all } \sigma \in S\}$$

is a subfield of E that contains K. The subfield ^{S}E is known as the **fixed field** of S.

Definition 8.3. Let E/K be an algebraic extension and $G = \mathrm{Gal}(E/K)$. Then E/K is a **Galois extension** if ${}^{G}E = K$.

Clearly, K/K is a Galois extension. Note that $\mathbb{Q}(\sqrt[3]{2})/\mathbb{Q}$ is not a Galois extension. Why?

Exercise 8.4. Prove that $\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}$ is a Galois extension.

Exercise 8.5. If the characteristic of K is different from two, then every quadratic extension of K is a Galois extension.

Exercise 8.6. Let E/K be an algebraic extension and $G = \mathrm{Gal}(E/K)$. Let $F = {}^{G}E$. Prove that $\mathrm{Gal}(E/F) = G$ and hence E/F is a Galois extension.

pro:normal+separable

Proposition 8.7. *Let E/K be an algebraic extension. Then E/K is a Galois extension if and only if E/K is normal and separable.*

Proof. Let $G = \mathrm{Gal}(E/K)$. Let us first assume that E/K is Galois. For $x \in E$ let $f_x = \prod_{y \in O_G(x)}(X - y) = \sum a_i X^i \in E[X]$. If $\varphi \in G$, then

$$\overline{\varphi}(f_x) = \prod_{y \in O_G(x)} (X - \varphi(y)) = f_x,$$

as if $O_G(x) = \{\sigma_1(x), \dots, \sigma_r(x)\}$, then if $\varphi(\sigma_i(x)) = (\varphi\sigma_i)(x) = \sigma_j(x)$ for some j. Since

$$\sum a_i X^i = f_x = \overline{\varphi}(f_x) = \sum \varphi(a_i) X^i,$$

it follows that $a_i \in {}^{G}E = K$ for all i. Thus $f_x \in K[X]$ and E/K is a decomposition field of the family $\{f_x : x \in E\}$. In particular, E/K is normal. Moreover, x is a simple root of $f_x \in K[X]$ and hence x is separable over K.

Conversely, let $x \in {}^{G}E$. Since E/K is normal, then $f(x,K) = \prod_{y \in O_G(x)}(X - y)^m$ for some m. Since E/K is separable, $m = 1$. Thus $f(x,K) = \prod_{y \in O_G(x)}(X - y) = X - x$ and $x \in K$. □

Definition 8.8. Let K be a field and $f \in K[X]$. Then f is **separable** if all roots of f are simple (in some algebraic closure of K).

Proposition 8.9. *Let E/K be a finite extension. Then E/K is a Galois extension if and only if E is a decomposition field over K of a separable polynomial $f \in K[X]$.*

Proof. Let us assume first that E/K is a Galois extension. Since E/K is finite and separable, $E = K(x)$ by Proposition 7.9. Then E/K is a decomposition field of $f(x,K)$ since E/K is normal. Since E/K is separable, x is separable over K. Thus x is a simple root of $f(x,K)$ and hence $f(x,K)$ is separable.

Conversely, let $x_1, \dots, x_r$ be the roots of a separable polynomial $f \in K[X]$. Then $E = K(x_1, \dots, x_r)$ is separable and normal. □

In the previous case, $\mathrm{Gal}(E/K)$ is known as the **Galois group** of the polynomial f. The notation is $\mathrm{Gal}(f,K)$. If $n = \deg f$ and $x_1,\dots,x_n$ are the roots of f, then any $\varphi \in \mathrm{Gal}(f,K)$ permutes the roots of f, that is φ permutes the set $\{x_1,\dots,x_n\}$. In particular, $\mathrm{Gal}(f,K)$ is isomorphic to a subgroup of $\mathbb{S}_n$ and hence $|\mathrm{Gal}(f,K)|$ divides $n!$.

Proposition 8.10. *Let E/K be a normal extension and F be the separable closure of K with respect to E. Then F/K is a Galois extension.*

Proof. Let C/K be an algebraic closure such that $E \subseteq C$. Let $\sigma \in \mathrm{Hom}(F/K, C/K)$. and let $\varphi \in \mathrm{Hom}(E/K, C/K)$ be such that $\varphi|_F = \sigma$. Since E/K is normal, $\varphi(E) = E$. Let $x \in F$. Then $\sigma(x) = \varphi(x) \in E$. Thus $f(\sigma(x), K) = f(x,K)$ and $\sigma(x)$ is separable over K, which implies that $\sigma(x) \in F$. Thus E/K is normal. Since E/K is separable, it follows that E/K is a Galois extension by Proposition 8.7. $\square$

Some easy facts.

Exercise 8.11. Let E/K be a separable extension and L/K be the normal closure of E in some algebraic closure C that contains E. Prove that L/K is a Galois extension.

Exercise 8.12. Let E/K be a finite extension. Prove that E/K is Galois if and only if $[E:K] = |\mathrm{Gal}(E/K)|$.

Exercise 8.13. Let E/K be a Galois extension and F/K be a subextension of E/K. Prove that E/F is a Galois extension.

Lecture 8

thm:ArtinGalois

Theorem 8.14 (Artin). *Let E be a field and G be a finite group of automorphisms of E. If $K = {}^G E$, then E/K is a Galois extension, $[E:K] = |G|$ and* $\mathrm{Gal}(E/K) = G$.

Before proving the theorem, we need a lemma.

Lemma 8.15. *Let E/K be a separable extension such that* $\deg(x,K) \leq m$ *for all $x \in E$. Then E/K is finite and $[E:K] \leq m$.*

Proof. Let $z \in E$ be of maximal degree. If $x \in E$, then $K(x,z)/K$ is separable. Then $K(x,z) = K(y)$ for some y. It follows that

$$K(z) \subseteq K(x,z) = K(y).$$

Since $\deg(z,K) \leq \deg(y,K)$, it follows that $\deg(z,K) = \deg(y,K)$ and hence $K(y) = K(z)$. In particular, $x \in K(z)$ and therefore $E = K(z)$. □

Now we are ready to prove Artin's theorem:

Proof of Theorem 8.14. Note that $G \subseteq \mathrm{Gal}(E/K)$. Let $x \in E$ and

$$f_x = \prod_{y \in O_G(x)} (X - y).$$

Since $f_x \in K[X]$, it follows that E/K is normal and separable, so E/K is a Galois extension. Moreover,

$$\deg(x,K) \leq \deg f_x = |O_G(x)| \leq |G|.$$

By the previous lemma, E/K is finite and $[E:K] \leq |G|$. This implies that $|G(E/K)| = [E:K] \leq |G|$ and hence $|G(E/K)| = |G|$. □

Example 8.16. Let $E = K(X,Y)$ and $\sigma\colon K[X,Y] \to E$ be the ring homomorphism given by $\sigma(X) = Y$ and $\sigma(Y) = X$. Note that σ is bijective, as $\sigma^2 = \mathrm{id}$. The map σ induces a field homomorphism $\overline{\sigma}\colon E \to E$ such that $\overline{\sigma}^2 = \mathrm{id}$. Recall that such a homomorphism is given by $f/g \mapsto \sigma(f)/\sigma(g)$. Let $G = \langle\overline{\sigma}\rangle$. Then $|G| = 2$. We claim that ${}^{G}E = K(X+Y, XY)$. Let $F == K(X+Y, XY)$. We only prove that ${}^{G}E \subseteq F$, as the other inclusion is trivial. Artin's theorem implies that $[E : {}^{G}E] = 2$ and $E = F(X)$, as X is a root of the polynomial $Z^2 - (X+Y)Z + XY$. Then $[E : F] \leq 2$ and $[{}^{G}E : F] = 1$.

§9. Galois' correspondence

Theorem 9.1 (Galois). *Let E/K be a finite Galois extension and $G = \mathrm{Gal}(E/K)$. There exists a bijective correspondence*

$$\{F : K \subseteq F \subseteq E \text{ subfields}\} \to \{\text{subgroups of } G\}$$

The correspondence is given by $F \mapsto G(E/F)$ and ${}^{S}E \leftarrow\!\shortmid S$. Moreover, normal subextensions of E/K correspond to normal subgroups of G.

$$\begin{tikzcd}[column sep=small]
 & & E \arrow[dl, dash] \arrow[dr, dash] & & \\
 & F \arrow[dl, dash] \arrow[dr, dash] & & \{1\} \arrow[dl, dash] \\
K \arrow[dr, dash] & & S \arrow[dl, dash] & \\
 & G & &
\end{tikzcd}$$

Proof. We first note that

$$\beta(\alpha(F)) = \beta(\mathrm{Gal}(E/F)) = {}^{\mathrm{Gal}(E/F)}E = F$$

since E/F is a Galois Extension. Moreover,

$$\alpha(\beta(S)) = \alpha({}^{S}E) = \mathrm{Gal}(E/{}^{S}E) = S$$

by Artin's theorem, as S is finite.

Let F be a subfield of E containing K and $S = \alpha(F)$. Then

$$[F : K] = \frac{[E : K]}{[E : F]} = \frac{|G|}{|S|} = (G : S).$$

Let C be an algebraic closure of K that contains E. If $S = \mathrm{Gal}(E/F)$, then $F = {}^{S}E$.

We need to prove that F/K is normal if and only if S is normal in G. Let us first prove $\Longrightarrow$. Let $\tau \in S$ and $\sigma \in G$. Since F/K is normal, $\sigma|_F \in \mathrm{Aut}(F)$. Thus $\sigma^{-1}(F) = F$. In particular, if $x \in F$, then $\sigma^{-1}(x) \in F$ and

$$\sigma\tau\sigma^{-1}(x) = \sigma\sigma^{-1}(x) = x.$$

Conversely, let $\varphi \in \mathrm{Hom}(F/K, C/K)$. There exists $\Phi \in\colon E \to C$ such that $\Phi|_F = \varphi$. Since E/K is normal, $\Phi(E) = E$ and hence $\Phi \in G$. We claim that $\varphi(x) \in F$ for all $x \in F$ for all $x \in F$. Note that $F = {}^S E$, so

$$\tau\varphi(x) = \tau\Phi(x) = \Phi\Phi^{-1}\tau\Phi(x) = \Phi(x) = \varphi(x)$$

for all $\tau \in S$, as $\Phi^{-1}\tau\Phi \in S$.

Let us compute $\mathrm{Gal}(F/K)$. Since F/K is normal, the map $\lambda\colon G \to \mathrm{Gal}(F/K)$, $\sigma \mapsto \sigma|_F$, is a surjective group homomorphism such that $\ker\lambda = S$. The first isomortphism theorem implies that $\mathrm{Gal}(F/K) \simeq G/S$. □

Some easy consequences.

Exercise 9.2. If E/K is a Galois extension of degree n and p is a prime number dividing n, then E/K admits a subextension of degree n/p.

Exercise 9.3. If E/K is a Galois extension of degree $p^\alpha m$ with p a prime number coprime with m, then E/K admits a subextension of degree m.

Definition 9.4. An extension E/K is **abelian** if E/K is a Galois extension with $\mathrm{Gal}(E/K)$ abelian.

Exercise 9.5. If E/K is an abelian extension of degree n and d divides n, then E/K admits a subextension of degree d.

Definition 9.6. An extension E/K is **cyclic** if E/K is a Galois extension with $\mathrm{Gal}(E/K)$ cyclic.

Exercise 9.7. If E/K is an abelian extension of degree n and d divides n, then E/K admits a subextension of degree d.

Example 9.8. The extension $\mathbb{Q}(\sqrt{2}, \sqrt{3})/\mathbb{Q}$ admits exactly three non-trivial subextensions:

$$\mathbb{Q}(\sqrt{2})/\mathbb{Q}, \quad \mathbb{Q}(\sqrt{3})/\mathbb{Q}, \quad \mathbb{Q}(\sqrt{6})/\mathbb{Q},$$

as $\mathrm{Gal}(\mathbb{Q}(\sqrt{2}, \sqrt{3})/Q) \simeq C_2 \times C_2$.

Example 9.9. Let $\omega \in \mathbb{C} \setminus \{1\}$ be such that $\omega^5 = 1$. Then

$$f(\omega, \mathbb{Q}) = 1 + X + X^2 + X^3 + X^4$$

and $\mathbb{Q}(\omega)/\mathbb{Q}$ has degree four. Moreover, $\mathbb{Q}(\omega)/\mathbb{Q}$ is a Galois extension and $\mathrm{Gal}(\mathbb{Q}(\omega)/\mathbb{Q}) \simeq C_4$. If $\sigma \in \mathrm{Gal}(\mathbb{Q}(\omega)/\mathbb{Q})$, then $\sigma(\omega) = \omega^i$ for some $i \in \{1, \dots, 4\}$. Moreover, for every $i \in \{1, \dots, 4\}$ the map $\omega_i \mapsto \omega^i$ induces an automorphism of $\mathbb{Q}(\omega)/\mathbb{Q}$. Thus $|\mathrm{Gal}(\mathbb{Q}(\omega)/\mathbb{Q})| = 4$. Now

$$\sigma_i^k = \mathrm{id} \iff \omega^{i^k} = \sigma_i^k(\omega) = \omega \iff i^k \equiv 1 \bmod 5.$$

Thus the map σ_2 given by $\omega \mapsto \omega^2$ has order four.

Since $\mathrm{Gal}(\mathbb{Q}(\omega)/\mathbb{Q}) = \langle\sigma\rangle$, where $\sigma(\omega) = \omega^2$, is cyclic of order four, the extension $\mathbb{Q}(\omega)/\mathbb{Q}$ has a unique degree-two subtextension $F/\mathbb{Q}$. Note that $|\langle\sigma^2\rangle| = 2$ and $\sigma^2(\omega) = \omega^4 = \omega^{-1}$. Thus $F = {}^{\langle\sigma^2\rangle}\mathbb{Q}(\omega)$. Let $\theta = \omega + \omega^{-1}$. Then

$$\theta^2 = \omega^2 + \omega^3 + 2 = -(1 + \omega + \omega^{-1}) + 2 = 1 - \theta$$

and hence θ is a root of $X^2 + X + 1$. Since $\theta \notin \mathbb{Q}$, it follows that

$$\theta \in \{(-1+\sqrt{5})/2, (-1-\sqrt{5})/2\}.$$

Therefore $F = \mathbb{Q}(\sqrt{5})$.

Let us mention some other consequences.

Exercise 9.10. Let E/K be a finite Galois extension and $F_1, \dots, F_n$ fields such that $K \subseteq F_i \subseteq E$ for all $i \in \{1, \dots, n\}$. For every i let $S_i = \mathrm{Gal}(E/F_i)$. Then

$$\mathrm{Gal}\left(E/\bigcap_{i=1}^{n} F_i\right) = \left\langle \bigcup_{i=1}^{n} S_i \right\rangle, \quad \mathrm{Gal}\left(E/\prod_{i=1}^{n} F_i\right) = \bigcap_{i=1}^{n} S_i.$$

The following statement is a concrete application of the previous exercise.

Exercise 9.11. Let E/K be a finite Galois extension and $G = \mathrm{Gal}(E/K)$. Assume that G is the direct product $G = S \times T$ of the groups S and T. Let $F = {}^{S}E$ and $L = {}^{T}E$. Then $F \cap L = K$ and $FL = E$.

Proposition 9.12. *Let $E_1/K, \dots, E_r/K$ be Galois extensions. If $E = \prod_{i=1}^{r} E_i$, then E/K is a Galois extension. If, moreover, each E_i/K is finite, then*

$$\theta \colon \mathrm{Gal}(E/K) \to \mathrm{Gal}(E_1/K) \times \cdots \times \mathrm{Gal}(E_r/K), \quad \sigma \mapsto (\sigma|_{E_1}, \dots, \sigma|_{E_r}),$$

is an injective group homomorphism.

Proof. We only do the first part in the case $r = 2$, the general case is left as an exercise. Since E_1/K is algebraic, then E_1E_2/E_2 is algebraic. Since E_2/K is algebraic, E_1E_2/K is algebraic. Similarly, E_1E_2/K is separable.

Let C/K be an algebraic closure such that $E_1E_2 \subseteq C$. If $\sigma \in \mathrm{Hom}(E_1E_2/K, C/K)$, then $\sigma(E_1E_2) \subseteq \sigma(E_1)\sigma(E_2) = E_1E_2$ (do this calculation as an exercise). Thus E_1E_2/K is normal.

If both E_1/K and E_2/K are finite, then E_1E_2/K is finite.

Clearly, θ is a group homomorphism. We claim that the map θ is injective. Let $\sigma \in \ker\theta$. Then $\sigma|_{E_i} = \mathrm{id}_{E_i}$ for all $i \in \{1, \dots, r\}$. Let $S = \langle\sigma\rangle \subseteq \mathrm{Gal}(E/K)$ and $F = {}^{S}E$. Then $E_i \subseteq F$ for all $i \in \{1, \dots, r\}$ and hence $E \subseteq F$. It follows that $F = E = {}^{\{\mathrm{id}\}}E$ and therefore $S = \{\mathrm{id}\}$, so $\sigma = \mathrm{id}$. □

Exercise 9.13. Let $E_1/K, \dots, E_r/K$ be finite Galois extensions such that for each j one has $E_j \cap (E_1 \cdots E_{j-1}E_{j+1} \cdots E_r) = K$. Then

$$\mathrm{Gal}(E/K) \simeq \mathrm{Gal}(E_1/K) \times \cdots \times \mathrm{Gal}(E_r/K).$$

In this case, $[E : K] = \prod_{i=1}^{r} [E_i : K]$.

Lecture 9

§10. The fundamental theorem of algebra

We now present an easy proof of the fundamental theorem of algebra based on the ideas of Galois Theory. We need the following well-known facts:

1) Every real polynomial of odd degree admits a real root. This means that $\mathbb{R}$ does not admit extension of odd degree > 1.
2) Every complex number admits a square root in $\mathbb{C}$. This means that $\mathbb{C}$ does not admit degree-two extensions.

Theorem 10.1. *The field $\mathbb{C}$ is algebraically closed.*

Proof. Let $E/\mathbb{C}$ be an algebraic finite extension. Then $E/\mathbb{R}$ is finite separable extension of even degree. There exists a Galois extension $L/\mathbb{R}$ such that $E \subseteq L$, so $[L : \mathbb{R}]$ is even. Let $G = \mathrm{Gal}(L/\mathbb{R})$. Then $|G| = 2^m s$ for some odd number s. If T is a 2-Sylow subgroup of G, then there exists a subextension $F/\mathbb{R}$ of degree s. Since $\mathbb{R}$ does not admit extensions of odd degree > 1, $s = 1$ and hence G is a 2-group. In particular, $|\mathrm{Gal}(L/\mathbb{C})| = 2^{m-1}$. If $m > 1$, let U be a subgroup of $\mathrm{Gal}(L/\mathbb{C})$ of order 2^{m-2}. Then U corresponds to a subextension $L_1/\mathbb{C}$ of degree two, a contradiction. Hence $m = 1$ and $[L : \mathbb{C}] = 1$, so $L = \mathbb{C}$ and $E = \mathbb{C}$. □

§11. Purely inseparable extensions

Let E/K be an algebraic extension. In page 7 we defined the **separable closure** of K with respect to E as the field

$$F = \{x \in E : x \text{ is separable over } K\}.$$

Note that $K \subseteq F \subseteq E$ and $F = K(F)$. Moreover, F/K is separable and E/F is a **purely inseparable** extension, meaning that for every $x \in E \setminus F$, the polynomial $f(x, F)$ is not separable.

The number $[E : F]$ is known as the **degree of inseparability** of E/K.

Clearly, E/K is separable if and only if $[E : F] = 1$ and E/K is purely inseparable if and only if $[E : F] = [E : K]$.

Proposition 11.1. *Let K be a field of characteristic $p > 0$ and E/K be an algebraic extension. The following statements are equivalent:*

1) *E/K is purely inseparable.*
2) *If $x \in E$, then $x^{p^m} \in K$ for some $m \geq 0$.*
3) *If $x \in E$, then $f(x, K) = X^{p^m} - a$ for some $a \in K$ and $m \geq 0$.*
4) *$\gamma(E/K) = 1$.*

Proof. □

Some solutions

6.1 Let $\{v_i : i \in I\}$ be a basis of V over K. For each $i \in I$ let $f_i \colon V \longrightarrow F$, $f_i(v_j) = \delta_{ij}$. Then $\{f_i : i \in I\}$ is linearly independent over F. In fact, let $\sum a_i f_i = 0$, where each $a_i \in F$. Then $a_i = 0$ for almost all i. If $j \in I$, then

$$0 = \left(\sum a_i f_i\right)(v_j) = \sum a_i f_i(v_j) = a_j.$$

Now assume that $\dim_K V = n$. Let $\{v_1, \dots, v_n\}$ be a basis of V over K. We claim that $\{f_1, \dots, f_n\}$ is a basis of $\operatorname{Hom}_K(V, F)$ over F. If $g \in \operatorname{Hom}_K(V, F)$, then $g = \sum g(v_i) f_i$. If $1 \le k \le n$, then

$$\left(\sum g(v_i) f_i\right)(v_k) = \sum g(v_i) f_i(v_k) = g(v_k).$$

6.4 We need to find a bijective map

$$\operatorname{Hom}(E/K, C/K) \longrightarrow \operatorname{Hom}(E/K, C_1/K).$$

If $\sigma \in \operatorname{Hom}(E/K, C/K)$, then $\theta^{-1}\sigma \in \operatorname{Hom}(E/K, C_1/K)$. If $\varphi \in \operatorname{Hom}(E/K, C_1/K)$, then $\theta\varphi \in \operatorname{Hom}(E/K, C/K)$. The maps $\sigma \mapsto \theta^{-1}\sigma$ and $\varphi \mapsto \theta\varphi$ are inverse to each other.

References

1. J. Rotman. *Galois theory*. Universitext. Springer-Verlag, New York, second edition, 1998.

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