MATH 457 Notes : Galois Theory

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These notes are based on lectures given by Professor Henri Darmon at McGill University in Winter 2025. The subject of these lectures is Representation Theory and Galois Theory but I chose to take notes only for the Galois Theory part.
As a disclaimer, it is more than possible that I made some mistakes. Feel free to correct me or ask me anything about the content of this document at the following address : samy.lahloukamal@mcgill.ca

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1 Fields Extensions

Definition (Field Extension)**.** *If and $\mathbb{E}$ and $\mathbb{F}$ are fields, we say that E is an extension of F if F is a subfield of E.*

Remark: If $\mathbb{E}$ is an extension of $\mathbb{F}$, then $\mathbb{E}$ is also a vector space over $\mathbb{F}$.

Definition. *Given a fields $\mathbb{E}$ and $\mathbb{F}$ and $\alpha \in \mathbb{E}$ where $\mathbb{E}$ is an extension of $\mathbb{F}$, we denote by $\mathbb{F}[\alpha]$ the ring generated by $\mathbb{F}$ and α, i.e., $\mathbb{F}[\alpha]$ is the intersection of all the fields containing both $\mathbb{F}$ and α. Similarly, we denote by $\mathbb{F}(\alpha)$ the field generated by $\mathbb{F}$ and α. Hence, there is a natural inclusion from $\mathbb{F}[\alpha]$ to $\mathbb{F}(\alpha)$.*

Definition. *The degree of $\mathbb{E}$ over $\mathbb{F}$ is the dimension of $\mathbb{E}$ as a $\mathbb{F}$ vector space. It is written as $[\mathbb{E} : \mathbb{F}]$. If the degree is finite, we say that $\mathbb{E}/\mathbb{F}$ is finite.*

Example:

- $[\mathbb{C} : \mathbb{R}] = 2$ since $\mathbb{R} \subset \mathbb{C}$ and $\mathbb{C}$ is a 2-dimensional $\mathbb{R}$-vector space.
- $[\mathbb{C} : \mathbb{Q}] = \infty$ since $\mathbb{Q} \subset \mathbb{C}$ and $\mathbb{C}$ is an ∞-dimensional $\mathbb{Q}$-vector space. Using the Axiom of Choice, we can construct a basis for this vector space, it is called the Hamel basis.
- Let $\mathbb{F}$ be a field and $\mathbb{E} = \mathbb{F}[x]/(p)$ where p is an irreducible polynomial of degree n, then
$$\mathbb{E} = \{a_0 + a_1 x + ... + a_{n-1} x^{n-1}\}$$
so $[\mathbb{E} : \mathbb{F}] = n$ since $\mathbb{E}$ contains $\mathbb{F}$ (the constant polynomials) and has basis $\{1, x, ..., x^{n-1}\}$.
- Let $\mathbb{F}$ be a field and $\mathbb{E} = \mathbb{F}(x)$ be the fraction field of $\mathbb{F}[x]$, then $[\mathbb{E} : \mathbb{F}] = \infty$.
- Given an irreducible polynomial p over $\mathbb{Q}$ and a root α of p, then
$$\mathbb{Q}[\alpha] = \mathbb{Q}(\alpha) = \mathbb{Q}[x]/(p)$$
is an extension of $\mathbb{Q}$ of degree $\deg p$. The isomorphism $\mathbb{Q}(\alpha) \cong \mathbb{Q}[x]/(p)$ comes from the valuation map $ev_\alpha : \mathbb{Q}[x]/(p) \to \mathbb{Q}(\alpha)$.

Theorem (Multiplicativity of the degree)**.** *Given three fields $\mathbb{K} \subset \mathbb{F} \subset \mathbb{E}$, we have*
$$[\mathbb{E} : \mathbb{K}] = [\mathbb{E} : \mathbb{F}][\mathbb{F} : \mathbb{K}].$$

Proof. If one of the degree is infinite, the proof is trivial, hence, assume that the degrees are finite. Call $[\mathbb{E} : \mathbb{F}] = n$ and $[\mathbb{F} : \mathbb{K}] = m$. Let $\alpha_1, ..., \alpha_n \in \mathbb{F}$ be a basis for $\mathbb{E}$ as a $\mathbb{F}$-vector space and $\beta_1, ..., \beta_m \in \mathbb{K}$ be a basis for $\mathbb{F}$ as a $\mathbb{K}$-vector space. Notice that for all $a \in \mathbb{E}$, there exist elements $\lambda_1, ..., \lambda_n \in \mathbb{F}$ such that
$$a = \lambda_1 \alpha_1 + ... + \lambda_n \alpha_n$$
is the unique representation of a as a linear combination of the basis $\alpha_1, ..., \alpha_n$. But for each λ_i, we know that there exist elements $\lambda_{i1}, ..., \lambda_{im} \in \mathbb{K}$ such that
$$\lambda_i = \lambda_{i1}\beta_1 + ... + \lambda_{im}\beta_m$$

. Thus,

$$a = \sum_{i=1}^{n} \sum_{j=1}^{m} \lambda_{ij} \alpha_i \beta_j.$$

Therefore, $\{\alpha_i \beta_j\}_{i,j}$ is a $\mathbb{K}$ basis for $\mathbb{E}$. Hence, it follows that the dimension of $\mathbb{E}$ as K-vector space is $n \cdot m$. ■

2 Ruler and Compass Constructions

Definition. *A complex number is constructible by ruler and compass if it can be obtained from rational numbers by successive applications of field operations (+, -, ×, division) and square roots. Using fields, we can say that a number is cinstructible if it is contained in a sequence of quadratic extensions of $\mathbb{Q}$.*

The set of elements constructible by ruler and compass is an extension of $\mathbb{Q}$ of infinite degree. The goal is to characterize the set of numbers which can be constructible by ruler and compass.

Theorem. *If $\alpha \in \mathbb{R}$ is a root of an irreducible cubic polynomial over $\mathbb{Q}$, then α is not constructible by ruler and compass.*

Proof. Suppose that α is constructible, then there are finite field extensions

$$\mathbb{Q} \subset \mathbb{F}_1 \subset ... \subset \mathbb{F}_n$$

with $\mathbb{F}_{i+1} = \mathbb{F}_i(\sqrt{a_i})$ for some $a_i \in \mathbb{F}_i$. Hence, for all i, we have that $[F_{i+1} : F_i]$ since $\{1, \sqrt{a_i}\}$ is a basis for F_{i+1} as a $\mathbb{F}_i$-vector space. Thus, by multiplicativity of the degree, $[\mathbb{F}_n : \mathbb{Q}] = 2^n$. Moreover, we know that $[\mathbb{Q}(\alpha) : \mathbb{Q}] = 3$ so we get the following diagram : **TODO**. Contradiction. ■

Example:

- (Duplicating the cube) $p(x) = x^3 - 2$ and $\alpha = \sqrt[3]{2}$ cannot be constructible.
- (Trissection of angle) $p(x) = x^3 - 3x + \frac{1}{2}$ and $\alpha = \cos(2\pi/9)$:

$$\cos(3\theta) = \cos^3\theta - 3\cos(\theta)(1 - \cos^2\theta)$$

Definition (Algebraic Numbers)**.** *Let $\mathbb{E}/\mathbb{F}$ be a finite extension. An element $\alpha \in \mathbb{E}$ is algebraic over $\mathbb{F}$ if α is the root of a polynomial in $\mathbb{F}[x]$.*

Example:

- $\sqrt{2} \in \mathbb{R}$ is algebraic over $\mathbb{Q}$ since it solves the polynomial $x^2 - 1 \in \mathbb{Q}[x]$.
- $i \in \mathbb{C}$ is algebraic over $\mathbb{Q}$ since it solves the polynomial $x^2 + 1 \in \mathbb{Q}[x]$.
- π is not algebraic over $\mathbb{Q}$ but it is algebraic over $\mathbb{Q}(\pi^3)$.
- The set of $\alpha \in \mathbb{R}$ which are algebraic over $\mathbb{Q}$ is countable (Cantor).

Lemma. *If $\mathbb{E}/\mathbb{F}$ is a finite extension, then every $\alpha \in \mathbb{E}$ is algebraic over $\mathbb{F}$.*

Proof. Let n be the degree of $\mathbb{E}/\mathbb{F}$, then the set $\{1, \alpha, \alpha^2, ..., \alpha^n\}$ cannot be linearly independent since it contains $n+1$ elements. Hence, there exist scalars **TODO** ■

Definition (Automorphism Group)**.** *The automorphism group of $\mathbb{E}/\mathbb{F}$ is*

$$Aut(\mathbb{E}/\mathbb{F}) = \{\sigma : \mathbb{E} \to \mathbb{E} : \sigma \textit{ preserves the operations and } \sigma|_{\mathbb{F}} = id\}$$

As a consequence, if $\sigma \in \mathrm{Aut}(\mathbb{E}/\mathbb{F})$, then $\sigma(0) = 0$, $\sigma(1) = 1$ and $\sigma(a^{-1}) = \sigma(a)^{-1}$.

Proposition. *If $[\mathbb{E} : \mathbb{F}]$ is finite then $Aut(\mathbb{E}/\mathbb{F})$ acts on $\mathbb{E}$ with finite orbits.*

Proof. Let $\alpha \in \mathbb{E}$, let's show that α has only finitely many translates by the action of $\mathrm{Aut}(\mathbb{E}/\mathbb{F})$. By the previous Lemma, we know that α is algebraic so there is a polynomial $a_n x^n + ... + a_0 \in \mathbb{F}[x]$ satisfied by α. By plugging-in $x = \alpha$, we have

$$a_n \alpha^n + ... a_1 \alpha + a_0 = 0.$$

Let $\sigma \in \mathrm{Aut}(\mathbb{E}/\mathbb{F})$, then applying σ on both sides of the previous equation gives us

$$\sigma(a_n \alpha^n + ... a_1 \alpha + a_0) = 0.$$

Using the fact that σ preserves addition and multiplication, we get

$$\sigma(a_n)\sigma(a_n)^n + ... + \sigma(a_1)\sigma(\alpha) + \sigma(a_0) = 0.$$

Finally, since σ fixes the elements of $\mathbb{F}$, then

$$a_n \sigma(a_n)^n + ... + a_1 \sigma(\alpha) + a_0 = 0.$$

It follows that $\sigma(\alpha)$ must be a root of the same polynomial. Hence, the orbit of α is a subset of the roots of the polynomial that it satisfies (that we fixed at the beginning of the proof). Since polynomials over fields have finitely many roots, then α has a finite orbit. ■

Notice that the same proof can be applied if $\mathbb{E}/\mathbb{F}$ is a finite extension such that all elements of $\mathbb{E}$ are algebraic over $\mathbb{F}$, i.e., if $\mathbb{E}/\mathbb{F}$ is an algebraic extension.

Theorem. *If $[\mathbb{E} : \mathbb{F}] < \infty$, then $\#Aut(\mathbb{E}/\mathbb{F}) < \infty$.*

Proof. Let $\alpha_1, ..., \alpha_n$ be generators for $\mathbb{E}$ over $\mathbb{F}$, then for all $\sigma \in \mathrm{Aut}(\mathbb{E}/\mathbb{F})$, if we know the behavior of σ on the generators, then we know the behavior of σ on $\mathbb{E}$. Since there are finitely many generators and each generator has a finite orbit, then there are finitely many possible σ. ■

Example:

- Suppose that $\mathbb{E}$ is generated over $\mathbb{F}$ be a single element α. Let $p \in \mathbb{F}[x]$ be the minimal polynomial of α. Consider the evaluation map

$$\begin{aligned} ev_\alpha : \mathbb{F}[x] &\to \mathbb{F}[\alpha] \\ x &\mapsto \alpha \\ f(x) &\mapsto f(\alpha) \end{aligned}$$

  We get that $\ker(ev_\alpha) = (p)$. Hence, by the isomorphism theorem, $\mathbb{F}[\alpha]/(p) \cong \mathbb{F}[\alpha]$. Since $\mathbb{F}[\alpha]$ is an integral domain, then $\mathbb{F}[\alpha]/(p)$ **TODO**