

Algebra III

April 1, 2024

Chapter 0: Review

Definition: Category

A category \mathcal{C} consists of the following data:

1. A class of objects, $\text{Obj}(\mathcal{C})$.
2. For any pair of objects $X, Y \in \text{Obj}(\mathcal{C})$, a set of morphisms $\text{Mor}_{\mathcal{C}}(X, Y)$, $\text{Hom}_{\mathcal{C}}(X, Y)$ or $\mathcal{C}(X, Y)$.
3. For any triple of objects $X, Y, Z \in \text{Obj}(\mathcal{C})$, a map

$$\begin{aligned}\text{Hom}_{\mathcal{C}}(Y, Z) \times \text{Hom}_{\mathcal{C}}(X, Y) &\rightarrow \text{Hom}_{\mathcal{C}}(X, Z) \\ (g, f) &\mapsto g \circ f\end{aligned}$$

called compositions subject to the following axioms:

1. Associativity: $f \circ (g \circ h) = (f \circ g) \circ h$ whenever this makes sense.
2. For every object $X \in \text{Obj}(\mathcal{C})$, there exists a morphism $\text{id}_X \in \text{Hom}_{\mathcal{C}}(X, X)$ such that

$$\text{id}_X \circ f = f \quad \text{and} \quad g \circ \text{id}_X = g, \quad \forall f \in \text{Hom}_{\mathcal{C}}(W, X), g \in \text{Hom}_{\mathcal{C}}(X, W)$$

Example 1

Let E be a set (or a class).

Define \mathcal{C} by taking $\text{Obj}(\mathcal{C}) = E$ and $\text{Hom}_{\mathcal{C}}(X, Y) = \begin{cases} \emptyset & \text{if } x \neq y \\ \{\text{id}_X\} & \text{if } x = y \end{cases}$.

Example 2

Let $\mathcal{C} = \text{Set}$ the category of all sets with set functions acting as morphisms.

Let $\mathcal{C} = \text{Grp}$ the category of all groups with group homomorphisms acting as morphisms.

Abelian Rings: Ab, Rings: Ring, Commutative Rings: CRing, Vector Spaces over F : Vect_F , Topological Spaces: Top, etc.

Example 3

Let G be a group (or more generally a monoid).

Define $\text{Obj}(\mathcal{C}) = \{*\}$, $\text{Hom}_{\mathcal{C}}(*, *) = G$ and

$$\text{Hom}_{\mathcal{C}}(*, *) \times \text{Hom}_{\mathcal{C}}(*, *) \rightarrow \text{Hom}_{\mathcal{C}}(*, *)$$

the group operator.

Example 4

Let (E, \leq) be a preordered set (i.e. reflexive and transitive).
Define \mathcal{C} by $\text{Obj}(\mathcal{C}) = E$,

$$\text{Hom}_{\mathcal{C}}(x, y) = \begin{cases} \emptyset & \text{if } x \not\leq y \\ \{f_{xy}\} & \text{if } x \leq y \end{cases}$$

Notation

If $f \in \text{Hom}_{\mathcal{C}}(X, Y)$ we write $X \xrightarrow{f} Y$ in \mathcal{C} .

Definition: Isomorphism

A morphism $f : X \rightarrow Y$ in \mathcal{C} is an isomorphism if $\exists g : Y \rightarrow X$ such that $g \circ f = \text{id}_X$ and $f \circ g = \text{id}_Y$.

Definition: Endomorphism

A morphism on X with $f : X \rightarrow X$.

Definition: Automorphism

An automorphism on X is just an isomorphism $f : X \xrightarrow{\sim} X$ from X to itself.
Note that $\text{Aut}_{\mathcal{C}}(X) \subseteq \text{End}_{\mathcal{C}}(X) = \text{Hom}_{\mathcal{C}}(X, X)$.

Remark:

The collection of all endomorphisms on X form a monoid.
The collection of all automorphisms on X forms a group called the automorphism group of X .

Example 1

Let $\mathcal{C} = \text{Set}$, $X = \{1, \dots, n\}$. Then $\text{Aut}_{\text{Set}}(\{1, \dots, n\}) = \text{Perm}(X) = S_n$.

Example 2

Let $\mathcal{C} = \text{Vect}_F$, $X = F^n$. Then $\text{Aut}_{\text{Vect}_F}(F^n) = \text{GL}_n(F)$.

Definition: Functors

Let \mathcal{C} and \mathcal{D} be categories.
A functor $F : \mathcal{C} \rightarrow \mathcal{D}$ from \mathcal{C} to \mathcal{D} consists of the following data

1. For each object $X \in \text{Obj}(\mathcal{C})$, a chosen object $F(X) \in \text{Obj}(\mathcal{D})$.
2. For each pair of objects $X, Y \in \text{Obj}(\mathcal{C})$, a function

$$\begin{aligned} \text{Hom}_{\mathcal{C}}(X, Y) &\rightarrow \text{Hom}_{\mathcal{D}}(F(X), F(Y)) \\ f &\mapsto F(f) \end{aligned}$$

such that

1. For any two composable morphisms $X \xrightarrow{f} Y \xrightarrow{g} Z$ in \mathcal{C} , we have $F(g \circ f) = F(g) \circ F(f)$.
2. For each object $X \in \text{Obj}(\mathcal{C})$, $F(\text{id}_X) = \text{id}_{F(X)}$.

Example 1

For $\mathcal{D} := \mathcal{C}$, $\text{Id} : \mathcal{C} \rightarrow \mathcal{C}$, $X \mapsto X$, $f \mapsto f$.

Example 2: Forgetful Functors

$\mathcal{U} : \text{Grp} \rightarrow \text{Set}$ given as $(G, \cdot) \mapsto G$.

$\text{Ring} \rightarrow \text{Ab}$ given as $(R, +, \cdot) \mapsto (R, +)$.

Example 3: Tensors

Let R be a commutative ring, $M \in \text{Mod}_R$.

Then $\otimes_R M : \text{Mod}_R \rightarrow \text{Mod}_R$ and $\text{Hom}_R(M, -) : \text{Mod}_R \rightarrow \text{Mod}_R$.

Definition:

Let X be an object in a category \mathcal{C} and G a group.

An action of G on X is a group homomorphism $G \rightarrow \text{Aut}_{\mathcal{C}}(X)$.

Example 1

Let $\mathcal{C} = \text{Set}$.

A G -set is a set $X \in \text{Set}$ equipped with a group homomorphism

$$G \rightarrow \text{Perm}(X) = \text{Aut}_{\text{Set}}(X)$$

Exercise 1

A G -set is the same thing as a functor $G \rightarrow \text{Set}$, $* \mapsto X$, $\text{Hom}_{\mathcal{C}}(*, *) \rightarrow \text{Hom}_{\text{Set}}(X, X)$ ($G \rightarrow \text{Aut}_{\text{Set}}(X)$).

Definition: Adjunctions

Let \mathcal{C} and \mathcal{D} be categories and $F : \mathcal{C} \rightarrow \mathcal{D}$ and $G : \mathcal{D} \rightarrow \mathcal{C}$ be functors.

We say that F is left adjoint to G (and that G is right adjoint to F , and that we have a pair of adjoint functors) if for each object $X \in \text{Obj}(\mathcal{C})$ and $Y \in \text{Obj}(\mathcal{D})$, we have a bijection

$$\text{Hom}_{\mathcal{D}}(F(X), Y) \xrightarrow{\sim} \text{Hom}_{\mathcal{C}}(X, G(Y))$$

which is “natural in X and Y ”:

For any $f : X \rightarrow X'$ in \mathcal{C} ,

$$\begin{array}{ccc} \text{Hom}_{\mathcal{D}}(F(X'), Y) & \xrightarrow{\sim} & \text{Hom}_{\mathcal{C}}(X', G(Y)) \\ \downarrow - \circ F(f) & & \downarrow - \circ f \\ \text{Hom}_{\mathcal{D}}(F(X), Y) & \xrightarrow{\sim} & \text{Hom}_{\mathcal{C}}(X, G(Y)) \end{array}$$

and for every $g : Y \rightarrow Y'$ in \mathcal{D}

$$\begin{array}{ccc}
\mathrm{Hom}_{\mathcal{D}}(F(X), Y) & \xrightarrow{\sim} & \mathrm{Hom}_{\mathcal{C}}(X, G(Y)) \\
\downarrow -\circ F(f) & & \downarrow -\circ f \\
\mathrm{Hom}_{\mathcal{D}}(F(X), Y') & \xrightarrow{\sim} & \mathrm{Hom}_{\mathcal{C}}(X, G(Y'))
\end{array}$$

We write

$$\begin{array}{c}
\mathcal{C} \\
F \downarrow \uparrow G \\
\mathcal{D}
\end{array}$$

Example 1

For $M \in \mathrm{Mod}_R$ we have

$$\begin{array}{ccc}
& \mathrm{Mod}_R & \\
-\otimes_R M \downarrow & \uparrow \mathrm{Hom}_R(M, -) & \\
& \mathrm{Mod}_R &
\end{array}$$

where

$$\begin{aligned}
\mathrm{Hom}_R(M_1 \otimes M_2, N) &\cong \mathrm{Hom}_R(M_1, \mathrm{Hom}_R(M, \mathrm{Hom}_R(M_2, N))) \\
f &\mapsto (x \mapsto (y \mapsto f(x \otimes y)))
\end{aligned}$$

Example 2

Let $R \xrightarrow{\phi} S$ be a ring homomorphism.

We can regard an S -module N as an R -module via

$$r \cdot x := \phi(r)x, \quad \forall r \in R, x \in N$$

This defines a functor $\mathrm{Mod}_S \rightarrow \mathrm{Mod}_R$ called a “restriction of scalars”, which has a left adjoint called “extension of scalars.”

$$\begin{array}{ccc}
& \mathrm{Mod}_R & \\
S \otimes_R - \downarrow & \uparrow & \\
& \mathrm{Mod}_R &
\end{array}$$

Recall

For commutative ring R , $\sim \mathrm{Mod}_R$.

e.g. $R = F$ a field, $\mathrm{Mod}_R \equiv \mathrm{Vect}_F$; $R = \mathbb{Z}$, $\mathrm{Mod}_R \equiv \mathrm{Ab}$.

Definition: R-Algebra

An R -algebra is an Abelian group $(A, +)$ that has both the structure of

1. an R -module and
2. a ring

which are compatible in that

$$r(ab) = (ra)b = a(rb), \quad \forall r \in R, a, b \in A$$

Example 1

The polynomial ring $R[x]$ is an R -algebra.

Example 2

The ring of $n \times n$ matrices $M_n(R)$ is an R -algebra.

Example 3

If $R \xrightarrow{\phi} S$ is a homomorphism of commutative rings, then S is an R -algebra via $r := \phi(r)a$, $\forall r \in R, a \in S$.

Example 4

$\mathbb{R} \hookrightarrow \mathbb{C}$. So \mathbb{C} is an \mathbb{R} -algebra.

$R \hookrightarrow R[x]$.

More generally, $R[x_1, x_2, \dots, x_n]$ is an R -algebra.

Commutative R-Algebras

An R -algebra is commutative if it is commutative as a ring.

$\text{CAlg}_R \subset \text{Alg}_R$.

Question: Why are polynomials important?

An algebraic perspective: they are the “free commutative algebras.”

Recall

For R a commutative ring, we have the notion of a free R -module – one that admits a basis.

Categorically, we have an adjunction.

$$\begin{array}{ccc}
& \text{Set} & \\
& \downarrow f & \uparrow \mathcal{U} \\
& \text{Mod}_R &
\end{array}$$

The left adjoint of the forgetful functor sends a set I to the free R -module with basis I .

$$F(I) = R^{(I)} = \bigoplus_{i \in I} R$$

The adjunction says that for any set I and R -module M ,

$$\begin{aligned}
& \text{Hom}_{\text{Mod}_R}(R^{(I)}, M) \xrightarrow{\sim} \text{Hom}_{\text{Set}}(I, M) \\
& \exists! R\text{-linear map } f: R^{(I)} \rightarrow M \quad \leftarrow \{x_i\}_{i \in I} \\
& \quad e_i \mapsto x_i
\end{aligned}$$

Similarly, the forgetful functor $\mathcal{U} : \text{CAlg}_R \rightarrow \text{Set}$ has a left adjoint

$$\begin{array}{ccc}
& \text{Set} & \\
& \downarrow f & \uparrow \mathcal{U} \\
& \text{CAlg}_R &
\end{array}$$

which sends a set I to the “free commutative R -algebra on I .”

Explicitly, $F(I) = R[\{x_i\}_{i \in I}]$ the polynomial algebra with an indeterminate x_i for each $i \in I$.

Example 1

$$I = \{*\} \rightsquigarrow F(\{*\}) = R[x].$$

$$I = \{1, \dots, n\} \rightsquigarrow F(\{1, \dots, n\}) = R[x_1, \dots, x_n].$$

$$I = \mathbb{N} \rightsquigarrow F(\mathbb{N}) = R[x_1, x_2, \dots].$$

Adjunction

For any set I and commutative R -algebra $A \in \mathbf{CAlg}_R$, we have a bijection

$$\begin{aligned} \text{Hom}_{\mathbf{CAlg}_R}(R[\{x_i\}_{i \in I}], A) &\cong \text{Hom}_{\mathbf{Set}}(I, A) \\ \exists! R\text{-algebra homomorphism } R[\{x_i\}_{i \in I}] &\xrightarrow{x_i \mapsto a_i} A \leftarrow \{a_i\}_{i \in I} \end{aligned}$$

Example 1

Let A be a commutative R -algebra.

For any $a \in A$, there exists a unique R -algebra homomorphism $R[x] \rightarrow A$ which sends $X \mapsto a$.

Explicitly, $f(x) \mapsto f(a)$.

Corollary

Let $R \xrightarrow{\phi} S$ be a homomorphism of commutative rings.

For any $a \in S$, there is a unique ring $R[x] \xrightarrow{\bar{\phi}} S$ such that $\bar{\phi}|_R = \phi$ and $\bar{\phi}(X) = a$.

Example 1

Let $R \subseteq S$ be a subring.

For each $a \in S$, there is a unique ring homomorphism $R[x] \xrightarrow{\phi} S$ such that $\phi|_R = \text{id}$ and $\phi'(X) = a$.

We call this the “evaluation at a .”

$$\begin{aligned} R[x] &\xrightarrow{\text{ev}_a} S \\ f &\mapsto f(a) \end{aligned}$$

Definition: Subalgebra

Let A be a commutative R -algebra, and let $S \subset A$ be a subset.

The subalgebra of A generated by S , denoted $R[S]$, is the intersection of all subalgebras of A which contain S .

Explicitly,

$$R[S] = \{a \in A : \exists n \geq 1, s_1, \dots, s_n \in S, f \in R[x_1, \dots, x_n], a = f(s_1, \dots, s_n)\}$$

Example 1

Let $A = R[x]$. Then $A = R[x]$. That is, A is generated by $\{x\}$ as an algebra.

Similarly, $R[x_1, \dots, x_n]$ is generated as an algebra by $\{x_1, \dots, x_n\}$.

Example 2

If $R[x]/I$ with $I \subset R[x]$ an ideal, and $x := \bar{X} \in A$, then $A = R[x]$. That is, A is generated by $x = \bar{X}$ as an algebra.

More generally, if $I \subset R[x_1, \dots, x_n]$ an ideal, then $R[x_1, \dots, x_n]/I$ is generated by $\{\bar{x}_1, \dots, \bar{x}_n\}$.

Proposition

If $A \in \text{CAlg}_R$ is a finitely generated, commutative R -algebra, then $A \cong R[x_1, \dots, x_n]/I$ for some $n \geq 1$ and ideal $I \subset R[x_1, \dots, x_n]$.

April 3, 2024

Definition: Symmetric Polynomials

Let R be a commutative ring.

A polynomial $f \in R[x_1, \dots, x_n]$ is symmetric if $f(x_{\sigma(1)}, \dots, x_{\sigma(n)}) = f(x_1, \dots, x_n)$ for all $\sigma \in S_n$.

In more detail: the symmetric group S_n acts on $R[x_1, \dots, x_n]$ by R -algebra homomorphism.

$\sigma \in S_n \curvearrowright R[x_1, \dots, x_n] \rightarrow R[x_1, \dots, x_n]$ given by $x_i \mapsto x_{\sigma(i)}$.

The canonical action of S_n on $\{1, \dots, n\}$ is

$$\begin{aligned} S_n &\rightarrow \text{Set} \xrightarrow{F} \text{CAlg}_R \\ * &\mapsto \{1, \dots, n\} \mapsto R[x_1, \dots, x_n] \end{aligned}$$

Exercise 1

The symmetric polynomials form a subalgebra of $R[x_1, \dots, x_n]$.

Example 1

Consider the polynomial

$$(*) \quad (t - x_1)(t - x_2) \cdots (t - x_n) \in R[x_1, \dots, x_n][t]$$

Write

$$t^n - s_1 t^{n-1} + s_2 t^{n-2} + \cdots + (-1)^n s_n$$

where $s_1, \dots, s_n \in R[x_1, \dots, x_n]$.

Examples

Let $n = 2$.

$$(t - x_1)(t - x_2) = t^2 - \underbrace{(x_1 + x_2)}_{s_1} t + \underbrace{x_1 x_2}_{s_2}$$

Let $n = 3$.

$$(t - x_1)(t - x_2)(t - x_3) = t^3 - \underbrace{(x_1 + x_2 + x_3)}_{s_1} t^2 + \underbrace{(x_1 x_2 + x_2 x_3 + x_1 x_3)}_{s_2} t - \underbrace{x_1 x_2 x_3}_{s_3}$$

Exercise 2

Show that the polynomials $s_1, \dots, s_n \in R[x_1, \dots, x_n]$ are symmetric using the fact that $(*)$ is unchanged by permuting the x_i s.

Definition: Elementary Symmetric Polynomials

The polynomials $s_1, \dots, s_n \in R[x_1, \dots, x_n]$ are the elementary symmetric polynomials in n variables. Explicitly,

$$\begin{aligned} s_1 &= x_1 + x_2 + \dots + x_n \\ s_2 &= \sum_{1 \leq i < j \leq n} x_i x_j \\ &\vdots \\ s_k &= \sum_{1 \leq i_1 < \dots < i_k \leq n} x_{i_1} x_{i_2} \dots x_{i_k} \\ &\vdots \\ s_n &= x_1 x_2 \dots x_n \end{aligned}$$

Theorem: Fundamental Theorem on Symmetric Polynomials

Every symmetric polynomial $f \in R[x_1, \dots, x_n]$ can be expressed in a unique way as a polynomial in the elementary symmetric polynomials.

In particular, $R[s_1, \dots, s_n] \subseteq R[x_1, \dots, x_n]$ is the subalgebra of symmetric polynomials.

Recall: Group of Units

If R is a ring, then $U(R) = R^\times = \{a \in R : a \text{ is invertible}\}$.

This is the multiplicative group of units in R .

Exercise 3

This determines a functor $\text{Ring} \rightarrow \text{Grp}$.

Definition: Field

A field is a nonzero commutative ring F in which every nonzero element is invertible (i.e. $F^\times = F \setminus \{0\}$).

Remarks:

A field has no nontrivial ideals.

A commutative ring R is a field if and only if (0) is a maximal ideal.

If $I \subset R$ is an ideal in a commutative ring then R/I is a field if and only if I is a maximal ideal.

Definition: Domain

A (integral) domain is a nonzero commutative ring R such that $\forall a, b \in R, ab = 0 \implies a = 0 \text{ or } b = 0$.

Remarks:

A commutative ring R is a domain if and only if (0) is a prime ideal.

If $I \subset R$ is an ideal in a commutative ring, then R/I is a domain if and only if I is a prime ideal.

Example 1

Every field is a domain.

In fact, every subring of a field is a domain.
Conversely, domains can be characterized as the subrings of fields.

Definition: Field of Fractions

Let R be a domain.
Its field of fractions, $\text{Frac}(R)$, is the set of all “formal fractions”

$$\text{Frac}(R) = \left\{ \frac{a}{b} : a, b \in R, b \neq 0 \right\}$$

More precisely, $\text{Frac}(R) = (R \times (R \setminus \{0\})) / \sim$ where

$$(a_1, b_1) \sim (a_2, b_2) \iff a_1 b_2 = a_2 b_1$$

and we define $\frac{a}{b} := [(a, b)]$.

It is a field under addition and multiplication of fractions

$$\frac{a_1}{b_1} + \frac{a_2}{b_2} = \frac{a_1 b_2 + a_2 b_1}{b_1 b_2} \quad \text{and} \quad \frac{a_1}{b_1} \frac{a_2}{b_2} = \frac{a_1 a_2}{b_1 b_2}$$

We have an injective ring homomorphism

$$\begin{aligned} R &\hookrightarrow \text{Frac}(R) \\ a &\mapsto \frac{a}{1} \end{aligned}$$

Example 1

$$\mathbb{Q} = \text{Frac}(\mathbb{Z}).$$

Remark:

\mathbb{Z} is a domain.

Its ideals are $n\mathbb{Z}$ for $n = 0, 1, 2, \dots$

Its prime ideals are (0) and $p\mathbb{Z}$ for p prime.

Definition: Root

Let R be a commutative ring and $f \in R[x]$.

A root or zero of f is an element $r \in R$ such that $f(r) = 0$.

$$\begin{aligned} R[x] &\xrightarrow{\text{ev}_a} R \\ f &\longmapsto 0 \end{aligned}$$

The kernel is $(x - a)$.

That is $f(a) = 0$ if and only if $f \in (x - a)$, if and only if $x - a \mid f$, if and only if $f(x) = (x - a)g(x)$ for some $g \in R[x]$.

Proposition:

Let R be a domain. Then

1. $R[x]$ is a domain.
2. $\deg(fg) = \deg(f) + \deg(g)$.
3. $R[x]^\times = R^\times$ (i.e. $f \in R[x]^\times \iff f(x) = b_0$ with $b_0 \in R^\times$).

Example 1

If $R = F$ a field, $F[x]^\times =$ the nonzero constant polynomials.

Remark:

If R a domain and $a \in R$ a root of $f \in R[x]$, then

$$f(x) = (x - a)^m g(x)$$

with $g(a) \neq 0$. The m is uniquely determined and called the multiplicity of the root. Roots of multiplicity 1 are called simple roots.

Remark:

If R is a domain, a polynomial $f \in R[x]$ of degree d has at most d roots. In fact, at most d roots counted with multiplicity.

Definition: Formal Derivative

The formal derivative of a polynomial

$$f(x) = a_d x^d + a_{d-1} x^{d-1} + \cdots + a_2 x^2 + a_1 x + a_0 \in R[x]$$

is the polynomial $Df = f' \in R[x]$ defined by

$$f'(x) = d a_d x^{d-1} + \cdots + 2 a_2 x + a_1$$

Remark: Properties

$$\begin{aligned} (f + g)' &= f' + g' & R[x] \rightarrow R[x] \text{ is } R\text{-linear} \\ (af)' &= a f' & \text{for } a \in R \\ (fg)' &= f g' + f' g & \text{(Leibniz Formula)} \end{aligned}$$

Proposition:

$a \in R$ is a multiple root of $f \in R[x]$ if and only if $f(a) = 0$ and $f'(a) = 0$.

Proof

$$f(x) = (x-a)^m g(x), g(a) \neq 0.$$

Therefore, by Leibniz, $f'(x) = m(x-a)^{m-1}g(x) + (x-a)^m g'(x)$.

Recall:

For a field F , the polynomial ring $F[x]$ is a PID.

\mathbb{Z} is also a PID.

Proposition:

Let R be a PID.

Every nonzero prime ideal is maximal.

Proof

Let $0 \neq p$ be a nonzero prime ideal.

Suppose $p \subseteq I$. Then $p = (p)$ and $I = (a)$ for some $a \in R$ and prime element $p \in R$.

Then $(p) \subseteq (a)$ and $p = ab$ for some $b \in R$. So $p|a$ or $p|b$.

If $p|a$, then $p = I$. If, instead, $b = pc$ for some $c \in R$, then

$$p = acp \implies 1 = ac \implies a \in R^\times \implies (a) = R$$

Example 1

If $f \in F[x]$ is an irreducible polynomial then $F[x]/(f)$ is a field.

For example, $R[x]/(x^2 + 1)$ is a field ($\cong \mathbb{C}$).

Also, $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ is a field.

Example 2

On the other hand,

$$(\mathbb{Z}/n)^\times = \{a \in \mathbb{Z}/n : \gcd(a, n) = 1\}$$

$$|(\mathbb{Z}/n)^\times| = |\{0 \leq k \leq n-1 : \gcd(k, n) = 1\}| = \phi(n)$$

Euler's Totient Function.

Remark

Later in the course, we will prove the Fundamental Theorem of Algebra which states that every nonconstant complex polynomial $f \in \mathbb{C}[x]$ has a root.

This implies that if $f \in \mathbb{C}[x]$ is a monic polynomial with complex coefficients then $f(x) = (x - \alpha_1)(x - \alpha_2) \cdots (x - \alpha_n)$ with $\alpha_1, \dots, \alpha_n \in \mathbb{C}$.

Write it as

$$f(x) = x^d + a_1 x^{d-1} + \cdots + a_n$$

with coefficients $a_1, \dots, a_n \in \mathbb{C}$. Then

$$a_1 = -s_1(\alpha_1, \dots, \alpha_n) = -(\alpha_1 + \dots + \alpha_n)$$

$$a_k = (-1)^k s_k(\alpha_1, \dots, \alpha_n)$$

$$a_n = (-1)^n \alpha_1 \cdots \alpha_n$$

Example 1

$$f(x) = x^2 + bx + c = (x - \alpha_1)(x - \alpha_2)$$

where $\alpha_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2}$ and $\alpha_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2}$.

So $\alpha_1 + \alpha_2 = -b$ and $\alpha_1 \alpha_2 = c$.

Bottom Line

The coefficients of a monic polynomial are very simple expressions of the roots of the polynomial.

Motivating Question

Can we go the other around?

Can we find simple expressions of the roots of a polynomial in terms of the coefficients.

April 8, 2024

Chapter 1: Field Theory

Definition: Field Homomorphism

If F and K are fields, a field homomorphism $F \xrightarrow{\phi} K$ is just a ring homomorphism.

Remark

The kernel of a field homomorphism $\phi : F \rightarrow K$ is an ideal of F .

Hence, it is either (0) or F . Since $\phi(1_F) = 1_K \neq 0$, $\ker(\phi) = (0)$.

Thus every field homomorphism is automatically injective and embeds F as a subfield of K .

Notation

If $F \subseteq K$ is a subfield, we say that K is an extension of F or that K/F is a field extension.

Remark

The ring of integers \mathbb{Z} is the initial object in the category of rings.

That is, given any ring R , there is a unique ring homomorphism $\mathbb{Z} \rightarrow R$ given by $n \mapsto n1_R = \begin{cases} \overbrace{1_R + \dots + 1_R}^n & \text{if } n \geq 0 \\ -\underbrace{(1_R + \dots + 1_R)}_n & \text{if } n < 0 \end{cases}$.

The kernel of an ideal of \mathbb{Z} . We have three possibilities

1. $\ker = \mathbb{Z} \implies 1_R = 0 \text{ in } R \implies R = 0$.

$$2. \ker = (0) \implies \mathbb{Z} \hookrightarrow R.$$

$$3. \ker = n\mathbb{Z} \text{ for some } n \geq 2 \implies \mathbb{Z}/n\mathbb{Z} \hookrightarrow R.$$

Proposition

Let F be a field and consider the unique ring homomorphism $\mathbb{Z} \xrightarrow{\phi} F$. Then the kernel of ϕ is either (0) or $p\mathbb{Z}$ for some prime number p .

Proof

Note that $\mathbb{Z}/n\mathbb{Z} \hookrightarrow F$, but all subrings of fields are domains and $\mathbb{Z}/n\mathbb{Z}$ is a domain if and only if $n\mathbb{Z}$ is a prime ideal of \mathbb{Z} .

Corollary

Let F be a field. It contains precisely one of the following as a subfield

1. \mathbb{Q} or
2. \mathbb{F}_p for p prime.

Proof

The proposition implies either $\mathbb{Z} \hookrightarrow F$ or $\mathbb{Z}/p\mathbb{Z} \hookrightarrow F$ for p prime.

If $\mathbb{Z} \hookrightarrow F$ then this extends to an embedding $\mathbb{Q} \hookrightarrow F$ by the universal property of the field of fractions.

On the other hand, $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ by definition.

Claim: we can't have more than one such field as a subfield of F .

Observe that if F has a subfield isomorphic to \mathbb{F}_p , then $p \cdot 1 = 0$ in F .

On the other hand, if $\mathbb{Q} \subseteq F$ then $p \cdot 1 \neq 0$ for all p .

Finally, if $p \neq q$ primes and $\mathbb{F}_p \subseteq F$ and $\mathbb{F}_q \subseteq F$, then $p \cdot 1 = 0$ and $q \cdot 1 = 0$ in F .

By Bezout's, this means that $a, b \in \mathbb{Z} : ap + bq = 1$. So

$$1 = 1 \cdot 1 = (ap + bq) \cdot 1 = (ap)1 + (bq)1 = a(p \cdot 1) + b(q \cdot 1) = 0 + 0 = 0$$

which cannot be true.

Definition: Field Characteristic

We define the characteristic of a field F by $\text{char}(F) = \begin{cases} 0 & \text{if } \mathbb{Q} \subseteq F \\ p & \text{if } \mathbb{F}_p \subseteq F \end{cases}$.

Remark

Note that the kernel of $\mathbb{Z} \rightarrow F$ is $\text{char}(F)\mathbb{Z} \subseteq \mathbb{Z}$.

The characteristic of F is the smallest positive integer n such that $n \cdot 1 = 0$ in F or 0 if $n \cdot 1 \neq 0$ in F for all $n \geq 1$.

Remark

If K/F is a field extension, then K and F have the same characteristic.

$n \cdot 1 = 0$ in F if and only if $n \cdot 1 = 0$ in K . Observe that the composition $\mathbb{Z} \rightarrow F \hookrightarrow K$ requires matching kernels.

Aside

In math, one sometimes passes between characteristic zero and characteristic p through the integers.

$$\begin{array}{ccc} \mathbb{Z} & \hookrightarrow & \mathbb{Q} \\ \downarrow & & \\ \mathbb{F}_p & & \end{array}$$

Examples

$\mathbb{Q}, \mathbb{R}, \mathbb{C}$ have characteristic 0.

$\mathbb{F}_p := \mathbb{Z}/p\mathbb{Z}$ has characteristic p .

$\mathbb{C}(t) := \text{Frac}(\mathbb{C}[t])$.

$\mathbb{F}_p(t) := \text{Frac}(\mathbb{F}_p[t])$ is an infinite field of characteristic p .

Remark

If R is a domain, then $R[t]$ is a domain and

$$R(t) := \text{Frac}(R[t]) = \left\{ \frac{f}{g} : f, g \in R[t], g \neq 0 \right\}$$

the field of rational functions.

More generally, $R[t_1, \dots, t_n]$ is a domain and

$$R(t_1, \dots, t_n) := \text{Frac}(R[t_1, \dots, t_n])$$

is the field of rational functions in n variables.

Definition: Degree of a Field Extension

Let K/F be a field extension.

We can regard K as a vector space over F (restriction of scalars $F \hookrightarrow K$).

The degree of the field extension K/F is \dim of the F -vector space K .

Notation

$$[K : F] := \dim_F(K).$$

Example

\mathbb{C}/\mathbb{R} is a degree 2 extension. An \mathbb{R} -basis for \mathbb{C} is $\{1, i\}$.

Remark

K/F has degree 1 if and only if $K = F$.

Terminology

A degree 2 extension K/F is a quadratic extension.

A degree 3 extension K/F is a cubic extension.

Etc.

Definition: Finite Extension

A field extension K/F is said to be a finite extension if $[K : F]$ is finite.

Example

$F(t)/F$, noting $F \subseteq F[t] \subseteq F(t)$, is an infinite extension. Write $[F(t) : F] = \infty$.

Proposition

Let $L/K/F$ be field extensions.

Then $[L : F] = [L : K][K : F]$.

Proof (Sketch)

Idea: if $\{a_i\}_{i \in I}$ is a basis for L/K and $\{b_j\}_{j \in J}$ is a basis for K/F , then $\{a_i b_j\}_{(i,j) \in I \times J}$ is a basis for L over F .
Note that $|I \times J| = |I||J|$.

Definition: Algebraic and Transcendental Elements

Let K/F be a field extension.

An element $a \in K$ is said to be algebraic over F if it is a root of a nonzero polynomial with coefficients in F .

Otherwise, we say that a is transcendental over F .

Example

Consider \mathbb{C}/\mathbb{Q} .

$\sqrt{2} \in \mathbb{C}$ is algebraic over \mathbb{Q} since $t^2 - 2 \in \mathbb{Q}[t]$.

$i \in \mathbb{C}$ is algebraic over \mathbb{Q} since $t^2 + 1 \in \mathbb{Q}[t]$.

$\omega_n = e^{2\pi i/n} \in \mathbb{C}$ is algebraic over \mathbb{Q} since $t^n - 1 \in \mathbb{Q}[t]$.

Remark

Whether or not an element is algebraic or transcendental depends a lot on the ground field F .

e.g. every element $a \in K$ is algebraic over K , since it is a root of $t - a \in K[t]$.

Remark

Often the terms “algebraic number” and “transcendental number” mean a complex number which is algebraic or transcendental over \mathbb{Q} .

Theorem: (Hermite 1873)

e is a transcendental number.

Theorem: (Lindemann 1882)

π is a transcendental number.

Exercise (Cantor)

There are only countably many algebraic numbers.

Remark

Whether $a \in K$ is algebraic or transcendental over F is described by the evaluation homomorphism

$$\begin{aligned} F[t] &\xrightarrow{\text{ev}_a} K \\ f &\longmapsto f(a) \end{aligned}$$

That is, a is transcendental if and only if $\ker(\text{ev}_a) = (0)$.

Then a is algebraic if and only if $\ker(\text{ev}_a) \neq (0)$.

$F[t]$ is PID, so if $a \in K$ is algebraic over F then $\ker(\text{ev}_a)$ is a nonzero principal ideal of $F[t]$.

A generator of this principal ideal is only determined up to association (that is up to multiplication by a nonzero constant polynomial).

We can pin it down by requiring the generator to be monic.

Definition: Minimal Polynomial

The unique monic polynomial f of lowest degree with coefficients in F such that $f(a) = 0$ is called the minimal polynomial of a over F .

Notation

$$m_a(t) \in F[t].$$

Remark

It generates $\ker(\text{ev}_a)$. For any $f \in F[t]$, $f(a) = 0$ if and only if $m_a | f$.

Note

$F[t]/(m_a(t))$ is isomorphic to a subring of K .

So $F[t]/(m_a(t))$ is a domain and $m_a \in F[t]$ is an irreducible polynomial.

Exercise

The minimal polynomial of $a \in K$ over F is the unique, monic, irreducible polynomial $f \in F[t]$ such that $f(a) = 0$.

Example

Take $\sqrt{2} \in \mathbb{C}$, the root of $t^2 - 2 \in \mathbb{Q}[t]$. This is the minimal polynomial of $\sqrt{2}$ over \mathbb{Q} since it is irreducible.

$i \in \mathbb{C}$ is a root of $t^2 + 1 \in \mathbb{Q}[t]$ which is also irreducible and hence the minimal polynomial of i over \mathbb{Q} .

$a = \frac{1+i}{2} \in \mathbb{C}$ (\sqrt{i}) is a root of $t^4 + 1 \in \mathbb{Q}[t]$, irreducible and therefore minimal of a over \mathbb{Q} .

Consider $F = \mathbb{Q}[i] = \{\alpha + i\beta : \alpha, \beta \in \mathbb{Q}\}$. Observe that $t^4 + 1 = (t^2 - i)(t^2 + i) \in F[t]$. We can show that the minimal polynomial of a over F is $t^2 - i$.

Definition: Generated Subring

Let K/F be a field extension and let $S \subseteq K$ be a subset.

The subring generated by S over F is defined to be $F[S] :=$ the intersection of all subrings of K which contain F and S .

That is, the F -subalgebra generated by S .

Exercise

$$F[S] = \{a \in K : a = f(s_1, \dots, s_n) \text{ for some } n \geq 0, f \in F[x_1, \dots, x_n], s_1, \dots, s_n \in S\}.$$

Notation

$$S = \{a\} \rightsquigarrow F[a].$$

$$S = \{a_1, \dots, a_n\} \rightsquigarrow F[a_1, \dots, a_n].$$

Note that $F[a] = \text{im}(F[t] \xrightarrow{\text{ev}_a} K)$ and $F[a_1, \dots, a_n] = \text{im}(F[t_1, \dots, t_n] \xrightarrow{\text{ev}_a} K)$.

Definition: Generated Subfield

Let K/F be a field extension and let $S \subseteq K$ be a subset.

Then the subfield generated by S over F is defined to be $F(S) :=$ the intersection of all subfields of K which contain F and S .

Observe that $F[S] \subset F(S)$.

Exercise

$$F(S) = \left\{ a \in K : a = \frac{\alpha}{\beta} \text{ for } \alpha, \beta \in F[S] \right\} = \text{Frac}(F[S]).$$

Notation

$$S = \{a\} \rightsquigarrow F(a).$$

$$S = \{a_1, \dots, a_n\} \rightsquigarrow F(a_1, \dots, a_n).$$

Definition: Finitely Generated Field Extension

A field extension K/F is finitely generated if $K = F(S)$ for some $S \subset K$ finite.

That is, finitely generated as a field over F not as an algebra over F or a vector space over F .

Example

$F(t)/F$ is a finitely generated field extension but is not finitely generated as an F -algebra (exercise) nor as an F -vector space.

Example

In $F(t)/F$, the indeterminant $t \in F(t)$ is transcendental over f .

The evaluation homomorphism $F[t] \hookrightarrow F(t)$.

April 10, 2024

Last time: K/F , $S \subset K$, $F[S] \subset F(S)$.

Example: $S, T \subset K \rightsquigarrow F(S)(T) = F(S \cup T)$.

$$F(a_1, \dots, a_n) = F(a_1, \dots, a_{n-1})(a_n).$$

Remark

Let K/F be a field extension.

If $a \in K$ is transcendental over F , then

$$F[t] \xrightarrow[\sim]{\text{ev}_a} F[a]$$

is an isomorphism. Hence,

$$F(a) \simeq \text{Frac}(F[t]) = F(t)$$

the field of rational functions.

Thus, the field extensions $F(a)$ for $a \in K$ transcendental over F are all isomorphic.

Example

$\mathbb{Q}(\pi) \simeq \mathbb{Q}(e)$ are isomorphic fields.

Bottom Line

Transcendental elements behave like indeterminates t .

The prototypical example is $F(t)/F$.

Proposition

Let K/F be a field extension.

If $a \in K$ is algebraic over F , then $F[a] \simeq F[t]/(m_a(t))$ where $m_a(t) \in F[t]$ is the minimal polynomial of a over F .

Moreover, $F[a]$ is a field. Hence $F[a] = F(a)$.

Also, $[F(a) : F] = \deg(m_a(t))$.

An explicit F -basis of $F(a)$ is $\{1, a, a^2, \dots, a^{d-1}\}$ where $d := \deg(m_a(t))$.

Proof

$$\begin{array}{ccc} F[t] & \xrightarrow{\text{ev}_a} & K \\ \downarrow & & \uparrow \\ F[t]/m_a(t) & \xrightarrow{\sim} & F[a] \end{array}$$

Now $m_a(t)$ is irreducible, so $(m_a(t))$ is a nonzero prime ideal.

$F[t]$ is PID, therefore every nonzero prime ideal is maximal.

Hence $F[t]/(m_a(t))$ is a field.

Also, $\dim_F(F[t]/(f(t))) = \deg(f)$.

A basis $\{\bar{1}, \bar{t}, \bar{t}^2, \dots, \bar{t}^{d-1}\}$.

Suppose $a_0\bar{t} + a_1\bar{t}^2 + \dots + a_{d-1}\bar{t}^{d-1} = 0 = a_0 + a_1\bar{t} + \dots + a_{d-1}\bar{t}^{d-1}$.

That is, $g(t) = a_0 + a_1t + \dots + a_{d-1}t^{d-1} \in (f(t))$.

So f divides g but $\deg(f) = d > d-1$. Then $g = 0$ in the new polynomial.

That is $a_0 = a_1 = \dots = a_{d-1} = 0$.

What is the span? $g(t) = b_0 + b_1t + \dots + b_nt^n = b_0 + b_1t + \dots + b_{d-1}t^{d-1} + t^d(\dots)$.

In $F[t]/(f(t))$, $f(t) = 0$, $f(t) = t^d = a_{d-1} + \dots + a_0$, $t^d = (a_{d-1}t^{d-1} + \dots + a_0)$ where $g(t)$ is some polynomial of degree less than d .

Finally, note that $F[t]/(m_a(t)) \xrightarrow{\sim} F[a]$ is given by $\overline{f(t)} \mapsto f(a)$.

Then $\bar{1} \mapsto 1$, $\bar{t} \mapsto a$, \dots , $\bar{t}^{d-1} \mapsto a^{d-1}$.

Remark

This proposition explains the choice of the term “degree” for $[K : F]$. If $K = F(a)$ is generated by a single, algebraic element $a \in K$, then the $[F(a) : F]$ is the degree of the minimal polynomial of a over F .

Example 1

$\mathbb{Q}(i) = \mathbb{Q}[i] = \{a + bi : a, b \in \mathbb{Q}\}$ (since the minimal polynomial $t^2 + 1$ of i over \mathbb{Q} has degree 2).
 $\mathbb{Q}(\sqrt{2}) = \mathbb{Q}[\sqrt{2}] = \{a + b\sqrt{2} : a, b \in \mathbb{Q}\}$.

Example 2

$\xi_p := e^{2\pi i/p} \in \mathbb{C}$ for a prime p is a root of unity for

$$x^p - 1 = (x - 1) \overbrace{(x^{p-1} + x^{p-2} + \cdots + x + 1)}^{\Phi_p(x)}$$

Since $\xi_p \neq 1$, ξ_p is a root of $\Phi_p(x)$.

Eisenstein's Criterion applied to $\Phi_p(x+1)$ that $\Phi_p(x)$ is irreducible over \mathbb{Z} and hence over \mathbb{Q} .

Hence $\Phi_p(x)$ is the minimal polynomial of ξ_p over \mathbb{Q} .

Thus, $\mathbb{Q}(\xi_p) = \mathbb{Q}[\xi_p] = \{a_0 + a_1\xi_p + a_2\xi_p^2 + \cdots + a_{p-2}\xi_p^{p-2} : a_i \in \mathbb{Q}\}$.

Example

Let $p = 3$. $\mathbb{Q}(\xi_3) = \{a_0 + a_1\xi_3 : a_0, a_1 \in \mathbb{Q}\}$.

So $\mathbb{Q}(\xi_3) = \mathbb{Q}(\sqrt{3}i) = \mathbb{Q}(\sqrt{-3}) = \{a + b\sqrt{-3} : a, b \in \mathbb{Q}\}$.

Example 3

$\mathbb{R}(i) = \mathbb{R}[i] = \{a + bi : a, b \in \mathbb{R}\} = \mathbb{C}$.

$\mathbb{R}[i] \simeq \mathbb{R}[t]/(t^2 + 1)$.

To Study:

Eisenstein's Criterion

Gauss' Lemma

Remark

Given a field extension K/F , an element $a \in K$ is algebraic over F if and only if $[F(a) : F] < \infty$.

The above proposition gives the \implies direction.

On the other hand, if a is transcendental then $F(a) \simeq F(t)$ and $[F(t) : F] = \infty$.

Proposition

Let K/F be a finite extension of degree n .

Every element of K is algebraic over F and has degree dividing n .

Proof

$$[K : F] = [K : F(a)][F(a) : F]$$

Corollary

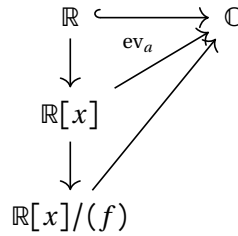
Every irreducible polynomial $f \in \mathbb{R}[x]$ has degree 1 or 2.

Proof

(Assuming the FTA)

Let $f \in \mathbb{R}[x]$ be irreducible. Then $K : \mathbb{R}[x]/(f)$ is a field.

By the Fundamental Theorem of Algebra, f has a root $a \in \mathbb{C}$.



So $\mathbb{R} \hookrightarrow \mathbb{R}[x]/(f) \hookrightarrow \mathbb{C}$, and

$$2 = [\mathbb{C} : \mathbb{R}] = [\mathbb{C} : \mathbb{R}[x]/(f)][\mathbb{R}[x]/(f) : \mathbb{R}]$$

Therefore $[\mathbb{R}[x]/(f) : \mathbb{R}] = \deg(f)$ is either 1 or 2.

Definition: Algebraic Extension

A field extension K/F is said to be an algebraic extension if every element of K is algebraic over F .

Example

We showed above that every finite extension is an algebraic extension.

Theorem:

Let $L/K/F$ be field extensions.

Then L/F is algebraic if and only if L/K is algebraic and K/F is algebraic.

Proof

(\implies) trivial.

(\impliedby) Let $a \in L$. Then $f(a) = 0$ for some nonzero polynomial $f(t) \in K[t]$. Write

$$f(t) = b_0 + b_1 t + \cdots + b_d t^d$$

with $b_0, \dots, b_d \in K$.

Each of these b_i is algebraic over F . Hence $E := F(b_0, b_1, \dots, b_d)$ is a finite extension of F .

$$F(b_0, \dots, b_d)/F(b_0, \dots, b_{d-1})/\dots/F(b_0)/F$$

Note that $f(t) \in E[t]$ and $f(a) = 0$, so $a \in L$ is algebraic over E .

Observe

$$[E(a) : F] = \underbrace{[E(a) : E]}_{\text{finite}} \underbrace{[E : F]}_{\text{finite}}$$

so $E(a)/F$ is finite, hence an algebraic extension.

Therefore $a \in L$ is algebraic over F .

Corollary

Let K/F be a field extension.

The elements of K which are algebraic over F form a subfield of K .

Proof

Let $a, b \in K$ be algebraic over F .

Then $F(a, b)/F$ factors as $F(a, b)/F(a)/F$.

So $F(a, b)/F$ is a finite, hence algebraic, extension.

Therefore $a + b, a - b, ab, a^{-1}$ (for $a \neq 0$) are algebraic over F .

Example

Apply to \mathbb{C}/\mathbb{Q} to see that the collection of all algebraic numbers forms a subfield of \mathbb{C} .

$\overline{\mathbb{Q}}$ is defined as the field of algebraic numbers.

Recall: Theorem (Cantor), $\overline{\mathbb{Q}}$ is countable.

Exercise: $\overline{\mathbb{Q}}/\mathbb{Q}$ is an infinite extension.

Adjoining Elements

Let F be a field and $f(x) \in F[x]$ be irreducible.

Then $K := F[x]/(f)$ is a field extension of degree $\deg(f)$.

Note: $K = F(a)$ when $a := \bar{x}$.

Note also that a is a root of $f(x)$.

$$f(a) = f(\bar{x}) = \overline{f(x)} = 0$$

in K .

Example 1

We could define $\mathbb{C} := \mathbb{R}[x]/(x^2 + 1)$ and define $i := \bar{x}$.

Example 2

Let F be a field.

Suppose $a \in F$ which does not have a square root in F (i.e. $\nexists \delta \in F$ such that $\delta^2 = a$).

Then $x^2 - a \in F[x]$ is irreducible.

Then $K := F[x]/(x^2 - a)$ is a degree 2 extension.

Setting $\delta := \bar{x} \in K$, $K = F(\delta)$ and $\delta^2 = a \in F$.

In fact, every quadratic extension arises in this way – adjoining a square root.

Example 3

Let F be a field of characteristic $\neq 2$.

Let K/F be a quadratic extension (i.e. $[K : F] = 2$).

Let $\delta \in K$ be an element such that $\delta \notin F$, then $K = F(\delta)$ ($K = F(\delta)/F$).

So the minimal polynomial of δ over F is a quadratic polynomial.

$$m_\delta(t) = t^2 + bt + c \in F[t]$$

Consider $\Delta := b^2 - 4c \in F$.

Claim: Δ does not have a square root in F . Otherwise

$$m_\delta(t) = \left(t - \frac{-b + \sqrt{\Delta}}{2}\right) \left(t - \frac{-b - \sqrt{\Delta}}{2}\right)$$

would not be irreducible.

Note: $2\delta + b = \pm\sqrt{\Delta}$. So

$$K = F(\delta) = F(2\delta + b) = F(\sqrt{\Delta})$$

April 15, 2024

Remarks on Ruler and Compass Construction

Game

Start with some “known” points in the plane and then we construct new points using a ruler and compass.

The ruler you may draw lines between two known points.

With the compass you may draw a circle with known center and known radius (distance between two known points).

Example Problems

Squaring the circle: given a circle, construct, using ruler and compass, a square with the same area.

Trisecting a given angle.

Can you construct a regular n -gon using ruler and compass?

Doubling the cube: given a cube, construct a cube with double the volume.

Remark

Starting with two given points, call one zero and the other one. Then we can construct a coordinate system system which identifies the plane with $\mathbb{R}^2 = \mathbb{C}$.

One can readily check that the constructible points (the points which are constructible starting from zero and one) form a subfield of \mathbb{C} .

One can readily check that every point whose coordinates are rational is constructible.

This transforms the geometric problems into problems of field theory.

That is, the field of constructible numbers is some field extension of $\mathbb{Q}(i)$.

Key Point

Let K be a subfield of \mathbb{C} which contains i and is closed under complex conjugation.

e.g. $K = \mathbb{Q}(i)$. Then $z = x + iy \in K$ if and only if $x, y \in K$.

Consider the intersection of two lines. Then the point of intersection is in K .

The coordinates of the points of intersection are rational expressions of the coordinates of the points which determine the lines.

Consider instead the intersection of a circle $(x - a)^2 + (y - b)^2 = r^2$ and a line $px + qy = h$ ($p \neq 0$).

Then $x = \frac{h - qy}{p}$ and

$$\left(\frac{h - qy}{p} - a\right)^2 + (y - b)^2 = r^2$$

is a quadratic equation in y . So y may be expressed as a rational expression, including square roots, of the coordinates of the points which determine the line and the circle.

Therefore, the point of intersection is contained in a quadratic extension of K .
 Finally, the intersection of two circles is the same as the intersection of line and circle.

Theorem:

A point $z \in \mathbb{C}$ is constructible if and only if there exists a tower of field extension $\mathbb{Q} = F_0 \subseteq \cdots \subseteq F_m$ such that $z \in F_m$ and each F_i/F_{i-1} is a quadratic extension.
 That is, $F_i = F_{i-1}(u_i)$ where $u_i^2 \in F_{i-1}$.

Corollary

If $z \in \mathbb{C}$ is constructible, then z is algebraic and $[\mathbb{Q}(z) : \mathbb{Q}]$ is a power of 2.

Proof

$$[F_m : \mathbb{Q}(z)][\mathbb{Q}(z) : \mathbb{Q}] = [F_m : F_0] = 2^m$$

Corollary

It is impossible to square the circle.

Proof

A square of side length $\sqrt{\pi}$, $\sqrt{\pi}$ and π would be constructible. But Lindemann demonstrated that π is transcendental.

Remark

Note that some angles can be trisected (e.g. $\pi/2$).

Corollary

Not every angle may be trisected.
 In particular, $2\pi/3$ cannot be trisected.

Proof

If we could trisect $2\pi/3$, then we could construct $e^{2\pi i/9}$.
 Let $\xi = e^{2\pi i/9}$. If ξ were constructible, then $\alpha := \xi + \xi^{-1}$ would be constructible.
 Observe that $\xi^3 = e^{2\pi i/3}$. Then $(\xi^3)^2 + \xi^3 = -1$.
 Given that

$$\alpha^3 = (\xi + \xi^{-1})^3 = \xi^3 + 3\xi + 3\xi^{-1} + \overbrace{\xi^{-3}}^{\xi^6} = 3(\xi + \xi^{-1}) - 1 = 3\alpha - 1$$

we have that $\alpha^3 - 3\alpha + 1 = 0$. That is, α is a root of $x^3 - 3x + 1$ which is irreducible (check directly that it is irreducible over \mathbb{Z} and then Gauss implies it is irreducible over \mathbb{Q}).
 Then $[\mathbb{Q}(\alpha) : \mathbb{Q}] = 3$, and we are done.

Proposition

We can construct a regular n -gon using ruler and compass if and only if $e^{2\pi i/n}$ is constructible.

Corollary

We cannot construct a regular 9-gon using ruler and compass.

Definition: Algebraic Independence

Let K/F be a field extension.

A collection of distinct elements $a_1, \dots, a_n \in K$ are said to be algebraically independent over F if $\forall f \in F[x_1, \dots, x_n]$, $f(a_1, \dots, a_n) = 0$ implies $f = 0$.

A subset $S \subseteq K$ is said to be algebraically independent over F if every finite subset of S is algebraically independent over F .

Definition: Purely Transcendental Extension

K/F is a purely transcendental extension if $K = F(S)$ for some algebraically independent $S \subseteq K$.

Example

$F(t_1, \dots, t_n)/F$ is a purely transcendental extension.

Exercise

K/F is purely transcendental if and only if $K \cong F(\{t_i\}_{i \in S}) = \text{Frac}(F[\{t_i\}_{i \in S}])$.

Definition: Transcendence Basis

Let K/F be a field extension.

A transcendence basis for K/F is an algebraically independent subset $S \subseteq K$ such that $K/F(S)$ is an algebraic extension.

Theorem:

Let K/F be a field extension and $S \subseteq K$. The following are equivalent

1. S is a transcendence basis for K/F .
2. S is maximal among all algebraically independent subsets of K/F .
3. S is minimal among all subsets of K such that $K/F(S)$ is algebraic.

Lemma:

A subset $S \subseteq K$ is algebraically independent over F if and only if every element $u \in S$ is transcendental over $F(S \setminus \{u\})$.

Exercise

Using this lemma, prove the previous theorem.

Theorem:

Let K/F be a field extension.

1. Any algebraically independent subset $S \subseteq K$ is contained in the transcendence basis.
2. Any subset $S \subseteq K$ such that $K/F(S)$ is algebraic contains a transcendence basis.

In particular, a transcendence basis exists.

Remark

Every field extension is an algebraic extension of a purely transcendental extension.

Corollary / Exercise

Every finitely generated field extension K/F is an algebraic extension of $F(t_1, \dots, t_n)$ for some n .

Theorem:

Any two transcendence bases of K/F have the same cardinality.

Definition: Transcendence Degree

Let K/F be a field extension.

The cardinality of a transcendence basis is called the transcendence degree of K/F .

$$\text{trdeg}_F(K) \quad \text{or} \quad \text{trdeg}(K/F)$$

Examples

$$\text{trdeg}_F(F(t_1, \dots, t_n)) = n.$$

$$\text{trdeg}_F(K) = 0 \text{ if and only if } K/F \text{ is algebraic.}$$

Exercise

$$\text{Given } L/K/F, \text{trdeg}(L/F) = \text{trdeg}(L/K) + \text{trdeg}(K/F).$$

Example

Let X be a compact Riemann surface.

Then we have a field $M(x)$ of meromorphic functions, $M(x)/\mathbb{C}$.

e.g. $X = \mathbb{P}_{\mathbb{C}}^1 = S^2$. Then, since every meromorphic function is rational, $M(x) \cong \mathbb{C}(t)$.

In general, $\text{trdeg}_{\mathbb{C}}(M(x)) = 1$.

For every finite extension, $K/\mathbb{C}(t)$, there exists a compact Riemann surface X such that $M(x) = K$.

There is an equivalence of categories between the compact Riemann surfaces with nonconstant holomorphic maps and the opposite category of finite extensions of $\mathbb{C}(t)$.

April 17, 2023

Definition: Splitting Field

Given a polynomial, $f \in F[t]$ we want to construct a field extension K/F in which f splits into linear factors:

$$f(t) = c(t - a_1)(t - a_2) \cdots (t - a_n)$$

where $c \in F$, $a_1, \dots, a_n \in K$.

A splitting field for $f \in F[t]$ is a field extension K/F such that f splits completely into linear factors as above over K and K is generated by the roots of f in K such that $K = F(a_1, \dots, a_n)$.

Theorem:

Every polynomial $f \in F[t]$ admits a splitting field.

Proof

Key: if $f \in F[t]$ is irreducible, then $F[t]/(f(t))$ is a field which is an extension of F

$$F \hookrightarrow F[t] \rightarrow F[t]/(f(t))$$

and $f(t)$ has a root in it, namely $\bar{t} \in F[t]/(f(t))$ ($f(\bar{t}) = \overline{f(t)} = 0$).

For a general polynomial $f(t) \in F[t]$,

$$f = cf_1f_2 \cdots f_m$$

with $c \in F$, f_i irreducible ($F[x]$ a UFD).

Take $K_1 := F[t]/(f_1)$. Over K_1 , one of the irreducible factors (namely f_1) gets a root.

Then consider the factorization of f into irreducibles over K_1 and continue. Then

$$F = K_0 \hookrightarrow K_1 \hookrightarrow K_2 \hookrightarrow \cdots$$

By injection on the sum of the degrees of the nonlinear irreducible factors, this implies that we eventually obtain a field K_N in which f splits completely.

Remark

Note that if $K = F(a_1, \dots, a_n)$ is a splitting field of f where a_1, \dots, a_n are the roots of f in K , then K is a finite, hence algebraic, extension of F .

Remark

Be careful. Even if $f \in F[t]$ is irreducible, it is not enough in general just to go to $K := F[t]/(f(t))$ in order to obtain a complete splitting.

Example

Let $F = \mathbb{Q}$, $f(X) = X^4 - 2 \in \mathbb{Q}[X]$.

This is irreducible by Eisenstein.

Take $K := \mathbb{Q}[X]/(X^4 - 2)$. Then $x := \bar{X}$ is a root of the polynomial.

In K , we have that $x^4 = 2$; in $K[X]$, $X^4 - 2 = x^4 - x^4 = (X^2 - x^2)(X^2 + x^2) = (X - x)(X + x)(X^2 + x^2)$.

The last polynomial, $X^2 + x^2$ is irreducible in $K[X]$.

We still need to do one more quadratic extension (adjoining $i = \sqrt{-1}$) for $X^2 + x^2$ to split as $(X - ix)(X + ix)$.

A splitting field of $X^4 - 2$ over \mathbb{Q} is a degree 8 extension $\mathbb{Q}(\sqrt[4]{2}, i)$.

$$\begin{array}{c}
 \mathbb{Q}(\sqrt[4]{2}, i) \\
 \mid_2 \\
 \mathbb{Q}(\sqrt[4]{2}) \\
 \mid_4 \\
 \mathbb{Q}
 \end{array}$$

Corollary

Let $f_1, f_2, \dots, f_s \in F[t]$ be a finite collection of polynomials.

Then there exists a field extension K/F in which each polynomial f_1, \dots, f_s splits completely.

Proof

Apply the theorem to $f := f_1 f_2 \cdots f_s$.

Definition: Algebraically Closed Field

A field F is algebraically closed if it admits no non-trivial algebraic extension.

That is, K/F algebraic $\implies K = F$.

Proposition:

A field F is algebraically closed if and only if every polynomial in $F[t]$ splits completely into linear factors.

Proof

(\implies) Let $f \in F[t]$.

By the theorem above, there exists a splitting field K of f . So K/F is algebraic, and therefore $K = F$.

So f splits completely over F .

(\impliedby) Suppose K/F is algebraic.

Let $a \in K$. The minimal polynomial of a over F is irreducible, hence linear. Therefore $a \in F$.

So $K = F$.

Remark / Exercise

Every polynomial in $F[t]$ splits completely if and only if every non-constant polynomial in $F[t]$ has a root in F .

Theorem:

Let F be a field.

There exists a field extension E/F with E algebraically closed.

Aside: Zorn's Lemma

Take $S := \{\text{proper ideals } I \subsetneq R\}$ ordered by inclusion, $S \neq \emptyset$ since $R \neq \emptyset$.

If $\{I_i\}$ a chain, then $\bigcup I_i$ is an ideal.

Further, it is a proper ideal since $1 \in \bigcup I_i \implies 1 \in I_i \implies I_i = R$ a contradiction.

Zorn's lemma implies that S contains a maximal ideal.

Proof

Zorn's lemma implies that every non-zero commutative ring has a maximal ideal.

Therefore, every non-zero commutative ring admits a ring homomorphism $R \rightarrow K$ to a field.

Let $A := F[X_f]_{f \in F[t] \setminus F}$, the (huge) polynomial algebra in infinitely many indeterminates, one for each non-constant polynomial $f \in F[t] \setminus F$.

Consider the ideal $I := (f(X_f))_{f \in F[t] \setminus F} \subseteq A$.

Here $f(X_f)$ is the single-variable polynomial f in the variable X_f .

Key: $I \neq A$. Let $Q = \sum_{i=1}^n Q_i f_i(X_{f_i}) \in I$, for some $Q_i \in A$ and $f_i \in F[t] \setminus F$.

There exists a field K/F in which f_1, \dots, f_n split completely.

In particular, $\exists \alpha_1, \dots, \alpha_n \in K$ such that $f_i(\alpha_i) = 0$, $\forall i = 1, \dots, n$.

Evaluate $Q(X_{f_1}, \dots, X_{f_n}, X_{q_1}, \dots, X_{q_k})$ by setting $X_{f_i} \mapsto \alpha_i$ and $X_{q_j} \mapsto 0$ (for example).

Then $Q \mapsto 0$. Therefore, $Q \neq 1$ because $1 \mapsto 1$ in K .

So $1 \notin I$ (i.e. $I \neq A$), hence $R := A/I$ is a non-zero ring and there exists a ring homomorphism $R \rightarrow L$ for some field L .

This field L is an extension of F .

$$\begin{array}{ccccc} F & \hookrightarrow & & & L \\ & \searrow & \phi & \nearrow & \uparrow \\ & F[\{X_f\}] = A & \longrightarrow & A/I = R & \end{array}$$

Let $f \in F[t] \setminus F$.

Consider $\alpha_f := \phi(X_f) \in L$.

Well

$$f(\alpha_f) = f(\phi(X_f)) = \phi(\underbrace{f(X_f)}_{\in I}) = 0$$

That is, every non-constant polynomial in $F[t]$ has a root in L .

Repeat this process inductively,

$$F = L_0 \hookrightarrow L_1 \hookrightarrow \dots \hookrightarrow L_n \hookrightarrow \dots$$

with the property that every non-constant polynomial with coefficients in L_n has a root in L_{n+1} .

Take $L := \text{colim}_{n \rightarrow \infty} L_n = \bigcup_{n \geq 1} L_n$. This L is algebraically closed.

$$L[T] = \bigcup_{n \geq 1} L_n[T]$$

Every non-constant polynomial over L is realized over L_n , hence has a root in L_{n+1} and therefore has a root in L .

Definition: Algebraic Closure

Let F be a field.

An algebraic closure of F is an algebraic extension E/F with E algebraically closed.

Corollary

Every field admits an algebraic closure.

Proof

By the theorem, $F \hookrightarrow L$ with L algebraically closed.

Consider $E := \{a \in L : a \text{ is algebraic over } F\}$. We previously proved that E is a subfield of L .

By construction, E/F is algebraic.

We claim E is algebraically closed.

Let $f \in E[t]$ be a polynomial. Well

$$f(t) = c(t - \alpha_1) \cdots (t - \alpha_n)$$

in $L[t]$ with $c \in E$ and $\alpha_1, \dots, \alpha_n \in L$.

Each α_i is algebraic over E (since $f(\alpha_i) = 0$).

So $E(\alpha_i)/E$ is algebraic and E/F is an algebraic extension.

Therefore $E(\alpha_i)/F$ is algebraic. Therefore α_i is algebraic over F so $\alpha_i \in E$.

So f splits on E .

Example

The Fundamental Theorem of Algebra asserts that \mathbb{C} is algebraically closed.

Example

$\overline{\mathbb{Q}} = \{z \in \mathbb{C} : z \text{ is algebraic over } \mathbb{Q}\}$ is an algebraic closure of \mathbb{Q} .

Example

\mathbb{C} is an algebraic closure of \mathbb{R} .

April 22, 2024

Proposition

Let K/F be an algebraic extension.

Any embedding $\sigma : F \hookrightarrow L$ with L algebraically closed can be extended to an embedding

$$\begin{array}{ccc} K & \xhookrightarrow{\bar{\sigma}} & L \\ | & \nearrow \sigma & \\ F & & \end{array}$$

Proof

First, consider the case where $K = F(a)$ for some $a \in K$.

Let $f \in F[t]$ be the minimal polynomial of $a \in K$.

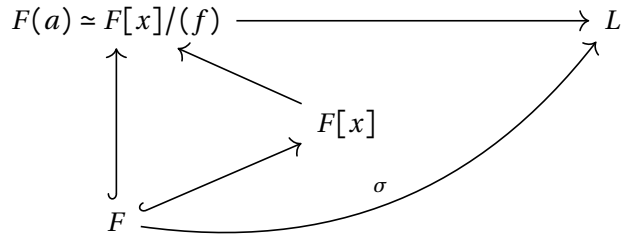
We know that $F(a) \simeq F[t]/(f)$.

The embedding $F \xrightarrow{\sigma} L$ induces a ring homomorphism $F[x] \hookrightarrow L[x]$.

Let $f^\sigma \in L[x]$ denote the polynomial obtained by applying σ to the coefficients of f .

Now L is algebraically closed, so f^σ splits completely.

Choose some root $\beta \in L$ of f^σ . Then consider the unique homomorphism $F[x] \rightarrow L$ which does σ to F and sends $x \mapsto \beta$, $F[x] \rightarrow L$, $f \mapsto f^{\sigma(\beta)=0}$.



Now for an arbitrary algebraic extension K/F , consider $S = \{(F_1, \sigma_1) : F \subseteq F_1 \subseteq K, \sigma_1 : F_1 \rightarrow L, \text{ such that } \sigma_1|_F = \sigma\}$.

Define a partial order on S by $(F_1, \sigma_1) \leq (F_2, \sigma_2)$ if $F_1 \subseteq F_2$ and $\sigma_2|_{F_1} = \sigma_1$.

Note that $S \neq \emptyset$ since $(F, \sigma) \in S$.

Suppose $\{(F_\alpha, \sigma_\alpha)\}_\alpha$ is a totally ordered subset. Then $\bigcup_\alpha F_\alpha$ is a field and we can define $\tau : \bigcup_\alpha F_\alpha \rightarrow L$ by $\tau|_{F_\alpha} := \sigma_\alpha$.

Thus every totally ordered subset has an upper bound.

Then, by Zorn's lemma, this implies there is a maximal extension (F_0, σ_0) .

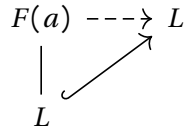
Claim: $F_0 = K$. Otherwise, consider $\alpha \in K$ with $\alpha \notin F_0$.

We can extend $\sigma_0 : F_0 \hookrightarrow L$ to a homomorphism $F_0(\alpha) \hookrightarrow L$ which contradicts the maximality of (F_0, σ_0) .

Therefore, $F_0 = K$.

Remark

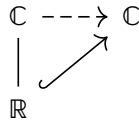
The extension is not unique.



We chose a root β in L of the minimum polynomial of a .

A different choice of root will give a different extension.

Example



We have that $\mathbb{C} = \mathbb{R}(i)$ and $X^2 + 1 = (x - i)(x + i)$.

So there are two such extensions, $i \mapsto i$ the identity map and $z \mapsto \bar{z}$ ($i \mapsto -i$) the complex conjugate.

Definition: F-Homomorphism

Let K_1/F and K_2/F be field extensions.

An F -homomorphism or homomorphism over F is a field homomorphism

$$K_1 \xrightarrow{\phi} K_2$$

such that $\phi(a) = a$ for all $a \in F$.

$$\begin{array}{ccc} K_1 & \xrightarrow{\phi} & K_2 \\ \uparrow & \nearrow & \\ \mathbb{R} & & \end{array}$$

If ϕ is an isomorphism of fields, we call it an F -isomorphism or an isomorphism over F .

Example

Complex conjugation $z \mapsto \bar{z}$ is an \mathbb{R} -isomorphism of the field \mathbb{C} .

Corollary: Uniqueness of Algebraic Closure

Let L_1/F and L_2/F be algebraic closures.
Then there is an F -isomorphism $L_1 \xrightarrow{\sim} L_2$.

Proof

$$\begin{array}{ccc} L_1 & \xrightarrow{\exists \sigma} & L_2 \\ \text{alg.} \uparrow & \nearrow & \\ \mathbb{R} & & \end{array}$$

So there exists an F -homomorphism $\sigma : L_1 \rightarrow L_2$ by the proposition.

Claim: σ is an isomorphism.

It is automatically injective.

$$\begin{array}{ccc} L_1 & \xrightarrow{\sim} & \sigma(L_1) \subseteq L_2 \\ | & \nearrow & \\ \mathbb{R} & & \end{array}$$

Since L_2/F is algebraic, $L_2/\sigma(L_1)$ is algebraic.

Hence $L_2 = \sigma(L_1)$ since $\sigma(L_1) \simeq L_1$ is algebraically closed.

Remark

Thus, “the” algebraic closure of a field F is unique up to a non-unique isomorphism.

Remark

Any algebraic extension K/F can be realized as (i.e. is F -isomorphic to) a subfield of the algebraic closure \bar{F} .
But again there can be many such embeddings.

Definition: Splitting Field

Let $\mathcal{F} \subseteq F[t]$ be a family of polynomials.

A splitting field for \mathcal{F} is a field extension K/F such that every $f \in \mathcal{F}$ splits completely over K and $K = F(S)$ where $S := \{a \in K : a \text{ is a root of some } f \in \mathcal{F}\}$.

Proposition:

Let $\mathcal{F} \subseteq F[t]$ be a family of polynomials.

1. A splitting field for \mathcal{F} exists. For example, $K := F(\{a \in \bar{F} : a \text{ is a root of some } f \in \mathcal{F}\})$ is such a splitting field.
2. Any 2 splitting fields for \mathcal{F} are F -isomorphic.

Proof of 1

Over K , every polynomial $f \in \mathcal{F}$ splits completely and K is generated by these roots.

Proof of 2

Consider $F \hookrightarrow \bar{F}$, and let K'/F be a splitting field for \mathcal{F} .

We can extend the embedding $F \hookrightarrow \bar{F}$ to an embedding

$$\begin{array}{ccc} K' & \xrightarrow{\sigma} & \bar{F} \\ \uparrow & \nearrow & \\ \mathbb{R} & & \end{array}$$

Observe that $\alpha \in K'$ is a root of $f \in \mathcal{F}$ if and only if $\sigma(\alpha) \in \sigma(K') \subseteq \bar{F}$ is a root of $f \in \mathcal{F}$.

We know that $K' = F(S)$ where $S = \{\alpha \in K' : f(\alpha) = 0 \text{ for some } f \in \mathcal{F}\}$.

So $\sigma(K') = \sigma(F(S)) = F(\sigma(S)) = K$. That is $K' \xrightarrow{\sigma} \sigma(K') = K \subseteq \bar{F}$.

Definition: Normal Extensions

A normal extension K/F is an algebraic extension such that for every irreducible polynomial $f \in F[t]$, if f has a root in K , then f splits completely in K .

Examples

- F/F is a normal extension.
- \bar{F}/F is a normal extension.
- $\mathbb{Q}(\sqrt[4]{2})/\mathbb{Q}$ is not a normal extension.

$X^4 - 2 \in \mathbb{Q}[x]$ is irreducible which has a root but does not split completely (roots $\pm \sqrt[4]{2} \in \mathbb{Q}(\sqrt[4]{2})$ and $\pm i \sqrt[4]{2} \notin \mathbb{Q}(\sqrt[4]{2})$).

Proposition

Let K/F be an algebraic extension and choose an algebraic closure $K \hookrightarrow \bar{K} = \bar{F}$.

1. K/F is a normal extension.
2. For any F -homomorphism $\sigma : K \rightarrow \bar{K}$, we have $\sigma(K) \subseteq K$.

3. For any F -homomorphism $\sigma : \bar{K} \rightarrow \bar{K}$, we have $\sigma(K) \subseteq K$.

Proof 1 Implies 2

Take $\sigma : K \rightarrow \bar{K}$.

Let $x \in K$ and consider its minimal polynomial $f \in F[t]$.

Then $\sigma(x)$ is also a root of f .

But f is an irreducible polynomial which has a root x in K , so every root of f in \bar{K} is contained in K (since K/F is normal).

Therefore $\sigma(x) \in K$.

Proof 2 Implies 3

Trivial.

Proof 3 Implies 1

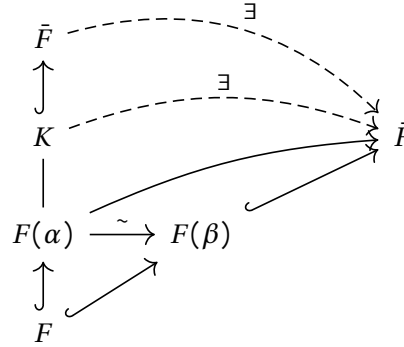
Let $f \in F[t]$ be an irreducible polynomial which has a root $\alpha \in K$.

We want to claim that all the roots of f (which exist in $\bar{K} = \bar{F}$) also lie in K .

Let $\beta \in \bar{K}$ be such a root. We have that

$$K \supseteq F(\alpha) \simeq F[t]/(f(t)) \simeq F(\beta) \subseteq \bar{F} = \bar{K}$$

with the F -isomorphism $\alpha \mapsto \beta$.



By hypothesis, $\sigma(K) \subseteq K$. Hence, $\sigma(\alpha) = \beta \in K$.

Remark

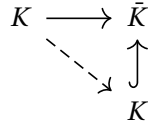
The intuition is that an F -homomorphism $\bar{K} \rightarrow \bar{K}$ must send $a \in K$ to a root of the minimal polynomial of a . Normality of K/F ensures that all these roots are also in K .

Remark

$$K \xrightarrow{\iota} \text{Hom}_F(K, K) \xrightarrow{\iota \circ -} \text{Hom}_F(K, \bar{K})$$

is injective since ι is a monomorphism.

K/F is normal if and only if the map above is a bijection.



Proposition

Let K/F be a field extension. The following are equivalent

1. K/F is a normal extension.
2. K is the splitting field of a family of polynomials $\mathcal{F} \subseteq F[t]$.

Proof 1 Implies 2

Let $\mathcal{F} = \{\text{the minimal polynomials of all } x \in K\}$.

Then $K = F(S)$ where $S = \{a \in K : f(a) = 0 \text{ for some } f \in \mathcal{F}\}$.

Moreover, every polynomial $f \in \mathcal{F}$ splits completely in K since K/F is normal.

Therefore K is the splitting field of \mathcal{F} .

Proof 2 Implies 1

Choosing $F \hookrightarrow \bar{F}$, we know

$$K \simeq F(S) \subseteq \bar{F}$$

where $S = \{a \in \bar{F} : f(a) = 0 \text{ for some } f \in \mathcal{F}\}$.

Claim: $F(S)/F$ is a normal extension.

Consider an F -homomorphism $F(S) \xrightarrow{\sigma} \bar{F}$.

If $a \in S$, then $f(a) = 0$ for some $f \in \mathcal{F}$. Hence $f(\sigma(a)) = 0$ and $\sigma(a) \in S$.

Therefore $\sigma(F(S)) \subseteq F(\sigma(S)) \subseteq F(S)$.

Corollary

Finite normal extensions are precisely splitting fields of single polynomials.

Remark

Let $L/K/F$ be algebraic extensions.

Then L/F normal implies L/K normal.

On the other hand, L/F normal does not imply K/F normal.

e.g. $\bar{\mathbb{Q}}/\mathbb{Q}(\sqrt[4]{2})/\mathbb{Q}$

L/K and K/F normal does not imply L/F normal.

e.g. $\mathbb{Q}(\sqrt[4]{2})/\mathbb{Q}(\sqrt{2})/\mathbb{Q}$

Definition: Normal Closure

Let K/F be an algebraic extension.

Then there exists an extension L/K such that L/F is normal (hence L/K is normal) and which is minimal for this property.

We call L/F the normal closure of the extension K/F .

Moreover, if K/F is finite then L/F is finite.

Also, the normal closure L/F is unique up to F -isomorphism.

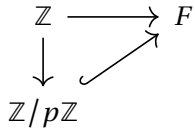
Proof left as an exercise.

April 24, 2024

Recall

For any prime p , $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$ is a field of order p .

Note that if F is a finite field – i.e. a field with only finitely many elements – then $\text{char}(F) = p > 0$.



It contains \mathbb{F}_p as a subfield. We can regard F as an \mathbb{F}_p -vector space.

Since F is finite, its dimensions as an \mathbb{F}_p -vector space is finite.

That is, the degree $[F : \mathbb{F}_p] = n$ is finite.

As an \mathbb{F}_p -vector space, $F \simeq \mathbb{F}_p^n$. So $|F| = p^n$.

It is customary to use $q = p^n$ for the order of a finite field.

How can we construct finite fields? If $f \in \mathbb{F}_p[x]$ is an irreducible polynomial of degree n , then $\mathbb{F}_p[x]/(f)$ is a field of order p^n .

- Example

$x^2 + x + 1 \in \mathbb{F}_2[x]$ is irreducible, hence $\mathbb{F}_2[x]/(x^2 + x + 1)$ is a field of order 4.

But it is not obvious whether there exists an irreducible polynomial of degree n in $\mathbb{F}_p[x]$.

Definition: Frobenius Homomorphism

Let F be a field of characteristic $p > 0$.

The Frobenius homomorphism is the map $F \xrightarrow{\text{Frob}} F$ defined by $a \mapsto a^p$.

This is obviously multiplicative $(ab)^p = a^p b^p$.

It is additive, since $(a+b)^p = a^p + b^p$ in characteristic p since $p \mid \binom{p}{i}$ for $i \neq 0, p$.

That is, the Frobenius is a field homomorphism.

Remark

The Frobenius is injective: $a^p = b^p \implies a = b$.

Remark

We can also consider iterates of the Frobenius

$$F \xrightarrow{\text{Frob}} F \xrightarrow{\text{Frob}} F \xrightarrow{\text{Frob}} \dots \xrightarrow{\text{Frob}} F$$

which maps $a \mapsto a^{p^m}$.

Exercise

Since the Frobenius is a homomorphism, for any $m \geq 1$,

$$\{a \in F : a^{p^m} = a\}$$

is a subfield of F .

Theorem: (Kroenecker)

Let F be a field and let $G \leq F^*$ be a finite subgroup of the multiplicative group of units of F . Then G is cyclic.

Proof

G is a finite, abelian group, therefore

$$G \simeq \mathbb{Z}/a_1 \oplus \mathbb{Z}/a_2 \oplus \cdots \oplus \mathbb{Z}/a_s$$

where $a_1 | a_2 | \cdots | a_s$.

Written multiplicatively,

$$G \simeq C_{a_1} \times C_{a_2} \times \cdots \times C_{a_s}$$

where C_{a_i} is the cyclic group of order a_i .

If $x \in G$, then $x^{a_s} = 1$. It follows that

$$G \subseteq \{x \in F : x^{a_s} = 1\}$$

which are the roots of the polynomial $X^{a_s} - 1$. This polynomial has at most a_s roots in F .

Therefore, $a_1 a_2 \cdots a_s = |G| \leq a_s$ which implies $s = 1$ and $G \simeq C_{a_s}$ is cyclic.

Corollary

If F is a finite field, then the multiplicative group of units F^* is cyclic.

Remark

Let F be a finite field of order $q = p^n$.

Then F^* is a cyclic group of order $q - 1$ and for any $a \in F^*$ we have $a^{q-1} = 1$.

That is, for any $a \in F$, we have $a^q = a$. Thus every element of F is a root of the polynomial $X^q - X$.

In particular, $X^q - X$ has q distinct roots in F

$$X^q - X = \prod_{a \in F} (X - a)$$

in $F[x]$. Therefore F is a splitting field of $X^q - X$ over \mathbb{F}_p .

Proposition

If a finite field of order $q = p^n$ exists, then it is uniquely determined up to isomorphism as the splitting field of $X^q - X$ over \mathbb{F}_p .

Remark

Let F be a splitting field of $X^q - X$ over \mathbb{F}_p ($q = p^n$). That is, $F = \mathbb{F}_p(\{\text{roots of } X^q - X \text{ in } \overline{\mathbb{F}_p}\})$.

The derivative of $X^q - X$ is $qX^{q-1} - 1 = -1$. Thus, $X^q - X$ has no multiple roots. That is, there are precisely q distinct roots in $\overline{\mathbb{F}_p}$.

Moreover, from the Frobenius homomorphism, these q roots form a subfield of $\overline{\mathbb{F}_p}$. Thus

$$F = \mathbb{F}_p(\{\text{roots of } X^q - X\}) = \{\text{roots of } X^q - X \text{ in } \mathbb{F}_p\}$$

is a field of order q .

Theorem:

For any prime p and integer $n \geq 1$, there exists a unique up to isomorphism field of order p^n , denoted \mathbb{F}_{p^n} , which is the splitting field of $X^{p^n} - X$ over \mathbb{F}_p .

Every finite field is isomorphic to a unique such \mathbb{F}_{p^n} .

Corollary

In a fixed algebraic closure $\overline{\mathbb{F}_p}$, there is a unique \mathbb{F}_{p^n} , namely the set of roots in $\overline{\mathbb{F}_p}$ of $X^{p^n} - X$.

Definition: Roots of Unity

Let F be a field and $n \geq 1$.

An n th root of unity in F is an element $a \in F$ such that $a^n = 1$.

That is, a root of the polynomial $X^n - 1$.

Remark

If $\text{char}(F) = p > 0$, then we have the Frobenius map which is injective: $a^{p^m} = b^{p^m} \implies a = b$.

Thus, the only p^m th root of unity in F is 1. Indeed, $X^{p^m} - 1 = (x - 1)^{p^m}$.

Remark

Let F be a field with $\text{char}(F) \nmid n$.

The derivative of $X^n - 1$ is nX^{n-1} whose only root is 0.

Thus $X^n - 1$ has no multiple roots. There are exactly n distinct roots of unity in \overline{F} .

Kronecker's Theorem implies that they form a cyclic group of order n .

The generators of this cyclic group are called the primitive n th roots of unity.

Example

The n th roots of unity in $\overline{\mathbb{Q}} \subset \mathbb{C}$ are

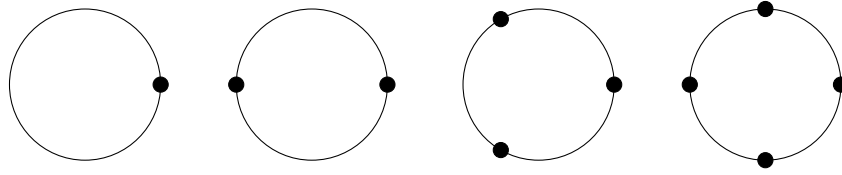
$$\{e^{2\pi i k/n} : 0 \leq k < n\}$$

and $e^{2\pi i k/n}$ is primitive if and only if $\gcd(k, n) = 1$.

e.g. $\xi = e^{2\pi i/n}$ is a primitive n th root of unity.

$$1 = \xi^0, \xi^1, \dots, \xi^{n-1}$$

Take, for example, $n = 1, 2, 3, 4$.



Remark

$$X^n - 1 = (x - 1)(x^{n-1} + x^{n-2} + \cdots + X + 1)$$

If $\xi \neq 1$ is an n th root of unity, then $1 + \xi + \xi^2 + \cdots + \xi^{n-1} = 0$.

Note

$$X^n - 1 = \prod_{\xi \text{ } n\text{th root of unity}} (X - \xi) \text{ in } \mathbb{C}[x].$$

Definition: Cyclotomic Polynomial

Let $n \geq 1$. The n th cyclotomic polynomial is

$$\Phi_n(X) := \prod_{\substack{\xi \text{ primitive} \\ n\text{th root of unity}}} (X - \xi) \in \mathbb{C}[X]$$

Examples

$n = 1$ gives $\Phi_1(X) = X - 1$.

$n = 2$ gives $\Phi_2(X) = X + 1$.

$n = 3$ gives

$$\Phi_3(X) = (X - \xi)(X - \xi^2) = X^2 - \overbrace{(\xi + \xi^2)}^{-1} + \xi^3 = X^2 + X + 1$$

with $\xi = e^{2\pi i/3}$.

$n = 4$ gives $\Phi_4(X) = (X - i)(X + i) = X^2 + 1$.

Remark

If p prime, $X^p - 1 = (X - 1)(X^{p-1} + \cdots + X + 1)$.

Therefore, $\Phi_p(X) = X^{p-1} + \cdots + X + 1$.

Proposition

$$X^n - 1 = \prod_{d|n} \Phi_d(x)$$

Proof

The n th roots of unity form a cyclic group of order n .

The primitive n th roots of unity are the n th roots of 1 of order n .

The n th roots of unity of order $d|n$ are d th roots of unity and, in fact, are the primitive d th roots of unity.

$$X^n - 1 = \prod_{\substack{\xi \text{ } n\text{th} \\ \text{root of unity}}} (X - \xi) = \prod_{d|n} \prod_{\substack{\xi \text{ } d\text{th} \\ \text{root of unity}}} (X - \xi) = \prod_{d|n} \Phi_d(X)$$

Proposition

Let $n \geq 1$.

The n th cyclotomic polynomial $\Phi_n(X)$ has integer coefficients

$$\Phi_n(X) \in \mathbb{Z}[X]$$

Proof

Recall the following consequence of Gauss' lemma: if $f \in \mathbb{Z}[X]$ monic and $f = gh$ with $g, h \in \mathbb{Q}[X]$, then $g, h \in \mathbb{Z}[X]$.

When $n = 1$, $\Phi_1(X) = X - 1$. Then we have

$$X^n - 1 = \prod_{d|n} \Phi_d(X) = \Phi_n(X) \underbrace{\prod_{\substack{d|n \\ d \neq n}} \Phi_d(X)}_{f(X)}$$

By the inductive hypothesis, $f(X) \in \mathbb{Z}[X]$ monic.

In the Euclidean domain $\mathbb{Q}[X]$, $X^n - 1 = f(X)q(X) + r(X)$ for some $q, r \in \mathbb{Q}[X]$ with $\deg(r) < \deg(f)$.

On the other hand, in $\mathbb{C}[x]$ we have that

$$X^n - 1 = \Phi_n(X)f(X)$$

Therefore

$$\begin{aligned} f(X)q(X) &= r(X) = \Phi_n(X)f(X) \\ (\Phi_n(X) - q(X))f(X) &= r(X) \end{aligned}$$

which implies that $\Phi_n(X) = q(X) \in \mathbb{Q}[X]$.

Therefore, by the consequence of Gauss' lemma we have $\Phi_n(X) \in \mathbb{Z}[X]$.

Theorem: (Gauss, 1798)

Let $n \geq 1$.

The n th cyclotomic polynomial $\Phi_n(X) \in \mathbb{Z}[X]$ is irreducible.

Proof

Let ξ be a primitive n th root of unity, and let f be the minimal polynomial of ξ over \mathbb{Q} .

Then $f|\Phi_n$ and $\Phi_n(X) = f(X)g(X)$ for some $g(X) \in \mathbb{Z}[X]$ monic.

Claim: if $p \nmid n$, then $f(\xi^p) = 0$.

Note that $p \nmid n$ implies that ξ^p is also a primitive n th root of unity.
 Suppose, for sake of contradiction, that $f(\xi^p) \neq 0$. Then it must be that $g(\xi^p) = 0$
 It follows that ξ would be a root of $g(X^p)$ and $f(X) \mid g(X^p)$. So

$$g(X^p) = f(X)h(X)$$

for some $h \in \mathbb{Z}[X]$ monic.

Apply the ring homomorphism $\mathbb{Z}[X] \rightarrow \mathbb{F}_p[X]$ which applies $\mathbb{Z} \rightarrow \mathbb{F}_p$ to the coefficients. In $\mathbb{F}_p[X]$

$$g(X)^p = g(X^p) = f(X)h(X)$$

Let $k(X)$ be an irreducible factor of $f(X)$ in $\mathbb{F}_p[X]$. Then $k(X)$ divides $g(X)$.

Then $k(X)^2 \mid X^n - 1$ in \mathbb{F}_p and, consequently, $X^n - 1$ has multiple roots in $\overline{\mathbb{F}_p}$.

But the derivative of $X^n - 1$ is nX^{n-1} whose only root is 0 since $p \nmid n$ which is a contradiction.

We have therefore established that if $p \nmid n$, then $f(\xi^p) = 0$.

Recall that ξ^p is itself a primitive, n th root of unity. Repeating the process above with ξ replaced by ξ^p leads to

$$f(\xi^{p_1 p_2 \cdots p_r}) = 0$$

for any primes $p_1 p_2 \cdots p_r$ which do not divide n .

Therefore, $f(\xi^k) = 0$ for all k such that $\gcd(k, n) = 1$ and $f(\xi) = 0$ for every primitive n th root of unity.

This tells us that $\Phi_n \mid f$ so $f = \Phi_n$.

Remark

$\mathbb{Z}[X]$ is a UFD. So

$$X^n - 1 = \prod_{d \mid n} \Phi_d(X)$$

is the unique factorization of $X^n - 1$ into irreducible polynomials.

Remark

If ξ is a primitive n th root of unity, then $\Phi_n(\xi) = 0$.

Since Φ_n is irreducible, Φ_n is the minimal polynomial of ξ .

Then $[\mathbb{Q}(\xi_n) : \mathbb{Q}] = \deg(\Phi_n) = |\xi^{0 \leq k < n}|$ such that $\gcd(k, n) = 1$.

That is, it is equal to Euler's totient function $\phi(n)$.

Note that every n th root of unity is contained in $\mathbb{Q}(\xi_n)$.

Thus, $\mathbb{Q}(\xi_n)$ is the splitting field of $X^n - 1$ over \mathbb{Q} (and also the splitting field of $\Phi_n(X)$ over \mathbb{Q}).

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Recall:

For K/F a field extension, $\text{Gal}(K/F) = \{F\text{-automorphisms } \phi : K \xrightarrow{\sim} K\}$.

Remark:

If K/F is a finite extension, then every F -homomorphism $\phi : K \rightarrow K$ is an F -automorphism. Indeed, ϕ is an injective linear endomorphism of the finite-dimensional F -vector space K . Hence ϕ is surjective. More generally, this is true for any algebraic extension.

Remark:

If K/F is a finite extension, $|\text{Gal}(K/F)| \leq [K : F]_S \leq [K : F]$. Indeed

$$\begin{array}{ccccc} K & \xrightarrow{\sigma} & K & \xrightarrow{\exists \sigma_1} & \overline{F} \\ & \searrow & \downarrow & \nearrow & \\ & & F & & \end{array}$$

We have a map $\text{Gal}(K/F) \rightarrow \text{Hom}_F(K, \overline{F})$, $\sigma \mapsto \sigma_1 \circ \sigma$ which is injective, since σ_1 is a monomorphism.

Proposition

Let K/F be a finite extension. The following are equivalent.

1. K/F is Galois.
2. $|\text{Gal}(K/F)| = [K : F]$.

Proof

Note K/F is separable if and only if $[K : F]_S = [K : F]$.

On the other hand, we claim that K/F is normal if and only if $|\text{Gal}(K/F)| = [K : F]_S$.

Well, choose an embedding

$$\begin{array}{ccc} K & \hookrightarrow & \overline{K} = \overline{F} \\ & \searrow & \nearrow \\ & & F \end{array}$$

K/F is normal if and only if for every F -homomorphism, $\sigma : K \rightarrow \overline{K}$ we have $\sigma(K) \subseteq K$. That is

$$\begin{array}{ccc} K & \xrightarrow{\sigma} & \overline{K} \\ & \searrow \sigma/K & \nearrow \\ & & F \end{array}$$

Moreover, note that $\sigma/K : K \rightarrow K$ is automatically an automorphism by the remark.

Thus K/F is normal if and only if the injective map $\text{Gal}(K/F) \hookrightarrow \text{Hom}_F(K, \overline{F})$ is surjective.

That is, if and only if $|\text{Gal}(K/F)| = [K : F]_S$.

Theorem: Artin's Theorem

Let K be a field, and let $G \leq \text{Aut}(K)$ be a finite subgroup.

Let $K^G := \{x \in K : \sigma(x) = x, \forall \sigma \in G\}$.

Then K/K^G is Galois with Galois group G .

In particular, $[K : K^G] = |G|$.

Proof: Galois

Let $x \in K$.

Consider the finite set $G.x = \{\sigma(x) : \sigma \in G\} \subseteq K$ (i.e. the orbit of x under the action of G).

Consider the polynomial $f = f_x = \prod_{y \in G.x} (t - y) \in K[t]$.

Note that f has only simple roots and $f_x(x) = 0$ since $x \in G.x$.

Now G acts on K , hence G acts on $K[t]$ by acting on the coefficients. Given $\sigma \in G$, this gives

$$\begin{array}{ccc} K & \xrightarrow{\sigma} & K \\ \downarrow & & \downarrow \\ K[t] & \dashrightarrow & K[t] \end{array}$$

$$f \longmapsto f^\sigma$$

This is an action on $K[t]$ by ring homomorphisms.

Therefore, $\forall \sigma \in G$,

$$f_x^\sigma = \prod_{y \in G.x} (t - \sigma(y)) \stackrel{(!)}{=} f_x$$

That is, the coefficients of f_x are fixed by σ for every $\sigma \in G$.

It follows that $f_x \in K^G[t]$. Since $f_x(x) = 0$, the minimal polynomial of x over K^G divides f_x and hence has simple roots.

This tells us that x is separable over K^G and therefore that K/K^G is a separable (and algebraic) extension.

Also, K is the splitting field over K^G of $\{f_x : x \in K\} \subseteq K^G[t]$. So K/K^G is a normal extension.

Since the extension is normal and separable, it is Galois.

Proof: Galois Group

Claim: $[K : K^G] \leq |G|$.

It will follow that the Galois extension K/K^G is a finite extension, hence $[K : K^G] = |\text{Gal}(K/K^G)|$ by the previous proposition.

This will imply that $\text{Gal}(K/K^G) = G$ since we have $G \subseteq \text{Gal}(K/K^G)$ and

$$|G| \leq |\text{Gal}(K/K^G)| = [K : K^G] \leq |G|$$

The remainder of the proof is devoted to proving the claim.

Let $n := |G|$ and suppose for a contradiction that there are m linearly independent (over K^G) elements $x_1, \dots, x_m \in K$ with $m > n$.

Let $G = \{\sigma_1, \dots, \sigma_n\}$. Consider the matrix

$$A(\sigma_i(x_j))_{\substack{1 \leq i \leq n \\ 1 \leq j \leq m}} \in M_{n \times m}(K)$$

Consider the linear map $K^m \xrightarrow{A} K^n$. Since $m > n$, $\ker(A) \neq 0$. Let

$$\lambda = \begin{pmatrix} \lambda_1 \\ \vdots \\ \lambda_m \end{pmatrix} \in \ker(A) \subseteq K^m$$

be such that $\lambda \neq 0$ and has the fewest number of nonzero entries.

Without loss of generality, we may assume $\lambda_1 \neq 0$ (e.g. by permuting the x_j if necessary). Note that $\lambda_1^{-1}\lambda$ satisfies the properties that λ has so we may assume without loss of generality that $\lambda_1 = 1$. Now we have that $A\lambda = 0$, so for each $1 \leq i \leq n$,

$$\sum_{j=1}^m \sigma_i(x_j)\lambda_j = 0$$

We can't have $\lambda_j \in K^G$ for all j , otherwise we would have

$$0 = \sum_{j=1}^m \sigma_1(x_j)\lambda_j = \sigma_1\left(\sum_{j=1}^m x_j\lambda_j\right) \implies \sum_{j=1}^m x_j\lambda_j = 0$$

which contradicts the linear independence of the x_j 's.

Since $\lambda_1 = 1 \in K^G$, suppose without loss of generality that $\lambda_2 \in K^G$.

Hence, there is some $1 \leq k \leq n$ such that $\sigma_k(\lambda_2) \neq \lambda_2$ (i.e. there is a σ which does not fix λ_2). Consider

$$\sigma_k\lambda = \begin{pmatrix} \sigma_k(\lambda_1) \\ \vdots \\ \sigma_k(\lambda_m) \end{pmatrix}$$

Consider $A\sigma_k(\lambda)$. For each $1 \leq i \leq n$, consider $\sum_{j=1}^m \sigma_i(x_j)\sigma_k(\lambda_j)$. There exists an l such that $\sigma_i = \sigma_k \circ \sigma_l$. Then

$$\sum_{j=1}^m \sigma_i(x_j)\sigma_k(\lambda_j) = \sum_{j=1}^m \sigma_k(\sigma_l(x_j))\sigma_k(\lambda_j) = \sigma_k\left(\underbrace{\sum_{j=1}^m \sigma_l(x_j)\lambda_j}_{0 \text{ since } A\lambda=0}\right) = 0$$

Therefore $\sigma_k\lambda \in \ker(A)$. Thus $\lambda - \sigma_k(\lambda) \in \ker(A)$. Obvserve

$$\lambda - \sigma_k(\lambda) = \begin{pmatrix} 1 - 1 = 0 \\ \lambda_2 - \sigma_k(\lambda_2) \neq 0 \\ \vdots \\ \lambda_m - \sigma_k(\lambda_m) \end{pmatrix}$$

Note that if $\lambda_j = 0$, then $\lambda_j - \sigma_k(\lambda_j) = 0$. This $\lambda - \sigma_k(\lambda)$ is a nonzero element of the kernel of A which has strictly fewer nonzero entries than λ which is a contradiction.

We conclude that $[K : K^G] \leq n = |G|$.

Corollary

If K/F is a finite Galois extension, then $F = K^{\text{Gal}(K/F)}$.

Proof

Let $G := \text{Gal}(K/F)$.

For K/F a finite Galois extension, $[K:F] = |G|$.

By Artin's Theorem, K/K^G is a finite Galois extension with Galois group G . In particular, $[K:K^G] = |G|$. So

$$\underbrace{[K:K^G]}_{|G|} \underbrace{[K^G:F]}_{|G|} \implies [K:F] = |G|^2 \implies K^G = F$$

Reminder

For $K/E/F$ algebraic extensions.

K/E separable and E/F separable implies that K/F is separable.

K/F separable implies that K/E and E/F are separable.

K/E normal and E/F normal does not imply that K/F is normal.

But K/F normal does imply that K/E is normal but not necessarily that E/F is normal.

We conclude that K/E Galois and E/F Galois does not imply K/F Galois.

Likewise, K/F Galois ensures K/E Galois but not necessarily E/F .

Theorem: Fundamental Theorem of Galois Theory

Let K/F be a finite Galois extension.

Then there are inclusion-reversing bijections of sets

$$\{\text{intermediate fields of } K/F\} \xrightarrow{\sim} \{\text{subgroups of } \text{Gal}(K/F)\}$$

$$E \longmapsto \text{Gal}(K/E)$$

$$K^H \longleftarrow H$$

Moreover, E/F is Galois if and only if E/F is normal if and only if $\text{Gal}(K/E) \trianglelefteq \text{Gal}(K/F)$.

In this case, restriction induces an isomorphism

$$\text{Gal}(K/F) / \text{Gal}(K/E) \simeq \text{Gal}(E/F)$$

Proof: Bijection

$G := \text{Gal}(K/F)$. Let $F \subseteq E \subseteq K$.

K/F Galois implies K/E Galois.

By the corollary of Artin's Theorem, this implies that $E = K^{\text{Gal}(K/E)}$.

On the other hand, let $H \leq G$.

Then Artin's theorem applied to K and H implies that K/K^H is Galois with Galois group H .

That is $\text{Gal}(K/K^H) = H$. So we have an inverse bijection.

Proof: Normality

Note that K/F separable implies that E/F is separable.

So E/F is Galois if and only if E/F is normal.

Since K/F is normal, $\text{Gal}(K/F) \simeq \text{Hom}_F(K, \bar{F})$. Observe that

$$\begin{array}{ccc} K & & \\ | & \searrow \exists & \\ E & \xrightarrow{\quad} & \bar{F} \\ | & \nearrow & \\ F & & \end{array}$$

So every F -homomorphism $E \rightarrow \bar{F}$ is the restriction of an F -homomorphism $K \rightarrow \bar{F}$ and hence is the restriction of some $\sigma \in \text{Gal}(K/F)$.

Consider $\sigma(E) \subseteq K$. This corresponds to some subgroup of $\text{Gal}(K/F)$ by the correspondence theorem.

Let $G := \text{Gal}(K/F)$ and $H := \text{Gal}(K/E)$.

Claim: $\sigma(E)$ corresponds to the subgroup $\sigma H \sigma^{-1}$. That is, $\sigma(E) = K^{\sigma H \sigma^{-1}}$. Well

$$\begin{aligned} K^{\sigma H \sigma^{-1}} &= \{x \in K : \sigma(\tau(\sigma^{-1}(x))) = x, \forall \tau \in H\} \\ &= \{x \in K : \tau(\sigma^{-1}(x)) = \sigma^{-1}(x), \forall \tau \in H\} \\ &= \{x \in K : \sigma^{-1}(x) \in K^H = E\} = \sigma(E) \end{aligned}$$

Hence, E/F is normal if and only if $\sigma(E) \leq E$, $\forall \sigma \in G$; if and only if $\sigma(E) = E$, $\forall \sigma \in G$; if and only if $\sigma H \sigma^{-1} = H$, $\forall \sigma \in G$; if and only if $H \triangleleft G$.

Restricting from K to E gives a surjective map $\text{Gal}(K/F) \twoheadrightarrow \text{Gal}(E/F)$ by the discussion above whose kernel is $\text{Gal}(K/E)$. Hence

$$\text{Gal}(K/F) / \text{Gal}(K/E) \simeq \text{Gal}(E/F)$$

Remark

The bijection is called the Galois correspondence.

Remark

If $F \subseteq E \subseteq K$, then K/E is Galois and $[K : E] = |\text{Gal}(K/E)|$.

$$\{\text{intermediate fields of degree } d \mid [E : F] = d\} \xleftrightarrow{\sim} \{\text{subgroups of index } d\}$$

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Example

The splitting field of $X^3 - 2 \in \mathbb{Q}[X]$ is $K = \mathbb{Q}(\sqrt[3]{2}, \omega) = \mathbb{Q}(\sqrt[3]{2}, \sqrt[3]{2}\omega, \sqrt[3]{2}\omega^2)$ where $\omega = e^{2\pi i/3}$.

Since $[K : \mathbb{Q}] = 6$, $|\text{Gal}(K/\mathbb{Q})| = 6$.

Any $\sigma \in \text{Gal}(K/\mathbb{Q})$ must send each root of $X^3 - 2$ to another root. That is, each $\sigma \in \text{Gal}(K/\mathbb{Q})$ permutes the roots.

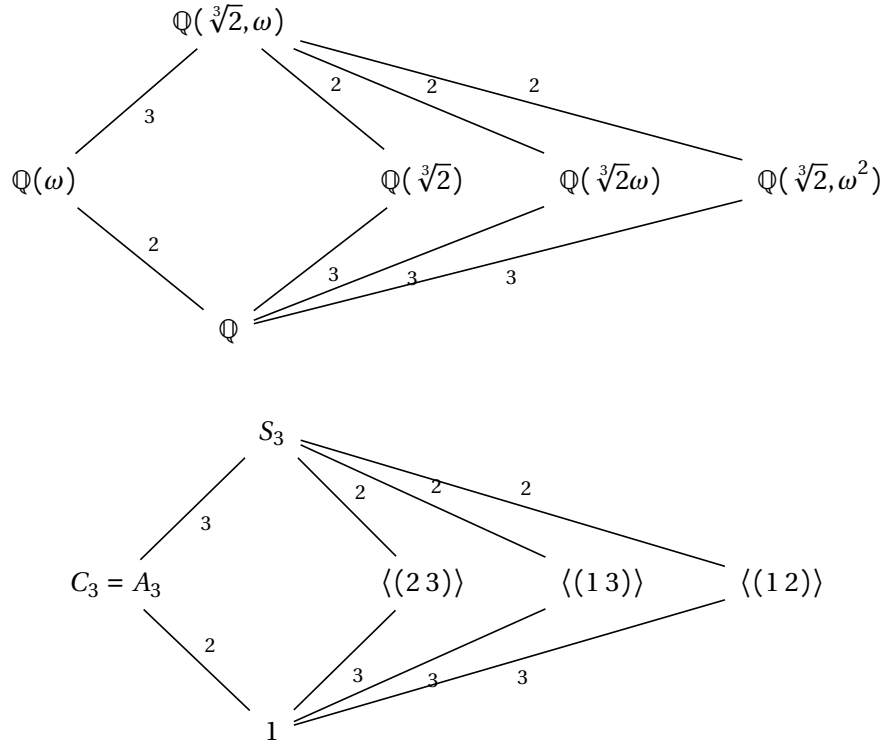
$$\text{Gal}(K/\mathbb{Q}) \hookrightarrow S_3$$

Since $|\text{Gal}(K/\mathbb{Q})| = |S_3| = 6$, $\text{Gal}(K/\mathbb{Q}) \xrightarrow{\sim} S_3$.

Alternatively, any $\sigma \in \text{Gal}(K/\mathbb{Q})$ is completely determined by $\sigma(\sqrt[3]{2})$ and $\sigma(\omega)$.

There are at most three possibilities for $\sigma(\sqrt[3]{2})$, namely the three roots of its minimal polynomial $\{\sqrt[3]{2}, \sqrt[3]{2}\omega, \sqrt[3]{2}\omega^2\}$. On the other hand, there are at most two possibilities for $\sigma(\omega)$, namely the two roots of its minimal polynomial $\{\omega, \omega^2\}$. So there are at most six possibilities, all of which are actually realized.

If we set ρ to send $\sqrt[3]{2} \mapsto \sqrt[3]{2}\omega$ and fix $\omega \mapsto \omega$, then $\sqrt[3]{2}\omega \mapsto \sqrt[3]{2}\omega^2$ and $\sqrt[3]{2}\omega^2 \mapsto \sqrt[3]{2}$. So ρ is an element of order three. Letting τ be the guy $\omega \mapsto \omega^2$ and $\sqrt[3]{2} \mapsto \sqrt[3]{2}$, an element of order two, we get that $\text{Gal}(K/\mathbb{Q}) \xrightarrow{\sim} D_6 \simeq S_3$.



So $\text{Gal}(K/\mathbb{Q}(\sqrt[3]{2}))$ is a subgroup of S_3 of $[K : \mathbb{Q}(\sqrt[3]{2})] = 2$ which fixes 1. That is, $\text{Gal}(K/\mathbb{Q}(\sqrt[3]{2})) = \langle (2\ 3) \rangle$. The only normal subgroups of S_3 are 1, A_3 and S_3 .

Definition: Galois Group of a Separable Polynomial

The Galois group of a separable polynomial $f \in \mathbb{F}[t]$ is defined to be the Galois group of its splitting field:

$$\text{Gal}(f) := \text{Gal}(K/\mathbb{F})$$

where K is the splitting field of f over \mathbb{F} .

Remark

Any $\sigma \in \text{Gal}(K/\mathbb{F})$ must send each root of f to another root of f .

That is, the Galois group permutes the roots of f . Said another way, the Galois group acts on the set of roots.

Remark

If f is irreducible, then it has $d := \deg(f)$ distinct roots and so we get a map

$$\text{Gal}(K/\mathbb{F}) \hookrightarrow S_d$$

which is injective since K is generated over \mathbb{F} by the roots.

On the other hand, if f is not irreducible then it might have fewer than d distinct roots.

Exercise:

The following are equivalent for a separable polynomial $f \in \mathbb{F}[t]$:

1. f has $\deg(f)$ distinct roots in $\bar{\mathbb{F}}$.
2. $f = f_1 f_2 \cdots f_r$ with f_i irreducible and $f_i \neq f_j$ for $i \neq j$.

In this case, then certainly we have an embedding

$$\text{Gal}(K/\mathbb{F}) \hookrightarrow S_d$$

where $d = \deg(f)$, but much more can be said. If a is a root of f_1 , then $\forall \sigma \in \text{Gal}(K/\mathbb{F})$ we have that $\sigma(a)$ is also a root of f_1 .

So really $\text{Gal}(K/\mathbb{F})$ is permuting the roots of the irreducible factors of f . We get an embedding

$$\text{Gal}(K/\mathbb{F}) \hookrightarrow S_{d_1} \times S_{d_2} \times \cdots \times S_{d_r}$$

where $d_i = \deg(f_i)$. For $d = \sum d_i$, we have that

$$S_{d_1} \times S_{d_2} \times \cdots \times S_{d_r} \subseteq S_d$$

Remark

If $f = f_1^{m_1} f_2^{m_2} \cdots f_r^{m_r}$ with f_i irreducible, and $f_i \neq f_j$, $\forall i \neq j$, then the splitting field for f coincides with the splitting field for

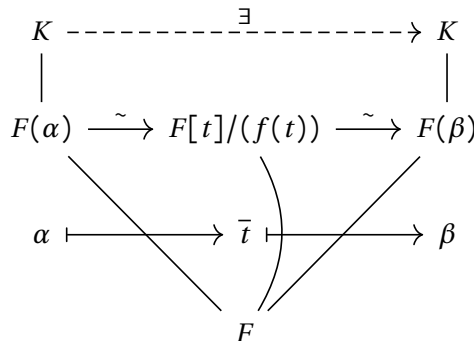
$$g := f_1 f_2 \cdots f_r$$

and note that g is also separable.

By replacing f with g we can, without loss of generality, assume our separable polynomial f has $\deg(f)$ distinct roots in $\bar{\mathbb{F}}$.

Remark

If f is irreducible, then the action of $\text{Gal}(K/\mathbb{F})$ on the set of roots is transitive: for all roots $\alpha, \beta \in K$ of f , $\exists \sigma \in \text{Gal}(K/\mathbb{F})$ such that $\sigma(\alpha) = \beta$.



Thus $\text{Gal}(K/\mathbb{F}) \hookrightarrow S_d$ identifies $\text{Gal}(K/\mathbb{F})$ with a transitive subgroup of S_d .

Definition:

A subgroup $H \subseteq S_n$ is a transitive subgroup if the induced action of $\text{Hom}\{1, \dots, n\}$ is transitive.

Example

The splitting field of $X^4 - 2 \in \mathbb{Q}[X]$ is $K := \mathbb{Q}(\sqrt[4]{2}, i)$. The roots are

$$\begin{aligned} a_1 &= \sqrt[4]{2} \\ a_2 &= -\sqrt[4]{2} = -\alpha_1 \\ a_3 &= i\alpha_1 \\ a_4 &= -i\alpha_1 \end{aligned}$$

Now $[K : \mathbb{Q}] = 8$. Hence $|\text{Gal}(K/\mathbb{Q})| = 8$. Let $G = \text{Gal}(K/\mathbb{Q})$. $G \hookrightarrow S_4$ by permuting the roots.
 $|S_4| = 4 \cdot 3 \cdot 2 = 24 = 8 \cdot 3$. Therefore, G is isomorphic to a 2-Sylow subgroup of S_4 .

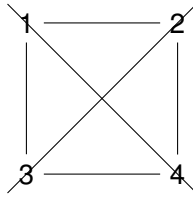
What are the 2-Sylow subgroups of S_4 ?

Observe that D_8 acts faithfully on the vertices of \square . Therefore $D_8 \hookrightarrow S_4$.

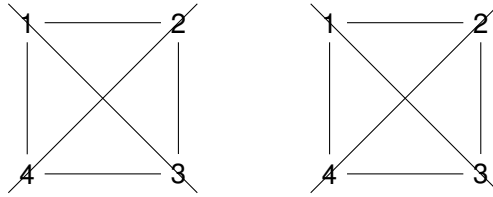
It follows that $G \simeq D_8$, the dihedral group of order 8.

We have that $n_2 | 3$ and $n_2 \equiv 1 \pmod{2}$, but $D_8 \subseteq S_4$ is not normal.

Therefore S_4 has 3 2-Sylow subgroups, each containing a pair of disjoint transpositions.



This copy of D_8 sitting inside S_4 contains $(1\ 3)$ and $(2\ 4)$ but no other transpositions. The other copies are given by



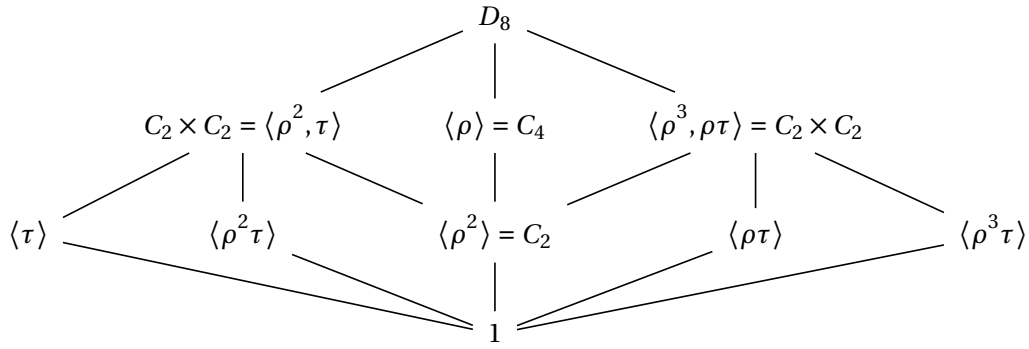
Back to the Galois group, $G \hookrightarrow S_4$. The complex conjugation gives $\sigma \in G$

$$\begin{aligned} \alpha_1 &\mapsto \alpha_1 \\ \alpha_2 &\mapsto \alpha_2 \\ \alpha_3 &\mapsto \alpha_4 \\ \alpha_4 &\mapsto \alpha_3 \end{aligned}$$

That is, the transposition $(3\ 4)$.

We conclude that $G \hookrightarrow S_4$ identifies G with the 2-Sylow D_8 in S_4 which contains $(3\ 4)$.

Subgroups of $G \simeq D_8$.



Then $H \mapsto K^H$ should give (exercise) a picture like $\mathbb{Q}(\sqrt[4]{2}, i)$.

Example

$\mathbb{Q}(\sqrt{2}, \sqrt{3})$ is the splitting field of $(X^2 - 2)(X^2 - 3) \in \mathbb{Q}[X]$.

Let us write the roots as

$$\begin{aligned}\alpha_1 &= \sqrt{2} \\ \alpha_2 &= -\sqrt{2} \\ \alpha_3 &= \sqrt{3} \\ \alpha_4 &= -\sqrt{3}\end{aligned}$$

$G := \text{Gal}(\sqrt{2}, \sqrt{3}/\mathbb{Q})$, $|G| = 4$, $G \hookrightarrow S_4$. Let

$$\sigma : \begin{cases} \sqrt{2} \mapsto -\sqrt{2} \\ \sqrt{3} \mapsto \sqrt{3} \end{cases} \quad \text{and} \quad \tau : \begin{cases} \sqrt{3} \mapsto -\sqrt{3} \\ \sqrt{2} \mapsto \sqrt{2} \end{cases}$$

Then $G = \{1, \sigma, \tau, \sigma\tau\} = C_2 \times C_2 \simeq \langle (1\ 2), (3\ 4) \rangle \subseteq S_4$.

Alternatively, $G \hookrightarrow C_2 \times C_2$ isomorphically by direct means.

Example

Let \mathbb{F} be any field and consider $\mathbb{F}[X_1, \dots, X_n] \subseteq \mathbb{F}(X_1, \dots, X_n)$.

We say that a rational function $f \in \mathbb{F}(X_1, \dots, X_n)$ if $f(X_{\sigma(1)}, X_{\sigma(2)}, \dots, X_{\sigma(n)}) = f(X_1, X_2, \dots, X_n)$ for all $\sigma \in S_n$.

Recall that S_n acts on $\mathbb{F}[X_1, X_2, \dots, X_n]$ by \mathbb{F} -algebra homomorphisms

$$\begin{array}{ccc} \mathbb{F}[X_1, \dots, X_n] & \xrightarrow{\sigma} & \mathbb{F}[X_1, \dots, X_n] \\ \downarrow & & \downarrow \\ \mathbb{F}(X_1, \dots, X_n) & \xrightarrow{\exists \sigma} & \mathbb{F}(X_1, \dots, X_n) \end{array}$$

This action extends to an action of S_n on $\mathbb{F}(X_1, \dots, X_n)$ by \mathbb{F} -algebra homomorphisms.

$$S_n \rightarrow \text{Aut}_{\mathbb{F}\text{-alg}}(\mathbb{F}(X_1, \dots, X_n)) = \text{Aut}_{\mathbb{F}}(\mathbb{F}(X_1, \dots, X_n)) = \text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F})$$

Explicitly,

$$\frac{f(X_1, \dots, X_n)}{g(X_1, \dots, X_n)} \mapsto \frac{f(X_{\sigma(1)}, \dots, X_{\sigma(n)})}{g(X_{\sigma(1)}, \dots, X_{\sigma(n)})}$$

Therefore the collection $\mathbb{F}(X_1, \dots, X_n)^{S_n}$ of symmetric rational functions is a subfield of $\mathbb{F}(X_1, \dots, X_n)$.
Artin's Theorem implies that $\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(X_1, \dots, X_n)^{S_n}$ is a finite Galois extension with Galois group S_n .

Corollary

Let G be a finite group.

Then G is the Galois group of some finite Galois extension.

Proof

Caley's Theorem implies $G \hookrightarrow S_n$.

Let $K := \mathbb{F}(X_1, \dots, X_n)^{S_n}$.

$$\begin{array}{c} \mathbb{F}(X_1, \dots, X_n) \\ | \\ K \end{array}$$

is a finite Galois extension with Galois group S_n . So $\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(X_1, \dots, X_n)^G$ is a finite Galois extension with Galois group

$$\text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(X_1, \dots, X_n)^G) \simeq G$$

by the Fundamental Theorem of Galois Theory.

Remark

In algebraic number theory, one is primarily interested in “number fields” (i.e. finite extensions of \mathbb{Q}).

Inverse Galois Problem (Major Open Problem)

Does every finite group arise as the Galois group of some finite extension of \mathbb{Q} ?

Proposition

Let \mathbb{F} be a field and let $s_1, \dots, s_n \in \mathbb{F}[X_1, \dots, X_n]$ be the n elementary symmetric polynomials. Then

$$\mathbb{F}(X_1, \dots, X_n)^{S_n} = \mathbb{F}(s_1, \dots, s_n)$$

Proof

$$\begin{array}{c} \mathbb{F}(X_1, \dots, X_n) \\ | \\ \mathbb{F}(X_1, \dots, X_n)^{S_n} \\ | \\ \mathbb{F}(s_1, \dots, s_n) \end{array}$$

Recall that

$$(t - X_1)(t - X_2) \cdots (t - X_n) = t^n - s_1 t^{n-1} + \cdots + (-1)^n s_n \in \mathbb{F}(s_1, \dots, s_n)[t]$$

Thus $\mathbb{F}(X_1, \dots, X_n)$ is the splitting field of this polynomial over $\mathbb{F}(s_1, \dots, s_n)$. Moreover, note that the polynomial is separable (since the X_i are distinct). Therefore

$$\text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(s_1, \dots, s_n)) \hookrightarrow S_n$$

On the other hand, $S_n = \text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(X_1, \dots, X_n)^{S_n}) \hookrightarrow \text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(s_1, \dots, s_n))$. Therefore

$$\text{Gal}(\mathbb{F}(X_1, \dots, X_n)/\mathbb{F}(s_1, \dots, s_n)) = S_n$$

and $\mathbb{F}(s_1, \dots, s_n) = \mathbb{F}(X_1, \dots, X_n)^{S_n}$ by the Fundamental Theorem of Galois Theory.

May 15, 2024

Theorem: Fundamental Theorem of Algebra

Every nonconstant polynomial $f \in \mathbb{C}[t]$ has a root in \mathbb{C} .

Proof

First, observe that the Intermediate Value Theorem implies that any real polynomial of odd degree greater than one has a real root.

Thus there are no irreducible polynomials $f \in \mathbb{R}[t]$ of odd degree greater than one.

Then \mathbb{R} does not admit any (finite) extension of odd degree greater than one. Why?

Suppose that E/\mathbb{R} is some finite (separable) extension. By the Primitive Element Theorem, $E = \mathbb{R}[\alpha]$ for some α .

So $[E : \mathbb{R}]$ is equal to the degree of the minimal polynomial of α over \mathbb{R} which cannot have odd degree greater than one.

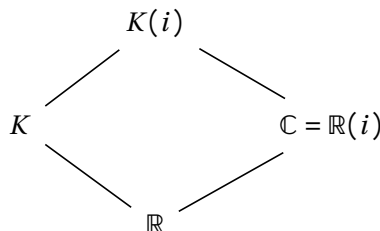
Second, observe that every quadratic polynomial $f \in \mathbb{C}[t]$ has a root by the quadratic formula.

This implies that \mathbb{C} does not admit any extension of degree two by a similar argument from the Primitive Element Theorem.

Third, if $f \in \mathbb{C}[t]$ then $f(t)\overline{f(t)} \in \mathbb{R}[t]$. Moreover, if f has not roots in \mathbb{C} then $f(t)\overline{f(t)}$ has no roots in \mathbb{C} .

Therefore we may assume without loss of generality that $f(t) \in \mathbb{R}[t]$.

Let K be the splitting field of f over \mathbb{R} and consider $K(i)$.



Claim/Exercise: $K(i)$ is the splitting field of $f(t)(t^2 + 1)$.

Hence, $K(i)/\mathbb{R}$ is a finite Galois extension. Write

$$[K(i) : \mathbb{R}] = [K(i) : \mathbb{C}] \underbrace{[\mathbb{C} : \mathbb{R}]}_2$$

So $2 \mid [K(i) : \mathbb{R}]$ and $2 \mid |G|$ where $G := \text{Gal}(K(i)/\mathbb{R})$.

Let $H \subseteq G$ be a 2-Sylow subgroup of G , then $[G : H]$ is odd (since $|G| = 2^m n$ and $2 \nmid n$).

This subgroup corresponds to an intermediate field $K(i)/E/\mathbb{R}$ with $[E : \mathbb{R}] = [G : H]$ odd.

From above, this implies that $[G : H] = 1$, $E = \mathbb{R}$ and hence that $H = G$.

We have therefore established that $G = \text{Gal}(K(i)/\mathbb{R})$ is a 2-group.

Now $G' := \text{Gal}(K(i)/\mathbb{C}) \subseteq G$. So G' is also a 2-group, and $|G'| = 2^k$ for some $k \geq 0$.

If $k \geq 0$, then G' has a subgroup of index 2 which would correspond to an extension of \mathbb{C} of degree 2, which is not possible.

Therefore, $k = 0$. That is, $G' = 1 \subseteq G$. So $\mathbb{C} = K(i)$ and f splits completely in \mathbb{C} .

Proposition

Let K/F be an extension of finite fields.

Then K/F is a finite Galois extension. Moreover $\text{Gal}(K/F)$ is cyclic.

More precisely, if $|K| = p^n$ and $|F| = p^m$, then $\text{Gal}(K/F)$ is generated by the automorphism $x \mapsto x^{p^m}$.

Proof

We know that K is the splitting field over \mathbb{F}^p of the separable polynomial $X^{p^m} - X$.

Hence K/\mathbb{F}_p (and hence K/F) is finite Galois.

The Frobenius map $\sigma : x \mapsto x^p$ is an injective field homomorphism and hence is an automorphism $\sigma : K \rightarrow K$ since K has only finitely many elements. That is $\sigma \in \text{Aut}(K)$.

Consider $\sigma^m \in \text{Aut}(K)$. Recall that if $x \in F$, then $x^{p^m} = x$ (since F^\times is cyclic of order $p^m - 1$ by Kronecker's). That is, $\sigma^m(x) = x$.

Therefore $\sigma^m \in \text{Gal}(K/F)$. Consider the cyclic subgroup it generates

$$\langle \sigma^m \rangle \subseteq \text{Gal}(K/F)$$

We have $K^{\langle \sigma^m \rangle} \supseteq F$. On the other hand, if $x \in K^{\langle \sigma^m \rangle}$, then $\sigma^m(x) = x$.

That is, $x^{p^m} = x$, x is a root of $X^{p^m} - X$, and there are at most p^m such roots. Therefore

$$|K^{\langle \sigma^m \rangle}| \leq p^m = |F|$$

Then $K^{\langle \sigma^m \rangle} = F$ and, by the Fundamental Theorem of Galois Theory, $\langle \sigma^m \rangle = \text{Gal}(K/F)$.

Example

If \mathbb{F}_q is a finite field ($q = p^n$) then $\mathbb{F}_q/\mathbb{F}_p$ is a finite Galois extension and $\text{Gal}(\mathbb{F}_q/\mathbb{F}_p)$ is cyclic of order n , generated by the Frobenius automorphism σ .

For each $d \mid n$, \mathbb{F}_q contains a unique subfield of order p^d . Namely

$$E = \mathbb{F}_q^{\langle \sigma^d \rangle} = \left\{ x \in \mathbb{F}_q : x^{p^d} = x \right\}$$

If $G = \langle \sigma \rangle$ then $\langle \sigma^d \rangle$ is the unique subgroup of order n/d of index d .

Bottom Line

The finite fields of characteristic p contain each other in the same way that the finite cyclic groups contain each other.

Proposition

Let $n \geq 1$ and $\xi_n := e^{2\pi i/n} \in \mathbb{C}$ (or any primitive n th root of unity).

Then the so-called cyclotomic extension $\mathbb{Q}(\xi_n)/\mathbb{Q}$ is a finite Galois extension of degree $\phi(n)$.

Moreover, we have an isomorphism

$$\text{Gal}(\mathbb{Q}(\xi_n)/\mathbb{Q}) \xrightarrow{\sim} (\mathbb{Z}/n\mathbb{Z})^\times$$

Proof

Φ_n is irreducible. Therefore, Φ_n is the minimal polynomial of ξ_n over \mathbb{Q} .

Therefore $[\mathbb{Q}(\xi_n) : \mathbb{Q}] = \deg(\Phi_n) = \phi(n)$.

Since $\mathbb{Q}(\xi_n)$ contains ξ_n^j for all j , we see that $\mathbb{Q}(\xi_n)$ is the splitting field of Φ_n (and, in fact, also the splitting field of $X^n - 1$).

Hence $\mathbb{Q}(\xi_n)/\mathbb{Q}$ is a finite Galois extension.

For any element $\sigma \in \text{Gal}(\mathbb{Q}(\xi_n)/\mathbb{Q})$, $\sigma(\xi_n)$ must be another root of Φ_n . That is, $\sigma(\xi_n)$ is another primitive n th root of unity.

Hence $\sigma(\xi_n) = \xi_n^j$ for some $j \in \mathbb{Z}/n$ such that $\gcd(j, n) = 1$.

In this way, we get a map

$$\begin{aligned} \text{Gal}(\mathbb{Q}(\xi_n)/\mathbb{Q}) &\rightarrow (\mathbb{Z}/n\mathbb{Z})^\times \\ \sigma &\mapsto j : \sigma(\xi_n) = \xi_n^j \end{aligned}$$

which is injective since σ is completely determined by $\sigma(\xi_n)$.

One can readily check that this map is a group homomorphism (exercise).

So we have a monomorphism

$$\text{Gal}(\mathbb{Q}(\xi_n)/\mathbb{Q}) \hookrightarrow (\mathbb{Z}/n\mathbb{Z})^\times$$

but both are finite sets of the same cardinality $\phi(n)$ so it is an isomorphism.

Remark

More generally, if F is a field with $\text{char}(F) \nmid n$ and $\xi_n \in \overline{F}$ is a primitive n th root of unity, then $F(\xi_n)/F$ is a finite Galois extension and we have a monomorphism

$$\begin{aligned} \text{Gal}(F(\xi_n)/F) &\hookrightarrow (\mathbb{Z}/n\mathbb{Z})^\times \\ \sigma &\mapsto j : \sigma(\xi_n) = \xi_n^j \end{aligned}$$

This need to be surjective – it depends on the field F .

Example

Take $F = \mathbb{R}$.

For any $n \geq 3$, $\mathbb{R}(\xi_n)/\mathbb{R}$ is just \mathbb{C}/\mathbb{R} . The nontrivial automorphism of \mathbb{C}/\mathbb{R} is complex conjugation $z \mapsto \overline{z}$.

Note that $\overline{\xi_n} = \xi_n^{-1}$, thus

$$\begin{aligned} \text{Gal}(\mathbb{C}/\mathbb{R}) &\hookrightarrow (\mathbb{Z}/n\mathbb{Z})^\times \\ \sigma &\mapsto [-1] \end{aligned}$$

This identifies $\text{Gal}(\mathbb{C}/\mathbb{R})$ with the cyclic subgroup of $(\mathbb{Z}/n\mathbb{Z})^\times$ generated by the order 2 element $[-1]$. Usually, $(\mathbb{Z}/n\mathbb{Z})^\times$ is much larger.

Example

We proved that $\text{Gal}(F(\xi_n)/F) \hookrightarrow (\mathbb{Z}/n\mathbb{Z})^\times$ is an isomorphism when $F = \mathbb{Q}$ by using the fact that $\mathbb{Q}(\xi_n)/\mathbb{Q}$ is a degree $\phi(n)$ extension, which used that Φ_n is irreducible over \mathbb{Q} . But Φ_n need not be irreducible over \mathbb{R} . Take $n = 5$, $\phi(5) = 4$. Then

$$\begin{aligned}\Phi_5(X) &= X^4 + X^3 + X^2 + X + 1 \\ &= (X - \xi)(X - \xi^{-1})(X - \xi^2)(X - \xi^{-2}) \\ &= (X^2 - (\xi + \xi^{-1})X + 1)(X^2 - (\xi^2 + \xi^{-2})X + 1) \\ &= (X^2 - 2\Re(\xi)X + 1)(X^2 - 2\Re(\xi^2)X + 1)\end{aligned}$$

in $\mathbb{R}[x]$.

Example

Consider \mathbb{F}_p and assume that $p \nmid n$, and let $\xi_n \in \overline{\mathbb{F}_p}$ be a primitive n th root of unity. We have an embedding

$$\text{Gal}(\mathbb{F}_p(\xi_n)/\mathbb{F}_p) \hookrightarrow (\mathbb{Z}/n\mathbb{Z})^\times$$

The Galois group is cyclic and generated by the Frobenius σ

$$\begin{aligned}\sigma &\mapsto j : \sigma(\xi) = \xi^j \\ \sigma &\mapsto [p]\end{aligned}$$

That is, this identifies $\text{Gal}(\mathbb{F}_p(\xi_n)/\mathbb{F}_p)$ with the cyclic subgroup of $(\mathbb{Z}/n\mathbb{Z})^\times$ generated by p . Note that $(\mathbb{Z}/n\mathbb{Z})^\times$ is usually not cyclic.

Definition: Abelian Extension

An Abelian extension is a finite Galois extension whose Galois group is Abelian.

Example

For F a field with $\text{char}(F) \nmid n$ and $\xi_n \in \overline{F}$ a primitive n th root of unity, $F(\xi_n)/F$ is an Abelian extension. Why? Any subgroup of $(\mathbb{Z}/n\mathbb{Z})^\times$ is Abelian.

Definition: Cyclic Extension

A cyclic extension is a finite Galois extension whose Galois group is cyclic.

Example

Any extension of finite fields is a cyclic extension.

Proposition

Let F be a field with $\text{char}(F) \nmid n$. Assume that F contains all n th roots of unity (equivalently that F contains a primitive n th root of unity).

Let $F \ni a \neq 0$ and consider $t^n - a \in F[t]$.

Let K be the splitting field of $t^n - a$ and let $\alpha \in K$ be an element such that $\alpha^n = a$.

Then $K = F(\alpha)$ is a cyclic extension of F of degree $d \mid n$. Moreover, $\alpha^d \in F$.

Proof

Let $\xi \in F$ be a primitive n th root of unity.

Then the n distinct roots of $t^n - a$ in K are $\{\alpha \xi^j : 0 \leq j \leq n-1\}$. Hence $t^n - a$ is separable.

Also note that $K = F(\alpha)$. We have that $K = F(\alpha)/F$ is a finite Galois extension. Now $\sigma \in \text{Gal}(K/F)$ must send α to another root of $t^n - a$ (i.e. $\sigma(\alpha) = \alpha \xi^j$ for some $j \in \mathbb{Z}/n$). We get a map

$$\begin{aligned} \text{Gal}(K/F) &\rightarrow (\mathbb{Z}/n\mathbb{Z}, +) \\ \sigma &\mapsto j : \sigma(\alpha) = \alpha \xi^j \end{aligned}$$

which is injective, since σ is determined by $\sigma(\alpha)$. One can check that it is a group homomorphism.

Thus $\text{Gal}(K/F)$ is isomorphic to a subgroup of $(\mathbb{Z}/n\mathbb{Z}, +)$ and so is cyclic of some order $d \mid n$.

Now $\pi_{\sigma \in \text{Gal}(K/F)} \sigma(\alpha)$ is contained in $K^{\text{Gal}(K/F)} = F$.

So, since $\alpha^d \xi^i \in F$ and $\xi^i \in F$, $\alpha^d \in F$.

Proposition

The following belongs to Artin-Schreier Theory.

Let F be a field of characteristic $p > 0$.

Let $a \in F$, and consider $f(t) := t^p - t - a \in F[t]$.

Assume that $f(t)$ has no roots in F ($a \notin \{x^p - x : x \in F\}$).

Let $\alpha \in \overline{F}$ be a root of $f(t)$. Then $F(\alpha)/F$ is a cyclic extension and

$$\begin{aligned} \text{Gal}(F(\alpha)/F) &\simeq \mathbb{Z}/p\mathbb{Z} \\ \sigma: F(\alpha) &\rightarrow F(\alpha) \\ \alpha &\mapsto \alpha + i \end{aligned} \leftarrow i$$

Observe that

$$\begin{aligned} (\alpha + i)^p - (\alpha + i) - a &= \alpha^p + i^p - \alpha - i - a \\ &= i^p - i \\ &= (\underbrace{1 + 1 + \dots + 1}_i)^p - i \\ &= \underbrace{1^p + \dots + 1^p}_i - i \\ &= i - i = 0 \end{aligned}$$

June 3, 2024

Recall:

If $f \in F[t]$ is separable, the following are equivalent

1. f is solvable by radicals.
2. the Galois group of f is a solvable group.

Example

Consider $f(t) = t^5 - 8t + 2 \in \mathbb{Q}[t]$.

By Eisenstein's criteria, f is irreducible. Recall that over a characteristic zero field, f is separable. Therefore, it has five distinct roots in \mathbb{C} and, hence,

$$\text{Gal}(K/\mathbb{Q}) \hookrightarrow S_5$$

where K is the splitting field of f .

Note that if α is any root of f , then $[K : \mathbb{Q}] = [K : \mathbb{Q}(\alpha)][\mathbb{Q}(\alpha) : \mathbb{Q}]$ where $[\mathbb{Q}(\alpha) : \mathbb{Q}] = \deg(f) = 5$.

This implies that $5 \mid [K : \mathbb{Q}] = |\text{Gal}(K/\mathbb{Q})|$. By Cauchy's theorem, $\text{Gal}(K/\mathbb{Q})$ contains an element of order five.

Therefore $\text{Gal}(K/\mathbb{Q}) \hookrightarrow S_5$ is a subgroup of S_5 containing a 5-cycle.

On the other hand, calculus implies that there are exactly three real roots of f .

Note that if $\alpha \in \mathbb{C}$ is a root, then $0 = f(\alpha) = \overline{f(\alpha)} = f(\overline{\alpha})$. Thus the two non-real roots form a complex conjugate pair α and $\overline{\alpha}$.

$$\begin{array}{ccc} \mathbb{C} & \xrightarrow{z \mapsto \overline{z}} & \mathbb{C} \\ \cup & & \cup \\ K & \longrightarrow & K \in \text{Gal}(K/\mathbb{Q}) \end{array}$$

Which interchanges $\alpha \leftrightarrow \overline{\alpha}$ and fixes the three real roots.

Therefore, $\text{Gal}(K/\mathbb{Q})$ is a subgroup of S_5 which contains a transposition and a 5-cycle.

But a transposition and a 5-cycle generate S_5 , therefore $\text{Gal}(K/\mathbb{Q}) \simeq S_5$ and the polynomial $f(t)$ is not solvable by radicals (since S_5 is not a solvable group).

Remark

Some quintic polynomials are solvable by radicals (e.g. t^5 or $t^5 - t^4 - t + 1 = (t^2 + 1)(t - 1)^2(t + 1)$).

But these are a bit trivial as they are reducible. In fact, any reducible quintic polynomial is solvable by radicals.

The irreducible factors all have degree less than five, so $\text{Gal} \hookrightarrow S_{d_1} \times S_{d_2} \times \cdots \times S_{d_r}$ where r is the number of irreducible factors and $d_i < 5$.

So the Galois group is a subgroup of a product of solvable groups and hence solvable itself.

Example

Consider $t^5 - 1 = (t - 1)\Phi_5(t)$. $t^5 - 1$ is solvable by radicals.

The roots of this polynomial are $1, \omega, \omega^2, \omega^3, \omega^4$ where $\omega = e^{2\pi i/5}$. Let $\alpha \neq 1$ be one of the roots.

Then α is a root of $\Phi_5(t)$ and $\alpha^{-1} = \overline{\alpha}$. Further,

$$\begin{aligned} \alpha^4 + \alpha^3 + \alpha^2 + \alpha + 1 &= 0 \\ \alpha^2 + \alpha + 1 + \alpha^{-1} + \alpha^{-2} &= 0 \\ (\alpha + \alpha^{-1})^2 + (\alpha + \alpha^{-1}) - 1 &= 0 \\ \alpha^2 + \alpha - 1 &= 0 \quad (\dagger) \end{aligned}$$

has roots $\frac{-1 \pm \sqrt{5}}{2}$. Let $\phi = \frac{1+\sqrt{5}}{2}$ be the Golden ratio (i.e. $\lim_{n \rightarrow \infty} \frac{F_{n+1}}{F_n}$).

The roots of (\dagger) are $-\phi$ and $\phi - 1$. Therefore

$$\alpha + \alpha^{-1} = -\phi$$

$$\alpha^2 + \phi\alpha + 1 = 0$$

$$\alpha = \frac{-\phi \pm \sqrt{\phi^2 - 4}}{2}$$

$$\alpha = \frac{-\phi \pm \sqrt{\phi - 5}}{2}$$

$$\alpha + \alpha^{-1} = \phi - 1$$

$$\alpha^2 - (\phi - 1)\alpha + 1 = 0$$

$$\alpha = \frac{-(\phi - 1) \pm \sqrt{(\phi - 1)^2 - \phi}}{2}$$

$$\alpha = \frac{1 - \phi \pm \sqrt{-\phi - 2}}{2}$$

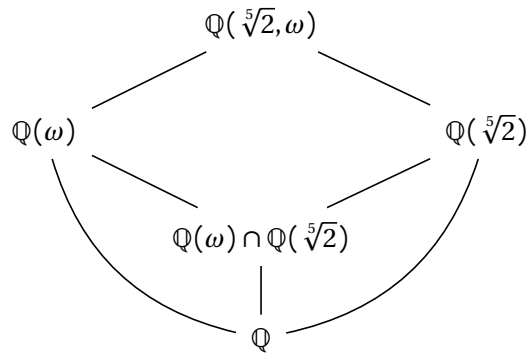
are roots of $t^5 - 1$ along with $\alpha = 1$.

Example

A less trivial example of a solvable quintic.

Consider $f(t) = t^5 - 2 \in \mathbb{Q}[t]$ which is irreducible by Eisenstein.

The splitting field is $K = \mathbb{Q}(\sqrt[5]{2}, \omega)$ where $\omega = e^{2\pi i/5}$.



Thus the Galois group is isomorphic to a transitive subgroup of S_5 of order 20.

Every group of order $20 = 4 \times 5$ is solvable.

Let P be a Sylow 5-subgroup, $n_5 \equiv 1 \pmod{5}$ and $n_5 | 4$. Therefore $n_5 = 1$ which implies $P \trianglelefteq G$ and $|G/P| = 4$. Hence G/P is abelian.

Therefore $t^5 - 2$ is solvable by radicals. The roots are $\{\sqrt[5]{2}\omega^k : 0 \leq k \leq 4\}$.

Use the previous formula for ω^k to get formulas.

Remark

It is not obvious, but $t^5 - 5t + 12 \in \mathbb{Q}[t]$ is an irreducible polynomial whose Galois group is D_{10} (the dihedral group of order 10) which is solvable ($D_{2n} = C_n \rtimes C_2$). See Solving Solvable Quintics by Dummit (Math Comp, 1991)

Remark

As we previously noted, if f is a polynomial of degree less than five the irreducible factors have degree less than five and hence the Galois group is a subgroup of $S_{d_1} \times S_{d_2} \times \cdots \times S_{d_r}$ with $d_i < 5$ for each i .

Hence the Galois group is solvable and every polynomial of degree less than five is solvable.

However, when we speak of solving a degree n polynomial we really mean finding a general formula for the roots in terms of the coefficients which works for all polynomials of degree n .

For example, the quadratic formula $f(X) = X^2 + bX + c$ gives $X = \frac{-b \pm \sqrt{b^2 - 4c}}{2}$ and we think about the coefficients b and

c as indeterminates.

The formula holds for all (monic) quadratic polynomials.

Definition: General Polynomial

Let F be a field and $n \geq 1$.

The general polynomial of degree n over F is

$$f(X) = X^n - t_1 X^{n-1} + t_2 X^{n-2} + \cdots + (-1)^n t_n \in F(t_1, \dots, t_n)[X]$$

It is a polynomial with coefficients in the function field $F(t_1, \dots, t_n)$.

Any polynomial of degree n over F can be obtained for $f(X)$ by substituting for t_1, \dots, t_n .

We say that the general equation of degree n over F is solvable by radicals if the general polynomial $f(X)$ is solvable by radicals over $F(t_1, \dots, t_n)$.

Theorem:

The Galois group of the general polynomial of degree n over F is S_n .

Proof

Let $K/F(t_1, \dots, t_n)$ be the splitting field of f over $F(t_1, \dots, t_n)$.

$$\begin{array}{ccc} K & \implies & \text{trdeg}_F(K) \\ | & & \\ F(t_1, \dots, t_n) & & = \text{trdeg}_F(F(t_1, \dots, t_n)) \\ | & & \\ F & & = n \end{array}$$

That is $\{t_1, \dots, t_n\}$ is a transcendence basis for K/F . Now let $\alpha_1, \dots, \alpha_n \in K$ be the roots of f .

Then for each $k = 1, \dots, n$, we have $t_k = S_k(\alpha_1, \dots, \alpha_n)$. Take the k th symmetric polynomial evaluated at $\alpha_1, \dots, \alpha_n$.

By definition, $K = F(t_1, \dots, t_n)(\alpha_1, \dots, \alpha_n) = F(\alpha_1, \dots, \alpha_n)$.

Recall the theorem on existence of transcendence bases:

- Every algebraically independent subset S can be extended to a transcendence basis.
- Every subset S such that $K/F(S)$ is algebraic contains a transcendence basis.

Therefore $\{\alpha_1, \dots, \alpha_n\}$ contains a transcendence basis for K/F . Since $\text{trdeg}_F(K) = n$, $\{\alpha_1, \dots, \alpha_n\}$ is a transcendence basis for K/F .

We have an isomorphism

$$K = F(\alpha_1, \dots, \alpha_n) \xrightarrow{\sim} F(X_1, \dots, X_n)$$

under which $F(t_1, \dots, t_n) \xrightarrow{\sim} F(S_1, \dots, S_n) = F(X_1, \dots, X_n)$.

Therefore $\text{Gal}(K/F) \simeq \text{Gal}(F(X_1, \dots, X_n)/F(X_1, \dots, X_n)^{S_n}) \simeq S_n$ by Artin's Theorem.

Corollary: Abel's Theorem

The general polynomial of degree n over F is solvable by radicals if and only if $n \leq 4$.

Proof

S_n is solvable if and only if $n \leq 4$.

Recall:

A Galois extension is an extension which is both normal and separable (e.g. $\overline{\mathbb{Q}}/\mathbb{Q}$).

Can we develop Galois theory to apply to infinite Galois extensions?

Yes, but we need to consider additional structure on the Galois group – namely we need to regard it as a topological group.

Definition: Topological Group

A topological group is a topological space G equipped with a group structure such that

$$\begin{array}{l} G \times G \rightarrow G \\ (g, h) \mapsto gh \end{array} \quad \text{and} \quad \begin{array}{l} G \rightarrow G \\ g \mapsto g^{-1} \end{array}$$

are continuous. We obtain a category of topological groups and continuous group homomorphisms. More info about topological groups can be found in Higgins' An Introduction to Topological Groups.

Facts

Let G be a topological group. Then

$$\begin{array}{l} G \xrightarrow{\lambda_g} G \\ x \mapsto gx \end{array}$$

is a homomorphism. So G is a homogeneous space (i.e. $\forall x, y \in G, \exists$ a homomorphism $G \xrightarrow{\sim} G$ which sends x to y). Therefore, topologically, all points look the same. We can just look at neighborhoods of the identity element.

1. Every open subgroup $H \subseteq G$ is closed.

Every left coset gH is a subset of G and consequently $G \setminus H$ is a union of (open) left cosets.

2. Every closed subgroup of finite index $H \subseteq G$ is open.

Every left coset gH is closed and finite index implies there are only finitely many so $G \setminus H$ is a finite union of (closed) left cosets.

3. $H \subseteq G$ is open if and only if $G \setminus H$ is discrete.
4. $H \subseteq G$ is closed if and only if $G \setminus H$ is Hausdorff.
5. G is Hausdorff if and only if $\{e\}$ is closed.

6. If G is connected, then G has no proper open subgroups.

Example: \mathbb{R}/\mathbb{Q} is not Hausdorff because $\mathbb{Q} \subseteq \mathbb{R}$ is not a closed subgroup.

Example: $\{0\} \subseteq \mathbb{R}$ is closed but not open.

If G is quasi-compact (meaning compact but not Hausdorff) topological group and $H \subseteq G$, then H is open if and only if H is closed of finite index.

From (3), G open implies $G \setminus H$ is discrete so (since G quasi-compactness) $G \setminus H$ is discrete and quasi-compact and therefore finite.

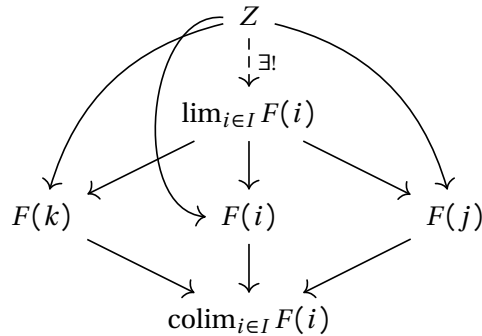
Limits (and Colimits)

$$I \xrightarrow{F} \mathbb{C}$$

$$I : \cdot \longrightarrow \cdot \quad X \xrightarrow{f} Y$$

$$I : \cdot \quad \cdot \quad X \quad Y$$

$$\begin{array}{ccc} & \cdot & Z \\ & \downarrow & \downarrow \\ \cdot & \longrightarrow & \cdot \end{array} \quad X \longrightarrow Y$$



In Set, $\lim_{i \in I} F(i) = \left\{ \prod_{i \in I} F(i) : F(f)(x_i) = x_j, \forall f : i \rightarrow j \text{ in } I \right\}$.

Remark

The forgetful functors from $\text{TopGrp} \rightarrow \text{Grp}$ and $\text{TopGrp} \rightarrow \text{Top}$ both preserve limits.

$$\lim_{i \in I} F(i) = \left\{ (x_i)_{i \in I} \in \prod_{i \in I} F(i) : F(f)(x_i) = x_j, \forall f : i \rightarrow j \text{ in } I \right\}$$

It is just the limit in the set of groups equipped with the subspace topology.

June 5, 2024

Definition: Profinite Group

A profinite group is a topological group which is a limit (in the category of topological groups) of a diagram of finite discrete groups.

Definition: Totally Disconnected Space

A topological space X is totally disconnected if the only connected subsets are the singletons $\{x\}$ for $x \in X$.

Example

Every discrete space is totally disconnected.

$\mathbb{Q} \subseteq \mathbb{R}$ is totally disconnected, but not discrete.

Proposition

For a topological group G , the following are equivalent

1. G is profinite.
2. G is Hausdorff, quasi-compact and totally disconnected.

Proof

(1) \implies (2) is point-set topology.

$G = \lim_{i \in I} G_i = \{(x_i) \in \prod G_i : \phi(x_i) = x_j, \forall i \rightarrow j\} \subseteq \prod_{i \in I} h_i$ with G_i finite discrete for all i .

(2) \implies (1) sketch.

Hausdorff, quasi-compact and totally disconnected imply (via point-set topology) that every point has a neighborhood basis consisting of clopen subsets. (difficult exercise)

This implies that the open subgroups form a neighborhood basis of $e \in G$. (less difficult exercise)

Note: that $H \subseteq G$ open implies (by quasi-compactness) that H has finite index. This implies that H has finitely many conjugates gHg^{-1} (exactly $[G : N_G(H)]$).

Therefore the normal subgroup $\bigcap_{g \in G} gHg^{-1}$ is open and the open normal subgroups form a neighborhood basis of $e \in G$.

Consider the canonical map $G \xrightarrow{\phi} \lim_U G/U$ over the normal subgroups $U \trianglelefteq G$, partially ordered by inclusion.

The kernel is $\bigcap U = \{e\}$ because G is Hausdorff and the U form a neighborhood basis.

For surjectivity, let $(x_U) \in \lim_U G/U$.

$$\begin{array}{ccc} G & \longrightarrow & G/U' \\ & \searrow & \uparrow \\ & & G/U \end{array} \quad \begin{array}{c} x_U' \\ \uparrow \\ x_U \end{array}$$

Then $\phi^{-1}(\{x_U\})$ is a nonempty closed subset of G .

Then $\phi^{-1}(\{(x_U)\}) = \bigcap_U \phi_U^{-1}(\{x_U\})$ is an intersection of nonempty closed subsets. Moreover, any finite intersection of these is nonempty.

$$\bigcap_i \phi_{u_i}^{-1}(\{x_{u_i}\}) \supseteq \phi_{U_1 \cap \dots \cap U_n}^{-1}(\{x_{U_1 \cap \dots \cap U_n}\})$$

$$\begin{array}{ccc}
 G & \longrightarrow & G/U_1 \cap \cdots \cap U_n \\
 & \searrow & \downarrow \\
 & & G/U_i
 \end{array}
 \qquad
 \begin{array}{ccc}
 x_{U_1 \cap \cdots \cap U_n}^! & & \\
 & \downarrow & \\
 & X_{U_i} &
 \end{array}$$

Therefore ϕ is a continuous bijection between quasi-compact Hausdorff spaces, hence a homeomorphism.

Examples

Every finite discrete group is profinite.

p -adic integers $\mathbb{Z}_p^\wedge = \varprojlim \mathbb{Z}/p^n = \varprojlim (\cdots \rightarrow \mathbb{Z}_{p^3} \rightarrow \mathbb{Z}_{p^2} \rightarrow \mathbb{Z}_p)$

Let G be a discrete group. Then

$$\overline{G} := \varprojlim_{\substack{H \trianglelefteq G \\ [G:H] < +\infty}} G/H$$

is the profinite completion of G . Then $\ker(G \rightarrow \hat{G})$ is the intersection of all normal subgroups of finite index which is equal to the intersection of all subgroups of finite index.

Exercise

Let K/F be a field extension. The following are equivalent

1. K/F is Galois.
2. K is the union of all its finite Galois subextensions E/F

$$K = \bigcup_{\substack{K/E/F: \\ E/F \text{ finite Galois}}} E$$

Example

Let K/F be a Galois extension. Then there is an isomorphism of groups

$$\text{Gal}(K/F) \rightarrow \varprojlim_{\substack{K/E/F \\ E/F \text{ finite Galois}}} \text{Gal}(E/F)$$

The kernel is given by

$$\bigcap_E \ker \left(\text{Gal}(K/F) \xrightarrow{\text{res}} \text{Gal}(E/F) \right) = \{ \sigma \in \text{Gal}(K/F) : \sigma|_E = \text{id}_E, \forall E/F \text{ finite Galois} \} = \{\text{id}\}$$

since $K = \bigcup E$ by the exercise.

On the other hand, given $(\sigma_E)_E \in \varprojlim \text{Gal}(E/F)$, we can define $\sigma : K \rightarrow K$ by $\sigma_E := \sigma_E$.

This is a well-defined homomorphism since if $E_1 \subseteq E_2$, then $\sigma_{E_2}|_{E_1} = \sigma_{E_1}$ and $K = \bigcup E$.

Really, any F -homomorphism $K \rightarrow K$ is an F -automorphism for K/F algebraic.

Hence $\text{Gal}(K/F)$ is a profinite group. We sometimes call the topology on $\text{Gal}(K/F)$ the Krull topology.

Example

Let K/F be a Galois extension and let $\sigma \in \text{Gal}(K/F)$.

Then for each finite Galois subextension, E/F , define $U_{\sigma,E} := \{\tau \in \text{Gal}(K/F) : \tau|_E = \sigma|_E\}$.

These subsets (as E ranges over all finite Galois extensions E/F) form a system of open neighborhoods of σ in the Krull topology.

Note that the identity e has open neighborhood basis given by $U_{e,E} = \{\tau \in \text{Gal}(K/F) : \tau_E = \text{id}_E\} = \text{Gal}(K/E)$.

Theorem: (Krull)

Let K/F be a Galois extension.

1. For any intermediate field $K/E/F$, the subgroup $\text{Gal}(K/E)$ is closed.
2. For any $H \subseteq \text{Gal}(K/F)$, we have that $\text{Gal}(K/K^H) = \overline{H}$.
3. We have an inclusion reversing bijection between the

$$\begin{array}{ccc} \left\{ \begin{array}{l} \text{intermediate} \\ \text{fields of } K/F \end{array} \right\} & \xleftrightarrow{\sim} & \left\{ \begin{array}{l} \text{closed subgroups} \\ \text{of } \text{Gal}(K/F) \end{array} \right\} \\ E \mapsto \text{Gal}(K/E) & & \\ K^H \mapsto H & & \end{array}$$

Proof of 1

We will show that $G/\text{Gal}(K/E)$ is open where $G = \text{Gal}(K/F)$.

Let $\sigma \in G/\text{Gal}(K/E)$. So $\sigma(\alpha) \neq \alpha$ for some $\alpha \in E$.

There exists a finite Galois extension E'/F in K with $\alpha \in E'$.

Claim: $U_{\sigma,E'}$ is an open neighborhood of σ which does not intersect $\text{Gal}(K/E)$.

Indeed, if $\tau \in U_{\sigma,E'}$ then $\tau|_{E'} = \sigma|_{E'}$, so $\tau(\alpha) = \sigma(\alpha) \neq \alpha$. So $\tau \notin \text{Gal}(K/E)$.

Recall

Let F be a field and \overline{F} its algebraic closure.

Its separable closure is $F^{\text{sep}} := \{a \in \overline{F} : a \text{ is separable over } F\}$.

Then F^{sep}/F is a Galois extension.

Definition: Absolute Galois Group

The absolute Galois group of a field F is defined to be $\text{Gal}(F^{\text{sep}}/F)$.

Background: Galois Descent

Let K/F be a field extension.

Given an algebraic object which is defined over F (e.g. F -vector space, or a commutative algebra over F , or an algebraic variety over F), we can extend scalars from F to K .

This is the left adjoint of the corresponding forgetful functor.

$$\begin{array}{cccc}
\text{Vect}_F & \text{CAlg}_F & \text{AlgVar}_F & \mathcal{C}(F) \\
K \otimes_F \downarrow \uparrow & K \otimes_F \downarrow \uparrow & \downarrow \uparrow & \downarrow \uparrow \\
\text{Vect}_K & \text{CAlg}_K & \text{AlgVar}_K & \mathcal{C}(K)
\end{array}$$

Example

\mathbb{C}/\mathbb{R} . For V a real vector space $\leadsto V_{\mathbb{C}} := \mathbb{C} \otimes_{\mathbb{R}} V$ a complex vector space. Observe that $V_{\mathbb{C}}$ comes equipped with a map

$$V_{\mathbb{C}} = \mathbb{C} \otimes_{\mathbb{R}} V \rightarrow \mathbb{C} \otimes_{\mathbb{R}} V = V_{\mathbb{C}}$$

which does complex conjugation on \mathbb{C} . The map

$$\begin{aligned}
\mathbb{C} \times V &\rightarrow \mathbb{C} \times V \rightarrow \mathbb{C} \otimes_{\mathbb{R}} V \\
(z, v) &\mapsto (\bar{z}, v) \mapsto \bar{z} \otimes v
\end{aligned}$$

is \mathbb{R} -bilinear because $\overline{(-)} \in \text{Gal}(\mathbb{C}/\mathbb{R})$, hence it induces an \mathbb{R} -linear map

$$\begin{aligned}
\mathbb{C} \otimes_{\mathbb{R}} V &\rightarrow \mathbb{C} \otimes_{\mathbb{R}} V \\
z \otimes v &\mapsto \bar{z} \otimes v
\end{aligned}$$

This map is not \mathbb{C} linear, rather it is antilinear $\phi(\alpha v) = \bar{\alpha} \phi(v)$ for $\alpha \in \mathbb{C}$, $v \in V$.

Therefore a complex vector space which is extended from \mathbb{R} has an antilinear involution.

More generally: for K/F a field extension, $V \in \text{Vect}_F$, $\sigma \in \text{Gal}(K/F) \leadsto F$ -linear map

$$\begin{aligned}
V_K := K \otimes_F V &\rightarrow K \otimes_F V = V_K \\
a \otimes v &\mapsto \sigma(a) \otimes v
\end{aligned}$$

Definition: Semilinear Action

Let K/F be a field extension and let $G := \text{Gal}(K/F)$.

A semilinear action of G on a K -vector space V is an F -linear action of G on V which satisfies

$$\sigma(\alpha v) = \sigma(\alpha) \sigma(v), \quad \forall \sigma \in G, \alpha \in K, v \in V$$

Example

$$V \in \text{Vect}_F \leadsto V_K = K \otimes_F V$$

is a K -vector space equipped with a semilinear action of G .

Example

\mathbb{C}/\mathbb{R} . A semilinear $\text{Gal}(\mathbb{C}/\mathbb{R})$ -action on a complex vector space is exactly the same thing as a chosen antilinear involution.

Remark

We have a category $\text{Vect}_K^{\odot G}$ of K -vector spaces equipped with a semilinear G -action.

Definition:

Let $K[G]$ denote the K -vector space with basis G .
It is an algebra over K with multiplication defined by

$$\left(\sum a_\sigma \sigma\right) \left(\sum b_\tau \tau\right) := \sum a_\sigma \sigma(b_\tau) \sigma \tau$$

Exercise

$$\text{Vect}_K^{\circlearrowleft G} \equiv K[G]\text{-Mod}.$$

Remark

$K[G]$ acts F -linearly on K by $(\sum a_\sigma \sigma) c := \sum a_\sigma \sigma(c)$.
That is, we can regard K as a $K[G]$ - F -bimodule.

$$\begin{array}{c} \text{Vect}_F \\ \downarrow \uparrow \text{Hom}_{K[G]}(K_F, -) = (-)^G \\ K[G]\text{-Mod} \equiv \text{Vect}_K^{\circlearrowleft G} \end{array}$$

Theorem

Let K/F be a finite Galois extension. The functor

$$\begin{array}{c} \text{Vect}_F \rightarrow \text{Vect}_K^{\circlearrowleft \text{Gal}(K/F)} \\ V \mapsto V_K \end{array}$$

is an equivalence of categories. The inverse is given by taking fixed points

$$\begin{array}{c} W^{\text{Gal}(K/F)} \leftrightarrow W \\ \\ \begin{array}{ccc} & GF \text{ monad} & \\ & \downarrow & \\ \text{Vect}_F & \xrightarrow{FG \text{ comonad}} & FG\text{-CoMod} \\ \updownarrow F & \updownarrow G & \nearrow \\ \text{Vect}_K & \mathcal{D} & \end{array} \end{array}$$