

1 Small prefix

Recall:

- L numberfield : $\iff L$ is a finite extension of \mathbb{Q}
In particular: L/\mathbb{Q} is separable $\Rightarrow L/\mathbb{Q}$ is primitive, i.e. $L = \mathbb{Q}(\alpha), \mathbb{Q}[X] \ni f_\alpha =$ minimal polynomial of α over \mathbb{Q} and $[L : \mathbb{Q}] = \deg(f_\alpha)$.
- $\mathcal{O} := \{\alpha \in L \mid f_\alpha \in \mathbb{Z}[X]\}$ is called *ring of integers* (generalization of $\mathbb{Z} \subseteq \mathbb{Q}$).
 \mathcal{O} is an integral domain.
- Goal: study the ring \mathcal{O}
- Questions:
 1. What is \mathcal{O}^\times ? What is its structure?
 2. What are the prime ideals of \mathcal{O} ?
 3. Do we have a unique prime factorization, i.e. is \mathcal{O} a UFD?

1.1 Motivation

Problem 1.1.1 (Fermat's conjecture, ~ 1640). Show that the equation $x^n + y^n = z^n$ has no nontrivial integer solutions, i.e. solutions (x, y, z) with $x, y, z \in \mathbb{Z} \setminus \{0\}$ for $n \geq 3$.

History:

- 1770: Euler found solution for $n = 3$
- 1825: Dirichlet and Legendre using Germain
- Kummer showed it for many primes, he showed as well that his idea doesn't work for all $n \in \mathbb{N}_{>2}$
- Conjecture was proved by Wiles in 1997

Remark 1.1.2. i) If Fermat's is true for n , then also for nk for all $k \in \mathbb{N}$.

ii) It is sufficient to prove Fermat's conjecture for $n = 4$ and all odd primes.

Proof. i) Suppose (x, y, z) is a nontrivial solution of $x^{nk} + y^{nk} = z^{nk} \Rightarrow (x^k, y^k, z^k)$ is a nontrivial solution to $x^n + y^n = z^n$.

ii) Follows from i).

□

Proposition 1.1.3 ($n = 2$). Suppose $x, y, z \in \mathbb{Z}$, $\gcd(x, y, z) = 1$

- i) x, y, z are pairwise coprime if $x^2 + y^2 = z^2$
- ii) $x^2 + y^2 = z^2 \Rightarrow$ either x or y is even
- iii) $x^2 + y^2 = z^2 \iff \exists r, s \in \mathbb{N}_0, \gcd(r, s) = 1$ s.t. $x = \pm 2rs, y = \pm(r^2 - s^2), z = \pm(r^2 + s^2)$.

Proof. i) clear \checkmark

ii) One of x, y, z has to be even, since $odd + odd \neq odd$. Suppose z is even. Then look at equation mod 4, this gives a contradiction. By i) only one of x and y is even.

iii) „ \Leftarrow “: calculation

„ \Rightarrow “: Wlog. assume $x, y, z \in \mathbb{N}_0$, x even, y, z odd:

$$\begin{aligned} \Rightarrow x = 2u, z + y = 2v, z - y = 2w, \gcd(w, v) = 1 (y, z \text{ are coprime}), x^2 + y^2 = z^2 \\ \Rightarrow 4u^2 = x^2 = z^2 - y^2 = (z - y)(z + y) = 4wv \Rightarrow u^2 = vw \\ \xRightarrow{\gcd(v, w)=1} v = r^2, w = s^2 \Rightarrow z = v + w = r^2 + s^2, y = v - w = r^2 - s^2 \\ \text{and } x = 2u = 2\sqrt{vw} = 2rs \end{aligned}$$

□

Remark. $(x, y, z) \in \mathbb{Z}^3$ with $x^2 + y^2 = z^2$ are called *pythagorean triples*.

Proposition 1.1.4 ($n = 4$). The equation $x^4 + y^4 = z^2$ (and $x^4 + y^4 = z^4$) have no nontrivial integer solutions.

Proof. Suppose $x, y, z \in \mathbb{Z}$ with $x^4 + y^4 = z^2, xyz \neq 0$. Wlog $x, y, z > 0, x, y, z$ coprime, $x = 2\tilde{x}$ for some $\tilde{x} \in \mathbb{N}$. Choose z minimal with this conditions.

$$\begin{aligned} \text{Prop. 1.2} \Rightarrow \exists r, s \in \mathbb{N} \text{ s.t. } x^2 = 2rs, y^2 = r^2 - s^2, z = r^2 + s^2 \text{ and } \gcd(r, s) = 1 \\ \Rightarrow y^2 + s^2 = r^2 \text{ with } y, s, r \text{ coprime.} \end{aligned}$$

$$\text{Prop. 1.2} \Rightarrow \exists a, b \in \mathbb{N} \text{ s.t. } s = 2ab, y = a^2 - b^2, r = a^2 + b^2 \text{ and } \gcd(a, b) = 1.$$

$$\text{plug in} \Rightarrow x^2 = 4ab(a^2 + b^2)$$

$$\Rightarrow \tilde{x}^2 = ab(a^2 + b^2) \text{ and } a, b, a^2 + b^2 \text{ pairwise coprime}$$

As in proof of Prop. 1.2 (they are coprime but a square number)

$$\begin{aligned} \Rightarrow \exists c, d, e \in \mathbb{N} \text{ s.t. } a = c^2, b = d^2, a^2 + b^2 = e^2 \\ \Rightarrow c^4 + d^4 = a^2 + b^2 = e^2 \text{ and } e \leq a^2 + b^2 = r < z \end{aligned}$$

!since z was chosen to be minimal.

□

From now on: $n = p$ odd prime.

Idea 1.1.5 (by Germain). Distinguish 2 cases in Fermat's problem:

1. „First case“: x, y, z with p does not divide xyz .
2. „Second case“: exactly one of x, y, z is divided by p .

Some approach:

- Use primitive p -th root of unity $\zeta = \zeta_p$.
- Reminder: $X^p - 1 = (X - 1)(X - \zeta) \dots (X - \zeta^{p-1})$
- Setting $\tilde{y} = -y$ we get:

$$\begin{aligned}
 x^p + y^p &= x^p - \tilde{y}^p = \tilde{y}^p \left(\left(\frac{x}{\tilde{y}} \right)^p - 1 \right) \\
 &= \tilde{y}^p \left(\frac{x}{\tilde{y}} - 1 \right) \left(\frac{x}{\tilde{y}} - \zeta \right) \dots \left(\frac{x}{\tilde{y}} - \zeta^{p-1} \right) \\
 &= (x - \tilde{y})(x - \tilde{y}\zeta) \dots (x - \tilde{y}\zeta^{p-1}) \\
 &= (x + y)(x + y\zeta) \dots (x + y\zeta^{p-1})
 \end{aligned}$$

Lemma 1.1.6. For $x, y, z \in \mathbb{Z}$ we have $x^p + y^p = z^p \iff (x+y)(x+y\zeta) \dots (x+y\zeta^{p-1}) = z^p$

Idea: Look at prime divisors in $\mathbb{Z}[\zeta]$.

Problem: Would be good to have unique prime factorization. This will not be true in general.

1.2 The ring $\mathbb{Z}[\zeta]$

Suppose ζ is a primitive n -th root of unity

Reminder 1.2.1. i) $\mathbb{Q}(\zeta)/\mathbb{Q}$ is algebraic extension of degree $[\mathbb{Q}(\zeta) : \mathbb{Q}] = \varphi(n)$

ii) $\mathbb{Q}(\zeta)/\mathbb{Q}$ is a Galois extension. In particular:

$$\text{Hom}(\mathbb{Q}(\zeta)/\mathbb{Q}) \cong \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q}) = \{\sigma_i \text{ with } \sigma_i(\zeta) = \zeta^i \mid i \in (\mathbb{Z}/n\mathbb{Z})^\times\} \cong (\mathbb{Z}/n\mathbb{Z})^\times$$

iii) Consider the norm map $\mathcal{N} : \mathbb{Q}(\zeta) \rightarrow \mathbb{Q}$, $\alpha \mapsto \det(\gamma \mapsto \alpha\gamma)$. We have for $\alpha = r(\zeta)$ ($r \in \mathbb{Q}[X]$ polynomial) with min. polynomial $f_\alpha = X^k + c_{k-1}X^{k-1} + \dots + c_0$:

- If we have $\mathbb{Q}(\alpha) = \mathbb{Q}(\zeta)$, then $\mathcal{N}(\alpha) = (-1)^{\varphi(n)} c_0$
- $\mathcal{N}(\alpha) = \prod_{\sigma \in \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q})} \sigma(\alpha) = \prod_{i \in (\mathbb{Z}/n\mathbb{Z})^\times} r(\zeta^i)$
- $\alpha \in \mathbb{Q} \Rightarrow \mathcal{N}(\alpha) = \alpha^{\varphi(n)}$

iv) $X^{n-1} + X^{n-2} + \dots + 1 = \frac{X^n - 1}{X - 1} = (X - \zeta)(X - \zeta^2) \dots (X - \zeta^{n-1})$
 $\xrightarrow{X=1} n = (1 - \zeta)(1 - \zeta^2) \dots (1 - \zeta^{n-1})$

Reminder 1.2.2 (and preview). i) $\mathcal{O} := \mathbb{Z}[\zeta] := \{r(\zeta) \mid r \in \mathbb{Z}[X]\}$

ii) $\mathbb{Z}[\zeta] = \{\alpha \in \mathbb{Q}(\zeta) \mid f_\alpha \in \mathbb{Z}[X]\}$ (proof later)

iii) $\mathbb{Z}[\zeta]$ is a free \mathbb{Z} -module with basis $\{1, \zeta, \dots, \zeta^{d-1}\}$ with $d = \varphi(n)$ (proof later)

iv) $\alpha \in \mathbb{Z}[\zeta] \Rightarrow \mathcal{N}(\alpha) \in \mathbb{Z}$ (proof later)

v) $\{\alpha \in \mathcal{O} \mid |\alpha| = 1\}$ is finite (proof later)

Reminder 1.2.3. Suppose R is an integral domain:

i) $\alpha \in R$ is *irreducible* : \iff If $\alpha = \alpha_1 \alpha_2$ with $\alpha_i \in R$, then $\alpha_1 \in R^\times$ or $\alpha_2 \in R^\times$

ii) $\alpha, \alpha' \in R$ are *associated to each other* : $\iff \exists \varepsilon \in R^\times : \alpha = \varepsilon \alpha'$

iii) R is called *factorial* : \iff each $\alpha \in R, \alpha \neq 0$ can be written in a unique way as $\alpha = \varepsilon \pi_1 \cdot \dots \cdot \pi_r$ with π_i irreducible up to multiplication with $\varepsilon \in R^\times$

iv) $\alpha_1, \alpha_2 \in R$ are called *coprime* : \iff If $\alpha' \in R$ with $\exists \beta_1, \beta_2 \in R : \alpha_1 = \alpha' \beta_1, \alpha_2 = \alpha' \beta_2$ then $\alpha' \in R^\times$.

Remark (and correction). 1. Recall: L/\mathbb{Q} field extensions:

$$\mathcal{O} := \{\alpha \in L \mid f_\alpha \in \mathbb{Z}[X]\}$$

!! Here: f_α is by definition monic, i.e. leading coefficient is 1.

Remark: $\mathcal{O} = \{\alpha \in L \mid \exists f \in \mathbb{Z}[X] \text{ with } f \text{ monic and } f(\alpha) = 0\}$

„ \subseteq “: clear

„ \supseteq “: Lemma of Gauss

2. Recall: Definition of field norm for L/K finite field extension How is norm defined?

$\mathcal{N} : L \rightarrow K$ defined as follows:

Suppose $\alpha \in L \Rightarrow \varphi_\alpha : \beta \mapsto \alpha\beta$ is linear map over K . Then:

$$\mathcal{N}_{L/K}(\alpha) := \det(\phi_\alpha)$$

Properties:

a) If $L = K(\alpha)$ and $X^n + c_{n-1}X^{n-1} + \dots + c_0$ is a minimal polynomial of α over K , then $\mathcal{N}_{L/K}(\alpha) = (-1)^n c_0$.

b) $\mathcal{N}_{L/K}(\alpha) = (\prod_{i=1}^r \sigma_i(\alpha))^q$ with $\text{Hom}_K(L, \bar{K}) = \{\sigma_1, \dots, \sigma_r\}$ and $q = \text{inseparable degree, i.e. } [L : K] = [L : K]_s \cdot q$.

c) $\alpha \in K \Rightarrow \mathcal{N}_{L/K}(\alpha) = \alpha^d$ with $d = [L : K]$ (see Bosch „Algebra“ 4.7).

General reference: NEUKIRCH

This chapter: BOREVICH + SHAFEREVICH Chapter 3.1.

Recall: Goal: prove for p prime and odd

$$x^p + y^p = z^p$$

has no non-trivial solutions. Last time:

$$x^p + y^p = z^p = (x + y)(x + y\zeta)(x + y\zeta^2) \dots (x + y\zeta^{p-1}) \in \mathbb{Z}[\zeta]$$

From now on: p odd prime, $\zeta = e^{\frac{2\pi i}{p}}$ primitive p -th root of unity $\mathcal{O} = \mathbb{Z}[\zeta]$.

Proposition 1.2.4. *For the group of units \mathcal{O}^\times of $\mathcal{O} = \mathbb{Z}[\zeta]$ we have:*

$$\mathcal{O}^\times = \{\alpha \in \mathcal{O} \mid \mathcal{N}(\alpha) = \pm 1\}$$

Notation: $\mathcal{N} = \mathcal{N}_{\mathbb{Q}(\zeta)/\mathbb{Q}}$ in this chapter.

Proof. „ \subseteq “: “ $\alpha \in \mathcal{O}^\times \Rightarrow \exists \beta \in \mathcal{O}$ with $\alpha\beta = 1 \Rightarrow 1 = N(\alpha\beta) \stackrel{!}{=} \underbrace{\mathcal{N}(\alpha)}_{\in \mathbb{Z}} \underbrace{\mathcal{N}(\beta)}_{\in \mathbb{Z} \text{ by 2.2 v)} \Rightarrow \text{claim}$

„ \supseteq “: Suppose $\alpha \in \mathcal{O}$ with $\mathcal{N}(\alpha) = \pm 1$.

$$\Rightarrow \pm 1 = \mathcal{N}(\alpha) = \prod_{\sigma \in \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q})} \sigma(\alpha)$$

Note: $\alpha = a_0 + a_1\zeta + \dots + a_{p-2}\zeta^{p-2} \in \mathbb{Z}[\zeta]$

$$\Rightarrow \sigma(\alpha) = a_0 + a_1\zeta^i + \dots + a_{p-2}\zeta^{i(p-2)} \text{ for some } i \in \{1, \dots, p-1\} \Rightarrow \sigma(\alpha) \in \mathbb{Z}[\zeta]$$

$\Rightarrow \alpha$ is a divisor of 1 in $\mathbb{Z}[\zeta] \Rightarrow \alpha \in \mathcal{O}^\times$. □

Lemma 1.2.5.

i) $\mathcal{N}(1 - \zeta^s) = p$ for $s \in \mathbb{Z}$ with $s \not\equiv 0 \pmod{p}$

ii) $1 - \zeta$ is irreducible in $\mathcal{O} = \mathbb{Z}[\zeta]$.

iii) $p = \varepsilon \cdot (1 - \zeta)^{p-1}$ with some $\varepsilon \in \mathcal{O}^\times$.

Proof. i) 2.1. iv) $\Rightarrow p = (1 - \zeta)(1 - \zeta^2) \dots (1 - \zeta^{p-1})$

$$2.1. \text{ iii) } \Rightarrow \mathcal{N}(1 - \zeta^s) = \prod_{\sigma \in \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q})} \sigma(1 - \zeta^s) = \prod_{i=1}^{p-1} (1 - \zeta^{si}) = \prod_{j=1}^{p-1} (1 - \zeta^j) = p$$

ii) We obtain from i) that $1 - \zeta \notin \mathcal{O}^\times$. Suppose $1 - \zeta = \alpha\beta$ with $\alpha, \beta \in \mathcal{O}$

$$\Rightarrow p = \mathcal{N}(1 - \zeta) = \mathcal{N}(\alpha)\mathcal{N}(\beta) \Rightarrow \mathcal{N}(\alpha) = \pm 1 \text{ or } \mathcal{N}(\beta) = \pm 1 \xrightarrow{\text{Prop 2.4}} \alpha \in \mathcal{O}^\times \text{ or } \beta \in \mathcal{O}^\times.$$

iii) Use: $1 - \zeta^s = (1 - \zeta) \underbrace{(1 + \zeta + \zeta^2 + \dots + \zeta^{s-1})}_{\varepsilon_s} = (1 - \zeta)\varepsilon_s$

$$\Rightarrow p = \mathcal{N}(1 - \zeta^s) = \underbrace{\mathcal{N}(1 - \zeta)}_{=p} \cdot \mathcal{N}(\varepsilon_s) \Rightarrow \mathcal{N}(\varepsilon_s) = 1 \Rightarrow \varepsilon_s \in \mathcal{O}^\times$$

$$\text{Hence } p = \prod_{s=1}^{p-1} (1 - \zeta^s) = \prod_{s=1}^{p-1} \underbrace{\varepsilon_s}_{\in \mathcal{O}^\times} (1 - \zeta) = (1 - \zeta)^{p-1} \underbrace{\prod_{s=1}^{p-1} \varepsilon_s}_{\in \mathcal{O}^\times}$$

□

Notation: $\varepsilon_s = 1 + \zeta + \dots + \zeta^s$.

Lemma 1.2.6.

i) $a \in \mathbb{Z}$ with $1 - \zeta$ divides a in $\mathcal{O} \Rightarrow p$ divides a .

ii) An n -th root of unity lies in $\mathbb{Q}(\zeta) \iff n$ divides $2p$.

Proof. i) $a = (1 - \zeta)\beta$ with $\beta \in \mathcal{O} \Rightarrow a^{p-1} = \mathcal{N}(a) = p\mathcal{N}(\beta) \xrightarrow{(\mathcal{N}(\beta) \in \mathbb{Z})} p$ divides a .

ii) „ \Leftarrow “: $-1 \in \mathbb{Q}(\zeta)$ and thus $e^{\frac{2\pi i}{2p}} \in \mathbb{Q}(\zeta)$

„ \Rightarrow “: Consider $H := \{\omega \in \mathbb{Q}(\zeta) \mid \omega \text{ is a root of unity}\}$

- a) $H \subseteq \mathbb{Z}[\zeta]$: Suppose $\omega \in H \Rightarrow \omega^n - 1 = 0$ for some $n \in \mathbb{N} \Rightarrow f_\omega$ is a divisor of $X^n - 1 \Rightarrow f_\omega \in \mathbb{Z}[X] \xrightarrow{2.2ii)} \omega \in \mathbb{Z}[\zeta]$.
- b) $\tilde{\omega}$ some conjugate of $\omega \Rightarrow \tilde{\omega}$ is a root of $X^n - 1 \Rightarrow |\tilde{\omega}| = 1 \xrightarrow{2.2v)} H$ is finite $\Rightarrow H$ is a cyclic subgroup of $\mathbb{Q}(\zeta)^\times$.
 Choose some generator ω_0 of H and denote $m := \text{ord}(\omega_0)$. Since $\zeta \in H$ and $\text{ord}(\zeta) = p \Rightarrow p$ divides m . Decompose $m = p^s \cdot m'$ with $s \geq 1$ and $\gcd(m', p) = 1$. Consider the field extensions chain:

$$\mathbb{Q} \subseteq \mathbb{Q}(\omega_0) \subseteq \mathbb{Q}(\zeta)$$

with degrees $[\mathbb{Q}(\zeta) : \mathbb{Q}] = p - 1 = \varphi(p)$ and $[\mathbb{Q}(\omega_0) : \mathbb{Q}] = \varphi(m) = p^{s-1}(p-1)\varphi(m') \leq p-1 \Rightarrow s = 1$ and $\varphi(m') = 1$ and thus $m' = 1, 2 \Rightarrow \text{ord}(\omega_0) \leq 2p$. □

Notation 1.2.7.

1. L/K field extension, $\alpha \in L, \bar{K}$ given algebraic closure. The elements $\sigma(\alpha)$ with $\sigma \in \text{Hom}_K(L, \bar{K})$ are called *conjugates of α* . In particular: L/K normal \Rightarrow conjugates live in L .
2. R ring, I ideal in R , $p : R \rightarrow R/I$ canonical projection. For $\alpha, \beta \in R$ we denote $\alpha \equiv \beta \pmod{I} : \iff p(\alpha) = p(\beta)$.
 If $I = \langle q \rangle$ is a principal ideal, we denote $\alpha \equiv \beta \pmod{q} : \iff \alpha \equiv \beta \pmod{\langle q \rangle}$

Example 1.2.8. Consider $\mathbb{Q}(\zeta)/\mathbb{Q}$ with $\zeta^p = 1, R = \mathcal{O} = \mathbb{Z}[\zeta], \alpha = a_0 + a_1\zeta + a_2\zeta^2 + \cdots + a_{p-2}\zeta^{p-2}$

- i) The conjugates of α are: $\alpha_h = a_0 + a_1\zeta^h + a_2\zeta^{2h} + \cdots + a_{p-2}\zeta^{h(p-2)}$ with $h \in \{1, \dots, p-1\}$.
- ii) Consider $\lambda = 1 - \zeta$ and $I = \langle \lambda \rangle$.
 $1 \equiv \zeta \pmod{\lambda}$ and $\alpha \equiv a_0 + a_1 + \cdots + a_{p-2} \pmod{\lambda} (\in \mathbb{Z})$.
- iii) $\alpha^p \equiv a_0^p + (a_1\zeta)^p + \cdots + (a_{p-2}\zeta^{p-2})^p = \underbrace{a_0^p + a_1^p + \cdots + a_{p-1}^p}_{\in \mathbb{Z}} \pmod{p}$

Theorem 1.2.9 (Kummer's Lemma). *If $\varepsilon \in \mathbb{Z}[\zeta]$ is a unit, i.e. $\varepsilon \in \mathbb{Z}[\zeta]^\times$,*

$$\frac{\varepsilon}{\bar{\varepsilon}} = \zeta^a \quad \text{for some } a \in \mathbb{Z}$$

Here $\bar{\varepsilon} = \tau(\varepsilon)$, where τ is the complex conjugation.

Recall: $\tau \in \text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q})$.

Proof. Denote $\varepsilon = a_0 + a_1\zeta + \cdots + a_{p-2}\zeta^{p-2} = r(\zeta)$ with $r(X) = \sum_{i=0}^{p-2} a_i X^i \in \mathbb{Z}[X]$.
Observe:

1. $\varepsilon \in \mathcal{O}^\times \Rightarrow \exists \varepsilon' \in \mathcal{O} \text{ s.t. } \varepsilon \varepsilon' = 1 \Rightarrow \bar{\varepsilon} \bar{\varepsilon}' = 1 \Rightarrow \bar{\varepsilon} \in \mathcal{O}^\times$
2. $\mu := \frac{\varepsilon}{\bar{\varepsilon}} = \frac{r(\zeta)}{r(\bar{\zeta})}$ and the conjugate μ_k of μ is $\frac{r(\zeta^k)}{r(\bar{\zeta}^k)} = \frac{r(\zeta^k)}{r(\zeta^k)}$. In particular $|\mu_k| = 1$.
 It follows that $\mu_k \in \{\alpha \in \mathcal{O}^\times \mid |\alpha| = 1\}$ which is by 2.2. v) a finite subgroup of $\mathbb{Q}(\zeta)^\times \Rightarrow \mu$ is a root of unity
 Lemma 2.6 $\Rightarrow \mu = \pm \zeta^a$ for some $a \in \mathbb{Z}$.
Claim: $\mu = \zeta^a$
Proof of claim: suppose $\mu = -\zeta^a$, i.e. $\varepsilon = -\bar{\varepsilon} \zeta^a$ (\star)
Idea: calculation mod $\lambda = 1 - \zeta$ $\varepsilon = a_0 + a_1 \zeta + \dots + a_{p-2} \zeta^{p-2}$
 Ex. 2.8.ii) $\Rightarrow \varepsilon \equiv \underbrace{a_0 + a_1 + \dots + a_{p-2}}_{=: M \in \mathbb{Z}} \equiv \bar{\varepsilon} \pmod{\lambda}$
 $(\star) \Rightarrow \varepsilon \equiv -\bar{\varepsilon} \pmod{\lambda} \Rightarrow M \equiv -M \pmod{\lambda} \Rightarrow 2M \equiv 0 \pmod{\lambda} \xrightarrow{\text{Lemma 2.6 i)}} p \text{ divides } 2M \text{ in } \mathbb{Z} \xrightarrow{p \text{ odd}} p \text{ divides } M$
 $\Rightarrow \lambda = 1 - \zeta \text{ divides } M \text{ in } \mathcal{O} \text{ by Lemma 2.5.}$
 $\Rightarrow \varepsilon \equiv \bar{\varepsilon} \equiv M \equiv 0 \pmod{\lambda = 1 - \zeta} \Rightarrow \text{Contradiction to } \varepsilon \text{ is unit and } 1 - \zeta \text{ is irreducible}$

□

Corollary 1.2.10. $\varepsilon \text{ unit in } \mathbb{Z}[\zeta] \Rightarrow \varepsilon = r \zeta^s \text{ with some } r \in \mathbb{R}, s \in \mathbb{Z}.$

Proof. Prop 2.9 $\Rightarrow \exists a \in \mathbb{Z}, \varepsilon = \zeta^a \cdot \bar{\varepsilon}$.

Choose $s \in \mathbb{Z}$ with $2s \equiv a \pmod{p}$

$\Rightarrow \frac{\varepsilon}{\zeta^s} = \zeta^s \cdot \bar{\varepsilon} = \frac{\bar{\varepsilon}}{\zeta^{-s}} = \frac{\bar{\varepsilon}}{\bar{\zeta}^s} = r \in \mathbb{R} \text{ and } \varepsilon = r \cdot \zeta^s.$

□

Lemma 1.2.11. Suppose $x, y, m, n \in \mathbb{Z}$ with $m \not\equiv n \pmod{p}$. $x + y \zeta^n$ and $x + y \zeta^m$ are relatively prime $\iff (x \text{ and } y \text{ are relatively prime}) \text{ and } (x + y \text{ not divisible by } p)$

Proof. „ \Rightarrow “:

- $d \mid x \text{ and } d \mid y \Rightarrow d \mid x + \zeta^n y \text{ and } d \mid x + \zeta^m y \nmid$
- „ $p \mid x + y$ “ Recall: $p = \varepsilon(1 - \zeta)^{p-1}$ with $\varepsilon \in \mathcal{O}^\times$
 $\Rightarrow x + \zeta^m y = \underbrace{x + y}_{\text{divisible by } p} + y \cdot \underbrace{(\zeta^m - 1)}_{(\zeta - 1)(1 + \zeta + \zeta^2 + \dots + \zeta^{m-1})} \equiv 0 \pmod{1 - \zeta}$
 same way $x + \zeta^n y \equiv 0 \pmod{1 - \zeta} \nmid$

„ \Leftarrow “: Idea: show: $\exists \alpha_0, \beta_0 \in \mathcal{O}$ with:

$$1 = \alpha_0(x + \zeta^m y) + \beta_0(x + \zeta^n y)$$

Consider: $A := \{\alpha(x + \zeta^m y) + \beta(x + \zeta^n y) \mid \alpha, \beta \in \mathcal{O}\}$

A is an ideal in \mathcal{O} . We have:

1. $(x + \zeta^m y) - (x + \zeta^n y) = \zeta^m(1 - \zeta^{n-m})y = \underbrace{\zeta^n \varepsilon_{n-m}}_{\in \mathcal{O}^\times} (1 - \zeta)y \Rightarrow (1 - \zeta)y \in A$

2. $\zeta^n(x + \zeta^m y) - \zeta^m(x + \zeta^n y) = (\zeta^n - \zeta^m)x = \zeta^n \cdot (1 - \zeta^{n-m})x = \underbrace{\zeta^n \varepsilon_{m-n}}_{\in \mathcal{O}^\times} \cdot (1 - \zeta)x \Rightarrow (1 - \zeta)x \in A.$
3. $\gcd(x, y) = 1 \Rightarrow \exists a, b \in \mathbb{Z} \text{ with } 1 = ax + by \Rightarrow (1 - \zeta)xa + (1 - \zeta)yb = 1 - \zeta \xrightarrow{1. \& 2.} 1 - \zeta \in A$
4. $x + y = \underbrace{x + \zeta^n y}_{\in A} + \underbrace{(1 - \zeta^n)y}_{\in A} \in A$
5. $\gcd(p, x + y) = 1 \Rightarrow \exists \bar{a}, \bar{b} \in \mathbb{Z} : 1 = \underbrace{\bar{a}p}_{\in A} + \underbrace{\bar{b}(x + y)}_{\in A} \in A.$
 \Rightarrow Hence $x + \zeta^n y$ and $x + \zeta^m y$ are coprime.

□

Remark 1.2.12. Suppose $\alpha = a_0 + a_1\zeta + \dots + a_{p-1}\zeta^{p-1} \in \mathcal{O}$ with $a_i \in \mathbb{Z}$ and at least one $a_j \neq 0$.

If $n \in \mathbb{Z}$ with n divides α in \mathcal{O} , then n divides all a_i

Proof. Recall from 2.2 (preview): $1, \zeta, \zeta^2, \dots, \zeta^{p-2}$ is a basis of \mathcal{O} .

Furthermore: $1 + \zeta + \dots + \zeta^{p-1} = 0$

$\Rightarrow \{1, \zeta, \dots, \zeta^{p-1}\} \setminus \{\zeta^j\}$ is a basis \Rightarrow claim.

□

1.3 First case of Fermat in case of $\mathbb{Z}[\zeta]$ is a UFD (unique factorization domain)

Reference: BOREVICH + SHAFEREVIC + WASHINGTON Chapter 1

As before: p odd prime, $\zeta = e^{\frac{2\pi i}{p}}$ p -th root of unity.

Theorem 1.3.1. Suppose that $\mathbb{Z}[\zeta]$ is a UFD, then $x^p + y^p = z^p$ has no non-trivial solutions (x, y, z) , such that neither x, y nor z is divisible by p .

Theorem 1.3.2 ($p = 3$). Suppose $x, y, z \in \mathbb{Z}$ with $x^3 + y^3 = z^3 \pmod{9} \Rightarrow 3$ divides x, y or z .

Proof. Recall: Little Fermat's theorem $x^p \equiv x, y^p \equiv y, z^p \equiv z \pmod{p}$.

$$\begin{aligned}
 x^3 + y^3 &= z^3 \pmod{3} \Rightarrow x + y \equiv z \pmod{3} \\
 &\Rightarrow z = x + y + 3u \text{ with } u \in \mathbb{Z} \\
 \Rightarrow \underline{x^3 + y^3} &\equiv (x + y + 3u)^3 \equiv \underline{x^3 + y^3} + 3xy^2 + 3x^2y \pmod{9} \\
 &\Rightarrow 0 \equiv xy^3 + x^2y \equiv xy(x + y) \equiv xyz \pmod{3} \\
 &\Rightarrow x, y \text{ or } z \text{ is divisible by } 3
 \end{aligned}$$

□

Lemma 1.3.3. *Let $p \geq 5$. Suppose $x, y, z \in \mathbb{Z}$ with $x^p + y^p = z^p$. If $x \equiv y \equiv -z \pmod{p}$, then $p|z$.*

Proof. $z \equiv z^p = x^p + y^p \equiv -2z^p \equiv -2z \pmod{p} \Rightarrow 3z \equiv 0 \pmod{p} \xrightarrow{p \neq 3} p|z$. \square

Remark 1.3.4. It follows from Lemma 3.2 that in the first case of Fermat we may assume for $p \geq 5$ that $x \not\equiv y \pmod{p}$ because we can replace $x^p + y^p = z^p$ by $x^p + (-z)^p = (-y)^p$ and $x \not\equiv -z \pmod{p}$.

of Thm. 1. $p = 3 \Rightarrow$ claim follows from Prop 3.1.

Now: $p \geq 5$. Suppose $x, y, z \in \mathbb{Z}$ with p divides neither x, y nor z , x, y, z are pairwise coprime and $x \not\equiv y \pmod{p}$. Suppose $z^p = x^p + y^p = (x + y)(x + \zeta y) \dots (x + \zeta^{p-1}y)$.

Apply Lemma 2.11:

- $\gcd(x, y) = 1 \checkmark$
- Little Fermat $\Rightarrow x + y \equiv x^p + y^p \equiv z^p \not\equiv 0 \pmod{p}$

$\xrightarrow{2.11} x + y, x + \zeta y, \dots, x + \zeta^{p-1}y$ are pairwise coprime.

$\xrightarrow{\mathbb{Z}[\zeta] \text{ UFD}} \text{„}x + \zeta^i y \text{ have to be } p\text{-power“}$ More precisely: $x + \zeta y = \varepsilon \alpha^p$ with $\varepsilon \in \mathcal{O}^\times, \alpha \in \mathcal{O}$, since they are coprime factors of a p -th power.

1. Cor. 2.10 $\Rightarrow \varepsilon = r\zeta^s$ with $r \in \mathbb{R}, s \in \mathbb{Z}$
2. Example 2.8. iii) $\Rightarrow \exists a \in \mathbb{Z}$ with $\alpha^p \equiv a \pmod{p}$.

$$\begin{aligned}
 x + \zeta y &= r\zeta^s \alpha^p \equiv r\zeta^s a \pmod{p} \\
 x + \zeta^{-1}y &= \overline{x + \zeta y} \equiv r\zeta^{-s} a \pmod{p} \\
 \Rightarrow \zeta^{-s}(x + \zeta y) &\equiv ra \equiv \zeta^s(x + \zeta^{-1}y) \pmod{p} \\
 \Rightarrow \underbrace{x + \zeta y - \zeta^{2s}x - \zeta^{2s-1}y}_{=x \cdot 1 + y\zeta - x\zeta^{2s} - y\zeta^{2s-1}} &\equiv 0 \pmod{p}
 \end{aligned}$$

Idea: Use Rem. 2.12

Case 1: $1, \zeta, \zeta^{2s-1}, \zeta^{2s}$ are distinct $\xrightarrow{p \geq 5, \text{ Rem } 2.12} p|x$ and $p|y$. Contradiction to first case.

\square

Recall: $L = \mathbb{Q}(\zeta)$, $\mathcal{O} = \mathbb{Z}[\zeta]$, where ζ is a p -th root of unity

Last time:

- (1) $a_1 1 + a_2 \zeta + \dots + a_p \zeta^{p-1} = \alpha$ and at least one $a_j = 0$
If α is divided by $n \in \mathbb{Z}$ then all the a_i are divided by n .
- (2) $x + y\zeta - x\zeta^{2s} - y\zeta^{2s-1} \equiv 0 \pmod{p}$

Continuation of proof of Theorem 1. “Case 2” $1, \zeta, \dots, \zeta^{2s}$ are not distinct.

Observe: $1 \neq \zeta$ and $\zeta^{2s-1} \neq \zeta^{2s}$

“Case 2A” $1 = \zeta^{2s} (\Leftrightarrow p|s)$.

(2) implies $y\zeta - y\zeta^{2s-1} \equiv 0 \pmod{p}$ such that Remark 2.12 yields the contradiction $p|y$.

“Case 2B” $1 = \zeta^{2s-1} (\Leftrightarrow \zeta = \zeta^{2s})$.

(2) implies $(x - y)1 + (y - x)\zeta \equiv 0 \pmod{p}$ such that Remark 2.12 yields $p|y - x$, which contradicts the assumption $x \not\equiv y \pmod{p}$.

“Case 2C” $\zeta = \zeta^{2s-1}$.

(2) implies $x - x\zeta^2 \equiv 0 \pmod{p}$ such that Remark 2.12 yields the contradiction $p|x$. \square

Questions:

(1) Under which assumption is \mathcal{O} a UFD?

(2) What can we do if \mathcal{O} is not a UFD?

→ Idea of Kummer: “calculate with ideals”

Prospect: Theorem (Montgomery, Uchida, 1971)

$\mathbb{Z}[\zeta]$ is a UFD if and only if $p \leq 19$, p prime.

Preview: From Kummer’s idea we obtain a better criterion for p called **regular**, which ensures that Fermat’s conjecture holds for p .

Conjecture. *There are infinitely many regular primes.*

2 Ring of integers

In this chapter, all rings are assumed to be commutative with 1.

2.1 Integral ring extensions

Definition 2.1.1 (“ganze Ringerweiterungen”). Let $A \subset B$ be a ring extension.

- (i) $b \in B$ is **integral** over A if there exists a monic polynomial $f(X) = X^n + a_{n-1}X^{n-1} + \dots + a_0 \in A[X]$ with $f(b) = 0$.
- (ii) B is **integral** over A if all $b \in B$ are integral over A .

Proposition 2.1.2. Let $A \subset B$ be a ring extension and $b_1, \dots, b_n \in B$. Then b_1, \dots, b_n are integral over A if and only if

$$A[b_1, \dots, b_n] = \{f(b_1, \dots, b_n) \mid f \in A[X_1, \dots, X_n]\}$$

is a finitely generated A -module.

Reminder 2.1.3 (“Adjunkte”). Let R be a ring and $A \in R^{n \times n}$

- (i) $A^\# = (a_{i,j}^\#)$ with $a_{i,j}^\# = (-1)^{i+j} \det(A_{j,i})$, where $A_{j,i}$ is obtained from A by deleting the j -th row and i -th column of A .
- (ii) We have $AA^\# = A^\#A = \det(A)I$. In particular, $Ax = 0$ implies $A^\#Ax = 0$ such that $\det(A)x = 0$.

Proof of Proposition 1.2. “ \Rightarrow ” If $n = 1$ and b is integral over A , then there is an $f \in A[X]$ with f monic such that $f(b) = 0$. Let $g \in A[X]$ be arbitrary. Then

$$g(X) = q(X)f(X) + r(X)$$

with $q, r \in A[X]$ and $\deg r < \deg f = d$. Hence $g(b) = r(b)$ with $\deg r < d$. Thus $\{1, b, \dots, b^{d-1}\}$ generate $A[b]$ as an A -module. The case $n \geq 2$ follows by induction.

“ \Leftarrow ” $A[b_1, \dots, b_n]$ is finitely generated as an A -module by w_1, \dots, w_r . If $b \in A[b_1, \dots, b_n]$ then

$$bw_i = \sum_{j=1}^r a_{j,i} w_j$$

such that

$$(bI - (a_{i,j}))w = 0.$$

Thus, $\det(bI - (a_{i,j}))w = 0$ and hence

$$\det(bI - (a_{i,j}))w_i = 0$$

for all $i = 1, \dots, r$. If we now use that

$$1 = c_1w_1 + \dots + c_rw_r$$

we can infer $\det(bI - (a_{i,j}))1 = 0$. Consider

$$M = bI - (a_{i,j}) = \begin{pmatrix} b - a_{1,1} & -a_{1,2} & \cdots & -a_{1,r} \\ -a_{2,1} & b - a_{2,2} & \cdots & -a_{2,r} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{r,1} & -a_{r,2} & \cdots & b - a_{r,r} \end{pmatrix}.$$

By the Leibniz formula we have

$$\det(M) = \sum_{\sigma \in S_n} \operatorname{sgn}(\sigma) \prod_{i=1}^n m_{\sigma(i),i}$$

which is a polynomial over b with leading coefficient 1. Hence b is integral over A . \square

Corollary 2.1.4 (And Definition). *(i) If $A \subset B$ is an extension of rings then*

$$\overline{A} = \{b \in B \mid b \text{ is integral over } A\}$$

*is a ring. It is called the **integral closure** of A in B . If $\overline{A} = A$ then A is called **integrally closed** in B .*

(ii) We have transitivity, that is to say, if A, B, C are rings with $A \subset B \subset C$ such that C is integral over B and B is integral over A then C is integral over A .

(iii) The integral closure of A in B is integrally closed, i.e., $\overline{\overline{A}} = \overline{A}$.

Proof. “(i)” If $b_1, b_2 \in \overline{A}$ then $A[b_1], A[b_2]$ are finitely generated A -modules. Hence $A[b_1, b_2]$ is a finitely generated A -module. Thus, by Proposition 1.3, $b_1 + b_2$ and b_1b_2 are integral, i.e., elements of \overline{A} .

“(ii)” If $c \in C$ then c is integral over B and hence there is a monic polynomial $f = X^n + b_{n-1}X^{n-1} + \dots + b_0 \in B[X]$ with $f(c) = 0$. This shows that c is integral over $R = A[b_1, \dots, b_{n-1}]$ such that Proposition 1.3 shows that $R[c]$ is a finitely generated R -module. Furthermore, b_0, \dots, b_{n-1} are integral over A such that another application of Proposition 1.3 shows that R is a finitely generated A -module. Hence, $R[c]$ is a finitely generated A module such that c is integral over A by Proposition 1.3.

“(iii)” Follows from (ii). \square

Definition 2.1.5 (“ganzer Abschluss und normaler Ring”). If A is an integral domain we call its integral closure \overline{A} in $K = \text{Quot}(A)$ the **normalization** or the **integral closure** of A . We say A is **integrally closed** if A is integrally closed in K .

Remark 2.1.6. If A is a UFD then A is integrally closed.

Proof. Suppose $b = \frac{a}{a'} \in \text{Quot}(A)$ with $\gcd(a, a') = 1$ is integral over A . Then there exist $a_0, \dots, a_{n-1} \in A$ with

$$\left(\frac{a}{a'}\right)^n + a_{n-1} \left(\frac{a}{a'}\right)^{n-1} + a_{n-2} \left(\frac{a}{a'}\right)^{n-2} + \dots + a_0 = 0$$

such that

$$a^n + a_{n-1}a'a^{n-1} + a_{n-2}a'^2a^{n-2} + \dots + a_0a'^n = 0.$$

Let $a' = \varepsilon\pi_1 \cdots \pi_r$ be the prime factorization of a' with $\varepsilon \in A^\times$ and π_1, \dots, π_r primes. Since $\pi_i | a'$ the above equation shows that actually $\pi_i | a^n$. But this implies $\pi_i | a$ which is a contradiction to $\gcd(a, a') = 1$. Hence we have $a' = \varepsilon \in A^\times$ such that $b \in A$. \square

2.2 Integral closures in field extensions

Setting:

- A is an integral domain.
- A is integrally closed.
- $K = \text{Quot}(A)$.
- L/K is a finite field extension with $\overline{A}_K = A \subset K = \text{Quot}(A) \hookrightarrow L \supset B = \overline{A}_L$.
- B is the integral closure of A in L . Observe: $B \cap K = A$

Remark 2.2.1. (i) B is integrally closed in L .

(ii) If $\beta \in L$ then there are $b \in B$ and $a \in A \setminus \{0\}$ such that $\beta = \frac{b}{a}$.

In particular, $L = \text{Quot}(B)$.

(iii) For $\beta \in L$ we have $\beta \in B$ if and only if $f_\beta \in A[X]$, where f_β is the minimal polynomial of β over K .

Proof. “(i)” Follows from the transitivity in Corollary 1.4.

“(ii)” Choose $a \in A$ with $a^n f_\beta(X) = a^n X^n + a^{n-1} c_{n-1} X^{n-1} + \dots + c_0 \in A[X]$. Then we have

$$a^n \beta^n + c_{n-1} a^{n-1} \beta^{n-1} + \dots + c_0 = 0$$

and hence

$$(a\beta)^n + c_{n-1} (a\beta)^{n-1} + \dots + c_0 = 0$$

such that $a\beta$ is integral over A . Consequently, $b = a\beta \in B$ and $\beta = \frac{b}{a}$.

“(iii)” “ \Leftarrow ” Obvious. “ \Rightarrow ” Let β be a zero of $g(X) = X^n + a_{n-1}X^{n-1} + \cdots + a_0 \in A[X]$. Then f_β divides g . If β_1, \dots, β_n are the zeros of f_β in \overline{K} then they are also zeros of g and thus integral over A . Hence the coefficients of f_β are integral over A and are elements of K such that $f_\beta \in A[X]$ as claimed. \square

Reminder 2.2.2 (Trace, Norm). Let $K \subseteq L$ be a finite field extension. For α in L consider the map $T_\alpha : \beta \mapsto \alpha\beta$. The following holds

- i) $\text{Tr}_{L/K}(\alpha) = \text{Tr}(T_\alpha)$ and $\mathcal{N}_{L/K}(\alpha) = \det(T_\alpha)$,
- ii) If $L = K(\alpha)$ and $f_\alpha(X) = X^n + \sum_{i=0}^{n-1} a_i X^i$ then

$$\text{Tr}_{L/K}(\alpha) = -a_{n-1} \text{ and } \mathcal{N}_{L/K}(\alpha) = (-1)^n \cdot a_0,$$

- iii) Since $T_{\alpha+\beta} = T_\alpha + T_\beta$ and $T_{\alpha\beta} = T_\alpha \circ T_\beta$, we conclude that

$$\text{Tr}_{L/K} : (L, +) \rightarrow (K, +) \text{ and } \mathcal{N}_{L/K} : (L^*, \cdot) \rightarrow (K^*, \cdot)$$

are group homomorphisms,

- iv) Suppose $K \subseteq L$ is a separable field extension with $L = K(\alpha)$. Further assume $\text{Hom}_K(L, \overline{K}) = \{\sigma_1, \dots, \sigma_n\}$. Then the following holds

- $f_\alpha = \prod_{i=1}^n (X - \sigma_i(\alpha))$,
- $\text{Tr}_{L/K}(\alpha) = \sum_{i=1}^n \sigma_i(\alpha)$,
- $\mathcal{N}_{L/K}(\alpha) = \prod_{i=1}^n \sigma_i(\alpha)$,

- v) Trace and norm are transitive, i.e., for field extensions $K \subseteq L \subseteq M$ it holds

- $\mathcal{N}_{L/K} \circ \mathcal{N}_{M/L} = \mathcal{N}_{M/K}$,
- $\text{Tr}_{L/K} \circ \text{Tr}_{M/L} = \text{Tr}_{M/K}$.

Definition 2.2.3 (Discriminant). Let $K \subseteq L$ be a separable field extension and let $\alpha_1, \dots, \alpha_n$ be a K -basis of L . Further let $\text{Hom}_K(L, \overline{K}) = \{\sigma_1, \dots, \sigma_n\}$. Consider the matrix

$$A := \begin{pmatrix} \sigma_1(\alpha_1) & \sigma_1(\alpha_2) & \cdots & \sigma_1(\alpha_n) \\ \sigma_2(\alpha_1) & \sigma_2(\alpha_2) & \cdots & \sigma_2(\alpha_n) \\ \vdots & \vdots & \cdots & \vdots \\ \sigma_n(\alpha_1) & \sigma_n(\alpha_2) & \cdots & \sigma_n(\alpha_n) \end{pmatrix} = (\sigma_i(\alpha_j))_{i,j} \in L^{n \times n}.$$

We call $d(\alpha_1, \dots, \alpha_n) := \det(A^2)$ the **discriminant** of L over K with respect to the basis $\alpha_1, \dots, \alpha_n$.

Remark 2.2.4. In the situation of Definition (??) the following holds.

- i) Consider the matrix $B = (\text{Tr}_{L/K}(\alpha_i \alpha_j))_{i,j}$ in $K^{n \times n}$. Then the discriminant is given by $d(\alpha_1, \dots, \alpha_n) = \det(B)$. In particular, the discriminant $d(\alpha_1, \dots, \alpha_n)$ lies in K .
- ii) Suppose we have Θ in L such that $1, \Theta, \dots, \Theta^{n-1}$ forms a basis of L . Then the following equality holds

$$d(1, \Theta, \dots, \Theta^{n-1}) = \prod_{1 \leq i < j \leq n} (\Theta_i - \Theta_j)^2.$$

Here Θ_i denotes $\sigma_i(\Theta)$. If $L = K(\Theta)$ then $d(1, \Theta, \dots, \Theta^{n-1})$ coincides with the discriminant of the minimal polynomial f_Θ . Note that we use the notion of discriminants for polynomials here.

Proof. We begin by proving statement i). One computes

$$\det(A)^2 = \det(A^t) \cdot \det(A) = \det(A^t \cdot A).$$

The following calculation proves the claim

$$\begin{aligned} A^t \cdot A &= (\sigma_j(\alpha_i))_{i,j} \cdot (\sigma_k(\alpha_\ell))_{k,\ell} \\ &= \left(\sum_{j=1}^n \sigma_j(\alpha_i) \cdot \sigma_j(\alpha_\ell) \right)_{i,\ell} \\ &= \left(\sum_{j=1}^n \sigma_j(\alpha_i \cdot \alpha_\ell) \right)_{i,\ell} \\ &= (\text{Tr}_{L/K}(\alpha_i \cdot \alpha_\ell))_{i,\ell} \\ &= B. \end{aligned}$$

For statement ii), we will compute the determinant of the following Vandermonde matrix

$$\det(A) = \det \begin{pmatrix} 1 & \Theta_1 & \dots & \Theta_1^{n-1} \\ 1 & \Theta_2 & \dots & \Theta_2^{n-1} \\ \vdots & \vdots & \dots & \vdots \\ 1 & \Theta_n & \dots & \Theta_n^{n-1} \end{pmatrix} =: V_n(\Theta_1, \dots, \Theta_n).$$

By induction, we prove that $V_n(\Theta_1, \dots, \Theta_n)$ is nonzero and that the following equality holds

$$V_n(\Theta_1, \dots, \Theta_n) = \prod_{1 \leq i < j \leq n} (\Theta_j - \Theta_i).$$

For $n = 2$, we have

$$\det(A) = \det \begin{pmatrix} 1 & \Theta_1 \\ 1 & \Theta_2 \end{pmatrix} = \Theta_2 - \Theta_1 \neq 0.$$

Hence the claim holds for $n = 2$. Now we assume that the claim holds for a $n \in \mathbb{N}_{\geq 2}$. We want to prove that viewed as polynomials in Z the following equality holds

$$V_{n+1}(\Theta_1, \dots, \Theta_n, Z) = V_n(\Theta_1, \dots, \Theta_n) \cdot \prod_{i=1}^n (Z - \Theta_i). \quad (2.1)$$

This implies that

$$V_n(\Theta_1, \dots, \Theta_{n+1}) = V_n(\Theta_1, \dots, \Theta_n) \cdot \prod_{i=1}^n (\Theta_{n+1} - \Theta_i) = \prod_{1 \leq i < j \leq n} (\Theta_j - \Theta_i).$$

To show equality (??), recall that

$$V_{n+1}(\Theta_1, \dots, \Theta_n, Z) = \det \begin{pmatrix} 1 & \Theta_1 & \dots & \Theta_1^n \\ 1 & \Theta_2 & \dots & \Theta_2^n \\ \vdots & \vdots & \dots & \vdots \\ 1 & \Theta_n(\alpha_2) & \dots & \Theta_n^n \\ 1 & Z & \dots & Z^n \end{pmatrix}.$$

One sees that the polynomials on both sides of equality (??) have degree n . Moreover, $\{\Theta_1, \dots, \Theta_n\}$ is the set of zeros for both polynomials. Since the leading coefficient in both cases is $V_n(\Theta_1, \dots, \Theta_n)$, the polynomials are equal. This proves the claim. \square

Example 2.2.5. Consider $L = \mathbb{Q}(\sqrt{D})$ for a square free integer D different from 0 and 1. Then the following holds

- $\mathfrak{B}_1 = \{1, \sqrt{D}\}$ is a \mathbb{Q} -basis of L .
- Define $\sigma_2 : L \rightarrow \overline{\mathbb{Q}}, a + b\sqrt{D} \mapsto a - b\sqrt{D}$. Then we have

$$\text{Hom}_{\mathbb{Q}}(L, \overline{\mathbb{Q}}) = \{\sigma_1 = \text{id}, \sigma_2\}.$$

- $\text{Tr}_{L/\mathbb{Q}}(a + b\sqrt{D}) = a + b\sqrt{D} + a - b\sqrt{D} = 2a$.
- $\mathcal{N}_{L/\mathbb{Q}}(a + b\sqrt{D}) = (a + b\sqrt{D}) \cdot (a - b\sqrt{D}) = a^2 - b^2 \cdot D$.
- $d(\mathfrak{B}_1) = \det \begin{pmatrix} 1 & \sqrt{D} \\ 1 & -\sqrt{D} \end{pmatrix}^2 = (-2\sqrt{D})^2 = 4D$.
- We have

$$(\alpha_i \alpha_j)_{i,j} = \begin{pmatrix} 1 & \sqrt{D} \\ \sqrt{D} & D \end{pmatrix}.$$

Hence we compute

$$\det((\text{Tr}(\alpha_i \alpha_j))_{i,j}) = \det \begin{pmatrix} 2 & 0 \\ 0 & 2D \end{pmatrix} = 4D.$$

- Consider the \mathbb{Q} -basis of L given by $\mathfrak{B}_2 = \{1 + \sqrt{D}, 1 - \sqrt{D}\}$. Computing the discriminant for this basis yields

$$d(1 + \sqrt{D}, 1 - \sqrt{D}) = \det \begin{pmatrix} 1 + \sqrt{D} & 1 - \sqrt{D} \\ 1 - \sqrt{D} & 1 + \sqrt{D} \end{pmatrix}^2 = 16D.$$

Hence we see that the discriminant depends on the basis we choose.

Proposition 2.2.6. *Let $K \subseteq L$ be a separable field extension.*

i) *The bilinear map*

$$h : L^2 \rightarrow K, (x, y) \mapsto \text{Tr}_{L/K}(xy)$$

is non degenerate, i.e., $h(x, y) = 0$ for all $y \in L$ implies that $x = 0$.

ii) *If $\alpha_1, \dots, \alpha_n$ forms a basis of L/K then $d(\alpha_1, \dots, \alpha_n) \neq 0$.*

Proof. For statement i), we choose a primitive element Θ . Then $1, \Theta, \dots, \Theta^{n-1}$ is a K -basis of L . Let B be the matrix representation of h with respect to this basis. We find

$$\begin{aligned} \det(B) &\stackrel{(2.4) \text{ i)}}{=} d(1, \Theta, \dots, \Theta^{n-1}) \\ &\stackrel{(2.4) \text{ ii)}}{=} \prod_{1 \leq i < j \leq n} (\Theta_i - \Theta_j)^2 \neq 0. \end{aligned}$$

Here Θ_i denotes $\sigma_i(\Theta)$. This shows that h is non degenerate. We now prove statement ii). Observe that the matrix $M = (\text{Tr}_{L/K}(\alpha_i \alpha_j))_{i,j}$ is the matrix representation of h with respect to $\alpha_1, \dots, \alpha_n$. By Remark (2.4), we conclude

$$d(\alpha_1, \dots, \alpha_n) = \det(M).$$

Now, i) implies that $\det(M)$ is nonzero. □

Remark 2.2.7. Let $A \subseteq B$ be an integral ring extension with $B \subseteq L$ and $A = B \cap K \subseteq K$. Assuming that $\text{Hom}_K(L, \overline{K}) = \{\text{id} = \sigma_1, \dots, \sigma_n\}$ the following holds

- i) If $x \in B$ then $\sigma_i(x) \in B$ for all $1 \leq i \leq n$.
- ii) For all $x \in B$ the trace $\text{Tr}_{L/K}(x)$ and the norm $\mathcal{N}_{L/K}(x)$ lie in A .
- iii) Let $x \in B$. Then x lies in B^* if and only if the norm $\mathcal{N}_{L/K}(x)$ lie in A^* .

Proof. We start by proving i). Let x in B . By Remark (2.1), we have that the minimal polynomial f_x lies in $A[X]$. Since $\sigma(x)$ is also a zero of f_x , it is contained in B . This shows i). Now, statement ii) follows from i), Remark (2.2) iv) and the fact that $A = B \cap K$. For iii), assume that x is a unit in B , i.e., we find y in B with $xy = 1$. Hence

$$\mathcal{N}_{L/K}(x) \cdot \mathcal{N}_{L/K}(y) = \mathcal{N}_{L/K}(xy) = 1.$$

Using ii), we deduce that $\mathcal{N}_{L/K}(x)$ lies in A^* . This proves one direction. For the other direction, assume that $\mathcal{N}_{L/K}(x)$ lies in A^* , i.e., we find $a \in A$ with

$$\begin{aligned} 1 &= a \cdot \mathcal{N}_{L/K}(x) \\ &= a \cdot \prod_{i=1}^n \sigma_i(x) \\ &= a \cdot x \cdot \underbrace{\prod_{i=2}^n \sigma_i(x)}_{\in B, \text{ by i)}}. \end{aligned}$$

Hence x lies in B^* . This proves iii). \square

Proposition 2.2.8. Suppose $\alpha_1, \dots, \alpha_n \in B$ forms a K -basis of L . Let d denote the discriminant $d(\alpha_1, \dots, \alpha_n) \in A$. Then $d \cdot B$ is contained in $A\alpha_1 + \dots + A\alpha_n$.

Proof. Suppose $\alpha = \sum_{j=1}^n c_j \alpha_j \in B$ for $c_i \in K$. We want to solve for (c_1, \dots, c_n) . Applying the trace to the equalities

$$\alpha_i \alpha = \sum_{j=1}^n c_j \alpha_i \alpha_j, \quad 1 \leq i \leq n,$$

we obtain

$$\text{Tr}_{L/K}(\alpha_i \alpha) = \sum_{j=1}^n c_j \text{Tr}_{L/K}(\alpha_i \alpha_j), \quad 1 \leq i \leq n.$$

Hence $x = (c_1, \dots, c_n)$ is the solution of the linear system $Mx = y$, where

$$M = ((\text{Tr}_{L/K}(\alpha_i \alpha_j)))_{i,j} \in A^{n \times n}, \quad y = (\text{Tr}_{L/K}(\alpha_i \alpha))_i \in A^n.$$

By Remark (1.3), we have

$$\det(M) \cdot x = M^\# Mx = M^\# y \in A^n.$$

Using Remark (2.4), we know $\det(M) = d(\alpha_1, \dots, \alpha_n) =: d$. We conclude that dc_i lies in A for $1 \leq i \leq n$, which proves the claim. \square

Definition 2.2.9 (Ganzheitsbasis). Suppose $\omega_1, \dots, \omega_n \in B$ forms a basis of B over A , i.e., every $\alpha \in B$ can be written in a unique way as an A -linear combination $\sum_{i=1}^n c_i \omega_i$. Then $\omega_1, \dots, \omega_n$ is called an **integral basis** of B over A .

Example 2.2.10. Same situation as in Ex. 2.5. $\mathcal{B}_1 = \{1, \sqrt{D}\} \subseteq B$. Consider:

$$\begin{aligned} \alpha &= \frac{1}{2}(1 + \sqrt{D}) \Rightarrow 2\alpha = 1 + \sqrt{D} \\ \Rightarrow (2\alpha - 1)^2 &= D \Rightarrow 4\alpha^2 - 4\alpha + 1 = D \\ \Rightarrow f_\alpha(X) &= X^2 - X + \frac{1-D}{4} \end{aligned}$$

Hence if $D \equiv 1 \pmod{4} \Rightarrow \alpha \in B$ and \mathcal{B}_1 is not an integral basis.

Proposition 2.2.11. *Let $D \in \mathbb{Z}$, D square-free, $D \neq 0, 1$, $B :=$ integral closure of \mathbb{Z} in $\mathbb{Q}(\sqrt{D}) = L$.*

i) $D \equiv 2, 3 \pmod{4} \Rightarrow \{1, \sqrt{D}\}$ is an integral basis of B/\mathbb{Z} in particular $B = \mathbb{Z}[\sqrt{D}]$.

ii) $D \equiv 1 \pmod{4} \Rightarrow \{1, \frac{1}{2}(\sqrt{D}+1)\}$ is an integral basis of B/\mathbb{Z} . and $B = \mathbb{Z}[\frac{1}{2}(1+\sqrt{D})]$.

Proof. Consider $\alpha = a + b\sqrt{D} \in \mathbb{Q}(\sqrt{D})$ with $a, b \in \mathbb{Q}$.

$\Rightarrow f_\alpha = X^2 - 2aX + a^2 - b^2D$.

Rem 2.1: $\alpha \in B \iff f_\alpha \in \mathbb{Z}[X] \iff 2a \in \mathbb{Z} \text{ and } a^2 - b^2D \in \mathbb{Z}$.

(1) Show: $\alpha \in B \Rightarrow 2b \in \mathbb{Z}$.

$\alpha \in B \Rightarrow 4a^2 - 4b^2D = 4z$ with $z \in \mathbb{Z}$. Write $b = \frac{p}{q}$ with $p, q \in \mathbb{Z}, \gcd(p, q) = 1$

$\Rightarrow 4p^2D = ((2a)^2 - 4z)q^2 \quad (\star)$

$\Rightarrow q = 1$ or 2 .

(2) Show: $q = 2 \Rightarrow D \equiv 1 \pmod{4}$

$(\star) \Rightarrow p^2D = (2a)^2 - 4z \equiv (2a)^2 \pmod{4}$

p is odd, hence $p^2 \equiv 1 \pmod{4} \Rightarrow (2a)^2$ is odd (i.e. $a = \frac{2n-1}{2} \in \mathbb{Q}$)

$\Rightarrow (2a)^2 \equiv 1 \pmod{4} \Rightarrow D \equiv 1 \pmod{4}$.

(3) It follows from (2) if $D \equiv 1 \pmod{4}$:

$\alpha \in B \iff \alpha = a + b\sqrt{D}$ or $\alpha = \frac{1}{2}(a + b\sqrt{D})$ with $a, b \in \mathbb{Z}$. Hence we obtain:

$$B = \begin{cases} \mathbb{Z}[\sqrt{D}] & , \text{ if } D \equiv 2, 3 \pmod{4} \\ \mathbb{Z}[\frac{1}{2}(1 + \sqrt{D})] & , \text{ if } D \equiv 1 \pmod{4} \end{cases}$$

For the second case observe that $\frac{a}{2} + \frac{b}{2}\sqrt{D} = \frac{a-b}{2} + \frac{b}{2}(1 + \sqrt{D}) \in \mathbb{Z}[\frac{1}{2}(1 + \sqrt{D})]$.

This implies the claim. □

Proposition 2.2.12. *Suppose L/K separable and A is a principal ideal domain. Let $M \neq 0$ be a finitely generated B -submodule of $L \Rightarrow M$ is a free A -module. In particular: B is a free A -module of rank $n := [L : K]$.*

Reminder 2.2.13. Suppose A is a principal ideal domain and M_0 is a finitely generated free A -module.

i) Any submodule M of M_0 is free.

ii) $\text{rank}(M_0) \geq \text{rank}(M)$

of Prop 2.12. Let $\mu_1, \dots, \mu_r \in M \subseteq L$ be generators of M as B -module and let $\alpha_1, \dots, \alpha_n$ be a basis of L/K in B and $d := d(\alpha_1, \dots, \alpha_n) \in A$.

Recall: $L = \{\frac{b}{a} \mid b \in B, a \in A \setminus \{0\}\}$.

(1) Prop 2.7 $\Rightarrow dB \subseteq A\alpha_1 + \dots + A\alpha_n$

$$(2) \exists a \in A : a\mu_1, \dots, a\mu_r \in B$$

Hence: $daM \subseteq dB \subseteq A\alpha_1 + \dots + A\alpha_n =: M_0$

(M_0 is a free A -module, since $\alpha_1, \dots, \alpha_n$ are basis of L/K).

Reminder 2.13 $\Rightarrow adM$ is a free A -module $\Rightarrow M$ is a free A -module.

Furthermore: $\text{rank}(M) = \text{rank}(adM) \stackrel{\text{Rem. 2.13}}{\leq} \text{rank}(M_0) = n$.

Suppose that $M = B$. So far we got that B is a free A -module and $\text{rank}(B) \leq n$.

Show: $\text{rank}(B) \geq n$.

Let μ_1, \dots, μ_r be a basis of B as A -module. By $L = \{\frac{b}{a} \mid b \in B, a \in A \setminus \{0\}\}$ we have that μ_1, \dots, μ_r generate L over K . \square

Hence: if A is a principal ideal domain, then B has always an integral basis.

Proposition 2.2.14. *Suppose we are in the following situation:*

- L/K and L'/K are Galois extensions of degree n and m in some field E
- A a subring of K such that $K = \text{Quot}(A)$ and B and B' are the integral closures of A in L and L' .
- $\{\omega_1, \dots, \omega_n\}$ and $\{\omega'_1, \dots, \omega'_m\}$ are integral basis for B/A and B'/A .
- $d := d(\omega_1, \dots, \omega_n)$ and $d' := d(\omega'_1, \dots, \omega'_m) \in A$ with d and d' are coprime in A , i.e. $\exists x, x' \in A$ with $1 = dx + d'x'$.
- $K = L \cap L'$

Then we have: $\{\omega_i \omega'_j \mid i \in \{1, \dots, n\}, j \in \{1, \dots, m\}\}$ is an integral basis and its discriminant is $d^m (d')^n$.

Proof. Recall: $L \cap L' = K \Rightarrow [LL' : K] = nm$ and $\{\omega_i \omega'_j\}$ is a basis of the field extension LL'/K .

$\text{Gal}(L/K) = \{\sigma_1, \dots, \sigma_n\}$ and $\text{Gal}(L'/K) = \{\sigma'_1, \dots, \sigma'_m\}$

\Rightarrow obtain unique lifts $\hat{\sigma}_i \in \text{Gal}(LL'/L')$ and $\hat{\sigma}'_j \in \text{Gal}(LL'/L)$ and $\text{Gal}(LL'/K) = \{\hat{\sigma}_i \hat{\sigma}'_j \mid i \in \{1, \dots, n\}, j \in \{1, \dots, m\}\}$.

Consider: $\alpha \in \tilde{B} :=$ integral closure of A in LL' .

Write $\alpha = \sum_{i,j} \alpha_{i,j} \omega_i \omega'_j = \sum_j \beta_j \omega'_j$ with $\alpha_{i,j} \in K$ and $\beta_j = \sum_i \alpha_{i,j} \omega_i \in L$.

$\Rightarrow \hat{\sigma}'_i(\alpha) = \sum_j \beta_j \hat{\sigma}'_i(\omega'_j)$, since $\hat{\sigma}'_i \in \text{Gal}(LL'/L)$.

\Rightarrow We have a linear system:

$$a = Tb \text{ with } a = \begin{pmatrix} \hat{\sigma}'_1(\alpha) \\ \vdots \\ \hat{\sigma}'_m(\alpha) \end{pmatrix} \in \tilde{B}^m, \quad b = \begin{pmatrix} \beta_1 \\ \vdots \\ \beta_m \end{pmatrix} \in L^m, \quad T = (\hat{\sigma}'_i(\omega'_j))_{(i,j)} \in \tilde{B}^{m \times m}$$

Observe: $\det(T)^2 = d'$

$$\&Rightarrow \det(T)b = T^\# T b = T^\# a \in \tilde{B}^m \Rightarrow d'b \in \tilde{B}^m$$

$$\Rightarrow \forall j : d'\beta_j = \sum_i d'\alpha_{i,j}\omega_i \in \tilde{B} \cap L = B$$

$$\Rightarrow d'\alpha_{i,j} \in A, \text{ since } \{\omega_1, \dots, \omega_n\} \text{ is an integral basis.}$$

$$\Rightarrow d\alpha_{i,j} \in A \text{ in the same way}$$

$$\Rightarrow \alpha_{i,j} = (x'd' + xd)\alpha_{i,j} = x'd'\alpha_{i,j} + xd\alpha_{i,j} \in A.$$

Hence: $\{\omega_i\omega'_j \mid (i,j) \in \{(1,1), \dots, (n,m)\}\}$ is an integral basis of \tilde{B}/A .

For calculating the discriminant consider the matrix $M = (\hat{\sigma}_k \circ \hat{\sigma}'_l(\omega_i\omega'_j))_{(k,l),(i,j)} = (\hat{\sigma}_k(\omega_i)\hat{\sigma}'_l(\omega'_j))$.

Consider $Q = (\hat{\sigma}_k(\omega_i))$

$$\Rightarrow M = \begin{pmatrix} Q & 0 & \dots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & Q \end{pmatrix} \cdot \begin{pmatrix} I \cdot \hat{\sigma}'_1(\omega'_1) & \dots & I \cdot \hat{\sigma}'_1(\omega'_1) \\ \vdots & & \vdots \\ \vdots & & \vdots \\ I \cdot \hat{\sigma}'_m(\omega'_m) & \dots & I \cdot \hat{\sigma}'_m(\omega'_m) \end{pmatrix}$$

Observe:

$$(1) \det(Q)^2 = d(\omega_1, \omega_n) = d$$

$$(2) \text{ The second matrix can be transformed by switching rows and columns to } \begin{pmatrix} Q' & 0 & \dots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & Q' \end{pmatrix}$$

$$\text{with } Q' = (\sigma'_l(\omega'_j)) \text{ and } \det(Q') = d'$$

$$\Rightarrow \det(M)^2 = \det(Q)^{2m} \cdot \det(Q')^{2n} = d^m d'^n. \quad \square$$

Remark 2.2.15 (and Definition). Suppose $K = \mathbb{Q}$, $A = \mathbb{Z}$, L a number field and $B = \mathcal{O}_k$.

(i) There is always an integral basis w_1, \dots, w_n .

(ii) The **discriminant** $d_k = d_k(\mathcal{O}_k) = d(w_1, \dots, w_n)$ does not depend on the choice of integral basis.

Proof. “(i)” Proposition 2.12 “(ii)” Let w'_1, \dots, w'_n be another integral basis. Then there exists a base change matrix $T \in \text{GL}_n(\mathbb{Z})$ with

$$\begin{pmatrix} w'_1 \\ \vdots \\ w'_n \end{pmatrix} = T \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix}.$$

Hence

$$\begin{pmatrix} \sigma(w'_1) \\ \vdots \\ \sigma(w'_n) \end{pmatrix} = T \begin{pmatrix} \sigma(w_1) \\ \vdots \\ \sigma(w_n) \end{pmatrix}.$$

such that

$$d(w'_1, \dots, w'_n) = \underbrace{\det T}_{\in \{1, -1\}}^2 d(w_1, \dots, w_n) = d_k.$$

□

Example 2.2.16. Let $L = \mathbb{Q}(\sqrt{D})$ with $D \in \mathbb{Z}$ square-free. By Proposition 2.14 we have:

- (i) $\mathcal{O}_k = \mathbb{Z}[\sqrt{D}]$ and $\{1, \sqrt{D}\}$ is an integral basis for $D \equiv 2, 3 \pmod{4}$ and $d_k = 4D$.
- (ii) $\mathcal{O}_k = \mathbb{Z}\left[\frac{1+\sqrt{D}}{2}\right]$ and $\left\{1, \frac{1+\sqrt{D}}{2}\right\}$ is an integral basis for $D \equiv 1 \pmod{4}$ and $d_k = D$.

In particular, this holds for $D = -1$, i.e., the Gaussian integers $\mathbb{Z}[i]$.

2.3 Ideals

Let R be a commutative ring with 1.

Problem: \mathcal{O}_k is not a UFD in many cases, e.g. in $\mathbb{Z}[\sqrt{-5}]$ we have

$$(1 + \sqrt{-5})(1 - \sqrt{-5}) = 1 + 5 = 6 = 2 \cdot 3,$$

that is, two different ways to factor 6 in irreducible elements.

Idea:

- (1) Maybe we have too few elements, i.e.,

$$1 + \sqrt{-5} = p_1 p_2, 1 - \sqrt{-5} = p_3 p_4 \text{ and } 2 = p_2 p_3, 3 = p_1 p_4$$

for some primes p_i .

- (2) An element is determined (up to units) by the set of elements it divides, e.g.

$$p_i \longleftrightarrow \{x \in \mathcal{O}_k; p_i | x\} = p_i \mathcal{O}_k \text{ (this is an ideal)}.$$

Notation 2.3.1. Let $I, J \subset R$ be ideals. We define

- $I + J = \{a + b; a \in I, b \in J\}$,
- $IJ = \{\sum_i a_i b_i; a_i \in I, b_i \in J\}$.

Definition 2.3.2 (and Reminder). Let $I \subsetneq R$ be an ideal.

- (a) I is called **prime** if for all $a, b \in R$ with $ab \in I$ we already have $a \in I$ or $b \in I$.
 \Leftrightarrow For all ideals $A, B \subset R$ with $AB \subset I$ we have $A \subset I$ or $B \subset I$.
- (b) I is called **maximal** if for any ideal $I \subset J \subset R$ we have $J = I$ or $J = R$.
 $\Leftrightarrow R/I$ is a field.
- (c) R is called **Noetherian** if every ascending chain of ideals

$$I_1 \subset I_2 \subset \dots$$

becomes stationary, i.e., if there is an $N \in \mathbb{N}$ such that $I_n = I_N$ for all $n \geq N$.

\Leftrightarrow Every ideal in R is finitely generated.

- (d) R is called a **Dedekind domain** if
- R is an integral domain,
 - R is integrally closed,
 - R is Noetherian, and
 - every prime ideal in R is maximal.

Proposition 2.3.3. *If \mathcal{O} is the integral closure of \mathbb{Z} in a number field then \mathcal{O} is a Dedekind domain.*

Proof. It is clear that \mathcal{O} is an integral domain and integrally closed. Furthermore, by Proposition 2.12 each \mathbb{Z} -submodule is finitely generated as a \mathbb{Z} -module, thus also as an \mathcal{O} -module. Hence \mathcal{O} is Noetherian.

Now, let $I \subset \mathcal{O}$ be a prime ideal. Then $I \cap \mathbb{Z} \subset \mathbb{Z}$ is a prime ideal such that $\mathbb{Z}/(I \cap \mathbb{Z}) = \mathbb{F}_p$. Using $\mathcal{O} = \mathbb{Z}[w_1, \dots, w_n]$ we conclude

$$\mathcal{O}/I = \mathbb{Z}/(I \cap \mathbb{Z})[w'_1, \dots, w'_n] = \mathbb{F}_p[w'_1, \dots, w'_n] = \mathbb{F}_p(w'_1, \dots, w'_n),$$

where $w'_i \equiv w_i \pmod{I}$. Thus \mathcal{O}/I is a field and hence I maximal. \square

From now on: Let \mathcal{O} denote a Dedekind domain.

Theorem 2.3.4. *Every ideal $0 \neq I \subset \mathcal{O}$ has a unique factorization*

$$I = P_1 \cdots P_n$$

into prime ideals $P_i \subset \mathcal{O}$.

Lemma 2.3.5. *For every ideal $0 \neq I \subset \mathcal{O}$ there exist nonzero prime ideals $P_i \subset \mathcal{O}$ such that*

$$P_1 \cdots P_n \subset I.$$

Proof. Set $M = \{0 \neq I \subset \mathcal{O} \text{ ideal; } I \text{ does not have such } P_i\}$ and suppose $M \neq \emptyset$. Then M is partially ordered by inclusion and since \mathcal{O} is Noetherian, every chain in M has an upper bound. Thus, the Lemma of Zorn yields a maximal element $I_0 \in M$. Since I_0 cannot be prime there are $a, b \in \mathcal{O}$ such that $ab \in I_0$ but $a, b \notin I_0$. Consider the ideals $I_1 = (a) + I_0$ and $I_2 = (b) + I_0$ which satisfy $I_0 \subsetneq I_1$, $I_0 \subsetneq I_2$ and $I_1 I_2 \subset I_0$. Since I_0 is a maximal ideal in M , we have $I_{1,2} \notin M$ hence we find prime ideals $P_1, \dots, P_n, P'_1, \dots, P'_m \subset \mathcal{O}$ with

$$P_1 \dots P_n \subset I_1 \text{ and } P'_1 \dots P'_m \subset I_2.$$

Finally, we conclude $P_1 \dots P_n P'_1 \dots P'_m = I_1 I_2 \subset I_0 \Rightarrow I_0 \notin M \nRightarrow M = \emptyset$. \square

Lemma 2.3.6. Let $0 \neq P \subset \mathcal{O}$ be a prime ideal, $I \subset \mathcal{O}$ an ideal and $K = \text{Quot}(\mathcal{O})$. Then:

$$(i) \ P^{-1} := \{x \in K; xP \subset \mathcal{O}\} \supsetneq \mathcal{O}$$

$$(ii) \ I \subsetneq P^{-1}I := \{\sum_i a_i x_i; a_i \in I, x_i \in P^{-1}\}$$

Proof. “(i)” Let $0 \neq a \in P$, $P_1 \dots P_n \subset (a) \subset P$ as in Lemma 3.5 with n minimal.

Claim: Without loss of generality we can assume that $P_1 = P$.

Proof of the claim: Since $P_1 \dots P_n \subset P$ and P is prime, there is an index i such that $P_i \subset P$, by reindexing we may assume that $i = 1$. However, we assumed \mathcal{O} to be Dedekind, hence P_1 is a maximal ideal in \mathcal{O} . Thus, $P_1 \subset P \subsetneq \mathcal{O}$ implies that $P_1 = P$ as claimed.

Now, since n was chosen minimal we have $P_2 \dots P_n \not\subset (a)$, i.e., there exists an element $b \in (a) \setminus P_2 \dots P_n$. On the one hand we thus have

$$a^{-1}b \notin \mathcal{O}$$

and on the other hand $bP \subset (a)$ such that $a^{-1}bP \subset \mathcal{O}$ and hence

$$a^{-1}b \in P^{-1}.$$

Both of this together shows that $P^{-1} \supsetneq \mathcal{O}$.

“(ii)” Assume there is an ideal $I \subset \mathcal{O}$ such that $P^{-1}I \subset I$. Let $\{\alpha_1, \dots, \alpha_n\} \subset I$ be a generating set and choose $x \in P^{-1} \setminus \mathcal{O}$. Then,

$$x\alpha_i = \sum_j a_{ij}\alpha_j$$

for some $a_{ij} \in \mathcal{O}$. Consider the matrix $A = xE_n - (a_{ij})_{i,j}$, which satisfies

$$A \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{pmatrix} = 0.$$

Since $A^\# A = \det A$ we conclude $\det A = 0$ such that x is a zero of the monic polynomial $\det(XE_n - (a_{ij})_{i,j})$ over \mathcal{O} . But since \mathcal{O} is integrally closed this implies $x \in \mathcal{O}$, a contradiction. \square

Proof of Theorem 3.4. Existence of a factorization: Let

$$M = \{0 \neq I \subset \mathcal{O} \text{ ideal; } I \text{ has no factorization}\}$$

and assume that $M \neq \emptyset$. As in Lemma 3.5, let $I_0 \in M$ be a maximal element and let $P \supset I_0$ be a maximal ideal containing I_0 . Since I_0 is not prime we have $I_0 \neq P$ such that by Lemma 3.6,

$$I_0 \subsetneq P^{-1}I_0 \subset P^{-1}P = \mathcal{O}.$$

Note that $I_0 = I_0\mathcal{O} = I_0P^{-1}P$ and $I_0 \neq P$ imply $P^{-1}I_0 \subsetneq \mathcal{O}$. Since I_0 was maximal in M we thus have $P^{-1}I_0 \notin M$, i.e., there are prime ideals $P_1, \dots, P_n \subset \mathcal{O}$ with $P^{-1}I = P_1 \cdots P_n$. This leads to the contradiction $I = PP_1 \cdots P_n$.

Uniqueness of the factorization: Suppose that

$$I = P_1 \cdots P_n = Q_1 \cdots Q_m$$

are two prime factorizations. Then $P_1 \supset I = Q_1 \cdots Q_m$, hence without loss of generality we can assume that $Q_1 \subset P_1$. Since \mathcal{O} is Dedekind we conclude $Q_1 = P_1$ such that

$$P_2 \cdots P_n = P_1^{-1}I = Q_2 \cdots Q_m.$$

The claim follows by induction. □

Definition 2.3.7. We call two ideals $0 \neq I, J \subset \mathcal{O}$ **coprime** $:\Leftrightarrow I + J = \mathcal{O}$. For example, one could take two distinct prime ideals in a Dedekind ring.

Remark 2.3.8. Let $P_1, \dots, P_n \subset \mathcal{O}$ be pairwise coprime. Then P_1 and $P_2 \cdots P_n$ are coprime and we have $\prod_{i=1}^n P_i = \bigcap_{i=1}^n P_i$.

Proof. Induction on n : The case $n = 2$ is clear. Let $n > 2$. Since P_1 and P_2 are coprime, $\exists p_1 \in P_1, p_2 \in P_2$, such that we can write $1 = p_1 + p_2$. By induction hypothesis, $\exists p'_1 \in P_1, p \in P_3 \cdots P_n$, such that $1 = p'_1 + p$. It follows

$$1 = p_1 + p_2 \cdot (p'_1 + p) = \underbrace{p_1 + p_2 p'_1}_{\in P_1} + \underbrace{p_2 p}_{\in P_2 \cdots P_n},$$

which yields the first claim.

For the second claim, first note that $\prod P_i \subset \bigcap P_i$ is clear.

For the converse, let $a \in \bigcap P_i$, which of course implies that $a \in P_i$ for all i . As above, we write $1 = p_1 + p$, $p_1 \in P_1, p \in P_2 \cdots P_n$. We get $a = ap_1 + ap$, which implies that $a \in aP_1 + P_1 \cdot \prod_{i=2}^n P_i$ for all i and by induction hypothesis, we get $a \in \prod P_i$. □

Theorem 2.3.9 (Chinese Remainder Theorem). *Let $P_1, \dots, P_n \subset \mathcal{O}$ be pairwise coprime ideals, $I = \bigcap_{i=1}^n P_i$. Then we have*

$$\mathcal{O}/I \cong \bigoplus_{i=1}^n \mathcal{O}/P_i$$

Proof. Consider the map

$$\phi : \mathcal{O} \longrightarrow \bigoplus_i \mathcal{O}/P_i, \quad a \mapsto \bigoplus_i a \pmod{P_i}.$$

Obviously, $\ker(\phi) = I$. It remains to show, that ϕ is surjective. Let first $n = 2$: For $p_1 \in P_1, p_2 \in P_2$ let $1 = p_1 + p_2$ and for any $a_1, a_2 \in \mathcal{O}$ write $a = a_2 p_1 + a_1 p_2$. Then $\phi(a) = a_1 \oplus a_2 \in \mathcal{O}/P_1 \oplus \mathcal{O}/P_2$.

In general, by 3.8, we know that $\exists y_i \in \mathcal{O}$ with $y_i \equiv 1 \pmod{P_i}$ and $y_i \equiv 0 \pmod{\bigcap_{j \neq i} P_j}$. Hence the element $a = \sum_{i=1}^n a_i y_i$ is mapped to $\bigoplus_{i=1}^n a_i \pmod{P_i}$ \square

Definition 2.3.10. A **fractional ideal** of K is a finitely generated \mathcal{O} -module $0 \neq I$ of K . Since \mathcal{O} is noetherian, this is equivalent to: $\exists c \in \mathcal{O}$, such that $c \cdot I \subset \mathcal{O}$ is an ideal (since every submodule of \mathcal{O} is finitely generated). The product of two fractional ideals is denoted in the same way as introduced in 3.3. Ideals in \mathcal{O} are called **integral ideals**.

Theorem 2.3.11. *The fractional ideals of K , together with the product, form an abelian group, which we denote by \mathcal{J}_K .*

Proof. Commutativity and associativity are clear. The unit in \mathcal{J}_K is given by \mathcal{O} . We define $I^{-1} := \{x \in K \mid x \cdot I \subset \mathcal{O}\}$ and show, that this defines an inverse for all $I \in \mathcal{J}_K$.

For a prime ideal $P \subset \mathcal{O}$, we have already seen in 3.4 that $P^{-1}P = \mathcal{O}$ and for an integral ideal $I = P_1 \cdots P_n$, we have $J = P_1^{-1} \cdots P_n^{-1}$ as an inverse:

$J \subset I^{-1}$ is clear. For the converse, let $x \in I^{-1}$, we then have $x \cdot IJ \subset \mathcal{O}$, with $x \cdot I \subset \mathcal{O}$ and $IJ = \mathcal{O}$, therefore $x \cdot 1 \in J$ and $I^{-1} \subset J$ follows.

Let now I be fractional. Then $\exists c \in \mathcal{O}$, such that cI is integral. But then $(cI)^{-1} = c^{-1}I^{-1}$ and hence $II^{-1} = (cI)(c^{-1}I^{-1}) = \mathcal{O}$ \square

Corollary 2.3.12. *Every fractional ideal I has a unique factorization $I = \prod P_i^{n_i}$, with $n_i \in \mathbb{Z}$, $P_i \subset \mathcal{O}$ distinct prime ideals and only finitely many $n_i \neq 0$. In particular, \mathcal{J}_K is a free abelian group on the prime ideals of \mathcal{O} .*

Proof. By 3.11, every element $I \in \mathcal{J}_K$ can be written as $I = AB^{-1}$ for some integral ideals $A, B \subset \mathcal{O}$. Therefore, by 3.4, we get $I = \prod P_i^{n_i}$ and by multiplying denominators, we see that this presentation is unique. \square

Definition 2.3.13. The principle ideals generate a subgroup \mathcal{P}_K of \mathcal{J}_K . We call the quotient group $\text{Cl}_K := \mathcal{J}_K/\mathcal{P}_K$ the **ideal class group**. We have an exact sequence of groups

$$1 \longrightarrow \mathcal{O}^\times \longrightarrow K^\times \xrightarrow{a \mapsto a\mathcal{O}} \mathcal{J}_K \longrightarrow \text{Cl}_K \longrightarrow 1.$$

2.4 Lattices and Minkowski

Definition 2.4.1. Let V be an n -dimensional \mathbb{R} -vector space. A **lattice** $\Lambda \subset V$ is a subgroup of the form $\mathbb{Z}v_1 + \dots + \mathbb{Z}v_m$, where v_1, \dots, v_m are linearly independent over V . We call (v_1, \dots, v_m) a **basis** of Λ and $\phi := \{x_1v_1 + \dots + x_mv_m \mid x_i \in [0, 1)\}$ a **fundamental domain** of Λ . We call Λ **complete**, if $n = m$.

CAUTION: For many people, lattices are always complete!

Example 2.4.2. (a) $\mathbb{Z} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \mathbb{Z} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \subset \mathbb{R}^2$ is a complete lattice

(b) $\mathbb{Z} + \mathbb{Z}\sqrt{2} \subset \mathbb{R}$ is not a lattice, since 1 and $\sqrt{2}$ are not linearly independent.

(c) $\mathbb{Z} \begin{pmatrix} \sqrt{2} \\ 1 \end{pmatrix} \subset \mathbb{R}^2$ is a non-complete lattice.

Proposition 2.4.3. A subgroup $\Lambda \subset V$ is a lattice $\Leftrightarrow \Lambda$ is a discrete subgroup of V .

Proof. " \Rightarrow ": Take $\{\lambda + x_1v_1 + \dots + x_nv_n + \text{rest of basis} \mid |x_n| < 1\}$ as a neighbourhood for $\lambda \in \Lambda$.

" \Leftarrow ": Let $V_0 = \langle \Lambda \rangle_{\mathbb{R}}$. Then we can choose a basis v_1, \dots, v_m of V_0 in Λ , such that $\Lambda_0 := \mathbb{Z}v_1 + \dots + \mathbb{Z}v_m$ is a lattice in V_0 .

Claim: The index $[\Lambda : \Lambda_0]$ is finite.

Proof of the claim: Since Λ_0 is complete, $V = \bigsqcup_{\lambda \in \Lambda_0} \phi_0 + \lambda$. Since Λ is discrete and ϕ_0 bounded, $\Lambda \cap \phi_0$ is finite. Hence we have only finitely many residue classes $\lambda + \Lambda_0$ of Λ and therefore $[\Lambda : \Lambda_0] =: d < \infty$.

From this follows, that $\Lambda \subset \frac{1}{d}\Lambda_0 = \mathbb{Z}(\frac{1}{d}v_1) + \dots + \mathbb{Z}(\frac{1}{d}v_m)$. Therefore, Λ has a \mathbb{Z} -basis $w_1 = v_1n_1, \dots, w_r = v_rn_r$ for some $n_i \in \frac{1}{d}\mathbb{N}$ and since Λ spans V_0 , we get $r = m$ and they are linearly independent. \square

Let $\Gamma = v_1\mathbb{Z} + \dots + v_n\mathbb{Z} \subset \mathbb{R}^n$ be a complete lattice. We define

$$\text{vol } \Gamma = \text{vol } \phi = |\det(v_1, \dots, v_n)|.$$

Note that this definition is independent of the chosen basis since for a transformation

$$A(v_1, \dots, v_n) = (v'_1, \dots, v'_n)$$

between two bases we have $\det A = \pm 1$.

Theorem 2.4.4 (Minkowski). Let $X \subset \mathbb{R}^n$ be a convex, symmetric central (i.e., $x \in X$ implies $-x \in X$) subset and let $\Gamma \subset \mathbb{R}^n$ be a complete lattice. If

$$\text{vol } X > 2^n \text{vol } \Gamma$$

then there exists some $\gamma \in \Gamma \setminus \{0\}$ such that $\gamma \in X$.

Proof. **Claim:** It suffices to show that there are $\gamma_1, \gamma_2 \in \Gamma$, $\gamma_1 \neq \gamma_2$, such that

$$\left(\frac{1}{2}X + \gamma_1\right) \cap \left(\frac{1}{2}X + \gamma_2\right) \neq \emptyset.$$

Proof of claim: Let $x = \frac{1}{2}x_1 + \gamma_1 = \frac{1}{2}x_2 + \gamma_2$ with some $x_1, x_2 \in X$. Then

$$y = \frac{1}{2}(x_1 - x_2) = \gamma_2 - \gamma_1 \in \Gamma \setminus \{0\}$$

with $y \in X$ since X is symmetrical central.

Now let us assume that the family $\left(\frac{1}{2}X + \gamma\right)_{\gamma \in \Gamma}$ is pairwise disjoint. Then

$$\left(\left[\frac{1}{2}X + \gamma\right] \cap \phi\right)_{\gamma \in \Gamma}$$

also consists of pairwise disjoint sets such that we obtain the contradiction

$$\begin{aligned} \text{vol } \Gamma = \text{vol } \phi &\geq \sum_{\gamma \in \Gamma} \text{vol} \left(\left[\frac{1}{2}X + \gamma\right] \cap \phi \right) = \sum_{\gamma \in \Gamma} \text{vol} \left(\frac{1}{2}X \cap [\phi - \gamma] \right) \\ &= \text{vol} \left(\frac{1}{2}X \right) = \frac{1}{2^n} \text{vol } X. \end{aligned}$$

□

2.5 Minkowski theory

Let $[K : \mathbb{Q}] = n$ be a field extension, $\tau_i: K \hookrightarrow \mathbb{C}$ different embeddings and consider the embedding

$$j: K \hookrightarrow K_{\mathbb{C}} = \prod_{\tau_i} \mathbb{C}, \quad a \mapsto (\tau_1(a), \dots, \tau_n(a)).$$

Define a hermitian scalar product on $K_{\mathbb{C}}$ by

$$\langle (x_{\tau_i}), (y_{\tau_i}) \rangle = \sum_{\tau_i} x_{\tau_i} \overline{y_{\tau_i}}$$

and consider the complex conjugation $F \in \text{Gal}(\mathbb{C}/\mathbb{R})$ given by $\mathbb{C} \rightarrow \mathbb{C}, z \mapsto \bar{z}$. Let

$$F(\tau) = \bar{\tau}: a \mapsto \overline{\tau(a)}$$

and extend it to $K_{\mathbb{C}}$ by

$$F: K_{\mathbb{C}} \rightarrow K_{\mathbb{C}}, (x_{\tau}) \mapsto (\bar{x}_{\bar{\tau}}).$$

Example. Let $D > 0$ be square-free. Consider

$$\mathbb{Q}(\sqrt{D}) \hookrightarrow \mathbb{Q}(\sqrt{D})_{\mathbb{C}} = \prod_{\tau_i} \mathbb{C}$$

with

$$\tau_1(a + b\sqrt{D}) = a + b\sqrt{D} \quad \text{and} \quad \tau_2(a + b\sqrt{D}) = a - b\sqrt{D}.$$

Then

$$j(a + b\sqrt{D}) = (a + b\sqrt{D}, a - b\sqrt{D})$$

and $F(\tau_1) = \tau_1, F(\tau_2) = \tau_2$ such that

$$F(x_{\tau_1}, x_{\tau_1}) = (\bar{x}_{\tau_1}, \bar{x}_{\tau_2}).$$

Remark. • $F(\langle x, y \rangle) = \langle F(x), F(y) \rangle$

• $\text{Tr}: K_{\mathbb{C}} \rightarrow \mathbb{C}, (x_{\tau}) \mapsto \sum_{\tau} x_{\tau}$ such that $(\text{Tr} \circ j)(a) = \text{Tr}_{K/\mathbb{Q}}(a)$

Now define the F -invariant \mathbb{R} -vector space

$$K_{\mathbb{R}} = K_{\mathbb{C}}^+ = \{x \in K_{\mathbb{C}} \mid F(x) = x\} = \{x \in K_{\mathbb{C}} \mid x_{\bar{\tau}} = \overline{x_{\tau}} \text{ for all } \tau\}.$$

Since $\bar{\tau}(a) = \overline{\tau(a)}$ for all $a \in K$ and all τ , we have $j(K) \subset K_{\mathbb{R}}$. We call $K_{\mathbb{R}}$ the **Minkowski space** and $\langle \cdot, \cdot \rangle|_{K_{\mathbb{R}}}$ the **canonical metric**.

Remark. Note that $j: K \rightarrow K_{\mathbb{R}} \cong K \otimes_{\mathbb{Q}} \mathbb{R}$, where the isomorphism is given by $a \otimes x \mapsto j(a)x$ for $x \in \mathbb{R}$.

Explicit description of $K_{\mathbb{R}}$: Let $n = r + 2s$, where r and s are the number of embeddings

$$\varphi_1, \dots, \varphi_r: K \hookrightarrow \mathbb{R}$$

and

$$\sigma_1, \overline{\sigma_1}, \dots, \sigma_s, \overline{\sigma_s}: K \hookrightarrow \mathbb{C},$$

respectively. Notice that $F(\varphi_i) = \varphi_i$ and $F(\sigma_j) = \overline{\sigma_j}$. Then elements of $K_{\mathbb{C}}$ are of the form

$$x = (x_{\varphi(1)}, \dots, x_{\varphi(r)}, x_{\sigma_1}, x_{\overline{\sigma_1}}, \dots, x_{\sigma_s}, x_{\overline{\sigma_s}})$$

with

$$F(x) = (\overline{x_{\varphi_1}}, \dots, \overline{x_{\varphi_r}}, \overline{x_{\sigma_1}}, \overline{x_{\sigma_1}}, \dots, \overline{x_{\sigma_s}}, \overline{x_{\sigma_s}}).$$

Hence we have

$$K_{\mathbb{R}} = \{x \in K_{\mathbb{C}} \mid x_{\varphi_i} \in \mathbb{R}, x_{\overline{\sigma_j}} = \overline{x_{\sigma_j}}\}.$$

Proposition 2.5.1. *The map*

$$f: K_{\mathbb{R}} \xrightarrow{\cong} \mathbb{R}^{r+2s} = \prod_{\tau} \mathbb{R},$$

$$x \mapsto (x_{\varphi_1}, \dots, x_{\varphi_r}, \operatorname{Re} x_{\sigma_1}, \operatorname{Im} x_{\sigma_1}, \dots, \operatorname{Re} x_{\sigma_s}, \operatorname{Im} x_{\sigma_s}).$$

is an isomorphism. It transforms the canonical metric into the scalar product

$$\langle x, y \rangle = \sum_{\tau} \alpha_{\tau} x_{\tau} y_{\tau},$$

where

$$\alpha_{\tau} = \begin{cases} 1, & \tau = \varphi_i \text{ for some } i, \\ 2, & \tau = \sigma_j \text{ for some } j. \end{cases}$$

Proof. Obviously, f is an isomorphism. For $x = (x_{\tau}), y = (y_{\tau}) \in K_{\mathbb{R}}$ we have

$$\begin{aligned} \langle x, y \rangle|_{K_{\mathbb{R}}} &= \sum_{\tau} x_{\tau} \overline{y_{\tau}} \\ &= \sum_{\varphi_i} x_{\varphi_i} y_{\varphi_i} + \sum_{\sigma_j} x_{\sigma_j} \overline{y_{\sigma_j}} + \sum_{\overline{\sigma_j}} \overline{(x_{\sigma_j} y_{\sigma_j})} \\ &= \dots = (f(x), f(y)). \end{aligned}$$

□

Remark. • The canonical metric induces a volume $\operatorname{vol}_{\text{can}}$ on $K_{\mathbb{R}}$ and thus on \mathbb{R}^{r+2s} .

- If we denote the Lebesgue measure on \mathbb{R}^{r+2s} by $\operatorname{vol}_{\text{Leb}}$ then, for $X \subset K_{\mathbb{R}}$,

$$2^s \operatorname{vol}_{\text{Leb}} f(X) = \operatorname{vol}_{\text{can}} X.$$

- We will thus consider $K \supset U \xrightarrow{j} j(U) \xrightarrow{f} \mathbb{R}^{r+2s}$.

Example. Let $e_j = (0, \dots, 1, \dots, 0)$. Note that we have $\langle e_{\varphi_i}, e_{\varphi_i} \rangle = 1$ and $\langle e_{\sigma_j}, e_{\varphi_j} \rangle = 2$, such that $\langle \frac{e_{\sigma_j}}{\sqrt{2}}, \frac{e_{\sigma_j}}{\sqrt{2}} \rangle = 1$. Hence

$$\left\{ e_{\varphi_1}, \dots, e_{\varphi_r}, \frac{e_{\sigma_1}}{\sqrt{2}}, \frac{e_{\overline{\sigma_1}}}{\sqrt{2}}, \dots \right\}$$

is an orthonormal basis. Using the correspondence

$$X \subset K_{\mathbb{R}} \leftrightarrow f(X) \subset \mathbb{R}^{r+2s}$$

we thus define

$$\operatorname{vol}_{\text{can}} X = \operatorname{vol}_{\text{can}} f(X) = 2^s \operatorname{vol}_{\text{Leb}} f(X).$$

Proposition 2.5.2. *If $I \neq 0$ is an \mathcal{O}_k -ideal then $\Gamma = j(I)$ is a complete lattice in $K_{\mathbb{R}}$. Its fundamental domain has volume*

$$\text{vol } \Gamma = \text{vol } \phi = \sqrt{|d_k|} \cdot [\mathcal{O}_k : I].$$

Proof. Choose α_i such that $I = \alpha_1\mathbb{Z} + \cdots + \alpha_n\mathbb{Z}$. Then $\Gamma = j(I) = j(\alpha_1)\mathbb{Z} + \cdots + j(\alpha_n)\mathbb{Z}$. Define

$$A = (j(\alpha_1), \dots, j(\alpha_n))^T = \begin{pmatrix} \tau_1(\alpha_1) & \cdots & \tau_n(\alpha_1) \\ \vdots & \ddots & \vdots \\ \tau_1(\alpha_n) & \cdots & \tau_n(\alpha_n) \end{pmatrix}$$

such that

$$\text{vol } \phi = |\det A| = \sqrt{|d_k|} \cdot [\mathcal{O}_k : I].$$

Furthermore,

$$d(I) = d(\alpha_1, \dots, \alpha_n) = |\det A|^2 = d(\mathcal{O}_k) \cdot [\mathcal{O}_k : I]^2,$$

with $[\mathcal{O}_k : I] = |\det M|$ for the change of basis M from \mathcal{O}_k to I . \square

Theorem 2.5.3. *Let $I \neq 0$ be an ideal in \mathcal{O}_k . Let $(c_\tau)_\tau$ be a collection of real number such that $c_\tau > 0$, $c_\tau = c_{\bar{\tau}}$ and*

$$\prod_{\tau} c_\tau > \left(\frac{2}{\pi}\right)^s \sqrt{|d_k|} \cdot [\mathcal{O}_k : a].$$

Then there exists $a \in I \setminus \{0\}$ such that

$$|\tau(a)| < c_\tau$$

for all $\tau \in \text{Hom}(K, \mathbb{C})$.

Proof. Consider the convex, central symmetric set

$$X = \{(x_\tau) \in K_{\mathbb{R}} \mid |x_\tau| < c_\tau \text{ for all } \tau\}$$

and let $f: K_{\mathbb{R}} \rightarrow \mathbb{R}^n$, $n = r + 2s$, as in Proposition 5.1. Notice that for $x \in X$ we have $f(x) = (x_{\varphi_1}, \dots, x_{\varphi_r}, a_1, b_1, \dots, a_s, b_s)$ with $|x_{\varphi_i}| < c_{\varphi_i}$ and $a_j^2 + b_j^2 < c_{\sigma_j}^2$. Hence

$$\text{vol}_{\text{can}} X = 2^s \text{vol}_{\text{Leb}} f(X) = 2^s \left(\prod_{i=1}^r 2c_{\varphi_i} \right) \left(\prod_{j=1}^s \pi c_{\sigma_j}^2 \right) = 2^{r+s} \pi^s \prod_{\tau} c_\tau,$$

and thus, by Proposition 5.2,

$$\begin{aligned} 2^n \text{vol } \Gamma &= 2^{r+2s} \sqrt{|d_k|} \cdot [\mathcal{O}_k : I] \\ &= 2^{r+s} \pi^s \left[\left(\frac{2}{\pi}\right)^s \sqrt{|d_k|} \cdot [\mathcal{O}_k : a] \right] \\ &< 2^{r+s} \pi^s \prod_{\tau} c_\tau \\ &= \text{vol}_{\text{can}} X. \end{aligned}$$

Consequently, by Minkowski's theorem, there exists $j(a) \in \Gamma \setminus \{0\}$ with $j(a) \in X$ and $|\tau(a)| < c_\tau$ for all τ . \square

Multiplicative Minkowsky theory

Define

$$j: K^* \hookrightarrow K_{\mathbb{C}}^* = \prod_{\tau} \mathbb{C}^*, a \mapsto (\tau(a))_{\tau}$$

and

$$\mathcal{N}: K_{\mathbb{C}}^* \rightarrow \mathbb{C}^*, (x_{\tau}) \mapsto \prod_{\tau} x_{\tau}.$$

Denote the composition of these maps by $\mathcal{N}_{K/\mathbb{Q}} = \mathcal{N} \circ j$. Furthermore, consider

$$l: \mathbb{C}^* \rightarrow \mathbb{R}, z \mapsto \log |z|$$

and its extension

$$l: K_{\mathbb{C}}^* \rightarrow \prod_{\tau} \mathbb{R}, (x_{\tau}) \mapsto (\log |x_{\tau_1}|, \dots, \log |x_{\tau_n}|).$$

All in all, we have

$$\begin{array}{ccccc} K^* & \xrightarrow{j} & K_{\mathbb{C}}^* & \xrightarrow{l} & \prod_{\tau} \mathbb{R} \\ \mathcal{N}_{K/\mathbb{Q}} \downarrow & & \downarrow \mathcal{N} & & \downarrow \text{Tr} \\ \mathbb{Q}^* & \xrightarrow{i} & \mathbb{C}^* & \xrightarrow{l} & \mathbb{R} \end{array}$$

with

$$\left[\prod_{\tau} \mathbb{R} \right]^+ = \prod_{\varphi_i} \mathbb{R} \times \prod_{\sigma_j} [\mathbb{R} \times \mathbb{R}]^+ \xrightarrow{\cong} \mathbb{R}^{r+s},$$

where the isomorphism is given by

$$(x_{\varphi_1}, \dots, x_{\varphi_r}, x_{\sigma_1}, x_{\overline{\sigma_1}}, \dots, x_{\sigma_s}, x_{\overline{\sigma_s}}) \mapsto (x_{\varphi_1}, \dots, x_{\varphi_r}, 2x_{\sigma_1}, \dots, 2x_{\sigma_s}),$$

and we have

$$K_{\mathbb{R}} \rightarrow \mathbb{R}^{r+s}, (x_{\tau}) \mapsto (\log |x_{\varphi_1}|, \dots, \log |x_{\varphi_r}|, \log |x_{\sigma_1}|^2, \dots, \log |x_{\sigma_s}|^2).$$

2.6 The class number

Let $n = [K : \mathbb{Q}]$, denote by J_K the group of fractional ideals of K , by P_k its subgroup of principal ideals and by $\text{Cl}_k = J_k/P_k$ the ideal class group. Define the **absolute norm** of an ideal $I \subset \mathcal{O}_k$ by

$$n(I) = [\mathcal{O}_k : I].$$

For $I = (\alpha)$, we have $n(I) = \mathcal{N}_{K/\mathbb{Q}}(\alpha)$. If $\mathcal{O}_k = w_1\mathbb{Z} + \dots + w_n\mathbb{Z}$ and $I = \alpha w_1\mathbb{Z} + \dots + \alpha w_n\mathbb{Z}$ we have

$$\alpha w_i = \sum_j a_{ij} w_j$$

for some matrix $A = (a_{ij})$ such that $\mathcal{N}_{K/\mathbb{Q}}(\alpha) = |\det A| = [\mathcal{O}_k : I]$.

Proposition 2.6.1. *If $I = P_1^{\nu_1} \cdots P_r^{\nu_r}$ then $n(I) = n(P_1)^{\nu_1} \cdots n(P_r)^{\nu_r}$.*

Proof. By the Chinese remainder theorem,

$$\mathcal{O}_k/I \cong (\mathcal{O}_k/P_1^{\nu_1}) \oplus \cdots \oplus (\mathcal{O}_k/P_r^{\nu_r}),$$

such that

$$n(I) = [\mathcal{O}_k : I] = \prod_j [\mathcal{O}_k : P_j^{\nu_j}] = \prod_j n(P_j)^{\nu_j}.$$

Claim: $P \supsetneq P^2 \supsetneq \cdots \supsetneq P^\nu$ and P^i/P^{i+1} is a (\mathcal{O}_k/P) -vector space of dimension 1

Proof of Claim: Let $a \in P^i/P^{i+1}$. Then we have

$$P^i \supset J = (a) + P^{i+1} \supsetneq P^{i+1}$$

and

$$\mathcal{O}_k \supset J' = JP^{-i} \supsetneq P = P^{i+1}P^{-i}.$$

Since $J'|P$ we have $J = P^i$ and thus $[a] \in P^i/P^{i+1}$ is a basis.

Now, the Claim yields

$$n(P^\nu) = [\mathcal{O}_k : P^\nu] = [\mathcal{O}_k : P] [P : P^2] \cdots [P^{\nu-1} : P^\nu] n(P)^\nu.$$

□

In particular, for integral ideals I, J we have $n(IJ) = n(I)n(J)$ such that we can extend n to J_k by

$$n: J_k \rightarrow \mathbb{R}_+^*, I = P_1^{\nu_1} \cdots P_r^{\nu_r} \mapsto n(I) = n(P_1)^{\nu_1} \cdots n(P_r)^{\nu_r}.$$

Reminder 2.6.2. \mathcal{J}_K = group of fractional ideals = abelian group generated by all prime ideals

\mathcal{P}_K = group of all principal fractional ideals.

$\text{Cl}_K := \mathcal{J}_K/\mathcal{P}_K$

\Rightarrow obtain following exact sequence:

$$1 \rightarrow \underbrace{\mathcal{O}_K^\times}_{\text{How big?}} \rightarrow K^\times \rightarrow \mathcal{J}_K \rightarrow \underbrace{\text{Cl}_K}_{\text{How big?}} \rightarrow 1$$

$$a \mapsto (a) = a\mathcal{O}_K$$

Last Time: \mathfrak{a} ideal in \mathcal{O}_K , $\mathfrak{a} \neq 0$.

- $\mathcal{N}(\mathfrak{a}) = (\mathcal{O}_K : \mathfrak{a})$ absolute norm.

In particular: $\mathcal{N}((a)) := |\mathcal{N}_{K/\mathbb{Q}}(a)|$.

- $\mathfrak{a} = \mathcal{P}_1^{\nu_1} \cdots \mathcal{P}_r^{\nu_r}$ decomposition into primes
 $\Rightarrow \mathcal{N}(\mathfrak{a}) = \mathcal{N}(\mathcal{P}_1)^{\nu_1} \cdots \mathcal{N}(\mathcal{P}_r)^{\nu_r}$

In particular: $\mathcal{N}(\mathfrak{a}_1\mathfrak{a}_2) = \mathcal{N}(\mathfrak{a}_1)\mathcal{N}(\mathfrak{a}_2)$.

- Hence \mathcal{N} can be extended to fractional ideals: $\mathcal{N} : \mathcal{J}_K \rightarrow \mathbb{R}_+^\times$.

Goal: Show that Cl_K is finite.

Idea:

- Find in each integral ideal \mathfrak{a} an element $a \neq 0$ of norm bounded by $\mathcal{N}(\mathfrak{a})$.
- Show: For $M > 0$ there are only finitely many integral ideals \mathfrak{a} with $\mathcal{N}(\mathfrak{a}) \leq M$.
- Show: Each class $[\mathfrak{a}] \in \text{Cl}_K$ contains an integral ideal \mathfrak{a}_1 s.t. $\mathcal{N}(\mathfrak{a}_1) \leq M_0 = \left(\frac{2}{\pi}\right)^s \sqrt{|d_K|}$.
Recall: s = number of not-real embeddings of K into \mathbb{C} .

Lemma 2.6.3. *Suppose: $\mathfrak{a} \neq 0$ is an integral ideal $\Rightarrow \exists a \in \mathfrak{a}, a \neq 0$ s.t. $|\mathcal{N}_{K/\mathbb{Q}}(a)| \leq \left(\frac{2}{\pi}\right)^s \sqrt{|d_K|} \mathcal{N}(\mathfrak{a})$.*

Proof. $M_0 := \left(\frac{2}{\pi}\right)^s \sqrt{|d_K|}$

Idea: Use „Thm. 5.3“

given: $c_\tau \in \mathbb{R}_{>0} (\tau \in \text{Hom}(K, \mathbb{C}))$ with $c_\tau = c_{\bar{\tau}}$ and $\prod_\tau c_\tau > M_0 \mathcal{N}(\mathfrak{a})$

$\Rightarrow \exists a \in \mathfrak{a}, a \neq 0$ with $|\tau(a)| < c_\tau$ for all τ .

For each $\varepsilon > 0$ choose a sequence $c_\tau \in \mathbb{R}_{>0}$ with $c_\tau = c_{\bar{\tau}}$ and $\prod_\tau c_\tau = M_0 \mathcal{N}(\mathfrak{a}) + \varepsilon$

$\xRightarrow{\text{Thm 5.3}}$ Find $a_\varepsilon \neq 0$ in \mathfrak{a} with

$$|\mathcal{N}_{K/\mathbb{Q}}(a)| = \prod_\tau |\tau(a)| < M_0 \mathcal{N}(\mathfrak{a}) + \varepsilon$$

Since left side is integer, we obtain: $\exists a \neq 0$ in \mathfrak{a} with $|\mathcal{N}_{K/\mathbb{Q}}(a)| \leq M_0 \mathcal{N}(\mathfrak{a})$. \square

Lemma 2.6.4. *Let $M \in \mathbb{R}_{>0}$. There are only finitely many integral ideals \mathfrak{a} with $\mathcal{N}(\mathfrak{a}) \leq M$.*

Proof. (1) Consider first only prime ideals $\mathcal{P} \neq 0$: Suppose $\mathcal{N}(\mathcal{P}) \leq M$

Recall: $\mathcal{P} \cap \mathbb{Z} = p\mathbb{Z}$ with p prime number (Prop. 3.3)

\Rightarrow obtain embedding $\mathcal{F}_p = \mathbb{Z}/p\mathbb{Z} \hookrightarrow \mathcal{O}_K/\mathcal{P} \Rightarrow \mathcal{N}(\mathcal{P}) = (\mathcal{O}_K : \mathcal{P}) = \#\mathcal{O}_K/\mathcal{P} = p^f$

Hence: $p^f \leq M$. In particular P is bounded.

Furthermore: There are only finitely many prime ideals \mathcal{P} with $\mathcal{P} \cap \mathbb{Z} = p\mathbb{Z}$.

Since $\mathcal{P} \cap \mathbb{Z} = p\mathbb{Z} \Rightarrow p \in \mathcal{P} \Rightarrow (p) \subseteq \mathcal{P}$ But there are only finitely many prime ideals in \mathcal{O}_K which divide (p) .

(2) Suppose now \mathfrak{a} is an arbitrary integral ideal, $\mathfrak{a} \neq 0$:

$\Rightarrow \mathfrak{a} = \mathcal{P}_1^{\nu_1} \cdots \mathcal{P}_r^{\nu_r}$ with \mathcal{P}_i prime ideal and $\nu_i \in \mathbb{N}$ and $\mathcal{N}(\mathfrak{a}) = \mathcal{N}(\mathcal{P}_1)^{\nu_1} \cdots \mathcal{N}(\mathcal{P}_r)^{\nu_r}$.

Now the claim follows from (1). \square

Theorem 2.6.5 (Finiteness of Cl_K). *The ideal class group of $\text{Cl}_K = \mathcal{J}_K/\mathcal{P}_K$ is finite.*

Proof. Let $M_0 := \left(\frac{2}{\pi}\right)^s \sqrt{|d_K|}$

Show that each class $[\mathfrak{a}] \in \text{Cl}_K$ contains an integral ideal \mathfrak{a}_1 with $\mathcal{N}(\mathfrak{a}_1) \leq M_0$. Then the

claim follows from Lemma 6.3.

Let $[\mathfrak{a}] \in \text{Cl}_K$. Choose $\gamma \in \mathcal{O}_K, \gamma \neq 0$ with $\gamma \mathfrak{a}^{-1}$ is integral.

$$\begin{aligned} \text{Lemma 6.2} &\Rightarrow \exists b \in \mathfrak{b} := \gamma \mathfrak{a}^{-1} \text{ with } b \neq 0 \text{ and } |\mathcal{N}_{K/\mathbb{Q}}(b)| \leq M_0 \mathcal{N}(\mathfrak{b}) \\ &\Rightarrow \mathcal{N}((b)\mathfrak{b}^{-1}) = \mathcal{N}((b))\mathcal{N}(\mathfrak{b}^{-1}) \leq M_0 \end{aligned}$$

Observe: The factorial ideal $(b)\mathfrak{b}^{-1} = (b)\gamma^{-1}\mathfrak{a} \in [\mathfrak{a}]$, hence $\mathfrak{a}_1 := b\gamma^{-1}\mathfrak{a}$ does the job. \mathfrak{a}_1 is an integral ideal, since $(b) \subseteq \gamma \mathfrak{a}^{-1}$ \square

Definition 2.6.6 („Klassenzahl“). $h_K := \# \text{Cl}_K := (\mathcal{J}_K : \mathcal{P}_K)$ is called the class number of K .

Proposition 2.6.7. *Suppose R is a Dedekind domain.
 R is a UFD $\iff R$ is a PID (principal ideal domain).*

Proof. „ \Leftarrow “: true for general domains.

„ \Rightarrow “: Suppose R is a UFD.

Step 1: Every prime ideal is principal.

Let \mathcal{P} be a prime ideal, $\mathcal{P} \neq 0$. Choose $a \in \mathcal{P}, a \neq 0$. Let $a = p_1 \cdots p_n$ be its prime factor decomposition. \mathcal{P} prime $\Rightarrow p_i \in \mathcal{P}$ for one of the i 's $\Rightarrow \mathcal{P} \supseteq (p_i) \Rightarrow \mathcal{P} = (p_i)$, since (p_i) is a prime ideal and R is a Dedekind domain.

Step 2: \mathfrak{a} arbitrary ideal.

$\Rightarrow \mathfrak{a} = \mathcal{P}_1 \cdots \mathcal{P}_n$ is a product of prime ideals

$\Rightarrow \mathfrak{a}$ is principal, since each \mathcal{P}_i is. \square

Corollary 2.6.8. *We have for a number field K :*

$h_K = 1 \iff \mathcal{O}_K$ is a principal domain $\iff \mathcal{O}_K$ is a UFD.

2.7 The theorem of Dirichlet

Goal: Describe \mathcal{O}_K^\times

Recall:

- $\mathcal{O}^\times = \{\varepsilon \in \mathcal{O}_K \mid \mathcal{N}_{K/\mathbb{Q}}(\varepsilon) = \pm 1\}$
- $\mu(K) := \{x \in \mathcal{O}_K \mid \exists n \in \mathbb{N} \text{ with } x^n = 1\} \subseteq \mathcal{O}_K^\times$ is a finite subgroup.

Idea: Use multiplicative Minkowsky theory:

- $\text{Hom}(K, \mathbb{C}) = \{\tau_1, \dots, \tau_r, \tau_{r+1}, \overline{\tau_{r+1}}, \tau_{r+s}, \overline{\tau_{r+s}}\}$
- $j : K^\times \hookrightarrow K_{\{\mathbb{R}\}}^\times = \{x \in \prod_\tau \mathbb{C}^\times \mid x_{\bar{\tau}} = \overline{x_\tau}\}, a \mapsto (\tau(a))_\tau$
- $l : K_{\mathbb{R}}^\times \rightarrow [\prod_\tau \mathbb{R}]^+ := \{z \in \prod_\tau \mathbb{R} \mid z_{\bar{\tau}} = z_\tau\}, x = (x_\tau) \mapsto (\log |x_\tau|)_\tau$

\Rightarrow commutative diagramm:

$$\begin{array}{ccccc}
 \mathcal{O}_K^\times & & S & & H \\
 \wr & & \wr & & \wr \\
 K^\times & \xhookrightarrow{j} & K_{\mathbb{R}}^\times & \xrightarrow{l} & [\prod_{\tau} \mathbb{R}]^+ \\
 \downarrow \mathcal{N}_{K/\mathbb{Q}} & & \downarrow \mathcal{N} & & \downarrow \text{Tr} \\
 \mathbb{Q}^\times & \longrightarrow & \mathbb{R} & \longrightarrow & \mathbb{R}
 \end{array}$$

with $\mathcal{N}(x) = \prod_{\tau} x_{\tau}$, $\text{Tr}(z) = \sum_{\tau} z_{\tau}$.

Consider the three groups:

- (1) $\mathcal{O}_K^\times = \{\varepsilon \in \mathcal{O}_K \mid \mathcal{N}_{K/\mathbb{Q}}(\varepsilon) = \pm 1\}$
- (2) $S := \{x \in K_{\mathbb{R}}^\times \mid \mathcal{N}(x) = \pm 1\}$ „Norm 1 hyper surface“
- (3) $H := \{z \in [\prod_{\tau} \mathbb{R}]^+ \mid \text{Tr}(z) = 0\}$ „Trace 0 hypersurface“