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## 0.1. Prerequisites

**Definition.**  $I \subset R$  is **prime ideal** if  $\forall a, b \in R, ab \in I \implies a \in I \vee b \in I$ .

**Definition.** Ideal  $I$  is **maximal** if  $I \neq R$  and there is no ideal  $J \subset R$  such that  $I \subset J$ .

**Example.**

- $p \in \mathbb{Z}$  is prime iff  $\langle p \rangle = p\mathbb{Z}$  is prime ideal.
- $\langle 0 \rangle$  is prime ideal iff  $R$  is integral domain.

**Lemma.** If  $I$  is maximal ideal, then it is prime.

**Proposition.** For commutative ring  $R$ , ideal  $I$ :

- $I \subset R$  is prime ideal iff  $R/I$  is an integral domain.
- $I$  is maximal iff  $R/I$  is field.

**Proposition.** Let  $R$  be PID and  $a \in R$  irreducible. Then  $\langle a \rangle = \langle a \rangle_R$  is maximal.

**Theorem.** Let  $F$  be field,  $f(x) \in F[x]$  irreducible. Then  $F[x]/\langle f(x) \rangle$  is a field and a vector space over  $F$  with basis  $B = \{1, \bar{x}, \dots, \bar{x}^{n-1}\}$  where  $n = \deg(f)$ . That is, every element in  $F[x]/\langle f(x) \rangle$  can be uniquely written as linear combination

$$\overline{a_0 + a_1x + \dots + a_{n-1}x^{n-1}}, \quad a_i \in F$$

## 1. Divisibility in rings

### 1.1. Every ED is a PID

**Definition.** Let  $R$  integral domain.  $\varphi : R - \{0\} \rightarrow \mathbb{N}_0$  is **Euclidean function (norm)** on  $R$  if:

- $\forall x, y \in R - \{0\}, \varphi(x) \leq \varphi(xy)$ .
- $\forall x \in R, y \in R - \{0\}, \exists q, r \in R : x = qy + r$  with either  $r = 0$  or  $\varphi(r) < \varphi(y)$ .

$R$  is **Euclidean domain (ED)** if Euclidean function is defined on it.

**Example.**

- $\mathbb{Z}$  is ED with  $\varphi(n) = |n|$ .
- $F[x]$  is ED for field  $F$  with  $\varphi(f) = \deg(f)$ .

**Lemma.**  $\mathbb{Z}[-\sqrt{2}]$  is ED with Euclidean function

$$\varphi(a + b\sqrt{-2}) = N(a + b\sqrt{-2}) := a^2 + 2b^2$$

**Proposition.** Every ED is a PID.

### 1.2. Every PID is a UFD

**Definition.** Integral domain  $R$  is **unique factorisation domain (UFD)** if every non-zero non-unit in  $R$  can be written uniquely (up to order of factors and multiplication by units) as product of irreducible elements in  $R$ .

**Example.** Let  $R = \{f(x) \in \mathbb{Q}[x] : f(0) \in \mathbb{Z}\}$ . Its units are  $\pm 1$ . Any factorisation of  $x \in R$  must be of the form  $f(x)g(x)$  where  $\deg f = 1, \deg g = 0$ , so  $x = (ax + b)c$ ,  $a \in \mathbb{Q}, b, c \in \mathbb{Z}$ . We have  $bc = 0$  and  $ac = 1$  hence  $x = \frac{x}{c} \cdot c$ . So  $x$  irreducible if

$c \neq \pm 1$ . Also, any factorisation of  $\frac{x}{c}$  in  $R$  is of the form  $\frac{x}{c} = \frac{x}{cd} \cdot d$ ,  $d \in \mathbb{Z}$ ,  $d \neq 0$ . Again, neither factor is a unit when  $d \neq \pm 1$ . So  $x = \frac{x}{c} \cdot c = \frac{x}{cd} \cdot c \cdot c = \dots$  can never be decomposed into irreducibles (the first factor is never irreducible).

**Lemma.** Let  $R$  be PID. Then every irreducible element is prime in  $R$ .

**Theorem.** Every PID is a UFD.

**Example.**  $\mathbb{Z}[\sqrt{-2}]$  is ED so by the above theorem it is a UFD. Let  $x, y \in \mathbb{Z}$  such that  $y^2 + 2 = x^3$ .

- $y$  must be odd, since if  $y = 2a$ ,  $a \in \mathbb{Z}$  then  $x = 2b$ ,  $b \in \mathbb{Z}$  but then  $2a^2 + 1 = 4b^3$ .
- $y \pm \sqrt{-2}$  are relatively prime: if  $a + b\sqrt{-2}$  divides both, then it divides their difference  $2\sqrt{-2}$ , so norm  $a^2 + 2b^2 \mid N(2\sqrt{-2}) = 8$ . Only possible case is  $a = \pm 1, b = 0$  so  $a + b\sqrt{-2}$  is unit. Other cases  $a = 0, b = \pm 1$ ,  $a = \pm 2, b = 0$  and  $a = 0, b = \pm 2$  are impossible since  $y$  not even.
- If  $a + b\sqrt{-2}$  is unit,  $\exists x, y \in \mathbb{Z} : (a + b\sqrt{-2})(x + y\sqrt{-2}) = 1$ . If  $b \neq 0$  then  $(-a^2 - 2b^2)y = 1 \implies b = 0$ : contradiction. If  $b = 0$ ,  $a = \pm 1$ . So only units in  $\mathbb{Z}[\sqrt{-2}]$  are  $\pm 1$ .

## 2. Finite field extensions

**Definition.** Let  $F, L$  fields. If  $F \subseteq L$  and  $F$  and  $L$  share the same operations then  $F$  is a **subfield** of  $L$  and  $L$  is **field extension** of  $F$  (denoted  $L/F$ ).  $L$  is vector space over  $F$ :

- $0 \in L$  (zero vector).
- $u, v \in L \implies u + v \in L$  (additivity).
- $a \in F, u \in L \implies au \in L$  (scalar multiplication).

**Definition.** Let  $L/F$  field extension. **Degree** of  $L$  over  $F$  is dimension of  $L$  as vector space over  $F$ :

$$[L : F] := \dim_F(L)$$

If  $[L : F]$  finite,  $L/F$  is **finite field extension**.

**Example.**  $\mathbb{Q}(\sqrt{-2}) = \{a + b\sqrt{-2} : a, b \in \mathbb{Q}\}$  is isomorphic as a vector space to  $\mathbb{Q}^2$  so is 2-dimensional vector space over  $\mathbb{Q}$ . Isomorphism is  $a + b\sqrt{-2} \leftrightarrow (a, b)$ . Standard basis  $\{e_1, e_2\}$  in  $\mathbb{Q}^2$  corresponds to the basis  $\{1, \sqrt{-2}\}$  in  $\mathbb{Q}(\sqrt{-2})$ .  $[\mathbb{Q}(\sqrt{-2}) : \mathbb{Q}] = 2$ .

**Example.**  $[\mathbb{C} : \mathbb{R}] = 2$  (a basis is  $\{1, i\}$ ).  $[\mathbb{R} : \mathbb{Q}]$  is not finite, due to the existence of transcendental numbers (if  $\alpha$  transcendental, then  $\{1, \alpha, \alpha^2, \dots\}$  is linearly independent).

**Definition.** Let  $L/F$  field extension.  $\alpha \in L$  is **algebraic** over  $F$  if

$$\exists f(x) \in F[x] : f(\alpha) = 0$$

If all elements in  $L$  are algebraic, then  $L/F$  is **algebraic field extension**.

**Example.**  $i \in \mathbb{C}$  is algebraic over  $\mathbb{R}$  since  $i$  is root of  $x^2 + 1$ .  $\mathbb{C}/\mathbb{R}$  is algebraic since  $z = a + bi$  is root of  $(x - z)(x - \bar{z}) = x^2 - 2ax + a^2 + b^2$ .

**Proposition.** If  $L/F$  is finite field extension then it is algebraic.

**Definition.** Let  $L/F$  field extension,  $\alpha \in L$  algebraic over  $F$ . **Minimal polynomial**  $p_\alpha(x) = p_{\alpha,F}(x)$  of  $\alpha$  over  $F$  is the monic polynomial  $f$  of smallest degree such that  $f(\alpha) = 0$ . **Degree** of  $\alpha$  over  $F$  is  $\deg(p_\alpha)$ .

**Proposition.**  $p_\alpha(x)$  is unique and irreducible. Also, if  $f(x) \in F[x]$  is monic, irreducible and  $f(\alpha) = 0$ , then  $f = p_\alpha$ .

**Example.**

- $p_{i,\mathbb{R}}(x) = p_{i,\mathbb{Q}}(x) = x^2 + 1$ ,  $p_{i,\mathbb{Q}(i)}(x) = x - i$ .
- Let  $\alpha = \sqrt[7]{5}$ .  $f(x) = x^7 - 5$  is minimal polynomial of  $\alpha$  over  $\mathbb{Q}$  by above proposition, as it is irreducible by Eisenstein's criterion with  $p = 5$ .
- Let  $\alpha = e^{2\pi i/p}$ ,  $p$  prime.  $\alpha$  is algebraic as root of  $x^p - 1$  which isn't irreducible as  $x^p - 1 = (x - 1)\Phi(x)$  where  $\Phi(x) = (x^{p-1} + \dots + 1)$ .  $\Phi(\alpha) = 0$  since  $\alpha \neq 1$ ,  $\Phi(x)$  is monic and  $\Phi(x + 1) = ((x + 1)^p - 1)/x$  irreducible by Eisenstein's criterion with  $p = p$ , hence  $\Phi(x)$  irreducible. So  $p_\alpha(x) = \Phi(x)$ .

## 2.1. Fields generated by elements

**Definition.** Let  $L/F$  field extension,  $\alpha \in L$ . The **field generated by  $\alpha$  over  $F$**  is the smallest subfield of  $L$  containing  $F$  and  $\alpha$ :

$$F(\alpha) := \bigcap_{\substack{K \text{ field,} \\ F \subseteq K \subseteq L, \\ \alpha \in K}} K$$

Generally,  $F(\alpha_1, \dots, \alpha_n)$  is smallest field extension of  $F$  containing  $\alpha_1, \dots, \alpha_n$ .

- We have  $F(\alpha_1, \dots, \alpha_n) = F(\alpha_1) \cdots F(\alpha_n)$  (show  $F(\alpha, \beta) \subseteq F(\alpha)(\beta)$  and  $F(\alpha)(\beta) \subseteq F(\alpha, \beta)$  by minimality and use induction).

**Definition.**  $F[\alpha] = \{\sum_{i=0}^n a_i \alpha^i : a_i \in F, n \in \mathbb{N}\} = \{f(\alpha) : f(x) \in F[x]\}$ .

**Lemma.** Let  $L/F$  field extension,  $\alpha \in L$  algebraic over  $F$ . Then  $F[\alpha]$  is field, hence  $F(\alpha) = F[\alpha]$ .

**Lemma.** Let  $\alpha$  algebraic over  $F$ . Then  $[F(\alpha) : F] = \deg(p_\alpha)$ .

**Definition.** Let  $K/F$  and  $L/K$  field extensions, then  $F \subseteq K \subseteq L$  is **tower of fields**.

**Theorem** (Tower theorem). Let  $F \subseteq K \subseteq L$  tower of fields. Then

$$[L : F] = [L : K] \cdot [K : F]$$

**Example.** Let  $L = \mathbb{Q}(\sqrt{2}, \sqrt{3})$ . Show  $[L : \mathbb{Q}] = 4$ .

- Let  $K = \mathbb{Q}(\sqrt{2})$ . Let  $\sqrt{3} = a + b\sqrt{2}$ ,  $a, b \in \mathbb{Q}$  so  $3 = a^2 + 2b^2 + 2ab\sqrt{2}$ . So  $0 \in \{a, b\}$ , otherwise  $\sqrt{2} \in \mathbb{Q}$ . But if  $a = 0$ , then  $\sqrt{6} = 2b \in \mathbb{Q}$ , if  $b = 0$  then  $\sqrt{3} = a \in \mathbb{Q}$ : contradiction. So  $x^2 - 3$  has no roots in  $K$  so is irreducible over  $K$  so  $p_{\sqrt{3},K}(x) = x^2 - 3$ .
- So  $[L : K] = 2$  so by the tower theorem,  $[L : \mathbb{Q}] = [L : K] \cdot [K : \mathbb{Q}] = 4$ .

## 2.2. Norm and trace

- Let  $L/F$  finite field extension,  $n = [L : F]$ . For any  $\alpha \in L$ , there is  $F$ -linear map

$$\hat{\alpha} : L \longrightarrow L, \quad x \mapsto \alpha x$$

- With basis  $\{\alpha_1, \dots, \alpha_n\}$  of  $L$  over  $F$ , let  $T_\alpha = T_{\alpha, L/F} \in M_n(F)$  be the corresponding matrix of the linear map  $\alpha$  with respect to the basis  $\{\alpha_i\}$ :

$$\begin{aligned} \hat{\alpha}(\alpha_1) &= \alpha\alpha_1 = a_{1,1}\alpha_1 + \dots + a_{1,n}\alpha_n, \\ &\vdots \\ \hat{\alpha}(\alpha_n) &= \alpha\alpha_n = a_{n,1}\alpha_1 + \dots + a_{n,n}\alpha_n \end{aligned}$$

with  $a_{i,j} \in F$ ,  $T_\alpha = (a_{i,j})$ , so  $\alpha$  is eigenvalue of  $T_\alpha$ :

$$\alpha \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix} = T_\alpha \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix}$$

**Definition.** Norm of  $\alpha$  is

$$N_{L/F}(\alpha) := \det(T_\alpha)$$

**Definition.** Trace of  $\alpha$  is

$$\text{tr}_{L/F}(\alpha) := \text{tr}(T_\alpha)$$

**Remark.** Norm and trace are independent of choice of basis so are well-defined (uniquely determined by  $\alpha$ ).

**Example.** Let  $L = \mathbb{Q}(\sqrt{m})$ ,  $m \in \mathbb{Z}$  non-square, let  $\alpha = a + b\sqrt{m} \in L$ . Fix basis  $\{1, \sqrt{m}\}$ . Now

$$\begin{aligned} \hat{\alpha}(1) &= \alpha \cdot 1 = a + b\sqrt{m}, \\ \hat{\alpha}(\sqrt{m}) &= \alpha\sqrt{m} = bm + a\sqrt{m}, \\ T_\alpha &= \begin{bmatrix} a & b \\ bm & a \end{bmatrix} \end{aligned}$$

So  $N_{L/F}(\alpha) = a^2 - b^2m$ ,  $\text{tr}_{L/F}(\alpha) = 2a$ .

**Lemma.** The map  $L \rightarrow M_n(F)$  given by  $\alpha \mapsto T_\alpha$  is injective ring homomorphism. So if  $f(x) \in F[x]$ ,

$$T_{f(\alpha)} = f(T_\alpha)$$

( $f(T_\alpha)$  is a polynomial in  $T_\alpha$ , not  $f$  applied to each entry).

**Proposition.** Let  $L/F$  finite field extension.  $\forall \alpha, \beta \in L$ ,

- $N_{L/F}(\alpha) = 0 \iff \alpha = 0$ .
- $N_{L/F}(\alpha\beta) = N_{L/F}(\alpha)N_{L/F}(\beta)$ .
- $\forall a \in F$ ,  $N_{L/F}(a) = a^{[L:F]}$  and  $\text{tr}_{L/F}(a) = [L:F]\alpha$ .
- $\forall a, b \in F$ ,  $\text{tr}_{L/F}(a\alpha + b\beta) = a \text{tr}_{L/F}(\alpha) + b \text{tr}_{L/F}(\beta)$  (so  $\text{tr}_{L/F}$  is  $F$ -linear map).

## 2.3. Characteristic polynomials

- Let  $A \in M_n(F)$ , then characteristic polynomial is  $\chi_A(x) = \det(xI - A) \in F[x]$  and is monic,  $\deg(\chi_A) = n$ . If  $\chi_A(x) = x^n + \sum_{i=0}^{n-1} c_i x^i$  then

$\det(A) = (-1)^n \det(0 - A) = (-1)^n \chi_A(0) = (-1)^n c_0$  and  $\text{tr}(A) = -c_{n-1}$ , since if  $\alpha_1, \dots, \alpha_n$  are eigenvalues of  $A$  (in some field extension of  $F$ ), then

$$\text{tr}(A) = \alpha_1 + \dots + \alpha_n,$$

$$\chi_A(x) = (x - \alpha_1) \cdots (x - \alpha_n) = x^n - (\alpha_1 + \dots + \alpha_n)x^{n-1} + \dots$$

- For finite extension  $L/F$ ,  $n = [L : F]$ ,  $\alpha \in L$ , **characteristic polynomial**  
 $\chi_\alpha(x) = \chi_{\alpha, L/F}(x)$  is characteristic polynomial of  $T_\alpha$ . So  $N_{L/F}(\alpha) = (-1)^n c_0$ ,  
 $\text{tr}_{L/F}(\alpha) = -c_{n-1}$ . By the Cayley-Hamilton theorem,  $\chi_\alpha(T_\alpha) = 0$  so  
 $T_{\chi_\alpha(\alpha)} = \chi_\alpha(T_\alpha) = 0$ , where  $\chi_\alpha(x) = x^n + c_{n-1}x^{n-1} + \dots + c_0$ . Since  $\alpha \rightarrow T_\alpha$  is  
 injective,  $\chi_\alpha(\alpha) = 0$ .

**Lemma.** Let  $L/F$  finite extension,  $\alpha \in L$  with  $L = F(\alpha)$ . Then  $\chi_\alpha(x) = p_\alpha(x)$ .

**Proposition.** Let  $F \subseteq F(\alpha) \subseteq L$ , let  $m = [L : F(\alpha)]$ . Then  $\chi_\alpha(x) = p_\alpha(x)^m$ .

**Corollary.** Let  $L/F$ ,  $\alpha \in L$  as above,  $p_\alpha(x) = x^d + a_{d-1}x^{d-1} + \dots + a_0$ ,  $a_i \in F$ . Then

$$N_{L/F}(\alpha) = (-1)^{md} a_0^m, \quad \text{tr}_{L/F}(\alpha) = -ma_{d-1}$$

## 3. Algebraic number fields and algebraic integers

### 3.1. Algebraic numbers

**Definition.**  $\alpha \in \mathbb{C}$  is **algebraic number** if algebraic over  $\mathbb{Q}$ .

**Definition.**  $K$  is **(algebraic) number field** if  $\mathbb{Q} \subseteq K \subseteq \mathbb{C}$  and  $[K : \mathbb{Q}] < \infty$ .

- Every element of an algebraic number field is an algebraic number.

**Example.** Let  $\theta = \sqrt{2} + \sqrt{3}$ , then  $\mathbb{Q}(\theta) \subseteq \mathbb{Q}(\sqrt{2}, \sqrt{3})$  but also  $\theta^3 = 11\sqrt{2} + 9\sqrt{3}$  so

$$\sqrt{2} = \frac{\theta^3 - 9\theta}{2}, \quad \sqrt{3} = \frac{-\theta^3 + 11\theta}{2}$$

so  $\mathbb{Q}(\sqrt{2}, \sqrt{3}) \subseteq \mathbb{Q}(\theta)$  hence  $\mathbb{Q}(\sqrt{2}, \sqrt{3}) = \mathbb{Q}(\theta)$ .

**Theorem** (Simple extension theorem). Every number field  $K$  has form  $K = \mathbb{Q}(\theta)$  for some  $\theta \in K$ .

- Set of all algebraic numbers (union of all number fields) is denoted  $\overline{\mathbb{Q}}$  and is a field, since if  $\alpha \neq 0$  algebraic over  $\mathbb{Q}$ ,  $[\mathbb{Q}(\alpha) : \mathbb{Q}] = \deg(p_\alpha) < \infty$  so  $\mathbb{Q}(\alpha)/\mathbb{Q}$  algebraic, so  $-\alpha, \alpha^{-1} \in \mathbb{Q}(\alpha)$  algebraic, so  $\alpha^{-1}, -\alpha \in \overline{\mathbb{Q}}$ , and if  $\alpha, \beta \in \overline{\mathbb{Q}}$  then  $\mathbb{Q}(\alpha, \beta) = \mathbb{Q}(\alpha)(\beta)$  is finite extension of  $\mathbb{Q}$  by tower theorem so  $\alpha + \beta, \alpha\beta \in \mathbb{Q}(\alpha, \beta)$  so are algebraic.
- $[\overline{\mathbb{Q}} : \mathbb{Q}] = \infty$  since if  $[\overline{\mathbb{Q}} : \mathbb{Q}] = d \in \mathbb{N}$  then every algebraic number would have degree  $\leq d$ , but  $\sqrt[d+1]{2}$  has degree  $d+1$  since it is a root of  $x^{d+1} - 2$  which is irreducible by Eisenstein's criterion with  $p = 2$ .

**Definition.** Let  $\alpha \in \overline{\mathbb{Q}}$ . **Conjugates** of  $\alpha$  are roots of  $p_\alpha(x)$  in  $\mathbb{C}$ .

**Example.**

- Conjugate of  $a + bi \in \mathbb{Q}(i)$  is  $a - bi$ .
- Conjugate of  $a + b\sqrt{2} \in \mathbb{Q}(\sqrt{2})$  is  $a - b\sqrt{2}$ .

- Conjugates of  $\theta$  do not always lie in  $\mathbb{Q}(\theta)$ , e.g. for  $\theta = \sqrt[3]{2}$ ,  $p_\theta(x) = x^3 - 2$  has two non-real roots not in  $\mathbb{Q}(\theta) \subset \mathbb{R}$ .

**Notation.** When base field is  $\mathbb{Q}$ ,  $N_K$  and  $\text{tr}_K$  denote  $N_{K/\mathbb{Q}}$  and  $\text{tr}_{K/\mathbb{Q}}$ .

**Lemma.** Let  $K/\mathbb{Q}$  number field,  $\alpha \in K$ ,  $\alpha_1, \dots, \alpha_n$  conjugates of  $\alpha$ . Then

$$N_K(\alpha) = (\alpha_1 \cdots \alpha_n)^{[K:\mathbb{Q}(\alpha)]}, \quad \text{tr}_K(\alpha) = (\alpha_1 + \cdots + \alpha_n)[K:\mathbb{Q}(\alpha)]$$

### 3.2. Algebraic integers

**Definition.**  $\alpha \in \overline{\mathbb{Q}}$  is **algebraic integer** if it is root of a monic polynomial in  $\mathbb{Z}[x]$ .

The set of algebraic integers is denoted  $\overline{\mathbb{Z}}$ . If  $K/\mathbb{Q}$  is number field, set of algebraic integers in  $K$  is denoted  $\mathcal{O}_K$ ,  $\alpha \in \mathcal{O}_K$  is called **integer in  $K$** .

**Example.**  $i, (1 + \sqrt{3})/2 \in \overline{\mathbb{Z}}$  since they are roots of  $x^2 + 1$  and  $x^2 - x + 1$  respectively.

**Theorem.** Let  $\alpha \in \overline{\mathbb{Q}}$ . The following are equivalent:

- $\alpha \in \overline{\mathbb{Z}}$ .
- $p_\alpha(x) \in \mathbb{Z}[x]$ .
- $\mathbb{Z}[\alpha] = \{\sum_{i=0}^{d-1} a_i \alpha^i : a_i \in \mathbb{Z}\}$  where  $d = \deg(p_\alpha)$ .
- There exists non-trivial finitely generated abelian additive subgroup  $G \subset \mathbb{C}$  such that

$$\alpha G \subseteq G \text{ i.e. } \forall g \in G, \alpha g \in G$$

( $\alpha g$  is complex multiplication).

**Remark.**

- For third statement, generally we have  $\mathbb{Z}[\alpha] = \{f(\alpha) : f(x) \in \mathbb{Z}[x]\}$  and in this case,  $\mathbb{Z}[\alpha] = \{f(\alpha) : f(x) \in \mathbb{Z}[x], \deg(f) < d\}$ .
- Fourth statement means that

$$G = \{a_1 \gamma_1 + \cdots + a_r \gamma_r : a_i \in \mathbb{Z}\} = \gamma_1 \mathbb{Z} + \cdots + \gamma_r \mathbb{Z} = \langle \gamma_1, \dots, \gamma_r \rangle_{\mathbb{Z}}$$

$G$  is typically  $\mathbb{Z}[\alpha]$ . E.g. if  $\alpha = \sqrt{2}$ ,  $\mathbb{Z}[\sqrt{2}]$  is generated by  $1, \sqrt{2}$  and  $\sqrt{2} \cdot \mathbb{Z}[\sqrt{2}] \subseteq \mathbb{Z}[\sqrt{2}]$ .

**Proposition.**  $\overline{\mathbb{Z}}$  is a ring. Also, for every number field  $K$ ,  $\mathcal{O}_K$  is a ring.

**Lemma.** Let  $\alpha \in \overline{\mathbb{Z}}$ . For every number field  $K$  with  $\alpha \in K$ ,

$$N_K(\alpha) \in \mathbb{Z}, \quad \text{tr}_K(\alpha) \in \mathbb{Z}$$

**Lemma.** Let  $K$  number field. Then

$$K = \left\{ \frac{\alpha}{m} : \alpha \in \mathcal{O}_K, m \in \mathbb{Z}, m \neq 0 \right\}$$

**Lemma.** Let  $\alpha \in \overline{\mathbb{Z}}$ ,  $K$  number field,  $\alpha \in K$ . Then

$$\alpha \in \mathcal{O}_K^\times \iff N_K(\alpha) = \pm 1$$

### 3.3. Quadratic fields and their integers

**Definition.**  $d \in \mathbb{Z}$  is **squarefree** if  $d \notin \{0, 1\}$  and there is no prime  $p$  such that  $p^2 \mid d$ .

**Definition.**  $K = \mathbb{Q}(\sqrt{d})$  is a **quadratic field** if  $d$  is squarefree. If  $d > 0$  then it is **real quadratic**. If  $d < 0$  it is **imaginary quadratic**.

**Proposition.** Let  $K/\mathbb{Q}$  have degree 2. Then  $K = \mathbb{Q}(\sqrt{d})$  for some squarefree  $d \in \mathbb{Z}$ .

**Lemma.** Let  $K = \mathbb{Q}(\sqrt{d})$ ,  $d \equiv 1 \pmod{4}$ . Then

$$\mathbb{Z}\left[\frac{1+\sqrt{d}}{2}\right] = \left\{ \frac{r+s\sqrt{d}}{2} : r, s \in \mathbb{Z}, r \equiv s \pmod{2} \right\}$$

**Theorem.** Let  $K = \mathbb{Q}(\sqrt{d})$  quadratic field, then

$$\mathcal{O}_K = \begin{cases} \mathbb{Z}[\sqrt{d}] & \text{if } d \not\equiv 1 \pmod{4} \\ \mathbb{Z}\left[\frac{1+\sqrt{d}}{2}\right] & \text{if } d \equiv 1 \pmod{4} \end{cases}$$

## 4. Units in quadratic rings

**Notation.** In this section, let  $K = \mathbb{Q}(\sqrt{d})$  be quadratic number field,  $d \in \mathbb{Z} - \{0\}$ ,  $|d|$  is not a square. Let  $\mathcal{O}_d = \mathcal{O}_K$ . Let  $a + b\sqrt{d} = a - b\sqrt{d}$ . The map  $x \rightarrow \bar{x}$  is a  $\mathbb{Q}$ -automorphism from  $K$  to  $K$ .

**Definition.**  $S$  is **quadratic number ring of  $K$**  if  $S = \mathcal{O}_d$  or  $S = \mathbb{Z}[\sqrt{d}]$ .

- We have

$$\alpha \in S^\times \implies \exists x \in S : \alpha x = 1 \implies N_K(\alpha)N_K(x) = 1 \implies N_K(\alpha) = \pm 1$$

and for  $\alpha \in S - \mathbb{Z}$ , since  $[\mathbb{Q}(\alpha) : \mathbb{Q}] = 2$  and so  $[K : \mathbb{Q}(\alpha)] = 1$  by the Tower Theorem,

$$N_K(\alpha) = \pm 1 \implies \alpha \bar{\alpha} = \pm 1 \implies \alpha \in S^\times$$

So  $\alpha \in S^\times \iff N_K(\alpha) = \pm 1$ .

**Theorem.** To determine the group of units for imaginary quadratic fields:

- - For  $d < -1$ ,  $\mathbb{Z}[\sqrt{d}]^\times = \{\pm 1\}$ .
  - $\mathcal{O}_{-1}^\times = \mathbb{Z}[i]^\times = \{\pm 1, \pm i\}$ .
- - For  $d \equiv 1 \pmod{4}$  and  $d < -3$ ,  $\mathbb{Z}\left[\frac{1+\sqrt{d}}{2}\right]^\times = \{\pm 1\}$ .
  - $\mathbb{Z}\left[\frac{1+\sqrt{-3}}{2}\right]^\times = \{\pm 1, \pm \omega, \pm \omega^2\}$  where  $\omega = \frac{1+\sqrt{-3}}{2} = e^{\pi i/3}$ .

**Theorem** (Main theorem). Let  $d > 1$ ,  $d$  non-square,  $S$  be quadratic number ring of  $K = \mathbb{Q}(\sqrt{d})$  (i.e.  $S = \mathcal{O}_d$  or  $S = \mathbb{Z}[\sqrt{d}]$ ). Then

- $S$  has a smallest unit  $u > 1$  (smaller than all units except 1).
- $S^\times = \{\pm u^r : r \in \mathbb{Z}\} = \langle -1, u \rangle$ .

**Definition.** The smallest unit  $u > 1$  above is the **fundamental unit** of  $S$  (or of  $K$ , in the case  $S = \mathcal{O}_d$ ).



## 4.1. Proof of the main theorem

**Remark.** If  $\alpha = a + b\sqrt{d}$  is unit in  $\mathbb{Z}[\sqrt{d}]$ ,  $a, b > 0$ , then  $N_K(\alpha) = \alpha\bar{\alpha} = \pm 1$ , so

$$|\bar{\alpha}| = |a - b\sqrt{d}| = \frac{|N_K(\alpha)|}{|\alpha|} = \frac{1}{|\alpha|} < \frac{1}{b\sqrt{d}} < \frac{1}{b}$$

Define

$$A = \left\{ \alpha = a + b\sqrt{d} : a, b \in \mathbb{N}_0, |\bar{\alpha}| < \frac{1}{b} \right\}$$

**Lemma.**  $|A| = \infty$ .

**Lemma.** If  $\alpha \in A$ , then  $|N_K(\alpha)| < 1 + 2\sqrt{d}$ .

**Lemma.**  $\exists \alpha = a + b\sqrt{d}, \alpha' = a' + b'\sqrt{d} \in A : \alpha > \alpha', |N_K(\alpha)| = |N_K(\alpha')| =: n$  and

$$\alpha \equiv \alpha' \pmod{n}, \quad b \equiv b' \pmod{n}$$

**Lemma.** There exists a unit  $u$  in  $\mathbb{Z}[\sqrt{d}]$  such that  $u > 1$ .

**Lemma.** Let  $0 \neq \alpha = a + b\sqrt{d} \in \mathbb{Q}(\sqrt{d})$ . Then  $\alpha > \sqrt{|N_K(\alpha)|}$  iff  $a, b > 0$ .

## 4.2. Computing fundamental units

**Theorem.** Let  $d > 1$  non-square.

- If  $S = \mathbb{Z}[\sqrt{d}]$  and  $a + b\sqrt{d} \in S^\times$ ,  $a, b > 0$  such that  $b$  is minimal, then  $a + b\sqrt{d}$  is the fundamental unit in  $S$ .
- If  $S = \mathbb{Z}[\frac{1+\sqrt{d}}{2}]$  (so  $d \equiv 1 \pmod{4}$ ), then
  - $\frac{1+\sqrt{5}}{2}$  is the fundamental unit in  $\mathcal{O}_5$ .
  - If  $d > 5$  and  $\frac{s+t\sqrt{d}}{2} \in \mathcal{O}_d^\times$  with  $s, t > 0$  such that  $t$  is minimal, then  $\frac{s+t\sqrt{d}}{2}$  is the fundamental unit in  $\mathcal{O}_d$ .

**Remark.** Both  $u = \frac{1+\sqrt{5}}{2}$  and  $u^2 = \frac{3+\sqrt{5}}{2}$  have  $t$  minimal (equal to 1), which is why a separate case is needed for  $d = 5$ .

**Example.**

- $1 + \sqrt{2}$  is fundamental unit in  $\mathbb{Z}[\sqrt{2}] = \mathcal{O}_2$ , since  $N_K(1 + \sqrt{2}) = -1$  so is a unit, and here  $b = 1$ , so is minimal (as  $b > 0$ ).
- $2 + \sqrt{5}$  is the fundamental unit in  $\mathbb{Z}[\sqrt{5}]$  (since  $b = 1$  is minimal) but is not the fundamental unit in  $\mathcal{O}_5$ .

**Example.** Find fundamental unit in  $\mathcal{O}_7$ .  $7 \not\equiv 1 \pmod{4}$  so  $\mathcal{O}_7 = \mathbb{Z}[\sqrt{7}]$ .  $a + b\sqrt{7}$  is a unit iff  $a^2 - 7b^2 = \pm 1$ . Also, by the above theorem, it is the fundamental unit if  $a, b > 0$  and  $b$  is minimal. We use trial and error: for each  $b = 1, 2, \dots$ , check whether  $7b^2 \pm 1$  is a square

$b$	$7b^2 - 1$	$7b^2 + 1$	$a^2$
1	6	8	—
2	27	29	—
3	62	64	$64 = 8^2$

So the unit with minimal  $b$  such that  $a, b > 0$  is  $8 + 3\sqrt{7}$ , so is the fundamental unit.

### 4.3. Pell's equation and norm equations

**Definition.** **Pell's equation** is  $x^2 - dy^2 = 1$  for nonsquare  $d$ , where solutions are  $x, y \in \mathbb{Z}$ . Since LHS is norm of  $x + y\sqrt{d}$ , solutions are given by  $x + y\sqrt{d} \in \mathbb{Z}[\sqrt{d}]$  with norm 1.

**Example.** Consider  $x^2 - 2y^2 = \pm 1$ . Fundamental unit in  $\mathbb{Z}[\sqrt{2}]$  is  $u = 1 + \sqrt{2}$ , with norm  $-1$ . So if  $x + y\sqrt{2} \in \mathbb{Z}[\sqrt{2}]$  is such that  $N_{\mathbb{Z}(\sqrt{2})}(x + y\sqrt{2}) = 1$ , then  $x + y\sqrt{2}$  is an even power of  $u$ . Thus elements of norm  $\pm 1$  are

$$\pm u^{2n} \text{ (RHS} = 1), \quad \pm u^{2n+1} \text{ (RHS} = -1)$$

To extract solutions  $x, y$ , note that if  $x + y\sqrt{2} = \pm u^r$ , then  $x - y\sqrt{2} = \pm \bar{u}^r$ , hence

$$x = \pm \frac{u^r + \bar{u}^r}{2}, \quad y = \pm \frac{u^r - \bar{u}^r}{2\sqrt{2}}$$

Solutions when  $\text{RHS} = 1$  are given by even  $r$ , solutions when  $\text{RHS} = -1$  are given by odd  $r$ .

**Example.** Consider  $x^2 - 75y^2 = 1$ .  $75 = 3 \cdot 5^2$  is not square-free, so rewrite as

$$x^2 - 3z^2 = 1$$

where  $z = 5y$ . Fundamental unit in  $\mathbb{Z}[\sqrt{3}]$  is  $u = 2 + \sqrt{3}$  of norm 1 so solutions are

$$x = \pm \frac{u^n + \bar{u}^n}{2}, \quad z = \pm \frac{u^n - \bar{u}^n}{2\sqrt{3}}, \quad n \in \mathbb{Z}$$

To get solution for  $(x, y)$ , we need  $5 \mid z$  (which doesn't always hold). Note that

$$u^2 = 7 + 4\sqrt{3} \notin \mathbb{Z}[\sqrt{75}] = \mathbb{Z}[5\sqrt{3}], \quad u^3 = 26 + 3\sqrt{75} \in \mathbb{Z}[\sqrt{75}]$$

Thus when  $n = 2$ ,  $(x, z)$  is not solution, but is when  $n = 3$ , and hence when  $n = 3k$  for  $k \in \mathbb{Z}$ :

$$x = \pm \frac{u^{3k} + \bar{u}^{3k}}{2}, \quad y = \pm \frac{u^{3k} - \bar{u}^{3k}}{5 \cdot 2\sqrt{3}}, \quad k \in \mathbb{Z}$$

$u^{3k+1}$  and  $u^{3k+2}$  never give solutions, since if  $u^{3k+1} \in \mathbb{Z}[\sqrt{75}]$ , then  $u \in \mathbb{Z}[\sqrt{75}]$  (since  $u^{-3k} \in \mathbb{Z}[\sqrt{75}]$ ). Similarly, if  $u^{3k+2} \in \mathbb{Z}[\sqrt{75}]$ , then  $u^2 \in \mathbb{Z}[\sqrt{75}]$ : contradiction. Note  $\mathbb{Z}[\sqrt{75}] \subset \mathbb{Z}[\sqrt{3}]$  and any unit in  $\mathbb{Z}[\sqrt{75}]$  is unit in  $\mathbb{Z}[\sqrt{3}]$ , so is  $\pm u^r$  for some  $r \in \mathbb{Z}$ . So by taking powers of  $u$ , eventually we find the fundamental unit in  $\mathbb{Z}[\sqrt{75}]$  (as it will be smallest unit  $> 1$  assuming we increment powers from 1).

## 5. Discriminants and integral bases

### 5.1. Discriminant of an $n$ -tuple

**Definition.** Let  $K$  number field of degree  $n$ . **Discriminant** of  $\gamma = (\gamma_1, \dots, \gamma_n) \in K^n$  is

$$\Delta_K(\gamma) := \det(Q(\gamma))$$

where  $Q(\gamma) = (\text{tr}_K(\gamma_i \gamma_j))_{1 \leq i, j \leq n} \in M_n(\mathbb{Q})$ .

**Example.** Let  $K = \mathbb{Q}(\sqrt{d})$ ,  $d \neq 1$  squarefree.

$$\gamma = (1, \sqrt{d}) \implies Q(\gamma) = \begin{bmatrix} 2 & 0 \\ 0 & 2d \end{bmatrix} \implies \Delta_K(\gamma) = 4d$$

$$\gamma = (1, \frac{1+\sqrt{d}}{2}) \implies Q(\gamma) = \begin{bmatrix} 2 & 1 \\ 1 & \frac{1+d}{2} \end{bmatrix} \implies \Delta_K(\gamma) = d$$

**Proposition.**

- $\Delta_K(\gamma) \in \mathbb{Q}$  and if every  $\gamma_i \in \mathcal{O}_K$ , then  $\Delta_K(\gamma) \in \mathbb{Z}$ .
- Let  $M \in M_n(\mathbb{Q})$ , then  $\Delta_K(M\gamma) = \det(M)^2 \Delta_K(\gamma)$ .
- $\Delta_K(\gamma)$  is invariant under permutations of  $\gamma_1, \dots, \gamma_n$ .

**Lemma.** Let  $\theta_1, \dots, \theta_n \in \mathbb{C}$ , let

$$D = \begin{bmatrix} 1 & \theta_1 & \dots & \theta_1^{n-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \theta_n & \dots & \theta_n^{n-1} \end{bmatrix}$$

then

$$\det(D) = (-1)^{\binom{n}{2}} \prod_{1 \leq r < s \leq n} (\theta_r - \theta_s)$$

**Theorem.** Let  $K = \mathbb{Q}(\theta)$  be number field. Let  $\theta_1, \dots, \theta_n$  be roots of  $p_\theta(x)$ , let  $\gamma = (1, \dots, \theta^{n-1})$ . Then

$$\Delta_K(\gamma) = \prod_{1 \leq i < j \leq n} (\theta_i - \theta_j)^2 = (-1)^{\binom{n}{2}} \prod_{i=1}^n p'_\theta(\theta_i) = (-1)^{\binom{n}{2}} N_K(p'_\theta(\theta))$$

**Example.**

- Let  $K = \mathbb{Q}(\sqrt{d})$ ,  $d$  square-free,  $\theta = \frac{1+\sqrt{d}}{2}$ , then

$$\Delta_K((1, \theta)) = \left( \frac{1+\sqrt{d}}{2} - \frac{1-\sqrt{d}}{2} \right)^2 = d$$

- Let  $\theta = \sqrt{d}$ , so  $p_\theta(x) = x^2 - d$ ,  $p'_\theta(x) = 2x$ , so

$$\Delta_K(1, \theta) = (-1)^{\binom{2}{2}} N_K(2\theta) = -4N_K(\theta) = 4d$$

- Let  $\theta = \sqrt[3]{3}$ , so  $p_\theta(x) = x^3 - d$ ,  $p'_\theta(x) = 3x^2$  so

$$\Delta_K(1, \theta, \theta^2) = (-1)^{\binom{3}{2}} N_K(3\theta^2) = -27d^2$$

- Let  $\theta$  be root of  $p_\theta(x) = x^3 - x + 2$ , so  $p'_\theta(x) = 3x^2 - 1$ .

$$\Delta_K(1, \theta, \theta^2) = (-1)^{\binom{3}{2}} N_K(3\theta^2 - 1)$$

Now  $\theta^3 = \theta - 2$  so

$$N_K(3\theta^2 - 1) = \frac{N_K(2)N_K(\theta - 3)}{N_K(\theta)} = \frac{8}{2}N_K(3 - \theta) = 4(3 - \theta_1)(3 - \theta_2)(3 - \theta_3) = 4p_\theta(3) = 104$$

so  $\Delta_K(1, \theta, \theta^2) = -104$ . Note: in general, this method doesn't work, and generally we have to compute matrix  $T_\theta$  and  $\det(f(T_\theta))$ . **As a generalisation,**

$$N_{\mathbb{Q}(\theta)}(a - b\theta) = b^n p_\theta(a/b)$$

**Lemma.**

- Roots  $\theta_1, \dots, \theta_n$  of  $p_\theta(x)$  are distinct.
- $\forall f \in \mathbb{Q}[x], \text{tr}_K(f(\theta)) = \sum_{i=1}^n f(\theta_i)$ .
- $\forall f \in \mathbb{Q}[x], N_K(f(\theta)) = \prod_{i=1}^n f(\theta_i)$ .

**Proposition.** Let  $K = \mathbb{Q}(\theta)$  number field. Then  $\Delta_K(\gamma) \neq 0$  iff  $\gamma$  is  $\mathbb{Q}$ -basis of  $K$ .

## 5.2. Full lattices and integral bases

**Definition.** Let  $A$  subgroup of  $\mathbb{Q}$ -vector space  $V$ .  $A$  is **full lattice** in  $V$  if there are  $\gamma_1, \dots, \gamma_n \in V$  such that

- $\{\gamma_1, \dots, \gamma_n\}$  is basis for  $V$ .
- $A = \{a_1\gamma_1 + \dots + a_n\gamma_n : a_i \in \mathbb{Z}\}$  (i.e.  $\gamma_1, \dots, \gamma_n$  generate  $A$  as a group). Note  $a_1, \dots, a_n$  are uniquely determined for each  $a \in A$ .

$\{\gamma_1, \dots, \gamma_n\}$  is **generating basis** for  $A$ .

**Example.** Let  $K = \mathbb{Q}(\theta)$ ,  $\theta \in \mathcal{O}_K$ ,  $[K : \mathbb{Q}] = n$ , then  $\mathbb{Z}[\theta]$  has generating basis  $\{1, \dots, \theta^{n-1}\}$  and is full lattice in  $K$ .

**Example.**  $\mathbb{Z}, \mathbb{Z}[\sqrt{2}/2]$  are not full lattices in  $\mathbb{Q}(\sqrt{2})$ .

**Proposition.** Let  $K$  number field. Every non-zero ideal  $I \subseteq \mathcal{O}_K$  is full lattice in  $K$ .

**Definition.** Generating basis for  $\mathcal{O}_K$  is **integral basis** for  $K$ .

**Example.** Let  $K = \mathbb{Q}(\sqrt{d})$ , then an integral basis for  $K$  is  $\{1, \sqrt{d}\}$  if  $d \not\equiv 1 \pmod{4}$ ,  $\{1, (1 + \sqrt{d})/2\}$  if  $d \equiv 1 \pmod{4}$ .

**Theorem.** If  $V$  is  $\mathbb{Q}$ -vector space,  $\dim(V) = n$ , and  $B \subset A \subset V$ ,  $A$  and  $B$  full lattices,  $\{\beta_1, \dots, \beta_n\}$  is generating basis for  $B$ ,  $\{\alpha_1, \dots, \alpha_n\}$  is generating basis for  $A$ , where  $\beta = M\alpha$ ,  $M \in M_n(\mathbb{Z})$ , then

- $|A/B| = |\det(M)|$  (in particular,  $A/B$  is finite)
- If  $V = K$  is number field, these satisfy **index-discriminant formula**:  

$$\Delta_K(B) = |A/B|^2 \Delta_K(A).$$

(Note  $M$  exists since  $\alpha$  is generating basis for  $A$  so spans  $B$  over  $\mathbb{Z}$ ).

**Lemma.** If  $A \subset K$  is full lattice and  $\{\gamma_1, \dots, \gamma_n\}, \{\delta_1, \dots, \delta_n\}$  are generating bases for  $A$ , then  $\Delta_K(\gamma_1, \dots, \gamma_n) = \Delta_K(\delta_1, \dots, \delta_n)$ . We define discriminant of  $A$  to be  $\Delta_K(A) = \Delta_K(\gamma_1, \dots, \gamma_n)$  for any generating basis  $\{\gamma_1, \dots, \gamma_n\}$ .

**Definition.** **Discriminant** of number field  $K$  is

$$\Delta_K = \Delta_K(\mathcal{O}_K) = \Delta_K(\gamma_1, \dots, \gamma_n)$$

for any integral basis  $\{\gamma_1, \dots, \gamma_n\}$ .

### 5.3. When is $R = \mathbb{Z}[\theta]$ ?

**Proposition.** If  $S \subseteq \mathcal{O}_K$  is full lattice in  $K = \mathbb{Q}(\theta)$ ,  $\{\gamma_1, \dots, \gamma_n\}$  is generating basis for  $S$ , and  $p$  prime,  $p \mid |\mathcal{O}_K/S|$ , then

- $p^2 \mid \Delta_K(S)$
- There exists  $\alpha = m_1\gamma_1 + \dots + m_n\gamma_n \in S$ ,  $m_i \in \mathbb{Z}$ , such that  $\alpha/p \in \mathcal{O}_K - S$  and

$$\begin{cases} 0 \leq |m_i| < p/2 & \text{if } p \text{ is odd} \\ m_i \in \{0, 1\} & \text{if } p = 2 \end{cases}$$

**Example.** If  $K = \mathbb{Q}(\sqrt{d})$ ,

$$\Delta_K = \begin{cases} 4d & \text{if } d \not\equiv 1 \pmod{4} \\ d & \text{if } d \equiv 1 \pmod{4} \end{cases}$$

**Example.** Let  $\theta$  be root of  $x^3 + 4x + 1$ ,  $K = \mathbb{Q}(\theta)$ . We have  $\mathbb{Z}[\theta] \subseteq \mathcal{O}_K$  and  $\Delta_K(\mathbb{Z}[\theta]) = \Delta_K(1, \theta, \theta^2) = 281 = |\mathcal{O}_K/\mathbb{Z}[\theta]|^2 \Delta_K(\mathcal{O}_K)$ . As 281 is squarefree,  $|\mathcal{O}_K/\mathbb{Z}[\theta]| = 1$  so  $\mathcal{O}_K = \mathbb{Z}[\theta]$ .

**Example.** Let  $K = \mathbb{Q}(\theta)$ ,  $\theta = \sqrt[3]{5}$ . let  $R = \mathcal{O}_K$ ,  $S = \mathbb{Z}[\theta]$ .  $\Delta_K(S) = -3^3 \cdot 5^2$ . If  $p$  prime and  $p \mid |R/S|$ , then  $p \in \{3, 5\}$  and there is  $\alpha = a + b\theta + c\theta^2$  such that  $\alpha/p \in R - S$ ,  $|a|, |b|, |c| < p/2$ . Note  $\alpha \neq 0$ , as otherwise  $\alpha \in S$ .

- If  $5 \mid |R/S|$ , then  $|a|, |b|, |c| \in \{0, 1, 2\}$ . Then  $\text{tr}_{K/\mathbb{Q}}(\alpha/5) = 3a/5 \in \mathbb{Z}$  so  $5 \mid a$  so  $a = 0$ .  $\theta\alpha = c + (b\theta^2)/5 \in \mathcal{O}_K$  so  $(b\theta^2)/5 \in \mathcal{O}_K$  so

$$N_K((b\theta^2)/5) = \frac{N_K(b)N_K(\theta)^2}{N_K(5)} = \frac{b^3}{5} \in \mathbb{Z}$$

so  $5 \mid b$ , so  $b = 0$ . Finally,

$$N_K\left(\frac{\alpha}{5}\right) = N_K\left(\frac{c\theta^2}{5}\right) = \frac{c^3(-5)^2}{5^3} = \frac{c^3}{5} \in \mathbb{Z} \implies c = 0$$

Contradiction.

- If  $3 \mid |R/S|$ , then  $|a|, |b|, |c| \in \{0, 1\}$  and can assume  $a \geq 0$  (by possibly multiplying by  $-1$ ). Then

$$N_K\left(\frac{a + b\theta + c\theta^2}{3}\right) \in \mathbb{Z} \implies a^3 + 5b^3 + 25c^3 - 15abc \equiv 0 \pmod{3^3}$$

If  $a = 0$ , then  $5b^3 + 25c^3 \equiv 2b + c \equiv 0 \pmod{3}$  (as  $b, c \in \{0, 1, -1\}$ ), so if  $b = 0$ , then  $c \equiv 0 \pmod{3} \implies c = 0$ : contradiction. So  $b = 1$  (by possibly multiplying by  $-1$ ) hence  $c = 1$ . But then

$$N_K(\alpha/3) = N_K\left(\frac{\theta + \theta^2}{3}\right) = \frac{N_K(\theta)N_K(1 + \theta)}{3^3} = \frac{5 \cdot 6}{27} \notin \mathbb{Z}$$

Contradiction. If  $a = 1$ , then

$$1 + 5b^3 + 25c^3 \equiv 1 + 2b + c \equiv 0 \pmod{3}$$

which also leads to a contradiction.

- So  $5 \nmid |R/S|$ ,  $3 \nmid |R/S|$ , so  $|R/S| = 1$ , so  $\mathbb{Z}[\theta] = \mathcal{O}_K$ .

## 6. Unique factorisation of ideals

**Definition.** Product of ideals  $I, J \subseteq R$  is

$$IJ := \left\{ \sum_{i=1}^k x_i y_i : k \in \mathbb{N}, x_i \in I, y_i \in J \right\}$$

If  $I = \langle a_1, \dots, a_m \rangle$ ,  $J = \langle b_1, \dots, b_n \rangle$  then

$$IJ = \langle a_i b_j \mid i \in [m], j \in [n] \rangle$$

**Definition.**  $I$  divides  $J$ ,  $I \mid J$ , if there is ideal  $K$  such that  $IK = J$ .

**Note.** to divide is to contain:  $I \mid J \implies J \subseteq I$ .

**Example.** Let  $R = \mathbb{Z}[\sqrt{-6}]$ ,  $I = \langle 5, 1 + 3\sqrt{-6} \rangle$ ,  $J = \langle 5, 1 - 3\sqrt{-6} \rangle$ , then

$$IJ = \langle 25, 5(1 + 3\sqrt{-6}), 5(1 - 3\sqrt{-6}), 55 \rangle \subseteq \langle 5 \rangle$$

But also  $5 = 55 - 2 \cdot 25 \in I$ ,  $\langle 5 \rangle \subseteq IJ$ , so  $IJ = \langle 5 \rangle$ .

**Lemma.** Let  $I, J$  ideals,  $P$  prime ideal. Then

$$IJ \subseteq P \iff (I \subseteq P \vee J \subseteq P)$$

**Example.**  $\langle 5, 1 + 3\sqrt{-6} \rangle \subset \mathbb{Z}[\sqrt{-6}]$  is prime: define  $\varphi : \mathbb{Z}[\sqrt{-6}] \rightarrow \mathbb{F}_5$ ,  $\varphi(a + b\sqrt{-6}) = a - 2b$ .  $\varphi$  is surjective homomorphism. Also,  $5, 1 + 3\sqrt{-6} \in \ker(\varphi)$ , and

$$\begin{aligned} a + b\sqrt{-6} \in \ker(\varphi) &\implies b \equiv 3a \pmod{5} \\ &\implies (a + b\sqrt{-6}) - a(1 + 3\sqrt{-6}) = (b - 3a)\sqrt{-6} \in \langle 5 \rangle \end{aligned}$$

so  $\ker(\varphi) = \langle 5, 1 + 3\sqrt{-6} \rangle$ . So by first isomorphism theorem,  $R/\langle 5, 1 + \sqrt{-6} \rangle \cong \mathbb{F}_5$  which is field, so  $\langle 5, 3 + \sqrt{-6} \rangle$  is maximal, so prime.

**Definition.** Let  $K$  number field,  $R = \mathcal{O}_K$ . **Fractional ideal** of  $R$  is subset of  $K$  of the form

$$\lambda I = \{ \lambda x : x \in I \}$$

where  $\langle 0 \rangle \neq I \subseteq R$  and  $\lambda \in K^\times$ . If  $I = R$ ,  $\lambda I$  is **principal fractional ideal**. Set of fractional ideals in  $R$  is denoted  $\mathcal{I}(R)$ , set of principal fractional ideals is denoted  $\mathcal{P}(R)$ . Multiplication of fractional ideals is defined similarly to that of ideals.

**Example.**

- $\frac{n}{m}\mathbb{Z}$  is fractional ideal in  $\mathbb{Q}$  for all  $m, n \in \mathbb{Z} - \{0\}$ .
- Every non-zero ideal is fractional ideal (take  $\lambda = 1$ ).

- If  $\lambda I$  is fractional ideal, then  $\lambda^{-1}\lambda I = I$  is ideal.

**Definition.** A fractional ideal  $A$  is **invertible** if there is fractional ideal  $B$  such that  $AB = \mathcal{O}_K$ .  $B$  is the **inverse** of  $A$ . The invertible fractional ideals form a group.

**Example.** In  $\mathbb{Z}[\sqrt{-6}] = \mathcal{O}_K$ ,  $\langle 5, 1 + 3\sqrt{-6} \rangle \langle 5, 1 - 3\sqrt{-6} \rangle = \langle 5 \rangle$  so

$$\langle 5, 1 + 3\sqrt{-6} \rangle \cdot \frac{1}{5} \langle 5, 1 - 3\sqrt{-6} \rangle = \mathcal{O}_K$$

so inverse of  $\langle 5, 1 + 3\sqrt{-6} \rangle$  is  $\frac{1}{5} \langle 5, 1 - 3\sqrt{-6} \rangle$ .

## 6.1. The norm of an ideal

**Definition.** Let  $\langle 0 \rangle \neq I$  ideal of  $\mathcal{O}_K$ . **Norm** of  $I$  is

$$N(I) := |\mathcal{O}_K/I|$$

We have  $N(I) \in \mathbb{N}$ ,  $N(R) = 1$ , and  $I \subsetneq J \implies N(I) > N(J)$  (in fact,  $N(I) = N(J) |J/I|$ ).

**Proposition.** Every non-zero prime ideal in  $\mathcal{O}_K$  is maximal.

**Lemma.** Every nonzero ideal in  $\mathcal{O}_K$  contains product of one or more non-zero prime ideals.

## 6.2. Ideals are invertible

**Theorem.** Every non-zero prime ideal in  $\mathcal{O}_K$  is invertible.

**Lemma.** If  $\lambda I$  is fractional ideal and  $\lambda I \subseteq \mathcal{O}_K$ , then  $\lambda I$  is ideal in  $\mathcal{O}_K$ .

**Lemma.** Let  $J \subseteq I$  ideals in  $\mathcal{O}_K$  with  $I$  invertible. Then

- $I^{-1}J$  is ideal in  $\mathcal{O}_K$  and so  $I \mid J$ .
- $J \subseteq I^{-1}J$  with equality iff  $I = R$ .

**Theorem.** Let  $I \subsetneq \mathcal{O}_K$  be non-zero ideal. Then  $I$  is unique (up to reordering) product of prime ideals.

**Example.** In  $\mathbb{Z}[\sqrt{-6}]$ ,  $(1 + 3\sqrt{-6})(1 - 3\sqrt{-6}) = 55 = 5 \cdot 11$ .  $P_5 = \langle 5, 1 + 3\sqrt{-6} \rangle$  and  $\overline{P_5} = \langle 5, 1 - 3\sqrt{-6} \rangle$  are prime, as are  $P_{11} = \langle 11, 1 + 3\sqrt{-6} \rangle$  and  $\overline{P_{11}} = \langle 11, 1 - 3\sqrt{-6} \rangle$ .  $P_5 \overline{P_5} = \langle 5 \rangle$ ,  $P_{11} \overline{P_{11}} = \langle 11 \rangle$ ,  $P_5 P_{11} = \langle 1 + 3\sqrt{-6} \rangle$ ,  $\overline{P_5} \overline{P_{11}} = \langle 1 - 3\sqrt{-6} \rangle$  so

$$(P_5 P_{11})(\overline{P_5} \overline{P_{11}}) = (P_5 \overline{P_5})(P_{11} \overline{P_{11}})$$

**Corollary.** Let  $R = \mathcal{O}_K$ .

- Every fractional ideal (and hence every nonzero ideal) in  $R$  is invertible.
- $\mathcal{J}(R)$  is abelian group under multiplication, with identity element  $R$ .

**Corollary** (to divide is to contain and to contain is to divide).  $I \mid J \iff J \subseteq I$ .

## 7. Splitting of primes and the Kummer-Dedekind theorem

### 7.1. Properties of the ideal norm

**Lemma.** For every non-zero ideal  $I$  of  $\mathcal{O}_K$ ,  $N(I) \in I$ , hence  $I \cap \mathbb{Z} \neq \langle 0 \rangle$ .

**Notation.** For  $0 \neq \alpha \in \mathcal{O}_K$ , define  $N(\alpha) := N(\langle \alpha \rangle_{\mathcal{O}_K})$ .

**Lemma.**  $\forall 0 \neq \alpha \in \mathcal{O}_K$ ,  $N(\alpha) = |N_K(\alpha)|$ .

**Lemma.** Ideal norm is multiplicative: for any non-zero ideals  $I, J$  in  $\mathcal{O}_K$ ,

$$N(IJ) = N(I)N(J)$$

## 7.2. The Kummer-Dedekind theorem

**Definition.** If  $p \in \mathbb{Z}$  prime, and  $\langle p \rangle_{\mathcal{O}_K} = P_1^{e_1} \cdots P_r^{e_r}$  then  $P_1, \dots, P_r$  are the prime ideals **lying above**  $p$ .

**Remark.** If  $P \subset \mathcal{O}_K$  nonzero prime ideal, then  $N(P) \in P \cap \mathbb{Z}$  so  $P \cap \mathbb{Z} \neq \langle 0 \rangle$ . But  $P \cap \mathbb{Z}$  is prime ideal of  $\mathbb{Z}$  so  $P \cap \mathbb{Z} = \langle p \rangle_{\mathbb{Z}}$  for some prime  $p \in \mathbb{Z}$ . Hence  $p \in P$ ,  $\langle p \rangle_{\mathcal{O}_K} \subseteq P$  so  $P \mid \langle p \rangle_{\mathcal{O}_K}$ . Hence every  $P$  lies over some prime  $p$ .

**Lemma.** Prime ideal  $P$  of  $\mathcal{O}_K$  lies above  $p$  iff  $N(P) = p^r$  for some  $1 \leq r \leq n = [K : \mathbb{Q}]$ .

**Theorem** (Kummer Dedekind). Let  $p$  prime. Suppose  $\mathcal{O}_K = \mathbb{Z}[\theta]$  for some  $\theta \in \mathcal{O}_K$  with minimal polynomial  $p_\theta$ . Let  $\overline{f}(x)$  be reduction of  $f(x) \in \mathbb{Z}[x]$  mod  $p$ , so  $\overline{f}(x) \in \mathbb{F}_p[x]$ . Let

$$\overline{p_\theta}(x) = \overline{f_1}(x)^{e_1} \cdots \overline{f_r}(x)^{e_r}$$

be factorisation of  $\overline{p_\theta}$  where  $\overline{f_i}$  are distinct, monic, irreducible. For each  $i$ , let  $f_i(x) \in \mathbb{Z}[x]$  be monic polynomial whose reduction mod  $p$  is  $\overline{f_i}(x)$ . Let  $P_i = (p, f_i(\theta))_{\mathcal{O}_K}$ . Then  $P_i$  are distinct prime ideals,  $N(P_i) = p^{\deg(f_i)}$  and

$$\langle p \rangle_{\mathcal{O}_K} = P_1^{e_1} \cdots P_r^{e_r}$$

**Example.** Let  $K = \mathbb{Q}(\sqrt{6})$ , so  $\mathcal{O}_K = \mathbb{Z}[\sqrt{6}]$ .  $p_\theta(x) = x^2 - 6$  factorises modulo small primes as:

$$\begin{array}{ll} \overline{x^2 - 6} = x^2 & \text{in } \mathbb{F}_2[x] \\ \overline{x^2 - 6} = x^2 & \text{in } \mathbb{F}_3[x] \\ \overline{x^2 - 6} = x^2 - 1 = (x-1)(x+1) & \text{in } \mathbb{F}_5[x] \\ \overline{x^2 - 6} \text{ irreducible} & \text{in } \mathbb{F}_7[x] \\ \overline{x^2 - 6} \text{ irreducible} & \text{in } \mathbb{F}_{11}[x] \end{array}$$

Since 6 is not square mod 7 or 11. By Kummer-Dedekind,

$$\begin{aligned} \langle 2 \rangle_{\mathcal{O}_K} &= \langle 2, \sqrt{6} \rangle^2, & \langle 3 \rangle_{\mathcal{O}_K} &= \langle 3, \sqrt{6} \rangle^2, \\ \langle 5 \rangle_{\mathcal{O}_K} &= \langle 5, \sqrt{6} + 1 \rangle \langle 5, \sqrt{6} - 1 \rangle, \\ \langle 7 \rangle_{\mathcal{O}_K} &= \langle 7, \sqrt{6}^2 - 6 \rangle = \langle 7, 0 \rangle = \langle 7 \rangle, \\ \langle 11 \rangle_{\mathcal{O}_K} &= \langle 11, \sqrt{6}^2 - 6 \rangle = \langle 11, 0 \rangle = \langle 11 \rangle \end{aligned}$$



**Definition.** When  $K$  is quadratic, Kummer-Dedekind implies there are 3 mutually exclusive possibilities for prime  $p \in \mathbb{Z}$ :

- If  $\langle p \rangle_{\mathcal{O}_K}$  is prime ideal,  $p$  is **inert**.
- If  $\langle p \rangle_{\mathcal{O}_K} = P^2$  for prime ideal  $P$ , then  $p$  **ramifies** (or **is ramified**) (otherwise, it is **unramified**).
- If  $\langle p \rangle_{\mathcal{O}_K} = P_1 P_2$  for distinct prime ideals  $P_1, P_2$ , then  $p$  **splits** (or **is split**).

**Remark.** If  $K/\mathbb{Q}$  is quadratic,  $K = \mathbb{Q}(\sqrt{d})$ , then Kummer-Dedekind always applies since  $R = \mathbb{Z}[\theta]$  for some  $\theta \in K$ .

**Notation.** Let  $K$  quadratic extension. If  $I \subseteq \mathcal{O}_K$  ideal, let  $\bar{I} = \{\bar{x} : x \in I\}$  where  $a + b\sqrt{d} = a - b\sqrt{d}$ . We have  $I$  prime iff  $\bar{I}$  prime and  $N(\bar{I}) = N(I)$ .

**Lemma.** Let  $K$  quadratic number field,  $p \in \mathbb{Z}$  prime,  $P$  non-zero prime ideal in  $\mathcal{O}_K$  lying above  $p$ . Then  $\bar{P}$  is prime ideal lying above  $p$  and:

- If  $p$  inert, then  $P = \bar{P}$  and  $N(P) = p^2$ .
- If  $p$  ramifies, then  $P = \bar{P}$  and  $N(P) = p$ .
- If  $p$  splits, then  $\langle p \rangle_{\mathcal{O}_K} = P\bar{P}$ ,  $P \neq \bar{P}$  and  $N(P) = N(\bar{P}) = p$ .

In all cases,  $P\bar{P} = \langle N(P) \rangle_{\mathcal{O}_K}$ .

**Example.** Let  $\theta^3 + 3\theta - 1 = 0$ ,  $K = \mathbb{Q}(\theta)$ . We have  $\mathcal{O}_K = \mathbb{Z}[\theta]$ . To factorise  $\langle 5 \rangle_{\mathcal{O}_K}$  and  $\langle 11 \rangle_{\mathcal{O}_K}$ :  $-1$  and  $2$  are roots of  $x^3 + 3x - 1 \pmod{5}$ , so we get  $x^3 + 3x - 1 \equiv (x + 1)(x + 2)^2 \pmod{5}$ . So by Kummer-Dedekind,

$$\langle 5 \rangle_{\mathcal{O}_K} = \langle 5, \theta + 1 \rangle \langle 5, \theta + 2 \rangle^2$$

Only root in  $\bar{p}_\theta$  in  $\mathbb{F}_{11}$  is  $-4$ , so  $\bar{p}_\theta(x) = (x + 4)(x^2 - 4x + 8) \pmod{11}$  and  $x^2 - 4x + 8 = (x - 2)^2 + 4$  is irreducible as  $-4$  is not square mod 11. So by Kummer-Dedekind,

$$\langle 11 \rangle_{\mathcal{O}_K} = \langle 11, \theta + 4 \rangle \langle 11, \theta^2 - 4\theta + 8 \rangle$$

To factorise  $\langle 2\theta - 3 \rangle_{\mathcal{O}_K}$ :

$$N_K(2\theta - 3) = -N_K(2)N_K\left(\frac{3}{2} - \theta\right) = -8 \cdot p_\theta\left(\frac{3}{2}\right) = -8\left(\frac{27}{8} + \frac{9}{2} - 1\right) = -55$$

So  $\langle 2\theta - 3 \rangle = P_5 P_{11}$  where  $N(P_5) = 5$ ,  $N(P_{11}) = 11$ ,  $P_5, P_{11}$  prime. So  $P_5 \mid \langle 5 \rangle$ , so  $P_5 = \langle 5, \theta + 1 \rangle$  or  $\langle 5, \theta + 2 \rangle$ . Now  $2\theta - 3 = 2(\theta + 1) - 5 \in \langle 5, \theta + 1 \rangle$ , so  $\langle 5, \theta + 1 \rangle \mid \langle 2\theta - 3 \rangle$ , hence  $P_5 = \langle 5, \theta + 1 \rangle$ . Now  $P_{11} \mid \langle 11 \rangle$  so  $P_{11} = \langle 11, \theta + 4 \rangle$  or  $\langle 11, \theta^2 - 4\theta + 8 \rangle$ . But by Kummer-Dedekind, the latter has norm  $11^2$  which is a contradiction (since  $11^2 \nmid N(\langle 2\theta - 3 \rangle) = 55$ ). So  $P_{11} = \langle 11, \theta + 4 \rangle$ .

## 8. The ideal class group

**Notation.** Let  $R = \mathcal{O}_K$  for number field  $K$ .

**Definition. (Ideal) class group** of  $R$  (or of  $K$ ) is  $\text{Cl}(R) := \mathcal{I}(R)/\mathcal{P}(R)$ . For fractional ideal  $I \in \mathcal{I}(R)$ , let  $[I] = I \cdot \mathcal{P}(R) = \{ \langle \lambda \rangle_R I : \lambda \in K^\times \} = \{ \lambda I : \lambda \in K^\times \}$  denote **class** of  $I$  in  $\text{Cl}(R)$ .

**Proposition.**

- $[I] = e$  iff  $I \in \mathcal{P}(R)$  iff  $I$  is principal.
- $[I] = [J]$  iff  $I = \langle \lambda \rangle_R J$  for some  $\lambda \in K^\times$  \* iff  $\alpha I = \beta J$  for some  $\alpha, \beta \in R - \{0\}$ .
- $[I] \cdot [J] = IJ \cdot \mathcal{P}(R) = [IJ]$ .
- $[I]^{-1} = [I^{-1}]$ .

**Proposition.**  $\text{Cl}(R)$  is the trivial group ( $\text{Cl}(R) = e$ ) iff  $R$  is a UFD iff  $R$  is a PID.

**Remark.** If  $\langle \alpha \rangle_R = PQ$  then  $e = [\langle \alpha \rangle_R] = [PQ] = [P][Q]$  so  $[P] = [Q]^{-1}$ .

**Proposition.** If  $K$  is quadratic number field,  $I, J$  ideals, then  $[\bar{I}] = [I]^{-1}$  and  $I\bar{I}$  is principal iff  $[I] = [J]$ .

**Example.**

- Let  $K = \mathbb{Q}(\sqrt{-29})$  so  $\mathcal{O}_K = \mathbb{Z}[\sqrt{-29}] = R$ .  $p_{\sqrt{-29}}(x) = x^2 + 29$  so by Kummer-Dedekind and [Lemma 7.2.11](#),

$$\langle 2 \rangle_R = P_2^2, \quad P_2 = \langle 2, 1 + \sqrt{-29} \rangle_R, \quad N(P_2) = 2,$$

$$\langle 3 \rangle_R = P_3 \bar{P}_3, \quad P_3 = \langle 3, 1 - \sqrt{-29} \rangle_R, \quad N(P_3) = 3,$$

$$\langle 5 \rangle_R = P_5 \bar{P}_5, \quad P_5 = \langle 5, 1 - \sqrt{-29} \rangle_R, \quad N(P_5) = 5$$

- If  $P_2$  were principal, then  $P_2 = \langle a + b\sqrt{-29} \rangle$  but  $N(P_2) = 2 = a^2 + 29b^2$ : contradiction. So  $[P_2] \neq e$  but  $[P_2]^2 = e$  as  $P_2^2 = \langle 2 \rangle_R$  is principal.
- Similarly,  $P_5$  is not principal, but also  $P_5^2$  is not principal, as if it was, then  $P_5^2 = \langle a + b\sqrt{-29} \rangle$  so  $25 = a^2 + 29b^2 \implies a = \pm 5$ , but then  $P_5^2 = \langle 5 \rangle = P_5 \bar{P}_5$ , but  $P_5 \neq \bar{P}_5$ .
- But  $N(3 + 2\sqrt{-29}) = 5^3$ , so  $\langle 3 + 2\sqrt{-29} \rangle_R \mid (5^3)_R$  by [Lemma 7.1.1](#), so  $\langle 3 + 2\sqrt{-29} \rangle = P_5^a \bar{P}_5^{3-a}$ ; but  $5 \nmid 3 + 2\sqrt{-29}$ , so we can't have  $P_5 \bar{P}_5 \mid \langle 3 + 2\sqrt{-29} \rangle$ . So  $\langle 3 + 2\sqrt{-29} \rangle = P_5^3$  or  $\bar{P}_5^3$ , and  $3 + 2\sqrt{-29} \in P_5$  so  $\langle 3 + 2\sqrt{-29} \rangle = P_5^3$ , hence  $[P_5]^3 = e$ , so  $[P_5]$  has order 3.
- Again,  $[P_3] \neq e$ . As  $N(1 + \sqrt{-29}) = 30$ ,  $\langle 1 + \sqrt{-29} \rangle \mid \langle 30 \rangle = \langle 2 \rangle \langle 3 \rangle \langle 5 \rangle$ , so we see  $\langle 1 + \sqrt{-29} \rangle = P_2 \bar{P}_3 \bar{P}_5$ , hence  $e = [P_2][P_3]^{-1}[P_5]^{-1}$  and so  $[P_3] = [P_2][P_5]^{-1}$ . Since product of two elements of coprime orders  $m, n$  in abelian group has order  $mn$ , we have

$$\text{ord}([P_3]) = \text{ord}([P_2][\bar{P}_5]) = 2 \cdot 3 = 6$$

Also,  $[P_3]^2 = [\bar{P}_5]^2 = [P_5]$  so  $[P_3]^3 = [P_2]$  and  $[P_3]^4 = [P_5]^{-1}$ . Hence  $\text{Cl}(R)$  contains a cyclic subgroup of order 6 generated by  $[P_3]$ .

## 8.1. Finiteness of the class group

**Lemma.** Let  $C > 0$ , then there are finitely many ideals of  $R$  of norm  $\leq C$ .

**Lemma.** For any number field  $K$ , there is  $C_K \in \mathbb{N}$  such that for any nonzero ideal  $J \subseteq R$ ,

$$\exists 0 \neq s \in J : N(s) \leq C_K \cdot N(J)$$

**Corollary.** Let  $\underline{c} \in \text{Cl}(R)$ , then there is ideal  $I \subseteq R$  with  $[I] = \underline{c}$  and  $N(I) \leq C_K$ .

**Theorem.** Let  $K$  number field,  $R = \mathcal{O}_K$ , then  $\text{Cl}(R)$  is finite.

**Definition.** Class number of  $K$  is  $h_K := |\text{Cl}(R)|$ .

## 8.2. The Minkowski bound

**Theorem** (Minkowski bound). If  $K = \mathbb{Q}(\theta)$  and  $p_\theta$  has  $s$  real roots,  $2t$  complex roots,  $n := s + 2t$ , then for every  $\underline{c} \in \text{Cl}(R)$ , we can find a (non-fractional) ideal  $I$  with  $[I] = \underline{c}$  and

$$N(I) \leq B_K := \left(\frac{4}{\pi}\right)^t \frac{n!}{n^n} \sqrt{|\Delta_K|}$$

i.e. we can take  $C_K = B_K$ .

**Example.** Let  $K = \mathbb{Q}(\sqrt{-29})$ , so  $R = \mathbb{Z}[\sqrt{-29}]$ , then every ideal class has representative of norm  $\leq (4/\pi)\sqrt{29} < 7$  so of norm 1, 2, ..., 6, so is product of  $P_2, P_3, \overline{P_3}, P_5, \overline{P_5}$ , so  $\text{Cl}(R) = \langle [P_3] \rangle$  is cyclic of order 6.

**Example.** Let  $K = \mathbb{Q}(\sqrt{-19})$ , so  $R = \mathcal{O}_K = \mathbb{Z}[\frac{1+\sqrt{-19}}{2}]$ ,  $\Delta_K = -19$ , then

$$B_K = \left(\frac{4}{\pi}\right) \frac{2!}{2^2} \sqrt{19} = \frac{2\sqrt{19}}{\pi} < 3$$

So every element in  $\text{Cl}(\mathcal{O}_K)$  is represented by an ideal of norm 1 or 2. Let  $N(I) = 2$ , then  $I$  is prime and  $I \mid \langle 2 \rangle_R$ . But minimal polynomial of  $\frac{1+\sqrt{-19}}{2}$  is  $x^2 - x + 5$  and  $x^2 - x + 4 = x^2 + x + 1$  irreducible in  $\mathbb{F}_2[x]$  so 2 is inert in  $R$ , hence  $I = \langle 2 \rangle_R$  and  $N(\langle 2 \rangle_R) = 4$ : contradiction. So  $\text{Cl}(\mathcal{O}_K) = \{e\}$ , i.e.  $\mathcal{O}_K$  is PID, and in particular a UFD. Note that it is not an ED though.

**Example.** Let  $K = \mathbb{Q}(\sqrt{-14})$ , so  $R = \mathcal{O}_K = \mathbb{Z}[\sqrt{-14}]$ .  $\Delta_K = 4 \cdot -14 = -56$ , so

$$B_K = \left(\frac{4}{\pi}\right)^1 \frac{2!}{2^2} \sqrt{56} = \frac{4\sqrt{14}}{\pi} < 5$$

In general,  $\text{Cl}(\mathcal{O}_K)$  is generated by prime ideals of norm  $\leq B_K$ . By Kummer-Dedekind,  $(2)_R = (2, \sqrt{-14})^2 = P_2^2$  and  $(3)_R = (3, \sqrt{-14} - 1)(3, \sqrt{-14} + 1)$ . Hence if  $N(I) = 4$ , then  $I \mid (2)_R^2 = P_2^4$  so  $I = P_2^2 = (2)_R$ . So as a set,

$$\text{Cl}(R) = \{e, [P_2], [P_3], [\overline{P_3}] = [P_3]^{-1}, [P_2^2] = e\}$$

The norm of a principal ideal is  $N(\langle a + b\sqrt{-14} \rangle) = a^2 + 14b^2 \neq 2, 3, 6$  hence  $P_2, P_3, \overline{P_3}, P_2P_3, P_2\overline{P_3}$  are not principal. We have  $[P_2][\overline{P_3}] \neq e \implies [P_2] \neq [P_3]$ , similarly  $[P_2] \neq [\overline{P_3}]$ . We have  $[P_3] \neq [\overline{P_3}]$ , since otherwise  $[P_3]^2 = e$ , so  $P_3^2$  is principal and so  $P_3^2 = \langle 3 \rangle$  but then  $P_3 = \overline{P_3}$ . Thus  $e, [P_2], [P_3], [\overline{P_3}]$  are distinct, so  $|\text{Cl}(R)| = 4$ , so  $\text{Cl}(R) \cong \mathbb{Z}/2 \times \mathbb{Z}/2$  or  $\mathbb{Z}/4$ . But  $[P_3]^2 \neq e$  so  $[P_3]$  has order 4, hence  $\text{Cl}(R) \cong \mathbb{Z}/4$  is generated by  $[P_3]$ . Note  $[\overline{P_3}]^2$  and  $[P_2]$  have order 2, so  $[\overline{P_3}]^2 = [P_2]$ , so  $[P_2P_3^2] = e$ , hence  $P_2P_3^2$  is principal and there exists element in  $\mathcal{O}_K$  of norm  $2 \cdot 3^2 = 18$ .

**Example.** Let  $K = \mathbb{Q}(\sqrt{79})$ . Prove that  $\text{Cl}(R) \cong \mathbb{Z}/3$ .

- $79 \not\equiv 1 \pmod{4}$  so  $\Delta_K = 4 \cdot 79$  so by the Minkowski bound, any element in  $\text{Cl}(R)$  contains an ideal of norm at most

$$B_K = \left(\frac{4}{\pi}\right)^0 \frac{2!}{2^2} \sqrt{|\Delta_K|} = \sqrt{79} \in (8, 9)$$

Hence  $\text{Cl}(R)$  is generated by the ideal classes of prime ideals dividing 2, 3, 5 and 7. By Kummer-Dedekind,

$p$	$x^2 - 79 \in \mathbb{F}_p[x]$	$\langle p \rangle_R$	norm of prime ideals above $p$
2	$x^2 - 1 = (x+1)^2$	$P_2^2$	2
3	$x^2 - 1 = (x+1)(x-1)$	$P_3 \overline{P}_3$	3
5	$x^2 - 4 = (x+2)(x-2)$	$P_5 \overline{P}_5$	5
7	$x^2 - 9 = (x+3)(x-3)$	$P_7 \overline{P}_7$	7

Thus  $\text{Cl}(R)$ , as a set, is

$$\begin{aligned} \text{Cl}(R) = & \{e, [P_2], [P_3], [P_5], [P_7], [P_2]^2 = e, [P_2]^3 = [P_2], [P_2 P_3]\} \\ & \cup \{[\overline{P}_3], [\overline{P}_5], [\overline{P}_7], [P_2 \overline{P}_3]\} \end{aligned}$$

(since the ideals representing these classes have norm  $\leq 8$ ). Computing norms of some principal ideals  $\langle a + \sqrt{79} \rangle$ , letting  $a$  increase up to  $\sqrt{79} \approx 9$  to find minimal value and other small values of the norm:

$a$	$N(\langle a + \sqrt{79} \rangle_R) =  a^2 - 79 $
0	79
1	$2 \cdot 3 \cdot 13$
2	$3 \cdot 5^2$
3	$2 \cdot 5 \cdot 7$
4	$3^2 \cdot 7$
5	$2 \cdot 3^3$
6	43
7	$2 \cdot 3 \cdot 5$
8	$3 \cdot 5$
9	2
10	$3 \cdot 7$

- So  $N(\langle 9 + \sqrt{79} \rangle) = 2 \implies \langle 7 + \sqrt{79} \rangle = P_2$  so  $[P_2] = e$ .
- $N(\langle 8 + \sqrt{79} \rangle) = 3 \cdot 5$  so  $[P_3][P_5] = e$  ( $\Leftrightarrow [\overline{P}_3][\overline{P}_5] = e$ ) or  $[P_3][\overline{P}_5] = e$  ( $\Leftrightarrow [\overline{P}_3][P_5] = e$ ). In both cases,

$$\{[P_5], [\overline{P_5}]\} = \{[P_3], [\overline{P_3}]\}$$

- Similarly, since  $N(\langle 10 + \sqrt{79} \rangle) = 3 \cdot 7$ , we have

$$\{[P_7], [\overline{P_7}]\} = \{[P_3], [\overline{P_3}]\}$$

- Thus  $\text{Cl}(R)$  is generated by  $[P_3]$  and as a set,  $\text{Cl}(R) = \{e, [P_3], [P_3]^{-1}\}$ .
- Since  $N(\langle 5 + \sqrt{79} \rangle) = 2 \cdot 27$ , we have

$$\langle 5 + \sqrt{79} \rangle = P_2 P_3^a \overline{P_3}^{3-a} \quad \text{for some } a \in \{0, 1, 2, 3\}$$

- If  $a \in \{1, 2\}$ , then  $P_3 \overline{P_3} = \langle 3 \rangle_R \mid \langle 5 + \sqrt{79} \rangle$ : contradiction, since  $3 \nmid (5 + \sqrt{79})$ . So WLOG assume  $a = 3$  (if  $a = 0$ , swap  $P_3$  and  $\overline{P_3}$ ). So  $\langle 5 + \sqrt{79} \rangle = P_2 P_3^3$ , hence  $e = [P_3]^3$ , so  $[P_3]$  has order 1 or 3.
- Assume that  $P_3 = \langle \alpha \rangle_R$ , then

$$P_2 P_3^3 = \langle 9 + \sqrt{79} \rangle \langle \alpha^3 \rangle = \langle 5 + \sqrt{79} \rangle$$

and so

$$\alpha^3 = \frac{5 + \sqrt{79}}{9 + \sqrt{79}} u = (-17 + 2\sqrt{79})u \quad \text{for some } u \in R^\times$$

- For any  $a \in R^\times$ ,  $\langle \pm a \alpha \rangle_R = \langle \alpha \rangle_R$  and  $(\pm a \alpha)^3 = (-17 + 2\sqrt{79})u(\pm a)^3$ . So without changing  $P_3$ , we can rescale  $\alpha$  by a unit and so rescale  $u$  by a unit cube.
- The fundamental unit of  $R$  (by trial and error) is  $v = 80 + 9\sqrt{79}$ . By [Theorem 4.4](#),

$$R^\times / \langle \pm v^3 \rangle \cong \mathbb{Z}/3$$

(consider the map  $R^\times \rightarrow \mathbb{Z}/3$ ,  $\pm v^r = r \bmod 3$  and use FIT). Thus, up to multiplication by unit cubes, there are only three possible units  $1, v, v^2$  (can take  $v^{-1}$  instead of  $v^2$ ). So we can choose  $\alpha$  such that  $u$  is  $1, v$  or  $v^{-1}$ .

- So  $\alpha^3$  is one of

$$-17 + 2\sqrt{79}, \quad (-17 + 2\sqrt{79})v = 62 + 7\sqrt{79}, \quad (-17 + 2\sqrt{79})v^{-1} = -2782 + 313\sqrt{79}$$

- Let  $\alpha = a + b\sqrt{79}$ ,  $a, b \in \mathbb{Z}$ , then  $\alpha^3 = a(a^2 + 3 \cdot 79b^2) + b(3a^2 + 79b^2)\sqrt{79}$ . We have  $3 = N(P_3) = |N(\alpha)| = |a^2 - 79b^2|$  so  $a, b \neq 0$  so coefficient in  $\sqrt{79}$  in  $\alpha^3$  satisfies  $|b(3a^2 + 79b^2)| \geq 3 + 79 = 82$ , hence  $\alpha^3 = -2782 + 313\sqrt{79}$ . So  $b(3a^2 + 79b^2) = 313$  which is prime, hence  $b = 1$  and so  $a^2 = 78$ : contradiction.
- So  $P_3$  is not principal so has order 3, so  $\text{Cl}(R) \cong \mathbb{Z}/3$ .

## 9. Diophantine applications

### 9.1. Mordell equations

**Definition.** A **Mordell equation** is of the form  $x^2 + d = y^3$ ,  $d \in \mathbb{Z}$ , with solutions  $x, y \in \mathbb{Z}$  sought.

**Example.** Find all solutions to the Mordell equation  $y^3 = x^2 + 5$ .

- Let  $K = \mathbb{Q}(\sqrt{-5})$ , then  $R = \mathcal{O}_K = \mathbb{Z}[\sqrt{-5}]$ . By the Minkowski bound, every element in  $\text{Cl}(R)$  has representative ideal of norm at most

$$\left(\frac{4}{\pi}\right)\sqrt{5} < 3$$

so as a set,  $\text{Cl}(R) = \{e, [P_2]\}$  where  $P_2 = \langle 2, 1 + \sqrt{-5} \rangle$  by Kummer-Dedekind.

- $P_2$  is not principal as  $a^2 + 5b^2 = 2$  has no solutions, hence  $\text{Cl}(R) \cong \mathbb{Z}/2$ .
- Let  $\langle \alpha \rangle = \langle x + \sqrt{-5} \rangle$ , so  $\langle \bar{\alpha} \rangle = \langle x - \sqrt{-5} \rangle$ . If a prime ideal  $P$  divides  $\langle \alpha \rangle$  and  $\langle \bar{\alpha} \rangle$ , then  $P \mid \langle \alpha - \bar{\alpha} \rangle = \langle 2\sqrt{-5} \rangle = \langle 2 \rangle_R \langle \sqrt{-5} \rangle_R = P_2^2 P_{51}$ . 2 and 5 ramify, so  $P_2 = \overline{P_2}$  and  $\overline{P_5} = P_5$ .
- Hence

$$\begin{aligned}\langle \alpha \rangle &= P_2^a P_5^b Q_1^{r_1} \dots Q_n^{r_n}, \\ \langle \bar{\alpha} \rangle_R &= P_2^a P_5^b \overline{Q_1}^{r_1} \dots \overline{Q_n}^{r_n}\end{aligned}$$

where  $a, b, r_i \geq 0$ , all  $Q_i, \overline{Q_i}$  are distinct and different from  $P_2, P_5$ .

- Then

$$\langle y \rangle^3 = \langle y^3 \rangle = \langle \alpha \bar{\alpha} \rangle = \langle \alpha \rangle \langle \bar{\alpha} \rangle = P_2^{2a} P_5^{2b} (Q_1 \overline{Q_1})^{r_1} \dots (Q_n \overline{Q_n})^{r_n}$$

By uniqueness of prime ideal factorisation, all exponents in RHS are divisible by 3, so let  $I = P_2^{a/3} P_5^{b/3} Q_1^{r_1/3} \dots Q_n^{r_n/3}$ , so that  $I^3 = \langle \alpha \rangle_R$ .

- Since  $h_K = 2$ , the square of any fractional ideal of  $R$  is principal, so  $(I^{-1})^2$  is principal, hence  $I = I^3 (I^{-1})^2 = \alpha (I^{-1})^2$  is principal, so let  $I = \langle \beta \rangle_R$ , for  $\beta = s + t\sqrt{-5} \in R$ .
- Now  $\langle \beta^3 \rangle = I^3 = \langle \alpha \rangle$  so  $\beta^3 = u\alpha$  for some  $u \in R^\times$ . But only units in  $R$  are  $\pm 1$ . Since  $I = \langle -\beta \rangle$ , can assume that  $\beta^3 = \alpha$ . Then

$$s^3 + 3st^2(-5) + (3s^2t + t^3(-5))\sqrt{-5} = x + \sqrt{-5}$$

- So  $s^3 - 15st^2 = x$ ,  $3s^2t - 5t^3 = 1$ . Hence  $t = \pm 1$ , and both possibilities yield no integer solutions to the second equation, so  $x^2 + 5 = y^3$  has no integer solutions.

**Example.** Let  $K = \mathbb{Q}(\sqrt{-31})$ , it can be shown with Minkowski bound that  $h_K = 3$  so  $\text{Cl}(R) = \langle [P_2] \rangle \cong \mathbb{Z}/3$  where  $P_2 = \langle 2, (1 + \sqrt{-31})/2 \rangle$ . Show that

$$x^2 + 31 = y^3$$

has no solutions  $x, y \in \mathbb{Z}$ .

- Assume  $x, y$  is a solution.  $31 \nmid x$ , as otherwise  $31^2 \mid (y^3 - x^2) = 31$  (since 31 is prime): contradiction.
- $x$  is odd and  $y$  is even:
  - If  $x$  even,  $y$  is odd and  $y^3 \equiv 31 \equiv -1 \pmod{4}$  so  $y \equiv -1 \pmod{4}$ . Now  $x^2 + 4 = y^3 - 27 = (y - 3)(y^2 + 3y + 9)$ .
  - $y^2 + 3y + 9 \equiv -1 \pmod{4}$ . Hence  $y^2 + 3y + 9$  is divisible by prime  $p \equiv 3 \pmod{4}$  (since product two numbers of form  $4n + 1$  is also of this form). So  $x^2 + 4 \equiv 0 \pmod{p}$ . Hence  $(x/2)^2 \equiv -1 \pmod{p}$  so  $(x/2)^{p-1} \equiv (-1)^{\frac{p-1}{2}} \equiv -1$  as  $p \equiv 3 \pmod{4}$  which contradicts Fermat's little theorem. Hence  $x$  is odd so  $y$  is even.

- Now  $(x + \sqrt{-31})(x - \sqrt{-31}) = y^3$ .  $x$  is odd, so  $\alpha := (x + \sqrt{-31})/2 \in R$ . Let  $y = 2z$ ,  $z \in \mathbb{Z}$ , then  $\alpha\bar{\alpha} = 2z^3$  and  $\langle\alpha\rangle\langle\bar{\alpha}\rangle = \langle 2\rangle\langle z\rangle^3$ .
- If  $P \mid \langle\alpha\rangle, \langle\bar{\alpha}\rangle$ , then  $\alpha, \bar{\alpha} \in P$ , so  $\sqrt{-31} = \alpha - \bar{\alpha} \in P$ , hence  $P = \langle\sqrt{-31}\rangle$  (this is prime since norm is 31, a prime).
- But then  $x = \alpha + \bar{\alpha} \in P \cap \mathbb{Z} = \langle 31\rangle_{\mathbb{Z}}$ , but  $31 \nmid x$ , so we have a contradiction. So  $\langle\alpha\rangle, \langle\bar{\alpha}\rangle$  are coprime ideals.
- WLOG,  $\langle\alpha\rangle = P_2^a Q_1^{r_1} \dots Q_n^{r_n}$  and  $\langle\bar{\alpha}\rangle = \overline{P_2}^a \overline{Q_1}^{r_1} \dots \overline{Q_n}^{r_n}$  with  $P_2, \overline{P_2}$ , all  $Q_i, \overline{Q_i}$  distinct.
- Then  $\langle\alpha\rangle\langle\bar{\alpha}\rangle = \langle 2\rangle^a (Q_1 \overline{Q_1})^{r_1} \dots (Q_n \overline{Q_n})^{r_n} = \langle 2\rangle\langle z\rangle^3$ .
- Hence  $a \equiv 1 \pmod 3$  and for all  $i$ ,  $3 \mid r_i$ . So  $\langle\alpha\rangle = P_2 I^3$  for some ideal  $I$ .
- Now  $[\langle\alpha\rangle] = e$  and  $[I^3] = [I]^3 = e$  as  $h_K = 3$ . Hence  $[P_2] = e$  so  $P_2$  is principal.
- So  $P_2 = \langle(u + v\sqrt{-31})/2\rangle$ ,  $u, v \in \mathbb{Z}$ ,  $u \equiv v \pmod 2$ .
- Then  $2 = N(P_2) = (u^2 + 31v^2)/4$  hence  $8 = u^2 + 31v^2$ : contradiction.

## 9.2. Generalised Pell equations

**Definition.** A **generalised Pell equation** is of the form

$$x^2 - dy^2 = n, \quad n \in \mathbb{Z}, d \in \mathbb{N} \text{ square-free}$$

i.e. determine whether  $n$  is a norm from  $\mathbb{Z}[\sqrt{d}]$ .

**Definition.** Let  $K = \mathbb{Q}(\sqrt{14})$ . Solve  $x^2 - 14y^2 = \pm 5$ . We can assume  $R = \mathbb{Z}[\sqrt{14}]$  is PID and so a UFD (can be proven using Minkowski bound by showing  $h_K = 1$ ).

- By trial and error, fundamental unit is  $u = 15 + 4\sqrt{14}$  and  $N(u) = 15^2 - 14 \cdot 16 = 1$ .
- We have  $N(3 - \sqrt{14}) = -5$  so  $\langle 5\rangle = \langle 3 + \sqrt{14}\rangle\langle 3 - \sqrt{14}\rangle$  by Kummer-Dedekind.
- Now  $\langle x + y\sqrt{14}\rangle\langle x - y\sqrt{14}\rangle = \langle 3 + \sqrt{14}\rangle\langle 3 - \sqrt{14}\rangle$ . The ideals on the LHS are conjugate, and ideals on RHS are prime so  $\langle x + y\sqrt{14}\rangle = \langle 3 \pm \sqrt{14}\rangle$ .
- Hence  $x + y\sqrt{14} = \pm(15 + 4\sqrt{14})^n(3 \pm \sqrt{14})$  for some  $n \in \mathbb{Z}$  and  $x - y\sqrt{14} = \pm(15 - 4\sqrt{14})^n(3 \mp \sqrt{14})$  which gives all solutions  $x, y \in \mathbb{Z}$ .
- **Note:**  $N(x + y\sqrt{14}) = x^2 - 14y^2 = N(u)^n N(3 \pm \sqrt{14}) = 1^n \cdot -5 = -5$  so all solutions must have  $-5$  on RHS.

**Example.** Solve  $x^2 - 79y^2 = \pm 15$  for  $x, y \in \mathbb{Z}$ .

- Let  $K = \mathbb{Q}(\sqrt{79})$ , so  $R = \mathcal{O}_K = \mathbb{Z}[\sqrt{79}]$ . We have that  $\text{Cl}(R) \cong \mathbb{Z}/3$ , generated by  $[P_3]$ .
- $x^2 - 79 \equiv (x+1)(x-1) \pmod 3$  so  $\langle 3\rangle_R = P_3 \overline{P_3} = \langle 3, 1 + \sqrt{79}\rangle\langle 3, 1 - \sqrt{79}\rangle$  by Kummer-Dedekind.
- $x^2 - 79 \equiv (x+2)(x-2) \pmod 5$  so  $\langle 5\rangle_R = P_5 \overline{P_5} = \langle 2 + \sqrt{79}\rangle\langle 2 - \sqrt{79}\rangle$  by Kummer-Dedekind.
- We have  $\langle x + y\sqrt{79}\rangle\langle x - y\sqrt{79}\rangle = \langle 15\rangle_R = P_3 \overline{P_3} P_5 \overline{P_5}$ . Since  $\langle x + y\sqrt{79}\rangle = \langle x - y\sqrt{79}\rangle$ , we have  $x \pm y\sqrt{79} = P_3 P_5$  or  $P_3 \overline{P_5}$ .
- Note  $8^2 - 79 = -15$ , thus  $\langle 8 + \sqrt{79}\rangle = \overline{P_3} P_5$  as  $8 + \sqrt{79} = 9 - (1 - \sqrt{79}) = 10 - (2 - \sqrt{79})$ . Hence  $[P_3][P_5] = e$  so  $[P_5] = [P_3]^{-1} \neq [P_3]$ .
- So  $P_3 P_5$  is principal and  $P_3 \overline{P_5}$  isn't. Hence  $\langle x \pm y\sqrt{79}\rangle = P_3 P_5 = \langle 8 - \sqrt{79}\rangle$ .

- Therefore,  $x \pm y\sqrt{79} = \pm u^n(8 - \sqrt{79})$  where  $u = 80 + 9\sqrt{79}$  is fundamental unit in  $R$ ,  $n \in \mathbb{Z}$  and this gives all solutions to  $x, y \in \mathbb{Z}$ .
- Since  $N(u) = 1$ ,  $x^2 - 79y^2 = N(\text{LHS}) = N(8 - \sqrt{79}) = -15$  so the only solutions are for  $-15$ , there are none for  $15$ .