

# Number Fields

January 23, 2018

<i>CONTENTS</i>	2
-----------------	---

## Contents

<b>-1</b> Miscellaneous	<b>3</b>
<b>0</b> Motivation	<b>4</b>
<b>1</b> Ring of integers	<b>5</b>
<b>2</b> Complex embeddings	<b>8</b>

## **-1 Miscellaneous**

Book: Number Fields, Marcus

Course notes: [www.dpmms.ac.uk/~jat58/nfl2018](http://www.dpmms.ac.uk/~jat58/nfl2018)

## 0 Motivation

**Theorem.** If  $p$  is an odd prime, then  $p = a^2 + b^2$  for  $a, b \in \mathbb{Z} \iff p \equiv 1 \pmod{4}$ .

*Proof.* If  $p = a^2 + b^2$ , then  $p \equiv 0, 1, 2 \pmod{4}$ . So this condition on  $p$  is necessary.

Suppose instead  $p \equiv 1 \pmod{4}$ . Then  $\left(\frac{-1}{p}\right) = 1$ . Thus  $\exists a \in \mathbb{Z}$  such that  $a^2 \equiv -1 \pmod{p}$ , or  $p \mid a^2 + 1$ . We can factor  $a^2 + 1 = (a + i)(a - i)$  in the ring  $\mathbb{Z}[i]$ . Here we introduce a notation: if  $R \subseteq S$  are rings and  $\alpha \in S$ , then

$$R[\alpha] = \left\{ \sum_{i=0}^n a_i \alpha^i \in S \mid a_i \in R \right\}$$

, the smallest subring of  $S$  containing both  $R$  and  $\alpha$ .

We know from IB GRM that  $\mathbb{Z}[i]$  is a UFD. Now  $p \mid (a + i)(a - i)$ . If  $p$  is irreducible in  $\mathbb{Z}[i]$  then  $p \mid a + i$  or  $p \mid a - i$ , contradiction. Thus  $p$  is reducible in  $\mathbb{Z}[i]$ , hence  $p = z_1 z_2$  with  $z_1, z_2 \in \mathbb{Z}[i]$ . If  $z_1 = A + Bi$ ,  $A, B \in \mathbb{Z}$ , then  $A^2 + B^2 = p$ .  $\square$

Another example is when  $p$  is an odd prime. Does the equation

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

have solutions with  $x, y, z \in \mathbb{Z}$  and  $xyz \neq 0$ ?

**Theorem.** (Kummer, 1850)

If  $\mathbb{Z}[e^{2\pi i/p}]$  is a UFD, then there are no solutions.

Strategy: factor  $x^p + y^p = \prod_{j=0}^{p-1} (x + e^{2\pi i j/p} y)$  in  $\mathbb{Z}[e^{2\pi i/p}]$ .

However, we now know  $\mathbb{Z}[e^{2\pi i/p}]$  is a UFD  $\iff p \leq 19$ .

**Theorem.** (Kummer, 1850)

If  $p$  is a *regular* prime, then there are no solutions.

If  $p < 100$ , then  $p$  is regular  $\iff p \neq 37, 59, 67$ .

We have seen various examples such as  $\mathbb{Z} \subseteq \mathbb{Q}$ ,  $\mathbb{Z}[i] \subseteq \mathbb{Q}[i]$ ,  $\mathbb{Z}[e^{2\pi i/p}] \subseteq \mathbb{Q}[e^{2\pi i/p}]$ , or in general,  $\mathcal{O}_L \subseteq L$ , where a ring of "integers" lies in a number field.

## 1 Ring of integers

Recall: A field extension  $L/K$  is an inclusion  $K \leq L$  of fields. The degree of  $L/K$  is  $[L : K] = \dim_K L$ . We say  $L/K$  is finite if  $[L : K] < \infty$ .

**Definition.** (1.1)

A number field is a finite extension  $L/\mathbb{Q}$ . Here are two ways to construct number fields:

- (1) Let  $\alpha \in \mathbb{C}$  be an algebraic number. Then  $L = \mathbb{Q}(\alpha)$  is a number field;
  - (2) Let  $K$  be a number field, and let  $f(X) \in K[X]$  be an irreducible polynomial. Then  $L = K[X]/(f(X))$  is a number field.
- (Recall Tower Law:  $[L : \mathbb{Q}] = [L : K][K : \mathbb{Q}] < \infty$ ).

**Definition.** (1.2)

- (1) Let  $L/K$  be a field extension. Then we say  $\alpha \in L$  is algebraic over  $K$  if there exists a monic  $f(X) \in K[X]$  such that  $f(\alpha) = 0$ ;
- (2) Let  $L/\mathbb{Q}$  be a field extension. Then we say  $\alpha \in L$  is an algebraic integer if there exists a monic  $f(X) \in \mathbb{Z}[X]$  such that  $f(\alpha) = 0$ .

**Definition.** (1.3)

Let  $L/K$  be a field extension, and let  $\alpha \in L$  be algebraic over  $K$ . We call the minimal polynomial of  $\alpha$  over  $K$  the monic polynomial  $f_\alpha(X) \in K[X]$  of least degree such that  $f_\alpha(\alpha) = 0$ .

We recall why  $f_\alpha(X)$  is well-defined: there exists some monic  $f(X) \in K[X]$  with  $f(\alpha) = 0$  as  $\alpha$  is algebraic. If  $f_\alpha(\alpha), f'_\alpha(\alpha) \in K[X]$  both satisfy the definition of minimal polynomial, then we apply the polynomial division algorithm to write

$$f_\alpha(X) = p(X)f'_\alpha(X) + r(X)$$

where  $p(X), r(X) \in K[X]$ , and  $\deg r < \deg f'_\alpha$ . Evaluate at  $X = \alpha$ , we have  $0 = f_\alpha(\alpha) = p(\alpha)f'_\alpha(\alpha) + r(\alpha) = r(\alpha)$ . By minimality of  $\deg f'_\alpha$ , we must have  $r = 0$ . Then  $\deg f_\alpha = \deg f'_\alpha$ , and  $f_\alpha(X), f'_\alpha(X)$  are both monic, i.e.  $p(X) = 1$  and  $f_\alpha(X) = f'_\alpha(X)$ .

**Lemma.** (1.4)

Let  $L/\mathbb{Q}$  be a field extension, and let  $\alpha \in L$  be an algebraic integer. Then:

- (1) The minimal polynomial  $f_\alpha(X)$  of  $\alpha$  over  $\mathbb{Q}$  lies in  $\mathbb{Z}[X]$ ;
- (2) If  $g(X) \in \mathbb{Z}[X]$  satisfies  $g(\alpha) = 0$ , then there exists  $q(X) \in \mathbb{Z}[X]$  such that  $g(X) = f_\alpha(X)q(X)$ ;
- (3) The kernel of the ring homomorphism  $\mathbb{Z}[X] \rightarrow L$  by  $f(X) \mapsto f(\alpha)$  equals  $(f_\alpha(X))$ , the ideal generated by  $f_\alpha(X)$ .

*Proof.* (1) Recall that if  $f(X) = a_n X^n + \dots + a_0 \in \mathbb{Z}[X]$ , then we define from GRM, the content  $c(f) = \gcd(a_n, \dots, a_0)$ . Recall Gauss' Lemma: If  $f(X), g(X) \in \mathbb{Z}[X]$ , then  $c(fg) = c(f)c(g)$ . Since  $\alpha \in L$  is an algebraic integer, there exists monic  $f(X) \in \mathbb{Z}[X]$  such that  $f(\alpha) = 0$ , i.e.  $c(f) = 1$ . Apply polynomial division in  $\mathbb{Q}[X]$  to get  $f(X) = p(X)f_\alpha(X) + r(X)$ , where  $p(X), r(X) \in \mathbb{Q}[X]$ ,  $\deg r < \deg f_\alpha$ . The definition of  $f_\alpha(X)$  implies that  $r(X) = 0$ , hence  $f(X) = p(X)f_\alpha(X)$ . Now choose integers  $n, m \geq 1$  such that  $np(X) \in \mathbb{Z}[X]$ ,  $c(np) = 1$ , and  $mf_\alpha(X) \in$

$\mathbb{Z}[x]$ ,  $c(mf_\alpha) = 1$ . Then  $nmf(x) = (np(x))(mf_\alpha(x)) \implies c(nmf(x)) = nm = 1$ . So  $n = m = 1$ , hence  $f_\alpha(x) \in \mathbb{Z}[X]$ .

(2) Let  $g(X) \in \mathbb{Z}[X]$  be such that  $g(\alpha) = 0$ . WLOG  $g(x) \neq 0$  and  $c(g) = 1$ . Now apply polynomial division to write  $g(x) = q(x)f_\alpha(x) + s(x)$  where  $q(x), s(x) \in \mathbb{Q}[x]$ ,  $\deg s < \deg f_\alpha$ . Again by definition we have  $s(x) = 0$ . Choose an integer  $k \geq 1$  such that  $kq(x) \in \mathbb{Z}[x]$  and  $c(kq) = 1$ . Then  $kg(x) = kq(x)f_\alpha(x) \implies k = c(kg) = c(kq)c(f_\alpha) = 1$ . So  $k = 1$ , hence  $q(x) \in \mathbb{Z}[x]$ .

(3) is a reformulation of (2).  $\square$

Let  $L/\mathbb{Q}$  be a field extension. Last time we said  $\alpha \in L$  is an algebraic integer if  $\exists$  monic polynomial  $f(x) \in \mathbb{Z}[x]$  such that  $f(\alpha) = 0$ . We proved that if  $\alpha \in L$  is an algebraic integer and  $f_\alpha(x) \in \mathbb{Q}[x]$  is the minimal polynomial of  $\alpha$  over  $\mathbb{Q}$ , then  $f_\alpha(x) \in \mathbb{Z}[x]$ . However there is a small problem, so we'll prove again.

*Proof.* Choose  $f(x) \in \mathbb{Z}[x]$  monic with  $f(\alpha) = 0$ , and write

$$f(x) = q(x)f_\alpha(x) + r(x)$$

where  $q(x), r(x) \in \mathbb{Q}[x]$ ,  $\deg r < \deg f_\alpha$ . Then  $r(\alpha) = 0 \implies r(x) = 0$ , by minimality of  $\deg f_\alpha$ . I said that we can find integer  $n, m \geq 1$  s.t.  $nf_\alpha(x) \in \mathbb{Z}[x]$ ,  $c(nf_\alpha) = 1$ ,  $mq(x) \in \mathbb{Z}[x]$ ,  $c(mq) = 1$ . However we need to explain why do they exist. Note  $f_\alpha(x)$  and  $q(x)$  are both monic. Choose integers  $N, M \geq 1$  such that  $Nf_\alpha(x) \in \mathbb{Z}[x]$ ,  $Mq(x) \in \mathbb{Z}[x]$ . Then  $c(Nf_\alpha) | N$ ,  $c(Mq) | M$  as those are the leading term of the polynomial. Now let  $N/c(Nf_\alpha) = n \in \mathbb{Z}$ ,  $M/c(Mq) = m \in \mathbb{Z}$ . Now  $nmf(x) = (nf_\alpha(x))(mq(x))$ , so  $c(nmf(x)) = nm = 1 \implies n = m = 1$ .  $\square$

**Corollary.** (1.5)

If  $\alpha \in \mathbb{Q}$ , then  $\alpha$  is an algebraic integer  $\iff \alpha \in \mathbb{Z}$ .

*Proof.* By lemma 1.4,  $\alpha$  is an algebraic integer  $\iff f_\alpha(x) \in \mathbb{Z}[x]$ . But if  $\alpha \in \mathbb{Q}$ , then  $f_\alpha(x) = x - \alpha$ , and the first needs to divide the second polynomial.  $\square$

**Notation.** If  $L/\mathbb{Q}$  is any field extension, we write  $\mathcal{O}_L = \{\alpha \in L | \alpha \text{ is an algebraic integer}\}$ .

Now we proceed to the first non-trivial result of the course:

**Proposition.** (1.6)

If  $L/\mathbb{Q}$  is a field extension,  $\mathcal{O}_L$  is a ring.

*Proof.* Clearly  $0, 1 \in \mathcal{O}_L$ . Now if  $\alpha \in \mathcal{O}_L$ , then  $f_{-\alpha}(x) = (-1)^{\deg f_\alpha} f_\alpha(-x) \implies -\alpha \in \mathcal{O}_L$ .

The hard part is to show that if  $\alpha, \beta \in \mathcal{O}_L$ , then  $\alpha + \beta \in \mathcal{O}_L$  and  $\alpha\beta \in \mathcal{O}_L$ .

Observe that if  $\alpha \in \mathcal{O}_L$ , then  $\mathbb{Z}[\alpha] \subseteq L$  is a finitely generated  $\mathbb{Z}$ -module. By definition,  $\mathbb{Z}[\alpha]$  is generated by  $1, \alpha, \alpha^2, \alpha^3, \dots$ . Let  $f_\alpha(x) = x^d + a_1x^{d-1} + \dots + ad$ ,  $a_i \in \mathbb{Z}$ . Then  $\alpha^d = -(a_1\alpha^{d-1} + \dots + ad)$ , so  $\alpha^d \in \sum_{i=0}^{d-1} \mathbb{Z}\alpha^i$ . By induction, we see that  $\alpha^n \in \sum_{i=0}^{d-1} \mathbb{Z}\alpha^i$  for all  $n \geq d$ . Hence  $\mathbb{Z}[\alpha] = \sum_{i=0}^{d-1} \mathbb{Z}\alpha^i$ . Now take  $\alpha, \beta \in \mathcal{O}_L$  and let  $d = \deg f_\alpha$ ,  $e = \deg f_\beta$ .

By definition,  $\mathbb{Z}[\alpha, \beta] = \mathbb{Z}[\alpha][\beta]$  is generated as a  $\mathbb{Z}$ -module by  $\{\alpha^i \beta^j\}_{i,j \in \mathbb{N}}$ . The same argument show that in fact this ring is generated as a  $\mathbb{Z}$ -module by  $\{\alpha^i \beta^j\}$  for  $0 \leq i \leq d-1, 0 \leq j \leq e-1$ . So  $\mathbb{Z}[\alpha, \beta]$  is finitely generated. From GRM we know the classification of finitely generated  $\mathbb{Z}$ -modules implies that there's an isomorphism  $\mathbb{Z}[\alpha, \beta] \cong \mathbb{Z}^r \oplus T$  for some  $r \geq 1$  and finite abelian group  $T$ . In fact,  $T = 0$ : if  $\gamma \in T$ , then  $|T|\gamma = 0$ , by Lagrange's theorem. But  $\mathbb{Z}[\alpha, \beta] \subseteq L$ , a  $\mathbb{Q}$ -vector space, so this forces  $\gamma = 0$ . Now we can therefore fix an isomorphism  $\mathbb{Z}[\alpha, \beta] \cong \mathbb{Z}^r$  ( $r \geq 1$ ). There's an endomorphism  $m_{\alpha\beta} : \mathbb{Z}[\alpha, \beta] \rightarrow \mathbb{Z}[\alpha, \beta]$  by  $\gamma \rightarrow \alpha\beta\gamma$  (as a  $\mathbb{Z}$ -module).  $m_{\alpha\beta}$  corresponds to an  $r \times r$  matrix  $A_{\alpha\beta} \in M_{r \times r}(\mathbb{Z})$ . Let  $F_{\alpha\beta}(x) = \det(x \cdot 1_r - A_{\alpha\beta}) \in \mathbb{Z}[x]$ , a monic polynomial. By the Cayley-Hamilton theorem,  $F_{\alpha\beta}(m_{\alpha\beta}) = 0$  as endomorphisms of  $\mathbb{Z}[\alpha, \beta]$ . Write  $F_{\alpha\beta}(x) = x^r + b_1 x^{r-1} + \dots + b_r$  for  $b_i \in \mathbb{Z}$ . Thus  $m_{\alpha\beta}^r + b_1 m_{\alpha\beta}^{r-1} + \dots + b_r \cdot 1_r = 0$  as endomorphisms of  $\mathbb{Z}[\alpha, \beta]$ . Now the image of 1 is  $(\alpha\beta)^r + b_1(\alpha\beta)^{r-1} + \dots + b_r = F_{\alpha\beta}(\alpha\beta) = 0$ . So  $\alpha\beta \in \mathcal{O}_L$ . The argument to show  $\alpha + \beta \in \mathcal{O}_L$  is identical, replacing  $m_{\alpha\beta}$  by  $m_{\alpha+\beta} : \mathbb{Z}[\alpha, \beta] \rightarrow \mathbb{Z}[\alpha, \beta]$  by  $\gamma \rightarrow (\alpha + \beta)\gamma$ . The detail is omitted here.  $\square$

We call  $\mathcal{O}_L$  the ring of algebraic integers of  $L$ .

**Lemma.** (1.7)

Let  $L/\mathbb{Q}$  be a number field, and let  $\alpha \in L$ . Then  $\exists n \geq 1$  an integer such that  $n\alpha \in \mathcal{O}_L$ .

*Proof.* Let  $f(x) \in \mathbb{Q}[x]$  be a monic polynomial such that  $f(\alpha) = 0$ . Then  $\exists n \in \mathbb{Z}, n \geq 1$  such that  $g(x) = n^{\deg f} f(x/n) \in \mathbb{Z}[x]$  is monic. But then  $g(n\alpha) = n^{\deg f} f(\alpha) = 0$ . So  $n\alpha \in \mathcal{O}_L$ .  $\square$

## 2 Complex embeddings

Let  $L$  be a number field.

**Definition.** (2.1)

A *complex embedding* of  $L$  is a field homomorphism  $\sigma : L \rightarrow \mathbb{C}$ . Note: in this case,  $\sigma$  is injective, and  $\sigma|_{\mathbb{Q}}$  is the usual embedding  $\mathbb{Q} \rightarrow \mathbb{C}$ .

**Proposition.** (2.2)

Let  $L/K$  be an extension of number fields, and let  $\sigma_0 : K \rightarrow \mathbb{C}$  be a complex embedding. Then there exist exactly  $[L : K]$  embeddings  $\sigma : L \rightarrow \mathbb{C}$  which extends  $\sigma_0$  ( $\sigma|_K = \sigma_0$ ).

*Proof.* Induction on  $[L : K]$ . If  $[L : K] = 1$ , then  $L = K$ , so  $\sigma_0$  determines  $\sigma$ .

In general, choose  $\alpha \in L - K$  and consider  $L/K(\alpha)/K$ . By the Tower law,  $[L : K] = [L : K(\alpha)][K(\alpha) : K]$  and  $[K(\alpha) : K] > 1$ . By induction, it's enough to show there are exactly  $[K(\alpha) : K]$  embeddings  $\sigma : K(\alpha) \rightarrow \mathbb{C}$  extending  $\sigma_0$ . Let  $f_\alpha(x) \in K[x]$  be the minimal polynomial of  $\alpha$  over  $K$ . Observe there's an isomorphism  $K[x]/(f_\alpha(x)) \rightarrow K(\alpha)$  by sending  $x \rightarrow \alpha$ . To give a complex embedding  $\sigma : K(\alpha) \rightarrow \mathbb{C}$  extending  $\sigma_0$ , it's equivalent to give a root  $\beta$  of  $(\sigma_0 f)(x)$  in  $\mathbb{C}$  ( $\sigma_0 f(x) \in \mathbb{C}[x]$  means apply  $\sigma_0$  to the coefficients of  $f(x)$ ). Dictionary:  $\sigma \rightarrow \beta = \sigma(\alpha)$ . We have  $[K(\alpha) : K] = \deg f_\alpha = \deg \sigma_0 f_\alpha$ . It's enough to show  $\sigma_0 f_\alpha$  has distinct roots in  $\mathbb{C}$ . The polynomial  $f_\alpha(x) \in K[x]$  is irreducible, so is prime to its derivative  $f'_\alpha(x)$  ( $\text{char } K = 0$ ). So  $\alpha$  is separable over  $K$ .  $\square$