

Number Fields: Example Sheet 3 of 3

1. Let $K = \mathbb{Q}(\sqrt{26})$ and let $\varepsilon = 5 + \sqrt{26}$. Use Dedekind's theorem to show that the ideal equations

$$(2) = (2, \varepsilon + 1)^2, \quad (5) = (5, \varepsilon + 1)(5, \varepsilon - 1), \quad (\varepsilon + 1) = (2, \varepsilon + 1)(5, \varepsilon + 1)$$

hold in K . Using Minkowski's bound, show that K has class number 2. Verify that ε is the fundamental unit. Deduce that all solutions in integers x, y to the equation $x^2 - 26y^2 = \pm 10$ are given by $x + \sqrt{26}y = \pm \varepsilon^n(\varepsilon \pm 1)$ for $n \in \mathbb{Z}$.

2. Find the factorisations into prime ideals of (2) and (3) in $K = \mathbb{Q}(\sqrt{-23})$. Verify that $(\omega) = (2, \omega)(3, \omega)$ where $\omega = \frac{1}{2}(1 + \sqrt{-23})$. Prove that K has class number 3.
3. Find the factorisations into prime ideals of (2), (3) and (5) in $K = \mathbb{Q}(\sqrt{-71})$. Verify that

$$(\alpha) = (2, \alpha)(3, \alpha)^2 \quad \text{and} \quad (\alpha + 2) = (2, \alpha)^3(3, \alpha - 1)$$

where $\alpha = \frac{1}{2}(1 + \sqrt{-71})$. Find an element of \mathcal{O}_K with norm $2^a \cdot 3^b \cdot 5$ for some $a, b \geq 0$. Hence prove that the class group of K is cyclic and find its order.

4. Compute the ideal class group of $\mathbb{Q}(\sqrt{d})$ for $d = -30, -13, -10, 19$ and 65 .
5. (i) Find the fundamental unit in $\mathbb{Q}(\sqrt{3})$. Determine all the integer solutions of the equations $x^2 - 3y^2 = m$ for $m = -1, 13$ and 121 .
(ii) Find the fundamental unit in $\mathbb{Q}(\sqrt{10})$. Determine all the integer solutions of the equations $x^2 - 10y^2 = m$ for $m = -1, 6$ and 7 .
6. Find all integer solutions of the equations $y^2 = x^3 - 13$ and $y^2 = x^5 - 10$.
7. Let $K = \mathbb{Q}(\sqrt{-d})$ where $d > 3$ is a square-free integer.

- (i) Show that if \mathcal{O}_K is Euclidean then it contains a principal ideal of norm 2 or 3. [Hint: Suppose that $\phi : \mathcal{O}_K - \{0\} \rightarrow \mathbb{N}$ is a Euclidean function. Then choose $x \in \mathcal{O}_K - \{0, \pm 1\}$ with $\phi(x)$ minimal.]

- (ii) Use your answer to Problem Sheet 2, question 11 to give an example where \mathcal{O}_K is a PID, but is not Euclidean.

8. Let $K = \mathbb{Q}(\sqrt{d})$ where $d \neq 0, 1$ is a square-free integer. Describe the ring $\mathcal{O}_K/2\mathcal{O}_K$ as explicitly as you can. [The answer depends on $d \bmod 8$.] Show that $\mathbb{Z}[\sqrt{d}]^\times \subset \mathcal{O}_K^\times$ has index 1 or 3. Give an example where the index is 3.

9. Let p be an odd prime.

- (i) Compute the discriminant of $(X^p - 1)/(X - 1)$. Deduce that $\mathbb{Q}(\zeta_p)$ contains a quadratic field with discriminant $\pm p$.
- (ii) Show using the Minkowski bound that $\mathbb{Z}[\zeta_p]$ is a UFD for $p = 5$ and $p = 7$.

10. Let $K = \mathbb{Q}(\zeta_8)$ and $\mathfrak{p} = (1 - \zeta_8)$. Show that $N\mathfrak{p} = 2$ and that complex conjugation acts trivially on $\mathcal{O}_K/\mathfrak{p}^2$. Find a fundamental unit in K . [Hint: First find a fundamental unit in $\mathbb{Q}(\zeta_8) \cap \mathbb{R} = \mathbb{Q}(\sqrt{2})$. Then imitate a proof in lectures.]
11. Let $K = \mathbb{Q}(\alpha)$ where α is a root of $f(X) = X^3 - 3X + 1$.
 - (i) Show that f is irreducible over \mathbb{Q} and compute its discriminant.
 - (ii) Show that $3\mathcal{O}_K = \mathfrak{p}^3$ where $\mathfrak{p} = (\alpha + 1)$ is a prime ideal in \mathcal{O}_K with residue field \mathbb{F}_3 . Deduce that $\mathcal{O}_K = \mathbb{Z}[\alpha] + 3\mathcal{O}_K$. [Hint: See Sheet 2, Question 5.]
 - (iii) Show that $\mathcal{O}_K = \mathbb{Z}[\alpha]$. Compute the class group of K .

The following extra questions are just for fun. Questions 18 and 19 need Galois Theory.

13. Let K be a number field. Show that there is a number field L containing K such that for every ideal $\mathfrak{a} \subset \mathcal{O}_K$ the ideal in \mathcal{O}_L generated by \mathfrak{a} (denoted $\mathfrak{a}\mathcal{O}_L$) is principal. [Hint: Use that some power of \mathfrak{a} is principal.]
14. Let L/K be an extension of number fields.
 - (i) Show that if \mathfrak{P} is a prime ideal in \mathcal{O}_L then $\mathfrak{p} = \mathfrak{P} \cap \mathcal{O}_K$ is a prime ideal in \mathcal{O}_K and $N\mathfrak{P}$ is a power of $N\mathfrak{p}$.
 - (ii) Let $L = \mathbb{Q}(i, \sqrt{5})$. Show that $|D_L| \leq 400$ and that the primes 2 and 3 are inert in some quadratic field $K \subset L$. Deduce that L has class number 1.
15. Show that there are no integer solutions to $x^2 - 82y^2 = \pm 2$.
16. Let L/K be an extension of number fields. Show that if \mathfrak{p} is a prime of \mathcal{O}_K then $\mathfrak{p}\mathcal{O}_L \neq \mathcal{O}_L$. [Hint: Let x_1, \dots, x_m generate \mathcal{O}_L as an \mathcal{O}_K -module. If $\mathfrak{p}\mathcal{O}_L = \mathcal{O}_L$ then we can write $x_i = \sum a_{ij}x_j$ for some $a_{ij} \in \mathfrak{p}$.] Deduce that if \mathfrak{a} and \mathfrak{b} are ideals in \mathcal{O}_K with $\mathfrak{a}\mathcal{O}_L = \mathfrak{b}\mathcal{O}_L$ then $\mathfrak{a} = \mathfrak{b}$.
17. Let L/K be an extension of number fields. Let p be a rational prime. Show using Questions 14(i) and 16 that (i) If p is unramified in L then it is unramified in K . (ii) If p is totally ramified in L then it is totally ramified in K .
18. Let K be a number field with K/\mathbb{Q} Galois. Let p be a rational prime with $p\mathcal{O}_K = \mathfrak{p}_1^{e_1} \dots \mathfrak{p}_r^{e_r}$, where the \mathfrak{p}_i are distinct prime ideals. Use the Chinese Remainder Theorem (Sheet 2, Question 1) to find $x \in \mathfrak{p}_1$ with $x \notin \mathfrak{p}_i$ for $2 \leq i \leq r$. By considering $N_{K/\mathbb{Q}}(x)$ show that $\text{Gal}(K/\mathbb{Q})$ acts transitively on $\{\mathfrak{p}_1, \dots, \mathfrak{p}_r\}$.
19. Let $K = \mathbb{Q}(\sqrt{-23}) \subset L = \mathbb{Q}(\zeta_{23})$. Let $\mathfrak{p} \subset \mathcal{O}_K$ be a prime dividing 2. Show that if $\mathfrak{p}\mathcal{O}_L = x\mathcal{O}_L$ for some $x \in \mathcal{O}_L$ then $\mathfrak{p}^{11}\mathcal{O}_L = N_{L/K}(x)\mathcal{O}_L$. Deduce by Questions 2 and 16 that $\mathbb{Z}[\zeta_{23}]$ is not a UFD.
20. Let $d \neq 0, 1$ be a square free integer, $K = \mathbb{Q}(\sqrt{d})$, $D = D_K$. Define $\chi_D(p) = \left(\frac{D}{p}\right)$ if $p > 2$, and p prime, and $\chi_D(2) = 1$ if $d \equiv 1 \pmod{8}$, $\chi_D(2) = -1$ if $d \equiv 5 \pmod{8}$, and $\chi_D(2) = 0$ otherwise. Extend this to a function on \mathbb{Z} by setting $\chi_D(mn) = \chi_D(m)\chi_D(n)$. Using quadratic reciprocity, show that χ_D is D -periodic: $\chi_D(a + Db) = \chi_D(a)$, $a, b \in \mathbb{Z}$. [Hint: You will find it easier to do the cases $d \equiv 3, 2, 1 \pmod{4}$ separately].