

Solutions to the book: *Jürgen Neukirch, Algebraic Number Theory*

Meng-Gen Tsai
plover@gmail.com

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Chapter I: Algebraic Integers

I.1. The Gaussian Integers

Exercise I.1.1.

$\alpha \in \mathbb{Z}[i]$ is a unit if and only if $N(\alpha) = 1$.

Proof.

- (1) (\implies) Since α is a unit, there is $\beta \in \mathbb{Z}[i]$ such that $\alpha\beta = 1$. So $N(\alpha\beta) = N(1)$, or $N(\alpha)N(\beta) = 1$. Since the image of N is nonnegative integers, $N(\alpha) = 1$.
- (2) (\impliedby) $N(\alpha) = \alpha\bar{\alpha}$, or $1 = \alpha\bar{\alpha}$ since $N(\alpha) = 1$. That is, $\bar{\alpha} \in \mathbb{Z}[i]$ is the inverse of $\alpha \in \mathbb{Z}[i]$. (Or we solve the equation $N(\alpha) = a^2 + b^2 = 1$, and show that all four solutions (± 1 and $\pm i$) are units.)
- (3) Conclusion: a unit $\alpha = a + bi$ of $\mathbb{Z}[i]$ is satisfying the equation $N(\alpha) = a^2 + b^2 = 1$ by (1)(2). That is, the only unit of $\mathbb{Z}[i]$ are ± 1 and $\pm i$.

□

Exercise I.1.4.

Show that the ring $\mathbb{Z}[i]$ cannot be ordered.

Proof. Similar to the fact that i cannot be ordered in \mathbb{C} . Thus i cannot be ordered in $\mathbb{Z}[i]$ either. □

Exercise I.1.5.

Show that the only units of the ring $\mathbb{Z}[\sqrt{-d}] = \mathbb{Z} + \mathbb{Z}\sqrt{-d}$, for any rational integer $d > 1$, are ± 1 .

Proof.

- (1) Define the norm N on $\mathbb{Z}[\sqrt{-d}]$ by

$$N(x + y\sqrt{-d}) = (x + y\sqrt{-d})(x - y\sqrt{-d}) = x^2 + y^2d,$$

i.e., by $N(z) = |z|^2$. It is multiplicative.

(2) Similar to Exercise I.1.1,

$$\begin{aligned} x + y\sqrt{-d} \in \mathbb{Z}[\sqrt{-d}] \text{ is a unit} &\iff N(x + y\sqrt{-d}) = x^2 + y^2d = 1 \\ &\iff x^2 = 1 \text{ and } y = 0 \\ &\iff x = \pm 1 \text{ and } y = 0. \end{aligned}$$

Hence the only units of the ring $\mathbb{Z}[\sqrt{-d}]$ are ± 1 ($d > 1$).

□

I.2. Integrality

Exercise I.2.1.

Is $\frac{3+2\sqrt{6}}{1-\sqrt{6}}$ an algebraic integer?

Proof.

- (1) $\alpha := \frac{3+2\sqrt{6}}{1-\sqrt{6}} = -3 - \sqrt{6}$. Since the set of all algebraic integers is a ring, α is an algebraic integer.
- (2) Or show that α satisfies a monic equation $x^2 + 6x + 3 = 0 \in \mathbb{Z}[x]$.

□

Exercise I.2.3.

In the polynomial ring $A = \mathbb{Q}[x, y]$, consider the principal ideal $\mathfrak{p} = (x^2 - y^3)$. Show that \mathfrak{p} is a prime ideal, but A/\mathfrak{p} is not integrally closed.

Proof.

- (1) It is easy to show that $x^2 - y^3$ is irreducible in A . Hence $\mathfrak{p} = (x^2 - y^3)$ is prime since A is a UFD.
- (2) By substituting $x = t^3$, $y = t^2$, $A/\mathfrak{p} \cong \mathbb{Q}[t^3, t^2]$, with quotient field $\mathbb{Q}(t)$ (by noting $t = \frac{x}{y}$). Note that $\mathbb{Q}[t]$ is a UFD, thus is already integrally closed. So the integral closure will be $\mathbb{Q}[t] \supsetneq \mathbb{Q}[t^3, t^2]$. It suggests that A/\mathfrak{p} might not be integrally closed.
- (3) (Reductio ad absurdum) If not, then the element $\frac{x}{y}$ satisfies a monic equation $t^2 - y = 0 \in (A/\mathfrak{p})[t]$. $\frac{x}{y} \in A/\mathfrak{p}$ or $t \in \mathbb{Q}[t^3, t^2]$, which is absurd.

□

Note.

- (1) Serre's criterion for normality.
- (2) Hence smoothness is the same as normality for affine curves in $\mathbb{Q}[x, y]$. Note that $x^2 - y^3$ is an irreducible cubic with a cusp at the origin $(0, 0)$.
- (3) There is an affine variety $X \in \mathbb{Q}[x, y, z]$ such that X is normal but not smooth. ($X = V(x^2 + y^2 - z^2)$ for example.)

Exercise I.2.4.

Let D be a squarefree rational integer $\neq 0, 1$ and d the discriminant of the quadratic number field $K = \mathbb{Q}(\sqrt{D})$. Show that

$$d = \begin{cases} D & \text{if } D \equiv 1 \pmod{4}, \\ 4D & \text{if } D \equiv 2, 3 \pmod{4}. \end{cases}$$

and that an integral basis of K is given by $\{1, \sqrt{D}\}$ in the second case, by $\left\{1, \frac{1+\sqrt{D}}{2}\right\}$ in the first case, and by $\left\{1, \frac{d+\sqrt{d}}{2}\right\}$ in both case.

Proof.

- (1) The Galois group of $K|\mathbb{Q}$ has two elements, the identity and an automorphism sending \sqrt{D} to $-\sqrt{D}$.
- (2) Note that $\alpha \in \mathcal{O}_K$ iff $\text{Tr}_{K|\mathbb{Q}}(\alpha), N_{K|\mathbb{Q}}(\alpha) \in \mathbb{Z}$ (by noting that the equation $x^2 - \text{Tr}_{K|\mathbb{Q}}(\alpha)x + N_{K|\mathbb{Q}}(\alpha) = 0$ has a root $x = \alpha$). So given $\alpha = x + y\sqrt{D} \in \mathcal{O}_K$, we have

$$\begin{aligned} \text{Tr}_{K|\mathbb{Q}}(\alpha) &= 2x \in \mathbb{Z}, \\ N_{K|\mathbb{Q}}(\alpha) &= x^2 - Dy^2 \in \mathbb{Z}. \end{aligned}$$

- (3) So $4(x^2 - Dy^2) = (2x)^2 - D(2y)^2 \in \mathbb{Z}$. So $D(2y)^2 \in \mathbb{Z}$ since $2x \in \mathbb{Z}$. So $2y \in \mathbb{Z}$ since D is squarefree $\neq 0, 1$. Let $r = 2x, s = 2y$. Then $r^2 - Ds^2 \equiv 0 \pmod{4}$. Note that a square $\equiv 0, 1 \pmod{4}$.

(4) If $D \equiv 1 \pmod{4}$, then

$$\begin{aligned}
r^2 - Ds^2 &\equiv r^2 - s^2 \pmod{4} \\
\implies r \text{ and } s &\text{ has the same parity} \\
\implies \mathcal{O}_K &= \left\{ \frac{r + s\sqrt{D}}{2} : r \equiv s \pmod{2} \right\} \\
\implies \mathcal{O}_K &= \left\{ \frac{r-s}{2} + s \cdot \frac{1+\sqrt{D}}{2} : r \equiv s \pmod{2} \right\} \\
\implies \mathcal{O}_K &= \mathbb{Z} + \mathbb{Z} \frac{1+\sqrt{D}}{2}.
\end{aligned}$$

So $\left\{1, \frac{1+\sqrt{D}}{2}\right\}$ is an integral basis of K . Hence

$$d = \begin{vmatrix} 1 & \frac{1+\sqrt{D}}{2} \\ 1 & \frac{1-\sqrt{D}}{2} \end{vmatrix}^2 = D.$$

(5) If $D \equiv 2, 3 \pmod{4}$, then

$$\begin{aligned}
r^2 - Ds^2 &\equiv r^2 + 2s^2 \text{ or } r^2 + s^2 \pmod{4} \\
\implies \text{both } r \text{ and } s &\text{ are even} \\
\implies \text{both } x \text{ and } y &\text{ are rational integers} \\
\implies \mathcal{O}_K &= \mathbb{Z} + \mathbb{Z}\sqrt{D}.
\end{aligned}$$

So $\{1, \sqrt{D}\}$ is an integral basis of K . Hence

$$d = \begin{vmatrix} 1 & \sqrt{D} \\ 1 & -\sqrt{D} \end{vmatrix}^2 = 4D.$$

(6) By (4)(5), $\left\{1, \frac{d+\sqrt{d}}{2}\right\}$ is an integral basis of K for any case.

□

Exercise I.2.7. (Stickelberger's discriminant relation)

The discriminant d_K of an algebraic number field K is always $\equiv 0 \pmod{4}$ or $\equiv 1 \pmod{4}$. (Hint: The discriminant $\det(\sigma_i \omega_j)$ of an integral basis ω_j is a sum of terms, each prefixed by a positive or a negative sign. Writing P (resp. N) for the sum of the positive (resp. negative) terms, one find $d_K = (P - N)^2 = (P + N)^2 - 4PN$.)

Proof (Hint).

- (1) Let S_n be the symmetric group of degree n , and A_n be the alternating group of degree n . So

$$\begin{aligned}\det(\sigma_i \omega_j) &= \sum_{\pi \in S_n} \left(\operatorname{sgn}(\pi) \prod_{i=1}^n \sigma_i \omega_{\pi(i)} \right) \\ &= \underbrace{\sum_{\pi \in A_n} \prod_{i=1}^n \sigma_i \omega_{\pi(i)}}_{:=P} - \underbrace{\sum_{\pi \in S_n - A_n} \prod_{i=1}^n \sigma_i \omega_{\pi(i)}}_{:=N}.\end{aligned}$$

- (2) Note that $\sigma_i(P + N) = P + N$ and $\sigma_i(PN) = PN$ for all σ_i . Hence $P + N, PN \in \mathbb{Q}$. Therefore $P + N, PN \in \mathbb{Q} \cap \mathcal{O}_K = \mathbb{Z}$.

- (3) By (1)(2),

$$\begin{aligned}d_K &= \det(\sigma_i \omega_j)^2 \\ &= (P - N)^2 \\ &= (P + N)^2 - 4PN \\ &\equiv 0, 1 \pmod{4}.\end{aligned}$$

□