

Introduction to Algebraic Number Theory 2020 Note, Ross Program

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0 Introduction

This course is hosted by professor Paul Pollack during the 2020 Ross Mathematics Program. The organization of the whole course and the problems in this note is taken from his lectures, problem sets and problem sessions.

The two-week course after the usual analytic number theory sessions aims to give a short introduction on algebraic number theory, and particularly, how ideas in the algebraic number theory applies to the quadratic fields. (The content of the course will be updated after the course is finished as the note is updated.)

I studied the style of the \LaTeX note by Evan Chen's *An Infinitely Large Napkin*, which is open-source on Github.

1 Introduction to Algebraic Number Theory, Ross Program 2020

§1.1 Lecture 1, July 29

Definition 1.1.1 (Algebraic Number)

$\alpha \in \mathbb{C}$ is called an algebraic number iff it's a root of some nonzero polynomial in $\mathbb{Q}[x]$. We denote the set of all algebraic numbers as $\bar{\mathbb{Q}}$.

Definition 1.1.2 (Algebraic Integer)

An algebraic integer $\alpha \in \mathbb{C}$ is the root of some monic polynomial in $\mathbb{Z}[x]$. We denote the set of all algebraic integers as $\bar{\mathbb{Z}}$.

In summary, we have $\bar{\mathbb{Z}} \subset \bar{\mathbb{Q}} \subset \mathbb{C}$. We can also check that $\bar{\mathbb{Z}} \cap \mathbb{Q} = \mathbb{Z}$. This leads us to the general discussions about number fields.

Definition 1.1.3 (Number Field)

A number field is a field of the form $\mathbb{Q}[\theta]$ where $\theta \in \bar{\mathbb{Q}}$.

For example, $\mathbb{Z}[i], \mathbb{Q}[i], \mathbb{Q}[\omega]$ are all number fields.

Definition 1.1.4

If K is a number field, the ring of integers of K is defined to be $\bar{\mathbb{Z}} \cap K$. For example, the ring of integers of \mathbb{Q} is just \mathbb{Z} .

The reason why we want to study the ring of integers instead of all algebraic integers is that there are "too many" numbers to be studied. One observation is that $\bar{\mathbb{Z}}$ has no irreducibles, because for any non-unit $\alpha \in \bar{\mathbb{Z}}$, $\sqrt{\alpha}$ is also in $\bar{\mathbb{Z}}$. (Definition of units and irreducibles will be given in Lecture 2.)

§1.2 Problem Session 1, July 30

Problem 1.2.1

$\bar{\mathbb{Z}}$ is a ring and $\bar{\mathbb{Q}}$ is a field.

Proof. We want to borrow the **Fundamental Theorem of Symmetrical Functions** here.

Lemma 1.2.2 (Fundamental Theorem of Symmetrical Functions)

Let R be a ring and let $P(x_1, x_2, \dots, x_n) \in R[x_1, x_2, \dots, x_n]$ be a symemtric polynomial. Then $P(x_1, x_2, \dots, x_n) = G(s_1, s_2, \dots, s_n)$ for some polynomial G with coefficients from R . s_i denotes the i -th elementary symmetrical function in x_1, x_2, \dots, x_n , i.e., the sum of all products of i terms in x_1, x_2, \dots, x_n .

Now we prove that \mathbb{Z} is closed under addition and multiplication. The closure of \mathbb{Q} can be proved in a similar way. Suppose that α_1 and β_1 are roots of $P(x)$ and $Q(x)$, respectively. And suppose that $P(x) = (x - \alpha_1)(x - \alpha_2) \cdots (x - \alpha_t)$ and $Q(x) = (x - \beta_1)(x - \beta_2) \cdots (x - \beta_s)$. We now find the polynomial $S(x)$ where

$$S(x) = \prod_{1 \leq i \leq t, 1 \leq j \leq s} (x - (\alpha_i + \beta_j))$$

and its coefficients should lie in \mathbb{Z} using Lemma 1.2.2 twice. Similarly we can construct

$$T(x) = \prod_{1 \leq i \leq t, 1 \leq j \leq s} (x - \alpha_i \beta_j)$$

to prove the multiplicative closure. □

Problem 1.2.3

It's known that the sum $1 + \sqrt{2} + \sqrt[3]{3} + \cdots + \sqrt[100]{100}$ lies strictly between 111 and 112. Explain how we can quickly deduce that the sum is irrational. (From what we've already known)

Proof. Because $\bar{\mathbb{Z}}$ is a ring, and each of the elements in the sum is in $\bar{\mathbb{Z}}$, the number is also in $\bar{\mathbb{Z}}$. Suppose by contradiction that it's in \mathbb{Q} , then it's in $\bar{\mathbb{Z}} \cap \mathbb{Q} = \mathbb{Z}$, which is impossible because it lies between two integers. Thus, the sum is irrational. □

Problem 1.2.4

Exhibit a monic polynomial in $\mathbb{Q}[x]$ which has $\sin(2\pi/7)$ as a root.

Exhibit a monic polynomial in $\mathbb{Z}[x]$ which has $2\cos(2\pi/9)$ as a root.

Proof. For the first problem, notice that

$$\left(\cos \frac{2\pi}{7} + \sin \frac{2\pi}{7} i\right)^7 = e^{2\pi i} = 1$$

$$\sum_{j=0}^7 \binom{7}{j} \cos^j \frac{2\pi}{7} (\sin^{7-j} \frac{2\pi}{7}) i^{7-j} = 1$$

Because both sides represent a real number, the term when j is even can be treated as 0. When j is odd, $7-j$ is even, so we can represent $\cos^2(2\pi/7)$ by $1 - \sin^2(2\pi/7)$. This generates a monic polynomial in $\mathbb{Q}[x]$ which has $\sin(2\pi/7)$ as a root.

For the second problem, let $\zeta = e^{2\pi i/9}$ denote the ninth root of unity. Then

$$2\cos \frac{2\pi}{9} = \zeta + \bar{\zeta} = \zeta + \zeta^{-1}$$

As $\zeta^9 = 1$ and $\zeta \neq 1$, we also have

$$\zeta^8 + \zeta^7 + \cdots + \zeta + 1 = 0$$

$$(\zeta^4 + \zeta^{-4}) + (\zeta^3 + \zeta^{-3}) + \cdots + 1 = 0$$

Because each $\zeta^k + \zeta^{-k}$ can be represented by a polynomial of $\zeta + \zeta^{-1}$, we have now found a monic polynomial for our $\zeta + \zeta^{-1}$, which is $2\cos(2\pi/9)$. \square

Problem 1.2.5

Show that $\sin 1^\circ$ is an algebraic number.

Proof. The proof is similar to Problem 1.2.4. \square

Problem 1.2.6

Show that $\bar{\mathbb{Q}}$ is a fraction field of $\bar{\mathbb{Z}}$. That is (it remains to show that), every number in $\bar{\mathbb{Q}}$ can be represented as the fraction of two numbers in $\bar{\mathbb{Z}}$.

Proof. For any $\alpha \in \bar{\mathbb{Q}}$, it's a root to the polynomial $P(x) = a_n x^n + \cdots + a_1 x + a_0$ (we can let $a_n = 1$ so that the polynomial is monic). Let L denotes the least common multiplier of the denominators of a_i 's written in their reduced form. Now, $P(L\alpha) = L^n(P(\alpha)) = 0$ gives $L\alpha$ is a root of the monic polynomial $L^n P(x)$ in $\mathbb{Z}[x]$. Therefore, $L\alpha \in \bar{\mathbb{Z}}$. Because L is trivially in $\bar{\mathbb{Z}}$, we have $\alpha = L\alpha/L$ as the desired form. \square

Problem 1.2.7

Is $1/(3 + \sqrt{2})$ an algebraic integer? How to characterize the units in $\bar{\mathbb{Z}}$?

Proof. For the first problem, if $\alpha = 1/(3 + \sqrt{2})$ is an algebraic integer, then $\bar{\alpha} = 1/(3 - \sqrt{2})$ is also an algebraic integer. (This can be easily checked by the knowledge of polynomial and "conjugate" roots, or viewing the map from one root to its conjugate as a ring automorphism). Because $\bar{\mathbb{Z}}$ is a ring, we know that $\alpha\bar{\alpha} = 1/7$ is also in $\bar{\mathbb{Z}}$, contradiction.

For the second problem, the units in $\bar{\mathbb{Z}}$ can be characterized as "those α with minimal polynomial ending with constant term ± 1 ". (Equivalently, the product of all its conjugates should be ± 1). \square

§1.3 Lecture 2, July 31

Recall that the study of algebraic integers focuses on $\bar{\mathbb{Z}} \cap K := \mathbb{Z}_K$, called the ring of integers of K , where $K = \mathbb{Q}[\theta]$ for some $\theta \in \bar{\mathbb{Q}}$. Now we restrict our discussion on those K such that θ is a root of a degree-two polynomial.

Definition 1.3.1 (Quadratic Number Field)

A quadratic number field is of the form $\mathbb{Q}[\theta]$ where θ is a root of a degree-two polynomial in $\mathbb{Q}[x]$ and $\theta \notin \mathbb{Q}$.

If the polynomial given in the definition is $P(x) = ax^2 + bx + c$, then we can express θ as $\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ where $D := b^2 - 4ac$ is a non-square. Then actually $\mathbb{Q}[\theta] = \mathbb{Q}[\sqrt{D}]$.

Moreover, we can uniquely determine $\mathbb{Q}[\sqrt{D}] = \mathbb{Q}[\sqrt{D'}]$ where D' is not only non-square but also square-free. (Given as exercise)

Another remark is on the convention of \sqrt{d} : when $d < 0$, this represents $i \cdot \sqrt{|d|}$.

Now let $\alpha \in \mathbb{Q}[\sqrt{d}]$ with $d \neq 1$ being square-free. Then $\alpha = x + y\sqrt{d}$ with x, y uniquely determined. Define $\bar{\alpha} = x - y\sqrt{d}$.

Remark 1.3.2. $\alpha \in \bar{\mathbb{Z}} \Leftrightarrow \alpha + \bar{\alpha} \in \mathbb{Z}, \alpha\bar{\alpha} \in \mathbb{Z}$.

Proof. (\Rightarrow) $\alpha \in \bar{\mathbb{Z}}$ implies $\bar{\alpha} \in \bar{\mathbb{Z}}$, $\alpha + \bar{\alpha} \in \bar{\mathbb{Z}}$. On the other hand, $\alpha + \bar{\alpha} \in \mathbb{Q}$. Therefore, $\alpha + \bar{\alpha} \in \bar{\mathbb{Z}} \cap \mathbb{Q} = \mathbb{Z}$. By the same argument, $\alpha\bar{\alpha} \in \mathbb{Z}$.

(\Leftarrow) α is the root of the polynomial $P(x) = (x - \alpha)(x - \bar{\alpha})$ and $P(x) \in \mathbb{Z}[x]$. Thus, $\alpha \in \bar{\mathbb{Z}}$. \square

Remark 1.3.3 (Traces and Norms in quadratic field). $\text{Tr}(\alpha) = \alpha + \bar{\alpha}$, $N(\alpha) = \alpha\bar{\alpha}$.

Definition 1.3.4 (Unit)

An $\alpha \in \mathbb{Z}_K$ is called a unit if there exists $\beta \in \mathbb{Z}_K$ such that $\alpha\beta = 1$.

Definition 1.3.5 (Irreducible)

A $\pi \in \mathbb{Z}_K$ is irreducible (an irreducible) if π is a non-zero, non-unit element and if $\pi = \alpha\beta$, $\alpha, \beta \in \mathbb{Z}_K$ implies either α or β is a unit.

Definition 1.3.6 (Unique Factorization Domain, UFD)

Let R be an integral domain (a commutative ring with no zero divisors.) R is a UFD if $\forall \alpha \in R$, α being a non-zero and non-unit, α can be uniquely expressible as $\alpha = \pi_1\pi_2 \cdots \pi_k$ where the π_i 's are irreducibles.

Example 1.3.7 (A classical example of a non-UFD)

$\mathbb{Z}[\sqrt{-5}]$ is not a UFD, as $6 = 2 \times 3 = (1 + \sqrt{-5})(1 - \sqrt{-5})$.

Some exercises that characterize the quadratic field, its units and the unique factorization will be included in next section as exercises.

The problem with the non-UFD domains is that "there are not enough numbers". For example, a famous "four-number theorem" is valid in \mathbb{Z} : if $ab = cd$ and $\gcd(a, b, c, d) = 1$, then we can write $a = (a, c)(a, d)$, $b = (b, c)(b, d)$, $c = (a, c)(b, c)$, $d = (a, d)(b, d)$, where (m, n) denotes the $\gcd(m, n)$. However, the theorem is not true in $\mathbb{Z}[\sqrt{-5}]$ for the four irreducible factors in Example 1.3.7 because $\gcd(2, 1 + \sqrt{-5})$ doesn't exist.

The way that we "restore" the unique factorization in these fields is to introduce new "numbers" that play the role of " $(2, 1 + \sqrt{-5})$ ", etc.

§1.4 Problem Session 2, August 1

Problem 1.4.1

Prove the Four Numbers Theorem: Suppose a, b, c, d are positive integers with $ab = cd$ and $\gcd(a, b, c, d) = 1$. Then:

$$a = (a, c)(a, d), b = (b, c)(b, d), c = (a, c)(b, c), d = (a, d)(b, d).$$

Proof. Let $a = (a, c)m$, $c = (a, c)n$ where $(m, n) = 1$. Let $b = (b, d)t$, $d = (b, d)s$ where $(t, s) = 1$. Then $ab = cd$ gives $mt = ns$, which gives $m = s$, $n = t$.

Now we have $a = (a, c)m, d = (b, d)m$. $m \mid a, d$ gives $m \mid (a, d)$. On the other hand, $(a, d) \mid a$ and $(a, d) \mid d$ gives $(a, d) \mid m(a, c)$ and $(a, d) \mid m(b, d)$. Therefore, $(a, d) \mid \gcd((a, c), (b, d)) = m$. Together we get $m = (a, d)$. Similarly, $n = (b, c)$ and we are done. \square

Problem 1.4.2

Show that if K is a quadratic field, then $K = \mathbb{Q}[\sqrt{d}]$ for some squarefree integer d . Show further that d is uniquely determined.

Problem 1.4.3

Suppose $K = \mathbb{Q}[\sqrt{d}]$ where $d \neq 1$ is a squarefree integer. Show that if $d \equiv 2, 3 \pmod{4}$, then

$$\mathbb{Z}_K = \{a + b\sqrt{d} : a, b \in \mathbb{Z}\} = \mathbb{Z}[\sqrt{d}]$$

while if $d \equiv 1 \pmod{4}$, then

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

Proof. Recall Remark 1.3.2: $\alpha \in \bar{\mathbb{Z}} \Leftrightarrow \alpha + \bar{\alpha} \in \mathbb{Z}, \alpha\bar{\alpha} \in \mathbb{Z}$. It suffices to check the latter claim. Let $\alpha = m + n\sqrt{d}$ where $m, n \in \mathbb{Q}$, then for $\alpha \in \mathbb{Z}_K$, we need

$$2m \in \mathbb{Z}, m^2 - dn^2 \in \mathbb{Z}$$

Thus, we write $m = t/2, n = p/q$ where $t, p, q \in \mathbb{Z}, \gcd(p, q) = 1$. This reduces to

$$\frac{t^2}{4} - \frac{p^2d}{q^2} \in \mathbb{Z}$$

If $q = 1$, then $2 \mid t$. If $q = 2$, then $4 \mid t^2 - p^2d$. When $d \equiv 1 \pmod{4}$, we now that t and p can have the same parity (the second case in the problem). Otherwise, both t and q should be even. If $q > 2$, the number above cannot be in \mathbb{Z} .

The argument shows that for α to be in \mathbb{Z}_K , it has to satisfy $m, n \in \mathbb{Z}$ when $d \equiv 2, 3 \pmod{4}$ and $2m, 2n \in \mathbb{Z}$ where $2m \equiv 2n \pmod{2}$. We now check that for all number that satisfy the condition, it's really in \mathbb{Z}_K . This can be check by

$$(x - \alpha)(x - \bar{\alpha}) \in \mathbb{Z}[x]$$

in either case. \square

Problem 1.4.4 (Units when $d < 0$)

Let $K = \mathbb{Q}[\sqrt{d}]$ where $d < 0$ and d squarefree. Show that:

- When $d \neq -1, -3$, the (only) units of \mathbb{Z}_K are ± 1 .
- When $d = -1$, the units are $\pm 1, \pm i$.
- When $d = -3$, the units are $\pm 1, \pm \omega, \pm \omega^2$ where $\omega = e^{2\pi i/3}$.

This is easily checked by the above problem and consider the fact that the norm of the unit is 1.

Problem 1.4.5 (Units when $d > 1$)

Let $K = \mathbb{Q}[\sqrt{d}]$ where $d > 1$ and d squarefree. Show that:

- If $\epsilon = x + y\sqrt{d} > 1$ is a unit, then $x, y > 0$.
- The set of units of \mathbb{Z}_K that are larger than 1 has a smallest element.
- Let ϵ_0 be the unit you found in part (b). Show that every unit of \mathbb{Z}_K has a unique expression in the form $\pm \epsilon_0^n$. ϵ_0 is called the "fundamental unit".

Proof. First, $x^2 - dy^2 = \pm 1$ gives $\epsilon|\bar{\epsilon}| = 1$. We know that $|\bar{\epsilon}| < 1/\epsilon < \epsilon$

$$x = \frac{\epsilon + \bar{\epsilon}}{2} > \frac{1}{2}(1 - 1) = 0$$

$$y = \frac{\epsilon - \bar{\epsilon}}{2\sqrt{d}} > \frac{1}{2\sqrt{d}}(\epsilon - \epsilon) = 0$$

The second claim is similar to the Well-Ordering Principle by noticing we have to compare the pair $(x, y) \in \mathbb{Z}^2$ or $(2x, 2y) \in \mathbb{Z}^2$. We can first pick the smallest y by considering $\{2y\} \subset \mathbb{Z}$ and then argue that the corresponding x should also be the smallest.

The third claim is a direct consequence of the second one by noticing that the units are multiplicative. If there are some unit $u > 1$ and $u \in (\epsilon_0^k, \epsilon_0^{k+1})$, then $u\epsilon_0^{-k}$ is a unit in $(1, \epsilon_0)$, contradiction. \square

Example 1.4.6

The fundamental units in $\mathbb{Z}[\sqrt{2}]$, $\mathbb{Z}[\sqrt{3}]$, $\mathbb{Z}[\sqrt{5}]$ and $\mathbb{Z}[\sqrt{7}]$ are $1 + \sqrt{2}$, $2 + \sqrt{3}$, $(1 + \sqrt{5})/2$, $8 + 3\sqrt{7}$, respectively.

Remark 1.4.7. A better procedure to calculate the units of these quadratic fields is to use the continued fractions.

Problem 1.4.8

Suppose that $d \equiv 1 \pmod{4}$ is squarefree, $d \neq 1$. Show that the ring $\mathbb{Z}[\sqrt{d}]$ does not have unique factorization.

Proof. Let $d = 4t + 1$ where $t \in \mathbb{Z}$.

$$(\sqrt{d} + 1)(\sqrt{d} - 1) = d - 1 = 2 \cdot (2t)$$

but $2 \nmid (\sqrt{d} + 1)$, $2 \nmid (\sqrt{d} - 1)$ and 2 is an irreducible (there is no solution to $x^2 - y^2d = 2$ in this case). \square

Problem 1.4.9

Let K be a field and let R be a subring of K having K as its fraction field. (This means that every element of K is a quotient of two elements of R .) Suppose that R is a unique factorization domain. Prove that if $a \in K$ is a root of a monic polynomial in $R[x]$, then $a \in R$. What does this have to do with the last exercise?

Proof. The proof is analogous to the "rational root theorem" where \mathbb{Q} and \mathbb{Z} are used instead of K and R . With this hindsight, we let $R = \mathbb{Z}[\sqrt{d}]$ and $K = \mathbb{Q}[\sqrt{d}]$. When $d \equiv 1 \pmod{4}$, $\frac{1 + \sqrt{d}}{2}$ doesn't belong to R , but it is a root of the polynomial

$$\left(x - \frac{1 + \sqrt{d}}{2}\right) \left(x - \frac{1 - \sqrt{d}}{2}\right) = x^2 - x + \frac{1 - d}{4} \in R[x]$$

Thus, $\mathbb{Z}[\sqrt{d}]$ is not a UFD. \square

Remark 1.4.10. This explains why \mathbb{Z}_K is the right to study for it better ensures unique factorization.