# Contents

# 1 Elliptic curves

## 1.1 Reduction of Weierstrass equations

In this subsection, we want to investigate the important constants of elliptic curves such as $c_4$, $c_6$, $\Delta$, $j$ by calculating equations with hands.

**Step 1.** The Riemann-Roch theorem proves that every curve of genus 1 with a specified base point can be described by the first kind of Weierstrass equation. Explicitly, the first form of Weierstrass equation is

$$y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6. \tag{1}$$

**Step 2.** *Elimination of $xy$ and $y$.* Factorize the left hand side

$$y\,(y + a_1x + a_3) = x^3 + a_2x^2 + a_4x + a_6.$$

By translation

$$\boxed{x \mapsto x, \qquad y \mapsto y - \tfrac{1}{2}(a_1x + a_3)}$$

we have

$$\begin{aligned} y^2 - (\tfrac{1}{2}(a_1x + a_3))^2 &= x^3 + a_2x^2 + a_4x + a_6, \\ y^2 &= x^3 + (\tfrac{1}{4}a_1^2 + a_2)x^2 + (\tfrac{1}{2}a_1a_3 + a_4)x + (\tfrac{1}{4}a_3^2 + a_6), \\ y^2 &= x^3 + \frac{1}{4}(a_1^2 + 4a_2)x^2 + \frac{1}{2}(a_1a_2 + 2a_4)x + \frac{1}{4}(a_3^2 + 4a_6). \end{aligned}$$

Introduce new coefficients $b$ to write it as

$$y^2 = x^3 + \frac{1}{4}b_2x^2 + \frac{1}{2}b_4x + \frac{1}{4}b_6.$$

By scaling

$$\boxed{x \mapsto x, \qquad y \mapsto \tfrac{1}{2}y}$$

we get

$$y^2 = 4x^3 + b_2x^2 + 2b_4x + b_6. \tag{2}$$

**Step 3.** *Elimination of $x^2$.* By translation

$$\boxed{x \mapsto x - \tfrac{1}{12}b_2}$$

we have

$$\begin{aligned}y^2 = 4\left(x^3 - 3\cdot\frac{1}{12}b_2x^2 + 3\cdot\frac{1}{12^2}b_2^2x - \frac{1}{12^3}b_2^3\right) \\ +b_2\left(x^2 - 2\cdot\frac{1}{12}b_2x + \frac{1}{12^2}b_2^2\right) \\ +2b_4\left(x - \frac{1}{12}b_2\right) \\ +b_6,\end{aligned}$$

so

$$\begin{aligned}y^2 &= 4x^3 + \left(4\cdot 3\cdot\frac{1}{12^2}b_2^2 - 2\cdot\frac{1}{12}b_2^2 + 2b_4\right)x + \left(-4\cdot\frac{1}{12^3}b_2^3 + \frac{1}{12^2}b_2^3 - 2\cdot\frac{1}{12}b_2b_4 + b_6\right) \\ &= 4x^3 + \frac{1}{12}\left(-b_2^2 + 24b_4\right)x + \frac{1}{216}\left(b_2^3 - 36b_2b_4 + 216b_6\right).\end{aligned}$$

Write it as

$$y^2 = 4x^3 - \frac{1}{12}c_4x - \frac{1}{216}c_6.$$

We want to match the coefficients of $y^2$ and $x^3$ but also want the coefficients of $c_4x$ and $c_6$ to be integers. Iterative scaling implies

$$\begin{aligned} x \mapsto \tfrac{1}{6}x: &\qquad 216y^2 = 4x^3 - 3c_4x - c_6 \\ y \mapsto \tfrac{1}{36}y: &\qquad y^2 = 24x^3 - 18c_4x - 6c_6 \\ x \mapsto \tfrac{1}{6}x: &\qquad 9y^2 = x^3 - 27c_4x - 54c_6 \\ y \mapsto \tfrac{1}{3}y: &\qquad y^2 = x^3 - 27c_4x - 54c_6. \end{aligned}$$

Thus, we get the famous third form of Weierstrass equation:

$$y^2 = x^3 - 27c_4x - 54c_6. \tag{3}$$

**Theorem 1.1.** *Let*

$$E : y^2 = x^3 - Ax - B.$$

*TFAE:*

(1) *A point $(x, y)$ is a singular point of $E$.*

(2) *$y = 0$ and $x$ is a double root of $x^3 - Ax - B$.*

(3) $\Delta = 0$.

*Proof.* (1)⇒(2) $\partial_y f = 0$ implies $y = 0$. $f = \partial_x f = 0$ implies $x$ is a double root of $x^3 - Ax - B$. $A$ determines whether $x$ is either cusp of node. □

# 2 Algebraic integer

## 2.1 Quadratic integer

**Theorem 2.1.** *Every quadratic field is of the form $\mathbb{Q}(\sqrt{d})$ for a square-free $d$.*

**Theorem 2.2.** *Let $d$ be a square-free.*

$$\mathcal{O}_{\mathbb{Q}(\sqrt{d})} = \begin{cases} \mathbb{Z}[\sqrt{d}] & , d \equiv 2, 3 \pmod 4 \\ \mathbb{Z}[\frac{1+\sqrt{d}}{2}] & , d \equiv 1 \pmod 4 \end{cases}$$

$$\Delta_{\mathbb{Q}(\sqrt{d})} = \begin{cases} 4d & , d \equiv 2, 3 \pmod 4 \\ d & , d \equiv 1 \pmod 4 \end{cases}$$

**Example 2.1.**

$$\Delta_{\mathbb{Q}(i)} = -4, \quad \Delta_{\mathbb{Q}(\sqrt{2})} = 8, \quad \Delta_{\mathbb{Q}(\gamma)} = 5, \quad \Delta_{\mathbb{Q}(\omega)} = -3$$

where $\gamma := \frac{1+\sqrt{5}}{2}$ and $\omega = \zeta_3$.

**Theorem 2.3.** *Let $\theta^3 = hk^2$ for $h, k$ square-free's.*

$$\mathcal{O}_{\mathbb{Q}(\theta)} = \begin{cases} \mathbb{Z} + \theta\mathbb{Z} + \dfrac{\theta^2}{k}\mathbb{Z} & , m \not\equiv \pm 1 \pmod 9 \\ \mathbb{Z} + \theta\mathbb{Z} + \dfrac{\theta^2 \pm \theta k + k^2}{3k}\mathbb{Z} & , m \equiv \pm 1 \pmod 9 \end{cases}$$

**Corollary 2.4.** *If $\theta^3$ is a square free integer, then*

$$\mathcal{O}_{\mathbb{Q}(\theta)} = \mathbb{Z}[\theta].$$

## 2.2 Integral basis

**Theorem 2.5.** *Let $\alpha \in K$. $Tr_K(\alpha) \in \mathbb{Z}$ if $\alpha \in \mathcal{O}_K$. $N_K(\alpha) \in \mathbb{Z}$ if and only if $\alpha \in \mathcal{O}_K$.*

**Theorem 2.6.** *Let $\{\omega_1, \cdots, \omega_n\}$ be a basis of $K$ over $\mathbb{Q}$. If $\Delta(\omega_1, \cdots, \omega_n)$ is square-free, then $\{\omega_1, \cdots, \omega_n\}$ is an integral basis.*

**Theorem 2.7.** *Let $\{\omega_1, \cdots, \omega_n\}$ be a basis of $K$ over $\mathbb{Q}$ consisting of algebraic integers. If $p^2 \mid \Delta$ and it is not an integral basis, then there is a nonzero algebraic integer of the form*

$$\frac{1}{p}\sum_{i=1}^{n} \lambda_i \omega_i.$$

## 2.3 Fractional ideals

**Theorem 2.8.** *Every fractional ideal of $K$ is a free $\mathbb{Z}$-module with rank $[K : \mathbb{Q}]$.*

*Proof.* This theorem holds because $K/\mathbb{Q}$ is separable and $\mathbb{Z}$ is a PID. $\square$

### 2.4 Frobenius element

**Definition 2.1.** Let $L/K$ be abelian. Let $\mathfrak{p}$ be a prime in $\mathcal{O}_K$ and $\mathfrak{q}$ be a prime in $\mathcal{O}_L$ over $\mathfrak{p}$. The *decomposition group* $D_{\mathfrak{q}|\mathfrak{p}}$ is a subgroup of $\mathrm{Gal}(L/K)$ whose element fixes the prime $\mathfrak{q}$. Since $L/K$ is Galois, the followings do not depend on the choice of $\mathfrak{q}$ over $\mathfrak{p}$.

By definition, $D_{\mathfrak{q}|\mathfrak{p}}$ acts on the set $\mathcal{O}_L/\mathfrak{q}$ and fixes $\mathcal{O}_K$.

**Lemma 2.9.** *The following sequence of abelian groups is exact:*

$$0 \longrightarrow I_{\mathfrak{q}|\mathfrak{p}} \longrightarrow D_{\mathfrak{q}|\mathfrak{p}} \longrightarrow \mathrm{Gal}(k(\mathfrak{q})/k(\mathfrak{p})) \longrightarrow 0,$$

*where* $k(\mathfrak{q}) := \mathcal{O}_L/\mathfrak{q}$ *and* $k(\mathfrak{p}) := \mathcal{O}_K/\mathfrak{p}$ *are residue fields.*

*Proof.* We first show □

The Frobenius element is defined as an element of $D_{\mathfrak{q}|\mathfrak{p}}/I_{\mathfrak{q}|\mathfrak{p}} \cong \mathrm{Gal}(k(\mathfrak{q})/k(\mathfrak{p}))$, which is a cyclic group.

**Definition 2.2.** The Frobenius element is defined by $\phi_{\mathfrak{q}|\mathfrak{p}} \in \mathrm{Gal}(L/K)$ such that $\phi_{\mathfrak{q}|\mathfrak{p}}(\mathfrak{q}) = \mathfrak{q}$ and

$$\phi_{\mathfrak{q}|\mathfrak{p}}(x) \equiv x^{|\mathcal{O}_K/\mathfrak{p}|} \pmod{\mathfrak{q}} \quad \text{for } x \in \mathcal{O}_L.$$

It gives a generator of the cyclic group $D_{\mathfrak{q}|\mathfrak{p}}/I_{\mathfrak{q}|\mathfrak{p}}$.

*Remark.* Fermat's little theorem states $\phi_{\mathfrak{q}|\mathfrak{p}} = \mathrm{id}_{\mathcal{O}_K/\mathfrak{p}}$, i.e.

$$\phi_{\mathfrak{P}|\mathfrak{p}}(x) \equiv x \pmod{\mathfrak{p}} \quad \text{for } x \in \mathcal{O}_K,$$

which means $\phi_{\mathfrak{P}|\mathfrak{p}}$ fixes the field $\mathcal{O}_K/\mathfrak{p}$ so that $\phi_{\mathfrak{P}|\mathfrak{p}} \in \mathrm{Gal}(k(\mathfrak{P})/k(\mathfrak{p}))$.

### 2.5 Quadratic Dirichlet character

Let $D$ be a quadratic discriminant. For $\zeta_D = e^{\frac{2\pi i}{D}}$, it is known that the cyclotomic field $\mathbb{Q}(\zeta_D)$ is the smallest cyclotomic extension of the quadratic field $\mathbb{Q}(\sqrt{D})$. Let $K = \mathbb{Q}(\sqrt{D})$ and $L = \mathbb{Q}(\zeta_D)$.

$$\begin{array}{ccccccc}
\sigma_p & \in & D_{\mathfrak{q}|p} & \leq & \mathrm{Gal}(L/\mathbb{Q}) & \cong & (\mathbb{Z}/|D|\mathbb{Z})^\times \\
\big\downarrow{\scriptstyle \cdot|_K} & & & & \big\downarrow{\scriptstyle \cdot|_K} & & \big\downarrow{\scriptstyle \chi_K = \left(\frac{D}{\cdot}\right)} \\
\sigma_p|_K & \in & D_{\mathfrak{p}|p} & \leq & \mathrm{Gal}(K/\mathbb{Q}) & \cong & \langle \pm 1 \rangle.
\end{array}$$

For $p \nmid D$ so that $p$ is unramified, let $\sigma_p := (\zeta_D \mapsto \zeta_D^p) \in \mathrm{Gal}(L/\mathbb{Q})$. Then, what is $\sigma_p|_K$ in $\mathrm{Gal}(K/\mathbb{Q})$? In other words, which is true: $\sigma_p(\sqrt{D}) = \pm\sqrt{D}$?

Notice that $\sigma$ satisfies the condition to be the Frobenius element: $\sigma_p I_{\mathfrak{q}|p} = \phi_{\mathfrak{q}|p}$. Therefore, $\phi_{\mathfrak{p}|p} = \sigma_p|_K$ is also a Frobenius element. There are only two cases:

(1) If $f = |D(\mathfrak{p}/p)| = 1$, then $\sigma_p|_K$ is the identity, so $\chi_K(p) = 1$

(2) If $f = |D(\mathfrak{p}/p)| = 2$, then $\sigma_p|_K$ is not trivial, so $\chi_K(p) = -1$

Artin reciprocity: $(\mathbb{Z}/D\mathbb{Z})^\times$ is extended to $I_K^S$.

# 3 Diophantine equations

## 3.1 Quadratic equation on a plane

Ellipse is reduced by finitely many computations.

Especially for hyperbola, here is a strategy to use infinite descent.

(1) Let midpoint to be origin.

(2) Find the subgroup of $\mathrm{SL}_2(\mathbb{Z})$ preserving the image of hyperbola(which would be isomorphic to $\mathbb{Z}$).

(3) Find an impossible region.

(4) Assume a solution and reduce it to the either impossible region or the ground solution.

**Example 3.1** (Pell's equation)**.** Consider

$$x^2 - 2y^2 = 1.$$

A generator of hyperbola generating group is $g = \begin{pmatrix} 3 & 4 \\ 2 & 3 \end{pmatrix}$. It has a ground solution $(1,0)$ and impossible region $1 < x < 3$. If $(a,b)$ is a solution with $a > 0$, then we can find $n$ such that $g^n(a,b)$ is in the region $[1,3)$. The possible case is $g^n(a,b) = (1,0)$.

**Example 3.2** (IMO 1988, the last problem)**.** Consider a family of equations

$$x^2 + y^2 - kxy - k = 0.$$

By the vieta jumping, a generator is $g : (a,b) \mapsto (b, kb - a)$. It has an impossible region $xy < 0 : x^2 + y^2 - kxy - k \geq x^2 + y^2 > 0$. If $(a,b)$ is a solution with $a > b$, then we can find $n$ such that $g^n(a,b)$ is in the region $xy \leq 0$. Only possible case is $g^n(a,b) = (\sqrt{k}, 0)$ or $g^n(a,b) = (0, -\sqrt{k})$. In ohter words, the equation has a solution iff $k$ is a perfect square.

### 3.2 The Mordell equations

(The reciprocity laws let us learn not only which prime splits, but also which prime factors a given polynomial has.)

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

There are two strategies for the Mordell equations:

- $x^2 - 2x + 4$ has a prime factor of the form $4k + 3$
- $x^3 = N(y - a)$ for some $a$.

First case: $k = 7, -5, -6, 45, 6, 46, -24, -3, -9, -12$.

**Example 3.3.** Solve $y^2 = x^3 + 7$.

*Proof.* Taking mod 8, $x$ is odd and $y$ is even. Consider

$$y^2 + 1 = (x + 2)(x^2 - 2x + 4).$$

Since

$$x^2 - 2x + 4 = (x - 1)^2 + 3,$$

there is a prime $p \equiv 3 \pmod 4$ that divides the right hand side. Taking mod $p$, we have

$$y^2 \equiv -1 \pmod p,$$

which is impossible. Therefore, the equation has no solutions. $\square$

**Example 3.4.** Solve $y^2 = x^3 - 2$.

*Proof.* Taking mod 8, $x$ and $y$ are odd. Consider a ring of algebraic integers $\mathbb{Z}[\sqrt{-2}]$. We have

$$N(y - \sqrt{-2}) = (y - \sqrt{-2})(y + \sqrt{-2}) = x^3.$$

For a common divisor $\delta$ of $y \pm \sqrt{-2}$, we have

$$N(\delta) \mid N((y - \sqrt{-2}) - (y + \sqrt{-2})) = N(2\sqrt{-2}) = |(2\sqrt{-2})(-2\sqrt{-2})| = 8.$$

On the other hand,

$$N(\delta) \mid x^3 \equiv 1 \pmod 2,$$

so $N(\delta) = 1$ and $\delta$ is a unit. Thus, $y \pm \sqrt{-2}$ are relatively prime. Since the units in $\mathbb{Z}[\sqrt{-2}]$ are $\pm 1$, which are cubes, $y \pm \sqrt{-2}$ are cubics in $\mathbb{Z}[\sqrt{-2}]$.

Let

$$y + \sqrt{-2} = (a + b\sqrt{-2})^3 = a(a^2 - 6b^2) + b(3a^2 - 2b^2)\sqrt{-2},$$

so that $1 = b(3a^2 - 2b^2)$. We can conclude $b = \pm 1$. The possible solutions are $(x, y) = (3, \pm 5)$, which are in fact solutions. $\square$

# 4 The local-global principle

## 4.1 The local fields

Let $f \in \mathbb{Z}[x]$.

*Does $f = 0$ have a solution in $\mathbb{Z}$?*

*Does $f = 0$ have a solution in $\mathbb{Z}/(p^n)$ for all $n$?*

*Does $f = 0$ have a solution in $\mathbb{Z}_p$?*

In the first place, here is the algebraic definition.

**Definition 4.1.** Let $p \in \mathbb{Z}$ be a prime. The ring of the $p$-adic integers $\mathbb{Z}_p$ is defined by the inverse limit:

$$\mathbb{Z}_p := \varprojlim_{n \in \mathbb{N}} \mathbb{F}_{p^n} \longrightarrow \cdots \longrightarrow \mathbb{Z}/(p^3) \longrightarrow \mathbb{Z}/(p^2) \longrightarrow \mathbb{F}_p.$$

**Definition 4.2.** $\mathbb{Q}_p = \operatorname{Frac} \mathbb{Z}_p$.

Secondly, here is the analytic definition.

**Definition 4.3.** Let $p \in \mathbb{Z}$ be a prime. Define a absolute value $|\cdot|_p$ on $\mathbb{Q}$ by $|p^m a|_p = \frac{1}{p^m}$. The local field $\mathbb{Q}_p$ is defined by the completion of $\mathbb{Q}$ with respect to $|\cdot|_p$.

**Definition 4.4.** $\mathbb{Z}_p := \{x \in \mathbb{Q}_p : |x|_p \leq 1\}$.

**Example 4.1.** Observe

$$\begin{aligned} 3^{-1} &\equiv 2_5 \pmod 5 \\ &\equiv 32_5 \pmod{5^2} \\ &\equiv 132_5 \pmod{5^3} \\ &\equiv 1313132_5 \quad (\text{mod } 5)^7 \cdots . \end{aligned}$$

Therefore, we can write

$$3^{-1} = \overline{13}2_5 = 2 + 3p + p^2 + 3p^3 + p^4 + \cdots$$

for $p = 5$. Since there is no negative power of 5, $3^{-1}$ is a $p$-adic integer for $p = 5$.

**Example 4.2.**

$$\begin{aligned} 7 &\equiv 1_3^2 \pmod 3 \\ &\equiv 111_3^2 \pmod{3^3} \\ &\equiv 20111_3^2 \pmod{3^5} \\ &\equiv 120020111_3^2 \pmod{3^9} \cdots . \end{aligned}$$

Therefore, we can write

$$\sqrt{7} = \cdots 120020111_3 = 1 + p + p^2 + 2p^4 + 2p^7 + p^8 + \cdots$$

for $p = 3$. Since there is no negative power of 3, $\sqrt{7}$ is a $p$-adic integer for $p = 3$.

There are some pathological and interesting phenomena in local fields. Actually note that the values of $|\cdot|_p$ are totally disconnected.

**Theorem 4.1.** *The absolute value $|\cdot|_p$ is nonarchimedean: it satisfies $|x+y|_p \leq \max\{|x|_p, |y|_p\}$.*

*Proof.* Trivial. $\square$

**Theorem 4.2.** *Every triangle in $\mathbb{Q}_p$ is isosceles.*

**Theorem 4.3.** *$\mathbb{Z}_p$ is a discrete valuation ring: it is local PID.*

*Proof.* asdf $\square$

**Theorem 4.4.** *$\mathbb{Z}_p$ is open and compact. Hence $\mathbb{Q}_p$ is locally compact Hausdorff.*

*Proof.* $\mathbb{Z}_p$ is open clearly. Let us show limit point compactness. Let $A \subset \mathbb{Z}_p$ be infinite. Since $\mathbb{Z}_p$ is a finite union of cosets $p\mathbb{Z}_p$, there is $\alpha_0$ such that $A \cap (\alpha_0 + p\mathbb{Z}_p)$ is infinite. Inductively, since

$$\alpha_n + p^{n+1}\mathbb{Z}_p = \bigcup_{1 \leq x < p} (\alpha_n + xp^{n+1} + p^{n+2}\mathbb{Z}_p),$$

we can choose $\alpha_{n+1}$ such that $\alpha_n \equiv \alpha_{n+1} \pmod{p^{n+1}}$ and $A \cap (\alpha_{n+1} + p^{n+2}\mathbb{Z}_p)$ is infinite. The sequence $\{\alpha_n\}$ is Cauchy, and the limit is clearly in $\mathbb{Z}_p$. $\square$

## 4.2 Hensel's lemma

**Theorem 4.5** (Hensel's lemma)**.** *Let $f \in \mathbb{Z}_p[x]$. If $f$ has a simple solution in $\mathbb{F}_p$, then $f$ has a solution in $\mathbb{Z}_p$.*

*Proof.* asdf $\square$

*Remark.* Hensel's lemma says: for $X$ a scheme over $\mathbb{Z}_p$, $X$ is smooth iff $X(\mathbb{Z}_p) \twoheadrightarrow X(\mathbb{F}_p)$....???

**Example 4.3.** $f(x) = x^p - x$ is factorized linearly in $\mathbb{Z}_p[x]$.

## 4.3 Sums of two squares

**Theorem 4.6** (Euler)**.** *A positive integer $m$ can be written as a sum of two squares if and only if $v_p(m)$ is even for all primes $p \equiv 3 \pmod 4$.*

**Lemma 4.7.** *Let $p$ be a prime with $p \equiv 1 \pmod 4$. Every $p$-adic integer is a sum of two squares of $p$-adic integers.*

# 5 Dedekind domain

$$\begin{tikzcd}
\text{Notherian:} & \text{ED} \arrow[r] & \text{PID} \arrow[r] \arrow[d] & \text{UFD} \arrow[d] & \\
\text{Non-noetherian:} & & \text{Bézout} \arrow[r] & \text{GCD} \arrow[r] & \text{Euclid's lemma.}
\end{tikzcd}$$

**Proposition 5.1.** *Let $A$ be a Dedekind domain. Then, $A$ is a PID if and only if Euclid's lemma holds.*

If $R$ satisfies the *ascending chain condition for principal ideals*, then $R$ is a PID iff $R$ is a Bézout domain, and $R$ is a UFD iff Euclid's lemma holds in $R$.

Every valuation ring is a Bézout domain.