

Elliptic Curves over \mathbb{C} and over Finite Fields

Matthew Dupraz

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Introduction

Throughout this paper we assume known the content of the course *Algebraic curves* given by Dimitri Wyss. Whenever we talk about algebraic varieties defined over a field K , we will assume K is algebraically closed, unless stated otherwise.

1 Algebraic Varieties

The projective space \mathbb{P}^n can be covered by copies of \mathbb{A}^n . Define

$$U_i := \{[x_0, \dots, x_n] \in \mathbb{P}^n \mid x_i \neq 0\},$$

then U_i is isomorphic to \mathbb{A}^n via the chart

$$\phi_i : U_i \rightarrow \mathbb{A}^n, [x_0, \dots, x_n] \mapsto \left(\frac{x_1}{x_i}, \dots, \frac{x_{i-1}}{x_i}, \frac{x_{i+1}}{x_i}, \dots, \frac{x_n}{x_i} \right)$$

Notation. Thanks to the above isomorphism, we can see \mathbb{A}^n as a chosen $U_i \subset \mathbb{P}^n$. Hence we can see any affine variety $V \subseteq \mathbb{A}^n$ as a subset of \mathbb{P}^n . Similarly, if $V \subseteq \mathbb{P}^n$ is a projective variety, then for a chosen $\mathbb{A}^n \subseteq \mathbb{P}^n$, $V \cap \mathbb{A}^n$ is an affine variety.

Definition 1.1. For $V \subseteq \mathbb{P}^n$ a subset, we define \overline{V} the (Zariski) *closure*, the closure of V in the Zariski topology of \mathbb{P}^n .

Proposition 1.1. 1. For V an affine variety, \overline{V} is a projective variety, and

$$V = \overline{V} \cap \mathbb{A}^n.$$

2. Let V be a projective variety. Then $V \cap \mathbb{A}^n$ is an affine variety, and either

$$V \cap \mathbb{A}^n = \emptyset \text{ or } V = \overline{V \cap \mathbb{A}^n}$$

Proof. 1. Follows from Lemma 3.5 from the course "Algebraic curves".

2. Suppose $V \cap \mathbb{A}^n \neq \emptyset$. We have that $V \supseteq V \cap \mathbb{A}^n$ and V is closed, hence $V \supseteq \overline{V \cap \mathbb{A}^n}$. $V \setminus \mathbb{A}^n$ is closed, and

$$V = \overline{V \cap \mathbb{A}^n} \cup (V \setminus \mathbb{A}^n).$$

By irreducibility of V and the fact $V \cap \mathbb{A}^n \neq \emptyset$ and so $V \neq (V \setminus \mathbb{A}^n)$, we get $V = \overline{V \cap \mathbb{A}^n}$. □

Definition 1.2. Let $V \subseteq \mathbb{A}^n$ be an affine variety, $P \in V$ and $f_1, \dots, f_m \in K[X_1, \dots, X_n]$ a set of generators of $I(V)$. Then V is *non-singular*, or *smooth* at P if the Jacobian of (f_1, \dots, f_m) at P has rank $n - \dim(V)$. If V is non-singular at every point, then V is *non-singular*, or *smooth*.

Definition 1.3. Let $V \subseteq \mathbb{P}^n$ be a projective variety, $P \in V$ and choose $\mathbb{A}^n \subseteq \mathbb{P}^n$ such that $P \in \mathbb{A}^n$. Then V is *non-singular*, or *smooth* at P if $V \cap \mathbb{A}^n$ is smooth at P (as an affine variety).

Proposition 1.2. Let $V \subseteq \mathbb{P}^n$ be a projective variety, for any $\mathbb{A}^n \subseteq \mathbb{P}^n$, $K(V) = K(V \cap \mathbb{A}^n)$.

Proof. Follows from Proposition 3.11 from the course "Algebraic curves". \square

Definition 1.4. Let $V_1 \subseteq \mathbb{P}^n, V_2 \subseteq \mathbb{P}^m$ be projective varieties. A *rational map* from V_1 to V_2 is a map of the form

$$\begin{aligned}\phi : V_1 &\rightarrow V_2 \\ P &\mapsto [f_0(P), \dots, f_m(P)],\end{aligned}$$

where $f_0, \dots, f_m \in K(V_1)$ are such that for all $P \in V_1$ at which f_0, \dots, f_m are all defined, $\phi(P) \in V_2$.

Definition 1.5. A rational map $\phi = [f_0, \dots, f_m] : V_1 \rightarrow V_2$ is *regular* at $P \in V_1$ if there is a function $g \in K(V_1)$, such that

- (i) each gf_i is regular at P
- (ii) for some i , $(gf_i)(P) \neq 0$

If such a g exists, we set

$$\phi(P) = [(gf_0)(P), \dots, (gf_m)(P)]$$

Proposition 1.3. Let $\phi = [f_0, \dots, f_m] : V_1 \rightarrow V_2$ be a rational map. Then ϕ is regular at all $P \in V_1$ if and only if ϕ is a morphism.

Proof. Suppose first that ϕ is a morphism, let $P \in V_1$. Choose i such that $\phi(P) \in U_i \subseteq V_2$, where $U_i = \{[x_0, \dots, x_m] \in \mathbb{P}^m \mid x_i \neq 0\}$. For each j , define the map

$$\begin{aligned}h_j : V_2 \cap U_i &\rightarrow K \\ [x_0, \dots, x_m] &\mapsto \frac{x_j}{x_i}\end{aligned}$$

By definition, $h_j \in \mathcal{O}(V_2 \cap U_i)$. Since ϕ is a morphism, we get that $h_j \circ \phi = \frac{f_j}{f_i} : \phi^{-1}(V_2 \cap U_i) \rightarrow K$ is regular. Setting $g = 1/f_i \in K(V_1)$, we get that gf_j is regular at P for all j and $gf_i = 1 \neq 0$. Hence ϕ is regular at P .

For the other implication, suppose ϕ is regular at all $P \in V_1$. Let $W \subseteq V_2$ open and $f \in \mathcal{O}(W)$, we have to show that $f \circ \phi : \phi^{-1}(W) \rightarrow K$ is regular. Let $P \in \phi^{-1}(W)$, then since ϕ is regular at P , there exists $g \in K(V_1)$ such that each gf_i is regular at P and for some i , $(gf_i)(P) \neq 0$. Since f is regular at $\phi(P)$, there exist polynomials $p, q \in K[x_0, \dots, x_m]$ homogeneous of the same degree with $q(\phi(P)) \neq 0$ and $f(Q) = \frac{p(Q)}{q(Q)}$ for all $Q \in W \setminus q^{-1}(0)$. Then

$$f \circ \phi = \frac{p(f_0, \dots, f_m)}{q(f_0, \dots, f_m)} = \frac{p(gf_0, \dots, gf_m)}{q(gf_0, \dots, gf_m)}$$

We have that both $p(gf_0, \dots, gf_m)$ and $q(gf_0, \dots, gf_m)$ are regular. Furthermore, $q(gf_0, \dots, gf_m)(P) = q(\phi(P)) \neq 0$ and hence we deduce that $f \circ \phi$ is regular. This implies that ϕ is a morphism. \square

2 Algebraic Curves

2.1 Basic properties

By a *curve* we always mean a projective variety of dimension one.

Proposition 2.1. *Let C be a curve and $P \in C$ a smooth point. Then $K[C]_P$ is a discrete valuation ring.*

Definition 2.1. Let C be a curve and $P \in C$ a smooth point. The *valuation* on $K[C]_P$ is given by

$$\begin{aligned} \text{ord}_P : K[C]_P &\rightarrow \mathbb{N} \cup \{\infty\} \\ f &\mapsto \max\{d \in \mathbb{N} \mid f \in \mathfrak{m}_P^d\}. \end{aligned}$$

We extend this definition to $K(C)$ using

$$\begin{aligned} \text{ord}_P : K(C) &\rightarrow \mathbb{N} \cup \{\infty\} \\ f/g &\mapsto \text{ord}_P(f) - \text{ord}_P(g). \end{aligned}$$

For $f \in K(C)$, we call $\text{ord}_P(f)$ the order of f at P . If $\text{ord}_P(f) > 0$, then f has a *zero* at P , if $\text{ord}_P(f) < 0$, then f has a *pole* at P , if $\text{ord}_P(f) \geq 0$, then f is *regular* at P .

A *uniformizer* for C at P is a function $t \in K(C)$ with $\text{ord}_P(t) = 1$ (so a generator of \mathfrak{m}_P)

Proposition 2.2. *Let C be a curve, $V \subseteq \mathbb{P}^n$ a variety, $P \in C$ a smooth point, and $\phi : C \rightarrow V$ a rational map. Then ϕ is regular at P . In particular, if C is smooth, then ϕ is a morphism.*

Theorem 2.3. *Let $\phi : C_1 \rightarrow C_2$ be a morphism of curves. Then ϕ is either constant or surjective.*

Definition 2.2. Let $\phi : C_1 \rightarrow C_2$ be a map of curves defined over K . If ϕ is constant, we define the *degree* of ϕ to be 0. Otherwise we define the degree of ϕ by

$$\deg \phi = [K(C_1) : \phi^* K(C_2)]$$

Let S be the separable closure of $\phi^* K(C_2)$ inside $K(C_1)$. we define the *separable degree* of ϕ to be

$$\deg_s \phi = [S : \phi^* K(C_2)]$$

and the *inseparable degree*

$$\deg_i \phi = [K(C_1) : S].$$

Definition 2.3. Let $\phi : C_1 \rightarrow C_2$ be a non-constant map of smooth curves, and let $P \in C_1$. The *ramification index* of ϕ at P , denoted $e_\phi(P)$, is given by

$$e_\phi(P) = \text{ord}_P(\phi^* t_{\phi(P)})$$

where $t_{\phi(P)} \in K(C_2)$ is a uniformizer at $\phi(P)$. We say that ϕ is *unramified* at P if $e_\phi(P) = 1$. ϕ is *unramified* if it is unramified at every point C_1 .

Definition 2.4. Suppose $\text{char}(K) = p \neq 0$ and let $q = p^r$. For any polynomial $f \in K[X]$ define $f^{(q)}$ to be the polynomial obtained from f by raising each coefficient of f to the q^{th} power. For any curve C/K we can define a new curve $C^{(q)}/K$ corresponding to the ideal generated by $\{f^{(q)} : f \in I(C)\}$.

The q^{th} -power Frobenius morphism is defined by

$$\begin{aligned}\phi : C &\rightarrow C^{(q)} \\ [x_0, \dots, x_n] &\mapsto [x_0^q, \dots, x_n^q]\end{aligned}$$

This map is well defined as for any $P = [x_0, \dots, x_n] \in C$, and for any generator $f^{(q)}$ of $I(C^{(q)})$,

$$\begin{aligned}f^{(q)}(\phi(P)) &= f^{(q)}(x_0^q, \dots, x_n^q) \\ &= (f(x_0, \dots, x_n))^q && \text{since } \text{char}(K) = p \\ &= (f(P))^q = 0\end{aligned}$$

2.2 Divisors

Definition 2.5. The *divisor group of a curve* C , denoted $\text{Div}(C)$ is the free abelian group generated by the points of C . We write $D \in \text{Div}(C)$ as the formal sum

$$D = \sum_{P \in C} n_P \cdot (P)$$

with $n_P \in \mathbb{Z}$ and $n_P = 0$ for all but finitely many $P \in C$.

The *degree* of D is defined by

$$\deg D = \sum_{P \in C} n_P.$$

The *divisors of degree 0* form a subgroup of $\text{Div}(C)$, which we denote by

$$\text{Div}^0(C) = \{D \in \text{Div}(C) \mid \deg D = 0\}.$$

Definition 2.6. Let C be a smooth curve and $f \in K(C) \setminus \{0\}$. We associate to f the divisor $\text{div}(f)$ given by

$$\text{div}(f) = \sum_{P \in C} \text{ord}_P(f) \cdot (P)$$

Remark. Since each ord_P is a valuation, the map

$$\text{div} : K(C)^\times \rightarrow \text{Div}(C)$$

is a homomorphism of abelian groups.

Definition 2.7. A divisor $D \in \text{Div}(C)$ is *principal* if it has the form $D = \text{div}(f)$ for some $f \in K(C)$. The subgroup of principal divisors is denoted $\text{PDiv}(C)$. Two divisors D_1, D_2 are *linearly equivalent*, which we denote $D_1 \sim D_2$, if $D_1 - D_2$ is principal.

Definition 2.8. The *divisor class group* of a curve C , denoted $\text{Cl}(C)$, is the quotient $\text{Div}(C)/\text{PDiv}(C)$. Principal divisors have degree 0 and hence it makes sense to speak about the degree of elements in $\text{Cl}(C)$. The subgroup of elements of $\text{Cl}(C)$ of degree 0 is denoted $\text{Cl}^0(C)$.

Definition 2.9. Let $\phi : C_1 \rightarrow C_2$ be a non-constant between smooth curves. Then ϕ induces maps between the divisor groups of C_1 and C_2 . The *pullback* is defined by

$$\begin{aligned}\phi^* : \text{Div}(C_2) &\rightarrow \text{Div}(C_1) \\ (Q) &\mapsto \sum_{P \in \phi^{-1}(Q)} e_\phi(P) \cdot (P).\end{aligned}$$

The *pushforward* is defined by

$$\begin{aligned}\phi_* : \text{Div}(C_1) &\rightarrow \text{Div}(C_2) \\ (P) &\mapsto (\phi P).\end{aligned}$$

Definition 2.10. A divisor $D = \sum n_P(P) \in \text{Div}(C)$ is *positive* (or *effective*), denoted by $D \geq 0$, if $n_P \geq 0$ for all $P \in C$. For two divisors $D_1, D_2 \in \text{Div}(C)$, we write $D_1 \geq D_2$ to indicate that $D_1 - D_2$ is positive.

Definition 2.11. Let $D \in \text{Div}(C)$. We associate to D the set of functions

$$\mathcal{L}(D) = \{f \in K(C)^\times : \text{div}(f) \geq -D\} \cup \{0\}.$$

It can be shown $\mathcal{L}(D)$ is finite-dimensional. We denote its dimension by

$$l(D) = \dim_K \mathcal{L}(D).$$

2.3 Differentials

To be able to define the genus of a curve, and state the Riemann-Roch theorem, we need to introduce the notion of differentials. Since these are not central for the goals of this paper, we will gloss over the main definitions and properties without providing proofs.

Definition 2.12. Let C be a curve. The *space of (meromorphic) differential forms* on C , denoted Ω_C , is the $K(C)$ -vector space generated by symbols of the form df for $f \in K(C)$, subject to the following relations:

1. $d(x + y) = dx + dy$
2. $d(xy) = x dy + y dx$
3. $da = 0$

for all $x, y \in K(C)$ and $a \in K$.

Definition 2.13. Let $\phi : C_1 \rightarrow C_2$ be a non-constant map of curves. Then ϕ induces maps between the spaces of meromorphic forms of C_1 and C_2 . The *pullback* is defined by

$$\begin{aligned}\phi^* : \Omega_{C_2} &\rightarrow \Omega_{C_1} \\ f dx &\mapsto (\phi^* f) d(\phi^* x)\end{aligned}$$

Proposition 2.4. Let C be a curve, then Ω_C is a 1-dimensional $K(C)$ -vector space. Furthermore, if $t \in K(C)$ is a uniformizer at P , then dt generates Ω_C .

Notation. Let $\omega \in \Omega_C$. Then by there exists $g \in K(C)$ such that $\omega = g dt$. We denote g by ω/dt .

The following proposition will allow us to define the order of a differential.

Proposition 2.5. Let $P \in C$ and $t \in K(C)$ a uniformizer at P . For $\omega \in \Omega_C$, the quantity

$$\text{ord}_P(\omega/dt)$$

is independent of the choice of uniformizer t .

Definition 2.14. We call $\text{ord}_P(\omega/dt)$ the order of ω at P and denote it by $\text{ord}_P(\omega)$.

We now state (without proof) a corollary of the Riemann-Roch theorem, which will be useful in the following chapters.

Theorem 2.6 (Riemann-Roch). Let C be a smooth curve of genus g . Let $D \in \text{Div}(C)$, then if $\deg(D) > 2g - 2$, we have that

$$l(D) = \deg(D) - g + 1$$

3 Basic Definitions and Facts

3.1 Weierstrass Equation

Our main interest are *elliptic curves*, which are curves in \mathbb{P}^2 of genus 1. These are characterized by the homogeneous equation

$$Y^2Z + aXYZ + bYZ^2 = X^3 + cX^2Z + dXZ^2 + eZ^3 \quad (1)$$

for some $a, b, c, d, e \in \mathbb{F}$. Setting $U_Z = \{[X, Y, Z] \in \mathbb{P}^2 \mid Z \neq 0\}$, we can study the solutions of (1) on U_Z using the change of coordinates $x = X/Z$ and $y = Y/Z$. We obtain the following equation

$$y^2 + axy + by = x^3 + cx^2 + dx + e \quad (2)$$

We can further simplify this equation with linear changes of variables. First notice that if $\text{char}(\mathbb{F}) \neq 2$, the left hand side can be written as

$$\begin{aligned} y(y + ax + b) &= (y + \frac{1}{2}(ax + b) - \frac{1}{2}(ax + b))(y + \frac{1}{2}(ax + b) + \frac{1}{2}(ax + b)) \\ &= (y + \frac{1}{2}(ax + b))^2 - \frac{1}{4}(ax + b)^2 \end{aligned}$$

Hence by replacing y with $y + \frac{1}{2}(ax + b)$ and collecting the terms in each monomial, we get an equation of the form

$$y^2 = x^3 + \alpha x^2 + \beta x + \gamma \quad (3)$$

If $\text{char}(\mathbb{F}) \neq 3$, we can also get rid of the term in x^2 with a linear change of variables. replacing x with $x - \frac{1}{3}\alpha$ yields

$$\begin{aligned} y^2 &= (x - \frac{1}{3}\alpha)^3 + \alpha(x - \frac{1}{3}\alpha)^2 + \beta(x - \frac{1}{3}\alpha) + \gamma \\ &= x^3 - \alpha x^2 + \frac{1}{3}\alpha^2 x - \frac{1}{27}\alpha^3 + \alpha x^2 - \frac{2}{3}\alpha^2 x + \frac{1}{9}\alpha^3 + \beta x - \frac{1}{3}\alpha\beta + \gamma \end{aligned}$$

Collecting the terms in each monomial, we get an equation of the form

$$y^2 = x^3 + Ax + B \quad (4)$$

with $A, B \in \mathbb{F}$. Plugging back the substitutions $x = X/Z$ and $y = Y/Z$, we obtain the homogeneous equation

$$Y^2Z = X^3 + AXZ^2 + BZ^3 \quad (5)$$

3.2 Singularities

We suppose \mathbb{F} is algebraically closed.

We have that an elliptic curve $V \subset \mathbb{P}_2(\mathbb{F})$ is the projective variety

$$V = V(X^3 + AXZ^2 + BZ^3 - Y^2Z) = V(F) \quad (6)$$

We are interested in the case where the curve is smooth. By the regular preimage theorem, V is smooth if all its points are non-singular, i.e. if for all $P = [x, y, z] \in V$,

$$\nabla F(P) = \begin{bmatrix} 3x^2 + Az^2 \\ -2yz \\ 2Axz + 3Bz^2 - y^2 \end{bmatrix} \neq 0$$

If $P = [0, 1, 0]$, then

$$\nabla F(P) = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \neq 0$$

hence the point at infinity is never singular. It follows that when looking for singularities, we can consider just the case where $z \neq 0$, since else we have necessarily $x = 0$ and so $P = [0, 1, 0]$. So if there are any singularities of V , they are on $V \cap U_Z$. So V is non-singular precisely when $V \cap U_Z$ is non-singular. Using the isomorphism $V \cap U_Z \rightarrow W, [X, Y, Z] \mapsto (\frac{X}{Z}, \frac{Y}{Z})$ it suffices to study singularities on $W = V(x^3 + Ax + B - y^2) = V(f)$

Let $\Delta = 4A^3 + 27B^2$ be the discriminant of the polynomial $g(x) = x^3 + Ax + B$, we have the following criteria for the existence of singularities of V .

Proposition 3.1. *W (and equivalently V) is non-singular if and only if $\Delta \neq 0$.*

Proof. Suppose there is a point $P = (x_0, y_0) \in W$ that is singular, then we have

$$\begin{bmatrix} 3x_0^2 + A \\ -2y_0 \end{bmatrix} = 0$$

Hence we have that $g'(x_0) = 3x_0^2 + A = 0$ and $y_0 = 0$. In particular, since $P \in W$, also $g(x_0) = 0$, and hence since $g(x_0) = g'(x_0) = 0$, x_0 is a double root of g and so the discriminant $\Delta = 4A^3 + 27B^2$ of g is zero.

Suppose instead that $\Delta = 0$, then g admits a double root $x_0 \in \mathbb{F}$ (since we supposed \mathbb{F} algebraically closed) which is unique since g is a cubic polynomial. Then $P = (x_0, 0) \in V$. Furthermore,

$$\nabla f(P) = \begin{bmatrix} 3x^2 + A \\ 0 \end{bmatrix}$$

We have that $3x^2 + A = g'(x) = 0$, hence $\nabla f(P) = 0$ and so W is singular at P . \square

3.3 Group Law

Let E be an elliptic curve. For any line $L \subset \mathbb{P}^2$, L intersects E in exactly 3 points (taken with multiplicity). This allows us to define a composition law $+$ on E as follows.

Definition 3.1. Let $P, Q \in E$ and L the line connecting P and Q (or the tangent line to E at P if $P = Q$). Let R be the third point of intersection of L with E . Let L' be the line connecting R and O . We define $P + Q$ be the third point of intersection of L' with E .

Notation. For $m \in \mathbb{N} \setminus \{0\}$ and $P \in E$ we define

$$[m]P = \underbrace{P + \cdots + P}_{m \text{ times}}.$$

We extend this definition to $m \in \mathbb{Z}$ with $[0]P = O$ and $[m]P = [-m](-P)$ for $m < 0$.

As we have seen, any elliptic curve can be written up to isomorphism under the form

$$E : y^2 = x^3 + ax + b$$

Since this isomorphism is induced by linear changes of variables, it sends lines to lines and hence this preserves the group structure on E induced by $+$. Hence in what follows, we consider simply elliptic curves of the above form. Let $F(x, y) = y^2 - x^3 - ax - b$, so that E is given by the equation $F(x, y) = 0$.

Let $P = (x_P, y_P) \in E$, then we

$$-P = (x_P, -y_P),$$

which is clear by inspection of the composition law.

Now let $Q = (x_Q, y_Q) \in E$ different from $-P$. Then $P + Q \neq O$. Suppose $P \neq Q$, then $x_P \neq x_Q$. We have that the line passing through P and Q is given by

$$L : y = \frac{y_Q - y_P}{x_Q - x_P}(x - x_P) + y_P$$

Setting

$$\lambda = \frac{y_Q - y_P}{x_Q - x_P} \quad \text{and} \quad \nu = \frac{x_Q y_P - x_P y_Q}{x_Q - x_P}$$

we can rewrite $L : y = \lambda x - \nu$.

If $P = Q$, then L is the tangent to E at P , which is given by

$$L : (3x_P^2 + a)(x - x_P) - 2y_P(y - y_P) = 0$$

If $y_P = 0$, L is the line $x = x_P$ and so the third point of intersection is O , whence $P + Q = O$, which contradicts our assumption, and so $y_P \neq 0$. To obtain again an equation of the form $L = \lambda x - \nu$, we have to set

$$\lambda = \frac{3x_P^2 + a}{2y_P} \quad \text{and} \quad \nu = \frac{-3x_P^3 - ax_P + 2y_P^2}{2y_P} = \frac{-x_P^3 + ax_P + 2b}{2y_P}.$$

So let λ and ν be as above corresponding to the case. Let R be the third point of intersection of L with E . We have that the equation $F(x, \lambda x + \nu) = 0$ with respect to x admits exactly the zeroes x_P, x_Q, x_R and hence

$$F(x, \lambda x + \nu) = c(x - x_P)(x - x_Q)(x - x_R)$$

Since the coefficient of x^3 in $F(x, \lambda x + \nu)$ is -1 , we obtain $c = -1$. By equating the coefficient of x^2 , we obtain $\lambda^2 = x_P + x_Q + x_R$ and hence

$$\begin{aligned}x_R &= \lambda^2 - x_P - x_Q \\y_R &= \lambda x_R + \nu\end{aligned}$$

Finally, we obtain $P + Q = (x_R, -y_R)$.

This can be summarized in the following proposition:

Proposition 3.2. *Let E be an elliptic curve given by the Weierstrass equation*

$$E : y^2 = x^3 + ax + b.$$

Let $P = (x_P, y_P), Q = (x_Q, y_Q) \in E$ be two points with $P \neq \pm Q$. Then

1. The addition formula:

$$\begin{aligned}x_{P+Q} &= \left(\frac{y_Q - y_P}{x_Q - x_P} \right)^2 - x_P - x_Q \\y_{P+Q} &= -\frac{y_Q - y_P}{x_Q - x_P} x_{P+Q} + \frac{x_Q y_P - x_P y_Q}{x_Q - x_P}\end{aligned}$$

2. The duplication formula. Write $P = (x, y)$, then

$$\begin{aligned}x_{[2]P} &= \left(\frac{3x^2 + a}{2y} \right)^2 - 2x \\&= \frac{x^4 - 2ax^2 - 8bx + a^2}{4(x^3 + ax + b)} \\y_{[2]P} &= -\frac{3x^2 + a}{2y} x_{[2]P} + \frac{-x^3 + ax + 2b}{2y}\end{aligned}$$

Lemma 3.3. *Let C be a curve of genus 1, and let $P, Q \in C$. Then*

$$(P) \sim (Q) \quad \text{if and only if} \quad P = Q$$

Proof. Suppose $(P) \sim (Q)$, then there exists some $f \in K(C)$ such that

$$\operatorname{div}(f) = (P) - (Q).$$

We have that $f \in \mathcal{L}((Q))$ and by Riemann-Roch (2.6), it follows that

$$\dim \mathcal{L}((Q)) = \deg((Q)) - g + 1 = 1.$$

Since $\mathcal{L}((Q))$ already contains the constant functions, $f \in \mathcal{L}((Q)) = K$ and so $P = Q$. \square

Proposition 3.4. *Let E be an elliptic curve. Then E equipped with the group law from 3.1 and $\operatorname{Cl}^0(E)$ are isomorphic. The isomorphism is given by the map*

$$\begin{aligned}\kappa : E &\rightarrow \operatorname{Cl}^0(E) \\P &\mapsto [(P) - (O)]\end{aligned}$$

Proof. Let $D \in \text{Div}^0(E)$ be a divisor. Since E has genus 1, by the Riemann-Roch theorem (2.6), we have that

$$\dim \mathcal{L}(D + (O)) = 1.$$

Let $f \in K(E)$ be a generator for $\mathcal{L}(D + (O))$. Since

$$\text{div}(f) \geq -D - (O) \quad \text{and} \quad \deg(\text{div}(f)) = 0,$$

we have necessarily that

$$\text{div}(f) = -D - (O) + (P)$$

for some $P \in E$. Hence

$$D \sim (P) - (O).$$

Suppose there is some other $P' \in E$, such that $D \sim (P') - (O)$. Then $(P) \sim (P')$, but then $P = P'$ from 3.3.

This allows us to define

$$\sigma : \text{Div}^0(E) \rightarrow E,$$

which sends a divisor $D \in \text{Div}^0(E)$ to the corresponding point $P \in E$ as above.

This map is clearly surjective, as $\sigma((P) - (O)) = P$. Furthermore, we have that $\sigma(D_1) = \sigma(D_2)$ if and only if $D_1 \sim D_2$. Indeed, if $D_1 \sim D_2$, then

$$(\sigma(D_1)) - (O) \sim (\sigma(D_2)) - (O)$$

and hence $\sigma(D_1) = \sigma(D_2)$ by 3.3. Conversely, if $\sigma(D_1) = \sigma(D_2)$, then clearly

$$D_1 \sim (\sigma(D_1)) - (O) = (\sigma(D_2)) - (O) \sim D_2.$$

We deduce that σ induces a bijection $\bar{\sigma} : \text{Cl}^0(E) \rightarrow E$. Furthermore, clearly $\bar{\sigma} = \kappa^{-1}$.

It remains to show that κ is a group homomorphism. Clearly, $\kappa(O) = 0$, so we have to show that for $P, Q \in E$, $\kappa(P + Q) = \kappa(P) + \kappa(Q)$.

Let

$$f(X, Y, Z) = \alpha X + \beta Y + \gamma Z = 0$$

give the line L in \mathbb{P}^2 going through P, Q and let R be the third point of intersection. We then have that $f/Z \in K(E)$ and since Z intersects E at O with multiplicity 3, we have

$$\text{div}(f/Z) = \sum_{P \in E} \text{ord}_P(f/Z)(P) - \text{ord}_P(Z)(P) = (P) + (Q) + (R) - 3(O).$$

Now let

$$f'(X, Y, Z) = \alpha' X + \beta' Y + \gamma' Z = 0$$

be the line L' through R and O . Then by the definition of addition on E , we have that the third point of intersection of L' with E is $P + Q$. As above, $f'/Z \in K(E)$ and we have

$$\operatorname{div}(f'/Z) = (R) + (O) + (P + Q) - 3(O) = (R) + (P + Q) - 2(O).$$

It follows that

$$\operatorname{div}(f'/f) = \operatorname{div}(f'/Z) - \operatorname{div}(f/Z) = (P + Q) - (P) - (Q) + (O)$$

And hence

$$\begin{aligned} \kappa(P + Q) - \kappa(P) - \kappa(Q) &= [(P + Q) - (O)] - [(P) - (O)] - [(Q) - (O)] \\ &= [(P + Q) - (P) - (Q) + (O)] = 0. \end{aligned}$$

□

Corollary 3.4.1. *Let E be an elliptic curve and $D = \sum n_P(P) \in \operatorname{Div}(E)$. Then D is principal if and only if $\sum n_P = 0$ and $\sum [n_P]P = O$*

Proof. Suppose D is principal, so $D \sim 0$. Principal divisors have degree 0, hence $\sum n_P = 0$. It follows that

$$\begin{aligned} \kappa\left(\sum [n_P]P\right) &= \sum n_P \kappa(P) = \sum n_P [(P) - (O)] \\ &= \left[\sum n_P(P)\right] = 0 \end{aligned}$$

And hence $\sum [n_P]P = 0$ by injectivity of κ .

Now suppose $\sum n_P = 0$ and $\sum [n_P]P = O$, then by the above calculation,

$$[D] = \left[\sum n_P(P)\right] = \kappa\left(\sum [n_P]P\right) = 0$$

and so $D \sim 0$.

□

3.4 Isogenies

Definition 3.2. Let E_1 and E_2 be elliptic curves. An *isogeny* between E_1 and E_2 is a morphism

$$\phi : E_1 \rightarrow E_2$$

satisfying $\phi(O) = O$. E_1 and E_2 are *isogenous* if there exists a non-constant isogeny ϕ between them.

Definition 3.3. Let E be an elliptic curve and $m \in \mathbb{Z}$, $m \neq 0$. The *m-torsion subgroup* of E , denoted $E[m]$, is the set of points of order m in E .

$$E[m] = \{P \in E \mid [m]P = O\}.$$

The *torsion subgroup* of E , denoted E_{tors} , is the set of points of finite order in E .

$$E_{\text{tors}} = \bigcup_{m=1}^{\infty} E[m]$$

3.5 The Dual Isogeny

3.6 The Tate Module

3.7 The Weil Pairing

4 Elliptic Curves over \mathbb{C}

The goal of this section is to show an elliptic curve is isomorphic to a torus as a Riemann surface.

First, let's discuss the Riemann surface structure that an elliptic curve has.

Definition 4.1. The *complex topology* on \mathbb{P}^n is the quotient topology induced by the Euclidean topology on \mathbb{C}^{n+1} .

Throughout this section we will consider \mathbb{P}^n with the complex topology, and hence an elliptic curve $E(\mathbb{C}) \subset \mathbb{P}^2$ will be equipped with the subspace topology.

Proposition 4.1. *Let $E(\mathbb{C}) \subset \mathbb{P}^2$ be an elliptic curve, then $E(\mathbb{C})$ admits the structure of a Riemann surface.*

Proof. Let $y^2 - x^3 - ax - b = f(x, y) = 0$ be the equation defining $E(\mathbb{C})$. So for all $P = (x_P, y_P) \in E(\mathbb{C})$ with $y_P \neq 0$, $\frac{\partial f}{\partial y}(P) \neq 0$ and hence by the implicit function theorem there exists an open set $V_P \subseteq \mathbb{C}$ containing x_P and an analytic function $g_P : V_P \rightarrow \mathbb{C}$, such that $g_P(x_P) = y_P$ and $f(x, g_P(x)) = 0$ for all $x \in V_P$. Furthermore $U_P = (\text{id} \times g_P)(V_P) \subset E(\mathbb{C})$, is an open subset of $E(\mathbb{C})$. Indeed, $U_P = \pi_x^{-1}(V_P)$, where $\pi_x : E(\mathbb{C}) \setminus \{O\} \rightarrow \mathbb{C}, (x, y) \mapsto x$. Hence we define $\phi_P = \pi_x|_{U_P}$ which is a homeomorphism to its image $\phi_P(U_P) = V_P$ (the inverse to which is given by $x \mapsto (x, g_P(x))$).

For all $P = (x_P, 0) \in E(\mathbb{C})$ we define the chart $\phi_P : U_P \rightarrow \mathbb{C}$ similarly, except we inverse the roles of x and y in the above reasoning. Indeed, $\frac{\partial f}{\partial x}(P) \neq 0$, since $E(\mathbb{C})$ is smooth, hence we get the existence of $V_P \subset \mathbb{C}$ containing y_P and $h_P : V_P \rightarrow \mathbb{C}$, such that $h_P(y_P) = x_P$ and $f(h_P(y), y) = 0$ for all $y \in V_P$. We set $U_P := (h_P \times \text{id})(V_P)$ and $\phi_P : U_P \rightarrow \mathbb{C}, (x, y) \mapsto y$.

Finally, we have yet to define a chart whose domain covers the point at infinity $O = [0, 1, 0] \in E(\mathbb{C})$. To do this, we can look at $E(\mathbb{C})$ in $\{[X, Y, Z] \in \mathbb{P}^2 \mid Y \neq 0\}$ instead. We get that in this copy of \mathbb{A}^2 , $E(\mathbb{C})$ is given by the equation.

$$z - x^3 - axz^2 - bz^3 = \tilde{f}(x, z) = 0.$$

We have that $\frac{\partial \tilde{f}}{\partial z}(O) = 1 \neq 0$, hence we can again apply the reasoning from above. We obtain the chart $\phi_O : U_O \rightarrow \mathbb{C}, [x, 1, z] \mapsto x$ with inverse $\phi_O^{-1} : \phi_O(U_O) \rightarrow \mathbb{C}, x \mapsto [x, 1, \tilde{g}(x)]$.

Now let $P, Q \in E(\mathbb{C}) \setminus \{O\}$, with $y_P \neq 0$ and $y_Q = 0$. We have that

$$\begin{aligned} \phi_P \circ \phi_Q^{-1}(y) &= \phi_P(h_Q(y), y) = h_Q(y) \\ \phi_Q \circ \phi_P^{-1}(x) &= \phi_Q(x, g_P(x)) = g_P(x) \\ \phi_P \circ \phi_O^{-1}(x) &= \phi_P([x, 1, \tilde{g}(x)]) = \phi_P\left(\frac{x}{\tilde{g}(x)}, \frac{1}{\tilde{g}(x)}\right) = \frac{x}{\tilde{g}(x)} \\ \phi_O \circ \phi_P^{-1}(x) &= \phi_O(x, g_P(x)) = \phi_O\left(\left[\frac{x}{g_P(x)}, 1, \frac{1}{g_P(x)}\right]\right) = \frac{x}{g_P(x)} \end{aligned}$$

All of these transition maps are holomorphic and by transitivity so are $\phi_O \circ \phi_Q^{-1}$ and $\phi_Q \circ \phi_O^{-1}$. Hence the atlas $\mathcal{A} = \{\phi_P \mid P \in E(\mathbb{C})\}$ is holomorphic and so gives $E(\mathbb{C})$ the structure of a Riemann surface. \square

Let's introduce the definition and some basic properties of elliptic functions. For the rest of this section, let $\Lambda \subseteq \mathbb{C}$ be an arbitrary lattice.

Definition 4.2. An *elliptic function* (relative to the lattice Λ) is a meromorphic function f on \mathbb{C} , which satisfies

$$f(z + \lambda) = f(z) \quad \text{for all } \lambda \in \Lambda, z \in \mathbb{C}$$

Notation. The set of elliptic functions relative to the lattice Λ is denoted $\mathbb{C}(\Lambda)$.

Remark. $\mathbb{C}(\Lambda)$ is a field with the usual operations of addition and multiplication of complex functions.

Definition 4.3. A *fundamental parallelogram* for Λ is a set of the form

$$D = \{a + r\lambda_1 + s\lambda_2 \mid r, s \in [0, 1)\},$$

where $a \in \mathbb{C}$ and λ_1, λ_2 is a basis for Λ .

Proposition 4.2. An elliptic function with no poles (or no zeros) is constant.

Notation. For $f \in \mathbb{C}(\Lambda)$, $z \in \mathbb{C}/\Lambda$, we write $f(z)$, $\text{res}_z(f)$ and $\text{ord}_z(f)$ for $f(\bar{z})$, $\text{res}_{\bar{z}}(f)$ and $\text{ord}_{\bar{z}}(f)$ respectively, for any one representative $\bar{z} \in \mathbb{C}$ of the coset z . This is well defined by the Λ -periodicity of f .

Proposition 4.3. Let $f \in \mathbb{C}(\Lambda)$.

$$(a) \sum_{z \in \mathbb{C}/\Lambda} \text{res}_z(f) = 0.$$

$$(b) \sum_{z \in \mathbb{C}/\Lambda} \text{ord}_z(f) = 0.$$

Next let us introduce the Weierstrass \wp -function, which will serve as a connecting link between elliptic curves and elliptic functions.

Definition 4.4. (a) The Weierstrass elliptic function (\wp -function), is defined by the series

$$\wp(z; \Lambda) = \frac{1}{z^2} + \sum_{\lambda \in \Lambda \setminus \{0\}} \left(\frac{1}{(z - \lambda)^2} - \frac{1}{\lambda^2} \right)$$

(b) The Eisenstein series (of Λ) of weight k , where $k \geq 2$ is an integer is the series

$$G_k(\Lambda) = \sum_{\lambda \in \Lambda \setminus \{0\}} \lambda^{-k}$$

Notation. If Λ is known from context, we write simply $\wp(z)$ and G_k for $\wp(z; \Lambda)$, $G_k(\Lambda)$ respectively.

Proposition 4.4. (a) *The Eisenstein series $G_k(\Lambda)$ is absolutely convergent for all $k \geq 3$.*

(b) *The series defining the Weierstrass \wp -function converges absolutely and uniformly on every compact subset of $\mathbb{C} \setminus \Lambda$. It defines a meromorphic function on \mathbb{C} with double poles of residue 0 at each lattice point.*

(c) *The Weierstrass \wp -function is an even elliptic function.*

Proof. (a) Let λ_1, λ_2 be basis vectors of Λ . Let

$$A_N := \{n\lambda_1 + m\lambda_2 \in \Lambda \mid n, m \in \mathbb{Z}, \max(|n|, |m|) = N\}.$$

Let also

$$m = \min\{|a\lambda_1 + b\lambda_2| \mid a, b \in \mathbb{R}, \max(|a|, |b|) = 1\},$$

then m is well defined and strictly positive, as it's the minimum of a compact subset of \mathbb{R} , which does not contain zero. We have that

$$\#A_N = (2N+1)^2 - (2N-1)^2 = 8N.$$

Furthermore, $\min\{|\lambda|, \lambda \in A_N\} \geq Nm$, so we get

$$\sum_{\lambda \in \Lambda \setminus 0} \frac{1}{|\lambda|^k} \leq \sum_{N=1}^{\infty} \frac{\#A_N}{\min\{|\lambda|, \lambda \in A_N\}^k} = \sum_{N=1}^{\infty} \frac{8}{m^k N^{k-1}} < \infty.$$

(b) If $|\lambda| > 2|z|$, then we have that

$$|2\lambda - z| \leq 2|\lambda| + |z| \leq \frac{5}{2}|\lambda|$$

and

$$|z - \lambda| = |\lambda| \left| \frac{z}{\lambda} - 1 \right| \geq \frac{1}{2}|\lambda|.$$

These imply that

$$\left| \frac{1}{(z - \lambda)^2} - \frac{1}{\lambda^2} \right| = \left| \frac{z(2\lambda - z)}{\lambda^2(z - \lambda)^2} \right| \leq 10 \frac{|z|}{|\lambda|^3}$$

Hence using (a) we see that for $z \in \mathbb{C} \setminus \Lambda$, the series for $\wp(z)$ converges absolutely and uniformly on any compact subset of $\mathbb{C} \setminus \Lambda$. It follows that the series defines a holomorphic function on $\mathbb{C} \setminus \Lambda$, furthermore, it is clear from the series expansion that \wp has a double pole with residue 0 at each point of Λ .

(c) TO BE ADDED

□

Theorem 4.5. *We have that*

$$\mathbb{C}(\Lambda) = \mathbb{C}(\wp, \wp')$$

Definition 4.5. The *Weierstrass σ -function* (relative to Λ) is the function defined by

$$\sigma(z; \Lambda) = z \prod_{\lambda \in \Lambda \setminus 0} \left(1 - \frac{z}{\lambda}\right) \exp\left(\frac{z}{\lambda} + \frac{1}{2} \left(\frac{z}{\lambda}\right)^2\right)$$

Notation. As before, we write just $\sigma(z)$ for $\sigma(z; \Lambda)$ when Λ is clear from context.

Proposition 4.6. *Let $n_1, \dots, n_r \in \mathbb{Z}$ and $z_1, \dots, z_n \in \mathbb{C}$, such that*

$$\sum n_i = 0 \text{ and } \sum n_i z_i \in \Lambda.$$

Then there exists an elliptic function $f(z) \in \mathbb{C}(\Lambda)$ satisfying

$$\text{div}(f) = \sum n_i(z_i).$$

Proposition 4.7. *For all $z \in \mathbb{C} \setminus \Lambda$, we have that*

$$\wp'(z)^2 = 4\wp(z)^3 - 60G_4\wp(z) - 140G_6$$

Remark. We write

$$g_2 = g_2(\Lambda) = 60G_4 \text{ and } g_3 = g_3(\Lambda) = 60G_6.$$

Then the equation in 4.7 becomes

$$\wp'(z)^2 = 4\wp(z)^3 - g_2\wp(z) - g_3$$

Theorem 4.8. *Let g_2, g_3 be the quantities associated to Λ as in the above remark. Let E/\mathbb{C} be the curve given by the equation*

$$E : y^2 = 4x^3 - g_2x - g_3$$

then E is an elliptic curve and the map

$$\begin{aligned} \phi : \mathbb{C}/\Lambda &\rightarrow E \\ z &\mapsto \begin{cases} [\wp(z), \wp'(z), 1] & \text{if } z \notin \Lambda \\ [0, 1, 0] & \text{if } z \in \Lambda \end{cases} \end{aligned}$$

is a complex analytic isomorphism of complex Lie groups.

Proof. To show E is an elliptic curve, we have to show that it is non-singular. From 3.1 this is the case if and only if the determinant Δ of the polynomial $f(x) = 4x^3 - g_2x - g_3$ is non-zero, in other words if and only if f has no

repeated roots. Let $\{\lambda_1, \lambda_2\}$ be a basis of Λ , let $\lambda_3 = \lambda_1 + \lambda_2$. then since \wp' is an odd elliptic function, we have that for $i \in \{1, 2, 3\}$

$$\wp'(\lambda_i/2) = -\wp'(-\lambda_i/2) = -\wp'(\lambda_i/2)$$

and hence $\wp'(\lambda_i/2) = 0$. It follows from 4.7 that $\wp(\lambda_i/2)$ is a root of f . So we need to show that the $\wp(\lambda_i/2)$ are all distinct. The function $\wp(z) - \wp(\lambda_i/2)$ has a double zero at $\lambda_i/2$, since its derivative is $\wp'(z)$ which vanishes at $\lambda_i/2$. Using 4.3 and 4.4, we deduce that these are the only zeroes and hence the $\wp(\lambda_i/2)$ are all distinct. Hence E is indeed an elliptic curve.

The image of ϕ is contained in $E(\mathbb{C})$ by 4.7. Let $[x, y, 1] \in E(\mathbb{C})$, then we have that $\wp(z) - x$ is a non-constant elliptic function, so by 4.2, it has a zero $a \in \mathbb{C}$. Hence $\wp(a) = x$ and hence by 4.7,

$$\wp'(a)^2 = f(\wp(a)) = f(x) = y^2.$$

It follows that $\wp'(a) = \pm y$, hence by replacing a with $-a$ in the case $\wp'(a) = -y$, we get that $\wp'(a) = y$. Hence $\phi(a) = [x, y, 1]$. This shows the surjectivity of ϕ .

Now to show injectivity, suppose $z_1, z_2 \in \mathbb{C}$ are such that $\phi(z_1) = \phi(z_2)$. Suppose $z_1 \not\equiv -z_1 \pmod{\Lambda}$. The function $\wp(z) - \wp(z_1)$ admits the roots $z_1, -z_1, z_2$, but being of order 2, two of these values are congruent mod Λ . Hence $z_2 \equiv \pm z_1 \pmod{\Lambda}$. But since $\wp'(z_1) = \wp'(z_2)$, we get necessarily $z_2 \equiv z_1 \pmod{\Lambda}$.

Now, if $z_1 \equiv -z_1 \pmod{\Lambda}$, then

$$\frac{\partial}{\partial z}(\wp(z) - \wp(z_1)) = \wp'(z)$$

and $\wp'(z_1) = \wp'(-z_1) = -\wp'(z_1)$ and hence $\wp'(z_1) = 0$. It follows that z_1 is a double root of $\wp(z) - \wp(z_1)$, which is of order 2. Hence z_2 , being also a root of $\wp(z) - \wp(z_1)$, is necessarily congruent to $z_1 \pmod{\Lambda}$. This shows the injectivity of ϕ .

Now we will show ϕ is an isomorphism of Riemann surfaces. Denote by $\xi : \mathbb{C} \mapsto \mathbb{C}/\Lambda$, the quotient map. Then the charts of \mathbb{C}/Λ are given by local sections of ξ . Let $z \in \mathbb{C}$ and $U \subseteq \mathbb{C}$ containing z an open set such that $\xi|_U$ is injective. Let ψ be a chart of $E(\mathbb{C})$ which we can suppose (up to shrinking U) to be defined on $\phi(\xi(U))$. Depending on the value of $P = \phi(\xi(z))$, ψ will be of one of the three forms as described in the proof of Proposition 4.1. We get that

$$\psi \circ \phi \circ \xi = \begin{cases} \wp & \text{if } P \neq O \text{ and } \wp'(z) \neq 0 \\ \wp' & \text{if } P \neq O \text{ and } \wp'(z) = 0 \\ \frac{\wp}{\wp'} & \text{if } P = O \end{cases}$$

and hence $\psi \circ \phi \circ \xi$ is holomorphic (and seen as a map to its image, it is bijective, and hence biholomorphic). Since ϕ is bijective and locally biholomorphic, it is biholomorphic and hence an isomorphism of Riemann surfaces.

Finally, we want to show that ϕ is a group homomorphism. Let $z_1, z_2 \in \mathbb{C}$, then from 4.6, there exists a function $f \in \mathbb{C}(\Lambda)$ with divisor

$$\text{div}(f) = (z_1 + z_2) - (z_1) - (z_2) + (0)$$

Now, by 4.5, we can write $f(z) = F(\wp(z), \wp'(z))$ for some rational function $F(X, Y) \in \mathbb{C}(X, Y)$. We can see F in

$$\mathbb{C}(E) = \mathbb{C}(E \cap \mathbb{A}^2) = \text{Frac}(\mathbb{C}[x, y]/(y^2 - 4x^3 + g_2x + g_3))$$

and hence $f = F \circ \phi$. It follows that

$$\text{div}(F) = (\phi(z_1 + z_2)) - (\phi(z_1)) - (\phi(z_2)) + (0)$$

By Proposition ??, it follows that

$$\phi(z_1 + z_2) = \phi(z_1) + \phi(z_2)$$

□

The following theorem (which we will not prove) gives the converse to 4.8

Theorem 4.9. *Let E/\mathbb{C} be a non-singular curve given by the equation*

$$E : y^2 = 4x^3 - ax - b.$$

Then there exists a lattice $\Lambda \subseteq \mathbb{C}$ unique up to homothety, such that $a = g_2(\Lambda)$ and $b = g_3(\Lambda)$

Since any elliptic curve is isomorphic to a curve given by an equation as in 4.9, we deduce that all curves are homeomorphic to a torus \mathbb{T}^2 . This allows us to calculate its homology groups.

To calculate the homology groups of a torus, we will use simplicial homology, as in [Hat01, §2.1]. The torus can be given a Δ -complex structure as in Figure 1. The associated chain complex for taking simplicial homology is

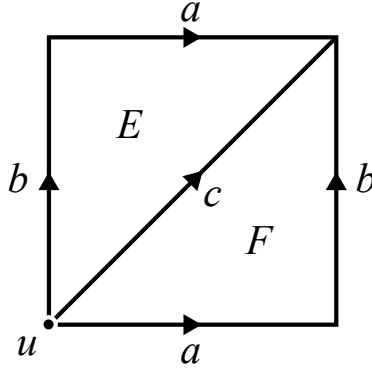


Figure 1: Δ -complex structure of a torus

$$\begin{aligned} \cdots \longrightarrow 0 \longrightarrow E\mathbb{Z} \oplus F\mathbb{Z} &\xrightarrow{\partial_2} a\mathbb{Z} \oplus b\mathbb{Z} \oplus c\mathbb{Z} \xrightarrow{\partial_1} u\mathbb{Z} \longrightarrow 0 \\ & a, b, c \longmapsto 0 \\ E, F &\longmapsto a + b - c \end{aligned}$$

Hence we get that

$$H_0(\mathbb{T}^2) \cong \mathbb{Z},$$

$$H_1(\mathbb{T}^2) = \ker \partial_1 / \operatorname{im} \partial_2 = a\mathbb{Z} \oplus b\mathbb{Z} \oplus c\mathbb{Z} / (a + b - c)\mathbb{Z} \cong \mathbb{Z}^2,$$

$$H_2(\mathbb{T}^2) = \ker \partial_2 = (E - F)\mathbb{Z} \cong \mathbb{Z},$$

and $H_n(\mathbb{T}^2) = 0$ for $n \geq 3$. We deduce that the associated Betti numbers are

$$b_0(\mathbb{T}^2) = \operatorname{rk}(\mathbb{Z}) = 1,$$

$$b_1(\mathbb{T}^2) = \operatorname{rk}(\mathbb{Z}^2) = 2,$$

$$b_2(\mathbb{T}^2) = \operatorname{rk}(\mathbb{Z}) = 1,$$

and $b_n(\mathbb{T}^2) = 0$ for $n \geq 3$.

5 Elliptic Curves over Finite Fields

For this section we fix a prime p and q a power of p .

Definition 5.1. The zeta function of V/\mathbb{F}_q is defined as the power series

$$Z(V/\mathbb{F}_q; T) = \exp \left(\sum_{n=1}^{\infty} (\#V(\mathbb{F}_{q^n})) \frac{T^n}{n} \right)$$

Notation. When V/\mathbb{F}_q is known from context, we write simply $Z(T)$ instead of $Z(V/\mathbb{F}_q; T)$

Theorem 5.1 (Weil Conjectures). *Let V/\mathbb{F}_q be a smooth projective variety of dimension N .*

(a) *Rationality: $Z(T) \in \mathbb{Q}(T)$. More precisely, there is a factorization*

$$Z(T) = \frac{P_1(T) \cdots P_{2n-1}(T)}{P_0(T)P_2(T) \cdots P_{2n}(T)},$$

where $P_0(T) = 1 - T$, $P_{2n}(T) = 1 - q^n T$ and for each $1 \leq i \leq 2n - 1$, $P_i(T)$ factors (over \mathbb{C}) as

$$P_i(T) = \prod_j (1 - \alpha_{ij} T)$$

(b) *Functional Equation: The zeta function satisfies*

$$Z \left(\frac{1}{q^N T} \right) = \pm q^{N \frac{\epsilon}{2}} T^{\epsilon} Z(T),$$

for some integer ϵ (called the Euler characteristic of V)

(c) *Riemann Hypothesis: $|\alpha_{ij}| = q^{i/2}$ for all $1 \leq i \leq 2n - 1$ and all j .*

(d) *Betti Numbers: If V/\mathbb{F}_q is a reduction mod p of a non-singular projective variety W/K , where K is a number field embedded in the field of complex numbers, then the degree of P_i is the i^{th} Betti number of the space of complex points of W .*

We will now verify Weil's conjecture for elliptic curves. For this we will make use of the homomorphism $\text{End}(E) \rightarrow \text{End}(T_l(E)), \psi \mapsto \psi_l$, where l is a prime different from p . If we fix a \mathbb{Z}_l -basis of $T_l(E)$, we can write ψ_l as a 2×2 matrix and so we can compute $\det(\psi_l), \text{tr}(\psi_l) \in \mathbb{Z}_l$.

The following proposition tells us that these quantities are not only independent of the choice of basis, but also of the choice of l .

Proposition 5.2. *Let $\psi \in \text{End}(E)$. Then*

$$\det(\psi_l) = \deg(\psi) \text{ and } \text{tr}(\psi_l) = 1 + \deg(\psi) - \deg(1 - \psi).$$

In particular, $\det(\psi_l), \text{tr}(\psi_l) \in \mathbb{Z}$

Proposition 5.3. *Let E/\mathbb{F}_q be an elliptic curve, and*

$$\phi : E \rightarrow E, (x, y) \mapsto (x^q, y^q)$$

the q^{th} Frobenius endomorphism. Let $\alpha, \beta \in \mathbb{C}$ be the roots of the characteristic polynomial of ϕ_l , that is

$$\det(T - \phi_l) = T^2 - \text{tr}(\phi_l)T + \det(\phi_l),$$

then α, β are complex conjugates satisfying $|\alpha| = |\beta| = \sqrt{q}$. Furthermore, for every $n \geq 1$, we have

$$\#E(\mathbb{F}_{q^n}) = q^n + 1 - \alpha^n - \beta^n$$

Proof. Fix v_1, v_2 a \mathbb{Z}_l -basis for $T_l(E)$, and write the matrix of ψ_l for this basis as

$$\psi_l = \begin{bmatrix} a & b \\ c & d \end{bmatrix}.$$

We have the non-degenerate, bilinear, alternating pairing

$$e : T_l(E) \times T_l(E) \rightarrow T_l(\mu)$$

□

Theorem 5.4. *Let E/\mathbb{F}_q be an elliptic curve. Then there exists an $a \in \mathbb{Z}$ such that*

$$Z(T) = \frac{1 - aT + qT^2}{(1 - T)(1 - qT)}.$$

Furthermore,

$$Z\left(\frac{1}{qT}\right) = Z(T)$$

and

$$1 - aT + qT^2 = (1 - \alpha T)(1 - \beta T)$$

with $|\alpha| = |\beta| = \sqrt{q}$

Proof. Using the definition of $Z(E/\mathbb{F}_q; T)$, we get

$$\begin{aligned} \log Z(E/\mathbb{F}_q; T) &= \sum_{n=1}^{\infty} (\#E(\mathbb{F}_{q^n})) \frac{T^n}{n} \\ &= \sum_{n=1}^{\infty} (q^n + 1 - \alpha^n - \beta^n) \frac{T^n}{n} \quad (5.3) \\ &= -\log(1 - qT) - \log(1 - T) + \log(1 - \alpha T) + \log(1 - \beta T) \end{aligned}$$

and hence we get

$$Z(E/\mathbb{F}_q; T) = \frac{(1 - \alpha T)(1 - \beta T)}{(1 - T)(1 - qT)},$$

which has the desired form. Indeed from (5.3), $|\alpha| = |\beta| = \sqrt{q}$, and

$$\begin{aligned} a = \alpha + \beta &= \text{tr}(\phi_l) = 1 + \deg(\phi) - \deg(1 - \phi) \\ &= 1 + q - \#E(\mathbb{F}_q) \in \mathbb{Z}. \end{aligned}$$

□

Hence the Weil conjectures are verified for elliptic curves. Notice that using the notation from theorem 5.1, $\deg P_0 = 1$, $\deg P_1 = 2$, $\deg P_2 = 1$, hence we would expect the Betti numbers of E/\mathbb{C} to coincide with these values, and indeed, these are exactly the Betti numbers we calculated in Section 4.

References

[Hat01] Allen Hatcher. *Algebraic Topology*. Cambridge University Press, 2001.