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## 1 Hasse-Weil Theorem

$p$  prime,  $q = p^n$

$$\Phi : \bar{\mathbb{F}}_q \rightarrow \bar{\mathbb{F}}_q = \bar{\mathbb{F}}_p = \bigcup_n \mathbb{F}_{p^n}$$

$$\Phi(x) = x^q$$

it is a field homomorphism. Induces a map for  $E/\mathbb{F}_q$

$$\Phi : E(\bar{\mathbb{F}}_q) \rightarrow E(\bar{\mathbb{F}}_q)$$

$$\Phi(x, y) = (x^q, y^q)$$

Frobenius is compatible with group structure on  $E(\bar{\mathbb{F}}_q)$ .

### 1.1 Definition: Isogeny

$E, E'$  are EC on  $K$ . An isogeny  $\alpha : E \rightarrow E'$  is a rational map such that the induced map

$$E(\bar{K}) \rightarrow E'(\bar{K})$$

is a group homomorphism

## 1.2 Example: Frobenius

### 1.3 Isogeny $\alpha : E \rightarrow E$ is an endomorphism.

If  $\alpha : E/K \rightarrow E'/K$  is an isogeny then

$$\alpha : E(L) \rightarrow E'(L)$$

for  $K \subseteq L \subseteq \bar{K}$  is an isogeny.

$$E(L) \subseteq E(\bar{K})$$

### 1.4 Example

Let  $E/K$  be any EC, for all  $n$  multiplication by  $n$  is an endomorphism.

$$[n] : E \rightarrow E$$

$$P \rightarrow nP$$

Everything we do is polynomials and it preserves group structure.

### 1.5 Recall:

An isogeny  $\alpha : E \rightarrow E'$  viewed as a rational map, has a canonical form.

$$\alpha(x, y) = (r_1(x), yr_2(x))$$

where  $r_1(x) = \frac{p(x)}{q(x)}$ ,  $r_2(x) = \frac{u(x)}{v(x)}$  and each quotient is reduced, so no common factors over  $\bar{K}$ .

If  $q(x) = 0$  for some  $x, y \in E(\bar{K})$ , then we set  $\alpha(x, y) = 0_{E'}$  and otherwise we showed  $v(x) \neq 0$  and hence  $\alpha$  is well defined.

### 1.6 Def

Let  $\alpha : E/K \rightarrow E'/K$  be an isogeny.

1. The degree of  $\alpha$  is  $\deg(\alpha) = \max\{\deg(p), \deg(q)\}$ .
2.  $\alpha$  is called separable if the formal derivative  $r'_1(x)$  is not identically zero  $p(x)q'(x) - p'(x)q(x) \neq 0$

$$\Phi_q = \alpha : E(\bar{\mathbb{F}}_q) \rightarrow E(\bar{\mathbb{F}}_q)$$

$$\infty \rightarrow \infty$$

$$(x, y) \rightarrow (x^q, y^q) \in E(\bar{\mathbb{F}}_q)$$

$$(y^q)^2 = (x^q)^3 + Ax^q + B$$

$$(y^2)^q = (x^3 + Ax + B)^q$$

Is  $\Phi_q$  separable?

$$(x^q)' = qx^{q-1} = 0 \text{ in } \mathbb{F}_q$$

so it is not separable.

### 1.7 Prop

Let  $\alpha : E \rightarrow E'$  be a nonzero isogeny. If  $\alpha$  is separable then

$$\#\ker(\alpha : E(\bar{K}) \rightarrow E'(\bar{K})) = \deg(\alpha)$$

and otherwise  $\#\ker(\alpha) < \deg(\alpha)$

**1.7.1 Observe**  $\#E(\mathbb{F}_q) = \#\ker(\alpha)$

For  $E/\mathbb{F}_q$

$$\begin{aligned}\alpha &: \Phi_q^n - \text{id} : E \rightarrow E \\ P &\rightarrow \Phi_q^n(P) - P \\ \ker(\alpha : E(\bar{\mathbb{F}}_q) &\rightarrow E(\bar{\mathbb{F}}_q)) = \#E(\mathbb{F}_{q^n})\end{aligned}$$

(or without  $n$  easier)

For  $E/\mathbb{F}_q$

$$\begin{aligned}\alpha &: \Phi_q - \text{id} : E \rightarrow E \\ P &\rightarrow \Phi_q(P) - P \\ \ker(\alpha : E(\bar{\mathbb{F}}_q) &\rightarrow E(\bar{\mathbb{F}}_q)) = \#E(\mathbb{F}_q) \\ P \in \ker(\alpha) &\Leftrightarrow \Phi_q(P) - P = \infty \\ &\Leftrightarrow \Phi_q(P) = P\end{aligned}$$

we saw that these points  $P$  are exactly  $E(\mathbb{F}_q)$

The only points frobenius acts as identity is those in  $\mathbb{F}_q$ , so only unchanged points are in the kernel. In higher extensions, frobenius doesn't act as the identity.

## 1.8 Proof

Since  $\alpha \neq 0$  and is a group homomorphism on  $E(\bar{K}) \rightarrow E'(\bar{K})$  it is non-constant.

Thus  $\alpha : E(\bar{K}) \rightarrow E'(\bar{K})$  is surjective. Let  $Q = (a, b) \in E'(\bar{K})$  and  $P = (x_0, y_0) \in E(\bar{K})$ .

## 1.9 Exercise: Show the prop on surjectivity generalizes to the case of $E \rightarrow E'$

Since  $E'(\bar{K})$  is infinite we can choose  $Q$  st

1.  $a, b \neq 0$
2.  $\deg(p - qa) = \max\{\deg(p), \deg(q)\} = \deg(\alpha)$

the only case in which  $\deg(p - qa) < \deg(\alpha)$  is when  $\deg(p) = \deg(q)$  and their leading coefficients  $\lambda, \delta$  respectively satisfy

$$\lambda - a\delta = 0 \Leftrightarrow a = \frac{\lambda}{\delta}$$

so we choose  $Q$  such that  $a \neq \frac{\lambda}{\delta}$ .

Since  $\deg(p - aq) = \deg(\alpha)$ ,  $p(x) - aq(x)$  has exactly  $\deg(\alpha)$  roots over  $\bar{K}$  (possibly repeated roots).

We claim that the number of distinct roots of  $p - aq$  is exactly the number of sources  $P$  of  $Q$  (under  $\alpha$ ).

Since  $(a, b) \neq (\infty, \infty)$ , then

$$r_1(x_0) \neq 0 \Leftrightarrow q(x_0) \neq 0$$

since  $b \neq 0$  and we have

$$y_0 r_2(x) = b$$

we have  $y_0 = b/r_2(x_0)$ , so  $y_0$  is completely determined by  $x_0$ .

So it is enough to count the  $x_0$ 's which in turn must satisfy  $\frac{p(x_0)}{q(x_0)} = a$

$$\Leftrightarrow p(x_0) - aq(x_0) = 0$$

i.e the roots of  $p - aq$

Since  $\alpha$  is a group homomorphism on  $E(\bar{K}) \rightarrow E'(\bar{K})$ , then  $\#\ker(\alpha)$  is the same as the number of sources of any given point  $Q \in E'(\bar{K})$

Which is enough to analyze the number of distinct roots  $x_0$  of  $p - aq$ .

$x_0$  is a repeated root of  $p - aq \Leftrightarrow p(x_0) - aq(x_0) = 0$  and also  $p'(x_0) - aq'(x_0) = 0$ . Multiply both equations to get

$$ap(x_0)q'(x_0) = ap'(x_0)q(x_0)$$

Since  $a \neq 0$

$$\begin{aligned} p(x_0)q'(x_0) - p'(x_0)q(x_0) &= 0 \\ r'_1(x_0) &= 0 \end{aligned}$$

by the quotient rule applied to  $r'_1$ .

If  $\alpha$  is not separable

$$r'_1(x) = 0$$

which means  $p - aq$  has repeated roots and  $\#\ker(\alpha) < \deg(\alpha)$ .

If  $\alpha$  is separable

$$r'_1(x) \neq 0$$

and hence has a finite number of roots  $S$ . We may add a constraint on the choice of  $Q$  saying that  $a \notin r_1(S)$ . Then since  $r_1(x_0) = a$

$$x_0 \notin S$$

so  $p - aq$  will not have repeated roots, i.e.  $\#\ker(\alpha) = \deg(\alpha)$ .

$$r'_1(x) = \frac{p(x)q'(x) - q'(x)p(x)}{q(x)^2}$$

## 2 Weil Pairing

Recall  $\gcd(n, \text{char}K) = 1$ . For  $Q \in E[n]$  take  $f_Q \in K(E) : \text{div}(f_Q) = n[Q] - n[\infty]$ , there exists  $g_Q \in K(E) : \text{div}(g_Q^n) = \text{div}(f_Q \circ [n])$ .

For arbitrary  $S \in E(K), P \in E[n]$

$$e_n(P, Q) = \frac{g_Q(S + P)}{g_Q(S)}$$

(this does not depend on the choice of  $S$ )

$$e_n : E[n] \times E[n] \rightarrow \mu_n(K)$$

$$\mathbf{2.1} \quad e_n(\alpha(P), \alpha(Q)) = e_n(P, Q)^{\deg \alpha}$$

Let  $\alpha : E \rightarrow E$  be a separable endomorphism.

Observe that  $\alpha(P), \alpha(Q) \in E[n]$  since

$$n\alpha(P) = \alpha(nP) = \alpha(\infty) = \infty$$

Let  $\{T_1, \dots, T_k\} = \ker(\alpha)$ . Since  $\alpha$  is separable,  $k = \deg(\alpha)$ .

$$\begin{aligned} \text{div}(f_Q) &= n[Q] - n[\infty] \\ \text{div}(f_{\alpha(Q)}) &= n[\alpha(Q)] - n[\infty] \\ g_Q^n &= f_Q \circ [n] \\ g_{\alpha(Q)}^n &= f_{\alpha(Q)} \circ [n] \end{aligned}$$

Let  $\tau_T : E \rightarrow E$  be  $X \rightarrow X + T$  translation by  $T$ .

Then  $\text{div}(f_Q \circ \tau_{-T_i}) = n[Q + T_i] - n[T_i]$ .

Now notice that  $\text{div}(f_{\alpha(Q)}) = n[\alpha(Q)] - n[\infty]$  and so

$$\begin{aligned} \text{div}(f_{\alpha(Q)} \circ \alpha) &= n \sum_{Q'' : \alpha(Q'') = \alpha(Q)} [Q''] - n \sum_{T : \alpha(T) = \infty} [T] \\ &= n \sum_{i=1}^k ([Q + T_i] + [T_i]) \\ &= \text{div}\left(\prod_{i=1}^k f_Q \circ \tau_{-T_i}\right) \end{aligned}$$

For  $1 \leq i \leq k$  choose  $T'_i \in E[n^2] : nT'_i = T_i$  then

$$\begin{aligned} g_Q(S - T'_i)^n &= f_Q \circ [n](S - T'_i) \\ &= f_Q(nS - T_i) \end{aligned}$$

by the definition of  $g_Q$ .

Now using this identity, we can see that

$$\begin{aligned} \operatorname{div}\left(\prod_{i=1}^k (g_Q \circ \tau_{-T'_i})^n\right) &= \operatorname{div}\left(\prod_{i=1}^k f_Q \circ \tau_{-T_i} \circ [n]\right) \\ &= \operatorname{div}(f_{\alpha(Q)} \circ \alpha \circ [n]) \end{aligned}$$

where we use the expression from above for  $\operatorname{div}(f_{\alpha(Q)} \circ \alpha)$ .

Notice  $\alpha \circ [n] = [n] \circ \alpha$  because  $n\alpha(P) = \alpha(nP)$ , so multiplication by  $n$  commutes with endomorphisms.

$$\begin{aligned} \operatorname{div}(f_{\alpha(Q)} \circ \alpha \circ [n]) &= \operatorname{div}(f_{\alpha(Q)} \circ [n] \circ \alpha) \\ &= \operatorname{div}((g_{\alpha(Q)}^n) \circ \alpha) \\ &= \operatorname{div}((g_{\alpha(Q)} \circ \alpha)^n) \end{aligned}$$

Finally we get

$$\begin{aligned} \prod_{i=1}^k (g_Q \circ \tau_{-T'_i}) &= g_{\alpha(Q)} \circ \alpha \\ e_n(\alpha(P), \alpha(Q)) &= \frac{g_{\alpha(Q)}(\alpha(P) + \alpha(S))}{g_{\alpha(Q)}(\alpha(S))} \\ &= \prod_{i=1}^k \frac{g_Q(P + S - T'_i)}{g_Q(S - T'_i)} \\ &= \prod_{i=1}^k e_n(P, Q) = e_n(P, Q)^k \\ &= e_n(P, Q)^{\deg \alpha} \end{aligned}$$

### 3 General Direction

$$\begin{aligned} \#E(\mathbb{F}_q) &= \# \ker(\Phi_q - \operatorname{id}) \\ &= \deg(\Phi_q - \operatorname{id}) \end{aligned}$$

then we can estimate this degree.

### 4 Separable Map

Definition of separable map

$$\deg \alpha = \# \ker(\alpha)$$

alternatively  $r'_1(x) \neq 0$ .

$P, Q \in E[n]$  and  $\alpha$  is separable then  $e_n(\alpha(P), \alpha(Q)) = e_n(P, Q)^{\deg \alpha}$ .

### 5 Invariance of Weil Pairing under “action of Galois group”

$$\operatorname{Gal}(\bar{K}/K) = \{\sigma \in \operatorname{Aut}(\bar{K}) : \sigma|_K = \operatorname{id}_K\}$$

$$\Phi_q \in \operatorname{Gal}(\bar{\mathbb{F}}_q/\mathbb{F}_q)$$

## 5.1 Proposition

$$\sigma \in \text{Gal}(\bar{\mathbb{F}}_q/\mathbb{F}_q)$$

$$\sigma(e_n(P, Q)) = e_n(\sigma P, \sigma Q)$$

Note  $\sigma P \in E$  since  $\sigma(y)^2 = \sigma(x)^3 + A\sigma(x) + B$ , and then adding is rational so  $P \in E[n] \Rightarrow n \cdot \sigma P = \infty$ .

Recall that  $f_Q, g_Q \in K(E)$

$$\text{div}(f_Q) = n[Q] - n[\infty]$$

and  $g_Q$  that satisfy

$$g_Q^n = f_Q \circ [n]$$

and for any  $S \in E(K)$

$$e_n(P, Q) = \frac{g_Q(P + S)}{g_Q(S)}$$

Write out  $f_Q$  and then when it equals zero, applying  $\sigma$  you see that  $\sigma Q$  is now a root of  $f_Q^\sigma$ , so

$$\text{div}(f_Q^\sigma) = n[\sigma Q] - n[\infty]$$

and similarly for  $g_Q^\sigma$ .

$$\begin{aligned} (g_Q^\sigma)^n &= (g_Q^n)^\sigma \\ &= (f_Q \circ [n])^\sigma \\ &= f_Q^\sigma \circ [n] \end{aligned}$$

Thus

$$\begin{aligned} \sigma(e_n(P, Q)) &= \sigma\left(\frac{g_Q(P + S)}{g_Q(S)}\right) \\ &= \frac{g_Q^\sigma(\sigma P + \sigma S)}{g_Q^\sigma(\sigma S)} \\ &= e_n(\sigma P, \sigma Q) \end{aligned}$$

Where the last step comes from the construction of the Weil pairing. Namely  $g_Q^\sigma = g_{\sigma Q}$ .

$$\begin{aligned} (g_{\sigma Q})^n &= f_{\sigma Q} \circ [n] \\ &= f_Q^\sigma \circ [n] \\ &= (g_Q^n)^\sigma \\ &= (g_Q^\sigma)^n \\ &= (f_Q \circ [n])^\sigma \\ &= f_Q^\sigma \circ [n] \end{aligned}$$

## 6 Restriction of $\alpha$ to $E[n]$ stays in $E[n]$

$$E[n] = \mathbb{Z}_n \times \mathbb{Z}_n$$

so  $E[n] = \langle T_1, T_2 \rangle$ .

$$\alpha_n = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

$$\begin{aligned} \alpha(T_1) &= aT_1 + cT_2 \\ \alpha(T_2) &= bT_1 + dT_2 \\ \alpha(P) &= \alpha(rT_1 + sT_2) \\ &= r\alpha(T_1) + s\alpha(T_2) \end{aligned}$$

$$\begin{aligned}
P &= rT_1 + sT_2 \\
\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} r \\ s \end{pmatrix} &= \begin{pmatrix} x \\ y \end{pmatrix} \\
\alpha(P) &= xT_1 + yT_2
\end{aligned}$$

## 7 $\det(\alpha_n) = \deg(\alpha) \bmod n$

By weil pairing property  $e_n(T_1, T_2)$  maps to a generator for  $\mu_n(\mathbb{F}_q)$ . Let  $\eta = e_n(T_1, T_2)$ . Since  $\alpha$  is separable of  $\Phi_q$

$$\eta^{\deg(\alpha)} = e_n(T_1, T_2)^{\deg(\alpha)} = e_n(\alpha(T_1), \alpha(T_2))$$

But using the matrix we get

$$\begin{aligned}
e_n(aT_1 + cT_2, bT_1 + dT_2) &= e_n(T_1, T_1)^{ab} e_n(T_1, T_2)^{ad} e_n(T_2, T_1)^{bc} e_n(T_2, T_2)^{cd} \\
&= 1^{ab} e_n(T_1, T_2)^{ad} e_n(T_2, T_1)^{bc} 1^{cd} \\
&= 1^{ab} e_n(T_1, T_2)^{ad} e_n(T_1, T_2)^{-bc} 1^{cd} \quad \text{by pairing rule about swapping args} \\
&= e_n(T_1, T_2)^{ad-bc} \\
&= e_n(T_1, T_2)^{\det(\alpha_n)} \\
&= \eta^{\det(\alpha_n)}
\end{aligned}$$

since  $\eta$  is a generator, we must have

$$\deg(\alpha) \equiv \det(\alpha_n) \pmod{n}$$

## 8 $\deg(a\alpha + b\beta) = a^2 \deg(\alpha) + b^2 \deg(\beta) + ab(\deg(\alpha + \beta) - \deg(\alpha) - \deg(\beta))$

Restrict  $\alpha, \beta$  using matrices  $\alpha_n, \beta_n$ , where  $\text{char } K \nmid n$ .

Note from linear algebra matrix determinant rules  $\det(a\alpha_n + b\beta_n) = a^2 \det(\alpha_n) + b^2 \det(\beta_n) + ab(\det(\alpha_n + \beta_n) - \det(\alpha_n) - \det(\beta_n))$ .

Now replace determinant by degree for mod  $n$ .

Since this is true for infinitely many  $n$ 's, we have ordinary equality.

## 9 $\deg(r\Phi_q + s) = r^2q + s^2 - rst$

$r, s \in \mathbb{Z}, \gcd(s, q) = 1$  then

$$t = q + 1 - \deg(\Phi_q - 1)$$

By previous proposition

$$\deg(r\Phi_q - s) = r^2 \deg(\Phi_q) + s^2 \deg(-1) + rs(\deg(\Phi_q - 1) - \deg(\Phi_q) - \deg(-1))$$

Since  $\deg(\Phi_q) = q$  and  $\deg(-1) = 1$

$$\deg(r\Phi_q - s) = r^2q + s^2 + rs(\deg(\Phi_q - 1) - q - 1)$$

## 10 Hasse-Weil Theorem

$$|q + 1 - \#E(\mathbb{F}_q)| \leq 2\sqrt{q}$$

$$\deg(\Phi_q - 1) = \# \ker(\Phi_q - 1) = \#E(\mathbb{F}_q)$$

For any  $r, s \in \mathbb{Z}$  such that  $\gcd(s, q) = 1$ , we have

$$0 \leq \deg(r\Phi_q - s)$$

because degrees are greater than 0.

$$r^2q + s^2 - rst \geq 0$$

$$\Leftrightarrow q\left(\frac{r}{s}\right)^2 - t\left(\frac{r}{s}\right) + 1 \geq 0$$

The set of all rational numbers  $r/s$  such that  $\gcd(s, q) = 1$  is dense in  $\mathbb{R}$  so the polynomial

$$qx^2 - tx + 1$$

gets only non-negative values, and has non-positive discriminant.

$$t^2 - 4q \leq 0$$

## 10.1 Dense Set

If  $\forall x \in \mathbb{R}$ , there exists a sequence

$$s_1, s_2, \dots, s_n, \dots$$

$$\lim_{n \rightarrow \infty} s_n = x$$

For example  $\pi$  can be approximated with an infinite sequence of rationals.

Take  $x_0 \in \mathbb{R}$  since there exists a sequence  $\sigma_n = r_n/s_n$  such that  $\lim \sigma_n = x_0$ .

$$0 \leq \lim_{n \rightarrow \infty} (q\sigma_n^2 - t\sigma_n + 1) = q\left(\lim_{n \rightarrow \infty} \sigma_n\right)^2 - t \lim_{n \rightarrow \infty} (\sigma_n) + 1$$

$$\Rightarrow qx_0^2 - tx_0 + 1 \geq 0$$

## 11 Hasse-Weil Corollary

In  $\text{End}(E)$

$$\Phi_q^2 - [t] \circ \Phi_q + [q] = 0$$

For all  $p \nmid n$

$$E[n] \cong \mathbb{Z}_n \times \mathbb{Z}_n$$

so we represent  $\Phi_q|_{E[n]} : E[n] \rightarrow E[n]$  as a matrix  $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$  (choose generators  $\{T_1, T_2\} \subseteq E[n]$  which correspond to  $\{(1, 0), (0, 1)\} \in \mathbb{Z}_n \times \mathbb{Z}_n$ )

Any  $2 \times 2$  satisfies

$$A^2 - \text{tr}(A)A + \det(A)I = 0$$

where  $\text{tr}(A) = a + d$ .

We showed that

$$\det(A_n) = \deg(\Phi_n) \pmod n$$

and another direct calc shows

$$\text{tr}(A_n) = 1 + \det(A_n) - \det(I - A_n)$$

thus

$$\begin{aligned} \text{tr}(A_n) &= 1 + \deg \Phi_q + \deg(\text{id} - \Phi_q) \\ &= 1 + \deg \Phi_q + \deg(\Phi_q - \text{id}) \\ &= 1 + q - (q + 1 - t) \pmod n \\ &= t \pmod n \end{aligned}$$

substituting, we get

$$A^2 - t \cdot A + q \cdot I = 0$$

Now since this is true for infinitely many  $n$ , it should be true in  $\text{End}(E) \Rightarrow$

$$\Phi_q^2 + [t] \cdot \Phi_q + [q] = 0$$