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ISOGENY CLASSES AND ENDOMORPHISMS ALGEBRAS OF ABELIAN VARIETIES OVER FINITE FIELDS

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Abstract. We construct non-isogenous simple ordinary abelian varieties over an algebraic closure of a finite field with isomorphic endomorphism algebras.

1. Introduction

1.1. If K is a number field then we write $\mathrm{Cl}(K)$ for the (finite commutative) ideal class group of K, $\mathrm{cl}(K)$ for the class number of K (i.e., the cardinality of $\mathrm{Cl}(K)$) and $\exp(K)$ for the exponent of $\mathrm{Cl}(K)$. Clearly, $\exp(K)$ divides $\mathrm{cl}(K)$. (The equality holds if and only if $\mathrm{Cl}(K)$ is cyclic, which is not always the case, see [1, Tables].) In addition, $\exp(K)$ is odd if and only if $\mathrm{cl}(K)$ is odd. We write $\mathcal{O}_K$ for the ring of integers in K and U_K for the group of *units*, i.e., the multiplicative group of invertible elements in $\mathcal{O}_K$. As usual, an element of U_K is called a unit in K or a K-unit. It is well known (and can be easily checked) that if a unit u in K is a square in K then it is also a square in U_K.

Let p be a prime and q a positive integer that is a power of p. We write $\mathbb{F}_p$ for the p-element finite field and $\mathbb{F}_q$ for its q-element overfield. As usual, $\bar{\mathbb{F}}_p$ stands for an algebraic closure of $\mathbb{F}_p$, which is also an algebraic closure of $\mathbb{F}_q$. We have

$$\mathbb{F}_p \subset \mathbb{F}_q \subset \bar{\mathbb{F}}_p.$$

If X is an abelian variety over $\bar{\mathbb{F}}_p$ then we write $\mathrm{End}^0(X)$ for its endomorphism algebra $\mathrm{End}(X) \otimes \mathbb{Q}$, which is a finite-dimensional semisimple algebra over the field $\mathbb{Q}$ of rational numbers. If X is defined over $k = \mathbb{F}_q$ then we write $\mathrm{End}_k(X)$ for its ring of k-endomorphisms and $\mathrm{End}_k^0(X)$ for the $\mathbb{Q}$-algebra $\mathrm{End}_k(X) \otimes \mathbb{Q}$; one may view $\mathrm{End}_k^0(X)$ as the $\mathbb{Q}$-subalgebra of $\mathrm{End}^0(X)$ with the same 1.

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It is well known that isogenous abelian varieties have isomorphic endomorphism algebras and the same dimension (and p-adic Newton polygon). In addition, an abelian variety is simple if and only if its endomorphism algebra is a division algebra over $\mathbb{Q}$. It is also known (Grothendieck-Tate) that $\mathrm{End}^0(X)$ uniquely determines the dimension of X [8]. Namely, $2\dim(X)$ is the maximal $\mathbb{Q}$-dimension of a semisimple commutative $\mathbb{Q}$-subalgebra of $\mathrm{End}^0(X)$. However, it turns out that there are non-isogenous abelian varieties over $\bar{\mathbb{F}}_p$ with isomorphic endomorphism algebras.

The aim of this note is to provide explicit examples of such varieties.

Let me start with a classical result of M. Deuring about elliptic curves [3], [14, Ch. 4].

Proposition 1.2. *Let K be an imaginary quadratic field.*

- (i) *Let p be a prime and E an elliptic curve over $\bar{\mathbb{F}}_p$ such that $\mathrm{End}^0(E)$ is isomorphic to K.*
  Then p splits in K and E is ordinary.
- (ii) *Let p be a prime that splits in K.*
  Then all the elliptic curves E over $\bar{\mathbb{F}}_p$ with $\mathrm{End}^0(E) \cong K$ are mutually isogenous.

I did not find in the literature the following assertion that complements Proposition 1.2.

Proposition 1.3. *Let K be an imaginary quadratic field and p a prime that splits in K. Let us put $q = p^{\exp(K)}$.*

Then there exists an elliptic curve E that is defined with all its endomorphisms over $\mathbb{F}_q$ and such that $\mathrm{End}^0(E) \cong K$.

Remark 1.4. One may deduce from ([4, Satz 3], [9, Sect. 6, Cor. 1 on p. 507]) that if we put $q_1 = p^{\mathrm{cl}(K)}$ then there exists an elliptic curve E that is defined with all its endomorphisms over $\mathbb{F}_{q_1}$ and such that $\mathrm{End}(E) \cong \mathcal{O}_K$ (and therefore $\mathrm{End}^0(E) \cong K$).

The next result is an analogue of Proposition 1.2 for abelian surfaces and quartic fields.

Proposition 1.5. *Let K be a CM quartic field that is a cyclic extension of $\mathbb{Q}$.*

- (i) *Let p be a prime and Y an abelian surface over $\bar{\mathbb{F}}_p$ such that $\mathrm{End}^0(Y)$ is isomorphic to K.*
  Then p splits completely in K and Y is simple ordinary.
- (ii) *Let p be a prime that splits in K.*

Then all the abelian surfaces Y over $\bar{\mathbb{F}}_p$ with $\mathrm{End}^0(Y) \cong K$ *are mutually isogenous. In addition, there exists such an Y that is defined with all its endomorphisms over $\mathbb{F}_{p^{2c}}$ where $c = \exp(K)$.*

Our main result is the following assertion.

Theorem 1.6. *Let n be a positive integer and K is a CM field that is a cyclic degree 2^n extension of $\mathbb{Q}$. Let K_0 be the only degree 2^{n-1} subfield of K, which is the maximal totally real subfield of K. Let us put $c = \exp(K)$.*

(i) *Let p be a prime and A an abelian variety over $\bar{\mathbb{F}}_p$ such that* $\mathrm{End}^0(A)$ *is isomorphic to K.*
Then p splits completely in K and A is an ordinary simple abelian variety of dimension 2^{n-1}.

(ii) *Let p be a prime that splits completely in K. Let us put $q = p^c$.*
  (1) *There are precisely $2^{2^{n-1}-n}$ isogeny classes of abelian varieties A over $\bar{\mathbb{F}}_p$, whose endomorphism algebra* $\mathrm{End}^0(A)$ *is isomorphic to K.*
  (2) *Each of these isogeny classes contains an abelian variety that is defined with all its endomorphisms over $\mathbb{F}_{q^2}$.*
  (3) *Assume additionally that every totally positive unit in K_0 is a square in K_0.*
  Then each of these isogeny classes contains an abelian variety that is defined with all its endomorphisms over $\mathbb{F}_q$.

Remark 1.7. (a) If $n = 1$ then K is an imaginary quadratic field and therefore $K_0 = \mathbb{Q}$ and $\mathrm{U}_{\mathbb{Q}} = \{\pm 1\}$. The only (totally) positive unit in $\mathbb{Q}$ is 1, which is obviously a square in $\mathbb{Q}$. Hence, Propositions 1.2 and 1.3 are the special case of Theorem 1.6 with $n = 1$. On the other hand, Proposition 1.5 follows readily from the special case of Theorem 1.6 with $n = 2$.

(b) If $n \geq 3$ then the number $2^{2^{n-1}-n}$ of the corresponding isogeny classes is strictly greater than 1. This gives us examples of non-isogenous abelian varieties over $\bar{\mathbb{F}}_p$, whose endomorphism algebras are isomorphic to K and therefore are mutually isomorphic.

(c) Now let n be an arbitrary positive integer. By Chebotarev's density theorem, the set of primes that split completely in K is infinite (and even has a positive density $1/2^n$).

Corollary 1.8. *Let r be a Fermat prime (e.g., $r = 3, 5, 17, 257, 65537$). Let p be a prime that is congruent to 1 modulo r. Let us put*

$$\operatorname{isg}(r) = \frac{2^{(r-1)/2}}{(r-1)}. \tag{1}$$

Then there are precisely $\operatorname{isg}(r)$ *isogeny classes of simple $(r-1)/2$-dimensional ordinary abelian varieties A over $\bar{\mathbb{F}}_p$, whose endomorphism algebra*

$$\operatorname{End}^0(A) = \operatorname{End}(A) \otimes \mathbb{Q}$$

is isomorphic to the rth cyclotomic field $\mathbb{Q}(\zeta_r)$. In addition, if $c =$ $\exp(\mathbb{Q}(\zeta_r))$ *and $q = p^c$ then each of these isogeny classes contains an abelian variety that is defined with all its endomorphisms over $\mathbb{F}_q$.*

Remark 1.9. The congruence condition on p means that p splits completely in $\mathbb{Q}(\zeta_r)$. There are infinitely many such p, thanks to Dirichlet's theorem about primes in an arithmetic progression. More precisely, the set of such primes has density $1/(r-1)$.

Remark 1.10. It is well known that the property of being simple (resp. ordinary) is invariant under isogenies.

Remark 1.11. Let r be a Fermat prime. Clearly, $\operatorname{isg}(r) = 1$ if and only if $r \le 5$.

Let p be a prime p that is congruent to $1 \bmod r$. It follows from Theorem 1.6 that $r \le 5$ if and only if there is a precisely one isogeny class of simple ordinary $(r-1)/2$-dimensional abelelian varieties over $\bar{\mathbb{F}}_p$, whose endomorphiam algebra is isomorphic to $\mathbb{Q}(\zeta_r)$. In other words, all such abelian varieties are mutually isogenous over $\bar{\mathbb{F}}_p$, if and only if $r \in \{3, 5\}$.

Example 1.12.
(i) Take $r = 3$. We have $\operatorname{isg}(3) = 1$. It follows from Remark 1.11 that if $p \equiv 1 \bmod 3$ then all ordinary elliptic curves over $\bar{\mathbb{F}}_p$ with endomorphism algebra $\mathbb{Q}(\zeta_3)$ are isogenous. (This assertion seems to be well known.) This implies that each such elliptic curve is isogenous over $\bar{\mathbb{F}}_p$ to $y^2 = x^3 - 1$.
(ii) Take $r = 5$. We have $\operatorname{isg}(5) = 1$. It follows from Remark 1.11 that if $p \equiv 1 \bmod 5$ then all abelian varieties over $\bar{\mathbb{F}}_p$ with endomorphism algebra $\mathbb{Q}(\zeta_5)$ are two-dimensional simple ordinary and mutually isogenous. This implies that each such abelian variety is isogenous to the jacobian of the genus 2 curve $y^2 = x^5 - 1$.

Example 1.13. Let us take $r = 17$. Then $\operatorname{cl}(\mathbb{Q}(\zeta_{17})) = 1$ [13]. Let us choose a prime p that is congruent to 1 modulo 17 (e.g., $p = 103$). We have

$$\mathrm{isg}(17) = \frac{2^8}{16} = 16.$$

By Theorem 1.6, there are precisely 16 isogeny classes of simple ordinary $\frac{16}{2} = 8$-dimensional abelian varieties over $\bar{\mathbb{F}}_p$ with endomorphism algebras $\mathbb{Q}(\zeta_{17})$. In addition, each of these isogeny classes contains an abelian eightfold that is defined with all its endomorphisms over $\mathbb{F}_p$.

This implies that there exist sixteen 8-dimensional ordinary simple abelian varieties $A_1, \dots, A_{16}$ over $\bar{\mathbb{F}}_p$ that are mutually *non*-isogenous but each endomorphism algebra $\mathrm{End}^0(A_i)$ is isomorphic to $\mathbb{Q}(\zeta_{17})$ (for all i with $1 \le i \le 16$). In particular,

$$\mathrm{End}^0(A_i) \cong \mathrm{End}^0(A_j)\ \forall i, j\ (1 \le i < j \le 16).$$

In addition, each A_i and all its endomorphisms are defined over $\mathbb{F}_p$. This gives an answer to a question of L. Watson [15].

The following assertion is a natural generalization of Corollary 1.8.

Corollary 1.14. *Let r be an odd prime and $(r-1) = 2^n \cdot m$ where n is a positive integer and m is a positive odd integer. Let $\mathbf{H}$ be the only order m subgroup of the cyclic Galois group*

$$\mathrm{Gal}(\mathbb{Q}(\zeta_r)/\mathbb{Q}) = (\mathbb{Z}/r\mathbb{Z})^*$$

of order $(r-1)$. Let

$$K = K^{(r)} := \mathbb{Q}(\zeta_r)^{\mathbf{H}} \tag{2}$$

be the subfield of $\mathbf{H}$-invariants in $\mathbb{Q}(\zeta_r)$.

Then:

(0) *$K^{(r)}$ is a CM field that is a cyclic degree 2^n extension of $\mathbb{Q}$. In addition, a prime p splits completely in $K^{(r)}$ if and only if $p \ne r$ and $p \bmod r$ is a 2^nth power in $\mathbb{F}_r$.*

(i) *Let p be a prime and A an abelian variety over $\bar{\mathbb{F}}_p$ such that $\mathrm{End}^0(A)$ is isomorphic to $K^{(r)}$.*

Then p splits completely in $K^{(r)}$ and A is an ordinary simple abelian variety of dimension 2^{n-1}.

(ii) *Let p be a prime that splits completely in $K^{(r)}$ and let $q = p^c$ where $c = \exp(K^{(r)})$.*

Then there are precisely $2^{2^{n-1}-n}$ isogeny classes of abelian varieties A over $\bar{\mathbb{F}}_p$, whose endomorphism algebra $\mathrm{End}^0(A)$ is isomorphic to $K^{(r)}$. In addition, each of these isogeny classes contains an abelian variety that is defined with all its endomorphisms over $\mathbb{F}_q$.

Remark 1.15. Let $K = K^{(r)}$. It is well known that r is totally ramified in $\mathbb{Q}(\zeta_r)$ and therefore in its subfield K as well. This implies that if K_0 is the only degree 2^{n-1} subfield of K, which is the maximal totally real subfield of K, then the quadratic extension K/K_0 is *ramified*. On the other hand, it is known that ([5, Sect. 38], [2, p. 77-78]) that $\mathrm{cl}(K^{(r)})$ is *odd* (and therefore $c = \exp(K^{(r)})$ is also odd). It follows from [5, Sect. 37, Satz 42] (see also [2, Cor. 13.10 on p. 76]) that K_0 has *units with independent signs* (there are units of K_0 of every possible signature), which implies (thanks to [2, Lemma 12.2 on p. 55]) that every *totally positive* unit in K_0 is a square in K_0 and therefore is a square in U_{K_0}.

Example 1.16. Let us fix an integer $n \geq 2$. Here is a construction of infinitely many mutually non-isomorphic CM fields that are cyclic degree 2^n extensions of $\mathbb{Q}$. Let us consider the infinite (thanks to Dirichlet's theorem) set of primes r that are congruent to $1+2^n$ modulo 2^{n+1}. Then $r-1 = 2^n \cdot m$ where m is an odd positive integer. In light of Corollary 1.14, the corresponding subfield $K^{(r)}$ of $\mathbb{Q}(\zeta_r)$ defined by (2) enjoys the desired properties. Since $K^{(r)}$ is a subfield of $\mathbb{Q}(\zeta_r)$, the field extension $K^{(r)}/\mathbb{Q}$ is ramified precisely at r. This implies that the fields $K^{(r)}$ are mutually non-isomorphic (and even linearly disjoint) for distinct r.

The paper is organized as follows. In Section 2 we review basic results about maximal ideals of $\mathcal{O}_K$. In Section 3 we concentrate on so called *ordinary* Weil's q-numbers in K. In Section 4 we discuss simple abelian varieties over $\mathbb{F}_q$, whose Weil's numbers lie in K. In Section 5 we discussed some basic facts of Honda-Tate theory [11, 6, 12]. Section 6 contains proofs of main results.

In what follows we will freely use the following elementary well known observation. *Any $\mathbb{Q}$-subalgebra with 1 of a number field K is actually a subfield of K; in particular, it is also a number field. E.g., if u is an element of L then the subfield $\mathbb{Q}(u)$ generated by u coincides with the $\mathbb{Q}$-subalgebra $\mathbb{Q}[u]$ generated by u.*

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2. Preliminaries

2.1. We keep the notation and assumptions of Subsection 1.1 and Theorem 1.6. As usual, $\mathbb{Q}, \mathbb{R}, \mathbb{C}$ stand for the fields of rational, real and complex numbers and $\bar{\mathbb{Q}}$ for the (algebraically closed) subfield of all algebraic numbers in $\mathbb{C}$. We write $\mathbb{Z}$ (resp. $\mathbb{Z}_+$) for the ring of integers (resp. for the additive semigroup of **nonnegative** integers). If T is a finite set then we write $\#(T)$ for the number of its elements.

Recall [6, 12] that an algebraic integer $\pi \in \bar{\mathbb{Q}}$ is called a *Weil's q-number* if all its Galois-conjugates have the archimedean absolute value $\sqrt{q}$.

Throughout this paper, n is a positive integer and K is a CM field that is a degree 2^n cyclic extension of $\mathbb{Q}$. We view K as a subfield of $\mathbb{C}$; in particuar, K is a subfield of $\bar{\mathbb{Q}}$ that is stable under the *complex conjugation*. We denote by

$$\rho : K \to K$$

the restriction of the complex conjugation to K; one may view ρ as an element of order 2 in the Galois group

$$G := \mathrm{Gal}(K/\mathbb{Q})$$

where G is a cyclic group of order 2^n.

Remark 2.2. Let $\pi \in K \subset \mathbb{C}$.

- Suppose that π is a Weil's q-number. Then π is a algebraic integer, i.e., $\pi \in \mathcal{O}_K$. Since the absolute value of π is the square root of q, we have $\pi \cdot \rho(\pi) = q$.
- Conversely, suppose that $\pi \in \mathcal{O}_K$ (i.e., π is an algebraic integer) and
$$\pi \cdot \rho(\pi) = q \tag{3}$$
Since $K/\mathbb{Q}$ is Galois, all the Galois-conjugates of π also lie in $\mathcal{O}_K$ and constitute the orbit
$$G\pi = \{\sigma(\pi) \mid \sigma \in G\}$$
of G. Since G is commutative and contains ρ, it follows from (3) that for all $\sigma \in G$
$$\sigma(\pi) \cdot \rho(\sigma(\pi)) = \sigma(\pi) \cdot \sigma(\rho(\pi)) = \sigma(\pi \cdot \rho(\pi)) = \sigma(q) = q.$$

It follows readily that $\pi \in K$ *is a Weil's q-number if and only if* $\pi \in \mathcal{O}_K$ *and* (3) *holds.*

We write $W(q, K)$ for the set of Weil's q-numbers in K and μ_K for the (finite cyclic) multiplicative group of roots of unity in K. Clearly, $W(q, K)$ is a finite G-stable subset of $\mathcal{O}_K$, which is also stable under multiplication by elements of μ_K. The latter gives rise to the free action of μ_K on $W(q, K)$ defined by

$$\mu_K \times W(q, K) \to W(q, K),\ \zeta, \pi \mapsto \zeta\pi\ \forall \zeta \in \mu_K, \pi \in W(q, K).$$

Remark 2.3. It is well known (and follows easily from a theorem of Kronecker [16, Ch. IV, Sect. 4, Th.8]) that $\pi_1, \pi_2 \in W(q, K)$ lie in the same μ_K-orbit (i.e., π_2/π_1 is a root of unity) if and only if the ideals $\pi_1\mathcal{O}_K$ and $\pi_2\mathcal{O}_K$ of $\mathcal{O}_K$ do coincide.

Recall (Subsection 2.1) that K is a subfield of the field $\mathbb{C}$ of complex numbers that is stable under the complex conjugation. Then

$$K_0 := K \bigcap \mathbb{R}$$

is a (maximal) *totally real* number (sub)field, whose degree $[K_0 : \mathbb{Q}]$ is

$$\frac{[K : \mathbb{Q}]}{2} = \frac{2^n}{2} = 2^{n-1}.$$

2.4. Recall that the Galois group $G = \mathrm{Gal}(K/\mathbb{Q})$ is a cyclic group of order 2^n. Hence, it has precisely one element of order 2 and therefore this element must coincide with the *complex conjugation*

$$\rho : K \to K.$$

The properties of G imply that every nontrivial subgroup H of G contains ρ. It follows that every proper subfield of K is *totally real*. Indeed, each such subfield is the subfield K^H of H-invariants for a certain nontrivial subgroup H of G. Since H contains ρ, the subfield K^H consists of ρ-invaraiants and therefore is totally real; in particular,

$$K^H \subset \mathbb{R}.$$

2.5. Let ℓ be a prime and $S(\ell)$ be the set of maximal ideals $\mathfrak{P}$ of $\mathcal{O}_K$ that divide ℓ. Since $K/\mathbb{Q}$ is a Galois extension, G acts transitively on $S(\ell)$. In particular, $\#(S(\ell))$ divides $\#(G) = 2^n$. This implies that if ℓ *splits completely* in K, i.e.,

$$\#(S(\ell)) = 2^n = \#(G)$$

then the action of G on $S(\ell)$ is *free*.

On the other hand, if a prime ℓ does *not* split completely in K, i.e.,

$$\#(S(\ell)) < 2^n = \#(G),$$

then the action of G on $S(\ell)$ is *not* free. Let $H(\ell)$ be the stabilizer of any $\mathfrak{P} \in S(\ell)$, which does not depend on a choice of $\mathfrak{P}$, because G is commutative. Then $H(\ell)$ is a nontrivial subgroup of G and therefore contains ρ, i.e.,

$$\rho(\mathfrak{P}) = \mathfrak{P} \ \forall \mathfrak{P} \in S(\ell)$$

if ℓ does *not* split completely in K.

Let $e(\ell)$ be the *ramification index* in $K/\mathbb{Q}$ of $\mathfrak{P} \in S(\ell)$, which does *not* depend on $\mathfrak{P}$, because $K/\mathbb{Q}$ is Galois. We have the equality of ideals

$$\ell \mathcal{O}_K = \prod_{\mathfrak{P} \in S(\ell)} \mathfrak{P}^{e(\ell)}. \tag{4}$$

It follows that $K/\mathbb{Q}$ is *unramified* at ℓ if and only if $e(\ell)=1$. We write

$$\mathrm{ord}_{\mathfrak{P}} : K^* \twoheadrightarrow \mathbb{Z} \tag{5}$$

for the discrete valuation map attached to $\mathfrak{P}$. We have

$$\mathrm{ord}_{\mathfrak{P}}(\ell) = e(\ell) \ \forall \mathfrak{P} \in S(\ell); \tag{6}$$

$$\mathrm{ord}_{\mathfrak{P}}(u) \ge 0 \ \forall u \in \mathcal{O}_R \setminus \{0\}, \mathfrak{P} \in S(\ell); \tag{7}$$

$$\mathrm{ord}_{\mathfrak{P}}(\rho(u)) = \mathrm{ord}_{\rho(\mathfrak{P})}(u) \ \forall u \in K^*, \mathfrak{P} \in S(\ell). \tag{8}$$

2.6. Let p be a prime, j a positive integer, and $q=p^j$.

Let $\pi \in O_K$ be a Weil's $q=p^j$-number. Let us consider the ideal $\pi\mathcal{O}_K$ in $\mathcal{O}_K$. Then there is a nonnegative integer-valued function

$$d_\pi : S(p) \to \mathbb{Z}_+, \ \mathfrak{P} \mapsto d_\pi(\mathfrak{P}) := \mathrm{ord}_{\mathfrak{P}}(\pi) \tag{9}$$

such that

$$\pi\mathcal{O}_K = \prod_{\mathfrak{P}\in S(p)} \mathfrak{P}^{d_\pi(\mathfrak{P})}. \tag{10}$$

It follows from (3) that

$$d_\pi(\mathfrak{P}) + d_\pi(\rho(\mathfrak{P})) = \mathrm{ord}_{\mathfrak{P}}(q) = j\cdot e(\ell) \ \forall \mathfrak{P} \in S(p). \tag{11}$$

Lemma 2.7. *Let $\pi \in O_K$ be a Weil's $q=p^j$-number. If p does not split completely in K then π^2/q is a root of unity.*

Proof. Since p does not split completely in K, it follows from arguments of Subsection 2.4 that

$$\rho(\mathfrak{P}) = \mathfrak{P} \ \forall \mathfrak{P} \in S(p).$$

It follows from (11) that

$$d_\pi(\mathfrak{P}) = \frac{j\cdot e(p)}{2} \ \forall \mathfrak{P} \in S(p);$$

in particular, j is *even* if $e(p)=1$ (i.e., if $K/\mathbb{Q}$ is *unramified* at p). This implies that π^2/q is a $\mathfrak{P}$-adic unit for all $\mathfrak{P} \in S(p)$. On the other hand, it follows from (3) that π^2/q is an ℓ-adic unit for all primes $\ell \ne p$. It follows from the very definition of Weil's numbers that

$$|\sigma\left(\pi^2/q\right)|_\infty = 1 \ \forall \sigma \in G.$$

(Here $| \ |_\infty : \mathbb{C} \to \mathbb{R}_+$ is the standard archimedean value on $\mathbb{C}$.) Now it follows from a classical theorem of Kronecker [16, Ch. IV, Sect. 4, Th. 8] that π^2/q is a root of unity. □

Lemma 2.8. *Suppose that a prime p completely splits in K. (In particular, $K/\mathbb{Q}$ is unramified at p.) Let $\pi \in O_K$ be a Weil's $q=p^j$-number.*

Then either $\mathbb{Q}(\pi)=K$ or j is even and $\pi = \pm p^{j/2}$.

Proof. So, $K/\mathbb{Q}$ is unramified at p, i.e., $e(p) = 1$ and

$$p\mathcal{O}_K = \prod_{\mathfrak{P}\in S(p)} \mathfrak{P}. \tag{12}$$

This implies that

$$q\mathcal{O}_K = \prod_{\mathfrak{P}\in S(p)} \mathfrak{P}^j. \tag{13}$$

Since p splits completely in K, the group G acts freely on $S(p)$, in light of Subsection 2.5. In particular,

$$\mathfrak{P} \neq \rho(\mathfrak{P}) \ \forall \mathfrak{P} \in S(p). \tag{14}$$

If the subfield $\mathbb{Q}(\pi)$ of K does *not* coincide with K then it is *totally real*, thanks to arguments of Subsection 2.4. This implies that $\rho(\pi) = \pi$. It follows from (3) that $\pi^2 = q$, i.e., $\pi = \pm p^{j/2}$. This implies that the ideal $q\mathcal{O}_K$ is a *square*. It follows from (13) that j is *even*. □

2.9. Suppose that a prime p completely splits in K.

Definition 2.10. Let $\pi \in O_K$ be a Weil's $q = p^j$-number. We say that π is an *ordinary* Weil's q-number if the "slope" $\mathrm{ord}_{\mathfrak{P}}(\alpha)/\mathrm{ord}_{\mathfrak{P}}(q)$ is an *integer* for all $\mathfrak{P} \in S(p)$.

It (is well known and) follows from (3), (7) and (8) that if π is an ordinary Weil's q-number then

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = 0 \ \text{ or } 1. \tag{15}$$

3. Equivalence classes of ordinary Weil's q-numbers

Let p be a prime that splits completely in K. Throughout this section, by Weil's numbers we mean Weil's q-numbers where q is a power of p. We write $W(q, K)$ for the set of Weil's q-numbers in K. We write μ_K for the (finite cyclic) multiplicative group of roots of unity in K.

Definition 3.1. Let q and q' be integers > 1 that are integral powers of p. Let $\pi \in K$ (resp. $\pi' \in K$) be a Weil's q-number (resp. Weil's q'-number). Following Honda [6], we say that π and π' are equivalent, if there are positive integers a and b such that π^a is Galois-conjugate to π'^b.

Clearly, if π and π' are equivalent then π is ordinary if and only if π' is ordinary. In order to classify ordinary Weil's numbers in K up to equivalence, we introduce the following notion that is inspired by the notion of CM type for complex abelian varieties [10] (see also [6, Sect. 1, Th. 2] and [12, Sect. 5]).

Definition 3.2. We call a subset $\Phi \subset S(p)$ a *p-type* if S is a disjoint union of Φ and $\rho(\Phi)$.

Clearly, $\Phi \subset S(p)$ is a p-type if and only if the following two conditions hold (recall that $[K:\mathbb{Q}] = 2^n$).

(i) $\#(\Phi) = 2^{n-1}$.

(ii) If $\mathfrak{P} \in \Phi$ then $\rho(\mathfrak{P}) \notin \Phi$.

It is also clear that $\Phi \subset S(p)$ is a p-type if and only if $\rho(\Phi)$ is a p-type.

Let $H(p)$ be the set of nonzero ideals $\mathfrak{B}$ of $\mathcal{O}_K$ such that

$$\mathfrak{B} \cdot \rho(\mathfrak{B}) = p \cdot \mathcal{O}_K.$$

In light of (12) and (14), an ideal $\mathfrak{B}$ of $\mathcal{O}_K$ lies in $H(p)$ if and only if there exists a 2^{n-1}-element subset $\Phi = \Phi(\mathfrak{B})$ of $H(p)$ that meets every ρ-orbit of $S(p)$ at exactly one place and

$$\mathfrak{B} = \prod_{\mathfrak{P} \in \Phi(\mathfrak{B})} \mathfrak{P}. \tag{16}$$

Such a $\Phi(\mathfrak{B})$ is uniquely determined by $\mathfrak{B} \in H(p)$: namely, it coincides with the set of maximal ideals in $\mathcal{O}_K$ that contain $\mathfrak{B}$. This implies that

$$\#(H(p)) = 2^{2^{n-1}}. \tag{17}$$

Clearly,

$$\Phi(\sigma(\mathfrak{B})) = \sigma(\Phi(\mathfrak{B}))\ \forall \sigma \in G. \tag{18}$$

Lemma 3.3. *Let m be a positive integer and π be a Weil's $q = p^m$-number in K. Then the following conditions are equivalent.*

(i) *π is ordinary.*

(ii) *There exists an ideal $\mathfrak{B} \in H(p)$ such that*

$$\pi\mathcal{O}_K = \mathfrak{B}^m. \tag{19}$$

(iii) *The subset*

$$\Psi(\pi) := \{\mathfrak{P} \in S(p) \mid \frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = 1\} \tag{20}$$

is a p-type.

If these equivalent conditions hold then such an ideal $\mathfrak{B}$ is unique and

$$\Phi(\mathfrak{B}) = \Psi(\pi).$$

Proof. We have

$$\pi\mathscr{O}_K = \prod_{\mathfrak{P}\in S(p)} \mathfrak{P}^{d(\mathfrak{P})}, \tag{21}$$

for some $d(\mathfrak{P}) \in \mathbb{Z}_+$ such that

$$d(\mathfrak{P}) + d(\rho(\mathfrak{P})) = m, \tag{22}$$

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = \frac{d(\mathfrak{P})}{m} \quad \forall \mathfrak{P} \in S(p). \tag{23}$$

This implies that

$$\Psi(\pi) := \{\mathfrak{P} \in S(p) \mid d(\mathfrak{P}) = m\} \subset S(p). \tag{24}$$

Combining (24) with (22), we obtain that

$$\rho(\Psi(\pi)) := \{\mathfrak{P} \in S(p) \mid d(\mathfrak{P}) = 0\} = \{\mathfrak{P} \in S(p) \mid \frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = 0\} \subset S(p); \tag{25}$$

in particular, the subsets $\Psi(\pi)$ and $\rho(\Psi(\pi))$ do *not meet* each other. In light of (20) and (25) combined with (15), π is ordinary if and only if $S(p)$ is a disjoint union of $\Psi(\pi)$ and $\rho(\Psi(\pi))$, i.e., $\Psi(\pi)$ is a p-type. This proves the equivalence of (i) and (iii). If (i) and (iii) hold then it follows from (21) that

$$\pi\mathscr{O}_K = \prod_{\mathfrak{P}\in\Psi(\pi)} \mathfrak{P}^m = \mathfrak{B}^m \quad \text{where } \mathfrak{B} := \prod_{\mathfrak{P}\in\Psi(\pi)} \mathfrak{P}.$$

Since $\Psi(\pi)$ is a p-type, $\mathfrak{B} \in H(p)$ and obviously $\Phi(\mathfrak{B}) = \Psi(\pi)$. This proves that equivalent (i) and (iii) imply (ii).

Let us assume that (ii) holds. This means that there is $\mathfrak{B} \in H(p)$ that satisfies (19). This implies that

$$\mathfrak{B} = \prod_{\mathfrak{P}\in\Phi(\mathfrak{B})} \mathfrak{P}, \ \pi\mathscr{O}_K = \mathfrak{B}^m = \prod_{\mathfrak{P}\in\Phi(\mathfrak{B})} \mathfrak{P}^m.$$

It follows that

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = 1 \ \forall \mathfrak{P} \in \Phi(\mathfrak{B}),$$

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\pi)}{\mathrm{ord}_{\mathfrak{P}}(q)} = 0 \ \forall \mathfrak{P} \notin \Phi(\mathfrak{B}).$$

This implies that π is ordinary and therefore (ii) implies (i). So, we have proven the equivalence of (i),(ii), (iii). The uniqueness of such $\mathfrak{B}$ is obvious. □

Lemma 3.4. *The natural action of G on $H(p)$ is free. In particular, $H(p)$ partitions into a disjoint union of $2^{2^{n-1}-n}$ orbits of G, each of which consists of 2^n elements.*

Proof. Suppose that there exists $\mathfrak{B} \in H(p)$ such that its stabilizer

$$G_{\mathfrak{B}} = \{\sigma \in G \mid \sigma(\mathfrak{B}) = \mathfrak{B}\}$$

is a nontrivial subgroup. Then $G_{\mathfrak{B}}$ must contain ρ, thanks to the arguments of Subsection 2.4. This means that $\rho(\mathfrak{B}) = \mathfrak{B}$ and therefore

$$p \cdot \mathscr{O}_K = \mathfrak{B} \cdot \rho(\mathfrak{B}) = \mathfrak{B}^2,$$

which is not true, since p is unramified in K. The obtained contradiction proves that the action of G on $H(p)$ is free. Hence, every G-orbit in $H(p)$ consists of $\#(G) = 2^n$ elements and the number of such orbits is

$$\frac{\#(H(p))}{\#(G)} = \frac{2^{2^{n-1}}}{2^n} = 2^{2^{n-1}-n}.$$

□

In what follows we define (non-canonically) certain G-equivariant injective maps $\mathscr{Z}$, Π and Π_1 from $H(p)$ to K; they will play a crucial role in the classification of ordinary Weil's numbers in K up to equivalence.

Corollary 3.5. *Let $c = \exp(K)$. Then there exists a G-equivariant map*

$$\mathscr{Z} : H(p) \hookrightarrow \mathscr{O}_K \setminus \{0\} \subset \mathscr{O}_K \subset K \tag{26}$$

such that $\mathscr{Z}(\mathfrak{B})$ is a generator of $\mathfrak{B}^c$ for all $\mathfrak{B} \in H(p)$.

Proof. We define $\mathscr{Z}$ separately for each G-orbit $O \subset H(p)$. Pick $\mathfrak{B}_O \in O$ and choose a generator z_O of the principal ideal $\mathfrak{B}_O^c$. In light of Lemma 3.4, if $\mathfrak{B} \in O$ then there is precisely one $\sigma \in G$ such that $\mathfrak{B} = \sigma(\mathfrak{B}_O)$. This implies that

$$\mathfrak{B}^c = \sigma(\mathfrak{B}_O)^c = \sigma(\mathfrak{B}_O^c) = \sigma(z_O)\mathscr{O}_K,$$

i.e., $\sigma(z_O)$ is a generator of $\mathfrak{B}^c$. It remains to put

$$\mathscr{Z}(\mathfrak{B}) := \sigma(z_O).$$

□

Theorem 3.6. *Let us put*

$$c := \exp(K), \; q := p^c.$$

Let $K_0 = K^\rho$ be the maximal totally real subfield of K.

(1) *There exists an injective map*

$$\Pi : H(p) \hookrightarrow W(q^2, K), \; \mathfrak{B} \mapsto \Pi(\mathfrak{B}) \tag{27}$$

that enjoys the following properties.

(0) Π *is G-equivariant, i.e.,*

$$\Pi(\sigma(\mathfrak{B})) = \sigma(\Pi(\mathfrak{B})) \; \forall \sigma \in G, \mathfrak{B} \in H(p).$$

(i) *For all* $\mathfrak{B} \in H(p)$ *the ideal* $\Pi(\mathfrak{B})\mathcal{O}_K$ *coincides with* $\mathfrak{B}^{2c}$.
(ii) *The image* $\Pi(H(p))$ *consists of ordinary Weil's* q^2*-numbers.*
(iii) *If* π' *is an ordinary Weil's* p^m*-number in* K *then there exists prcisely one* $\mathfrak{B} \in H(p)$ *such that the ratio* $(\pi')^{2c}/\Pi(\mathfrak{B})^m$ *is a root of unity.*
(iv) *Let* $\mathfrak{B}_1, \mathfrak{B}_2 \in H(p)$. *Then Weil's* q^2*-numbers* $\Pi(\mathfrak{B}_1)$ *and* $\Pi(\mathfrak{B}_2)$ *are equivalent if and only if* $\mathfrak{B}_1$ *and* $\mathfrak{B}_2$ *lie in the same* G*-orbit.*
(v) *If* h *is a positive integer then the subfield* $\mathbb{Q}\left(\Pi(\mathfrak{B})^h\right)$ *of* K *generated by* $\Pi(\mathfrak{B})^h$ *coincides with* K.
(vi) *Suppose that every totally positive unit in* U_{K_0} *is a square in* K_0 *(anf therefore in* U_{K_0}*). Then there exists a map*

$$\Pi_0 : H(p) \to W(q, K)$$

that enjoys the following properties.
(a) $\Pi_0(\mathfrak{B})^2 = \Pi(\mathfrak{B})$ *for all* $\mathfrak{B}$.
(b) Π_0 *is* G*-equivariant "up to sign", i.e.,*

$$\Pi_0(\sigma(\mathfrak{B})) = \pm\sigma(\Pi_0(\mathfrak{B}))\ \forall \sigma \in G, \mathfrak{B} \in H(p).$$

(c) *If* h *is a positive integer then the subfield* $\mathbb{Q}\left(\Pi_0(\mathfrak{B})^h\right)$ *of* K *generated by* $\Pi(\mathfrak{B})^h$ *coincides with* K
(d) $\Pi_0(\mathfrak{B})$ *is an ordinary Weil's* q*-number for all* $\mathfrak{B} \in H(p)$.

Proof. Let us choose $\mathscr{Z} : H(p) \to \mathcal{O}_E \setminus \{0\}$ that enjoys the properties described in Corollary 3.5. Let $\mathfrak{B} \in H(p)$. In order to define $\Pi(\mathfrak{B})$, notice that

$$\mathfrak{B} \cdot \rho(\mathfrak{B}) = p\mathcal{O}_K,\ \mathfrak{B}^c = z\mathcal{O}_K$$

where

$$z = \mathscr{Z}(\mathfrak{B}) \in \mathcal{O}_K \setminus \{0\}. \tag{28}$$

Then $z\rho(z)$ is a generator of the ideal

$$\mathfrak{B}^c \cdot \rho(\mathfrak{B}^c) = (\mathfrak{B} \cdot \rho(\mathfrak{B}))^c = p^c \cdot \mathcal{O}_K = q\mathcal{O}_K.$$

Since ρ is the complex conjugation, $z\rho(z)$ is a real (i.e., ρ-invariant) totally positive element of $\mathcal{O}_K$. Clearly,

$$u := \frac{z\rho(z)}{q}$$

is an invertible element of $\mathcal{O}_K$ that is also ρ-invariant and totally positive unit in U_{K_0}. Obviously,

$$q = \frac{z \cdot \rho(z)}{u}.$$

Now let us put

$$\Pi(\mathfrak{B}) := q \cdot \frac{z}{\rho(z)} = \frac{z^2}{z\rho(z)/q} = \frac{z^2}{u} \in \mathscr{O}_K. \tag{29}$$

If u is a square in K_0 then there is a unit u_0 in K_0 such that $u = u_0^2$. If this is the case then let us put

$$\Pi_0(\mathfrak{B}) := \frac{z}{u_0} \in \mathscr{O}_K \text{ and get } \Pi_0(\mathfrak{B})^2 = \left(\frac{z}{u_0}\right)^2 = \frac{z^2}{u} = \Pi(\mathfrak{B}). \tag{30}$$

Clearly,

$$\Pi(\mathfrak{B}) \cdot \mathscr{O}_K = z^2 \cdot \mathscr{O}_K = (z \cdot \mathscr{O}_K)^2 = (\mathfrak{B}^c)^2 = \mathfrak{B}^{2c}, \tag{31}$$

which proves (i). In order to check that $\Pi(\mathfrak{B})$ is a Weil's q^2-number, notice that

$$\Pi(\mathfrak{B}) \cdot \rho(\Pi(\mathfrak{B})) = q \cdot \frac{z}{\rho(z)} \cdot \rho\left(q \cdot \frac{z}{\rho(z)}\right) = q^2 \cdot \frac{z}{\rho(z)} \cdot \frac{\rho(z)}{z} = q^2.$$

In light of Remark 2.2, this proves that $\Pi(\mathfrak{B})$ is a Weil's q^2-number. It follows from (30) that if $\Pi_0(\mathfrak{B})$ is defined then it is a Weil's q-number. By construction,

$$\Pi(\mathfrak{B})\mathscr{O}_K = \mathfrak{B}^{2c},$$

which also implies that $\Pi(\mathfrak{B})$ is $p^{2c} = q^2$-ordinary Weil's number. The G-invariance of $\mathscr{X}$ (see Corollary 3.5) combined with (28) and (29) implies the G-equivariance of Π, which proves (0). The injectiveness of Π follows from (31). This proves (i) and (ii).

In order to prove (v), notice that if $\mathbb{Q}\left(\Pi(\mathfrak{B})^h\right)$ does *not* coincide with K then it consists of ρ-invariants (Subsection 2.4). In particular, the ideal $\Pi(\mathfrak{B})^h\mathscr{O}_K = \mathfrak{B}^{2ch}$ coincides with its complex-conjugate

$$\rho\left(\Pi(\mathfrak{B})^h\mathscr{O}_K\right) = \rho\left(\mathfrak{B}^{2ch}\right) = \rho(\mathfrak{B})^{2ch}.$$

This implies that $\mathfrak{B} = \rho(\mathfrak{B})$, which is not the case, since $\mathfrak{B} \in H(p)$. The obtained contradiction proves (v).

In order to prove (iii), we need to check that if π' is an ordinary Weil's p^m-number in K then it is equivalent to $\Pi(\mathfrak{B})$ for some $\mathfrak{B} \in H(p)$. In order to do that, let us consider the ideal $\mathfrak{M} := \pi'\mathscr{O}_K$ in $\mathscr{O}_K$. Since $\pi' \cdot \rho(\pi') = p^m$, we get $\mathfrak{M} \cdot \rho(\mathfrak{M}) = p^m\mathscr{O}_K$. It follows that

$$\mathfrak{M} = \prod_{\mathfrak{P} \in S(p)} \mathfrak{P}^{d(\mathfrak{P})}, \; d(\mathfrak{P}) + d(\rho(\mathfrak{P})) = m \; \forall \mathfrak{P} \in S(p).$$

The ordinarity of $\mathfrak{M}$ implies that

$$d(\mathfrak{P}) = 0 \text{ or } m \; \forall \mathfrak{P} \in S(p).$$

This implies that if we put

$$\Phi = \{\mathfrak{P} \in S(p) \mid d(\mathfrak{P}) = m\} \subset S(p)$$

then Φ is a p-type and

$$\mathfrak{M} = \prod_{\mathfrak{P}\in\Phi} \mathfrak{P}^m = \left(\prod_{\mathfrak{P}\in\Phi} \mathfrak{P}\right)^m .$$

It is also clear that

$$\mathfrak{B} := \prod_{\mathfrak{P}\in\Phi} \mathfrak{P} \in H(p),$$

and

$$(\pi')^{2c}\mathscr{O}_K = \mathfrak{M}^{2c} = \mathfrak{B}^{2cm} = \left(\mathfrak{B}^{2c}\right)^m = (\Pi((\mathfrak{B})\mathscr{O}_K)^m = \Pi\left(\mathfrak{B}^m\right)\mathscr{O}_K.$$

It follows from Remark 2.3 that the ratio $\Pi(\mathfrak{B})^m/(\pi')^{2c}$ is a root of unity. The uniqueness follows from the already proven (i).

Let us prove (iv). The already proven (0) tells us that if $\mathfrak{B}_2 = \sigma(\mathfrak{B}_2)$ for $\sigma \in G$ then $\Pi(\mathfrak{B}_2) = \sigma(\Pi(\mathfrak{B}_1)$ and therefore Weil's numbers $\Pi(\mathfrak{B}_1)$ and $\Pi(\mathfrak{B}_2)$ are equivalent.

Conversely, suppose that $\Pi(\mathfrak{B}_1)$ and $\Pi(\mathfrak{B}_2)$ are equivalent. This means that there are positive integers a, b, a Galois automorphism $\sigma \in G$, and a root of unity $\zeta \in \mu_K$ such that

$$\Pi(\mathfrak{B}_2)^a = \zeta \cdot \sigma(\Pi(\mathfrak{B}_1))^b.$$

This implies the equality of the corresponding ideals in $\mathscr{O}_K$:

$$\Pi(\mathfrak{B}_2)^a\mathscr{O}_K = \sigma(\Pi(\mathfrak{B}_1))^b\mathscr{O}_K = \Pi(\sigma(\mathfrak{B}_1))^b.$$

This means (in light of already proven (i)) that

$$\mathfrak{B}_2^{2ca} = (\sigma(\mathfrak{B}_1))^{2cb},$$

which implies $\mathfrak{B}_2 = \sigma(\mathfrak{B}_1)$. Hence $\mathfrak{B}_1$ and $\mathfrak{B}_2$ lie in the same G-orbit.

Let us prove (vi). Actually, we have already constructed the map $\Pi_0 : H(p) \to \mathscr{O}_K$, checked that its image lies in $W(q, K)$; we have also proven property (vi)(a). As for (vi)(b), it follows readily from (30) combined with the G-equivariance of Π. As for (vi)((c), it follows readily from (v) combined with (30). In order to prove (vi)(d), it suffices to recall that $\Pi(\mathfrak{B})$ is an ordinary Weil's q^2-number and notice that in light of (30), the integer

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\Pi(\mathfrak{B})}{\mathrm{ord}_{\mathfrak{P}}(q^2)} = \frac{2\mathrm{ord}_{\mathfrak{P}}(\Pi_0(\mathfrak{B})}{2\mathrm{ord}_{\mathfrak{P}}(q)} = \frac{\mathrm{ord}_{\mathfrak{P}}(\Pi_0(\mathfrak{B})}{\mathrm{ord}_{\mathfrak{P}}(q)}.$$

□

4. Abelian varieties with Weil's numbers in K

As above, p is a prime, m a positive integer and $q = p^m$.

Theorem 4.1. *Let A be a simple abelian variety over $k = \mathbb{F}_q$ such that the corresponding Weil's q-number*

$$\pi_A \in K.$$

Let $\mathbb{Q}(\pi_A)$ be the subfield of K generated by π_A.

(i) *Suppose that either $\mathbb{Q}(\pi_A) \ne K$ or p does not split completely in K.*
Then A is supersingular.

(ii) *If p splits completely in K, $\mathbb{Q}(\pi_A) = K$ and π_A is not ordinary then the division $\mathbb{Q}$-algebra $\mathrm{End}_k^0(A)$ is not commutative.*

(iii) *If π_A is ordinary then $K = \mathbb{Q}(\pi_A)$, and $\mathrm{End}_k^0(A) \cong K$; in particular, $\mathrm{End}_k^0(A)$ is commutative.*

Proof. (i) It follows from Lemmas 2.7 and 2.8 that π_A^2/q is a root of unity. This means that A is supersingular.

(ii-iii) Recall [11, 12] that $E := \mathrm{End}_k^0(A)$ is a *central* division algebra over the field $\mathbb{Q}(\pi_A) = K$. Since p splits completely in K, the $\mathfrak{P}$-adic completion $K_{\mathfrak{P}}$ of K coincides with $\mathbb{Q}_p$, i.e.,

$$[K_{\mathfrak{P}} : \mathbb{Q}_p] = 1 \ \forall \mathfrak{P} \in S(p).$$

By [12, Th. 1], the local $\mathfrak{P}$-adic invariant

$$\mathrm{inv}_{\mathfrak{P}}(E) \in \mathbb{Q}/\mathbb{Z}$$

of the central division K-algebra E is given by the formula

$$\mathrm{inv}_{\mathfrak{P}}(E) = \frac{\mathrm{ord}_{\mathfrak{P}}(\pi_A)}{\mathrm{ord}_{\mathfrak{P}}(q)}[K_{\mathfrak{P}} : \mathbb{Q}_p] \bmod \mathbb{Z} = \frac{\mathrm{ord}_{\mathfrak{P}}(\pi_A)}{\mathrm{ord}_{\mathfrak{P}}(q)} \bmod \mathbb{Z} \in \mathbb{Q}/\mathbb{Z}. \tag{32}$$

All other local invariants of E (outside $S(p)$) are 0 (ibid).

Suppose that π_A is *ordinary*. Then $\mathbb{Q}(\pi_A) = K$, because otherwise $\mathbb{Q}(\pi_A) \subset \mathbb{R}$ and therefore π_A is *real*, i.e., A is *supersingular* [12, Examples], which is not the case. Since π_A is ordinary, all the *slopes* $\mathrm{ord}_{\mathfrak{P}}(\pi_A)/\mathrm{ord}_{\mathfrak{P}}(q)$ are *integers* and therefore $\mathrm{inv}_{\mathfrak{P}}(E) = 0$ for all $\mathfrak{P} \in S(p)$. This implies that the division algebra $E = \mathrm{End}_k^0(A)$ is actually a *field*, i.e., is isomorphic to K. This proves (iii).

In order to prove (ii), assume that π_A is *not ordinary*. Then there is a maximal ideal $\mathfrak{P} \in S(p)$ such that the ratio $\mathrm{ord}_{\mathfrak{P}}(\pi_A)\mathrm{ord}_{\mathfrak{P}}(q)$ is *not an integer*, i.e.

$$\frac{\mathrm{ord}_{\mathfrak{P}}(\pi_A)}{\mathrm{ord}_{\mathfrak{P}}(q)} \bmod \mathbb{Z} \ne 0 \ \text{ in } \mathbb{Q}/\mathbb{Z}. \tag{33}$$

Combining (33) with (32), we obtain that $\mathrm{inv}_{\mathfrak{P}}(E) \ne 0$. It follows that $E = \mathrm{End}_k^0(A)$ does *not* coincide with its center, i.e., is *noncommutative*. This proves (ii). $\square$

Remark 4.2. Let A be a simple abelian variety over $\mathbb{F}_q$ such that $\pi_A \in K$. Obviously, A is ordinary if and only if π_A is ordinary.

5. Honda-Tate theory for ordinary abelian varieties

As above, p is a prime that splits completely in K, m a positive integer and $q = p^m$.

Let $\pi \in K$ be a Weil's q-number. The Honda-Tate theory [11, 6, 12] attaches to π a *simple* abelian variety $\mathscr{A}$ over $\mathbb{F}_q$ that is defined up to an $\mathbb{F}_q$-isogeny and enjoys the following properties.

Let $\mathrm{Fr}_{\mathscr{A}} : \mathscr{A} \to \mathscr{A}$ be the Frobenius endomorphism of $\mathscr{A}$ and $F := \mathbb{Q}[\mathrm{Fr}_{\mathscr{A}}]$ be the $\mathbb{Q}$-subalgebra of the division $\mathbb{Q}$-algebra $E := \mathrm{End}^0_{\mathbb{F}_q}(\mathscr{A})$ (which is actually a subfield). Then F is the *center* of E and there is a field embedding

$$i : F \hookrightarrow \mathbb{C} \text{ such that } i(\mathrm{Fr}_{\mathscr{A}}) = \pi.$$

Lemma 5.1. *Suppose π is ordinary and $\mathbb{Q}(\pi^h) = K$ for all positive integers h. Then $\mathscr{A}$ is an absolutely simple 2^{n-1}-dimensional ordinary abelian variety,* $\mathrm{End}^0(A) \cong K$*, and all endomorphisms of $\mathscr{A}$ are defined over $\mathbb{F}_q$.*

Proof. Since $\mathbb{Q}(\pi) = K$, we get $i(F) = K$. In particular, number fields K and F are isomorphic. In light of Theorem 4.1, $\mathscr{A}$ is an ordinary abelian variety with commutative endomorphism algebra $E = F \cong K$. By Theorem 2(c) of [11, Sect. 3],

$$\dim(\mathscr{A}) = \frac{[E : \mathbb{Q}]}{2} = \frac{[K : \mathbb{Q}]}{2} = 2^{n-1}.$$

We are going to prove that $\mathscr{A}$ is absolutely simple and all its endomorphisms are defined over $\mathbb{F}_q$. Let h be a positive integer and $k = \mathbb{F}_{q^h}$ a degree h field extension of $\mathbb{F}_q$. Let $\mathscr{A}_k = \mathscr{A} \times_{\mathbb{F}_q} k$ be the abelian variety over k obtained from $\mathscr{A}$ by the extension of scalars. There is the natural embedding (inclusion) of $\mathbb{Q}$-algebras

$$\mathrm{End}^0_{\mathbb{F}_q}(\mathscr{A}) \subset \mathrm{End}^0_k(\mathscr{A}_k)$$

such that the Frobenius endomorphism $\mathrm{Fr}_{\mathscr{A}_k}$ coincides with $\mathrm{Fr}^h_{\mathscr{A}}$. In particular,

$$\mathbb{Q}[\mathrm{Fr}_{\mathscr{A}_k}] \subset \mathbb{Q}[\mathrm{Fr}_{\mathscr{A}}] = F.$$

In addition,

$$i(\mathrm{Fr}_{\mathscr{A}_k}) = i\left(\mathrm{Fr}^h_{\mathscr{A}}\right) = i\left(\mathrm{Fr}_{\mathscr{A}}\right)^h = \pi^h.$$

Since $\mathbb{Q}[\pi^h] = K = \mathbb{Q}(\pi)$, we get

$$i(\mathbb{Q}[\mathrm{Fr}_{\mathscr{A}_k}]) = K = i(\mathbb{Q}[\mathrm{Fr}_{\mathscr{A}}]).$$

Hence, $\mathbb{Q}[\mathrm{Fr}_{\mathscr{A}_k}] = \mathbb{Q}[\mathrm{Fr}_{\mathscr{A}}]$ is a number field of degree $2\dim(\mathscr{A}) = 2\dim(\mathscr{A}_k)$. Applying again Theorem 2(c) of [11, Sect. 3] to $\mathscr{A}_k$, we conclude that

$$\mathrm{End}^0(\mathscr{A}_k) = \mathbb{Q}[\mathrm{Fr}_{\mathscr{A}_k}] = \mathbb{Q}[\mathrm{Fr}_{\mathscr{A}}] = \mathrm{End}^0_{\mathbb{F}_q}(\mathscr{A})$$

for all finite overfields k of $\mathbb{F}_q$. This implies that

$$\mathrm{End}^0(\mathscr{A}_k) = \mathrm{End}^0_{\mathbb{F}_q}(\mathscr{A}),$$

i.e., all the endomorphisms of $\mathscr{A}$ are defined over $\mathbb{F}_q$. In particular, $\mathscr{A}$ is absolutely simple and $\mathrm{End}^0(\mathscr{A}) \cong K$.

□

6. Proofs of main results

As above, $c = \exp(K)$, a prime p splits completely in K and $q = p^c$.

Proof of Theorem 1.6. Let $\Pi : H(p) \to W(q^2, K)$ be as in Theorem 3.6. Let $\mathscr{B} \in H(p)$ and let $\Pi(\mathscr{B})$ be the corresponding ordinary Weil's q^2-number in K. In light of Theorem 3.6(v), $\mathbb{Q}[\Pi(\mathfrak{B})^h] = K$ for all positive integers h. In light of Lemma 5.1 applied to q^2 and $\Pi(\mathfrak{B})$, the Honda-Tate theory [11, 6, 12] attaches to $\Pi(\mathscr{B})$ an *absolutely simple* 2^{n-1}-dimensional abelian variety $\mathscr{A} = A(\mathscr{B})$ over $\mathbb{F}_{q^2}$ (that is defined up to an $\mathbb{F}_{q^2}$-isogeny) such that $\mathrm{End}^0(A(\mathscr{B}) \cong K$, and all endomorphisms of $A(\mathscr{B})$ are defined over $\mathbb{F}_{q^2}$.

By Theorem 3.6(iv), if $\mathfrak{B}_1, \mathfrak{B}_2 \in H(p)$ then the Weil numbers $\Pi(\mathfrak{B}_1)$ and $\Pi(\mathfrak{B}_2)$ are *equivalent* if and only if $\mathfrak{B}_1$, and $\mathfrak{B}_2$ belong to the same G-orbit. In light of [11, Theorem 1], [6, p. 84] combined with Lemma 3.4, all the $A(\mathfrak{B})$ lie in precisely $2^{2^{n-1}-n}$ isogeny classes of abelian varieties over $\bar{\mathbb{F}}_p$. We also know that each of these varieties is ordinary, has dimension 2^{n-1} and their endomorphism algebras are isomorphic to K.

Now, let us prove that each abelian variety $\mathscr{B}$ over $\bar{\mathbb{F}}_p$, whose endomorphism algebra is isomorphic to K, is isogenous to one of $A(\mathfrak{B})$ over $\bar{\mathbb{F}}_p$,

In order to do that, first, notice that since K is a field, $\mathscr{B}$ is simple over $\bar{\mathbb{F}}_p$. Second, $\mathscr{B}$ is defined with all its endomorphisms over a certain finite field $k = \mathbb{F}_{q^{2h}}$ (where h is a certain positive integer), i.e., there is a simple abelian variety $\mathscr{B}_k$ over k such that

$$\mathscr{B} = \mathscr{B}_k \times_k \bar{\mathbb{F}}_p, \ \mathrm{End}^0_k(\mathscr{B}_k) = \mathrm{End}^0(\mathscr{B}) \cong K.$$

Applying Theorem 2(c) of [11, Sect. 3] to $\mathscr{B}_k$, we get

$$K \cong \mathrm{End}^0(\mathscr{B}) = \mathrm{End}^0_k(\mathscr{B}_k) = \mathbb{Q}[\mathrm{Fr}_{\mathscr{B}_k}]$$

where $\mathrm{Fr}_{\mathscr{B}_k}$ is the Frobenius endomorphism of $\mathscr{B}_k$. This gives us a field isomorphism $\mathbb{Q}[\mathrm{Fr}_{\mathscr{B}_k}] \to K$; let us denote by $\pi_{\mathscr{B}_k}$ the image of $\mathrm{Fr}_{\mathscr{B}_k}$ in K. Clearly, $\mathbb{Q}(\pi_{\mathscr{B}_k}) = K$; according to a classical result of Weil [7], $\pi_{\mathscr{B}_k}$ is a Weil's q^{2h}-number. By Theorem 4.1(i) (applied to q^{2h} instead of q), $\pi_{\mathscr{B}_k}$ is *ordinary*, because $\mathrm{End}^0_k(\mathscr{B}_k) \cong K$ is *commutative*. It follows from Theorem 3.6(iii) that there is $\mathfrak{B} \in H(p)$ such that Weil's numbers $\pi_{\mathscr{B}_k}$ and $\Pi(\mathfrak{B})$ are *equivalent*. This means (thanks to Theorem 1 of [11], see also [6, pp. 83–84]) that *absolutely simple* abelian varieties $\mathscr{B}_k$ and $A(\mathfrak{B})$ become isogenous over $\bar{\mathbb{F}}_p$. It follows that *absolutely simple* abelian varieties $\mathscr{B} = \mathscr{B}_k \times_k \bar{\mathbb{F}}_p$ and $A(\mathfrak{B})$ are isogenous over $\bar{\mathbb{F}}_p$.

This proves (i), (ii)(1) and (ii)(2). It remains to prove (ii)(3). It suffices to check that for each $\mathscr{B} \in H(p)$ there exists an abelian variety A_0 that is defined over $\mathbb{F}_q$ with all its endomorphism and such that $A(\mathscr{B})$ is isogenous to A_0 over $\bar{\mathbb{F}}_p$.

Let $\Pi_0 : H(p) \to W(q, K)$ be as in Theorem 3.6(vi) and $\Pi_0(\mathscr{B})$ be the corresponding ordinary Weil's q-number in K. In light of Theorem 3.6(vi)(c), $\mathbb{Q}[\Pi_0(\mathfrak{B})^h] = K$ for all positive integers h. In light of Lemma 5.1 applied to q and $\Pi_0(\mathfrak{B})$, the Honda-Tate theory [11, 6, 12] attaches to Weil's q-number $\Pi_0(\mathscr{B})$ an *absolutely simple* 2^{n-1}-dimensional abelian variety $\mathscr{A}_0$ over $\mathbb{F}_q$ (that is defined up to an $\mathbb{F}_q$-isogeny) such that $\mathrm{End}^0(\mathscr{A}_0) \cong K$, and all endomorphisms of $\mathscr{A}_0$ are defined over $\mathbb{F}_q$.

Since $\Pi_0(\mathscr{B})^2 = \Pi(\mathscr{B})$, Weil's numbers $\Pi_0(\mathscr{B})$ and $\Pi(\mathscr{B})$ are *equivalent*. As above, in light of Theorem 1 of [11] (see also [6, pp. 83–84]), the corresponding *absolutely simple* abelian varieties $\mathscr{A}_0$ and $A(\mathscr{B})$ are isogenous over $\bar{\mathbb{F}}_p$. This ends the proof.

□

Proof of Corollary 1.14. Recall that r is an odd prime and ζ_r is a primitive rth root of unity. Clearly, $\mathbb{Q}(\zeta_r)$ is a CM field. Hence, its subfield K is either CM or a totally real. Since $\mathbf{H}$ has odd order m, it does *not* contain the complex conjugation $\rho : \mathbb{Q}(\zeta_r) \to \mathbb{Q}(\zeta_r)$, because ρ has order 2. Hence, ρ acts nontrivially on $K = \mathbb{Q}(\zeta_r)^{\mathbf{H}} = K^{(r)}$, which implies that K is a CM field. (See also [2, p. 78].) Its degree

$$[K : \mathbb{Q}] = \frac{[\mathbb{Q}(\zeta_r) : \mathbb{Q}]}{\#(\mathbf{H})} = \frac{m \cdot 2^n}{m} = 2^n.$$

We also know (Remark 1.15) that every totally positive unit in K_0 is a square in K_0.

Clearly, $K/\mathbb{Q}$ is ramified at r and unramified at every prime $p \neq r$. Let us find which $p \neq r$ split completely in K. Let

$$f_p \in \mathrm{Gal}(\mathbb{Q}(\zeta_r)/\mathbb{Q}) = (\mathbb{Z}/r\mathbb{Z})^*$$

be the Frobenius element attached to p, which is characterized by the property

$$f_p(\zeta_r) = \zeta_r^p.$$

In other words,

$$f_p = p \bmod r \in (\mathbb{Z}/r\mathbb{Z})^* = \mathrm{Gal}(\mathbb{Q}(\zeta_r)/\mathbb{Q}).$$

Clearly, p splits completely in K if and only if $f_p \in \mathbf{H}$. So, we need to find when f_p lies in $\mathbf{H}$. In order to do it, notice that

$$\mathbf{H} = \{\sigma^{2^n} \mid \sigma \in \mathrm{Gal}(\mathbb{Q}(\zeta_r)/\mathbb{Q}) = (\mathbb{Z}/r\mathbb{Z})^*\}.$$

This implies that f_p lies in $\mathbf{H}$ if and only if $p \bmod r$ is a 2^rth power in $\mathbb{Z}/r\mathbb{Z} = \mathbb{F}_r$. This ends the proof of (0).

The remaining assertions (i) and (ii) follow from Theorem 1.6 combined with (0).

□

Proof of Corollary 1.8. In the notation of Corollary 1.14, this is the case when $m = 1$ and $2^n = r - 1$. By little Fermat's theorem, every nonzero $a \in \mathbb{Z}/r\mathbb{Z}$ satisfies

$$a^{2^n} = a^{r-1} = 1.$$

Now the desired result follows readily from Corollary 1.14.

□

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