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A NOTE ON ELLIPTIC CURVES OVER FINITE FIELDS

BY

J. F. VOLOCH (*)

RÉSUMÉ. — Nous déterminons tous les groupes que l'on peut obtenir comme groupe des points rationnels d'une courbe elliptique sur un corps fini donné.

ABSTRACT. — We determine all groups that can occur as the group of rational points of an elliptic curve over a given finite field.

Let $\mathbb{F}_q$ denote the finite field of q elements. Given t an integer, $|t| \leq 2q^{1/2}$ then WATERHOUSE [3] proved that there exists an elliptic curve over $\mathbb{F}_q$ with $q+1-t$ rational points if and only if, writing $q = p^h$, p prime, one of the following conditions is satisfied :

(i) $(t, q) = 1$,
(ii) $t = 0, h$ odd or $p \not\equiv 1(4)$,
(iii) $t = \pm q^{1/2}$, h even or $p \not\equiv 1(3)$,
(iv) $t = \pm 2q^{1/2}$, h even,
(v) $t = \pm\sqrt{2q}$, h odd and $p = 2$,
(vi) $t = \pm\sqrt{3q}$, h odd and $p = 3$.

SCHOOF then proved [2] that the possible structures for the group in cases (ii)–(vi) are :

(ii) $\mathbb{Z}/2 \oplus \mathbb{Z}/(q+1)/2$ or cyclic if $q = 3(4)$, cyclic otherwise,
(iii) Cyclic,
(iv) $(\mathbb{Z}/(q^{1/2} \pm 1))^2$,
(v) Cyclic,
(vi) Cyclic.

The purpose of this paper is to give the list of possibilities for the groups occurring as elliptic curves over $\mathbb{F}_q$ in case (i). Let, for a prime ℓ, $v_\ell(n)$ be the largest integer with $\ell^{v_\ell(n)} \mid n$.

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THEOREM. — *If t is an integer with $|t| \leq 2q^{1/2}$ and $(t,q) = 1$, the possible groups that an elliptic curve over $\mathbb{F}_q$ with $N = q+1-t$ can be are*

$$(*) \qquad \mathbb{Z}/p^{v_p(N)} \oplus \bigoplus_{\ell \neq p} \mathbb{Z}/\ell^{r_\ell} \oplus \mathbb{Z}/\ell^{s_\ell}$$

with $r_\ell + s_\ell = v_\ell(N)$ and $\min(r_\ell, s_\ell) \leq v_\ell(q-1)$.

Proof. — Let $E[n]$ stand for the group of n-torsion points of an elliptic curve E over the algebraic closure of $\mathbb{F}_q$. It is well known that $E[p] = \{0\}$ or $\mathbb{Z}/p$ and that $E[\ell] = (\mathbb{Z}/\ell)^2$, ℓ prime, $\ell \neq p$ (see, e.g. [1, Theorem 8.1]). So, clearly the group of points of an elliptic curve over $\mathbb{F}_q$ is of the form $(*)$ with $r_\ell + s_\ell = v_\ell(N)$. To see that also $\min(r_\ell, s_\ell) \leq v_\ell(q-1)$, we notice that, if $r_\ell \leq s_\ell$, then all points of $E[\ell^{r_\ell}]$ are defined over $\mathbb{F}_q$, hence $\ell^{r_\ell} | q-1$ by [2, Proposition 3.8]. It then follows that the conditions of the theorem are necessary. We now prove that they are sufficient. For this we need two lemmas.

LEMMA 1. — *Given $N \not\equiv 1 \pmod p$ such that there exists an elliptic curve with N points over $\mathbb{F}_q$ then there exists at least one such elliptic curve with its group of rational points being cyclic.*

Proof. — Let $\ell_1, \ldots, \ell_r$ be the primes such that $\ell_i^2 | N$ and $\ell_i | q-1$. If there is no such prime then by the preceding discussion any elliptic curve over $\mathbb{F}_q$ with N points will do. So we assume that $r \geq 1$.

In [2, Theorem 4.9 (i)], SCHOOF proves that given an integer n, the number of isomorphism classes of elliptic curves with $N = q+1-t$ points over $\mathbb{F}_q$ with all points of $E[n]$ defined over $\mathbb{F}_q$, when $p \nmid t$ and $n^2 | N$, $n | q-1$, is $H(t^2 - 4q)/n^2)$ where $H(\Delta)$ is the class number of binary quadratic forms of discriminant D. (note that although Theorem 4.9 of [2] its stated only for n odd the proof of item (i) is valid for all n). Hence the number M, say, of elliptic curves satisfying the conclusion of the lemma is clearly:

$$M = H(t^2 - 4q) - \sum_{i=1}^{r} H\big((t^2 - 4q)/\ell_i^2\big) + \sum_{1 \leq i < j \leq t} H\big((t^2 - 4q)/\ell_i^2 \ell_j^2\big) + \cdots + (-1)^r H\big((t^2 - 4q)/\ell_1^2 \ldots \ell_r^2\big)$$

$$H(\Delta) = \sum_{\mathcal{O}(\Delta) \subseteq \mathcal{O} \subseteq \mathcal{O}_{\max}} h(\mathcal{O}),$$

where $\mathcal{O}(\Delta)$ is the quadratic order of discriminant Δ, $h(\mathcal{O})$ is the class number of $\mathcal{O}$ and $\mathcal{O}$ runs through the orders of $\mathcal{O}(\Delta) \otimes \mathbb{Q}$. It follows that $M \geq h(\mathcal{O}(t^2 - 4q)) \geq 1$. The lemma is thus proved.

Definition. — We shall call two elliptic curves ℓ^∞-isogenous, for a prime ℓ, if there exists an isogeny between them of degree a power of ℓ.

LEMMA 2. — *If E is an elliptic curve defined over $\mathbb{F}_q$ and $\ell \neq p$ is a prime such that E has a cyclic subgroup of order ℓ^n, then for any $r \leq s$ with $r+s=n$ and $\ell^r | q-1$, there exists an elliptic curve defined over $\mathbb{F}_q$, ℓ^∞-isogenous to E and containing a subgroup isomorphic to $\mathbb{Z}/\ell^r \oplus \mathbb{Z}/\ell^s$.*

Proof. — Let $P \in E$ be a point of order ℓ^n in E and let Γ be the group generated by $\ell^s P$. Let $E' = E/\Gamma$ and $\lambda : E \to E'$ the natural isogeny [1, Lemma 8.5]. λ has degree ℓ^r, hence is an ℓ^∞ isogeny. We shall prove that E' satisfies the conclusions of the lemma. Let $\hat{\lambda}$ be the dual isogeny [1, pg. 216] and $M = \ker \hat{\lambda}$, the points of M are defined over $\mathbb{F}_q$ by [1, Lemma 8.4]. Let N be the group generated by $\lambda(P)$, then N is cyclic of order ℓ^s and as $\hat{\lambda} \circ \lambda$ is multiplication by ℓ^r [1, 8.7], it follows that $\hat{\lambda}$ is injective on N. So $M \cap N = \{0\}$ and as $\#M = \deg \hat{\lambda} = \ell^r$ [1, 8.8] it follows that $M \oplus N \simeq \mathbb{Z}/\ell^r \oplus \mathbb{Z}/\ell^s$, as desired.

We now complete the proof of the theorem. Take $N \not\equiv 1 \pmod p$ and E the elliptic curve given by LEMMA 1, so $E(\mathbb{F}_q)$ is cyclic of order N. Let $\ell_1, \ldots, \ell_r$ be the primes such that $\ell_i^2 | N$ and $\ell_i | q-1$. (If there is no such prime there is nothing to prove). Let $s_1, \ldots, s_r$ be integers with $s_i \leq v_{\ell i}(N)$ and $v_{\ell_i}(N) - s_i \leq v_{\ell i}(q-1)$, $i = 1, \ldots, r$. Construct successively by LEMMA 2, elliptic curves $E_1, \ldots, E_r$, with E_1 being ℓ_1^∞-isogenous to E and containing a subgroup isomorphic to $\mathbb{Z}/\ell_1^{s_1} \oplus \mathbb{Z}/\ell_1^{v_{\ell_1}(N)-s_1}, \ldots, E_r$, ℓ_r^∞-isogenous to E_{r-1} and containing a subgroup isomorphic to $\mathbb{Z}/\ell_r^{v_{\ell_r}(N)-s_r}$. Notice that an ℓ^∞-isogeny induces an isomorphism between the subgroups of order prime to ℓ, so the construction is justified since, for $i < r$, E_i has a cyclic subgroup of order $\ell_{i+1}^{v_{\ell_{i+1}}(N)}$. Then

$$E_r \simeq \mathbb{Z}/p^{v_p(N)} \oplus \bigoplus_{\ell \neq p, \ell_i} \mathbb{Z}/\ell^{v_\ell(N)} \oplus \bigoplus_{i=1}^{r} \mathbb{Z}/\ell_i^{s_i} \oplus \mathbb{Z}/\ell_i^{v_{\ell_i}(N)-s_i}.$$

As the s_i were arbitrary satisfying $s_i \leq v_{\ell_i}(N)$ and $v_{\ell i}(N) - s_i \leq v_{\ell i}(q-1)$, the proof of the theorem is complete.

Added in proof. — After this paper was submitted, there appeared in print an article by H. G. RUCH (*Math. of Comp.*, t. **49**, 1987, p. 301–304), proving the same result but with a different proof.

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