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MOD 2 REPRESENTATIONS OF ELLIPTIC CURVES

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Abstract. Explicit equations are given for the elliptic curves (in characteristic $\neq 2, 3$) with mod 2 representation isomorphic to that of a given one.

1. Introduction

If N is a positive integer and E is an elliptic curve defined over a field F, one can ask for a description of the set of elliptic curves whose mod N representation (of the absolute Galois group) is symplectically isomorphic to that of E (see [2]). For $N = 3$, 4, and 5, we gave explicit equations in [3] and [5]. The case $N = 1$ is trivial, and when $N \geq 7$ the set in question is always finite and the situation is quite different from the ones we consider. In [4] we gave a description for $N = 6$ (but did not give explicit equations).

This note, which can be viewed as a footnote to those papers, deals with the easier case $N = 2$. Note that since there is only one nondegenerate alternating pairing on $\mathbf{Z}/2\mathbf{Z} \times \mathbf{Z}/2\mathbf{Z}$, isomorphic and symplectically isomorphic are the same for mod 2 representations. Theorem 1 gives explicit equations for the family of elliptic curves whose mod 2 representation is isomorphic to that of a given one. Given two elliptic curves, Corollary 2 gives an easy way to determine whether or not their mod 2 representations are isomorphic. The proofs are given in §2. In §3 we give a different approach, using the algorithm from [3].

If F is a field, let F^{sep} denote a separable closure of F and let $G_F = \mathrm{Gal}(F^{\mathrm{sep}}/F)$. If E is an elliptic curve over F, let $j(E)$ denote its j-invariant, let $\Delta(E)$ denote its discriminant, and let $E[2]$ denote the G_F-module of 2-torsion points on E.

Theorem 1. *Suppose F is a field of characteristic different from 2 and 3, and $E : y^2 = x^3 + ax + b$ is an elliptic curve over F. If $u, v \in F$, let $\mathcal{E}_{u,v}$ denote the curve*

$$y^2 = x^3 + 3(3av^2 + 9buv - a^2u^2)x + 27bv^3 - 18a^2uv^2 - 27abu^2v - (2a^3 + 27b^2)u^3.$$

If E' is an elliptic curve over F, and $E'[2] \cong E[2]$ as G_F-modules, then E' is isomorphic to $\mathcal{E}_{u,v}$ for some $u, v \in F$. Conversely, if $u, v \in F$ and $\mathcal{E}_{u,v}$ is nonsingular, then $\mathcal{E}_{u,v}[2] \cong E[2]$ as G_F-modules,

$$j(\mathcal{E}_{u,v}) = \frac{(3av^2 + 9buv - a^2u^2)^3 j(E)}{27a^3(v^3 + au^2v + bu^3)^2},$$

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and

$$\Delta(\mathcal{E}_{u,v}) = 3^6(v^3 + au^2v + bu^3)^2\Delta(E).$$

Corollary 2. *Suppose F is a field of characteristic different from 2 and 3, and $E : y^2 = x^3 + ax + b$ is an elliptic curve over F. Let*

$$C(u,v) = \frac{(3av^2 + 9buv - a^2u^2)^3}{27a^3(v^3 + au^2v + bu^3)^2}.$$

Suppose E' is an elliptic curve over F. If $j(E') \neq 0, 1728$, and for some $(u,v) \in \mathbf{P}^1(F)$ we have

(i) $\dfrac{j(E')}{j(E)} = C(u,v)$ *if* $a \neq 0$, *or*

(ii) $\dfrac{j(E')}{j(E) - 1728} = \dfrac{-4C(u,v)a^3}{27b^2}$ *if* $b \neq 0$,

then $E'[2] \cong E[2]$. Conversely, if $E'[2] \cong E[2]$, then there is a point $(u,v) \in \mathbf{P}^1(F)$ such that $j(E')$ satisfies (i) *if $a \neq 0$ and* (ii) *if $b \neq 0$.*

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2. Proofs

Lemma 3. *Suppose F is a field and $\varphi(x) \in F[x]$ is a polynomial with no multiple roots. Let Ψ_φ denote the set of roots of φ.*

(i) *There is a G_F-equivariant bijection $\Psi_\varphi \xrightarrow{\sim} \mathrm{Hom}_{F\text{-algebra}}(F[x]/(\varphi(x)), F^{\mathrm{sep}})$.*
(ii) *The F-algebra of G_F-equivariant maps from Ψ_φ to F^{sep} is isomorphic to $F[x]/(\varphi(x))$.*

Proof. Assertion (i) is clear, and (ii) follows from Lemma 5 on p. A.V.75 of [1]. □

Lemma 4. *Suppose $E : y^2 = f(x)$ and $E' : y^2 = g(x)$ are elliptic curves over a field F with $f(x), g(x) \in F[x]$ of degree 3. Then $E[2] \cong E'[2]$ as G_F-modules if and only if $F[x]/(f(x)) \cong F[x]/(g(x))$ as F-algebras.*

Proof. We apply Lemma 3 with $\varphi = f$ and g. Since the roots of f are the x-coordinates of the elements of $E[2] - 0$, there is a G_F-equivariant bijection $\Psi_f \xrightarrow{\sim} E[2] - 0$. Similarly we have $\Psi_g \xrightarrow{\sim} E'[2] - 0$. Thus by Lemma 3, $F[x]/(f(x)) \cong F[x]/(g(x))$ as F-algebras if and only if $E[2] - 0 \cong E'[2] - 0$ as G_F-sets. Since every bijection $E[2] - 0 \xrightarrow{\sim} E'[2] - 0$ extends to a group isomorphism $E[2] \xrightarrow{\sim} E'[2]$, the lemma follows. □

Proof of Theorem 1. Write $f(x) = x^3 + ax + b$, so E is the elliptic curve $y^2 = f(x)$, and let E' be an elliptic curve $y^2 = g(x) = x^3 + \alpha x + \beta$ with $\alpha, \beta \in F$.

Suppose $E[2] \cong E'[2]$ as G_F-modules. By Lemma 4, there is an isomorphism of F-algebras $\phi : F[z]/(g(z)) \xrightarrow{\sim} F[x]/(f(x))$. Write $\phi(z) = 3ux^2 + 3vx + w$ with $u, v, w \in F$. (The extra factors of 3 remove denominators which would otherwise occur in the equation for $\mathcal{E}_{u,v}$ and the formulas below.) The matrix for x acting by multiplication on $F[x]/(f(x))$, with respect to the F-basis $\{1, x, x^2\}$, is $\left(\begin{smallmatrix} 0 & 0 & -b \\ 1 & 0 & -a \\ 0 & 1 & 0 \end{smallmatrix}\right)$.

Therefore the matrix for the action of $\phi(z)$ on $F[x]/(f(x))$ is

$$\begin{pmatrix} w & -3bu & -3bv \\ 3v & w-3au & -3bu-3av \\ 3u & 3v & w-3au \end{pmatrix},$$

which has trace $3w-6au$. However, the trace of z acting by multiplication on $F[z]/(g(z))$ is zero. Since ϕ is an isomorphism, we must have $w=2au$. It follows that the characteristic polynomial of $\phi(z)$ acting on $F[x]/(f(x))$ is

$$\begin{aligned} h(T) = T^3 &+ 3(3av^2+9buv-a^2u^2)T + 27bv^3 - 18a^2uv^2 \\ &- 27abu^2v - (2a^3+27b^2)u^3. \end{aligned}$$

Again, since ϕ is an isomorphism, we conclude that $h(T)=g(T)$, i.e., E' is $\mathcal{E}_{u,v}$ as desired.

Conversely, suppose that $u,v \in F$ are such that

$$\alpha = 3(3av^2+9buv-a^2u^2), \quad \beta = 27bv^3 - 18a^2uv^2 - 27abu^2v - (2a^3+27b^2)u^3.$$

Then working backwards through the argument above, one can show that the map $z \mapsto 3ux^2+3vx+2au$ induces a homomorphism $\phi : F[z]/(g(z)) \to F[x]/(f(x))$. The determinant of ϕ with respect to the bases $\{1,z,z^2\}$ and $\{1,x,x^2\}$ is $27(v^3+au^2v+bu^3)$. However, the discriminant of g is

$$3^6(4a^3+27b^2)(v^3+au^2v+bu^3)^2.$$

Since E' is an elliptic curve, the discriminant of g must be nonzero, and hence the determinant of ϕ is nonzero so ϕ is an isomorphism. By Lemma 4, it follows that $E[2] \cong E'[2]$ as G_F-modules.

The formulas for the j-invariant and the discriminant are immediate. □

Proof of Corollary 2. If $u,v \in F$ are such that $j(E')$ satisfies (i) or (ii), then $\mathcal{E}_{u,v}$ is nonsingular (by the computation of its discriminant in Theorem 1) and $j(E') = j(\mathcal{E}_{u,v})$. If $j(E') \neq 0, 1728$, then E' is a quadratic twist of $\mathcal{E}_{u,v}$. Therefore using Theorem 1, we have $E'[2] \cong \mathcal{E}_{u,v}[2] \cong E[2]$. Conversely, if $E'[2] \cong E[2]$, then by Theorem 1 we can find $u,v \in F$ such that $E' \cong \mathcal{E}_{u,v}$. By Theorem 1 we have (i) and (ii). □

3. A different method

Applying the method of [3] (see also §3 of [5]) to the case $N=2$, one again obtains explicit equations for the family of elliptic curves with mod 2 representation isomorphic to that of E. We show below how the algorithm works in this case. Suppose F is a field with $\mathrm{char}(F) \neq 2,3$, and $E : y^2 = x^3+ax+b$ is an elliptic curve over F. Note that mod 2 representations do not change under quadratic twist. Every elliptic curve E' over F such that the G_F-action on $E'[2]$ is trivial is a quadratic twist of

$$A_\lambda : y^2 = x(x-1)(x-\lambda)$$

with $\lambda \in F - \{0,1\}$. Putting A_λ in Weierstrass form we obtain

$$E_\lambda : y^2 = x^3 + a_4(\lambda)x + a_6(\lambda),$$

where

$$a_4(\lambda) = -\frac{1}{3}(\lambda^2-\lambda+1), \quad a_6(\lambda) = -\frac{1}{27}(2\lambda^3-3\lambda^2-3\lambda+2).$$

The algorithm in §3 of [3] shows that the equations we are looking for are of the form

$$dy^2 = x^3 + a(t)x + b(t) \tag{1}$$

with

$$d \in F, \quad a(t) = \mu^{-2}(\gamma t + 1)^2 a_4(A(t)), \quad \text{and} \quad b(t) = \mu^{-3}(\gamma t + 1)^3 a_6(A(t)),$$

where u_0 satisfies $j(E_{u_0}) = j(E)$, μ satisfies

$$a_4(u_0) = a\mu^2 \qquad \text{and} \qquad a_6(u_0) = b\mu^3,$$

and

$$A(t) = \frac{\alpha t + u_0}{\gamma t + 1}$$

with α and γ chosen so that $a(t), b(t) \in F[t]$.

If $ab \neq 0$, let $j = j(E)$ and let u_0 be a root of the numerator (as a polynomial in λ) of

$$j(E_\lambda) - j = \frac{256 - 768\lambda + (1536 - j)\lambda^2 + (2j - 1792)\lambda^3 + (1536 - j)\lambda^4 - 768\lambda^5 + 256\lambda^6}{\lambda^2(\lambda - 1)^2}.$$

Let

$$\mu = \frac{a_6(u_0)a}{a_4(u_0)b} = \frac{(2u_0^3 - 3u_0^2 - 3u_0 + 2)a}{9(u_0^2 - u_0 + 1)b} \in (F^{\text{sep}})^\times,$$

$$\alpha = \frac{3(u_0 - 2)\mu^3 b}{u_0(u_0 - 1)}, \qquad \gamma = \frac{3(2u_0 - 1)\mu^3 b}{u_0(u_0 - 1)} \quad \in F^{\text{sep}}.$$

With these values, equation (1) becomes

$$dy^2 = x^3 + a(1 + (J - 1)t^2)x + b(1 + 3t - 3(J - 1)t^2 - (J - 1)t^3),$$

where

$$J = \frac{j(E)}{1728} = \frac{4a^3}{4a^3 + 27b^2}.$$

For $d \in F$ and $t \in \mathbf{P}^1(F)$, this gives the elliptic curves over F with mod 2 representation isomorphic to that of E, when $ab \neq 0$.

Similarly, if $b = 0$, then

$$j(E_\lambda) - j(E) = \frac{64\,(-2 + \lambda)^2\,(1 + \lambda)^2\,(-1 + 2\,\lambda)^2}{(-1 + \lambda)^2\,\lambda^2}.$$

With $u_0 = 2$, $\mu = 1/\sqrt{-a}$, $\alpha = 0$, and $\gamma = 3\sqrt{-a}$, equation (1) becomes

$$dy^2 = x^3 + a(1 - 3at^2)x + 2a^2t(1 + at^2).$$

If $a = 0$, then

$$u_0 = \frac{1 + \sqrt{-3}}{2}, \quad \mu = \frac{-1}{b^{1/3}\sqrt{-3}}, \quad \alpha = \frac{b^{1/3}(1 - \sqrt{-3})}{2}, \quad \text{and} \quad \gamma = b^{1/3}$$

yield the equation

$$dy^2 = x^3 + 3btx + b(1 - bt^3).$$

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