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Elliptic curves over totally real cubic fields are modular

Maarten Derickx, Filip Najman and Samir Siksek

We prove that all elliptic curves defined over totally real cubic fields are modular. This builds on previous work of Freitas, Le Hung and Siksek, who proved modularity of elliptic curves over real quadratic fields, as well as recent breakthroughs due to Thorne and to Kalyanswamy.

1. Introduction

Let K be a totally real number field and let E be an elliptic curve over K with conductor $\mathcal{N}$. It is conjectured that such a curve E is *modular* in the following sense: there is a level $\mathcal{N}$ Hilbert newform $\mathfrak{f}$ over K of parallel weight 2 and rational Hecke eigenvalues such that $\mathrm{L}(E, s) = \mathrm{L}(\mathfrak{f}, s)$, where the L-function on the left is the Hasse–Weil L-function of E, and the L-function on the right is the Hecke L-function of $\mathfrak{f}$. This *modularity conjecture* is the natural generalization to totally real fields of the Shimura–Taniyama conjecture for elliptic curves over the rationals. The latter is a celebrated theorem due to Wiles [1995] and Breuil, Conrad, Diamond and Taylor [Breuil et al. 2001]. The earliest results towards the modularity conjecture for elliptic curves going beyond the rationals were due to Jarvis and Manoharmayum [2008], and established modularity of semistable elliptic curves over $\mathbb{Q}(\sqrt{2})$ and $\mathbb{Q}(\sqrt{17})$. In the last 10 years there has been a dramatic strengthening of modularity lifting theorems due to, for example, Breuil and Diamond [2014], Kisin [2009], Gee [2011], and Barnet-Lamb, Gee and Geraghty [Barnet-Lamb et al. 2012, 2013].

By the aforementioned modularity lifting theorems and by now standard modularity switching arguments due to Wiles and to Manoharmayum [2001], a hypothetical nonmodular E/K would therefore necessarily have small $\bmod p$ image for $p = 3, 5, 7$ and would give rise to a K-point on one of a number of modular curves — we make this precise later. In [Freitas et al. 2015], the real quadratic points of these modular curves are shown to be either cuspidal, or to correspond to elliptic curves that have complex multiplication, or rational j-invariants, or that are $\mathbb{Q}$-curves. The authors deduce the following.

Theorem 1 (Freitas, Le Hung and Siksek). *Elliptic curves over real quadratic fields are modular.*

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Recently these modularity lifting results have been substantially strengthened in the cases $p = 5$ and $p = 7$, respectively by Thorne [2016] and Kalyanswamy [2018]. This means that several difficult steps in the proof of Theorem 1 can now be eliminated. In this paper we build on these theorems of Thorne and Kalyanswamy to prove the following.

Theorem 2. *Let K be a totally real cubic number field. Let E be an elliptic curve over K. Then E is modular.*

The computations in this paper were carried out in the computer algebra system `Magma` [Bosma et al. 1997]. The reader can find the `Magma` scripts for verifying these computations in the online supplement.

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2. Images mod 3, 5, 7 and modularity

Let $p \geq 3$ be a prime. Write $B(p)$ for a Borel subgroup of $\mathrm{GL}_2(\mathbb{F}_p)$, and $C_{\mathrm{s}}(p)$ and $C_{\mathrm{ns}}(p)$ respectively for a split and nonsplit Cartan subgroup. Let $C_{\mathrm{s}}^+(p)$ and $C_{\mathrm{ns}}^+(p)$ respectively be their normalizers.

The proof of Theorem 2 is based on the fact that a putative nonmodular curve must have small mod p images for $p = 3$, 5 and 7 simultaneously. We now make the conditions for each prime precise.

Theorem 3. *Let K be a totally real field and E an elliptic curve over K. Suppose that $\bar{\rho}_{E,3}(G_K)$ is not conjugate to a subgroup of $B(3)$ or $C_{\mathrm{s}}^+(3)$. Then E is modular.*

Proof. By the aforementioned modularity lifting results, if $\bar{\rho}_{E,3}(G_{K(\zeta_3)})$ is absolutely irreducible, then E is modular; a proof is given in [Freitas et al. 2015, Theorem 3] but the arguments are well-known.

By [Rubin 1997, Proposition 6], if $\bar{\rho}_{E,3}(G_{K(\zeta_3)})$ is absolutely reducible, then it is conjugate to a subgroup of $B(3)$ or $C_{\mathrm{s}}^+(3)$. □

For $p = 5$ we use the following result due to Thorne [2016].

Theorem 4 (Thorne). *Let K be a totally real field and E an elliptic curve over K. Suppose 5 is not a square in K, and $\bar{\rho}_{E,5}$ is irreducible. Then E is modular.*

For $p = 7$ we use the following result of Kalyanswamy [2018, Proposition 4.3 and Theorem 4.4].

Theorem 5 (Kalyanswamy). *Let K be a totally real field and E an elliptic curve over K. Suppose*:

- $K \cap \mathbb{Q}(\zeta_7) = \mathbb{Q}$.
- *$\bar{\rho}_{E,7}$ is irreducible.*
- *$\bar{\rho}_{E,7}(G_K)$ is not conjugate to a subgroup of $C_{\mathrm{ns}}^+(7)$.*

Then E is modular.

Kalyanswamy's theorem is somewhat more precise, but we shall not need its full strength. We note that $\mathbb{Q}(\zeta_7)^+$ is the only totally real cubic field for which Kalyanswamy's theorem is inapplicable. It is for this reason that we consider elliptic curves defined over that field separately in Section 4.

3. Modular curves

We quickly sketch some background on modular curves; for fuller details the reader may want to consult [Deligne and Rapoport 1973; Freitas et al. 2015, Section 2.2.2; Rohrlich 1997]. Let $\mathbb{H}^* = \mathbb{H} \cup \mathbb{Q} \cup \{\infty\}$ denote the extended upper half-plane. The modular group $\mathrm{SL}_2(\mathbb{Z})$ acts on $\mathbb{H}$ by fractional linear transformations. The quotient $\mathrm{SL}_2(\mathbb{Z})\backslash\mathbb{H}^*$ is a compact Riemann surface of genus 0, and hence is the analytification of a genus 0 algebraic curve defined (a priori) over $\mathbb{C}$ which is denoted by $X(1)$. The set $\mathbb{Q} \cup \{\infty\} \subset \mathbb{H}^*$ forms a single orbit under the action of $\mathrm{SL}_2(\mathbb{Z})$, and hence that orbit corresponds to a point of $X(1)$ which is called the cusp. In fact $X(1)$ has a model defined over $\mathrm{Spec}(\mathbb{Z})$ in which it is identified with $\mathbb{P}^1$, and where the cusp is simply the point at infinity.

Let p be a prime and let H be a subgroup of $\mathrm{GL}_2(\mathbb{F}_p)$ satisfying $\det(H) = \mathbb{F}_p^*$. Associated to H is a congruence subgroup Γ_H which is defined as the preimage of $H \cap \mathrm{SL}_2(\mathbb{F}_p)$ under the map $\mathrm{SL}_2(\mathbb{Z}) \to \mathrm{SL}_2(\mathbb{F}_p)$. The modular curve $X_H/\mathbb{C}$ is the proper algebraic curve whose analytification is the compact Riemann surface $\Gamma_H\backslash\mathbb{H}^*$. In fact the condition $\det(H) = \mathbb{F}_p^*$ ensures that X_H has a model over $\mathrm{Spec}(\mathbb{Z}[1/p])$. The inclusion $\Gamma_H \subset \mathrm{SL}_2(\mathbb{Z})$ induces a morphism $j : X_H \to X(1)$, which is also defined over $\mathrm{Spec}(\mathbb{Z}[1/p])$. The cusps of X_H are the preimages of $\infty \in X(1)$, and thus also the orbits of $\mathbb{Q} \cup \{\infty\}$ under the action of Γ_H.

We now come to the modular interpretation of rational points on X_H, and here it is convenient to make an additional assumption, namely $-I \in H$. Let K be a field of characteristic $\neq p$. Let E/K be an elliptic curve such that $\bar{\rho}_{E,p}(G_K)$ is conjugate to a subgroup of H. Then there is at least one noncuspidal point $P \in X_H(K)$ such that $j(P) = j(E)$ where $j(E)$ is the j-invariant of the elliptic curve E. The converse of this statement is false in general. There is however a partial converse which is true: if $P \in X_H(K)$ is a noncuspidal point and $j(P) \neq 0, 1728$ then there is an elliptic curve E/K such that $\bar{\rho}_{E,p}(G_K)$ is conjugate to a subgroup of H and $j(E) = j(P)$.

If we take $H = B_0(p)$, $C_{\mathrm{s}}^+(p)$, $C_{\mathrm{ns}}^+(p)$ then X_H is the modular curve usually denoted by $X_0(p)$, $X_{\mathrm{split}}(p)$ and $X_{\mathrm{nonsplit}}(p)$ respectively. For convenience, instead of using the standard notation for these modular curves, we shall mostly follow the notation of [Freitas et al. 2015] and denote these modular curves by $X(\mathrm{b}p) := X_0(p)$, $X(\mathrm{s}p) := X_{\mathrm{split}}(p)$ and $X(\mathrm{ns}p) := X_{\mathrm{nonsplit}}(p)$.

Now let K be a totally real cubic field, and for simplicity suppose $K \neq \mathbb{Q}(\zeta_7)^+$. By Theorems 3, 4 and 5, a potentially nonmodular elliptic curve E defined over K would give rise to a noncuspidal K-point P on either $X(\mathrm{b}3)$ or $X(\mathrm{s}3)$, and simultaneously a noncuspidal K-point Q on $X(\mathrm{b}5)$, and simultaneously a noncuspidal K-point R on either $X(\mathrm{b}7)$ or $X(\mathrm{ns}7)$. Observe that $j(P) = j(Q) = j(R) = j(E)$. Thus we obtain a K-point on one of the fiber products

$$X(\mathrm{u}3) \times_{X(1)} X(\mathrm{b}5) \times_{X(1)} X(\mathrm{v}7), \quad \mathrm{u} \in \{\mathrm{b}, \mathrm{s}\}, \quad \mathrm{v} \in \{\mathrm{b}, \mathrm{ns}\}. \tag{1}$$

We denote the normalization of (1) by $X(\mathrm{u}3, \mathrm{b}5, \mathrm{v}7)$. As E is hypothetically nonmodular, it is non-CM, and in particular $j(E) \neq 0, 1728$. The maps $X_H \to X(1)$ are ramified only above $0, 1728$ and ∞, and thus the K-point we obtain from E on (1) is a smooth point and hence gives rise to a K-point on the

normalization $X(\mathrm{u3}, \mathrm{b5}, \mathrm{v7})$. Thus to prove Theorem 2 for $K \neq \mathbb{Q}(\zeta_7)^+$ it is enough to show that K-points on the four possible curves $X(\mathrm{u3}, \mathrm{b5}, \mathrm{v7})$ are cuspidal. In fact it is plainly enough to do this for the two curves $X(\mathrm{b5}, \mathrm{b7})$ and $X(\mathrm{b5}, \mathrm{ns7})$.

An overview of the proof of Theorem 2. In Section 4 we prove modularity of elliptic curves defined over $\mathbb{Q}(\zeta_7)^+$. In view of the above discussion the following two theorems immediately imply Theorem 2.

Theorem 6. *Let K be a totally real cubic field. Then $X(\mathrm{b5}, \mathrm{b7})(K)$ consists only of cusps.*

Theorem 7. *Let K be a cubic field. Then $X(\mathrm{b5}, \mathrm{ns7})(K)$ consists only of cusps.*

The remainder of the paper is devoted to the proof of these two theorems.

4. Modularity of elliptic curves over $\mathbb{Q}(\zeta_7)^+$

In this section we prove Theorem 2 for $K = \mathbb{Q}(\zeta_7)^+$.

Lemma 4.1. *Let $K = \mathbb{Q}(\zeta_7)^+$. Let E be an elliptic curve defined over K. Then E is modular.*

Proof. By Theorem 4 we may suppose that $\bar{\rho}_{E,5}$ is reducible. By Theorem 3 we may suppose that the image of $\bar{\rho}_{E,3}$ is contained in $B(3)$ or $C_s^+(3)$. Thus E gives rise to a noncuspidal K-point on one of the two modular curves $X(\mathrm{b3}, \mathrm{b5})$, $X(\mathrm{s3}, \mathrm{b5})$. It is shown in [Freitas et al. 2015, Section 5.4.2] that these are in fact elliptic curves defined over $\mathbb{Q}$ with Cremona labels `15A1` and `15A3`. We computed the Mordell–Weil groups $X(K)$ for $X = X(\mathrm{b3}, \mathrm{b5}), X(\mathrm{s3}, \mathrm{b5})$ using `Magma`. In both cases we found

$$X(K) = X(\mathbb{Q}) \cong \mathbb{Z}/4\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}.$$

In particular E gives rise to $\mathbb{Q}$-point on X and so is a twist of an elliptic curve defined over $\mathbb{Q}$. It is therefore modular by [Breuil et al. 2001]. □

5. Proof of Theorem 6

Let $X = X(\mathrm{b5}, \mathrm{b7})$ (in standard notation denoted by $X_0(35)$). It is known that X has four $\mathbb{Q}$-points and that these are cusps. Let K be a totally real cubic field. For the proof of Theorem 6 it will be sufficient to show that $X(K) = X(\mathbb{Q})$. Suppose $P \in X(K)\backslash X(\mathbb{Q})$. Let P_1, P_2, P_3 be the conjugates of P given by the three embeddings of K in $\overline{\mathbb{Q}}$, and write $D = P_1 + P_2 + P_3$. Then D is an irreducible $\mathbb{Q}$-rational divisor on X of degree 3. We shall determine all the irreducible $\mathbb{Q}$-rational divisors of degree 3 on X and show that none of them arise from totally real cubic points, giving a contradiction.

The arithmetic of X and its Jacobian are studied in [Freitas et al. 2015, Section 5.1]. The curve X is hyperelliptic of genus 3. A model for X, derived by Galbraith [1996, Section 4.4], is given by

$$X \ : \ y^2 = (x^2 + x - 1)(x^6 - 5x^5 - 9x^3 - 5x - 1). \tag{2}$$

Write $\infty_\pm$ for the two points at infinity. Write J for $J_0(35)$ — the Jacobian of X. Then

$$J(\mathbb{Q}) = \frac{\mathbb{Z}}{24\mathbb{Z}} \cdot [\infty_- - \infty_+] + \frac{\mathbb{Z}}{2\mathbb{Z}} \cdot [3(0, -1) - 3\infty_+].$$

Let $D_1, \ldots, D_{48}$ be rational divisors of degree 0 on X representing the 48 classes in $J(\mathbb{Q})$, and let $D_i' = D_i + 3\infty_+$. Recall that D is an irreducible $\mathbb{Q}$-rational divisor of degree 3. Then $D \sim D_i'$ for some i. We shall write $\mathcal{L}(D_i')$ for the Riemann–Roch space corresponding to D_i' and $|D_i'|$ for the corresponding complete linear system. By Riemann–Roch and Clifford's inequality, $\dim \mathcal{L}(D_i') = 1$ or 2. Moreover, if $\dim \mathcal{L}(D_i') = 2$, then $|D_i'|$ contains a base point (see [Arbarello et al. 1985, Chapter I, Exercise D.9]), and therefore cannot contain an irreducible divisor. To sum up, $D \sim D_i'$ for some $1 \le i \le 48$ such that $\dim \mathcal{L}(D_i') = 1$. We computed these spaces using `Magma`; for this `Magma` uses an algorithm of Hess [2002]. We found that $\dim \mathcal{L}(D_i') = 1$ for precisely 44 of the 48 divisors D_i'. For these, letting f_i be a $\mathbb{Q}$-basis for $\mathcal{L}(D_i')$, gives $D = D_i' + \mathrm{div}(f_i)$ for some i. We found that precisely 28 of the effective degree 3 divisors $D_i' + \mathrm{div}(f_i)$ are irreducible. However, all of these split over a cubic field with a complex embedding giving the required contradiction.

6. The modular curve X(b5, ns7)

We shall henceforth restrict our attention to $X(\mathrm{b5}, \mathrm{ns7})$. To simplify the notation we write $X = X(\mathrm{b5}, \mathrm{ns7})$. We denote the Jacobian of X by $J = J(\mathrm{b5}, \mathrm{ns7})$. The curve X and its Jacobian J are studied in Le Hung's thesis [2014, Section 6.4] and we make extensive use of his results. In particular, this curve is nonhyperelliptic and has genus 6.

The Jacobian $J = J$(b5, ns7). Le Hung shows that

$$J \sim A_1 \times A_2 \times A_3$$

where $\sim$ here denotes isogeny over $\mathbb{Q}$, and A_1, A_2, A_3 are modular abelian surfaces defined over $\mathbb{Q}$. Moreover the A_i are absolutely simple. The involution w_5 on J is compatible with the isogeny and acts by multiplication by $1, -1, -1$ respectively on A_1, A_2, A_3. The analytic ranks of A_1, A_2, A_3 are respectively 2, 0, 0. In particular, by the work of Kolyvagin and Logachëv [1989], the Mordell–Weil groups $A_2(\mathbb{Q})$ and $A_3(\mathbb{Q})$ are torsion. We immediately deduce the following.

Lemma 6.1. *Let $A/\mathbb{Q}$ be the abelian subvariety of J that is the image of $w_5 - 1$. Then $A \sim A_2 \times A_3$ has dimension 4. Moreover, the Mordell–Weil group $A(\mathbb{Q})$ is torsion.*

Le Hung's model for $X = X$(b5, ns7). We need a good model for $X(\mathrm{b5}, \mathrm{ns7})$. Le Hung [2014, page 47] gives a model which will be a good starting point for us. We briefly sketch Le Hung's derivation of his model, but work with projective rather than affine coordinates. Later we explain how to derive a better model. The curves $X(\mathrm{b5})$ and $X(\mathrm{ns7})$ are both isomorphic to $\mathbb{P}^1$ over $\mathbb{Q}$. Let

$$\begin{aligned}
F_1(x_1, x_2) &= (x_1^2 + 10x_1x_2 + 5x_2^2)^3,\\
F_2(x_1, x_2) &= x_1x_2^5,\\
G_1(y_1, y_2) &= 64 \cdot (y_1 \cdot (y_1^2 + 7y_2^2) \cdot (y_1^2 - 7y_1y_2 + 14y_2^2) \cdot (5y_1^2 - 14y_1y_2 - 7y_2^2))^3, \text{ and}\\
G_2(y_1, y_2) &= (y_1^3 - 7y_1^2y_2 + 7y_1y_2^2 + 7y_2^3)^7.
\end{aligned}$$

For appropriate choices of projective coordinates $(x_1 : x_2)$ for $X(\mathrm{b5})$ and $(y_1 : y_2)$ on $X(\mathrm{ns7})$, the j-maps are given by

$$j : X(\mathrm{b5}) \to X(1), \quad (x_1 : x_2) \mapsto (F_1(x_1, x_2) : F_2(x_1, x_2)),$$

and

$$j : X(\mathrm{ns7}) \to X(1), \quad (y_1, y_2) \mapsto (G_1(y_1, y_2) : G_2(y_1, y_2)).$$

As X is the normalization of $X(\mathrm{b5}) \times_{X(1)} X(\mathrm{ns7})$ we immediately deduce the following model for X in $\mathbb{P}^1 \times \mathbb{P}^1$:

$$C : F_1(x_1, x_2)G_2(y_1, y_2) = F_2(x_1, x_2)G_1(y_1, y_2).$$

The curve X is the normalization of this model. The parametrization $(x_1 : x_2)$ on $X(\mathrm{b5})$ is chosen so that the 0 and ∞ cusps are $(x_1 : x_2) = (0 : 1)$ and $(x_1 : x_2) = (1 : 0)$, respectively. We shall denote these by a_0, and a_∞. Let ζ_7 be a primitive 7-th root of unity. Let $\eta = 2(\zeta_7 + \zeta_7) + 3 \in \mathbb{Q}(\zeta_7)^+$. Then $G_2(\eta : 1) = 0$. The three cusps of $X(\mathrm{ns7})$ are $(\eta : 1)$ and its Galois conjugates. It follows that the cusps of X are the points belonging to the normalization of C lying above the points $(x_1 : x_2, y_1 : y_2) = (0 : 1, \eta : 1)$, $(1 : 0, \eta : 1)$ and their Galois conjugates. Although these points on C are singular, it is easy to check (see [Freitas et al. 2015, Section 5.5.1]) that there is only one point on the normalization above each, and to deduce:

- X has two Galois orbits of cusps, both of degree 3 and defined over $\mathbb{Q}(\zeta_7)^+$, which we denote by c_0, c_∞.
- The three cusps in c_0 map to a_0, and the three cusps in c_∞ map to a_∞ on $X(\mathrm{b5})$.
- The divisor of x_1/x_2 interpreted as a function on X is $7 \cdot (c_0 - c_\infty)$. In particular, the class $[c_0 - c_\infty]$ is an element of order 1 or 7. There are several ways to show that the divisor $c_0 - c_\infty$ is not principal, and so its class has order 7. One way is by direct computation using `Magma`, working with the model D introduced below. Here is another way: we shall show below that X has gonality 4. As c_0, c_∞ have degree 3 they cannot be linearly equivalent.

A plane degree 6 model for $X = X(\mathrm{b5}, \mathrm{ns7})$. We used `Magma` to compute, starting with the model C, the canonical map and its image. The latter is indeed a smooth genus 6 curve cut out in $\mathbb{P}^5$ by six homogeneous degree 2 polynomials. By the Enriques–Babbage theorem [Arbarello et al. 1985, page 124], we know that X is neither trigonal, nor isomorphic to a plane quintic. Moreover, as the factors A_i of the Jacobian are 2-dimensional and absolutely simple, we see that the curve is not bielliptic. It follows (see [loc. cit., pages 209–210]) that X has gonality 4 and a degree 6 planar model, with four ordinary double points as singularities. We used the inbuilt `Magma` implementation for writing down this model, and found that two of the four double points are defined over $\mathbb{Q}(i)$ and the other two over $\mathbb{Q}(\sqrt{5})$. After applying a $\mathbb{Q}$-rational automorphism of $\mathbb{P}^2$ to slightly simplify this degree 6 model, it is given by the following equation:

$$\begin{aligned} D : {} & 5u^6 - 50u^5v + 206u^4v^2 - 408u^3v^3 + 321u^2v^4 + 10uv^5 - 100v^6 + 9u^4w^2 \\ & - 60u^3vw^2 + 80u^2v^2w^2 + 48uv^3w^2 + 15v^4w^2 + 3u^2w^4 - 10uvw^4 + 6v^2w^4 - w^6 = 0. \end{aligned}$$

On this model D the double points are

$$p_1 = (i : 0 : 1), \quad p_2 = (-i : 0 : 1), \quad p_3 = \left(0 : \frac{1}{\sqrt{5}} : 1\right), \quad p_4 = \left(0 : -\frac{1}{\sqrt{5}} : 1\right).$$

It is clear that D has an automorphism $(u : v : w) \mapsto (-u : -v : w)$. The curve X has an obvious modular involution which is w_5. The following lemma proves that w_5 coincides with the automorphism $(u : v : w) \mapsto (-u : -v : w)$.

Lemma 6.2. *The $\mathbb{Q}$-rational automorphism group of $X(b5, ns7)$ is generated by w_5, i.e.,* $\mathrm{Aut}_{\mathbb{Q}}(X) = \langle w_5 \rangle \cong \mathbb{Z}/2\mathbb{Z}$.

Proof. As described in [Arbarello et al. 1985, pages 210–211] a degree 6 planar curve with four ordinary double points such as D has exactly five different g_4^1. Namely, one given by the pencil of quadrics going through all four points, and the other four coming from the pencil of lines through each of the p_i. Since none of the p_i are $\mathbb{Q}$-rational, only the first g_4^1 is defined over $\mathbb{Q}$. Now every g_6^2 on such a curve is residual to a g_4^1. This means that there is only one $\mathbb{Q}$-rational g_6^2, namely the one corresponding to the degree 6 model given by u, w, v above. In particular every $\mathbb{Q}$-rational automorphism has to come from an automorphism $h : \mathbb{P}^2_{\mathbb{Q}} \to \mathbb{P}^2_{\mathbb{Q}}$ in the degree 6 model. Such an automorphism h has to preserve the singular locus $\{p_1, p_2, p_3, p_4\}$ and is in fact uniquely determined by what it does on this singular locus. Of the 24 automorphisms of $\mathbb{P}^2_{\mathbb{Q}}$ preserving $\{p_1, p_2, p_3, p_4\}$, only the ones of the form $(u : v : w) \mapsto (\pm u : \pm v : w)$ are $\mathbb{Q}$-rational. One easily sees that of these four only the identity and $(u : v : w) \mapsto (-u : -v : w)$ are actually automorphisms of the curve. □

Transferring c_0 and c_∞ to our new model D, we find that they respectively are the Galois orbits of the following two points defined over $\mathbb{Q}(\eta) = \mathbb{Q}(\zeta_7)^+$ by

$$(-4\eta^2 + 21\eta + 7 : -\eta^2 + 7\eta : 14), \quad (4\eta^2 - 21\eta - 7 : \eta^2 - 7\eta : 14).$$

We note that these are interchanged by $w_5 : (u : v : w) \mapsto (-u : -v : w)$ as expected.

The Mordell–Weil group $A(\mathbb{Q})$. In Lemma 6.1 we defined the abelian subvariety A of J as the image of $w_5 - 1$ and observed that $A(\mathbb{Q})$ is torsion. We can now pin down $A(\mathbb{Q})$ precisely. In particular, applying the function field class group algorithm of Hess [2002] (implemented in `Magma`) to our model D, we obtain

$$J(\mathbb{F}_3) \cong \mathbb{Z}/7\mathbb{Z} \times \mathbb{Z}/(7 \cdot 23)\mathbb{Z}, \quad \text{and} \quad J(\mathbb{F}_{17}) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/(2^2 \cdot 7^3 \cdot 31 \cdot 271)\mathbb{Z}.$$

Hence $J(\mathbb{Q})_{\mathrm{tors}}$ is isomorphic to a subgroup of $\mathbb{Z}/7\mathbb{Z}$. Recall that the class $[c_0 - c_\infty]$ has order 7. Thus $[c_0 - c_\infty]$ generates $J(\mathbb{Q})_{\mathrm{tors}}$. Now since w_5 interchanges c_0 and c_∞,

$$(w_5 - 1)([3c_0 - 3c_\infty]) = 6[c_\infty - c_0] = [c_0 - c_\infty].$$

Therefore $[c_0 - c_\infty] \in A(\mathbb{Q})$. As $A(\mathbb{Q}) = A(\mathbb{Q})_{\mathrm{tors}} \subseteq J(\mathbb{Q})_{\mathrm{tors}} = \mathbb{Z}/7\mathbb{Z}$ we have now proved the following.

Lemma 6.3. $A(\mathbb{Q}) = (\mathbb{Z}/7\mathbb{Z}) \cdot [c_0 - c_\infty]$.

7. Proof of Theorem 7

In this section we prove Theorem 7 thereby completing the proof of Theorem 2. Recall $X = X(\mathrm{b5}, \mathrm{ns7})$. Write $X^{(3)}$ for the third symmetric power of X. We shall prove the following result which immediately implies Theorem 7.

Proposition 7.1. $$X^{(3)}(\mathbb{Q}) = \{c_0,\ c_\infty\}.$$

Proof. Let $x \in X^{(3)}(\mathbb{Q})$. By Lemma 6.3 we have $(1 - w_5)[x - c_\infty] = \ell \cdot [c_0 - c_\infty]$ for some $\ell \in \mathbb{Z}/7\mathbb{Z}$. As $w_5(c_\infty) = c_0$ we may rewrite this as

$$(x - w_5(x)) \sim k \cdot (c_0 - c_\infty)$$

for some $k \in \{-3, \ldots, 3\}$. We write $x_{\mathbb{F}_3}, c_{0,\mathbb{F}_3}, c_{\infty,\mathbb{F}_3} \in X^{(3)}(\mathbb{F}_3)$ for the reductions of x, c_0, c_∞ modulo 3 respectively. It follows that

$$(y - w_5(y)) \sim k \cdot (c_{0,\mathbb{F}_3} - c_{\infty,\mathbb{F}_3}) \tag{3}$$

where $y = x_{\mathbb{F}_3}$. Using our model D we enumerated $X^{(3)}(\mathbb{F}_3)$; this has precisely 40 elements. For each $y \in X^{(3)}(\mathbb{F}_3)$ and for each $k = -3, \ldots, 3$ we tested the relation (3) and found that it holds only for $y = c_{0,\mathbb{F}_3}$ and $k = 1$ and for $y = c_{\infty,\mathbb{F}_3}$ and $k = -1$. We therefore deduce that $x_{\mathbb{F}_3} = c_{0,\mathbb{F}_3}$ or $c_{\infty,\mathbb{F}_3}$. We would like to conclude that $x = c_0$ or c_∞. As w_5 swaps c_0 and c_∞ and also their mod 3 reductions, we may suppose that $x_{\mathbb{F}_3} = c_\infty$. Let $\mu : X^{(3)} \to J$ be given by $z \mapsto [z - c_\infty]$ and $t : J \to A$ be simply $t = w_5 - 1$. Since $x_{\mathbb{F}_3} = c_{\infty,\mathbb{F}_3}$, the point $(t \circ \mu)(x) \in A(\mathbb{Q})$ belongs to the kernel of reduction $A(\mathbb{Q}) \to A(\mathbb{F}_3)$. However as $A(\mathbb{Q})$ is torsion, this kernel of reduction is trivial [Katz 1981, Appendix]. Thus $(t \circ \mu)(x) = 0$. To conclude that $x = c_\infty$ it is now enough to check that $t \circ \mu$ is a formal immersion at $c_{\infty,\mathbb{F}_3}$, and for this we shall use the formal immersion criterion due to Derickx, Kamienny, Stein and Stoll [Derickx et al. 2017, Proposition 3.7].

Write $\Omega_X \cong \Omega_J$ for the 6-dimensional space of 1-forms on $X/\mathbb{F}_3$. We would like to write down the 4-dimensional subspace $t^*(\Omega_A)$. We easily do this since it is precisely that -1-eigenspace of w_5^* acting on Ω_X, and we know the action of w_5 on our model D from which can write down the corresponding action on the 1-forms. Let $\omega_1, \ldots, \omega_4$ be an $\mathbb{F}_3$-basis for $t^*(\Omega_A)$. To check the formal immersion criterion of Derickx et al. at $c_{\infty,\mathbb{F}_3}$ we need to check that a certain 4×3 matrix defined in [Derickx et al. 2017, Proposition 3.7], which we denote by M, has rank 3. As 3 is inert in $\mathbb{Q}(\zeta_7)^+$, we have $c_{\infty,\mathbb{F}_3} = P_1 + P_2 + P_3$, where $P_i \in X(\mathbb{F}_{27})$ are distinct. This slightly simplifies the description of the matrix M. Let $u_j \in \mathbb{F}_{27}(X)$ be a uniformizing element for P_j. Then ω_i/du_j is a regular function at P_j and we may evaluate $(\omega_i/du_j)(P_j) \in \mathbb{F}_{27}$. That matrix is simply

$$M = ((\omega_i/du_j)(P_j))_{i=1,2,3,4;\ j=1,2,3}.$$

We computed M and checked that it has rank 3 as required. This completes the proof. □

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