

Pacific Journal of Mathematics

**TORSION POINTS AND GALOIS REPRESENTATIONS ON
CM ELLIPTIC CURVES**

ABBÉY BOURDON AND PETE L. CLARK

Volume 305 No. 1

March 2020

TORSION POINTS AND GALOIS REPRESENTATIONS ON CM ELLIPTIC CURVES

ABBIEY BOURDON AND PETE L. CLARK

We prove several results on torsion points and Galois representations for complex multiplication (CM) elliptic curves over a number field containing the CM field. One result computes the degree in which such an elliptic curve has a rational point of order N , refining results of Silverberg (*Compositio Math.* **68:3** (1988), 241–249; *Contemp. Math.* **133** (1992)). Another result bounds the size of the torsion subgroup of an elliptic curve with CM by a nonmaximal order in terms of the torsion subgroup of an elliptic curve with CM by the maximal order. Our techniques also yield a complete classification of both the possible torsion subgroups and the rational cyclic isogenies of a K -CM elliptic curve E defined over $K(j(E))$.

1. Introduction	43
2. Preliminaries	48
3. Proof of the Isogeny Torsion Theorem	54
4. The projective torsion point field	56
5. Proof of Theorem 1.4 and its corollaries	59
6. Applications	62
7. The Torsion Degree Theorem	74
Acknowledgments	86
References	86

1. Introduction

Let F be a field of characteristic 0, and let E/F be an elliptic curve. We say E has *complex multiplication* (CM) if the endomorphism algebra

$$\operatorname{End}^0 E = \operatorname{End}(E_{/\bar{F}}) \otimes_{\mathbb{Z}} \mathbb{Q}$$

is strictly larger than \mathbb{Q} , in which case it is necessarily an imaginary quadratic field K and $\mathcal{O} := \operatorname{End}(E_{/\bar{F}})$ is a \mathbb{Z} -order in K .

The general theory of complex multiplication has a long and rich history, with important contributions made by Kronecker, Weber, Fricke, Hasse, Deuring, and

MSC2010: 11G05, 11G15.

Keywords: torsion points, elliptic curves, Galois representations, complex multiplication.

Shimura. For a summary of these foundational results, see [Silverman 1994, Chapter 2]. More recent contributions to the study of torsion points and Galois representations on CM elliptic curves defined over number fields have been made by Olson [1974], Silverberg [1988; 1992], Parish [1989], Aoki [1995; 2006], Ross [1994], Kwon [1999], Prasad and Yogananda [2001], Stevenhagen [2001], Breuer [2010], Lombardo [2017], Lozano-Robledo [2018b], Gaudron and Rémond [2018] and the present authors and our collaborators [Clark et al. 2013; 2014; Bourdon et al. 2017a; 2017b; Clark and Pollack 2015; Bourdon and Pollack 2017]. In this paper, we consider the case of a CM elliptic curve defined over a number field that contains the CM field. The case in which the ground field is a number field not assumed to contain the CM field is pursued in [Bourdon and Clark 2019]. There is related work of Á. Lozano-Robledo [2018a] done concurrently with the present work, which determines all possible images of the ℓ -adic Galois representations of a CM elliptic curve E over $\mathbb{Q}(j(E))$ up to conjugacy.

Throughout this introduction we maintain the following notation: K is an imaginary quadratic field, \mathcal{O} is an order in K , \mathfrak{f} is the conductor of \mathcal{O} , $K(\mathfrak{f})$ is the \mathfrak{f} -ring class field of K (i.e., $K(\mathfrak{f}) = K(j(E))$ for any \mathcal{O} -CM elliptic curve E), F is a number field containing K and N is a positive integer.

1A. The Torsion Degree Theorem. Let \mathcal{O} be an order in the imaginary quadratic field K , and let $N \in \mathbb{Z}^+$. The following result was first proven by Silverberg [1988; 1992] and then subsequently by Prasad and Yogananda [2001].

Theorem 1.1 (Silverberg). *Let $F \supset K$ be a number field, and suppose that there is an \mathcal{O} -CM elliptic curve $E_{/F}$ with an F -rational point of order N . Then*

$$\varphi(N) \leq \#\mathcal{O}^\times \cdot [F : K].$$

Theorem 1.1 is a crucial result in the study of torsion subgroups of CM elliptic curves over general number fields. For instance, it was the main tool in the complete enumeration of torsion subgroups of CM elliptic curves defined over number fields of small degree [Clark et al. 2013; 2014].

The hypotheses of Theorem 1.1 force $F \supset K(\mathfrak{f}) = K(j(E))$. Thus it is natural to define $T(\mathcal{O}, N)$ to be the least degree $[F : K(\mathfrak{f})]$ of a number field $F \supset K$ over which some \mathcal{O} -CM elliptic curve admits an F -rational point of order N . We show in Theorem 6.2 that

$$(1) \quad \varphi(N) \mid \#\mathcal{O}^\times \cdot T(\mathcal{O}, N),$$

i.e., Theorem 1.1 holds as a divisibility.

Our first main result computes $T(\mathcal{O}, N)$ in all cases and gives the analogous divisibility refinement.

Theorem 1.2. *Let \mathcal{O} be an order in the imaginary quadratic field K , and let N be a positive integer. There is an integer $T(\mathcal{O}, N)$, explicitly computed in Section 7, such that*

- (i) *if $F \supset K$ is a number field and $E_{/F}$ is an \mathcal{O} -CM elliptic curve with an F -rational point of order N , then $T(\mathcal{O}, N) \mid [F : K(\mathfrak{f})]$, and*
- (ii) *there is a number field $F \supset K$ and an \mathcal{O} -CM elliptic curve $E_{/F}$ such that $[F : K(\mathfrak{f})] = T(\mathcal{O}, N)$ and $E(F)$ has a point of order N .*

Equivalently, Theorem 1.2 determines the least degree of a closed \mathcal{O} -CM point on $X_1(N)_{/K}$ and shows that this degree divides the degree of all closed \mathcal{O} -CM points.

1B. The Isogeny Torsion Theorem. A key feature of the present work is that we work with *all* imaginary quadratic orders \mathcal{O} , not just the maximal order \mathcal{O}_K . Working with nonmaximal orders entails certain technical complications. For instance, if $F \supset K$ is a number field, then $E(F)[\text{tors}]$ is a finite \mathcal{O} -submodule of $E(\mathbb{C})$. As we will see in Section 2B, every finite \mathcal{O} -submodule of $E(\mathbb{C})$ is cyclic if and only if the order \mathcal{O} is maximal.

The phenomenon of “ascending isogenies” can sometimes be used to study \mathcal{O} -CM elliptic curves in terms of \mathcal{O}_K -CM elliptic curves, and this happens twice in the present paper. Specifically, let E be an \mathcal{O} -CM elliptic curve defined over a number field F , and let \mathfrak{f}' be a positive integer that divides \mathfrak{f} . Then by [Bourdon and Pollack 2017, Proposition 2.2], there is an elliptic curve $(E_{\mathfrak{f}'})_{/F}$ such that $\mathcal{O}(\mathfrak{f}') := \text{End } E_{\mathfrak{f}'}$ is the order of conductor \mathfrak{f}' in K and an F -rational isogeny $\iota_{\mathfrak{f}'} : E \rightarrow E_{\mathfrak{f}'}$ that is cyclic of degree $\mathfrak{f}/\mathfrak{f}'$. There is an embedding $F \hookrightarrow \mathbb{C}$ such that the base change of $\iota_{\mathfrak{f}'}$ to \mathbb{C} is the natural map $\mathbb{C}/\mathcal{O} \rightarrow \mathbb{C}/\mathcal{O}(\mathfrak{f}')$ of complex elliptic curves. The map $\iota_{\mathfrak{f}'}$ is universal for maps from an \mathcal{O} -CM elliptic curve to an $\mathcal{O}(\mathfrak{f}')$ -CM elliptic curve [Bourdon and Clark 2019, §2.6] and is thus unique, up to isomorphism on the target. Here is the first result making use of this canonical isogeny.

Theorem 1.3 (Isogeny Torsion Theorem). *Let \mathcal{O} be an order in an imaginary quadratic field K , of conductor \mathfrak{f} , and let \mathfrak{f}' be a positive integer dividing \mathfrak{f} . Let $F \supset K$ be a number field, and let $E_{/F}$ be an \mathcal{O} -CM elliptic curve. Let $\iota_{\mathfrak{f}'} : E \rightarrow E_{\mathfrak{f}'}$ be the F -rational isogeny to an elliptic curve $E_{\mathfrak{f}'}$ with CM by the order in K of conductor \mathfrak{f}' , as described above. Then we have*

$$\#E(F)[\text{tors}] \mid \#E_{\mathfrak{f}'}(F)[\text{tors}].$$

In particular, taking $\mathfrak{f}' = 1$, we see that $\#E(F)[\text{tors}]$ is bounded by $\#E_1(F)[\text{tors}]$, where $(E_1)_{/F}$ is an \mathcal{O}_K -CM elliptic curve. We give examples where the exponent of $E_{\mathfrak{f}'}(F)[\text{tors}]$ is strictly smaller than that of $E(F)[\text{tors}]$, showing in general we cannot view $E(F)[\text{tors}]$ as a subgroup of $E_{\mathfrak{f}'}(F)[\text{tors}]$, and we prove

that $\#E_{\mathfrak{f}}(F)[\text{tors}]/\#E(F)[\text{tors}]$ can be arbitrarily large (see Propositions 6.8 and 6.9). Moreover, the statement is false if we do not require $F \supset K$. Theorem 1.3 has applications to determining fields of moduli of partial level N structures (Sections 6B and 6C).

1C. The reduced Galois representation. There is a well-known interplay between points on modular curves over number fields and Galois representations of elliptic curves. The proofs of Theorems 1.2 and 1.3 make use of Galois representations, and in the former case we build on a nearly complete description of the image of the mod N Galois representation on an \mathcal{O} -CM elliptic $E_{/K(\mathfrak{f})}$.

For an elliptic curve E defined over a number field F and a positive integer N , the \mathbb{Z} -linear action of $\mathfrak{g}_F := \text{Aut}(\bar{F}/F)$ on $E[N]$ gives rise to the mod N Galois representation:

$$\rho_N : \mathfrak{g}_F \rightarrow \text{GL}_2(\mathbb{Z}/N\mathbb{Z}).$$

When E does not have CM, a celebrated result of Serre [1972] asserts that as N varies over all positive integers, the index $[\text{GL}_2(\mathbb{Z}/N\mathbb{Z}) : \rho_N(\mathfrak{g}_F)]$ remains bounded. This is certainly not the case when E has CM: as usual, here we consider the case in which F is a number field containing the CM field K . Then for $N \in \mathbb{Z}^+$, Galois acts by \mathcal{O} -linear endomorphisms of $E[N]$, which is a free $\mathcal{O}/N\mathcal{O}$ -module of rank one. Thus the mod N Galois representation takes the form

$$\rho_N : \mathfrak{g}_F \rightarrow (\mathcal{O}/N\mathcal{O})^\times \hookrightarrow \text{GL}_2(\mathbb{Z}/N\mathbb{Z}).$$

In the CM case, the analogue of Serre's result is the boundedness of the index of ρ_N in $(\mathcal{O}/N\mathcal{O})^\times$ as N varies. In fact more is true: a slight variant of ρ_N is surjective for all \mathcal{O} and N . To motivate this, observe that fixing \mathcal{O} is the same as fixing $j(E)$ (up to Galois conjugacy), but fixing $j(E)$ does not determine the $K(\mathfrak{f})$ -rational model of E and thus not ρ_N . One gets from one model to another via a twist by $d \in K(\mathfrak{f})^\times/K(\mathfrak{f})^{\times\#\mathcal{O}^\times}$. If E and E^d are elliptic curves over $K(\mathfrak{f})$ and $\rho_E, \rho_{E^d} : \mathfrak{g}_{K(\mathfrak{f})} \rightarrow (\mathcal{O}/N\mathcal{O})^\times$ are their mod N Galois representations, then $\rho_{E^d} = \rho_E \otimes \chi_d$, where $\chi_d : \mathfrak{g}_{K(\mathfrak{f})} \rightarrow \mathcal{O}^\times$ is the character corresponding to d . Thus we define the *reduced mod N Cartan subgroup*

$$\overline{C_N(\mathcal{O})} = C_N(\mathcal{O})/q_N(\mathcal{O}^\times)$$

to be the quotient of $C_N(\mathcal{O}) = (\mathcal{O}/N\mathcal{O})^\times$ by the image of \mathcal{O}^\times under the natural map $q_N : \mathcal{O} \rightarrow \mathcal{O}/N\mathcal{O}$ and the *reduced mod N Galois representation* to be the composite homomorphism

$$\overline{\rho}_N : \mathfrak{g}_F \xrightarrow{\rho_N} C_N(\mathcal{O}) \rightarrow \overline{C_N(\mathcal{O})}.$$

The key feature of $\overline{\rho}_N$ is that it is independent of the $K(\mathfrak{f})$ -rational model.

For an elliptic curve E defined over a field F of characteristic 0, there is an F -rational isomorphism $\iota : E/\text{Aut}(E) \xrightarrow{\sim} \mathbb{P}^1$, and a *Weber function* on E is

any function $\mathfrak{h} : E \rightarrow \mathbb{P}^1$ obtained by composing the quotient map with such an isomorphism ι . Then the field extension cut out by the reduced Galois representation is the field obtained by adjoining to $K(\mathfrak{f})$ the values of the Weber function on the N -torsion points of E :

$$\overline{\mathbb{Q}}^{\ker \overline{\rho}_N} = K(\mathfrak{f})(\mathfrak{h}(E[N])).$$

When $\mathcal{O} = \mathcal{O}_K$ the first main theorem of complex multiplication tells us that for any ideal I of \mathcal{O}_K we have that $K(\mathfrak{f})(\mathfrak{h}(E[I]))$ is $K^{(I)}$, the I -ray class field of K . It turns out that

$$[K^{(I)} : K^{(1)}] = \#C_N(\mathcal{O})$$

and thus $\overline{\rho}_N$ is surjective. The case of an arbitrary order is much less classical but still known: Stevenhagen [2001] used Shimura's reciprocity law to show that for all $N \in \mathbb{Z}^+$, the Weber function field $K(\mathfrak{f})(\mathfrak{h}(E[N]))$ is $K(\mathfrak{f})^{N\mathcal{O}_K}$, the N -ray class field of \mathcal{O} —this is the finite abelian extension of K corresponding to the image of the subgroup $\mathbb{C}^\times \times \{x \in \widehat{\mathcal{O}}^\times \mid x \equiv 1 \pmod{N}\}$ in the norm one idèle class group of K . Moreover, it follows from the adelic description [Stevenhagen 2001, p. 8] that

$$\text{Aut}(K(\mathfrak{f})^{N\mathcal{O}_K} / K(\mathfrak{f})) = \overline{C_N(\mathcal{O})}.$$

Thus we have the following result.

Theorem 1.4 (Stevenhagen). *Let \mathcal{O} be an order in the imaginary quadratic field K , and let $N \in \mathbb{Z}^+$. Then the reduced mod N Galois representation*

$$\overline{\rho}_N : \mathfrak{g}_{K(\mathfrak{f})} \rightarrow \overline{C_N(\mathcal{O})}$$

is surjective and $\overline{\mathbb{Q}}^{\ker \overline{\rho}_N} = K(\mathfrak{f})^{N\mathcal{O}_K}$, the N -ray class field of \mathcal{O} .

We will give a new proof of Theorem 1.4, as follows. Let $E_{/K(\mathfrak{f})}$ be an \mathcal{O} -CM elliptic curve. Using the canonical isogeny $\iota_1 : E \rightarrow E_1$ to an \mathcal{O}_K -CM elliptic curve, we show that the torsion field $K(\mathfrak{f})(E[N])$ contains the ray class field $K^{N\mathcal{O}_K}$; Theorem 2.11(b). Using an observation of Parish we show that $K(\mathfrak{f})(E[N])$ contains the ring class field $K(N\mathfrak{f})$; Theorem 4.1. By Theorem 2.10(c), we have

$$K(\mathfrak{f})(\mathfrak{h}(E[N])) \supset K^{N\mathcal{O}_K} K(N\mathfrak{f}) = K(\mathfrak{f})^{N\mathcal{O}_K},$$

where the last equality can be shown using class field theory (Section 5A). Since

$$[K(\mathfrak{f})(\mathfrak{h}(E[N])) : K(\mathfrak{f})] \leq \#\overline{C_N(\mathcal{O})} = [K(\mathfrak{f})^{N\mathcal{O}_K} : K(\mathfrak{f})],$$

we get

$$\overline{\mathbb{Q}}^{\ker \overline{\rho}_N} = K(\mathfrak{f})(\mathfrak{h}(E[N])) = K(\mathfrak{f})^{N\mathcal{O}_K}.$$

Theorem 1.4 has the following useful consequences:

Corollary 1.5. *For all number fields $F \supset K$ and all \mathcal{O} -CM elliptic curves $E_{/F}$ we have*

$$[C_N(\mathcal{O}) : \rho_N(\mathfrak{g}_F)] \mid \#\mathcal{O}^\times[F : K(\mathfrak{f})] \leq 6[F : K(\mathfrak{f})].$$

Remark 1.6. Corollary 1.5 strengthens a result of D. Lombardo [2017, Theorem 1.5], who showed that $[C_N(\mathcal{O}) : \rho_N(\mathfrak{g}_F)] \leq 6[F : K]$.

Corollary 1.7. *Let $N \in \mathbb{Z}^+$. There is a number field $F \supset K$ and an \mathcal{O} -CM elliptic curve $E_{/F}$ such that $E[N] = E[N](F)$ and $[F : K(j(E))] = \#\overline{C_N(\mathcal{O})}$.*

Corollary 1.8. *For all $N \in \mathbb{Z}^+$, there is an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ such that $\rho_{E,N}(\mathfrak{g}_{K(\mathfrak{f})}) = C_N(\mathcal{O})$.*

Using Theorems 1.2 and 1.4 we also obtain a complete classification of the set of $N \in \mathbb{Z}^+$ such that an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ admits a $K(\mathfrak{f})$ -rational cyclic N -isogeny, and of the possible torsion subgroups of an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$. See Sections 6F and 6G.

2. Preliminaries

2A. Foundations. We begin by setting some terminology for orders in imaginary quadratic fields. Let K be an imaginary quadratic field, with ring of integers \mathcal{O}_K , and let $w_K := \#\mathcal{O}_K^\times$ be the number of roots of unity in K . Let \mathcal{O} be a \mathbb{Z} -order in K . Let $\mathfrak{f} = [\mathcal{O}_K : \mathcal{O}]$ be the conductor of \mathcal{O} , and let Δ be the discriminant of \mathcal{O} . Then

$$\mathcal{O} = \mathbb{Z} + \mathfrak{f}\mathcal{O}_K, \quad \Delta = \mathfrak{f}^2 \Delta_K.$$

For fixed K and $\mathfrak{f} \in \mathbb{Z}^+$ there is a unique order $\mathcal{O}(\mathfrak{f})$ in K of conductor \mathfrak{f} . Thus an imaginary quadratic order is determined by its discriminant Δ , a negative integer which is 0 or 1 modulo 4. Conversely, for any negative integer Δ which is 0 or 1 modulo 4, we put

$$\tau_\Delta = \frac{\Delta + \sqrt{\Delta}}{2},$$

and then $\mathbb{Z}[\tau_\Delta]$ is an order in $K = \mathbb{Q}(\sqrt{\Delta})$ of discriminant Δ .

Throughout this paper we will use the following terminological convention: by “an order \mathcal{O} ” we always mean a \mathbb{Z} -order \mathcal{O} in an imaginary quadratic field, which is determined as the fraction field of \mathcal{O} and denoted by K . We may specify an order \mathcal{O} by giving its discriminant, which also determines K . If K is already given, then we specify an order \mathcal{O} in K by giving the conductor \mathfrak{f} .

For any \mathcal{O} -CM elliptic curve E we have $K(j(E)) = K(\mathfrak{f})$, the ring class field of K of conductor \mathfrak{f} ([Cox 1989, Theorem 11.1]) Thus $[K(j(E)) : K]$ is determined via the following formula.

Theorem 2.1. For $N \in \mathbb{Z}^+$, let $K(N)$ denote the *N -ring class field* of K . Then $K(1) = K^{(1)}$ is the Hilbert class field of K , and for all $N \geq 2$ we have

$$[K(N) : K^{(1)}] = \frac{2}{w_K} N \prod_{p|N} \left(1 - \left(\frac{\Delta_K}{p}\right) \frac{1}{p}\right).$$

Proof. See, e.g., [Cox 1989, Corollary 7.24]. \square

For a number field F , $N \in \mathbb{Z}^+$ and E/F an elliptic curve, we denote by ρ_N the homomorphism

$$\mathfrak{g}_F \rightarrow \text{Aut } E[N] \cong \text{GL}_2(\mathbb{Z}/N\mathbb{Z}),$$

the *modulo N Galois representation*. If E/F has CM by the order \mathcal{O} in K , then $E[N] \cong_{\mathcal{O}} \mathcal{O}/N\mathcal{O}$ — i.e., we have an isomorphism of \mathcal{O} -modules (see [Parish 1989, Lemma 1], generalized in Lemma 2.4 below) — and provided $F \supset K$ we have

$$\rho_N : \mathfrak{g}_F \hookrightarrow \text{Aut}_{\mathcal{O}} E[N] \cong \text{GL}_1(\mathcal{O}/N\mathcal{O}) = (\mathcal{O}/N\mathcal{O})^{\times}.$$

In other words, the image of the mod N Galois representation lands in the *mod N Cartan subgroup*

$$C_N(\mathcal{O}) = (\mathcal{O}/N\mathcal{O})^{\times}.$$

Lemma 2.2. Let \mathcal{O} be an order of discriminant Δ , and let $N = p_1^{a_1} \cdots p_r^{a_r} \in \mathbb{Z}^+$.

(a) We have $C_N(\mathcal{O}) = \prod_{i=1}^r C_{p_i^{a_i}}(\mathcal{O})$ (canonical isomorphism).

(b) We have $\#C_N(\mathcal{O}) = N^2 \prod_{p|N} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right) \left(1 - \frac{1}{p}\right)$.

Proof. (a) It suffices to tensor the Chinese remainder theorem isomorphism $\mathbb{Z}/N\mathbb{Z} = \prod_{i=1}^r \mathbb{Z}/p_i^{a_i}\mathbb{Z}$ with the \mathbb{Z} -module \mathcal{O} and pass to the unit groups.

(b) By [Clark et al. 2013], for any prime number p we have

$$\#C_p(\mathcal{O}) = p^2 \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right) \left(1 - \frac{1}{p}\right).$$

The natural map $C_{p^a}(\mathcal{O}) \rightarrow C_p(\mathcal{O})$ is surjective with kernel of size p^{2a-2} [Clark and Pollack 2015, p. 3]. Together with part (a) this shows that if $N = p_1^{a_1} \cdots p_r^{a_r}$ then

$$\#C_N(\mathcal{O}) = \prod_{i=1}^r p_i^{2a_i-2} (p_i - 1) \left(p_i - \left(\frac{\Delta}{p_i}\right)\right) = N^2 \prod_{p|N} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right) \left(1 - \frac{1}{p}\right). \quad \square$$

2B. Torsion kernels. Let E/\mathbb{C} be an \mathcal{O} -CM elliptic curve. For a nonzero ideal I of \mathcal{O} , we define the *I -torsion kernel*

$$E[I] := \{P \in E \mid \text{for all } \alpha \in I, \alpha P = 0\}.$$

There is an invertible ideal $\Lambda \subset \mathcal{O}$ such that

$$E \cong \mathbb{C}/\Lambda.$$

If we put

$$(\Lambda : I) := \{x \in \mathbb{C} \mid xI \subset \Lambda\} = \{x \in K \mid xI \subset \Lambda\}$$

then we have (immediately) that

$$E[I] = \{x \in \mathbb{C}/\Lambda \mid xI \subset \Lambda\} = (\Lambda : I)/\Lambda.$$

Let $|I| := \#\mathcal{O}/I$.

Lemma 2.3. *Let $I, J \subset \mathcal{O}$ be nonzero ideals and E/\mathbb{C} be an \mathcal{O} -CM elliptic curve.*

- (a) *If $I \subset J$, then $E[J] \subset E[I]$.*
- (b) *We have $E[I] \subset E[|I|]$. In particular,*

$$\#E[I] \leq |I|^2.$$

Proof. (a) This is immediate from the definition.

(b) By Lagrange's theorem, every element of \mathcal{O}/I is killed by $|I|$, so $|I| \in |I|\mathcal{O} \subset I$. Apply part (a). \square

Lemma 2.4. *If I is an invertible \mathcal{O} -ideal, then*

$$E[I] = I^{-1}\Lambda/\Lambda \cong_{\mathcal{O}} \mathcal{O}/I.$$

In particular, $\#E[I] = |I| = \#\mathcal{O}/I$.

Proof. An ideal I is invertible if and only if there is an \mathcal{O} -submodule I^{-1} of K such that $II^{-1} = \mathcal{O}$. If so, then for $x \in K$ we have

$$xI \subset \Lambda \iff xII^{-1} = x\mathcal{O} \subset I^{-1}\Lambda \iff x \in I^{-1}\Lambda,$$

giving $E[I] = I^{-1}\Lambda/\Lambda$. Because Λ is a locally free \mathcal{O} -module, for all $\mathfrak{p} \in \text{Spec } \mathcal{O}$ we have $\Lambda_{\mathfrak{p}} \cong \mathcal{O}_{\mathfrak{p}}$ and thus $(I^{-1}\Lambda/\Lambda)_{\mathfrak{p}} \cong (I^{-1}/\mathcal{O})_{\mathfrak{p}} \cong (\mathcal{O}/I)_{\mathfrak{p}}$. Thus $I^{-1}\Lambda/\Lambda$ is locally free of rank one as an \mathcal{O}/I -module. But the ring \mathcal{O}/I is semilocal, and hence has trivial Picard group: any locally free rank one \mathcal{O}/I -module is isomorphic to \mathcal{O}/I [Clark 2015, Corollary 13.38]. \square

Lemma 2.5. *Let R be a Dedekind domain, and let M be a cyclic torsion R -module, and let $N \subset M$ be an R -submodule. Then:*

- (a) *N is also a cyclic R -module.*
- (b) *We have $N \cong R/\text{ann } N$.*

Proof. Let $I = \text{ann } M$. Since M is a finitely generated torsion module over a domain, we have $I \neq 0$ and $M \cong R/I$. Thus $N \cong I'/I$ for some ideal $I' \supset I$. The ring R/I

is principal Artinian [Clark 2015, Theorem 20.11], so the ideal I'/I of R/I is principal. Thus N is a cyclic, torsion R -module, so $N \cong R/\text{ann } N$. \square

Theorem 2.6. *Let E/\mathbb{C} be an \mathcal{O}_K -CM elliptic curve, and let $M \subset E(\mathbb{C})$ be a finite \mathcal{O}_K -submodule. Then $M = E[\text{ann } M] \cong_{\mathcal{O}_K} \mathcal{O}_K/\text{ann } M$ and thus $\#M = |\text{ann } M|$.*

Proof. That $M \subset E[\text{ann } M]$ is a tautology. Because \mathcal{O}_K is a Dedekind domain, every nonzero \mathcal{O}_K -ideal is invertible, so Lemma 2.4 gives $\#E[\text{ann } M] = |\text{ann } M|$. On the other hand, let $t = \#M$. Then $M \subset E[t] \cong_{\mathcal{O}_K} \mathcal{O}_K/t\mathcal{O}_K$, a finite cyclic \mathcal{O}_K -module. By Lemma 2.5 we have $M \cong \mathcal{O}_K/\text{ann } M$ so $\#M = |\text{ann } M|$. Thus $M = E[\text{ann } M]$, so Lemma 2.4 gives $M \cong \mathcal{O}_K/\text{ann } M$ and $\#M = |\text{ann } M|$. \square

Example 2.7. Theorem 2.6 fails for all nonmaximal orders. Indeed, let \mathcal{O} be a nonmaximal order in an imaginary quadratic field K . There is nonzero prime ideal \mathfrak{p} of \mathcal{O} such that the local ring $\mathcal{O}_{\mathfrak{p}}$ is not a DVR. If $\mathfrak{p} \cap \mathbb{Z} = (\ell)$, then $\mathcal{O}/\mathfrak{p} \cong \mathbb{Z}/\ell\mathbb{Z}$. Since every ideal of \mathcal{O} can be generated by two elements, we have $\dim_{\mathcal{O}/\mathfrak{p}} \mathfrak{p}/\mathfrak{p}^2 = 2$. Thus $\#\mathcal{O}/\mathfrak{p}^2 = \ell^3$ and $(\ell^3) \subset \mathfrak{p}^2$. It follows that in the quotient ring $\mathcal{O}/\ell^3\mathcal{O}$, the maximal ideal $\mathfrak{p} + \ell^3\mathcal{O}$ is not principal. Let E/\mathbb{C} be an \mathcal{O} -CM elliptic curve, so $E[\ell^3] \cong_{\mathcal{O}} \mathcal{O}/\ell^3\mathcal{O}$. So the \mathcal{O} -submodule $M = \mathfrak{p}E[\ell^3]$ of $E[\ell^3]$ is not cyclic and thus not isomorphic to $\mathcal{O}/\text{ann } M$.

For a nonzero ideal I of \mathcal{O}_K , let K^I denote the I -ray class field of K .

Theorem 2.8 (first main theorem of complex multiplication). *Let E/\mathbb{C} be an \mathcal{O}_K -CM elliptic curve, and let I be a nonzero ideal of \mathcal{O}_K . Let $\mathfrak{h} : E \rightarrow \mathbb{P}^1$ be a Weber function. Then:*

$$K^{(1)}(\mathfrak{h}(E[I])) = K^I.$$

Proof. See, e.g., [Silverman 1994, Theorem II.5.6]. \square

Combining Theorems 2.6 and 2.8, we get the class-field theoretic containment corresponding to any finite \mathcal{O}_K -submodule of $E(\bar{F})$, for any \mathcal{O}_K -CM elliptic curve E defined over a number field $F \supset K$.

For convenience, we record here the formulas for $[K^I : K^{(1)}]$. Here, φ denotes Euler's totient function and $\varphi_K(I)$ the natural generalization for a nonzero ideal I of \mathcal{O}_K . That is,

$$\varphi_K(I) = \#(\mathcal{O}_K/I)^\times = |I| \prod_{\mathfrak{p}|I} \left(1 - \frac{1}{|\mathfrak{p}|}\right).$$

Lemma 2.9. *Let I be a nonzero ideal of K . We put $U_I(K) = \{x \in U(K) \mid x - 1 \in I\}$ and $U(K) = \mathcal{O}_K^\times$.*

(a) *We have*

$$[K^I : K^{(1)}] = \frac{\varphi_K(I)}{[U(K) : U_I(K)]}.$$

(b) If $K \neq \mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{-3})$, then

$$[K^I : K^{(1)}] = \begin{cases} \varphi_K(I), & I \mid (2), \\ \frac{\varphi_K(I)}{2}, & I \nmid (2). \end{cases}$$

(c) If $K = \mathbb{Q}(\sqrt{-1})$, then

$$[K^I : K^{(1)}] = \begin{cases} \varphi_K(I), & I \mid (1+i), \\ \frac{\varphi_K(I)}{2}, & I \nmid (1+i) \text{ and } I \mid (2), \\ \frac{\varphi_K(I)}{4}, & I \nmid (2). \end{cases}$$

(d) If $K = \mathbb{Q}(\sqrt{-3})$, then

$$[K^I : K^{(1)}] = \begin{cases} 1, & I = (1), \\ \frac{\varphi_K(I)}{2}, & I \neq (1) \text{ and } I \mid (\zeta_3 - 1), \\ \frac{\varphi_K(I)}{3}, & I = (2), \\ \frac{\varphi_K(I)}{6}, & \text{otherwise.} \end{cases}$$

Proof. Parts (b)–(d) can be deduced from (a), which appears as [Cohen 2000, Corollary 3.2.4]. \square

2C. On Weber functions. Let F be a field of characteristic 0. For an elliptic curve E/F , let $\mathfrak{h} : E \rightarrow \mathbb{P}^1$ be a Weber function for E (cf. Section 1C).

Theorem 2.10 (Weber function principle). *Let $N \in \mathbb{Z}^{\geq 2}$, let \mathcal{O} be the order of conductor \mathfrak{f} in K , and let $F = K(\mathfrak{f})$. For an \mathcal{O} -CM elliptic curve E/F , fix an embedding $F \hookrightarrow \mathbb{C}$ such that $j(E) = j(\mathbb{C}/\mathcal{O})$. Define*

$$W(N, \mathcal{O}) = K(\mathfrak{f})(\mathfrak{h}(E[N])).$$

(a) $W(N, \mathcal{O})$ is a subfield of $F(E[N])$ and $[F(E[N]) : W(N, \mathcal{O})]$ divides

$$\begin{cases} \#\mathcal{O}^\times, & N \geq 3, \\ \frac{\#\mathcal{O}^\times}{2}, & N = 2. \end{cases}$$

(b) There is an elliptic curve E/F such that

$$[F(E[N]) : W(N, \mathcal{O})] = \begin{cases} \#\mathcal{O}^\times, & N \geq 3, \\ \frac{\#\mathcal{O}^\times}{2}, & N = 2. \end{cases}$$

(c) As we range over all elliptic curves E/F with $j(E) = j(\mathbb{C}/\mathcal{O})$, we have

$$\bigcap_E F(E[N]) = W(N, \mathcal{O}).$$

Proof. (a) Let

$$w = \begin{cases} \#\mathcal{O}^\times, & N \geq 3, \\ \frac{\#\mathcal{O}^\times}{2}, & N = 2. \end{cases}$$

Let μ_w be the image of $\mathcal{O}^\times \rightarrow C_N(\mathcal{O})$, a cyclic group of order w . The field $F(E[N])/F$ is Galois with Galois group $\rho_N(\mathfrak{g}_F) \subset C_N(\mathcal{O})$. Since $\mathfrak{h}(P) = \mathfrak{h}(Q)$ for points P, Q on E if and only if there is $\xi \in \mathcal{O}^\times$ such that $\xi(P) = Q$ (e.g., [Lang 1987, Theorem I.7]), it follows that

$$W(N, \mathcal{O}) = F(E[N])^{\rho_N(\mathfrak{g}_F) \cap \mu_w}.$$

Thus

$$[F(E[N]) : W(N, \mathcal{O})] \mid w.$$

(b) and (c) If $E/F, E'/F$ with $j(E) = j(E')$, then $K(\mathfrak{f})(\mathfrak{h}(E[N])) = K(\mathfrak{f})(\mathfrak{h}(E'[N]))$ by the model independence of the Weber function. So $W(N, \mathcal{O}) \subset \bigcap_E F(E[N])$. To see that equality holds, let E/F have $j(E) = j(\mathbb{C}/\mathcal{O})$. Let \mathfrak{p} be a prime of \mathcal{O}_F that is unramified in $F' = F(E[N])$. By weak approximation, there is $\pi \in \mathfrak{p} \setminus \mathfrak{p}^2$. Put $L = F(\pi^{1/w})$, and let $\chi : \mathfrak{g}_F \rightarrow \mu_w$ be a character with splitting field $\bar{F}^{\ker \chi} = L$. (Explicitly, we may take $\chi(\sigma) = \sigma(\pi^{1/w})/\pi^{1/w}$.) Then L/F is totally ramified over \mathfrak{p} , so F' and L are linearly disjoint over F . It follows that

$$\rho_{N, E^\chi}(\mathfrak{g}_{F'}) = (\rho_{N, E/F'} \otimes \chi)(\mathfrak{g}_{F'}) = \chi(\mathfrak{g}_{F'}) = \mu_w.$$

Thus

$$w = [F(E^\chi[N]) : F(E[N]) \cap F(E^\chi[N])] \mid [F(E^\chi[N]) : W(N, \mathcal{O})] \mid w,$$

so $F(E^\chi[N])$ has degree w over $W(N, \mathcal{O}) = F(E[N]) \cap F(E^\chi[N])$. \square

2D. A containment of Weber function fields.

Theorem 2.11. *Let K be an imaginary quadratic field, and let $\mathcal{O} \subset \mathcal{O}'$ be orders in K .*

- (a) *For all $N \in \mathbb{Z}^+$ we have a containment of Weber function fields $W(N, \mathcal{O}) \supset W(N, \mathcal{O}')$.*
 - (b) *If E is a K -CM elliptic curve defined over a number field $F \supset K$, then we have*
- $$(2) \quad F(\mathfrak{h}(E[N])) \supset K^{N\mathcal{O}_K}.$$

Proof. (a) Let \mathfrak{f} (resp. \mathfrak{f}') be the conductor of \mathcal{O} (resp. of \mathcal{O}'), so $\mathfrak{f}' \mid \mathfrak{f}$. Let $E_{/K(\mathfrak{f})}$ be an \mathcal{O} -CM elliptic curve. Let $\iota = \iota_{\mathfrak{f}, \mathfrak{f}'} : E \rightarrow E'$ be the canonical cyclic $\mathfrak{f}/\mathfrak{f}'$ -isogeny to an \mathcal{O}' -CM elliptic curve $(E')_{/K(\mathfrak{f})}$. There is an embedding $K(\mathfrak{f}) \hookrightarrow \mathbb{C}$ such that $E(\mathbb{C}) \cong E/\mathcal{O}$ and $(E')(\mathbb{C}) \cong E/\mathcal{O}'$ and $\iota : E/\mathcal{O} \rightarrow E/\mathcal{O}'$ is the natural map. Then ι maps $\frac{1}{N} + \mathcal{O}$ to $\frac{1}{N} + \mathcal{O}'$, which generates $E'[N]$ as an \mathcal{O}' -module. Thus

$$K(\mathfrak{f})(E[N]) \supset K(\mathfrak{f})(E'[N]) \supset K(\mathfrak{f}')(E'[N]) \supset W(N, \mathcal{O}'),$$

and Theorem 2.10(c) gives

$$W(N, \mathcal{O}) \supset W(N, \mathcal{O}').$$

(b) This follows from part (a) and Theorem 2.8. \square

Though Theorem 2.11 is a consequence of Theorem 1.4, we prove it here as an ingredient in our new proof of Theorem 1.4. Part (b) had been proved earlier in [Bourdon et al. 2017b, Theorem 3.16], but the present argument seems more transparent.

3. Proof of the Isogeny Torsion Theorem

For a quadratic field K and $d \in \mathbb{Z}^+$ we will write $\mathcal{O}(d)$ for the unique order in K of conductor d . We recall the setup: let $F \supset K$ be a number field, let E/F be an elliptic curve with endomorphism ring an order \mathcal{O} of conductor \mathfrak{f} in K , and let \mathfrak{f}' be a positive integer that divides \mathfrak{f} . Then there is a canonical F -rational cyclic $\mathfrak{f}/\mathfrak{f}'$ -isogeny $\iota_{\mathfrak{f}'} : E \rightarrow E_{\mathfrak{f}'}$ such that $\text{End } E_{\mathfrak{f}'} = \mathcal{O}(\mathfrak{f}')$.

There is a field embedding $F \hookrightarrow \mathbb{C}$ such that $E(\mathbb{C}) \cong \mathbb{C}/\mathcal{O}(\mathfrak{f})$, $E_{\mathfrak{f}'}(\mathbb{C}) \cong \mathbb{C}/\mathcal{O}(\mathfrak{f}')$ and $(\iota_{\mathfrak{f}'})_{/\mathbb{C}}$ is the quotient map $\mathbb{C}/\mathcal{O}(\mathfrak{f}) \rightarrow \mathbb{C}/\mathcal{O}(\mathfrak{f}')$. Put $\tau_K = \frac{1}{2}(\Delta_K + \sqrt{\Delta_K})$, so $\mathcal{O}(\mathfrak{f}) = \mathbb{Z}[\mathfrak{f}\tau_K]$ and $\mathcal{O}(\mathfrak{f}') = \mathbb{Z}[\mathfrak{f}'\tau_K]$. For $N \in \mathbb{Z}^+$, let

$$\begin{aligned} e_{1,\mathfrak{f}}(N) &:= \frac{1}{N} + \mathcal{O}(\mathfrak{f}), & e_{2,\mathfrak{f}}(N) &:= \frac{\mathfrak{f}\tau_K}{N} + \mathcal{O}(\mathfrak{f}), \\ e_{1,\mathfrak{f}'}(N) &:= \frac{1}{N} + \mathcal{O}(\mathfrak{f}'), & e_{2,\mathfrak{f}'}(N) &:= \frac{\mathfrak{f}'\tau_K}{N} + \mathcal{O}(\mathfrak{f}'). \end{aligned}$$

Then $\ker(E[N] \xrightarrow{\iota_{\mathfrak{f}'}} E_{\mathfrak{f}'}[N])$ is cyclic of order $\gcd(N, \mathfrak{f}/\mathfrak{f}')$, generated by

$$\frac{N}{\gcd(N, \frac{\mathfrak{f}}{\mathfrak{f}'})} e_{2,\mathfrak{f}}(N),$$

and $\iota_{\mathfrak{f}'}(e_{1,\mathfrak{f}}(N)) = e_{1,\mathfrak{f}'}(N)$.

For finite commutative groups T_1 and T_2 , we have $\#T_1 \mid \#T_2$ if and only if $\#T_1[\ell^\infty] \mid \#T_2[\ell^\infty]$ for all prime numbers ℓ . So it suffices to show that for all prime numbers ℓ , we have $\#E(F)[\ell^\infty] \mid \#E_{\mathfrak{f}'}(F)[\ell^\infty]$. Write $\mathfrak{f} = \ell^{c_1} \bar{\mathfrak{f}}$ with $\gcd(\bar{\mathfrak{f}}, \ell) = 1$ and $\mathfrak{f}' = \ell^{c_2} \bar{\mathfrak{f}}'$ with $\gcd(\bar{\mathfrak{f}}', \ell) = 1$. Then we have

$$\#E(F)[\ell^\infty] = \#E_{\ell^{c_1}}(F)[\ell^\infty], \quad \#E_{\mathfrak{f}'}(F)[\ell^\infty] = \#E_{\ell^{c_2}}(F)[\ell^\infty],$$

so we may assume that $\mathfrak{f} = \ell^{c_1}$ and $\mathfrak{f}' = \ell^{c_2}$. Indeed, it is enough to treat the case $c_2 = c_1 - 1$, since repeated application of this case yields the general case. So suppose $\mathfrak{f} = \ell^c$ for some $c \in \mathbb{Z}^+$ and $\mathfrak{f}' = \ell^{c-1}$. By, for example, the Mordell–Weil theorem, there are integers $0 \leq a \leq b$ such that

$$E(F)[\ell^\infty] \cong \mathbb{Z}/\ell^a \mathbb{Z} \oplus \mathbb{Z}/\ell^b \mathbb{Z}.$$

Let $Q := \frac{1}{\ell^a} + \mathcal{O}(\mathfrak{f}) \in E(F)$. Since $\iota_{\mathfrak{f}}$ is F -rational, $Q' := \iota_{\mathfrak{f}}(Q) = \frac{1}{\ell^a} + \mathcal{O}(\mathfrak{f}')$ lies in $E_{\mathfrak{f}}(F)$ and generates $E_{\mathfrak{f}}[\ell^a]$ as an $\mathcal{O}(\mathfrak{f}')$ -module, so $E_{\mathfrak{f}}[\ell^a] = E_{\mathfrak{f}}(F)[\ell^a]$. If $a = b$, it follows that $\#E(F)[\ell^\infty] \mid \#E_{\mathfrak{f}}(F)[\ell^\infty]$, so we may assume $b > a$. Since $\ker(E[\ell^\infty] \xrightarrow{\iota_{\mathfrak{f}}} E_{\mathfrak{f}}[\ell^\infty])$ has order ℓ , we have $\mathbb{Z}/\ell^a\mathbb{Z} \oplus \mathbb{Z}/\ell^{b-1}\mathbb{Z} \hookrightarrow E_{\mathfrak{f}}(F)[\ell^\infty]$. Thus it suffices to show that $E_{\mathfrak{f}}(F)$ has either a point of order ℓ^b or has full ℓ^{a+1} -torsion.

Let $P = E(F)$ be a point of order ℓ^b , and write $P = \alpha e_{1,\mathfrak{f}}(\ell^b) + \beta e_{2,\mathfrak{f}}(\ell^b)$ with $\alpha, \beta \in \mathbb{Z}/\ell^b\mathbb{Z}$. If $\ell \nmid \alpha$ then since $\mathfrak{f} = \ell\mathfrak{f}'$ we have that $\iota_{\mathfrak{f}}(P) = \alpha e_{1,\mathfrak{f}'}(\ell^b) + \ell\beta e_{2,\mathfrak{f}'}(\ell^b)$ has order ℓ^b and we are done, so we may assume that $\ell \mid \alpha$, in which case $\ell \nmid \beta$. With respect to the basis $e_{1,\mathfrak{f}}(\ell^b), e_{2,\mathfrak{f}}(\ell^b)$ of $E[\ell^b]$, the image of the mod ℓ^b Galois representation on E consists of matrices of the form

$$(3) \quad \begin{bmatrix} a & b\ell^{2c} \frac{\Delta_K - \Delta_K^2}{4} \\ b & a + b\ell^c \Delta_K \end{bmatrix} \text{ with } a, b \in \mathbb{Z}/\ell^b\mathbb{Z}.$$

Since $E(F)$ has full ℓ^a -torsion, we have $a \equiv 1 \pmod{\ell^a}$ and $b \equiv 0 \pmod{\ell^a}$. Thus

$$\rho_{\ell^{a+1}}(\mathfrak{g}_F) \subset \left\{ \begin{bmatrix} 1 + \ell^a A & 0 \\ \ell^a B & 1 + \ell^a A \end{bmatrix} \mid A, B \in \mathbb{Z}/\ell^{a+1}\mathbb{Z} \right\}.$$

Since $\ell^{b-a-1}P = \alpha e_{1,\mathfrak{f}}(\ell^{a+1}) + \beta e_{2,\mathfrak{f}}(\ell^{a+1})$ is F -rational, all such matrices in the image of Galois satisfy

$$\begin{bmatrix} 1 + \ell^a A & 0 \\ \ell^a B & 1 + \ell^a A \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \alpha \\ \beta \end{bmatrix},$$

and thus $\ell^a \alpha B + \beta + \ell^a A \beta \equiv \beta \pmod{\ell^{a+1}}$. Since $\ell \mid \alpha$, we get

$$\ell^a A \beta \equiv -\ell^a \alpha B \equiv 0 \pmod{\ell^{a+1}},$$

and thus $\ell \mid A$ and $\rho_{\ell^{a+1}}(\mathfrak{g}_F)$ consists of matrices of the form

$$\begin{bmatrix} 1 & 0 \\ \ell^a B & 1 \end{bmatrix}$$

for $B \in \mathbb{Z}/\ell^{a+1}\mathbb{Z}$. It follows that for all $\sigma \in \mathfrak{g}_F$, there is $B \in \mathbb{Z}/\ell^{a+1}\mathbb{Z}$ such that

$$\begin{aligned} \sigma(\iota_{\mathfrak{f}}(e_{1,\mathfrak{f}}(\ell^{a+1}))) &= \iota_{\mathfrak{f}}(e_{1,\mathfrak{f}}(\ell^{a+1}) + B\ell^a \iota_{\mathfrak{f}}(e_{2,\mathfrak{f}}(\ell^{a+1}))) \\ &= \iota_{\mathfrak{f}}(e_{1,\mathfrak{f}}(\ell^{a+1})) + B\ell^a (\ell e_{2,\mathfrak{f}'}(\ell^{a+1})) = \iota_{\mathfrak{f}}(e_{1,\mathfrak{f}}(\ell^{a+1})). \end{aligned}$$

Thus $e_{1,\mathfrak{f}}(\ell^{a+1}) = \iota_{\mathfrak{f}}(e_{1,\mathfrak{f}}(\ell^{a+1})) \in E_{\mathfrak{f}}(F)$. Since the $\mathcal{O}(\mathfrak{f}')$ -submodule generated by $e_{1,\mathfrak{f}}(\ell^{a+1})$ is $E_{\mathfrak{f}}[\ell^{a+1}]$, we get $\mathbb{Z}/\ell^{a+1}\mathbb{Z} \oplus \mathbb{Z}/\ell^{a+1}\mathbb{Z} \hookrightarrow E_{\mathfrak{f}}(F)$, completing the proof of Theorem 1.3.

4. The projective torsion point field

Let F be a field. For a positive integer N not divisible by the characteristic of F and E/F an elliptic curve, we define the *projective modulo N Galois representation* as the composite map

$$\mathbb{P}\rho_N : \mathfrak{g}_F \xrightarrow{\rho_N} \text{Aut } E[N] \cong \text{GL}_2(\mathbb{Z}/N\mathbb{Z}) \rightarrow \text{PGL}_2(\mathbb{Z}/N\mathbb{Z}) := \text{GL}_2(\mathbb{Z}/N\mathbb{Z})/(\mathbb{Z}/N\mathbb{Z})^\times.$$

The *projective torsion field* is

$$F(\mathbb{P}E[N]) = \bar{F}^{\ker \mathbb{P}\rho_N}.$$

Thus $F(\mathbb{P}E[N])$ is the unique minimal field extension of F on which the image of ρ_N consists of scalar matrices. It follows that $F(E[N])/F(\mathbb{P}E[N])$ is a Galois extension with automorphism group a subgroup of $(\mathbb{Z}/N\mathbb{Z})^\times$.

Observe that the projective Galois representation and thus the projective torsion field are unchanged by *quadratic* twists. If E/F has CM by an order of discriminant $\Delta = \mathfrak{f}^2 \Delta_K \neq -3, -4$ and $F \supset K$, then the projective N -torsion field is a well-defined abelian extension of $K(\mathfrak{f})$. When $\Delta = -4$ (resp. $\Delta = -3$) we have quartic twists (resp. sextic twists) which can change the projective Galois representation and the projective torsion field.

Theorem 4.1. *Let \mathcal{O} be an order of discriminant $\Delta = \mathfrak{f}^2 \Delta_K$. Let E be an \mathcal{O} -CM elliptic curve defined over $F = K(\mathfrak{f})$. Let $N \geq 2$.*

(a) ([Parish 1989]) *We have $F(\mathbb{P}E[N]) \supset K(N\mathfrak{f})$. Thus we may put*

$$d(E, N) = [F(\mathbb{P}E[N]) : K(N\mathfrak{f})].$$

(b) ([Parish 1989]) *If $\Delta \notin \{-3, -4\}$, then $d(E, N) = 1$, i.e., $F(\mathbb{P}E[N]) = K(N\mathfrak{f})$.*

(c) *If $\Delta = -4$, then $d(E, N) \mid 2$.*

(d) *If $\Delta = -3$, then $d(E, N) \mid 3$.*

Proof. For $N \in \mathbb{Z}^+$, let $\mathcal{O}(N)$ be the order of conductor N in K . Thus $\mathcal{O} = \mathcal{O}(\mathfrak{f})$.

Step 1: We show that $F(\mathbb{P}E[N]) \supset K(N\mathfrak{f})$ in all cases.

There is a field embedding $F \hookrightarrow \mathbb{C}$ such that $E(\mathbb{C}) \cong \mathbb{C}/\mathcal{O}$. The \mathbb{C} -linear map $z \mapsto Nz$ carries $\mathcal{O}(\mathfrak{f})$ into $\mathcal{O}(N\mathfrak{f})$ and induces a cyclic N -isogeny $\mathbb{C}/\mathcal{O}(\mathfrak{f}) \rightarrow \mathbb{C}/\mathcal{O}(N\mathfrak{f})$. Let C be the kernel of this isogeny, viewed as a finite étale subgroup scheme of E/\mathbb{C} . Then C has a (unique) minimal field of definition $F(C) \subset F(E[N])$, hence of finite degree over F . The field $F(\mathbb{P}E[N])$ is precisely the compositum of the minimal fields of definition of all order N cyclic subgroup schemes $C \subset E/\mathbb{C}$, so $F(C) \subset F(\mathbb{P}E[N])$. Since C is $F(\mathbb{P}E[N])$ -rational, the elliptic curve E/C has a model over this field, and thus

$$F(\mathbb{P}E[N]) \supset K(j(E/C)) = K(N\mathfrak{f}).$$

Step 2: In view of Step 1, we have $F(\mathbb{P}E[N]) \supset K(N\mathfrak{f}) \supset K(\mathfrak{f}) = K(j(E))$, so we have $F(\mathbb{P}E[N]) = K(N\mathfrak{f})$ if and only if $[F(\mathbb{P}E[N]) : K(\mathfrak{f})] \leq [K(N\mathfrak{f}) : K(\mathfrak{f})]$. We have

$$[F(\mathbb{P}E[N]) : K(\mathfrak{f})] = \# \mathbb{P} \rho_N(\mathfrak{g}_F) \leq \#(\mathcal{O}/N\mathcal{O})^\times / (\mathbb{Z}/N\mathbb{Z})^\times = N \prod_{p|N} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right).$$

- Suppose $\mathfrak{f} > 1$. Using Theorem 2.1 to compute $[K(N\mathfrak{f}) : K^{(1)}]$ and $[K(\mathfrak{f}) : K^{(1)}]$ gives

$$[K(N\mathfrak{f}) : K(\mathfrak{f})] = \frac{[K(N\mathfrak{f}) : K^{(1)}]}{[K(\mathfrak{f}) : K^{(1)}]} = N \prod_{p|N, p \nmid \mathfrak{f}} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right) = N \prod_{p|N} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right),$$

because $1 - \left(\frac{\Delta}{p}\right) \frac{1}{p} = 1$ for all $p \mid \mathfrak{f}$. Thus $d(E, N) = 1$ in this case.

- Suppose $\mathfrak{f} = 1$, so $\Delta = \Delta_K$. Then

$$[K(N\mathfrak{f}) : K(\mathfrak{f})] = [K(N) : K^{(1)}] = \frac{2}{w_K} N \prod_{p|N} \left(1 - \left(\frac{\Delta}{p}\right) \frac{1}{p}\right).$$

If $\Delta \notin \{-3, -4\}$ then $\frac{2}{w_K} = 1$, and again we get $d(E, N) = 1$. If $\Delta = -4$ then $\frac{2}{w_K} = \frac{1}{2}$, so the calculation shows $d(E, N) \in \{1, 2\}$, and if $\Delta = -3$ then $\frac{2}{w_K} = \frac{1}{3}$, so the calculation shows $d(E, N) \in \{1, 3\}$. \square

Remark 4.2. (a) Theorem 4.1(a) and (b) are due to Parish [1989, Proposition 3].

However, he alludes to a calculation of the above sort rather than explicitly carrying it out. Since Theorem 4.1 will play an important role in the proof of Theorem 1.4, we have given a complete proof.

(b) Parish [1989, Proposition 3] assumes $K \neq \mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{-3})$. Later [1989, p. 263], he claims

- if $\Delta = -4$ then $F(\mathbb{P}E[N]) = K(N)$ for all $N \geq 3$, and
- if $\Delta = -3$ then $F(\mathbb{P}E[N]) = K(N)$ for all $N \geq 4$.

As we will see shortly in Example 4.4, both claims are false.

The following result is an analogue of [Bourdon et al. 2017b, Theorem 5.6] for higher twists.

Proposition 4.3 (higher twisting at the bottom). *For $M \in \mathbb{Z}^+$, we denote the mod M cyclotomic character by χ_M .*

- (a) *Let $K = \mathbb{Q}(\sqrt{-1})$ and let $\ell \equiv 5 \pmod{8}$ be a prime number. There is a character $\Psi : \mathfrak{g}_K \rightarrow (\mathbb{Z}/\ell\mathbb{Z})^\times$ of order $\frac{\ell-1}{4}$ and an \mathcal{O}_K -CM elliptic curve E/K such that the mod ℓ Galois representation is*

$$\sigma \mapsto \rho_\ell(\sigma) = \begin{bmatrix} \Psi(\sigma) & 0 \\ 0 & \Psi^{-1}(\sigma)\chi_\ell(\sigma) \end{bmatrix}.$$

- (b) Let $K = \mathbb{Q}(\sqrt{-3})$ and let $\ell \equiv 7, 31 \pmod{36}$ be a prime number. There is a character $\Psi : \mathfrak{g}_K \rightarrow (\mathbb{Z}/\ell\mathbb{Z})^\times$ of order $\frac{\ell-1}{6}$ and an \mathcal{O}_K -CM elliptic curve E/K such that the mod ℓ Galois representation is

$$\sigma \mapsto \rho_\ell(\sigma) = \begin{bmatrix} \Psi(\sigma) & 0 \\ 0 & \Psi^{-1}(\sigma)\chi_\ell(\sigma) \end{bmatrix}.$$

Proof. (a) Let $(E_1)_K$ be an \mathcal{O}_K -CM elliptic curve. Because $\ell \equiv 1 \pmod{4}$, the Cartan subgroup $C_\ell(\mathcal{O}_K)$ is split. It follows that there are precisely two $C_\ell(\mathcal{O}_K)$ -stable one-dimensional $\mathbb{Z}/\ell\mathbb{Z}$ -subspaces of $E_1[\ell]$, so we may take basis vectors e_1 and e_2 for $E_1[\ell]$ lying in these two subspaces. For such a basis, the mod ℓ Galois representation has the form

$$\sigma \mapsto \rho_\ell(\sigma) = \begin{bmatrix} \Psi_1(\sigma) & 0 \\ 0 & \Psi_1^{-1}(\sigma)\chi_\ell(\sigma) \end{bmatrix}$$

for a character $\Psi_1 : \mathfrak{g}_K \rightarrow (\mathbb{Z}/\ell\mathbb{Z})^\times$. Under this isomorphism, the matrix representation of $i \in \mathcal{O}_K$ is a diagonal matrix

$$\begin{bmatrix} z & 0 \\ 0 & z^{-1} \end{bmatrix},$$

where z is a primitive fourth root of unity in $\mathbb{Z}/\ell\mathbb{Z}$. A general \mathcal{O}_K -CM elliptic curve over K is of the form E_1^ψ for a character $\psi : \mathfrak{g}_K \rightarrow \mu_4 \subset (\mathbb{Z}/\ell\mathbb{Z})^\times$. Let $Q_4(\ell) = (\mathbb{Z}/\ell\mathbb{Z})^\times / (\mathbb{Z}/\ell\mathbb{Z})^{\times 4}$. Then the image of z in $Q_4(\ell)$ has order 4: if not, there is $w \in (\mathbb{Z}/\ell\mathbb{Z})^\times$ such that $z = w^2$, and then w has order 8 in $(\mathbb{Z}/\ell\mathbb{Z})^\times$, contradicting the assumption that $\ell \equiv 5 \pmod{8}$. Thus the natural map $\mu_4 \rightarrow Q_4(\ell)$ given by $i \mapsto z \pmod{(\mathbb{Z}/\ell\mathbb{Z})^{\times 4}}$ is an isomorphism; we denote the inverse isomorphism $Q_4(\ell) \rightarrow \mu_4$ by ι . Now take

$$\psi : \mathfrak{g}_K \xrightarrow{\Psi_1^{-1}} (\mathbb{Z}/\ell\mathbb{Z})^\times \xrightarrow{q} Q_4(\ell) \xrightarrow{\iota} \mu_4;$$

here q is the quotient map. Let $\Psi_2 = \psi\Psi_1$. Then the twist E_1^ψ has mod ℓ Galois representation

$$\sigma \mapsto \rho_\ell(\sigma) = \begin{bmatrix} \Psi_2(\sigma) & 0 \\ 0 & \Psi_2^{-1}(\sigma)\chi_\ell(\sigma) \end{bmatrix}.$$

The composite $\Psi_2 : \mathfrak{g}_K \rightarrow (\mathbb{Z}/\ell\mathbb{Z})^\times \rightarrow Q_4(\ell)$ is trivial, so $\Psi_2(\mathfrak{g}_K)$ has order $c \mid \frac{\ell-1}{4}$. Thus

$$\#\rho_{\ell, E_1^\psi}(\mathfrak{g}_K) \mid c(\ell-1) \mid \frac{(\ell-1)^2}{4} = [K^{(\ell)} : K^{(1)}] = [K^{(\ell)} : K],$$

where the last equality holds since K has class number 1. Because $K(E_1^\psi[\ell]) \supset K^{(\ell)}$, we have $\#\rho_{\ell, E_1^\psi}(\mathfrak{g}_K) = \frac{1}{4}(\ell-1)^2$ and $c = \frac{1}{4}(\ell-1)$.

(b) Since $\ell \equiv 1 \pmod{3}$, we have a primitive sixth root of unity z in $\mathbb{Z}/\ell\mathbb{Z}$. Since $\ell \equiv 7, 31 \pmod{36}$, we have $4, 9 \nmid \ell - 1$, so z has order 6 in $Q_6(\ell) = (\mathbb{Z}/\ell\mathbb{Z})^\times / (\mathbb{Z}/\ell\mathbb{Z})^{\times 6}$. Also $\frac{1}{6}(\ell - 1)^2 = [K^{(\ell)} : K^{(1)}]$. The argument of part (a) carries over. \square

Example 4.4. (a) Let $K = \mathbb{Q}(\sqrt{-1})$, and let $\ell \equiv 5 \pmod{8}$. Let $E_{/K}$ be an \mathcal{O}_K -CM elliptic curve with mod ℓ Galois representation as in Proposition 4.3(a). Then for a number field $L \supset K$, $\rho_\ell|_{\mathfrak{g}_L}$ has scalar image if and only if $\chi_\ell \Psi^{-2}|_{\mathfrak{g}_L}$ is trivial. Since $\chi_\ell : \mathfrak{g}_K \rightarrow (\mathbb{Z}/\ell\mathbb{Z})^\times$ has order $\ell - 1$ — that is, for all $1 \leq k < \ell - 1$, $\chi_\ell^k \neq 1$ — and Ψ^{-2} has order dividing $\frac{\ell-1}{4}$, the character $\chi_\ell \Psi^{-2}$ has order $\ell - 1$. Thus $[K(\mathbb{P}E[\ell]) : K] = \ell - 1$, whereas $[K(\ell) : K] = \frac{\ell-1}{2}$. So $d(E, \ell) = 2$.

(b) Let $K = \mathbb{Q}(\sqrt{-3})$, and let $\ell \equiv 7, 31 \pmod{36}$. Let $E_{/K}$ be an \mathcal{O} -CM elliptic curve with mod ℓ Galois representation as in Proposition 4.3(b). As in part (a), we have $[K(\mathbb{P}E[\ell]) : K] = \ell - 1$ and $[K(\ell) : K] = \frac{\ell-1}{3}$. So $d(E, \ell) = 3$.

Proposition 4.5. *Let \mathcal{O} be an order of discriminant $\Delta = \mathfrak{f}^2 \Delta_K$, and let $N \in \mathbb{Z}^+$. Then there is an \mathcal{O} -CM elliptic curve $E_{/K(N\mathfrak{f})}$ such that the mod N Galois representation consists of scalar matrices.*

Proof. When $\Delta \notin \{-3, -4\}$, this is immediate from Theorem 4.1(b): in that case, the elliptic curve has a model defined over $K(\mathfrak{f})$. Thus we may assume that $\Delta \in \{-3, -4\}$, so $\mathfrak{f} = 1$. Let $\zeta \in \mathcal{O}_K^\times$ be a primitive w_K -th root of unity. Let $\mathcal{O}(N)$ be the order in K of conductor N , let $\tilde{E}_{/K(N)}$ be an $\mathcal{O}(N)$ -CM elliptic curve, let $\iota : \tilde{E} \rightarrow E$ be the canonical $K(N)$ -rational isogeny to an \mathcal{O}_K -CM elliptic curve E , let $\iota^\vee : E \rightarrow \tilde{E}$ be the dual isogeny, and let C be the kernel of ι^\vee . Identifying $E[N]$ with $N^{-1}\mathcal{O}_K/\mathcal{O}_K \subset \mathbb{C}/\mathcal{O}_K$, $\iota^\vee : \mathbb{C}/\mathcal{O}_K \rightarrow \mathbb{C}/\mathcal{O}(N)$ is the map $z + \mathcal{O}_K \mapsto Nz + \mathcal{O}(N)$, so C is the \mathbb{Z} -submodule of \mathbb{C}/\mathcal{O}_K generated by $P_1 = \frac{1}{N} + \mathcal{O}_K$. Because C is stable under the action of $\mathfrak{g}_{K(N)}$, this action is given by an isogeny character, say,

$$\sigma(P_1) = \Psi(\sigma)P_1.$$

Let $P_2 = \zeta P_1$. Then $\{P_1, P_2\}$ is a $\mathbb{Z}/N\mathbb{Z}$ -basis for $E[N]$. Moreover, for $\sigma \in \mathfrak{g}_{K(N)}$,

$$\sigma P_2 = \sigma \zeta P_1 = \zeta \sigma P_1 = \zeta \Psi(\sigma)P_1 = \Psi(\sigma)\zeta P_1 = \Psi(\sigma)P_2.$$

It follows that $\sigma \in \mathfrak{g}_{K(N)}$ acts on $E[N]$ via the scalar matrix $\Psi(\sigma)$. \square

5. Proof of Theorem 1.4 and its corollaries

5A. An equality of class fields. Let \mathcal{O} and \mathcal{O}' be orders in an imaginary quadratic field K of conductors \mathfrak{f} and $N\mathfrak{f}$, respectively. Here we prove $K(\mathfrak{f})^{N\mathcal{O}_K} = K^{N\mathcal{O}_K}K(N\mathfrak{f})$. We may assume that $N \geq 2$. Class field theory (see, for example, [Stevenhagen 2001, (3.2)]) gives a canonical isomorphism,

$$(4) \quad \Psi : \text{Aut}(K^{\text{ab}}/K(\mathfrak{f})) \xrightarrow{\sim} \widehat{\mathcal{O}}^\times / \mathcal{O}^\times.$$

Thus it suffices to prove an equality of open subgroups of $\widehat{\mathcal{O}_K}^\times / \mathcal{O}_K^\times$. We abbreviate

$$\mathcal{O}_p := \mathcal{O} \otimes \mathbb{Z}_p.$$

Put

$$A := \{x \in \widehat{\mathcal{O}}^\times \mid x \equiv 1 \pmod{N}\} = \prod_{p \nmid N} \mathcal{O}_p^\times \times \prod_{p \mid N} (1 + N\mathcal{O}_p), \quad \tilde{A} := A\mathcal{O}_K^\times,$$

$$B := \widehat{\mathcal{O}'}^\times = \prod_p (\mathcal{O}')_p^\times, \quad \tilde{B} := B\mathcal{O}_K^\times,$$

$$C := \{x \in \widehat{\mathcal{O}_K}^\times \mid x \equiv 1 \pmod{N}\} = \prod_{p \nmid N} (\mathcal{O}_K)_p^\times \times \prod_{p \mid N} (1 + N(\mathcal{O}_K)_p), \quad \tilde{C} := C\mathcal{O}_K^\times.$$

Under class field theory, the field $K(\mathfrak{f})^{N\mathcal{O}_K}$ corresponds to \tilde{A} (cf. [Stevenhagen 2001, p. 9]), the field $K(N\mathfrak{f})$ corresponds to \tilde{B} and the field $K^{N\mathcal{O}_K}$ corresponds to \tilde{C} , so showing that $K(\mathfrak{f})^{N\mathcal{O}_K} = K^{N\mathcal{O}_K} K(N\mathfrak{f})$ is equivalent to showing that

$$\tilde{A} = \tilde{B} \cap \tilde{C}.$$

Step 1: We show that $A = B \cap C$. Writing A_p , B_p and C_p for the components of p of each of these groups, it is enough to show that

$$A_p = B_p \cap C_p \text{ for all primes } p.$$

Case 1: Suppose $p \nmid N$. Then

$$\begin{aligned} A_p &= \mathcal{O}_p^\times, \\ B_p &= (\mathcal{O}')_p^\times = A_p, \\ C_p &= (\mathcal{O}_K)_p^\times, \end{aligned}$$

so $C_p \supset A_p = B_p$ and thus $B_p \cap C_p = A_p$.

Case 2: Suppose $p \mid N$. Write $\mathcal{O}_K = \mathbb{Z}1 + \mathbb{Z}\tau_K$, so $\mathcal{O} = \mathbb{Z}1 + \mathbb{Z}\mathfrak{f}\tau_K$. We have

$$\begin{aligned} A_p &= 1 + N\mathcal{O}_p = 1 + N\mathbb{Z}_p1 + N\mathfrak{f}\mathbb{Z}_p\tau_K, \\ B_p &= (1 + \mathbb{Z}_p1 + N\mathfrak{f}\mathbb{Z}_p\tau_K)^\times, \\ C_p &= 1 + N(\mathcal{O}_K)_p = 1 + N\mathbb{Z}_p1 + N\mathbb{Z}_p\tau_K, \end{aligned}$$

so indeed we have $B_p \cap C_p = A_p$.

It follows that $\tilde{B} \cap \tilde{C} = B\mathcal{O}_K^\times \cap C\mathcal{O}_K^\times \supset A\mathcal{O}_K^\times = \tilde{A}$, so it remains to show that $\tilde{B} \cap \tilde{C} \subset \tilde{A}$.

Step 2: Suppose $\Delta_K < -4$, so $\mathcal{O}_K^\times = \{\pm 1\}$. Then $\tilde{B} = B$, so if $z \in \tilde{B} \cap \tilde{C}$, then there is $\epsilon \in \{\pm 1\}$ such that $z \in B$, $-z \in B$ and $\epsilon z \in C$, so $\epsilon z \in B \cap C = A$ and thus $z \in \tilde{A}$.

Step 3: Suppose $K = \mathbb{Q}(\sqrt{-1})$ and let ζ be a primitive fourth root of unity, so $\mathcal{O}_K = \mathbb{Z}1 + \mathbb{Z}\zeta$ and $\mathcal{O}_K^\times = \{1, \zeta, \zeta^2, \zeta^3\}$. Suppose $z \in \tilde{B} \cap \tilde{C}$. Then there are $i, j \in \{0, 1, 2, 3\}$, $b \in B$ and $c \in C$ such that

$$z = \zeta^i b = \zeta^j c.$$

We have $z \in \tilde{A}$ if and only if $\zeta^{-j} z \in \tilde{A}$, so we may assume that $j = 0$. If i is even we may argue as in Step 2, so assume that $i \in \{1, 3\}$, and thus we have either $\zeta b = c$ or $\zeta c = b$. But we claim that there are no such elements b and c , which will complete the argument in this case. Indeed, choose a prime p dividing N , and let b_p and c_p be the components at p . There is a reduction map

$$(\mathcal{O}_K)_p \rightarrow \mathcal{O}_K \otimes \mathbb{Z}/p\mathbb{Z} = \mathbb{Z}/p\mathbb{Z}1 + \mathbb{Z}/p\mathbb{Z}\zeta.$$

Under this map, every element of $B_p \cup C_p$ lands in $\mathbb{Z}/p\mathbb{Z}1$, so $b_p, c_p \in \mathbb{Z}/p\mathbb{Z}1$ while $\zeta b_p, \zeta c_p \in \mathbb{Z}/p\mathbb{Z}\zeta$. Thus we cannot have $\zeta b_p = c_p$ or $\zeta c_p = b_p$.

If $K = \mathbb{Q}(\sqrt{-3})$, then we let ζ be a primitive sixth root of unity, so $\mathcal{O}_K = \mathbb{Z}1 + \mathbb{Z}\zeta$ and $\mathcal{O}_K^\times = \{1, \zeta, \zeta^2, \zeta^3, \zeta^4, \zeta^5\}$, and the argument is very similar: we cannot have $\pm\zeta b_p = c_p$ or $\pm b_p = \zeta c_p$.

5B. Proof of Theorem 1.4. By Theorems 2.11 and 4.1(a) and Section 5A, we have

$$K(\mathfrak{f})(\mathfrak{h}(E[N])) \supset K^{N\mathcal{O}_K} K(N\mathfrak{f}) = K(\mathfrak{f})^{N\mathcal{O}_K}.$$

For any \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$, the splitting field $\overline{K(\mathfrak{f})}^{\ker \overline{\rho_N}}$ of the reduced mod N Galois representation $\overline{\rho_N}$ on E (cf. Section 1C) is $K(\mathfrak{f})(\mathfrak{h}(E[N]))$, so

$$[K(\mathfrak{f})(\mathfrak{h}(E[N])) : K(\mathfrak{f})] \leq \# \overline{C_N(\mathcal{O})}.$$

As described in the introduction, it is immediate from (4) and the definition of $K(\mathfrak{f})^{N\mathcal{O}_K}$ that

$$\text{Aut}(H_{N, \mathcal{O}}/K(\mathfrak{f})) = \overline{C_N(\mathcal{O})},$$

and thus it follows that

$$K(\mathfrak{f})(\mathfrak{h}(E[N])) = K^{N\mathcal{O}_K} K(N\mathfrak{f}).$$

5C. Proof of Corollaries 1.5, 1.7 and 1.8.

Proof of Corollary 1.5. Theorem 1.4 implies that for any number field $F \supset K(j(E))$ and $N \in \mathbb{Z}^+$, we have

$$[\overline{C_N(\mathcal{O})} : \overline{\rho_N}(\mathfrak{g}_F)] \mid [F : K(j(E))]$$

and thus

$$[C_N(\mathcal{O}) : \rho_N(\mathfrak{g}_F)] \mid \#\mathcal{O}^\times [F : K(j(E))] \leq 6[F : K(j(E))]. \quad \square$$

Proof of Corollary 1.7. We may assume that $N \geq 2$. Let $w = \#q_N(\mathcal{O}^\times)$, so

$$w = \begin{cases} \#\mathcal{O}^\times, & N \geq 3, \\ \frac{\#\mathcal{O}^\times}{2}, & N = 2. \end{cases}$$

Once again we denote by μ_w the image of \mathcal{O}^\times in $C_N(\mathcal{O})$, a cyclic group of order w . Let $E_{/K(\mathfrak{f})}$ be any \mathcal{O} -CM elliptic curve. We may view $G = \text{Aut}(K(\mathfrak{f})(E[N])/K(\mathfrak{f}))$ as a subgroup of $C_N(\mathcal{O})$. Let $H = G \cap \mu_w$ and $L = (K(\mathfrak{f})(E[N]))^H$, so a suitable twist $(E')_{/L}$ of $E_{/L}$ has trivial mod N Galois representation. As shown in the proof of Theorem 2.10, we have $L = K(\mathfrak{f})(\mathfrak{h}(E[N]))$, so by Theorem 1.4 we have $[L : K(\mathfrak{f})] = \#C_N(\mathcal{O})$. \square

Proof of Corollary 1.8. We may assume that $N \geq 2$. Let $q_N : \mathcal{O}^\times \rightarrow C_N(\mathcal{O})$ be the natural homomorphism. By Theorem 2.10(b), there is an elliptic curve $E_{/K(\mathfrak{f})}$ such that

$$[K(\mathfrak{f})(E[N]) : K(\mathfrak{f})(\mathfrak{h}(E[N]))] = \#q_N(\mathcal{O}^\times) = \begin{cases} \#\mathcal{O}^\times, & N \geq 3, \\ \frac{\#\mathcal{O}^\times}{2}, & N = 2. \end{cases}$$

By Theorem 1.4, $[K(\mathfrak{f})(\mathfrak{h}(E[N])) : K(\mathfrak{f})] = \#C_N(\mathcal{O})$. Thus $\rho_{E,N}(\mathfrak{g}_{K(\mathfrak{f})}) = C_N(\mathcal{O})$. \square

6. Applications

6A. Divisibility in Silverberg's theorem.

Lemma 6.1. *Let J, M be subgroups of a group G . If M is normal and $J \cap M = \{1\}$, then $\#J \mid [G : M]$.*

Proof. The composite homomorphism $J \hookrightarrow G \rightarrow G/M$ is an injection. \square

The following result extends [Bourdon et al. 2017a, Corollary 2.5] from maximal orders to all imaginary quadratic orders, thereby confirming the expectation expressed in [Bourdon et al. 2017a, Remarks following the proof of Corollary 2.5].

Theorem 6.2. *Let \mathcal{O} be an order in an imaginary quadratic field K , and let E be an \mathcal{O} -CM elliptic curve defined over a number field $F \supset K$. If $E(F)$ has a point of order $N \in \mathbb{Z}^+$, then*

$$\varphi(N) \mid \frac{\#\mathcal{O}^\times [F : \mathbb{Q}]}{2 \cdot \#\text{Pic } \mathcal{O}}.$$

Proof. Let $\mathcal{I}_N = [C_N(\mathcal{O}) : \rho_N(\mathfrak{g}_F)]$ be the index of the mod N Galois representation in the Cartan subgroup. By Corollary 1.5 we have

$$\mathcal{I}_N \mid \frac{\#\mathcal{O}^\times [F : K(j(E))]}{2 \cdot \#\text{Pic } \mathcal{O}}.$$

Since there is a rational point of order N , the subgroup $\rho_N(\mathfrak{g}_F)$ contains no scalar matrices other than the identity. Applying Lemma 6.1 with $G = C_N(\mathcal{O})$, $M = \rho_N(\mathfrak{g}_F)$ and J the subgroup of scalar matrices, we get $\varphi(N) \mid \mathcal{I}_N$, and we are done. \square

6B. A theorem of Franz. Let \mathcal{O} be an order in K , of conductor \mathfrak{f} , and let $E_{/K(\mathfrak{f})}$ be an \mathcal{O} -CM elliptic curve. Choose a field embedding $K(\mathfrak{f}) \hookrightarrow \mathbb{C}$ such that $j(E) = j(\mathbb{C}/\mathcal{O})$ and an isomorphism $E(\mathbb{C}) \xrightarrow{\sim} \mathbb{C}/\mathcal{O}$. This induces an isomorphism $E(\overline{K(\mathfrak{f})})[\text{tors}] \xrightarrow{\sim} \mathbb{C}/\mathcal{O}[\text{tors}]$, which we use to view (the image in \mathbb{C}/\mathcal{O} of) $\tau_K = \frac{1}{2}(\Delta_K + \sqrt{\Delta_K})$ as a point of $E(\overline{K(\mathfrak{f})})[\text{tors}]$ of order \mathfrak{f} .

Theorem 6.3 [Franz 1935]. *With notation as above, we have*

$$K(\mathfrak{f})(\mathfrak{h}(\tau_K)) = K^{(\mathfrak{f})}.$$

Proof. As in the proof of Theorem 1.3, over \mathbb{C} we may view the canonical isogeny as $\iota: \mathbb{C}/\mathcal{O} \rightarrow \mathbb{C}/\mathcal{O}_K$. We take $e_1 = \frac{1}{\mathfrak{f}} + \mathcal{O}$ and $e_2 = \tau_K + \mathcal{O}$ as a basis for $E[\mathfrak{f}]$. Then e_2 generates $\ker(\iota)$, a $K(\mathfrak{f})$ -rational cyclic subgroup of order \mathfrak{f} , and with respect to $\{e_1, e_2\}$ the image of the mod \mathfrak{f} Galois representation associated to $E_{/K(\mathfrak{f})}$ consists of matrices of the form

$$\begin{bmatrix} a & b\mathfrak{f}^2 \frac{\Delta_K - \Delta_K^2}{4} \\ b & a + b\mathfrak{f}\Delta_K \end{bmatrix} \quad \text{with } a, b \in \mathbb{Z}/\mathfrak{f}\mathbb{Z}.$$

Viewing entries mod \mathfrak{f} , we see there is a character $\Psi: \mathfrak{g}_{K(\mathfrak{f})} \rightarrow (\mathbb{Z}/\mathfrak{f}\mathbb{Z})^\times$ such that

$$\rho_{E,\mathfrak{f}}(\sigma) = \begin{bmatrix} \Psi(\sigma) & 0 \\ * & \Psi(\sigma) \end{bmatrix}.$$

If $\mathfrak{f} \leq 2$, then $K(\mathfrak{f})(\mathfrak{h}(\tau_K)) = K(\mathfrak{f}) = K^{(\mathfrak{f})}$ and the result holds. Thus we may assume $\mathfrak{f} \geq 3$. Let $L := K(\mathfrak{f})(\mathfrak{h}(e_2))$. Since $\mathfrak{f} \geq 3$, we have $j(E) \neq 0, 1728$, so $[L(e_2) : L]$ divides 2 and the restriction $\Psi|_{\mathfrak{g}_L}: \mathfrak{g}_L \rightarrow \{\pm 1\}$ defines a quadratic character χ . On the twist E^χ of $E_{/L}$ the point e_2 becomes L -rational. As in the proof of Theorem 5.5 of [Bourdon et al. 2017b], let $\Psi^\pm: \mathfrak{g}_{K(\mathfrak{f})} \rightarrow (\mathbb{Z}/\mathfrak{f}\mathbb{Z}^\times)/\{\pm 1\}$ denote the composition of Ψ with the natural map $(\mathbb{Z}/\mathfrak{f}\mathbb{Z})^\times \rightarrow (\mathbb{Z}/\mathfrak{f}\mathbb{Z})^\times/\pm 1$. Then $L \subset (\overline{K(\mathfrak{f})})^{\ker \Psi^\pm}$, so $[L : K(\mathfrak{f})] \mid \frac{\varphi(\mathfrak{f})}{2}$. If $\iota: E^\chi \rightarrow E'$ is the canonical isogeny, then the proof of Theorem 1.3 shows that $\iota(e_1)$ is an element of $E'(L)$ which generates $E'[\mathfrak{f}]$ as an \mathcal{O}_K -module. Thus E' has full \mathfrak{f} -torsion over L , so by Theorem 2.8, $K^{(\mathfrak{f})} \subset L$. So

$$[L : K(\mathfrak{f})] \geq [K^{(\mathfrak{f})} : K(\mathfrak{f})] = \frac{\varphi(\mathfrak{f})}{2} \geq [L : K(\mathfrak{f})],$$

and thus $K(\mathfrak{f})(\mathfrak{h}(e_2)) = L = K^{(\mathfrak{f})}$. □

6C. The field of moduli of a point of prime order. Let $K \neq \mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{-3})$ be an imaginary quadratic field, and let $\mathcal{O} \subset K$ be the order of conductor \mathfrak{f} . Here we use Theorem 1.3 to determine the smallest field $F \supset K$ for which there exists an \mathcal{O} -CM elliptic curve $E_{/F}$ with an F -rational point of order $\ell > 2$.

Lemma 6.4. *Let K be an imaginary quadratic field, let $\mathfrak{f} \in \mathbb{Z}^+$, and let $\ell > 2$ be prime. Then $K^{(\ell)} \cap K(\ell\mathfrak{f}) = K(\ell)$.*

Proof. Let $\Delta = \mathfrak{f}^2 \Delta_K$. The statement is immediate if $\mathfrak{f} = 1$, so suppose $\mathfrak{f} > 1$. By Theorem 2.1,

$$[K(\ell\mathfrak{f}) : K(\mathfrak{f})] = \ell - \left(\frac{\Delta}{\ell}\right).$$

Since $[K^{(\ell)} K(\ell\mathfrak{f}) : K(\mathfrak{f})] = \#C_\ell(\mathcal{O})/2$ by Theorem 1.4, in both cases we have

$$[K^{(\ell)} K(\ell\mathfrak{f}) : K(\ell\mathfrak{f})] = \frac{\#C_\ell(\mathcal{O})}{2[K(\ell\mathfrak{f}) : K(\mathfrak{f})]} = \frac{1}{2}(\ell - 1).$$

Thus $[K^{(\ell)} : K^{(\ell)} \cap K(\ell\mathfrak{f})] = [K^{(\ell)} K(\ell\mathfrak{f}) : K(\ell\mathfrak{f})] = \frac{1}{2}(\ell - 1)$. As we have $K(\ell) \subset K^{(\ell)} \cap K(\ell\mathfrak{f})$ and $[K^{(\ell)} : K(\ell)] = \frac{1}{2}(\ell - 1)$, the result follows. \square

Theorem 6.5. *Let $K \neq \mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{-3})$ be an imaginary quadratic field, and let \mathcal{O} be the order of conductor \mathfrak{f} in K . Let $F \supset K$.*

- (a) *Let $E_{/F}$ be an \mathcal{O} -CM elliptic curve such that $E(F)$ contains a point of prime order $\ell > 2$. Then there is a prime \mathfrak{p} of \mathcal{O}_K lying over ℓ such that $K(\mathfrak{f})K^{\mathfrak{p}} \subset F$.*
- (b) *If $\left(\frac{\Delta}{\ell}\right) \neq -1$, then there is a prime \mathfrak{p} of \mathcal{O}_K lying over ℓ and an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})K^{\mathfrak{p}}}$ such that $E(K(\mathfrak{f})K^{\mathfrak{p}})$ has a point of order ℓ .*

If $\left(\frac{\Delta}{\ell}\right) = -1$, then an \mathcal{O} -CM elliptic curve $E_{/F}$ with an F -rational point of order ℓ must have full ℓ -torsion (see [Bourdon et al. 2017b, Theorem 4.8] or Lemma 6.12). In this case, $K(\ell\mathfrak{f})K^{(\ell)} \subset F$ by Theorem 1.4. The existence of an elliptic curve $E_{/K(\ell\mathfrak{f})K^{(\ell)}}$ with full ℓ -torsion is guaranteed by Corollary 1.7.

Proof. (a) Let $F \supset K$ and $E_{/F}$ be an \mathcal{O} -CM elliptic curve with an F -rational point of order ℓ . By Theorem 1.3, there is an \mathcal{O}_K -CM elliptic curve $E'_{/F}$ with an F -rational point P of order ℓ . If M is the \mathcal{O}_K -submodule of $E'(F)$ generated by P , then $M = E'[\text{ann } M]$ and $\#M = |\text{ann } M|$ by Theorem 2.6. Since $\ell \nmid \#M$, we must have $\mathfrak{p} \mid \text{ann } M$ for some prime \mathfrak{p} of \mathcal{O}_K above ℓ . By Theorem 2.8 we have

$$K(\mathfrak{f})K^{\mathfrak{p}} \subset K(\mathfrak{f})K^{\text{ann } M} = K(j(E))K^{(1)}(\mathfrak{h}(E'[\text{ann } M])) \subset F.$$

(b) If $\left(\frac{\Delta}{\ell}\right) \neq -1$, then an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ possesses a $K(\mathfrak{f})$ -rational cyclic subgroup of order ℓ . (See, e.g., [Clark et al. 2013, p. 13]. This is also a special case of Theorem 6.18.) By [Bourdon et al. 2017b, Theorem 5.5], there is an extension $L/K(\mathfrak{f})$ of degree $(\ell - 1)/2$ and a quadratic twist $(E_1)_{/L}$ such that $E_1(L)$ has a point of order ℓ . By part (a), there is a prime \mathfrak{p} of \mathcal{O}_K lying over ℓ such that $K(\mathfrak{f})K^{\mathfrak{p}} \subset L$, so it will suffice to show that $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] \geq \frac{\ell-1}{2}$.

If $\ell \nmid \mathfrak{f}$, then primes above ℓ are unramified in $K(\mathfrak{f})/K^{(1)}$. Thus $K(\mathfrak{f}), K^{\mathfrak{p}}$ are linearly disjoint over $K^{(1)}$, and we have $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] = [K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell - 1)$

since $(\frac{\Delta_K}{\ell}) = (\frac{\Delta}{\ell}) \neq -1$. If $\ell \mid \mathfrak{f}$, then applying Lemma 6.4 with $\frac{\mathfrak{f}}{\ell}$ in place of \mathfrak{f} , we have

$$K^{\mathfrak{p}} \cap K(\mathfrak{f}) \subset K^{(\ell)} \cap K(\mathfrak{f}) = K(\ell).$$

Thus $K^{\mathfrak{p}} \cap K(\mathfrak{f}) = K^{\mathfrak{p}} \cap K(\ell)$, so

$$[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] = [K^{\mathfrak{p}} : K^{\mathfrak{p}} \cap K(\mathfrak{f})] = [K^{\mathfrak{p}} : K^{\mathfrak{p}} \cap K(\ell)] = [K(\ell)K^{\mathfrak{p}} : K(\ell)]$$

and it is enough to show that $[K(\ell)K^{\mathfrak{p}} : K(\ell)] \geq \frac{\ell-1}{2}$.

• $(\frac{\Delta_K}{\ell}) = 1$: We will prove that $K^{\mathfrak{p}} \cap K(\ell) = K^{(1)}$ using CM elliptic curves. Let $(E_0)_{/K^{(1)}}$ be an \mathcal{O}_K -CM elliptic curve. Then $E_0[\mathfrak{p}]$ is stable under the action of $\mathfrak{g}_{K^{(1)}}$ and generated by a point P of order ℓ . By [Bourdon et al. 2017b, Theorem 5.5], there is an extension $L/K^{(1)}$ of degree $(\ell-1)/2$ and a quadratic twist $(E_1)_{/L}$ such that P becomes L -rational. By Theorem 2.8 we have $K^{\mathfrak{p}} \subset L$, and $K^{\mathfrak{p}} = L$ since $[K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell-1)$. Over $K(\ell)K^{\mathfrak{p}}$, the curve E_1 has a rational point of order ℓ , and the mod ℓ Galois representation is scalar by Theorem 4.1. Thus E_1 has full ℓ -torsion over $K(\ell)K^{\mathfrak{p}}$, and $K^{(\ell)} \subset K(\ell)K^{\mathfrak{p}}$. This implies $\frac{1}{2}(\ell-1) \mid [K(\ell)K^{\mathfrak{p}} : K(\ell)] = [K^{\mathfrak{p}} : K^{\mathfrak{p}} \cap K(\ell)]$. Since $[K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell-1)$, we have $K^{\mathfrak{p}} \cap K(\ell) = K^{(1)}$, and $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] = [K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell-1)$.

• $(\frac{\Delta_K}{\ell}) = -1$: In this case, $K^{\mathfrak{p}} = K^{(\ell)}$, so $K^{\mathfrak{p}} \cap K(\ell) = K(\ell)$. This implies $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] = [K^{\mathfrak{p}} : K(\ell)] = \frac{1}{2}(\ell-1)$.

• $(\frac{\Delta_K}{\ell}) = 0$: Since $[K(\ell) : K^{(1)}] = \ell$ and $[K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell-1)$, we have $K^{\mathfrak{p}} \cap K(\ell) = K^{(1)}$. Thus $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] = [K^{\mathfrak{p}} : K^{(1)}] = \frac{1}{2}(\ell-1)$. \square

Remark 6.6. Assume the setup of Theorem 6.5 but take $K = \mathbb{Q}(\sqrt{-1})$ or $K = \mathbb{Q}(\sqrt{-3})$. Then the assertion of Theorem 6.5(b) is false. Indeed, if $\ell \geq 5$ and $(\frac{\Delta}{\ell}) \neq -1$, we have $[K(\mathfrak{f})K^{\mathfrak{p}} : K(\mathfrak{f})] \mid \frac{1}{w_K}(\ell-1)$. (See Lemma 2.9.) Suppose $F \supset K$, and let $E_{/F}$ be an elliptic curve with CM by the order in K of conductor \mathfrak{f} . If $E(F)$ contains a rational point of order ℓ , then Theorem 6.2 implies $\frac{1}{2}(\ell-1) \mid [F : K(\mathfrak{f})]$. Thus F must properly contain $K(\mathfrak{f})K^{\mathfrak{p}}$.

6D. Sharpness in the Isogeny Torsion Theorem. The following result was established during the proof of Theorem 1.3.

Lemma 6.7. *Let E be an \mathcal{O} -CM elliptic curve defined over a number field F containing the CM field K , and for a positive integer \mathfrak{f}' dividing the conductor \mathfrak{f} of \mathcal{O} , let $\iota : E \rightarrow E'$ be the canonical F -rational isogeny to an elliptic curve E' with CM by the order in K of conductor \mathfrak{f}' . Write*

$$E(F)[\text{tors}] = \mathbb{Z}/s\mathbb{Z} \times \mathbb{Z}/e\mathbb{Z}, \quad E'(F)[\text{tors}] = \mathbb{Z}/s'\mathbb{Z} \times \mathbb{Z}/e'\mathbb{Z},$$

where $s \mid e$ and $s' \mid e'$. Then $s \mid s'$.

Ross [1994, §4], claims that if E is a CM elliptic curve defined over a number field F containing the CM field, then the exponent of the finite group $E(F)[\text{tors}]$ is an invariant of the F -rational isogeny class. In the setting of Lemma 6.7, this would give $e = e'$, and combining this with the conclusion of Lemma 6.7 we would get an injective group homomorphism $E(F)[\text{tors}] \hookrightarrow E(F')[\text{tors}]$. This conclusion is stronger than that of Theorem 1.3. However Ross's claim is false: in the setup of Lemma 6.7, one can have $e' < e$ (in which case there is no injective group homomorphism $E(F)[\text{tors}] \hookrightarrow E'(F)[\text{tors}]$), as the following result shows.

Proposition 6.8. *Let $\ell > 3$ be a prime number, let $K = \mathbb{Q}(\sqrt{-\ell})$, let $n \in \mathbb{Z}^{\geq 3}$, let \mathcal{O} be the order in K of conductor $\mathfrak{f} = \ell^{\lfloor \frac{n}{2} \rfloor}$, and let $F = K(\mathfrak{f})$. For any \mathcal{O} -CM elliptic curve E/F , there is an extension L/F of degree $\varphi(\ell^n)$ such that $E(L)$ has a point of order ℓ^n , and no \mathcal{O}_K -CM elliptic curve has an L -rational point of order ℓ^k for $k > \frac{1}{2}(n+1 + \lfloor \frac{n}{2} \rfloor)$ (hence no L -rational point of order ℓ^n).*

Proof. Let E/F be an \mathcal{O} -CM elliptic curve. As in (3) we may choose a basis $\{e_1, e_2\}$ for $E[\ell^n]$ so that the image of the mod ℓ^n Galois representation consists of matrices

$$\begin{bmatrix} a & b\mathfrak{f}^2 \frac{\Delta_K - \Delta_K^2}{4} \\ b & a + b\mathfrak{f}\Delta_K \end{bmatrix} \quad \text{with } a, b \in \mathbb{Z}/\ell^n\mathbb{Z}.$$

Since ℓ ramifies in K and $\mathfrak{f} = \ell^{\lfloor \frac{n}{2} \rfloor}$, we have $\text{ord}_\ell(b\mathfrak{f}^2(\Delta_K - \Delta_K^2)/4) = 1 + 2\lfloor \frac{n}{2} \rfloor \geq n$, so the matrices have the form

$$\begin{bmatrix} a & 0 \\ b & a + b\mathfrak{f}\Delta_K \end{bmatrix} \quad \text{with } a, b \in \mathbb{Z}/\ell^n\mathbb{Z}.$$

The action of \mathfrak{g}_F on $\langle e_2 \rangle$ gives a character $\Phi : \mathfrak{g}_F \rightarrow (\mathbb{Z}/\ell^n\mathbb{Z})^\times$. Take $M = (\bar{F})^{\ker \Phi}$. Then $[M : F] \mid \varphi(\ell^n)$ and $\Phi|_{\mathfrak{g}_M}$ is trivial. Thus there exists an extension L/F with $[L : F] = \varphi(\ell^n)$ such that $E(L)$ contains e_2 .

Let E'_L be an \mathcal{O}_K -CM elliptic curve, and suppose $E'(L)$ contains a point P of order ℓ^k . Let \mathfrak{p} be the prime ideal of \mathcal{O}_K such that $\ell\mathcal{O}_K = \mathfrak{p}^2$. We claim that the \mathcal{O}_K -submodule $M = \langle P \rangle_{\mathcal{O}_K}$ of $E'(L)$ generated by P contains $E[\mathfrak{p}^{2k-1}]$ and so, by Theorem 2.8, that $K^{\mathfrak{p}^{2k-1}} \subset L$. Indeed, by Theorem 2.6, we have $M = E[I]$ for some ideal I of \mathcal{O}_K such that $(\mathcal{O}_K/I, +)$ has ℓ -power order and exponent ℓ^k . Since ℓ ramifies in \mathcal{O}_K , this forces I to be of the form \mathfrak{p}^a for some $a \in \mathbb{Z}^+$, and the smallest a such that $(\mathcal{O}_K/\mathfrak{p}^a, +)$ has exponent ℓ^k is $a = 2k - 1$, establishing the claim. Thus

$$\text{ord}_\ell([K^{\mathfrak{p}^{2k-1}} : K^{(1)}]) = 2k - 2 \leq \text{ord}_\ell([L : K^{(1)}]) = \left\lfloor \frac{n}{2} \right\rfloor + n - 1,$$

so $k \leq \frac{1}{2}(n+1 + \lfloor \frac{n}{2} \rfloor)$. □

In the setting of Theorem 1.3, one wonders whether $\#E(F)[\text{tors}] = \#E'(F)[\text{tors}]$. In fact $\#E'(F)[\text{tors}]/\#E(F)[\text{tors}]$ can be arbitrarily large:

Proposition 6.9. *Let ℓ be an odd prime, let $K \neq \mathbb{Q}(\sqrt{-1}), \mathbb{Q}(\sqrt{-3})$ be an imaginary quadratic field, let \mathcal{O} be the order in K of conductor ℓ , and let $F = K(\ell)$. For any \mathcal{O} -CM elliptic curve $E_{/F}$ there is an extension L/F such that if $\iota : E \rightarrow E'$ is the canonical isogeny to an \mathcal{O}_K -CM elliptic curve E' , then*

$$\ell \mid \frac{\#E'(L)[\text{tors}]}{\#E(L)[\text{tors}]}.$$

Proof. Let $E_{/F}$ be an \mathcal{O} -CM elliptic curve. As above, there is a basis $\{e_1, e_2\}$ for $E[\ell]$ such that

$$\rho_\ell(\mathfrak{g}_F) \subset \left\{ \begin{bmatrix} a & 0 \\ b & a \end{bmatrix} \mid a, b \in \mathbb{Z}/\ell\mathbb{Z} \right\}$$

and there is an extension L/F with $[L : F] = \ell - 1$ such that $E(L)$ contains e_2 . In fact, $E(L)[\ell^\infty] \cong \mathbb{Z}/\ell\mathbb{Z}$. Indeed, E does not have full ℓ -torsion over L since Theorem 1.4 would imply $K^{(\ell)}K(\ell^2) \subset L$ and $\frac{1}{2}\ell(\ell - 1) = [K^{(\ell)}K(\ell^2) : K(\ell)]$. In addition, $E(L)$ has no point of order ℓ^2 by Theorem 6.2.

Let $\iota : E \rightarrow E'$ be the canonical L -rational isogeny from $E_{/L}$ to $E'_{/L}$, where E' has \mathcal{O}_K -CM. Since $e_2 \in E(L)$, the second paragraph of Section 3 shows that $\iota(e_1) \in E'(L)$, and $\iota(e_1)$ generates $E'[\ell]$ as an \mathcal{O}_K -module. In other words, $\mathbb{Z}/\ell\mathbb{Z} \times \mathbb{Z}/\ell\mathbb{Z} \hookrightarrow E'(L)[\text{tors}]$. It follows that $\ell \mid (\#E'(L)[\text{tors}]/\#E(L)[\text{tors}])$. \square

Finally, Theorem 1.3 requires $K \subset F$. This hypothesis cannot be omitted:

Proposition 6.10. *Let $\ell > 3$ be a prime with $\ell \equiv 3 \pmod{4}$ and let $n \in \mathbb{Z}^{\geq 3}$. Let $K = \mathbb{Q}(\sqrt{-\ell})$, and let \mathcal{O} be the order in K of conductor $\mathfrak{f} = \ell^{\lfloor \frac{n}{2} \rfloor}$. Let $F = \mathbb{Q}(j(\mathbb{C}/\mathcal{O}))$. There is an elliptic curve $E_{/F}$ and an extension L/F of degree $\frac{\varphi(\ell^n)}{2}$ such that*

- (i) $L \not\supset K$,
- (ii) $E(L)$ has a point of order ℓ^n , and
- (iii) for every \mathcal{O}_K -CM elliptic curve $E'_{/L}$ we have $\ell^n \nmid \#E'(L)[\text{tors}]$.

Proof. Let $E_{/F}$ be an \mathcal{O} -CM elliptic curve. By [Kwon 1999, Corollary 4.2], E has an F -rational subgroup which is cyclic of order ℓ^n . It follows from [Bourdon et al. 2017b, Theorem 5.6] that there is a twist E_1 of $E_{/F}$ and an extension L/F of degree $\varphi(\ell^n)/2$ such that $E_1(L)$ has a point of order ℓ^n . Note $[L : \mathbb{Q}] = h_K \ell^{\lfloor \frac{n}{2} \rfloor} \frac{\varphi(\ell^n)}{2}$ is odd (see [Cox 1989, Proposition 3.11]), so $K \not\subset L$.

Let $E'_{/L}$ be an \mathcal{O}_K -CM elliptic curve. Since $[L : \mathbb{Q}]$ is odd, $E'(L)[\ell^\infty]$ must be cyclic, as full ℓ^k -torsion would imply $\mathbb{Q}(\zeta_{\ell^k}) \subset L$ by the Weil pairing. As in the last paragraph of the proof of Proposition 6.8, $E'(LK)$ contains no point of order ℓ^n . Hence $E'(L)$ contains no point of order ℓ^n , and $\ell^n \nmid \#E'(L)[\text{tors}]$. \square

6E. Minimal and maximal Cartan orbits. Let \mathcal{O} be an order, let $N \in \mathbb{Z}^+$, and let $P \in \mathcal{O}/N\mathcal{O}$ be a point of order N . Since $C_N(\mathcal{O})$ contains all scalar matrices, if $P \in \mathcal{O}/N\mathcal{O}$ has order N , then the orbit of $C_N(\mathcal{O})$ on P has size at least $\varphi(N)$. On the other hand, the orbit of $C_N(\mathcal{O})$ on P is certainly no larger than the number of order N points of $\mathcal{O}/N\mathcal{O}$.

In this section we will find all pairs (\mathcal{O}, N) for which there exists a Cartan orbit of this smallest possible size and also all pairs for which there exists a Cartan orbit of this largest possible size.

We introduce the shorthand $H(\mathcal{O}, N)$ to mean: *there is a point P of order N in $\mathcal{O}/N\mathcal{O}$ such that the $C_N(\mathcal{O})$ -orbit of P has size $\varphi(N)$.*

Lemma 6.11. *Let \mathcal{O} be an order, and let $N = \ell_1^{a_1} \cdots \ell_r^{a_r} \in \mathbb{Z}^+$. Then $H(\mathcal{O}, N)$ holds if and only if $H(\mathcal{O}, \ell_i^{a_i})$ holds for all $1 \leq i \leq r$.*

Proof. This is an easy consequence of the Chinese remainder theorem. \square

Lemma 6.12. *Let \mathcal{O} be the order of discriminant Δ , ℓ a prime number and $a \in \mathbb{Z}^+$.*

- (a) *If $(\frac{\Delta}{\ell}) = 1$, there is an \mathcal{O} -submodule of $\mathcal{O}/\ell^a\mathcal{O}$ with underlying \mathbb{Z} -module $\mathbb{Z}/\ell^a\mathbb{Z}$.*
- (b) *If $(\frac{\Delta}{\ell}) = -1$, then $C_{\ell^a}(\mathcal{O})$ acts simply transitively on the order ℓ^a elements of $\mathcal{O}/\ell^a\mathcal{O}$.*

Proof. (a) If $(\frac{\Delta}{\ell}) = 1$, then $\mathcal{O}/\ell\mathcal{O} = \mathcal{O}_K/\ell\mathcal{O}_K \cong \mathbb{Z}/\ell\mathbb{Z} \times \mathbb{Z}/\ell\mathbb{Z}$, so $\mathcal{O} \otimes \mathbb{Z}_\ell$ is isomorphic as a ring to $\mathbb{Z}_\ell \times \mathbb{Z}_\ell$ (see, e.g., [Eisenbud 1995, Corollary 7.5]) and thus $\mathcal{O}/\ell^a\mathcal{O}$ is isomorphic as a ring to $\mathbb{Z}/\ell^a\mathbb{Z} \times \mathbb{Z}/\ell^a\mathbb{Z}$.

(b) If $(\frac{\Delta}{\ell}) = -1$, then $\mathcal{O} \otimes \mathbb{Z}_\ell = \mathcal{O}_K \otimes \mathbb{Z}_\ell$ is a complete DVR with uniformizer ℓ , so the ring $\mathcal{O}/\ell^a\mathcal{O}$ is finite, local and principal with maximal ideal $\langle \ell \rangle$. An element of $\mathcal{O}/\ell^a\mathcal{O}$ has order ℓ^a if and only if it lies in the unit group $C_{\ell^a}(\mathcal{O})$. \square

Lemma 6.13. *Let \mathcal{O} be the order of discriminant Δ , and let $N \in \mathbb{Z}^+$. The following are equivalent:*

- (i) *If $2 \mid N$, then $(\frac{\Delta}{2}) \neq 1$.*
- (ii) *The $\mathbb{Z}/N\mathbb{Z}$ -subalgebra of $\mathcal{O}/N\mathcal{O}$ generated by $C_N(\mathcal{O})$ is $\mathcal{O}/N\mathcal{O}$.*

Proof. Using the Chinese remainder theorem we reduce to the case of $N = \ell^a$ a power of a prime number ℓ . Let B be the $\mathbb{Z}/\ell^a\mathbb{Z}$ -subalgebra generated by $C_{\ell^a}(\mathcal{O})$, so $\#B = \ell^b$ for some $b \leq 2a$.

(i) \implies (ii) Since $0 \in B \setminus C_{\ell^a}(\mathcal{O})$, we have

$$\begin{aligned} \#B &\geq \#C_{\ell^a}(\mathcal{O}) + 1 \\ &= \ell^{2a} \left(1 - \frac{1}{\ell}\right) \left(1 - \left(\frac{\Delta}{\ell}\right) \frac{1}{\ell}\right) + 1 \geq \begin{cases} \frac{4}{9} \ell^{2a} + 1 > \ell^{2a-1} & \text{if } \ell \geq 3, \\ \frac{1}{2} \ell^{2a} + 1 > \ell^{2a-1} & \text{if } \ell = 2 \text{ and } \left(\frac{\Delta}{2}\right) \neq 1. \end{cases} \end{aligned}$$

Thus $b = 2a$ and $B = \mathcal{O}/\ell^a\mathcal{O}$.

$\neg(i) \Rightarrow \neg(ii)$ If $\ell = 2$ and $\left(\frac{\Delta}{2}\right) = 1$, then

$$\mathcal{O}/2^a\mathcal{O} \cong \left\{ \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix} \mid \alpha, \beta \in \mathbb{Z}/2^a\mathbb{Z} \right\}$$

and $C_{2^a}(\mathcal{O})$ consists of the set of such matrices with $\alpha, \beta \in (\mathbb{Z}/2^a\mathbb{Z})^\times$. Thus $C_{2^a}(\mathcal{O})$ is contained in the subalgebra

$$\mathcal{B} = \left\{ \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix} \mid \alpha, \beta \in \mathbb{Z}/2^a\mathbb{Z} \text{ and } \alpha \equiv \beta \pmod{2} \right\}$$

of order 2^{2a-1} , so $B \subset \mathcal{B} \subsetneq \mathcal{O}/2^a\mathcal{O}$.¹ □

Lemma 6.14. *For an order \mathcal{O} and $N \in \mathbb{Z}^+$, the following are equivalent:*

- (i) *There is an ideal I of \mathcal{O} with $\mathcal{O}/I \cong \mathbb{Z}/N\mathbb{Z}$.*
- (ii) *There is an \mathcal{O} -submodule of $\mathcal{O}/N\mathcal{O}$ with underlying commutative group $\mathbb{Z}/N\mathbb{Z}$.*
- (iii) *$H(\mathcal{O}, N)$ holds.*

Proof. (i) \Leftrightarrow (ii) Step 1: Let Λ be a free, rank 2 \mathbb{Z} -module, and let Λ' be a \mathbb{Z} -submodule of Λ containing $N\Lambda$. By the structure theory of modules over a PID, there is a \mathbb{Z} -basis e_1, e_2 for Λ and positive integers $a \mid b$ such that ae_1, be_2 is a \mathbb{Z} -basis for Λ' . Thus

$$\Lambda/\Lambda' \cong \mathbb{Z}/a\mathbb{Z} \oplus \mathbb{Z}/b\mathbb{Z}, \quad \Lambda'/N\Lambda \cong \mathbb{Z}/(N/b)\mathbb{Z} \oplus \mathbb{Z}/(N/a)\mathbb{Z}.$$

It follows that $\Lambda/\Lambda' \cong \mathbb{Z}/N\mathbb{Z} \Leftrightarrow \Lambda'/N\Lambda \cong \mathbb{Z}/N\mathbb{Z}$.

Step 2: If I is an ideal of \mathcal{O} with $\mathcal{O}/I \cong \mathbb{Z}/N\mathbb{Z}$, then $I \supset N\mathcal{O}$, so $I/N\mathcal{O} \cong \mathbb{Z}/N\mathbb{Z}$ by Step 1. Let M be an \mathcal{O} -submodule of $\mathcal{O}/N\mathcal{O}$ with underlying \mathbb{Z} -module $\mathbb{Z}/N\mathbb{Z}$. Then $M = I/N\mathcal{O}$ for an ideal I of \mathcal{O} , and by Step 1 we have $\mathcal{O}/I \cong \mathbb{Z}/N\mathbb{Z}$.

(ii) \Rightarrow (iii) Let $P \in \mathcal{O}/N\mathcal{O}$ have order N such that the subgroup generated by P is an \mathcal{O} -submodule. For all $g \in C_N(\mathcal{O})$, $gP = a_g P$ for $a_g \in (\mathbb{Z}/N\mathbb{Z})^\times$. Conversely, since $C_N(\mathcal{O})$ contains all scalar matrices, the orbit of $C_N(\mathcal{O})$ on P has size $\varphi(N)$.

(iii) \Rightarrow (ii) Case 1: Suppose $2 \nmid N$ or $\left(\frac{\Delta}{2}\right) \neq 1$. Let $P \in \mathcal{O}/N\mathcal{O}$ be a point of order N with $C_N(\mathcal{O})$ -orbit of size $\varphi(N)$. There is a $\mathbb{Z}/N\mathbb{Z}$ -basis e_1, e_2 of $\mathcal{O}/N\mathcal{O}$ with $e_1 = P$, and our hypothesis gives that with respect to this basis $C_N(\mathcal{O})$ lies in the subalgebra

$$\left\{ \begin{bmatrix} a & b \\ 0 & d \end{bmatrix} \mid a, b, d \in \mathbb{Z}/N\mathbb{Z} \right\}$$

of upper triangular matrices. By Lemma 6.13, $\mathcal{O}/N\mathcal{O}$ also lies in the subalgebra of upper triangular matrices, and thus $\langle P \rangle$ is an \mathcal{O} -stable submodule with underlying \mathbb{Z} -module $\mathbb{Z}/N\mathbb{Z}$.

¹Since $\#B \geq \#C_{2^a}(\mathcal{O}) + 1 = 2^{2a-2} + 1 > 2^{2a-2}$, in fact we have $B = \mathcal{B}$.

Case 2: Suppose $2 \mid N$ and $\left(\frac{\Delta}{2}\right) = 1$, and write $N = 2^a N'$ with $2 \nmid N'$. By Lemma 6.12 and the equivalence of (i) and (ii), there is an ideal I_1 in \mathcal{O} with $\mathcal{O}/I_1 \cong \mathbb{Z}/2^a\mathbb{Z}$, and by Case 1 there is an ideal I_2 in \mathcal{O} with $\mathcal{O}/I_2 \cong \mathbb{Z}/N'\mathbb{Z}$. By the Chinese remainder theorem, we have $\mathcal{O}/I_1 I_2 \cong \mathbb{Z}/N\mathbb{Z}$. Since (i) \iff (ii), this suffices. \square

Theorem 6.15. *Let \mathcal{O} be an order of discriminant Δ , and let $N \in \mathbb{Z}^+$. The following are equivalent:*

- (i) $H(\mathcal{O}, N)$ holds.
- (ii) Δ is a square in $\mathbb{Z}/4N\mathbb{Z}$.

Proof. Using Lemma 6.11, we reduce to the case in which $N = \ell^a$ is a power of a prime number ℓ .

Case 1 (ℓ is odd): Since $\gcd(4, \ell^a) = 1$, we may put $D = \frac{\Delta}{4} \in \mathbb{Z}/\ell^a\mathbb{Z}$. Then Δ is a square in $\mathbb{Z}/4\ell^a\mathbb{Z}$ if and only if D is a square in $\mathbb{Z}/\ell^a\mathbb{Z}$, and

$$(5) \quad \mathcal{O}/\ell^a\mathcal{O} \cong (\mathbb{Z}/\ell^a\mathbb{Z})[t]/(t^2 - D).$$

If there is $s \in \mathbb{Z}/\ell^a\mathbb{Z}$ such that $D = s^2$, then

$$\mathcal{O}/\ell^a\mathcal{O} \cong (\mathbb{Z}/\ell^a\mathbb{Z})[t]/((t+s)(t-s)),$$

so if I is the ideal $\langle t+s, \ell^a \rangle$ of \mathcal{O} , then $\mathcal{O}/I \cong \mathbb{Z}/\ell^a\mathbb{Z}$. By Lemma 6.14, $H(\mathcal{O}, \ell^a)$ holds. Conversely, suppose $H(\mathcal{O}, \ell^a)$ holds, so by Lemma 6.14 there is an ideal I of \mathcal{O} with $\mathcal{O}/I \cong \mathbb{Z}/\ell^a\mathbb{Z}$. Since $\ell^a \in I$, we may regard I as an ideal of $\mathcal{O}/\ell^a\mathcal{O}$ such that $(\mathcal{O}/\ell^a\mathcal{O})/I \cong \mathbb{Z}/\ell^a\mathbb{Z}$. In other words, we have a $\mathbb{Z}/\ell^a\mathbb{Z}$ -algebra homomorphism

$$f : \mathbb{Z}/\ell^a\mathbb{Z}[t]/(t^2 - D) \rightarrow \mathbb{Z}/\ell^a\mathbb{Z}.$$

Then $f(t)^2 = D \in \mathbb{Z}/\ell^a\mathbb{Z}$, so D is a square in $\mathbb{Z}/\ell^a\mathbb{Z}$.

Case 2 ($\ell = 2$, Δ is odd): Here, $\left(\frac{\Delta}{\ell}\right) = \pm 1$.

- If $\left(\frac{\Delta}{\ell}\right) = 1$, then $\Delta \equiv 1 \pmod{8}$; by Hensel's lemma, Δ is a square in $\mathbb{Z}/\ell^a\mathbb{Z}$. On the other hand, by Lemmas 6.12(a) and 6.14, $H(\mathcal{O}, \ell^a)$ holds.
- If $\left(\frac{\Delta}{\ell}\right) = -1$, then $\Delta \equiv 5 \pmod{8}$, so Δ is not a square modulo 8 and thus not a square modulo $4 \cdot 2^a$. On the other hand, by Lemma 6.12(b), $H(\mathcal{O}, \ell^a)$ does not hold.

Case 3 ($\ell = 2$, Δ is even): Again we may put $D = \frac{\Delta}{4} \in \mathbb{Z}/\ell^a\mathbb{Z}$, and again (5) holds. The argument of Case 1 shows that $H(\mathcal{O}, \ell^a)$ holds if and only if D is a square modulo $\mathbb{Z}/\ell^a\mathbb{Z}$ if and only if Δ is a square modulo $\mathbb{Z}/4\ell^a\mathbb{Z}$. \square

Proposition 6.16. *Let \mathcal{O} be an order, and let $N \in \mathbb{Z}^+$. The following are equivalent:*

- (i) $C_N(\mathcal{O})$ acts simply transitively on order N elements of $\mathcal{O}/N\mathcal{O}$.

(ii) $C_N(\mathcal{O})$ acts transitively on order N elements of $\mathcal{O}/N\mathcal{O}$.

(iii) For all primes $\ell \mid N$ we have $\left(\frac{\Delta}{\ell}\right) = -1$.

Proof. As usual, we may assume $N = \ell^a$ is a prime power. Certainly (i) \implies (ii).

(ii) \implies (iii): We have

$$\#C_{\ell^a}(\mathcal{O}) = \ell^{2a-2}(\ell - 1) \left(\ell - \left(\frac{\Delta}{\ell} \right) \right),$$

whereas the number of elements of order ℓ^a in $\mathcal{O}/\ell^a\mathcal{O}$ is

$$N(\mathcal{O}, \ell^a) := \#\mathcal{O}/\ell^a\mathcal{O} - \#\ell\mathcal{O}/\ell^a\mathcal{O} = \ell^{2a-2}(\ell - 1)(\ell + 1).$$

Transitivity of the action implies $\#C_{\ell^a}(\mathcal{O}) \geq N(\mathcal{O}, \ell^a)$, which holds if and only if $\left(\frac{\Delta}{\ell}\right) = -1$.

(iii) \implies (i): Since $\left(\frac{\Delta}{\ell}\right) \neq 0$, we have $\mathcal{O}/\ell^a\mathcal{O} \cong \mathcal{O}_K/\ell^a\mathcal{O}_K$, and thus also $C_{\ell^a}(\mathcal{O}) = (\mathcal{O}/\ell^a\mathcal{O})^\times \cong C_{\ell^a}(\mathcal{O}_K)$. Thus $\mathcal{O}/\ell^a\mathcal{O}$ is a finite local principal ring with maximal ideal $\mathfrak{m} = \langle \ell \rangle$ and unit group $C_{\ell^a}(\mathcal{O}) = \mathcal{O}/\ell^a\mathcal{O} \setminus \mathfrak{m}$. The set of order ℓ^a elements of $\mathcal{O}/\ell^a\mathcal{O}$ is $\mathcal{O}/\ell^a\mathcal{O} \setminus \mathfrak{m} = C_{\ell^a}(\mathcal{O})$, so the action of the unit group $C_{\ell^a}(\mathcal{O})$ on this set is the action of $C_{\ell^a}(\mathcal{O})$ on itself, which is simply transitive. \square

Corollary 6.17. *Let \mathcal{O} an order of conductor \mathfrak{f} . Let $N = \prod_{i=1}^r \ell_i^{a_i} \in \mathbb{Z}^+$ be such that $\left(\frac{\Delta}{\ell_i}\right) = -1$ for all i . Let F be a number field, and let $E_{/F}$ be an \mathcal{O} -CM elliptic curve such that $E(F)$ has a point of order N . Then*

$$(6) \quad \# \overline{C_N(\mathcal{O})} \mid [FK : K(\mathfrak{f})].$$

Further for all \mathcal{O} and N satisfying the above conditions, equality can occur in (6).

Proof. Replace F by FK ; then $F \supset K(\mathfrak{f})$. By Proposition 6.16, $C_N(\mathcal{O})$ acts transitively on order N elements of $\mathcal{O}/N\mathcal{O}$, so the \mathcal{O} -submodule generated by any one of them is $\mathcal{O}/N\mathcal{O}$. Thus the existence of one F -rational point of order N implies that ρ_N is trivial. Applying Theorem 1.4 gives (6). That equality can occur follows from Corollary 1.7. \square

6F. Torsion over $K(\mathfrak{f})$: Part I. Let \mathcal{O} be an order of discriminant $\Delta = \mathfrak{f}^2 \Delta_K$. We will give a complete classification of the possible torsion subgroups of \mathcal{O} -CM elliptic curves $E_{/K(\mathfrak{f})}$. In this section we will treat the cases $\Delta \neq -3, -4$. For the remaining cases we will make use of Theorem 7.2, so we will come back to those cases in Section 7E.

If $E(K(\mathfrak{f}))$ has a point of order N , then since $[C_N(\mathcal{O}) : \rho_N(\mathfrak{g}_{K(\mathfrak{f})})] \mid \#\mathcal{O}^\times$, there must be some $P \in \mathcal{O}/N\mathcal{O}$ of order N with a $C_N(\mathcal{O})$ -orbit of order dividing $\#\mathcal{O}^\times$.

- By Theorem 6.2, if $E(K(\mathfrak{f}))$ has a point of order N , then $\varphi(N) \mid 2$, so

$$N \in \{1, 2, 3, 4, 6\}.$$

• Lemma 2.2(b) implies that for all $N \geq 3$, we have $\#C_N(\mathcal{O}) \geq 4$ (equality holds if $N = 3$ and $\Delta \equiv 1 \pmod{3}$). By Theorem 1.4 we cannot have $E[N] = E[N](K(f))$.

Thus $E(K(f))[\text{tors}]$ is isomorphic to one of the groups in the following list:

$$\{e\}, \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/3\mathbb{Z}, \mathbb{Z}/4\mathbb{Z}, \mathbb{Z}/6\mathbb{Z}, \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z}, \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}.$$

We will show that all of these groups occur.

Points of order 2. By Theorem 1.4, $E(K(f))[2]$ has order 4 if 2 splits in \mathcal{O} , order 2 if 2 ramifies in \mathcal{O} and order 1 if 2 is inert in \mathcal{O} . Thus:

$$E(K(f))[2] \cong \begin{cases} \{e\}, & \Delta \equiv 5 \pmod{8}, \\ \mathbb{Z}/2\mathbb{Z}, & \Delta \equiv 0 \pmod{4}, \\ \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, & \Delta \equiv 1 \pmod{8}. \end{cases}$$

Points of order 3, 4, or 6. Let $E_{/K(f)}$ be any \mathcal{O} -CM elliptic curve. We claim that for $N \in \{3, 4, 6\}$, there is a quadratic twist E^D of E such that $E^D(K(f))$ has a point of order N if and only if $H(\mathcal{O}, N)$ holds. Indeed, as above, since the index of the mod N Galois representation in $C_N(\mathcal{O})$ divides 2, if some $E^D(K(f))$ has a point of order N , then $\mathcal{O}/N\mathcal{O}$ has a point of order N with a $C_N(\mathcal{O})$ -orbit of size 2. Since $\varphi(N) = 2$, there is a Cartan orbit of size 2 if and only if $H(\mathcal{O}, N)$ holds. Conversely, if $H(\mathcal{O}, N)$ holds then there is a point of order N with a $C_N(\mathcal{O})$ -orbit of size 2, hence on some quadratic twist E^D we have an F -rational point of order N . Applying Theorem 6.15, we get:

- Some \mathcal{O} -CM $E_{/K(f)}$ has a point of order 3 if and only if $\Delta \equiv 0, 1 \pmod{3}$.
- Some \mathcal{O} -CM $E_{/K(f)}$ has a point of order 4 if and only if $\Delta \equiv 0, 1, 4, 9 \pmod{16}$.
- Some \mathcal{O} -CM $E_{/K(f)}$ has a point of order 6 if and only if $\Delta \equiv 0, 1, 2, 9, 12, 16 \pmod{24}$.

Because the only full N -torsion we can have is full 2-torsion, and 2-torsion is invariant under quadratic twists, we immediately deduce the complete answer in all cases.

- If $\Delta \equiv 0 \pmod{48}$, then there are twists E_1, E_2, E_3 of E with

$$E_1(K(f))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(f))[\text{tors}] \cong \mathbb{Z}/4\mathbb{Z}, \quad E_3(K(f))[\text{tors}] \cong \mathbb{Z}/6\mathbb{Z}.$$

- If $\Delta \equiv 1, 9, 25, 33 \pmod{48}$ then there are twists E_1, E_2 of E with

$$E_1(K(f))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(f))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}.$$

- If $\Delta \equiv 4, 16, 36 \pmod{48}$, then there are twists E_1, E_2, E_3 of E with

$$E_1(K(f))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(f)) \cong \mathbb{Z}/4\mathbb{Z}, \quad E_3(K(f)) \cong \mathbb{Z}/6\mathbb{Z}.$$

- If $\Delta \equiv 5, 29 \pmod{48}$, then $E(K(\mathfrak{f}))[\text{tors}] = \{e\}$.
- If $\Delta \equiv 8, 44 \pmod{48}$, then $E(K(\mathfrak{f}))[\text{tors}] = \mathbb{Z}/2\mathbb{Z}$.
- If $\Delta \equiv 12, 24, 28, 40 \pmod{48}$, then there are twists E_1, E_2 of E with

$$E_1(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(\mathfrak{f})) \cong \mathbb{Z}/6\mathbb{Z}.$$

- If $\Delta \equiv 13, 21, 37, 45 \pmod{48}$, then there are twists E_1, E_2 of E with

$$E_1(K(\mathfrak{f}))[\text{tors}] = \{e\}, \quad E_2(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/3\mathbb{Z}.$$

- If $\Delta \equiv 17, 41 \pmod{48}$, then there are twists E_1, E_2 of E with

$$E_1(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z}.$$

- If $\Delta \equiv 20, 32 \pmod{48}$, then there are twists E_1, E_2 of E with

$$E_1(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/2\mathbb{Z}, \quad E_2(K(\mathfrak{f})) \cong \mathbb{Z}/4\mathbb{Z}.$$

6G. Isogenies over $K(j)$: Part I.

Theorem 6.18. *Let \mathcal{O} be an order of discriminant $\Delta = \mathfrak{f}^2 \Delta_K$, and let $N \in \mathbb{Z}^+$.*

• *If $\Delta \neq -3, -4$, then there is an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ with a $K(\mathfrak{f})$ -rational cyclic N -isogeny if and only if Δ is a square in $\mathbb{Z}/4N\mathbb{Z}$.*

• *If $\Delta = -4$, then there is an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ with a $K(\mathfrak{f})$ -rational cyclic N -isogeny if and only if N is of the form $2^\epsilon \ell_1^{a_1} \cdots \ell_r^{a_r}$ for primes $\ell_i \equiv 1 \pmod{4}$ and $\epsilon, a_1, \dots, a_r \in \mathbb{N}$ with $\epsilon \leq 2$.*

• *If $\Delta = -3$, then there is an \mathcal{O} -CM elliptic curve $E_{/K(\mathfrak{f})}$ with a $K(\mathfrak{f})$ -rational cyclic N -isogeny if and only if N is of the form $2^\epsilon 3^a \ell_1^{a_1} \cdots \ell_r^{a_r}$ for primes $\ell_i \equiv 1 \pmod{3}$, $\epsilon, a, a_1, \dots, a_r \in \mathbb{N}$ with $(\epsilon, a) \in \{(0, 0), (0, 1), (0, 2), (1, 0), (1, 1)\}$.*

Proof. Step 1: Let $E_{/K(\mathfrak{f})}$ be an \mathcal{O} -CM elliptic curve. If Δ is a square in $\mathbb{Z}/4N\mathbb{Z}$, then by Theorem 6.15 there is a point P of order N in $\mathcal{O}/N\mathcal{O}$ such that $C = \langle P \rangle$ is invariant under $C_N(\mathcal{O})$, so C is $\mathfrak{g}_{K(\mathfrak{f})}$ -stable and $E \rightarrow E/C$ is a cyclic N -isogeny. If $\Delta \notin \{-4, -3\}$, then the projective Galois representation $\mathbb{P}\rho_N : \mathfrak{g}_{K(\mathfrak{f})} \rightarrow C_N(\mathcal{O})/(\mathbb{Z}/N\mathbb{Z})^\times$ is a quotient of the reduced Galois representation, hence surjective. So $K(\mathfrak{f})$ -rational cyclic N -isogenies correspond to $C_N(\mathcal{O})$ -orbits on $\mathcal{O}/N\mathcal{O}$ of size $\varphi(N)$, which by Theorem 6.15 exist if and only if Δ is a square in $\mathbb{Z}/4N\mathbb{Z}$.

Step 2: If $\Delta \in \{-4, -3\}$, then as above the condition that Δ is a square modulo $4N$ is sufficient for the existence of a $K(\mathfrak{f})$ -rational cyclic N -isogeny, but it is no longer clear that it is necessary, and in both cases it turns out not to be. The complete analysis will make use of Theorem 7.2, so we defer the end of the proof until Section 7F. \square

7. The Torsion Degree Theorem

7A. Statement and preliminary reduction. Throughout this section \mathcal{O} denotes an order of conductor \mathfrak{f} and discriminant $\Delta = \mathfrak{f}^2 \Delta_K$.

For $N \in \mathbb{Z}^{\geq 2}$, let $\tilde{T}(\mathcal{O}, N)$ be the least size of an orbit of $C_N(\mathcal{O})$ on an order N point of $\mathcal{O}/N\mathcal{O}$.

Lemma 7.1. *We have $\tilde{T}(\mathcal{O}, 2) = \begin{cases} 1 & \text{if } (\frac{\Delta}{2}) \neq -1, \\ 3 & \text{if } (\frac{\Delta}{2}) = -1. \end{cases}$*

Proof. By Theorem 6.15, we have $(\frac{\Delta}{2}) \neq -1$ if and only if there is a $C_2(\mathcal{O})$ -orbit of size $\varphi(2) = 1$ on $\mathcal{O}/2\mathcal{O}$ if and only if $\tilde{T}(\mathcal{O}, 2) = 1$. In the remaining case, $(\frac{\Delta}{2}) = -1$, we have $\#C_2(\mathcal{O}) = 3$ and no orbit of size 1, hence $\tilde{T}(\mathcal{O}, 2) = 3$. \square

Theorem 7.2 (Torsion Degree Theorem). *Let \mathcal{O} be an order of conductor \mathfrak{f} , and let $N \in \mathbb{Z}^{\geq 3}$.*

(a) *There is $T(\mathcal{O}, N) \in \mathbb{Z}^+$ such that*

- *if $F \supset K(\mathfrak{f})$ is a number field and $E_{/F}$ is an \mathcal{O} -CM elliptic curve with an F -rational point of order N , then $T(\mathcal{O}, N) \mid [F : K(\mathfrak{f})]$, and*
- *there is a number field $F \supset K(\mathfrak{f})$ with $[F : K(\mathfrak{f})] = T(\mathcal{O}, N)$ and an \mathcal{O} -CM elliptic curve $E_{/F}$ with an F -rational point of order N .*

(b) *If $(\Delta, N) = (-3, 3)$, then $T(\mathcal{O}, N) = 1$.*

(c) *Suppose $(\Delta, N) \neq (-3, 3)$. Let $N = \ell_1^{a_1} \cdots \ell_r^{a_r}$ be the prime power decomposition of N . Then*

$$T(\mathcal{O}, N) = \frac{\prod_{i=1}^r \tilde{T}(\mathcal{O}, \ell_i^{a_i})}{\#\mathcal{O}^\times}.$$

(d) *If $\ell^a = 2$, then $\tilde{T}(\mathcal{O}, \ell^a) = 2$ is computed in Lemma 7.1. If $\ell^a > 2$, then $\tilde{T}(\mathcal{O}, \ell^a)$ is as follows, where $k = \text{ord}_\ell(\mathfrak{f})$:*

$$(1) \text{ If } \ell \nmid \mathfrak{f}, \text{ then } \tilde{T}(\mathcal{O}, \ell^a) = \begin{cases} \ell^{a-1}(\ell-1) & \text{if } (\frac{\Delta}{\ell}) = 1, \\ \ell^{2a-2}(\ell-1) & \text{if } (\frac{\Delta}{\ell}) = 0, \\ \ell^{2a-2}(\ell^2-1) & \text{if } (\frac{\Delta}{\ell}) = -1. \end{cases}$$

$$(2) \text{ If } \ell \mid \mathfrak{f}, \text{ then } \tilde{T}(\mathcal{O}, \ell^a) = \begin{cases} \ell^{a-1}(\ell-1) & \text{if } (\frac{\Delta_K}{\ell}) = 1, \\ \ell^{a-1}(\ell-1) & \text{if } (\frac{\Delta_K}{\ell}) = -1 \text{ and } a \leq 2k, \\ \ell^{2a-2k-1}(\ell-1) & \text{if } (\frac{\Delta_K}{\ell}) = -1 \text{ and } a > 2k, \\ \ell^{a-1}(\ell-1) & \text{if } (\frac{\Delta_K}{\ell}) = 0 \text{ and } a \leq 2k+1, \\ \ell^{2a-2k-2}(\ell-1) & \text{if } (\frac{\Delta_K}{\ell}) = 0 \text{ and } a > 2k+1. \end{cases}$$

Remark 7.3. The case $N = 2$ is excluded because of the somewhat anomalous behavior of 2-torsion. But it is easy to see that Theorem 7.2(a) remains true when

$N = 2$, and, moreover:

- If $\Delta \in \{-4, -3\}$ then $T(\mathcal{O}, 2) = 1$.
- Otherwise, $T(\mathcal{O}, 2) = \begin{cases} 1 & \text{if } (\frac{\Delta}{2}) \neq -1, \\ 3 & \text{if } (\frac{\Delta}{2}) = -1. \end{cases}$

Let $F \supset K(\mathfrak{f})$ be a number field, and let $E_{/F}$ be an \mathcal{O} -CM elliptic curve. As usual, we choose an embedding $F \hookrightarrow \mathbb{C}$ such that $j(E) = j(\mathbb{C}/\mathcal{O})$. Let $P \in E[\text{tors}]$ have order N . We call the field

$$K(\mathfrak{f})(\mathfrak{h}(P))$$

the *field of moduli* of P . It is independent of the chosen model of $E_{/F}$, and there exists an elliptic curve $E'_{/K(\mathfrak{f})(\mathfrak{h}(P))}$ with an isomorphism $\psi : E \rightarrow E'$ such that $\psi(P)$ is $K(\mathfrak{f})(\mathfrak{h}(P))$ -rational. Further, the pair (E, P) induces a closed point \mathcal{P} on the modular curve $X_1(N)_{/K}$, and $K(\mathfrak{f})(\mathfrak{h}(P))$ is the residue field $K(\mathcal{P})$. Theorem 7.2 concerns the degree $[K(\mathfrak{f})(\mathfrak{h}(P)) : K(\mathfrak{f})]$. Our setup shows that it is no loss of generality to assume $F = K(\mathfrak{f})$.

Let $q_N : \mathcal{O} \rightarrow \mathcal{O}/N\mathcal{O}$ be the natural map, and let $q_N^\times : \mathcal{O}^\times \rightarrow C_N(\mathcal{O})$ be the induced map on unit groups. As in the introduction, we define the *reduced mod N Cartan subgroup*:

$$\overline{C_N(\mathcal{O})} = C_N(\mathcal{O})/q_N(\mathcal{O}^\times).$$

Let $\overline{E[N]}$ be the set of \mathcal{O}^\times -orbits on $E[N]$. Then the action of $C_N(\mathcal{O})$ on $E[N]$ induces an action of $\overline{C_N(\mathcal{O})}$ on $\overline{E[N]}$. The field of moduli $K(\mathfrak{f})(\mathfrak{h}(P))$ depends only on the image \bar{P} of P in $\overline{E[N]}$. By Theorem 1.4, the composite homomorphism

$$\mathfrak{g}_F \xrightarrow{\rho_{E,N}} C_N(\mathcal{O}) \rightarrow \overline{C_N(\mathcal{O})}$$

is surjective (and model-independent). Let $H_{\bar{P}} = \{g \in \overline{C_N(\mathcal{O})} \mid g\bar{P} = \bar{P}\}$. It follows that

$$\text{Aut}(K(\mathfrak{f})(\mathfrak{h}(P))/K(\mathfrak{f})) \cong \overline{C_N(\mathcal{O})}/H_{\bar{P}}.$$

Thus $[K(\mathfrak{f})(\mathfrak{h}(P)) : K(\mathfrak{f})]$ is the size of the orbit of the reduced Cartan subgroup $\overline{C_N(\mathcal{O})}$ on \bar{P} . (As we will see, in almost every case this is the size of the orbit of $C_N(\mathcal{O})$ on P divided by $\#\mathcal{O}^\times$.) This reduces the proof of Theorem 7.2 to a purely algebraic problem.

7B. Generalities. For an order N point $P \in \mathcal{O}/N\mathcal{O}$, let $M_P = \{xP \mid x \in \mathcal{O}\}$ be the cyclic \mathcal{O} -submodule of $\mathcal{O}/N\mathcal{O}$ generated by P . If we put $I_P = \{x \in \mathcal{O} \mid xP = 0\}$, then we have

$$M_P \cong_{\mathcal{O}} \mathcal{O}/I_P.$$

The isomorphism is canonical and determined by mapping $P \in M_P$ to $1 + I_P \in \mathcal{O}/I_P$.

Lemma 7.4. (a) *With notation as above, let*

$$S(I_P) = \{g \in C_N(\mathcal{O}) \mid g \equiv 1 \pmod{I_P}\}.$$

Then with respect to the $C_N(\mathcal{O})$ -action, $S(I_P)$ is the stabilizer of P , so as a $C_N(\mathcal{O})$ -set the orbit of $C_N(\mathcal{O})$ on P is isomorphic to $C_N(\mathcal{O})/S(I_P)$.

(b) *Further, there is a canonical isomorphism of groups $C_N(\mathcal{O})/S(I_P) \xrightarrow{\sim} (\mathcal{O}/I_P)^\times$.*

Proof. (a) For $g \in C_N(\mathcal{O})$, we have $gP = P \iff (g-1)P = 0 \iff (g-1) \in I_P$, giving the first assertion. The orbit stabilizer theorem gives the second assertion.

(b) The ring homomorphism $f : \mathcal{O}/N\mathcal{O} \rightarrow \mathcal{O}/I$ induces a homomorphism on unit groups $f^\times : C_N(\mathcal{O}) \rightarrow (\mathcal{O}/I_P)^\times$, with kernel $S(I_P)$. Since $\mathcal{O}/N\mathcal{O}$ has finitely many maximal ideals, f^\times is surjective [Clark 2015, Theorem 4.32]. \square

Lemma 7.5. *There is a positive integer $M \mid N$ such that*

$$\mathcal{O}/I_P \cong_{\mathbb{Z}} \mathbb{Z}/N\mathbb{Z} \oplus \mathbb{Z}/M\mathbb{Z}.$$

Proof. As a \mathbb{Z} -module, \mathcal{O}/I_P is a quotient of $\mathcal{O}/N\mathcal{O} \cong_{\mathbb{Z}} \mathbb{Z}/N\mathbb{Z} \oplus \mathbb{Z}/N\mathbb{Z}$, so

$$\mathcal{O}/I_P \cong_{\mathbb{Z}} \mathbb{Z}/N'\mathbb{Z} \oplus \mathbb{Z}/M\mathbb{Z}$$

with $M \mid N' \mid N$. Since P has order N in $(\mathcal{O}/I_P, +)$, we have $N' = N$. \square

The following result computes the size of the reduced Cartan orbit on an order N point of $\mathcal{O}/N\mathcal{O}$ in terms of the size of the Cartan orbit. We recall that we have assumed $N \geq 3$.

Lemma 7.6. (a) *Suppose $(\Delta, N) \neq (-3, 3)$, and let $P \in \mathcal{O}/N\mathcal{O}$ have order N . Then the orbit of $C_N(\mathcal{O})$ on P has size $\#\mathcal{O}^\times$ times the size of the orbit of $\overline{C_N(\mathcal{O})}$ on \bar{P} .*

(b) *Suppose $(\Delta, N) = (-3, 3)$. Then the order 3 points of $\mathcal{O}/3\mathcal{O}$ lie in two orbits under $C_3(\mathcal{O})$: one of size 2 and one of size 6. The corresponding reduced Cartan orbits each have size 1.*

Proof. (a) The Cartan orbit has size $\#(\mathcal{O}/I_P)^\times$, and the reduced Cartan orbit is smaller by a factor of the cardinality of the image of $\mathcal{O}^\times \rightarrow (\mathcal{O}/I_P)^\times$.

- Suppose $\Delta \notin \{-4, -3\}$. Then $\mathcal{O}^\times = \{\pm 1\}$, and since $N \geq 3$, we have $-1 \not\equiv 1 \pmod{I_P}$.
- Suppose $\Delta = -4$. Since $I_P \not\supset (2)$, by Lemma 2.9 the group $U_{I_P}(K)$ is trivial, and thus the map $\mathcal{O}^\times \rightarrow (\mathcal{O}/I_P)^\times$ is injective.
- Suppose $\Delta = -3$. By assumption, $N \geq 4$, so $I_P \nmid (\zeta_3 - 1)$ and the map $\mathcal{O}^\times \rightarrow (\mathcal{O}/I_P)^\times$ is injective.

(b) The assertion about Cartan orbits is a case of [Clark et al. 2013, Lemma 19]. (Another proof will be given in the next section.) The fact that both reduced Cartan orbits have size 1 follows from the already established fact that there is an \mathcal{O} -CM $E/\mathbb{Q}(\sqrt{-3})$ with full 3-torsion. \square

In view of Lemma 7.6, to prove Theorem 7.2 it suffices to compute the least size of an orbit of $C_N(\mathcal{O})$ on an order N point of $\mathcal{O}/N\mathcal{O}$ and show that this divides the size of every such orbit. The following result further reduce us to the case of N a prime power.

Proposition 7.7. *Let $N \geq 2$ have prime power decomposition $N = \ell_1^{a_1} \cdots \ell_r^{a_r}$. Let $P \in \mathcal{O}/N\mathcal{O}$ have order N , and let $I_P = \text{ann } P$. For $1 \leq i \leq r$, let $P_i = N/\ell_i^{a_i} P$, and let $I_{P_i} = \text{ann } P_i$. Then:*

- (a) *The ideals I_{P_1}, \dots, I_{P_r} are pairwise comaximal, so $I_{P_i} + I_{P_j} = \mathcal{O}$ for all $i \neq j$.*
- (b) *We have $I_P = I_{P_1} \cdots I_{P_r}$.*
- (c) *We have a canonical isomorphism of rings*

$$\mathcal{O}/I_P \xrightarrow{\sim} \prod_{i=1}^r \mathcal{O}/I_{P_i}$$

which induces a canonical isomorphism of unit groups

$$(\mathcal{O}/I_P)^\times \xrightarrow{\sim} \prod_{i=1}^r (\mathcal{O}/I_{P_i})^\times.$$

- (d) *The Cartan orbit of P is isomorphic, as a $C_N(\mathcal{O})$ -set, to the direct product of the $C_{\ell_i^{a_i}}(\mathcal{O})$ -orbits of the P_i 's.*

Proof. (a) For $1 \leq i \leq r$, we have $(\mathcal{O}/I_{P_i}, +) \cong \mathbb{Z}/\ell_i^{a_i}\mathbb{Z} \oplus \mathbb{Z}/\ell_i^{b_i}\mathbb{Z}$ with $0 \leq b_i \leq a_i$; in particular it is an ℓ_i -group. Thus for $i \neq j$, $(\mathcal{O}/(I_i + I_j), +)$ is a homomorphic image of an ℓ_i -group and an ℓ_j -group, so it is trivial.

(b) By the Chinese remainder theorem, we have $I_{P_1} \cdots I_{P_r} = \bigcap_{i=1}^r I_{P_i}$. Since P_i is a multiple of P , we have $I_P \subset I_{P_i}$ for all i , and thus $I_P \subset \bigcap_{i=1}^r I_{P_i}$. Conversely, choose $y_1, \dots, y_r \in \mathbb{Z}$ such that $\sum_{i=1}^r y_i N/\ell_i^{a_i} = 1$. If $x \in \bigcap_{i=1}^r I_{P_i}$ then $xN/\ell_i^{a_i} P = 0$ for all i , hence

$$0 = \sum_{i=1}^r y_i \frac{N}{\ell_i^{a_i}} x P = x P,$$

so $x \in I_P$. Thus $I_P = \bigcap_{i=1}^r I_{P_i} = I_{P_1} \cdots I_{P_r}$.

(c) The Chinese remainder theorem gives the first isomorphism; the second follows by passing to unit groups.

(d) Apply Lemma 7.4 and part (c). \square

7C. The case $\ell \nmid f$.

Theorem 7.8. *Let $E_{/K(\mathfrak{f})}$ be an \mathcal{O} -CM elliptic curve. Let $\ell^a > 2$ be a prime power such that $\ell \nmid f$. We will give the sizes and multiplicities of all orbits of $C_{\ell^a}(\mathcal{O})$ on order ℓ^a points of $\mathcal{O}/\ell^a\mathcal{O}$.*

- (a) *If $(\frac{\Delta}{\ell}) = 1$, there are $2a + 1$ orbits: two orbits of size $\ell^{a-1}(\ell - 1)$, for all $1 \leq i \leq a - 1$, two orbits of size $\ell^{a+i-2}(\ell - 1)^2$, and one orbit of size $\ell^{2a-2}(\ell - 1)^2$.*
- (b) *If $(\frac{\Delta}{\ell}) = 0$, there are two orbits: an orbit of size $\ell^{2a-2}(\ell - 1)$ and an orbit of size $\ell^{2a-1}(\ell - 1)$.*
- (c) *If $(\frac{\Delta}{\ell}) = -1$, there is one orbit, of size $\ell^{2a-2}(\ell^2 - 1)$.*

Proof. Step 1: Suppose $\mathcal{O} = \mathcal{O}_K$. Then every \mathcal{O} -submodule of $E[N]$ is of the form $E[I]$ for an ideal $I \supset N\mathcal{O}$, and $E[I] \cong_{\mathcal{O}} \mathcal{O}/I$: thus every submodule is of the form $M_P = \langle P \rangle_{\mathcal{O}}$ and is determined by its annihilator ideal I_P . Conversely, if $I \supset N\mathcal{O}$ is an ideal, then Lemmas 2.3 and 2.4 give that $E[I]$ is an \mathcal{O} -submodule of $E[N]$ with annihilator ideal I .

Split case: $(\frac{\Delta}{\ell}) = 1$. Here, $\ell\mathcal{O} = \mathfrak{p}_1\mathfrak{p}_2$ for distinct prime ideals $\mathfrak{p}_1, \mathfrak{p}_2$ of norm ℓ . The ideals containing $\ell^a\mathcal{O}$ are precisely $\mathfrak{p}_1^c\mathfrak{p}_2^d$ with $\max(c, d) \leq a$. We have ring isomorphisms

$$\mathcal{O}/\mathfrak{p}_1^c\mathfrak{p}_2^d \cong \mathcal{O}/\mathfrak{p}_1^c \times \mathcal{O}/\mathfrak{p}_2^d \cong \mathbb{Z}/\ell^c\mathbb{Z} \times \mathbb{Z}/\ell^d\mathbb{Z},$$

and hence unit group isomorphisms

$$(\mathcal{O}/\mathfrak{p}_1^c\mathfrak{p}_2^d)^{\times} \cong (\mathcal{O}/\mathfrak{p}_1^c)^{\times} \times (\mathcal{O}/\mathfrak{p}_2^d)^{\times} \cong (\mathbb{Z}/\ell^c\mathbb{Z})^{\times} \times (\mathbb{Z}/\ell^d\mathbb{Z})^{\times},$$

so

$$\#(\mathcal{O}/\mathfrak{p}_1^c\mathfrak{p}_2^d)^{\times} = \varphi(\ell^c)\varphi(\ell^d).$$

To get points of order ℓ^a we impose the condition $\max(c, d) = a$. Thus \mathcal{O} -modules generated by the points of order ℓ^a are

$$E[\mathfrak{p}_1^a], E[\mathfrak{p}_1^a\mathfrak{p}_2], \dots, E[\mathfrak{p}_1^a\mathfrak{p}_2^a] = E[\ell^a], E[\mathfrak{p}_1^{a-1}\mathfrak{p}_2^a], \dots, E[\mathfrak{p}_1\mathfrak{p}_2^a], E[\mathfrak{p}_2^a].$$

So there are $2a + 1$ Cartan orbits, one of size $\varphi(\ell^a)\varphi(\ell^a)$ and, for all $0 \leq i \leq a - 1$, two of size $\varphi(\ell^a)\varphi(\ell^i)$. The smallest orbit size is $\ell^{a-1}(\ell - 1)$, and all the other orbit sizes are multiples of it.

Ramified case: $(\frac{\Delta}{\ell}) = 0$. Then $\ell\mathcal{O} = \mathfrak{p}^2$ for a prime ideal \mathfrak{p} of norm ℓ . For any $b \in \mathbb{Z}^+$, the ring $\mathcal{O}/\mathfrak{p}^b$ is local of order ℓ^b with residue field $\mathbb{Z}/\ell\mathbb{Z}$, so the maximal ideal has size ℓ^{b-1} and thus

$$\#(\mathcal{O}/\mathfrak{p}^b)^{\times} = \ell^b - \ell^{b-1} = \ell^{b-1}(\ell - 1).$$

Since $\mathfrak{p}^2 = (\ell)$, the least $c \in \mathbb{N}$ such that $\ell^c \in \mathfrak{p}^b$ is $c = \lceil \frac{b}{2} \rceil$. It follows that

$$(\mathcal{O}/\mathfrak{p}^b, +) \cong_{\mathbb{Z}} \mathbb{Z}/\ell^{\lceil \frac{b}{2} \rceil}\mathbb{Z} \oplus \mathbb{Z}/\ell^{\lfloor \frac{b}{2} \rfloor}\mathbb{Z}.$$

So the annihilator ideals of points of order ℓ^a in $\mathcal{O}/\ell^a\mathcal{O}$ are precisely \mathfrak{p}^{2a-1} and \mathfrak{p}^{2a} . We get two Cartan orbits, one of size $\#(\mathcal{O}/\mathfrak{p}^{2a-1})^\times = \ell^{2a-2}(\ell-1)$ and one of size $\#(\mathcal{O}/\mathfrak{p}^{2a})^\times = \ell^{2a-1}(\ell-1)$. The smallest orbit size is $\ell^{2a-2}(\ell-1)$, and the other orbit size is a multiple of it.

Inert case: $(\frac{\Delta}{\ell}) = -1$. Here, $\ell\mathcal{O}$ is a prime ideal, so the ideals containing $\ell^a\mathcal{O}$ are precisely $\ell^i\mathcal{O}$ for $i \leq a$. Clearly $\mathcal{O}/\ell^i\mathcal{O}$ has exponent ℓ^a if and only if $i = a$, so the \mathcal{O} -module generated by any point of order ℓ^a is $E[\ell^a]$. There is a single Cartan orbit, of size $\#(\mathcal{O}/\ell^a\mathcal{O})^\times = \varphi_K(\ell^a) = \ell^{2a-2}(\ell^2-1)$.

Step 2: Now let \mathcal{O} be an order with $\ell \nmid \mathfrak{f}$. The natural maps $\mathcal{O}/\ell^a\mathcal{O} \rightarrow \mathcal{O}_K/\ell^a\mathcal{O}_K$ and $C_{\ell^a}(\mathcal{O}) \rightarrow C_{\ell^a}(\mathcal{O}_K)$ are isomorphisms, so the sizes and multiplicities of orbits carry over from \mathcal{O}_K to \mathcal{O} . \square

7D. The case $\ell \mid \mathfrak{f}$. Suppose $\ell \mid \mathfrak{f}$. The ring $\mathcal{O}/\ell\mathcal{O}$ is isomorphic to $\mathbb{Z}/\ell\mathbb{Z}[\epsilon]/(\epsilon^2)$ — as one sees, e.g., using the explicit representation of (3) — and is thus a local Artinian ring with maximal ideal \mathfrak{p} , say, and residue field $\mathbb{Z}/\ell\mathbb{Z}$. Because $[\mathfrak{p} : \ell\mathcal{O}] = \ell$, the only proper nonzero \mathcal{O} -submodule of $\mathcal{O}/\ell\mathcal{O}$ is \mathfrak{p}/ℓ . Thus there are two Cartan orbits on the order ℓ elements of $\mathcal{O}/\ell\mathcal{O}$: one of order $\ell-1$ and one of order $\ell^2-\ell = \#(\mathcal{O}/\ell\mathcal{O})^\times$.

For all $a \in \mathbb{Z}^+$, the ring $\mathcal{O}/\ell^a\mathcal{O}$ is local — for a maximal ideal \mathfrak{m} of \mathcal{O} , we have $\ell^a \in \mathfrak{m} \iff \ell \in \mathfrak{m}$ — with residue field $\mathbb{Z}/\ell\mathbb{Z}$. In turn it follows that for any order ℓ^a point $P \in \mathcal{O}/\ell^a\mathcal{O}$ and $I_P = \{x \in \mathcal{O} \mid xP = 0\}$, the ring \mathcal{O}/I_P is local with residue field $\mathbb{Z}/\ell\mathbb{Z}$. By Lemma 7.5, we may write

$$(7) \quad M_P = \mathcal{O}/I_P \cong_{\mathbb{Z}} \mathbb{Z}/\ell^a\mathbb{Z} \oplus \mathbb{Z}/\ell^b\mathbb{Z}$$

for some $0 \leq b \leq a$, and then

$$\#(\mathcal{O}/I_P)^\times = \# \mathcal{O}/I_P - \frac{\# \mathcal{O}/I_P}{\ell} = \ell^{a+b-1}(\ell-1).$$

So the size of a Cartan orbit on an order ℓ^a element of $\mathcal{O}/\ell^a\mathcal{O}$ is of the form $(\ell-1)\ell^c$ for some $a-1 \leq c \leq 2a-1$. So in this case it is a priori clear that the minimal size of a Cartan orbit divides the size of all the Cartan orbits. We want to understand how Cartan orbits grow when we lift a point of order ℓ^a to a point of order ℓ^{a+1} . First observe that $x \mapsto \ell x$ gives an \mathcal{O} -module isomorphism

$$\mathcal{O}/\ell^a\mathcal{O} \xrightarrow{\sim} \ell\mathcal{O}/\ell^{a+1}\mathcal{O},$$

so we can view $\mathcal{O}/\ell^a\mathcal{O}$ as an \mathcal{O} -submodule of $\mathcal{O}/\ell^{a+1}\mathcal{O}$. With P as in (7), let $Q \in \mathcal{O}/\ell^{a+1}\mathcal{O}$ be such that $\ell Q = P$. Put

$$M_Q = \{xQ \mid x \in \mathcal{O}\} \quad \text{and} \quad I_Q = \{x \in \mathcal{O} \mid xQ = 0\},$$

and write

$$(8) \quad M_Q = \mathcal{O}/I_Q \cong_{\mathbb{Z}} \mathbb{Z}/\ell^{a+1}\mathbb{Z} \oplus \mathbb{Z}/\ell^{b'}\mathbb{Z}$$

for $0 \leq b' \leq a+1$. Because $\ell Q = P$, we have $\ell M_Q = M_P$. Thus we find: if $b = 0$,

then $b' \in \{0, 1\}$, whereas if $b \geq 1$ then necessarily $b' = b + 1$. So: if the $C_{\ell^a}(\mathcal{O})$ -orbit on P has the smallest possible size $\varphi(\ell^a)$, then the $C_{\ell^{a+1}}(\mathcal{O})$ -orbit on Q either has size $\varphi(\ell^{a+1})$ or size $\varphi(\ell^{a+2})$ (as we will see shortly, both possibilities can occur), whereas if the $C_{\ell^a}(\mathcal{O})$ -orbit on P has size $\varphi(\ell^{a+b}) > \varphi(\ell^a)$, then the $C_{\ell^{a+1}}(\mathcal{O})$ -orbit on Q has size $\varphi(\ell^{a+b+2})$: i.e., upon lifting from P to Q the size grows by a factor of ℓ^2 .

Since $H(\mathcal{O}, \ell^{a+1})$ implies $H(\mathcal{O}, \ell^a)$, for each fixed ℓ and \mathcal{O} there are two possibilities.

Type I: $H(\mathcal{O}, \ell^a)$ holds for all $a \in \mathbb{Z}^+$.

In Type I, for all $a \in \mathbb{Z}^+$, the least size of a $C_{\ell^a}(\mathcal{O})$ -orbit is $\varphi(\ell^a)$.

Type II: There is some $A \in \mathbb{Z}^+$ such that $H(\mathcal{O}, \ell^a)$ holds if and only if $a \leq A$.

In Type II, for $1 \leq a \leq A$, the least size of a $C_{\ell^a}(\mathcal{O})$ -orbit is $\varphi(\ell^a)$, but for all $a \geq A$, whenever we lift a point of order ℓ^a to a point of order ℓ^{a+1} the size of the Cartan orbit grows by a factor of ℓ^2 , so for all $a > A$ the least size of a $C_{\ell^a}(\mathcal{O})$ -orbit is $\ell^{a-A}\varphi(\ell^A)$.

We now determine the smallest size of a $C_{\ell^a}(\mathcal{O})$ -orbit on an order ℓ^a point of $\mathcal{O}/\ell^a\mathcal{O}$ by using Theorem 6.15 to determine the type and compute the value of A in Type II.

Case 1: Suppose $(\frac{\Delta_K}{\ell}) = 1$. Then $H(\mathcal{O}_K, \ell^a)$ holds for all $a \in \mathbb{Z}^+$, so Δ_K is a square modulo $4\ell^a$, hence $\Delta = \mathfrak{f}^2\Delta_K$ is also a square modulo $4\ell^a$, so $H(\mathcal{O}, \ell^a)$ holds, and we are in Type I.

Case 2: Suppose $(\frac{\Delta_K}{\ell}) = -1$, and put $k = \text{ord}_\ell(\mathfrak{f})$.

- Let $\ell > 2$. If $a \leq 2k$, then $\ell^a \mid \Delta$, so Δ is a square mod ℓ^a and hence also mod $4\ell^a$: thus $H(\mathcal{O}, \ell^a)$ holds. However, if $a = 2k + 1$ then we claim $H(\mathcal{O}, \ell^a)$ does not hold. Indeed, suppose there is $s \in \mathbb{Z}$ such that $\Delta = \mathfrak{f}^2\Delta_K \equiv s^2 \pmod{\ell^a}$. Then $\ell^k \mid s$; taking $S = s/\ell^k$ we have $\mathfrak{f}^2/\ell^{2k}\Delta_K \equiv S^2 \pmod{\ell^{a-2k}}$, which implies that Δ_K is a square modulo ℓ , which gives a contradiction. So we are in Type II with $A = 2k$.
- Let $\ell = 2$, and write $\mathfrak{f} = 2^k F$. Suppose $a \leq 2k$. Since $4 \mid \Delta_K - 1$, we have

$$2^{a+2} \mid (2^k F)^2(\Delta_K - 1) = \Delta - (2^k F)^2,$$

so $H(\mathcal{O}, 2^a)$ holds. Suppose $a \geq 2k + 1$. If Δ is a square modulo 2^{a+2} , then we find that $\Delta_K \equiv 1 \pmod{8}$, so $(\frac{\Delta_K}{2}) = 1$; this is a contradiction. So we are in Type II with $A = 2k$.

Case 3: Suppose $(\frac{\Delta_K}{\ell}) = 0$, and put $k = \text{ord}_\ell(\mathfrak{f})$.

- Let $\ell > 2$. If $a \leq 2k + 1$, then $\ell^a \mid \Delta$, so Δ is a square mod ℓ^a and hence also mod $4\ell^a$: thus $H(\mathcal{O}, \ell^a)$ holds. However, if $a = 2k + 2$ then we claim

$H(\mathcal{O}, \ell^a)$ does not hold. Indeed, $\text{ord}_\ell(\Delta) = 2k + 1 < a$, so if $\Delta \equiv s^2 \pmod{\ell^a}$, then $\text{ord}_\ell(s^2) = 2k + 2$: contradiction. So we are in Type II with $A = 2k + 1$.

- Let $\ell = 2$, and write $\mathfrak{f} = 2^k F$. Suppose $a \leq 2k + 1$. Since $4 \mid \Delta_K$, there is $s \in \mathbb{Z}$ such that $8 \mid \Delta_K - s^2$, so

$$2^{a+2} \mid 2^{2k+3} \mid (2^k F)^2 (\Delta_K - s^2) = \Delta - (2^k F s)^2,$$

so $H(\mathcal{O}, 2^a)$ holds. Suppose $a \geq 2k + 2$. If Δ is a square modulo 2^{a+2} , then Δ_K is a square modulo 2^{a+2-2k} , hence modulo 16: contradiction. So we are in Type II with $A = 2k + 1$.

7E. Torsion over $K(j)$: Part II. We return to complete the classification of torsion on \mathcal{O} -CM elliptic curves $E_{/K(j)}$ begun in Section 6F.

Suppose $\Delta = -4$, so $j = 1728$ and $K(j) = K = \mathbb{Q}(\sqrt{-1})$.

- By Theorem 6.2, if $E(K)$ has a point of order N , then $\varphi(N) \mid 4$, so

$$N \in \{1, 2, 3, 4, 5, 6, 8, 10\}.$$

- Using Theorem 7.2 we get

$$T(\mathcal{O}, 1) = T(\mathcal{O}, 2) = T(\mathcal{O}, 4) = T(\mathcal{O}, 5) = T(\mathcal{O}, 10) = 1,$$

$$T(\mathcal{O}, 3) = T(\mathcal{O}, 6) = 2, \quad T(\mathcal{O}, 8) = 4.$$

- We have $C_2(\mathcal{O}) = \mu_4 / \{\pm 1\}$. Thus $\#C_2(\mathcal{O}) = 2$ so every \mathcal{O} -CM elliptic curve $E_{/K}$ has a K -rational point of order 2, and some \mathcal{O} -CM elliptic curve $E_{/K}$ has $E[2] = E[2](K)$.
- Because $\tilde{T}(\mathcal{O}, 5) = 4$, if an \mathcal{O} -CM elliptic curve $E_{/K}$ has a K -rational point of order 5, the index of the mod 5 Galois representation in $C_5(\mathcal{O})$ is divisible by 4. Because $\#C_2(\mathcal{O}) = 2$, if an \mathcal{O} -CM elliptic curve $E_{/K}$ has full 2-torsion then the index of the mod 2 Galois representation in $C_2(\mathcal{O})$ is divisible by 2. Thus if an \mathcal{O} -CM elliptic curve $E_{/K}$ had $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/10\mathbb{Z} \hookrightarrow E(K)[\text{tors}]$, the index of the mod 10 Galois representation in $C_{10}(\mathcal{O})$ would be divisible by 8, contradicting Corollary 1.5.
- If $N \geq 3$ then $\#C_N(\mathcal{O}) > \#\mathcal{O}^\times$, so no \mathcal{O} -CM elliptic curve $E_{/K}$ has $E[N] = E[N](K)$.
- If there were a CM elliptic curve $E_{/K}$ with $E(K)[\text{tors}] \cong \mathbb{Z}/4\mathbb{Z}$, then there would be an ideal I of \mathcal{O} such that \mathcal{O}/I is isomorphic as a \mathbb{Z} -module to $\mathbb{Z}/4\mathbb{Z}$. But there is no such an ideal, a special case of the analysis done in the proof of Theorem 7.8.

Thus the groups which can occur as $E(K)[\text{tors}]$ are precisely

$$\mathbb{Z}/2\mathbb{Z}, \quad \mathbb{Z}/10\mathbb{Z}, \quad \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \quad \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z}.$$

Example 7.9. For $K = \mathbb{Q}(\sqrt{-1})$, every \mathcal{O}_K -CM elliptic curve E/K is isomorphic over K to

$$E_A : y^2 = x^3 + Ax$$

for some $A \in K^\times$. We exhibit such elliptic curves with all possible torsion subgroups:

A	$E(\mathbb{Q}(\sqrt{-1}))[\text{tors}]$
2	$\mathbb{Z}/2\mathbb{Z}$
$64 - 128\sqrt{-1}$	$\mathbb{Z}/10\mathbb{Z}$
1	$\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$
4	$\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z}$

For the groups $\mathbb{Z}/2\mathbb{Z}$, $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ and $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z}$, we have $A \in \mathbb{Q}^\times$ and thus E_A arises from an elliptic curve defined over \mathbb{Q} via base extension. González-Jiménez [2019, Theorem 1] has shown that for no $A \in \mathbb{Q}^\times$ do we have $E_A(K)[\text{tors}] \cong \mathbb{Z}/10\mathbb{Z}$. Najman [2010; 2011] has classified the torsion subgroups of all elliptic curves (CM or otherwise) defined over K .

Suppose $\Delta = -3$, so $j = 0$ and $K(\mathfrak{f}) = K = \mathbb{Q}(\sqrt{-3})$.

- By Theorem 6.2, if $E(K(\mathfrak{f}))$ has a point of order N , then $\varphi(N) \mid 6$, so

$$N \in \{1, 2, 3, 4, 6, 7, 9, 14, 18\}.$$

- Using Theorem 7.2 we get

$$T(\mathcal{O}, 1) = T(\mathcal{O}, 2) = T(\mathcal{O}, 3) = T(\mathcal{O}, 6) = T(\mathcal{O}, 7) = 1,$$

$$T(\mathcal{O}, 4) = 2,$$

$$T(\mathcal{O}, 9) = T(\mathcal{O}, 14) = 3,$$

$$T(\mathcal{O}, 18) = 9.$$

- We have $C_2(\mathcal{O}) = \mu_6/\{\pm 1\}$. Therefore as we range over all \mathcal{O} -CM elliptic curves E/K , the group $E(K)[2]$ can be trivial (using Corollary 1.8) or have size 4, but it cannot have size 2.
- We have $C_3(\mathcal{O}) = \mu_6$. Thus there is an \mathcal{O} -CM elliptic curve E/K with $E[3] = E[3](K)$.
- If $N \geq 4$ then $\#C_N(\mathcal{O}) > \#\mathcal{O}^\times$, so no \mathcal{O} -CM elliptic curve E/K has $E[N] = E[N](K)$.

Thus the groups which can occur as $E(K)[\text{tors}]$ are precisely

$$\{e\}, \quad \mathbb{Z}/3\mathbb{Z}, \quad \mathbb{Z}/7\mathbb{Z}, \quad \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}, \quad \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}, \quad \mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}.$$

Example 7.10. For $K = \mathbb{Q}(\sqrt{-3})$, every \mathcal{O}_K -CM elliptic curve E/K is isomorphic over K to

$$E_A : y^2 = x^3 + B$$

for some $B \in K^\times$. We exhibit such elliptic curves with all possible torsion subgroups:

B	$E(\mathbb{Q}(\sqrt{-1}))[\text{tors}]$
2	$\{e\}$
4	$\mathbb{Z}/3\mathbb{Z}$
$6\sqrt{-3} - 54$	$\mathbb{Z}/7\mathbb{Z}$
-1	$\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$
1	$\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}$
16	$\mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$

For the groups $\{e\}$, $\mathbb{Z}/3\mathbb{Z}$, $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$, $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}$ and $\mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$, we have $B \in \mathbb{Q}^\times$ and thus E_B arises from an elliptic curve defined over \mathbb{Q} via base extension. Again González-Jiménez [2019, Theorem 1] has shown that for no $B \in \mathbb{Q}^\times$ do we have $E_B(K)[\text{tors}] \cong \mathbb{Z}/7\mathbb{Z}$. And again Najman [2010; 2011] has classified the torsion subgroups of all elliptic curves (CM or otherwise) defined over K .

Remark 7.11. (a) The calculations in Section 6F where $\Delta \neq -3, -4$ give a more detailed and explicit version of one of the main results of [Parish 1989]. Parish offers addenda on the cases where $\Delta = -3$ and -4 , but without proof, and the possibilities $E(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/10\mathbb{Z}$ when $\Delta = -4$ and $E(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/7\mathbb{Z}$ and $E(K(\mathfrak{f}))[\text{tors}] \cong \mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$ when $\Delta = -3$ are not mentioned.

(b) If $\Delta = -3$ or -4 , a classification of the possibilities for $E(K(\mathfrak{f}))[\text{tors}]$ *apart* from the “Olson groups” $\{e\}$, $\mathbb{Z}/2\mathbb{Z}$, $\mathbb{Z}/3\mathbb{Z}$, $\mathbb{Z}/4\mathbb{Z}$, $\mathbb{Z}/6\mathbb{Z}$, $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ was made in [Bourdon et al. 2017b, Theorem 1.4] using computer calculations on degrees of preimages of $j = 0$ and $j = 1728$ on modular curves [Bourdon et al. 2017b, Table 2]. This result was used to find E_A with $E_A(\mathbb{Q}(\sqrt{-1}))[\text{tors}] \cong \mathbb{Z}/10\mathbb{Z}$ in Example 7.9 and E_B with $E_B(\mathbb{Q}(\sqrt{-3}))[\text{tors}] \cong \mathbb{Z}/7\mathbb{Z}$ in Example 7.10.

7F. Isogenies over $K(j)$: Part II. We return to complete the classification of $K(j)$ -rational cyclic isogenies for elliptic curves with CM by the orders of discriminants $\Delta = -4$ and $\Delta = -3$. Recall that these cases have additional complexity coming from the fact that μ_K acts nontrivially on the projectivized torsion group $\mathbb{P}E[N]$. In this case, there is an \mathcal{O} -CM elliptic curve $(E_0)_K$ for which the projective mod N Galois representation

$$\mathbb{P}\rho_N : \mathfrak{g}_K \rightarrow C_N(\mathcal{O})/(\mathbb{Z}/N\mathbb{Z})^\times$$

is surjective. As we vary over the K -models of E_0 , the representation $\mathbb{P}\rho_N$ twists by a character

$$\mathbb{P}\chi : \mathfrak{g}_K \rightarrow \mu_K/\{\pm 1\}.$$

Thus the index of $\mathbb{P}\rho_N(\mathfrak{g}_K)$ in $C_N(\mathcal{O})/(\mathbb{Z}/N\mathbb{Z})^\times$ divides 2 when $w_K = 4$ and divides 3 when $w_K = 6$.

We will rule out the existence of K -rational cyclic N -isogenies for various values of N using the following “ \tilde{T} -argument”: suppose that $\tilde{T}(\mathcal{O}, N) > \varphi(N)^{\frac{1}{2}} w_K$. Then every $C_N(\mathcal{O})$ -orbit on a point of order N in $\mathcal{O}/N\mathcal{O}$ has size a multiple of $\tilde{T}(\mathcal{O}, N)$, so every $C_N(\mathcal{O})/(\mathbb{Z}/N\mathbb{Z})^\times$ -orbit on $\mathbb{P}E[N]$ has size a multiple of $\tilde{T}(\mathcal{O}, N)/\varphi(N)$, which by our hypothesis is greater than $w_K/2$. So after passing to a field extension L of degree $w_K/2$ to trivialize $\mathbb{P}\chi$, we find that \mathfrak{g}_L acts without fixed points on $\mathbb{P}E[N]$, and there is no L -rational cyclic N -isogeny and thus no K -rational cyclic N -isogeny.

Let \mathcal{O} be the order of discriminant $\Delta = -4$, so $K(j) = K = \mathbb{Q}(\sqrt{-1})$ and $w_K = 4$.

- If $\ell \equiv 1 \pmod{4}$, then for all $a \in \mathbb{Z}^+$ we have that -4 is a square in $\mathbb{Z}/4\ell^a\mathbb{Z}$ so there is a K -rational cyclic ℓ^a -isogeny. In fact we get that every \mathcal{O} -CM elliptic curve E/K has a K -rational cyclic ℓ^a -isogeny.
- If $\ell \equiv 3 \pmod{4}$, since

$$\frac{\tilde{T}(\mathcal{O}, \ell)}{\varphi(\ell)^{\frac{w_K}{2}}} = \frac{\ell^2 - 1}{2(\ell - 1)} = \frac{\ell + 1}{2} > 1,$$

by the \tilde{T} -argument there is no K -rational ℓ -isogeny.

- If $\ell = 2$, then since $T(\mathcal{O}, 4) = 1$, we can have a K -rational point of order 4 (as already seen in Section 7E), hence a cyclic K -rational 4-isogeny. Since

$$\frac{\tilde{T}(\mathcal{O}, 8)}{\varphi(8)^{\frac{w_K}{2}}} = \frac{16}{4 \cdot 2} > 1,$$

by the \tilde{T} -argument there is no cyclic K -rational 8-isogeny.

Any elliptic curve over a number field admitting a rational cyclic N -isogeny also admits a rational cyclic M -isogeny for all $M \mid N$. Moreover, if an elliptic curve E/F admits F -rational cyclic N_1, \dots, N_r isogenies for pairwise coprime N_1, \dots, N_r , then the subgroup generated by the kernels of these isogenies is F -rational and cyclic of order $N_1 \cdots N_r$ so E admits an F -rational cyclic $N_1 \cdots N_r$ -isogeny. The assertion of Theorem 6.18(b) now follows.

Let \mathcal{O} be the order of discriminant $\Delta = -3$, so $K(j) = K = \mathbb{Q}(\sqrt{-3})$ and $w_K = 6$.

- If $\ell \equiv 1 \pmod{3}$, then much as in the $\Delta = -4$ case above we get that every \mathcal{O} -CM elliptic curve E/K has a K -rational cyclic ℓ^a -isogeny for all $a \in \mathbb{Z}^+$.
- If $\ell \equiv 2 \pmod{3}$ and $\ell > 2$, then since

$$\frac{\tilde{T}(\mathcal{O}, \ell)}{\varphi(\ell)^{\frac{w_K}{2}}} = \frac{\ell^2 - 1}{3(\ell - 1)} = \frac{\ell + 1}{3} > 1,$$

by the \tilde{T} -argument there is no cyclic K -rational ℓ -isogeny.

- If $\ell = 2$, then since $T(\mathcal{O}, 2) = 1$ there is an \mathcal{O} -CM elliptic curve E/K with a K -rational 2-isogeny.
- Since

$$\frac{\tilde{T}(\mathcal{O}, 4)}{\varphi(4)^{\frac{w_K}{2}}} = \frac{12}{2 \cdot 3} > 1,$$

by the \tilde{T} -argument there is no cyclic K -rational 4-isogeny.

- We claim that there is an \mathcal{O} -CM elliptic curve E/K with a K -rational cyclic 9-isogeny. Let \mathfrak{p} be the unique prime ideal of \mathcal{O} lying over 3, and let P be a generator of the cyclic \mathcal{O} -module $E[\mathfrak{p}^3] \subset E[9]$, so P has order 9. By Lemma 7.4, the $C_9(\mathcal{O})$ -orbit on P can be identified with the unit group $(\mathcal{O}/\mathfrak{p}^3)^\times$, of order 18. The \mathcal{O} -module generated by P is also isomorphic to $(\zeta_3 - 1)\mathcal{O}/9\mathcal{O}$, and using this representation it is easy to compute that the group $(\mathcal{O}/\mathfrak{p}^3)^\times$ is generated by the images of the scalar matrices $(\mathbb{Z}/9\mathbb{Z})^\times$ and the cube roots of unity. Thus Galois acts on the image of P in $\mathbb{P}E[9]$ via a character $\mathbb{P}\chi$. After twisting by the inverse of this character, the image of P in $\mathbb{P}E[9]$ becomes fixed by Galois and we get a K -rational cyclic 9-isogeny.

- Since

$$\frac{\tilde{T}(\mathcal{O}, 18)}{\varphi(18)^{\frac{w_K}{2}}} = \frac{54}{3 \cdot 6} > 1,$$

by the \tilde{T} -argument there is no K -rational cyclic 18-isogeny.

- Since

$$\frac{\tilde{T}(\mathcal{O}, 27)}{\varphi(27)^{\frac{w_K}{2}}} = \frac{162}{3 \cdot 18} > 1,$$

by the \tilde{T} -argument there is no K -rational cyclic 27-isogeny.

- From Section 7E (or Theorem 7.2) we know there is an \mathcal{O} -CM elliptic curve E/K with a rational point of order 6, hence certainly a cyclic K -rational 6-isogeny.

Using the same considerations as in the $\Delta = -4$ case above we get the assertion of Theorem 6.18(c).

Example 7.12. There are 13 imaginary quadratic discriminants Δ such that the corresponding order $\mathcal{O}(\Delta)$ has class number 1. For each such Δ we list in Table 1 the set of $N > 1$ for which there is an $\mathcal{O}(\Delta)$ -CM elliptic curve E defined over $K = \mathbb{Q}(\sqrt{\Delta})$ that admits a K -rational cyclic N -isogeny — otherwise put, for which there is an $\mathcal{O}(\Delta)$ -CM point on $X_0(N)(\mathbb{Q}(\sqrt{\Delta}))$.

Δ	N		
−3	$2^a 3^b \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1 \pmod{3}$,	$(a, b) \in \{(0, 0), (1, 0), (2, 0), (0, 1), (1, 1)\}$
−4	$2^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1 \pmod{4}$,	$a \leq 2$
−7	$7^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/7 = 1$,	$a \leq 1$
−8	$2^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1, 3 \pmod{8}$,	$a \leq 1$
−11	$11^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/11 = 1$,	$a \leq 1$
−12	$2^a 3^b \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1 \pmod{3}$,	$a \leq 2, b \leq 1$
−16	$2^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1 \pmod{4}$,	$a \leq 3$
−19	$19^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/19 = 1$,	$a \leq 1$
−27	$2^a 3^b \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i \equiv 1 \pmod{3}$,	$a \leq 2, b \leq 3$
−28	$7^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/7 = 1$,	$a \leq 1$
−43	$43^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/43 = 1$,	$a \leq 1$
−67	$67^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/67 = 1$,	$a \leq 1$
−163	$163^a \ell_1^{a_1} \dots \ell_r^{a_r}$	with $\ell_i/163 = 1$,	$a \leq 1$

Table 1. Values of $N > 1$ with an $\mathcal{O}(\Delta)$ -CM point on $X_0(N)(\mathbb{Q}(\sqrt{\Delta}))$.

Acknowledgments

We are deeply indebted to R. Bröker for making us aware of [Stevenhagen 2001]. We also thank the anonymous referee for helpful comments and suggestions.

References

- [Aoki 1995] N. Aoki, “Torsion points on abelian varieties with complex multiplication”, pp. 1–22 in *Algebraic cycles and related topics* (Kitasakado, 1994), edited by F. Hazama, World Sci. Publ., River Edge, NJ, 1995. MR Zbl
- [Aoki 2006] N. Aoki, “Torsion points on CM abelian varieties”, *Comment. Math. Univ. St. Pauli* **55**:2 (2006), 207–229. MR Zbl
- [Bourdon and Clark 2019] A. Bourdon and P. Clark, “Torsion points and isogenies on CM elliptic curves”, preprint, 2019. arXiv
- [Bourdon and Pollack 2017] A. Bourdon and P. Pollack, “Torsion subgroups of CM elliptic curves over odd degree number fields”, *Int. Math. Res. Not.* **2017**:16 (2017), 4923–4961. MR Zbl
- [Bourdon et al. 2017a] A. Bourdon, P. L. Clark, and P. Pollack, “Anatomy of torsion in the CM case”, *Math. Z.* **285**:3-4 (2017), 795–820. MR Zbl
- [Bourdon et al. 2017b] A. Bourdon, P. L. Clark, and J. Stankewicz, “Torsion points on CM elliptic curves over real number fields”, *Trans. Amer. Math. Soc.* **369**:12 (2017), 8457–8496. MR Zbl
- [Breuer 2010] F. Breuer, “Torsion bounds for elliptic curves and Drinfeld modules”, *J. Number Theory* **130**:5 (2010), 1241–1250. MR Zbl
- [Clark 2015] P. L. Clark, “Commutative algebra”, preprint, 2015, available at <http://math.uga.edu/~pete/integral2015.pdf>. To appear in *J. London Math. Soc.*

- [Clark and Pollack 2015] P. L. Clark and P. Pollack, “The truth about torsion in the CM case”, *C. R. Math. Acad. Sci. Paris* **353**:8 (2015), 683–688. MR Zbl
- [Clark et al. 2013] P. L. Clark, B. Cook, and J. Stankewicz, “Torsion points on elliptic curves with complex multiplication (with an appendix by Alex Rice)”, *Int. J. Number Theory* **9**:2 (2013), 447–479. MR Zbl
- [Clark et al. 2014] P. L. Clark, P. Corn, A. Rice, and J. Stankewicz, “Computation on elliptic curves with complex multiplication”, *LMS J. Comput. Math.* **17**:1 (2014), 509–535. MR Zbl
- [Cohen 2000] H. Cohen, *Advanced topics in computational number theory*, Graduate Texts in Mathematics **193**, Springer, 2000. MR Zbl
- [Cox 1989] D. A. Cox, *Primes of the form $x^2 + ny^2$: Fermat, class field theory and complex multiplication*, Wiley, New York, 1989. MR Zbl
- [Eisenbud 1995] D. Eisenbud, *Commutative algebra: with a view toward algebraic geometry*, Graduate Texts in Mathematics **150**, Springer, 1995. MR Zbl
- [Franz 1935] W. Franz, “Die Teilwerte der Weberschen Tau-Funktion”, *J. Reine Angew. Math.* **173** (1935), 60–64. MR Zbl
- [Gaudron and Rémond 2018] E. Gaudron and G. Rémond, “Torsion des variétés abéliennes CM”, *Proc. Amer. Math. Soc.* **146**:7 (2018), 2741–2747. MR Zbl
- [González-Jiménez 2019] E. González-Jiménez, “Explicit characterization of the torsion growth of rational elliptic curves with complex multiplication over quadratic fields”, preprint, 2019. arXiv
- [Kwon 1999] S. Kwon, “Degree of isogenies of elliptic curves with complex multiplication”, *J. Korean Math. Soc.* **36**:5 (1999), 945–958. MR Zbl
- [Lang 1987] S. Lang, *Elliptic functions*, 2nd ed., Graduate Texts in Mathematics **112**, Springer, 1987. MR Zbl
- [Lombardo 2017] D. Lombardo, “Galois representations attached to abelian varieties of CM type”, *Bull. Soc. Math. France* **145**:3 (2017), 469–501. MR Zbl
- [Lozano-Robledo 2018a] A. Lozano-Robledo, “Galois representations attached to elliptic curves with complex multiplication”, preprint, 2018. arXiv
- [Lozano-Robledo 2018b] A. Lozano-Robledo, “Uniform boundedness in terms of ramification”, *Res. Number Theory* **4**:1 (2018), art. no. 6, 39 pp. MR Zbl
- [Najman 2010] F. Najman, “Complete classification of torsion of elliptic curves over quadratic cyclotomic fields”, *J. Number Theory* **130**:9 (2010), 1964–1968. MR Zbl
- [Najman 2011] F. Najman, “Torsion of elliptic curves over quadratic cyclotomic fields”, *Math. J. Okayama Univ.* **53** (2011), 75–82. MR Zbl
- [Olson 1974] L. D. Olson, “Points of finite order on elliptic curves with complex multiplication”, *Manuscripta Math.* **14** (1974), 195–205. MR Zbl
- [Parish 1989] J. L. Parish, “Rational torsion in complex-multiplication elliptic curves”, *J. Number Theory* **33**:2 (1989), 257–265. MR Zbl
- [Prasad and Yogananda 2001] D. Prasad and C. S. Yogananda, “Bounding the torsion in CM elliptic curves”, *C. R. Math. Acad. Sci. Soc. R. Can.* **23**:1 (2001), 1–5. MR Zbl
- [Ross 1994] R. Ross, “Minimal torsion in isogeny classes of elliptic curves”, *Trans. Amer. Math. Soc.* **344**:1 (1994), 203–215. MR Zbl
- [Serre 1972] J.-P. Serre, “Propriétés galoisiennes des points d’ordre fini des courbes elliptiques”, *Invent. Math.* **15**:4 (1972), 259–331. MR Zbl

- [Silverberg 1988] A. Silverberg, “Torsion points on abelian varieties of CM-type”, *Compositio Math.* **68**:3 (1988), 241–249. MR Zbl
- [Silverberg 1992] A. Silverberg, “Points of finite order on abelian varieties”, pp. 175–193 in *p-adic methods in number theory and algebraic geometry*, edited by A. Adolphson et al., Contemp. Math. **133**, Amer. Math. Soc., Providence, RI, 1992. MR Zbl
- [Silverman 1994] J. H. Silverman, *Advanced topics in the arithmetic of elliptic curves*, Graduate Texts in Mathematics **151**, Springer, 1994. MR Zbl
- [Stevenhagen 2001] P. Stevenhagen, “Hilbert’s 12th problem, complex multiplication and Shimura reciprocity”, pp. 161–176 in *Class field theory—its centenary and prospect* (Tokyo, 1998), edited by K. Miyake, Adv. Stud. Pure Math. **30**, Math. Soc. Japan, Tokyo, 2001. MR Zbl

Received March 1, 2019. Revised September 15, 2019.

ABBÉY BOURDON
DEPARTMENT OF MATHEMATICS AND STATISTICS
WAKE FOREST UNIVERSITY
WINSTON-SALEM, NC
UNITED STATES
bourdoam@wfu.edu

PETE L. CLARK
DEPARTMENT OF MATHEMATICS
UNIVERSITY OF GEORGIA
ATHENS, GA
UNITED STATES
plclark@gmail.com

PACIFIC JOURNAL OF MATHEMATICS

Founded in 1951 by E. F. Beckenbach (1906–1982) and F. Wolf (1904–1989)

msp.org/pjm

EDITORS

Don Blasius (Managing Editor)
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
blasius@math.ucla.edu

Matthias Aschenbrenner
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
matthias@math.ucla.edu

Daryl Cooper
Department of Mathematics
University of California
Santa Barbara, CA 93106-3080
cooper@math.ucsb.edu

Jiang-Hua Lu
Department of Mathematics
The University of Hong Kong
Pokfulam Rd., Hong Kong
jhlu@maths.hku.hk

Paul Balmer
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
balmer@math.ucla.edu

Wee Teck Gan
Mathematics Department
National University of Singapore
Singapore 119076
matgwt@nus.edu.sg

Sorin Popa
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
popa@math.ucla.edu

Paul Yang
Department of Mathematics
Princeton University
Princeton NJ 08544-1000
yang@math.princeton.edu

Vyjayanthi Chari
Department of Mathematics
University of California
Riverside, CA 92521-0135
chari@math.ucr.edu

Kefeng Liu
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
liu@math.ucla.edu

Jie Qing
Department of Mathematics
University of California
Santa Cruz, CA 95064
qing@cats.ucsc.edu

PRODUCTION

Silvio Levy, Scientific Editor, production@msp.org

SUPPORTING INSTITUTIONS

ACADEMIA SINICA, TAIPEI
CALIFORNIA INST. OF TECHNOLOGY
INST. DE MATEMÁTICA PURA E APLICADA
KEIO UNIVERSITY
MATH. SCIENCES RESEARCH INSTITUTE
NEW MEXICO STATE UNIV.
OREGON STATE UNIV.

STANFORD UNIVERSITY
UNIV. OF BRITISH COLUMBIA
UNIV. OF CALIFORNIA, BERKELEY
UNIV. OF CALIFORNIA, DAVIS
UNIV. OF CALIFORNIA, LOS ANGELES
UNIV. OF CALIFORNIA, RIVERSIDE
UNIV. OF CALIFORNIA, SAN DIEGO
UNIV. OF CALIF., SANTA BARBARA

UNIV. OF CALIF., SANTA CRUZ
UNIV. OF MONTANA
UNIV. OF OREGON
UNIV. OF SOUTHERN CALIFORNIA
UNIV. OF UTAH
UNIV. OF WASHINGTON
WASHINGTON STATE UNIVERSITY

These supporting institutions contribute to the cost of publication of this Journal, but they are not owners or publishers and have no responsibility for its contents or policies.


See inside back cover or msp.org/pjm for submission instructions.

The subscription price for 2020 is US \$520/year for the electronic version, and \$705/year for print and electronic. Subscriptions, requests for back issues and changes of subscriber address should be sent to Pacific Journal of Mathematics, P.O. Box 4163, Berkeley, CA 94704-0163, U.S.A. The Pacific Journal of Mathematics is indexed by Mathematical Reviews, Zentralblatt MATH, PASCAL CNRS Index, Referativnyi Zhurnal, Current Mathematical Publications and Web of Knowledge (Science Citation Index).

The Pacific Journal of Mathematics (ISSN 1945-5844 electronic, 0030-8730 printed) at the University of California, c/o Department of Mathematics, 798 Evans Hall #3840, Berkeley, CA 94720-3840, is published twelve times a year. Periodical rate postage paid at Berkeley, CA 94704, and additional mailing offices. POSTMASTER: send address changes to Pacific Journal of Mathematics, P.O. Box 4163, Berkeley, CA 94704-0163.

PJM peer review and production are managed by EditFlow® from Mathematical Sciences Publishers.

PUBLISHED BY

 **mathematical sciences publishers**
nonprofit scientific publishing

<http://msp.org/>

© 2020 Mathematical Sciences Publishers

PACIFIC JOURNAL OF MATHEMATICS

Volume 305 No. 1 March 2020

The Poincaré homology sphere, lens space surgeries, and some knots with tunnel number two	1
KENNETH L. BAKER	
Fusion systems of blocks of finite groups over arbitrary fields	29
ROBERT BOLTJE, ÇISIL KARAGÜZEL and DENİZ YILMAZ	
Torsion points and Galois representations on CM elliptic curves	43
ABBEY BOURDON and PETE L. CLARK	
Stability of the positive mass theorem for axisymmetric manifolds	89
EDWARD T. BRYDEN	
Index estimates for free boundary constant mean curvature surfaces	153
MARCOS P. CAVALCANTE and DARLAN F. DE OLIVEIRA	
A criterion for modules over Gorenstein local rings to have rational Poincaré series	165
ANJAN GUPTA	
Generalized Cartan matrices arising from new derivation Lie algebras of isolated hypersurface singularities	189
NAVEED HUSSAIN, STEPHEN S.-T. YAU and HUAIQING ZUO	
On the commutativity of coset pressure	219
BING LI and WEN-CHIAO CHENG	
Signature invariants related to the unknotting number	229
CHARLES LIVINGSTON	
The global well-posedness and scattering for the 5-dimensional defocusing conformal invariant NLW with radial initial data in a critical Besov space	251
CHANGXING MIAO, JIANWEI YANG and TENGFEI ZHAO	
Liouville-type theorems for weighted p -harmonic 1-forms and weighted p -harmonic maps	291
KEOMKYO SEO and GABJIN YUN	
Remarks on the Hölder-continuity of solutions to parabolic equations with conic singularities	311
YUANQI WANG	
Deformation of Milnor algebras	329
ZHENJIAN WANG	
Preservation of log-Sobolev inequalities under some Hamiltonian flows	339
BO XIA	
Ground state solutions of polyharmonic equations with potentials of positive low bound	353
CAIFENG ZHANG, JUNGANG LI and LU CHEN	



0030-8730(2020)305:1;1-R