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Computing local constants for CM elliptic curves

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ABSTRACT. Let E/k be an elliptic curve with CM by $\mathcal{O}$. We determine a formula for (a generalization of) the arithmetic local constant of [**5**] at almost all primes of good reduction. We apply this formula to the CM curves defined over $\mathbf{Q}$ and are able to describe extensions $F/\mathbf{Q}$ over which the $\mathcal{O}$-rank of E grows.

1. Introduction. Let p be an odd rational prime. Let $k \subset K \subset L$ be a tower of number fields, with K/k quadratic, L/K p-power cyclic and L/k Galois with a dihedral Galois group, i.e., a lift of $1 \neq c \in \mathrm{Gal}\,(K/k)$ acts by conjugation on $g \in \mathrm{Gal}\,(L/K)$ as $cgc^{-1} = g^{-1}$. In [**5**] Mazur and Rubin define arithmetic local constants δ_v, one for each prime v of K, which describe the growth in $\mathbf{Z}$-rank of E over the extension L/K. Specifically (cf., [**5**, Theorem 6.4]), for $\chi : \mathrm{Gal}\,(L/K) \hookrightarrow \overline{\mathbf{Q}}^{\times}$ an injective character and S a set of primes of K containing all primes above p, all primes ramified in L/K and all primes where E has bad reduction,

$$\mathrm{rank}_{\mathbf{Z}[\chi]} E(L)^{\chi} - \mathrm{rank}_{\mathbf{Z}} E(K) \equiv \sum_{v \in S} \delta_v \pmod 2. \tag{1.1}$$

To phrase their result this way, we must assume the Shafarevich-Tate conjecture[1], and we keep this assumption throughout.

In [**1**], the theory of arithmetic local constants is generalized to address the $\mathcal{O}$-rank of varieties with complex multiplication (CM) by an order $\mathcal{O}$, and we continue in that direction with specific attention to the elliptic curve case. Following [**1**], we assume that $\mathcal{O} \subset \mathrm{End}_K(E)$ is the maximal order in a quadratic imaginary field $\mathbf{K}$, p is unramified in $\mathcal{O}$, and $\mathcal{O}^c = \mathcal{O}^{\dagger} = \mathcal{O}$ where † indicates the action of the Rosati

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involution (see [**6**, subsection I.14]). When $\mathbf{K} \not\subset k$, these assumptions imply $K = k\mathbf{K}$.

Our present aim is to provide a simple formula for the local constants δ_v (see Definition 2.2) for primes $v \nmid p$ of good reduction. We then will use a result [**1**, Section 6] which generalizes (1.1), with $\mathbf{Z}$ replaced by $\mathcal{O}$, to determine conditions under which the $\mathcal{O}$-rank of E grows. In Section 3 we will describe, via class field theory, dihedral extensions $F/\mathbf{Q}$ which satisfy those conditions, in order to give some concrete setting to the results of Section 2.

2. Computing the local constant. Suppose p splits[2] in $\mathcal{O}$, i.e., $p\mathcal{O} = \mathfrak{p}_1\mathfrak{p}_2$, with $\mathfrak{p}_1 \neq \mathfrak{p}_2$. We denote $R = \mathcal{O}/p\mathcal{O}$ and $R_i = \mathcal{O}/\mathfrak{p}_i$ for $i = 1, 2$, so that $R \cong R_1 \oplus R_2$.

Definition 2.1. If M is an $\mathcal{O}$-module of exponent p, define the R-rank of M by

$$\mathrm{rank}_R M := (\mathrm{rank}_{R_1} M \otimes_R R_1, \mathrm{rank}_{R_2} M \otimes_R R_2).$$

The following definition is the same as in [**1, 5**]. Fix a prime v of K, and let u and w be primes of k below v and of L above v, respectively. Denote k_u, K_v and L_w for the completions of k, K and L at u, v and w, respectively. If $L_w \neq K_v$, let L'_w be the extension of K_v inside L_w with $[L_w : L'_w] = p$, and otherwise let $L'_w = L_w = K_v$.

Definition 2.2. Define the arithmetic local constant $\delta_v := \delta(v, E, L/K)$ by

$$\delta_v \equiv \mathrm{rank}_R \frac{E(K_v)}{E(K_v) \cap N_{L_w/L'_w} E(L_w)} \pmod 2.$$

Now, we will consider primes v of K such that E has good reduction at v, $v \nmid p$, $v^c = v$ and v ramifies in L/K (corresponding to [**5**, Lemma 6.6]). Under these conditions, [**5**, Theorem 5.6] shows that

$$\dim_{\mathbf{F}_p} \frac{E(K_v)}{E(K_v) \cap N_{L_w/L'_w} E(L_w)} \equiv \dim_{\mathbf{F}_p} E(K_v)[p] \pmod 2. \tag{2.1}$$

Proposition 2.4 below shows that we are able to replace $\dim_{\mathbf{F}_p}$ by rank_R in (2.1). We first need Lemma 2.3, which follows Lemmas 5.4 and 5.5 of [**5**], and our proof is meant only to address the change from $\dim_{\mathbf{F}_p}$ to rank_R.

Let $\mathcal{K}$ and $\mathcal{L}$ be finite extensions of $\mathbf{Q}_\ell$, with $\ell \neq p$, and suppose $\mathcal{L}/\mathcal{K}$ is a finite extension.

Lemma 2.3. *Suppose $\mathcal{L}/\mathcal{K}$ is cyclic of degree p, E is defined over $\mathcal{K}$ and has good reduction. Then*:

(i) $\mathrm{rank}_R E(\mathcal{K})/pE(\mathcal{K}) = \mathrm{rank}_R E(\mathcal{K})[p]$.

(ii) *If $\mathcal{L}/\mathcal{K}$ is ramified, then $E(\mathcal{K})/pE(\mathcal{K}) = E(\mathcal{L})/pE(\mathcal{L})$ and*

$$N_{\mathcal{L}/\mathcal{K}} E(\mathcal{L}) = pE(\mathcal{K}).$$

(iii) *If $\mathcal{L}/\mathcal{K}$ is unramified, then $N_{\mathcal{L}/\mathcal{K}} E(\mathcal{L}) = E(\mathcal{K})$.*

Proof. When $\ell \neq p$, we have $E(\mathcal{K})/pE(\mathcal{K}) = E(\mathcal{K})[p^\infty]/pE(\mathcal{K})[p^\infty]$. Since $E(\mathcal{K})[p^\infty]$ is finite, (i) follows from the exact sequence of $\mathcal{O}$-modules

$$0 \longrightarrow E(\mathcal{K})[p] \longrightarrow E(\mathcal{K})[p^\infty] \longrightarrow pE(\mathcal{K})[p^\infty] \longrightarrow 0.$$

The content of (ii) and (iii) is on the level of sets, so the proof is exactly as in [**5**, Lemma 5.5]. $\square$

We return to the notation of Definition 2.2.

Proposition 2.4. *If $v \nmid p$ and L_w/K_v is nontrivial and totally ramified, then*

$$\delta_v \equiv \mathrm{rank}_R E(K_v)[p] \pmod 2.$$

Proof. As in [**5**, Proof of Theorem 5.6], Lemma 2.3 (ii) yields $N_{L_w/L'_w} E(L_w) = pE(L'_w)$, and hence $E(K_v) \cap pE(L'_w) = pE(K_v)$. So by Definition 2.2 and Lemma 2.3 (i),

$$\delta_v \equiv \mathrm{rank}_R \frac{E(K_v)}{pE(K_v)} \equiv \mathrm{rank}_R E(K_v)[p] \pmod 2. \qquad \square$$

Now, fix a prime v of K. We denote κ_u for the residue field of k_u, $q = \#\kappa_u$ for the size of finite field κ_u and $\widetilde{E}$ for the reduction of E to κ_u.

Proposition 2.5. *Suppose $v \nmid p$, v is ramified in L/K and $v^c = v$. If E has good reduction at v, then $\delta_v \equiv (1,1)$ if and only if $p \mid \#\widetilde{E}(\kappa_u)$.*

Proof. We follow the notation of [**5**, Lemma 6.6]. Since $v^c = v$, we know that K_v/k_u is quadratic, and it is unramified by [**5**, Lemma 6.5 (ii)]. Let Φ be the Frobenius generator of $\mathrm{Gal}\,(K_v^{ur}/k_u)$, so Φ^2 is the Frobenius of $\mathrm{Gal}\,(K_v^{ur}/K_v)$.

The proof of Lemma 6.6 [**5**] shows that the product of the eigenvalues α, β of Φ on $E[p]$ is -1. Also, $E(K_v)[p] = E[p]^{\Phi^2=1}$ is equal (as a set) to $E[p]$ or is trivial depending on whether or not $\{\alpha, \beta\} = \{1, -1\}$, respectively. Since E has CM by $\mathcal{O}$, $E[p]$ is a rank 1 R-module (see, e.g., [**10**, Section II.1]), so the former case yields

$$\delta_v \equiv \mathrm{rank}_R E(K_v)[p] = (1,1) \pmod 2.$$

By assumption, $v \nmid p$, so p is prime to the characteristic of κ_u, and therefore the reduction map restricted to p-torsion is injective [**9**, subsection VII.3]. We also know $E[p]$ is unramified [**9**, subsection VII.4], and so the eigenvalues of Φ acting on $E[p]$ coincide $\pmod p$ with the eigenvalues of the q-power Frobenius map ϕ_q on $\widetilde{E}[p]$. We know [**9**, Section V] that the characteristic polynomial of ϕ_q is $T^2 - aT + q$, where $a = q + 1 - \#\widetilde{E}(\kappa_u)$, and from the above comments $q \equiv -1 \pmod p$. Therefore, Φ having eigenvalues ± 1 is equivalent to $a \equiv 0 \pmod p$ and in turn equivalent to $\#\widetilde{E}(\kappa_u) \equiv 0 \pmod p$. ◻

Corollary 2.6. *If $\mathbf{K} \not\subset k$, then $\delta_v \equiv (1,1)$.*

Proof. To see that $p \mid \#\widetilde{E}(\kappa_u)$, we show that $a = 0$ under our assumptions on v, where $a = q + 1 - \#\widetilde{E}(\kappa_u)$ as above[3]. The theory of complex multiplication gives $a = \pi_u + \overline{\pi}_u$ for some $\pi_u \in \mathcal{O}$ such that $\pi_u \overline{\pi}_u = q$ (see, e.g., [**3**, Theorem 14.16], [**10**, subsection II.10] or [**8**] for a thorough discussion). As $\mathbf{K} \not\subset k$, we have $K = k\mathbf{K}$, and we let $\psi = \psi_{E/K}$ be the Grössencharacter associated to E and K (see

[**10**, subsection II.9] or [**4**]). By comparing their effect on $K(E[\ell])$, where ℓ is prime to v, we see that $\psi(v)^c = \psi(v^c)$, and since $v = v^c$, we have that $\psi(v)$ is fixed by c. It follows that $\psi(v)$ is rational, the corresponding $\pi_v \in \mathcal{O} \subset \mathrm{End}_K(E)$ is integral, and in fact, $\pi_v = \pm q$ by degree arguments. In addition, $\pi_u^2 = \pi_v$, and we will see that $\pi_u = \sqrt{-q}$ is purely imaginary. Indeed, π_u having no real part implies $a = \pi_u + \overline{\pi}_u = 0$; hence,

$$\#\widetilde{E}(\kappa_u) \equiv q + 1 \equiv 0 \pmod{p}$$

and $\delta_v \equiv (1,1)$ by Proposition 2.5.

Suppose instead that $\pi_u = \sqrt{q}$ is real[4]. If, in addition, we suppose π_u is integral then the reduction $\phi_q \in \mathrm{End}\,(\widetilde{E})$ of π_u would commute with all endomorphisms of $\widetilde{E}$. As $\mathbf{K} \not\subset k$, there is some $\rho \in \mathrm{End}_K(E)$ such that $\rho \neq \rho^c$, and hence, $\widetilde{\rho} \neq \widetilde{\rho}^c$. Thus, for some $P \in \widetilde{E}(\kappa_u)$, $P^c = P$ and $\widetilde{\rho}(P^c) \neq \widetilde{\rho}^c(P)$. As the action of c on κ_u coincides with that of Frobenius $\widetilde{\Phi}$, it follows that $\widetilde{\rho}$ does not commute with $\widetilde{\Phi}$, and in turn $\widetilde{\rho}$ does not commute with the Frobenius endomorphism $\phi_q \in \mathrm{End}\,(\widetilde{E})$ induced by $\widetilde{\Phi}$.

If $\pi_u = \sqrt{q}$ is real and irrational, then $k \subsetneq \mathbf{Q}(\pi_u)k \subset K$ and so $c \in \mathrm{Gal}\,(K/k)$ acts non-trivially on π_u, i.e., $\pi_u^c = -\sqrt{q}$. It follows that

$$q = N_{\mathbf{K}/\mathbf{Q}}(\pi_u) = \pi_u \pi_u^c = -q,$$

which is a contradiction, and we conclude π_u is purely imaginary as desired. □

Define a set $\mathfrak{S}_L$ of primes v of K by

$$\mathfrak{S}_L := \{v \mid p, \text{ or } v \text{ ramifies in } L/K, \text{ or where } E \text{ has bad reduction}\}.$$

Theorem 2.7 [**1**, Theorem 6.1]. *Let $\chi : \mathrm{Gal}\,(L/K) \hookrightarrow \overline{\mathbf{Q}}^{\times}$ be an injective character and $\mathcal{O}[\chi]$ the extension of $\mathcal{O}$ by the values of χ. Assuming the Shafarevich-Tate conjecture,*

$$\mathrm{rank}_{\mathcal{O}[\chi]} E(L)^{\chi} - \mathrm{rank}_{\mathcal{O}} E(K) \equiv \sum_{v \in \mathfrak{S}_L} \delta_v \pmod{2}.$$

We now consider a dihedral tower $k \subset K \subset F$ where F/K is p-power abelian. Following [**5**, Section 3], we note that there is a bijection between cyclic extensions L/K in F and irreducible rational representations ρ_L of $G = \mathrm{Gal}\,(F/K)$. The semi-simple group ring $\mathbf{K}[G]$ decomposes as

$$\mathbf{K}[G] \cong \oplus_L \mathbf{K}[G]_L,$$

where $\mathbf{K}[G]_L$ is the ρ_L-isotypic component of $\mathbf{K}[G]$. For each L, it suffices to deal with an injective character $\chi : \mathrm{Gal}\,(L/K) \hookrightarrow \overline{\mathbf{Q}}^{\times}$ appearing in the direct-sum decomposition of $\rho_L \otimes \overline{\mathbf{Q}}^{\times}$, and $\mathrm{rank}_{\mathcal{O}[\chi]} E(F)^{\chi}$ is independent[5] of the choice of χ.

Theorem 2.8. *Assume* $\mathbf{K} \not\subset k$.[6] *Suppose that, for every prime* v *satisfying* $v^c = v$ *and which ramifies in* F/K*, we have* $v \nmid p$ *and* E *has good reduction at* v*. For* m *equal to the number of such* v*, if* $\mathrm{rank}_{\mathcal{O}} E(K) + m$ *is odd, then*

$$\mathrm{rank}_{\mathcal{O}} E(F) \geq [F : K].$$

Proof. Fix a cyclic extension L/K inside F. If v is a prime of K and $v^c \neq v$, then $\delta_v \equiv \delta_{v^c}$ and hence $\delta_v + \delta_{v^c} \equiv (0,0) \pmod 2$ by [**5**, Lemma 5.1]. If $v^c = v$ and v is unramified in L/K, then v splits completely in L/K by [**5**, Lemma 6.5 (i)]. It follows that N_{L_w/L'_w} is surjective, and so $\delta_v \equiv (0,0)$ by Definition 2.2. The remaining primes v are precisely those named in the assumption, so Proposition 2.6 gives $\sum_v \delta_v \equiv (m,m) \pmod 2$. Thus,

$$\mathrm{rank}_{\mathcal{O}[\chi]} E(L)^{\chi} \equiv \mathrm{rank}_{\mathcal{O}} E(K) + m \pmod 2,$$

and we have assumed that the right-hand side is odd.

From [**5**, Corollary 3.7], it follows that

$$\mathrm{rank}_{\mathcal{O}} E(F) = \sum_L (\dim_{\mathbf{Q}} \rho_L) \cdot (\mathrm{rank}_{\mathcal{O}[\chi]} E(L)^{\chi}).$$

As the previous paragraph applies for every cyclic L/K in F we see from the decomposition of $\mathbf{K}[G]$ that $E(F) \otimes \mathbf{Q}$ contains a submodule isomorphic to $\mathbf{K}[G]$, and the claim follows. $\square$

3. CM elliptic curves defined over Q. Here, we will consider the CM elliptic curves E defined over $\mathbf{Q}$ (as in [**10**, A.3]). For each E, our aim is to determine[7] examples of dihedral towers $\mathbf{Q} \subset K \subset F$ over which, according to Theorem 2.8, the $\mathcal{O}$-rank of E grows. As we have assumed $\mathcal{O} \subset \mathrm{End}_K(E)$, we will consider towers in which $K = \mathbf{K}$ (see Section 1). All of our calculations will be done using Sage [**11**].

Let $E_D/\mathbf{Q}$ be the elliptic curve of minimal conductor[8] defined over $\mathbf{Q}$ with CM by $K_D = \mathbf{Q}(\sqrt{-D})$. We determine computationally[9] $\mathrm{rank}_{\mathbf{Z}} E_D(K_D)$, and for $D = 3$, we see that this group is finite. For $D = 4, 7$, the situation is less certain, as Sage only tells us that $E_D(\mathbf{Q})$ is finite and $\mathrm{rank}_{\mathbf{Z}} E_D(K_D) \leq 2$. For each of the remaining CM curves E_D defined over $\mathbf{Q}$, one can (provably) calculate that $\mathrm{rank}_{\mathbf{Z}} E_D(\mathbf{Q}) = 1$. We also have that $\mathrm{rank}_{\mathbf{Z}} E_D(K_D) \geq \mathrm{rank}_{\mathbf{Z}} E_D(\mathbf{Q}) = 1$ and $\mathrm{rank}_{\mathbf{Z}} E_D(K_D)$ cannot be even, so $\mathrm{rank}_{\mathcal{O}} E_D(K_D) \geq 1$. For $D = 8$, 11, 19, 43, 67 and 163, Sage gives an upper bound[7] of 3 for $\mathrm{rank}_{\mathbf{Z}} E_D(K_D)$ and so, for these D, we can conclude that in fact $\mathrm{rank}_{\mathcal{O}} E_D(K_D) = 1$.

3.1. Dihedral extensions of Q. Recall that p is a fixed odd rational prime. Presently, we also fix $D \in \{3, 4, 7, \ldots, 163\}$, and let $E = E_D$, $K = K_D$. We are interested in abelian extensions F/K which are dihedral over $\mathbf{Q}$, and these are exactly the extensions contained in the ring class fields of K (see [**3**, Theorem 9.18]).

Let $\mathcal{O}_f$ be an order in $\mathcal{O}_K$ of conductor f. We have a simple formula for the class number $h(\mathcal{O}_f)$ of $\mathcal{O}_f$ using, for example, [**3**, Theorem 7.24], and noting that, we have $h(\mathcal{O}_K) = 1$,

$$h(\mathcal{O}_f) = \frac{f}{[\mathcal{O}_K^\times : \mathcal{O}_f^\times]} \cdot \prod_{\text{primes } \ell | f} \left(1 - \left(\frac{-D}{\ell}\right)\frac{1}{\ell}\right).$$

For $D \neq 3, 4$, we have $\mathcal{O}_K^\times = \{\pm 1\}$ and, for $D = 4$, we have $\#\mathcal{O}_K^\times = 4$, so in both of these cases $[\mathcal{O}_K^\times : \mathcal{O}_f^\times]$ is prime to p. For $D = 3$, one can show that $[\mathcal{O}_K^\times : \mathcal{O}_f^\times] = 3$ when $f > 1$. The following paragraphs require only minor adjustments for the case $p = D = 3$.

Taking f to be an odd rational prime such that $(-D/f) = \pm 1$, the class number becomes $h(\mathcal{O}_f) = f \mp 1$, and so the ring class field $H_{\mathcal{O}_f}$ associated to $\mathcal{O}_f$ is an abelian extension of K of degree $f \mp 1$. Thus, for $f \equiv \pm 1 \pmod{p}$, we have a (non-trivial) p-power subextension F/K which is dihedral over $\mathbf{Q}$.

Next, we need to understand the ramification in F/K. As K has class number 1, we know there are no unramified extensions of K, and so we must ensure that F satisfies the hypotheses of Theorem 2.8. A prime v of K ramifies in $H_{\mathcal{O}_f}/K$ if and only if $v \mid f\mathcal{O}_K$ (see, for example, [**3**, Exercise 9.20] and recall f is odd). If we choose f so that $-D$ is not a square $\pmod{f}$, f is inert in $K/\mathbf{Q}$, and so $f\mathcal{O}_K$ is prime and, moreover, the only prime that ramifies in $H_{\mathcal{O}_f}/K$. If $f\mathcal{O}_K$ does not ramify in F/K, then the p-extension F/K is contained in the Hilbert class field H_K of K. As $H_K = K$, this is impossible, so $f\mathcal{O}_K$ ramifies in F/K and no other primes ramify in F/K. Taking f such that $f \nmid D$ and $-D$ is a square $\pmod{f}$, we have that f is not inert and does not ramify in $K/\mathbf{Q}$. As in the previous case, the primes of K above f both ramify in the p-extension F/K contained in $H_{\mathcal{O}_f}$.

Now, suppose $\operatorname{rank}_{\mathcal{O}} E(K)$ is odd[10]. To apply Theorem 2.8, we must have an even number m of primes v such that $v^c = v$, v ramifies in F/K, E has good reduction at v and for which $p \mid \#\widetilde{E}(\mathbf{Z}/f\mathbf{Z})$. First, we can guarantee $m = 0$ if the only primes v which ramify in F/K do not satisfy $v^c = v$, e.g., taking $f \nmid D$ with $(-D/f) = 1$. Table 3.1 gives, for each D and for $p = 3, 5, 7$, the smallest prime f which gives an extension of degree p following this recipe. We note that we do not need Proposition 2.5 for this case.

If we wish to allow for primes v satisfying $v^c = v$, we choose two p-extensions F_1 and F_2 from two distinct rational primes f_i as above with $f_i \equiv -1 \pmod{p}$ and $(-D/f_i) = -1$, for $i = 1, 2$. The compositum $F = F_1F_2$ will satisfy our requirements. Indeed, firstly F is an abelian p-extension of K and is contained in the ring class field $H_{\mathcal{O}_{f_1 f_2}}$, hence dihedral over $\mathbf{Q}$ with only $f_1\mathcal{O}_K$ and $f_2\mathcal{O}_K$ ramifying in F/K. Secondly, as each f_i is inert in $K/\mathbf{Q}$, each is a supersingular prime for E (this follows from the arguments in Corollary 2.6) and hence p divides $\#\widetilde{E}(\mathbf{Z}/f_i\mathbf{Z}) = f_i + 1$. Thus, E and the p-extension F/K satisfy the hypotheses of Theorem 2.8. Table 3.2 below gives, for each D and for $p = 3, 5, 7$, the smallest pair of distinct primes f_1, f_2 which give extensions of degree p^2 following this recipe.

Next, suppose $\operatorname{rank}_{\mathcal{O}} E(K)$ is even.[11] In this case, we need m to be odd in order to apply Theorem 2.8. The same ideas as above still work, and in Table 3.3 we list, for each D and for $p = 3, 5, 7$, the smallest prime f for which Theorem 2.8 guarantees rank $\geq p$.

Remark 3.1. Though there are algorithms in the literature to compute the defining polynomial of a class field (e.g., [**2**, Section 6], [**3**, subsection 11-3]) and such computational problems are of interest independently, we make no attempt here to explicitly determine the ring class fields $H_{\mathcal{O}_f}$. As is apparent from Table 3.2, our method of determining a field to which Theorem 2.8 applies involves ring class fields of large degree in a computationally inefficient way.

TABLE 3.1. Case $m = 0$.

	$p=3$		$p=5$		$p=7$	
D	f	$[F:K]$	f	$[F:K]$	f	$[F:K]$
4	13	3	41	5	29	7
7	43	3	11	5	29	7
8	43	3	11	5	43	7
11	31	3	31	5	71	7
19	7	3	11	5	43	7
43	13	3	11	5	127	7
67	103	3	71	5	29	7
163	43	3	41	5	43	7

TABLE 3.2. Case $m = 2$.

	$p=3$			$p=5$			$p=7$		
D	f_1	f_2	$[F:K]$	f_1	f_2	$[F:K]$	f_1	f_2	$[F:K]$
4	11	23	9	19	59	25	83	139	49
7	5	41	9	19	59	25	13	41	49
8	5	23	9	29	79	25	13	167	49
11	2	29	9	29	79	25	13	41	49
19	2	29	9	29	59	25	13	41	49
43	2	5	9	19	29	25	223	349	49
67	2	5	9	79	109	25	13	41	49
163	2	5	9	19	29	25	13	139	49

TABLE 3.3. Case $m = 1$.

	$p=3$		$p=5$		$p=7$	
D	f	$[F:K]$	f	$[F:K]$	f	$[F:K]$
3	17	3	29	5	41	7
4	11	3	19	5	83	7
7	5	3	19	5	13	7

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ENDNOTES

1. Without this assumption, all statements regarding $\mathcal{O}$-rank of E would be replaced by analogous statements regarding $\mathcal{O} \otimes \mathbf{Z}_p$-corank of the p^∞-Selmer group $\mathrm{Sel}_{p^\infty}(E/K)$ of E.

2. The simpler case of p being inert in $\mathcal{O}$, i.e., $\mathcal{O}/p\mathcal{O}$ is a field, is treated similarly.

3. That $a = 0$ in this case is known (see [**10**, Exercise 2.30], [**4**, Section 4, Theorem 10] or [**7**, Theorem 7.46] for generalization to higher dimensional abelian varieties); we include an argument for completeness.

4. The case $\pi_u = -\sqrt{q}$ follows the same argument.

5. We could instead write that $\dim_{\overline{\mathbf{Q}}}(E(F) \otimes \overline{\mathbf{Q}})^\chi$ is independent of the choice of χ.

6. The case $\mathbf{K} \subset k$ is similar, with m equal to the number of v such that $p \mid \#\widetilde{E}(\kappa_u)$.

7. Determined up to the correspondence of class field theory.

8. See [**10**, page 483], with $f = 1$ (in Silverman's notation), for a Weierstrauss equation.

9. Specifically with Sage's interface to John Cremona's '`mwrank`' and Denis Simon's '`simon_two_descent`.'

10. The cases $D = 8, 11, \ldots, 163$, and possibly $D = 4, 7$.
11. The case $D = 3$, and possibly $D = 4, 7$.

REFERENCES

1. S. Chetty, *Arithmetic local constants for abelian varieties with complex multiplication*, `http://www.csbsju.edu/Mathematics/sunil-chetty.htm` (preprint).

2. H. Cohen, *Advanced topics in computational number theory*, Grad. Texts Math. **193**, Springer, New York, 2000.

3. D. Cox, *Primes of the form $x^2 + ny^2$: Fermat, class field theory, and complex multiplication*, Wiley Interscience, New York, 1989.

4. S. Lang, *Elliptic functions*, second edition, Grad. Texts Math. **112**, Springer, New York, 1987.

5. B. Mazur and K. Rubin, *Finding large Selmer rank via an arithmetic theory of local constants*, Ann. Math. **166** (2007), 581–614.

6. J.S. Milne, *Abelian varieties*, in *Arithmetic geometry*, G. Cornell and J. Silverman, eds., Springer-Verlag, New York, 1986, available at `http://www.jmilne.org/math/`.

7. G. Shimura, *Introduction to the arithmetic theory of automorphic functions*, Princeton University Press, Princeton, 1971.

8. A. Silverberg, *Group order formulas for reductions of CM elliptic curves*, in *Arithmetic, geometry, cryptography and coding theory*, Contemp. Math. **521**, American Mathematical Society, 2010.

9. J. Silverman, *Arithmetic of elliptic curves*, Grad. Texts Math. **106**, Springer, New York, 1986.

10. ———, *Advanced topics in the arithmetic of elliptic curves*, Grad. Texts Math. **151**, Springer, New York, 1994.

11. W.A. Stein, et al., *Sage mathematics software* (Version 4.2.1), The Sage Development Team, 2009, `http://www.sagemath.org`.

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