

Towards Lang-Trotter for Elliptic Curves over Function Fields

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1. Introduction

Let K be a global field of char p and let $\mathbb{F}_q \subset K$ denote the algebraic closure of \mathbb{F}_p in K . We fix an elliptic curve E/K with non-constant j -invariant and a torsion-free subgroup $\Sigma \subseteq E(K)$ of rank $r > 0$. We write V for the open set of places v of K such that the special fiber E_v is an elliptic curve and, for v in V , we let $\Sigma_v \subset E_v(k_v)$ be the image of Σ under reduction modulo v , where k_v is the residue field of K at v . We fix a finite set of (rational) prime numbers \mathcal{S} which is large enough to include the exceptional primes which we will define explicitly in section 2.4 and section 3), and we let $\mathcal{G}(\Sigma, \mathcal{S})$ denote the subset of $v \in V$ such that Σ_v contains the prime-to- \mathcal{S} part of $E_v(k_v)$. For every $n > 0$, we write V_n for the subset of $v \in V$ such that $\deg(v) = n$ and let $\mathcal{G}_n(\Sigma, \mathcal{S}) = V_n \cap \mathcal{G}(\Sigma, \mathcal{S})$.

THEOREM 1. *Suppose $r \geq 6$. There exists constants a, b satisfying $0 < a < b < 1$ and depending only on r and \mathcal{S} such that, for each $n \geq 1$ there exists $\delta_n(\Sigma, \mathcal{S})$, depending on r, \mathcal{S} and the isomorphism class of $\text{Gal}(K(E[\ell])/K)$ for $\ell \notin \mathcal{S}$, satisfying $a \leq \delta_n(\Sigma, \mathcal{S}) \leq b$ such that*

$$|\mathcal{G}_n(\Sigma, \mathcal{S})| = \delta_n(\Sigma, \mathcal{S})|V_n| + o(q^n/n).$$

We prove the theorem in section 4.3. The rest of the paper establishes preliminary results. We remark that for a fixed K, r and \mathcal{S} , there are only finitely many possibilities for the entire set $\{\delta_n(\Sigma, \mathcal{S}) : n > 0\}$, as will follow from our results. However, the limit $\delta_n(\Sigma, \mathcal{S})$ as $n \rightarrow \infty$ does *not* exist in general. Rather one must consider an increasing sequence n_1, n_2, \dots such that n_i divides n_{i+1} in order to obtain a limit. Different sequences will lead to different limits. This is in contrast with the number field analogue in which the analogous δ_n converge and therefore can be taken independent of n .

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The number field analogue of the above theorem was conjectured by Lang and Trotter (for $r = 1$) and proved by Gupta and Murty ([**GM**]) for $r \geq 10$. Our proof of theorem 1 follows the function-field analogue of the strategy in [**GM**]. A literal translation of their argument, together with the improved error bounds of [**MS**], allows one to prove an analogue of their theorem for $r \geq 10$. The proof proceeds in several stages, and in one of these stages we replace the use of $K(E[\ell])$ with a smaller subextension of K , which we define in section 2.2. This allows us to extend the argument to $r \geq 6$. It is conceivable that these extensions might be used in the number field case to lower the bound on r . We hope to return to this question in a later paper. The case of constant j -invariant and $r = 1$ was treated by the second author in [**V**].

2. ℓ -adic Galois Theory

Throughout this section K is an arbitrary field and ℓ is a fixed rational prime which is invertible in K . We fix an elliptic E/K and write $L = K(E[\ell])$. There is an embedding $\Gamma = \text{Gal}(L/K) \rightarrow \text{GL}_2(\mathbb{Z}/\ell)$, which is well-defined, up to conjugation, and is given by identifying $\text{Aut}(E[\ell])$ with $\text{GL}_2(\mathbb{Z}/\ell)$. Moreover, for a fixed primitive ℓ th root of unity ζ , the quotient $\det(\Gamma)$ is the Galois group of the cyclotomic extension $K(\zeta)/K$. We call the kernel of $\Gamma \rightarrow \det(\Gamma)$ the subgroup of geometric elements, or simply the geometric Galois group of L/K . In all but the last section we assume that it is $\text{SL}_2(\mathbb{Z}/\ell)$. In the last section we consider the case when the geometric Galois group is a proper subgroup of $\text{SL}_2(\mathbb{Z}/\ell)$.

2.1. Kummer Theory. In this section we additionally assume $\ell > 2$. Recall $L = K(E[\ell])$ and $\Gamma = \text{Gal}(L/K)$ contains $\text{SL}_2(\mathbb{Z}/\ell)$.

LEMMA 1. *The natural map $E(K)/\ell(E(K)) \rightarrow E(L)/\ell(E(L))$ is injective.*

PROOF. For every finite extension F/K there is a natural embedding of $E(F)/\ell(E(F))$ into the Galois cohomology group $H^1(F, E[\ell])$, hence it suffices to show that the restriction map $H^1(K, E[\ell]) \rightarrow H^1(L, E[\ell])$ is injective. By the inflation-restriction sequence, the kernel of the restriction map is $H^1(\Gamma, E[\ell])$. Let Z be the center of Γ ; it is a normal subgroup of order prime to ℓ and $E[\ell]^Z = 0$. It follows that $H^1(\Gamma, E[\ell]) = 0$, proving the lemma. \square

For any $P \in E(K)$, we write P/ℓ for the ℓ^2 points Q such that $[\ell]Q = P$. The extension $K(P/\ell)/K$ is Galois and contains L , and we write $H = \text{Gal}(L(P/\ell)/L)$, $G = \text{Gal}(K(P/\ell)/K)$. There is a short exact sequence of groups

$$1 \longrightarrow H \longrightarrow G \longrightarrow \Gamma \longrightarrow 1.$$

We regard $E[\ell]$ as a Γ -module and write $E[\ell] \rtimes \Gamma$ for the semi-direct product. There is an embedding $G \rightarrow E[\ell] \rtimes \Gamma$, which is unique up to conjugation in $E[\ell] \rtimes \Gamma$, and $H = G \cap E[\ell]$.

LEMMA 2. *For every $P \in E(K) - \ell(E(K))$, $G = \text{Gal}(K(P/\ell)/K)$ is isomorphic to $E[\ell] \rtimes \Gamma$.*

PROOF. A priori G is a subgroup of $E[\ell] \rtimes \Gamma$ which maps surjectively to Γ . No line of $E[\ell]$ is stabilized by Γ , so $H = G \cap E[\ell]$ is either trivial or all of $E[\ell]$. Lemma 1 implies that P is not in $\ell(E(L))$, hence $H = E[\ell]$. \square

The lines $\mathcal{K} \subset E[\ell]$ correspond bijectively to cyclic ℓ -isogenies $\phi : E_\phi \rightarrow E$, where E_ϕ is some elliptic curve. Given \mathcal{K} , ϕ is the dual of the canonical map $E \rightarrow E/\mathcal{K}$ and, given $\phi : E_\phi \rightarrow E$, \mathcal{K} is the kernel of the dual isogeny $E \rightarrow E_\phi$.

LEMMA 3. *Let $P, Q \in E(K)$. The following are equivalent:*

- (1) $\langle P \rangle \equiv \langle Q \rangle \pmod{\ell(E(K))}$;
- (2) $\langle P \rangle \equiv \langle Q \rangle \pmod{\ell(E(L))}$;
- (3) $\langle P \rangle \equiv \langle Q \rangle \pmod{\phi(E_\phi(L))}$ for every cyclic ℓ -isogeny $\phi : E_\phi \rightarrow E$;
- (4) $\langle P \rangle \equiv \langle Q \rangle \pmod{\phi(E_\phi(L))}$ for some cyclic ℓ -isogeny $\phi : E_\phi \rightarrow E$.

PROOF. The first two statements are equivalent by lemma 1. The second statement implies the third. Given an ℓ -isogeny $\phi : E_\phi \rightarrow E$ we have an exact sequence

$$0 \rightarrow E[\hat{\phi}] \rightarrow E[\ell] \rightarrow E_\phi[\phi] \rightarrow 0$$

and the cohomology sequence gives the short exact sequence

$$0 \rightarrow H^1(L, E[\hat{\phi}]) \rightarrow H^1(L, E[\ell]) \rightarrow H^1(L, E_\phi[\phi]).$$

For isogenies $\phi_1 \neq \phi_2$, the intersection $H^1(L, E[\hat{\phi}_1]) \cap H^1(L, E[\hat{\phi}_2])$ is trivial, as $H^1(L, E[\ell])$ is a direct sum of these two subgroups, therefore the composite map

$$(1) \quad E(L)/\ell(E(L)) \rightarrow H^1(L, E[\ell]) \rightarrow H^1(L, E_{\phi_1}[\phi_1]) \oplus H^1(L, E_{\phi_2}[\phi_2])$$

is injective. It is the direct sum of the boundary maps corresponding to the cohomology sequence of

$$0 \rightarrow E_{\phi_i}[\phi_i] \rightarrow E_{\phi_i} \xrightarrow{\phi_i} E \rightarrow 0.$$

These maps induce embeddings $E(L)/\phi_i E_{\phi_i}(L) \rightarrow H^1(L, E_{\phi_i}[\phi_i])$. If we assume the third statement of the lemma holds, then $\langle P \rangle \equiv \langle Q \rangle$ in all the terms of (1), hence the second statement holds. The last two statements of the lemma are equivalent because Γ acts transitively on the isogenies and fixes P and Q . \square

One useful aspect of this lemma is that, in some circumstances, it allows us to replace L with the field of definition $K(\phi)$, for a fixed ϕ of our choosing (cf. section 2.2). We can also apply the lemma to the Galois theory of ‘ ℓ -descent’ of E/K .

THEOREM 2. *Let $P, Q \in E(K)$. The following are equivalent:*

- (1) $K(P/\ell) = K(Q/\ell)$;

$$(2) \langle P \rangle \equiv \langle Q \rangle \pmod{\ell(E(K))}.$$

Otherwise $K(P/\ell) \cap K(Q/\ell) = L$.

PROOF. The statement follows easily from lemma 2 when P or Q lies in $\ell(E(K))$, so we assume that $P, Q \in E(K) - \ell(E(K))$. We also assume there exists $F \subset K(P/\ell) \cap K(Q/\ell)$ which is a non-trivial extension of L of degree ℓ . F is not Galois over K because $E[\ell] \rtimes \Gamma$ has no normal subgroups of order ℓ , hence $K(P/\ell) = K(Q/\ell)$. $\text{Gal}(L(P/\ell)/L) = \text{Gal}(L(Q/\ell)/L)$ is isomorphic to $E[\ell]$, so the Galois group $\text{Gal}(F/L)$ is isomorphic to $E_\phi[\phi]$ for some cyclic ℓ -isogeny $\phi : E_\phi \rightarrow E$. The kernel of the restriction map $H^1(L, E_\phi[\phi]) \rightarrow H^1(F, E_\phi[\phi])$ is isomorphic to \mathbb{Z}/ℓ , and it is generated by the image of P, Q under the boundary map $E(L) \rightarrow H^1(L, E_\phi[\phi])$. Therefore $\langle P \rangle \equiv \langle Q \rangle \pmod{\phi(E_\phi(L))}$, hence $\langle P \rangle \equiv \langle Q \rangle \pmod{\ell(E(K))}$ by lemma 3, so we have the implication (1) \Rightarrow (2). The converse implication is clear. \square

For any $d \geq 0$, Γ acts diagonally on $E[\ell]^d$, and we write $E[\ell]^d \rtimes \Gamma$ for the semi-direct product.

COROLLARY 1. *If the image of $P_1, \dots, P_r \in E(K)$ in $E(K)/\ell(E(K))$ generates a d -dimensional subspace, then $\text{Gal}(K(P_1/\ell, \dots, P_r/\ell)/K) \simeq E[\ell]^d \rtimes \Gamma$.*

In general we will apply this for fixed P_1, \dots, P_r and varying ℓ in the proof of theorem 1. One can prove analogous results for any cyclic ℓ -isogeny.

THEOREM 3. *Let $\phi : E_\phi \rightarrow E$ be a cyclic ℓ -isogeny. For $P \in E(K)$ let P/ϕ denote the set of ℓ points Q such that $\phi(Q) = P$. If the images of $P_1, \dots, P_r \in E(K)$ in $E(K(\phi))/\phi(E_\phi(K(\phi)))$ generate a d -dimensional subspace, then*

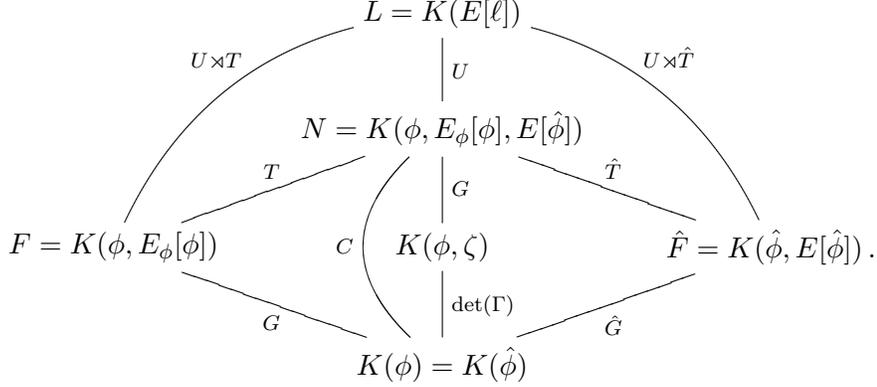
$$\text{Gal}(K(\phi, P_1/\phi, \dots, P_r/\phi)/K(\phi)) \simeq E_\phi[\phi]^d \rtimes \det(\Gamma).$$

We will be most interested in applying this with $r = 1$ in the proof of lemma 7.

2.2. Cyclotomic Twist. In this section we fix a cyclic ℓ -isogeny $\phi : E_\phi \rightarrow E$. We let $\mathcal{K} = \text{Ker}(\hat{\phi}) = \phi(E_\phi[\ell])$ and write $B \subset \Gamma$ for the unique Borel subgroup stabilizing \mathcal{K} . We may assume, without loss of generality, that B is the subgroup of upper-triangular matrices. Then the ℓ -syllow subgroup $U \subset B$ is the subgroup of upper-unipotent matrices. We choose a second Borel subgroup $\hat{B} \neq B$. The intersection $C = B \cap \hat{B}$ is a (split) Cartan subgroup, and B is canonically isomorphic to the semi-direct product $U \rtimes C$. Up to conjugation by an element of U , we may assume, without loss of generality, that \hat{B} is the subgroup of lower-triangular matrices, so $C \subset \Gamma$ is the subgroup of diagonal matrices. We write $\hat{\mathcal{K}} \subset E[\ell]$ for the unique line stabilized by \hat{B} , and we note that $\mathcal{K} \neq \hat{\mathcal{K}}$, hence $\hat{\phi} : \hat{\mathcal{K}} \rightarrow E_\phi[\phi]$ is an isomorphism.

We define $\hat{T}, T \subset C$, respectively, to be the subgroups which act trivially on $\mathcal{K}, \hat{\mathcal{K}}$, respectively. We note that the semi-direct products $U \rtimes T, U \rtimes \hat{T} \subset B$ are each stable

FIGURE 1



under conjugation by U , hence are independent of our choice of \hat{B} . We define the geometric subgroup $G = \hat{G} \subset C$ to be the kernel of $C \rightarrow \det(C)$. The fixed field of G is the cyclotomic extension $K(\phi, \zeta)/K(\phi)$, where ζ is a primitive ℓ th root of unity. The multiplication maps $T \times G \rightarrow C$ and $\hat{T} \times \hat{G} \rightarrow C$ are isomorphisms, so there are canonical isomorphisms $G \rightarrow \text{Gal}(K(\phi, E_\phi[\phi])/K(\phi))$ and $\hat{G} \rightarrow \text{Gal}(K(\hat{\phi}, E[\hat{\phi}])/K(\hat{\phi}))$. In summary, we have the lattice of Galois extensions shown in figure 1.

The extension N/K is an instance of the ‘balanced- $\Gamma_1(\ell)$ -moduli problem’ of (7.4.3) of [KM]. That is, it classifies pairs of embeddings $\mathbb{Z}/\ell \rightarrow E[\ell]$, $\mathbb{Z}/\ell \rightarrow E_\phi[\ell]$ of the trivial Galois module \mathbb{Z}/ℓ . Similarly, \hat{F}/K is an instance of the ‘ $\Gamma_1(\ell)$ -moduli problem’ of *loc. cit.*, which classifies embeddings of \mathbb{Z}/ℓ into $E[\ell]$. The inclusion of fields $\hat{F} \rightarrow N$ corresponds to ‘remembering’ the embedding $\mathbb{Z}/\ell \rightarrow E_\phi[\ell]$. One can also consider embeddings $\mu_\ell \rightarrow E[\ell]$, where μ_ℓ is the Galois module of ℓ th roots of unity. By Cartier duality these correspond to quotients $E[\ell] \rightarrow \mathbb{Z}/\ell$, hence embeddings $\mathbb{Z}/\ell \rightarrow E_\phi[\ell]$. The extension F/K corresponds to an instance of this other ‘moduli problem,’ and $F \rightarrow N$ corresponds to ‘remembering’ the embedding $\mathbb{Z}/\ell \rightarrow E[\ell]$. As ‘moduli problems,’ these last two are isomorphic if and only if μ_ℓ and \mathbb{Z}/ℓ are isomorphic Galois modules; that is, they classify the same objects if and only if $K(\zeta) = K$. Otherwise \hat{F} is an easily described ‘cyclotomic twist’ of F (and vice versa).

We observe that F/K , \hat{F}/K are geometric extensions, because $\det(U \rtimes T) = \det(U \rtimes \hat{T}) = \det(\Gamma)$. On the other hand, the extension $N = F(\zeta) = \hat{F}(\zeta)$ of F , \hat{F} , respectively, is ‘purely arithmetic’. Hence we can extract the ‘Cartesian square’ of Galois field extensions in figure 2 from the lattice in figure 1. There is a canonical isomorphism between Galois groups for either pair of parallel edges, and there is one, $T \rightarrow \hat{T}$, induced by the isomorphisms $T \rightarrow \det(C)$ and $\hat{T} \rightarrow \det(C)$. Composing the canonical maps $T \rightarrow \hat{T}$ and $\hat{T} \rightarrow G$ gives a

FIGURE 2

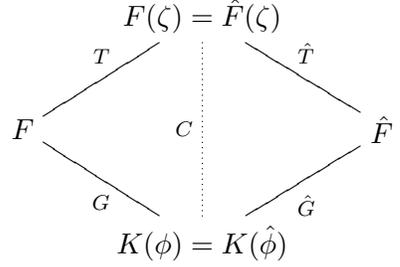
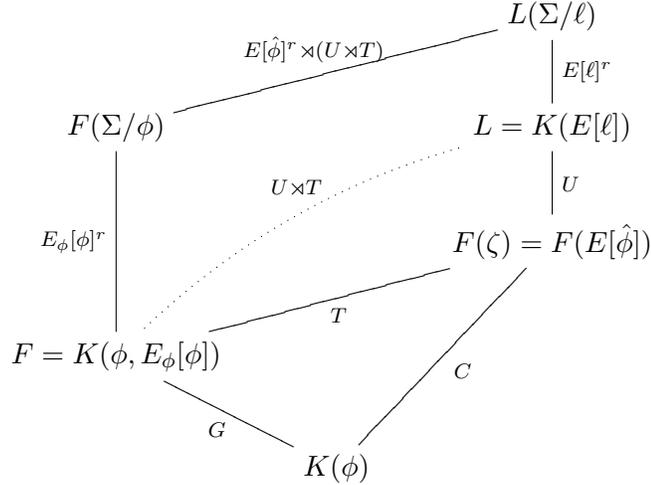


FIGURE 3



1-cocycle $\sigma \in H^1(T, G) \subset H^1(F, G)$. One can easily verify that $\hat{T} \subset C$ is the graph of σ in $T \times G = C$, hence \hat{F} is the ‘cyclotomic twist’ corresponding to σ .

2.3. Lang-Trotter Conjugacy Classes. We continue to use the notation of the previous two sections. We fix a free subgroup $\Sigma = \langle P_1, \dots, P_r \rangle \subset E(K)$ of rank r . We assume its image is an r -dimensional subspace of $E(K)/\ell(E(K))$, so that $K(E[\ell], \Sigma/\ell)$ is Galois over K with group $E[\ell]^r \rtimes \Gamma$ (by corollary 1). Then for every ϕ , we have the lattice of Galois extensions in figure 3.

We define the Lang-Trotter elements of Γ associated to ϕ by

$$\mathcal{C}(\phi) = \{\tau \in U \rtimes T : \tau = 1 \text{ or } \tau \notin U\}.$$

That is, $\mathcal{C}(\phi) \subset U \rtimes T$ is the subset of semisimple elements. We define $\mathcal{C}(\phi, \Sigma)$ to be the inverse image of $\mathcal{C}(\phi)$ under the natural map $E[\hat{\phi}]^r \rtimes (U \rtimes T) \rightarrow U \rtimes T$. Of course, every element of $\mathcal{C}(\phi, \Sigma)$ acts trivially on $F(\Sigma/\phi)$. The subsets of Lang-Trotter conjugacy classes are the unions $\mathcal{C} = \cup_{\phi} \mathcal{C}(\phi)$, $\mathcal{C}(\Sigma) = \cup_{\phi} \mathcal{C}(\phi, \Sigma)$ over all ϕ . One can easily show that for every $\delta \in \det(\Gamma)$,

$$|\{c \in \mathcal{C}(\Sigma) : \det(c) = \delta\}| = \begin{cases} \ell^{r+1}(\ell + 1) & \text{if } \delta \neq 1 \\ \ell(\ell^r + \ell^{r-1} - 1) & \text{if } \delta = 1 \end{cases}.$$

We note that for every δ there is at least one element of $E[\ell]^r \rtimes \Gamma$ which does not lie in $\mathcal{C}(\Sigma)$ and whose image in Γ has determinant δ .

For the rest of this section we fix a place v of K which is unramified in L and let $n = \deg(v)$. The prime decomposition of v in the extension L/K is relatively easy to describe, mainly because the latter is Galois. Let w be any prime of L lying over v and let $D(w) \subset \Gamma$ denote the decomposition group. There are $[\Gamma : D(w)]$ primes w over v , all of degree $f = |D(w)|$. Γ acts transitively on the w over v , and the induced action on $\{D(w)\}$ is conjugation. On the other hand, the prime decomposition of v in $K(\phi)$ is more difficult to describe because $K(\phi)/K$ is not a Galois extension. We will refrain from describing the general case, and instead will assume that the Frobenius conjugacy class $\text{Fr}_v \subset \Gamma$ is contained in $\mathcal{C} \subset \Gamma$.

For any prime w over v , we write \bar{w} for the prime in $K(\phi)$ under w . The decomposition group $D(\bar{w}) \subset B$ is the intersection $D(w) \cap B$, hence \bar{w} has degree $[D(w) : D(\bar{w})]$ over v . If $f = 1$, then $D(w)$ is trivial, hence v decomposes as a product of $\ell + 1$ primes of degree n in $K(\phi)$. On the other hand, if $f > 1$, then $D(w)$ is contained in a unique split-Cartan subgroup $C(w) \subset \Gamma$; $C(w)$ is the centralizer of $D(w)$ in Γ . Therefore $D(w) = D(\bar{w})$ if and only if $C(w) = C \subset B$, otherwise $D(\bar{w}) = \{1\}$. There are exactly two elements in the intersection $\text{Fr}_v \cap B$, exactly one of which lies in $\text{Fr}_v \cap \mathcal{C}(\phi)$. In particular, there are precisely two \bar{w} in $K(\phi)$ over v of degree n , and the remaining \bar{w} are of degree nf .

2.4. Geometrically-Degenerate Case. In this section we relax the condition that $\Delta = \text{Gal}(L/K)$ contain the subgroup $\text{SL}_2(\mathbb{Z}/\ell)$. More precisely, we assume the geometric subgroup, $\Delta \cap \text{SL}_2(\mathbb{Z}/\ell)$, is a proper subgroup of $\text{SL}_2(\mathbb{Z}/\ell)$. We fix a free subgroup $\Sigma = \langle P_1, \dots, P_r \rangle \subset E(K)$ and let $H = \text{Gal}(K(\Sigma/\ell)/K)$. In order to keep with notation of the previous sections, we write $\Gamma \subset \text{GL}_2(\mathbb{Z}/\ell)$ for the inverse image of $\det(\Delta) \subset (\mathbb{Z}/\ell)^\times$. Then Δ is a proper subgroup of Γ and H is a proper subgroup of $G = E[\ell]^r \rtimes \Gamma$.

For every Borel subgroup $B \subset \Gamma$, we write $U \rtimes T \subset B$ for the ‘semi-Borel subgroup’ of section 2.3, and $\mathcal{K} \subset E[\ell]$ for the line stabilized by B . The Lang-Trotter elements associated to B are the semisimple elements $\mathcal{C}(B) \subset U \rtimes T$, and the set of elements associated to Γ is the union $\mathcal{C} = \cup_B \mathcal{C}(B)$ over all B . We recall that $U \rtimes T$ stabilizes \mathcal{K} , so the semi-direct product $\mathcal{K}^r \rtimes (U \rtimes T)$ exists. Then we define $\mathcal{C}(B, \Sigma)$ to be the inverse image of $\mathcal{C}(B)$

under the natural map $\mathcal{K}^r \rtimes (U \rtimes T) \rightarrow U \rtimes T$ and $\mathcal{C}(\Sigma) \subset G$ to be the union $\cup_B \mathcal{C}(B, \Sigma)$. We define the Lang-Trotter conjugacy classes $\mathcal{C}(H) \subset H$ as the intersection $H \cap \mathcal{C}(\Sigma)$.

Because Δ is a proper subgroup of Γ such that $\det(\Delta) = \det(\Gamma)$, one can easily show that $|\mathcal{C}(H)|$ is maximized when $H = E[\ell]^r \rtimes C$ for some split Cartan subgroup $C \subset \Gamma$. Therefore, in general,

$$(2) \quad |\{c \in \mathcal{C}(H) : \det(c) = \delta\}| \leq |\{c \in \mathcal{C}(E[\ell]^r \rtimes C) : \det(c) = 1\}| \leq \ell(\ell^r + \ell^{r-1} - 1),$$

for any $\delta \in \det(\Gamma)$. A priori, every element of H or simply every element of a fixed determinant $\delta \in \det(\Gamma)$ may be a Lang-Trotter element, in which case we call ℓ and therefore assume it is contained in the set \mathcal{S} (cf. introduction). This applies to $\ell \neq p$ and the case $\ell = p$ is discussed in the next section.

3. p -adic Galois Theory

In this section we fix a global field K of char p and an elliptic curve E/K with non-constant j -invariant. Then $E[p]$ is isomorphic to \mathbb{Z}/p over an algebraic closure of K . There is a canonical cyclic p -isogeny $V : E_\phi \rightarrow E$ over K , the so-called Verschiebung; the dual isogeny $\hat{V} : E \rightarrow E_\phi$ is the (p -)Frobenius. While $K(E[p])/K$ is inseparable in general, the extension $L = K(E_\phi[\phi])/K$ is Galois and geometric, and there is an embedding of $\Delta = \text{Gal}(L/K)$ into $(\mathbb{Z}/p)^\times$.

LEMMA 4. *The canonical map $H^1(K, E_\phi[V]) \rightarrow H^1(L, E_\phi[V])^\Delta$ is an isomorphism.*

PROOF. The order of Δ is prime to p , so we consider the Hochschild-Serre sequence

$$0 \longrightarrow H^1(\Delta, E_\phi[V]) \longrightarrow H^1(K, E_\phi[V]) \longrightarrow H^1(L, E_\phi[V])^\Delta \longrightarrow H^2(\Delta, E_\phi[V]).$$

The first and last terms vanish, so the sequence degenerates to the desired isomorphism. \square

From the lemma we infer that $P \in V(E_\phi(K))$ if and only if $P \in V(E_\phi(L))$, which is what we need to prove the following theorem.

THEOREM 4. *Let $P_1, \dots, P_r \in E(K)$. Suppose the image of $\langle P_1, \dots, P_r \rangle$ in $E(K)/V(E_\phi(K))$ is an r -dimensional subspace. Then*

$$\text{Gal}(K(P_1/V, \dots, P_r/V)/K) \simeq E_\phi[V]^r \rtimes \Delta.$$

Finally, we define the Lang-Trotter conjugacy classes in $E_\phi[V]^r \rtimes \Delta$ to be the subgroup $E_\phi[V]^r$. Therefore, if $\Delta = 1$, then we say that p is exceptional and therefore must be added to our set \mathcal{S} (cf. introduction). Contrary to the ℓ -adic case, where there is a natural determinant $\det : \Delta \rightarrow (\mathbb{Z}/\ell)^\times$, there are two natural maps $\det : \Delta \rightarrow (\mathbb{Z}/p)^\times$ that we must consider: the identity map and the trivial map. In fact, the latter is what we want if we insist that $\det(\Gamma)$ should be the Galois group of the scalar part of L/K , hence is trivial because L/K is geometric.

4. Chebotarev Argument

4.1. Notation. We write $f(x) = O(g(x))$, as usual, to indicate that there is a constant $c > 0$ such that $f(x) < c \cdot g(x)$, for all x . Moreover, we assume that c depends at most on the genus of K , $\deg(S)$, and the ‘regulator’ $R = \det(\Sigma)$. We remark that the only place R appears is in the proof of lemma 9. We write $f(x) = o(g(x))$ to indicate that $f(x)/g(x)$ tends to 0 as x tends to ∞ .

4.2. Weil and Murty-Scherk Bounds. There is a finite set of places S of K such that $K(\Sigma/\ell)/K$, a fortiori $K(E[\ell])/K$, is unramified away from S for every $\ell \neq p$. On the other hand, if $V : E^{(p)} \rightarrow E$ is the Verschiebung, then $K(\Sigma/V)/K$ is unramified away from a divisor of degree $O(p \deg(S))$. In particular, every extension we encounter in this section will be unramified away from a divisor of uniformly bounded degree d , even tamely ramified, hence the following lemma will be useful.

LEMMA 5. *If F/K is a tame extension which is unramified away from a divisor of degree at most d , then the genus of F is $O([F : K])$.*

PROOF. This immediately from the Riemann-Hurwitz formula for the extension F/K :

$$2 \cdot \text{genus}(F) - 2 = [F : K](2 \cdot \text{genus}(K) - 2) + (\text{ramification part}).$$

The ramification term part is at most $d([F : K] - 1)$. □

Let V denote the open complement of S and $V_n \subset V$ the subset of v such that $\deg(v) = n$. One effective Chebotarev theorem we need is a simple form of the Weil bound.

THEOREM 5 (Weil). *Suppose F/K is a tame, finite, and geometric extension, which is unramified away from S , and L/K is a subextension. Let W_n denote the subset of places w of L of degree n . Then for any $n \geq 1$,*

$$|\{w \in W_n : w \text{ splits completely in } F/L\}| = \frac{1}{[F : L]} |W_n| + O([L : K] \frac{q^{n/2}}{n}).$$

We note that the geometric assumption is crucial, for otherwise none of the points in W_n split completely for general n . The factor $[L : K]$ in the error term accounts for the genus of L .

More generally, suppose F/K is a finite Galois extension and L/K is a geometric subextension. Let $G = \text{Gal}(F/L)$. For every place w of L , unramified in F , there is a well-defined conjugacy class $\text{Fr}_w \subset G$, the so-called Frobenius class. Let $\mathbb{F}_{q^m} \subset F$ be the algebraic closure of $\mathbb{F}_q \subset K$. By assumption $\mathbb{F}_{q^m} \cap L = \mathbb{F}_q$, and there is a short exact sequence

$$1 \longrightarrow \text{Gal}(F/\mathbb{F}_{q^m}L) \longrightarrow G \longrightarrow \text{Gal}(\mathbb{F}_{q^m}/\mathbb{F}_q) \longrightarrow 1.$$

We write $G(q^n) \subset G$ for the subset of elements whose image in $\text{Gal}(\mathbb{F}_{q^m}/\mathbb{F}_q)$ is the n th power of the Frobenius element. It is closed under conjugation by any element of G .

Similarly, for any union of conjugacy classes $\mathcal{C} \subset G$, we write $\mathcal{C}(q^n)$ for the intersection $\mathcal{C} \cap G(q^n)$.

THEOREM 6 (Murty-Scherk). *Suppose F/K is a tame, finite, and Galois extension which is unramified away from S , and L/K is a geometric subextension. Let $G = \text{Gal}(F/L)$ and let W_n denote the subset of places w of L of degree n . Suppose $\mathcal{C} \subset G$ is a union of conjugacy classes. Then for $n \geq 1$,*

$$|\{w \in W_n : \text{Fr}_w \subset \mathcal{C}(q^n)\}| = \frac{|\mathcal{C}(q^n)|}{|G(q^n)|} |W_n| + O([L : K] \cdot |\mathcal{C}(q^n)|^{1/2} q^{n/2} / n).$$

Except for the tameness condition, this is essentially theorem 2 in [MS]. As before, the factor $[L : K]$ in the error term accounts for the genus of L .

4.3. Proof of Theorem 1. We write V_n for the subset of places v of K such that $\deg(v) = n$. Let \mathcal{L} denote the rational primes excluding \mathcal{S} and let \mathcal{F} denote the positive integers which are a square-free product of primes in \mathcal{L} . We write $\mathcal{G}_n \subset V_n$ for the subset of places v which are good with respect to \mathcal{L} , that is, for which Σ generates the prime-to- \mathcal{S} part of E_v . Similarly, for any $f \in \mathcal{F}$, we write $\mathcal{B}_n(f) \subset V_n$ for the subset of v which are bad with respect to every ℓ dividing f .

For every $\ell \in \mathcal{L}, \ell \neq p$, we write K_ℓ for the extension $K(\Sigma/\ell)/K$. Similarly, for $\ell = p$, we write K_p for the extension $K(\Sigma/V)/K$, where $V : E^{(p)} \rightarrow E$ is the Verschiebung. In either case we let G_ℓ denote $\text{Gal}(K_\ell/K)$ and $\mathcal{C}_\ell \subset G_\ell$ the subset of Lang-Trotter conjugacy classes. For every $f = \ell_1 \cdots \ell_m \in \mathcal{F}$, we write G_f for the Galois group of the compositum $K_{\ell_1} \cdots K_{\ell_m}/K$. For every i , there is a natural map $G_f \rightarrow G_{\ell_i}$, and we define $\mathcal{C}_n \subset G_f$ to be the maximal subset whose image lies in \mathcal{C}_{ℓ_i} for all i . For every $v \in V_n$, we write $\text{Fr}_v \subset G_f$ for the Frobenius conjugacy class. Then $v \in \mathcal{B}_n(f)$ if and only if $\text{Fr}_v \subset \mathcal{C}_f$.

Given $x > 0$, let $\mathcal{L}(x)$ denote the $\ell \in \mathcal{L}$ such that $\ell \leq x$, and $\mathcal{F}(x)$ the $f \in \mathcal{F}$ such that $\ell \in \mathcal{L}(x)$ for every ℓ which divides f . Given $y > x > 0$, let $\mathcal{L}(x, y)$ denote the complement $\mathcal{L}(y) - \mathcal{L}(x)$. We write $\mathcal{G}_n(x)$ for the $v \in V_n$ which are good with respect to every $\ell \in \mathcal{L}(x)$. One way to compute the density of $\mathcal{G}_n(x) \subset V_n$ is to apply a standard inclusion-exclusion argument and show that

$$|\mathcal{G}_n(x)| = \sum_{f \in \mathcal{F}(x)} \mu(f) |\mathcal{B}_n(f)|,$$

where $\mu : \mathcal{F} \rightarrow \{\pm 1\}$ is the Mobius function. Let $\mathcal{B}_n(x, y)$ denotes the set of $v \in V_n$ which lie in $\mathcal{B}_n(\ell)$ for some $\ell \in \mathcal{L}(x, y)$. We make the trivial observation that $\mathcal{B}_n(\ell), \mathcal{B}_n(\ell, \infty)$ are empty for $\ell > q^n + q^{n/2} - 1$, because ℓ must divide the order of E_v , hence $|\mathcal{G}_n| = |\mathcal{G}_n(x)|$ for x sufficiently large. On the other hand, for any $x > 0$, one can still show that

$$|\mathcal{G}_n| \geq |\mathcal{G}_n(x)| - |\mathcal{B}_n(x, \infty)|.$$

In general, the expected density of $\mathcal{B}_n(f) \subset V_n$ is given by the constant $\delta_n(f) = |\mathcal{C}_f(q^n)|/|G_f(q^n)|$ (cf. theorem 6), so we write

$$|\mathcal{B}_n(f)| = \delta_n(f)|V_n| + \varepsilon_f.$$

Similarly, the expected density of $\mathcal{G}_n(x) \subset V_n$ is given by $\delta_n(x) = \prod_{\ell \in \mathcal{L}(x)} (1 - \delta_n(\ell))$, so we write

$$|\mathcal{G}_n(x)| = \delta_n(x)|V_n| + \varepsilon(x).$$

A priori $\mathcal{G}_n(x)$ and $\delta_n(x)$ depend on \mathcal{L} , but \mathcal{L} is fixed for the entire section, so we omit the dependence from the notation. By the results of 2.3 it follows that $\delta_n(\ell)$ is bounded above and below by multiples of $1/(\ell^{r+1}m_n(\ell))$, where $m_n(\ell)$ is the order of the multiplicative group generated by $q^n \pmod{\ell}$, which was denoted $\det(\Gamma)$ in 2.3. In fact, one can explicitly write down $\delta_n(\ell)$ in terms of these quantities. It follows from this estimate that $\prod_{\ell \in \mathcal{L}(x)} (1 - \delta_n(\ell))$ converges as $x \rightarrow \infty$ and we define $\delta_n(\Sigma, \mathcal{S})$, appearing in theorem 1, as the limit. We further define a, b as the lower and upper bound for this limit obtained from the bound just mentioned for $\delta_n(\ell)$ and the estimates $1 \leq m_n(\ell) \leq l - 1$.

We estimate $|\varepsilon(x)|$ using the identity $\varepsilon(x) = \sum_{f \in \mathcal{F}(x)} \mu(f) \varepsilon_f$, and in turn, we estimate $|\varepsilon_f|$ using the following lemma.

LEMMA 6. *For every $f \in \mathcal{F}$, we have*

$$\varepsilon_f = \mathcal{B}_n(f) - \delta_n(f)|V_n| = o(f^{(r+2)/2}q^{n/2}/n).$$

PROOF. The lemma is an application of theorem 6 to K_f/K . Applying the result of sections 2.3 and 2.4, we see that $|\mathcal{C}_f(q^n)| \leq 2f^{r+2}$, for every $f \in \mathcal{F}(x)$. \square

The lemma is useful only when x is sufficiently small. In fact, it suffices to take $x = x_n = n \log(q)/(2r + 6)$.

COROLLARY 2. $|\varepsilon(x_n)| = o(q^n/n)$.

PROOF. For every $f \in \mathcal{F}(x_n)$, we note that

$$\log(f) \leq \sum_{\ell \in \mathcal{L}(x_n)} \log(\ell) \leq |\mathcal{L}(x_n)| \log(x_n) \leq x_n + o(x_n),$$

and in particular, $\log(f) \leq 2x_n$ for n sufficiently large. Applying this to the error term of the lemma gives

$$|\varepsilon_f| = o(f^{(r+2)/2}q^{n/2}/n) = o(q^{n(r+2)/(2r+6)}q^{n/2}/n) = o(q^{n(2r+5)/(2r+6)}/n).$$

We also note that $|\mathcal{F}(x_n)| = 2^{|\mathcal{L}(x_n)|} \leq e^{x_n} = q^{n/(2r+6)}$, hence

$$|\varepsilon(x)| \leq \sum_{f \in \mathcal{F}(x)} |\varepsilon_f| = q^{n/(2r+6)} \cdot o(q^{n(2r+5)/(2r+6)}/n) = o(q^n/n).$$

\square

From the above we also have $\delta_n(f)|V_n| - \delta_n(\Sigma, \mathcal{S})|V_n| = o(q^n/n)$ and thus, to complete the proof of theorem 1, it suffices to show that $\mathcal{B}_n(x_n, \infty) = o(q^n/n)$, because then

$$|\mathcal{G}_n| = |\mathcal{G}_n(x_n)| + o(q^n/n) = \delta_n(\Sigma, \mathcal{S})|V_n| + o(q^n/n).$$

We proceed in three stages by defining $y_n = q^{n/4}/\log(q^n)$ and $z_n = q^{n/4} \log \log(q^n)$, decomposing $\mathcal{L}(x_n, \infty)$ into three disjoint intervals

$$\mathcal{L}(x_n, \infty) = \mathcal{L}(x_n, y_n) \cup \mathcal{L}(y_n, z_n) \cup \mathcal{L}(z_n, \infty),$$

and utilizing the inequality

$$|\mathcal{B}_n(x_n, \infty)| \leq |\mathcal{B}_n(x_n, y_n)| + |\mathcal{B}_n(y_n, z_n)| + |\mathcal{B}_n(z_n, \infty)|.$$

We complete the proof by showing, in the following three lemmas, that each of the terms on the right are $o(q^n/n)$. In each case we use the inequality

$$|\mathcal{B}_n(x, y)| \leq \sum_{\ell \in \mathcal{L}(x, y)} |\mathcal{B}_n(\ell)|,$$

but we must use different arguments to bound the sum on the right.

LEMMA 7 (Small ℓ). $|\mathcal{B}_n(x_n, y_n)| = o(q^n/n)$.

PROOF. For every $\ell \in \mathcal{L}(x_n, y_n)$, we fix a cyclic ℓ -isogeny $\phi : E_\phi \rightarrow E$. We note that, by theorem 2 of [CH], there is a constant $\ell_0 = O(1)$ such that $\Gamma = \text{Gal}(K(E[\ell])/K)$ contains $\text{SL}_2(\mathbb{Z}/\ell)$ for every $\ell \neq p$, $\ell > \ell_0$. We may assume, without loss of generality, that $x_n \geq \max\{\ell_0, p\}$. The implied constant may be chosen, depending only on $\text{genus}(K)$ and $\text{deg}(S)$, to account for the failure of this assumption, and there are only finitely many n and degenerate Γ one must worry about. We write $B \subset \Gamma$ for the Borel subgroup corresponding to ϕ and identify it with $\text{Gal}(K(E[\ell])/K(\phi))$. For every $w \in |K(\phi)|$, we write $\text{Fr}_w \subset B$ for the Frobenius conjugacy class.

If ℓ does not divide $q^n - 1$, then we showed in section 2.3 that, for every $v \in \mathcal{B}_n(\ell)$, there is a unique $w \in |K(\phi)|$ of degree n and lying over v such that $\text{Fr}_w \subset \mathcal{C}(\phi) \subset B$. For $i = 1, \dots, r$, we write $\mathcal{B}_{n,i}(\ell)$ for the subset of $v \in \mathcal{B}_n(\ell)$ such that w splits completely in $K(\phi, P_i/\phi)$. In particular, applying theorem 5 we have

$$|\mathcal{B}_n(\ell)| \leq \sum_{i=1}^r |\mathcal{B}_{n,i}(\ell)| = r(q^n/\ell^2 + O(\ell q^{n/2}))/n.$$

On the other hand, if ℓ divides $q^n - 1$ and $v \in \mathcal{B}_n(\ell)$, then $\text{Fr}_v = \{1\} \subset \Gamma$. Therefore v splits completely in $K(\phi, E_\phi[\phi])/K$, and theorem 5 implies

$$|\mathcal{B}_n(\ell)| \leq r(q^n/(\ell^2 + \ell) + O(q^{n/2}))/n \leq r(q^n/\ell^2 + O(\ell q^{n/2}))/n.$$

Combining the results for all $\ell \in \mathcal{L}(x_n, y_n)$ we have

$$|\mathcal{B}_n(x_n, y_n)| \leq \sum_{\ell \in \mathcal{L}(x_n, y_n)} |\mathcal{B}_n(\ell)| \leq r q^n \left(\sum_{\ell \in \mathcal{L}(x_n, y_n)} 1/\ell^2 \right) + (y_n - x_n) O(y_n q^{n/2})/n.$$

We note that $\sum_{\ell \in \mathcal{L}(x_n, y_n)} 1/\ell^2 = o(1)$, because x_n tends to infinity as n does, and $y_n = o(q^{n/4})$, hence $|\mathcal{B}_n(x_n, y_n)| = o(q^n/n)$ as desired. \square

LEMMA 8 (Medium ℓ). $|\mathcal{B}_n(y_n, z_n)| = o(q^n/n)$.

PROOF. We fix $\ell \in \mathcal{L}(y_n, z_n)$ and use the notation of the previous lemma. If ℓ does not divide $q^n - 1$ and $v \in \mathcal{B}_n(\ell)$, then we let $w \in |K(\phi)|$ be the canonical point over v as before. We write $\mathcal{B}'_{n,i}(\ell)$ for the subset of $v \in \mathcal{B}_n(\ell)$ such that w splits completely in $K(\phi, E_\phi[\phi])$. Applying theorem 5 gives

$$|\mathcal{B}'_{n,i}(\ell)| = (q^n/\ell + O(\ell q^{n/2}))/n.$$

On the other hand, if ℓ divides $q^n - 1$, we let $\mathcal{B}'_{n,i}(\ell)$ be the subset of $v \in V_n$ which split completely in $K(\phi, E_\phi[\phi])$. By another application of theorem 5 we have

$$|\mathcal{B}'_{n,i}(\ell)| = (q^n/\ell^2 + O(q^{n/2}))/n \leq (q^n/\ell + O(\ell q^{n/2}))/n.$$

Combining the results for all $\ell \in \mathcal{L}(y_n, z_n)$ gives

$$|\mathcal{B}_n(y_n, z_n)| \leq (q^n \left(\sum_{\ell \in \mathcal{L}(y_n, z_n)} 1/\ell \right) + |\mathcal{L}(y_n, z_n)| O(\ell q^{n/2}))/n.$$

Using the standard estimate $\sum_{\ell \leq x} 1/\ell = \log \log(x) + c + o(1)$, where c is a constant, gives

$$\begin{aligned} \sum_{\ell \in \mathcal{L}(y_n, z_n)} 1/\ell &= \log \log(z_n) - \log \log(y_n) + o(1) \\ &= \log \left(\frac{n \log(q) + 4 \log \log(q)}{n \log(q) - 4 \log \log \log(q)} \right) + o(1) = o(1). \end{aligned}$$

By the prime number theorem,

$$|\mathcal{L}(y_n, z_n)| \leq |\mathcal{L}(z_n)| \leq z_n/\log(z_n) + o(z_n/\log(z_n)),$$

hence

$$|\mathcal{L}(y_n, z_n)| O(\ell q^{n/2}) = O \left(\frac{4(\log \log(q^n))^2}{\log(q^n) + 4 \log \log \log(q^n)} q^n \right) = o(q^n/n).$$

\square

LEMMA 9 (Large ℓ). $|\mathcal{B}_n(z_n, \infty)| = o(q^n/n)$, for $r \geq 6$.

PROOF. For every $v \in V$, let Σ_v denote the image of Σ in E_v . The function field analogue of lemma 14 of [GM] asserts that the number of $v \in V$ such that $|\Sigma_v| < y$ is $O(y^{(r+2)/r})$, where the implied constant depends on the regulator $R = \det(\Sigma)$. Their proof actually proves more, namely that the sum of $\deg v$ over the v 's with $|\Sigma_v| < y$ is $O(y^{(r+2)/r})$. In particular, for every $v \in \mathcal{B}_n(z_n, \infty)$, we have

$$|\Sigma_v| = O(q^n/z_n) = o(q^{3/4}),$$

therefore

$$|\mathcal{B}(z_n, \infty)| = (o(q^{3/4})^{1+2/r})/n = o(q^{(3r+6)/4r}/n).$$

The lemma follows by observing that $(3r+6)/4r \leq 1$ if $r \geq 6$. □

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