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GLOBAL SOLVABLY CLOSED ANABELIAN GEOMETRY

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Abstract. In this paper, we study the *pro-Σ anabelian geometry of hyperbolic curves*, where Σ is a nonempty set of prime numbers, over Galois groups of *"solvably closed extensions"* of number fields — i.e., infinite extensions of number fields which have no nontrivial abelian extensions. The main results of this paper are, in essence, immediate corollaries of the following three ingredients: (a) classical results concerning the structure of Galois groups of number fields; (b) an anabelian result of Uchida concerning Galois groups of solvably closed extensions of number fields; (c) a previous result of the author concerning the pro-Σ anabelian geometry of hyperbolic curves over nonarchimedean local fields.

1. Introduction

In this paper, we study various properties of *solvably closed Galois groups of number fields*, i.e., Galois groups of field extensions of number fields that admit no nontrivial abelian field extensions [cf. Definition 1, (i)]. In §1, we show that such Galois groups satisfy many of the properties of *absolute Galois groups* of number fields that are of importance in the context of *anabelian geometry*. In particular, this includes properties concerning *Galois cohomology*, *center-free-ness*, *decomposition groups* of valuations, and *topologically finitely generated closed normal subgroups*. In §2, after reviewing a fundamental result of Uchida [cf. [11]] to the effect that solvably closed Galois groups of number fields are *anabelian*, we apply the various results obtained in §1 to give a new version of the main result of [6] concerning the *pro-Σ anabelian geometry of hyperbolic curves*, where Σ is a nonempty set of prime numbers, in the context of solvably closed Galois groups of number fields. Finally, in §3, we observe that *"relatively small"* solvably closed Galois groups of number fields exist in *"substantial abundance"*. For instance, in the case of *punctured elliptic curves*, it is possible in many instances to obtain solvably closed Galois groups of number fields that are, on the one hand, *"large enough"* to be *compatible* with the outer Galois action on the pro-Σ geometric fundamental group of the punctured elliptic curve [i.e., in the sense that this outer Galois action of the Galois group of the number field *factors* through the quotient determined by the solvably closed extension], but, on the other hand, *"small enough"* to be *linearly disjoint* from

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various field extensions arising from the *l-torsion points* of the elliptic curve, for a prime number $l \notin \Sigma$.

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2. Basic Properties

We begin by defining the notion of a *solvably closed Galois group of a number field* and showing that such Galois groups satisfy many properties that are well-known in the case of absolute Galois groups of number fields.

Let F be a *number field* [i.e., a finite extension of the field of rational numbers], $\overline{F}$ an *algebraic closure* of F, and $\widetilde{F} \subseteq \overline{F}$ a [not necessarily finite!] *Galois extension* of F. Write $G_F \overset{\mathrm{def}}{=} \mathrm{Gal}(\overline{F}/F)$, $Q_F \overset{\mathrm{def}}{=} \mathrm{Gal}(\widetilde{F}/F)$. Thus, one may think of Q_F as a *quotient* $G_F \twoheadrightarrow Q_F$ of G_F.

Definition 1.

(i) We shall say that a field is *solvably closed* if it has no nontrivial abelian extensions. If $\widetilde{F}$ is solvably closed, then we shall say that $\widetilde{F}/F$ is a *solvably closed extension* and refer to Q_F as a *solvably closed Galois group* of the number field F.

(ii) If G is any *profinite group*, and p is a prime number, then we shall write

$$\mathrm{cd}_p(G)$$

for the smallest positive integer i such that $H^j(G, A) = 0$ for all continuous p-torsion G-modules A and all $j > i$, if such an integer i exists; if such an integer i does not exist, then we set $\mathrm{cd}_p(G) \overset{\mathrm{def}}{=} \infty$ [cf. [8], Definition 3.3.1].

Remark 1. Observe that the Galois group Q_F is *solvably closed* if and only if, for any open subgroup $H_Q \subseteq Q_F$, whose inverse image in G_F we denote by $H_G \subseteq G_F$, the surjection induced on *maximal pro-solvable quotients*

$$H_G^{\mathrm{sol}} \twoheadrightarrow H_Q^{\mathrm{sol}}$$

by the quotient morphism $H_G \twoheadrightarrow H_Q$ is an isomorphism.

Remark 2. Thus, if we denote by $\widetilde{F}^{\mathrm{sol}} \subseteq \overline{F}$ the *maximal solvable [Galois] extension* of $\widetilde{F}$, then one verifies immediately that $\mathrm{Gal}(\widetilde{F}^{\mathrm{sol}}/F)$ is a *solvably closed Galois group* of the number field F. In particular, [by taking $\widetilde{F} = F$, it follows that] the *maximal pro-solvable quotient* G_F^{sol} of G_F is a *solvably closed Galois group* of the number field F.

Remark 3. One verifies immediately that any *open subgroup of a solvably closed Galois group of a number field* is again a solvably closed Galois group of a number field.

Proposition 2.1 (Galois Cohomology of Solvably Closed Galois Groups). *Suppose that Q_F is a* **solvably closed Galois group** *of the number field F. Then:*

(i) The natural surjection $G_F \twoheadrightarrow Q_F$ induces an **isomorphism**

$$H^i(Q_F, A) \xrightarrow{\sim} H^i(G_F, A)$$

for all continuous torsion Q_F-modules A and all integers $i \geq 0$. In particular, if F contains a **square root of** -1*, then* $\mathrm{cd}_p(Q_F) = 2$ *for all prime numbers p.*

(ii) Let p be a prime number; suppose that F contains a **primitive p-th root of unity***. Then for any automorphism σ of the field $\widetilde{F}$ that preserves and acts* **nontrivially** *on $F \subseteq \widetilde{F}$, the automorphism induced by σ of the set of* **one-dimensional $\mathbb{F}_p$-subspaces** *of the $\mathbb{F}_p$-vector space*

$$H^2(Q_F, \mathbb{F}_p)$$

is **nontrivial***.*

Proof. First, we consider assertion (i). Write $J_F \stackrel{\text{def}}{=} \ker(G_F \twoheadrightarrow Q_F)$. To show the desired isomorphism, it follows immediately from the Leray-Serre spectral sequence associated to the extension $1 \to J_F \to G_F \to Q_F \to 1$ that it suffices to show that $H^i(J_F, A) = 0$ for all $i \geq 1$. Since

$$H^i(J_F, A) \cong \varinjlim_{J_F \subseteq H \subseteq G_F} H^i(H, A)$$

[where H ranges over the open subgroups of G_F containing J_F], we thus conclude the desired vanishing as follows: If $i \geq 3$, then the fact that $H^i(H, A) = 0$ follows from the fact that $\mathrm{cd}_p(H) \leq 2$, for H sufficiently small [i.e., H that correspond to totally imaginary extensions of F — cf. [8], Proposition 8.3.17]. If $i = 2$, then we recall that by the well-known *"Hasse Principle for central simple algebras"* [cf., e.g., [8], Corollary 8.1.16; the discussion of [8], §7.1], it follows that we have an *exact sequence*

$$0 \to H^2(G_F, \mathbb{F}_p(1)) \to \bigoplus_v H^2(G_v, \mathbb{F}_p(1)) \to \mathbb{F}_p \to 0$$

where the "(1)" denotes a *"Tate twist"*; v ranges over the valuations of F; G_v denotes the decomposition group of v in G_F, which is well-defined up to conjugation; and we recall in passing that the restriction to the various direct summands of the map to $\mathbb{F}_p$ induces an *isomorphism* $H^2(G_v, \mathbb{F}_p(1)) \cong \mathbb{F}_p$ for all nonarchimedean v. Thus, by applying the analogue for H of this exact sequence for G_F, together with the *Grunwald-Wang Theorem* [which assures the existence of global abelian field extensions with prescribed behavior at a finite number of valuations — cf., e.g., [8], Corollary 9.2.3], we conclude immediately that

$$\varinjlim_{H} H^2(H, A) = 0$$

[where H ranges over the open subgroups of G_F containing J_F]. When $i = 1$, the fact that

$$\varinjlim_{H} H^1(H, A) = 0$$

follows formally from the definition of a *"solvably closed"* Galois group [cf. Definition 1, (i)]. Now the statement concerning $\mathrm{cd}_p(Q_F)$ follows immediately from the isomorphism just verified, together with the fact that, if F contains a *square root of* -1 [hence is *totally imaginary*], then $\mathrm{cd}_p(G_F) = 2$ [cf. [8], Proposition 8.3.17; the exact sequence just discussed concerning $H^2(G_F, \mathbb{F}_p(1))$]. This completes the proof of assertion (i).

Finally, we observe that assertion (ii) follows immediately from the exact sequence just discussed concerning

$$H^2(G_F, \mathbb{F}_p(1)) \cong H^2(Q_F, \mathbb{F}_p(1)) \cong H^2(Q_F, \mathbb{F}_p)$$

[cf. assertion (i); our assumption that F contains a *primitive p-th root of unity*], together with *Tchebotarev's density theorem* [cf., e.g., [3], Chapter VIII, §4, Theorem 10], which implies that if we write $F_0 \subseteq F$ for the subfield fixed by σ, then there exist *two distinct* nonarchimedean valuations v_1, v_2 of F_0 that *split completely* in F. That is to say, if w_1, w_2 are valuations of F lying over v_1, v_2, respectively, then there exists an element $h \in H^2(Q_F, \mathbb{F}_p) \cong H^2(G_F, \mathbb{F}_p(1))$ [where we note that this isomorphism is *compatible* with the natural actions by σ, up to multiplication by an element of $\mathbb{F}_p^\times$] which maps to a nonzero element of the direct sum in the above sequence whose unique nonzero components are the components labeled by v_1, v_2; thus, $\sigma(\mathbb{F}_p \cdot h) \neq \mathbb{F}_p \cdot h$, as desired. □

Remark 4. As was pointed out to the author by the referee, one may generalize Proposition 2.1, (i), substantially if one assumes the *Bloch-Kato conjecture* — i.e., the assertion that the cup product

$$\cup : H^1(G_K, \mathbb{F}_p(1))^{\otimes i} \to H^i(G_K, \mathbb{F}_p(i))$$

induces a *surjection* for every integer $i \geq 1$, every prime number p, and every field K of characteristic zero. Indeed, if $G_K \twoheadrightarrow Q_K$ is a *quotient* by a closed normal subgroup $J_K \subseteq G_K$ corresponding to a field extension $\widetilde{K}$ of

K which has *no nontrivial abelian extensions*, then to show that the natural morphism

$$H^i(Q_K, A) \to H^i(G_K, A)$$

is an *isomorphism* for all integers $i \geq 0$ and continuous torsion Q_K-modules A, it suffices to verify [cf. the proof of Proposition 2.1, (i)], in the case $A = \mathbb{F}_p$, that for all open subgroups $H \subseteq G_K$ containing J_K, an arbitrary class $\in H^i(H, A)$ *vanishes* upon restriction to a sufficiently small open subgroup $H_1 \subseteq H$ containing J_K; but this follows from the fact that $\widetilde{K}$ has *no nontrivial abelian extensions* if $i = 1$, hence by the *Bloch-Kato conjecture* if $i \geq 2$.

Before proceeding, we recall that a profinite group Δ is *slim* if every open subgroup of Δ has *trivial centralizer* in Δ [cf. [5], Definition 0.1, (i)].

Corollary 2.2 (Slimness). *Every* **solvably closed Galois group** *of a number field is* **slim**.

Proof. Suppose that Q_F is *solvably closed*. Let $H_Q \subseteq Q_F$ be an *open subgroup*, $\sigma \in Q_F$ an element of the *centralizer* of H_Q. Write $F_H \subseteq \widetilde{F}$ for the extension of F defined by H_Q. Since Q_F is *solvably closed*, by taking H_Q to be *sufficiently small*, we may assume that F_H contains a p-th root of unity, for some prime number p. Note that since σ *commutes* with H_Q, it follows that σ acts *trivially* on $H^2(H_Q, \mathbb{F}_p)$. Thus, by applying Proposition 2.1, (ii), to the action of σ on $\widetilde{F}/F_H$, we conclude that σ acts trivially on F_H, i.e., that $\sigma \in H_Q$. On the other hand, since H_Q may be taken to be arbitrarily small, it thus follows that $\sigma = 1$, as desired. □

The next two results, concerning *decomposition groups* and *topologically finitely generated closed normal subgroups*, respectively, are well-known in the case of *absolute Galois groups* [cf., e.g., [8], Corollary 12.1.3; [2], Proposition 16.11.6].

Proposition 2.3 (Decomposition Groups). *Suppose that Q_F is a* **solvably closed Galois group** *of the number field F. Let v, w be* **valuations** *of F such that $v \neq w$; write $G_v, G_w \subseteq Q_F$ for the corresponding* **decomposition groups** *[which are well-defined up to conjugation] in Q_F and F_v, F_w for the corresponding* **completions** *of F. Then:*

(i) Suppose that F contains a **square root of** -1*, and that v, w are* **nonarchimedean***; let K be a finite extension of F_v. Then there exists a finite Galois extension of F contained in $\widetilde{F}$ whose restriction to F_v contains K and whose restriction to F_w is the trivial extension.*

(ii) Suppose that v, w are **archimedean***; let K be a nontrivial finite extension of F_v. Then there exists a quadratic extension of F contained in*

$\widetilde{F}$ whose restriction to F_v contains K and whose restriction to F_w is the trivial extension.

(iii) The surjection $G_F \twoheadrightarrow Q_F$ induces an **isomorphism** *of G_v with the decomposition group of v in G_F. In particular, if v is* **nonarchimedean**, *then G_v is* **slim** *and* **torsion-free**.

(iv) $G_v \bigcap G_w = \{1\}$.

(v) Suppose that v is **archimedean** *(respectively,* **nonarchimedean***). Then the* **normalizer** *(respectively,* **commensurator***) of G_v in Q_F is equal to G_v.*

Proof. First, we consider assertion (i). Since the absolute Galois group of F_v is *pro-solvable* [cf., e.g., [8], Chapter VII, §5], we may assume, by recursion, that K is an *abelian extension* of F_v. Since, moreover, F contains a *square root of* -1, it follows that we may apply the *Grunwald-Wang Theorem* [cf., e.g., [8], Corollary 9.2.3] to F. Now assertion (i) follows immediately by applying the Grunwald-Wang Theorem to F. Assertion (ii) follows by considering the quadratic extension of F determined by taking the square root of an element $f \in F$ which is < 0 at v and either > 0 or nonreal at w [where we note that the *existence* of such an f follows immediately from the fact that the valuations v, w are *distinct*]. In the *nonarchimedean* case, assertion (iii) follows formally from assertion (i), together with the well-known facts that the absolute Galois group of a nonarchimedean local field is *slim* [cf., e.g., [5], Theorem 1.1.1, (ii)] and [of *finite cohomological dimension* — cf., e.g., [8], Corollary 7.2.5 — hence] *torsion-free.* In the *archimedean* case, assertion (iii) follows, for instance, by considering the extension of F obtained by adjoining a square root of -1. To verify assertion (iv), let us first observe that if at least one of v, w is *nonarchimedean*, then it follows from the *torsion-free-ness* portion of assertion (iii) that both v, w are *nonarchimedean* [cf. also the well-known fact that the absolute Galois group of an *archimedean* local field is finite, of order $\leq 2!$], and, moreover, that [from the point of view of verifying assertion (iv)] one may replace F by a finite abelian extension of F that satisfies the hypothesis of assertion (i). Now assertion (iv) follows immediately from assertions (i), (ii), (iii). Finally, assertion (v) follows formally from assertion (iv) [together with the *torsion-free-ness* portion of assertion (iii) in the *nonarchimedean* case]. □

Theorem 2.4 (Topologically Finitely Generated Closed Normal Subgroups). *Suppose that $\widetilde{F}$ is a Galois extension of the number field F such that for some prime number p, $\widetilde{F}$ has* **no cyclic extensions of degree p** *[e.g., a* **solvably closed extension** *of F]. Then every topologically finitely generated closed normal subgroup $N \subseteq Q_F$ is* **trivial**.

Proof. Although this fact only follows formally from the statement of [2], Proposition 16.11.6, in the case where $\widetilde{F}$ is algebraically closed, as was explained to the author by *A. Tamagawa*, the proof given in [2] generalizes immediately to the case of arbitrary $\widetilde{F}$ [i.e., as in the statement of Theorem 2.4]: Indeed, if we write $L \subseteq \widetilde{F}$ for the *Galois* [since N is normal] field extension of F determined by N, and assume that N is *nontrivial*, then it follows that there exists a *proper* normal open subgroup $N_1 \subseteq N$ of N. Thus, N_1 determines a finite Galois extension L_1/L of degree > 1. Now let us recall that *number fields* [such as F] are *Hilbertian* [cf., e.g., [2], Theorem 13.4.2]. Thus, by [2], Theorem 13.9.1, (b) [i.e., *"Weissauer's extension theorem for Hilbertian fields"*], we conclude that L_1 is *Hilbertian*, hence, by [repeated application of] [2], Theorem 16.11.2, that L_1 admits Galois extensions with Galois group isomorphic to a product of an arbitrary finite number of copies of $\mathbb{Z}/p\mathbb{Z}$. By our assumption on $\widetilde{F}$, it follows that such Galois extensions of L_1 are contained in $\widetilde{F}$, hence that N_1 admits finite quotients isomorphic to a product of an arbitrary finite number of copies of $\mathbb{Z}/p\mathbb{Z}$. But this contradicts the assumption that N is *topologically finitely generated.* □

3. Anabelian Results

Next, we consider the *anabelian geometry of hyperbolic curves*, in the context of *solvably closed Galois groups of number fields.*

The following result is due to *K. Uchida* [cf. the main theorem of [11]]:

Theorem 3.1 (Solvably Closed Galois Groups are Anabelian). *For $i = 1, 2$, let $\widetilde{F}_i/F_i$ be a* **solvably closed extension** *of a number field F_i; write $Q_i \overset{\text{def}}{=} \text{Gal}(\widetilde{F}_i/F_i)$. Then passing to the induced morphism on Galois groups determines a* **bijection** *between the set of* **isomorphisms of topological groups**

$$Q_1 \xrightarrow{\sim} Q_2$$

and the set of **isomorphisms of fields** $\widetilde{F}_1 \xrightarrow{\sim} \widetilde{F}_2$ *that map F_1 onto F_2.*

Next, let us assume that we have been given a *hyperbolic curve* [cf., e.g., [5], §0, for a discussion of hyperbolic curves] over F. Let Σ be a *nonempty set of prime numbers.* Write

$$\Delta_X$$

for the *maximal pro-Σ quotient* of the geometric fundamental group $\pi_1(X \times_F \overline{F})$ of X [relative to some basepoint]. Here, we note in passing that Σ *may be recovered from* Δ_X as the set of prime numbers that occur as factors of orders of finite quotients of Δ_X. Thus, one has a *natural outer action*

$$G_F \to \text{Out}(\Delta_X)$$

of G_F on Δ_X.

Lemma 3.2 (Slimness)**.** Δ_X *is* **slim**.

Proof. This follows immediately by considering Galois actions on abelianizations of open subgroups of Δ_X — cf. the proof of [5], Lemma 1.3.1, in the case where Σ is the set of all prime numbers. Another [earlier] approach to proving the slimness of Δ_X is given in [7], Corollary 1.3.4. □

Definition 2. We shall say that the [not necessarily solvably closed!] extension $\widetilde{F}/F$, or, alternatively, the Galois group Q_F, is Σ-*compatible with* X if the natural outer action

$$G_F \to \mathrm{Out}(\Delta_X)$$

factors through the quotient $G_F \twoheadrightarrow Q_F$. Thus, if Q_F is Σ-compatible with X, then one obtains an *exact sequence of profinite groups*

$$1 \to \Delta_X \to \Pi_X \to Q_F \to 1$$

by pulling back the natural exact sequence

$$1 \to \Delta_X \to \mathrm{Aut}(\Delta_X) \to \mathrm{Out}(\Delta_X) \to 1$$

[which is *exact* by Lemma 3.2!] via the resulting homomorphism $Q_F \to \mathrm{Out}(\Delta_X)$. Here, we note that since [it is an easily verified tautology that] the étale fundamental group $\pi_1(X)$ of X may be recovered as the result of pulling back this natural exact sequence via the homomorphism $G_F \to \mathrm{Out}(\Delta_X)$, it thus follows that Π_X may be thought of as a *quotient* of $\pi_1(X)$.

Proposition 3.3 (Geometric Subgroups are Characteristic)**.** *For* $i = 1, 2$, *let* $\widetilde{F}_i/F_i$ *be a* **solvably closed extension** *of a number field* F_i*;* $Q_i \overset{\mathrm{def}}{=} \mathrm{Gal}(\widetilde{F}_i/F_i)$*;* Σ_i *a nonempty set of prime numbers;* X_i *a* **hyperbolic curve** *over* F_i *with which* Q_i *is* Σ_i-**compatible***;* $1 \to \Delta_{X_i} \to \Pi_{X_i} \to Q_i \to 1$ *the resulting exact sequence of profinite groups [cf. Definition 2]. Then any* **isomorphism of topological groups**

$$\Pi_{X_1} \xrightarrow{\sim} \Pi_{X_2}$$

maps Δ_{X_1} *isomorphically onto* Δ_{X_2}*. In particular,* $\Sigma_1 = \Sigma_2$.

Proof. We give *two proofs* of Proposition 3.3. The *first proof* consists of simply observing [cf. the proof of [5], Lemma 1.1.4, (i), via [5], Theorem 1.1.2] that the image of Δ_{X_1} under the composite of the isomorphism $\Pi_{X_1} \xrightarrow{\sim} \Pi_{X_2}$ with the surjection $\Pi_{X_2} \twoheadrightarrow Q_2$ forms a *topologically finitely generated closed normal subgroup* of Q_2, hence is *trivial*, by Theorem 2.4.

The *second proof* of Proposition 3.3 only uses Theorem 2.4 in the well-known case of an *absolute Galois group* of a number field. Moreover, when either Σ_1 or Σ_2 is *not* equal to the set of *all prime numbers*, then this second proof does not use Theorem 2.4 *at all.*

For $i = 1, 2$, let $H_i \subseteq \Pi_{X_i}$ be corresponding [i.e., relative to the given isomorphism $\Pi_{X_1} \overset{\sim}{\rightarrow} \Pi_{X_2}$] normal open subgroups; write $H_i \twoheadrightarrow J_i$ for the quotients determined by the quotients $\Pi_{X_i} \twoheadrightarrow Q_i$. By taking the H_i to be *sufficiently small*, we may also assume that the number fields determined by the J_i contain *square roots of* -1. Thus, by Proposition 2.1, (i), it follows that

$$\mathrm{cd}_p(H_i) = 2 + d(p, i)$$

where $d(p, i)$ is equal to 1 or 2 [depending on whether X_i is *affine* or *proper*] if $p \in \Sigma_i$ and $d(p, i) = 0$ if $p \notin \Sigma_i$. Since $H_1 \overset{\sim}{\rightarrow} H_2$, we thus conclude that $\Sigma_1 = \Sigma_2$, and that X_1 is affine if and only if X_2 is. Now if $\Sigma_1 = \Sigma_2$ is the set of *all prime numbers*, and X_1, X_2 are *affine*, then it follows from *Matsumoto's injectivity theorem* [cf. [4], Theorem 2.1] that the field $\widetilde{F}_i$ is an *algebraic closure* of F_i; thus, in this case, Proposition 3.3 follows from [5], Lemma 1.1.4, (i) [i.e., Theorem 2.4 for absolute Galois groups of number fields].

Next, let us suppose that there exists a *prime number* p such that $p \notin \Sigma_1$, $p \notin \Sigma_2$. This implies that every finite quotient group of $D_i \overset{\mathrm{def}}{=} \ker(H_i \twoheadrightarrow J_i)$ has *order prime to* p, hence [by consideration of the Leray-Serre spectral sequence associated to the surjection $H_i \twoheadrightarrow J_i$] that, for $i = 1, 2$, the natural homomorphism

$$H^2(J_i, \mathbb{F}_p) \rightarrow H^2(H_i, \mathbb{F}_p)$$

is an *isomorphism.* In particular, it follows that Δ_{X_i} acts *trivially* on $H^2(H_i, \mathbb{F}_p)$. Thus, the natural action of Π_{X_i} on $H^2(H_i, \mathbb{F}_p)$ *factors* through the quotient $\Pi_{X_i} \twoheadrightarrow Q_i/J_i$. Now, by taking H_i to be *sufficiently small*, we may assume [since Q_i is *solvably closed*!] that the extension field of F_i determined by J_i contains a *primitive* p*-th root of unity.* Thus, by Proposition 2.1, (ii), we conclude that the action of Q_i/J_i on $H^2(H_i, \mathbb{F}_p)$ is *faithful.* Since the isomorphism $\Pi_{X_1} \overset{\sim}{\rightarrow} \Pi_{X_2}$ induces an isomorphism $H_1 \overset{\sim}{\rightarrow} H_2$, hence an isomorphism $H^2(H_1, \mathbb{F}_p) \overset{\sim}{\rightarrow} H^2(H_2, \mathbb{F}_p)$ which is compatible with the respective actions of Π_{X_1}, Π_{X_2}, we thus conclude that the isomorphism $\Pi_{X_1} \overset{\sim}{\rightarrow} \Pi_{X_2}$ preserves the kernels of the surjections $\Pi_{X_i} \twoheadrightarrow Q_i/J_i$, hence that the subgroup $\Delta_{X_i} = \ker(\Pi_{X_i} \twoheadrightarrow Q_i)$ may be recovered as the intersection of the kernels of the surjections $\Pi_{X_i} \twoheadrightarrow Q_i/J_i$, by letting the H_i range over all sufficiently small normal open subgroups of Π_{X_i}. This completes the proof of Proposition 3.3 in the case where there exists a *prime number* p such that $p \notin \Sigma_1$, $p \notin \Sigma_2$.

Finally, we consider the case where X_1, X_2 are *proper.* Let p be a prime number; suppose that the H_i have been taken to be *sufficiently small* so that the number fields determined by the J_i contain a *primitive p-th root of unity* and a *square root of* -1 [which, by Proposition 2.1, (i), implies that $\mathrm{cd}_p(J_i) = 2$]. Since $D_i \overset{\text{def}}{=} \ker(H_i \twoheadrightarrow J_i)$ also satisfies $\mathrm{cd}_p(D_i) \leq 2$, it thus follows from the Leray-Serre spectral sequence associated to the extension $1 \to D_i \to H_i \to J_i \to 1$ that there is a *natural isomorphism*

$$H^4(H_i, \mathbb{F}_p) \cong H^2(J_i, \mathbb{F}_p) \otimes H^2(D_i, \mathbb{F}_p)$$

which is *compatible* with the natural action of Π_{X_i} on the various cohomology modules involved. Here, we note that [by the well-known structure of the cohomology of the geometric fundamental group of an algebraic curve] $\Delta_{X_i} \subseteq \Pi_{X_i}$ acts *trivially* on $H^2(D_i, \mathbb{F}_p)$. Thus, Proposition 3.3 follows in the present case by applying Proposition 2.1, (ii), as in the argument given in the preceding paragraph. □

Theorem 3.4 (The Anabelian Geometry of Hyperbolic Curves over Solvably Closed Galois Groups)**.** *For $i = 1, 2$, let $\widetilde{F}_i/F_i$ be a* **solvably closed extension** *of a number field F_i; $Q_i \overset{\text{def}}{=} \mathrm{Gal}(\widetilde{F}_i/F_i)$; Σ_i a nonempty set of prime numbers; X_i a* **hyperbolic curve** *over F_i with which Q_i is Σ_i-***compatible***; $1 \to \Delta_{X_i} \to \Pi_{X_i} \to Q_i \to 1$ the resulting exact sequence of profinite groups [cf. Definition 2]; $\widetilde{X}_i \to X_i$ the* **pro-finite étale covering** *of X_i determined by Π_{X_i} [regarded as a quotient of the étale fundamental group of X_i]. Then passing to the induced morphism on fundamental groups determines a* **bijection** *between the set of* **isomorphisms of topological groups**

$$\Pi_{X_1} \overset{\sim}{\to} \Pi_{X_2}$$

and the set of **compatible pairs of isomorphisms of schemes** *$\widetilde{X}_1 \overset{\sim}{\to} \widetilde{X}_2$, $X_1 \overset{\sim}{\to} X_2$.*

Proof. By Proposition 3.3, any isomorphism $\Pi_{X_1} \overset{\sim}{\to} \Pi_{X_2}$ induces an isomorphism $Q_1 \overset{\sim}{\to} Q_2$, hence, by Theorem 3.1, a compatible pair of isomorphisms of fields $\widetilde{F}_1 \overset{\sim}{\to} \widetilde{F}_2$, $F_1 \overset{\sim}{\to} F_2$. Thus, we may apply "Theorem A" of [6] to the isomorphism $\Pi_{X_1} \overset{\sim}{\to} \Pi_{X_2}$ to conclude that this isomorphism arises from a unique compatible pair of isomorphisms of schemes $\widetilde{X}_1 \overset{\sim}{\to} \widetilde{X}_2$, $X_1 \overset{\sim}{\to} X_2$, as desired. □

4. Some Examples

Finally, we conclude by observing that in various situations, Σ-compatible solvably closed extensions which are, moreover, *"relatively small"* [e.g., by comparison to the entire absolute Galois group of a number field] exist in substantial abundance.

Proposition 4.1 (The Case of a Single Prime Number)**.** *Let* $\Sigma \overset{\text{def}}{=} \{r\}$, *where* r *is a prime number.*

(i) Let Δ *be a* **topologically finitely generated pro-*r* group***. [Thus, since* Δ *is topologically finitely generated, its topology admits a base of* **characteristic** *open subgroups, which determine a natural profinite topology on* $\mathrm{Out}(\Delta)$*.] Write* $\Delta \twoheadrightarrow \Delta^{\mathrm{ab}}$ *for the* **abelianization** *of* Δ*. Then the kernel of the natural morphism of profinite groups*

$$\mathrm{Out}(\Delta) \to \mathrm{Aut}(\Delta^{\mathrm{ab}} \otimes \mathbb{F}_r)$$

is a **pro-*r*** *[hence, in particular,* **pro-solvable***!]* **group***.*

(ii) Let X *be a* **hyperbolic curve** *over* F*. Then there exists a finite Galois extension* F_1 *over* F *such that the* **maximal solvable extension** *[which is* **solvably closed** *— cf. Remark 2]* $\widetilde{F} \overset{\text{def}}{=} F_1^{\mathrm{sol}}$ *of* F_1 *is* Σ-**compatible** *with* X*.*

Proof. First, we consider assertion (i). Since Δ admits a base of *characteristic* open subgroups, it suffices to verify assertion (i) when Δ is a *finite group* of order a power of r. But then consideration of the [manifestly characteristic!] *lower central series* of Δ reveals that any automorphism α of Δ that induces the identity on $\Delta^{\mathrm{ab}} \otimes \mathbb{F}_r$ is *"unipotent upper triangular"* with respect to the filtration given by the lower central series; thus, the order of α is a power of r. This completes the proof of assertion (i). Assertion (ii) follows formally from assertion (i) and the definitions. □

Proposition 4.2 (Basic Properties of Special Linear Groups)**.** *Let* l *be a prime number. Write* $SL_2(\mathbb{F}_l)$ *for the* **special linear group** *of* 2 *by* 2 *matrices with coefficients in* $\mathbb{F}_l$, $PSL_2(\mathbb{F}_l) \overset{\text{def}}{=} SL_2(\mathbb{F}_l)/\{\pm 1\}$*.*

(i) Suppose that $l \geq 5$*. Then* $PSL_2(\mathbb{F}_l)$ *is a* **simple finite group***.*

(ii) **No proper subgroup** *of* $SL_2(\mathbb{F}_l)$ *surjects onto* $PSL_2(\mathbb{F}_l)$*.*

(iii) $PSL_2(\mathbb{F}_2)$, $PSL_2(\mathbb{F}_3)$*, as well as every proper subgroup of* $PSL_2(\mathbb{F}_l)$ *[for arbitrary* l*], is either* **solvable** *or isomorphic to* $PSL_2(\mathbb{F}_5)$*.*

Proof. Assertions (i), (ii), (iii) are well-known — cf., e.g., [10], Chapter IV, §3.4, Lemmas 1, 2; [1], §1.2. □

Remark 5. The proper subgroups H of $SL_2(\mathbb{F}_l)$ may be analyzed as follows: If H is of *order divisible by* l, then H contains a *subgroup* U *of order* l. Since $\mathbb{F}_l^{\times}$, $\mathbb{F}_{l^2}^{\times}$ are of order prime to l, such a subgroup U is generated by a *unipotent matrix*; thus, [by possibly replacing H with a conjugate of H] we may assume that U is generated by a matrix $\left(\begin{smallmatrix}1 & 1\\ 0 & 1\end{smallmatrix}\right)$. In particular, [as is well-known or easily computed] the normalizer of U is given by the *solvable* subgroup of upper triangular matrices of $SL_2(\mathbb{F}_l)$. Thus, if U fails to be normal in H, the fact that $SL_2(\mathbb{F}_l)$ is generated by $\left(\begin{smallmatrix}1 & 1\\ 0 & 1\end{smallmatrix}\right)$, $\left(\begin{smallmatrix}1 & 0\\ 1 & 1\end{smallmatrix}\right)$ implies that $H = SL_2(\mathbb{F}_l)$, in contradiction to our assumption that H is *proper*. That is to say, since H is proper, we conclude that H is *solvable*, as desired. On the other hand, if the order of H is *prime to* l, then H may be classified by applying the *Hurwitz formula* to the *tamely ramified* Galois covering $\mathbb{P}^1_{\overline{\mathbb{F}}_l} \to \mathbb{P}^1_{\overline{\mathbb{F}}_l}/H$ [arising from the natural action of SL_2 on $\mathbb{P}^1_{\overline{\mathbb{F}}_l}$, where $\overline{\mathbb{F}}_l$ is an algebraic closure of $\mathbb{F}_l$], which gives rise to fairly *restrictive conditions* on the ramification indices of this covering. In particular, if H is *non-abelian*, then, by taking an appropriate isomorphism of $\mathbb{P}^1_{\overline{\mathbb{F}}_l}/H$ with $\mathbb{P}^1_{\overline{\mathbb{F}}_l}$, one concludes that this covering is ramified over the three points "0", "1", and "∞" of $\mathbb{P}^1_{\overline{\mathbb{F}}_l}$, with ramification index 2 at "0", ramification index $\in \{2, 3\}$ at "1", and ramification index $\in \{3, 4, 5\}$ (respectively, arbitrary, ≥ 2) at "∞" if the ramification index at "1" is equal to 3 (respectively, 2). Now it is an elementary exercise to classify the possible groups H that may occur. For instance, by considering *modular curves*, it follows immediately that the case $H = PSL_2(\mathbb{F}_5)$ corresponds to the case where the ramification indices are $(2, 3, 5)$.

Proposition 4.3 (Linear Disjointness I)**.** *Let $l > 5$ be a prime number; r a prime number $\neq l$; $\Sigma \overset{\text{def}}{=} \{r\}$; X a* **once-punctured elliptic curve** *over a* **number field** *F. Suppose further that F contains an* ***l*-th root of unity***, and that the resulting homomorphism*

$$G_F \to SL_2(\mathbb{F}_l)$$

determined by the action of the absolute Galois group G_F of F on the l-torsion points of the elliptic curve E compactifying X is **surjective***. Then there exists a* **solvably closed extension** *$\widetilde{F}/F$ which is* **Σ-compatible** *with X, and, moreover,* **linearly disjoint** *[over F] from the extension K of F determined by the kernel of the homomorphism $G_F \to SL_2(\mathbb{F}_l)$.*

Proof. Write $L \subseteq K$ for the extension of F determined by the kernel of the homomorphism $G_F \to PSL_2(\mathbb{F}_l)$ [obtained by composing the homomorphism $G_F \to SL_2(\mathbb{F}_l)$ with the natural surjection $SL_2(\mathbb{F}_l) \twoheadrightarrow PSL_2(\mathbb{F}_l)$]. Then it follows immediately from Proposition 4.2, (ii), that any Galois extension of F is linearly disjoint from K if and only if it is linearly disjoint from L. Now observe that $\text{Gal}(L/F) \cong PSL_2(\mathbb{F}_l)$ is *simple* [cf. Proposition 4.2, (i)] and *non-abelian*. Thus, by Proposition 4.1, (i), it suffices to show that the *finite* Galois extension R of F determined by the kernel of the homomorphism $G_F \to GL_2(\mathbb{F}_r)$ arising from the Galois action on the r-torsion points of E is *linearly disjoint* from L. On the other hand, again since

$\mathrm{Gal}(L/F)$ is *simple* and *non-abelian*, this linear disjointness property follows from the fact [cf. Proposition 4.2, (iii); our assumption that $r \neq l > 5$] that no subquotient of $GL_2(\mathbb{F}_r)$ [or, equivalently, $PSL_2(\mathbb{F}_r)$, since $PSL_2(\mathbb{F}_l)$ is simple and nonabelian] is isomorphic to $PSL_2(\mathbb{F}_l)$. This completes the proof of Proposition 4.3. □

Proposition 4.4 (Linear Disjointness II). *Let $l > 5$ be a prime number; Σ a nonempty* **set of prime numbers** *such that $l \notin \Sigma$; X a* **once-punctured elliptic curve** *over a* **number field** *F with* **stable reduction** *over the ring of integers $\mathcal{O}_F$ of F; F_μ the extension of F obtained by adjoining an* ***l*-th root of unity**. *Suppose further that $l \geq [F : \mathbb{Q}] + 2$; that $[F_\mu : F]$ divides $(l-1)/2$ [which implies that the homomorphism*

$$G_F \to PGL_2(\mathbb{F}_l) \overset{\text{def}}{=} GL_2(\mathbb{F}_l)/\mathbb{F}_l^\times$$

determined by the action of the absolute Galois group G_F of F on the l-torsion points of the elliptic curve E compactifying X **factors** *through the image of $PSL_2(\mathbb{F}_l)$ in $PGL_2(\mathbb{F}_l)$]; that the resulting homomorphism $G_F \to PSL_2(\mathbb{F}_l)$ is* **surjective***; and that, for each prime $\mathfrak{l}$ of F lying over l at which E has* **bad** *reduction, the following condition is satisfied:*

> *Write $F_\mathfrak{l}$ for the completion of F at $\mathfrak{l}$. Thus, the elliptic curve $E \times_F F_\mathfrak{l}$ is a* **Tate curve**, *hence has a well-defined* **"*q*-parameter"** *$q_\mathfrak{l}$ in the ring of integers $\mathcal{O}_{F_\mathfrak{l}}$. Then the valuation of $q_\mathfrak{l}$ is* **prime to** *l.*

Then:

(i) There exists an extension $\widetilde{F}/F$ which is **Σ-compatible** *with X, and, moreover,* **linearly disjoint** *[over F] from the extension K of F determined by the kernel of the homomorphism $G_F \to PSL_2(\mathbb{F}_l)$.*

(ii) Write K_μ for the extension of F determined by the kernel of the homomorphism $G_F \to GL_2(\mathbb{F}_l)$ [arising from the Galois action on the l-torsion points of E]. Thus, $F_\mu \subseteq K_\mu$; write $\widetilde{F}_\mu \overset{\text{def}}{=} F_\mu \cdot \widetilde{F}$ for the composite extension [over F]. Then the maximal solvable extension $\widetilde{F}_\mu^{\text{sol}}$ of $\widetilde{F}_\mu$ forms a **solvably closed** *extension of F_μ which is* **Σ-compatible** *with X and, moreover,* **linearly disjoint** *over F_μ from the extension K_μ of F_μ.*

Proof. First, we consider assertion (i). Let $\widetilde{F}/F$ be the extension determined by the kernel of the homomorphism $G_F \to \mathrm{Out}(\Delta_X)$ [cf. Definition 2]. Let $\mathfrak{l}$ be a prime of F lying over l. Since $PSL_2(\mathbb{F}_l)$ is *simple* [cf. Proposition 4.2, (i)], to complete the proof of assertion (i), it suffices to show that the composite [i.e., over F] field extension $K \cdot \widetilde{F}$ is *not equal* to $\widetilde{F}$. Thus, suppose that $K \cdot \widetilde{F} = \widetilde{F}$. Since $l \notin \Sigma$, if E has *good reduction* at $\mathfrak{l}$, then it follows that $\widetilde{F}/F$ is *unramified* at $\mathfrak{l}$; similarly, if E has *bad reduction* at $\mathfrak{l}$, then the fact that $l \notin \Sigma$ implies that $\widetilde{F}/F$ is *tamely ramified* at $\mathfrak{l}$. On the other hand, if E has *good reduction* at $\mathfrak{l}$, then the fact that $K \subseteq K \cdot \widetilde{F} = \widetilde{F}$ is unramified at $\mathfrak{l}$ implies, by applying, for instance, results of Raynaud on the *"fully faithfulness of restriction to the generic fiber" for finite flat group schemes over moderately ramified discrete valuation rings* [cf. [9], Corollaire 3.3.6, (1); our assumption that $l \geq [F : \mathbb{Q}] + 2$, which implies that the ring of integers $\mathcal{O}_{F_\mathfrak{l}}$ is indeed "moderately ramified"], that, if we write $\mathcal{E}$ for the stable model of the elliptic curve E over $\mathcal{O}_{F_\mathfrak{l}}$ and $\mathcal{E}[l]$ for the kernel of multiplication by l on $\mathcal{E}$, then $\mathcal{E}[l]$ may be written as a direct product

$$\mathcal{E}[l] \cong \mathcal{G} \times \mathcal{G}$$

of two copies of some finite flat group scheme $\mathcal{G}$ over $\mathcal{O}_{F_\mathfrak{l}}$ [which implies, for instance, that the tangent space of $\mathcal{E}[l]$, hence also of $\mathcal{E}$, is *even-dimensional*!] — a contradiction. Finally, if E has *bad reduction* at $\mathfrak{l}$, then the fact that $K \subseteq K \cdot \widetilde{F} = \widetilde{F}$ is tamely ramified at $\mathfrak{l}$ contradicts our assumption concerning the "valuation of the q-parameter" [which implies that K is *wildly ramified* at $\mathfrak{l}$]. This completes the proof of assertion (i).

To verify assertion (ii), let us first observe that by Proposition 4.2, (i) [cf. our assumption that $l > 5$], (ii), and the *surjectivity* assumption in the statement of the present Proposition 4.4, we have $\text{Gal}(K_\mu/F_\mu) \cong SL_2(\mathbb{F}_l)$. Now, by applying Proposition 4.2, (ii), as in the proof of Proposition 4.3, assertion (ii) follows immediately from assertion (i), together with the *simplicity* [and *non-solvability*] of $PSL_2(\mathbb{F}_l)$. □

References

[1] R. W. Carter, *Simple groups of Lie type*, *Pure and Applied Mathematics* **28**, John Wiley & Sons (1972).

[2] M. Fried and M. Jarden, *Field Arithmetic* (second edition), Springer-Verlag (2005).

[3] S. Lang, *Algebraic number theory*, Addison-Wesley Publishing Co. (1970).

[4] M. Matsumoto, Galois representations on profinite braid groups on curves, *J. Reine Angew. Math.* **474** (1996), pp. 169-219.

[5] S. Mochizuki, The Absolute Anabelian Geometry of Hyperbolic Curves, *Galois Theory and Modular Forms*, Kluwer Academic Publishers (2003), pp. 77-122.

[6] S. Mochizuki, The Local Pro-p Anabelian Geometry of Curves, *Invent. Math.* **138** (1999), pp. 319-423.

[7] H. Nakamura, Galois rigidity of pure sphere braid groups and profinite calculus, *J. Math. Sci. Univ. Tokyo* **1** (1994), pp. 71-136.

[8] J. Neukirch, A. Schmidt, K. Wingberg, *Cohomology of number fields*, *Grundlehren der Mathematischen Wissenschaften* **323**, Springer-Verlag (2000).

[9] M. Raynaud, Schémas en groupes de type $(p, \ldots, p)$, *Bull. Soc. Math. France* **102** (1974), pp. 241-280.

[10] J.-P. Serre, *Abelian l-adic Representations and Elliptic Curves*, Benjamin (1968).

[11] K. Uchida, Isomorphisms of Galois groups of solvably closed Galois extensions, *Tôhoku Math. J.* **31** (1979), pp. 359-362.

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