MINIMAL SUBFIELDS OF ELLIPTIC CURVES

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ABSTRACT. For an elliptic curve E defined over a number field K and L/K a Galois extension, we study the possibilities of the Galois group $\mathrm{Gal}(L/K)$, when the Mordell-Weil rank of $E(L)$ increases from that of $E(K)$ by a small amount (namely 1,2 and 3). In relation with the vanishing of corresponding L-functions at $s = 1$, we prove several elliptic analogues of classical theorems related to Artin's holomorphy conjecture. We then apply these to study the analytic minimal subfield, first introduced by Akbary and Murty, for the case when order of vanishing is 2. We also investigate how the order of vanishing changes as rank increases by 1 and vice versa, generalizing a theorem of Kolyvagin.

1. INTRODUCTION

Let E be an elliptic curve defined over a number field K and let L/K be a finite Galois extension with Galois group $G = \mathrm{Gal}(L/K)$. The famous Mordell-Weil Theorem tells us that, $E(L)$, the group of L-rational points of E, is finitely generated. Through out this paper we will focus on the "free part" of the Mordell-Weil group, that is, $E(L)$ modulo the torsion subgroup $E(L)_{\mathrm{tors}}$ and denote the rank of this quotient by $\mathbf{rk}\ E(L)$. The question of studying this free part of $E(L)$ as a $\mathbb{Z}[G]$-module is an appealing one and was raised in the works of Mazur and Swinnerton-Dyer [18], Coates and Wiles [5] etc. Towards this study, Akbary and Murty in [1] introduced the idea of a minimal subfield : $M \subseteq L$, minimal, such that $\mathbf{rk}\ E(M) = \mathbf{rk}\ E(L)$ and produced explicit examples. They gave a description of the possibilities for $\mathrm{Gal}(M/K)$ when the rank $E(L)$ is small (e.g. 1, 2 and 3). In the first part of this paper we generalize their results from small rank to small increase in rank. We show that similar descriptions of $\mathrm{Gal}(M/K)$ holds when
$\mathbf{rk}\ E(L) = \mathbf{rk}\ E(K) + t$ for $t = 1, 2$ and 3. In particular we prove :

Theorem 1.1. *Let L/K be a Galois extension of number fields and E/K be an elliptic curve such that $\mathbf{rk}\ E(L) = \mathbf{rk}\ E(K) + t$. Let M be the minimal subfield.*

(1) *If $t = 1$, M is a quadratic extension of K.*
(2) *If $t = 2$, M is either a cyclic extension of K with $[M : K] = 2, 3, 4, 6$ or a dihedral extension of K with $[M : K] = 4, 6, 8, 12$.*
(3) *If $t = 3$, $Gal(M/K)$ is isomorphic to one of the following :*
$C_n \times C_m$ *where* $n = 1, 2, 3, 4 \quad m = 1, 2$
$D_{2p} \times C_m$ *where* $p = 2, 3, 4, 6 \quad m = 1, 2$
$A_4 \times C_m \quad$ *or,* $\quad S_4 \times C_m$ *where* $m = 1, 2$

Section 2 is largely devoted to proving the above Theorem starting with a precise definition of the Minimal subfield.

We then venture on a more analytic side of things. The famous Birch-Swinnerton-Dyer conjecture connects the rank of an elliptic curve to the order of vanishing of its L-function at $s = 1$. In this regard, Akbary and Murty introduced the analytic notion of the minimal subfield in [1]. Its existence is dependent on the holomorphy of $L(E/K \otimes \chi, s)$ for irreducible characters χ of the Galois group. For number fields, classical theorems of Foote-Murty and Foote-Wales, shows holomorphy of Artin L-functions when the Dedekind zeta function has a zero of small order. In section 4 and 5 we develop elliptic analogues of these theorems. For example we show,

Theorem 1.2. *Suppose that E satisfies the generalized Taniyama conjecture over K. Let F be a galois extension of K with solvable galois group $G = Gal(F/K)$. Let χ be an irreducible character of G. Then, $L(E/K \otimes \chi, s)$ is holomorphic at $s = \omega$ if ω is a zero of $L(E/F, s)$ of order $r \leq p_2 - 2$, where p_2 is the second smallest prime factor of $|G|$.*

We also prove the $r = 2$ case. These results establish existence of the analytic minimal subfield unconditionally when the L-function of E over the top field has a zero of small order. In section 6, similar to the algebraic case, we investigate the possibilities of the galois group for the analytic minimal subfield, when the order of vanishing at $s = 1$ of $L(E/F, s)$ is 2. As an application, we show the following slight generalization of a theorem of Kolyvagin :

Theorem 1.3. *Let $K/\mathbb{Q}$ be a solvable Galois extension.*

(i) *rank $E(K)$ = rank $E(\mathbb{Q}) + 1 \Rightarrow ord_{s=1} L(E/K, s) \geq ord_{s=1} L(E/\mathbb{Q}, s) + 1$*
(ii) *If $L(E/\mathbb{Q} \otimes \chi, s)$ is holomorphic at $s = 1$, for every irreducible character χ of $Gal(K/\mathbb{Q})$ and $ord_{s=1} L(E/K, s) = ord_{s=1} L(E/\mathbb{Q}, s) + 1$, then rank $E(K) \geq$ rank $E(\mathbb{Q}) + 1$*

In both cases equality holds if the algebraic and the analytic minimal subfields are equal.

We also show that the holomorphy condition in (ii) can be dropped if E has CM.

2. Algebraic Minimal Subfield

Definition 2.0.1. Let E/K be an elliptic curve and let L/K be a finite extension (not necessarily Galois) of number fields. Suppose that rank $E(L) = r$. The algebraic minimal subfield M is a subfield with $K \subseteq M \subseteq L$ satisfying :

(i) $\mathbf{rk}\, E(M) = r$.
(ii) If $K \subseteq F \subseteq L$ with $\mathbf{rk}\, E(F) = r$, then $M \subseteq F$.

Akbary and Murty showed that for any finite extension L/K and elliptic curve E/K, the minimal subfield M exists and is unique. Also, if L/K is Galois then

M/K is Galois. (see Prop. 1 of Section 2 in [1].) For any finite Galois extension L/K, the Galois group $\mathrm{Gal}(L/K)$ acts on $E(L)\otimes\mathbb{Q}$ giving us a representation (writing $r = \mathbf{rk}\, E(L)$)

$$\rho_L : \mathrm{Gal}(L/K) \to \mathrm{Aut}\,(E(L)\otimes\mathbb{Q}) \cong GL_r(\mathbb{Q}) \tag{2.0.1}$$

Proposition 2.0.2. Let L/K be a finite Galois extension with $\mathbf{rk}\, E(L) = r$ and let M be the minimal subfield. Then

$$\rho : \mathrm{Gal}(M/K) \to \mathrm{Aut}\,(E(M)\otimes\mathbb{Q})$$

is faithful. Moreover, Im (ρ) is conjugate to a finite subgroup of $GL_r(\mathbb{Z})$

Proof. For a detailed proof see Prop 2, Section 2 in [1]. But the essential idea is that M is constructed as the fixed field of $\ker\rho_L$. □

2.1. **Working with the Quotient space.** We will write $V_F = E(F)\otimes\mathbb{Q}$ for any number field F. Our idea comes from elementary linear algebra : to work with the quotient space V_L/V_K ($\cong\ V_K^{\perp}$) instead of V_L and prove a similar version of the above proposition. Note that dimension of this quotient space is precisely the increase in rank, i.e.

$$\dim V_L/V_K \ =\ \mathbf{rk}\, E(L) - \mathbf{rk}\, E(K).$$

We can then consider the quotient representation coming from the Galois action. For the algebraic minimal subfield, this representation also turns out to be faithful.

Proposition 2.1.1. Let L/K be a finite Galois extension with $\mathbf{rk}\, E(L) = r$ and let M be the algebraic minimal subfield. If $\mathbf{rk}\, E(L) - \mathbf{rk}\, E(K) = t$, then there exists a faithful representation :

$$\tilde{\rho} : \mathrm{Gal}(M/K) \to GL(V_M/V_K) \cong GL_t(\mathbb{Q})$$

Moreover, Im $(\tilde{\rho})$ is conjugate to a finite subgroup of $GL_t(\mathbb{Z})$.

Proof. By Proposition 2.0.2, we know there is a faithful representation
$\rho : \mathrm{Gal}(M/K) \to GL(V_K)$. We can then consider the quotient representation :
$\tilde{\rho} : \mathrm{Gal}(M/K) \to GL(V_M/V_K)$, where $\tilde{\rho}(g)\cdot(v+V_K) = \rho(g)\cdot v + V_K$.
Now let us compute $\ker\tilde{\rho}$.

$$\begin{aligned}
&\tilde{\rho}(g)(v+V_K) = \tilde{\rho}(1)(v+V_K)\\
&\Rightarrow \rho(g)v - v \in V_K\\
&\Rightarrow \rho(g)(\rho(g)v - v) = \rho(g)v - v \quad [\text{Since } g \text{ acts trivially on } V_K]\\
&\Rightarrow (\rho(g)^2 - 2\rho(g) + I_t)v = 0 \quad \text{for all } v \in V_M
\end{aligned}$$

Thus the minimal polynomial of $\rho(g)$ divides the polynomial $x^2 - 2x + 1 = (x-1)^2$. Since $\mathrm{Gal}(M/K)$ is finite, the minimal polynomial will also divide $x^n - 1$, where
$n = |\mathrm{Gal}(M/K)|$. Thus the minimal polynomial must be $x - 1$, and hence $\rho(g) = I_t = \rho(1)$. Since, ρ is faithful, $g = 1$. Thus, $\tilde{\rho}$ is also faithful.
The other part is true more generally, any finite subgroup of $GL_n(\mathbb{Q})$ has a conjugate in $GL_n(\mathbb{Z})$. For a proof see, Theorem 1, App. 3 (P.124) of [23]. □

Remark 2.1.1. Note that this immediately proves part (i) of our main theorem 1.1. That is, if the rank increases by 1, it must do so in a quadratic extension. This is because $\tilde{\rho} : \mathrm{Gal}(M/K) \to GL_1(\mathbb{Q}) \cong \mathbb{Q}^*$. Moreover, since the Galois group is finite, this implies, $\mathrm{Gal}(M/K) \cong \{\pm 1\}$, and hence $[M : K] = 2$. For other parts, we need some more Group Theory.

2.2. **Results from Group Theory.** In this subsection we present a number of elementary results from Group Theory as lemmas. For proofs, please see Section 3 of [1].

Lemma 2.2.1. Let $\rho : G \to GL_2(\mathbb{Z})$ be a faithful representation.

(1) If ρ is reducible, then $G \cong C_n$ or, $\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$, where $n = 1, 2, 3, 4, 6$
(2) If ρ is reducible, then $G \cong D_{2n}$, where $n = 3, 4, 6$.

Lemma 2.2.2. Let $\rho : G \to GL_3(\mathbb{Z})$ be a faithful representation. Then G is isomorphic to one of the following :

$C_n \times C_m$ where $n = 1, 2, 3, 4 \quad m = 1, 2$
$D_{2p} \times C_m$ where $p = 2, 3, 4, 6 \quad m = 1, 2$
$A_4 \times C_m$ where $m = 1, 2$ and
$S_4 \times C_m$ where $m = 1, 2$

2.3. **Proof of Theorem 1.1.**

Proof. Applying Proposition 2.1.1 and the above two lemmas 2.2.1 and 2.2.2 we get our result directly. □

Theorem 1.1 (1) is particularly interesting as it implies the following :

Corollary 2.3.1. In a cubic extension or, for that matter, in any extension of odd degree, the rank can not increase by 1. It either remains the same or jumps by at least 2.

Remark 2.3.1. Note that generalization to larger values of t becomes heavily reliant on the knowledge of classification of finite subgroups of $GL_n(\mathbb{Z})$. However we present here the following easily observed result. We haven't included it as a theorem as the author is unsure of whether or not it is vacuous.

Let L/K be a solvable Galois extension of degree n such that $\mathbf{rk}\, E(L) = \mathbf{rk}\, E(K) + t$, where t is odd. Let M be its minimal subfield. If the quotient representation $\tilde{\rho} : \mathrm{Gal}(M/K) \to GL_t(\mathbb{Q})$ is **irreducible**, then $t \mid n$.

The proof follows from theses two results :

(a) Let G be a finite group. The degree of every irreducible representation of G over an algebraically closed field $\mathbf{k}$ of characteristic 0, divides the order of G.
For a proof see [22], 6.5.

(b) **Theorem (*Dixon*)** Let G be a finite solvable irreducible subgroup of $GL_n(K)$ where K is a real field and n is an odd integer. Then G is absolutely irreducible. (see Theorem 1 of [6] and [7].)

If in fact, $t = p$ is prime, then the above mentioned papers of Dixon will give a nice description of the Galois Group as well. But we think that requiring $\tilde{\rho}$ to be irreducible for larger ranks, might be asking too much.

3. Analytic Minimal Subfield

In this section we focus on the analytic counterpart of the algebraic minimal subfield.

Definition 3.0.1. Let E be an elliptic curve defined over K and F be any finite extension of K. For each zero ω of $L(E/F,s)$, the *analytic minimal subfield* F_ω is a subfield over K with $K \subseteq F_\omega \subseteq F$ such that
(i) $\mathrm{ord}_{s=\omega}\, L(E/F_\omega, s) = \mathrm{ord}_{s=\omega}\, L(E/F,s)$ and
(ii) If $K \subseteq M \subseteq F$ and $\mathrm{ord}_{s=\omega}\, L(E/M,s) = \mathrm{ord}_{s=\omega}\, L(E/F,s)$, then $F_\omega \subseteq M$.

Proposition 3.0.2. If F/K is Galois with Galois group G and $L(E/K \otimes \chi, s)$ is holomorphic at $s = \omega$ for any irreducible character χ of G, then F_ω exists and is Galois over K.

For a proof see Proposition 6 of Section 6 in [1]. We mention the construction here, as we will be using this in Section 6. The idea is to consider those characters for which the twisted L-function vanishes at ω, i.e.

$$Z_\omega = \{\chi \mid L(E/K \otimes \chi, \omega) = 0\}$$

Then define

$$H_\omega = \bigcap_{\chi \in Z_\omega} \mathrm{Ker}\ \chi$$

The minimal subfield F_ω is the fixed field, K^{H_ω} of H_ω in F.

Thus we are interested to investigate holomorphy of $L(E/K \otimes \chi, s)$. We recall some classical theorems on Artin's holomorphy conjecture. Let F/K be a Galois

extension.

Theorem (Stark) If s_0 is a simple zero of the Dedekind zeta function $\zeta_F(s)$, then $L(s,\chi)$ is analytic at $s=s_0$ for every irreducible character χ of $\mathrm{Gal}(F/K)$. (see Theorem 3, P144 in [25])

The following elliptic curve analogue of Stark's theorem is due to Akbary and Murty (see Proposition 7, [1]) :

Theorem (Akbary-Murty) Suppose that E satisfies the generalized Taniyama conjecture over K. Let F be a solvable extension of K and let χ be an irreducible character of $G=\mathrm{Gal}(F/K)$. Then, $L(E/K\otimes\chi,s)$ is holomorphic at $s=\omega$ if ω is a simple zero of $L(E/F,s)$.

Using this they showed, under the same assumptions as above (including zero being simple), the analytic minimal subfield F_ω exists. Moreover, F_ω is a cyclic extension of K and if ω is real then $[F_\omega:K]\leq 2$. We recall,

Definition 3.0.3. *E is said to satisfy the generalised Taniyama conjecture over a number field K if the L-function $L(E/K,s)$ is the L-function $L(\pi,s)$ of a cuspidal automorphic representation π of $GL_2(\mathbb{A}_K)$, where $\mathbb{A}_K$ is the adèle ring of K.*

Note that for $K=\mathbb{Q}$, in 1995 Wiles and Taylor first proved modularity for semi-stable elliptic curves defined over $\mathbb{Q}$. In 2001, B. Conrad, F. Diamond, Richard Taylor and C. Breuil, proved that any elliptic curve $E/\mathbb{Q}$ is modular. From works of Taylor, Kisin, Wintenberger etc the following result on potential modularity is also known: If E/K is a elliptic curve, where K is a totally real field, then there is a totally real extension L/K such that E/L is modular. See for example, [28], [26], [3], [15] etc.

In the classical case, some generalizations of Stark's theorem is known. These results, as stated below, due to Foote, Murty and Wales, eases the condition on ω, from being a simple zero to a zero of small order. In the next section, we will prove the elliptic curve analogue of such theorems.

Theorem (Foote-Wales) Let F/K be a Galois extension of number fields with solvable Galois group G. If the Dedekind zeta function of F, $\zeta_F(s)$ has a zero at $s=s_0$ of order less than or equal to 2, then all Artin L-series $L(s,\chi)$ are analytic at $s=s_0$ for every irreducible character χ of G.

For a proof, see the Corollary to Theorem II of [10].

Theorem (Foote-Murty) Let F/K be a Galois extension of number fields with solvable Galois group G and let p_2 be the second smallest prime number dividing $|G|$. If $\zeta_F(s)$ has a zero of order r at $s=s_0$, where $r\leq p_2-2$, then $L(s,\chi)$ is

analytic at s_0 for all irreducible characters χ of G.

For a proof see P.8 of [9]. Also note that, in case $|G|$ has only one prime factor, i.e. $|G|$ is a prime power, then G is nilpotent and $L(s,\chi)$ is known to be analytic in such cases. The key idea behind both of the above two results, was trying to find minimal counter examples to Artin's holomorphy conjecture.

3.1. **Known Cases.** Assuming the generalized Taniyama Conjecture for K, M. Ram Murty and V. Kumar Murty in [19] proved that if F/K is contained in a finite solvable Galois extension of K, then $L(E/F,s)$ is holomorphic. Their result is predicted by the more general conjecture in Langlands program which states that if π_1 and π_2 are cuspidal automorphic representations of $GL_n(\mathbb{A}_K)$ and $GL_m(\mathbb{A}_K)$, respectively, then $\pi_1 \otimes \pi_2$ is an automorphic representation of $GL_{nm}(\mathbb{A}_K)$. This is known for $m = 1$, as Abelian twists are automorphic. The $GL(2)\times GL(2)$ case was proved by Ramakrishnan in [21] and the $GL(2)\times GL(3)$ by Kim and Shahidi in [14]. In [2] Arthur and Clozel proved that the Langlands reciprocity is valid for all nilpotent Galois extensions using their theory of automorphic induction. Therefore assuming the generalized Taniyama conjecture for E/K, and $\mathrm{Gal}(F/K)$ nilpotent, we see that $L(E/K\otimes\chi,s)$ is automorphic for any irreducible character χ of $\mathrm{Gal}(F/K)$.

Recently Wong in [29] have generalized the above result to certain cases of "nearly nilpotent" and "abelian-by-nilpotent" galois extensions. In a subsequent section, while proving the elliptic analogue of Foote-Wales's theorem, we will use similar ideas to eliminate one of the possibilities.

4. Elliptic Analogue of Foote and Murty's Theorem

Theorem 4.0.1. Suppose that E satisfies the generalized Taniyama conjecture over K. Let F be a galois extension of K with solvable galois group $G = \mathrm{Gal}(F/K)$. Let χ be an irreducible character of G. Then, $L(E/K\otimes\chi,s)$ is holomorphic at $s = \omega$ if ω is a zero of $L(E/F,s)$ of order $r \leq p_2 - 2$, where p_2 is the second smallest prime factor of $|G|$.

Remark 4.0.1. Note that if $|G|$ has only one prime factor, then G is nilpotent and from the discussion above, $L(E/K\otimes\chi,s)$ is known to be automorphic.

As an immediate corollary we get

Corollary 4.0.2. Under the same conditions of the above theorem, the minimal subfield F_ω exists if ω is a zero of $L(E/F,s)$ of order $r \leq p_2 - 2$, where p_2 is the second smallest prime factor of $|G|$.

4.1. **Ingredients for the proof of Theorem 4.0.1.** The following Aramata-Brauer type theorem was proved in [19] :

Theorem 4.1.1. Suppose that E satisfies the generalized Taniyama conjecture over K. If F is a solvable Galois extension of K, then $L(E/F,s)$ extends to an entire function and $\frac{L(E/F,s)}{L(E/K,s)}$ is entire. In particular, $\text{ord}_{s=\omega}\ L(E/F,s) \geq\ \text{ord}_{s=\omega}\ L(E/K,s)$.

Let F/K be a solvable Galois extension with Galois goup G. Let H be a subgroup of G. Let χ and ψ denote the irreducible characters of G and H respectively. Consider the virtual Heilbronn characters

$$\theta_G = \sum n_\chi \chi \quad \text{and} \quad \theta_H = \sum n_\psi \psi$$

where n_χ denotes the order of zero of $L(E/K \otimes \chi, s)$ at $s = \omega$ and n_ψ denotes the order of zero of $L(E/F^H \otimes \psi, s)$ at $s = \omega$ (F^H being the fixed field of H).

Proposition 4.1.2. $\theta_G|_H = \theta_H$.

For a proof see Proposition 1 of [19].

We now look at some more group theoretic results which will be used in the proof of Theorem 4.0.1.

Theorem 4.1.3. (Blichfeldt) Let G be a finite group admitting a faithful, irreducible complex representation ρ. If G possesses a non-central abelian normal subgroup, then ρ is induced from a proper subgroup of G.

For a proof see, Corollary 50.7 at P348 of [4].

Theorem 4.1.4. (Ito) Let G be a solvable group such that G has a faithful character of degree $< p-1$, for a prime p. Then G admits an abelian normal Sylow p-subgroup.

For a proof see, Theorem 24.6, P128 of [8]

Proposition 4.1.5. Any solvable non-abelian group G has a normal subgroup K of prime index such that K contains $Z(G)$.

Proof. G being non-abelian, $G_1 = G/Z(G)$ is a non-trivial solvable group. Let H be a maximal normal subgroup of G_1. Then G_1/H is solvable and simple and hence is cyclic of prime order. Thus the index of H in G_1 is prime. Taking K to be the pre-image of H_1 proves the proposition. □

We also recall the following result from Clifford's theory (e.g see, P53-54, [8])

Proposition 4.1.6. Let N be a normal subgroup of G with $[G:N]=p$, a prime. Then for any irreducible character χ of G, either $\chi|_N$ is irreducible, or $\chi|_N = \sum_{i=1}^{p}\psi_i$, where ψ_i are distinct and irreducible characters of N. Moreover, $\chi = \mathrm{Ind}_H^G\,\psi_i$.

4.2. **Proof of Theorem 4.0.1.** The proof is based on the idea of minimal counter examples as that of its classical counterpart. Assume the Theorem is false and suppose $F,\ K$ are chosen to form a counter example with $[F:K]$ minimal. Thus there exists an irreducible character χ of G and a point $s=\omega$ such that ω is a zero of $L(E/F,s)$ of order satisfying the conditions in the theorem but $L(E/K\otimes\chi,s)$ has a pole at $s=\omega$, i.e. $n_\chi<0$ in the virtual Heilbronn character θ_G at $s=\omega$.

Note that G can not be cyclic, since $L(E/K\otimes\chi,s)$ is known to be analytic for cyclic extensions F/K for every irreducible character χ of G. See for example, proof of Theorem 2 in P492 of [19].

Step 1 : *Every irreducible character χ of G with $n_\chi<0$ is faithful.*

Note that by the generalized Aramata-Brauer Theorem 4.1.1, for every field D with $K\subseteq D\subseteq F$, we have $\mathrm{ord}_{s=\omega}\,L(E/D,s)\leq \mathrm{ord}_{s=\omega}\,L(E/F,s)$. Thus for any character χ with a pole at $s=\omega$, one can consider $D=F^{\ker\chi}$, the fixed field of $\ker\chi$. Thus the conditions of the hypothesis for the counter example carries over to $D,\ G/\ker\chi,\ K$. By minimality of $|G|$, we must have $\mathrm{Ker}\chi=\{1\}$.

Step 2 : *θ_H is a character of H, for all proper subgroups H of G.*

By Proposition 4.1.2, we have $\theta_G|_H=\theta_H$ for any subgroup H of G. We have the factorization :

$$L(E/F,s)=\prod_{\chi\,\in\,\mathrm{Irr}(G)} L(E/K\otimes\chi,s)^{\chi(1)}$$

Thus $\mathrm{ord}_{s=\omega}L(E/F,s)=r=\sum_{\chi\,\in\,\mathrm{Irr}(G)} n_\chi\chi(1)=\theta_G(1)$. Suppose ψ is an irreducible character of H. Consider the L-series $L(E/F^H\otimes\psi,s)$. Now $\theta_H(1)=\theta_G|_H(1)=r$. Thus if ω is a pole, the triple $F,\ H,\ F^H$ forms a counter example contradicting minimality. Thus for every irreducible character ψ of H, $L(E/F^H\otimes\psi,s)$ is analytic at $s=\omega$, in particular, $n_\psi\geq 0\Rightarrow\theta_H$ is a character. Note that, by assumption, θ_G is not a character.

Step 3 : *Any irreducible χ of G with $n_\chi < 0$, is not induced from any proper subgroup of G.*

Suppose $\chi = \mathrm{Ind}_H^G \psi$ for a character ψ of a proper subgroup H of G, then

$$L(E/K \otimes \chi, s) = L(E/F^H \otimes \psi, s) = \prod_\phi L(E/F^H \otimes \phi, s)^{a_\phi}$$

where characters ϕ are the irreducible constituent of ψ with coefficient a_ϕ. By the previous step, since H is a proper subgroup, the factors is analytic at $s = \omega$, in particular $L(E/F^H \otimes \psi, s)$ is analytic at $s = \omega$ contradicting $n_\chi < 0$.

Step 4 : *G has no faithful character of degree $\leq p_2 - 2$. In particular, if χ is an irreducible character of G with $n_\chi < 0$ then $\chi(1) > p_2 - 2$.*

If G has a faithful character of degree $\leq p_2 - 2$, then by Ito's Theorem 4.1.4, G will have normal abelian Sylow p_i-subgroups for all prime factors p_i, $i \geq 2$ of G. Also, all of them will be central and hence $Z(G)$ will have index, a power of p_1 in G. In particular, $G/Z(G)$ will be nilpotent and hence G will be nilpotent contradicting the existence of χ.

Note that, this in particular implies G is **non-abelian**.

Step 5 : We now decompose θ_G into three constituents θ_{nf}, θ_+ and θ_- as follows

- θ_{nf} is the sum of all constituents $n_\lambda \lambda$ of θ_G such that λ is an irreducible character of G that is **not faithful**. (hence the "nf").
- θ_+ is the sum of all constituents $n_\psi \psi$ of θ_G such that ψ is an irreducible character of G that is faithful and $n_\psi > 0$.
- $\theta_- = \sum(-n_\chi)\chi$, where $n_\chi \chi$ are all those constituents of θ_G such that χ is an irreducible character of G that is faithful and $n_\chi < 0$.

From Step 1, all the coefficients of θ_{nf} are non-negative. Thus θ_{nf} is either a character or 0. By construction θ_- is a character (since there is at least one irreducible character χ with $n_\chi < 0$) and θ_+ is either a character or 0. Also note that, by construction, $\langle \theta_{nf}, \theta_- \rangle = 0$ as well as $\langle \theta_+, \theta_- \rangle = 0$ and $\langle \theta_+, \theta_{nf} \rangle = 0$ and

$$\theta_G = \theta_{nf} - \theta_- + \theta_+$$

The final contradiction will come from showing $\theta_+ = \theta_-$.

Step 6 : In any finite group X, every normal subgroup appears as one of the subgroups in a chief series $X = X_1 \geq X_2 \geq \cdots \geq X_{n-1} \geq X_n = \{1\}$ where each $X_i \trianglelefteq G$. In particular, for our solvable G the chief factors G_i/G_{i+1} are elementary abelian p-groups. In particular the last chief factor $G_{n-1}/\{1\}$ is a non-trivial abelian group. That is, every normal subgroup of G contains a non-trivial abelian p-group that is normal in G. We have already seen that every abelian normal subgroup of G is central.

Thus for every irreducible character λ of G that is not faithful, Ker $\lambda \cap Z(G) \neq 1$.

By Proposition 4.1.5, G has a normal subgroup $N \supseteq Z(G)$, of prime index, say p.

Step 7 : $\langle \theta_-|_N, \theta_{nf}|_N \rangle_N = 0$

Firstly, note that $\chi|_N$ is irreducible, for every irreducible constituent χ of θ_-. Since, if not, then from Proposition 4.1.6, we have $\chi|_N = \psi_1 + \cdots + \psi_p$ for some irreducible characters ψ_i of N and $\chi = \mathrm{Ind}_H^G \psi_1$, contradicting Step 3.
Now for any irreducible constituent λ of θ_{nf}, we have seen Ker $\lambda \cap Z(G) \neq \{1\}$, i.e. $\lambda|_N$ is not faithful as $N \supseteq Z(G)$. Again by Prop. 4.1.6, either $\lambda|_N$ is irreducible, or is induced from irreducible constituents, thus they also have to be not faithful. Hence $\langle \theta_-|_N, \theta_{nf}|_N \rangle_N = 0$

Step 8 : $\theta_+|_N = \theta_-|_N$

By step 2, θ_N is a character. Also, by Proposition 4.1.2, $\theta_N = \theta_G|_N = \theta_+|_N - \theta_-|_N + \theta_{nf}|_N$. Therefore, by step 7, either $\theta_+|_N = \theta_-|_N$ or $\theta_+|_N = \theta_-|_N + \phi$ for some character ϕ of N. Assume the second, then

$$r = \theta_G(1) = \theta_G|_N(1) = \phi(1) + \theta_{nf}(1) \tag{4.2.1}$$

Let ϕ_1 be an irreducible constituent of ϕ, and hence of $\theta_+|_N$. If ψ is an irreducible constituent of θ_+ such that ϕ_1 occurs in $\psi|_N$, we see that $\psi|_N \neq \phi_1$. This is because, $\phi_1(1) \leq r$ by equation 4.2.1 where as ψ being faithful, $\psi|_N(1) > p_2 - 1 \geq r$ by step 4. Applying Prop. 4.1.6 again, $\psi_N = \phi_1 + \cdots + \phi_p$. These are distinct G-conjugate irreducible

characters of N. Since, ϕ_1 is an irreducible constituent of ϕ and $\phi = (\theta_+ - \theta_-)|_N$ is a G-stable character of N, each ϕ must also appear as a constituent of ϕ. Thus we conclude

$$\psi(1) = \phi_1(1) + \cdots + \phi_p(1) \leq \phi(1) \leq r$$

This is a contradiction, thus $\theta_+|_N = \theta_-|_N$.

Final Step : Let $g \in G \backslash N$ and let H be the subgroup generated by g and $Z(G)$. Since, H is Abelian, $H \neq G$. Let λ be a constituent of θ_{nf}, then from step 6, $\ker\lambda \cap Z(G) \neq \{1\}$, Thus the same holds for $\mathrm{Ind}_H^G(\lambda|_H)$. Let χ be an irreducible constituent of θ_-, hence is faithful and so, $\langle \chi, \mathrm{Ind}_H^G(\lambda|_H)\rangle = 0$. Hence by Frobenius reciprocity, $\langle \chi|_H, \lambda|_H\rangle = 0$ and so like in Step 7, $\langle \theta_-|_H, \theta_{nf}|_H\rangle_H = 0$. Now $\theta_H = \theta_G|_H = \theta_G|_H = \theta_+|_H - \theta_-|_H + \theta_{nf}|_H$. As before, either $\theta_+|_H - \theta_-|_H$ is zero or a character and arguing in the exact same way as step 8, we get $\theta_+|_H = \theta_-|_H$. Hence $\theta_+(g) = \theta_-(g)$ for all $g \in G \setminus N$. Combining with Step 8, gives $\theta_+ = \theta_-$.

This is a contradiction and hence the theorem is proved. □

5. Elliptic Analogue of Foote and Wales's Theorem

Theorem 5.0.1. Suppose that E satisfies the generalized Taniyama conjecture over K. Let F be a galois extension of K with solvable galois group $G = \mathrm{Gal}(F/K)$. Let χ be an irreducible character of G. Then, $L(E/K \otimes \chi, s)$ is holomorphic at $s = \omega$ if ω is a zero of $L(E/F, s)$ of order ≤ 2.

The proof of this theorem follows its counterpart more directly than the previous one, because of the following theorem :

Theorem 5.0.2. (Foote-Wales) Let G be a finite group with a virtual character θ satisfying the following conditions :

(1) $\theta(1) \leq 2$,
(2) θ is not a character of G but $\theta|_H$ is a character for every proper subgroup H of G and
(3) If χ is any irreducible constituent of θ such that $\langle \theta, \chi\rangle < 0$, then χ is faithful, non-linear and is not induced from any proper subgroup of G.

Then $\theta(1) = 2$ and $G \cong SL_2(p)$ for some prime $p \geq 5$, or $\widehat{SL_2}(3)$.

Note that in their notation, $\widehat{SL_2}(3)$ denotes any non-trivial semidirect product of the quaternion group of order 8 by a cyclic 3-group. For a proof, see

Theorem III, [10]

Note that our further assumption of G being solvable implies that G can't be $SL_2(p)$ ($p \geq 5$). For $\widehat{SL_2}(3)$, Foote-Wales tackles this possibility by quoting a deep result of Langlands which shows that Artin's holomorphy conjecture is true in the case when $G/Z(G) \cong A_4$. We address this in our next proposition. The proof can be seen as consequence of a theorem of Wong in [29]. But for the sake of completeness we present it here.

Proposition 5.0.3. Suppose that E satisfies the generalized Taniyama conjecture over K. Let F be a galois extension of K with solvable galois group isomorphic to $\widehat{SL_2}(3)$. Let χ be an irreducible character of G. Then, $L(E/K \otimes \chi, s)$ is automorphic and hence entire.

Proof. Note that $Q_8 \lhd \widehat{SL_2}(3)$ and the quotient is a 3-group, in particular, is nilpotent. A result of Horváth (see Proposition 2.7, [12]) says that this makes $\widehat{SL_2}(3)$ an SM-group relative to Q_8, i.e. every irreducible character χ of $\widehat{SL_2}(3)$, is induced from an irreducible character ψ of a subnormal subgroup H containing Q_8. Moreover, $\psi|_{Q_8}$ is irreducible and hence $\psi(1) = \psi|_{Q_8}(1) \leq 2$. Note that since the only prime factors of $\widehat{SL_2}(3)$ and hence of H, are 2 and 3, ψ can not be the icosahedral type (in degree 2).

Now if ψ is of degree 1, then from Artin reciprocity, ψ can be seen as an idèle class character. If ψ is of degree 2, from theorems of Langlands and Tunnell ([17], [27]), ψ is associated to a cuspidal automorphic representation π_ψ of $GL_2(\mathbb{A}_{K^H})$.

Since H is subnormal, there exists a subnormal series,

$$H = H_0 \lhd H_1 \lhd \cdots \lhd H_t = \widehat{SL_2}(3)$$

Moreover since we assumed solvability, H_{i+1}/H_i is of prime degree. Therefore, by repeated application of Arthur and Clozel's theory of base change for cyclic extensions, the base change map $B(\pi) \in GL_2(\mathbb{A}_{K^H})$ exists (recall, we are writing, $L(E/K, s) = L(\pi, s)$). Now

$$L(E/K \otimes \chi, s) = L(E/K \otimes \mathrm{Ind}_H^G \psi, s) = L(E/K^H \otimes \psi, s) = L(B(\pi) \otimes \pi_\psi, s)$$

Since functoriality is known in cases of $GL(n) \times GL(1)$ and $GL(2) \times GL(2)$, the latter due to Ramakrishnan, [21] and we saw that either ψ is an idèle class character or a automorphic representation of $GL(2)$, so $L(E/K \otimes \chi, s)$ is automorphic and hence entire. □

5.1. **Proof of Theorem 5.0.1.** As in the case of the elliptic analogue of Foote-Murty's theorem, take a counter-example F/K with $[F:K]$ minimal. Thus there exists an irreducible character ψ of $G = \mathrm{Gal}(F/K)$ and a point $s = \omega$ such that ω is a zero of $L(E/F,s)$ of order ≤ 2 but $L(E/K\otimes\psi,s)$ has a pole at $s=\omega$.

Set $\theta = \theta_G = \sum n_\chi \chi$. Note that $n_\psi < 0$. Since we have the factorization :

$$L(E/F,s) = \prod_{\chi\in \mathrm{Irr}(G)} L(E/K\otimes\chi,s)^{\chi(1)}$$

Thus $\theta_G(1) = \sum_{\chi\in\mathrm{Irr}(G)} n_\chi\chi(1) = \mathrm{ord}_{s=\omega}L(E/F,s) \leq 2$. Moreover, we can then carry out Steps 1 - 4, as it is, in the proof of Theorem 4.0.1.

Hence all the conditions of Theorem 5.0.2 are satisfied. But then the solvability assumption eliminates $SL_2(p)$ and Proposition 5.0.3 eliminates $\widehat{SL_2}(3)$ giving us a contradiction. □

Remark 5.1.1. Note that both Theorem 4.0.1 and Theorem 5.0.1 are unconditional if we assume the base field is $\mathbb{Q}$, modularity being known.

6. Applications to Minimal subfields

We now look at some applications of our theorems in the context of analytic and algebraic minimal subfields.

Theorem 6.0.1. Let E/K be an elliptic curve and F/K be a finite Galois extension with solvable Galois group $G = \mathrm{Gal}(F/K)$. Suppose that E satisfies the generalized Taniyama conjecture over K and $L(E/F,s)$ has a double zero at ω. Then the analytic minimal subfield F_ω exists. Further, if ω is real, then $G = \mathrm{Gal}(F_\omega/K)$ satisfies one of the following :

(i) G is either cyclic or dihedral.
(ii) $Z(G) \cong \mathbb{Z}/2\mathbb{Z}$ and $G/Z(G) \cong D_n, A_4$ or, S_4.

Proof. By Theorem 5.0.1, $L(E/K\otimes\chi,s)$ is holomorphic for every irreducible character χ of G. Hence by Proposition 3.0.2, F_ω exists.

Now suppose ω is real. We have the factorization,

$$L(E/F,s) = \prod_{\chi\in \mathrm{Irr}(G)} L(E/K\otimes\chi,s)^{\chi(1)}$$

Since $\mathrm{ord}_{s=\omega}\, L(E/F,s) = 2$, then there exists $\chi \in \mathrm{Irr}(G)$ such that $\mathrm{ord}_{s=\omega}\, L(E/K\otimes\chi,s) \geq 1$. Since ω is real, we have

$$\mathrm{ord}_{s=\omega}\, L(E/K\otimes\chi,s) = \mathrm{ord}_{s=\omega}\, L(E/K\otimes\overline{\chi},s)$$

Case I : $\chi \neq \overline{\chi}$, then $\chi(1) = 1 = \overline{\chi}(1)$. Thus χ is one dimensional. F_ω being the fixed field of $\ker\chi \cap \ker\overline{\chi} = \ker\chi$, is thus cyclic.

Case II : $\chi = \overline{\chi}$, and $\chi(1) = 1$, thus χ is a real, irreducible linear character. Since the order is 2, there exists another such character. Hence $\mathrm{Gal}(F_\omega)/K$ is a subgroup of $\mathbb{Z}_2 \oplus \mathbb{Z}_2$.

Case III : $\chi = \overline{\chi}$, and $\chi(1) = 2$.

Since F_ω is the fixed field of $\ker \chi$, $\mathrm{Gal}(F_\omega/K)$ admits a faithful, degree 2, irreducible representation. Therefore we know that $G/Z(G)$ is isomorphic to a finite subgroup of $\mathrm{PGL}_2(\mathbb{C})$ and therefore is isomorphic to C_n, D_{2n}, A_4, S_4 or A_5. (e.g. see [24]). By the solvability condition A_5 can be eliminated. Since $\chi = \bar{\chi}$, $Z(G) = \{1\}$ or $\mathbb{Z}/2\mathbb{Z}$.

Now $G/Z(G)$ cannot be cyclic as that will imply G is abelian.

Note that when $Z(G) = \{1\}$, then the only possibilities are D_{2n} and S_4. (Note that A_4 does not have any 2 dimensional irreducible representations.) Moreover, by Proposition 24 of [22], P. 61, (take $A = A_4 \Rightarrow H = A_4$) if $G \cong S_4$ then there exists an irreducible representation ψ of A_4 such that $\chi = \mathrm{Ind}_{A_4}^{S_4} \psi$ with $\psi(1) = 1$. But we also know that every representation of A_4 of dimension 1 has V_4 in its kernel. Since $V_4 \lhd S_4$, hence $V_4 \subset \ker \mathrm{Ind}_{A_4}^{S_4} \psi \subset \ker \chi$, contradicting faithfulness.

□

The celebrated Birch–Swinnerton-Dyer conjecture, predicts that the rank of $E(K)$ equals the order of vanishing of $L(E/K, s)$ at $s = 1$. Thanks to the spectacular work of Gross and Zagier [11] and Kolyvagin [16], this is known for $K = \mathbb{Q}$ and $\mathrm{ord}_{s=1} L(E/\mathbb{Q}, s) \leq 1$. In the next theorem we prove a slight generalization to this result, namely, we look at the case when rank increases by 1 in a solvable extension.

Theorem 6.0.2. Let $K/\mathbb{Q}$ be a solvable Galois extension.

(i) $\mathrm{rank}\, E(K) = \mathrm{rank}\, E(\mathbb{Q}) + 1 \Rightarrow \mathrm{ord}_{s=1}\, L(E/K, s) \geq \mathrm{ord}_{s=1}\, L(E/\mathbb{Q}, s) + 1$

(ii) If $L(E/\mathbb{Q} \otimes \chi, s)$ is holomorphic at $s = 1$, for every irreducible character χ of $\mathrm{Gal}(K/\mathbb{Q})$ and $\mathrm{ord}_{s=1}\, L(E/K, s) = \mathrm{ord}_{s=1}\, L(E/\mathbb{Q}, s) + 1$, then $\mathrm{rank}\, E(K) \geq \mathrm{rank}\, E(\mathbb{Q}) + 1$

In both cases equality holds if the algebraic and the analytic minimal subfields are equal.

Proof. (i) Let M be the algebraic minimal subfield. By Theorem 1.1, M is a quadratic extension of $\mathbb{Q}$, say of discriminant D. Consider the twisted elliptic curve E_D. Then we have

$$\mathbf{rk}\, E(M) = \mathbf{rk}\, E(\mathbb{Q}) + \mathbf{rk}\, E_D(\mathbb{Q})$$

(e.g. see Proposition 20.5.4, P357 of [13]). Thus, $\mathbf{rk}\, E_D(\mathbb{Q}) = 1 = \mathrm{ord}_{s=1} L(E_D/\mathbb{Q}, s)$. We also have $L(E/M, s) = L(E/\mathbb{Q}, s) \cdot L(E_D/\mathbb{Q}, s)$. Thus,

$$\mathrm{ord}_{s=1} L(E/K, s) \geq \mathrm{ord}_{s=1} L(E/M, s) = \mathrm{ord}_{s=1} L(E/\mathbb{Q}, s) + 1$$

where the first inequality follows from the Aramata-Brauer type result in Theorem 4.1.1. Note that equality holds if $M = F_1$, the analytic minimal subfield at $s = 1$.

(ii) The holomorphy condition ensures that the analytic minimal subfield exists. Now from the factorization

$$L(E/K, s) = \prod_{\chi} L(E/\mathbb{Q} \otimes \chi, s)^{\chi(1)}$$

Since the order of zero increases by 1, we see that there is a non-trivial character χ of degree 1 such that $L(E/\mathbb{Q} \otimes \chi, 1) = 0$. Since the analytic minimal subfield F_1 is the fixed field of $\ker \chi$, thus it is cyclic. Moreover, as $\mathrm{ord}_{s=1} L(E/\mathbb{Q} \otimes \chi, s) = \mathrm{ord}_{s=1} L(E/\mathbb{Q} \otimes \bar{\chi}, s) \Rightarrow \chi = \bar{\chi} \Rightarrow [F_1 : \mathbb{Q}] = 2$. So like before, suppose F_1 is of discriminant D. Since, $L(E/F_1, s) = L(E/\mathbb{Q}, s) \cdot L(E_D/\mathbb{Q}, s) \Rightarrow \mathrm{ord}_{s=1} L(E_D/\mathbb{Q}, s) = 1 \Rightarrow \mathrm{rank}\ E_D(\mathbb{Q}) = 1$ Thus,

$$\mathrm{rank}\ E(K) \geq \mathrm{rank}\ E(F_1) = \mathrm{rank}\ E(\mathbb{Q}) + 1$$

□

Corollary 6.0.3. If $\mathrm{ord}_{s=1}\ L(E/\mathbb{Q}, s) = \mathrm{rank}\ E(\mathbb{Q})$ and $K/\mathbb{Q}$ is a quadratic extension, then

$$\mathrm{rank}\ E(K) = \mathrm{rank}\ E(\mathbb{Q}) + 1 \iff \mathrm{ord}_{s=1} L(E/K, s) = \mathrm{ord}_{s=1} L(E/\mathbb{Q}) + 1$$

The corollary follows from the fact that in this case both the minimal subfields are equal to K. Also note that it is unconditional, as holomorphy of $L(E/\mathbb{Q} \otimes \chi, s)$ is known in cyclic case.

Remark 6.0.1. The holomorphy condition of $L(E/\mathbb{Q} \otimes \chi)$ in (ii) can be relaxed if E has complex multiplication. We discuss this next.

Let G be a finite group and $H \leq G$ be any subgroup. For every complex character ψ of H, we attach a complex number $n(H, \psi)$ satisfying :

(i) $n(H, \psi + \psi') = n(H, \psi) + n(H, \psi')$
(ii) $n(G, \mathrm{Ind}_H^G\, \psi) = n(H, \psi)$

Define $\theta_H = \sum_{\psi \in \mathrm{Irr}(G)} n(H, \psi)\psi$, then we have, $\theta_G|_H = \theta_H$. (see [19]).

Murty proves in [20] (Theorem 14)

Theorem 6.0.4. (M. Ram Murty) Suppose $n(H,1) \geq n(G,1)$ for every cyclic subgroup H of G. Then

$$\sum_{\chi \neq 1} |n(G,\chi)|^2 \leq (n(G,\text{reg}) - n(G,1))^2$$

where 'reg' denotes the regular character of G.

We also note the following theorem from [19] (Theorem 1)

Theorem 6.0.5. (M. Ram Murty and V. Kumar Murty)
Let E be an elliptic curve defined over K. Suppose that E has complex multiplication (CM) and F is a finite extension of K. If F is contained in a solvable extension of K, then $L(E/F,s)/L(E/K,s)$ is entire.

Combining these two we have

Theorem 6.0.6. Let $K/\mathbb{Q}$ be a solvable Galois extension. Suppose that $E/\mathbb{Q}$ has complex multiplication. If $\text{ord}_{s=1}\, L(E/K,s) = \text{ord}_{s=1}\, L(E/\mathbb{Q},s) + 1$, then rank $E(K) \geq$ rank $E(\mathbb{Q}) + 1$

Proof. We take $n(H,\psi) = \text{ord}_{s=1} L(E/K^H \otimes \psi, s)$. For any cyclic subgroup H of G, $L(E/K^H \otimes \psi, s)$ is entire, moreover by the above Theorem 6.0.5, $L(E/K^H,s)/L(E/\mathbb{Q},s)$ is entire and so conditions of the Theorem 6.0.4 are satisfied. In particular,

$$\sum_{\chi \neq 1} n(G,\chi)^2 \leq 1$$

Thus it must be that, there exists χ_1, linear, such that $n(G,\chi_1) = 1$ and $n(G,\chi) = 0$ for all $\chi \neq 1, \chi_1$. That is, $L(E/\mathbb{Q} \otimes \chi, s)$ is holomorphic at $s = 1$ for all irreducible characters χ of G. Rest follows from Theorem 6.0.2 (ii). □

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