Curves with few bad primes over cyclotomic $\mathbb{Z}_\ell$-extensions

Conference for Young Number Theorists in Bonn

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Theorem (Faltings 1983; conjectured by Shafarevich 1962)

Let $d \geq 1$ be a positive integer. Then there are only finitely many K-isomorphism classes of (p.p.) abelian varieties A/K of dimension d with good reduction outside S.

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$\mathbb{Z}_\ell$-cyclotomic extension of K

Let K be a number field and ℓ a fixed prime. For each $n \geq 1$, let ζ_{ℓ^n} be a primitive ℓ^n-th root of unity and let $\mathbb{Q}_{n,\ell}$ be the unique cyclic degree ℓ^n totally real subfield of $\mathbb{Q}(\zeta_{\ell^{n+2}})$. Let $\mathbb{Q}_{\infty,\ell} = \cup_{n=1}^{\infty}\mathbb{Q}_{n,\ell}$. The $\mathbb{Z}_\ell$-**cyclotomic extension of** K is the field $K \cdot \mathbb{Q}_{\infty,\ell}$.

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- $\mathrm{Gal}(\mathbb{Q}_{n,\ell}/\mathbb{Q}) \cong \mathbb{Z}/\ell^n\mathbb{Z}$ and $\mathrm{Gal}(K_{\infty,\ell}/K) \cong \mathbb{Z}_\ell$.

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- $\mathrm{Gal}(\mathbb{Q}_{n,\ell}/\mathbb{Q}) \cong \mathbb{Z}/\ell^n\mathbb{Z}$ and $\mathrm{Gal}(K_{\infty,\ell}/K) \cong \mathbb{Z}_\ell$.
- If $\ell = 2$, then $\mathbb{Q}_{n,2} = \mathbb{Q}(\zeta_{2^{n+2}})^+ = \mathbb{Q}(\zeta_{2^{n+2}} + \zeta_{2^{n+2}}^{-1})$, so $\mathbb{Q}_{\infty,2} = \bigcup_{n=1}^{\infty} \mathbb{Q}(\zeta_{2^n})^+$.

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- If $\ell = 3$, then $\mathbb{Q}_{n,3} = \mathbb{Q}(\zeta_{3^{n+1}})^+ = \mathbb{Q}(\zeta_{3^{n+1}} + \zeta_{3^{n+1}}^{-1})$, so $\mathbb{Q}_{\infty,3} = \displaystyle\bigcup_{n=1}^{\infty} \mathbb{Q}(\zeta_{3^n})^+$.

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Theorem (Zarhin 2010)

Let A, B be abelian varieties defined over $K_{\infty,\ell}$, and denote their respective ℓ-adic Tate modules by $T_\ell(A)$, $T_\ell(B)$. Then the natural embedding

$$Hom_{K_{\infty,\ell}}(A, B) \otimes \mathbb{Z}_\ell \hookrightarrow Hom_{Gal(\overline{K_{\infty,\ell}}/K_{\infty,\ell})}(T_\ell(A), T_\ell(B))$$

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- What about Siegel–Mahler's theorem or the Shafarevich conjecture over $K_{\infty,\ell}$?

Cyclotomic polynomials

Cyclotomic polynomial

Let $m \geq 1$ and let ζ_m be a primitive m-th root of unity. The ***m*-th cyclotomic polynomial** $\Phi_m(X) \in \mathbb{Z}[X]$ is

$$\Phi_m(X) := \prod_{\substack{1 \leq i \leq m \\ (i,m)=1}} (X - \zeta_m^i).$$

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Properties:

- $X^m - 1 = \prod_{d|m} \Phi_d(X)$ and $\Phi_m(X) = \prod_{d|m} (X^d - 1)^{\mu(m/d)}$.

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- $X^m - 1 = \prod_{d|m} \Phi_d(X)$ and $\Phi_m(X) = \prod_{d|m} (X^d - 1)^{\mu(m/d)}$.
- For ℓ prime, $\Phi_{\ell^n}(X) = \sum_{i=0}^{\ell-1} X^{i\ell^{n-1}}$, thus $\Phi_{\ell^n}(1) = \ell$.

Cyclotomic polynomials

- Recall that $\mathbb{Q}(\zeta_{\ell^n})/\mathbb{Q}$ is totally ramified above ℓ (and unramified above any $p \neq \ell$).
- Let v_ℓ be the unique prime in $\mathbb{Q}(\zeta_{\ell^n})$ lying above ℓ.

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Lemma

Let ℓ be a prime and $n, m \geq 1$ such that $\ell^n \nmid m$. Then $\Phi_m(\zeta_{\ell^n})$ is a $\{v_\ell\}$-unit in $\mathbb{Q}(\zeta_{\ell^n})$.

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Proof:

- Let $m = k\ell^t$ where $\ell \nmid k$. Note $\Phi_m(\zeta_{\ell^n})$ divides $\zeta_{\ell^n}^m - 1 = \zeta_{\ell^{n-t}}^k - 1$.

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Corollary (the "cyclotomic $\{\upsilon_\ell\}$-unit generator")

Let $F(X) := X^m \Phi_{m_1}(X)\Phi_{m_2}(X)\cdots\Phi_{m_k}(X)$ for some integers $m \geq 0$, $m_1, \ldots, m_k \geq 1$. Then $F(\zeta_{\ell^n})$ is a $\{\upsilon_\ell\}$-unit, for sufficiently large n.

S-unit equations

Problem (Siegel–Mahler for $\mathbb{Q}_{\infty,\ell}$)

For some fixed integer $k \in \mathbb{Z}$, can we find infinitely many $\{v_\ell\}$-units $\varepsilon, \delta \in \mathbb{Q}_{\infty,\ell}$ such that $\varepsilon + \delta = k$?

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$$X^{a_0}\Phi_{a_1}(X)\Phi_{a_2}(X)\cdots\Phi_{a_r}(X) - X^{b_0}\Phi_{b_1}(X)\Phi_{b_2}(X)\cdots\Phi_{b_s}(X) = k\,X^{c_0}\Phi_{c_1}(X)\Phi_{c_2}(X)\cdots\Phi_{c_t}(X)$$

for some nonnegative integers $a_i, b_i, c_i \geq 0$.

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for some nonnegative integers $a_i, b_i, c_i \geq 0$. Then, for each $n \geq 1$ we can define

$$\varepsilon_n := \frac{X^{a_0}\Phi_{a_1}(\zeta_{\ell^n})\Phi_{a_2}(\zeta_{\ell^n})\cdots\Phi_{a_r}(\zeta_{\ell^n})}{X^{c_0}\Phi_{c_1}(\zeta_{\ell^n})\Phi_{c_2}(\zeta_{\ell^n})\cdots\Phi_{c_t}(\zeta_{\ell^n})}, \quad \delta_n := -\frac{X^{b_0}\Phi_{b_1}(\zeta_{\ell^n})\Phi_{b_2}(\zeta_{\ell^n})\cdots\Phi_{b_s}(\zeta_{\ell^n})}{X^{c_0}\Phi_{c_1}(\zeta_{\ell^n})\Phi_{c_2}(\zeta_{\ell^n})\cdots\Phi_{c_t}(\zeta_{\ell^n})},$$

where ε_n, δ_n are $\{\upsilon_\ell\}$-units in $\mathbb{Q}(\zeta_{\ell^n})$ such that $\varepsilon_n + \delta_n = k$ (for sufficiently large n).

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\Phi_2(X)^2 - \Phi_6(X) &= 3X, \\
\Phi_2(X)^2 - \Phi_1(X)^2 &= 4X, \\
\Phi_2(X)^4 - \Phi_{10}(X) &= 5X\Phi_3(X), \\
\Phi_2^2(X)\Phi_3(X) - \Phi_1(X)^2\Phi_6(X) &= 6X\Phi_4(X), \\
\Phi_7(X) - \Phi_1(X)^6 &= 7X\Phi_6(X)^2, \\
\Phi_2(X)^4 - \Phi_1(X)^4 &= 8X\Phi_4(X), \\
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Question: Do there exist any cyclotomic relations for $k \notin \{1, 2, 3, 4, 5, 6, 7, 8, 10\}$?

S-unit equation over $\mathbb{Q}(\zeta_{\ell^n})^+$

Theorem (Siksek–V. 2023)

Let $\ell = 2$ or 3 and let $S = \{\upsilon_\ell\}$ be the unique prime above ℓ in $\mathbb{Q}_{\infty,\ell}$. Then, for each $k \in \{1, 2, 3, 4, 5, 6, 7, 8, 10\}$, there are infinitely many solutions $\varepsilon, \delta \in \mathcal{O}(\mathbb{Q}_{\infty,\ell}, S)^\times$ to the S-unit equation $\varepsilon + \delta = k$.

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Proof for $k = 10$:

- For each $n \geq 1$, define $\varepsilon_n, \delta_n \in \mathbb{Q}(\zeta_{\ell^n})$ as

$$\varepsilon_n = \frac{\Phi_2(\zeta_{\ell^n})^4 \Phi_5(\zeta_{\ell^n})}{\zeta_{\ell^n} \Phi_4(\zeta_{\ell^n})^3}, \qquad \delta_n = \frac{-\Phi_1(\zeta_{\ell^n})^4 \Phi_{10}(\zeta_{\ell^n})}{\zeta_{\ell^n} \Phi_4(\zeta_{\ell^n})^3}.$$

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- Using a multiplicative basis for the cyclotomic units, one can show ε_n is not generated by $\{\pm\zeta_{\ell^{n-1}},\ 1 - \zeta_{\ell^{n-1}}^k,\ 1 \leq k < \ell^{n-1}\}$, and so $\varepsilon_m \neq \varepsilon_n$ for any $m < n$. $\square$

S-unit equation over $\mathbb{Q}_{\infty,5}$

- For each $n \geq 1$, let $G_n := \mathrm{Gal}(\mathbb{Q}(\zeta_{5^n})/\mathbb{Q}_{n-1,5})$. This is a cyclic group of order 4, generated by some $\sigma \in G_n$ where $\sigma(\zeta_{5^n}) = \zeta_{5^n}^a$ for some integer a.

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- We want to now find cyclotomic relations in 4 variables x_1, x_2, x_3, x_4 which are invariant under the 4 cycle $(x_1, x_2, x_3, x_4) \mapsto (x_2, x_3, x_4, x_1)$.

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- Thus, evaluating these at $\left(\zeta_{5^n}, \zeta_{5^n}^a, \zeta_{5^n}^{-1}, \zeta_{5^n}^{-a}\right)$ yields an $\{\upsilon_5\}$-unit in $\mathbb{Q}_{n-1,5}$.

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$$x_4\Phi_2\left(\frac{x_1x_2^2}{x_3x_4^2}\right)\Phi_2\left(\frac{x_1^2x_4}{x_2x_3^2}\right) - x_2\Phi_2\left(\frac{x_1^2x_2}{x_3^2x_4}\right)\Phi_2\left(\frac{x_1x_4^2}{x_2^2x_3}\right) = x_4\Phi_1\left(\frac{x_1}{x_3}\right)\Phi_1\left(\frac{x_2}{x_4}\right)\Phi_1\left(\frac{x_1x_2}{x_3x_4}\right)\Phi_1\left(\frac{x_1x_4}{x_2x_3}\right),$$

$$x_4\Phi_3\left(\frac{x_1}{x_3}\right)\Phi_3\left(\frac{x_2}{x_4}\right) - x_4\Phi_6\left(\frac{x_1}{x_3}\right)\Phi_6\left(\frac{x_2}{x_4}\right) = 2\,x_2\Phi_2\left(\frac{x_1x_4}{x_2x_3}\right)\Phi_2\left(\frac{x_1x_2}{x_3x_4}\right),$$

$$x_4\Phi_2\left(\frac{x_1}{x_3}\right)^2\Phi_2\left(\frac{x_2}{x_4}\right)^2 - x_4\Phi_1\left(\frac{x_1}{x_3}\right)^2\Phi_1\left(\frac{x_2}{x_4}\right)^2 = 4\,x_2\Phi_2\left(\frac{x_1x_2}{x_3x_4}\right)\Phi_2\left(\frac{x_1x_4}{x_2x_3}\right).$$

S-unit equation over $\mathbb{Q}_{\infty,5}$

Theorem (Siksek–V. 2023)

Let $\ell = 5$. Let $S = \{\upsilon_5\}$ be the unique prime above 5 in $\mathbb{Q}_{\infty,5}$. For each $k \in \{1, 2, 4\}$, there are infinitely many solutions $\varepsilon, \delta \in \mathcal{O}(\mathbb{Q}_{\infty,\ell}, S)^\times$ to the S-unit equation $\varepsilon + \delta = k$.

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Proof for $k = 4$:

- For each $n \geq 1$, define $\varepsilon_n, \delta_n \in \mathcal{O}(\mathbb{Q}(\zeta_{5^n}), S)^\times$ as

$$\varepsilon_n = \frac{\zeta_{5^n}^{-a}\Phi_2(\zeta_{5^n}^2)^2\Phi_2(\zeta_{5^n}^{-1-a})^2}{\zeta_{5^n}^{a}\Phi_2(\zeta_{5^n}^{2+2a})\Phi_2(\zeta_{5^n}^{2-2a})}, \quad \delta_n = \frac{-\zeta_{5^n}^{-a}\Phi_1(\zeta_{5^n}^2)^2\Phi_1(\zeta_{5^n}^{-1-a})^2}{\zeta_{5^n}^{a}\Phi_2(\zeta_{5^n}^{2+2a})\Phi_2(\zeta_{5^n}^{2-2a})}$$

  where we've substituted $x_1 = \zeta_{5^n}$, $x_2 = \zeta_{5^n}^a$, $x_3 = \zeta_{5^n}^{-1}$ and $x_4 = \zeta_{5^n}^{-a}$ into the third cyclotomic relation shown previously. Therefore, $\varepsilon_n + \delta_n = 4$.

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- A similar argument to the $\ell = 2, 3$ case shows that $\varepsilon_m \neq \varepsilon_n$ for any $m < n$. $\square$

Elliptic curves over $\mathbb{Q}_{\infty,\ell}$

Theorem (Siksek–V. 2023)

Let $\ell = 2, 3, 5$ or 7. Let $S = \{\upsilon_2, \upsilon_\ell\}$. Then there are infinitely many $\overline{\mathbb{Q}}$-isomorphism classes of elliptic curves defined over $\mathbb{Q}_{\infty,\ell}$ with good reduction away from S and with full 2-torsion in $\mathbb{Q}_{\infty,\ell}$. Moreover, these elliptic curves form infinitely many distinct $\mathbb{Q}_{\infty,\ell}$-isogeny classes.

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- It's j-invariant is $256(\varepsilon_n^2 - \varepsilon_n + 1)^3/\varepsilon_n^2(1-\varepsilon_n)^2$, thus yielding infinitely many $\overline{\mathbb{Q}}$-isomorphism classes. $\square$

Hyperelliptic curves over $\mathbb{Q}_{\infty,\ell}$

Theorem (Siksek–V. 2023)

Let $g \geq 2$ and let $\ell = 3, 5, 7, 11$ or 13. Then there are infinitely many $\overline{\mathbb{Q}}$-isomorphism classes of genus g hyperelliptic curves over $\mathbb{Q}_{\infty,\ell}$ with good reduction away from $\{\upsilon_2, \upsilon_\ell\}$.

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- For $n \geq 1$, let $G_n = \mathrm{Gal}(\mathbb{Q}(\zeta_{\ell^n})^+/\mathbb{Q}_{n-1,\ell})$; this is a cyclic subgroup of order $(\ell - 1)/2$.

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$$D_n : Y^2 = h(X) \cdot \prod_{j=1}^{k} \prod_{\sigma \in G_n} \left(X - \left(\zeta_{\ell^n}^{1+\ell^{n-1}(j-1)} + \zeta_{\ell^n}^{-1-\ell^{n-1}(j-1)}\right)^{\sigma} \right)$$

  where we choose some integer $k \geq 1$ and polynomial $h(X)$ dividing $X(X-1)(X+1)$ such that $\deg(h) + k(\ell-1)/2 \in \{2g+1, 2g+2\}$.

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- Use the identities $\alpha + \alpha^{-1} - \beta - \beta^{-1} = \alpha^{-1}\Phi_1(\frac{\alpha}{\beta})\Phi_1(\alpha\beta)$, $\alpha + \alpha^{-1} = \alpha^{-1}\Phi_4(\alpha)$, $\alpha + \alpha^{-1} + 1 = \alpha^{-1}\Phi_3(\alpha)$, and $\alpha + \alpha^{-1} - 1 = \alpha^{-1}\Phi_6(\alpha)$ to prove D_n has good reduction away from S.

Summary

Conjectures/Theorems
Tate conjecture
$\mathrm{Hom}_{G_K}(T_\ell(A), T_\ell(B)) \cong \mathrm{Hom}_K(A, B) \otimes \mathbb{Z}_\ell$
Mordell conjecture
$\mathrm{genus}(C) \geq 2 \implies \#C(K) < \infty$
Mordell–Weil
$(A(K)$ finitely generated$)$
Siegel–Mahler
$\#\{x, y \in \mathcal{O}_{K,S}^\times : ax + by = 1\} < \infty$
Shafarevich (curves)
$\#\{C/K : \mathrm{genus}(C) = g \geq 2, \text{good outside } S\} < \infty$
Shafarevich (abelian varieties)
$\#\{A/K : \dim(C) = d, \text{good outside } S\} < \infty$

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Tate conjecture $\mathrm{Hom}_{G_K}(T_\ell(A), T_\ell(B)) \cong \mathrm{Hom}_K(A, B) \otimes \mathbb{Z}_\ell$	Yes	Yes
Mordell conjecture $\mathrm{genus}(C) \geq 2 \implies \#C(K) < \infty$	Yes	?
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Danke schön!