

THE S -INTEGRAL POINTS ON THE PROJECTIVE LINE MINUS THREE POINTS VIA FINITE COVERS AND SKOLEM'S METHOD

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ABSTRACT. We describe a p -adic proof of the finiteness of $(\mathbb{P}^1 - \{0, 1, \infty\})(\mathbb{Z}[S^{-1}])$ using only Skolem's method applied to finite covers.

1. INTRODUCTION

Let S be a finite set of primes of $\mathbb{Q}$. Let $R = \mathbb{Z}[S^{-1}]$. Let $X = \mathbb{P}_R^1 - \{0, 1, \infty\} = \text{Spec } R[x, x^{-1}, (1-x)^{-1}]$. The set $X(R)$ is in bijection with $\{(x, y) \in R^\times \times R^\times : x + y = 1\}$.

Siegel [Sie26] proved that $X(R)$ is finite. Kim [Kim05] gave a new, p -adic proof of this fact, as an application of his nonabelian analogue of the Skolem–Chabauty method. Inspired by Kim's proof, we give a different p -adic proof, using only Skolem's method applied to finite covers. (In fact, the proof we present dates from an April 23, 2005 email to Kim following a talk he gave on his method, but we have not published our proof before now.)

2. REVIEW OF THE SKOLEM–CHABAUTY METHOD

Let k be a finite extension of $\mathbb{Q}$. Let S be a finite set of places of k containing all the archimedean places. The ring of S -integers in k is $R := \{x \in k : v(x) \geq 0 \text{ for all } v \notin S\}$.

Skolem devised a method that, in modern terms, for some subvarieties X in an algebraic torus over R , could prove finiteness of $X(R)$ or even determine it explicitly [Sko34]. His method was generalized by Chabauty [Cha38], who also adapted Skolem's method to study rational points on a curve X in an abelian variety [Cha41]; see [MP12] for an introduction to the latter. Although we need only the torus case, it is not much extra work to describe the method in a more general setting, so we will do so.

A semiabelian variety J is a commutative group variety fitting in an exact sequence $1 \rightarrow T \rightarrow J \rightarrow A \rightarrow 1$ with T a torus and A an abelian variety.

Proposition 2.1. *Let R be a ring of S -integers in a number field k . Let J be a finite-type group scheme over R whose generic fiber J_k is a semiabelian variety. Then the abelian group $J(R)$ is finitely generated.*

Proof. By replacing k by a finite extension and enlarging S , we may assume that J fits in an exact sequence of R -group schemes

$$1 \longrightarrow \mathbb{G}_m^n \longrightarrow J \longrightarrow A \longrightarrow 1$$

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for some $n \geq 0$ and abelian scheme A over R . Taking R -points yields an exact sequence

$$(1) \quad 1 \longrightarrow (R^\times)^n \longrightarrow J(R) \longrightarrow A(R).$$

The group $R^\times$ is finitely generated by the Dirichlet S -unit theorem. By the valuative criterion for properness, $A(R) = A(K)$, which is finitely generated by the Mordell–Weil theorem. Now (1) shows that $J(R)$ is finitely generated. $\square$

For a group variety J over a field, say that a subvariety $X \subset J$ **generates** J if, for some n , the addition morphism $X^n \rightarrow J$ is surjective (which amounts to requiring that it gives a surjective map on points over an algebraically closed field).

Proposition 2.2. *Let J be a semiabelian variety over $\mathbb{Q}_p$. Equip $J(\mathbb{Q}_p)$ with the p -adic topology. Let Γ be a finitely generated subgroup of a compact subgroup $G \leq J(\mathbb{Q}_p)$. Let X be an irreducible curve over $\mathbb{Q}_p$. Let $\iota: X \rightarrow J$ be a morphism whose image generates J . If $\text{rk } \Gamma < \dim J$, then $\{x \in X(\mathbb{Q}_p) : \iota(x) \in \Gamma\}$ is finite.*

Sketch of proof. (The details are analogous to those in [MP12, §4].) We may assume that ι is proper. Since $J(\mathbb{Q}_p)$ has a basis of neighborhoods of 1 consisting of compact open subgroups K , we may replace G by $G + K$ for any such K to assume that G is open in $J(\mathbb{Q}_p)$. By [Bou98, III.§7.6], there is a canonical homomorphism

$$\log: G \rightarrow \text{Lie } G = \text{Lie } J.$$

The group $\log \Gamma$ is generated by at most $\text{rk } \Gamma$ elements, and $\text{rk } \Gamma < \dim J = \dim(\text{Lie } J)$, so there is a linear functional $\lambda: \text{Lie } J \rightarrow \mathbb{Q}_p$ that vanishes on $\log \Gamma$ and even its closure $\overline{\log \Gamma}$. Pulling λ back to the compact subset $\{x \in X(\mathbb{Q}_p) : \iota(x) \in G\}$ yields an analytic function η that is locally the integral of a nonzero 1-form on X , so the zero locus of η is discrete, and hence finite. Finally, $\{x \in X(\mathbb{Q}_p) : \iota(x) \in \Gamma\}$ is contained in the zero locus of η , by definition of λ . $\square$

Theorem 2.3 (The Skolem–Chabauty method). *Let R be a ring of S -integers in a number field k . Let X be a finite-type separated R -scheme such that X_k is an irreducible curve. Let J be a finite-type separated R -group scheme such that J_k is a semiabelian variety. Let $\iota: X_k \rightarrow J_k$ be a morphism whose image generates J_k . If $\text{rk } J(R) < \dim J_k$, then $X(R)$ is finite.*

Proof. Let $R_v \subset k_v$ denote the completions of $R \subset k$ at v . Let $\widehat{R} = \prod_{\ell \notin S} R_v$. Let $\mathbf{A}$ be the restricted product $\prod'_{v \notin S} (k_v, R_v)$, so the R -algebra $\widehat{R}$ is open in the k -algebra $\mathbf{A}$, and $\widehat{R} \cap k = R$. Since $X(\widehat{R})$ is compact and $J(\widehat{R})$ is open in $J(\mathbf{A})$, the map $\iota: X(\mathbf{A}) \rightarrow J(\mathbf{A})$ maps $X(\widehat{R})$ into a finite union of cosets of $J(\widehat{R})$. Intersecting with $J(k)$ shows that ι maps $X(R)$ into a finite union of cosets of $J(R)$ in $J(k)$.

Choose $\mathfrak{p} \notin S$ that is unramified of degree 1 over a prime p of $\mathbb{Q}$. Then $R_{\mathfrak{p}} \simeq \mathbb{Z}_p$ and $k_{\mathfrak{p}} \simeq \mathbb{Q}_p$. Proposition 2.2 applied to $\iota_{\mathbb{Q}_p}$ with $\Gamma = J(R)$ (finitely generated by Proposition 2.1) and $G = J(\mathbb{Z}_p)$ shows that $\{x \in X(R) : \iota(x) \in J(R)\}$ is finite. The same argument with ι composed with a translation shows that $\{x \in X(R) : \iota(x) \in j + J(R)\}$ is finite for each $j \in J(\mathbb{Q})$. By the first paragraph, $X(R)$ is contained in a finite union of these. $\square$

3. PROOF OF SIEGEL'S THEOREM

Let $R = \mathbb{Z}[S^{-1}]$ and $X = \mathbb{P}_R^1 - \{0, 1, \infty\}$. Let ℓ be a prime. Let A be a (finite) set of representatives for $R^\times/R^{\times\ell}$. For each $a \in A$, let $\pi_a: Y_a \rightarrow X$ be the finite cover obtained as the inverse image of X under the morphism

$$\begin{aligned} \mathbb{P}_R^1 &\longrightarrow \mathbb{P}_R^1 \\ y &\longmapsto ay^\ell. \end{aligned}$$

Any element of $X(R) \subset \mathbb{G}_m(R) = R^\times$ is ay^ℓ for some $a \in A$ and $y \in R^\times \subset \mathbb{P}^1(R)$, and then $y \in Y_a(R)$ by definition of Y_a . Thus $X(R) = \bigcup_{a \in A} \pi_a(Y_a(R))$. It remains to prove that each set $Y_a(R)$ is finite.

Let $\mathcal{O} = R[t]/(at^\ell - 1)$ and $K = \mathbb{Q}[t]/(at^\ell - 1)$. If a represents the trivial class in $R^\times/R^{\times\ell}$, then $K \simeq \mathbb{Q} \times K_0$ for a number field K_0 ; otherwise define $K_0 := K$, which is already a number field. Let $\mathcal{O}_0$ be the integral closure of R in K_0 .

We have $Y_a = \mathbb{P}_R^1 - \{0, \infty, \text{zeros of } ay^\ell - 1\}$. Over $\overline{\mathbb{Q}}$, the generalized Jacobian of Y_a (i.e., of $\mathbb{P}^1$ with modulus consisting of the $\ell + 2$ removed points) is a torus of dimension $\ell + 1$, and it has a natural model over R , namely $J := \mathbb{G}_{m,R} \times \text{Res}_{\mathcal{O}/R} \mathbb{G}_{m,\mathcal{O}}$, where Res denotes restriction of scalars. The usual morphism from $(Y_a)_\mathbb{Q}$ to its generalized Jacobian $J_\mathbb{Q}$, up to translation in $J_\mathbb{Q}$, is $y \mapsto (y, y - t)$, and its image generates $J_\mathbb{Q}$. Skolem's method (Theorem 2.3) applies if we can prove that $\text{rk } J(R) < \ell + 1$.

We will show that $\text{rk } J(R) < \ell + 1$ holds when ℓ is large. Below, $O(1)$ denotes a quantity whose size depends only on X and S , not on ℓ or a . We have

$$(2) \quad \text{rk } J(R) = \text{rk } R^\times + \text{rk } \mathcal{O}^\times \leq 2 \text{rk } R^\times + \text{rk } \mathcal{O}_0^\times = O(1) + \text{rk } \mathcal{O}_0^\times.$$

Since K_0 is of degree $\ell + O(1)$ and has at most one real place, the Dirichlet S -unit theorem implies that

$$(3) \quad \text{rk } \mathcal{O}_0^\times = \ell/2 + \#\{\text{primes in } K_0 \text{ above } S\} + O(1).$$

Let $s = \#S$. For fixed $p \in S$, the number of primes of K_0 above p having degree $< 3s$ is at most p^{3s} , because these primes correspond to distinct irreducible factors of $ax^\ell - 1 \pmod p$ of degree $< 3s$; on the other hand, there are at most $\ell/(3s)$ primes of K_0 above p having degree $\geq 3s$, because their degrees sum to at most $[K_0 : \mathbb{Q}] \leq \ell$. Thus

$$(4) \quad \#\{\text{primes in } K_0 \text{ above } S\} = \sum_{p \in S} (p^{3s} + \ell/(3s)) = \ell/3 + O(1).$$

Substituting (4) into (3) and then (3) into (2) yields

$$\text{rk } J(R) \leq \ell/2 + \ell/3 + O(1) < \ell + 1$$

if ℓ is sufficiently large in terms of S .

Remark 3.1. The proof does not seem to generalize readily to prove the analogue for rings of S -integers in number fields other than $\mathbb{Q}$. The limitations of this approach are investigated thoroughly in [Tri19].

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