THE SET OF NONSQUARES IN A NUMBER FIELD IS DIOPHANTINE

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ABSTRACT. Fix a number field k. We prove that $k^\times - k^{\times 2}$ is diophantine over k. This is deduced from a theorem that for a nonconstant separable polynomial $P(x) \in k[x]$, there are at most finitely many $a \in k^\times$ modulo squares such that there is a Brauer-Manin obstruction to the Hasse principle for the conic bundle X given by $y^2 - az^2 = P(x)$.

1. INTRODUCTION

Throughout, let k be a global field; occasionally we impose additional conditions on its characteristic. Warning: we write $k^n = \prod_{i=1}^n k$ and $k^{\times n} = \{a^n : a \in k^\times\}$.

1.1. **Diophantine sets.** A subset $A \subseteq k^n$ is diophantine over k if there exists a closed subscheme $V \subseteq \mathbb{A}_k^{n+m}$ such that A equals the projection of $V(k)$ under $k^{n+m} \to k^n$. The complexity of the collection of diophantine sets over a field k determines the difficulty of solving polynomial equations over k. For instance, it follows from [Mat70] that if $\mathbb{Z}$ is diophantine over $\mathbb{Q}$, then there is no algorithm to decide whether a multivariable polynomial equation with rational coefficients has a solution in rational numbers. Moreover, diophantine sets can be built up from other diophantine sets. In particular, diophantine sets over k are closed under taking finite unions and intersections. Therefore it is of interest to gather a library of diophantine sets.

1.2. **Main result.** Our main theorem is the following:

Theorem 1.1. *For any number field k, the set $k^\times - k^{\times 2}$ is diophantine over k.*

In other words, there is an algebraic family of varieties $(V_t)_{t\in k}$ such that V_t has a k-point if and only if t is *not* a square. This result seems to be new even in the case $k = \mathbb{Q}$.

Corollary 1.2. *For any number field k and for any $n \in \mathbb{Z}_{\geq 0}$, the set $k^\times - k^{\times 2^n}$ is diophantine over k.*

Proof. Let $A_n = k^\times - k^{\times 2^n}$. We prove by induction on n that A_n is diophantine over k. The base case $n = 1$ is Theorem 1.1. The inductive step follows from

$$A_{n+1} = A_1 \cup \{t^2 : t \in A_n \text{ and } -t \in A_n\}. \qquad \square$$

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1.3. **Brauer-Manin obstruction.** The main ingredient of the proof of Theorem 1.1 is the fact the Brauer-Manin obstruction is the only obstruction to the Hasse principle for certain Châtelet surfaces over number fields, so let us begin to explain what this means. Let Ω_k be the set of nontrivial places of k. For $v \in \Omega_k$, let k_v be the completion of k at v. Let $\mathbf{A}$ be the adèle ring of k. For a projective k-variety X, we have $X(\mathbf{A}) = \prod_{v \in \Omega_k} X(k_v)$; one says that there is a Brauer-Manin obstruction to the Hasse principle for X if $X(\mathbf{A}) \neq \emptyset$ but $X(\mathbf{A})^{\mathrm{Br}} = \emptyset$. See [Sko01, §5.2].

1.4. **Conic bundles and Châtelet surfaces.** Let $\mathcal{E}$ be a rank-3 vector sheaf over a base variety B. A nowhere-vanishing section $s \in \Gamma(B, \operatorname{Sym}^2 \mathcal{E})$ defines a subscheme X of $\mathbb{P}\mathcal{E}$ whose fibers over B are (possibly degenerate) conics. As a special case, we may take $(\mathcal{E}, s) = (\mathcal{L}_0 \oplus \mathcal{L}_1 \oplus \mathcal{L}_2, s_0 + s_1 + s_2)$ where each $\mathcal{L}_i$ is a line sheaf on B, and the $s_i \in \Gamma(B, \mathcal{L}_i^{\otimes 2}) \subset \Gamma(B, \operatorname{Sym}^2 \mathcal{E})$ are sections that do not simultaneously vanish on B.

We specialize further to the case where $B = \mathbb{P}^1$, $\mathcal{L}_0 = \mathcal{L}_1 = \mathcal{O}$, $\mathcal{L}_2 = \mathcal{O}(n)$, $s_0 = 1$, $s_1 = -a$, and $s_2 = -\tilde{P}(w,x)$ where $a \in k^\times$ and $\tilde{P}(w,x) \in \Gamma(\mathbb{P}^1, \mathcal{O}(2n))$ is a separable binary form of degree $2n$. Let $P(x) := \tilde{P}(1,x) \in k[x]$, so $P(x)$ is a separable polynomial of degree $2n-1$ or $2n$. We then call X the conic bundle given by

$$y^2 - az^2 = P(x).$$

A Châtelet surface is a conic bundle of this type with $n = 2$, i.e., with $\deg P$ equal to 3 or 4. See also [Poo09].

The proof of Theorem 1.1 relies on the Châtelet surface case of the following result about families of more general conic bundles:

Theorem 1.3. *Let k be a global field of characteristic not 2. Let $P(x) \in k[x]$ be a nonconstant separable polynomial. Then there are at most finitely many classes in $k^\times/k^{\times 2}$ represented by $a \in k^\times$ such that there is a Brauer-Manin obstruction to the Hasse principle for the conic bundle X given by $y^2 - az^2 = P(x)$.*

Remark 1.4. Theorem 1.3 is analogous to the classical fact that for an integral indefinite ternary quadratic form $q(x,y,z)$, the set of nonzero integers represented by q over $\mathbb{Z}_p$ for all p but not over $\mathbb{Z}$ fall into finitely many classes in $\mathbb{Q}^\times/\mathbb{Q}^{\times 2}$. J.-L. Colliot-Thélène and F. Xu explain how to interpret and prove this fact (and its generalization to arbitrary number fields) in terms of the integral Brauer-Manin obstruction: see [CTX07, §7], especially Proposition 7.9 and the very end of §7. Our proof of Theorem 1.3 shares several ideas with the arguments there.

1.5. **Definable subsets of k_v and their intersections with k.** The proof of Theorem 1.1 requires one more ingredient, namely that certain subsets of k defined by local conditions are diophantine over k. This is the content of Theorem 1.5 below, which is proved in more generality than needed. By a k-definable subset of k_v^n, we mean the subset of k_v^n defined by some first-order formula in the language of fields involving only constants from k, even though the variables range over elements of k_v.

Theorem 1.5. *Let k be a number field. Let k_v be a nonarchimedean completion of k. For any k-definable subset A of k_v^n, the intersection $A \cap k^n$ is diophantine over k.*

1.6. **Outline of paper.** Section 2 shows that Theorem 1.5 is an easy consequence of known results, namely the description of definable subsets over k_v, and the diophantineness of the valuation subring $\mathcal{O}$ of k defined by v. Section 3 proves Theorem 1.3 by showing that for most twists of a given conic bundle, the local Brauer evaluation map at one place is enough to rule out a Brauer-Manin obstruction. Finally, Section 4 puts everything together to prove Theorem 1.1.

2. Subsets of global fields defined by local conditions

Lemma 2.1. *Let $m \in \mathbb{Z}_{>0}$ be such that $\operatorname{char} k \nmid m$. Then $k_v^{\times m} \cap k$ is diophantine over k.*

Proof. The valuation subring $\mathcal{O}$ of k defined by v is diophantine over k: see the first few paragraphs of §3 of [Rum80]. The hypothesis $\operatorname{char} k \nmid m$ implies the existence of $c \in k^\times$ such that $1 + c\mathcal{O} \subset k_v^{\times m}$; fix such a c. The denseness of $k^\times$ in $k_v^\times$ implies $k_v^{\times m} \cap k = (1 + c\mathcal{O})k^{\times m}$. The latter is diophantine over k. □

Proof of Theorem 1.5. Call a subset of k_v^n simple if it is of one of the following two types: $\{\vec{x} \in k_v^n : f(\vec{x}) = 0\}$ or $\{\vec{x} \in k_v^n : f(\vec{x}) \in k_v^{\times m}\}$ for some $f \in k[x_1, \dots, x_n]$ and $m \in \mathbb{Z}_{>0}$. It follows from the proof of [Mac76, Theorem 1] (see also [Mac76, §2] and [Den84, §2]) that any k-definable subset A is a boolean combination of simple subsets. The complement of a simple set of the first type is a simple set of the second type (with $m = 1$). The complement of a simple set of the second type is a union of simple sets, since $k_v^{\times m}$ has finite index in $k_v^\times$. Therefore any k-definable A is a finite union of finite intersections of simple sets. Diophantine sets in k are closed under taking finite unions and finite intersections, so it remains to show that for every simple subset A of k_v^n, the intersection $A \cap k$ is diophantine. If A is of the first type, then this is trivial. If A is of the second type, then this follows from Lemma 2.1. □

3. Family of conic bundles

Given a k-variety X and a place v of k, let $\operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$ be the set of $f \in \operatorname{Hom}(\operatorname{Br} X, \operatorname{Br} k_v)$ such that the composition $\operatorname{Br} k \to \operatorname{Br} X \xrightarrow{f} \operatorname{Br} k_v$ equals the map induced by the inclusion $k \hookrightarrow k_v$. The v-adic evaluation pairing $\operatorname{Br} X \times X(k_v) \to \operatorname{Br} k_v$ induces a map $X(k_v) \to \operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$.

Lemma 3.1. *With notation as in Theorem 1.3, there exists a finite set of places S of k, depending on $P(x)$ but not a, such that if $v \notin S$ and $v(a)$ is odd, then $X(k_v) \to \operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$ is surjective.*

Proof. The function field of $\mathbb{P}^1$ is $k(x)$. Let Z be the zero locus of $\tilde{P}(w,x)$ in $\mathbb{P}^1$. Let G be the group of $f \in k(x)^\times$ having even valuation at every closed point of $\mathbb{P}^1 - Z$. Choose $P_1(x), \dots, P_m(x) \in G$ representing a $\mathbb{F}_2$-basis for the image of G in $k(x)^\times/k(x)^{\times 2}k^\times$. We may assume that $P_m(x) = P(x)$. Choose S so that each $P_i(x)$ is a ratio of polynomials whose nonzero coefficients are S-units, and so that S contains all places above 2.

Let $\kappa(X)$ be the function field of X. A well-known calculation (see [Sko01, §7.1]) shows that the class of each quaternion algebra $(a, P_i(x))$ in $\operatorname{Br} \kappa(X)$ belongs to the subgroup $\operatorname{Br} X$, and that the cokernel of $\operatorname{Br} k \to \operatorname{Br} X$ is an $\mathbb{F}_2$-vector space with the classes of $(a, P_i(x))$ for $i \le m-1$ as a basis.

Suppose that $v \notin S$ and $v(a)$ is odd. Let $f \in \operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$. The homomorphism f is determined by where it sends $(a, P_i(x))$ for $i \leq m-1$. We need to find $R \in X(k_v)$ mapping to f.

Let $\mathcal{O}_v$ be the valuation ring in k_v, and let $\mathbb{F}_v$ be its residue field. For $i \leq m-1$, choose $c_i \in \mathcal{O}_v^\times$ whose image in $\mathbb{F}_v^\times$ is a square or not, according to whether f sends $(a, P_i(x))$ to 0 or 1/2 in $\mathbb{Q}/\mathbb{Z} \simeq \operatorname{Br} k_v$. Since $v(a)$ is odd, we have $(a, c_i) = f((a, P_i(x)))$ in $\operatorname{Br} k_v$.

View $\mathbb{P}^1 - Z$ as a smooth $\mathcal{O}_v$-scheme, and let Y be the finite étale cover of $\mathbb{P}^1 - Z$ whose function field is obtained by adjoining $\sqrt{c_i P_i(x)}$ for $i \leq m-1$ and also $\sqrt{P(x)}$. Then the generic fiber $Y_{k_v} := Y \times_{\mathcal{O}_v} k_v$ is geometrically integral. Assuming that S was chosen to include all v with small $\mathbb{F}_v$, we may assume that $v \notin S$ implies that Y has a (smooth) $\mathbb{F}_v$-point, which by Hensel's lemma lifts to a k_v-point Q. There is a morphism from Y_{k_v} to the smooth projective model of $y^2 = P(x)$ over k_v, which in turn embeds as a closed subscheme of X_{k_v}, as the locus where $z = 0$. Let R be the image of Q under $Y(k_v) \to X(k_v)$, and let $\alpha = x(R) \in k_v$. Evaluating $(a, P_i(x))$ on R yields $(a, P_i(\alpha))$, which is isomorphic to (a, c_i) since $c_i P_i(\alpha) \in k_v^{\times 2}$. Thus R maps to f, as required. ☐

Lemma 3.2. *Let X be a projective k-variety. If there exists a place v of k such that the map $X(k_v) \to \operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$ is surjective, then there is no Brauer-Manin obstruction to the Hasse principle for X.*

Proof. If $X(\mathbf{A}) = \emptyset$, then the Hasse principle holds. Otherwise, pick $Q = (Q_w) \in X(\mathbf{A})$, where $Q_w \in X(k_w)$ for each w. For $A \in \operatorname{Br} X$, let $\operatorname{ev}_A \colon X(L) \to \operatorname{Br} L$ be the evaluation map for any field extension L of k. Let $\operatorname{inv}_w \colon \operatorname{Br} k_w \to \mathbb{Q}/\mathbb{Z}$ be the usual inclusion map. Define

$$\begin{aligned} \eta \colon \operatorname{Br} X &\to \mathbb{Q}/\mathbb{Z} \simeq \operatorname{Br} k_v \\ A &\mapsto -\sum_{w \neq v} \operatorname{inv}_w \operatorname{ev}_A(Q_w). \end{aligned}$$

By reciprocity, $\eta \in \operatorname{Hom}'(\operatorname{Br} X, \operatorname{Br} k_v)$. The surjectivity hypothesis yields $R \in X(k_v)$ giving rise to η. Define $Q' = (Q'_w) \in X(\mathbf{A})$ by $Q'_w := Q_w$ for $w \neq v$ and $Q'_v := R$. Then $Q' \in X(\mathbf{A})^{\operatorname{Br}}$, so there is no Brauer-Manin obstruction. ☐

Proof of Theorem 1.3. Let S be as in Lemma 3.1. Enlarge S to assume that $\operatorname{Pic} \mathcal{O}_{k,S}$ is trivial. Then the set of $a \in k^\times$ such that $v(a)$ is even for all $v \notin S$ has the same image in $k^\times/k^{\times 2}$ as the finitely generated group $\mathcal{O}_{k,S}^\times$, so the image is finite.

Suppose that $a \in k^\times$ has image in $k^\times/k^{\times 2}$ lying outside this finite set. Then we can fix $v \notin S$ such that $v(a)$ is odd. Let X be the corresponding surface. Combining Lemmas 3.1 and 3.2 shows that there is no Brauer-Manin obstruction to the Hasse principle for X. ☐

4. The set of nonsquares is diophantine

Proof of Theorem 1.1. For each place v of k, define $S_v := k^\times \cap k_v^{\times 2}$ and $N_v := k^\times - S_v$. By Theorem 1.5, the sets S_v and N_v are diophantine over k.

By [Poo09, Proposition 4.1], there is a Châtelet surface

$$X_1 \colon y^2 - bz^2 = P(x)$$

over k, with $P(x)$ a product of two irreducible quadratic polynomials, such that there is a Brauer-Manin obstruction to the Hasse principle for X_1. For $t \in k^\times$, let X_t be the (smooth projective) Châtelet surface associated to the affine surface

$$U_t\colon y^2 - tbz^2 = P(x).$$

We claim that the following are equivalent for $t \in k^\times$:

(i) U_t has a k-point.
(ii) X_t has a k-point.
(iii) X_t has a k_v-point for every v and there is no Brauer-Manin obstruction to the Hasse principle for X_t.

The implications (i) $\implies$ (ii) $\implies$ (iii) are trivial. The implication (iii) $\implies$ (ii) follows from [CTCS80, Theorem B]. Finally, in [CTCS80], the reduction of Theorem B to Theorem A combined with Remarque 7.4 shows that (ii) implies that X_t is k-unirational, which implies (i).

Let A be the (diophantine) set of $t \in k^\times$ such that (i) holds. The isomorphism type of U_t depends only on the image of t in $k^\times/k^{\times 2}$, so A is a union of cosets of $k^{\times 2}$ in $k^\times$. We will compute A by using (iii).

The affine curve $y^2 = P(x)$ is geometrically integral so it has a k_v-point for all places v outside a finite set F. So for any $t \in k^\times$, the variety X_t has a k_v-point for all $v \notin F$. Since X_1 has a k_v-point for all v and in particular for $v \in F$, if $t \in \bigcap_{v \in F} S_v$, then X_t has a k_v-point for all v.

Let $B := A \cup \bigcup_{v \in F} N_v$. If $t \in k^\times - B$, then X_t has a k_v-point for all v, and there is a Brauer-Manin obstruction to the Hasse principle for X_t. By Theorem 1.3, $k^\times - B$ consists of finitely many cosets of $k^{\times 2}$, one of which is $k^{\times 2}$ itself. Each coset of $k^{\times 2}$ is diophantine over k, so taking the union of B with all the finitely many missing cosets except $k^{\times 2}$ shows that $k^\times - k^{\times 2}$ is diophantine. □

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