Classification of Quadratic Forms over $\mathbb{Q}$[1]

Shubin Xue

Beijing Institute of Technology

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[1]Xinyu Zhong contributed equally to this report

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Notations

- We denote by K an arbitrary field of characteristic $\neq 2$.
- X, Y, Z are used as variables.
- $\left(\frac{a}{p}\right)$ is the Legendre symbol.
- We will often denote by the same letter an element and its class modulo.

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What is a Quadratic Form/Quadratic Space?

Definition (Quadratic Space)

Let V be a vector space (finite-dimensional) over a field K of characteristic $\neq 2$. A function $Q : V \to K$ is called quadratic form on V satisfying:

- $Q(\lambda v) = \lambda^2 Q(v)$ *for all* $\lambda \in K$, $v \in V$,
- *The function* $B_Q(u, v) = Q(u + v) - Q(u) - Q(v)$ *is a symmetric bilinear form on* V.

A quadratic space is such a pair (V, Q).

- Put $x \cdot y = \frac{1}{2} B_Q(x, y)$. One has $Q(x) = x \cdot x$.
- Given a basis $\{e_1, \ldots, e_n\}$ of V, the quadratic form Q can be associated with a symmetric matrix $A = (a_{ij})$ where $a_{ij} = e_i \cdot e_j$.

$$\text{If } x = \sum_{i=1}^{n} x_i e_i \in V, \text{ then } Q(x) = \sum_{i,j=1}^{n} a_{ij} x_i x_j.$$

Translations

Let us consider quadratic forms in a more familiar form:

- $f(X) = \sum_{i,j=1}^{n} a_{ij} X_i X_j$ is a quadratic form in n variables over K, where $a_{ij} = a_{ji}$.
- The pair (K^n, f) is a quadratic space.
- The matrix $A = (a_{ij})$ is associated with f.
- Let $f(X_1, \cdots, X_n)$ and $g(X_1, \cdots, X_m)$ be two quadratic forms, we denote $f \oplus g$ the quadratic form

$$f(X_1, \cdots, X_n) + g(X_{n+1}, \cdots, X_{n+m})$$

in $n + m$ variables.

Invariant: Discriminant

Change the basis $\{e_i\}$ to another basis $\{e_i'\}$; the associated symmetric matrix A transforms as $A' = PAP^T$.

- Two quadratic forms are equivalent if their matrices are congruent under such a transformation. *(Denoted as $f \sim g$)*
- We know that any symmetric matrix can always be diagonalized by a congruence transformation.
- Without loss of generality, assume quadratic forms are of the shape

$$f \sim \sum_{i=1}^{n} a_i X_i^2$$

  And $A' = PAP^T$ give us: $\det(A) = \det(A')\det(P)^2$.
- This means the image of $\det(A)$ in $K^\times/K^{\times 2}$ is a invariant, it's called discriminant of Q, and denoted by $d(Q)$ or simply d.

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The case over $\mathbb{R}$

Theorem (Sylvester's law of inertia)

Let $f = \sum_{i,j=1}^{n} a_{ij} X_i X_j$ be a quadratic form of rank n over $\mathbb{R}$. Then

$$f \sim X_1^2 + X_2^2 + \cdots + X_r^2 - X_{r+1}^2 - \cdots - X_{r+s}^2.$$

where r and s are non-negative integers, and $r + s = n$, the pair (r, s) is called signature of f.

By diagonalizing via congruence and factoring out squares on the diagonal, we see that the only invariants for classifying real quadratic forms are:

- the rank $\operatorname{rank} f = n$.
- the signature $(r, s) := (\#\text{positive eigenvalues}, \#\text{negative eigenvalues})$.

The *rank* and *signature* are invariants.

General Ideas

On an arbitrary field K:

- The rank is always an invariants. Hence we may (and we shall always) reduce to classify the non-degenerate quadratic forms of $\operatorname{rank} n$.
- Two quadratic forms $f = \sum_{i \neq j} a_{ij} X_i X_j$ and $f' = \sum_{i \neq j} a'_{ij} X_i X_j$ satisfy: there exist $t_{ij} \in {K^\times}^2$ s.t. $a_{ij} = t_{ij} a'_{ij}$, then $f \sim f'$.
- The distribution of diagonal elements in $K^\times/(K^\times)^2$ suffices to show the equivalence.
  - $\mathbb{C}^\times/(\mathbb{C}^\times)^2 \cong \{1\}$, suffices to classify by the rank.
  - $\mathbb{R}^\times/(\mathbb{R}^\times)^2 \cong \{1, -1\}$, signature is also needed.
  - $\mathbb{F}_q^\times/(\mathbb{F}_q^\times)^2 \cong \{1, a\}$, where $a \in \mathbb{F}_q$ isn't a square.
  - For $\mathbb{Q}_p$ and $\mathbb{Q}$?

Case over $\mathbb{F}_q$

- Following the above discussion, we might hope that the number of squares appearing on the diagonal would serve as a sufficient criterion for equivalence. However, this is not the case.
- Consider the non-degenerate quadratic form of rank 2 in 2 variables over $\mathbb{F}_q$ with a quadratic nonresidue a,

$$f_1 = aX^2 + aY^2 \sim f_2 = X^2 + Y^2$$

  - Do a change of basis: $X = sX' + tY'$ and $Y = tX' - sY'$. If we requier $aX'^2 + aY'^2 = X^2 + Y^2$, then $s^2 + t^2 = a$. Then we must focus on the existence of solution of eqation $s^2 + t^2 = a$.
  - s^2 and $a - t^2$ have both $(q+1)/2$ possible values, the pigeonhole principle implies the eqation has a nonzero solution.
- The discriminant $d(f_1) = d(f_2) = 1 \in \mathbb{F}_q^\times / (\mathbb{F}_q^\times)^2$ is an invariant for classifying quadratic forms.

Hilbert Symbol

The existence of nonzero solutions to the equation $aX^2 + bY^2 = Z^2$ in K^3 seems to be of great importance.

Definition (Hilbert symbol)

Let $a, b \in K^\times$:

$$(a,b)_K = \begin{cases} 1 & \text{if } Z^2 - aX^2 - bY^2 = 0 \text{ has a nontrivial solution in } K^3, \\ -1 & \text{if } Z^2 - aX^2 - bY^2 = 0 \text{ has no nontrivial solution in } K^3. \end{cases}$$

The number $(a,b)_K$ is called the Hilbert symbol of a and b relative to K.
(When there is no ambiguity, the subscript is often omitted.)

- The symbol may also be viewed in $K^\times/(K^\times)^2$ when working with non-degenerate forms.

The Hilbert Symbol over $\mathbb{Q}_p$

From now on, we always assume $K = \mathbb{Q}_p$ for a prime p:

Theorem ([Ser73] p. 20, chap. 3, sec. 1.2, theorem 1))

Say $a = p^\alpha u$ and $b = p^\beta v$ are p-adic numbers where $u, v \in \mathbb{Z}_p^\times$, then

$$(a,b) = (-1)^{\alpha\cdot\beta\cdot\frac{p-1}{2}} \left(\frac{u}{p}\right)^\beta \left(\frac{v}{p}\right)^\alpha \quad \text{if } p \neq 2$$

$$(a,b) = (-1)^{\frac{u-1}{2}\frac{v-1}{2}+\alpha\frac{v^2-1}{8}+\beta\frac{u^2-1}{8}} \quad \text{if } p = 2$$

- This means that Hilbert symbol is a symmetric non-degenerate bilinear form.

Product Formula of Hilbert Symbol

Let $\mathbb{V} = \mathbb{P} \cup \{\infty\}$, and $\mathbb{Q}_\infty = \mathbb{R}$. If $a, b \in \mathbb{Q}^\times$, $(a, b)_v$ denotes the Hilbert symbol of their images in $\mathbb{Q}_v$ for all $v \in \mathbb{V}$.

Proposition (Product formula)

If $a, b \in \mathbb{Q}^\times$, we have $(a, b)_v = 1$ for almost all $v \in \mathbb{V}$ and

$$\prod_{v \in \mathbb{V}} (a, b)_v = 1.$$

- We have seen that the Hilbert symbol works for rank 2, but how do we generalize to rank > 2?
- Let $\varepsilon(f) = \prod_{i<j} (a_i, a_j)$, which is called the Hasse invariant of f.

Two Invariants

We have reduced to work with non-degenerate diagonalized quadratic forms of rank n.

- Recall that the *discriminant*

$$d(f) = a_1 a_2 \dots a_n \in \mathbb{Q}_p^\times / (\mathbb{Q}_p^\times)^2$$

  is an invariant.
- Recall that the *Hasse invariant*

$$\varepsilon(f) := \prod_{1 \le i < j \le n} (a_i, a_j)$$

  is also an invariant.
- If $f = a_1 X_1^2 \oplus f_1$ where $f_1 = a_2 X_2^2 + \cdots + a_n X_n^2$, then we have:

$$d(f) = \prod_{i=1}^{n} a_i = a_1 \prod_{i=2}^{n} a_i = a_1 d(f_1).$$

$$\varepsilon(f) = \prod_{1 \le i < j \le n} (a_i, a_j) = \varepsilon(f_1) \cdot (a_1, a_2 \cdots a_n) = \varepsilon(f_1) \cdot (a_1, a_1 d(f))$$

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Decomposition of Quadratic Forms

On an arbitrary field K, we say that a quadratic form f *represents* $a \in K$ if there exists a nonzero $v \in V$ such that $f(v) = a$.

- It may be viewed in $\{0\} \cup K^\times/(K^\times)^2$.

Proposition ([Ser73] p. 33, chap. 4, sec. 1.6, corollary 1))

Let $a \in K^\times$. TFAE:

- *f represents a*
- *$f \sim g \oplus aZ^2$ where g is of rank $\operatorname{rank} f - 1$.*
- *$f \oplus -aZ^2$ represents 0.*

- To check if a can be represented by f, it suffices to examine when a quadratic form represents 0.
- Suppose f_1 and f_2 can both represent some $a \in K^\times$, then we hope to reduce their rank and use induction in subsequent proofs.

When does a quadratic form represent 0, a ($a \in K^\times$)?

Theorem ([Ser73] p. 36, chap. 4, sec. 2.2, theorem 6))

f *represents* 0 *iff:*

- *For* $n = 2$*:* $d = -1$*;*
- *For* $n = 3$*:* $(-1, -d) = \varepsilon$*;*
- *For* $n = 4$*:* $d \neq 1$ *or* $d = 1$ *and* $\varepsilon = (-1, -1)$*;*
- *For* $n \geq 5$*: no conditions.*

By applying Theorem to $f_a = f \oplus -aZ^2$, we obtain:

Corollary ([Ser73] p. 37, chap. 4, sec. 2.2, corollary to themrem 6))

f *represents* $a \in K^\times / K^\times$ *iff:*

- *For* $n = 1$*:* $a = d$*;*
- *For* $n = 2$*:* $(a, -d) = \varepsilon$*;*
- *For* $n = 3$*:* $a \neq d$ *or* $a = d$ *and* $\varepsilon = (-1, -d)$*;*
- *For* $n \geq 4$*: no conditions.*

Conditions for decomposing quadratic forms

Theorem (Witt ([Ser73] p. 31, chap. 4, sec. 1.5, theorem 3))

Every injective metric-preserving map from a subspace U of a quadratic space V to another quadratic space W may be extended to a metric-preserving map from V to W.

- If a quadratic space (V, Q) has two isometric subspaces U and W, then by Witt's theorem, the isometry can be extended to an automorphism of V. By restricting this automorphism to $U^\perp$, we see that $U^\perp$ and $W^\perp$ are also isometric. The results about quadratic spaces can be translated into results about quadratic forms:

Theorem (Witt's cancellation ([Ser73] p. 34, chap. 4, sec. 1.6, theorem 4))

$f_1 \oplus g_1 \sim f_2 \oplus g_2$ *and* $g_1 \sim g_2$ *implies* $f_1 \sim f_2$.

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Quadratic Forms $f \sim g$ over $\mathbb{Q}_p$

Theorem ([Ser73] p. 39, chap. 4, sec. 2.3, theorem 7))

Two non-degenerate quadratic forms of rank n over $\mathbb{Q}_p$ are equivalent iff they have the same discriminant d and Hasse invariant ε.

- f, g have same d and ε, thus there exists $a \in \mathbb{Q}_p^\times$ which both represented by f and g.
- Then $f \sim f_1 \oplus aZ^2$, where f_1 is of rank $n-1$. Similarly for g.
- d and ε of f_1 can be determined:
  - $d(f_1) = ad(f) = ad(g) = d(g_1)$
  - $\varepsilon(f_1) = \varepsilon(f) \cdot (a, ad(f)) = \varepsilon(g) \cdot (a, ad(g)) = \varepsilon(g_1)$
- Thus f_1, g_1 share the same d and ε. QED by induction.

Classification of Quadratic Forms over $\mathbb{Q}_p$

The invariants d and ε are not independent; they satisfy the following relations:

- For $n = 1$: $\varepsilon = 1$;
- For $n = 2$: $d \neq -1$ or $\varepsilon = 1$;
- For $n \geq 3$: no conditions.

Skeleton of Proof:

- $n = 1$: $f = aX^2$ has $\varepsilon = 1$ and $d = a$ is arbitrary.
- $n = 2$: $f = aX^2 + bY^2$ has $\varepsilon = (a, b) = (a, -ab)$. If $d = ab = -1$, then $\varepsilon = 1$. Conversely:
  - if $d = -1$, $\varepsilon = 1$: take $f = X^2 - Y^2$
  - if $d \neq -1$, since the Hilbert symbol is non-degenerate, there exists $a \in \mathbb{Q}_p^\times$ such that $(a, -d) = \varepsilon$. Take $f = aX^2 + adY^2$.
  - *(when $d = -1$, $f = X^2 - Y^2 = aX^2 + adY^2$)*
- $n = 3$: Choose $a \in \mathbb{Q}_p^\times / {\mathbb{Q}_p^\times}^2$ and $a \neq d$. There exsits form g of rank 2 s.t. $d(g) = ad, \varepsilon(g) = \varepsilon(a, -d)$. The form $f = g \oplus aZ^2$ works.
- $n > 3$: Take $f = g(X_1, X_2, X_3) \oplus X^2 \oplus \cdots \oplus X_n^2$.

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Quadratic Forms $f \sim g$ over $\mathbb{Q}$

Theorem (Hasse-Minkowski)

f represents 0 over $\mathbb{Q}$ iff it represents 0 over $\mathbb{R}$ and all $\mathbb{Q}_p$.

Theorem (([Ser73] p. 44, chap. 4, sec. 3.3, theorem 9))

Two non-degenerate quadratic forms of rank n over $\mathbb{Q}$ are equivalent iff they are equivalent over each $\mathbb{Q}_v$.

- Suppose $f \sim g$ over $\mathbb{Q}_v$ for all v, then there exists $a \in \mathbb{Q}$ represented by both f and g.
- Thus $f \sim aZ^2 \oplus f_1$, $g \sim aZ^2 \oplus g_1$, where $\operatorname{rank} f_1 = \operatorname{rank} g_1 = n - 1$.
- By Witt's cancellation theorem, we have $f_1 \sim g_1$ over $\mathbb{Q}_v$ for all $v \in \mathbb{V}$.
- By induction on rank n, $f_1 \sim g_1$ over $\mathbb{Q}$, thus $f \sim g$ over $\mathbb{Q}$.

Classification of Quadratic Forms over $\mathbb{Q}$

Proposition (Conclusion over $\mathbb{Q}$)

The invariants d_v and ε_v are not independent; they satisfy the following relations:

- $\varepsilon_v = 1$ *for almost* $v \in \mathbb{V}$, *and* $\prod_{v\in\mathbb{V}} \varepsilon_v = 1$.
- $\varepsilon_v = 1$ *if* $n = 1$ *and if* $n = 2$ *and if the image* d_v *of* d *in* $\mathbb{Q}_p^\times/\mathbb{Q}_p^{\times 2}$ *is equal to* -1.
- $r, s \geq 0$ *and* $r + s = \mathrm{rank}$.
- $d_\infty = (-1)^s$
- $\varepsilon_\infty = (-1)^{s(s-1)/2}$

Let d, $(\varepsilon_v)_{v\in\mathbb{V}}$, and (r, s) vertify the relations above, then there exists a quadratic form of rank n over $\mathbb{Q}$ having for invariants d, $(\varepsilon_v)_{v\in\mathbb{V}}$, and (r, s).

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Lemmas

Lemma

Let $f_i \in \mathbb{Z}_p[X_1, \cdots, X_m]$ be homogeneous polynomials with p-adic integer coefficents. TFAE:

- *The f_i have a non trivial common zero in $(\mathbb{Q}_p)^m$*
- *The f_i have a common primitive zero(i.e. solution $(z, x, y) \not\equiv (0, 0, 0) (\mathrm{mod}\, p)$) in $(\mathbb{Z}_p)^m$*
- *For all $n > 1$, the f_i have a common primitive zero in $(\mathbb{Z}/p^n\mathbb{Z})^m$.*

Lemma

Let $a, b \in K^\times$ and let $K_b = K(\sqrt{b})$. For $(a, b) = 1 \iff a \in N(K_b^\times)$ of norms of elements of $K_b^\times$.

Lemmas

Lemma

Let $f = g \oplus -h$, TFAE:

- *f represents 0*
- *There exists $a \in K^\times$ which is represented by g and h.*

Theorem

Let $(a_i)_{i\in I}$ be a finite family of elements in $\mathbb{Q}^\times$ and let $(\varepsilon_{i,v})_{i\in I, v\in\mathbb{V}}$ be a family of numbers equal to ± 1. In order that there exists $x \in \mathbb{Q}\times$ such that $(a_i, x)_v = \varepsilon_{i,v}$ for all $i \in I$ and $v \in \mathbb{V}$ iff the following conditions be satisfied:

- *Almost all the $\varepsilon_{i,v} = 1$*
- *$\prod_{v\in\mathbb{V}} \varepsilon_{i,v} = 1$ for all $i \in I$*
- *For all $v \in \mathbb{V}$ there exists $x_v \in \mathbb{Q}_p^\times$ such that $(a_i, x_v)_v = \varepsilon_{i,v}$ for all $i \in I$.*

Lemmas

Theorem (Approximation Theorem)

Let $S \subseteq \mathbb{V}$ be a finite set. The image of $\mathbb{Q}$ in $\prod_{v \in S} \mathbb{Q}_v$ is dense.

Lemma

All quadratic forms in at least 3 variavles over $\mathbb{F}_q$ have a non trivial zero.

Lemma

Suppose $p \neq 2$. Let f be a quadratic form with coefficients in $\mathbb{Z}_p$ whose discriminant $\det(\mathrm{a_{ij}})$ is invertible. Let $a \in \mathbb{Z}_p$, every primitive solution of the equation $f(x) \equiv a (\mathrm{mod}\, p)$ lifts to a true solutons.

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Proof

Theorem (Hasse-Minkowski)

f represents 0 over $\mathbb{Q}$ iff it represents 0 over $\mathbb{R}$ and all $\mathbb{Q}_p$.

- The necessity is trivial. W.L.O.G., $f = \sum_{i=1}^{n} a_i X_i^2$, $a_i \in \mathbb{Q}^\times$. By replacing f by $a_1 f$, we can soppose $a_i = 1$
- $n = 2$: Suppose $f = X_1^2 - aX_2^2$
  - f_∞ represents 0 implies $a > 0$. Let $a = \prod_{p \text{ prime}} p^{\nu_p(a)}$.
  - f_v represents 0 implies that $\nu_p(a)$ is even. Then a is a square, f represents 0 over $\mathbb{Q}$.

Proof

- $n = 3$: Suppose $f = X_1^2 - aX_2^2 - bX_3^2$, we can assume a, b are square-free and $|a| \leq |b|$. Proceed by induction on $m = |a| + |b|$.
- If $m = 2$, then $f = X_1^2 \pm X_2^2 \pm X_3^2$.
  - f_∞ represents 0 implies $f \neq X_1^2 + X_2^2 + X_3^2$.
  - In other cases, f represents 0 by $f(1, 1, 0)$.
- If $m > 2$, then $b \geq 2$, let $b = \pm p_1 \cdots p_k$.
- We need to show a is a square modulo p_i for all i.

Proof

- It is obvious if $a \equiv 0 \pmod{p_i}$.
- Otherwise, a is a p_i-adic unit.
- By hypothesis, $f = X_1^2 - aX_2^2 - bX_3^2$ represents 0, i.e. $z^2 - ax^2 - by^2$ has a nontrivial zero in $(\mathbb{Q}_{p_i})^3$.
- By the lemma, $z^2 - ax^2 - by^2$ has a primitive zero (z, x, y) in $(\mathbb{Z}_{p_i})^3$.
- We have $z^2 - ax^2 \equiv 0 \pmod{p_i}$.
- If $x \equiv 0 \pmod{p_i}$, then $z \equiv 0 \pmod{p_i}$.
- Then $p_i^2 \mid by^2 = z^2 - ax^2$, but $\nu_{p_i}(b) = 1$ implies $y \equiv 0 \pmod{p_i}$.
- Thus $(z, x, y) \equiv (0, 0, 0) \pmod{p_i}$, which is a contradiction, hence $x \not\equiv 0 \pmod{p_i}$.
- Moreover, $a = \left(\frac{z}{x}\right)^2$ is a square modulo p_i.
- Since $\mathbb{Z}/b\mathbb{Z} \cong \prod_{i=1}^{k} \mathbb{Z}/p_i\mathbb{Z}$, a is a square modulo b.

Proof

- There exist t, b' integers such that $t^2 = a + bb'$.
- We can choose t such that $|t| \leq |\frac{b}{2}|$. $bb' = t^2 - a$ is a norm from $K(\sqrt{a})$ where $K = \mathbb{Q}$ or $\mathbb{Q}_p$.
- By above lemma $(a, bb') = 1$, hence $(a, b) = 1 \iff (a, b') = 1$.
- That means $f = X_1^2 - aX_2^2 - bX_3^2$ represents 0 iff $f' = X_1^2 - aX_2^2 - b'X_3^2$ represents 0.
- $|b'| = |\frac{t^2 - a}{b}| \leq |\frac{t^2}{b}| + |\frac{a}{b}| \leq \frac{|b|}{4} + 1 \leq |b|$.
- Write $b' = u^2 b''$, where b'' is square-free. We have $|b''| \leq |b|$.
- The inductive hypothesis applies to $f'' = X_1^2 - aX_2^2 - b''X_3^2$, so it represents 0, and the same is true for f.

Proof

- $n = 4$: Suppose $f = aX_1^2 + bX_2^2 - (cX_3^2 + dX_4^2)$. There exists $a \in K^\times$ which is represented by $aX_1^2 + bX_2^2$ and $cX_3^2 + dX_4^2$.
  - $(x_v, -ab)_v = (a, b)_v$ and $(x_v, -cd)_v = (c, d)_v$ for all $v \in \mathbb{V}$
  - By above theorem there exists $x \in \mathbb{Q}^\times$ s.t. $(x, -ab)_v = (a, b)_v$ and $(x, -cd)_v = (c, d)_v$ for all $v \in \mathbb{V}$
  - This means $aX_1^2 + bX_2^2$ and $cX_3^2 + dX_4^2$ represents x in $\mathbb{Q}_p$
  - i.e. $aX^2 + bY^2 - xZ^2$ represents 0 in all $\mathbb{Q}_v$ also $\mathbb{Q}$, and the same argument applied to $cX_3^2 + dX_4^2$, the fact that f represents 0 in $\mathbb{Q}$ follows from this.

Proof

- $n \geq 5$: we use induction on n. Suppose $f = h \oplus -g$ with $h = a_1X_1^2 + a_2X_2^2$, $g = -(a_3X_3^2 + \cdots + a_nX_n^2)$.
- Let $S = \{p \in \mathbb{V} \mid \nu_p(a_i) \neq 0, i \geq 3\} \cup \{2, \infty\}$, it is a finite set.
- Let $v \in S$, f_v represents 0, so there exists $a_v \in \mathbb{Q}_v^\times$ which is represented by both h and g in $\mathbb{Q}_v$.
- That is, there exist $x_1^{(v)}, x_2^{(v)} \in \mathbb{Q}_v$ such that $h(x_1^{(v)}, x_2^{(v)}) = a_v$, and $x_3^{(v)}, \ldots, x_n^{(v)} \in \mathbb{Q}_v$ such that $g(x_3^{(v)}, \ldots, x_n^{(v)}) = a_v$.
- The set $\mathbb{Q}_v^{\times 2}$ is open in $\mathbb{Q}_v^\times$, so $\prod a_v Q_v^{\times 2}$ is also open in $\prod_{v \in S} \mathbb{Q}_v^\times$, and h is a continuous map.

Proof

- By the Approximation Theorem, there exists $a \in \mathbb{Q}^\times$ such that $a \in a_v Q_v^{\times 2}$ for all $v \in S$.
- Thus, $(x_1, x_2) \in (\mathbb{Q})^2$ s.t. $h(x_1, x_2) = a$, and $a/a_v \in \mathbb{Q}^{\times 2}$ for all $v \in S$.
- Consider $f_1 = aZ^2 \oplus -g$.
  - if $v \in S$, g represents a_v, also a since $a/a_v \in \mathbb{Q}^{\times 2}$.
  - if $v \notin S$, the coeffients are v-adic units, the $d(g)$ is also a unit. And because $v \neq 2$, we have $\varepsilon(g) = 1$.
- By above lemma, there exist a solution, and it lifts a true solution.
- In all case we see f_1 represents 0 in $\mathbb{Q}_v$, and $\operatorname{rank} f_1 = n - 1$.
- By inductive hypothesis: f_1 represents 0 in $\mathbb{Q}$. i.e. g represents a, and h represents a.
- The proof is complete.

References I

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