

# Classification of Quadratic Forms over $\mathbb{Q}$ <sup>1</sup>

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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  $Q : V \rightarrow K$  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  $\{e_1, \dots, e_n\}$  of  $V$ , the quadratic form  $Q$  can be associated with a symmetric matrix  $A = (a_{ij})$  where  $a_{ij} = e_i \cdot e_j$ .

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

Let us consider quadratic forms in a more familiar form:

- $f(X) = \sum_{i,j=1}^n a_{ij}X_iX_j$  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  $f(X_1, \dots, X_n)$  and  $g(X_1, \dots, X_m)$  be two quadratic forms, we denote  $f \oplus g$  the quadratic form

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

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  $f = \sum_{i,j=1}^n a_{ij}X_iX_j$  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  $\text{rank } f = n$ .
- the signature  $(r, s) := (\# \text{positive eigenvalues}, \# \text{negative eigenvalues})$ .

The *rank* and *signature* are invariants.

On an arbitrary field  $K$ :

- The rank is always an invariant. Hence we may (and we shall always) reduce to classify the non-degenerate quadratic forms of 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 require  $aX'^2 + aY'^2 = X^2 + Y^2$ , then  $s^2 + t^2 = a$ . Then we must focus on the existence of solution of equation  $s^2 + t^2 = a$ .
- $s^2$  and  $a - t^2$  have both  $(q+1)/2$  possible values, the pigeonhole principle implies the equation 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*

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

is also an invariant.

- If  $f = a_1 X_1^2 \oplus f_1$  where  $f_1 = a_2 X_2^2 + \dots + a_n X_n^2$ , then we have:

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

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



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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  $\text{rank } f - 1$ .
- $f \oplus -aZ^2$  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 theorem 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  $\varepsilon$ .*

- $f, g$  have same  $d$  and  $\varepsilon$ , 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  $\varepsilon$  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  $\varepsilon$ . QED by induction.

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

The invariants  $d$  and  $\varepsilon$  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 exists 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  $f = g(X_1, X_2, X_3) \oplus X^2 \oplus \dots \oplus X_n^2$ .



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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  $\text{rank } f_1 = \text{rank } g_1 = n - 1$ .
- 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  $\varepsilon_v$  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  $r + s = \text{rank}$ .
- $d_\infty = (-1)^s$
- $\varepsilon_\infty = (-1)^{s(s-1)/2}$

*Let  $d$ ,  $(\varepsilon_v)_{v \in \mathbb{V}}$ , and  $(r, s)$  verify 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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## Lemma

Let  $f_i \in \mathbb{Z}_p[X_1, \dots, X_m]$  be homogeneous polynomials with  $p$ -adic integer coefficients. 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  $(z, x, y) \not\equiv (0, 0, 0) \pmod{p}$ ) 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  $K_b^\times$ .

## 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  $\pm 1$ . 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  $i \in I$ .

## 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 variables 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  $\det(a_{ij})$  is invertible. Let  $a \in \mathbb{Z}_p$ , every primitive solution of the equation  $f(x) \equiv a \pmod{p}$  lifts to a true solution.*



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## 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 suppose  $a_i = 1$
- $n = 2$ : Suppose  $f = X_1^2 - aX_2^2$ 
  - $f_\infty$  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  $\mathbb{Q}$ .

- $n = 3$ : 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  $f = X_1^2 \pm X_2^2 \pm X_3^2$ .
  - $f_\infty$  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  $i$ .

- 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  $b$ .

- 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  $f$ .

- $n = 4$ : 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.

- $n \geq 5$ : 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  $x_3^{(v)}, \dots, x_n^{(v)} \in \mathbb{Q}_v$  such that  $g(x_3^{(v)}, \dots, x_n^{(v)}) = a_v$ .
- The set  $\mathbb{Q}_v^{\times 2}$  is open in  $\mathbb{Q}_v^\times$ , so  $\prod a_v \mathbb{Q}_v^{\times 2}$  is also open in  $\prod_{v \in S} \mathbb{Q}_v^\times$ , and  $h$  is a continuous map.

- By the Approximation Theorem, there exists  $a \in \mathbb{Q}^\times$  such that  $a \in a_v \mathbb{Q}_v^{\times 2}$  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 coefficients 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  $\text{rank } f_1 = n - 1$ .
- By inductive hypothesis:  $f_1$  represents 0 in  $\mathbb{Q}$ . i.e.  $g$  represents  $a$ , and  $h$  represents  $a$ .
- The proof is complete.



- [Ser73] Jean-Pierre Serre. *A Course in Arithmetic*. Vol. 7. Graduate Texts in Mathematics. New York, NY: Springer, 1973. ISBN: 978-0-387-90041-4 978-1-4684-9884-4. DOI: [10.1007/978-1-4684-9884-4](https://doi.org/10.1007/978-1-4684-9884-4).