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► **To cite this version:**

| William Dallaporta. Quadratic forms and Genus Theory. 2022. hal-03889227v1

**HAL Id: hal-03889227**

**<https://hal.science/hal-03889227v1>**

Preprint submitted on 7 Dec 2022 (v1), last revised 28 Apr 2024 (v3)

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# Quadratic forms and Genus Theory : a link with 2-descent and an application to non-trivial specializations of ideal classes

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December 2022

*Keywords* : binary quadratic form, Picard group, Genus Theory, 2-descent on hyperelliptic curves, density on  $\mathcal{S}$ -integers

*MSC classes* : 11E16, 14H25, 14H40 (Primary); 11R45 (Secondary)

**Abstract** Genus Theory is a classical feature of integral binary quadratic forms. Using the author's generalization of the well-known correspondence between quadratic form classes and ideal classes of quadratic algebras, we extend it to the case when quadratic forms are twisted and have coefficients in any PID  $R$ . When  $R = \mathbb{K}[X]$ , we show that the Genus Theory map is the quadratic form version of the 2-descent map on a certain hyperelliptic curve. As an application, we make a contribution to a question of Agboola and Pappas regarding a specialization problem of divisor classes on hyperelliptic curves. Under suitable assumptions, we prove that the set of non-trivial specializations has density 1.

## 1 Introduction

It is well-known since the work of Gauss in his *Disquisitiones Arithmeticae* that, given  $\Delta \in \mathbb{Z}$ , the set

$$\left\{ \begin{array}{l} \text{equivalence classes of primitive binary quadratic forms} \\ ax^2 + bxy + cy^2 \text{ with } a, b, c \in \mathbb{Z} \text{ and discriminant } b^2 - 4ac = \Delta \end{array} \right\}$$

can be endowed with a group structure, whose group operation is called the composition law (see Section 2 for the definitions).

Before going further, we must take care which notion of equivalence class we use. Over  $\mathbb{Z}$ , the natural action of  $\mathrm{SL}_2(\mathbb{Z})$  on quadratic forms is usually considered. In that setting, and when  $\Delta$  is a negative integer, it is a classical fact that the above group (restricted to classes of positive definite quadratic forms) is isomorphic to the Picard group of the quadratic  $\mathbb{Z}$ -algebra of discriminant  $\Delta$  (see [Cox13, Theorem 7.7] for a modern exposition). There have been numerous generalizations of this group structure and of this correspondence to other rings than  $\mathbb{Z}$ , possibly with a different action (see for example [Tow80] with  $\mathrm{SL}_2$  or [Kne82] with  $\mathrm{GL}_2$ ). More recently, Wood gave a set-theoretical bijection over an arbitrary base scheme [Woo11], and the present author derived from her work the sought group isomorphism, when 2 is not a zero divisor on the base scheme [Dal21]. In her work, Wood pointed out the importance of the *twisted action* of  $\mathrm{GL}_2$ , which we denote by  $\mathrm{GL}_2^{tw}$  (see Definition 2.2). This is the only action we consider through this article, except in Subsection 3.2, where we make the link with the classical  $\mathrm{SL}_2$  action over  $\mathbb{Z}$ .

This general group isomorphism from [Dal21] is stated over any base scheme  $S$ . Here, we shall consider affine schemes  $S = \text{Spec}(R)$ , where  $R$  is an integral domain of characteristic different from 2 such that every locally free  $R$ -module of finite rank is free. Under additional assumption (see Proposition 2.4), the set of (twisted-)equivalence classes of primitive binary quadratic forms with coefficients in  $R$  and with discriminant  $\Delta \in R$  is a group, which we denote by  $\text{Cl}_R^{tw}(\Delta)$  (Proposition 2.4). The neutral element of  $\text{Cl}_R^{tw}(\Delta)$  is called the *principal form class*.

Given a primitive binary quadratic form, it is natural to wonder if it lies in the principal form class or not. A classical feature of quadratic forms over  $\mathbb{Z}$  is *Genus Theory*, which partially answers this question and which is the main topic of this paper. Roughly speaking, the operation associating a class of quadratic forms to its set of values modulo its discriminant  $\Delta$  yields a group morphism

$$\psi: \text{Cl}_{\mathbb{Z}}^{tw}(\Delta) \longrightarrow \left(\mathbb{Z}/\Delta\mathbb{Z}\right)^{\times} / H_0$$

whose kernel is called the *principal genus* (Theorem 3.8). Here,  $H_0$  denotes the set of values of the principal form class. In particular, a quadratic form whose class is not in the principal genus cannot be equivalent to the principal form.

In this article, we extend Genus Theory (for the twisted action  $\text{GL}_2^{tw}$ ) to quadratic forms over principal ideal domains. In this general setting, it is already a difficult problem to determine precisely the principal genus. A simple argument shows that it always contains the subgroup of squares. Over  $\mathbb{Z}$ , when the discriminant is negative, we show in Proposition 3.14 that the converse is true.

We then study the case when the base ring is  $\mathbb{K}[X]$  (where  $\mathbb{K}$  is a field of characteristic 0), and when the discriminant is of the form  $\Delta = 4f$  with  $f \in \mathbb{K}[X]$  a square-free monic polynomial of odd degree at least 3. In this situation, the group of (twisted-)equivalence classes of quadratic forms of discriminant  $4f$  is isomorphic to the group of  $\mathbb{K}$ -points of the Jacobian variety of the hyperelliptic curve  $\mathcal{C}$  defined over  $\mathbb{K}$  by the equation  $Y^2 = f(X)$ . This correspondence is closely related to Mumford's description of the Jacobian, and was already used by Gillibert in that setting [Gil21]. We prove in Subsection 3.3 that Genus Theory over  $\mathbb{K}[X]$  turns out to be the quadratic form version of the 2-descent map on the Jacobian of  $\mathcal{C}$ . More precisely, by combining Proposition 3.19 and Theorem 3.20, we obtain

**Theorem 1.1.** *Let  $\mathbb{K}$  be a field of characteristic 0, let  $f \in \mathbb{K}[X]$  be a square-free monic polynomial of odd degree at least 3, let  $L := \mathbb{K}[X]/\langle f(X) \rangle$ , and let  $J$  be the Jacobian variety of the hyperelliptic curve defined by the affine equation  $Y^2 = f(X)$  over  $\mathbb{K}$ . Let us denote by  $\Psi$  the Genus Theory morphism (3.15) and by  $\lambda$  the 2-descent map on  $J(\mathbb{K})$ . Then the following diagram commutes*

$$\begin{array}{ccc} \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) / \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^{\square} & \xrightarrow{\sim} & J(\mathbb{K}) / 2J(\mathbb{K}) \\ \Psi \downarrow & & \downarrow \lambda \\ L^{\times} / \mathbb{K}^{\times} L^{\times \square} & \xleftarrow{pr} & L^{\times} / L^{\times \square} \end{array} \quad (1.2)$$

where the exponent  $\square$  denotes the subgroup of squares, and  $pr$  is the natural projection. Furthermore,  $\Psi$  is injective; in other words, the principal genus is precisely the subgroup of squares.

The fact that our base ring is a principal ideal domain is heavily used to find an adequate representative of a given class of quadratic forms (Lemma 3.4). This is a property which is at the heart of most of the technical arguments. If one wants to extend Genus Theory to quadratic forms over more general rings than PIDs, then one must in particular extend Lemma 3.4 or find a way to deal without it.

An as application of Genus Theory, the last Section of our article is devoted to the following question, which is closely related to a question raised by Agboola and Pappas [AP00].

**Question 1.3.** *Let  $\mathbb{K}$  be a number field. Let  $\mathcal{C}$  be a hyperelliptic curve over  $\mathbb{K}$  of genus  $g \geq 1$ , with a  $\mathbb{K}$ -rational Weierstrass point. Let us choose an affine equation of  $\mathcal{C}$  of the form  $Y^2 = f(X)$  where  $f \in \mathcal{O}_{\mathbb{K}}[X]$  is a square-free monic polynomial of odd degree  $2g + 1$ . Let  $I \in \text{Pic} \left( \mathcal{O}_{\mathbb{K}}[X, Y] / \langle Y^2 - f(X) \rangle \right)$  be a non-trivial ideal class. Can we find  $n \in \mathcal{O}_{\mathbb{K}}$  such that the specialization of  $I$  at  $X = n$  gives a non-trivial ideal class  $I_n$  in  $\text{Pic}(\mathcal{O}_{\mathbb{K}(\sqrt{f(n)})})$ , or at least in  $\text{Pic} \left( \mathcal{O}_{\mathbb{K}}[Y] / \langle Y^2 - f(n) \rangle \right)$  ?*

We answer positively the second part of Question 1.3 for ideal classes  $I$  which are not squares, allowing us to invert a finite number of prime ideals of  $\mathcal{O}_{\mathbb{K}}$ . We further prove that the density of non-trivial specializations is 1, for any “reasonable” density. In the case of square ideal classes, our arguments which rely on Genus Theory cannot be extended, since squares are already in the principal genus.

Regarding hyperelliptic curves, several results have already been established about non-trivial specializations :

- when  $\mathcal{C}$  is an elliptic curve over  $\mathbb{K} = \mathbb{Q}$  and  $I$  has infinite order, Soleng proved that there exist infinitely many non-trivial specializations  $I_n$  in imaginary quadratic extensions of  $\mathbb{Q}$  whose order is unbounded as  $n$  goes to infinity [Sol94, Theorem 4.1];
- when  $\mathbb{K} = \mathbb{Q}$  and  $I$  has finite order, Gillibert and Levin used Kummer Theory and Hilbert’s Irreducibility Theorem to show that, after inverting primes of bad reduction, there exist infinitely many non-trivial specializations  $I_n$  in imaginary quadratic extensions of  $\mathbb{Q}$  [GL12, Corollary 3.8];
- when  $\mathbb{K} = \mathbb{Q}$  and  $I$  has infinite order, Gillibert showed that there exist infinitely many negative integers  $n$  such that  $I_n$  is a non-trivial ideal class of the order  $\mathbb{Z}[\sqrt{f(n)}]$ . With the additional assumption that the irreducible factors of  $f$  all have degree at most 3, this leads to infinitely many non-trivial ideal classes in  $\text{Pic} \left( \mathcal{O}_{\mathbb{Q}(\sqrt{f(n)})} \right)$  [Gil21, Theorems 1.2 and 1.3]. Among Gillibert’s main ingredients, one can find Wood’s correspondence with binary quadratic forms and a generalization of Soleng’s argument.

Let us assume that  $\mathbb{K} = \mathbb{Q}$  for the time being. Given a non-trivial ideal class  $I$  of  $\mathbb{Z}[X, Y] / \langle Y^2 - f(X) \rangle$ , can we find non-trivial specializations of  $I$  in real quadratic extensions of  $\mathbb{Q}$  ? Soleng’s argument relies on properties which are specific to negative discriminants, and do not generalize to the positive case. This leads us to consider a different approach.

Numerical experiments show that, depending on the ideal class  $I$  we start from, there may exist congruence classes of  $n \in \mathbb{Z}$  leading to non-trivial specializations (see Example 4.1), whatever the sign of the discriminant.

As Gillibert, we use Wood’s bijection between invertible ideal classes of quadratic algebras and equivalence classes of primitive binary quadratic forms as described in [Dal21, Corollary 3.22]. In this setting, the ideal class  $I$  we start from corresponds to the equivalence class of a primitive quadratic form  $q(x, y) = ax^2 + bxy + cy^2$  with discriminant  $b^2 - 4ac = 4f$ , where  $a, b, c \in \mathcal{O}_{\mathbb{K}}[X]$ . Question 1.3 now asks whether one can find  $n \in \mathcal{O}_{\mathbb{K}}$  such that the specialized quadratic form  $a(n)x^2 + b(n)xy + c(n)y^2$  is equivalent to the principal form  $x^2 - f(n)y^2$ , that is, the class of quadratic forms corresponding to the trivial ideal class in Wood’s bijection.

Genus Theory as exposed in this article requires to work over a principal ideal domain. As  $\mathcal{O}_{\mathbb{K}}$  may not be a PID, we slightly modify it by inverting finitely many prime ideals. Thus,

we will work over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  instead of  $\mathcal{O}_{\mathbb{K}}$ , where  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  is the *ring of  $\mathcal{S}$ -integers of  $\mathbb{K}$* . Despite the fact that  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  is not a PID, by making a suitable choice of  $\mathcal{S}$ , one can identify classes of quadratic forms over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  to classes of quadratic forms over  $\mathbb{K}[X]$  (Proposition 4.2). Notice that in the terminology of divisors, this operation is the restriction to the generic fibre.

We then prove that, given a class  $q$  of quadratic forms over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  which is not in the principal genus when viewed over  $\mathbb{K}[X]$ , there exist infinitely many  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that the specialized class  $q_n$  of quadratic forms is not in the principal genus. We achieve this in Theorem 4.14. Together with Theorem 4.26, a complete version of the main result is the following.

**Theorem 1.4.** *Let  $\mathbb{K}$  be a number field. Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3. Let  $I_1, \dots, I_r$  be nonzero ideals generating  $\text{Pic}(\mathcal{O}_{\mathbb{K}})$ , and let*

$$\mathcal{S} := \{\mathfrak{p} \in \text{Spec}(\mathcal{O}_{\mathbb{K}}) \mid \mathfrak{p} \text{ divides } 2 \text{ disc}(f) I_1 \dots I_r\}.$$

*Let  $I \in \text{Pic}(\mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle)$  be a non-trivial ideal class. Assume that  $I$  is not a square. Then the set of  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that the specialization of  $I$  at  $X = n$  gives a non-trivial ideal class  $I_n$  of  $\mathcal{O}_{\mathbb{K}}[Y] / \langle Y^2 - f(n) \rangle$  has density 1, for any density on  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  as in Definition 4.19. In particular, there are infinitely many  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that  $I_n$  is non-trivial.*

Theorem 1.4 gives a partial answer to a question raised by Agboola and Pappas [AP00]. More precisely, following [Gil21, §2.1], there exists a smooth projective model  $\overline{\mathcal{W}} \rightarrow \text{Spec}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$  of  $\mathcal{C}$  such that, set-theoretically,

$$\overline{\mathcal{W}} = \text{Spec} \left( \mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle \right) \cup \{\infty\}$$

together with an isomorphism  $\text{Pic}(\mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle) \simeq \text{Pic}^0(\overline{\mathcal{W}})$ , where  $\{\infty\}$  is the scheme-theoretic closure of the point at infinity of  $\mathcal{C}$ . The result of Theorem 1.4 implies that a degree 0 line bundle on  $\overline{\mathcal{W}}$  which is not a square has infinitely many non-trivial specializations over suitable quadratic  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ -orders.

**Notations.** All through this paper, the rings we consider are commutative and endowed with a multiplicative identity denoted by 1. If  $R$  is a ring,  $R^\times$  denotes its group of units. Given  $r_1, \dots, r_m \in R$ , the ideal generated by  $r_1, \dots, r_m$  is denoted by  $\langle r_1, \dots, r_m \rangle$ . If  $G$  is a group, then  $G^\square$  denotes its subgroup of squares (thinking the group law multiplicatively).

Given two integers  $a < b$ , we denote by  $\llbracket a, b \rrbracket$  the set of integers  $n$  such that  $a \leq n \leq b$ .

If  $T$  is a scheme, we denote by  $\text{Pic}(T)$  the Picard group of  $T$ . When  $T$  is Noetherian and reduced, we shall identify  $\text{Pic}(T)$  with the group of Cartier divisors modulo linear equivalence. When  $R$  is a domain, we write by abuse of notations  $\text{Pic}(R)$  instead of  $\text{Pic}(\text{Spec}(R))$ , which we also identify with the group of invertible fractional ideals modulo principal ones.

We refer the reader to Definition 2.2 and Proposition 2.4 for the meaning of  $\text{GL}_2^{tw}$  and of  $\text{Cl}_R^{tw}(\Delta)$  respectively.

**Acknowledgements.** The author is grateful to Sander Mack-Crane, Ignazio Longhi, Florent Jouve and Yuri Bilu for helpful discussions about densities over rings of  $\mathcal{S}$ -integers. He also addresses special thanks to Jean Gillibert and Marc Perret who made this work possible, who regularly gave precious advice, and who were particularly encouraging all along this work.

## 2 Binary quadratic forms and Picard groups of quadratic algebras

The kind of rings  $R$  we consider in this paper are mostly of the form  $R'$  or  $R'[X]$  with  $R'$  a principal ideal domain of characteristic different from 2. An important property they share is the fact that every locally free  $R$ -module of finite rank must be free, according to [Ses58].

**Definition 2.1.** Let  $R$  be a ring such that every locally free  $R$ -module of finite rank is free. A (binary) *quadratic form*  $q$  over  $R$  is a homogeneous degree 2 polynomial in  $R[x, y]$ . It is of the form  $ax^2 + bxy + cy^2$  for some  $a, b, c \in R$ , and is denoted by  $[a, b, c]$ . It is called *primitive* if the ideal generated by  $a, b, c$  in  $R$  is the unit ideal. Its *discriminant* is the quantity  $\Delta := b^2 - 4ac \in R$ .

**Definition 2.2.** Let  $M = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \in \mathrm{GL}_2(R)$ . Following [Woo11], we define the *twisted action* of  $\mathrm{GL}_2(R)$  over the set of quadratic forms via  $M \cdot q := \frac{1}{\det(M)}(q \circ M)$ , that is

$$\left( \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \cdot q \right) (x, y) := \frac{1}{\alpha\delta - \beta\gamma} q(\alpha x + \beta y, \gamma x + \delta y) \quad \forall x, y \in R.$$

We denote this action by  $\mathrm{GL}_2^{tw}$ . Two quadratic forms  $q$  and  $q'$  are  $\mathrm{GL}_2^{tw}$ -*equivalent* (equivalent for short) if there exists  $M \in \mathrm{GL}_2(R)$  such that  $q' = M \cdot q$ . In the following, a *class of quadratic forms*  $[a, b, c]$  refers to the equivalence class of the quadratic form  $[a, b, c]$ .

*Remark 2.3.* With the same notations, if  $q = [a, b, c]$ , then

$$\begin{aligned} \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \cdot [a, b, c] &= \frac{1}{\alpha\delta - \beta\gamma} [a\alpha^2 + b\alpha\gamma + c\gamma^2, b(\alpha\delta + \beta\gamma) + 2(a\alpha\beta + c\gamma\delta), a\beta^2 + b\beta\delta + c\delta^2] \\ &= \frac{1}{\alpha\delta - \beta\gamma} [q(\alpha, \gamma), q(\alpha + \beta, \gamma + \delta) - q(\alpha, \gamma) - q(\beta, \delta), q(\beta, \delta)]. \end{aligned}$$

We recall the main link between quadratic forms and ideals in our setting ([Dal21, Corollary 3.22]).

**Proposition 2.4.** *Let  $R$  be an integral domain of characteristic different from 2 such that every locally free  $R$ -module of finite rank is free. Let  $\Delta \in R$  be such that the equation  $\Delta \equiv x^2 \pmod{4R}$  has a unique solution  $x$  modulo  $2R$ , and let  $\pi$  be any lift of  $x$  to  $R$ . Denote by  $\mathrm{Cl}_R^{tw}(\Delta)$  the set of  $\mathrm{GL}_2^{tw}$ -equivalence classes of primitive quadratic forms over  $R$  with discriminant  $\Delta$ . Then we have a bijection*

$$\begin{aligned} \mathrm{Cl}_R^{tw}(\Delta) &\xrightarrow{1:1} \mathrm{Pic} \left( R[\omega] \left\langle \omega^2 + \pi\omega - \frac{\Delta - \pi^2}{4} \right\rangle \right). \\ [a, b, c] \text{ with } a \neq 0 &\longmapsto \left\langle \omega + \frac{\pi - b}{2}, a \right\rangle \end{aligned} \tag{2.5}$$

This allows us to endow  $\mathrm{Cl}_R^{tw}(\Delta)$  with a group structure, whose operation  $*$  is called composition law.

*Remark 2.6.* In general, one must care about the existence of different solutions  $x \pmod{2R}$  of the equation  $\Delta \equiv x^2 \pmod{4R}$  in Proposition 2.4, for instance when  $R = \mathbb{Z}[\sqrt{8}]$  ([Dal21, Example 2.28]). The value of such an  $x$  modulo  $2R$  is called *parity* and is an invariant of our

quadratic forms. For the rings  $R$  we shall consider, the parity is completely determined by the discriminant  $\Delta$ , that is, there is a unique solution  $x \pmod{2R}$ . Indeed, if  $R$  is a PID, or verifies either the fact that 2 is a unit or the fact that  $\langle 2 \rangle$  is a prime ideal, as will always be the case in the following, then uniqueness is guaranteed by [Dal21, Proposition 2.26].

**Definition 2.7.** The *principal form class* is the neutral element of  $\text{Cl}_R^{tw}(\Delta)$ . A representative of this class is  $[1, \pi, -\frac{\Delta-\pi^2}{4}]$ , for every  $\pi \in R$  such that  $\Delta \equiv \pi^2 \pmod{4R}$ .

Composition of quadratic forms classes over  $\mathbb{Z}$  is well-known since Gauss, and has already been extended to other rings. For example, Cantor described it over  $R = \mathbb{K}[X]$  for every field  $\mathbb{K}$  of characteristic different from 2 ([Can87, §3]). At least over  $\mathbb{Z}$ , there exist various formulae to compute the composition of two given quadratic forms. We extend one such formula to the case when  $R$  is a PID, without any particular difficulty. However, our formula requires a coprimality condition on the first coefficients of the quadratic forms, which will be enough for our purpose and easily fulfilled (Lemma 3.4).

**Proposition 2.8.** *Let  $R$  be a PID with  $2 \neq 0$ . Let  $q_1 = [a_1, b_1, c_1], q_2 = [a_2, b_2, c_2] \in \text{Cl}_R^{tw}(\Delta)$ , and assume that  $a_1$  and  $a_2$  are nonzero and coprime. Let  $a_1r_1 + a_2r_2 = 1$  be a Bézout relation. Then, the composition  $q_1 * q_2$  of  $q_1$  and  $q_2$  is the class of  $[a_1a_2, B, -\frac{\Delta-B^2}{4a_1a_2}]$ , where  $B = a_1r_1b_2 + a_2r_2b_1$ .*

*Remark 2.9.* When  $R = \mathbb{Z}$ , the quadratic form  $[a_1a_2, B, -\frac{\Delta-B^2}{4a_1a_2}]$  with  $B$  as above is known as the *Dirichlet composition* of  $q_1$  and  $q_2$  ([Cox13, (3.7)]).

*Proof.* Denote  $\alpha_i := \frac{\pi-b_i}{2}$ , where  $\pi \in R$  is any element such that  $\Delta \equiv \pi^2 \pmod{4R}$ . By definition of  $*$  from Proposition 2.4, using the same notations,  $q_1 * q_2$  corresponds to the product

$$\langle a_1, \omega + \alpha_1 \rangle \langle a_2, \omega + \alpha_2 \rangle = \left\langle a_1a_2, a_1(\omega + \alpha_2), a_2(\omega + \alpha_1), -\frac{b_1 + b_2}{2}\omega + \alpha_1\alpha_2 + \frac{\Delta - \pi^2}{4} \right\rangle.$$

Observe the relation

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & a_2 & -a_1 & 0 \\ 0 & r_1\frac{b_1+b_2}{2} & r_2\frac{b_1+b_2}{2} & 1 \\ 0 & -r_1 & -r_2 & 0 \end{pmatrix} \begin{pmatrix} a_1a_2 \\ a_1(\omega + \alpha_2) \\ a_2(\omega + \alpha_1) \\ -\frac{b_1+b_2}{2}\omega + \alpha_1\alpha_2 + \frac{\Delta-\pi^2}{4} \end{pmatrix} = \begin{pmatrix} a_1a_2 \\ a_1a_2\frac{b_1-b_2}{2} \\ -a_1a_2(r_2c_1 + r_1c_2) \\ -\omega - \frac{\pi-B}{2} \end{pmatrix}.$$

Since the square matrix on the left hand side has determinant 1, the above ideal is the same as the one spanned by the elements of the vector on the right hand side. Therefore,

$$\langle a_1, \omega + \alpha_1 \rangle \langle a_2, \omega + \alpha_2 \rangle = \left\langle a_1a_2, \omega + \frac{\pi - B}{2} \right\rangle.$$

The corresponding quadratic form in bijection (2.5) is the class of  $[a_1a_2, B, -\frac{\Delta-B^2}{4a_1a_2}]$ , concluding the proof.  $\square$

*Remark 2.10.* One can also prove Proposition 2.8 with a composition formula in Gauss' style, checking that the relation

$$(a_1x_1^2 + b_1x_1y_1 + c_1y_1^2)(a_2x_2^2 + b_2x_2y_2 + c_2y_2^2) = a_1a_2X^2 + BXY + \frac{B^2 - \Delta}{4a_1a_2}Y^2 \quad (2.11)$$

is true, where

$$X = x_1x_2 + r_2\frac{b_2 - b_1}{2}x_1y_2 + r_1\frac{b_1 - b_2}{2}x_2y_1 - (r_2c_1 + r_1c_2)y_1y_2$$

and  $Y = a_1x_1y_2 + a_2x_2y_1 + \frac{b_1 + b_2}{2}y_1y_2.$

*Remark 2.12.* If  $a_1$  and  $a_2$  are not supposed to be coprime, we are still able to give a composition algorithm over a PID, but the gcd of  $a_1, a_2$  and  $\frac{b_1+b_2}{2}$  shows up and  $B$  must be modified (see [Bue89, Theorem 4.10]).

### 3 Genus theory over a PID

Throughout this Section,  $R$  is a PID of characteristic different from 2. In this paper, Genus Theory will always refer to the construction of a particular group homomorphism from  $\text{Cl}_R^{tw}(\Delta)$  to a quotient of  $(R/\Delta R)^\times$ . This morphism essentially maps a quadratic form  $q$  to its set of values modulo the discriminant  $\Delta$ . This construction was introduced by Gauss over  $\mathbb{Z}$ , and we shall check that it extends to arbitrary PIDs.

All the techniques of Subsection 3.1 are classical, mainly adapted from the case of  $\mathbb{Z}$ , as exposed in [Cox13, §1-§3]. However, we must keep in mind a difference about the quadratic forms we consider : Genus Theory over  $\mathbb{Z}$  is usually done with  $\text{SL}_2(\mathbb{Z})$ -equivalence classes, while we are dealing with  $\text{GL}_2^{tw}$ -ones. We detail the relation between these two cases in Subsection 3.2.

#### 3.1 The general case

**Definition 3.1.** Let  $q$  be a primitive quadratic form of discriminant  $\Delta \in R$ . Its *set of values* in  $(R/\Delta R)^\times$  is given by

$$\text{val}_\Delta(q) := \left\{ q(x, y) \mid x, y \in R/\Delta R \right\} \cap (R/\Delta R)^\times.$$

The *set of values* in  $(R/\Delta R)^\times$  of the class of  $q$  is  $H_q := \bigcup_{q' \sim q} \text{val}_\Delta(q')$ .

*Remark 3.2.* Two equivalent quadratic forms represent the same values up to units of  $R$ , because of the twist by the determinant of the acting matrix. Therefore, for all  $q \in \text{Cl}_R^{tw}(\Delta)$ , we have  $H_q = R^\times \text{val}_\Delta(q)$ , where by abuse of notations  $R^\times$  stands for its image by the canonical projection  $R \rightarrow R/\Delta R$ .

**Proposition 3.3.** Let  $H_0$  be the set of values taken by the principal form class in  $(R/\Delta R)^\times$ . Then  $H_0$  is a subgroup of  $(R/\Delta R)^\times$ , containing the squares. Moreover, if 2 is invertible in  $R/\Delta R$ , then  $H_0 = R^\times (R/\Delta R)^{\times \square}$ , where the exponent  $\square$  denotes the subgroup of squares.

*Proof.* As already noticed in Remark 3.2,  $H_0 = R^\times \text{val}_\Delta(q_0)$  where  $q_0 = [1, \pi, -\frac{\Delta - \pi^2}{4}]$  is a representative of the principal form class as in Definition 2.7. We focus on  $\text{val}_\Delta(q_0)$ .

It is a straightforward computation to check the following equation, which is a particular case of the composition formula (2.11) :

$$\left( x_1^2 + \pi x_1 y_1 - \frac{\Delta - \pi^2}{4} y_1^2 \right) \left( x_2^2 + \pi x_2 y_2 - \frac{\Delta - \pi^2}{4} y_2^2 \right) = X^2 + \pi XY - \frac{\Delta - \pi^2}{4} Y^2$$

for all  $x_1, x_2, y_1, y_2 \in R$ , where  $X := x_1 x_2 + \frac{\Delta - \pi^2}{4} y_1 y_2$  and  $Y := x_1 y_2 + x_2 y_1 + \pi y_1 y_2$ . This formula proves us that  $\text{val}_\Delta(q_0)$  is stable under multiplication. Furthermore, it is



also stable under inversion : if  $\alpha \in \text{val}_\Delta(q_0)$ , then there exist  $x, y \in R/\Delta R$  such that  $\alpha \equiv x^2 + \pi xy - \frac{\Delta - \pi^2}{4} y^2 \pmod{\Delta}$ , hence

$$\alpha^{-1} \equiv (x\alpha^{-1})^2 + \pi(x\alpha^{-1})(y\alpha^{-1}) - \frac{\Delta - \pi^2}{4}(y\alpha^{-1})^2 \in \text{val}_\Delta(q_0).$$

Therefore,  $\text{val}_\Delta(q_0)$  and  $H_0$  are indeed subgroups of  $(R/\Delta R)^\times$ .

Clearly,  $\text{val}_\Delta(q_0)$  contains the squares since  $[1, \pi, -\frac{\Delta - \pi^2}{4}](x, 0) = x^2$  for all  $x$ . If 2 is invertible modulo  $\Delta$ , then for all  $x, y \in R$ , we have

$$\left[1, \pi, -\frac{\Delta - \pi^2}{4}\right](x, y) \equiv \left(x + \frac{\pi}{2}y\right)^2 \pmod{\Delta},$$

hence the result.  $\square$

The key point of most of the following results is the next Lemma, which makes heavy use of factorization and Bézout relations. Its main outcome for our purpose is the Bézout relation it induces.

**Lemma 3.4.** *Let  $q \in \text{Cl}_R^{tw}(\Delta)$  and let  $h \in R \setminus \{0\}$ . Then  $q$  is equivalent to some form  $[a, b, c]$  where  $a \neq 0$  is coprime to  $h$ .*

*Proof.* Denote  $q = [a_0, b_0, c_0]$ . First, note that if there exist  $x_0, y_0 \in R$  coprime such that  $q(x_0, y_0) = a$ , then  $q$  is equivalent to  $[a, b, c]$  for some  $b, c \in R$ . Indeed, if we find such  $x_0$  and  $y_0$ , then there exist  $\beta, \delta \in R$  such that  $x_0\delta - y_0\beta = 1$  (since  $R$  is a PID). By Remark 2.3, we deduce that  $\begin{pmatrix} x_0 & \beta \\ y_0 & \delta \end{pmatrix} \cdot [a_0, b_0, c_0] = [a, b, c]$  for some  $b, c \in R$ , where  $a$  is coprime to  $h$ .

As there is nothing to prove if  $h \in R^\times$ , we may assume that  $h$  is not a unit. Decompose it as a product of irreducibles :  $h = \prod_i p_i^{r_i}$  where  $p_i$  is prime and  $r_i \geq 1$  for all  $i$ . Since  $q$  is primitive, a given  $p_i$  cannot divide  $q(1, 0) = a_0$ ,  $q(0, 1) = c_0$  and  $q(1, 1) = a_0 + b_0 + c_0$  at the same time. Hence, for all  $i$ , there exist  $x_i, y_i$  coprime elements of  $R$  such that  $q(x_i, y_i) \not\equiv 0 \pmod{p_i}$ . We lift the pairs  $((x_i, y_i) \pmod{p_i})$  with the Chinese Remainder Theorem to some  $(x, y) \in R^2$ , and we set  $(x_0, y_0) := \left(\frac{x}{\gcd(x, y)}, \frac{y}{\gcd(x, y)}\right)$ . Then  $x_0$  and  $y_0$  are coprime, and  $a := q(x_0, y_0)$  is nonzero and coprime to  $h$ .  $\square$

*Remark 3.5.* We actually proved that every primitive quadratic form over  $R$  is  $\text{SL}_2(R)$ -equivalent to one whose first coefficient is coprime to  $h$ .

*Remark 3.6.* Notice that  $[a, b, c] \sim [c, -b, a]$  via the matrix  $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \in \text{SL}_2(R)$ . Hence,  $q$  is also equivalent to some form  $[a', b', c']$  where  $c'$  is coprime to  $h$ .

**Proposition 3.7.** *Let  $\Delta \in R \setminus \{0\}$  and let  $q \in \text{Cl}_R^{tw}(\Delta)$ . Denote by  $H_q$  its set of values in  $(R/\Delta R)^\times$ , and by  $H_0$  the set of values of the principal form class. Then  $H_q$  is a coset of  $H_0$  in  $(R/\Delta R)^\times$ . More precisely, if  $[a, b, c]$  is a representative of  $q$  with  $a \neq 0$  coprime to  $\Delta$ , then  $H_q = a^{-1}H_0$ .*

*Proof.* We shall prove the last part of the statement, from which the result follows. According to Lemma 3.4, there exists a representative  $[a, b, c]$  of the class  $q$  of quadratic forms such that

$a$  is nonzero and coprime to  $\Delta$ . Let  $x, y \in R$ , let  $\pi \in R$  such that  $\Delta \equiv \pi^2 \pmod{4R}$ , then

$$\begin{aligned} ax^2 + bxy + cy^2 &\equiv a^{-1} \left( ax + \frac{b-\pi}{2}y \right)^2 + \pi xy + \left( c - a^{-1} \left( \frac{b-\pi}{2} \right)^2 \right) y^2 \pmod{\Delta} \\ &\equiv a^{-1} \left( \left( ax + \frac{b-\pi}{2}y \right)^2 + \pi \left( ax + \frac{b-\pi}{2}y \right) y \right) \\ &\quad + \left( -a^{-1}\pi \frac{b-\pi}{2} + c - a^{-1} \left( \frac{b-\pi}{2} \right)^2 \right) y^2 \pmod{\Delta}. \end{aligned}$$

We compute the  $y^2$ -term : we have

$$\begin{aligned} -a^{-1}\pi \frac{b-\pi}{2} + c - a^{-1} \left( \frac{b-\pi}{2} \right)^2 &\equiv \frac{-2b\pi + 2\pi^2 + 4ac - b^2 + 2b\pi - \pi^2}{4a} \pmod{\Delta} \\ &\equiv \frac{\pi^2 - \Delta}{4a} \pmod{\Delta}. \end{aligned}$$

Thus, we have

$$ax^2 + bxy + cy^2 \equiv a^{-1} \left( X^2 + \pi XY - \frac{\Delta - \pi^2}{4} Y^2 \right)$$

where  $X := ax + \frac{b-\pi}{2}y$  and  $Y := y$ .

This being true for all  $x, y \in R$ , we infer that  $H_q \subseteq a^{-1}H_0$ . For the reverse inclusion, notice that  $\begin{pmatrix} ax + \frac{b-\pi}{2}y \\ y \end{pmatrix} = \begin{pmatrix} a & \frac{b-\pi}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$ , and the matrix  $\begin{pmatrix} a & \frac{b-\pi}{2} \\ 0 & 1 \end{pmatrix}$  is invertible in  $(R/\Delta R)^\times$ . Hence, for all  $X, Y \in R$ , we have

$$a^{-1} \left[ 1, \pi, -\frac{\Delta - \pi^2}{4} \right] (X, Y) \equiv [a, b, c] (a^{-1}X + a^{-1}\frac{\pi-b}{2}Y, Y) \pmod{\Delta}.$$

Thus,  $H_q = a^{-1}H_0$ , as desired.  $\square$

Finally, we can construct our desired group morphism.

**Theorem 3.8.** *Let  $R$  be a PID of characteristic different from 2, let  $\Delta \in R$  be a nonzero discriminant, and let  $H_0$  be the set of values of the principal form class in  $(R/\Delta R)^\times$ . The map*

$$\psi: \text{Cl}_R^{\text{tw}}(\Delta) \longrightarrow (R/\Delta R)^\times / H_0$$

*sending the class of a quadratic form to its set of values in  $(R/\Delta R)^\times$  modulo  $H_0$  is well-defined and is a group homomorphism.*

*Its kernel contains the squares, hence it factors through the map*

$$\Psi: \text{Cl}_R^{\text{tw}}(\Delta) / \text{Cl}_R^{\text{tw}}(\Delta)^\square \longrightarrow (R/\Delta R)^\times / H_0,$$

*where  $\text{Cl}_R^{\text{tw}}(\Delta)^\square$  denotes the subgroup of squares of  $\text{Cl}_R^{\text{tw}}(\Delta)$ . We call  $\Psi$  the Genus map.*

*Proof.* It follows from Proposition 3.7 that  $\psi$  is well-defined, and if  $q = [a, b, c] \in \text{Cl}_R^{tw}(\Delta)$  with  $a \neq 0$  coprime to  $\Delta$ , then  $\psi(q) = a^{-1}H_0$ .

Let  $q_1, q_2 \in \text{Cl}_R^{tw}(\Delta)$ , we need to check that  $\psi(q_1 * q_2) = \psi(q_1)\psi(q_2)$ . Write  $q_1 = [a_1, b_1, c_1]$  and  $q_2 = [a_2, b_2, c_2]$ . According to Lemma 3.4, we may suppose that  $a_1$  is coprime to  $\Delta$ , and that  $a_2$  is coprime to  $a_1\Delta$ . Hence,  $\psi(q_1) = a_1^{-1}H_0$  and  $\psi(q_2) = a_2^{-1}H_0$ . By Proposition 2.8,  $a_1$  and  $a_2$  being coprime, there exist  $b, c \in R$  such that  $q_1 * q_2 = [a_1a_2, b, c]$ , leading to  $\psi(q_1 * q_2) = a_1^{-1}a_2^{-1}H_0 = \psi(q_1)\psi(q_2)$ , hence  $\psi$  is a morphism.

According to Proposition 3.3, the group  $H_0$  contains the subgroup of squares of  $\left(R/\Delta R\right)^\times$ . Therefore, every square in  $\text{Cl}_R^{tw}(\Delta)$  has image in  $H_0$ , hence  $\text{Cl}_R^{tw}(\Delta)^\square \subseteq \ker(\psi)$ . Thus, taking the quotient gives the desired group homomorphism  $\Psi$ .  $\square$

*Remark 3.9.* Genus Theory as described in Theorem 3.8 does not cover the case  $\Delta = 0$ . However, in that case, the associated quadratic algebra  $R[\omega]/\langle \omega^2 \rangle$  is degenerate, and the class group  $\text{Cl}_R^{tw}(0)$  is trivial. Let us show this last point : if  $q = [a, b, c] \in \text{Cl}_R^{tw}(0)$ , then  $b^2 = 4ac$ . Write  $a = a_0^2\tilde{a}$  and  $c = c_0^2\tilde{c}$  for some square-free  $\tilde{a}, \tilde{c}$ . Since  $b^2 = 4a_0^2c_0^2\tilde{a}\tilde{c}$ , and because  $R$  is integrally closed,  $\tilde{a}\tilde{c}$  must be a square. Hence,  $\tilde{c} = \varepsilon\tilde{a}$  for some unit  $\varepsilon$ , since  $\tilde{a}$  and  $\tilde{c}$  are squarefree. Likewise,  $\varepsilon$  must be a square, say  $\varepsilon = \nu^2$ , and we finally get  $[a, b, c] = [a_0^2\tilde{a}, \pm 2a_0c_0\tilde{a}\nu, c_0^2\nu^2\tilde{a}]$ . Now, let  $r, s \in R$  be such that  $a_0r - (\pm c_0)s = \tilde{a}^{-1}$ , then  $\begin{pmatrix} a_0 & \pm c_0\nu \\ s & r \end{pmatrix} \cdot [1, 0, 0] = [a, b, c]$ , and our quadratic form is in the principal form class.

*Remark 3.10.* There are at least two other cases when the Genus map  $\Psi$  from Theorem 3.8 is trivial :

- if  $\Delta \in R^\times$ , then the codomain of  $\Psi$  is trivial;
- if  $\text{Cl}_R^{tw}(\Delta)$  is finite of odd order, then  $\text{Cl}_R^{tw}(\Delta) = \text{Cl}_R^{tw}(\Delta)^\square$  and the domain of  $\Psi$  is trivial.

**Definition 3.11.** The *principal genus* is the kernel of the map  $\psi$  defined in Theorem 3.8.

Thus, in order to check that a given class  $q$  of quadratic forms is non-trivial, it is sufficient to prove that  $q$  is not in the principal genus. However, it is not a necessary condition, as shown in the following example.

**Example 3.12.** Set  $R = \mathbb{Z}$  and  $\Delta = -56$ . The quadratic form  $q_0 = [1, 0, 14]$  is a representative of the principal form class, and the principal genus is  $\psi(q_0) = \pm \{1, 9, 15, 23, 25, 39\}$ . Notice by the way that  $\pm \left(\mathbb{Z}/56\mathbb{Z}\right)^{\times\square} \subsetneq \psi(q_0)$ . Let  $q_1 = [2, 0, 7]$ . Since  $q_1(1, 1) = 9 = q_0(3, 0)$ , and because sets of values in  $\left(\mathbb{Z}/56\mathbb{Z}\right)^\times$  of quadratic forms are either disjoint or equal as cosets of  $\psi(q_0)$ , we deduce that  $q_1$  also lies in the principal genus. On the other hand, they are not equivalent since the equation  $x^2 + 14y^2 = \pm 2$  has no solution  $(x, y) \in \mathbb{Z}^2$ .

### 3.2 The case $R = \mathbb{Z}$ , $\Delta < 0$

We compare our map  $\Psi$  from Theorem 3.8 with Cox's exposition of its construction over  $\mathbb{Z}$ , for negative discriminants [Cox13, §3.B]. The classical construction of the group of classes of primitive binary quadratic forms of given discriminant  $\Delta < 0$  rather uses  $\text{SL}_2(\mathbb{Z})$  equivalence classes instead of the  $\text{GL}_2^{tw}$ -ones. To achieve this, one notices that the  $\text{GL}_2^{tw}$ -equivalence class of a given quadratic form  $[a, b, c]$  consists in the union of the  $\text{SL}_2(\mathbb{Z})$ -equivalence classes of  $[a, b, c]$  and  $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \cdot [a, b, c] = [-a, b, -c]$ . In other words, there is a kind of duplication of

equivalence classes when one goes from  $\mathrm{GL}_2^{tw}$  to  $\mathrm{SL}_2(\mathbb{Z})$ , splitting positive definite and negative definite quadratic forms. Thus, when one considers  $\mathrm{SL}_2(\mathbb{Z})$ -classes, one first removes negative definite quadratic forms, so that there are as many  $\mathrm{SL}_2(\mathbb{Z})$ -equivalence classes of **positive definite** quadratic forms as  $\mathrm{GL}_2^{tw}$ -equivalence classes of quadratic forms (positive or negative).

Given some negative integer  $\Delta \equiv 0$  or  $1 \pmod{4}$  (the only possible cases over  $\mathbb{Z}$ ), we denote by  $\mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta)$  the group of  $\mathrm{SL}_2(\mathbb{Z})$ -equivalence classes of primitive positive definite binary quadratic forms of discriminant  $\Delta$ . According to the above discussion, the natural morphism  $\mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta) \rightarrow \mathrm{Cl}_{\mathbb{Z}}^{tw}(\Delta)$  (which assigns to an  $\mathrm{SL}_2(\mathbb{Z})$ -equivalence class the  $\mathrm{GL}_2^{tw}$ -equivalence class it spans) is an isomorphism.

The values in  $\left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times$  taken by a primitive quadratic form of discriminant  $\Delta$  are related to the kernel of the Dirichlet character  $\chi: \left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times \rightarrow \{\pm 1\}$  defined for all odd prime  $p$  not dividing  $\Delta$  by  $\chi(p) := \left(\frac{\Delta}{p}\right)$ , where  $\left(\frac{\cdot}{p}\right)$  is the Legendre symbol. See [Cox13, Lemma 1.14] for a detailed exposition.

Classically, the main result of Genus Theory over  $\mathbb{Z}$  is the following : if  $\Delta \equiv 0, 1 \pmod{4}$  is a negative integer, then we have an isomorphism of abelian groups

$$\mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta) / \mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta)^\square \xrightarrow{\sim} \ker(\chi) / \mathrm{val}_\Delta(q_0)$$

where  $\mathrm{val}_\Delta(q_0)$  is the subgroup of values taken by the principal form  $q_0$  in  $\left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times$ . See [Cox13, Theorem 3.15].

In order to compare with our version of Genus Theory, we consider the following diagram

$$\begin{array}{ccc} \mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta) / \mathrm{Cl}_{\mathbb{Z}}^{\mathrm{SL}_2}(\Delta)^\square & \xrightarrow{\sim} & \ker(\chi) / \mathrm{val}_\Delta(q_0) \\ \downarrow \wr & & \downarrow \varphi \\ \mathrm{Cl}_{\mathbb{Z}}^{tw}(\Delta) / \mathrm{Cl}_{\mathbb{Z}}^{tw}(\Delta)^\square & \xrightarrow{\Psi_{\mathbb{Z}}} & \left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times / \pm \mathrm{val}_\Delta(q_0) \end{array} \quad (3.13)$$

where  $\Psi_{\mathbb{Z}}$  is the morphism from Theorem 3.8 with  $R = \mathbb{Z}$ , and  $\varphi$  is the one induced by the inclusion  $\ker(\chi) \hookrightarrow \left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times$ . Diagram (3.13) is commutative since a given class of quadratic forms  $q = [a, b, c]$  in the top left corner with  $a$  coprime to  $\Delta$  (possible by Lemma 3.4 and Remark 3.5) has image  $\pm a^{-1} \mathrm{val}_\Delta(q_0)$  in the bottom right corner, whatever the chosen path.

**Proposition 3.14.** *Let  $\Delta \equiv 0, 1 \pmod{4}$  be a negative integer. Then the maps  $\varphi$  and  $\Psi_{\mathbb{Z}}$  from Diagram (3.13) are isomorphisms of abelian groups.*

*Proof.* By commutativity of Diagram (3.13), it is enough to show that  $\varphi$  is an isomorphism. We start by showing that the source and the target of  $\varphi$  have the same size. On the one hand,  $\left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times$  is the disjoint union of the fibres of  $\chi$ , hence  $\left|\left(\mathbb{Z}/\Delta\mathbb{Z}\right)^\times\right| = 2 |\ker(\chi)|$ . On the other hand,  $-1 \notin \mathrm{val}_\Delta(q_0)$  since  $\mathrm{val}_\Delta(q_0)$  is a subgroup of  $\ker(\chi)$ , but  $\chi(-1) = -1$  according to [Cox13, Lemma 1.14], since  $\Delta$  is negative. We thus find that the domain and codomain of  $\varphi$  have the same size.

Let us check that  $\varphi$  is injective. If  $\alpha \in \ker(\chi)$ , then  $-\alpha$  is not in  $\ker(\chi)$ , hence not in  $\mathrm{val}_\Delta(q_0)$ . This implies that if  $\varphi(\alpha) \in \pm \mathrm{val}_\Delta(q_0)$ , then  $\alpha$  must be in  $\mathrm{val}_\Delta(q_0)$ . So  $\varphi$  is injective, hence bijective by an argument of cardinality.  $\square$

In particular, when  $R = \mathbb{Z}$  and  $\Delta \equiv 0, 1 \pmod{4}$  is negative, the principal genus consists precisely in the subgroup of squares  $\text{Cl}_{\mathbb{Z}}^{tw}(\Delta)^{\square}$ .

### 3.3 The case $R = \mathbb{K}[X]$ , $\Delta = 4f$ , and the link with 2-descent

Let  $\mathbb{K}$  be a field of characteristic 0, and let  $f \in \mathbb{K}[X]$  be a square-free monic polynomial of odd degree  $2g + 1$  with  $g \geq 1$ . We now consider Genus Theory over  $R = \mathbb{K}[X]$  with discriminant of the specific form  $\Delta = 4f$ , and we compare it to the 2-descent map of some hyperelliptic curve. Notice that we can write the middle coefficient of a quadratic form as  $2b$  instead of  $b$ ; this is consistent with the fact that  $\Delta = 4f$ , and it enables us to avoid fractions while doing computations. Furthermore, if  $q = [a, 2b, c] \in \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ , then  $a \neq 0$  since  $f$  has odd degree.

For the following, denote  $L := \mathbb{K}[X] / \langle f(X) \rangle$ . Since 2 is a unit in  $\mathbb{K}[X]$ , the set  $H_0$  of values taken by the principal form class in  $L^{\times}$  is just  $\mathbb{K}^{\times} L^{\times \square}$  (Proposition 3.3). In that context, the group homomorphism from Theorem 3.8 can be written as

$$\Psi: \begin{cases} \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) / \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^{\square} \longrightarrow L^{\times} / \mathbb{K}^{\times} L^{\times \square} \\ \left[ [a, 2b, c] \right] \text{ with } \gcd(a, f) = 1 \longmapsto a^{-1} \mathbb{K}^{\times} L^{\times \square} \end{cases} \quad (3.15)$$

Recall that  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f) \simeq \text{Pic} \left( \mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle \right)$  by Proposition 2.4. In order to make the link with 2-descent, note that  $\text{Spec} \left( \mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle \right)$  is a degree 2-cover of  $\mathbb{A}_{\mathbb{K}}^1$ . As a smooth affine curve, it can be uniquely completed into a smooth projective curve  $\mathcal{C}$ . The curve  $\mathcal{C}$  is a *hyperelliptic curve over  $\mathbb{K}$* , that is, a smooth projective geometrically connected  $\mathbb{K}$ -curve of genus  $g \geq 1$ , endowed with a degree 2 map  $\mathcal{C} \rightarrow \mathbb{P}_{\mathbb{K}}^1$ .

*Remark 3.16.* Since  $f$  has odd degree, the hyperelliptic curve  $\mathcal{C}$  has a  $\mathbb{K}$ -rational Weierstrass point  $\infty$  lying above the point at infinity of  $\mathbb{P}_{\mathbb{K}}^1$ .

Conversely, given a hyperelliptic curve over  $\mathbb{K}$  with a rational Weierstrass point, we can shift it above the point at infinity. Then it is a standard fact that the curve deprived of this point can be described by an affine equation  $Y^2 = f(X)$  where  $f \in \mathbb{K}[X]$  is square-free and monic of odd degree.

Denote by  $J$  the Jacobian variety of  $\mathcal{C}$ . Let  $D = \sum_{i=1}^r n_i \left( (x_i, y_i) - \infty \right)$  be a degree 0 divisor on  $\mathcal{C}$ , and assume that none of the  $(x_i, y_i)$  is a Weierstrass point. Set  $\bar{L} := \overline{\mathbb{K}[X]} / \langle f(X) \rangle$  where  $\overline{\mathbb{K}}$  is the algebraic closure of  $\mathbb{K}$ . We define  $\lambda(D) := \prod_{i=1}^r (x_i - X)^{n_i} \in \bar{L}^{\times}$ , and it may be shown that this induces a group morphism

$$\lambda: J(\mathbb{K}) / 2J(\mathbb{K}) \longrightarrow L^{\times} / L^{\times \square},$$

which we refer to as the *2-descent map* [Sch95, Lemmas 2.1 and 2.2].

Now, let us describe the isomorphism between  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f) \simeq \text{Pic} \left( \mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle \right)$  and  $J(\mathbb{K}) = \text{Pic}^0(\mathcal{C}) \simeq \text{Pic}(\mathcal{C} \setminus \{\infty\})$ . Let  $[a, 2b, c] \in \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ . We know from bijection (2.5) that the class of the quadratic form  $[a, 2b, c]$  corresponds to the ideal class  $\langle a, Y - b \rangle$  in  $\text{Pic} \left( \mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle \right)$ . This induces a Weil divisor on  $\mathcal{C} \setminus \{\infty\}$  defined as the vanishing locus of  $\langle a, Y - b \rangle$ , which we denote by  $\text{div}(a) \cap \text{div}(Y - b)$ . Since our hyperelliptic curve

is smooth, this indeed corresponds to a Cartier divisor on  $\mathcal{C} \setminus \{\infty\}$ . We associate to it a degree 0 divisor on  $\mathcal{C}$ , that is, a point in  $J(\mathbb{K})$ , by removing a suitable multiple of  $\infty$ . We thus obtain a group isomorphism

$$\mathcal{D}: \begin{cases} \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) \longrightarrow J(\mathbb{K}) \\ [q = [a, 2b, c]] \longmapsto \text{div}(a) \cap \text{div}(Y - b) - \text{deg}(a)\infty \end{cases}.$$

Notice that  $\text{div}(a) \cap \text{div}(Y - b) = \sum_{i=1}^{\text{deg}(a)} (x_i, y_i)$  where  $\{x_1, \dots, x_{\text{deg}(a)}\} \subset \overline{\mathbb{K}}$  is the set of roots of  $a$ , and  $b(x_i) = y_i$  for all  $i$ .

*Remark 3.17.* Mumford parametrized divisor classes in  $J(\mathbb{K}) = \text{Pic}^0(\mathcal{C})$  by triples of polynomials, and it is well-known that they correspond to the coefficients of the associate quadratic forms as above. He further proved that a given divisor class has a unique reduced representative, whose associate triple of polynomials verifies some bounds on their degrees [Mum84, Proposition 1.2 and page 3.29]. Applying a reduction algorithm based on Euclidean division allows to fully recover his parametrization.

We still denote by  $\mathcal{D}$  the induced map  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f) / \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^\square \xrightarrow{\sim} J(\mathbb{K}) / 2J(\mathbb{K})$ , by abuse of notations. In order to compare Genus Theory and 2-descent, we reproduce Diagram (1.2) from the introduction :

$$\begin{array}{ccc} \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) / \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^\square & \xrightarrow{\sim \mathcal{D}} & J(\mathbb{K}) / 2J(\mathbb{K}) \\ \Psi \downarrow & & \downarrow \lambda \\ L^\times / \mathbb{K}^\times L^{\times \square} & \xleftarrow{pr} & L^\times / L^{\times \square} \end{array} \quad (3.18)$$

where  $pr$  is the natural projection, sending  $\alpha L^{\times \square}$  to  $\alpha \mathbb{K}^\times L^{\times \square}$  for all  $\alpha \in L^\times$ . Our first goal is to prove that this diagram is commutative. Then, we will derive the injectivity of  $\Psi$  from the injectivity of  $\lambda$ .

**Proposition 3.19.** *Let  $f \in \mathbb{K}[X]$  be a square-free monic polynomial of odd degree  $2g + 1$  with  $g \geq 1$ . Let  $q \in \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ , and let  $[a, 2b, c]$  be a representative of  $q$  with  $a$  coprime to  $f$  (possible by Lemma 3.4). Then we have*

$$\lambda(\mathcal{D}(q)) = \frac{(-1)^{\text{deg}(a)}}{\text{lc}(a)} a L^{\times \square},$$

where  $\text{lc}(a)$  denotes the leading coefficient of  $a$ .

In particular, Diagram (3.18) is commutative.

*Proof.* Write  $\text{div}(a) \cap \text{div}(Y - b) = \sum_{i=1}^{\text{deg}(a)} (x_i, y_i)$  with  $a(x_i) = 0$  and  $b(x_i) = y_i$ . If  $y_i = 0$ , then  $x_i$  is both a root of  $a$  and  $b$ , hence a root of  $b^2 - ac = f$ . Since  $a$  and  $f$  are coprime by assumption, this cannot happen, and  $y_i$  must be nonzero.

First, assume that  $a$  is an irreducible polynomial, and denote by  $d$  its degree. Since the points  $(x_i, y_i)$  appearing in  $\mathcal{D}(q)$  are such that  $a(x_i) = 0$ , we have

$$\text{div}(a) \cap \text{div}(Y - b) - d\infty = \sum_{i=1}^d (x_i, y_i) - d\infty = \sum_{i=1}^d \sigma_i((x_1, y_1)) - d\infty,$$

where the  $\sigma_i((x_1, y_1))$  are all the conjugates in  $\overline{\mathbb{K}}$  over  $\mathbb{K}$  of  $(x_1, y_1)$ . Applying [Sch95, Lemma 2.2], we get

$$\lambda(\mathcal{D}(q)) = \left( \prod_{i=1}^d (x_i - X) \right) L^{\times \square} = \frac{(-1)^d}{\text{lc}(a)} a L^{\times \square}.$$

In the general case, if  $a = \prod_i a_i$  is the decomposition of  $a$  into irreducible factors, then

$$\text{div}(a) \cap \text{div}(Y - b) - \deg(a)\infty = \sum_i \left( \text{div}(a_i) \cap \text{div}(Y - b) - \deg(a_i)\infty \right),$$

hence the result follows from the irreducible case.

To conclude, the diagram is commutative since

$$pr \circ \lambda \circ \mathcal{D}(q) = pr \left( \frac{(-1)^{\deg(a)}}{\text{lc}(a)} a L^{\times \square} \right) = a \mathbb{K}^\times L^{\times \square} = \Psi(q),$$

hence the result □

Thus, the commutativity of Diagram (3.18) reveals a strong relation between Genus Theory over  $\mathbb{K}[X]$  and 2-descent on hyperelliptic curves over  $\mathbb{K}$ , at least when  $\deg(f)$  is odd.

**Theorem 3.20.** *Let  $f \in \mathbb{K}[X]$  be a square-free monic polynomial of odd degree  $2g + 1$  with  $g \geq 1$ . Then the Genus map  $\Psi$  from (3.15) is injective.*

*Proof.* Since  $\mathcal{D}$  is an isomorphism in Diagram (3.18), it is enough to show that  $pr \circ \lambda$  is injective. Let  $D \in \ker(pr \circ \lambda)$ . Then  $\lambda(D) = \mathbb{K}^\times L^{\times \square}$ , and we can choose a representative  $\varepsilon a^2$  of  $\lambda(D)$  for some  $\varepsilon \in \mathbb{K}^\times$  and some  $a \in L^\times$ .

According to [Sch95, Theorem 1.1], the quantity  $\varepsilon a^2$  is in the kernel of the norm  $N: L^\times / L^{\times \square} \rightarrow \mathbb{K}^\times / \mathbb{K}^{\times \square}$ , which is the restriction of the usual norm  $\overline{\mathbb{K}}[X] / \langle f(X) \rangle \simeq \overline{\mathbb{K}}^{2g+1} \rightarrow \overline{\mathbb{K}}$  given by  $(\alpha_1, \dots, \alpha_{2g+1}) \mapsto \prod_{i=1}^{2g+1} \alpha_i$ . We have  $N(\varepsilon a^2) = N(\varepsilon)N(a)^2 = N(\varepsilon)$ , since squares are in the kernel of  $N$ . As  $\varepsilon \in \mathbb{K}$ , we get  $N(\varepsilon) = \varepsilon^{2g+1}$ , which is in the same class as  $\varepsilon$  modulo the squares. From all of this we deduce that  $\varepsilon$  must be a square, and  $\lambda(D) = L^{\times \square}$ , meaning that  $D \in \ker(\lambda)$ . But  $\lambda$  is injective by [Sch95, Theorem 1.2], hence  $D = 0$  and  $pr \circ \lambda$  is injective, as desired. □

*Remark 3.21.* The fact that  $f$  has odd degree is crucial in the proof of Theorem 3.20. It also plays an important role in the construction of Diagram (3.18) : if  $f$  has even degree, then the corresponding hyperelliptic curve  $\mathcal{C}$  has two points  $\infty_+$  and  $\infty_-$  at infinity, and it is not clear how to relate  $\text{Pic}(\mathcal{C} \setminus \{\infty_+, \infty_-\})$  to  $\text{Pic}^0(\mathcal{C})$ . On the other hand, when  $\deg(f)$  is even, the 2-descent map  $\lambda$  is slightly different; in particular, its codomain is no longer  $L^\times / L^{\times \square}$  but  $L^\times / \mathbb{K}^\times L^{\times \square}$ . Furthermore, it may be non injective : according to [FPS97, Proposition 5], if  $f \in \mathbb{Q}[X]$  has degree 6, is irreducible and has Galois group  $S_6$ , then  $\ker(\lambda)$  has order 2. It would be interesting to see if this affects the possible injectivity of the Genus map in that context.

# 4 Non-trivial specializations in families of class groups of quadratic fields extensions

## 4.1 Description of the problem

From now onwards, we consider a hyperelliptic curve  $\mathcal{C}$  of genus  $g \geq 1$  over  $\mathbb{K}$  as in Subsection 3.3, but this time  $\mathbb{K}$  is a number field. We assume that  $\mathcal{C}$  has a rational Weierstrass point. As already mentioned in Remark 3.16, we shift this point above the point at infinity and we denote it by  $\infty$ . We then choose an affine equation of  $\mathcal{C} \setminus \{\infty\}$  of the form  $Y^2 = f(X)$  where  $f$  is a square-free monic polynomial of degree  $2g + 1$ . In this setting, we further assume without loss of generality that  $f \in \mathcal{O}_{\mathbb{K}}[X]$ .

Let  $\mathcal{W} := \text{Spec} \left( \mathcal{O}_{\mathbb{K}}[X, Y] / \langle Y^2 - f(X) \rangle \right)$ . Then  $\mathcal{W}$  is an affine  $\mathcal{O}_{\mathbb{K}}$ -scheme whose generic fibre is the curve  $\mathcal{C} \setminus \{\infty\}$ . Our motivation is the following. Given a non-trivial ideal class  $I$  in  $\text{Pic}(\mathcal{W})$ , can we find algebraic integers  $n \in \mathcal{O}_{\mathbb{K}}$  such that the “specialization” of  $I$  at  $X = n$  is a non-trivial ideal class in  $\text{Pic} \left( \mathcal{O}_{\mathbb{K}}[Y] / \langle Y^2 - f(n) \rangle \right)$ ? Or even better, in  $\text{Pic} \left( \mathcal{O}_{\mathbb{K}(\sqrt{f(n)})} \right)$ , provided  $f(n)$  is not a square?

**Example 4.1.** Let  $\mathbb{K} = \mathbb{Q}$  and let  $f(x) = X^3 - X + 9 \in \mathbb{Z}[X]$ . Then  $\mathcal{C}$  is an elliptic curve and  $I := \langle X, Y - 3 \rangle$  is an ideal of  $\mathbb{Z}[X, Y] / \langle Y^2 - X^3 + X - 9 \rangle$ . This ideal  $I$  is not principal. For which  $n \in \mathbb{Z}$  can we say that the specialized ideal  $I_n := \langle n, Y - 3 \rangle$  is principal in  $\mathbb{Z}[Y] / \langle Y^2 - n^3 + n - 9 \rangle$ ?

According to Proposition 2.4, this problem can be restated in terms of quadratic forms, using Proposition 2.4. For which  $n \in \mathbb{Z}$  can we say that the specialized integral quadratic form  $q(n) := [n, 6, -n^2 + 1]$  of discriminant  $4n^3 - 4n + 36$  is not  $\text{GL}_2^{tw}$ -equivalent to the principal form  $q_0(n) := [1, 0, -n^3 + n - 9]$ ?

The theory of reduced quadratic forms gives algorithms to compute whether a given quadratic form (of nonsquare discriminant) is equivalent to the principal form or not ([Coh93, §5.4.2, 5.6.1]). We experimented the algorithm for positive discriminant in our example, and we looked for simple patterns in the distribution of non-trivial specializations. Figure 4.1 sums up the data obtained for integers  $n$  from 1 to 100: a cell in the  $i^{\text{th}}$ -row and  $j^{\text{th}}$ -column corresponds to the integer  $n = j + 5i$  for  $i = 0, \dots, 19$  and  $j = 1, \dots, 5$ . The cell matching to the integer  $n$  is red and hatched when the corresponding quadratic form  $q(n) = [n, 6, -n^2 + 1]$  is equivalent to the principal form  $q_0(n)$ . It is yellow when  $q(n)$  is not equivalent to  $q_0(n)$ . It is blue and gridded when  $f(n)$  is a square, in which case the quadratic algebra  $\mathbb{Z}[Y] / \langle Y^2 - f(n) \rangle$  is degenerate.



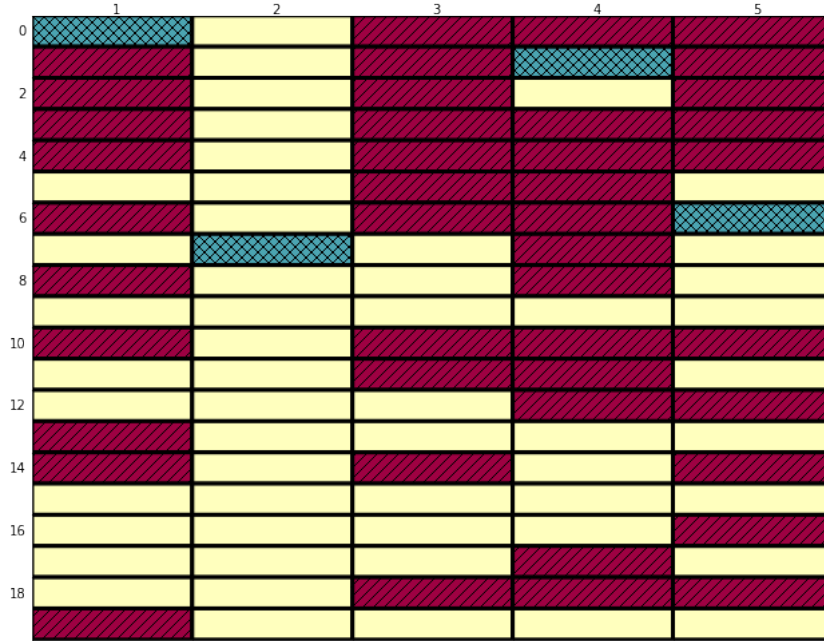


Figure 4.1: Sieve of non-trivial specializations of  $q_n$  for  $n \in \llbracket 1, 100 \rrbracket$

We observe that the second column in Figure 4.1 does not contain any red cell. This leads us to conjecture that when  $n \equiv 2 \pmod{5}$ , then  $q(n)$  is never equivalent to  $q_0(n)$ . Let us show this : when  $n \equiv 2 \pmod{5}$ , we have  $f(n) \equiv 2^3 - 2 + 9 \equiv 0 \pmod{5}$ ,  $q_n \equiv [2, 1, -3] \pmod{5}$ , and  $q_0(n) \equiv [1, 0, 0] \pmod{5}$ . For a contradiction, if  $q_0(n)$  were equivalent to  $q(n)$ , there would exist  $x, y \in \mathbb{Z}$  such that  $x^2 - f(n)y^2 = \pm n$ . This implies that  $x^2 \equiv \pm 2 \pmod{5}$ , which is impossible.

Thus, in this example, we have found an infinite family of non-trivial specializations of  $q$ , namely all the  $n \in \mathbb{Z}$  such that  $n \equiv 2 \pmod{5}$ . Actually, there are other modular criteria : if  $n \equiv 2 \pmod{12}$ , or if  $n \equiv 32 \pmod{37}$ , for example, then again  $q(n)$  is not equivalent to  $q_0(n)$ .

Our goal is now to prove that such congruence classes exist in general. Genus Theory will give a way to produce some of them. Let us come back to the general case, over a number field  $\mathbb{K}$ . For technical purpose, we are led to invert a suitable set of “bad” places. For  $\mathcal{S}$  a finite set of nonzero prime ideals of  $\mathcal{O}_{\mathbb{K}}$ , we consider the ring of  $\mathcal{S}$ -integers

$$\mathcal{O}_{\mathbb{K}, \mathcal{S}} = \{x \in \mathbb{K} \mid \nu_{\mathfrak{p}}(x) \geq 0 \ \forall \mathfrak{p} \notin \mathcal{S}\},$$

where  $\nu_{\mathfrak{p}}(x)$  is the  $\mathfrak{p}$ -adic valuation of  $x$ . Then, for a choice of  $\mathcal{S}$  that we will make precise soon, we modify the problem as follows : given a non-trivial ideal class  $I$  in  $\text{Pic}(\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle)$ , we look for  $n \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$  such that  $I$  is non-trivial in  $\text{Pic}(\mathcal{O}_{\mathbb{K}, \mathcal{S}}[Y] / \langle Y^2 - f(n) \rangle)$  after specialization at  $X = n$ .

The following Proposition tells us what set  $\mathcal{S}$  we should consider in order to take advantage of Genus Theory over  $\mathbb{K}[X]$ .

**Proposition 4.2.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3 and let  $\mathcal{S}$  be a finite set of nonzero prime ideals of  $\mathcal{O}_{\mathbb{K}}$ . The restriction to the generic fibre induces a homomorphism of abelian groups*

$$\theta: \text{Pic}(\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle) \longrightarrow \text{Pic}(\mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle).$$

Moreover,

- if  $\mathcal{S}$  contains all the prime ideals dividing  $2 \operatorname{disc}(f)$ , then  $\theta$  is surjective;
- if  $\mathcal{S}$  contains all the prime ideals dividing chosen generators of  $\operatorname{Pic}(\mathcal{O}_{\mathbb{K}})$ , then  $\theta$  is injective.

*Proof.* The map  $\theta$  corresponds to the restriction of a given divisor on  $\mathcal{W}_{\mathcal{S}} = \operatorname{Spec}(\mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle)$  to the generic fibre. The main steps of the proof are extracted from the first part of the proof of [Gil21, Lemma 2.4], which is stated over  $\mathbb{Z}$ , but directly extends to  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ .

Given a divisor on the generic fibre, its scheme-theoretic closure on the integral model  $\mathcal{W}_{\mathcal{S}}$  gives a Weil divisor on  $\operatorname{Spec}(\mathcal{W}_{\mathcal{S}})$ . When the prime ideals dividing  $2 \operatorname{disc}(f)$  are inverted, the Jacobian criterion shows that the affine  $\operatorname{Spec}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$ -scheme  $\mathcal{W}_{\mathcal{S}}$  is smooth over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ , hence Weil and Cartier divisors coincide on  $\mathcal{W}_{\mathcal{S}}$ . This proves surjectivity of  $\theta$  in that case.

For injectivity, let  $D \in \ker(\theta)$ . Then  $\theta(D) = \operatorname{div}_{\mathbb{K}}(h)$  for some  $h \in \mathbb{K}[X, Y] / \langle Y^2 - f(X) \rangle$ . Since  $\mathcal{W}_{\mathcal{S}}$  and  $\mathcal{C} \setminus \{\infty\}$  have same function field, we can consider  $\operatorname{div}(h)$  as a principal divisor over  $\mathcal{W}_{\mathcal{S}}$ . Thus, we see that  $D$  and  $\operatorname{div}(h)$  have same generic fibre, hence  $D - \operatorname{div}(h)$  is a vertical divisor. On the other hand, since  $f$  is monic of odd degree,  $f$  cannot be a square modulo any prime ideal of  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ , implying that the fibres of  $\mathcal{W}_{\mathcal{S}}$  are irreducible. Therefore, vertical divisors on  $\mathcal{W}_{\mathcal{S}}$  are sum of fibres. When the prime ideals dividing a chosen set of generators of  $\operatorname{Pic}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$  are inverted,  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  is a PID and the fibres of  $\mathcal{W}_{\mathcal{S}}$  are principal. If this happens,  $D$  is principal, and  $\theta$  is injective.  $\square$

Now, **we fix once and for all a finite set  $\mathcal{S}$**  of nonzero prime ideals of  $\mathcal{O}_{\mathbb{K}}$  as follows. Let  $I_1, \dots, I_r$  be nonzero ideals generating  $\operatorname{Pic}(\mathcal{O}_{\mathbb{K}})$ . We set

$$\mathcal{S} := \{\mathfrak{p} \in \operatorname{Spec}(\mathcal{O}_{\mathbb{K}}) \mid \mathfrak{p} \text{ divides } 2 \operatorname{disc}(f) I_1 \dots I_r\}. \quad (4.3)$$

Then the morphism  $\theta$  from Proposition 4.2 is an isomorphism.

*Remark 4.4.* Notice that in particular,  $\mathcal{S}$  contains all the primes of bad reduction for the curve  $\mathcal{C}$ , and that the ring  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  is a PID.

*Remark 4.5.* Sivertsen and Soleng gave an algorithm to compute effectively the inverse of the isomorphism  $\theta$  in Proposition 4.2 ([SS11, Lemma 3.2]).

Since  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  is a PID, every locally free  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$ -module of finite rank is free, according to [Ses58]. Therefore, every ideal class in  $\operatorname{Pic}(\mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle)$  has a representative of the form  $\langle A(X), Y - B(X) \rangle$  with  $A \neq 0$ , and corresponds to the class of the quadratic form  $q := [A(X), 2B(X), \frac{B(X)^2 - f(X)}{A(X)}]$ , by Proposition 2.4. Thus, we deduce the quadratic form version of Proposition 4.2.

**Corollary 4.6.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3. With  $\mathcal{S}$  as defined in (4.3), the isomorphism from Proposition 4.2 induces an isomorphism*

$$\operatorname{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f) \xrightarrow{\sim} \operatorname{Cl}_{\mathbb{K}[X]}^{tw}(4f).$$

From now on we will mainly work with quadratic forms.

Let  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$ . Given an ideal class in  $\operatorname{Pic}(\mathcal{O}_{\mathbb{K},\mathcal{S}}[X, Y] / \langle Y^2 - f(X) \rangle)$ , that is, given a class of quadratic forms in  $\operatorname{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$ , we obtain a class of quadratic forms in  $\operatorname{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))$  by applying the evaluation morphism

$$ev_n: \operatorname{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f) \longrightarrow \operatorname{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n)) \quad (4.7)$$

which sends the class of  $[A, 2B, C]$  to the class of  $[A(n), 2B(n), C(n)]$ .

*Remark 4.8.* When  $f(n)$  is not a square, the target of (4.7) is the Picard group of  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[\sqrt{f(n)}]$ . But when  $f(n)$  is a square, possibly 0, the quadratic algebra one obtains is no longer an integral domain.

## 4.2 Genus Theory gives a modular criterion

In the following,  $f$  still denotes a square-free monic polynomial of odd degree at least 3 with coefficients in  $\mathcal{O}_{\mathbb{K}}$ , and we let  $\mathcal{S}$  be defined by (4.3). Recall that the Genus Theory we exposed in Section 3 requires to work over a principal ideal domain. Thus, we will often use the isomorphism from Corollary 4.6 which makes a class of quadratic forms in  $\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$  correspond to a class of quadratic forms in  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ . On the other hand, once a given class of quadratic forms  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$  is evaluated at some  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$ , we get a class of quadratic forms over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$  which is a PID, hence Genus Theory directly applies.

Let  $L := \mathbb{K}[X]/\langle f(X) \rangle$ . Then, for all  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that  $f(n) \neq 0$ , we have the following landscape, where  $M_n := \mathcal{O}_{\mathbb{K},\mathcal{S}}/f(n)\mathcal{O}_{\mathbb{K},\mathcal{S}}$ :

$$\begin{array}{ccc}
 & \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)/\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)^{\square} & \\
 \swarrow \sim & & \searrow \overline{ev_n} \\
 \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)/\text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^{\square} & & \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))/\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))^{\square} \\
 \downarrow \Psi & & \downarrow \psi_n \\
 L^{\times}/\mathbb{K}^{\times}L^{\times\square} & & M_n^{\times}/\mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times}M_n^{\times\square}
 \end{array} \tag{4.9}$$

The two vertical maps are the morphisms corresponding to Genus Theory. The left one,  $\Psi$ , has already been defined in (3.15), and is injective by Theorem 3.20, whereas  $\psi_n$  is obtained when we set  $R := \mathcal{O}_{\mathbb{K},\mathcal{S}}$  and  $\Delta := 4f(n)$  in Theorem 3.8. Beside this, the map  $\overline{ev_n}$  is the one induced on the quotients by  $ev_n$ , defined in (4.7).

Given a class  $q$  of quadratic forms over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  which is not in the principal genus, Diagram (4.9) emphasizes what will be our strategy to find some  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that  $ev_n(q) \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))$  is non-trivial. We will use the map  $\Psi$  to get some information, namely the fact that certain quantities are not squares (see Corollary 4.13). Linking those quantities to  $\psi_n \circ \overline{ev_n}(q)$  will give us clues about what  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  we should choose (see PGS Theorem 4.14).

*Remark 4.10.* Our approach enables us to do a little bit more than finding non-trivial specializations of a given class of quadratic forms. Indeed, since the genus maps are group homomorphisms, we can directly extend our considerations to the question of finding non-equivalent specializations in  $\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))$  of two given distinct classes of quadratic forms  $q, q' \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$ . When  $q$  and  $q'$  are not in the same genus over  $\mathbb{K}[X]$ , that is, when they do not have the same image through  $\Psi$ , the arguments of this paper apply to  $q' * q^{-1}$ , implying that their specializations are non-equivalent.

We know from Corollary 4.6 that every quadratic form over  $\mathbb{K}[X]$  is  $\text{GL}_2^{tw}$ -equivalent to one with coefficients in  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$ . In order to compute its image by the Genus map, we need such a representative to have its first coefficient coprime to  $f$  in  $\mathbb{K}[X]$ .

**Lemma 4.11.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, and let  $\mathcal{S}$  be defined by (4.3). Then every class of quadratic forms in  $\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$  has a representative of the form  $[A, 2B, C]$  where  $A$  is coprime to  $f$  in  $\mathbb{K}[X]$ .*

*Proof.* Let  $q = [A, 2B, C] \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$ . By Remark 2.3, every quadratic form equivalent to  $q$  has its first coefficient of the form  $\varepsilon q(\alpha, \gamma) = \varepsilon(A\alpha^2 + 2B\alpha\gamma + C\gamma^2)$  for some  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times}$  and some

$\alpha, \gamma \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]$  such that  $\langle \alpha, \gamma \rangle = \mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]$ . Actually, restricting our search to  $\varepsilon = 1$ ,  $\gamma = 1$  and  $\alpha \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$  will be enough for our purpose.

Let  $\mathbb{K}(f)$  be the splitting field of  $f$ . For all  $\alpha \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$ , the polynomial  $q(\alpha, 1)$  is coprime to  $f$  in  $\mathbb{K}[X]$  if and only if we have  $q(\alpha, 1)(\rho) \neq 0$  for all  $\rho$  root of  $f$  in  $\mathbb{K}(f)$ . In other words, we look for  $\alpha \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$  such that

$$P(\rho) := A(\rho)\alpha^2 + 2B(\rho)\alpha + C(\rho) \neq 0 \quad \text{for all } \rho \text{ root of } f.$$

Fix some root  $\rho$  of  $f$ . Since  $[A, 2B, C]$  is primitive, we cannot have  $A(\rho) = B(\rho) = C(\rho) = 0$  at the same time, hence  $P(\rho)$  is a nonzero polynomial in the variable  $\alpha$ , and has at most 2 roots in  $\mathcal{O}_{\mathbb{K}, \mathcal{S}}$ . Doing this for all  $\rho$ , we have at most  $2 \deg(f)$  values of  $\alpha$  to avoid. Since  $\mathbb{K}$  is infinite, we can take  $\alpha \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$  not in the set of those values. Then the quadratic form  $[\tilde{A}, 2\tilde{B}, \tilde{C}] := \begin{pmatrix} \alpha & -1 \\ 1 & 0 \end{pmatrix} \cdot [A, 2B, C]$  is another representative of our class  $q$ , with  $\tilde{A}$  coprime to  $f$  in  $\mathbb{K}[X]$ .  $\square$

Given a class of quadratic forms  $[A, 2B, C] \in \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$  whose image through  $\Psi$  is non-trivial, we now analyse the consequences on  $A$ . We start with the case of quadratic forms over  $\mathbb{K}[X]$ .

For the sake of reader-friendliness, uppercase letters are used for quadratic forms  $[A, 2B, C]$  with coefficients in  $\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]$ , whereas lowercase letters are used for quadratic forms  $[a, 2b, c]$  with coefficients in  $\mathbb{K}[X]$ .

**Proposition 4.12.** *If  $q \in \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) \setminus \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^\square$ , and if  $[a, 2b, c]$  is a representative of  $q$  with  $a$  coprime to  $f$ , then for all  $\varepsilon \in \mathbb{K}^\times$ , there exists a root  $\rho_\varepsilon$  of  $f$  such that  $\varepsilon a(\rho_\varepsilon) \notin \mathbb{K}(\rho_\varepsilon)^\square$ .*

*Proof.* Let  $L := \mathbb{K}[X] / \langle f(X) \rangle$ , and let

$$\Psi: \text{Cl}_{\mathbb{K}[X]}^{tw}(4f) / \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)^\square \longrightarrow L^\times / \mathbb{K}^\times L^{\times \square}$$

be the Genus Theory morphism over  $\mathbb{K}[X]$  defined in (3.15). Since  $a$  is coprime to  $f$ , we have  $\Psi(q) = a^{-1} \mathbb{K}^\times L^{\times \square} = a \mathbb{K}^\times L^{\times \square}$  by Proposition 3.7. On the other hand,  $q$  is not a square, and  $\Psi$  is injective by Theorem 3.20, hence  $a \notin \mathbb{K}^\times L^{\times \square}$ .

Decompose  $f = \prod_{i=1}^r f_i$  as a product of irreducible polynomials in  $\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]$ . Recall that  $f$  is assumed to be square-free, hence the  $f_i$ 's are all distinct. For all  $i$ , denote by  $\rho_i$  a root of  $f_i$ . We then have

$$L = \mathbb{K}[X] / \langle f(X) \rangle \simeq \prod_{i=1}^r \mathbb{K}[X] / \langle f_i(X) \rangle \simeq \prod_{i=1}^r \mathbb{K}(\rho_i).$$

The image of  $a \in \mathbb{K}[X]$  through these isomorphisms is  $(a(\rho_1), \dots, a(\rho_r))$ .

By contraposition, if there exists some  $\varepsilon \in \mathbb{K}^\times$  such that  $\varepsilon a(\rho_i)$  is a square in  $\mathbb{K}(\rho_i)$  for all  $i$ , then  $\varepsilon a$  is a square in  $L$ . Recall that  $a$  is coprime to  $f$ , hence  $\varepsilon a(\rho_i) \neq 0$  for all  $i$ , so  $\varepsilon a \in L^{\times \square}$ , and  $a \in \mathbb{K}^\times L^{\times \square}$ . Thus,  $q$  must be a square in  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ , and this concludes the proof.  $\square$

**Corollary 4.13.** *Let  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ . Let  $[A, 2B, C]$  be a representative of  $q$  with  $A$  coprime to  $f$  in  $\mathbb{K}[X]$  (see Lemma 4.11). If  $q \notin \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)^\square$ , then for all  $\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times$ , there exists a root  $\rho_\varepsilon$  of  $f$  such that  $\varepsilon A(\rho_\varepsilon) \notin \mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon}^\square$  (where  $\mathcal{S}'_\varepsilon$  denotes the set of prime ideals above  $\mathcal{S}$  in  $\mathbb{K}(\rho_\varepsilon)$ ).*

*Proof.* Since  $\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f) \simeq \text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$  by Corollary 4.6,  $q$  is not a square in  $\text{Cl}_{\mathbb{K}[X]}^{tw}(4f)$ . Therefore, the conclusion of Proposition 4.12 holds : for all  $\varepsilon \in \mathbb{K}^\times$ , there exists  $\rho_\varepsilon$  a root of  $f$  such that  $\varepsilon A(\rho_\varepsilon) \notin \mathbb{K}(\rho_\varepsilon)^\square$ . On the other hand, for all  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times$ , we have  $\varepsilon A(\rho_\varepsilon) \in \mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}$ . Since this ring is integrally closed,  $\varepsilon A(\rho_\varepsilon)$  is a square in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}$  if and only if it is a square in  $\mathbb{K}(\rho_\varepsilon)$ . We end up with the desired conclusion.  $\square$

The following Theorem relates Genus Theory over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  to Genus Theory over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ , providing a modular criterion for non-trivial specializations.

**Principal Genus Specialization Theorem 4.14.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, and let  $\mathcal{S}$  be defined by (4.3). Let  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}[X]}^{tw}(4f)$ , and assume that  $q$  is not in the principal genus over  $\mathbb{K}[X]$ .*

*Let  $[A, 2B, C]$  be a representative of  $q$  with  $A$  coprime to  $f$  in  $\mathbb{K}[X]$  (see Lemma 4.11). Let  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that  $f(n) \neq 0$ . For all  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$ , let  $\rho_\varepsilon$  be a root of  $f$  such that  $\varepsilon A(\rho_\varepsilon)$  is not a square in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}$ , as in Corollary 4.13.*

*If, for all  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$ , there exists  $\mathfrak{p}_\varepsilon$  a prime ideal in  $\mathbb{K}(\rho_\varepsilon)$  not above  $\mathcal{S}$  such that  $\mathfrak{p}_\varepsilon$  is inert in the extension  $\mathbb{K}(\rho_\varepsilon) \hookrightarrow \mathbb{K}(\rho_\varepsilon, \sqrt{\varepsilon A(\rho_\varepsilon)})$  and  $n \equiv \rho_\varepsilon \pmod{\mathfrak{p}_\varepsilon}$ , then the quadratic form  $[A(n), 2B(n), C(n)]$  is not in the principal genus over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ .*

*Remark 4.15.* There are only finitely many  $\varepsilon$  to consider in Theorem 4.14. Indeed, the quotient  $\mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$  has finite order by Dirichlet's Unit Theorem, extended to  $\mathcal{S}$ -integers by Chevalley and Hasse [Nar04, Theorem 3.12]. More explicitly, one can write  $\mathcal{O}_{\mathbb{K},\mathcal{S}}^\times \simeq \mu \times \mathbb{Z}^r$  where  $\mu$  is the group of roots of unity, and then one has  $\mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square} \simeq \mu / 2\mu \times (\mathbb{Z} / 2\mathbb{Z})^r$ , which is finite.

*Remark 4.16.* If we further assume that the prime ideal  $\mathfrak{p}_\varepsilon$  interfering in Theorem 4.14 has inertia degree 1 over  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ , then the congruence relation  $n \equiv \rho_\varepsilon \pmod{\mathfrak{p}_\varepsilon}$  indeed has a solution  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$ .

*Remark 4.17.* By Chebotarev's Density Theorem, there are infinitely many prime ideals in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon)}$  which are inert in the Galois extension  $\mathbb{K}(\rho_\varepsilon) \hookrightarrow \mathbb{K}(\rho_\varepsilon, \sqrt{\varepsilon A(\rho_\varepsilon)})$ , hence removing a finite number of prime ideals ensures that there will still exist (infinitely many) inert prime ideals in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}$ .

*Proof.* Let  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  be such that  $f(n) \neq 0$ , and let  $M_n := \mathcal{O}_{\mathbb{K},\mathcal{S}} / f(n)\mathcal{O}_{\mathbb{K},\mathcal{S}}$ . To compute the image of  $q_n := [A(n), 2B(n), C(n)] \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))$  by the Genus map

$$\psi_n: \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n)) / \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))^\square \longrightarrow M_n^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times M_n^{\times\square},$$

we would need  $A(n)$  and  $f(n)$  to be coprime, but this has no reason to happen. Nevertheless, we know from Lemma 3.4 and Remark 3.5 that there exists another representative of  $q_n$  whose first coefficient  $A_n$  is nonzero and coprime to  $f(n)$ , and such that  $A_n = A(n)\alpha^2 + 2B(n)\alpha\gamma + C(n)\gamma^2$  for some coprime  $\mathcal{S}$ -integers  $\alpha$  and  $\gamma$ . According to Proposition 3.7, we have  $\psi_n(q_n) = A_n^{-1} \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times M_n^{\times\square} = A_n \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times M_n^{\times\square}$ , hence  $q_n$  is in the principal genus if and only if  $(A_n + f(n)\mathcal{O}_{\mathbb{K},\mathcal{S}}) \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times M_n^{\times\square}$ . This means that for all  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$ , we must show that  $(\varepsilon A_n + f(n)\mathcal{O}_{\mathbb{K},\mathcal{S}}) \notin M_n^{\times\square}$ .

Fix some  $\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}$ . Let  $\mathfrak{p}_\varepsilon$  be a prime ideal in  $\mathbb{K}(\rho_\varepsilon)$  satisfying the hypotheses. Since  $n \equiv \rho_\varepsilon \pmod{\mathfrak{p}_\varepsilon}$ , we have  $f(n) \equiv 0 \pmod{\mathfrak{p}_\varepsilon}$ , that is,  $\mathfrak{p}_\varepsilon$  divides  $f(n)\mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon}$ . This gives a ring homomorphism

$$M_n = \mathcal{O}_{\mathbb{K}, \mathcal{S}} / f(n)\mathcal{O}_{\mathbb{K}, \mathcal{S}} \longrightarrow \mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon} / f(n)\mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon} \longrightarrow \mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon} / \mathfrak{p}_\varepsilon.$$

By contraposition, if  $\varepsilon A_n$  is a square in  $M_n$ , then  $\varepsilon A_n$  is a square in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon} / \mathfrak{p}_\varepsilon$ . We show that the latter condition is not possible.

Since  $\mathfrak{p}_\varepsilon$  is inert in the quadratic extension  $\mathbb{K}(\rho_\varepsilon) \hookrightarrow \mathbb{K}(\rho_\varepsilon, \sqrt{\varepsilon A(\rho_\varepsilon)})$ , the quantity  $\varepsilon A(\rho_\varepsilon)$  cannot be a square modulo  $\mathfrak{p}_\varepsilon$ . Moreover, as  $n \equiv \rho_\varepsilon \pmod{\mathfrak{p}_\varepsilon}$ , we have  $\varepsilon A(\rho_\varepsilon) \equiv \varepsilon A(n) \pmod{\mathfrak{p}_\varepsilon}$ , hence  $A(n)$  is invertible modulo  $\mathfrak{p}_\varepsilon$ . Next,  $f(n) \equiv 0$  implies  $B^2(n) \equiv A(n)C(n) \pmod{\mathfrak{p}_\varepsilon}$ , hence

$$\varepsilon A_n = \varepsilon(A(n)\alpha^2 + 2B(n)\alpha\gamma + C(n)\gamma^2) \equiv \varepsilon A(n) \left( \alpha + \frac{B(n)}{A(n)}\gamma \right)^2 \pmod{\mathfrak{p}_\varepsilon}.$$

Since  $A_n$  is coprime to  $f(n)$ ,  $A_n$  is invertible modulo  $\mathfrak{p}_\varepsilon$ , hence  $\alpha + \frac{B(n)}{A(n)}\gamma$  is invertible too and  $\varepsilon A(n) \equiv \varepsilon A_n \left( \alpha + \frac{B(n)}{A(n)}\gamma \right)^{-2} \pmod{\mathfrak{p}_\varepsilon}$ . We deduce from that equation that  $\varepsilon A_n$  is not a square modulo  $\mathfrak{p}_\varepsilon$ , hence modulo  $f(n)$ . We infer that  $(\varepsilon A_n + f(n)\mathcal{O}_{\mathbb{K}, \mathcal{S}}) \notin M_n^{\times \square}$  for all  $\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}$ , hence  $\psi_n(q_n) \neq \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times M_n^{\times \square}$  and we are done.  $\square$

**Corollary 4.18.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, let  $\mathcal{S}$  be defined by (4.3), and let  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ . Recall that for  $n \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$ ,  $ev_n$  is the specialization map defined by (4.7).*

*If  $q$  is not a square in  $\text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ , then there exist infinitely many  $n \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}$  such that the specialized class of quadratic forms  $ev_n(q)$  is non trivial in  $\text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}}^{tw}(4f(n))$ .*

*Proof.* Let  $\rho$  be a root of  $f$  in some extension, and let  $\nu$  be a non-square element of  $\mathbb{K}(\rho)$ . According to the PGS Theorem 4.14 and the Chinese Remainder Theorem, and because the set  $\mathcal{S}$  is finite, it is enough to show that there exist infinitely many different prime ideals  $\mathfrak{p}$  of  $\mathcal{O}_{\mathbb{K}(\rho)}$  verifying :

- $\mathfrak{p}$  is inert in  $\mathcal{O}_{\mathbb{K}(\rho, \sqrt{\nu})}$ ;
- $\mathfrak{p}$  has inertia degree 1 over  $\mathcal{O}_{\mathbb{K}}$  (this ensures that  $n \equiv \rho \pmod{\mathfrak{p}}$  has a solution  $n \in \mathcal{O}_{\mathbb{K}}$ ).

The first point is guaranteed by Chebotarev's Density Theorem : the set of prime ideals of  $\mathcal{O}_{\mathbb{K}(\rho)}$  inert in some (Galois) quadratic extension has Dirichlet density  $\frac{1}{2}$ . For the second point, it is a standard fact that the set of prime ideals of  $\mathcal{O}_{\mathbb{K}(\rho)}$  having inertia degree 1 over  $\mathcal{O}_{\mathbb{K}}$  has Dirichlet density 1 (see for example [Nar04, 7.2.1, Corollary 3]). Therefore, we may choose our prime ideals among a set of Dirichlet density  $\frac{1}{2}$ , hence there are infinitely many such ideals, as desired.  $\square$

### 4.3 Density of non-trivial specializations in $\mathcal{O}_{\mathbb{K}, \mathcal{S}}$

As in the previous Subsections, let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, and let  $\mathcal{S}$  be defined by (4.3). Let  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ , and assume that  $q$  is not in the principal genus over  $\mathbb{K}[X]$ . Then the PGS Theorem 4.14 and its Corollary 4.18

tell us that the set of  $\mathcal{S}$ -integers  $n \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  such that the specialized class of quadratic forms  $ev_n(q) \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}}}^{tw}(4f(n))$  is non-trivial is infinite. The present Section aims at estimating the density of this set in  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ . In general, there are various notions of density one can choose, depending on the problem one considers. Therefore, we give a list of properties that our density should verify.

**Definition 4.19.** Denote by  $\mathcal{P}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$  the set of subsets of  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ . In this paper, a *density* is a map  $\delta: \mathcal{P}(\mathcal{O}_{\mathbb{K},\mathcal{S}}) \rightarrow [0, 1]$  verifying the following properties :

- (d<sub>1</sub>)  $\delta(\mathcal{O}_{\mathbb{K},\mathcal{S}}) = 1$ ;
- (d<sub>2</sub>) if  $P \subseteq Q$  in  $\mathcal{P}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$ , then  $\delta(P) \leq \delta(Q)$ ;
- (d<sub>3</sub>) if  $P, Q \subseteq \mathcal{O}_{\mathbb{K},\mathcal{S}}$ , then  $\delta(P \cup Q) \leq \delta(P) + \delta(Q)$ ;
- (d<sub>4</sub>)  $\delta$  is translation invariant, that is,  $\delta(\alpha + P) = \delta(P)$  for all  $\alpha \in \mathcal{O}_{\mathbb{K},\mathcal{S}}$  and  $P \in \mathcal{P}(\mathcal{O}_{\mathbb{K},\mathcal{S}})$ ;
- (d<sub>5</sub>) for all  $I$  ideal of  $\mathcal{O}_{\mathbb{K},\mathcal{S}}$ , we have  $\delta(I) = \frac{1}{N(I)}$ , where  $N(I) := \left| \mathcal{O}_{\mathbb{K},\mathcal{S}}/I \right| = \left| \mathcal{O}_{\mathbb{K}}/I \cap \mathcal{O}_{\mathbb{K}} \right|$  is the norm of  $I$ .

**Example 4.20.** Let  $\mathcal{S}_\infty$  be the set of archimedean places of  $\mathcal{O}_{\mathbb{K}}$ . For all  $\nu \in \mathcal{S} \cup \mathcal{S}_\infty$ , let  $\mathbb{K}_\nu$  be the completion of  $\mathbb{K}$  with respect to  $|\cdot|_\nu$ . Then the map defined for all  $P \subseteq \mathcal{O}_{\mathbb{K},\mathcal{S}}$  by

$$\delta_{\mathcal{S}}(P) := \limsup_{r \in \mathbb{K}^\times} \frac{\#\{n \in P \mid |n|_\nu \leq |r|_\nu \ \forall \nu \in \mathcal{S} \cup \mathcal{S}_\infty\}}{\#\{n \in \mathcal{O}_{\mathbb{K},\mathcal{S}} \mid |n|_\nu \leq |r|_\nu \ \forall \nu \in \mathcal{S} \cup \mathcal{S}_\infty\}}$$

is a density, according to [DL21, Proposition 4.18].

**Notations.** Here,  $f \in \mathcal{O}_{\mathbb{K}}[X]$  is a monic square-free polynomial of degree  $2g + 1$ . Recall that  $\mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$  has finite order by Dirichlet's Unit Theorem. Let  $q \in \text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}[X]}}^{tw}(4f)$ ; according to Lemma 4.11, there exists a representative  $[A, 2B, C]$  of  $q$  such that  $A, B, C \in \mathcal{O}_{\mathbb{K},\mathcal{S}}[X]$  and  $A$  is coprime to  $f$  in  $\mathbb{K}[X]$ . Recall that  $[A, 2B, C]$  is a primitive quadratic form of discriminant  $4B^2 - 4AC = 4f$ .

Moreover, we assume that  $q$  is not a square in  $\text{Cl}_{\mathcal{O}_{\mathbb{K},\mathcal{S}[X]}}^{tw}(4f)$ . By Corollary 4.13, for all  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$ , there exists a root  $\rho_\varepsilon$  of  $f$  such that  $\varepsilon A(\rho_\varepsilon)$  is not a square in  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}$ , where  $\mathcal{S}'_\varepsilon$  is the set of prime ideals of  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon)}$  lying over those of  $\mathcal{S}$ .

Our set of interest is

$$\mathcal{T}_{triv} := \left\{ n \in \mathcal{O}_{\mathbb{K},\mathcal{S}} \mid [A(n), 2B(n), C(n)] \text{ is } \text{GL}_2^{tw}\text{-equivalent over } \mathcal{O}_{\mathbb{K},\mathcal{S}} \text{ to } [1, 0, -f(n)] \right\} \quad (4.21)$$

and our goal is to show that  $\mathcal{T}_{triv}$  has density 0.

**Definition 4.22.** Let  $\varepsilon \in \mathcal{O}_{\mathbb{K},\mathcal{S}}^\times / \mathcal{O}_{\mathbb{K},\mathcal{S}}^{\times\square}$ . We define the set  $\mathcal{P}_\varepsilon \subseteq \text{Spec}(\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon})$  by

$$\mathcal{P}_\varepsilon := \left\{ \mathfrak{p} \in \text{Spec}(\mathcal{O}_{\mathbb{K}(\rho_\varepsilon),\mathcal{S}'_\varepsilon}) \mid \begin{array}{l} \text{the inertia degree of } \mathfrak{p} \text{ over } \mathbb{K} \text{ is } 1 \\ \text{and } \mathfrak{p} \text{ is inert in the extension } \mathbb{K}(\rho_\varepsilon) \hookrightarrow \mathbb{K}(\rho_\varepsilon, \sqrt{\varepsilon A(\rho_\varepsilon)}) \end{array} \right\}.$$

The contrapositive of the PGS Theorem 4.14 directly implies the following inclusion.

**Proposition 4.23.** *With the above notations, we have*

$$\mathcal{T}_{triv} \subseteq \{n \mid f(n) = 0\} \cup \bigcup_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \bigcap_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \{n \in \mathcal{O}_{\mathbb{K},S} \mid n \not\equiv \rho_\varepsilon \pmod{\mathfrak{p}}\}.$$

**Definition 4.24.** Let  $\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}$  and let  $\rho_\varepsilon$  be the associated root of  $f$ . We set

$$\mathcal{T}^{(\varepsilon)} := \bigcap_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \{n \in \mathcal{O}_{\mathbb{K},S} \mid n \not\equiv \rho_\varepsilon \pmod{\mathfrak{p}}\} \quad \text{and} \quad \mathcal{T} := \bigcup_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \mathcal{T}^{(\varepsilon)}.$$

For all  $x \in \mathbb{R}_+^\times$ , we also set

$$\mathcal{T}_x^{(\varepsilon)} := \bigcap_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} \{n \in \mathcal{O}_{\mathbb{K},S} \mid n \not\equiv \rho_\varepsilon \pmod{\mathfrak{p}}\},$$

where  $N(\mathfrak{p})$  is the norm of the ideal  $\mathfrak{p}$ .

Clearly, for all  $x \in \mathbb{R}_+^\times$ , we have  $\mathcal{T}^{(\varepsilon)} \subseteq \mathcal{T}_x^{(\varepsilon)}$ .

**Theorem 4.25.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, let  $S$  be defined by (4.3), let  $\delta$  be a density, and let  $q = [A, 2B, C] \in \text{Cl}_{\mathcal{O}_{\mathbb{K},S}[X]}^{tw}(4f)$  with  $A$  coprime to  $f$  in  $\mathbb{K}[X]$  (see Lemma 4.11). Assume that  $q$  is not in the principal genus over  $\mathbb{K}[X]$ .*

*Then the density of the set  $\mathcal{T}_{triv}$  of  $n \in \mathcal{O}_{\mathbb{K},S}$  such that the specialized class of quadratic forms  $[A(n), 2B(n), C(n)] \in \text{Cl}_{\mathcal{O}_{\mathbb{K},S}}^{tw}(4f(n))$  is trivial verifies*

$$\delta(\mathcal{T}_{triv}) \leq \sum_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \left(1 - \frac{1}{N(\mathfrak{p})}\right).$$

*Proof.* Recall that  $\mathcal{T}_{triv} \subseteq \mathcal{T} \cup \{n \in \mathcal{O}_{\mathbb{K},S} \mid f(n) = 0\}$  by Proposition 4.23, where  $\mathcal{T}$  comes from Definition 4.24. Hence,  $\delta(\mathcal{T}_{triv}) = \delta(\mathcal{T})$ .

Moreover,

$$\mathcal{T} = \bigcup_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \mathcal{T}^{(\varepsilon)} \subseteq \bigcup_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \mathcal{T}_x^{(\varepsilon)}$$

for all  $x \in \mathbb{R}_+^\times$ , hence  $\delta(\mathcal{T}_{triv}) \leq \sum_{\varepsilon \in \mathcal{O}_{\mathbb{K},S}^\times / \mathcal{O}_{\mathbb{K},S}^{\times\Box}} \delta(\mathcal{T}_x^{(\varepsilon)})$  by properties  $(d_2)$  and  $(d_3)$ .

By Definition 4.22), if  $\mathfrak{p} \in \mathcal{P}_\varepsilon$ , then it has inertia degree 1 above  $\mathbb{K}$ , hence the congruence  $n \equiv \rho_\varepsilon \pmod{\mathfrak{p}}$  has a solution  $n \in \mathcal{O}_{\mathbb{K},S}$ . Therefore, the congruence relation  $n \not\equiv \rho_\varepsilon \pmod{\mathfrak{p}}$  has  $N(\mathfrak{p}) - 1$  solutions modulo  $\mathfrak{p}$ . Using the Chinese Remainder Theorem, since all non-zero prime ideals of the Dedekind domain  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon), S'_\varepsilon}$  are maximal, we know that the system of congruences  $(n \not\equiv \rho_\varepsilon \pmod{\mathfrak{p}})_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x}$  has  $\prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} (N(\mathfrak{p}) - 1)$  solutions modulo  $\prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} \mathfrak{p}$ .

Denote by  $\mathcal{R}_x^{(\varepsilon)}$  a set of lifts of those solutions to  $\mathcal{O}_{\mathbb{K},S}$ . Then, we can write

$$\begin{aligned} \mathcal{T}_x^{(\varepsilon)} &= \bigsqcup_{\alpha \in \mathcal{R}_x^{(\varepsilon)}} \left\{ n \in \mathcal{O}_{\mathbb{K},S} \mid n \equiv \alpha \pmod{\prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} \mathfrak{p}} \right\} \\ &= \bigsqcup_{\alpha \in \mathcal{R}_x^{(\varepsilon)}} \left( \alpha + \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} \mathfrak{p} \right). \end{aligned}$$



Since  $\#\mathcal{R}_x^{(\varepsilon)} = \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} (N(\mathfrak{p}) - 1)$ , we have

$$\delta(\mathcal{T}_x^{(\varepsilon)}) \leq \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon, N(\mathfrak{p}) \leq x} \left(1 - \frac{1}{N(\mathfrak{p})}\right)$$

by properties  $(d_4)$  and  $(d_5)$ . This being true for all  $x \in \mathbb{R}_+^\times$ , we infer that

$$\delta(\mathcal{T}_{triv}) \leq \sum_{\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}} \lim_{x \rightarrow +\infty} \delta(\mathcal{T}_x^{(\varepsilon)}) \leq \sum_{\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}} \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \left(1 - \frac{1}{N(\mathfrak{p})}\right).$$

□

The only remaining step is to show that  $\prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \left(1 - \frac{1}{N(\mathfrak{p})}\right) = 0$  for all  $\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}$ . Actually, this will be a consequence of the fact that the set  $\mathcal{P}_\varepsilon$  has strictly positive Dirichlet density.

**Theorem 4.26.** *Let  $f \in \mathcal{O}_{\mathbb{K}}[X]$  be a square-free monic polynomial of odd degree at least 3, let  $\mathcal{S}$  be defined by (4.3), let  $\delta$  be a density, and let  $q = [A, 2B, C] \in \text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ .*

*If  $q$  is not a square in  $\text{Cl}_{\mathcal{O}_{\mathbb{K}, \mathcal{S}}[X]}^{tw}(4f)$ , then the set*

$$\mathcal{T}_{triv} = \{n \in \mathcal{O}_{\mathbb{K}, \mathcal{S}} \mid [A(n), 2B(n), C(n)] \text{ is } \text{GL}_2^{tw}\text{-equivalent over } \mathcal{O}_{\mathbb{K}, \mathcal{S}} \text{ to } [1, 0, -f(n)]\}$$

*has density  $\delta(\mathcal{T}_{triv}) = 0$  in  $\mathcal{O}_{\mathbb{K}, \mathcal{S}}$ .*

*Proof.* According to Theorem 4.25, it remains to compute the product  $\prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \left(1 - \frac{1}{N(\mathfrak{p})}\right)$  for all  $\varepsilon \in \mathcal{O}_{\mathbb{K}, \mathcal{S}}^\times / \mathcal{O}_{\mathbb{K}, \mathcal{S}}^{\times \square}$ . Let us fix such an  $\varepsilon$ . As already noticed in the proof of Corollary 4.18, the set  $\mathcal{P}_\varepsilon$  from Definition 4.22 has Dirichlet density  $\frac{1}{2}$ , being the intersection of a set of Dirichlet density 1 (the prime ideals having inertia degree 1 over  $\mathbb{K}$ ) and another one of density  $\frac{1}{2}$  (the prime ideals inert in some quadratic extension). This implies that  $\sum_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \frac{1}{N(\mathfrak{p})^s} \xrightarrow{s \rightarrow 1^+} +\infty$ , since otherwise, the Dirichlet density of  $\mathcal{P}_\varepsilon$  would vanish by definition.

Beside this, one can order prime ideals of  $\mathcal{O}_{\mathbb{K}(\rho_\varepsilon), \mathcal{S}'_\varepsilon}$  such that the sequence  $(N(\mathfrak{p}_j))_j$  is increasing. Applying [Jan96, Lemma IV.4.4] with  $u_j := N(\mathfrak{p}_j)$  leads to

$$\sum_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \frac{1}{N(\mathfrak{p})^s} = - \sum_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \ln \left(1 - \frac{1}{N(\mathfrak{p})^s}\right) + O(1)$$

for all  $s > 1$ . Taking the exponential, we get

$$\begin{aligned} \prod_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \left(1 - \frac{1}{N(\mathfrak{p})^s}\right) &= \exp \left( \sum_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \ln \left(1 - \frac{1}{N(\mathfrak{p})^s}\right) \right) \\ &= \exp \left( - \sum_{\mathfrak{p} \in \mathcal{P}_\varepsilon} \frac{1}{N(\mathfrak{p})^s} \right) \exp \left( O(1) \right) \xrightarrow{s \rightarrow 1^+} 0. \end{aligned}$$

The conclusion is now straightforward, applying Theorem 4.25. □

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