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# Computing the equisingularity type of a pseudo-irreducible polynomial

Adrien Poteaux · Martin Weimann

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**Abstract** Germs of plane curve singularities can be classified accordingly to their equisingularity type. For singularities over  $\mathbb{C}$ , this important data coincides with the topological class. In this paper, we characterise a family of singularities, containing irreducible ones, whose equisingularity type can be computed in an expected quasi-linear time with respect to the discriminant valuation of a Weierstrass equation.

**Keywords** Polynomials · Plane curves · Equisingularity · Pseudo-irreducibility · Approximate roots

**Mathematics Subject Classification (2010)** 14Q20 · 12Y05 · 13P05 · 68W30

## 1 Introduction

Equisingularity is the main notion of equivalence for germs of plane curves. It was developed in the 60's by Zariski over algebraically closed fields of characteristic zero in [29–31] and generalised in arbitrary characteristic by Campillo [2]. This concept is of particular importance as for complex curves, it agrees with the topological equivalence class [29]. As illustrated by an extensive literature (see e.g. the book [9] and the references therein), equisingularity plays nowadays an important role in various active fields of singularity theory (resolution, equinormalisable deformation, moduli problems, analytic classification, etc). It is thus an important issue of computer

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algebra to design efficient algorithms for computing the equisingularity type of a singularity. This paper is dedicated to characterise a family of reduced germs of plane curves, containing irreducible ones, for which this task can be achieved in quasi-linear time with respect to the discriminant valuation of a Weierstrass equation.

*Main result.* We say that two germs of reduced plane curves are equisingular if there is a one-to-one correspondence between their branches which preserves the characteristic exponents and the pairwise intersection multiplicities (see e.g. [2, 3, 27] for other equivalent definitions). This equivalence relation leads to the notion of equisingularity type of a singularity. In this paper, we consider a square-free Weierstrass polynomial  $F \in \mathbb{K}[[x]][y]$  of degree  $d$ , with  $\mathbb{K}$  a perfect field of characteristic zero or greater than  $d$ <sup>1</sup>. Under such an assumption, the Puiseux series of  $F$  are well defined and allow to determine the equisingularity type of the germ  $(F, 0)$  (the case of small characteristic requires Hamburger-Noether expansions [2]). In particular, it follows from [22] that we can compute the equisingularity type in an expected  $\mathcal{O}(\delta d)^2$  operations over  $\mathbb{K}$ , where  $\delta$  stands for the valuation of the discriminant of  $F$ . If  $F$  is irreducible, it is shown in [23] that we can reach the lower complexity  $\mathcal{O}(\delta)$  thanks to the theory of approximate roots. A natural question arises : can we reach this quasi-optimal complexity  $\mathcal{O}(\delta)$  for a larger class of reducible polynomials ?

We say that  $F$  is *pseudo-irreducible*<sup>3</sup> or *balanced*<sup>4</sup> if all its absolutely irreducible factors have the same set of characteristic exponents and the same set of pairwise intersection multiplicities, see Section 2. Irreducibility over any algebraic field extension of  $\mathbb{K}$  implies pseudo-irreducibility by a Galois argument, but the converse does not hold. As a basic example, the Weierstrass polynomial  $F = (y-x)(y-x^2)$  is pseudo-irreducible, but is obviously reducible (see Example 1 for more). We prove:

**Theorem 1.** *There exists an algorithm which tests if  $F$  is pseudo-irreducible with an expected  $\mathcal{O}(\delta)$ <sup>5</sup> operations over  $\mathbb{K}$ . If  $F$  is pseudo-irreducible, the algorithm computes also  $\delta$  and the number of absolutely irreducible factors of  $F$  together with their sets of characteristic exponents and sets of pairwise intersection multiplicities. In particular, it computes the equisingularity type of the germ  $(F, 0)$ .*

*Remark 1.* The algorithm contains a Las Vegas subroutine for computing primitive elements in residue rings; however it should become deterministic thanks to [13].

Our algorithm does not perform univariate irreducible factorisation, but uses only square-free factorisation instead. However, for a given field extension  $\mathbb{L}$  of  $\mathbb{K}$ , we can also compute the degrees, residual degrees and ramification indices of the irreducible factors of  $F$  in  $\mathbb{L}[[x]][y]$  by performing an extra univariate factorisation of degree at most  $d$  over  $\mathbb{L}$ . Our long term objective being fast factorisation in  $\mathbb{K}[[x]][y]$ , we extend in Section 5.3 the definition of pseudo-irreducibility to non Weierstrass polynomials,

<sup>1</sup> Our results still hold under the weaker assumption that the characteristic of  $\mathbb{K}$  does not divide  $d$ .

<sup>2</sup> As usual, the notation  $\mathcal{O}()$  hides logarithmic factors

<sup>3</sup> The terminology *pseudo-irreducible* is also used in [14] to design polynomials which cannot be factored into comaximal polynomials. These two notions are not related to each other.

<sup>4</sup> In the sequel, we rather use the terminology *balanced* and give an alternative definition of pseudo-irreducibility based on a Newton-Puiseux type algorithm. Both notions agree from Theorem 2.

<sup>5</sup> Note that  $F$  being Weierstrass, we have  $d \leq \delta$  and  $\delta \log(d) \in \mathcal{O}(\delta)$ .

taking into account all germs of curves defined by  $F$  along the line  $x = 0$ . In this more general setting, we get a complexity  $\mathcal{O}(\delta + d)^6$ .

*Main tools.* We generalise the irreducibility test obtained in [23], which is itself a generalisation of Abhyankhar’s absolute irreducibility criterion [1], based on the theory of approximate roots. The main idea is to compute recursively some suitable approximate roots  $\psi_0, \dots, \psi_g$  of  $F$  of strictly increasing degrees such that  $F$  is pseudo-irreducible if and only if we reach  $\psi_g = F$ . At step  $k$ , we compute the  $(\psi_0, \dots, \psi_k)$ -adic expansion of  $F$  from which we can construct a generalised Newton polygon. If the corresponding boundary polynomial of  $F$  is not pseudo-degenerate (Definition 4), then  $F$  is not pseudo-irreducible. Otherwise, we deduce the degree of the next approximate root  $\psi_{k+1}$  that has to be computed.

Our algorithm is optimised in the sense that it computes only the minimal amount of information required for testing pseudo-irreducibility and computing the equisingularity type (roughly speaking, it computes only the initial terms of the Puiseux series  $y_i - y_j$  where  $y_i, y_j$  run over the roots of  $F$ , see Remark 6).

*Differences and additional interest with the irreducibility test of [23].* The key difference when compared to the irreducibility test developed in [23] is that we may allow the successive generalised Newton polygons to have several edges, although no splittings and no Hensel liftings are required. Except this slight modification, most of the algorithmic considerations have already been studied in [23] and the main interest of this paper is more of a theoretical nature, focused on two main points: proving that pseudo-degeneracy is the right condition for characterising pseudo-irreducibility, and giving formulas for the intersection multiplicities and characteristic exponents in terms of the underlying edge data sequence. This is our main Theorem 2.

Additionally to the statements of our main theorems, their proofs enlighten the important following fact : *a polynomial  $F$  is pseudo-irreducible if and only if its equisingularity type can be read on a suitable sequence of approximate roots of  $F$ .* As a consequence, the underlying algorithm relies only on a few “black box” functions. In particular, the dynamic evaluation inherent to arithmetic operations in the towers of residue rings is in such a case reduced to univariate computations (the remaining tasks being simply Newton iterations and multiplications in  $\mathbb{K}[[x]][y]$ ), which makes this algorithm easy to implement. If  $F$  is not pseudo-irreducible, then we need at some point to compute a factorisation  $F = GH$  (up to some suitable precision) in order to apply the approximate roots strategy on each discovered factor  $G, H$ . In [22], it is shown that these factorisation steps cost  $\mathcal{O}(d\delta)$ , assuming a divide and conquer strategy. The underlying algorithm is much more tricky to implement as it uses dynamic evaluation for bivariate computations (for instance, the extension of the half-gcd [16, Algorithm 1] in the context of dynamic evaluation, a key point of the divide and conquer strategy, is not available in any classical library for the moment). These considerations show that, up to our knowledge, pseudo-irreducible polynomials constitute the largest class of polynomials whose equisingularity type can be efficiently computed with quasi-linear complexity  $\mathcal{O}(\delta)$  in the current state

<sup>6</sup> When  $F$  is Weierstrass, we have  $d \leq \delta$ . Otherwise, we might have  $d \notin \mathcal{O}(\delta)$ .

of the art. As such, they deserve to be considered as elementary bricks for a fast and easy-to-implement algorithm which computes the equisingularity type of a general germ of curve. This larger program is an ongoing work.

*Related results.* Computing the equisingularity type of a plane curve singularity is a classical topic for which both symbolic and numerical methods exist. A classical approach is derived from the Newton-Puiseux algorithm, as a combination of blow-ups (monomial transforms and shifts) and Hensel liftings. This approach allows to compute the roots of  $F$  - represented as fractional Puiseux series - up to an arbitrary precision, from which the equisingularity type of the germ  $(F, 0)$  can be deduced (see e.g. Theorem 2 for precise formulas). The Newton-Puiseux algorithm has been studied by many authors (see e.g. [4, 5, 19–23, 26, 28] and the references therein). Up to our knowledge, the best current arithmetic complexity was obtained in [22], computing the singular parts of all Puiseux series above  $x = 0$  - hence the equisingularity type of all germs of curves defined by  $F$  along this line - in an expected  $\mathcal{O}(d \delta)$  operations over  $\mathbb{K}$ . Here, we get rid of the  $d$  factor for pseudo-irreducible polynomials, generalising the irreducible case considered in [23]. For complex curves, the equisingularity type agrees with the topological class and there exists other numerical-symbolic methods of a more topological nature (see e.g. [10–12, 17, 25] and the references therein). The main results of this paper and the irreducibility test in [23] are grouped together in a long preprint [24]. The length of this preprint finally led us to publish it into two separate parts.

*Organisation.* We define balanced polynomials in Section 2. Section 3 introduces the notion of pseudo-degeneracy. This leads to an alternative definition of a pseudo-irreducible polynomial, based on a Newton-Puiseux type algorithm. In Section 4, we prove that being balanced is equivalent to being pseudo-irreducible and we give explicit formulas for characteristic exponents and intersection multiplicities in terms of edge data (Theorem 2). In the last Section 5, we design a pseudo-irreducibility test based on approximate roots with quasi-linear complexity, thus proving Theorem 1. We finally illustrate our method on various examples.

## 2 Balanced polynomials

Let us fix  $F \in \mathbb{K}[[x]][y]$  a Weierstrass polynomial defined over a perfect field  $\mathbb{K}$  of characteristic zero or greater than  $d = \deg(F)$ . We denote by  $(F, 0)$  the germ of the plane curve defined by  $F$  at the origin of the affine plane  $\overline{\mathbb{K}}^2$ . We say that  $F$  is absolutely irreducible if it is irreducible in  $\overline{\mathbb{K}}[[x]][y]$ . The germs of curves defined by the absolutely irreducible factors of  $F$  are called the branches of the germ  $(F, 0)$ .

### 2.1 Characteristic exponents

We assume here that  $F$  is absolutely irreducible. As the characteristic of  $\mathbb{K}$  does not divide  $d$ , there exists a unique series  $S(T) = \sum c_i T^i \in \overline{\mathbb{K}}[[T]]$  such that  $F(T^d, S(T)) =$

0. The pair  $(T^d, S(T))$  is the classical Puiseux parametrisation of the branch  $(F, 0)$ . The *characteristic exponents* of  $F$  are defined as

$$\beta_0 = d, \quad \beta_k = \min(i \text{ s.t. } c_i \neq 0, \gcd(\beta_0, \dots, \beta_{k-1}) \nmid i), \quad k = 1, \dots, g,$$

where  $g$  is the least integer for which  $\gcd(\beta_0, \dots, \beta_g) = 1$  (characteristic exponents are sometimes referred to the rational numbers  $\beta_i/d$  in the literature). These are the exponents  $i$  for which a non trivial factor of the ramification index is discovered. It is well known that the data

$$C(F) = (\beta_0; \beta_1, \dots, \beta_g)$$

determines the equisingularity type of the germ  $(F, 0)$ , see e.g. [29]. Conversely, the Weierstrass equations of two equisingular germs of curves which are not tangent to the  $x$ -axis have same characteristic exponents [3, Corollary 5.5.4]. If tangency occurs, we rather need to consider the characteristic exponents of the local equation obtained after a generic change of local coordinates, which form a complete set of equisingular (hence topological if  $\mathbb{K} = \mathbb{C}$ ) invariants. The set  $C(F)$  and the set of generic characteristic exponents determine each others assuming that we are given the contact order  $\beta_0$  with  $x$ -axis ([18, Proposition 4.3] or [3, Corollary 5.6.2]). It is well known that a data equivalent to  $C(F)$  is given by the semi-group of  $F$ , and that this semi-group admits the intersection multiplicities of  $F$  with its characteristic approximate roots  $\psi_{-1}, \psi_0, \dots, \psi_g$  as a minimal system of generators (see Section 5.1 and [3, Corollaries 5.8.5 and 5.9.11]).

## 2.2 Intersection sets

If we want to determine the equisingularity type of a reducible germ  $(F, 0)$ , we need to consider also the pairwise intersection multiplicities between the absolutely irreducible factors of  $F$ . The intersection multiplicity between two coprime Weierstrass polynomials  $G, H \in \mathbb{K}[[x]][y]$  is defined as

$$(G, H)_0 := v_x(\text{Res}_y(G, H)) = \dim_{\overline{\mathbb{K}}} \frac{\overline{\mathbb{K}}[[x]][y]}{(G, H)}, \quad (1)$$

where  $\text{Res}_y$  stands for the resultant with respect to  $y$  and  $v_x$  is the usual  $x$ -valuation. The right hand equality follows from classical properties of the resultant. Suppose that  $F$  has (distinct) absolutely irreducible factors  $F_1, \dots, F_f$ . We introduce *the intersection sets* of  $F$ , defined for  $i = 1, \dots, f$  as

$$\Gamma_i(F) := ((F_i, F_j)_0, 1 \leq j \leq f, j \neq i).$$

By convention, we take into account repetitions,  $\Gamma_i(F)$  being considered as an unordered list with cardinality  $f - 1$ . If  $F$  is Weierstrass, the equisingular type (hence the topological class if  $\mathbb{K} = \mathbb{C}$ ) of the germ  $(F, 0)$  is uniquely determined by the characteristic exponents and the intersections sets of the branches of  $F$  [32]. Note that the set  $C(F_i)$  only depends on  $F_i$  while  $\Gamma_i(F)$  depends on  $F$ .

### 2.3 Balanced polynomials

**Definition 1.** We say that a square-free Weierstrass<sup>7</sup> polynomial  $F \in \mathbb{K}[[x]][y]$  is *balanced* if  $C(F_i) = C(F_j)$  and  $\Gamma_i(F) = \Gamma_j(F)$  for all  $i, j$ . In such a case, we denote simply these sets by  $C(F)$  and  $\Gamma(F)$ .

Thus, if  $F$  is balanced, its branches are equisingular and have the same set of pairwise intersection multiplicities. The converse holds if no branch is tangent to the  $x$ -axis or all branches are tangent to the  $x$ -axis.

**Example 1.** Let us illustrate this definition with some basic examples. Note that the second and third examples show in particular that no condition implies the other in Definition 1.

1. If  $F \in \mathbb{K}[[x]][y]$  is irreducible, a Galois argument shows that it is balanced (follows from Theorem 2 below). The converse doesn't hold:  $F = (y-x)(y+x^2)$  is reducible, but it is balanced. This example also shows that being balanced does not imply the Newton polygon to be straight.
2.  $F = (y^2-x^3)(y^2+x^3)(y^2+x^3+x^4)$  is not balanced. It has 3 absolutely irreducible factors with same sets of characteristic exponents  $C(F_i) = (2;3)$  for all  $i$ , but  $\Gamma_1(F) = (6,6)$  while  $\Gamma_2(F) = \Gamma_3(F) = (6,8)$ .
3.  $F = (y-x-x^2)(y-x+x^2)(y^2-x^3)$  is not balanced. It has 3 absolutely irreducible factors with same sets of pairwise intersection multiplicities  $\Gamma_i(F) = (2,2)$ , but  $C(F_1) = C(F_2) = (1)$  while  $C(F_3) = (2;3)$ .
4.  $F = (y^2-x^2)^2 - 2x^4y^2 - 2x^6 + x^8$  has four absolutely irreducible factors, namely  $F_1 = y+x+x^2$ ,  $F_2 = y+x-x^2$ ,  $F_3 = y-x+x^2$  and  $F_4 = y-x-x^2$ . We have  $C(F_i) = (1)$  and  $\Gamma_i(F) = (1,1,2)$  for all  $i$  so  $F$  is balanced. Note that this example shows that being balanced does not imply that all factors intersect each others with the same multiplicity.
5.  $F = (y^2-x^3)(y^3-x^2)$  is not balanced. However, it defines two equisingular germs of plane curves (but one is tangent to the  $x$ -axis while the other is not).

*Noether-Merle's Formula.* If  $F, G \in \overline{\mathbb{K}}[[x]][y]$  are two irreducible Weierstrass polynomials of respective degrees  $d_F$  and  $d_G$ , their intersection multiplicity  $(F, G)_0$  is closely related to the characteristic exponents  $(\beta_0, \dots, \beta_g)$  of  $F$ . Let us denote by

$$\text{Cont}(F, G) := d_F \max(v_x(y-y') \mid F(y) = 0, G(y') = 0) \quad (2)$$

the *contact order* of the branches  $F$  and  $G$  and let  $\kappa = \max\{k \mid \text{Cont}(F, G) \geq \beta_k\}$ . Then Noether-Merle's formula [15, Proposition 2.4] states

$$(F, G)_0 = \frac{d_G}{d_F} \left( \sum_{k \leq \kappa} (E_{k-1} - E_k) \beta_k + E_\kappa \text{Cont}(F, G) \right), \quad (3)$$

where  $E_k := \gcd(\beta_0, \dots, \beta_k)$ . A proof can be found in [18, Proposition 6.5] (and references therein), where a formula is given in terms of the semi-group generators, which turns out to be equivalent to (3) thanks to [18, Proposition 4.2]. Note that the original proof in [15] assumes that the germs  $F$  and  $G$  are transverse to the  $x$ -axis.

<sup>7</sup> We can extend this definition to non-Weierstrass polynomials, see Section 5.3.

### 3 Pseudo-irreducible polynomials

#### 3.1 Pseudo-degenerate polynomials.

We first recall classical definitions that play a central role for our purpose, namely the Newton polygon and the residual polynomial. We will have to work over various residue rings isomorphic to some direct product of field extensions of the base field  $\mathbb{K}$ . Let  $\mathbb{A} = \mathbb{L}_0 \oplus \cdots \oplus \mathbb{L}_r$  be such a ring. If  $S = \sum c_i x^i \in \mathbb{A}[[x]]$ , we define  $v_x(S) = \min(i, c_i \neq 0)$  with convention  $v_x(0) = +\infty$ . Note that in contrast to usual valuations, we have  $v_x(S_1 S_2) \geq v_x(S_1) + v_x(S_2)$  and strict inequality might occur since  $\mathbb{A}$  is allowed to contain zero divisors. We let  $\mathbb{A}^\times$  stands for the group of units of  $\mathbb{A}$ .

In the following definitions, we assume that  $F \in \mathbb{A}[[x]][y]$  is a Weierstrass polynomial and we let  $F = \sum_{i=0}^d a_i(x)y^i = \sum_{i,j} a_{ij}x^i y^j$ . The support  $\text{Supp}(F) \subset \mathbb{N}^2$  is the set of exponents  $(i, j)$  for which  $a_{ij} \neq 0$ .

**Definition 2.** The *Newton polygon* of  $F$  is the lower convex hull  $\mathcal{N}(F)$  of its support. The unique edge with vertice  $(d, 0)$  is called the lower edge, denoted by  $\mathcal{N}_0(F)$ .

The lower edge has equation  $mi + qj = l$  for some uniquely determined coprime positive integers  $q, m$  and  $l \in \mathbb{N}$ . We say for short that  $\mathcal{N}_0(F)$  has slope  $(q, m)$ , with convention  $(q, m) = (1, 0)$  if the Newton polygon of  $F$  is reduced to a point.

**Definition 3.** We call  $\bar{F} := \sum_{(i,j) \in \mathcal{N}_0(F)} a_{ij}x^i y^j$  the *lower boundary polynomial* of  $F$ .

We say that a polynomial  $P \in \mathbb{A}[Z]$  is *square-free* if its images under the natural morphisms  $\mathbb{A} \rightarrow \mathbb{L}_i$  are square-free (in the usual sense over a field).

**Definition 4.** We say that  $F \in \mathbb{A}[[x]][y]$  is *pseudo-degenerate* if there exists  $N \in \mathbb{N}$  and  $P \in \mathbb{A}[Z]$  monic and square-free such that

$$\bar{F} = \left( P \left( \frac{y^q}{x^m} \right) x^{m \deg(P)} \right)^N, \quad (4)$$

with moreover  $P(0) \in \mathbb{A}^\times$  if  $q > 1$ . We call  $P$  the *residual polynomial* of  $F$ . The tuple  $(q, m, P, N)$  is the *edge data* of  $F$ .

*Remark 2.* In practice, we check pseudo-degeneracy as follows. If  $q$  does not divide  $d$ , then  $F$  is not pseudo-degenerate. If  $q$  divides  $d$ , then  $q \mid i$  for all  $(i, j) \in \mathcal{N}_0(F)$  as  $(d, 0) \in \mathcal{N}_0(F)$  by assumption. Hence we may consider  $Q = \sum_{(i,j) \in \mathcal{N}_0(F)} a_{ij}Z^{i/q} \in \mathbb{A}[Z]$  and  $F$  is pseudo-degenerate if and only if  $Q = P^N$  for some square-free polynomial  $P$  such that  $P(0) \in \mathbb{A}^\times$  if  $q > 1$ .

*Remark 3.* If  $q > 1$ , the extra condition  $P(0) \in \mathbb{A}^\times$  implies that  $\mathcal{N}(F)$  is straight (i.e. it has a unique edge). If  $q = 1$ , we allow  $P(0)$  to be a zero-divisor (in contrast to Definition 4 of quasi-degeneracy in [23]), in which case  $\mathcal{N}(F)$  may have several edges. Note that if  $F$  is pseudo-degenerate,  $\bar{F}$  is the power of a square-free quasi-homogeneous polynomial, but the converse doesn't hold (case 4 below).

#### Example 2.

1. Let  $F = (y^2 - x^2)^2(y - x^3)$ . Then  $\mathcal{N}(F)$  has three edges, the lower one of slope  $(q, m) = (1, 1)$ . We get  $\bar{F} = (y^3 - x^2y)^2$  and  $Q = (Z^3 - Z)^2$ . Hence,  $F$  is pseudo-degenerate, with  $P = Z^3 - Z$  and  $N = 2$ .



2. Let  $F = (y^2 - x^2)^2(y - x^2)$ . Then  $\mathcal{N}(F)$  has two edges, the lower one of slope  $(q, m) = (1, 1)$ . We get  $\bar{F} = y(y^2 - x^2)^2$  and  $Q = Z(Z^2 - 1)^2$  is not a power of a square-free polynomial. Hence,  $F$  is not pseudo-degenerate.
3. Let  $F = (y^2 - x^3)^2(y - x^4)$ . Then  $\mathcal{N}(F)$  has two edges, the lower one of slope  $(q, m) = (2, 3)$ . As  $q$  does not divide  $d = 5$ ,  $F$  is not pseudo-degenerate.
4. Let  $F = (y^2 - x^3)^2(y - x^4)^2$ . Then  $\mathcal{N}(F)$  is straight of slope  $(q, m) = (2, 3)$ . Here  $q$  divides  $d = 6$ . We get  $\bar{F} = y^2(y^2 - x^3)^2$  which is a power of a square-free polynomial. However,  $Q = Z(Z - 1)^2$  is not. Hence,  $F$  is not pseudo-degenerate.
5. Let  $F = (y^2 - x^3)^2(y^2 - x^4)^2$ . Then  $\mathcal{N}(F)$  has two edges, the lower one of slope  $(q, m) = (2, 3)$ . Here  $q$  divides  $d = 8$ . We get  $\bar{F} = (y^4 - y^2x^3)^2$  and  $Q = (Z^2 - Z)^2$  is the power of the square-free polynomial  $P = Z^2 - Z$ . However,  $q > 1$  and  $P(0) = 0$  so  $F$  is not pseudo-degenerate.

Note that we could also treat cases 3, 4 and 5 simply by using Remark 3:  $q > 1$  and  $\mathcal{N}(F)$  not straight imply that  $F$  is not pseudo-degenerate.

The next lemma allows to associate to a pseudo-degenerate polynomial  $F$  a new Weierstrass polynomial of smaller degree, generalising the usual case (e.g. [5, Section 4] or [21, Proposition 3]) to the case of product of fields.

**Lemma 1.** *Suppose that  $F$  is pseudo-degenerate with edge data  $(q, m, P, N)$  and denote  $(s, t)$  the unique positive integers such that  $sq - tm = 1$ ,  $0 \leq t < q$ . Let  $z$  be the residue class of  $Z$  in the ring  $\mathbb{A}_P := \mathbb{A}[Z]/(P(Z))$  and  $\ell := \deg(P)$ . Then*

$$F(z^\ell x^q, x^m(y + z^s)) = x^{qm\ell N} UG, \quad (5)$$

where  $U, G \in \mathbb{A}_P[[x]][y]$ ,  $U(0, 0) \in \mathbb{A}_P^\times$  and  $G$  is a Weierstrass polynomial of degree  $N$  dividing  $d$ . Moreover, if  $F \neq y^d$  and  $F$  has no terms of degree  $d - 1$ , then  $N < d$ .

*Proof.* As  $F$  is pseudo-degenerate, its lower edge  $\mathcal{N}_0(F)$  has equation  $mi + qj = qm\ell N$  and we may write  $F = \bar{F} + Q$ , with  $\bar{F}$  as in (4) and where  $\text{Supp}(Q)$  lies strictly above  $\mathcal{N}_0(F)$ . In particular,  $v_x(Q(z^\ell x^q, x^m(y + z^s))) > qm\ell N$ . Combined with (4), we get that  $\tilde{F}(x, y) := x^{-qm\ell N} F(z^\ell x^q, x^m(y + z^s))$  satisfies  $\tilde{F} \in \mathbb{A}_P[[x]][y]$  and  $\tilde{F}(0, y) = R(y)^N$  where  $R(y) = P((y + z^s)^q / z^{tm})$ . In particular, we have  $R(0) = P(z) = 0$  and  $R'(0) = qz^{1-s}P'(0)$ . As  $P$  is square-free and the characteristic of  $\mathbb{A}$  does not divide  $\deg(P)$  by assumption, we have  $P'(0) \in \mathbb{A}^\times$ . As  $qz^{1-s} \in \mathbb{A}_P^\times$  (if  $q > 1$ , the assumption  $P(0) \in \mathbb{A}^\times$  implies  $P$  and  $Z$  coprime, that is  $z \in \mathbb{A}_P^\times$ ; if  $q = 1$ , then  $s = 1$ ), it follows that  $R'(0) \in \mathbb{A}_P^\times$ . We deduce that  $\tilde{F}(0, y) = y^N S(y)$  where  $y^N$  and  $S(y)$  are coprime in  $\mathbb{A}_P[y]$ . We conclude thanks to the Weierstrass preparation theorem that  $F$  factorises as in (5). Note that  $N|d$  by (4). If  $N = d$ , then (4) forces  $\bar{F} = (y + \alpha x^m)^d$  for some  $\alpha \in \mathbb{A}$ . If  $\alpha = 0$ , then  $\mathcal{N}(F)$  is reduced to a point and we must have  $F = y^d$ . If  $\alpha \neq 0$ , the coefficient of  $y^{d-1}$  in  $F$  is  $d\alpha x^{md} + h.o.t.$ , hence is non zero since the characteristic of  $\mathbb{A}$  does not divide  $d$ .  $\square$

*Remark 4.* As  $P \in \mathbb{A}[Z]$  is square-free, the ring  $\mathbb{A}_P = \mathbb{A}[Z]/(P(Z))$  is still isomorphic to a direct product of perfect fields thanks to the Chinese Remainder Theorem. Note also that  $z^\ell$  is invertible: if  $z$  is a zero divisor, we must have  $q = 1$  so that  $t = 0$  and  $z^\ell = 1$ .

### 3.2 Pseudo-irreducible polynomials

The definition of a pseudo-irreducible polynomial is based on a variation of the classical Newton-Puiseux algorithm. Thanks to Lemma 1, we associate to  $F$  a sequence of Weierstrass polynomials  $H_0, \dots, H_g$  of strictly decreasing degrees  $N_0, \dots, N_g$  such that  $H_k$  is pseudo-degenerate if  $k < g$  and such that either  $H_g$  is not pseudo-degenerate or  $N_g = 1$ . We proceed recursively as follows:

*Rank  $k = 0$ .* Let  $N_0 = d$ ,  $\mathbb{K}_0 = \mathbb{K}$ ,  $c_0(x) := -\text{Coef}(F, y^{N_0-1})/N_0$  and

$$H_0(x, y) := F(x, y + c_0(x)) \in \mathbb{K}_0[[x]][y]. \quad (6)$$

Then  $H_0$  is a new Weierstrass polynomial of degree  $N_0$  with no terms of degree  $N_0 - 1$ . If  $N_0 = 1$  or  $H_0$  is not pseudo-degenerate, we let  $g = 0$ .

*Rank  $k > 0$ .* Suppose given  $\mathbb{K}_{k-1}$  a direct product of fields extension of  $\mathbb{K}$  and  $H_{k-1} \in \mathbb{K}_{k-1}[[x]][y]$  a pseudo-degenerate Weierstrass polynomial of degree  $N_{k-1} > 1$ , with no terms of degree  $N_{k-1} - 1$ . Denote by  $(q_k, m_k, P_k, N_k)$  its edge data and  $\ell_k := \deg(P_k)$ . As  $P_k$  is square-free, the ring  $\mathbb{K}_k := \mathbb{K}_{k-1}[Z_k]/(P_k(Z_k))$  is again (isomorphic to) a direct product of fields. We let  $z_k \in \mathbb{K}_k$  be the residue class of  $Z_k$  and  $(s_k, t_k)$  the unique positive integers such that  $s_k q_k - t_k m_k = 1$ ,  $0 \leq t_k < q_k$ . As  $H_{k-1}$  is pseudo-degenerate, we deduce from Lemma 1 that

$$H_{k-1}(z_k^{t_k} x^{q_k}, x^{m_k} (y + z_k^{s_k})) = x^{q_k m_k \ell_k N_k} U_k G_k, \quad (7)$$

where  $U_k(0, 0) \in \mathbb{K}_k^\times$  and  $G_k \in \mathbb{K}_k[[x]][y]$  is a Weierstrass polynomial of degree  $N_k$ . Letting  $c_k := -\text{Coef}(G_k, y^{N_k-1})/N_k$ , we define

$$H_k(x, y) = G_k(x, y + c_k(x)) \in \mathbb{K}_k[[x]][y]. \quad (8)$$

It is a degree  $N_k$  Weierstrass polynomial with no terms of degree  $N_k - 1$ .

*The  $N_k$ -sequence stops.* We have the relations  $N_k = q_k \ell_k N_{k-1}$ . As  $H_{k-1}$  is pseudo-degenerate with no terms of degree  $N_{k-1} - 1$ , we have  $N_k < N_{k-1}$  by Lemma 1. Hence the sequence of integers  $N_0, \dots, N_k$  is strictly decreasing and there exists a smallest index  $g$  such that either  $N_g = 1$  (and  $H_g = y$ ), either  $N_g > 1$  and  $H_g$  is not pseudo-degenerate. We collect the edge data of the polynomials  $H_0, \dots, H_{g-1}$  in a list

$$\text{Data}(F) := ((q_1, m_1, P_1, N_1), \dots, (q_g, m_g, P_g, N_g)).$$

Note that  $m_k > 0$  for all  $1 \leq k \leq g$ . We include the  $N_k$ 's in the list for convenience (they could be deduced from the remaining data via the relations  $N_k = N_{k-1}/q_k \ell_k$ ).

**Definition 5.** We say that  $F$  is *pseudo-irreducible* if  $N_g = 1$ .

### 4 Pseudo-irreducible is equivalent to balanced.

We prove here our main result, Theorem 2: a square-free Weierstrass polynomial  $F \in \mathbb{K}[[x]][y]$  is pseudo-irreducible if and only if it is balanced, in which case we compute characteristic exponents and intersection sets of the irreducible factors.

#### 4.1 Notation and main results.

We use the notations of Section 3; in particular  $(q_1, m_1, P_1, N_1), \dots, (q_g, m_g, P_g, N_g)$  denote the edge data of  $F$ . We define  $e_k := q_1 \cdots q_k$  (current index of ramification),  $e := e_g$ ,  $\hat{e}_k := e/e_k$  and in an analogous way  $f_k := \ell_1 \cdots \ell_k$  (current residual degree),  $f := f_g$  and  $\hat{f}_k := f/f_k$ . For all  $k = 1, \dots, g$ , we define

$$B_k = m_1 \hat{e}_1 + \cdots + m_k \hat{e}_k \quad \text{and} \quad M_k = m_1 \hat{e}_0 \hat{e}_1 + \cdots + m_k \hat{e}_{k-1} \hat{e}_k \quad (9)$$

and we let  $B_0 = e$ . These are positive integers related by the formula

$$M_k = \sum_{i=1}^k (\hat{e}_{i-1} - \hat{e}_i) B_i + \hat{e}_k B_k. \quad (10)$$

Note that  $0 < B_1 \leq \cdots \leq B_g$ <sup>8</sup> and  $B_0 \leq B_g$ . We have  $B_0 \leq B_1$  if and only if  $q_1 \leq m_1$ , if and only if  $F = 0$  is not tangent to the  $x$ -axis at the origin. We check easily that  $\hat{e}_k = \gcd(B_0, \dots, B_k)$ . In particular,  $\gcd(B_0, \dots, B_g) = 1$ .

**Theorem 2.** *A Weierstrass polynomial  $F \in \mathbb{K}[[x]][y]$  is balanced if and only if it is pseudo-irreducible. In such a case,  $F$  has  $f$  irreducible factors in  $\overline{\mathbb{K}}[[x]][y]$ , all with degree  $e$ , and*

1.  $C(F) = (B_0; B_k | q_k > 1)$  - so  $C(F) = (1)$  if  $q_k = 1$  for all  $k$ .
2.  $\Gamma(F) = (M_k | \ell_k > 1)$ , where  $M_k$  appears  $\hat{f}_{k-1} - \hat{f}_k$  times.

Taking into account repetitions, the intersection set has cardinality  $\sum_{k=1}^g (\hat{f}_{k-1} - \hat{f}_k) = f - 1$ , as required. It is empty if and only if  $F$  is absolutely irreducible.

**Corollary 1.** *Let  $F \in \mathbb{K}[[x]][y]$  be a balanced Weierstrass polynomial. Then, the discriminant of  $F$  has valuation*

$$\delta = f \left( \sum_{\ell_k > 1} (\hat{f}_{k-1} - \hat{f}_k) M_k + \sum_{q_k > 1} (\hat{e}_{k-1} - \hat{e}_k) B_k \right)$$

and the discriminants of the absolutely irreducible factors of  $F$  all have the same valuation  $\sum_{q_k > 1} (\hat{e}_{k-1} - \hat{e}_k) B_k$ .

*Proof.* (of Corollary 1) When  $F$  is balanced, it has  $f$  irreducible factors  $F_1, \dots, F_f$  of same degree  $e$ , with discriminant valuations say  $\delta_1, \dots, \delta_f$ . The multiplicative property of the discriminant gives the well-known formula

$$\delta = \sum_{1 \leq i \leq f} \delta_i + \sum_{1 \leq i \neq j \leq f} (F_i, F_j)_0. \quad (11)$$

Let  $y_1, \dots, y_e$  be the roots of  $F_i$ . Thanks to [27, Proposition 4.1.3 (ii)] combined with point 1 of Theorem 2, we deduce that for each fixed  $a = 1, \dots, e$ , the list  $(v_x(y_a - y_b), b \neq a)$  consists of the values  $B_k/e$  repeated  $\hat{e}_{k-1} - \hat{e}_k$  times for  $k = 1, \dots, g$ . Since  $\delta_i = \sum_{1 \leq a \neq b \leq e} v_x(y_a - y_b)$ , we deduce that  $\delta_1 = \cdots = \delta_f = \sum_{q_k > 1} (\hat{e}_{k-1} - \hat{e}_k) B_k$ . The formula for  $\delta$  follows directly from (11) combined with point 2 of Theorem 2.  $\square$

<sup>8</sup> We may allow  $m_1 = B_1 = 0$  when considering non Weierstrass polynomials, see Section 5.3.

The remaining part of this section is dedicated to the proof of Theorem 2. It is quite technical, but has the advantage to be self-contained. We first establish the relations between the (pseudo)-rational Puiseux expansions and the classical Puiseux series of  $F$  (Section 4.2). This allows us to deduce the characteristic exponents and the intersection sets of a pseudo-irreducible polynomial (thanks to Noether-Merle's formula), proving in particular that pseudo-irreducible implies balanced (Section 4.3). We prove the more delicate reverse implication in Section 4.4.

#### 4.2 Pseudo-rational Puiseux expansion.

Keeping the notations of Section 3, let  $\pi_0(x, y) = (x, y + c_0(x))$  and  $\pi_k = \pi_{k-1} \circ \sigma_k$  where

$$\sigma_k(x, y) := (z_k^{I_k} x^{q_k}, x^{m_k} (y + z_k^{S_k} + c_k(x))) \quad (12)$$

for  $k \geq 1$ . It follows from equalities (6), (7) and (8) that

$$\pi_k^* F = x^{v_x(\pi_k^* F)} V_k H_k \in \mathbb{K}_k[[x, y]] \quad (13)$$

for some  $V_k$  such that  $V_k(0, 0) \in \mathbb{K}_k^\times$ . We deduce from (12) that

$$\pi_k(x, y) = (\mu_k x^{e_k}, \alpha_k x^{r_k} y + S_k(x)), \quad (14)$$

where  $\mu_k, \alpha_k \in \mathbb{K}_k^\times$ ,  $r_k \in \mathbb{N}$  and  $S_k \in \mathbb{K}_k[[x]]$  satisfies  $v_x(S_k) \leq r_k$ . Following [22], we call the parametrisation

$$(\mu_k T^{e_k}, S_k(T)) := \pi_k(T, 0)$$

a pseudo-rational Puiseux expansion (pseudo-RPE for short). Its ring of definition equals the current residue ring  $\mathbb{K}_k$ , which is a reduced zero-dimensional  $\mathbb{K}$ -algebra of degree  $f_k$  over  $\mathbb{K}$ . When  $F$  is irreducible, the  $\mathbb{K}_k$ 's are fields and the parametrisation  $\pi_k(T, 0)$  allows to compute the Puiseux series of  $F$  truncated up to precision  $\frac{r_k}{e_k}$ , which increases with  $k$  [22, Section 3.2]. We show here that the same conclusion holds when  $F$  is pseudo-irreducible, taking care of possible zero-divisors in  $\mathbb{K}_k$ . To this aim, we prove by induction an explicit formula for  $\pi_k(T, 0)$ . We need further notations.

*Exponents data.* For all  $0 \leq i \leq k \leq g$ , we define  $Q_{k,i} = q_{i+1} \cdots q_k$  with convention  $Q_{k,k} = 1$  and let

$$B_{k,i} = m_1 Q_{k,1} + \cdots + m_i Q_{k,i}$$

with convention  $B_{k,0} = 0$ . Note that  $Q_{i,0} = e_i$ ,  $Q_{g,i} = \hat{e}_i$  and  $B_{g,i} = B_i$  for all  $i \leq g$ . We have the relations  $Q_{k+1,i} = q_{k+1} Q_{k,i}$  and  $B_{k+1,i} = q_{k+1} B_{k,i}$  for all  $i \leq k$  and  $B_{k+1,k+1} = q_{k+1} B_{k,k} + m_{k+1}$ .

*Coefficients data.* For all  $0 \leq i \leq k \leq g$ , we define  $\mu_{k,i} := z_{i+1}^{t_{i+1}Q_{i,i}} \cdots z_k^{t_k Q_{k-1,i}}$  with convention  $\mu_{k,k} = 1$  and let

$$\alpha_{k,i} := \mu_{k,1}^{m_1} \cdots \mu_{k,i}^{m_i},$$

with convention  $\alpha_{k,0} = 1$ . We have  $\mu_{k+1,i} = \mu_{k,i} z_{k+1}^{t_{k+1}Q_{k,i}}$  and  $\alpha_{k+1,i} = \alpha_{k,i} z_{k+1}^{t_{k+1}B_{k,i}}$  for all  $1 \leq i \leq k$ , and  $\alpha_{k+1,k+1} = \alpha_{k+1,k}$ .

**Lemma 2.** *Let  $z_0 = 0$  and  $s_0 = 1$ . For all  $k = 0, \dots, g$ , we have the formula*

$$\pi_k(x, y) = \left( \mu_{k,0} x^{e_k}, \sum_{i=0}^k \alpha_{k,i} x^{B_{k,i}} (z_i^{s_i} + c_i (\mu_{k,i} x^{Q_{k,i}})) + \alpha_{k,k} x^{B_{k,k}} y \right).$$

*Proof.* This is correct for  $k = 0$ : the formula becomes  $\pi_0(x, y) = (x, y + c_0(x))$ . For  $k > 0$ , we conclude by induction, using the recursive relations for  $B_{k,i}$ ,  $\mu_{k,i}$  and  $\alpha_{k,i}$  above with the definition  $\pi_k(x, y) = \pi_{k-1}(z_k^t x^{q_k}, x^{m_k} (z_k^{s_k} + c_k(x) + y))$ .  $\square$

Given  $\alpha$  an element of a ring  $\mathbb{L}$ , we denote by  $\alpha^{1/e}$  the residue class of  $Z$  in  $\mathbb{L}[Z]/(Z^e - \alpha)$ . For all  $k = 0, \dots, g$ , we define the ring extension

$$\mathbb{L}_k := \mathbb{K}_k [z_1^{\frac{1}{e}}, \dots, z_k^{\frac{1}{e}}].$$

Note that  $\mathbb{L}_0 = \mathbb{K}$ . Moreover, since  $z_k^{1/e}$  has degree  $e\ell_k > 1$  over  $\mathbb{L}_{k-1}$ , the natural inclusion  $\mathbb{L}_{k-1} \subset \mathbb{L}_k$  is *strict*.

*Remark 5.* Note that  $\theta_k := \mu_{k,0}^{-1/e_k}$  is a well defined invertible element of  $\mathbb{L}_k$  (use Remark 4), which by Lemma 2 plays an important role in the connections between pseudo-RPE and Puiseux series (proof of Proposition 1 below). In fact, we could replace  $\mathbb{L}_k$  by the subring  $\mathbb{K}_k[\theta_k]$  of sharp degree  $e_k f_k$  over  $\mathbb{K}$ , see [24]. We use  $\mathbb{L}_k$  for convenience, especially since  $z_k^{1/q_k}$  might not lie in  $\mathbb{K}_k[\theta_k]$ . The key points are:  $\theta_k \in \mathbb{L}_k$  and the inclusion  $\mathbb{L}_{k-1} \subset \mathbb{L}_k$  is strict.

**Proposition 1.** *Let  $F \in \mathbb{K}[[x]][y]$  be Weierstrass and consider  $\tilde{S} := S(\mu^{-1/e} T)$ , where  $(\mu T^e, S(T)) := \pi_g(T, 0)$ . We have*

$$\tilde{S}(T) = \sum_{B > 0} a_B T^B \in \mathbb{L}_g[[T]],$$

where  $\gcd(B_0, \dots, B_k) | B$  and  $a_B \in \mathbb{L}_k$  for all  $B < B_{k+1}$  (with convention  $B_{g+1} := +\infty$ ). Moreover, we have for all  $1 \leq k \leq g$

$$a_{B_k} = \begin{cases} \varepsilon_k z_k^{\frac{1}{q_k}} & \text{if } q_k > 1 \\ \varepsilon_k z_k + \rho_k & \text{if } q_k = 1 \end{cases} \quad (15)$$

for some  $\varepsilon_k \in \mathbb{L}_{k-1}^\times$  and  $\rho_k \in \mathbb{L}_{k-1}$ . In particular  $a_{B_k} \in \mathbb{L}_k \setminus \mathbb{L}_{k-1}$ .

*Proof.* Note first that  $\mu = \mu_{g,0}$  by Lemma 2, so that  $\theta_g := \mu^{-1/e}$  is a well defined invertible element of  $\mathbb{L}_g$  (Remark 5). In particular,  $\tilde{S} \in \mathbb{L}_g[[T]]$  as required. Lemma 2 applied at rank  $k = g$  gives

$$S(T) = \sum_{k=0}^g \alpha_{g,k} T^{B_k} (z_k^{s_k} + c_k(\mu_{g,k} T^{\hat{e}_k})). \quad (16)$$

Denote by  $\theta_k := \mu_{k,0}^{-1/e_k} \in \mathbb{L}_k^\times$  (Remark 5). Using the definitions of  $\mu_{g,k}$  and  $\alpha_{g,k}$ , a straightforward computation gives

$$\mu_{g,k} \theta_g^{\hat{e}_k} = \theta_k \in \mathbb{L}_k \quad \text{and} \quad \alpha_{g,k} \theta_g^{B_k} = \prod_{j=1}^k (\mu_{g,j} \theta_g^{\hat{e}_j})^{m_j} = \prod_{j=1}^k \theta_j \in \mathbb{L}_k. \quad (17)$$

Combining (16) and (17), we deduce that  $\tilde{S}(T) = S(\theta_g T)$  may be written as

$$\tilde{S}(T) = \sum_{k=0}^g C_k(\theta_k T^{\hat{e}_k}) T^{B_k}, \quad C_k(T) := (z_k^{s_k} + c_k(T)) \prod_{j=1}^k \theta_j \in \mathbb{L}_k[[T]]. \quad (18)$$

As  $\hat{e}_k = \gcd(B_0, \dots, B_k)$  divides both  $\hat{e}_i$  and  $B_i$  for all  $i \leq k$ , this forces  $\gcd(B_0, \dots, B_k)$  to divide  $B$  for all  $B < B_{k+1}$ . In the same way, as  $\mathbb{L}_i \subset \mathbb{L}_k$  for all  $i \leq k$ , we get  $a_B \in \mathbb{L}_k$  for all  $B < B_{k+1}$ . There remains to show (15). As  $c_k(0) = 0$ , we deduce that

$$C_k(0) = z_k^{s_k} \prod_{j=1}^k \theta_j^{m_j} = \varepsilon_k z_k^{1/q_k} \quad \text{with} \quad \varepsilon_k := \prod_{j=1}^{k-1} \theta_j z_j^{\frac{-j m_k}{q_j \cdots q_k}} \in \mathbb{L}_{k-1}, \quad (19)$$

the second equality using the Bézout relation  $s_k q_k - t_k m_k = 1$ . Note that  $\varepsilon_k \in \mathbb{L}_{k-1}^\times$  (Remarks 4 and 5). Let  $\rho_k$  be the sum of the contributions of the terms  $T^{B_i} C_i(\theta_i T^{\hat{e}_i})$ ,  $i \neq k$  to the coefficient  $T^{B_k}$  of  $\tilde{S}$ . So  $a_{B_k} = C_k(0) + \rho_k$ . As  $B_1 \leq \dots \leq B_g$  and  $k \geq 1$ , we deduce that if  $C_i(\theta_i T^{\hat{e}_i}) T^{B_i}$  contributes to  $T^{B_k}$ , then  $i < k$  so that  $C_i(\theta_i T^{\hat{e}_i}) T^{B_i} \in \mathbb{L}_{k-1}[[T^{\hat{e}_{k-1}}]]$ . We deduce that  $\rho_k \in \mathbb{L}_{k-1}$ . Moreover,  $\rho_k \neq 0$  forces  $\hat{e}_{k-1} | B_k$ . Since  $m_k$  is coprime to  $q_k$ , we deduce from (9) that  $q_k = 1$ .  $\square$

*Remark 6.* In contrast to the Newton-Puiseux type algorithms of [22] which compute  $\sum_B a_B T^B$  (up to some truncation bound), algorithm `Pseudo-Irreducible` of Section 5.2 only allows to compute  $(a_{B_k} - \rho_k) T^{B_k}$ ,  $k = 0, \dots, g$  in terms of the edge data thanks to (15) and (19). As shown in this section, this is precisely the minimal information required to test pseudo-irreducibility and compute the equisingularity type. For instance, the Puiseux series of  $F = (y - x - x^2)^2 - 2x^4$  are  $S_1 = T + T^2(1 - \sqrt{2})$  and  $S_2 = T + T^2(1 + \sqrt{2})$  and we only compute here the “separating” terms  $-\sqrt{2}T^2$  and  $\sqrt{2}T^2$ . Computing all terms of the singular part of the Puiseux series of a (pseudo)-irreducible polynomial in quasi-linear time remains an open challenge.

Let us denote by  $W \subset \overline{\mathbb{K}}^g$  the zero locus of the polynomial system defined by the canonical liftings of  $P_1, \dots, P_g$  in  $\mathbb{K}[Z_1, \dots, Z_g]$ . Note that  $\text{Card}(W) = f$ . Given  $\zeta = (\zeta_1, \dots, \zeta_g) \in W$ , the choice of some  $e^{\text{th}}$ -roots  $\zeta_1^{1/e}, \dots, \zeta_g^{1/e}$  in  $\overline{\mathbb{K}}$  induces a natural evaluation map

$$\text{ev}_\zeta : \mathbb{L}_g \simeq \mathbb{K}[z_1^{\frac{1}{e}}, \dots, z_g^{\frac{1}{e}}] \longrightarrow \overline{\mathbb{K}}$$

and we denote for short  $a(\zeta) \in \overline{\mathbb{K}}$  the evaluation of  $a \in \mathbb{L}_g$  at  $\zeta$ . There is no loss to assume that when  $\zeta, \zeta' \in W$  satisfy  $\zeta_k = \zeta'_k$ , we choose  $\zeta_k^{1/e} = \zeta_k'^{1/e}$ . We thus have

$$(\zeta_1, \dots, \zeta_k) = (\zeta'_1, \dots, \zeta'_k) \implies a(\zeta) = a(\zeta') \quad \forall a \in \mathbb{L}_k. \quad (20)$$

The following lemma is crucial for our purpose.

**Lemma 3.** *Let us fix  $\omega$  such that  $\omega^e = 1$  and let  $\zeta, \zeta' \in W$ . For all  $k = 0, \dots, g$ , the following assertions are equivalent:*

1.  $a_B(\zeta) = a_B(\zeta')\omega^B$  for all  $B \leq B_k$ .
2.  $a_B(\zeta) = a_B(\zeta')\omega^B$  for all  $B < B_{k+1}$ .
3.  $(\zeta_1, \dots, \zeta_k) = (\zeta'_1, \dots, \zeta'_k)$  and  $\omega^{\hat{e}_k} = 1$ .

*Proof.* By Proposition 1, we have  $a_B \in \mathbb{L}_k$  and  $\hat{e}_k | B$  for all  $B < B_{k+1}$  from which we deduce 3)  $\Rightarrow$  2) thanks to hypothesis (20). As 2)  $\Rightarrow$  1) is obvious, we need to show 1)  $\Rightarrow$  3). We show it by induction on  $k$ . If  $k = 0$ , the claim follows immediately since  $\hat{e}_0 = e$ . Suppose 1)  $\Rightarrow$  3) holds true at rank  $k - 1$  for some  $k \geq 1$ . If  $a_B(\zeta) = a_B(\zeta')\omega^B$  for all  $B \leq B_k$ , then this holds true for all  $B \leq B_{k-1}$ . As  $\varepsilon_k \in \mathbb{L}_{k-1}^\times$  and  $\rho_k \in \mathbb{L}_{k-1}$ , the induction hypothesis combined with (20) gives  $\varepsilon_k(\zeta) = \varepsilon_k(\zeta') \neq 0$  and  $\rho_k(\zeta) = \rho_k(\zeta')$ . We use now the assumption  $a_{B_k}(\zeta) = a_{B_k}(\zeta')\omega^{B_k}$ . Two cases occur:

- If  $q_k > 1$ , we deduce from (15) that  $\zeta_k^{1/q_k} = \zeta_k'^{1/q_k} \omega^{B_k}$ , so that  $\zeta_k = \zeta_k' \omega^{q_k B_k}$ . As  $\hat{e}_{k-1}$  divides  $q_k B_k$  and  $\omega^{\hat{e}_{k-1}} = 1$  by induction hypothesis, we deduce  $\zeta_k = \zeta_k'$ , as required. Moreover, we get  $a_{B_k}(\zeta_k) = a_{B_k}(\zeta_k')$  thanks to (20), so that  $\omega^{B_k} = 1$ .
- If  $q_k = 1$ , we deduce from (15) that  $\zeta_k + \rho_k(\zeta) = \omega^{B_k}(\zeta_k' + \rho_k(\zeta'))$ . As  $q_k = 1$  implies  $\hat{e}_{k-1} = \hat{e}_k | B_k$ , we deduce again  $\omega^{B_k} = 1$  and  $\zeta_k = \zeta_k'$ .

As  $B_k = \sum_{s \leq k} m_s \hat{e}_s$ , induction hypothesis gives  $(\omega^{\hat{e}_k})^{m_k} = 1$ . Since  $m_k$  is coprime to  $q_k$  and  $(\omega^{\hat{e}_k})^{q_k} = \omega^{\hat{e}_{k-1}} = 1$ , this forces  $\omega^{\hat{e}_k} = 1$ .  $\square$

Finally, we can recover all the Puiseux series of a pseudo-irreducible polynomial from the parametrisation  $\pi_g(T, 0)$ , as required. More precisely :

**Corollary 2.** *Suppose that  $F$  is pseudo-irreducible and Weierstrass. Then  $F$  admits exactly  $f$  distinct monic irreducible factors  $F_\zeta \in \overline{\mathbb{K}}[[x]][y]$  indexed by  $\zeta \in W$ . Each factor  $F_\zeta$  has degree  $e$  and defines a branch with classical Puiseux parametrisations  $(T^e, \tilde{S}_\zeta(T))$  where*

$$\tilde{S}_\zeta(T) = \sum_B a_B(\zeta) T^B. \quad (21)$$

The  $e$  Puiseux series of  $F_\zeta$  are given by  $\tilde{S}_\zeta(\omega x^{\frac{1}{e}})$  where  $\omega$  runs over the  $e^{\text{th}}$ -roots of unity and this set of Puiseux series does not depend of the choice of the  $e^{\text{th}}$ -roots  $\zeta_1^{1/e}, \dots, \zeta_k^{1/e}$ .

*Proof.* As  $F$  is pseudo-irreducible,  $H_g = y$  (see Section 3.2) and  $\pi_g^* F(x, 0) = 0$  by (13). We deduce  $F(T^e, \tilde{S}_\zeta(T)) = 0$  for all  $\zeta \in W$ . By (15), we have  $a_{B_k}(\zeta) \neq 0$  for all  $k$  such that  $q_k > 1$ . Since  $\gcd(B_0 = e, B_k | q_k > 1) = \gcd(B_0, \dots, B_g) = \hat{e}_g = 1$ , the parametrisation  $(T^e, \tilde{S}_\zeta(T))$  is primitive, that is the greatest common divisor of the

exponents of the series  $T^e$  and  $\tilde{S}_\zeta(T)$  equals one. Hence, this parametrisation defines a branch  $F_\zeta = 0$ , where  $F_\zeta \in \overline{\mathbb{K}}[[x]][y]$  is an irreducible monic factor of  $F$  of degree  $e$ . Thanks to Lemma 3, these  $f$  branches are distinct when  $\zeta$  runs over  $W$ . As  $\deg(F) = ef$ , we obtain all the irreducible factors of  $F$  in such a way. Considering other choices of the  $e^{\text{th}}$  roots of the  $\zeta_k$ 's would lead to the same conclusion by construction, and the last claim follows straightforwardly.  $\square$

#### 4.3 Pseudo-irreducible implies balanced

**Proposition 2.** *Let  $F \in \mathbb{K}[[x]][y]$  be pseudo-irreducible. Then each branch  $F_\zeta$  of  $F$  has characteristic exponents  $(B_0; B_k | q_k > 1)$ ,  $k = 1, \dots, g$ .*

*Proof.* Thanks to Corollary 2, all polynomials  $F_\zeta$  have same first characteristic exponent  $B_0 = e$ . We also showed in the proof of Corollary 2 that  $a_{B_k}(\zeta) \neq 0$  for all  $k \geq 1$  such that  $q_k > 1$ . We conclude by Proposition 1.  $\square$

**Proposition 3.** *Let  $F \in \mathbb{K}[[x]][y]$  be pseudo-irreducible with at least two branches  $F_\zeta, F_{\zeta'}$ . We have*

$$(F_\zeta, F_{\zeta'})_0 = M_\kappa, \quad \kappa := \min \{k = 1, \dots, g \mid \zeta_k \neq \zeta'_k\}.$$

and this value is reached exactly  $\hat{f}_{\kappa-1} - \hat{f}_\kappa$  times when  $\zeta'$  runs over the set  $W \setminus \{\zeta\}$ .

*Proof.* Noether-Merle's formula (3) combined with Proposition 2 gives

$$(F_\zeta, F_{\zeta'})_0 = \sum_{k \leq K} (\hat{e}_{k-1} - \hat{e}_k) B_k + \hat{e}_K \text{Cont}(F_\zeta, F_{\zeta'}) \quad (22)$$

with  $K = \max\{k \mid \text{Cont}(F_\zeta, F_{\zeta'}) \geq B_k\}$ . Note that the  $B_k$ 's which are not characteristic exponents do not appear in the first summand of formula (22) ( $q_k = 1$  implies  $\hat{e}_{k-1} - \hat{e}_k = 0$ ). It is a classical fact that we can fix any root  $y$  of  $F$  for computing the contact order in formula (2) (see e.g. [6, Lemma 1.2.3]). Combined with Corollary 2, we obtain the formula

$$\text{Cont}(F_\zeta, F_{\zeta'}) = \max_{\omega^e=1} (v_T(\tilde{S}_\zeta(T) - \tilde{S}_{\zeta'}(\omega T))). \quad (23)$$

We deduce from Lemma 3 that

$$v_T(\tilde{S}_\zeta(T) - \tilde{S}_{\zeta'}(\omega T)) = B_{\bar{\kappa}}, \quad \bar{\kappa} := \min \{k = 1, \dots, g \mid \zeta_k \neq \zeta'_k \text{ or } \omega^{\hat{e}_k} \neq 1\}.$$

As  $\omega = 1$  satisfies  $\omega^{\hat{e}_k} = 1$  for all  $k$ , we deduce from the last equality that the maximal value in (23) is reached for  $\omega = 1$  (it might be reached for other values of  $\omega$ ). It follows that  $\text{Cont}(F_\zeta, F_{\zeta'}) = B_\kappa$  with  $\kappa = \min \{k \mid \zeta_k \neq \zeta'_k\}$ . We thus have  $K = \kappa$  and (22) gives  $(F_\zeta, F_{\zeta'})_0 = \sum_{k=1}^{\kappa} (\hat{e}_{k-1} - \hat{e}_k) B_k + \hat{e}_\kappa B_\kappa = M_\kappa$ , the last equality by (10). Let us fix  $\zeta$ . As said above, we may choose  $\omega = 1$  in (23). We have  $v_T(\tilde{S}_\zeta(T) - \tilde{S}_{\zeta'}(T)) = B_\kappa$  if and only if  $\zeta'_k = \zeta_k$  for  $k < \kappa$  and  $\zeta'_\kappa \neq \zeta_\kappa$ . This concludes, as the number of possible such values of  $\zeta'$  is precisely  $\hat{f}_{\kappa-1} - \hat{f}_\kappa$ .  $\square$

If  $F$  is pseudo-irreducible, then it is balanced and satisfies both items of Theorem 2 thanks to Propositions 2 and 3. There remains to show the converse.



#### 4.4 Balanced implies pseudo-irreducible

We need to show that  $N_g = 1$  if  $F$  is balanced. We denote more simply  $H := H_g \in \mathbb{K}_g[[x]][y]$ , and  $\pi_g(T, 0) = (\mu T^e, S(T))$ . We denote  $H_\zeta, S_\zeta, \mu_\zeta$  the images of  $H, S, \mu$  after applying (coefficient wise) the evaluation map  $ev_\zeta : \mathbb{K}_g \rightarrow \overline{\mathbb{K}}$ . In what follows, irreducible means absolutely irreducible.

**Lemma 4.** *Suppose that  $F$  is balanced. Then all irreducible factors of all  $H_\zeta, \zeta \in W$  have same degree.*

*Proof.* Let  $\zeta \in W$  and let  $y_\zeta$  be a root of  $H_\zeta$ . As  $H_\zeta$  divides  $(\pi_g^* F)_\zeta$  by (13), we deduce from Lemma 2 (remember  $B_{gg} = B_g$ ) that

$$F(\mu_\zeta x^e, S_\zeta(x) + x^{B_g} y_\zeta(x)) = 0.$$

Hence,  $y_0(x) := \tilde{S}_\zeta(x^{\frac{1}{e}}) + \mu_\zeta^{-\frac{B_g}{e}} x^{\frac{B_g}{e}} y_\zeta(\mu_\zeta^{-\frac{1}{e}} x^{\frac{1}{e}})$  is a root of  $F$  and we have moreover the equality

$$\deg_{\overline{\mathbb{K}}((x))}(y_0) = e \deg_{\overline{\mathbb{K}}((x))}(y_\zeta), \quad (24)$$

where we consider here the degrees of  $y_0$  and  $y_\zeta$  seen as algebraic elements over the field  $\overline{\mathbb{K}}((x))$ . As  $F$  is balanced, all its irreducible factors - hence all its roots - have same degree. Combined with (24), this implies that all roots - hence all irreducible factors - of all  $H_\zeta, \zeta \in W$  have same degree.  $\square$

**Corollary 3.** *Suppose  $F$  balanced and  $N_g > 1$ . Then there exists some coprime positive integers  $(q, m)$  and  $Q \in \mathbb{K}_g[Z]$  monic with non zero constant term such that  $H$  has lower boundary polynomial*

$$\tilde{H}(x, y) = Q(y^q/x^m) x^{m \deg(Q)}.$$

*Proof.* As  $N_g > 1$ , the Weierstrass polynomial  $H = H_g$  is not pseudo-degenerate and admits a lower slope  $(q, m)$  (we can not have  $H_g = y^{N_g}$  as  $F$  would not be square-free). Hence, its lower boundary polynomial may be written in a unique way

$$\tilde{H}(x, y) = y^r \tilde{Q}(y^q/x^m) x^{m \deg(\tilde{Q})} \quad (25)$$

for some non constant monic polynomial  $\tilde{Q} \in \mathbb{K}_g[Z]$  with non zero constant term and some integer  $r \geq 0$ . If  $r = 0$ , we are done, taking  $Q = \tilde{Q}$ . Suppose  $r > 0$ . Let  $\zeta \in W$  such that  $\tilde{Q}_\zeta(0) \neq 0$ . Applying  $ev_\zeta$  to (25), we deduce that  $\mathcal{N}(H_\zeta)$  has a vertex of type  $(r, i)$ ,  $0 < r < d$  from which follows the well-known fact that  $H_\zeta = AB \in \overline{\mathbb{K}}[[x]][y]$ , with  $\deg(A) = r$  and  $\deg(B) = q \deg(\tilde{Q})$ . By Lemma 4, this forces  $q$  to divide  $r$ . Hence  $r = nq$  for some  $n \in \mathbb{N}$  and the claim follows by taking  $Q(Z) = Z^n \tilde{Q}(Z)$ .  $\square$

**Lemma 5.** *Suppose  $F$  balanced and  $N_g > 1$ . We keep the notations of Corollary 3. Let  $G$  be an irreducible factor of  $F$  in  $\overline{\mathbb{K}}[[x]][y]$ . Then  $e q$  divides  $n := \deg(G)$  and there exists a unique  $\zeta \in W$  and a unique root  $\alpha$  of  $Q_\zeta$  such that  $G$  admits a parametrisation  $(T^n, S_G(T))$ , where*

$$S_G(T) \equiv \tilde{S}_\zeta(T^{\frac{n}{e}}) + \alpha^{\frac{1}{q}} \mu_\zeta^{-\frac{B_g}{e}} T^a \pmod{T^{a+1}}, \quad (26)$$

with  $a = \frac{n}{e}B_g + \frac{nm}{eq} \in \mathbb{N}$ ,  $\alpha^{1/q}$  an arbitrary  $q^{\text{th}}$ -root of  $\alpha$ . Conversely, given  $\zeta \in W$  and  $\alpha$  a root of  $Q_\zeta$ , there exists at least one irreducible factor  $G$  for which (26) holds.

*Proof.* Let  $y_\zeta^{(i)}$ ,  $i = 1, \dots, N_g$  be the roots of  $H_\zeta$ . Following the proof of Lemma 4, we know that each root  $y_\zeta^{(i)}$  gives rise to a family of  $e$  roots of  $F$

$$y_{\zeta, \omega}^{(i)} := \tilde{S}_\zeta(\omega x^{1/e}) + \omega^{B_g} \mu_\zeta^{-\frac{B_g}{e}} x^{-\frac{B_g}{e}} y_\zeta^{(i)}(\omega \mu_\zeta^{-\frac{1}{e}} x^{1/e}), \quad \omega^e = 1. \quad (27)$$

As  $H_\zeta$  has distinct roots and  $\tilde{S}_\zeta(\omega x^{1/e}) \neq \tilde{S}_{\zeta'}(\omega' x^{1/e})$  for  $(\zeta, \omega) \neq (\zeta', \omega')$  (Lemma 3), we deduce that the  $efN_g = \deg(F)$  Puiseux series  $y_{\zeta, \omega}^{(i)}$  are distinct, getting all roots of  $F$ . Let  $G$  be an irreducible factor of  $F$  vanishing say at  $y_0 = y_{\zeta, \omega}^{(i)}$ . The roots of  $G$  are  $y_0(\omega' x)$ ,  $\omega'^n = 1$ , where  $n := \deg(G) = \deg_{\overline{\mathbb{K}}(x)}(y_{\zeta, \omega}^{(i)})$ . As  $e$  divides  $n$  (use (24)), it follows from (27) that  $G$  vanishes at  $y_{\zeta, 1}^{(i)}$ , hence admits a parametrisation  $(T^n, S_G(T))$ , where  $S_G(T) := y_{\zeta, 1}^{(i)}(T^n)$ . Corollary 3 ensures that  $y_{\zeta, 1}^{(i)}(x) = \alpha^{1/q} x^{m/q} + h.o.t.$  for some uniquely determined root  $\alpha$  of  $Q_\zeta$ . Combined with (27), we get the claimed formula for  $S_G$ . Conversely, if  $\zeta \in W$  and  $Q_\zeta(\alpha) = 0$ , there exists at least one root  $y_\zeta^{(i)}$  of  $H_\zeta$  such that  $y_\zeta^{(i)}(x) = \alpha^{1/q} x^{m/q} + h.o.t.$  and by the same arguments as above, there exists at least one irreducible factor  $G$  such that (26) holds. Finally, since  $S_G \in \overline{\mathbb{K}}[[T]]$  and since there exists at least one root  $\alpha \neq 0$  of  $Q_\zeta$ , we must have  $nm/eq \in \mathbb{N}$ . As  $e|n$  and  $q$  and  $m$  are coprime, we get  $eq|n$ , as required.  $\square$

For a given irreducible factor  $G$  of  $F$ , we denote by  $(\zeta(G), \alpha(G)) \in W \times \overline{\mathbb{K}}$  the unique pair  $(\zeta, \alpha)$  such that (26) holds. Given  $\zeta \in W$ , Corollary 3 and Lemma 5 imply that

$$\bar{H}_\zeta = \prod_{i|\zeta(G_i)=\zeta} (y^q - \alpha(G_i)x^m)^{N(G_i)}, \quad (28)$$

where  $G_1, \dots, G_\rho$  are the irreducible factors of  $F$  and where  $N(G_i) := \deg(G_i)/eq$ . Note that by Lemma 4,  $\deg(G_i)$  and  $N(G_i)$  are constant for all  $i = 1, \dots, \rho$ .

**Corollary 4.** *Suppose  $F$  balanced and  $N_g > 1$ . Keeping the above notations, the lists of the characteristic exponents of the  $G_i$ 's all begin as  $\{n\} \cup \{\frac{n}{e}B_k, q_k > 1, k = 1, \dots, g\}$ . The next characteristic exponent is greater or equal than  $\frac{n}{e}B_g + \frac{nm}{eq} \in \mathbb{N}$ , with equality if and only if  $q > 1$  and  $\alpha(G_i) \neq 0$ .*

*Proof.* This follows straightforwardly from Lemma 5 combined with Proposition 1 (similar argument that for Proposition 2).  $\square$

**Corollary 5.** *Suppose  $F$  balanced with  $N_g > 1$ . Then*

$$(G_i, G_j)_0 > \frac{n^2}{e^2} \left( M_g + \frac{m}{q} \right) \iff (\zeta(G_i), \alpha(G_i)) = (\zeta(G_j), \alpha(G_j)).$$

*Proof.* Using similar arguments to Proposition 3, we get  $\text{Cont}(G_i, G_j) = v_T(S_{G_i} - S_{G_j})$  and we deduce from (26) and Lemma 3 that  $\text{Cont}(G_i, G_j) > \frac{n}{e}B_g + \frac{nm}{eq}$  if and only if  $\zeta(G_i) = \zeta(G_j)$  and  $\alpha(G_i) = \alpha(G_j)$ . The claim then follows from Noether-Merle's formula (3) combined with Corollary 4.  $\square$

**Proposition 4.** *If  $F$  is balanced, then it is pseudo-irreducible.*

*Proof.* We need to show that  $N_g = 1$ . Suppose on the contrary that  $N_g > 1$ . We deduce from (28) that the polynomial  $Q$  of Corollary 3 satisfies

$$Q_\zeta(Z) = \prod_{i|\zeta(G_i)=\zeta} (Z - \alpha(G_i))^{n/eq} \quad (29)$$

for all  $\zeta \in W$ . Let  $\alpha$  be a root of  $Q_\zeta$  and  $I_{\zeta,\alpha} := \{i \mid (\zeta(G_i), \alpha(G_i)) = (\zeta, \alpha)\}$ . Hence, (29) implies that  $\alpha$  has multiplicity  $\frac{n}{eq} \text{Card}(I_{\zeta,\alpha})$ . As  $F$  is balanced, all factors have same intersection sets and Corollary 5 implies that all sets  $I_{\zeta,\alpha}$  have same cardinality. Thus all roots  $\alpha$  of all specialisations  $Q_\zeta$ ,  $\zeta \in W$  have same multiplicity. In other words,  $Q$  is the power of some square-free polynomial  $P \in \mathbb{K}_g[Z]$ . If  $q = 1$ , this implies that  $H = H_g$  is pseudo-degenerate (Definition 4), contradicting  $N_g > 1$ . If  $q > 1$ , we need to show moreover that  $P$  has invertible constant term. Since there exists at least one non zero root  $\alpha$  of some  $Q_\zeta$  (Corollary 3), we deduce from Corollary 4 that at least one factor  $G_i$  has next characteristic exponent  $\frac{n}{e}B_g + \frac{nm}{eq}$  (use  $q > 1$ ). As  $F$  is balanced, it follows that all  $G_i$ 's have next characteristic exponent  $\frac{n}{e}B_g + \frac{nm}{eq}$ , which by Corollary 4 forces all  $\alpha(G_i)$  - thus all roots  $\alpha$  of all  $Q_\zeta$  by last statement of Lemma 5 - to be non zero. Thus  $P$  has invertible constant term and  $H = H_g$  is pseudo-degenerate, contradicting  $N_g > 1$ . Hence  $N_g = 1$  and  $F$  is pseudo-irreducible.  $\square$

The proof of Theorem 2 is complete.  $\square$

## 5 A quasi-optimal pseudo-irreducibility test

Finally, we explain here the main steps of an algorithm which tests the pseudo-irreducibility of a Weierstrass polynomial and computes its equisingularity type in quasi-linear time with respect to  $\delta$ , and we illustrate it on some examples. Details can be found in [23, 24].

### 5.1 Computing the lower boundary polynomial

We still consider  $F \in \mathbb{K}[[x]][y]$  a degree  $d$  square-free Weierstrass polynomial. In the following, we fix an integer  $0 \leq k \leq g$  and assume that  $N_k > 1$ . For readability, we will omit the index  $k$  for the objects  $\Psi, V, \Lambda, \mathcal{B}$  introduced below.

Given the edge data  $(q_1, m_1, P_1, N_1), \dots, (q_k, m_k, P_k, N_k)$ , we want to compute  $\tilde{H}_k$  in quasi-linear time with respect to  $\delta$ .

*The  $(V, \Lambda)$  sequence.* We define recursively two lists

$$V = (v_{k,-1}, \dots, v_{k,k}) \in \mathbb{N}^{k+2} \text{ and } \Lambda = (\lambda_{k,-1}, \dots, \lambda_{k,k}) \in \mathbb{K}_k^{k+2}.$$

If  $k = 0$ , we let  $V = (1, 0)$  and  $\Lambda = (1, 1)$ . Assume  $k \geq 1$ . Given the lists  $V$  and  $\Lambda$  at rank  $k - 1$  and given the  $k$ -th edge data  $(q_k, m_k, P_k, N_k)$ , we update both lists at rank  $k$  thanks to the formulæ:

$$\begin{cases} v_{k,i} = q_k v_{k-1,i} & -1 \leq i < k-1 \\ v_{k,k-1} = q_k v_{k-1,k-1} + m_k \\ v_{k,k} = q_k \ell_k v_{k,k-1} \end{cases} \quad \begin{cases} \lambda_{k,i} = \lambda_{k-1,i} z_k^{t_k v_{k-1,i}} & -1 \leq i < k-1 \\ \lambda_{k,k-1} = \lambda_{k-1,k-1} z_k^{t_k v_{k-1,k-1} + s_k} \\ \lambda_{k,k} = q_k z_k^{1-s_k-\ell_k} P_k'(z_k) \lambda_{k,k-1}^{q_k \ell_k} \end{cases} \quad (30)$$

where  $q_k s_k - m_k t_k = 1$ ,  $0 \leq t_k < q_k$  and  $z_k = Z_k \pmod{P_k}$ .

*Approximate roots and  $\Psi$ -adic expansion.* Given an integer  $N$  dividing  $d$ , there exists a unique polynomial  $\psi \in \mathbb{K}[[x]][y]$  monic of degree  $d/N$  such that  $\deg(F - \psi^N) < d - d/N$  (see e.g. [18, Proposition 3.1]). We call it the  $N^{\text{th}}$  approximate root of  $F$ . Approximate roots are used in an irreducibility criterion in  $\mathbb{C}[[x, y]]$  due to Abhyankhar [1].

We denote by  $\psi_k$  the  $N_k^{\text{th}}$ -approximate root of  $F$  and we let  $\psi_{-1} := x$ . We denote  $\Psi = (\psi_{-1}, \psi_0, \dots, \psi_k)$  and introduce the set

$$\mathcal{B} := \{(b_{-1}, \dots, b_k) \in \mathbb{N}^{k+2}, b_{i-1} < q_i \ell_i, i = 1, \dots, k\}. \quad (31)$$

Thanks to the relations  $\deg(\psi_i) = \deg(\psi_{i-1}) q_i \ell_i$  for all  $1 \leq i \leq k$ , an induction argument shows that  $F$  admits a unique expansion

$$F = \sum_{B \in \mathcal{B}} f_B \Psi^B, \quad f_B \in \mathbb{K},$$

where  $\Psi^B := \prod_{i=-1}^k \psi_i^{b_i}$ . We call it the  $\Psi$ -adic expansion of  $F$ . We have necessarily  $b_k \leq N_k$  while we do not impose any *a priori* condition to the powers of  $\psi_{-1} = x$  in this expansion.

*A formula for the lower boundary polynomial.* We let  $B_0 := (0, \dots, 0, N_k) \in \mathcal{B}$  and for  $i \in \mathbb{N}$ , we define the integer

$$w_i := \min \{ \langle B, V \rangle, b_k = i, f_B \neq 0 \} - \langle B_0, V \rangle, \quad (32)$$

where  $\langle \cdot, \cdot \rangle$  stands for the usual scalar product and with convention  $w_i := \infty$  if the minimum is taken over the empty set. We introduce the set

$$\mathcal{B}(i, w) := \{ B \in \mathcal{B}(i) \mid \langle B, V \rangle = w \}$$

for any  $i \in \mathbb{N}$  and any  $w \in \mathbb{N} \cup \{\infty\}$ , with convention  $\mathcal{B}(i, \infty) = \emptyset$ . We get the following key result:

**Theorem 3.** *The lower edge  $\mathcal{N}_0(H_k)$  coincides with the lower edge of the convex hull of  $(i, w_i)_{0 \leq i \leq N_k}$ . The lower boundary polynomial of  $H_k$  equals*

$$\bar{H}_k = \sum_{(i, w_i) \in \mathcal{N}_0(H_k)} \left( \sum_{B \in \mathcal{B}(i, w_i)} f_{B+B_0} \Lambda^B \right) x^{w_i} y^i. \quad (33)$$

*Proof.* This is a variant of Theorems 2, 3 and 4 in [23], where degeneracy conditions are now replaced by pseudo-degeneracy conditions. The delicate point is that  $z_k$  might here be a zero divisor when  $q_k = 1$ . However, we can show that we always have  $\lambda_{kk} \in \mathbb{K}_k^\times$ . In particular, (33) is well-defined and a careful reading shows that the proofs of Theorem 2, 3 and 4 in [23] remain valid under the weaker hypothesis of pseudo-degeneracy. We refer to Proposition 6 in the longer preprint [24] for details.  $\square$

**Example 3.** If  $F = \sum_{i=0}^d a_i y^i$ , then  $\psi_0 = y - c_0(x)$  where  $c_0 = -\frac{a_{d-1}}{d}$ . It follows that at rank  $k = 0$ , the coefficients of the  $\Psi$ -adic expansion of  $F$  coincide with the coefficients of the  $(x, y)$ -adic expansion of  $H_0$  as defined in (6). This illustrates that (33) holds at rank  $k = 0$ .

## 5.2 The algorithm

We obtain the following sketch of algorithm. Subroutines `AppRoot`, `Expand` and `EdgeData` respectively compute the approximate root, the  $\Psi$ -adic expansion and the edge data.

**Algorithm:** `Pseudo-Irreducible( $F$ )`

**Input:**  $F \in \mathbb{K}[[x]][y]$  Weierstrass with  $\text{Char}(\mathbb{K})$  not dividing  $\deg(F)$ .

**Output:** `True` if  $F$  is pseudo-irreducible, and `False` otherwise.

- 1  $N \leftarrow \deg(F)$ ,  $V \leftarrow (1, 0)$ ,  $\Lambda \leftarrow (1, 1)$ ,  $\Psi \leftarrow (x)$ ;
- 2 **while**  $N > 1$  **do**
- 3      $\Psi \leftarrow \Psi \cup \text{AppRoot}(F, N)$ ;
- 4      $\sum_B f_B \Psi^B \leftarrow \text{Expand}(F, \Psi)$ ;
- 5     Compute  $\bar{H}$  using (33);
- 6     **if**  $\bar{H}$  is not pseudo-degenerate **then return** `False`;
- 7      $(q, m, P, N) \leftarrow \text{EdgeData}(\bar{H})$ ;
- 8     Update  $V, \Lambda$  using (30)
- 9 **return** `True`

**Theorem 4.** *Algorithm `Pseudo-Irreducible` returns the correct answer.*

*Proof.* Follows from Definition 5, Theorem 2 and Theorem 3.  $\square$

*Proof of Theorem 1.* Algorithm `Pseudo-Irreducible` may run with an expected  $\mathcal{O}(\delta)$  operations over  $\mathbb{K}$  thanks to [23, Proposition 12]<sup>9</sup>. To this aim, we use:

<sup>9</sup> In [23, Prop.12], the condition  $P_k(0) \in \mathbb{K}_k^\times$  is imposed even if  $q_k = 1$ , but this has no impact from a complexity point of view.

- Suitable truncation bounds for the powers of  $x$ , updated at each step.
- Primitive representation of the various residue rings  $\mathbb{K}_k$  (Las-Vegas subroutines)
- Suitable implementation of subroutines `AppRoot`, `Expand`, `EdgeData` and of the pseudo-degeneracy tests (square-free univariate factorisation over direct product of fields, see Remark 2).

If  $F$  is pseudo-irreducible, we can deduce from the edge data of  $F$  the characteristic exponents and the intersection sets of  $F$  (Theorem 2), together with the discriminant valuation  $\delta$  (Corollary 1). Theorem 1 follows.  $\square$

*Remark 7.* Note that if we rather use computations (7) and (8) up to suitable precision to check if  $F$  is pseudo-irreducible (hence balanced), the underlying algorithm has complexity  $\mathcal{O}(d\delta)$  when using similar cautious algorithmic tricks as above (see [22, Section 3]). This bound is sharp (see e.g. [23, Example 1]) and is too high for our purpose. One of the main reason is that computing the intermediate polynomials  $G_k$  in (7) via Hensel lifting up to sufficient precision might cost  $\Omega(d\delta)$ . This shows the importance of using approximate roots.

### 5.3 Non-Weierstrass polynomials.

From a computational aspect with a view towards factorisation in  $\mathbb{K}[[x]][y]$ , it seems interesting to extend Theorems 1 and 2 to the case of non Weierstrass polynomials.

*Non-Weierstrass balanced polynomials.* If  $F$  is absolutely irreducible but not necessarily Weierstrass, it defines a unique germ of irreducible curve on the line  $x = 0$ , with center  $(0, c)$ ,  $c \in \overline{\mathbb{K}} \cup \{\infty\}$ . It seems to be a natural option to require that the equisingularity type of a germ of plane curve along the line  $x = 0$  does not depend on its center. This point of view leads us to define the characteristic exponents of  $F$  as those of the shifted polynomial  $F(x, y + c)$  if  $c \in \overline{\mathbb{K}}$  or of the reciprocal polynomial  $\tilde{F} = y^d F(x, y^{-1})$  if  $c = \infty$  (note that these change of coordinates have no impact on the tangency with the  $x$ -axis). The formula (1) of the intersection multiplicity also extends by linearity to arbitrary coprime polynomials  $G, H \in \overline{\mathbb{K}}[[x]][y]$ , taking into account the sum of intersection multiplicities between all germs of curves defined by  $G$  and  $H$  along the line  $x = 0$ . The intersection multiplicity might now be zero if (and only if)  $G$  and  $H$  do not have branches with the same center. We can thus extend the definition of intersection sets to non-Weierstrass polynomials, allowing now  $0 \in \Gamma(F_i)$ . Finally, we may extend Definition 1 to an arbitrary square-free polynomial  $F \in \mathbb{K}[[x]][y]$ .

*Pseudo-Irreducibility of non-Weierstrass polynomials.* We distinguish two cases: the monic one, for which approximate roots are defined, and the non monic one.

If  $F$  is monic, the construction of Section 3 remains valid, a slight difference being that the first polynomial  $H_0$  is monic but might now be non-Weierstrass (and  $m_1 = 0$  is allowed). However the remaining polynomials  $H_k$  are still Weierstrass for  $k \geq 1$ . Hence the definition of a pseudo-irreducible polynomial extends to the monic case and we can check that Theorem 2 still holds for monic polynomials.

Moreover, the approximate roots of a monic polynomial  $F$  are still defined, and it is shown in [23] that Theorem 3 holds too in this case. Hence, we can run algorithm `Pseudo-Irreducible` as in the Weierstrass case. However to keep a small complexity, we do not compute primitive elements of  $\mathbb{K}_k$  over the field  $\mathbb{K}$  but only over the next residue ring  $\mathbb{K}_1 = \mathbb{K}_{p_1}$ . The overall complexity of this slightly modified algorithm becomes  $\mathcal{O}(\delta + d)$ . We refer the reader to [23] for details.

If  $F$  is not monic, we can use a projective change of the  $y$  coordinates in order to reduce to the monic case. Since  $\mathbb{K}$  has at least  $d + 1$  elements by assumption, we can compute  $z \in \mathbb{K}$  such that  $F(0, z) \neq 0$  with at most  $d + 1$  evaluation of  $F(0, y)$  at  $z = 0, 1, \dots, d$ . This costs at most  $\mathcal{O}(d)$  using fast multipoint evaluation [7, Corollary 10.8]. One such a  $z$  is found, we can apply the previous strategy to the polynomial  $\tilde{F} := y^d F\left(\frac{zy+1}{y}\right) \in \mathbb{K}[[x]][y]$  which has by construction an invertible coefficient that we simply invert up to suitable precision. We have  $\deg(F) = \deg(\tilde{F})$  and  $\delta(F) = \delta(\tilde{F})$  (assuming that  $\delta$  is then defined as the valuation of the resultant between  $F$  and  $F_y$  instead of the valuation of the discriminant which may vary under projective change of coordinates). So the complexity remains the same. Moreover,  $F$  and  $\tilde{F}$  have same number of absolutely irreducible factors, same sets of characteristic exponents (by the very definition) and same intersection sets (use that the  $x$ -valuation of the resultant is invariant under projective change of the  $y$  coordinate (see e.g. [8, Chapter 12]). In particular,  $F$  is balanced if and only if  $\tilde{F}$  is. This shows that we can test if an arbitrary square-free polynomial  $F$  is balanced - and if so, compute the equisingular types of all germs of curves it defines along the line  $x = 0$  - within  $\mathcal{O}(\delta + d)$  operations over  $\mathbb{K}$ . We refer the reader to [23] for details.

*Remark 8.* If  $F$  is not monic, we could also have followed the following option. We can extend the construction of Section 3 by allowing positive slopes at the first call (so  $m_1 < 0$  is allowed) and extend Theorem 2 by considering approximate roots in the larger ring  $\mathbb{K}((x))[y]$ . However, it turns out that this option is not compatible with our  $PGL_2(\mathbb{K})$ -invariant point of view when  $F$  defines a germ centered at  $(0, \infty)$ , and Theorem 2 would require some slight modifications to hold in this larger context.

*Bivariate polynomials.* If the input  $F$  is given as a bivariate polynomial  $F \in \mathbb{K}[x, y]$  with partial degrees  $n := \deg_x(F)$  and  $d = \deg_y(F)$ , the well known upper bound  $\delta \leq 2nd$  leads to a complexity estimate  $\mathcal{O}(nd)$  which is quasi-linear with respect to the arithmetic size of the input. Moreover, up to a slight modification of the algorithm, there is no need to assume  $F$  square-free in this ‘‘algebraic’’ case (see again [23] for details).

## 5.4 Some examples

**Example 4 (balanced).** Let  $F = y^6 - 3x^3y^4 - 2x^2y^4 + 3x^6y^2 + x^4y^2 - x^9 + 2x^8 - x^7 \in \mathbb{Q}[x, y]$ . This example is constructed in such a way that  $F$  has 3 irreducible factors  $(y - x)^2 - x^3$ ,  $(y + x)^2 - x^3$ ,  $y^2 - x^3$  and we can check that  $F$  is balanced, with  $e = 2$ ,  $f = 3$  and  $C(F_i) = (2; 3)$  and  $\Gamma_i(F) = (4, 4)$  for all  $i = 1, 2, 3$ . Let us recover this with algorithm `Pseudo-Irreducible`.

*Initialise.* We have  $N_0 = d = 6$ , and we let  $\psi_{-1} = x$ ,  $V = (1, 0)$  and  $\Lambda = (1, 1)$ .

*Step 0.* The 6<sup>th</sup>-approximate root of  $F$  is  $\psi_0 = y$  and we deduce that  $\bar{H}_0 = y^6 - 2x^2y^4 + x^4y^2 = (y(y^2 - x^2))^2$ . Thus,  $H_0$  is pseudo-degenerate and it has edge data  $(q_1, m_1, P_1, N_1) = (1, 1, Z_1^3 - Z_1, 2)$ . Accordingly to (30), we update  $V = (1, 1, 1)$  and  $\Lambda = (1, z_1, 3z_1^2 - 1)$ . Note that  $\mathcal{N}(F)$  is not straight. In particular,  $F$  is reducible in  $\mathbb{Q}[[x]][y]$ .

*Step 1.* The 2<sup>nd</sup>-approximate root of  $F$  is  $\psi_1 = y^3 - \frac{3}{2}x^3y - x^2y$  and  $F$  has  $\Psi$ -adic expansion  $F = \psi_1^2 - 3\psi_0^2\psi_{-1}^5 + \frac{3}{4}\psi_0^2\psi_{-1}^6 - \psi_{-1}^7 + 2\psi_{-1}^8 - \psi_{-1}^9$ . The monomials reaching the minimal values (32) are  $\psi_1^2$  (for  $j = 2$ ) and  $-3\psi_0^2\psi_{-1}^5$  and  $\psi_{-1}^7$  (for  $j = 0$ ). We deduce from (33) that  $\bar{H}_1 = y^2 - \alpha x$ , where  $\alpha = (3z_1^2 + 1)/(3z_1^2 - 1)^2$  is easily seen to be invertible in  $\mathbb{Q}_1$  (in practice, we compute  $P \in \mathbb{Q}[Z_1]$  such that  $\alpha = P \pmod{P_1}$  and we check  $\gcd(P_1, P) = 1$ ). We deduce that  $H_1$  is pseudo-degenerate with edge data  $(q_2, m_2, P_2, N_2) = (2, 1, Z_2 - \alpha, 1)$ . As  $N_2 = 1$ , we deduce that  $F$  is balanced with  $g = 2$ .

*Conclusion.* We deduce from Theorem 2 that  $F$  has  $f = \ell_1\ell_2 = 3$  irreducible factors over  $\mathbb{K}[[x]][y]$  of same degrees  $e = q_1q_2 = 2$ . Thanks to (9), we compute  $B_0 = e = 2$ ,  $B_1 = 2$ ,  $B_2 = 3$  and  $M_1 = 4$ ,  $M_2 = 6$ . We deduce that all factors of  $F$  have same characteristic exponents  $C(F_i) = (B_0; B_2) = (2; 3)$  and same intersection sets  $\Gamma_i(F) = (M_1, M_1) = (4, 4)$  (i.e.  $M_1$  which appears  $\hat{f}_0 - \hat{f}_1 = 3 - 1$  times), as required.

**Example 5 (non balanced).** Let  $F = y^6 - x^6y^4 - 2x^4y^4 - 2x^2y^4 + 2x^{10}y^2 + 3x^8y^2 - 2x^6y^2 + x^4y^2 - x^{14} + 2x^{12} - x^{10} \in \mathbb{Q}[x, y]$ . This second small example is constructed in such a way that  $F$  has 6 irreducible factors  $y + x - x^2$ ,  $y + x - x^2$ ,  $y - x - x^2$ ,  $y - x + x^2$ ,  $y - x^3$  and  $y + x^3$  and we check that  $F$  is not balanced, as  $\Gamma_i(F) = (1, 1, 1, 1, 2)$  for  $i = 1, \dots, 4$  while with  $\Gamma_i(F) = (1, 1, 1, 1, 3)$  for  $i = 5, 6$ . Let us recover this with algorithm Pseudo-Irreducible.

*Initialise.* We have  $N_0 = d = 6$ , and we let  $\psi_{-1} = x$ ,  $V = (1, 0)$  and  $\Lambda = (1, 1)$ .

*Step 0.* The 6<sup>th</sup>-approximate root of  $F$  is  $\psi_0 = y$  and we deduce that  $\bar{H}_0 = y^6 - 2x^2y^4 + x^4y^2 = (y(y^2 - x^2))^2$ . Thus, as in Example 4,  $H_0$  is pseudo-degenerate with edge data  $(q_1, m_1, P_1, N_1) = (1, 1, Z_1^3 - Z_1, 2)$ . Accordingly to (30), we update  $V = (1, 1, 1)$  and  $\Lambda = (1, z_1, 3z_1^2 - 1)$ .

*Step 1.* The 2<sup>nd</sup>-approximate root of  $F$  is  $\psi_1 = y^3 - yx^2 - yx^4 - \frac{1}{2}yx^6$  and  $F$  has  $\Psi$ -adic expansion  $F = \psi_1^2 - \psi_{-1}^{10} + 2\psi_{-1}^{12} - \psi_{-1}^{14} - 4\psi_{-1}^6\psi_0^2 + \psi_{-1}^8\psi_0^2 + \psi_{-1}^{10}\psi_0^2 - \frac{1}{4}\psi_{-1}^{12}\psi_0^2$ . The monomials reaching the minimal values (32) are  $\psi_1^2$  (for  $j = 2$ ) and  $-4\psi_{-1}^6\psi_0^2$  (for  $j = 0$ ). We deduce from (33) that  $\bar{H}_1 = y^2 - \alpha x^2$ , where  $\alpha = 4z_1^2/(3z_1^2 - 1)^2$ . As  $z_1$  is a zero divisor in  $\mathbb{Q}_1 = \mathbb{Q}[Z_1]/(Z_1^3 - Z_1)$  and  $(3z_1^2 - 1) = P_1'(z_1)$  is invertible in  $\mathbb{Q}_1$ , we deduce that  $\alpha$  is a zero divisor. It follows that  $\bar{H}_1$  is not the power of a square-free polynomial. Hence  $H_1$  is not pseudo-degenerate and  $F$  is not balanced (with  $g = 1$ ), as required. In order to factor  $F$ , we would need to split the algorithm at this stage according to the discovered factorisation  $P_1 = Z_1(Z_1^2 - 1)$  before continuing the process, as described in [22].

**Example 6 (non-Weierstrass).** Let  $F = (y + 1)^6 - 3x^3(y + 1)^4 - 2(y + 1)^4 + 3x^6(y + 1)^2 + (y + 1)^2 - x^9 + 2x^6 - x^3$ . We have  $F = ((y + 2)^2 - x^3)((y + 1)^2 - x^3)(y^2 - x^3)$



from which we deduce that  $F$  is balanced with three irreducible factors with characteristic exponents  $C(F_i) = (2, 3)$  and intersection sets  $I_i(F) = (0, 0)$ . Let us recover this with algorithm `Pseudo-Irreducible`.

*Initialise.* We have  $N_0 = d = 6$ , and we let  $\psi_{-1} = x$ ,  $V = (1, 0)$  and  $\Lambda = (1, 1)$ .

*Step 0.* The  $6^{\text{th}}$ -approximate root of  $F$  is  $\psi_0 = y + 1$ . We have  $F = \psi_0^6 - 3\psi_{-1}^3\psi_0^4 - 2\psi_0^4 + 3\psi_{-1}^6\psi_0^2 + \psi_0^2 - \psi_{-1}^9 + 2\psi_0^6 - \psi_{-1}^3$ . By (32), the monomials involved in the lower edge of  $H_0$  are  $\psi_0^6, -2\psi_0^4, \psi_0^2$ . We deduce from (33) that  $\bar{H}_0 = (y^3 - y)^2$  so that  $H_0$  is pseudo-degenerate with edge data  $(q_1, m_1, P_1, N_1) = (1, 0, Z_1^3 - Z_1, 2)$ . Note that  $m_1 = 0$ . This is the only step of the algorithm where this may occur. Using (30), we update  $V = (1, 0, 0)$  and  $\Lambda = (1, z_1, 3z_1^2 - 1)$ .

*Step 1.* The  $N_1 = 2^{nd}$  approximate root of  $F$  is  $\psi_1 = (y + 1)^3 - 3/2x^3(y + 1) - (y + 1)$  and  $F$  has  $\Psi$ -adic expansion  $F = \psi_1^2 - \psi_{-1}^3 - 3\psi_{-1}^3\psi_0^2 + 2\psi_{-1}^6 - \psi_{-1}^9 + 3/4\psi_{-1}^6\psi_0^2$ . We deduce that the monomials reaching the minimal values (32) are  $\psi_1^2$  (for  $j = 2$ ) and  $-\psi_{-1}^3, -3\psi_{-1}^3\psi_0^2$  (for  $j = 0$ ). We deduce from (33) that  $\bar{H}_1 = y^2 - \alpha x^3$ , where  $\alpha = (\lambda_{1,-1}^3 + 3\lambda_{1,-1}^3\lambda_{1,0}^2)\lambda_{1,1}^{-2} = (3z_1^2 + 1)/(3z_1^2 - 1)^2$  is easily seen to be invertible in  $\mathbb{Q}_1$ . We deduce that  $H_1$  is pseudo-degenerate with edge data  $(q_2, m_2, P_2, N_2) = (2, 3, Z_2 - \alpha, 1)$ . As  $N_2 = 1$ , we deduce that  $F$  is balanced with  $g = 2$ . By Theorem 2 (assuming only  $F$  monic), we get that  $F$  has  $f = \ell_1\ell_2 = 3$  irreducible factors over  $\bar{\mathbb{K}}[[x]][y]$  of same degrees  $e = q_1q_2 = 2$ . Thanks to (9), we compute  $B_0 = e = 2$ ,  $B_1 = 0$ ,  $B_2 = 3$  and  $M_1 = 0$ ,  $M_2 = 6$ . By Theorem 2, we deduce that all factors of  $F$  have same characteristic exponents  $C(F_i) = (B_0; B_2) = (2; 3)$  and same intersection sets  $I_i(F) = (M_1, M_1) = (0, 0)$  as required.

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