

## COMPUTING ISOGENIES BETWEEN ELLIPTIC CURVES OVER $F_{p^n}$ USING COUVEIGNES'S ALGORITHM

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ABSTRACT. The heart of the improvements by Elkies to Schoof's algorithm for computing the cardinality of elliptic curves over a finite field is the ability to compute isogenies between curves. Elkies' approach is well suited for the case where the characteristic of the field is large. Couveignes showed how to compute isogenies in small characteristic. The aim of this paper is to describe the first successful implementation of Couveignes's algorithm. In particular, we describe the use of fast algorithms for performing incremental operations on series. We also insist on the particular case of the characteristic 2.

### 1. INTRODUCTION

Elliptic curves have been used successfully to factor integers [27, 39], and to prove the primality of large integers [5, 20, 3]. Moreover, they turned out to be an interesting alternative to the use of  $\mathbb{Z}/N\mathbb{Z}$  or finite fields in cryptographical schemes (see [38, 25], [36], and the survey in [31]).

One of the main algorithmic problems to be solved is the efficient computation of the cardinality of elliptic curves over finite fields. It was not until recently that Schoof's polynomial time algorithm for solving this problem could be used efficiently, due to the work of Atkin [1, 2] and Elkies [16, 17] (see also [44, 40], and the results of the implementations given in [40, 31, 26, 42]). The main ingredient is the use of explicit isogenies between elliptic curves. The methods developed there gave satisfactory results in the large characteristic case, but could not be used when the characteristic was small, which explains why the implementation of [37] did not give satisfactory results. The first solution to this problem was given in Couveignes's thesis [9].

The aim of this paper is to explain how Couveignes's algorithm can be implemented in an efficient way. The structure is as follows. Section 2 recalls basic facts on elliptic curves. In Section 3 the particular case of isogenies of degree  $p$  is treated, which will yield properties of the multiplication by  $p$  on elliptic curves. We also deduce from these an algorithm for computing a factor of the  $p^e$ -division polynomial. Properties of the formal group are presented in Section 4. Section 5 explains the decisive ideas of Couveignes for the computation of isogenies in small characteristic. Section 6 is concerned with fast algorithms for incremental computations on series.

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Section 7 details the algorithms we need to implement Couveignes's ideas. The complexity of Couveignes's approach is then derived. Section 8 is devoted to the implementation in the special case of characteristic 2.

To simplify the exposition, we will consider non-supersingular elliptic curves only. (Note that this is enough for the application to point counting, the cardinality of supersingular curves having been studied in [35, 41].)

## 2. PRELIMINARIES AND NOTATIONS

Throughout the paper, we let  $\mathbb{K} = \mathbb{F}_q = \mathbb{F}_{p^n}$  be a finite field of characteristic  $p$  and denote by  $\overline{\mathbb{K}}$  its Galois closure. The norm of an element  $x$  of  $\mathbb{K}$  is written  $N_{\mathbb{K}/\mathbb{F}_p}(x)$  and the trace is noted  $\text{Tr}_{\mathbb{K}/\mathbb{F}_p}(x)$ .

We will encounter many  $p$ -th roots in characteristic  $p$  and it will be convenient to write them as  $\tilde{a} = \sqrt[p]{a}$  (note that every element  $a$  in  $\mathbb{K}$  has exactly one  $p$ -th root given by  $a^{p^{n-1}}$ ). Moreover, if  $A(X)$  is a series (or a polynomial) in  $\mathbb{K}[X] : A(X) = \sum_i a_i X^i$ , we will write  $\tilde{A}(X) = \sum_i \tilde{a}_i X^i$ .

As far as time complexity is concerned, our unit of cost will be the time needed to perform a multiplication in  $\mathbb{K}$ , a unit being thus  $O(n^2(\log p)^2)$  bit complexity if ordinary multiplication is used. The space unit will be that of storing an element of  $\mathbb{K}$ , that is  $O(n \log p)$  bits.

We recall well-known properties of elliptic curves. All these can be found in [45]. Let  $E$  be an elliptic curve defined over  $\mathbb{K}$  with defining equation  $\mathfrak{E}(X, Y) = 0$ , where

$$\mathfrak{E}(X, Y) = Y^2 + a_1XY + a_3Y - (X^3 + a_2X^2 + a_4X + a_6).$$

The curve  $E$  will be abbreviated as  $[a_1, a_3, a_2, a_4, a_6]$ . Remember that by Hasse's theorem, one has  $\#E(\mathbb{K}) = q + 1 - c$  for some integer  $c$ ,  $|c| \leq 2\sqrt{q}$ .

For an integer  $m$  there exist  $\phi_m, \psi_m$  and  $\omega_m$  in  $\mathbb{Z}[a_1, a_2, a_3, a_4, a_6, X, Y]$  such that

$$[m](X, Y) = \left( \frac{\phi_m(X, Y)}{\psi_m^2(X, Y)}, \frac{\omega_m(X, Y)}{\psi_m^3(X, Y)} \right).$$

A particular role is played by  $\psi_m$ . We let  $\psi'_m(X)$  denote  $\psi_m(X, Y) \bmod \mathfrak{E}(X, Y)$ . When  $m$  is even, we let  $f_m = \psi'_m/(2Y + a_1X + a_3)$  and if  $m$  is odd, then  $f_m = \psi'_m$ . The  $m$ -torsion points of  $E$ , noted  $E[m] = \{P \in E(\overline{\mathbb{K}}), mP = O_E\}$ , can be described using  $f_m(X)$ : if  $P$  is a point on  $E(\overline{\mathbb{K}})$  such that  $2P \neq O_E$ , then  $P \in E[m]$  if and only if  $f_m(X) = 0$ .

## 3. ISOGENIES OF DEGREE $p$

The aim of this section is to explain the properties of isogenies of degree  $p$  in characteristic  $p$ , and to deduce from these results about the multiplication by  $p$  on  $E$ . These results will be used in the following section and will be a key to simplifying some parts of the subsequent algorithms. We are indebted to J.-M. Couveignes for the following facts.

Let  $\Phi_\ell(X, Y)$  denote the  $\ell$ -th modular polynomial, that is the polynomial for which the roots of  $\Phi_\ell(X, j(E))$  are the  $j$ -invariants of the elliptic curves  $E^*$  related to  $E$  by an isogeny of degree  $\ell$ . A theorem of Kronecker tells us (see, for instance, [4]) that

$$\Phi_p(X, Y) \equiv (X^p - Y)(X - Y^p) \bmod p.$$

This immediately shows that if  $E$  and  $E^*$  are  $p$ -isogenous, then  $j(E^*) = j(E)^p$  or  $j(E^*) = j(E)^{1/p}$ .

If  $E = [a_1, a_3, a_2, a_4, a_6]$ , then define  $E^p = [a_1^p, a_3^p, a_2^p, a_4^p, a_6^p]$  and  $\tilde{E} = [\tilde{a}_1, \tilde{a}_3, \tilde{a}_2, \tilde{a}_4, \tilde{a}_6]$ . Let us look at the following diagram.

$$\begin{array}{ccc} \tilde{E} & \xrightarrow{\iota} & E \\ & \searrow [p] & \downarrow \varsigma \\ & & E \end{array}$$

Multiplication by  $p$  on  $\tilde{E}$  factors as a product of isogenies  $[p] = \varsigma \circ \iota$ , where  $\iota : (X, Y) \mapsto (X^p, Y^p)$  is inseparable and  $\varsigma$  is separable. We can reformulate this as

**Proposition 3.1.** *Multiplication by  $p$  on  $E$  is given by*

$$(1) \quad [p](X, Y) = (F_p(X)^p, G_p(X, Y)^p),$$

where  $F_p(X)$  and  $G_p(X, Y)$  are two rational functions.

As a useful corollary, we note

**Corollary 3.1.** *There exists a polynomial  $f_{p^e} \in \mathbb{K}[X]$  such that the division polynomial  $f_{p^e}$  can be written as  $f_{p^e}(X) = (f_{p^e}(X))^{p^e}$ .*

*Proof.* From (1), it follows that

$$[p^e](X, Y) = (F_{p^e}(X)^{p^e}, G_{p^e}(X, Y)^{p^e})$$

for all  $e \geq 1$ . In particular, this implies that  $\psi_{p^e}$  and a fortiori  $f_{p^e}$  are  $p^e$ -th powers. From this it follows that the degree of  $f_{p^e}$  is in fact at most  $(p^{2e} - p^e)/2$ .  $\square$

*Remark.* As shown in [30], there is an elementary approach to the fact that  $f_p(X)$  is a  $p$ -th power in characteristic  $p$ , using Fricke’s differential equation [18, vol. II, pp. 191].

**Corollary 3.2.** *For  $e > 1$ ,  $f_{p^{e-1}}(X)|f_{p^e}(X)$  and the resulting quotient is a factor of  $f_{p^e}$  of degree  $p^{e-1}(p - 1)/2$  if  $p$  is odd and  $2^{e-2}$  if  $p = 2$ .*

In practice, the computation of  $f_p$  is done using [37] for  $p = 2$  and [21] when  $p$  is odd. Then  $f_{p^e}$  is computed using the isogenies given by Vélú’s formulae as in [15] and the methods of [13, 12].

#### 4. FORMAL GROUPS

The material below is taken from [45, Chap. IV].<sup>1</sup> Let  $t = -X/Y$  and  $s = -1/Y$ . We transform the equation of  $E$  to get

$$(2) \quad s = A(t, s) = t^3 + a_1ts + a_2t^2s + a_3s^2 + a_4ts^2 + a_6s^3.$$

Substituting this equation into itself, we get  $s$  as a power series in  $t$ , that we will note  $\mathcal{S}(t)$ . Since equation (2) is again cubic, we can add two points  $(t_1, s(t_1))$  and  $(t_2, s(t_2))$  to get  $(t_3, s(t_3))$  in the usual way using the tangent-and-chord law. As a result, we find  $t_3$  as a power series  $F_a(t_1, t_2)$  in  $\mathbb{K}[[t_1, t_2]]$  whose first terms are

$$(3) \quad \begin{aligned} F_a(t_1, t_2) = & t_1 + t_2 - a_1t_1t_2 - a_2(t_1^2t_2 + t_1t_2^2) \\ & - (2a_3t_1^3t_2 - (a_1a_2 - 3a_3)t_1^2t_2^2 + 2a_3t_1t_2^3) + \dots \end{aligned}$$

This series  $F_a$  defines what is known as the *formal group*  $\mathcal{E}$  associated to  $E$ .

<sup>1</sup>Be careful—there are some typos and missing equations in [23, Chap. 12].

4.1. **Computing  $\mathcal{S}(t)$ .** From the equation  $\mathcal{S} = A(t, \mathcal{S})$ , it is easy to compute the first  $L$  coefficients of  $\mathcal{S}$  as a formal series in  $t$  by an iterative process in  $O(L^2)$  operations. We can do better using standard techniques from combinatorics [8, 43]. In particular,  $\mathcal{S}$  satisfies a second order linear differential equation with polynomial coefficients in  $t$ , from which we easily deduce recurrence relations between the coefficients of  $\mathcal{S}$ . Hence, these coefficients can be computed in  $O(L)$  operations modulo precomputations. See subsection 8.1 for the computations in characteristic 2.

The first coefficients of  $\mathcal{S}$  are

$$(4) \quad \mathcal{S}(t) = \sum_{i=3}^{\infty} s_2 t^i = t^3 + a_1 t^4 + (a_1^2 + a_2) t^5 + O(t^6).$$

Given any  $t(\tau)$  in  $\mathcal{E}$ , we can compute  $\mathcal{S}(t(\tau))$  by the same algorithms.

We deduce from this that

$$Y = -\frac{1}{s} = -t^{-3} + a_1 t^{-2} + a_2 t^{-1} + a_3 + (a_1 a_3 + a_4) t + O(t^2),$$

and

$$X = \frac{t}{s} = -tY = t^{-2} - a_1 t^{-1} - a_2 - a_3 t - (a_1 a_3 + a_4) t^2 + O(t^3),$$

$$Z = \frac{1}{X} = t^2 + a_1 t^3 + (a_1^2 + a_2) t^4 + O(t^5).$$

4.2. **Group law.** In this subsection we give the formulas that will be used for computing the group law on  $\mathcal{E}$ , that we will note  $\oplus$ , multiplication by  $k$  being noted as  $[k]$ . The neutral element is  $O_{\mathcal{E}} = (0, 0)$  and the equation of  $\mathcal{E}$  is  $F(t, s) := A(t, s) - s = 0$ . Proofs can be found in the reference.

We start from two points  $P_1 = (t_1, s_1)$  and  $P_2 = (t_2, s_2)$ , different from  $O_{\mathcal{E}}$ , and we compute the sum  $(t_3, s_3) = (t_1, s_1) \oplus (t_2, s_2)$ . This is done as usual: the line passing through  $P_1$  and  $P_2$  intersects  $\mathcal{E}$  at a third point  $P_i = (t_i, s_i)$  and the line passing through  $P_i$  and  $(0, 0)$  intersects  $\mathcal{E}$  at  $P_3$ .

We let  $y = \lambda t + \nu$  be the line passing through the two points  $P_1$  and  $P_2$ . If  $(t_1, s_1) \neq (t_2, s_2)$ , then

$$(5) \quad \lambda = \frac{s_2 - s_1}{t_2 - t_1} = t_1^2 + t_1 t_2 + t_2^2 + \dots$$

and if the two points are equal

$$(6) \quad \lambda = -\frac{\frac{\partial F}{\partial t}}{\frac{\partial F}{\partial s}} = -\frac{a_1 s_1 + 3t_1^2 + 2a_2 t_1 s_1 + a_4 s_1^2}{-1 + a_1 t_1 + 2a_3 s_1 + a_2 t_1^2 + 2a_4 t_1 s_1 + 3a_6 s_1^2} = 3t_1^2 + 4a_1 t_1^3 + O(t_1^4).$$

One also computes  $\nu = s_1 - \lambda t_1$ . For  $P_i$  one finds

$$(7) \quad t_i = -t_1 - t_2 - \frac{a_1 \lambda + 2a_4 \nu \lambda + a_2 \nu + 3a_6 \nu \lambda^2 + a_3 \lambda^2}{a_4 \lambda^2 + a_2 \lambda + 1 + a_6 \lambda^3},$$

and from this we deduce  $s_i = \lambda t_i + \nu$ .

If  $t_i = 0$ , then  $P_2$  is the opposite of  $P_1$  and we are done,  $P_3 = O_{\mathcal{E}}$ . Otherwise, we have to compute the addition of  $(t_i, s_i)$  and the origin point  $(0, 0)$  to get  $(t_3, s_3)$ .

Finally, we obtain

$$(8) \quad t_3 = \frac{t_i}{-1 + a_1 t_i + a_3 s_i}, \quad s_3 = \frac{s_i}{t_i} t_3,$$

from which we recover  $t_3 = F_a(t_1, t_2)$ .

It is now easy to compute the opposite of  $P$ , simply noting that this opposite is the third point of intersection of the line joining  $P$  and  $O_{\mathcal{E}}$  with  $\mathcal{E}$ . Precisely, if  $-P = (t', s')$ , one has

$$(9) \quad t' = \frac{t}{-1 + a_1 t + a_3 s}.$$

When  $t_1 = t_2$ , we get

$$(10) \quad F_d(t_1) = [2]t_1 = 2t_1 - a_1 t_1^2 - 2a_2 t_1^3 + (a_1 a_2 - 7a_3) t_1^4 + O(t_1^5).$$

**4.3. The Hasse invariant.** Using Proposition 3.1, we see that

$$(11) \quad [p](t) = - \left( \frac{F_p(t/\mathcal{S}(t))}{G_p(t/\mathcal{S}(t), -1/\mathcal{S}(t))} \right)^p, \quad \mathcal{S}([p](t)) = - \left( \frac{1}{G_p(t/\mathcal{S}(t), -1/\mathcal{S}(t))} \right)^p.$$

Let us introduce the rational fraction

$$(12) \quad \mathcal{R}_{p,E}(t, s) = (-1)^p \frac{F_p(t/s)}{G_p(t/s, -1/s)}$$

and put  $\Psi_{p,E}(t) = \mathcal{R}_{p,E}(t, \mathcal{S}(t))$ . Then  $[p](t) = \Psi_{p,E}(t)^p$ . We will see the interest of such a definition in subsection 7.2.2.

**Example.** If  $p = 2$  and  $E = [1, 0, 0, 0, a_6]$ , one has

$$(13) \quad \mathcal{R}_{2,E}(t, s) = \frac{(t^2 + \tilde{a}_6 s^2)t}{t^3 + (1 + \tilde{a}_6 s)t^2 + (\tilde{a}_6 s^2 + s)t + \tilde{a}_6 s^2 + s}.$$

**Theorem 4.1.** *Assume  $E$  is not supersingular. Then*

$$[p](t) = c_p(E)t^p + O(t^{p^2}),$$

where the coefficient  $c_p(E)$  of  $t^p$  is called the (relative) Hasse invariant of  $E$ .

One important property of the Hasse invariant is the following [45, Chap. V, §4].

**Theorem 4.2.** *Let  $\#E(\mathbb{K}) = q + 1 - c$ . The Hasse invariant satisfies*

$$N_{\mathbb{K}/\mathbb{F}_p}(c_p(E)) \equiv c \pmod{p}.$$

Remembering that two isogenous curves have the same number of points (see [14, 46]), the preceding theorem tells us the following.

**Corollary 4.1.** *Two isogenous curves  $E$  and  $E^*$  have Hasse invariants related by*

$$c_p(E^*) \equiv \varepsilon^{p-1} c_p(E) \pmod{p}$$

for some  $\varepsilon$  in  $\mathbb{K}^*$ .

In characteristic 2, one has  $c_p(E) = a_1$ ; in characteristic 3, for the curve  $[0, 0, a_2, 0, a_6]$ , it is  $a_2$ . When  $p > 3$ , one can compute the Hasse invariant using the work of Deuring [14] or Atkin's method using hypergeometric polynomials (see [2, 24]).

5. COUVEIGNES’S ALGORITHM: THE THEORY

5.1. **An overview.** Let  $E$  and  $E^*$  be two elliptic curves defined over  $\mathbb{K}$  by

$$E : Y^2 + a_1XY + a_3Y = X^3 + a_2X^2 + a_4X + a_6,$$

$$E^* : Y^2 + a_1^*XY + a_3^*Y = X^3 + a_2^*X^2 + a_4^*X + a_6^*,$$

such that there exists an isogeny  $\mathfrak{J}$  of degree  $\ell$  between them. In view of Corollary 4.1, we can assume without loss of generality that  $c_p(E^*) = c_p(E) = \gamma$ .

We assume that the isogeny  $\mathfrak{J}$  between  $E$  and  $E^*$  is given by

$$\mathfrak{J} : E \rightarrow E^*$$

$$(X, Y) \mapsto \left( \frac{g(X)}{h^2(X)}, \frac{r(X) + Yt(X)}{h^3(X)} \right),$$

where  $g(X), h(X), r(X)$  and  $t(X)$  are polynomials of degree  $\ell, (\ell - 1)/2, 3(\ell + 1)/2$  and  $3(\ell - 1)/2$ . The aim of Couveignes’s algorithm [9] is the computation of  $g(X)$  and  $h(X)$  given the equations of  $E$  and  $E^*$ .

Let  $I(X) = g(X)/h^2(X)$ . It is equivalent to search for  $g$  and  $h$  such that

$$I : X \mapsto X^* = I(X) = \frac{g(X)}{h(X)^2},$$

or for  $\hat{I}$  which sends  $Z = 1/X$  to  $Z^* = 1/X^*$ , that is

$$\hat{I} : Z \mapsto Z^* = \hat{I}(Z) = Z \frac{\hat{h}^2(Z)}{\hat{g}(Z)}$$

with  $\hat{g}(Z) = Z^\ell g(1/Z)$  and  $\hat{h}(Z) = Z^{(\ell-1)/2} h(Z)$ . We note that  $\hat{g}$  has degree  $\ell$ . It is well known that the coefficients of the expansion of a rational fraction  $F(Z)$  with denominator of degree  $\ell$  around  $Z = 0$  satisfy a recurrence relation of depth  $\ell$  (see subsection 7.3.2 for more details). Reciprocally, given the  $2\ell$  first coefficients, one can recover  $F(Z)$  exactly. Couveignes’s idea is just this: find a series that looks like an isogeny and then check whether it comes from a fraction whose denominator has degree  $\ell$ . In fact, we compute  $2\ell + 2$  terms of the series, thus obtaining in general a fraction with denominator of degree a priori  $\ell + 1$ . If this denominator turns out to have degree  $\ell$ , then we are almost sure to have the correct value for  $\hat{I}$ . See subsection 7.3 for more details.

Enumerating the putative isogenies is possible using the formal groups associated to  $E$  and  $E^*$  as described below.

5.2. **Morphisms of formal groups.** As shown in Section 2, there are two formal groups  $\mathcal{E}$  and  $\mathcal{E}^*$  associated to  $E$  and  $E^*$

$$\mathcal{E} : t^3 + a_1ts + a_2t^2s + a_3s^2 + a_4ts^2 + a_6s^3 - s = 0,$$

$$\mathcal{E}^* : t^3 + a_1^*ts + a_2^*t^2s + a_3^*s^2 + a_4^*ts^2 + a_6^*s^3 - s = 0.$$

A *morphism* of formal groups is given by  $\mathcal{M}$  such that for all formal points  $(t_1(\tau), s_1(\tau))$  and  $(t_2(\tau), s_2(\tau))$  of  $\mathcal{E}$

$$\mathcal{M}((t_1(\tau), s_1(\tau)) \oplus (t_2(\tau), s_2(\tau))) = \mathcal{M}((t_1(\tau), s_1(\tau))) \oplus \mathcal{M}((t_2(\tau), s_2(\tau))).$$

Associated to a morphism  $\mathcal{M}$  between  $\mathcal{E}$  and  $\mathcal{E}^*$ , there is a series

$$\mathcal{U}(t) = \sum_{i \geq 1} u_i t^i,$$

such that a point  $(t(\tau), s(\tau))$  of  $\mathcal{E}$  is sent to the point  $\mathcal{M}(t(\tau), s(\tau)) = (\mathcal{U}(t(\tau)), \mathcal{S}^*(\mathcal{U}(t(\tau))))$  of  $\mathcal{E}^*$  ( $\mathcal{S}^*$  is defined by (4)). A fortiori, the series  $\mathcal{U}(t)$  satisfies

$$(14) \quad \mathcal{U}(t_1 \oplus t_2(\tau)) = \mathcal{U}(t_1(\tau)) \oplus \mathcal{U}(t_2(\tau))$$

from which  $\mathcal{U} \circ [n] = [n] \circ \mathcal{U}$  for any integer  $n$ .

Coming back to our problem,  $\widehat{I}$  gives rise to a morphism  $\mathcal{I}$  between  $\mathcal{E}$  and  $\mathcal{E}^*$ , and to a series  $\mathcal{W}$ . The problem is now the following: among all morphisms between  $\mathcal{E}$  and  $\mathcal{E}^*$ , determine which is the one coming from  $\mathcal{I}$ , or equivalently, among all series satisfying (14), determine which is the one coming from  $\widehat{I}$ . Since the set of morphisms from  $\mathcal{E}$  to  $\mathcal{E}^*$  is a  $\mathbb{Z}_p$ -module of rank 1 (see [19]), we run through all the powers of a generator of this module and test for each morphism whether we can recover  $\widehat{I}$ . Our first task is then to find a generator of this module.

Since  $2\ell + 2$  terms of  $\widehat{I}(Z)$  are needed, and since  $Z = 1/X = s/t = t^2 + O(t^3)$ , this means that we need  $\mathcal{L} = 4\ell + 2$  terms of the series  $\mathcal{W}$  associated to  $\mathcal{I}$ . In other words, we need to consider a finite number of series in order to find the good one. We will compute the precise number of such series in the following section.

**5.3. Finding conditions satisfied by morphisms.** Let us now look at the properties satisfied by morphisms between  $\mathcal{E}$  and  $\mathcal{E}^*$ , or more precisely by the associated series. We will compute the first  $\mathcal{L}$  coefficients of

$$\mathcal{U}(t) = \sum_{i=1}^{\infty} u_i t^i$$

by induction. Let us assume that  $u_1, \dots, u_{i-1}$  are known. An ingenious exploitation of equation (14) will allow us to calculate  $u_i$ .

Let us specialize  $t_1(\tau) = \tau$  and  $t_2(\tau) = A\tau$ , where  $A$  is in  $\mathbb{K}$ . Considering the left-hand side of  $\mathcal{U}(\tau \oplus A\tau) = \mathcal{U}(\tau) \oplus \mathcal{U}(A\tau)$ , we find that  $u_i$  appears alone in the coefficient of  $\tau^i$  as  $(1 + A)^i u_i$  among terms depending only on  $u_1, u_2, \dots, u_{i-1}$ . On the other hand,

$$\mathcal{U}(\tau) \oplus \mathcal{U}(A\tau) = \mathcal{U}(\tau) + \mathcal{U}(A\tau) + P(\mathcal{U}(\tau), \mathcal{U}(A\tau)),$$

where  $P(\mathcal{U}(\tau), \mathcal{U}(A\tau))$  contains monomials of total degree greater than 1 in  $\mathcal{U}(\tau)$  and  $\mathcal{U}(A\tau)$ . This means that  $u_i$  appears in the coefficient of  $\tau^i$  as  $(1 + A^i)u_i$  among terms depending only on  $u_1, u_2, \dots, u_{i-1}$ . From this, we deduce that

$$(15) \quad u_i((1 + A)^i - 1 - A^i) + e_i(A, u_1, \dots, u_{i-1}) = 0,$$

with  $e_i$  a multivariate polynomial. If  $(1 + A)^i \neq 1 + A^i$ , this relation gives us  $u_i$ . We see that this condition on  $A$  cannot be met when  $i$  is a power of  $p$ , but for other values of  $i$ , we can find  $A$  such that it is realized, at least if  $i < q$ .

Suppose now that  $i = p^e$ . Exploiting the equation  $\mathcal{U}([p]\tau) = [p](\mathcal{U}(\tau))$ , we find that  $u_i$  satisfies

$$(16) \quad \left(\frac{u_i}{\eta}\right) - \left(\frac{u_i}{\eta}\right)^p = f_i(u_1, \dots, u_{i-1}),$$

where

$$\eta = \gamma^{(p^e - 1)/(p - 1)}$$

and  $f_i$  is a multivariate polynomial. We will see in subsection 7.1.2 how to solve this equation. Obviously, it has at most  $p$  solutions.

Let us look at the case  $i = 1 = p^0$ . The corresponding equation is simply  $u_1^{p-1} = 1$ . Therefore,  $u_1$  is in the prime field and without loss of generality we can take  $u_1 = 1$ .

**5.4. Enumerating all morphisms.** We can summarize the results of the preceding subsection as follows. Once  $u_{p^e}$  is fixed, all coefficients  $u_j$  for  $p^e < j < p^{e+1}$  are uniquely determined. In this way, we can count the number of different truncated morphisms up to order  $\mathcal{L}$ . Let  $p^r < \mathcal{L} < p^{r+1}$ . Then there are at most  $p^{r+1}$  distinct series. For each  $e$ ,  $1 \leq e \leq r$ , there are at most  $p$  values for  $u_{p^e}$ ; if  $e = 0$ , this number is at most  $p - 1$  since  $u_1 = 0$  is not valid. Therefore, there are  $p^r(p - 1)$  morphisms  $\mathcal{U}$ . We need to enumerate them in order to find the one that comes from an isogeny.

*5.4.1. First approach.* This consists in testing all possible values of  $u_{p^e}$  for each  $e$ , using a backtracking procedure that is straightforward from the explanations given above.

*5.4.2. Second approach.* Let  $\mathcal{U}$  be any generator of the set of morphisms between  $\mathcal{E}$  and  $\mathcal{E}^*$ , found as in the preceding subsection. There exists a  $p$ -adic integer  $N$  such that  $\mathcal{W} = [N] \circ \mathcal{U}$ . Write

$$N = \sum_{i=0}^{\infty} n_i p^i.$$

Remembering that  $p^r < \mathcal{L} < p^{r+1}$ , we write

$$[N] \circ \mathcal{U} = \bigoplus_{i=0}^r ([n_i] \circ ([p^i] \circ \mathcal{U})) \oplus \bigoplus_{i>r} ([n_i] \circ ([p^i] \circ \mathcal{U})).$$

But the valuation of the series  $[p^i](t)$  is  $p^i$ , which implies that when  $i > r$ , the terms coming from  $[p^i] \circ \mathcal{U}$  do not provide any contribution to the first  $\mathcal{L}$  coefficients of  $[N] \circ \mathcal{U}$ . So, it is enough to check whether one of the series  $[N] \circ \mathcal{U}$  comes from an isogeny for  $N < p^{r+1}$ . Moreover,  $n_0$  cannot be 0.

We can reduce the number of tentative morphisms using the following result.

**Proposition 5.1.** *Let  $N$  be an integer satisfying  $0 \leq N < p^{r+1}$ . Then one has*

$$(17) \quad ([p^{r+1} - N] \circ \mathcal{U})(t) = ([-N] \circ \mathcal{U})(t) + O(tp^{r+1}).$$

*Proof.* The result follows easily from (4.1). □

This relation expresses the fact that the morphism  $-\mathcal{W}$  associated with the isogeny  $-\widehat{I}$ , has the same abscissa as  $\widehat{I}$ . So, at least one morphism  $\mathcal{M} = [N] \circ \mathcal{U}$  for  $N < p^{r+1}/2$  and  $N$  prime to  $p$  is equal to  $\mathcal{W}$  or  $-\mathcal{W}$  and is associated to the abscissa of  $\widehat{I}$ . That is to say, we have to compute at most  $p^r(p - 1)/2$  morphisms  $\mathcal{M}$ .

## 6. INCREMENTAL SERIES COMPUTATIONS

The implementation of Couveignes’s algorithm requires the use of fast algorithms for series computations. As will be described in Section 7, the algorithms we need are concerned with incremental computations. Starting from series whose coefficients are known up to order  $i$ , we will find the terms of order  $i + 1$  of these series.

In the following subsections, we note for any series  $\mathcal{A}(\tau) = \sum_{i \geq v} a_i \tau^i$  of valuation  $v$  in  $\mathbb{K}[[\tau]]$ ,  $\mathcal{A}(\tau)_k$  the finite sum  $\sum_{i=v}^k a_i \tau^i$ . The  $i$ -th coefficient of a series  $\mathcal{A}$  will always denote  $a_i$ . We make the general assumption that multiplying two series with  $m$  terms uses  $O(m^\mu)$  units; of course, we assume  $1 < \mu \leq 2$ .

Incremental algorithms for the four basic operations  $+, -, \times, /$  are easy to derive and we will not give them.

**6.1. Computations in the formal group.** Let  $(\mathcal{V}(t), \mathcal{S}(\mathcal{V}(t)))$  be a formal point of  $\mathcal{E}$ . We note

$$\mathcal{V}(t) = \sum_{i=1}^{\infty} v_i t^i \quad \text{and} \quad \mathcal{S}(\mathcal{V}(t)) = \sum_{i=3}^{\infty} \varpi_i t^i.$$

The following propositions summarize our approach.

**Proposition 6.1.** *We can obtain  $\varpi_L$  from  $(\varpi_3, \dots, \varpi_{L-1})$  and  $(v_1, \dots, v_{L-2})$  with  $O(L)$  multiplications in  $\mathbb{K}$ .*

*Proof.* As  $(\mathcal{V}(t), \mathcal{S}(\mathcal{V}(t)))$  is an element of the formal group defined by  $\mathcal{E}$ ,

$$(18) \quad \mathcal{V}^3 + a_1 \mathcal{V} \mathcal{S}(\mathcal{V}) + a_2 \mathcal{V}^2 \mathcal{S}(\mathcal{V}) + a_3 \mathcal{S}(\mathcal{V})^2 + a_4 \mathcal{V} \mathcal{S}(\mathcal{V})^2 + a_6 \mathcal{S}(\mathcal{V})^3 = \mathcal{S}(\mathcal{V}).$$

By inspection of the valuations and indices of  $\mathcal{V}$  and  $\mathcal{S}$ , the result follows. □

The same work can be done for addition in  $\mathcal{E}$ .

**Proposition 6.2.** *Let  $\mathcal{A}(t) = \sum_i a_i t^i$  and  $\mathcal{A}'(t) = \sum_i a'_i t^i$  be two formal series and put  $\mathcal{S}(t) = \mathcal{S}(\mathcal{A}(t)) = \sum_{i=3}^{\infty} \varpi_i t^i$  (resp.  $\mathcal{S}'(t) = \mathcal{S}(\mathcal{A}'(t)) = \sum_{i=3}^{\infty} \varpi'_i t^i$ ). We can obtain the  $L$ -th coefficient of  $(\mathcal{A}(t) \oplus \mathcal{A}'(t))_L$  from the truncated formal points  $(\mathcal{A}(t)_L, \mathcal{S}_{L+1}(t))$  and  $(\mathcal{A}'(t)_L, \mathcal{S}'_{L+1}(t))$  with  $O(L)$  operations.*

Finally, we have

**Proposition 6.3.** *We can obtain the  $L$ -th term of the series  $\mathcal{R}(t, \mathcal{S}(t)) \circ \mathcal{V}(t)$  from the truncated formal point  $(\mathcal{V}(t)_L, \mathcal{S}(\mathcal{V}(t))_{L+1})$  using  $O(L)$  operations.*

**6.2. An incremental algorithm for composition of series.** Let  $f(t) = \sum_{i=1}^{\infty} a_i t^i$  and  $g(t) = \sum_{i=0}^{\infty} b_i t^i$  be two formal series in  $\mathbb{K}[[t]]$ . We want to compute the series

$$h(t) = (g \circ f)(t) = \sum_{i=0}^{\infty} c_i t^i$$

incrementally. More precisely, we assume  $f$  is known up to order  $L$  and that we need to compute the coefficients  $h_0, h_1, \dots, h_L$  one at a time, or equivalently, given all series at order  $i$ , find  $h_i$ . We do this by an incremental version of the algorithm of Brent and Kung [7].

Let  $B$  be an integer  $\leq L$  that we will determine later. Let  $i$  be an integer less than  $L$  and assume we know all coefficients of  $g$  (resp.  $h$ ) of index  $< i$ . We are looking for  $c_i$ . To compute  $g_i \circ f$ , we write

$$g_i(t) = \sum_{k=0}^i b_k t^k = \sum_{0 \leq j \leq i/B} G_j(t) t^{Bj},$$

where  $G_j(t)$  is a polynomial of degree at most  $B - 1$  in  $t$ . Then

$$g_i \circ f = \sum_{0 \leq j \leq i/B} G_j(f) f^{Bj}.$$

We precompute  $f_j = f^j$  for  $0 \leq j \leq B$  and  $F_j = f_B^j$  for  $0 \leq j \leq L/B$ , up to order  $L$ . Now, put  $i = JB + I$  with  $0 \leq I < B$ . One gets

$$g_i \circ f = \sum_{0 \leq j < J} G_j(f_1)F_j + \left( \sum_{k=0}^{I-1} b_{JB+k}f_k \right) F_J + b_I f_I F_J = \Sigma_{1,i} + \Sigma_{2,i}F_J + b_I f_I F_J.$$

(We use the convention that if  $I = 0$ , then  $\Sigma_{2,i} = 0$ .) It is easy to see that all terms of  $\Sigma_{1,i}$  and  $\Sigma_{2,i}$  up to order  $L$  (not  $i$ ) depend only on the first coefficients  $b_1, \dots, b_{i-1}$ . Now, it is easy to get the  $i$ -th term of  $\Sigma_{2,i}F_J$  in  $O(i)$  steps, as well as that of  $f_I F_J$ , which enables us to find the desired coefficient  $c_i$ .

Once this is done, we have to update the series. Note that we do not need the terms of indices  $\leq i$ . We see that if  $I < B - 1$ , then  $\Sigma_{1,i+1} = \Sigma_{1,i}$  and

$$\Sigma_{2,i+1} = \Sigma_{2,i} + b_I f_I.$$

In this case, updating the series costs  $O(L - i)$ . If  $I = B - 1$ , then

$$\Sigma_{1,i+1} = \Sigma_{1,i} + (\Sigma_{2,i} + c_i f_I)F_J$$

and  $\Sigma_{2,i+1} = 0$ . Since we only need the terms of degree  $> i$ , this costs  $O((L - i)^\mu)$ .

Precomputing the  $f_j$ 's costs  $\sum_{j=2}^B (L - j)^\mu$ , that of the  $F_j$ 's is  $\sum_{j=2}^{L/B} (L - jB)^\mu$  and leads to a storage of  $O(B + L/B)$  series with  $L$  terms. The cost of the computations of all  $\Sigma_{1,i}$  and  $\Sigma_{2,i}$  is also  $\sum_{j=2}^{L/B} (L - jB)^\mu$ . So we need to minimize:

$$\sum_{j=2}^B (L - j)^\mu + 2 \sum_{j=2}^{L/B} (L - jB)^\mu.$$

After some computations, we find

**Proposition 6.4.** *The cost of the incremental version of Brent and Kung [7] is minimal for  $B = \sqrt{\frac{2}{\mu+1}}L^{1/2}$ , giving a running time of approximately  $2BL^{1/2}$  with a storage of  $O(L^{1/2})$ .*

### 7. EFFICIENT IMPLEMENTATION OF COUVEIGNES'S ALGORITHM

In this section, we give the algorithms needed to implement Couveignes's ideas, and deduce from this the complexity of the method. We will note  $\Psi(t)$  for  $\Psi_{p,E}(t)$  and  $\mathcal{R}(t, s)$  for  $\mathcal{R}_{p,E}(t, s)$ ;  $\Psi^*(t)$  for  $\Psi_{p,E^*}(t)$  and  $\mathcal{R}^*(t, s)$  for  $\mathcal{R}_{p,E^*}(t, s)$ .

#### 7.1. Precomputations for $p$ alone.

7.1.1. *Multiplication by  $p$ .* The first thing we need is to compute the multiplication by  $p$  and the fraction  $\mathcal{R}(t, s)$ , as indicated in subsection 4.3. These computations do not depend on  $\ell$ . The cost is  $O(p^2 \log p)$  elementary operations.

7.1.2. *Solving  $X - X^p = \alpha$ .* We use the following result due to Hilbert (see for example [34]).

**Proposition 7.1.** *The equation*

$$(19) \quad \beta - \beta^p = \alpha$$

*has a solution in  $\mathbb{K}$  if and only if  $\text{Tr}_{\mathbb{K}/\mathbb{F}_p}(\alpha) = 0$ . Moreover, if  $\theta$  has trace 1, then a solution of this equation is*

$$(20) \quad \beta = \alpha\theta^p + (\alpha + \alpha^p)\theta^{p^2} + \dots + (\alpha + \alpha^p + \dots + \alpha^{p^{n-2}})\theta^{p^{n-1}}.$$

We remark that if (19) has a solution  $\beta$ , then  $\beta + k$  is a solution for all  $k$  in the prime field  $\mathbb{F}_p$ . It is also easy to see that the map  $\alpha \mapsto \beta$  is linear. Having computed the matrix of this application, all equations (16) can be solved by applying this matrix to the coefficients of this equation.

Note also the very important fact that the computation of this matrix depends only on  $p$  and  $n$  and not on  $\ell$ . This means that it can be performed only once before any isogeny computation. The cost of setting up this matrix can thus be neglected. Note that we need to store  $O(n^2)$  elements in  $\mathbb{F}_p$  and that the time needed to apply the matrix is  $O(\log p)$  (multiplications in  $\mathbb{K}$ ).

**7.2. Finding one morphism.** We distinguish two steps: a precomputation step and then the actual computation.

**7.2.1. Precomputation phase.** Series which are independent of  $\mathcal{U}$  are completely computed while only a few terms of the other series can be initialized. We also perform some precomputations for use in the composition of series as in subsection 6.2. We assume we want  $\mathcal{L}$  terms of  $\mathcal{U}$ .

Precisely, we precompute the following.

1.  $\mathcal{S}(\tau)_{\mathcal{L}+1}$  from  $(\tau)_{\mathcal{L}}$  with Proposition 6.1.
2.  $A$  such that  $(1 + A)^i \neq 1 + A^i$  for all  $i \leq \mathcal{L}$  (this implies in particular that  $q > \mathcal{L}$ ).
3.  $\mathcal{S}(A\tau)_{\mathcal{L}+1}$  from  $\mathcal{S}(\tau)_{\mathcal{L}+1}$ .
4. The series

$$((\tau \oplus A\tau)_{\mathcal{L}}, \mathcal{S}^*(\tau \oplus A\tau)_{\mathcal{L}+1}) = ((\tau)_{\mathcal{L}}, \mathcal{S}(\tau)_{\mathcal{L}+1}) \oplus ((A\tau)_{\mathcal{L}}, \mathcal{S}(A\tau)_{\mathcal{L}+1})$$

from the addition law of subsection 4.2, as well as the powers needed in the composition of series.

5. The truncated series  $\Psi(\tau)_{p^r} = \mathcal{R}(\tau, \mathcal{S}(\tau))_{p^r+1}$  and its powers up to the order needed for the fast substitution algorithm (see subsection 6.2).
6. All the intermediate series to compute  $\mathcal{R}^*(\mathcal{U}(\tau), \mathcal{S}^*(\mathcal{U}(\tau)))$  as far as possible as in Proposition 6.3. For instance, in characteristic 2,

$$\mathcal{R}^*(t, s) = \frac{t^3 + \tilde{a}_6^* s^2 t}{t^2 + \tilde{a}_6^* s^2 + \tilde{a}_6^* t^2 s + s + ts + t^3 + \tilde{a}_6^* ts^2},$$

and we initialize all the monomials of this fraction once substituted  $(\mathcal{U}(\tau), \mathcal{S}^*(\mathcal{U}(\tau)))$  for  $(t, s)$ ;  $\mathcal{U}(\tau)_1 = \tau, \mathcal{S}^*(\mathcal{U}(\tau))_3 = \tau^3, \mathcal{U}(\tau)\mathcal{S}^*(\mathcal{U}(\tau))_4 = \tau^4, \mathcal{U}^2(\tau)_2 = \tau^2, \mathcal{S}^*(\mathcal{U}(\tau))_6^2 = \tau^6, \dots$

7. As in step 6, all the intermediate series to compute  $\mathcal{U}(\tau) \oplus \mathcal{U}(A\tau)$  as in the proof of Proposition 6.2;  $\mathcal{U}(A\tau)_1 = A\tau, \mathcal{S}^*(\mathcal{U}(\tau))_3 = A^3\tau^3, \lambda(\tau)_2 = (A^2 + A + 1)\tau^2, \nu(\tau)_3 = (A^2 + A)\tau^3, \dots$

*Complexity considerations.* We summarize the time and space complexity in the following table.

step	1	2	3	4	5	6	7
time	$O(\mathcal{L}^2)$	$O(\mathcal{L})$	$O(\mathcal{L})$	$O(\mathcal{L}^\mu)$	$O(p\mathcal{L}^\mu)$	$O(p)$	$O(p)$
space	$O(\mathcal{L})$		$O(\mathcal{L})$	$O(\mathcal{L}^{3/2})$	$O(\mathcal{L}^{3/2})$	$O(\mathcal{P})$	$O(\mathcal{P})$

We conclude that the time complexity of this phase is at most  $O(\max(p\mathcal{L}^\mu, \mathcal{L}^2))$  with a storage at most  $O(\mathcal{L}^{3/2})$ .

7.2.2. *Finding the morphism.* At the beginning of the  $i$ -th iteration,  $\mathcal{U}(\tau)_{i-1}$  is known and as far as the intermediate series are concerned,  $\mathcal{S}(\mathcal{U}(\tau))_{i+1}, \mathcal{U}(A\tau)_{i-1}, \mathcal{S}(\mathcal{U}(\tau))_{i+1}, \lambda(\tau)_i, \nu(\tau)_{i+1} \dots$  are known by Proposition 6.1. Then, formal computations enable us to compute  $u_i$  whose knowledge allows us to update the intermediate series in order to be ready for the  $(i+1)$ -th iteration. We study the cases  $i \neq p^e$  and  $i = p^e$  separately.

*The case  $i \neq p^e$ .* We find  $u_i$  using  $\mathcal{U}(\tau \oplus A\tau) = \mathcal{U}(\tau) \oplus \mathcal{U}(A\tau)$ .

**Step 1-a.** We need to compute the  $i$ -th coefficient of  $\mathcal{U}(\tau \oplus A\tau)$ . We do this using the algorithm described in subsection 6.2. We get an equation of the type  $(1+A)^i u_i + d$ .

**Step 1-b.** We have to calculate the  $i$ -th coefficient of  $\mathcal{U}(\tau) \oplus \mathcal{U}(A\tau)$  as a function of  $u_i$ . Since each intermediate series needed for computing this coefficient is known up to  $i$ , one can obtain as a function of  $u_i$  the  $(i+2)$ -th coefficient of  $\mathcal{S}(\mathcal{U}(\tau))$ , the  $i$ -th coefficient of  $\mathcal{U}(A\tau)$ , the  $(i+2)$ -th coefficient of  $\mathcal{S}(\mathcal{U}(\tau))$ , the  $(i+1)$ -th coefficient of  $\lambda(\tau)$ , and so on. Finally, the coefficient we are looking for is equal to  $(1+A^i)u_i + b$ .

The complexity of this phase is  $O(i)$ .

*The case  $i = p^e$ .* We find  $u_i$  with equation  $[p] \circ \mathcal{U} = \mathcal{U} \circ [p]$ , which we rewrite as

$$\tilde{\mathcal{U}}(\Psi(\tau)) = \mathcal{R}^*(\mathcal{U}(\tau), \mathcal{S}^*(\mathcal{U}(\tau))).$$

This enables us to use the same techniques as described above; namely, applying  $\tilde{\mathcal{U}}$  to a known series using precomputations and computing a rational fraction in two series.

**Step 2-a.** We compute as a function of  $u_i$  the  $i$ -th coefficient of  $\tilde{\mathcal{U}}(\tau) \circ \Psi(\tau)$ . This is done as in Step 1-a. This coefficient is equal to  $a\tilde{u}_i + d$ .

**Step 2-b.** We compute formally the  $i$ -th coefficient of  $\mathcal{R}^*(\mathcal{U}(\tau), \mathcal{S}^*(\mathcal{U}(\tau)))$ . To perform that, we proceed as in Step 1-b. We have to compute as a function of  $u_i$  the  $(i+2)$ -th coefficient of  $\mathcal{S}^*(\mathcal{U}(\tau))$ , the  $(i+2)$ -th coefficient of  $\mathcal{S}^*(\mathcal{U}(\tau))$ ,  $\dots$ . This coefficient is equal to  $u_i + b$ .

Finally,  $u_i^p - a^p u_i + b^p - d^p = 0$  and we choose one of the roots for  $u_i$ .

We update the intermediate series, that is to say we obtain from  $\mathcal{U}(\tau)_i$  the intermediate truncated series  $\mathcal{S}(\mathcal{U}(\tau))_{i+2}, \mathcal{U}(A\tau)_i, \mathcal{S}(\mathcal{U}(\tau))_{i+2}, \lambda(\tau)_{i+1}, \nu(\tau)_{i+2}$ , etc.

*Complexity.* We see that the computation of one morphism is dominated by the composition of series. Hence, the overall cost of this is  $O(\mathcal{L}^{\mu+1/2}) = O(\ell^{\mu+1/2})$ . All intermediate series will need up to  $O(p\mathcal{L})$  terms.

**7.3. Isogeny testing.** Suppose we are given a morphism  $\mathcal{M}(t)$  between  $\mathcal{E}$  and  $\mathcal{E}^*$ . Put

$$Z^*(t) = \frac{\mathcal{S}^*(\mathcal{M}(t))}{\mathcal{M}(t)},$$

and we want to find a series  $\widehat{M}$  such that  $Z^*(t) = \widehat{M}(Z(t))$ . Once we have done this, we need to compute a fraction whose expansion coincides with that of  $\widehat{M}$ .

7.3.1. *From  $\mathcal{M}$  to  $\widehat{M}$ .* We know the expansions of  $Z(t) = t^2 + a_1t^3 + (a_1^2 + a_2)t^4 + O(t^5)$  and  $Z^*(t) = m_2t^2 + \dots + m_{4\ell+1}t^{4\ell+1} + O(t^{4\ell+2})$ . We are looking for the coefficients of  $\widehat{M}(u) = \widehat{m}_1u + \widehat{m}_3u^3 + \dots + \widehat{m}_{2\ell+1}u^{2\ell+1} + O(u^{2\ell+2})$ . We will find these coefficients one at a time. Since we will have to perform many isogeny tests, it is worth precomputing all odd powers of  $Z(t)$ ; namely,  $Z_i(t) = Z(t)^i$  for  $1 \leq i \leq 4\ell+1$ ,  $i$  odd. This takes  $O(\ell^2)$  elements. This precomputation phase requires  $O(\ell^{\mu+1})$  operations and is done only once for all  $\ell$  (which really means we do that for the maximal value of  $\ell$  to be used). The procedure follows.

**procedure** RECOVERSERIESINZ

1.  $\widehat{m}_1 := m_2; W := W - \widehat{m}_1Z_1;$
2. **for**  $i = 1$  **to**  $\ell$  **do**  
 {at this point,  $W = wt^{2i+1} + O(t^{2i+2})$ }
  - (a)  $\widehat{m}_{2i+1} := w;$
  - (b)  $W := W - \widehat{m}_{2i+1}Z_{2i+1}.$

The computation phase takes  $O(\ell^2)$  operations.

7.3.2. *Recovering the fraction.* Assume  $F(z) = f_0 + f_1z + \dots + f_mz^m$  and  $G(z) = g_0 + g_1z + \dots + g_mz^m$  are two polynomials of  $\mathbb{K}[z]$ . Then

$$\frac{F(z)}{G(z)} = A(z) = \sum_{k=0}^{\infty} a_k z^k,$$

where the  $a_k$ 's satisfy recurrence relations deduced from the coefficients of  $G$ .

Conversely, given a series  $A(z)$ , known up to order  $2m$ , we can compute its  $(m, m)$  Padé approximant defined as a rational fraction  $U(z)/V(z)$  with  $\deg(U) \leq m, \deg(V) \leq m$ , and

$$A(z)V(z) - U(z) = O(z^{2m+1}).$$

The  $(m, m)$  approximant can be computed using Berlekamp's algorithm [33] in  $O(m^2)$  operations, or using algorithm EMGCD of [6] in  $O(m(\log m)^2)$  operations. Note that from a practical point of view, Berlekamp's algorithm is faster.

7.3.3. *The final algorithm and its complexity.* The isogeny test can be summarized as follows.

**procedure** ISOGENYTEST( $\ell, \mathcal{M}(t), \mathcal{S}^*(\mathcal{M}(t))$ )

1. compute  $Z^*(t) = \mathcal{S}^*(\mathcal{M}(t))/\mathcal{M}(t);$
2. compute  $\widehat{M}(Z) = \widehat{m}_1Z + \widehat{m}_3Z^3 + \dots + \widehat{m}_{2\ell+1}Z^{2\ell+1} + O(Z^{2\ell+2})$  using algorithm RECOVERSERIESINZ;
3. recover the fraction  $F(Z)/G(Z)$  which is an  $(\ell + 1, \ell + 1)$  Padé approximant of  $\widehat{M}(Z)$ ; at this point,  $F$  and  $G$  have degree  $\leq \ell + 1$  a priori;
4. if  $\deg(F) = \deg(G) = \ell$  and  $F$  is  $Z$  times the square of a polynomial, then  $\widehat{M}$  comes from the isogeny we are looking for.

The first step takes  $O(\ell^\mu)$  operations, the second  $O(\ell^2)$  dominates the third step. Therefore, we see that the cost of the isogeny test is  $O(\ell^2)$ .

Note also that in the "multiplication" strategy, one already has  $\mathcal{S}^*(\mathcal{M}(t))$  at one's disposal.

#### 7.4. Enumerating all the morphisms.

7.4.1. *Backtracking.* It is easy to see that the cost of this approach is  $O(\mathcal{L})$  times the cost of finding one morphism plus that of an isogeny test. The total cost is thus  $O(\ell^{\max(\mu+3/2,3)})$ .

7.4.2. *Multiplication by a  $p$ -adic integer.* In fact, we do not really multiply by a  $p$ -adic integer, but merely perform additions in the formal group, until we find the isogeny. The algorithm is as follows.

**procedure** COMPUTEISOGENY( $\ell, \mathcal{E}, \mathcal{E}^*$ )

1. compute a generator  $\mathcal{U}$  of the set of morphisms between  $\mathcal{E}$  and  $\mathcal{E}^*$  using the algorithms of subsection 7.2;
2. **for**  $N = 1$  to  $p^{r+1}/2$  and  $N$  prime to  $p$  **do**
  - (a) compute  $(\mathcal{M}(t), \mathcal{S}^*(\mathcal{M}(t))) = [N] \circ (\mathcal{U}(t), \mathcal{S}(\mathcal{U}(t)))$ ;
  - (b) use ISOGENYTEST to test whether  $\mathcal{M}$  comes from an isogeny; if yes, stop.

Note that we compute  $(\mathcal{M}(t), \mathcal{S}^*(\mathcal{M}(t)))$  using a formal addition between the preceding computed value and  $(\mathcal{U}(t), \mathcal{S}(\mathcal{U}(t)))$  or  $[2](\mathcal{U}(t), \mathcal{S}(\mathcal{U}(t)))$ .

The cost of the second approach is the cost of finding one morphism,  $O(\mathcal{L}^{\mu+1/2})$  multiplications, plus  $O(\mathcal{L})$  times the cost of an addition in the formal group— $O(\mathcal{L}^\mu)$  multiplications—plus  $O(\mathcal{L})$  times the cost of the isogeny test of cost  $O(\mathcal{L}^2)$ . So, the complexity of this second approach is  $O(\ell^{\max(\mu+1,3)})$ .

7.4.3. *Complexity and choice of the method.* Asymptotically, if  $\mu \leq 3/2$ , both methods have the same complexity  $O(\ell^3)$ . If  $\mu > 3/2$ , the second one is better and the complexity is  $O(\ell^3)$ . However, from a practical point of view, the second approach is always better, since, apart from the isogeny test, we replace a substitution of series whose complexity is  $O(\mathcal{L}^{\mu+1/2})$  by a formal addition whose complexity is only  $O(\mathcal{L}^\mu)$  (remember that  $1 \leq \mu \leq 2$ ).

7.5. **Overall complexity.** We summarize the preceding results.

**Proposition 7.2.** *After preprocessing, the cost of Couveignes's algorithm is  $O(\ell^3)$ . The storage is  $O(\ell^2)$ .*

## 8. IMPLEMENTATION IN CHARACTERISTIC 2

We give an example of our implementation of Couveignes's idea for  $q = 2^n$ . Let  $E : Y^2 + XY = X^3 + a_6$  be an elliptic curve.

8.1. **Simplifying formulas.** After the classical change of variables  $t = -x/y$ ,  $s = -1/y$  to set  $O_E = (0, 0)$ , the equation of  $\mathcal{E}$  becomes

$$(21) \quad s = t^3 + ts + a_6 s^3.$$

In the special case  $t(\tau) = \tau$ , the coefficients of the series  $\mathcal{S}(\tau) = \sum_{i=3}^{\infty} \mathcal{S}_i \tau^i$  are

$i$	3	4	5	6	7	8	9	10	11
$\mathcal{S}_i$	1	1	1	1	1	1	$1 + a_6$	1	1

and for  $i \geq 6$ ,

$$\begin{aligned} \mathcal{S}_{2i} &= \mathcal{S}_{2i-1} + a_6 \left( \mathcal{S}_{2i-6} + \sum_{j=4}^{i-2} \mathcal{S}_j^2 \mathcal{S}_{2i-2j} \right), \\ \mathcal{S}_{2i+1} &= \mathcal{S}_{2i} + a_6 \left( \mathcal{S}_{2i-5} + \mathcal{S}_{i-1}^2 + \sum_{j=4}^{i-2} \mathcal{S}_j^2 \mathcal{S}_{2i-2j+1} \right). \end{aligned}$$

Using standard tools [43], we also find that  $\mathcal{S}(t)$  satisfies the differential equation

$$\begin{aligned} &(-54a_6t^5 - 4t^3 + 14t^2 - 18t + 8)y \\ &+ (54t^6a_6 + 6t^4 - 28t^3 + 54t^2 - 48t + 16)y' \\ &+ (-27t^8a_6 + 54t^7a_6 - 4t^5 + 20t^4 - 36t^3 + 28t^2 - 8t)y'' = 0 \end{aligned}$$

over  $\mathbb{Z}[a_6]$ , from which we find that the  $s_i$ 's satisfy the recurrence relation

$$\begin{aligned} &27a_6n(-n + 1)s(n) + 54a_6n(2 + n)s(n + 1) \\ &- 2(2n^2 + 7n + 5)s(n + 3) + 2(10n^2 + 56n + 71)s(n + 4) \\ &- 18(2n^2 + 15n + 26)s(n + 5) \\ &+ 4(7n^2 + 65n + 140)s(n + 6) - 8(n^2 + 11n + 28)s(n + 7) = 0 \end{aligned}$$

together with the initial values  $s_0 = s_1 = s_2 = 0, s_3 = s_4 = s_5 = s_6 = 1$ . Using these formulae, we can compute the  $s_n$  over  $\mathbb{Z}[a_6]$  and then reduce them modulo 2.

We can rewrite the formulae of subsection 4.2 in order to decrease their computational cost. In particular, if  $t_1 \neq t_2$ , then  $t_1 \oplus t_2$  is computed as

$$t_1 \oplus t_2(\tau) = \frac{t_1(\tau) + t_2(\tau) + \lambda(\tau) + a_6\lambda^2(\tau)(s_1(\tau) + s_2(\tau) + \nu(\tau))}{1 + t_1(\tau) + t_2(\tau) + \lambda(\tau) + a_6\lambda^2(\tau)(s_1(\tau) + s_2(\tau) + \nu(\tau) + \lambda(\tau))}.$$

Arranging computations so as to reuse series already computed and adding two distinct formal points requires 4 multiplications of series and 2 divisions. For computing  $([2]t(\tau), \mathcal{S}([2]t(\tau))) = [2](t(\tau), s(\tau))$ , we use (11). This computation costs 4 multiplications of series and 2 divisions.

**8.2. Example.** Let  $\mathbb{K} = \mathbb{F}_{2^8} = \mathbb{F}_2[T]/(T^8 + T^4 + T^3 + T + 1)$ . Every element of  $\mathbb{K}$  can be written as a polynomial in  $T$ . In order to reduce the space needed to write the different results, we will write such a polynomial  $a(T) = \sum_{i=0}^{n-1} a_i T^i$  as  $\overline{a(2)}$ . For instance, the polynomial  $T^2 + T$  will be abbreviated as  $\overline{6}$ .

Let us compute an isogeny of degree  $\ell = 5$  between  $E = \overline{[7]}$  and  $E^* = \overline{[8]}$ . We first find that  $A = \overline{2}$  is valid. The equation for  $u_2$ , coming from equating  $[2] \circ \mathcal{U} = \mathcal{U} \circ [2]$ , is

$$\sqrt{u_2^2} + \sqrt{u_2} = 0$$

and we select  $u_2 = 0$ . Next, we find that  $u_3$  is a root of

$$\overline{6}u_2 + \overline{6}u_3 = 0,$$

which gives  $u_3 = 0$ . For  $u_4$ , we have

$$\sqrt{u_4^2} + \sqrt{u_4} \sqrt{\overline{15}} = 0$$

and we choose  $u_4 = \overline{56}$ . Once all computations are done, we find

$$\begin{aligned} \mathcal{U}(t) = & t + \overline{56}t^4 + \overline{56}t^5 + \overline{15}t^7 + \overline{16}t^8 + \overline{31}t^9 + \overline{219}t^{10} + \overline{124}t^{11} + \overline{5}t^{12} + \overline{44}t^{13} + \overline{91}t^{14} \\ & + \overline{47}t^{15} + \overline{210}t^{16} + \overline{201}t^{17} + \overline{231}t^{18} + \overline{198}t^{19} + \overline{188}t^{20} + \overline{118}t^{21} + O(t^{22}). \end{aligned}$$

We first have that

$$\begin{aligned} Z(t) = \frac{\mathcal{S}(t)}{t} = & t^2 + t^3 + t^4 + t^5 + t^6 + t^7 + \overline{6}t^8 + t^9 + t^{10} + t^{11} + \overline{6}t^{12} + t^{13} + \overline{20}t^{14} \\ & + \overline{20}t^{15} + \overline{6}t^{16} + t^{17} + t^{18} + t^{19} + \overline{6}t^{20} + t^{21} + \overline{20}t^{22} + O(t^{23}). \end{aligned}$$

Now we have to look for  $N$ ,  $1 \leq N \leq 16$ ,  $N$  odd, such that  $[N] \circ \mathcal{U}$  is the series associated with  $\mathcal{I}$ . After a first test it turns out that  $\mathcal{U}$  is not the morphism we are looking for. On the other hand, we have

$$\begin{aligned} [3](\mathcal{U}(t)) = & t + t^2 + t^3 + \overline{56}t^4 + \overline{56}t^5 + \overline{56}t^6 + \overline{55}t^7 + \overline{39}t^8 \\ & + \overline{39}t^9 + \overline{244}t^{10} + \overline{84}t^{11} + \overline{154}t^{12} + \overline{28}t^{13} + \overline{79}t^{14} + \overline{52}t^{15} \\ & + \overline{247}t^{16} + \overline{51}t^{17} + \overline{44}t^{18} + \overline{66}t^{19} + \overline{102}t^{20} + \overline{84}t^{21} + O(t^{22}) \end{aligned}$$

for which

$$\begin{aligned} Z^*(t) = \frac{\mathcal{S}^*(U(t))}{U(t)} = & t^2 + t^3 + t^4 + t^5 + \overline{56}t^6 + \overline{56}t^7 + \overline{6}t^8 + t^9 + \overline{39}t^{10} + \overline{39}t^{11} \\ & + \overline{182}t^{12} + \overline{30}t^{13} + \overline{143}t^{14} + \overline{32}t^{15} + \overline{91}t^{16} + t^{17} + \overline{241}t^{18} \\ & + \overline{241}t^{19} + \overline{67}t^{20} + \overline{200}t^{21} + \overline{138}t^{22} + O(t^{23}), \end{aligned}$$

which can be rewritten as

$$Z(t) + \overline{57}Z^3(t) + \overline{31}Z^5(t) + \overline{13}Z^7(t) + \overline{214}Z^9(t) + \overline{120}Z^{11}(t) + O(t^{23}).$$

Now we use the Berlekamp-Massey algorithm to recover the fraction, which in this particular case gives

$$\frac{\overline{140}Z^5(t) + \overline{15}Z^3(t) + Z(t)}{\overline{239}Z^4(t) + \overline{54}Z^2(t) + 1},$$

and via  $Z(t) = 1/X(t)$ , we obtain

$$\mathcal{I}(X(t)) = \frac{X^5(t) + \overline{15}X^3(t) + \overline{140}X(t)}{(X^2(t) + \overline{57}X(t) + \overline{74})^2}.$$

### 8.3. Implementation and results.

8.3.1. *Benchmarks.* In [31], we benchmarked our implementation using curves defined over small finite fields, as was done in [22]. We also explained in the same paper how we can tune our program using parameters which describe several strategies. In the case of the field  $\mathbb{K} = \mathbb{F}_{2^{300}}$ , we have made precise statistics on every part of the algorithm. The results are given in Tables 1, 2, and 3. In Table 3, one finds for each Elkies prime power  $\ell^d$  the time `PreC` needed for the precomputations,  $\oplus$  designates the time of a formal addition, `BM` the time for the Berlekamp-Massey algorithm, and  $N$  is the 2-adic integer such that  $[N] \circ \mathcal{U}$  comes from an isogeny (we take all coefficients  $u_{2^i} = P_i(T)$  of  $\mathcal{U}$  such that  $P_i(0) = 0$ ).

TABLE 1. Values of  $c$  such that  $\#E_X = q + 1 - c$

$n$	$f(T)$	$c$
155	$T^7 + T^5 + T^4 + 1$	80860670297104421704641
196	$T^3 + 1$	168959031790830995673970347393
300	$T^5 + 1$	-10571281829901220624668774504748712108091263
400	$T^5 + T^3 + T^2 + 1$	831311719593373938759692923178171920626211278774147\ 9820465793
500	$T^8 + T^6$ $+ T^5 + T^2 + T + 1$	-1022525379417220053537215648371674704330886180912\ 84615423424533825936526975
601	$T^7 + T^4$ $+ T^3 + T^2 + T + 1$	37775742763172180654637698179922762979897172920800\ 67701458146624068364548898667013349009665
701	$T^9 + T^8$ $+ T^7 + T^4 + T^2 + 1$	-6359955034208948319000311216309478917321579803329\ 46517959827018542105004396465148187664452889226358\ 9295359
1009	$T^{11} + T^4 + T^2 + 1$	55007905849934614144624409501712379419197634620524\ 53456763226048365537759705821387697628232022965034\ 0954505941334049799934180550652777226376997856386305

TABLE 2. Records for the second implementation

	$\mathbb{F}_{2^{155}}$	$\mathbb{F}_{2^{196}}$	$\mathbb{F}_{2^{300}}$	$\mathbb{F}_{2^{701}}$	$\mathbb{F}_{2^{1009}}$
$\ell_{\max}$	59	73	109	337	577
isogenies	24	580	22974	4842770	13457961
total	217	1381	30221	7897343	21018853

TABLE 3. Data for  $\mathbb{F}_{2^{300}}$

$\ell$	$d$	Prec	$\mathcal{U}$	$Z(t)^i$	$\oplus$	$Z^* = M(Z)$	BM	$N$	Isogenies	%	Total
3	1	0	0.2	0	0	0	0	3	0.4	67	0.6
5	1	0	0.5	0	0.1	0	0	7	1.3	62	2.1
7	1	0.1	0.8	0	0.1	0	0	7	2.1	64	3.3
11	1	0.4	1.9	0.1	0.4	0	0	7	6	50	12.1
	2	0.5	2.1	0.1	0.4	0	0	7	10.4	5	220.1
19	1	5.2	5.6	0.6	1.2	0	0.1	47	56	77	72.8
31	1	2.8	13.1	2.3	2.3	0.1	0.2	63	131.4	74	177.1
37	1	7.3	21	3.7	4.5	0.2	0.3	127	446.3	86	516.3
41	1	8	25.2	5	5.2	0.2	0.4	81	343.6	78	439.6
47	1	8.9	32.3	7.5	5.8	0.3	0.5	111	525.2	84	627
59	1	11.1	49.6	13.6	7.3	0.6	0.7	103	639.2	80	798.4
61	1	11.3	55	14.7	7.8	0.6	0.8	3	112.3	40	278.4
67	1	47.6	68.9	18.5	11.4	0.7	0.8	93	927.6	80	1157.2
79	1	28.2	94.4	29.8	15.8	1.1	1.2	133	1692.9	86	1970
97	1	33.6	136.3	52.6	20.2	1.7	1.7	79	1408.4	78	1802.3
101	1	34.6	142.5	58.6	20.5	1.8	1.8	161	2695.9	83	3259.2
103	1	35.1	147.4	62	20.7	1.8	1.9	37	853.4	70	1212.6
107	1	144.4	159.1	68.3	21.6	2	2	251	4433.4	90	4907.6
Total		379.1	955.9	68.3	-	-	-	-	14285.8	82	17456.7

8.3.2. *Records.* In [37, 36] the authors gave timings for larger fields  $\mathbb{F}_{2^{155}}$  and  $\mathbb{F}_{2^{195}}$ . For these and larger fields (the last one being the current record,  $\mathbb{F}_{2^{1009}}$ , as of January 1996), our implementation gave the following timings for the curve:

$$E_X : y^2 + xy = x^3 + T^{16} + T^{14} + T^{13} + T^9 + T^8 + T^7 + T^6 + T^5 + T^4 + T^3$$

(the coefficient was chosen as the binary expression of 91128—our zip code—converted to a polynomial if  $\mathbb{F}_{2^n}$ ). Table 1 gives for some values of  $n$  a polynomial  $f(T)$  such that  $T^n + f(T)$  is a defining polynomial of  $\mathbb{F}_{2^n} = \mathbb{F}_2[T]/(T^n + f(T))$  and the value of  $c$  such that  $\#E_X(\mathbb{F}_{2^n}) = 2^n + 1 - c$ .

The interested reader can find the timings for our first implementation in [31], as well as a comparison with the case of prime fields of large characteristic. Table 2 refers to the implementation that uses all features described in the present article. All these records have been done using a network of DecAlpha workstations, using an obvious distributed implementation of the algorithm.

## 9. CONCLUSION

There are basically two approaches for computing isogenies between elliptic curves over a finite field. The Atkin-Elkies method works well when the characteristic is large, while Couveignes's method works for the small characteristic. A new method is being developed by the first author [28] in the particular case of the characteristic 2. This method does not use formal groups and is much faster than Couveignes's method in practice.

In the general case of  $p$  small, Couveignes [10] (and [11] for a more detailed version) has very recently proposed a new algorithm that uses properties of the  $p$ -torsion to compute the isogenies. The implementation and comparison of these new methods are currently being done by the first author (see [32] for a comparison of the algorithms and [29] for more details).

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