

WEAKNESS OF $\mathbb{F}_{3^{6 \cdot 509}}$ FOR DISCRETE LOGARITHM CRYPTOGRAPHY

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ABSTRACT. In 2013, Joux, and then Barbulescu, Gaudry, Joux and Thomé, presented new algorithms for computing discrete logarithms in finite fields of small and medium characteristic. We show that these new algorithms render the finite field $\mathbb{F}_{3^{6 \cdot 509}} = \mathbb{F}_{3^{3054}}$ weak for discrete logarithm cryptography in the sense that discrete logarithms in this field can be computed significantly faster than with the previous fastest algorithms. Our concrete analysis shows that the supersingular elliptic curve over $\mathbb{F}_{3^{509}}$ with embedding degree 6 that had been considered for implementing pairing-based cryptosystems at the 128-bit security level in fact provides only a significantly lower level of security.

1. INTRODUCTION

Let \mathbb{F}_q denote a finite field of order q , and let $Q = q^n$. The discrete logarithm problem (DLP) in \mathbb{F}_Q is that of determining, given a generator g of \mathbb{F}_Q^* and an element $h \in \mathbb{F}_Q^*$, the integer $x \in [0, Q-2]$ satisfying $h = g^x$. The integer x is called the discrete logarithm of h to the base g and is denoted by $\log_g h$. In the remainder of the paper, we shall assume that the characteristic of \mathbb{F}_q is 2 or 3.

The fastest general-purpose algorithm known for solving the DLP is Coppersmith's 1984 index-calculus algorithm [15] with a running time¹ of $L_Q[\frac{1}{3}, (32/9)^{1/3}] \approx L_Q[\frac{1}{3}, 1.526]$, where as usual $L_Q[\alpha, c]$ with $0 < \alpha < 1$ and $c > 0$ denotes the expression

$$\exp((c + o(1))(\log Q)^\alpha (\log \log Q)^{1-\alpha})$$

that is subexponential in $\log Q$. In 2006, Joux and Lercier [31] presented an algorithm with a running time of $L_Q[\frac{1}{3}, 3^{1/3}] \approx L_Q[\frac{1}{3}, 1.442]$ when q and n are balanced in the sense that

$$q = \exp\left(3^{1/3} \cdot (\log Q)^{1/3} (\log \log Q)^{2/3}\right) \text{ and } n = 3^{-1/3} \cdot \left(\frac{\log Q}{\log \log Q}\right)^{2/3}.$$

In 2012, Joux [27] introduced a 'pinpointing' technique that improves the running time of the Joux-Lercier algorithm to $L_Q[\frac{1}{3}, 2/3^{2/3}] \approx L_Q[\frac{1}{3}, 0.961]$, where now the balance between q and n is

$$q = \exp\left(3^{-2/3} \cdot (\log Q)^{1/3} (\log \log Q)^{2/3}\right) \text{ and } n = 3^{2/3} \cdot \left(\frac{\log Q}{\log \log Q}\right)^{2/3}.$$

Date: July 15, 2013.

¹All running times in this paper have been determined using *heuristic* arguments, and have not been rigorously proven.

In February 2013, Joux [28] presented a new DLP algorithm with a running time of $L_Q[\frac{1}{4} + o(1), c]$ (for some undetermined c) when q and n are balanced in the sense that $q \approx m$ where $n = 2m$. Also in February 2013, Gögloğlu, Granger, McGuire and Zumbrägel [22] proposed a variant of the Joux-Lercier algorithm that imposes a further divisibility condition on ℓ where $q = 2^\ell$. The running time of the Gögloğlu et al. algorithm is (i) $L_Q[\frac{1}{3}, 2/3^{2/3}] \approx L_Q[\frac{1}{3}, 0.961]$ when $n \approx 2^m d_1$, $d_1 \approx 2^m$, and $m \mid \ell$; and (ii) between $L_Q[\frac{1}{3}, (2/3)^{2/3}] \approx L_Q[\frac{1}{3}, 0.763]$ and $L_Q[\frac{1}{3}, 1/2^{1/3}] \approx L_Q[\frac{1}{3}, 0.794]$ when $n \approx 2^m d_1$, $2^m \gg d_1$, and $m \mid \ell$. The new algorithms were used to compute discrete logarithms in $\mathbb{F}_{2^{8 \cdot 3 \cdot 255}} = \mathbb{F}_{2^{6120}}$ in only 750 CPU hours [23], and in $\mathbb{F}_{2^{8 \cdot 3 \cdot 257}} = \mathbb{F}_{2^{6168}}$ in only 550 CPU hours [29]. The astoundingly small computational effort expended in these experiments depends crucially on the special nature of the fields $\mathbb{F}_{2^{6120}}$ and $\mathbb{F}_{2^{6168}}$ — namely that $\mathbb{F}_{2^{6120}}$ is a degree-255 extension of $\mathbb{F}_{2^{8 \cdot 3}}$ with $255 = 2^8 - 1$, and $\mathbb{F}_{2^{6168}}$ is a degree-257 extension of $\mathbb{F}_{2^{8 \cdot 3}}$ with $257 = 2^8 + 1$. Despite these remarkable achievements, the effectiveness of the new algorithms for computing discrete logarithms in general finite fields of small characteristic remains unclear.

In June 2013, Barbulescu, Gaudry, Joux and Thomé [6] presented a new DLP algorithm that, for many choices of field sizes, is asymptotically faster than all previous algorithms. Most impressively, in the case where $q \approx n$ and $n \leq q + 2$, the discrete logarithm problem in $\mathbb{F}_{q^{2n}} = \mathbb{F}_Q$ can be solved in *quasi-polynomial time*

$$(1) \quad (\log Q)^{O(\log \log Q)}.$$

Note that (1) is asymptotically smaller than $L_Q[\alpha, c]$ for any $\alpha > 0$ and $c > 0$. However, the practical relevance of the new algorithm has not yet been determined.

The aforementioned advances in DLP algorithms are potentially relevant to the security of pairing-based cryptosystems that use bilinear pairings derived from supersingular elliptic curves E or genus-2 hyperelliptic curves C defined over finite fields \mathbb{F}_q of characteristic 2 or 3. Such a symmetric pairing, classified as a Type 1 pairing in [21], is a non-degenerate bilinear map $e : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ where \mathbb{G} and \mathbb{G}_T are groups of prime order N . Here, \mathbb{G} is either a subgroup of $E(\mathbb{F}_q)$, the group of \mathbb{F}_q -rational points on E , or a subgroup of $\text{Jac}_C(\mathbb{F}_q)$, the jacobian of C over \mathbb{F}_q , and \mathbb{G}_T is the order- N subgroup of $\mathbb{F}_{q^k}^*$ where k is the embedding degree (the smallest positive integer such that $\#\mathbb{G} \mid (q^k - 1)$). A necessary condition for the security of pairing-based cryptosystems that employ the pairing e is the intractability of the discrete logarithm problem in \mathbb{G}_T . Hence, any advance in algorithms for solving the DLP in \mathbb{F}_{q^k} can potentially impact the security of pairing-based cryptosystems.

Three symmetric pairings that have received a great deal of attention in the literature are: (i) the $k = 6$ pairings derived from supersingular elliptic curves $Y^2 = X^3 - X + 1$ and $Y^2 = X^3 - X - 1$ over \mathbb{F}_{3^ℓ} ; (ii) the $k = 4$ pairings derived from supersingular elliptic curves $Y^2 + Y = X^3 + X$ and $Y^2 + Y = X^3 + X + 1$ over \mathbb{F}_{2^ℓ} ; and (iii) the $k = 12$ pairing derived from supersingular genus-2 curves $Y^2 + Y = X^5 + X^3$ and $Y^2 + Y = X^5 + X^3 + 1$ over \mathbb{F}_{2^ℓ} ; in all cases, ℓ is chosen to be prime. These symmetric pairings were considered in some early papers [13, 19, 8, 20] on pairing-based cryptography. Since then, many papers have reported on software and hardware implementation of these pairings; some examples are [7, 24, 35, 3, 25, 11, 14, 16, 10, 4, 1].

In all the papers cited in the previous paragraph, the pairing parameters were chosen under the assumption that Coppersmith's algorithm is the fastest method for finding discrete logarithms in \mathbb{F}_{q^k} . For example, to achieve the 128-bit security level, [3] chose $\ell = 1223$ for the $k = 4$ pairing and $\ell = 509$ for the $k = 6$ pairing, [14] chose $\ell = 439$ for the $k = 12$ pairing, and [4] chose $\ell = 367$ for the $k = 12$ pairing. These choices were made because Coppersmith's algorithm, as analyzed by Lenstra [32], has running time approximately 2^{128} for computing logarithms in $\mathbb{F}_{2^4 \cdot 1223}$, $\mathbb{F}_{3^6 \cdot 509}$, $\mathbb{F}_{2^{12} \cdot 439}$, and $\mathbb{F}_{2^{12} \cdot 367}$, respectively.

In 2012, Hayashi et al. [26] reported on their implementation of the Joux-Lercier algorithm for computing logarithms in $\mathbb{F}_{3^6 \cdot 97}$. Their work demonstrated that in practice the Joux-Lercier algorithm is considerably faster than Coppersmith's algorithm for DLP computations in $\mathbb{F}_{3^6 \cdot 97}$; note that the $k = 6$ pairing with $\ell = 97$ was considered in [8, 20]. In contrast, the largest discrete logarithm computation reported using Coppersmith's algorithm (and its generalizations [2, 30]) is the April 2013 computation by Barbulescu et al. [5] of logarithms in $\mathbb{F}_{2^{809}}$; note that 809 is prime and $3^{6 \cdot 97} \approx 2^{922}$. Shinohara et al. [36] estimated that $\mathbb{F}_{3^6 \cdot 509}$ offers only 111-bits of security against Joux-Lercier attacks, considerably less than the assumed 128-bits of security against Coppersmith attacks.

The purpose of this paper is to demonstrate that the new algorithms by Joux [28] and Barbulescu et al. [6] can be combined to solve the discrete logarithm problem in $\mathbb{F}_{3^6 \cdot 509}$ significantly faster than the Joux-Lercier algorithm. More precisely, we estimate that logarithms in this field can be computed in $2^{73.7}$ time with the new algorithms, which is significantly faster than the estimate of $2^{102.69}$ for the Joux-Lercier algorithm with pinpointing; the unit of time here is the cost of an integer multiplication modulo an 804-bit prime. While the $2^{73.7}$ computation is certainly a formidable challenge, we argue that it is within the realm of feasibility for a very well-funded adversary in the foreseeable future. Thus, we conclude that $\mathbb{F}_{3^6 \cdot 509}$ does not offer adequate security for discrete logarithm cryptosystems and, in particular, the supersingular elliptic curve over $\mathbb{F}_{3^6 \cdot 509}$ with embedding degree 6 is not suitable for implementing pairing-based cryptosystems.

The remainder of the paper is organized as follows. §2 collects some results on the number of smooth polynomials over a finite field. The new discrete logarithm algorithms are outlined in §3. Our estimates for discrete logarithm computations in $\mathbb{F}_{3^6 \cdot 509}$ are presented in §4. We draw our conclusions in §5.

2. SMOOTH POLYNOMIALS

2.1. Number of smooth polynomials. The number of monic polynomials of degree n over \mathbb{F}_q is q^n . The number of monic irreducible polynomials of degree n over \mathbb{F}_q is

$$(2) \quad I_q(n) = \frac{1}{n} \sum_{d|n} \mu(n/d) q^d,$$

where μ is the Möbius function. A polynomial in $\mathbb{F}_q[X]$ is said to be m -smooth if all its irreducible factors in $\mathbb{F}_q[X]$ have degree at most m . Define

$$F(u, z) = \prod_{\ell=1}^m \left(1 + \frac{uz^\ell}{1-z^\ell} \right)^{I_q(\ell)}.$$

$F(u, z)$ is the generating function for m -smooth monic polynomials in $\mathbb{F}_q[X]$, where u marks the number of distinct irreducible factors, and z marks the degree of the polynomial. Thus, the number of monic m -smooth degree- n polynomials in $\mathbb{F}_q[X]$ that have exactly k distinct monic irreducible factors is

$$(3) \quad N_q(m, n, k) = [u^k z^n] F(u, z)$$

where $[]$ denotes the coefficient operator, whereas the total number of monic m -smooth degree- n polynomials in $\mathbb{F}_q[X]$ is

$$(4) \quad N_q(m, n) = [z^n] F(1, z).$$

Furthermore, the average number of distinct monic irreducible factors among all monic m -smooth degree- n polynomials in $\mathbb{F}_q[X]$ is

$$(5) \quad A_q(m, n) = \frac{[z^n] \left(\frac{\partial F}{\partial u} \Big|_{u=1} \right)}{N_q(m, n)}.$$

For any given q , m and n , $N_q(m, n)$ can be obtained by using a symbolic algebra package such as Maple [34] to compute the first $n + 1$ terms of the Taylor series expansion of $F(1, z)$ and then extracting the coefficient of z^n . Similarly, one can compute $N_q(m, n, k)$ and $A_q(m, n)$. For example, we used Maple 17 on a 3.2 GHz Intel Xeon CPU X5672 machine to compute $N_{3^{12}}(30, 254)$ in 3.2 seconds, $A_{3^{12}}(30, 254) = 14.963$ in 102.9 seconds, and $N_{3^{12}}(30, 254, 9)$ in 4305 seconds.

Example 1. ($q = 3^{12}$, $n = 33$, $m = 7$) Table 1 lists, for each $t \in [1, 33]$, the proportion of monic 7-smooth degree-33 polynomials in $\mathbb{F}_{3^{12}}[X]$ that have exactly t distinct monic irreducible factors, and the proportion that have at most t distinct monic irreducible factors (cf. §4.6). We see that most 7-smooth degree-33 polynomials in $\mathbb{F}_{3^{12}}[X]$ will have 6, 7, 8, 9 or 10 distinct monic irreducible factors. In fact, the average number of distinct monic irreducible factors is $A_{3^{12}}(7, 33) = 8.072$.

2.2. Smoothness testing. A degree- d polynomial $f \in \mathbb{F}_q[X]$ can be tested for m -smoothness by computing

$$(6) \quad w(X) = f'(X) \cdot \prod_{i=\lceil m/2 \rceil}^m (X^{q^i} - X) \pmod{f(X)}$$

and checking whether $w(X) = 0$ [15]. Here, f' denotes the formal derivative of f . If f is indeed m -smooth, then $w(X) = 0$. On the other hand, if f is not m -smooth then a necessary condition to have $w(X) = 0$ is that f be divisible by the square of an irreducible polynomial of degree $> m$. Since randomly selected polynomials f are unlikely to satisfy this condition, the vast majority of polynomials that pass the smoothness test are indeed m -smooth. The polynomials that are declared to be m -smooth are then factored using a general-purpose polynomial factorization algorithm, at which time the polynomials falsely declared to be m -smooth are identified.

Without loss of generality, we can assume that f is monic. Then the product of two polynomials of degree $< d$ can be multiplied modulo f in time $2d^2$, where the unit of time is an \mathbb{F}_q -multiplication. To compute $w(X)$, one first precomputes $X^q \pmod{f}$. This can be accomplished by repeated square-and-multiplication at a cost of at most $2\|q\|_2$ modular multiplications, where $\|q\|_2$ denotes the bitlength of q . Then, $X^{q^i} \pmod{f}$ for

t	Exactly t distinct irred. factors	At most t distinct irred. factors
1	0.00000000000000000000000000000000	0.00000000000000000000000000000000
2	0.00000000000000000000000000000000	0.00000000000000000000000000000000
3	0.00000000000000000000000000000000	0.00000000000000000000000000000000
4	0.00000000000000000000000000000000	0.00000000000000000000000000000000
5	0.006943962587253657277835842266	0.006943962587253657277835842266
6	0.094508235237374712577063021493	0.101452197824628369854898863759
7	0.252394617047441064890337803216	0.353846814872069434745236666975
8	0.300996732023133627463574655796	0.654843546895203062208811322771
9	0.208505984721518279111258348913	0.863349531616721341320069671684
10	0.095666915122986916225455033585	0.959016446739708257545524705269
11	0.031431153500729712069119759222	0.990447600240437969614644464492
12	0.007781729666933963402298111588	0.998229329907371933016942576080
13	0.001504553977022317970302510303	0.999733883884394250987245086382
14	0.000233175504774219447997449230	0.999967059389168470435242535613
15	0.000029539839348629531062050590	0.999996599228517099966304586203
16	0.000003105026114577322728183235	0.999999704254631677289032769438
17	0.000000273913853891240679141964	0.999999978168485568529711911402
18	0.000000020455745079269350203882	0.999999998624230647799062115284
19	0.000000001301469873795730818942	0.99999999925700521594792934226
20	0.00000000070853335885380661976	0.99999999996553857480173596201
21	0.00000000003308814369077458356	0.99999999999862671849251054557
22	0.00000000000132633223456585201	0.99999999999995305072707639758
23	0.0000000000004557715382559271	0.99999999999999862788090199029
24	0.0000000000000133804578363524	0.9999999999999996592668562553
25	0.0000000000000000336091284541	0.9999999999999999928759847094
26	0.0000000000000000070002399226	0.99999999999999999998762246320
27	0.0000000000000000001220209967	0.9999999999999999999982456287
28	0.0000000000000000000017346134	0.999999999999999999999802422
29	0.000000000000000000000195878	0.999999999999999999999998300
30	0.000000000000000000000001690	0.999999999999999999999999990
31	0.000000000000000000000000010	1.00000000000000000000000000000
32	0.000000000000000000000000000	1.00000000000000000000000000000
33	0.000000000000000000000000000	1.00000000000000000000000000000

TABLE 1. Proportion of monic 7-smooth degree-33 polynomials in $\mathbb{F}_{3^{12}}[X]$ that have exactly t (resp. at most t) distinct monic irreducible factors.

$2 \leq i \leq d-1$ can be computed by repeated multiplication of $X^q \bmod f$ with itself at a cost of approximately d modular multiplications, and $X^{q^i} \bmod f$ for $2 \leq i \leq m$ can be computed by repeated exponentiation by q with each exponentiating having cost d^2 \mathbb{F}_q -multiplications. Finally, the product in (6) can be computed using $m/2$ modular multiplications at a cost of md^2 \mathbb{F}_q -multiplications. The total cost for testing m -smoothness of f is thus

$$(7) \quad S_q(m, d) = 2d^2(d + m + 2\|q\|_2) \quad \mathbb{F}_q\text{-multiplications.}$$

We will mostly be interested in the case $q = 3^{12}$. Then, $X^q \bmod f$ can be determined by first precomputing $X^3, X^6, \dots, X^{3(d-1)} \bmod f$ by repeated multiplication by X . Thereafter, cubing a polynomial modulo f can be accomplished by cubing the coefficients of the polynomial, and then multiplying the precomputed polynomials by these cubes (and adding the results). In this way, we get a loose upper bound of $3d^2 + 11 \cdot d^2 = 14d^2$ $\mathbb{F}_{3^{12}}$ -multiplications of the cost to compute $X^{3^{12}} \bmod f$, and the total cost for testing m -smoothness of f becomes

$$(8) \quad S_{3^{12}}(m, d) = 2d^2(d + m + 7) \quad \mathbb{F}_{3^{12}}\text{-multiplications.}$$

3. NEW DLP ALGORITHM OF JOUX AND BARBULESCU ET AL.

The DLP algorithm we describe is due to Joux [28], with a descent step from the quasi-polynomial time algorithm (QPA) of Barbulescu et al. [6]. For lack of a better name, we will call this algorithm the “new DLP algorithm”.

Let $\mathbb{F}_{q^{2n}}$ be a finite field where $n \leq q+2$. Let $N = q^{2n} - 1$. Let g be an element of order N in $\mathbb{F}_{q^{2n}}^*$, and let $h \in \mathbb{F}_{q^{2n}}^*$. We wish to compute $\log_g h$. The algorithm proceeds by first finding the logarithms of all degree-one (§3.2) and degree-two (§3.3) elements in $\mathbb{F}_{q^{2n}}$. Then, in the *descent stage*, $\log_g h$ is expressed as a linear combination of logarithms of degree-one and degree-two $\mathbb{F}_{q^{2n}}$ elements. The descent stage proceeds in several steps, each expressing the logarithm of a degree- D element as a linear combination of the logarithms of elements of degree $\leq m$ for some $m < D$. Four descent methods are used; these are described in §3.4–§3.7. The cost of each step is given in Table 2.

Finding logarithms of linear polynomials (§3.2)	
Relation generation	$6q^2 \cdot S_{q^2}(1, 3)$
Linear algebra	$q^5 \cdot M_N$
Finding logarithms of irreducible quadratic polynomials (§3.3)	
Relation generation	$q^{16}/N_{q^2}(1, 6) \cdot S_{q^2}(1, 6)$
Linear algebra	$q^7 \cdot M_N$
Descent (Degree D to degree m)	
Continued-fraction (§3.4)	$\{D = n - 1\} (q^{n-1}/N_{q^2}(m, (n-1)/2))^2 \cdot S_{q^2}(m, (n-1)/2)$
Classical (§3.5)	$q^{2(t_1-D+t_2)}/(N_{q^2}(m, t_1-D)N_{q^2}(m, t_2)) \cdot \min(S_{q^2}(m, t_1-D), S_{q^2}(m, t_2))$
QPA (§3.6)	$q^{6D+2}/N_{q^2}(m, 3D) \cdot S_{q^2}(m, 3D) + q^5 \cdot M_N$
Gröbner bases (§3.7)	$G_{q^2}(m, D) + q^{6m-2D}/N_{q^2}(m, 3m-D) \cdot S_{q^2}(m, 3m-D)$

TABLE 2. Estimated costs of the main steps of the new DLP algorithm for computing discrete logarithms in $\mathbb{F}_{q^{2n}}$. M_N and M_{q^2} denote the costs of a multiplication modulo N and a multiplication in \mathbb{F}_{q^2} . The smoothness testing cost $S_{q^2}(m, D)$ is given in (7). See §3.5 for the definitions of t_1 and t_2 . The Gröbner basis cost $G_{q^2}(m, D)$ is defined in §3.7.

Notation. For $\gamma \in \mathbb{F}_{q^2}$, $\overline{\gamma}$ denotes the element γ^q . For $P \in \mathbb{F}_{q^2}[X]$, \overline{P} denotes the polynomial obtained by raising each coefficient of P to the power q . The cost of an integer multiplication modulo N is denoted by M_N , and the cost of a multiplication in \mathbb{F}_{q^2} is noted by M_{q^2} . The projective general linear group of order 2 over \mathbb{F}_q is denoted $\text{PGL}_2(\mathbb{F}_q)$. \mathcal{P}_q is a set of distinct representatives of the left cosets of $\text{PGL}_2(\mathbb{F}_q)$ in $\text{PGL}_2(\mathbb{F}_{q^2})$; note that $\#\mathcal{P}_q = q^3 + q$.

3.1. Setup. Select polynomials $h_0, h_1 \in \mathbb{F}_{q^2}[X]$ of degree at most 2 so that $h_1X^q - h_0$ has an irreducible factor I_X of degree n in $\mathbb{F}_{q^2}[X]$; we will henceforth assume that $\max(\deg h_0, \deg h_1) = 2$. Note that $X^q \equiv h_0/h_1 \pmod{I_X}$. Then $\mathbb{F}_{q^{2n}}$ is represented as $\mathbb{F}_{q^{2n}} = \mathbb{F}_{q^2}[X]/(I_X)$, and the elements of $\mathbb{F}_{q^{2n}}$ can be represented as polynomials in $\mathbb{F}_{q^2}[X]$ of degree at most $n - 1$. Let g be a generator of $\mathbb{F}_{q^{2n}}^*$.

3.2. Finding logarithms of linear polynomials. Let $\mathcal{B}_1 = \{X + a \mid a \in \mathbb{F}_{q^2}\}$, and note that $\#\mathcal{B}_1 = q^2$. To compute the logarithms of \mathcal{B}_1 -elements, we first generate linear relations of these logarithms. Let $a, b, c, d \in \mathbb{F}_{q^2}$ with $ad - bc \neq 0$. Substituting $Y \mapsto (aX + b)/(cX + d)$ into the systematic equation

$$(9) \quad Y^q - Y = \prod_{\alpha \in \mathbb{F}_q} (Y - \alpha),$$

and then multiplying by $(cX + d)^{q+1}$ yields

$$(10) \quad (\bar{a}h_0 + \bar{b}h_1)(cX + d) - (aX + b)(\bar{c}h_0 + \bar{d}h_1) \\ \equiv h_1 \cdot (cX + d) \cdot \prod_{\alpha \in \mathbb{F}_q} [(a - \alpha c)X + (b - \alpha d)] \pmod{I_X}.$$

Note that the left-hand side of (10) is a polynomial of degree (at most) 3. If this polynomial is 1-smooth, then taking logarithms of both sides of (10) yields a linear relation of the logarithms of \mathcal{B}_1 -elements² and the logarithm of h_1 . As explained in [6], in order to avoid redundant relations one selects quadruples (a, b, c, d) from \mathcal{P}_q ; here we are identifying a quadruple (a, b, c, d) with the matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$.

Now, the probability that the left-hand side of (10) is 1-smooth is

$$\frac{N_{q^2}(1, 3)}{q^6} = \binom{q^2 + 2}{3} / q^6 \approx \frac{1}{6}.$$

Thus, after approximately $6q^2$ trials one expects to obtain (slightly more than) q^2 relations. The cost of the relation generation stage is $6q^2 \cdot S_{q^2}(1, 3)$. The logarithms can then be obtained by using standard techniques for solving sparse systems of linear equations. The expected cost of the linear algebra is $q^5 \cdot M_N$ since each equation has approximately q nonzero terms.

3.3. Finding logarithms of irreducible quadratic polynomials. Let $u \in \mathbb{F}_{q^2}$, and let $Q(X) = X^2 + uX + v \in \mathbb{F}_{q^2}[X]$ be an irreducible quadratic. Define $\mathcal{B}_{2,u}$ to be the set of all irreducible quadratics of the form $X^2 + uX + w$ in $\mathbb{F}_{q^2}[X]$; one expects that $\#\mathcal{B}_{2,u} \approx (q^2 - 1)/2$. The logarithms of all elements in $\mathcal{B}_{2,u}$ are found simultaneously using one application of QPA descent (see §3.6). More precisely, one first constructs the matrix $\mathcal{H}(Q)$. The expected number of relations one can obtain is

$$\frac{N_{q^2}(1, 6)}{q^{12}} \cdot (q^3 + q).$$

Provided that this number is significantly greater than $\#\mathcal{B}_{2,u}$, the matrix $\mathcal{H}(Q)$ is expected to have full (column) rank. One can then find expressions for the logarithm of

²It is understood that all polynomials of the right-hand side of (10) and factors of the left-hand side of (10) should be made monic. The same holds for (17) and (19).

each irreducible translate $Q + w$ of Q in terms of the logarithms of linear polynomials, thereby obtaining $\log_g(Q + w)$. This step is repeated for each $u \in \mathbb{F}_{q^2}$. Hence, there are q^2 independent linear systems of equations to be solved.

For each $u \in \mathbb{F}_{q^2}$, the cost of relation generation is $q^{14}/N_{q^2}(1, 6) \cdot S_{q^2}(1, 6)$, while the linear algebra cost is $q^5 \cdot M_N$.

3.4. Continued-fraction descent. Recall that we wish to compute $\log_g h$, where $h \in \mathbb{F}_{q^{2n}} = \mathbb{F}_{q^2}[X]/(I_X)$. Note that $\deg h \leq n - 1$; we will henceforth assume that $\deg h = n - 1$. The descent stage begins by multiplying h by a random power of g . The extended Euclidean algorithm is used to express the resulting field element h' in the form $h' = w_1/w_2$ where $\deg w_1, \deg w_2 \approx n/2$ [12]; for simplicity, we shall assume that n is odd and $\deg w_1 = \deg w_2 = (n - 1)/2$. This process is repeated until both w_1 and w_2 are m -smooth for some chosen $m < (n - 1)/2$. This gives $\log_g h'$ as a linear combination of logarithms of polynomials of degree at most m . The expected cost of this continued-fraction descent step is approximately

$$(11) \quad \left(\frac{q^{n-1}}{N_{q^2}(m, (n-1)/2)} \right)^2 \cdot S_{q^2}(m, (n-1)/2).$$

The expected number of distinct irreducible factors of w_1 and w_2 is $2A_{q^2}(m, (n-1)/2)$. In the analysis, we shall assume that each of these irreducible factors has degree exactly m . The logarithm of each of these degree- m polynomials is then expressed as a linear combination of logarithms of smaller degree polynomials using one of the descent methods described in §3.5, §3.6 and §3.7.

3.5. Classical descent. Let p be the characteristic of \mathbb{F}_q , and let $q = p^\ell$. Let $s \in [1, \ell]$, and let $R(X, Y) \in \mathbb{F}_{q^2}[X, Y]$. Then

$$R(X, X^{p^s})^{p^{\ell-s}} = R'(X^{p^{\ell-s}}, X^q) \equiv R'(X^{p^{\ell-s}}, \frac{h_0}{h_1}) \pmod{I_X},$$

where R' is obtained from R by raising all its coefficients to the power $p^{\ell-s}$. For the sake of simplicity, we will henceforth assume that $h_1 = 1$ and so

$$(12) \quad R(X, X^{p^s})^{p^{\ell-s}} \equiv R'(X^{p^{\ell-s}}, h_0) \pmod{I_X}.$$

Let $Q \in \mathbb{F}_{q^2}[X]$ with $\deg Q = D$, and let $m < D$. In the Joux-Lercier descent method [31], as modified by Joux [28], one selects suitable parameters d_1, d_2 and searches for a polynomial $R \in \mathbb{F}_{q^2}[X, Y]$ such that (i) $\deg_X R \leq d_1$ and $\deg_Y R \leq d_2$; (ii) $Q \mid R_1$ where $R_1 = R(X, X^{p^s})$; and (iii) R_1/Q and R_2 are m -smooth where $R_2 = R'(X^{p^{\ell-s}}, h_0)$. Taking logarithms of both sides of (12) then gives an expression for $\log_g Q$ in terms of the logarithms of polynomials of degree at most m .

A family of polynomials R satisfying (i) and (ii) can be constructed by finding the null space of the $D \times (D + \delta)$ matrix whose columns are indexed by monomials $X^i Y^j$ for $D + \delta$ pairs $(i, j) \in [0, d_1] \times [0, d_2]$, and whose $X^i Y^j$ -th column entries are the coefficients of the polynomial $X^i (X^{p^s})^j \bmod Q$. The components of the vectors in the null space of this matrix can be interpreted as the coefficients of polynomials $R \in \mathbb{F}_{q^2}[X, Y]$ satisfying (i) and (ii). The dimension of this null space is expected to be δ , and so the null space is expected to contain $(q^2)^{\delta-1}$ monic polynomials. Let $\deg R_1 = t_1$ and $\deg R_2 = t_2$. We have $t_1 \leq d_1 + p^s d_2$ and $t_2 \leq p^{\ell-s} d_1 + 2d_2$; the precise values of t_1 and t_2 depend

on the (i, j) pairs chosen (see §4.5 for an example). In order to ensure that the null space includes a monic polynomial R such that both R_1/Q and R_2 are m -smooth, the parameters must be selected so that

$$(13) \quad q^{2\delta-2} \gg \frac{q^{2(t_1-D)}}{N_{q^2}(m, t_1-D)} \cdot \frac{q^{2t_2}}{N_{q^2}(m, t_2)}.$$

Ignoring the time to compute the null space, the expected cost of finding a polynomial R satisfying (i)–(iii) is

$$(14) \quad \frac{q^{2(t_1-D)}}{N_{q^2}(m, t_1-D)} \cdot \frac{q^{2t_2}}{N_{q^2}(m, t_2)} \cdot \min(S_{q^2}(m, t_1-D), S_{q^2}(m, t_2)).$$

The expected number of distinct irreducible factors of R_1/Q and R_2 is $A_{q^2}(m, t_1-D) + A_{q^2}(m, t_2)$. In the analysis, we shall assume that each of these irreducible factors has degree exactly m .

3.6. QPA descent. The QPA descent method is so named because it was a crucial step in the Barbulescu et al. quasi-polynomial time algorithm for the DLP in finite fields of small characteristic [6].

Let $Q \in \mathbb{F}_{q^2}[X]$ with $\deg Q = D$, and let $m \in [[D/2], D-1]$. Let $(a, b, c, d) \in \mathcal{P}_q$, and recall that $\#\mathcal{P}_q = q^3 + q$. Substituting $Y \mapsto (aQ + b)/(cQ + d)$ into the systematic equation (9) and multiplying by $(cQ + d)^{q+1}$ yields

$$(15) \quad (aQ + b)^q(cQ + d) - (aQ + b)(cQ + d)^q = (cQ + d) \prod_{\alpha \in \mathbb{F}_q} [(a - \alpha c)Q + (b - \alpha d)].$$

The left-hand side of (15) can be written as

$$\begin{aligned} & (\bar{a}\bar{Q}(X^q) + \bar{b})(cQ + d) - (aQ + b)(\bar{c}\bar{Q}(X^q) + \bar{d}) \\ & \equiv (\bar{a}\bar{Q}(\frac{h_0}{h_1}) + \bar{b})(cQ + d) - (aQ + b)(\bar{c}\bar{Q}(\frac{h_0}{h_1}) + \bar{d}) \pmod{I_X}. \end{aligned}$$

Hence

$$(16) \quad \begin{aligned} & (\bar{a}\bar{Q}(\frac{h_0}{h_1}) + \bar{b})(cQ + d) - (aQ + b)(\bar{c}\bar{Q}(\frac{h_0}{h_1}) + \bar{d}) \\ & \equiv (cQ + d) \prod_{\alpha \in \mathbb{F}_q} [(a - \alpha c)Q + (b - \alpha d)] \pmod{I_X}. \end{aligned}$$

Multiplying (16) by h_1^D yields

$$(17) \quad \begin{aligned} & (\bar{a}\tilde{Q} + \bar{b})(cQ + d) - (aQ + b)(\bar{c}\tilde{Q} + \bar{d}) \\ & \equiv h_1^D \cdot (cQ + d) \cdot \prod_{\alpha \in \mathbb{F}_q} [(a - \alpha c)Q + (b - \alpha d)] \pmod{I_X}, \end{aligned}$$

where $\tilde{Q}(X) = h_1^D \cdot \bar{Q}(h_0/h_1)$. Note that the polynomial on the left-hand side of (17) has degree $\leq 3D$. If this polynomial is m -smooth, then (17) yields a linear relation of the logarithms of some degree- m polynomials and logarithms of translates of Q . After collecting slightly more than q^2 such relations, one searches for a linear combination of these relations that eliminates all translates of Q except for Q itself. To achieve this, consider row vectors in $(\mathbb{Z}_N)^{q^2}$ indexed by elements $\lambda \in \mathbb{F}_{q^2}$. For each relation, we

define a vector v whose entry v_λ is 1 if $Q - \lambda$ appears in the right-hand side (17), and 0 otherwise. If the resulting matrix $\mathcal{H}(Q)$ of row vectors has full column rank, then one obtains an expression for $\log_g Q$ in terms of the logarithms of polynomials of degree $\leq m$. The number of distinct polynomials of degree $\leq m$ in this expression is expected to be $A_{q^2}(m, 3D) \cdot q^2$; in the analysis we shall assume that each of the polynomials has degree exactly m .

Since the probability that a degree- $3D$ polynomial is m -smooth is $N_{q^2}(m, 3D)/(q^2)^{3D}$, one must ensure that

$$(18) \quad \frac{N_{q^2}(m, 3D)}{q^{6D}} \cdot (q^3 + q) \gg q^2$$

in order to ensure that $\mathcal{H}(Q)$ has $\gg q^2$ rows, whereby $\mathcal{H}(Q)$ can be expected to have full rank.

Example 2. If $q = 3^6$ (so $q^2 = 531,441$), $D = 11$, and $m = 6$, then the left-hand side of (18) is approximately 86,885 so QPA descent from 11 to 6 fails. On the other hand, if $q = 3^6$, $D = 11$, and $m = 7$ then the left-hand side of (18) is approximately 570,172 so QPA descent from 11 to 7 should succeed. For $q = 3^6$ and each $D \in [2, 28]$, Table 3 shows the smallest $m \in [\lceil D/2 \rceil, D - 1]$ for which inequality (18) is satisfied.

D	m	$3D$	ratio	D	m	$3D$	ratio	D	m	$3D$	ratio
2	1	6	1.0125	11	7	33	1.0729	20	13	60	1.0435
3	2	9	5.2634	12	8	36	1.6867	21	14	63	1.3637
4	3	12	9.6178	13	9	39	2.3927	22	15	66	1.7168
5	3	15	1.1193	14	9	42	1.0597	23	15	69	1.0382
6	4	18	2.6162	15	10	45	1.5305	24	16	72	1.3140
7	5	21	4.3795	16	11	48	2.0631	25	17	75	1.6154
8	5	24	1.0924	17	11	51	1.0503	26	17	78	1.0340
9	6	27	1.9687	18	12	54	1.4317	27	18	81	1.2762
10	7	30	2.9948	19	13	57	1.8571	28	19	84	1.5388

TABLE 3. Let $q = 3^6$. For each $D \in [2, 28]$, the table gives the smallest $m \in [\lceil D/2 \rceil, D - 1]$ for which QPA descent from degree D to degree m could succeed, i.e., inequality (18) is satisfied. The fourth column shows the ratio $[N_{q^2}(m, 3D) \cdot (q^3 + q)/q^{6D}]/q^2$.

The expected cost of the relation generation portion of QPA descent is

$$\frac{q^{6D}}{N_{q^2}(m, 3D)} q^2 \cdot S_{q^2}(m, 3D),$$

while the cost of the linear algebra is $q^5 \cdot M_N$.

3.7. Gröbner bases descent. Let $Q \in \mathbb{F}_{q^2}[X]$ with $\deg Q = D$, and let $m = \lceil (D + 1)/2 \rceil$. In Joux's new descent method [28, §5.3], one finds degree- m polynomials $k_1, k_2 \in \mathbb{F}_{q^2}[X]$ such that $Q \mid G$, where

$$G = h_1^m (k_1^q k_2 - k_1 k_2^q) \bmod I_X.$$

We then have

$$h_1^m \cdot k_2 \cdot \prod_{\alpha \in \mathbb{F}_q} (k_1 - \alpha k_2) \equiv G(X) \pmod{I_X}$$

as can be seen by making the substitution $Y \mapsto k_1/k_2$ into the systematic equation (9) and clearing denominators. Define $\tilde{k}(X) = h_1^m \cdot \bar{k}(h_0/h_1)$ and note that $\deg \tilde{k} = 2m$. We thus have $G \equiv \tilde{k}_1 k_2 - k_1 \tilde{k}_2 \pmod{I_X}$, and consequently $G = \tilde{k}_1 k_2 - k_1 \tilde{k}_2$ provided that $3m < n$. It follows that $G(X) = Q(X)R(X)$ for some $R \in \mathbb{F}_{q^2}[X]$ with $\deg R = 3m - D$. If R is m -smooth, we obtain a linear relationship between $\log_g Q$ and logs of degree- m polynomials by taking logarithms of both sides of the following:

$$(19) \quad h_1^m \cdot k_2 \cdot \prod_{\alpha \in \mathbb{F}_q} (k_1 - \alpha k_2) \equiv Q(X)R(X) \pmod{I_X}.$$

To determine (k_1, k_2, R) that satisfy

$$(20) \quad \tilde{k}_1 k_2 - k_1 \tilde{k}_2 = Q(X)R(X),$$

one can transform (20) into a system of multivariate bilinear equations over \mathbb{F}_q . Specifically, each coefficient of k_1 , k_2 and R is written using two variables over \mathbb{F}_q , the two variables representing the real and imaginary parts of that coefficient (which is in \mathbb{F}_{q^2}). The coefficients of \tilde{k}_1 and \tilde{k}_2 can then be written in terms of the coefficients of k_1 and k_2 . Hence, equating coefficients of X^i of both sides of (20) yields $3m+1$ quadratic equations. The real and imaginary parts of each of these equations are equated, yielding $6m+2$ bilinear equations in $10m-2D+6$ variables over \mathbb{F}_q . This system of equations can be solved by finding a Gröbner basis for the ideal it generates. Finally, solutions (k_1, k_2, R) are tested until one is found for which R is m -smooth. This yields an expression for $\log_g Q$ in terms of the logarithms of approximately $q+1 + A_{q^2}(m, 3m-D)$ polynomials of degree (at most) m ; in the analysis we shall assume that each of the polynomials has degree exactly m .

Now, the number of candidate pairs (k_1, k_2) is $((q^2)^{m+1})^2 = q^{4(m+1)}$. Since $(q^2)^{3m-D+1}$ of the $(q^2)^{3m+1}$ degree- $(3m)$ polynomials in $\mathbb{F}_{q^2}[X]$ are divisible by $Q(X)$, the number of solutions (k_1, k_2, R) is expected to be approximately

$$\frac{q^{2(3m-D+1)}}{q^{2(3m+1)}} \cdot q^{4(m+1)} = q^{4(m+1)-2D}.$$

However, the number of distinct R obtained will be significantly less than $q^{4(m+1)-2D}$. For example, any two pairs (k'_1, k'_2) and (k''_1, k''_2) with $k'_1/k'_2 = k''_1/k''_2$ will generate the same R , so the expected number of distinct R is at most $q^{4(m+1)-2D}/(q^2-1)$. Let us denote by $R(m, D)$ the expected number of distinct R obtainable. Then the condition

$$(21) \quad R(m, D) \gg \frac{q^{2(3m-D)}}{N_{q^2}(m, 3m-D)},$$

can ensure that there exists a solution (k_1, k_2, R) for which R is m -smooth.

The number $R(m, D)$ has not been determined in general. For the case $m=1$ and $D=2$, one must select $k_1 = aX+b$ and $k_2 = cX+d$ with $(a, b, c, d) \in \mathcal{P}_q$ to avoid collisions; hence $R(1, 2) \leq \frac{q^4}{q^8}(q^3+q) \approx \frac{1}{q}$ and descending from 2 to 1 is expected to

succeed only for 1 out of every q quadratics. In general, the success of the Gröbner bases descent step is best determined experimentally (cf. §4.7).

It is difficult to determine the exact cost $G_{q^2}(m, D)$ of the Gröbner basis finding step. After the Gröbner basis is found, the cost to find an m -smooth R is $(q^2)^{3m-D}/N_{q^2}(m, 3m-D) \cdot S_{q^2}(m, 3m-D)$. One then obtains an expression for $\log_g Q$ in terms of the logarithms of approximately $q+1 + A_{q^2}(m, 3m-D)$ elements of degree at most m .

4. COMPUTING DISCRETE LOGARITHMS IN $\mathbb{F}_{3^{6 \cdot 509}}$

We present a concrete analysis of the DLP algorithm described in §3 for computing discrete logarithms in $\mathbb{F}_{3^{6 \cdot 509}}$. In fact, this field is embedded in the quadratic extension field $\mathbb{F}_{3^{12 \cdot 509}}$, and it is the latter field where the DLP algorithm of §3 is executed. Thus, we have $q = 3^6 = 729$, $n = 509$, and $N = 3^{12 \cdot 509} - 1$. Note that $3^{12 \cdot 509} \approx 2^{9681}$. We wish to find $\log_g h$, where g is a generator of $\mathbb{F}_{3^{12 \cdot 509}}^*$ and $h \in \mathbb{F}_{3^{12 \cdot 509}}^*$.

As mentioned in §1, our main motivation for finding discrete logarithms in $\mathbb{F}_{3^{6 \cdot 509}}$ is to attack the elliptic curve discrete logarithm problem in $E(\mathbb{F}_{3^{509}})$, where E is the supersingular elliptic curve $Y^2 = X^3 - X + 1$ with $\#E(\mathbb{F}_{3^{509}}) = 7r$, and where $r = (3^{509} - 3^{255} + 1)/7$ is an 804-bit prime. Note that $r^2 \nmid N$. The elliptic curve discrete logarithm problem in the order- r subgroup of $E(\mathbb{F}_{3^{509}})$ can be efficiently reduced to the discrete logarithm problem in the order- r subgroup of $\mathbb{F}_{3^{12 \cdot 509}}^*$. In the latter problem, we are given two elements α, β of order r in $\mathbb{F}_{3^{12 \cdot 509}}^*$ and we wish to find $\log_\alpha \beta$. It can readily be seen that $\log_\alpha \beta = (\log_g \beta) / (\log_g \alpha) \pmod r$. Thus, we will henceforth assume that h has order r and that we only need to find $\log_g h \pmod r$. An immediate consequence of this restriction is that all the linear algebra in the new algorithm has to be performed modulo the 804-bit r instead of modulo the 9681-bit N .

The parameters for each step of the algorithm were carefully chosen in order to balance the running time of the steps. We also took into account the degree to which each step could be parallelized. A summary of the parameter choices for the descent is given in Figure 1. The costs of each step are given in Table 4.

4.1. Setup. We chose the representations $\mathbb{F}_{3^6} = \mathbb{F}_3[U]/(U^6 + 2U^4 + U^2 + 2U + 2)$ and $\mathbb{F}_{3^{12}} = \mathbb{F}_{3^6}[V]/(V^2 + U^{365})$. We selected $h_0 = X^2 + U^{398}V + U^{56} \in \mathbb{F}_{3^{12}}[X]$ and $h_1 = 1$, and $I_X \in \mathbb{F}_{3^{12}}[X]$ to be the monic degree-509 irreducible factor of $X^{3^6} - h_0$.

4.2. Finding logarithms of linear polynomials. The factor base \mathcal{B}_1 has size $3^{12} \approx 2^{19}$. The cost of relation generation is approximately $2^{30}M_{q^2}$, whereas the cost of the linear algebra is approximately $2^{48}M_r$. Note that relation generation can be effectively parallelized, unlike the linear algebra where parallelization provides relatively small benefits.

4.3. Finding logarithms of irreducible quadratic polynomials. For each $u \in \mathbb{F}_{3^{12}}$, the expected cost of computing logarithms of all quadratics in $\mathcal{B}_{2,u}$ is $2^{39}M_{q^2}$ for the computation of $\mathcal{H}(Q)$, and $2^{48}M_r$ for the linear algebra. Note that the number of columns in $\mathcal{H}(Q)$ can be halved since the logarithms of all reducible quadratics are known. Since the expected number of relations obtainable is

$$\frac{N_{q^2}(1, 6)}{q^{12}} \cdot (q^3 + q) \approx \frac{1}{719.98} \cdot (q^3 + q) \approx q^2 + 6659,$$

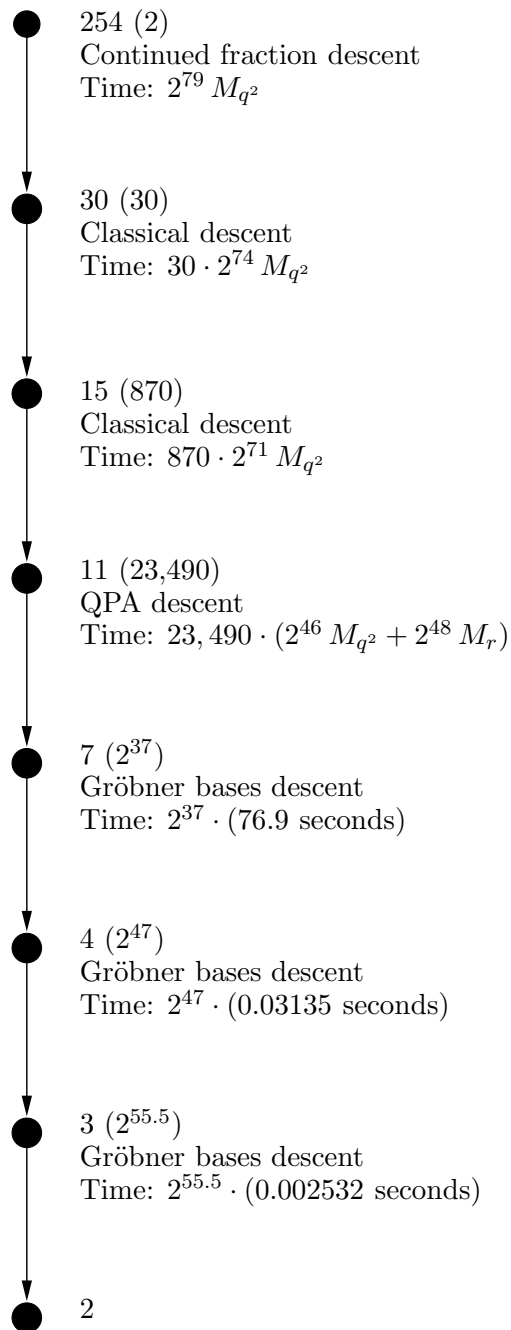


FIGURE 1. A typical path of the descent tree for computing an individual logarithm in $\mathbb{F}_{3^{12 \cdot 509}}$ ($q = 3^6$). The numbers in parentheses next to each node are the expected number of nodes at that level. ‘Time’ is the expected time to generate all nodes at a level.

Finding logarithms of linear polynomials		
Relation generation	$2^{30}M_{q^2}$	$2^{22}M_r$
Linear algebra	$2^{48}M_r$	$2^{48}M_r$
Finding logarithms of irreducible quadratic polynomials		
Relation generation	$3^{12} \cdot 2^{39}M_{q^2}$	$2^{50}M_r$
Linear algebra	$3^{12} \cdot 2^{48}M_r$	$2^{67}M_r$
Descent		
Continued-fraction (254 to 30)	$2^{79}M_{q^2}$	$2^{71}M_r$
Classical (30 to 15)	$30 \cdot 2^{74}M_{q^2}$	$2^{71}M_r$
Classical (15 to 11)	$870 \cdot 2^{71}M_{q^2}$	$2^{73}M_r$
QPA (11 to 7)	$23,490 \cdot (2^{46}M_{q^2} + 2^{48}M_r)$	$2^{63}M_r$
Gröbner bases (7 to 4)	$2^{37} \cdot (76.9 \text{ seconds})$	$2^{65}M_r$
Gröbner bases (4 to 3)	$2^{47} \cdot (0.03135 \text{ seconds})$	$2^{64}M_r$
Gröbner bases (3 to 2)	$2^{55.5} \cdot (0.002532 \text{ seconds})$	$2^{69}M_r$

TABLE 4. Estimated costs of the main steps of the new DLP algorithm for computing discrete logarithms in $\mathbb{F}_{3^{12 \cdot 509}}$ ($q = 3^6$). M_r and M_{q^2} denote the costs of a multiplication modulo the 804-bit prime $r = (3^{509} - 3^{255} + 1)/7$ and a multiplication in $\mathbb{F}_{3^{12}}$. We use the cost ratio $M_r/M_{q^2} = 2^8$, and also assume that 2^{22} multiplications modulo r can be performed in 1 second (cf. §4.8).

one can expect that the matrix $\mathcal{H}(Q)$ will have full rank.

This step is somewhat parallelizable since each set $\mathcal{B}_{2,u}$ can be handled by a different processor.

4.4. Continued-fraction descent. For the continued-fraction descent, we selected $m = 30$. The expected cost of this descent is $2^{79}M_{q^2}$. This descent can be effectively parallelized. The expected number of distinct irreducible factors of degree (at most) 30 obtained is $2A_{3^{12}}(30, 254) \approx 30$.

4.5. Classical descent. Two classical descent stages are employed. In the first stage, we have $D = 30$ and select $m = 15$, $s = 3$, $d_1 = 5$, $d_2 = 5$, and $\delta = 4$. The set of $D + \delta$ pairs (i, j) selected was

$$([0, 3] \times [0, 5]) \cup \{(4, 0), (4, 1), (4, 2), (4, 3), (4, 4), (5, 0), (5, 1), (5, 2), (5, 3), (5, 4)\},$$

yielding $t_1 = 138$ and $t_2 = 143$. Note that inequality (13) is satisfied. The expected cost of the descent for each of the 30 degree-30 polynomials is approximately $2^{52} \cdot S_{q^2}(15, 108)$. The expected total number of distinct irreducible polynomials of degree (at most) 15 obtained is approximately 870.

In the second classical descent stage, we have $D = 15$ and select $m = 11$, $s = 3$, $d_1 = 3$, $d_2 = 4$, and $\delta = 4$. The set of $D + \delta$ pairs (i, j) selected was

$$([0, 2] \times [0, 4]) \cup \{(3, 0), (3, 1), (3, 2), (3, 3)\},$$

yielding $t_1 = 110$ and $t_2 = 87$. Note that inequality (13) is satisfied. The expected cost of the descent for each of the 870 degree-15 polynomials is approximately $2^{50} \cdot S_{q^2}(11, 87)$. The expected total number of distinct irreducible polynomials of degree (at most) 11 obtained is approximately 23,490.

Note that both classical descent stages can be effectively parallelized.

4.6. QPA descent. The QPA descent method is then applied to each of the 23,490 degree-11 polynomials Q obtained from the classical descent stage. We have $D = 11$ and $m = 7$. For each Q , the expected number of rows in $\mathcal{H}(Q)$ is 570,172, so we can expect this matrix to have full column rank (namely, $q^2 = 531,441$). For each Q , the expected cost of relation generation is $2^{29} \cdot S_{q^2}(7, 33)$ and the cost of the linear algebra is $2^{48} M_7$. Also for each, Q , the expected number of distinct polynomials of degree at most 7 obtained is expected to be $A_{q^2}(7, 33) \cdot q^2 \approx 2^{22}$. Thus, the total number of distinct polynomials of degree at most 7 obtained after the QPA descent stage is approximately 2^{37} .

4.7. Gröbner bases descent. The Gröbner bases descent method is applied to each of the 2^{37} polynomials of degree (at most) 7 obtained after QPA descent. Our experiments were run using Magma v2.19-7 [33] on a 2.9 GHz Intel core i7-3520M.

First, one descends from 7 to 4, i.e., $D = 7$ and $m = 4$. For each degree-7 polynomial Q , we have to solve a system of 26 quadratic polynomial equations in 32 variables over \mathbb{F}_q (cf. (20)). Since the ideal generated by these polynomials typically has dimension greater than 0, we randomly fix some of the variables in the hope of obtaining a 0-dimensional ideal. (More precisely, we added some linear constraints involving pairs of variables, one variable from k_1 and the other from k_2 .) Each degree-5 R obtained from the variety of the resulting ideal is tested for 4-smoothness. If no 4-smooth R is obtained, we randomly fix some other subset of variables and repeat. We ran 17,510 Gröbner bases descent experiments with randomly-selected degree-7 polynomials Q . On average, we had to find 1.831 Gröbner bases for each Q . The average number of R 's tested for 4-smoothness for each Q was 1.252, which agrees with the expected number $q^{10}/N_{q^2}(4, 5) \approx 1.25$. The average time to find each Gröbner basis was 42.0 seconds, and the memory consumption was 64 Mbytes. In total, the expected number of polynomials of degree at most 4 obtained is $2^{37}(q + 1 + A_{q^2}(4, 5)) \approx 2^{47}$.

Next, one descends from 4 to 3, i.e., $D = 4$ and $m = 3$. For each degree-4 polynomial Q , we have to solve a system of 20 quadratic polynomial equations in 28 variables over \mathbb{F}_q . We proceed as above, by fixing some of the 28 variables. We ran 1,230,000 Gröbner bases descent experiments with randomly-selected degree-4 polynomials Q . On average, we had to find 2.361 Gröbner bases for each Q . The average number of R 's tested for 3-smoothness for each Q was 1.815, which agrees with the expected number $q^{10}/N_{q^2}(3, 5) \approx 1.818$. The average time to find each Gröbner basis was 0.01328 seconds, and the memory consumption was 32 Mbytes. In total, the expected number of polynomials of degree at most 3 obtained is $2^{47}(q + 1 + A_{q^2}(3, 5)) \approx 2^{57}$.

Finally, one descends from 3 to 2, i.e., $D = 3$ and $m = 2$. Since the total number of irreducible monic cubics over \mathbb{F}_{q^2} is approximately $2^{55.5}$, which is less than 2^{57} , we perform the 3 to 2 descent for all irreducible monic cubics. For each such polynomial Q , we have to solve a system of 14 quadratic polynomial equations in 20 variables over \mathbb{F}_q . We proceed as above, by fixing some of the 20 variables. We ran 8,100,000 Gröbner bases descent experiments with randomly-selected degree-3 polynomials Q . On average, we had to find 2.026 Gröbner bases for each Q . The average number of R 's tested for 2-smoothness for each Q was 1.499, which agrees with the expected number

$q^6/N_{q^2}(2, 3) \approx 1.5$. The average time to find each Gröbner basis was 0.00125 seconds, and the memory consumption was 32 Mbytes.

4.8. Overall running time. As can be seen in the second column of Table 4, the running time estimates for the main steps of the new DLP algorithm are given using three units of time: M_r , M_{q^2} , and seconds. In order to assess the overall time, we make some assumptions about the ratios of these units of time.

First, we shall assume that $M_r/M_{q^2} = 2^8$. To justify this, we observe that two 64-bit unsigned integers can be multiplied using a **Mul** operation on an Intel Core i7 machine in 3 clock cycles, and an integer modulo r can be accommodated in 13 64-bit words. Two such integers can be multiplied using a two-level Karatsuba algorithm using 121 **Mul** operations, and a reduction modulo r can be accomplished using Barrett's algorithm [9] in 222 **Mul** operations, for a total cost of 343 **Mul** operations or 1029 clock cycles. Unlike for 64-bit integer multiplication, there is no native support for $\mathbb{F}_{3^{12}}$ multiplication on an Intel Core i7 machine. However, we expect that a specially designed multiplier could be built to achieve a multiplication cost of 4 clock cycles. While building such a native multiplier would certainly be costly, this expense can be expected to be within the budget of a well-funded adversary who is contemplating implementing the new DLP algorithm. This gives us an M_r/M_{q^2} ratio of approximately 2^8 .

Next, since a multiplication modulo r can be done in 1029 clock cycles, we will transform one second on a 2.9 GHz machine (on which the Gröbner bases descent experiments were performed) into $2^{22}M_r$.

Using these estimates, we see from the third column of Table 4 that the overall running time of the new algorithm is approximately $2^{73.7}M_r$. We note that the relation generation, continued-fraction descent, classical descent, and Gröbner bases descent steps, and also the relation generation portion of QPA descent, are effectively parallelizable in the sense that one can essentially achieve a factor- C speedup if C processors are available. On the other hand, the linear system of equation for finding logarithms of linear polynomials, the $3^{12} \approx 2^{19}$ linear systems of equations for finding logarithms of irreducible quadratic polynomials, and the $23,490 \approx 2^{15}$ linear systems of equations in QPA descent enjoy relatively modest benefits from parallelization.

Remark 1. (*caveat emptor*) Although our analysis is concrete rather than asymptotic, it must be emphasized that the analysis makes several heuristic assumptions and approximations. For example, there are the usual heuristic assumptions that certain polynomials encountered are uniformly distributed over the set of all polynomials of the same degree. Furthermore, we have assumed that the matrix $\mathcal{H}(Q)$ in QPA descent indeed has full column rank. Also, our run time analysis only accounts for the number of multiplications and ignores other operations such as additions and memory accesses. Thus, further analysis and experimentation is needed before one can conclude with certainty that the $2^{73.7}M_r$ running time estimate is an accurate measure of the efficiency of the new DLP algorithm for computing logarithms in the order- r subgroup of $\mathbb{F}_{3^{6 \cdot 509}}$.

Remark 2. (*looseness of our upper bound on the running time*) Remark 1 notwithstanding, our analysis is quite conservative and there are several possible ways in which the upper bound on the running time can be improved. (i) In our estimates for the number of branches in a descent step, we assume that each distinct irreducible polynomial obtained has degree exactly m , whereas in practice many of these polynomials

will have degree significantly less than m . Thus, it would appear that our bound on the number of nodes in the descent tree is quite loose. (ii) The Gröbner bases descent running times reported in §4.7 can be expected to be significantly improved by a native implementation of the F4 [17] or F5 [18] Gröbner basis finding algorithms optimized for characteristic-three finite fields. (Magma implements the F4 algorithm, but is not optimized for characteristic-three finite fields.) (iii) An optimized Gröbner basis implementation might be successful in performing the descent from $D = 11$ to $D = 6$, thereby replacing the QPA descent from $D = 11$ to $D = 7$ and significantly reducing the number of nodes in the descent tree.

4.9. Comparisons with Joux-Lercier. Shinohara et al. [36] estimated that the running time of the Joux-Lercier algorithm [31] for computing discrete logarithms in $\mathbb{F}_{3^6 \cdot 509}$ is $2^{111.35}$ for the relation generation stage, and $2^{102.69}$ for the linear algebra stage. Since relation generation is effectively parallelizable whereas linear algebra is not, a conservative estimate for the running time of the Joux-Lercier algorithm is $2^{102.69}M_r$. Further justification for discounting the running time of relation generation is that Joux’s pin-pointing technique [27] can be employed to significantly reduce the relation generation time, while not having a noticeable impact on the linear algebra time.

Thus, we see that the new algorithm with an overall running time of $2^{73.7}M_r$, is about 2^{29} times faster for computing logarithms in $\mathbb{F}_{3^6 \cdot 509}$ than the previous fastest algorithm. Moreover, if one had access to a massive number of processors (e.g., 2^{30} processors), then the bottleneck of the new algorithm is a linear algebra computation with a run time of $2^{48}M_r$, whereas the bottleneck of the Joux-Lercier algorithms remains the linear algebra computation with a run time of $2^{102.69}M_r$.

We believe that these comparisons justify the claim made in the abstract about the weakness of the field $\mathbb{F}_{3^6 \cdot 509}$, and thereby also the supersingular elliptic curve over $\mathbb{F}_{3^6 \cdot 509}$ with embedding degree 6.

5. CONCLUDING REMARKS

Our concrete analysis of the new algorithm of Joux and Barbulescu et al. has shown that the supersingular elliptic curve over $\mathbb{F}_{3^6 \cdot 509}$ with embedding degree 6 is significantly less resistant to attacks on the elliptic curve discrete logarithm problem than previously believed. Consequently, this elliptic curve is not suitable for implementing pairing-based cryptosystems. Our analysis applies equally well to the supersingular elliptic curve over $\mathbb{F}_{3^5 \cdot 97}$ with embedding degree 6 that has been proposed for compact hardware implementation of pairing-based cryptosystems by Estibals [16].

An important open question is whether the new algorithm or its implementation can be improved to the extent that the discrete logarithm problem in $\mathbb{F}_{3^6 \cdot 509}$ can be feasibly solved using existing computer technology.

Another important question is whether the new attack is effective for finding discrete logarithms in other small-characteristic finite fields of interest in pairing-based cryptography. Our preliminary analysis suggests that the new algorithm is ineffective for computing discrete logarithms in $\mathbb{F}_{2^4 \cdot 1223}$. Moreover, the new algorithm only appears advantageous over Joux-Lercier for discrete logarithm computations in $\mathbb{F}_{2^{12 \cdot 367}}$ and $\mathbb{F}_{2^{12 \cdot 439}}$ in the situation where a massive number of processors (e.g., 2^{40} processors) are available.

ACKNOWLEDGEMENTS

We would like to thank Pierre-Jean Spaenlehauer for answering our questions about Gröbner basis finding algorithms.

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