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ISOMORPHISMS BETWEEN ARTIN-SCHREIER TOWERS

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ABSTRACT. We give a method for efficiently computing isomorphisms between towers of Artin-Schreier extensions over a finite field. We find that isomorphisms between towers of degree p^n over a fixed field $\mathbb{F}_q$ can be computed, composed, and inverted in time essentially linear in p^n. The method relies on an approximation process.

1. INTRODUCTION

Let $\mathbb{F}_q$ be a finite field with $q = p^d$ elements. Let L_n be an extension of degree p^n of $\mathbb{F}_q$ given as a tower

$$L_n \supset L_{n-1} \supset \cdots \supset L_1 \supset L_0 = \mathbb{F}_q \tag{1}$$

of nontrivial Artin-Schreier extensions each defined by

$$L_{k+1} = L_k(x_{k+1}) \text{ with } x_{k+1}^p - x_{k+1} - a_k = 0 \text{ and } a_k \in L_k.$$

We call n the *length* of the tower.

Artin-Schreier towers naturally arise in computational algebraic geometry. In particular, let $G = \mathrm{Gal}(\bar{\mathbb{F}}_q/\mathbb{F}_q)$ be the absolute Galois group of $\mathbb{F}_q$. Morphisms between abelian varieties A and B defined over $\mathbb{F}_q$ induce G-morphisms between the Tate modules $\mathcal{T}_\ell(A)$ and $\mathcal{T}_\ell(B)$. If $\ell \neq p$, this correspondence is known to be bijective by a theorem of Tate [8]. If $\ell = p$, A is simple, and $\mathcal{T}_\ell(A)$ is nonzero, then the correpondance is injective. Assume the p-torsion of A and B is defined over $\mathbb{F}_q$. One can easily show that the definition field L_k of the p^{k+1}-torsion of A is an extension of $L_0 = \mathbb{F}_q$ with degree dividing p^k. Similarly the definition field M_k of the p^{k+1}-torsion of B is an extension of $M_0 = L_0 = \mathbb{F}_q$ with degree dividing p^k. Assuming the existence of an isogeny between A and B with prime to p degree, the fields L_k and M_k are isomorphic. These fields can be constructed by taking successive preimages of a p-torsion point by separable isogenies of degree p. Thus they naturally come as Artin-Schreier towers. In the case of nonsupersingular elliptic curves, such isogenies are described in terms of Hasse functions. If we are looking for an isogeny with a given prime to p degree between A and B, we can compute it by interpolation at enough p^k-torsion points. This reduces to computing an isomorphism between the Artin-Schreier towers we have on each side. This method is of special interest for computing the cardinality of ordinary elliptic curves with the Schoof-Elkies-Atkin algorithm. See [2] where the fastest known algorithm for this purpose is given, assuming the characteristic p is fixed. Surveys on these questions are in [6, 4, 3, 5].

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We shall prove the following

Theorem 1. *An isomorphism between two Artin-Schreier towers L_n and M_n of degree p^n over $\mathbb{F}_q = L_0 = M_0$ can be computed in time $O(n^6 p^n)$ multiplications in $\mathbb{F}_q$ for fixed q and $n \longrightarrow \infty$.*

Computational aspects of Artin-Schreier towers have already been studied by D. G. Cantor in [1]. For any integer u in $[0, p^n[$ with p-adic expansion $u = u_1 + u_2 p + \cdots + u_n p^{n-1}$ he sets $\chi_u = x_1^{u_1} x_2^{u_2} \cdots x_n^{u_n}$. The monomials $(\chi_u)_{0 \le u < p^k}$ form a basis $\mathcal{X}$ of the L_0-vector space L_k. If $a_0 = 1$ and $a_k = \chi_{p^k-1} + \sum_{u=0}^{p^k-2} c_u \chi_u$ with all the $c_u \in \mathbb{F}_q$, we say that the tower in formula (1) is a *Cantor tower.* One of the results in [1] is that for any prime p there exists a constant K_p such that two elements in a Cantor tower of length n over $\mathbb{F}_p$ can be multiplied at the expense of $K_p n^2 p^n$ operations in $\mathbb{F}_p$. The same holds for Cantor towers over a nonnecessarily prime field $\mathbb{F}_q$. We shall need this result and the corresponding algorithm. In order to compute an isomorphism between two Artin-Schreier towers, we shall first compute isomophisms between each of the two towers and a given Cantor tower. The expected isomorphism will then be obtained as a composition of these two isomorphisms. It is the purpose of Lemma 1 to state how efficiently isomorphisms between Artin-Schreier towers can be dealt with.

If $\alpha, \beta \in L_n$, we define the *écart* $\mathbf{d}(\alpha, \beta)$ to be the logarithm (with base p) of the degree of the extension $\mathbb{F}_q(\alpha - \beta)/\mathbb{F}_q$. The triangle inequality is easily checked. Note that $\mathbf{d}$ is not a distance since $\mathbf{d}(\alpha, \beta) = 0$ if and only if $\alpha - \beta$ is in $\mathbb{F}_q$. On the other hand, $\mathbf{d}$ is invariant under translation.

For any two positive integers i and j we define the following polynomials in $\mathbb{F}_p[X]$

$$\Phi_i(X) = X^{p^i} \text{ and } \wp_i(X) = X^{p^i} - X \text{ and } T_{i,j} = X + X^{p^j} + X^{p^{2j}} + \cdots + X^{p^{(i-1)j}}$$

The polynomial $\wp_i$ is usually called an isogeny [7]. To simplify we set $T_i = T_{i,1}$. We have the trivial relations

$$\wp_i \circ \wp_j = \wp_j \circ \wp_i \text{ and } \wp_j \circ T_{i,j} = T_{i,j} \circ \wp_j = \wp_{ij} \text{ and } T_{j,k} \circ T_{i,jk} = T_{ij,k}.$$

If $\mathcal{K} \subset \mathcal{L}$ is an extension of finite fields with cardinalities p^j and p^{ij}, respectively, we have the following exact sequence of $\mathcal{K}$-vector spaces:

$$0 \rightarrow \mathcal{K} \rightarrow \mathcal{L} \xrightarrow{\wp_j} \mathcal{L} \xrightarrow{T_{i,j}} \mathcal{K} \rightarrow 0.$$

Assume we are looking for an isomorphism

$$\iota : M_n \rightarrow L_n$$

between two Artin-Schreier towers L_n and M_n, with M_n defined by

$$M_n \supset M_{n-1} \supset \cdots \supset M_1 \supset M_0 = \mathbb{F}_q$$

and

$$M_{k+1} = M_k(y_{k+1}) \text{ and } y_{k+1}^p - y_{k+1} - b_k = 0 \text{ with } b_k \in M_k.$$

We define $\zeta_u = y_1^{u_1} y_2^{u_2} \cdots y_n^{u_n}$ similarly to χ_u. We may assume that an isomorphism has already been constructed between L_{n-1} and M_{n-1}. In order to extend it, we have to solve in L_n an Artin-Schreier equation.

Consider such an equation

$$\wp_1(Y) = Y^p - Y = \beta. \tag{2}$$

with $\beta \in L_n$ and $\mathrm{Tr}_{L_n/\mathbb{F}_p}(\beta) = 0$.

This is a linear equation over $\mathbb{F}_p$. The corresponding linear system of dimension dp^n over $\mathbb{F}_p$ can be solved with Gauss's algorithm at the expense of $O(d^3p^{3n})$ operations in $\mathbb{F}_p$. We notice, however, that equation (2) implies

$$\wp_i(Y) = Y^{p^i} - Y = \beta + \beta^p + \cdots + \beta^{p^{i-1}} = T_i(\beta) \tag{3}$$

which is linear over the intermediate field $\mathbb{F}_{p^i}$. The corresponding linear system of dimension dp^n/i over $\mathbb{F}_{p^i}$ can be solved with Gauss's algorithm at the expense of $O(d^3p^{3n}/i^3)$ operations in $\mathbb{F}_{p^i}$. This is better when multiplication is fast in L_n (e.g., when L_n is a Cantor tower).

Equation (3), of course, does not imply equation (2) but if we know a solution γ to equation (3) and set $Y = Z + \gamma$ in equation (2) we get

$$\wp_1(Z) = Z^p - Z = \beta - \gamma^p + \gamma.$$

Let $\delta = \beta - \gamma^p + \gamma$. We have $\wp_i(\delta) = \wp_i(\beta) - \wp_i(\wp_1(\gamma)) = \wp_i(\beta) - \wp_1(\wp_i(\gamma)) = \wp_i(\beta) - \wp_1(T_i(\beta)) = 0$ so $\delta \in \mathbb{F}_{p^i}$. We also check easily that $T_i(\delta) = T_i(\beta) - \wp_1(T_i(\gamma)) = T_i(\beta) - \wp_i(\gamma) = 0$. We conclude that the *écart* between γ and any solution of (2) is at most $\log_p(i/\mathrm{pgcd}(d,i))$. We say that δ is an approximate solution to equation (2) with accuracy $\log_p(i/\mathrm{pgcd}(i,d))$.

Since our strategy is to deal with the smallest possible matrices, we shall take $i = dp^{n-1}$. This way, for $\beta \in L_n$ and $\mathrm{Tr}_{L_n/\mathbb{F}_p}(\beta) = 0$, a solution to $Y^p - Y = \beta$ can be found in three steps:

1. Compute $B = T_{dp^{n-1}}(\beta)$.
2. Find a solution γ to $Y^{p^{dp^{n-1}}} - Y = B$ which amounts to solving a linear system of dimension p over L_{n-1}.
3. Solve $Z^p - Z = \delta$, where $\delta = \beta - \gamma^p + \gamma$ is in L_{n-1} and $\mathrm{Tr}_{L_{n-1}/\mathbb{F}_p}(\delta) = 0$.

And the same method is applied recursively to the equation in step 3. After k steps, we obtain an approximate solution to equation (2) with accuracy $n - k$. After n steps, we reduce to an Artin-Schreier equation over the base field $\mathbb{F}_q$.

In the rest of this paper, we provide details and a complexity analysis for the algorithm sketched above.

2. Artin-Schreier towers

We recall a few elementary facts about Artin-Schreier extensions. Let $\mathcal{K}$ be a field of characteristic p, not necessarily finite, and $\mathcal{L} = \mathcal{K}[X]/(X^p - X - \alpha)$ an Artin-Schreier extension. Set $x = X \bmod X^p - X - \alpha$. Its conjugates are the $x + c$ with $c \in \mathbb{F}_p$. The trace is given by

$$\mathrm{Tr}_{\mathcal{L}/\mathcal{K}}(\sum_{0 \le i \le p-1} u_i x^i) = -u_{p-1} \text{ when } u_i \in \mathcal{K}$$

and the dual basis of $(1, x, x^2, \ldots, x^{p-1})$ is $(-x^{p-1} + 1, -x^{p-2}, -x^{p-3}, \ldots, -x, -1)$.

In such an Artin-Schreier extension, p-powers are easy to compute. Indeed

$$x^{ip^h} = (x + T_h(\alpha))^i. \tag{4}$$

In particular if $\mathcal{K}$ is the field $\mathbb{F}_q$ with $q = p^d$ elements then

$$x^{iq} = (x + \mathrm{Tr}_{\mathbb{F}_q/\mathbb{F}_p}(\alpha))^i,$$

and $\mathrm{Tr}_{\mathbb{F}_q/\mathbb{F}_p}(\alpha)$ is in $\mathbb{F}_p$. Thus the $p \times p$ matrix of the Frobenius automorphism $x \mapsto x^q$ has coefficients in $\mathbb{F}_p$.

We shall first prove a few complexity estimates concerning basic computations with isomorphisms bewteen Artin-Schreier towers over finite fields.

We consider an isomorphism ι between two towers L_n and M_n:

$$\iota : M_n \to L_n.$$

The computer representation of ι will consist of the images of the y_k^i by ι for $0 \leq i \leq p-1$ and $1 \leq k \leq n$.

We shall see that this representation is very efficient. For $0 \leq k \leq n$, we denote by $\mathcal{C}_\times^L(k)$ the complexity of multiplication in L_k. This complexity is given as a number of multiplications in the base field $\mathbb{F}_q$, disregarding additions. We denote by $\mathcal{C}_\times^M(k)$ the complexity of multiplication in M_k. Let $\mathcal{C}_\iota(n)$ be the cost of evaluating ι at some μ in M_n. Let $\mathcal{C}_\iota^\bullet(n)$ be the complexity of computing $\iota^{-1}(\nu)$ for ν in L_n.

We shall first prove the following

Lemma 1. *Given an isomorphism $\iota : M_n \to L_n$ between two Artin-Schreier towers, we have, with the notation given above*

$$\mathcal{C}_\iota(n) \leq pn\,\mathcal{C}_\times^L(n), \tag{5}$$

$$\mathcal{C}_\iota^\bullet(n) \leq 2np^3\,\mathcal{C}_\times^L(n), \tag{6}$$

$$\mathcal{C}_\times^M(n) \leq 4np^3\,\mathcal{C}_\times^L(n). \tag{7}$$

We first prove inequality (5). For $\mu \in M_n$, let us write $\mu = \sum_{0\leq i\leq p-1} \mu_i y_n^i$ with $\mu_i \in M_{n-1}$. Then $\iota(\mu) = \sum_i \iota(\mu_i)\iota(y_n^i)$ and since we have stored the $\iota(y_n^i)$, we reduce to computing p multiplications in L_n and the images $\iota(\mu_i)$. Therefore

$$\mathcal{C}_\iota(n) \leq p(\mathcal{C}_\iota(n-1) + \mathcal{C}_\times^L(n))$$

and the result follows iterating the above inequality and using the easy inequality

$$\mathcal{C}_\times^L(n) \geq p\,\mathcal{C}_\times^L(n-1).$$

In order to compute the inverse image of $\nu \in L_n$, we first express ν as a linear combination

$$\nu = \sum_{0\leq i\leq p-1} \nu_i \iota(y_n^i) \tag{8}$$

with $\nu_i \in L_{n-1}$ for all i. This is achieved at the expense of $2p^3$ multiplications in L_n using Gauss's algorithm. From equation (8) we deduce

$$\iota^{-1}(\nu) = \sum_{0\leq i\leq p-1} \iota^{-1}(\nu_i) y_n^i.$$

We thus reduce to computing the p preimages of the $\nu_i \in L_{n-1}$. Therefore

$$\mathcal{C}_\iota^\bullet(n) \leq 2p^3\,\mathcal{C}_\times^L(n) + p\,\mathcal{C}_\iota^\bullet(n-1)$$

and inequality (6) follows.

Inequality (7) follows easily from inequalities (5) and (6). This shows that if we can multiply efficiently in L_n, the knowledge of ι allows fast multiplication in M_n as well.

The crucial step in our isomorphism computations will be the evaluation of polynomials $T_{i,j}$ at numbers μ that are not necessarily in $\mathbb{F}_{p^{ij}}$. Lemma 2 states how efficiently one can compute $\Phi_{dp^l}(\mu) = \mu^{p^{dp^l}}$ and $T_{dp^l}(\mu)$ for $\mu \in L_k$ and $0 \leq l \leq k$.

We denote by $\mathcal{C}_\Phi^L(l,k)$ the complexity of computing $\Phi_{dp^l}(\mu)$ for $\mu \in L_k$. We denote by $\mathcal{C}_T^L(l,k)$ the complexity of computing $T_{dp^l}(\mu)$ for $\mu \in L_k$. In order to compute $T_{dp^l}(\mu)$ we notice that

$$T_{dp^l} = T_d \circ T_{p,d} \circ \cdots \circ T_{p,dp^{l-2}} \circ T_{p,dp^{l-1}}. \tag{9}$$

Using this formula we obtain

$$\mathcal{C}_T^L(l,k) \le p(\mathcal{C}_\Phi^L(l-1,k) + \mathcal{C}_\Phi^L(l-2,k) + \cdots + \mathcal{C}_\Phi^L(1,k) + \mathcal{C}_\Phi^L(0,k)) + pd\,\mathcal{C}_\times^L(k). \tag{10}$$

If we now want to compute $\Phi_{dp^l}(\mu)$ we use formula (4). Writing $\mu = \sum_{0\le i\le p-1} \mu_i x_k^i$ we have

$$\Phi_{dp^l}(\mu) = \sum_{0\le i\le p-1} \Phi_{dp^l}(\mu_i)\Phi_{dp^l}(x_k^i) = \sum_{0\le i\le p-1} \Phi_{dp^l}(\mu_i)(x_k + T_{dp^l}(a_{k-1}))^i \tag{11}$$

since $x_k^p - x_k = a_{k-1}$.

We first assume that we already computed and stored the $T_{dp^l}(a_\kappa)$ and their first p powers for all l and κ such that $0 \le l \le \kappa < k$, which is the same as computing the expansions of polynomials $(x + T_{dp^l}(a_\kappa))^i$ for $0 \le i \le p-1$.

We call $\tilde{\mathcal{C}}_\Phi^L(l,k)$ the complexity of computing $\Phi_{dp^l}(\mu)$ for $\mu \in L_k$ under this assumption. We define $\tilde{\mathcal{C}}_T^L(l,k)$ to be the complexity of computing $T_{dp^l}(\mu)$ for $\mu \in L_k$ in the same situation.

From equation (11) we deduce

$$\tilde{\mathcal{C}}_\Phi^L(l,k) \le p\,\tilde{\mathcal{C}}_\Phi^L(l,k-1) + p^2\,\mathcal{C}_\times^L(k-1).$$

Since $\mathcal{C}_\Phi^L(l,k) = 0$ as soon as $l \ge k$, we obtain

$$\tilde{\mathcal{C}}_\Phi^L(l,k) \le p(k-l)\,\mathcal{C}_\times^L(k),$$

and from equation (10) and the definition of T_{dp^l}

$$\tilde{\mathcal{C}}_T^L(l,k) \le (p^2kl + pd)\,\mathcal{C}_\times^L(k) \le 2p^2kld\,\mathcal{C}_\times^L(k). \tag{12}$$

We now bound the cost $\mathcal{C}_{\text{init}}^L(k)$ of precomputing all the $T_{dp^l}(a_\kappa)$ and their first p powers for all l and κ such that $0 \le l \le \kappa < k$.

We first bound $\mathcal{C}_{\text{init}}^L(k+1) - \mathcal{C}_{\text{init}}^L(k)$. Indeed if we already know the $T_{dp^l}(a_\kappa)$ and their first p powers for all $0 \le l \le \kappa < k$, then computing the $T_{dp^l}(a_k)$ for all $0 \le l \le k$ will require less than $2(k+1)p^2k^2d\,\mathcal{C}_\times^L(k)$ multiplications (using formula (12)) and computing the powers will take time $p(k+1)\,\mathcal{C}_\times^L(k)$. Therefore

$$\mathcal{C}_{\text{init}}^L(k+1) \le \mathcal{C}_{\text{init}}^L(k) + (k+1)(p + 2p^2k^2d)\,\mathcal{C}_\times^L(k).$$

We obtain

$$\mathcal{C}_{\text{init}}^L(k) \le 6p^2k^3d\,\mathcal{C}_\times^L(k).$$

Lemma 2. *For $0 \le l \le k$ and for any μ in L_k, one can compute $\Phi_{dp^l}(\mu)$ (resp. $T_{dp^l}(\mu)$) in time $\tilde{\mathcal{C}}_\Phi^L(l,k)$ (resp. $\tilde{\mathcal{C}}_T^L(l,k)$) with*

$$\tilde{\mathcal{C}}_\Phi^L(l,k) \le p(k-l)\,\mathcal{C}_\times^L(k), \tag{13}$$

$$\tilde{\mathcal{C}}_T^L(l,k) \le 2p^2kld\,\mathcal{C}_\times^L(k), \tag{14}$$

using data that only depend on L_k and can be computed once and for all in time $\mathcal{C}^L_{\text{init}}(k)$ with

$$\mathcal{C}^L_{\text{init}}(k) \leq 6p^2k^3d\,\mathcal{C}^L_\times(k). \tag{15}$$

We call $\mathcal{C}^L_{AS}(n)$ the complexity of solving equation (2) in L_n for $\beta \in L_n$ and $\mathrm{Tr}_{L_n/\mathbb{F}_p}(\beta) = T_{dp^n}(\beta) = 0$. We shall adopt the three steps strategy described in the introduction.

We first compute and store the $T_{dp^l}(a_\kappa)$ for all $0 \leq l \leq \kappa < n$. This takes time $\mathcal{C}^L_{\text{init}}(n)$. We call $\tilde{\mathcal{C}}^L_{AS}(n)$ the complexity of solving equation (2) once all this precomputation has been done.

In these conditions, step 1 (the computation of $B = T_{dp^{n-1}}(\beta)$) will take time $\tilde{\mathcal{C}}^L_T(n-1,n)$.

The second step reduces to computing the $p \times p$ matrix representing the L_{n-1}-linear map $\wp_{dp^{n-1}} : L_n \to L_n$ in the basis $(1, x_n, x_n^2, \ldots, x_n^{p-1})$. Using Gauss's algorithm, we then find a solution γ to the equation $\wp_{dp^{n-1}}(\gamma) = B$.

All this is achieved at the expense of $p\,\tilde{\mathcal{C}}^L_\Phi(n-1,n) + 2p^3\,\mathcal{C}^L_\times(n-1)$ multiplications.

The third step is done in time $p\,\mathcal{C}^L_\times(n) + \tilde{\mathcal{C}}^L_{AS}(n-1)$. We thus have

$$\tilde{\mathcal{C}}^L_{AS}(n) \leq \tilde{\mathcal{C}}^L_{AS}(n-1) + \tilde{\mathcal{C}}^L_T(n-1,n) + p\,\tilde{\mathcal{C}}^L_\Phi(n-1,n) + 2p^3\,\mathcal{C}^L_\times(n-1) + p\,\mathcal{C}^L_\times(n),$$

and using Lemma 2,

$$\tilde{\mathcal{C}}^L_{AS}(n) \leq \tilde{\mathcal{C}}^L_{AS}(n-1) + 6p^2n^2d\,\mathcal{C}^L_\times(n).$$

Thus

$$\tilde{\mathcal{C}}^L_{AS}(n) \leq 12n^2p^2d\,\mathcal{C}^L_\times(n) + \mathcal{C}_{AS}\,. \tag{16}$$

where $\mathcal{C}_{AS} = \mathcal{C}^L_{AS}(0)$ is the complexity of solving an Artin-Schreier equation in the base field $\mathbb{F}_q$.

We now want to compute an isomorphism between two Artin-Schreier towers of length n over $\mathbb{F}_q$:

$$L_n \supset L_{n-1} \supset \cdots \supset L_1 \supset L_0 = \mathbb{F}_q$$

and

$$M_n \supset M_{n-1} \supset \cdots \supset M_1 \supset M_0 = \mathbb{F}_q.$$

We look for an isomorphism $\iota : M_n \to L_n$ given by $\iota(y_k^i)$ for $0 \leq i < p$ and $0 \leq k \leq n$.

We let the length k increase from 0 to n. We call $\mathcal{C}^L_M(k)$ the complexity of computing an isomorphism from M_k to L_k. We call $\tilde{\mathcal{C}}^L_M(k)$ the complexity of computing an isomorphism from M_k to L_k assuming the $T_{dp^l}(a_\kappa)$ have been computed for all $0 \leq l \leq \kappa < k$. We want to bound $\tilde{\mathcal{C}}^L_M(n) - \tilde{\mathcal{C}}^L_M(n-1)$. Thus assume we have computed the isomorphism up to length $n-1$. In order to go further we have to solve the Artin-Schreier extension

$$Y^p - Y = \iota(b_{n-1}) \tag{17}$$

over L_n. We first apply ι to b_{n-1} in time $\mathcal{C}_\iota(n-1)$. Solving equation (17) takes time $\tilde{\mathcal{C}}^L_{AS}(n)$. We take $\iota(y_n)$ to be one of the solutions we found. We then compute the powers $\iota(y_n)^i$ for $0 \leq i \leq p-1$, which takes time $p\,\mathcal{C}^L_\times(n)$. We thus have

$$\tilde{\mathcal{C}}^L_M(n) \leq \tilde{\mathcal{C}}^L_M(n-1) + \mathcal{C}_\iota(n-1) + \tilde{\mathcal{C}}^L_{AS}(n) + p\,\mathcal{C}^L_\times(n),$$

and using Lemma 1 and inequality (16),

$$\tilde{\mathcal{C}}_M^L(n) \leq \tilde{\mathcal{C}}_M^L(n-1) + 14n^2p^2d\,\mathcal{C}_\times^L(n) + \mathcal{C}_{AS}\,.$$

Summing up we have

$$\tilde{\mathcal{C}}_M^L(n) \leq 28n^2p^2d\,\mathcal{C}_\times^L(n) + n\,\mathcal{C}_{AS},$$

and using (15),

$$\mathcal{C}_M^L(n) \leq 34n^3p^2d\,\mathcal{C}_\times^L(n) + n\,\mathcal{C}_{AS}\,. \tag{18}$$

Assume now we have a third Artin-Schreier tower N_n over $\mathbb{F}_q$. We shall relate the complexity $\mathcal{C}_\times^L(n)$ of multiplication in L_n and the complexity $\mathcal{C}_N^M(n)$ of computing an isomorphism from N_n to M_n. This makes sense in case L_n has been designed to allow fast multiplication (e.g., L_n is a Cantor tower).

We first compute an isomorphism ι_1 from M_n to L_n at the expense of $\mathcal{C}_M^L(n)$ multiplications in $\mathbb{F}_q$. We then compute an isomorphism ι_2 from N_n to M_n at the expense of

$$\mathcal{C}_N^M(n) \leq 34n^3p^2d\,\mathcal{C}_\times^M(n) + n\,\mathcal{C}_{AS}$$

multiplications in $\mathbb{F}_q$. Using inequality (18) and inequality (7) we find

Lemma 3. *Let L_n, M_n, N_n be three Artin-Schreier towers of length n over $\mathbb{F}_q$ the field with $q = p^d$ elements and let $\mathcal{C}_\times^L(n)$ be the complexity of multiplication in L_n. Let $\mathcal{C}_{AS}$ be the complexity of solving an Artin-Schreier equation in $\mathbb{F}_q$. An isomorphism between M_n and N_n can be found at the expense of $\mathcal{C}_N^M(n)$ multiplications in $\mathbb{F}_q$ with*

$$\mathcal{C}_N^M(n) \leq 170p^5n^4d\,\mathcal{C}_\times^L(n) + 2n\,\mathcal{C}_{AS}\,.$$

If we take L_n to be a Cantor tower we have $\mathcal{C}_\times^L(n) \leq K_q n^2 p^n$, where K_q only depends on q. Using the Berlekamp factorization algorithm we have $\mathcal{C}_{AS} = O(p^3d)$, and Theorem 1 follows.

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