



ALGORITHMIC ASPECTS OF MESTRE'S
p-ADIC POINT COUNTING IDEAS

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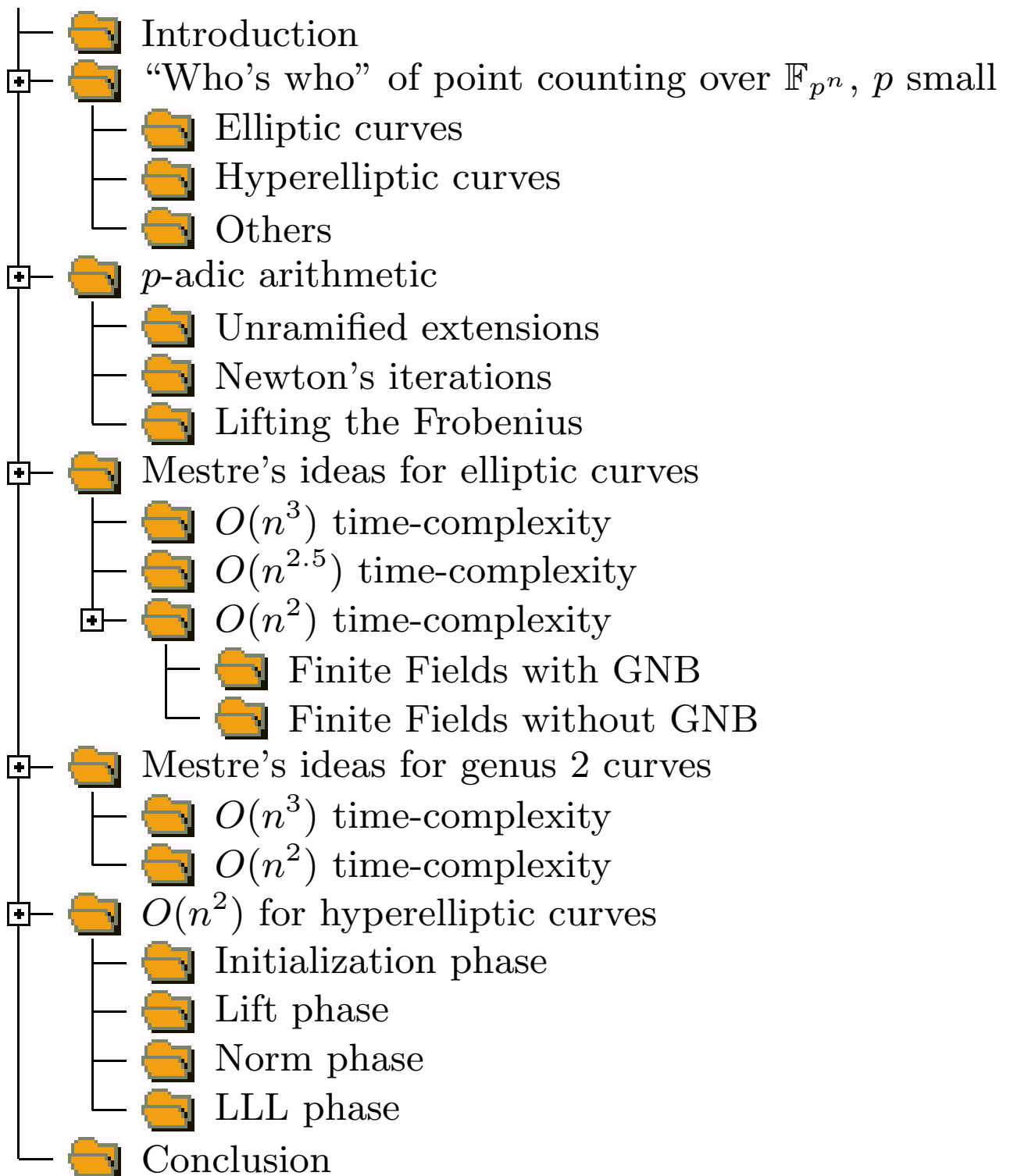
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Overview



Introduction
“Who’s who” of point counting over \mathbb{F}_{p^n} , p small
p -adic arithmetic
Mestre’s ideas for elliptic curves
Mestre’s ideas for genus 2 curves
$O(n^2)$ for hyperelliptic curves
Conclusion

Algebraic curves and cryptography

Algebraic curves are an alternative to the use of finite fields in cryptographic schemes (Miller 1986, Koblitz 1987, ...).

For non supersingular curves of small genus, the discrete logarithm problem is hard. The only known attack is a variant of Pollard’s algorithm with exponential running time.

A prerequisite is to count efficiently points on curves. It used to be a difficult task.

It is no more the case for curves defined over \mathbb{F}_{p^n} , p small, especially thanks to a **Sato**’s breakthrough for elliptic curves and clever simplifications and extensions due to **Mestre** for the “small” genus hyperelliptic case.

Goal of this talk : give a complete overview of the algorithmic tools needed to efficiently implement these ideas.

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Elliptic curves

$O(np^{n/4})$ in time:

- **D. Shanks**. *Class number, a theory of factorization, and genera*. In Proc. Symp. Pure Math., 20, 1971.
- **J.M. Pollard**. *Monte Carlo methods for index computation (mod p)*. Math. Comp., 32, 1978.

$O(n^{5+\varepsilon})$ in time, $O(n^2)$ in space:

- **R. Schoof**. *Elliptic curves over finite fields and the computation of square roots mod p* . Math. Comp., 44, 1985.
- **A. O. L. Atkin**. *The number of points on an elliptic curve modulo a prime*, 1988. Number Theory Mailing List.
- **A.J. Menezes, S.A. Vanstone, R. J. Zuccherato**. *Counting points on elliptic curves over \mathbb{F}_{2^m}* . Math. Comp., 60, 1993.

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Elliptic curves

$O(n^{4+\varepsilon})$ in time, $O(n^2)$ in space:

- **N. D. Elkies.** *Explicit isogenies*. Draft, 1991.
- **A. O. L. Atkin.** *The number of points on an elliptic curve modulo a prime*, 1991. Number Theory Mailing List.
- **R. Schoof.** *Counting points on elliptic curves over finite fields*. J. Théor. Nombres Bordeaux, 1995.
- **J. M. Couveignes.** *Quelques calculs en théorie des nombres*. thèse, Université de Bordeaux I, 1994.
- **R. Lercier.** *Computing isogenies in \mathbb{F}_{2^n}* . ANTS-II, LNCS, 1996.
- **J. M. Couveignes.** *Computing l -isogenies with the p -torsion*. ANTS-II, LNCS, 1996.

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Elliptic curves

$O(n^{3+\epsilon})$ in time, $O(n^3)$ in space:

- **T. Satoh**. *The canonical lift of an ordinary elliptic curve over a finite field and its point counting*. J. Ramanujan Math. Soc., 15, 2000.
- **M. Fouquet, P. Gaudry R.J. Harley**. *An extension of Satoh’s algorithm and its implementation*. J. Ramanujan Math. Soc., 2000.
- **B. Skjernaa**, *Satoh’s algorithm in characteristic 2*. To appear in Math. Comp., preprint, 2000.

$O(n^{3+\epsilon})$ in time, $O(n^2)$ in space:

- **F. Vercauteren, B. Preneel, J. Vandewalle**. *A Memory Efficient Version of Satoh’s Algorithm*. EUROCRYPT 2001, LNCS.
- **J.F. Mestre**. *AGM pour le genre 1 et 2*. Lettre à Gaudry et Harley, december 2000.



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Elliptic curves

$O(n^{2.5+\varepsilon})$ time, $O(n^2)$ in space:

- T. Satoh, B. Skjernaa, Y. Taguchi. *Fast computation of canonical lifts of elliptic curves and its application to point counting*, August 2001.
- T. Satoh. *On p -adic point counting algorithms for elliptic curves over finite fields*. ANTS-V, July 2002.
- H.Y. Kim, J.Y. Park, J.H. Cheon, J.H. Park, J.H. Kim, S.G. Hahn. *Fast elliptic curve point counting using gaussian normal basis*. ANTS-V, July 2002.
- P. Gaudry. *A comparison and a combination of SST and AGM algorithms for counting points of elliptic curves in characteristic 2*. ASIACRYPT 2002, December 2002.

$O(n^{2+\varepsilon})$ in time, $O(n^2)$ in space:

- R. Lercier, D. Lubicz. *Counting points on elliptic curves over finite fields in quadratic time*, submitted for publication, September 2002.
- R.J. Harley, *Algorithmes avancés pour l’arithmétique des courbes*, Thesis, draft, 2003.

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Hyperelliptic curves of any genus

Polynomial in time:

- **J. Pila.** *Frobenius maps of abelian varieties and finding roots of unity in finite fields.* Math. Comp., 1990.

$O(g^{6+\varepsilon}n^{3+\varepsilon})$ in time, $O(g^3n^3)$ in space:

- **A.G.B Lauder, D. Wan.** *Computing zeta functions of Artin-Schreier curves over finite fields.* London Mathematical Society JCM 5, 2002.

$O(g^{5+\varepsilon}n^{3+\varepsilon})$ in time, $O(g^3n^3)$ in space:

- **K. Kedlaya.** *Counting points on hyperelliptic curves using Monsky-Washnitzer cohomology,* J. Ramanujan Mathematical Society 16 (2001).
- **A.G.B Lauder, D. Wan.** *Computing zeta functions of Artin-Schreier curves over finite fields II.* Preprint, 2002.
- **J. Denef, F. Vercauteren.** *An Extension of Kedlaya’s Algorithm to Artin-Schreier Curves in Characteristic 2.* ANTS-V, 2002.
- **F. Vercauteren,** *Computing Zeta Functions of Hyperelliptic Curves over Finite Fields of Characteristic 2.* CRYPTO 2002.

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Hyperelliptic curves of small genus

Genus 2, $O(n^{3+\varepsilon})$ in time, $O(n^2)$ in space:

- **J.F. Mestre.** *AGM pour le genre 1 et 2.* Lettre à Gaudry et Harley, 2000.
- **P. Gaudry.** *Algorithms for counting points on curves.* ECC, Waterloo, 2001.

$O(p^g n^{3+\varepsilon})$ in time, $O(p^g n^2)$ in space:

- **J.F. Mestre.** *Algorithmes pour compter des points en petite caractéristique en genre 1 et 2.* Talk at the cryptographic seminar of Rennes, 2002.

$O(p^g n^{2+\varepsilon})$ in time, $O(p^g n^2)$ in space:

- **R. Lercier, D. Lubicz.** *A quasi-quadratic time algorithm for hyperelliptic curve point counting* preprint, 2003.

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Others

Superelliptic curves, $O(g^{4+\varepsilon}n^{3+\varepsilon})$ in time, $O(g^3n^3)$ in space:

- **P. Gaudry, N. Gurel.** *An extension of Kedlaya’s point-counting algorithm to superelliptic curves.* ASIACRYPT 2001, LNCS.

Genus 3, $O(n^{3+\varepsilon})$ in time, $O(n^2)$ in space:

- **C. Ritzenhaller.** *Problèmes arithmétiques relatifs à certaines familles de courbes sur les corps finis.* Thesis, Université Paris 7, 2003.

⇒ yields a $O(n^{2+\varepsilon})$ algorithm with these ideas.

Algebraic varieties, polynomial in time:

- **A.G.B Lauder, D. Wan.** *Counting rational points on varieties over finite fields of small characteristic.* MSRI, Algorithmic Number Theory, 2002.
- **A.G.B Lauder.** *Counting solutions to equations in many variables over finite fields.* Preprint, 2003.

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p-adic numbers

p-adic norm $|\cdot|_p$ of $r \in \mathbb{Q}^*$ is $|r|_p = p^{-\rho}$, $r = p^\rho u/v$,
 $\rho, u, v \in \mathbb{Z}$, $p \nmid u$, $p \nmid v$.

Field of **p-adic numbers** \mathbb{Q}_p is the completion of \mathbb{Q}
w.r.t. $|\cdot|_p$,

$$\sum_{i=\rho}^{\infty} a_i p^i, \quad a_i \in \{0, 1, \dots, p-1\}, \quad \rho \in \mathbb{Z}.$$

p-adic integers \mathbb{Z}_p is the ring with $|\cdot|_p \leq 1$ or
 $\rho \geq 0$.

Unique maximal ideal

$$M = \{x \in \mathbb{Q}_p \mid |x|_p < 1\} = p\mathbb{Z}_p$$

and $\mathbb{Z}_p/M \cong \mathbb{F}_p$.

Alternative construction.

Def. Let π_m be the projection from $\mathbb{Z}/p^{m+1}\mathbb{Z}$ onto
 $\mathbb{Z}/p^m\mathbb{Z}$, then a **p-adic integer** is a sequence
 $x = (x_1, x_2, \dots, x_m, \dots)$ with $x_m \in \mathbb{Z}/p^m\mathbb{Z}$ and
such that $\pi_m(x_{m+1}) = x_m$.

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Unramified extensions of p -adics

K extension of \mathbb{Q}_p of degree n with **valuation ring** \mathbb{Z}_q and **maximal ideal** $M_{\mathbb{Z}_q} = \{x \in K \mid |x|_K < 1\}$ where $|\cdot|_K$ is the unique extension of $|\cdot|_p$ to K .

K is said **unramified** iff $\mathbb{Z}_q/M_{\mathbb{Z}_q} \cong \mathbb{F}_q$ (**residue field**).

Def. The **Teichmuller Lift** is the map

$\omega : \mathbb{F}_q \rightarrow \mathbb{Z}_q$ defined by $\omega(0) = 0$ and for $x \neq 0$, $\omega(x)$ is the unique $q - 1$ -th root of unity in \mathbb{Z}_q such that $\pi(\omega(x)) = x$ with π the canonical projection of \mathbb{Z}_q to \mathbb{F}_q .

Def. The **semi-Witt** decomposition of $x \in \mathbb{Z}_q$ is the unique sequence $(x_i)_{i \geq 0}$ of \mathbb{F}_q such that

$$x = \sum_{i \geq 0} \omega(x_i) p^i.$$

Galois group of K over \mathbb{Q}_p is cyclic with generator **Frobenius substitution** σ and σ modulo $M_{\mathbb{Z}_q}$ equals to the small Frobenius on \mathbb{F}_q .

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Unramified extensions of p -adics

Polynomial Basis: Let $\mathbb{F}_q \cong \mathbb{F}_p[t]/(\overline{F}(t))$ then, K can be constructed as

$$K \cong \mathbb{Q}_p[t]/(F(t)),$$

with $F(t)$ any lift of $\overline{F}(t)$ to $\mathbb{Z}_p[t]$. Such a choice yields a basis $\{1, t, \dots, t^{n-1}\}$.

Multiplication at precision m of two p -adics costs

$$T_{m,n} = O((nm)^\mu).$$

Gaussian Normal Basis: For Galois extension K/\mathbb{Q}_p , there exists elements α which yields basis of the form $\{\alpha, \alpha^\sigma, \dots, \alpha^{\sigma^{n-1}}\}$.

Def. For some T such that \exists a primitive T -th root of unity τ in $\mathbb{Z}/(nT + 1)\mathbb{Z}$ and such that $\alpha = \sum_{i=0}^{T-1} \gamma^{\tau^i}$ (where γ is a primitive $(nT + 1)$ -th root of unity) generates a normal basis over \mathbb{Q}_p called a **Gaussian Normal Basis** (GNB) of type T .

In this case, $T_{m,n} = O((Tnm)^\mu)$.

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Newton iteration

To compute the root of a polynomial $f(x)$ from

$$f(x + p^w \delta) = f(x) + p^w \delta \frac{\partial f}{\partial x}(x) + O(p^{2w}).$$

Algorithm Newton

Algorithm to compute a root of $f(x) \bmod p^m$, knowing a solution x_0 modulo p^{2k+1} where $k = v(\partial f / \partial x(x_0))$.

INPUT: $x_0 \in \mathbb{Z}_q / p^{2k+1} \mathbb{Z}_q$, $m \in \mathbb{N}$.

OUTPUT: x a solution of $f(x) \bmod p^m$.

1. **if** $m \leq 2k + 1$ **then return** x_0 ;
2. $w := \lceil \frac{m}{2} \rceil + k$;
3. $x := \text{Newton}(x_0, w)$;
4. Lift x to precision m ;
5. $V := f(x) \bmod p^m$; $\Delta_x := \partial f / \partial x(x) \bmod p^{w-k}$;
6. **return** $x - V / \Delta_x$;

Remark. Very fast in practice (precision is nearly doubled at each step). For polynomials with $O(1)$ terms of degree $O(1)$, time complexity is $O(T_{m,n})$.

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Lifting the Frobenius at precision m

Prop. Let $(x_i)_{i \geq 0}$ be the semi-Witt decomposition of a p -adic x , then

$$x^\sigma = \sum_{i \geq 0} \omega(x_i)^p p^i.$$

Polynomial Basis by [Sato-Harley]:

At first, one lifts $\overline{F}(t)$ at precision m to the minimal polynomial $F(t)$ of $\omega(t)$ using the fact that

$$F(t^p) = \prod_{i=0}^{p-1} F(t\zeta^i) \text{ with } \zeta^p = 1.$$

This can be done by a newton iteration in $O(T_{m,n} \log n)$?

It follows that $t^\sigma = t^2$ and $x^\sigma = \sum_{i=0}^{n-1} x_i t^{2i}$ can be easily computed in $O(T_{m,n})$.

GNB by [Kim et al.]:

Computing σ^k can be done by a permutation of the nT components of x . This can be easily done in $S_{m,n} = O(nmT)$.

A more elaborated implementation strategy (with indexes) yields a $O(n)$ time complexity.

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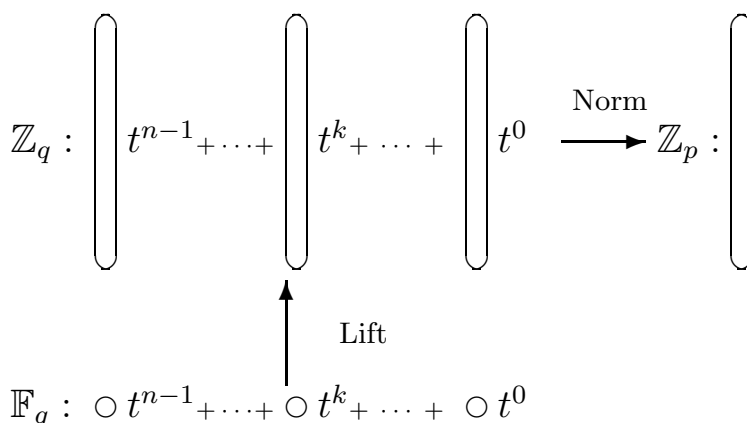
The “lift” and “norm” paradigm

Let E be an elliptic curve defined over the field \mathbb{F}_{2^n} by an equation $y^2 + xy = x^3 + \alpha$.

$$\#E(\mathbb{F}_{2^n}) = 2^n + 1 - c \text{ with } |c| \leq 2\sqrt{2^n}.$$

A first $O(n^3)$ algorithm given by **Satoh** to compute c , improved by Vercauteren et al. to get a $O(n^2)$ in space.

At the same time, a completely different method given by **Mestre** for the characteristic 2 case, same complexity, based on AGM.



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$O(n^3)$ time complexity

Given an explanation of the mathematics which are “behind” the scene is out of the scope of this talk.

A first explanation by Mestre based on isogenies of degree 2 between elliptic curves, more recently an explanation based on the Riemann θ functions (cf. [Carls2003], [Ritzenthaler2003]).

Algorithm AGM

Algorithm to compute the trace of an ordinary elliptic curve $E/\mathbb{F}_{2^n} : y^2 + xy = x^3 + \alpha$.

INPUT: $\alpha \in \mathbb{F}_{2^n}$.

OUTPUT: The trace c of E .

\\Lift phase

1. $a := 1 + 8\alpha \in \mathbb{Z}_q; b := 1 \in \mathbb{Z}_q;$
2. **for** ($i := 1; i < n/2 + O(1); i := i + 1$) {
3. $a, b := \frac{a+b}{2}, \sqrt{ab};$
4. }

\\Norm phase

5. $A := a; B := b;$
6. **for** ($i := 1; i < n; i := i + 1$) {
7. $a, b := \frac{a+b}{2}, \sqrt{ab};$
8. }
9. **return** $\frac{A}{a} \bmod 2^n$ as a signed integer in $[-2\sqrt{2^n}, 2\sqrt{2^n}]$.

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$O(n^{2.5})$ time complexity

First, the AGM iterations

$$\begin{cases} a_{i+1} &= \frac{a_i + b_i}{2}, \\ b_{i+1} &= \sqrt{a_i b_i}, \end{cases}$$

can be replaced via $c_i = a_i/b_i$ by

$$c_{i+1} = \frac{2 + c_i}{2\sqrt{c_i}}.$$

Second,

$$c_{i+1} = c_i^\sigma.$$

Consequently, one must solve at precision $n/2 + O(1)$,

$$4x(x^\sigma)^2 = (1+x)^2$$

This equation is an equation of the form $\phi(x, x^\sigma)$ where $\phi(x, y)$ is a bivariate polynomial.

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SST

Algorithm SSTLift

Algorithm to compute a root of $\phi(x, x^\sigma) \bmod p^m$, knowing a solution x_0 modulo p^{k+1} where $k = v(\partial\phi/\partial x(x_0, x_0^\sigma))$.

INPUT: $x_0 \in \mathbb{Z}_q/p^{k+1}\mathbb{Z}_q$, $m \in \mathbb{N}$.

OUTPUT: x a solution of $\phi(x, x^\sigma) \bmod p^m$.

1. $w := \lceil m^{\mu/(\mu+1)} \rceil$; d any lift of $(\partial_x \phi(x_0, x_0^\sigma))$ to $\mathbb{Z}_q/p^{w+k}\mathbb{Z}_q$;
2. x any lift of x_0 to $\mathbb{Z}_q/p^{w+k}\mathbb{Z}_q$
3. **for** ($i := k + 1$; $i < w + k$; $i := i + 1$) {
4. $y := x^\sigma$;
5. $x := x - \phi(x, y)/d$;
6. }
7. $y := x^\sigma \bmod p^{w+k}$;
8. $D_x := \partial_x \phi(x, y) \bmod p^{w+k}$; $D_y := \partial_y \phi(x, y) \bmod p^{w+k}$;
9. **for** ($j := 1$; $jw + k < m$; $j := j + 1$) {
10. Lift x to $\mathbb{Z}_q/p^{(j+1)w+k}\mathbb{Z}_q$;
11. $y := x^\sigma \bmod p^{(j+1)w+k}$;
12. $V := \phi(x, y) \bmod p^{(j+1)w+k}$;
13. **for** ($i := 0$; $i < w$; $i := i + 1$) {
14. $\Delta_x = -p^{-(jw+i)}V/d$;
15. $\Delta_y = \Delta_x^\sigma \bmod p^{w-i+k}$;
16. $x := x + p^{jw+i}\Delta_x \bmod p^{(j+1)w+k}$;
17. $V+ := p^{jw+i}(D_x\Delta_x + D_y\Delta_y) \bmod p^{(j+1)w+k}$;
18. }
19. }
20. **return** x ;

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The Norm phase

Once a root $c_{\lceil n/2 \rceil + 3}$ of

$$4x(x^\sigma)^2 = (1+x)^2$$

is computed, it remains to get c .

In fact, it turns out that

$$c = N_{\mathbb{Z}_{2^n}/\mathbb{Z}_2} \left(\frac{2c_{\lceil n/2 \rceil + 3}}{1 + c_{\lceil n/2 \rceil + 3}} \right).$$

Satoh outlines that when $\text{ord}_p(a-1) > \frac{1}{p-1}$, the following formula can be used

$$N_{\mathbb{Z}_q/\mathbb{Z}_p}(a) = \exp(\text{Tr}_{\mathbb{Z}_q/\mathbb{Z}_p}(\log a)).$$

This yields a $O(n^\mu m^{\mu + \frac{1}{2}})$ time complexity with space equal to $O(nm)$.

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Generalized Newton iterations

Recent results enable to generalize Newton iterations to equations of the form $\phi(x, x^\sigma) = 0$. Based on

$$\phi(x + p^w \delta, (x + p^w \delta)^\sigma) = \phi(x, x^\sigma) + p^w \delta \frac{\partial \phi}{\partial x}(x, x^\sigma) + p^w \delta^\sigma \frac{\partial \phi}{\partial y}(x, x^\sigma) + O(p^{2w}).$$

Algorithm NewtonLift

Algorithm to compute a root of $\phi(x, x^\sigma) \bmod p^m$, knowing a solution x_0 modulo p^{2k+1} where $k = v(\partial \phi / \partial y(x_0, x_0^\sigma))$.

INPUT: $x_0 \in \mathbb{Z}_q / p^{2k+1} \mathbb{Z}_q$, $m \in \mathbb{N}$.

OUTPUT: x a solution of $\phi(x, x^\sigma) \bmod p^m$.

1. **if** $m \leq 2k + 1$ **then return** x_0 ;
2. $w := \lceil \frac{m}{2} \rceil + k$;
3. $x := \text{NewtonLift}(x_0, w)$;
4. Lift x to $\mathbb{Z}_q / p^m \mathbb{Z}_q$; $y := x^\sigma \bmod p^m$;
5. $\Delta_x := \partial_x \phi(x, y) \bmod p^{w-k}$; $\Delta_y := \partial_y \phi(x, y) \bmod p^{w-k}$;
6. $V := \phi(x, y) \bmod p^m$;
7. $a, b := \text{ArtinSchreierRoot}(-V / (p^{w-k} \Delta_y), -\Delta_x / \Delta_y, w-k, n)$;
8. **return** $x + p^{w-k} (1 - a)^{-1} b$;

Remark. ArtinSchreierRoot is a “black box” which solves equations of the form

$$x^\sigma = ax + b, \quad a \text{ and } b \text{ in } \mathbb{Z}_q.$$

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Artin-Schreier equations with GNB [Lercier-Lubicz]

- For all $k \in \mathbb{N}$, $x^{\sigma^k} \equiv a_k x + b_k \pmod{p^w}$.
- $x^{\sigma^n} = x$, which means that $(1 - a_n)x = b_n$.
- A classical “square and multiply” composition formula, $\forall k, k' \in \mathbb{Z}^2$,

$$x^{\sigma^{k+k'}} = a_k^{\sigma^{k'}} a_{k'} x + a_k^{\sigma^{k'}} b_{k'} + b_k^{\sigma^{k'}}.$$

Algorithm ArtinSchreierRoot

Algorithm to compute a root of $x^\sigma = ax + b$ (when called with $\nu = n$).

INPUT: a and b in $\mathbb{Z}_q/p^m\mathbb{Z}_q$, m and ν in \mathbb{N} .

OUTPUT: A and B s.t. $x = Ax^{\sigma^{n-\nu}} + B \pmod{p^m}$.

1. if $\nu = 1$ then return $a^{\sigma^{n-1}}, b^{\sigma^{n-1}} \pmod{p^m}$;
2. $A, B := \text{ArtinSchreierRoot}(a, b, m, \lfloor \frac{\nu}{2} \rfloor)$;
3. $A, B := AA^{\sigma^{n-\lfloor \frac{\nu}{2} \rfloor}}, AB^{\sigma^{n-\lfloor \frac{\nu}{2} \rfloor}} + B \pmod{p^m}$;
4. if $\nu \bmod 2$ then $A, B := Aa^{\sigma^{n-\nu}}, Ab^{\sigma^{n-\nu}} + B \pmod{p^m}$;
5. return A, B ;

Then, the classical “divide and conquer” algorithm to compute the norm works very well for GNB.

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Timings for counting points on elliptic curves defined over \mathbb{F}_{2^n} (GNB)

On a 731 MHz Alpha EV6 CPU.

n	GNB type 1		
	Lift	Norm	Total
1018	2.5s	1.5s	4s
2052	10s	7s	17s
4098	1mn	45s	1mn 45
8218	6mn 30	4mn 30	11mn
16420	34mn	23mn	57mn
32770	3h 17	2h 18	5h 35
65538	15h 45	13h 20	1d 5
100002	1d 18	1d 16	3d 10

Current record : 130020 bits by Harley.

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Artin-Schreier equations **without** GNB [Harley-Gaudry]

A cross between Newton iterations and the SST algorithm.

Algorithm ArtinSchreierRoot

Algorithm to compute a root of $x^\sigma = ax + b$.

INPUT: x, y, V, i, j, a, b such that a and b in $\mathbb{Z}_q/p^m\mathbb{Z}_q$, $v(a) = 1$, $v(b) = 0$, i is the current precision, $j > i$ is the wanted precision, x a root at precision i , $y = x^\sigma \pmod{2^j}$ and $V = y + ax + b$.

OUTPUT: A root x' at precision j and $x'^\sigma \pmod{2^j}$.

1. **if** $j = i + 1$ **then return** $x + 2^i \sqrt{V/2^i}, y + V$;
2. $k := \lfloor \frac{i+j}{2} \rfloor$;
3. $x', y' := \text{ArtinSchreierRoot}(x, y, V, i, k, a, b)$;
4. $y' := y + (x' - x)^\sigma$;
5. $V+ := (x' - x)a + (y' - y)$;
6. **return** $\text{ArtinSchreierRoot}(x', y', V, k, j, a, b)$;

Norm computation through the use of Collins’ sub-resultant algorithm ?

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$O(n^{3+\varepsilon})$ time complexity

It works for curves with ordinary jacobian i.e. which have maximal p -rank.

Riemann formulas become for the genus 2, $p = 2$:

$$\left\{ \begin{array}{l} a_{i+1} = \frac{a_i + b_i + c_i + d_i}{4}, \\ b_{i+1} = \frac{\sqrt{a_i b_i} + \sqrt{c_i d_i}}{2}, \\ c_{i+1} = \frac{\sqrt{a_i c_i} + \sqrt{b_i d_i}}{2}, \\ d_{i+1} = \frac{\sqrt{a_i d_i} + \sqrt{b_i c_i}}{2}, \end{array} \right.$$

(the so called “Borchardt” mean).

Using an algorithm very similar to AGM algorithm, we are able to get A, B, C, D at the needed precision ($O(3/2n)$).

After n supplementary iterations, one gets

$$\frac{A}{a} = \frac{B}{b} = \frac{C}{c} = \frac{D}{d}$$

which, thanks to the Thomae-Fay formulas, equals to the product of the eigenvalues of the Frobenius morphism which are invertible modulo 2.

$\Rightarrow O(n^{3+\varepsilon})$ time complexity

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$O(n^{2+\varepsilon})$ time complexity

Let

$$\Phi(b, c, d) = \frac{(\sqrt{b} + \sqrt{c}\sqrt{d})/2}{(1 + b + c + d)/4},$$

then Borchartd iterations can be replaced by

$$\begin{pmatrix} b_{i+1} \\ c_{i+1} \\ d_{i+1} \end{pmatrix} = \begin{pmatrix} \Phi(b_i, c_i, d_i) \\ \Phi(c_i, b_i, d_i) \\ \Phi(d_i, b_i, c_i) \end{pmatrix} \quad \& \quad \begin{pmatrix} b_{i+1} \\ c_{i+1} \\ d_{i+1} \end{pmatrix} = \begin{pmatrix} b_i^\sigma \\ c_i^\sigma \\ d_i^\sigma \end{pmatrix}$$

Lift phase. solved through a generalization of **NewtonLift**.

Norm phase. Similar to the elliptic curve case.

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Timings for counting points on genus 2 curves defined over \mathbb{F}_{2^n} (GNB)

On a 731 MHz Alpha EV6 CPU.

n	GNB type 1		
	Lift	Norm	Total
1018	2mn	5s	2mn 5
2052	8mn 30	25s	8mn 55
4098	50mn 5s	2mn 15	52mn 20
8218	4h 52mn	13mn	5h 5
16420	1d 5	1h	1d 6
32770	7d 22	6h	8d 4

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$O(n^{2+\epsilon})$ for ordinary hyperelliptic curves

Four main phases:

Initialization phase. Given an hyperelliptic curve H/\mathbb{F}_{p^n} one computes at small precision the values at $z = 0$ taken by p^g theta functions with p^g characteristics.

Lift phase. Using Riemann duplication formulas, one has to solve a multivariate system $F(X) = X^\sigma$ in \mathbb{Z}_q at a precision m large enough. Solution from the theta constants computed in the initialization phase thanks to a lifting algorithm

Norm phase. Computing the norm $N_{\mathbb{Z}_q/\mathbb{Z}_p}$ of an element of \mathbb{Z}_q derived from X yields at precision m the product $\pi_1 \cdots \pi_g$ of the g eigenvalues (invertible modulo p) of the Frobenius defined by H .

LLL phase. With LLL algorithm, one obtains a symmetric polynomial $P_{sym}(X)$ whose roots are of the form $X + q/X$ (X is the product of g terms which belong to $\{\pi_1, q/\pi_1\}, \dots, \{\pi_g, q/\pi_g\}$). It remains to compute its roots over \mathbb{C} in order to find the characteristic polynomial $\chi(\pm X)$ of the Frobenius.

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Initialization phase

We first lift in \mathbb{Z}_{2^n} an affine model of H ,

$$y^2 + h(x)y = h(x)q(x),$$

as follows,

$$Y^2 = (2y + h(x))^2 = h(x)(h(x) + 2^2q(x)).$$

When $h(x)$ and $h(x) + 4q(x)$ completely split over \mathbb{Z}_{2^n} ,

$$Y^2 = \prod_{i=0}^{2g+1} (X - x_i) \text{ such that } x_i \in \mathbb{Z}_{2^n}^2$$

$$\text{and } x_{2i} \equiv x_{2i+1} \pmod{2^2}.$$

Then, Thomae-Fay formulas enable to compute 2^g theta constants $\theta_0, \dots, \theta_{2^g-1}$ at small precision through

$$\theta_e = \sqrt{\prod_{0 \leq i < j \leq g} (x_{2i+\epsilon_i} - x_{2j+\epsilon_j})(x_{2i+1-\epsilon_i} - x_{2j+1-\epsilon_j})},$$

where $\epsilon_0 = 0$ and where e is written in basis 2 as $\epsilon_g 2^{g-1} + \dots + \epsilon_1$ (the square root is chosen such that $\theta_e \equiv 1 \pmod{2^2}$).

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Lift phase

Let $R(t_1) = \frac{2\sqrt{t_1}}{1+t_1}$ for curves of genus $g = 1$ and

$$R(t_1, \dots, t_{2g-1}) = \frac{2\sqrt{t_1} + 2\sqrt{t_2}\sqrt{t_3} + \dots + 2\sqrt{t_{2g-2}}\sqrt{t_{2g-1}}}{1 + t_1 + \dots + t_{2g-1}} \text{ for } g > 1.$$

Riemann duplication formulas yield

$$\forall e \in \{1, \dots, 2^g - 1\}, \tau_e^\sigma = R(\tau_e, \tau_{i_2}, \tau_{i_3}, \dots, \tau_{i_{2g-2}}, \tau_{i_{2g-1}})$$

where, for each e , the indexes i_2, \dots, i_{2g-1} are s.t.

$$\{\{0, e\}, \{i_2, i_3\}, \dots, \{i_{2g-2}, i_{2g-1}\}\} = \{\{j, j \oplus e\} \mid j \in \{1, \dots, 2^g - 1\}\}$$

(\oplus denotes the exclusive or of two integers) and

$$\tau_e = \theta_e / \theta_0 \pmod{2^4}.$$

\Rightarrow solved through a generalization of NewtonLift.

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Norm phase

The product π of the g eigenvalues (invertible modulo 2) of the Frobenius defined by H satisfies

$$\pi \equiv N_{\mathbb{Z}_{2^n}/\mathbb{Z}_2} \left(\frac{2^g}{1 + \tau_1 + \cdots + \tau_{2^g-1}} \right) \pmod{2^m}.$$

\Rightarrow solved in a way similar to the elliptic curve case.

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LLL phase

At first, we build a symmetric polynomial of degree 2^{g-1} with root $\eta = \pi + 2^{g^n}/\pi$ thanks to a LLL reduction of the lattice \mathcal{L} given by

$$\begin{bmatrix} K \times M_1 & K \times M_2 & \cdots & K \times M_{2^{g-1}+1} & K \times 2^m \\ 0 & 0 & \cdots & 2^{\lfloor n \times S_{2^{g-1}+1} \rfloor} & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \\ 0 & 2^{\lfloor n \times S_2 \rfloor} & \cdots & 0 & 0 \\ 2^{\lfloor n \times S_1 \rfloor} & 0 & \cdots & 0 & 0 \end{bmatrix},$$

where

$$M = \left[2^{(2^{g-1}-1-i)n} \eta^i \bmod 2^m \mid i \in \{0, \dots, 2^{g-1} - 1\} \right] \cup [\eta^{2^{g-1}} \bmod 2^m, 2^m],$$

and

$$S = \left[\frac{(i-1)(g-2)}{2} \mid i \in \{1, \dots, 2^{g-1}\} \right] \cup \left[\frac{2^{g-1}(g-2)}{2} + 1 \right]$$

(K is some arbitrarily large constant).

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Precision needed

The coefficients of P_{sym} are components of a vector Π of small norm in \mathcal{L} .

Asymptotic estimates state that the LLL algorithm can compute the lattice reduction of \mathcal{L} if its euclidian norm $\| \cdot \|_2$ (or sup-norm $\| \cdot \|_1$) satisfy

$$\| \Pi \|_1 \leq \| \Pi \|_2 \leq \det(\mathcal{L})^{1/\dim \mathcal{L}}.$$

\Rightarrow the precision m needed for the lift must satisfy

$$m > \frac{2^{2g}(g-2) + 2^{g+1}(g+2)}{16} n.$$

Some numeric values:

g	1	2	3	4	5	6
m	$n/2$	$2n$	$9n$	$44n$	$220n$	$1088n$

g	7	8	9	10
m	$5264n$	$24896n$	$115392n$	$525824n$

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Timings for counting points on genus 3 curves defined over \mathbb{F}_{2^n} (GNB)

On a 731 MHz Alpha EV6 CPU.

n	GNB type 1		
	Lift	Norm	Total
1018	8h 30	1mn	8h 31
2052	1d 3	5mn	1d 3
4098	6d 8h	25mn	6d 8h

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Conclusions & Open Problems

- We have now algorithms to count points for many curves in time very close to the time needed to multiply a divisor by an integer in the Jacobian.
- Reasonable wishes...
 - Non ordinary hyperelliptic curves ?
 - Non hyperelliptic curves in small genus ?
 - $O(g^? n^{2+\varepsilon})$ time complexities algorithms for hyperelliptic curves of any genus ?
 - etc.
- **Golden Grail**: practical algorithms for large p ?