Computations in positive and zero characteristic

Antoine Leudière, for Alberta Number Theory Days XVI

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Introduction

Drinfeld modules

Computing a group action

Kronecker-Weber theorem

Every abelian number field lies in a cyclotomic field $\mathbb{Q}_n$.

$\mathbb{Q}_n$ is generated by the n-th roots of unity.

Alternative construction

Consider the $\mathbb{Z}$-module

$$\begin{aligned} \mathbb{Z} \times \overline{\mathbb{Q}}^* &\rightarrow \overline{\mathbb{Q}}^* \\ (n, z) &\mapsto z^n \end{aligned}$$

The n-th roots of unity are the n-torsion of this $\mathbb{Z}$-module.

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Class Field Theory

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Given a number field $K/\mathbb{Q}$, what can I say about the abelian extensions of K, using only objects defined in K?

Some explicit results:

- Kronecker-Weber.
- The case of quadratic imaginary number fields ($\mathbb{Q}(\sqrt{-d})$, where $d < 0$).

The *Hilbert class field* (maximal unramified abelian extension) of an imaginary quadratic number field $\mathbb{Q}(\sqrt{-d})$ is generated by: the j-invariants of elliptic curves with complex multiplication in $\mathbb{Q}(\sqrt{-d})$.

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Looking for an alternative framework

Common point between these results:

- Number fields (characteristic 0).
- $\mathbb{Z}$-modules.

Can we change these?

Zero characteristic	**Positive characteristic**
$\mathbb{Z}$	$\mathbb{F}_q[T]$
$\mathbb{Q}$	$\mathbb{F}_q(T)$
Number fields (finite ext.)	Function fields (finite ext.)
$\mathbb{R}$	$\mathbb{R}_\infty = \mathbb{F}_q((\frac{1}{T}))$
$\mathbb{C}$	$\mathbb{C}_\infty =$ completion of $\overline{\mathbb{R}_\infty}$
Roots of unity	Drinfeld modules
Elliptic curves	Drinfeld modules

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Advantages of function fields

- Geometrical interpretation.
- Non-Archimedean valuations.
- Faster algorithms (polynomial derivation and factorization).
- Some unconditional results (GRH).

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Drinfeld modules

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Ore polynomials $K\{\tau\}$

Consider an extension $K/\mathbb{F}_q$ and the Frobenius endomorphisms

$$\begin{array}{rccc} \tau^n : & K & \to & K \\ & x & \mapsto & x^{q^n}. \end{array}$$

Finite K-linear combinations of τ^n': ring $K\{\tau\}$ for addition and composition.

Properties

- Representation as polynomials: $K\{\tau\} = \{\sum_{i=0}^{n} x_i \tau^i, n \in \mathbb{Z}_{\geqslant 0}, x_i \in K\}$.
- Notion of τ-degree.
- Noncommutative: for $\lambda \in K$, $\tau^n \lambda = \lambda^{q^n} \tau^n$.

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Kernels and Ore polynomials

$K\{\tau\}$ is left-euclidean: $\forall A(\tau), B(\tau) \in K\{\tau\}$, $\exists Q(\tau), R(\tau) \in K\{\tau\}$ such that:

$$\begin{cases} A(\tau) = Q(\tau)B(\tau) + R(\tau), \\ \deg_\tau(R(\tau)) < \deg_\tau(B(\tau)). \end{cases}$$

A bijection

$$\left\{ \begin{array}{c} \text{Ore polynomials } f \in K\{\tau\} \\ \text{with constant term 1} \end{array} \right\} \to \left\{ \begin{array}{c} \text{finite dimensional } \mathbb{F}_q\text{-linear subspaces} \\ V \subset K_{\text{sep}} \text{ stable by } \operatorname{Gal}(K_{\text{sep}}/K) \end{array} \right\}$$
$$f \mapsto \operatorname{Ker} f.$$

$$\begin{array}{rcl} V_1 & \longleftrightarrow & f_1 \\ V_2 & \longleftrightarrow & f_2 \\ V_1 \cap V_2 & \longleftrightarrow & \operatorname{rgcd}(f_1, f_2) \end{array}$$

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Representing Drinfeld modules

Drinfeld modules ϕ and their morphisms are represented in terms of $K\{\tau\}$.

Representation

For $a \in \mathbb{F}_q[T]$, the endomorphism of multiplication by a is represented by an Ore polynomial $\phi_a \in K\{\tau\}$.

From now on, K is finite with $[K : \mathbb{F}_q] = d$.

Frobenius endomorphism

One extra endomorphism: $\mathrm{Frob} = \tau^d \in K\{\tau\}$.

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Joint-work with P.-J. Spaenlehauer.

Computing a group action from the class field theory of imaginary hyperelliptic function fields.

Journal of symbolic computation, 2024.
https://doi.org/10.1016/j.jsc.2024.102311.

The case of elliptic curves

- Quadratic imaginary number field $\mathbb{Q}(\sqrt{-d})$.
- Its ring of integers $\mathcal{O}$.
- The class group $\mathrm{Cl}(\mathcal{O})$ of $\mathcal{O}$.
- The set $X_{\mathcal{O}}$ isomorphism classes of elliptic curves with endomorphism ring $\mathcal{O}$.

Fix an ideal $\mathfrak{a} \subset \mathcal{O}$ and an elliptic curve E. There is a curve $E_{\mathfrak{a}}$ and morphism $E \to E_{\mathfrak{a}}$ with kernel

$$\bigcap_{f \in \mathfrak{a}} \mathrm{Ker}(f).$$

We define

$$\overline{\mathfrak{a}} * \overline{E} = \overline{E_{\mathfrak{a}}}.$$

Free and transitive group action of $\mathrm{Cl}(\mathcal{O})$ on $X_{\mathcal{O}}$.

Relevance of the problem

Theoretical applications

Class field theory.

Practical applications

Isogeny-based cryptography (Couveignes, 2006; Rostovtsev-Stolbunov, 2006).

Very slow computation! See de Feo-Kieffer-Smith, 2018.

The hyperelliptic case

Imaginary hyperelliptic curve $\mathcal{H}$ defined by $\chi \in \mathbb{F}_q[T][X]$, and its *coordinate ring*

$$\mathbb{F}_q[\mathcal{H}] = \mathbb{F}_q[T][X]/(\chi).$$

Mumford coordinates

Elements of $\mathrm{Cl}(\mathbb{F}_q[\mathcal{H}])$ are represented by couples $(u, v) \in \mathbb{F}_q[T]^2$ with:

$$(u, v) \longleftrightarrow (\overline{u(T)}, \overline{X - v(T)})$$

For a Drinfeld module ϕ such that $\mathrm{End}(\phi) = \mathbb{F}_q[\mathcal{H}]$, we have an isomorphism

$$\begin{array}{rcl} \mathbb{F}_q[\mathcal{H}] & \to & \mathrm{End}(\phi) \\ P(T, X) & \mapsto & P(\phi_T, \mathrm{Frob}). \end{array}$$

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Practical computation

We rely on:

- Mumford coordinates.
- The correspondence between kernels and Ore polynomials.

Computing the action essentially goes down to computing

$$\operatorname{rgcd}\left(\phi_u, \operatorname{Frob} - \phi_v\right).$$

Computation time on cryptographic sizes goes from ~ 10 min. to 400 ms.
Highly insecure though! (Wesolowski)

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Conclusive remarks

Applications of Drinfeld modules

- Geometric Langlands program, Class Field Theory of function fields, GRH for function fields.
- State of the art polynomial factorization (Doliskani-Narayanan-Schost, 2018).

Tools for Drinfeld modules

- Inspiration from elliptic curves.
- Function fields arithmetics.
- Ore polynomial arithmetics.
- Anderson motives.

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