Abelian varieties over finite fields isogenous to a power

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Introduction

Today's plan:

- Introduction.
- AV A isogenous to B^r, for B ordinary square-free defined over $\mathbb{F}_q$.
- Isomorphism classes.
- Polarizations.
- Computations of polarizations and period matrices ($r = 1$).

Also, all morphisms are defined over the field of definition!

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- AV are projective and commutative.
- In dimension 1: elliptic curves.
- If $chark \neq 2, 3$ we can always produce a model:

$$Y^2 Z = X^3 + AXZ^2 + BZ^3 \text{ with } 4A^3 + 27B^2 \neq 0$$

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$$\{\text{abelian varieties } /\mathbb{C}\} \longleftrightarrow \left\{\begin{matrix}\mathbb{C}^g/L \text{ with } L \simeq \mathbb{Z}^{2g} \\ \text{(eq. classes of) } + \\ \text{Riemann form}\end{matrix}\right\}$$

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- in positive characteristic we don't have such an equivalence (at least for the whole category).

Isogeny classes

Recall

- for an abelian variety $A/\mathbb{F}_q$ there are simple B_i and positive integers e_i s.t.

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Theorem (Honda-Tate)

There is a bijection between the set of simple abelian varieties over $\mathbb{F}_q$ up to isogeny and the set of q-Weil numbers up to conjugacy.

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Proposition

For B ordinary over $\mathbb{F}_q$:

$$h_B \text{ is irreducible} \iff B \text{ is simple}$$

Deligne's equivalence

Theorem (Deligne '69)

Let $q = p^d$, with p a prime. There is an equivalence of categories:

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$$\mathrm{AV}^{ord}(q) := \{\textbf{Ordinary}\ \textit{abelian varieties over}\ \mathbb{F}_q\}$$
$$\updownarrow$$
$$\mathcal{M}^{ord}(q) := \left\{ \begin{array}{l} \textit{pairs } (T, F), \textit{ where } T \simeq_{\mathbb{Z}} \mathbb{Z}^{2g} \textit{ and } T \xrightarrow{F} T \\ \textit{s.t.} \\ \textit{- } F \otimes \mathbb{Q} \textit{ is semisimple} \\ \textit{- the roots of } \mathrm{char}_{F\otimes\mathbb{Q}}(x) \textit{ have abs. value } \sqrt{q} \\ \textbf{- half of them are } p\textbf{-adic units} \\ \textit{- } \exists V : T \to T \textit{ such that } FV = VF = q \end{array} \right\}$$

Deligne's equivalence - the functor

- fix an embedding of $\varepsilon : W = W(\overline{\mathbb{F}}_p) \hookrightarrow \mathbb{C}$
- take $A \in \mathrm{AV}^{\mathrm{ord}}(q)$
- let A' be the canonical lift of A to W
- put $A_{\mathbb{C}} := A' \otimes_{\varepsilon} \mathbb{C}$
- finally, let $T(A) := H_1(A_{\mathbb{C}}, \mathbb{Z})$
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Observe if $\dim(A) = g$ then $\mathrm{Rank}(T(A)) = 2g$;

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Observe: if $A \in \mathrm{AV}(g^r)$ then

$$A \sim (B_1 \times \ldots \times B_s)^r$$

with

$$g = h_{B_1 \times \ldots \times B_s}$$

Main theorem

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Theorem (M.)

There are equivalences of categories

$$\mathrm{AV}(g^r) \overset{Deligne}{\longleftrightarrow} \mathcal{M}(g^r) \longleftrightarrow \mathcal{B}(g^r)$$

The category $\mathcal{B}(g^r)$

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We can think of modules $M \in \mathcal{B}(g^r)$ as **embedded** in K^r.
The category $\mathcal{B}(g^r)$ becomes more explicit and computable under certain assumptions on the order R.

Bass orders

Recall

- a fractional R-ideal I is a sub-R-module of K which is also a lattice
- a fractional R-ideal is invertible in R if $I(R:I) = R$.

Define

$$\mathrm{ICM}(R) = {}^{\{\text{fractional } R\text{-ideals}\}}\!\big/_{\simeq_R} \qquad \text{ideal class monoid}$$

and

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generalization of Steinitz theory

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Assume that R is Bass. Then for every $M \in \mathcal{B}(g^r)$ there are over orders $S_1 \subseteq \ldots \subseteq S_r$ of R and a fractional ideal I invertible in S_r such that

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and

$$\mathrm{Aut}_R(M) = \left\{ A \in \mathrm{End}_R(M) \cap \mathrm{GL}_r(K) : A^{-1} \in \mathrm{End}_R(M) \right\}.$$

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- *if*
$$A \longleftrightarrow \bigoplus_k I_k \text{ and } B \longleftrightarrow \bigoplus_k J_k$$
then $\mu \in \mathrm{Hom}(A, B) \longleftrightarrow \Lambda \in \mathrm{Mat}_{r \times r}(K)$ *s.t.* $\Lambda_{h,k} \in (J_h : I_k)$

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then $\mu \in \mathrm{Hom}(A,B) \longleftrightarrow \Lambda \in \mathrm{Mat}_{r\times r}(K)$ *s.t.* $\Lambda_{h,k} \in (J_h : I_k)$

Moreover, μ is an isogeny if and only if $\det(\Lambda) \in K^\times$

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Define $K = \mathbb{Q}[x]/(g) = \mathbb{Q}(F)$ and $R = \mathbb{Z}[F, V]$.
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We now list the representatives of the isomorphism classes in $\mathrm{AV}(g^3)$:

$$\begin{array}{lll} M_1 = R \oplus R \oplus R & M_2 = R \oplus R \oplus I & M_3 = R \oplus R \oplus I^2 \\ M_4 = R \oplus R \oplus \mathcal{O}_K & M_5 = R \oplus \mathcal{O}_K \oplus \mathcal{O}_K & M_6 = \mathcal{O}_K \oplus \mathcal{O}_K \oplus \mathcal{O}_K \end{array}$$

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$$\mathrm{End}(M_1) = \mathrm{Mat}_3(R) \text{ and } \mathrm{End}(M_2) = \begin{pmatrix} R & R & I \\ R & R & I \\ (R:I) & (R:I) & R \end{pmatrix}$$

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If $\mu : A \to B$ in $\mathrm{AV}(g^r)$ corresponds to $\Lambda : M \to N$ in $\mathcal{B}(g^r)$, then $\mu^\vee : B^\vee \to A^\vee$ in $\mathrm{AV}(g^r)$ corresponds to $\Lambda^\vee : N^\vee \to M^\vee$ in $\mathcal{B}(g^r)$, where

$$\Lambda^\vee := \overline{\Lambda}^T$$

"Proof": Howe (1995) described dual modules in $\mathcal{M}^{\mathrm{ord}}(q)$. We translated this notion to $\mathcal{B}(g^r)$.

Polarizations

Fix

$$\Phi := \{\varphi : K \to \mathbb{C} : v_p(\varphi(F)) > 0\}\,, \text{ tricky to compute!}$$

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- $\Lambda = -\overline{\Lambda}^T$, *and*
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"Proof": Howe (1995) put polarizations in Deligne's category $\mathcal{M}^{\mathrm{ord}}(q)$.
We translated this notion to $\mathcal{B}(g^r)$.

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Unfortunately

$$\mathrm{Pol}(M) / \mathrm{Aut}(M) \text{ is hard to understand if } r \geq 2$$

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  Also: $\deg \mu = [\bar{I}^t : \lambda I]$.
- if $(A, \mu) \leftrightarrow (I, \lambda)$ and $S = (I : I)$ then

$$\left\{ \begin{array}{l} \text{non-isomorphic} \\ \text{polarizations of } A \end{array} \right\} \longleftrightarrow \frac{\{\text{totally positive } u \in S^\times\}}{\{v\bar{v} : v \in S^\times\}}$$

  and $\mathrm{Aut}(A, \mu) = \{\text{torsion units of } S\}$

Example

- Let
  $h(x) = x^8 - 5x^7 + 13x^6 - 25x^5 + 44x^4 - 75x^3 + 117x^2 - 135x + 81$;
- $\rightsquigarrow$ isogeny class of an simple ordinary abelian varieties over $\mathbb{F}_3$ of dimension 4;
- Let F be a root of $h(x)$ and put $R := \mathbb{Z}[F, 3/F] \subset \mathbb{Q}(F)$;
- 8 over-orders of R: two of them are not Gorenstein;
- $\#\,\mathrm{ICM}(R) = 18 \rightsquigarrow 18$ isom. classes of AV in the isogeny class;
- 5 are not invertible in their multiplicator ring;
- 8 classes admit principal polarizations;
- 10 isomorphism classes of princ. polarized AV.

Example

Concretely:

$$\begin{aligned} I_1 =& 2645633792595191\mathbb{Z} \oplus (F + 836920075614551)\mathbb{Z} \oplus (F^2 + 1474295643839839)\mathbb{Z}\oplus \\ & \oplus (F^3 + 1372829830503387)\mathbb{Z} \oplus (F^4 + 1072904687510)\mathbb{Z}\oplus \\ & \oplus \frac{1}{3}(F^5 + F^4 + F^3 + 2F^2 + 2F + 6704806986143610)\mathbb{Z}\oplus \\ & \oplus \frac{1}{9}(F^6 + F^5 + F^4 + 8F^3 + 2F^2 + 2991665243621169)\mathbb{Z}\oplus \\ & \oplus \frac{1}{27}(F^7 + F^6 + F^5 + 17F^4 + 20F^3 + 9F^2 + 68015312518722201)\mathbb{Z} \end{aligned}$$

principal polarizations:

$$\begin{aligned} x_{1,1} =& \frac{1}{27}(- 121922F^7 + 588604F^6 - 1422437F^5 + \\ & + 1464239F^4 + 1196576F^3 - 7570722F^2 + 15316479F - 12821193) \\ x_{1,2} =& \frac{1}{27}(3015467F^7 - 17689816F^6 + 35965592F^5 - \\ & - 64660346F^4 + 121230619F^3 - 191117052F^2 + 315021546F - 300025458) \end{aligned}$$

$\mathrm{End}(I_1) = R$

$\# \mathrm{Aut}(I_1, x_{1,1}) = \# \mathrm{Aut}(I_1, x_{1,2}) = 2$

Example

$$
\begin{aligned}
I_7 =& 2\mathbb{Z} \oplus (F+1)\mathbb{Z} \oplus (F^2+1)\mathbb{Z} \oplus (F^3+1)\mathbb{Z} \oplus (F^4+1)\mathbb{Z} \oplus \frac{1}{3}(F^5+F^4+F^3+2F^2+2F+3)\mathbb{Z} \oplus \\
&\oplus \frac{1}{36}(F^6+F^5+10F^4+26F^3+2F^2+27F+45)\mathbb{Z} \oplus \\
&\oplus \frac{1}{216}(F^7+4F^6+49F^5+200F^4+116F^3+105F^2+198F+351)\mathbb{Z}
\end{aligned}
$$

principal polarization:

$$x_{7,1} = \frac{1}{54}(20F^7 - 43F^6 + 155F^5 - 308F^4 + 580F^3 - 1116F^2 + 2205F - 1809)$$

$$
\begin{aligned}
\mathrm{End}(I_7) = & \mathbb{Z} \oplus F\mathbb{Z} \oplus F^2\mathbb{Z} \oplus F^3\mathbb{Z} \oplus F^4\mathbb{Z} \oplus \frac{1}{3}(F^5+F^4+F^3+2F^2+2F)\mathbb{Z} \oplus \\
&\oplus \frac{1}{18}(F^6+F^5+10F^4+8F^3+2F^2+9F+9)\mathbb{Z} \oplus \\
&\oplus \frac{1}{108}(F^7+4F^6+13F^5+56F^4+80F^3+33F^2+18F+27)\mathbb{Z}
\end{aligned}
$$

$\# \mathrm{Aut}(I_7, x_{7,1}) = 2$

I_1 is invertible in R, but I_7 is not invertible in $\mathrm{End}(I_7)$.

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We have an isomorphism of complex tori

$$A'(\mathbb{C}) \simeq {\mathbb{C}^g}/{\Phi(I)}, \qquad \Phi(I) = \langle (\varphi_1(\alpha_i), \ldots, \varphi_g(\alpha_i) : i = 1, \ldots, 2g \rangle .$$

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This is big period matrix of (A', λ').

Period matrices - Example

Let $g = (x^4 - 4x^3 + 8x^2 - 12x + 9)(x^4 - 2x^3 + 2x^2 - 6x + 9)$.

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$$I = \frac{1}{54}\left(432 - 549\alpha + 441\alpha^2 - 331\alpha^3 + 186\alpha^4 - 81\alpha^5 + 33\alpha^6 - 7\alpha^7\right)\mathbb{Z}\oplus$$
$$\oplus\frac{1}{6}\left(63 - 78\alpha + 65\alpha^2 - 49\alpha^3 + 27\alpha^4 - 12\alpha^5 + 5\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus$$
$$\oplus\frac{1}{6}\left(81 - 99\alpha + 84\alpha^2 - 61\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus$$
$$\oplus\frac{1}{18}\left(-63 + 96\alpha - 86\alpha^2 + 68\alpha^3 - 39\alpha^4 + 18\alpha^5 - 8\alpha^6 + 2\alpha^7\right)\mathbb{Z}\oplus(-1)\mathbb{Z}\oplus$$
$$\oplus(-\alpha)\mathbb{Z}\oplus(-\alpha^2)\mathbb{Z}\oplus\frac{1}{9}\left(81 - 96\alpha + 81\alpha^2 - 64\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - \alpha^7\right)\mathbb{Z}$$

$$\lambda = \frac{537}{80} - \frac{1343}{120}\alpha + \frac{1343}{144}\alpha^2 - \frac{419}{60}\alpha^3 + \frac{337}{80}\alpha^4 - \frac{15}{8}\alpha^5 + \frac{559}{720}\alpha^6 - \frac{1}{5}\alpha^7$$

$$\Omega = \begin{pmatrix} 2.8 - i & -2.8 + 0.6i & 0 & 0 & 1 & 1.7 - 0.3i & 0 & 0 \\ -2.8 + i & 2.8 - 3.4i & 0 & 0 & 1 & 0.3 + 1.7i & 0 & 0 \\ 0 & 0 & -1 & -0.4 - 0.2i & 0 & 0 & -1.6 - 0.6i & -0.2 - 0.2i \\ 0 & 0 & -1 & -2.6 + 6.9i & 0 & 0 & 0.6 - 1.6i & -6.9 + 6.9i \end{pmatrix}$$

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$$
\begin{aligned}
I = &\frac{1}{54}\left(432 - 549\alpha + 441\alpha^2 - 331\alpha^3 + 186\alpha^4 - 81\alpha^5 + 33\alpha^6 - 7\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{6}\left(63 - 78\alpha + 65\alpha^2 - 49\alpha^3 + 27\alpha^4 - 12\alpha^5 + 5\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{6}\left(81 - 99\alpha + 84\alpha^2 - 61\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{18}\left(-63 + 96\alpha - 86\alpha^2 + 68\alpha^3 - 39\alpha^4 + 18\alpha^5 - 8\alpha^6 + 2\alpha^7\right)\mathbb{Z} \oplus (-1)\mathbb{Z}\oplus\\
&\oplus (-\alpha)\mathbb{Z} \oplus (-\alpha^2)\mathbb{Z} \oplus \frac{1}{9}\left(81 - 96\alpha + 81\alpha^2 - 64\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - \alpha^7\right)\mathbb{Z}
\end{aligned}
$$

$$
\lambda = \frac{537}{80} - \frac{1343}{120}\alpha + \frac{1343}{144}\alpha^2 - \frac{419}{60}\alpha^3 + \frac{337}{80}\alpha^4 - \frac{15}{8}\alpha^5 + \frac{559}{720}\alpha^6 - \frac{1}{5}\alpha^7
$$

Period matrices - Example

Let $g = (x^4 - 4x^3 + 8x^2 - 12x + 9)(x^4 - 2x^3 + 2x^2 - 6x + 9)$. We compute the principally polarized abelian varieties and we find that 4 isomorphism classes admit a unique principal polarization. Here is one of them with the period matrix of the canonical lift.

$$
\begin{aligned}
I = &\frac{1}{54}\left(432 - 549\alpha + 441\alpha^2 - 331\alpha^3 + 186\alpha^4 - 81\alpha^5 + 33\alpha^6 - 7\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{6}\left(63 - 78\alpha + 65\alpha^2 - 49\alpha^3 + 27\alpha^4 - 12\alpha^5 + 5\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{6}\left(81 - 99\alpha + 84\alpha^2 - 61\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - 1\alpha^7\right)\mathbb{Z}\oplus\\
&\oplus \frac{1}{18}\left(-63 + 96\alpha - 86\alpha^2 + 68\alpha^3 - 39\alpha^4 + 18\alpha^5 - 8\alpha^6 + 2\alpha^7\right)\mathbb{Z}\oplus(-1)\mathbb{Z}\oplus\\
&\oplus (-\alpha)\mathbb{Z}\oplus(-\alpha^2)\mathbb{Z}\oplus\frac{1}{9}\left(81 - 96\alpha + 81\alpha^2 - 64\alpha^3 + 33\alpha^4 - 15\alpha^5 + 6\alpha^6 - \alpha^7\right)\mathbb{Z}
\end{aligned}
$$

$$
\lambda = \frac{537}{80} - \frac{1343}{120}\alpha + \frac{1343}{144}\alpha^2 - \frac{419}{60}\alpha^3 + \frac{337}{80}\alpha^4 - \frac{15}{8}\alpha^5 + \frac{559}{720}\alpha^6 - \frac{1}{5}\alpha^7
$$

$$
\Omega = \begin{pmatrix}
2.8 - i & -2.8 + 0.6i & 0 & 0 & 1 & 1.7 - 0.3i & 0 & 0\\
-2.8 + i & 2.8 - 3.4i & 0 & 0 & 1 & 0.3 + 1.7i & 0 & 0\\
0 & 0 & -1 & -0.4 - 0.2i & 0 & 0 & -1.6 - 0.6i & -0.2 - 0.2i\\
0 & 0 & -1 & -2.6 + 6.9i & 0 & 0 & 0.6 - 1.6i & -6.9 + 6.9i
\end{pmatrix}
$$

Final remarks

- Computations of isomorphism classes can be done in the same way replacing "ordinary over $\mathbb{F}_q$" with "over $\mathbb{F}_p$, away from real primes", by using Centeleghe-Stix (2015)...
- ...but polarizations (and period matrices) are still work in progress.
- The Magma code is avalable on my webpage.

Thank you!