Optimal pairings on abelian varieties

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Outline

The Weil pairing on elliptic curves

- Let $E: y^2 = x^3 + ax + b$ be an elliptic curve over a field k ($\operatorname{char} k \neq 2, 3$, $4a^3 + 27b^2 \neq 0$.)
- Let $P, Q \in E[\ell]$ be points of ℓ-torsion.
- Let f_P be a function associated to the principal divisor $\ell(P) - \ell(0)$, and f_Q to $\ell(Q) - \ell(0)$. We define:

$$e_{W,\ell}(P,Q) = \frac{f_P((Q)-(0))}{f_Q((P)-(0))}.$$

- The application $e_{W,\ell} : E[\ell] \times E[\ell] \to \mu_\ell(\overline{k})$ is a non degenerate pairing: the Weil pairing.

Definition (Embedding degree)

If E is defined over a finite field $\mathbb{F}_q$, the Weil pairing has image in $\mu_\ell(\overline{\mathbb{F}}_q) \subset \mathbb{F}^*_{q^d}$ where d is the embedding degree, the smallest number such that $\ell \mid q^d - 1$.

The Tate pairing on elliptic curves over $\mathbb{F}_q$

Definition

The Tate pairing is a non degenerate bilinear application given by

$$\begin{array}{rccc} e_T \colon & E_0[\ell] \times E(\mathbb{F}_q)/\ell E(\mathbb{F}_q) & \longrightarrow & \mathbb{F}_{q^d}^* / \mathbb{F}_{q^d}^{*\,\ell} \\ & (P,Q) & \longmapsto & f_P((Q)-(0)) \end{array}.$$

where

$$E_0[\ell] = \{P \in E[\ell](\mathbb{F}_{q^d}) \mid \pi(P) = [q]P\}.$$

- On $\mathbb{F}_{q^d}$, the Tate pairing is a non degenerate pairing

$$e_T \colon E[\ell](\mathbb{F}_{q^d}) \times E(\mathbb{F}_{q^d})/\ell E(\mathbb{F}_{q^d}) \to \mathbb{F}_{q^d}^* / \mathbb{F}_{q^d}^{*\,\ell} \simeq \mu_\ell;$$

- If $\ell^2 \nmid E(\mathbb{F}_{q^d})$ then $E(\mathbb{F}_{q^d})/\ell E(\mathbb{F}_{q^d}) \simeq E[\ell](\mathbb{F}_{q^d})$;
- We normalise the Tate pairing by going to the power of $(q^d-1)/\ell$.

Miller's functions

- We need to compute the functions $f_{\ell,P}$ and $f_{\ell,Q}$. More generally, we define the Miller's functions:

Definition

Let $\lambda \in \mathbb{N}$ and $X \in E[\ell]$, we define $f_{\lambda,X} \in k(E)$ to be a function thus that:

$$(f_{\lambda,X}) = \lambda(X) - ([\lambda]X) - (\lambda - 1)(0).$$

- We want to compute (for instance) $f_{\ell,P}((Q)-(0))$.

Miller's algorithm

- The key idea in Miller's algorithm is that

$$f_{\lambda+\mu,X} = f_{\lambda,X} f_{\mu,X} \mathfrak{f}_{\lambda,\mu,X}$$

where $\mathfrak{f}_{\lambda,\mu,X}$ is a function associated to the divisor

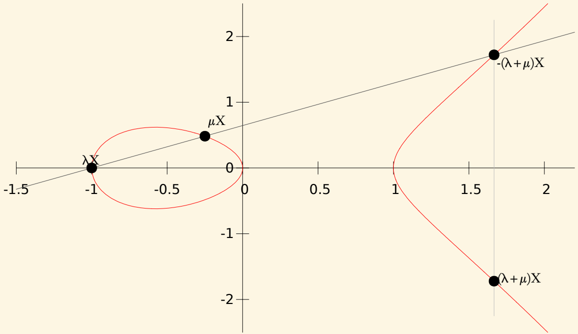
$$([\lambda]X) + ([\mu]X) - ([\lambda+\mu]X) - (0).$$

- We can compute $\mathfrak{f}_{\lambda,\mu,X}$ using the addition law in E: if $[\lambda]X = (x_1, y_1)$ and $[\mu]X = (x_2, y_2)$ and $\alpha = (y_1 - y_2)/(x_1 - x_2)$, we have

$$\mathfrak{f}_{\lambda,\mu,X} = \frac{y - \alpha(x - x_1) - y_1}{x + (x_1 + x_2) - \alpha^2}.$$

Miller's algorithm for elliptic curves

$$[\lambda]X = (x_1, y_1) \quad [\mu]X = (x_2, y_2)$$



$$f_{\lambda,\mu,X} = \frac{y - \alpha(x - x_1) - y_1}{x + (x_1 + x_2) - \alpha^2}.$$

Miller's algorithm for the Tate pairing on elliptic curves

Algorithm (Computing the Tate pairing)

Input: $\ell \in \mathbb{N}$, $P = (x_1, y_1) \in E[\ell](\mathbb{F}_q)$, $Q = (x_2, y_2) \in E(\mathbb{F}_{q^d})$.

Output: $e_T(P, Q)$.

1. *Compute the binary decomposition:* $\ell := \sum_{i=0}^{I} b_i 2^i$. *Let* $T = P, f_1 = 1, f_2 = 1$.
2. *For i in* $[I..0]$ *compute*
   1. α*, the slope of the tangent of* E *at* T.
   2. $T = 2T$. $T = (x_3, y_3)$.
   3. $f_1 = f_1^2(y_2 - \alpha(x_2 - x_3) - y_3)$, $f_2 = f_2^2(x_2 + (x_1 + x_3) - \alpha^2)$.
   4. *If* $b_i = 1$*, then compute*
      1. α*, the slope of the line going through* P *and* T.
      2. $T = T + Q$. $T = (x_3, y_3)$.
      3. $f_1 = f_1^2(y_2 - \alpha(x_2 - x_3) - y_3)$, $f_2 = f_2(x_2 + (x_1 + x_3) - \alpha^2)$.

Return

$$\left(\frac{f_1}{f_2}\right)^{\frac{q^d-1}{\ell}}.$$

Miller's algorithm on Jacobians

- Let $P \in \mathrm{Jac}(C)[\ell]$ and D_P a divisor on C representing P;
- By definition of $\mathrm{Jac}(C)$, ℓD_P corresponds to a principal divisor $(f_{\ell,P})$ on C;
- The same formulas as for elliptic curve define the Weil and Tate-Lichtenbaum pairings:

$$e_W(P,Q) = f_{\ell,P}(D_Q)/f_{\ell,Q}(D_P)$$
$$e_T(P,Q) = f_{\ell,P}(D_Q).$$

- A key ingredient for evaluating $f_P(D_Q)$ comes from Weil's reciprocity theorem.

Theorem (Weil)

Let D_1 and D_2 be two divisors with disjoint support linearly equivalent to (0) on a smooth curve C. Then

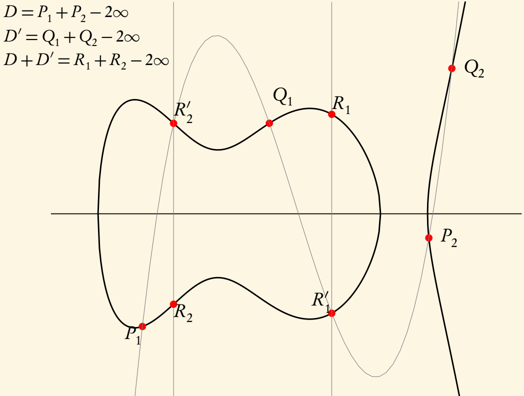
$$f_{D_1}(D_2) = f_{D_2}(D_1).$$

Miller's algorithm on Jacobians of genus 2 curves

- The extension of Miller's algorithm to Jacobians is "straightforward";
- For instance if $g=2$, the function $f_{\lambda,\mu,P}$ is of the form

$$\frac{y-l(x)}{(x-x_1)(x-x_2)}$$

where l is of degree 3.



Abelian varieties

Definition

An Abelian variety is a complete connected group variety over a base field k.

- Abelian variety = points on a projective space (locus of homogeneous polynomials) + an abelian group law given by rational functions.

Example

- Elliptic curves= Abelian varieties of dimension 1;
- If C is a (smooth) curve of genus g, its Jacobian is an abelian variety of dimension g;
- In dimension $g \geqslant 4$, not every abelian variety is a Jacobian.

The Weil-Cartier pairing

- Let $f: A \to B$ be a separable isogeny with kernel K between two abelian varieties defined over k;
- The isogeny f and its dual $\hat{f}$ fit into the diagram

$$\begin{array}{ccccccccc} 0 & \longrightarrow & K & \longrightarrow & A & \xrightarrow{f} & B & \longrightarrow & 0 \\ & & 0 & \longleftarrow & \hat{A} & \xleftarrow{\hat{f}} & \hat{B} & \longleftarrow & \hat{K} & \longleftarrow & 0 \end{array}$$

- Since $\hat{K}$ is the Cartier dual of K we have a non degenerate pairing $e_f : K \times \hat{K} \to \mathbb{G}_m$;
- Unravelling the identification, we can compute the Weil-Cartier pairing as follows:
  1. If $Q \in \hat{K}(\overline{k})$, Q defines a divisor D_Q on B;
  2. $\hat{f}(Q) = 0$ means that $f^* D_Q$ is equal to a principal divisor (g_Q) on A;
  3. $e_f(P,Q) = g_Q(x)/g_Q(x+P)$. (This last function being constant in its definition domain).
- The Weil pairing $e_{W,\ell}$ is the pairing associated to the isogeny $[\ell]: A \to A$

$$e_{W,\ell} : A[\ell] \times \hat{A}[\ell] \to \mu_\ell.$$

Reformulation

$$\begin{tikzcd} f^* D_Q \arrow[r, "\psi_Q"] \arrow[d, "\psi_P"] & \mathcal{O}_A \arrow[d, equal, "e_f(P,Q)"] \\ \tau_P^* f^* D_Q \arrow[r, "\tau_P^* \psi_Q"] & \tau_P^* \mathcal{O}_A \end{tikzcd}$$

(ψ_P is normalized via $A(P) \simeq A(0)$.)

- Since $f^* D_Q$ is trivial, by descent theory D_Q is the quotient of $A \times \mathbb{A}^1$ by an action of K:
$$g_x.(t, \lambda) = (t + x, \chi_Q(x)\lambda)$$
where χ_Q is a character on K;
$$e_f(P,Q) = \chi_Q(P).$$

Polarizations

If $\mathscr{L}$ is an ample line bundle, the polarization $\varphi_{\mathscr{L}}$ is a morphism $A \to \widehat{A}, x \mapsto t_x^* \mathscr{L} \otimes \mathscr{L}^{-1}$.

Definition (Weil pairing)

Let $\mathscr{L}$ be a principal polarization on A. The (polarized) Weil pairing $e_{W,\mathscr{L},\ell}$ is the pairing

$$\begin{array}{rcl} e_{W,\mathscr{L},\ell} : A[\ell] \times A[\ell] & \longrightarrow & \mu_\ell \\ (P,Q) & \longmapsto & e_{W,\ell}(P, \varphi_{\mathscr{L}}(Q)) \end{array}.$$

associated to the polarization $\varphi_{\mathscr{L}^\ell}$:

$$A \xrightarrow{[\ell]} A \xrightarrow{\mathscr{L}} \hat{A}$$

The commutator pairing

- In general for an ample line bundle $\mathscr{L}$, the polarization $\varphi_{\mathscr{L}}$ gives an isogeny

$$0 \longrightarrow K(\mathscr{L}) \longrightarrow A \longrightarrow \hat{A} \longrightarrow 0$$

  and thus a pairing

$$e_{\mathscr{L}} : K(\mathscr{L}) \times K(\mathscr{L}) \to \mathbb{G}_m.$$

- The following diagram is commutative up to a multiplication by $e_{\mathscr{L}}(P,Q)$:

$$\begin{tikzcd}
\mathscr{L} \arrow[r, "\psi_P"] \arrow[d, "\psi_Q"] & \tau_P^*\mathscr{L} \arrow[d, "\tau_P^*\psi_Q"] \\
\tau_Q^*\mathscr{L} \arrow[r, "\tau_Q^*\psi_P"] & \tau_{P+Q}^*\mathscr{L}
\end{tikzcd}$$

The commutator pairing

- The Theta group $G(\mathscr{L})$ is the group $\{(x,\psi_x)\}$ where $x \in K(\mathscr{L})$ and ψ_x is an isomorphism
$$\psi_x : \mathscr{L} \to \tau_x^* \mathscr{L}$$
The composition is given by $(y,\psi_y).(x,\psi_x) = (y+x, \tau_x^*\psi_y \circ \psi_x)$.
- $G(\mathscr{L})$ is an Heisenberg group:
$$0 \longrightarrow k^* \longrightarrow G(\mathscr{L}) \longrightarrow K(\mathscr{L}) \longrightarrow 0$$
- Let $g_P = (P,\psi_P) \in G(\mathscr{L})$ and $g_Q = (Q,\psi_Q) \in G(\mathscr{L})$,
$$e_{\mathscr{L}}(P,Q) = g_P g_Q g_P^{-1} g_Q^{-1};$$
- If $\psi : K(\mathscr{L}) \times K(\mathscr{L}) \to k^*$ is the 2-cocycle associated to $G(\mathscr{L})$, we also have
$$e_{\mathscr{L}}(P,Q) = \frac{\psi(P,Q)}{\psi(Q,P)}.$$

Kummer exact sequence

- The exact sequence
$$1 \to \mu_\ell \to \overline{k}^* \to \overline{k}^* \to 1$$
induces a connecting map
$$\delta : \overline{k}^* / \overline{k}^{*,\ell} \simeq H^1(k, \mu_\ell)$$
(the isomorphism comes from Hilbert 90: $H^1(k, k^*) = 0$).
- Thus for a finite field $k = \mathbb{F}_q$
$$\mathbb{F}_{q^d}^* / \mathbb{F}_{q^d}^{*,\ell} \simeq H^1(\mathbb{F}_{q^d}, \mu_\ell) \simeq \mu_\ell(\mathbb{F}_{q^d});$$
- The isomorphism is given by the exponentiation $x \mapsto x^{\frac{q^d-1}{\ell}}$.

The Tate-Cartier pairing on abelian varieties over finite fields

- Let $f : A \to B$ be an isogeny with $\operatorname{Ker} f \subset A[\ell]$;
- From the exact sequence
$$0 \to \operatorname{Ker} f \to A \to B \to 0$$
we get from Galois cohomology a connecting morphism
$$\delta : A(\mathbb{F}_{q^d})/f(B(\mathbb{F}_{q^d})) \simeq H^1(\mathbb{F}_{q^d}, \operatorname{Ker} f)$$
(this is an isomorphism since $H^1(\mathbb{F}_{q^d}, A) = 0$ for an abelian variety over a finite field);
- Composing with the Weil-Cartier pairing, we get a bilinear application
$$\operatorname{Ker} \hat{f}(\mathbb{F}_{q^d}) \times A(\mathbb{F}_{q^d})/f(B(\mathbb{F}_{q^d})) \to H^1(\mathbb{F}_{q^d}, \mu_\ell) \simeq \mathbb{F}_{q^d}^* / \mathbb{F}_{q^d}^{*\ \ell} \simeq \mu_\ell;$$
- Explicitely, if $P \in \operatorname{Ker} \hat{f}(\mathbb{F}_{q^d})$ and $Q \in A(\mathbb{F}_{q^d})$ then the (reduced) Tate pairing is given by
$$e_T(P,Q) = e_W(\pi^d(Q_0) - Q_0, P)$$
where $Q_0 \in A$ is any point such that $Q = f(Q_0)$ and π is the Frobenius of $\mathbb{F}_q$;

The Tate-Cartier pairing on abelian varieties over finite fields

Theorem

The Tate pairing

$$\operatorname{Ker}\hat{f}(\mathbb{F}_{q^d}) \times A(\mathbb{F}_{q^d})/f(B(\mathbb{F}_{q^d})) \to H^1(\mathbb{F}_{q^d}, \mu_\ell) \simeq \mathbb{F}_{q^d}^*/\mathbb{F}_{q^d}^{*\ell} \simeq \mu_\ell$$

is non degenerate.

Proof.

We have canonically

$$\begin{aligned}\operatorname{Ker}\hat{f}(\mathbb{F}_{q^d}) &= \operatorname{Hom}(\operatorname{Ker} f, \mathbb{G}_m)^{\operatorname{Gal}(\overline{\mathbb{F}}_{q^d}/\mathbb{F}_{q^d})}\\ &= \operatorname{Hom}(\operatorname{Ker} f/(\pi^d - 1), \mathbb{F}_{q^d}^*)\\ &= \operatorname{Hom}(H^1(\mathbb{F}_{q^d}, \operatorname{Ker} f), \mathbb{F}_{q^d}^*)\end{aligned}$$

and

$$A(\mathbb{F}_{q^d})/f(B(\mathbb{F}_{q^d})) \simeq H^1(\mathbb{F}_{q^d}, \operatorname{Ker} f).$$

□

Cycles and Lang reciprocity

- Let (A,Θ) be a principally polarized abelian variety;
- To a degree 0 cycle $\sum n_i(P_i)$ on A, we can associate the divisor $\sum n_i t_{P_i}^* \Theta$ on A;
- The cycle $\sum n_i(P_i)$ corresponds to a trivial divisor iff $\sum n_i P_i = 0$ in A;
- If f is a function on A and $D = \sum (P_i)$ a cycle whose support does not contain a zero or pole of f, we let

$$f(D) = \prod f(P_i)^{n_i}.$$

(In the following, when we write $f(D)$ we will always assume that we are in this situation.)

Theorem (Lang [Lan58])

Let D_1 and D_2 be two cycles equivalent to 0, and f_{D_1} and f_{D_2} be the corresponding functions on A. Then

$$f_{D_1}(D_2) = f_{D_2}(D_1)$$

The Weil and Tate pairings on abelian varieties

Theorem

Let $P,Q \in A[\ell]$. Let D_P and D_Q be two cycles equivalent to $(P)-(0)$ and $(Q)-(0)$. The Weil pairing is given by

$$e_W(P,Q)=\frac{f_{\ell D_P}(D_Q)}{f_{\ell D_Q}(D_P)}.$$

Theorem

Let $P \in A[\ell](\mathbb{F}_{q^d})$ and $Q \in A(\mathbb{F}_{q^d})$, and let D_P and D_Q be two cycles equivalent to $(P)-(0)$ and $(Q)-(0)$. The (non reduced) Tate pairing is given by

$$e_T(P,Q)=f_{\ell D_P}(D_Q).$$

Cryptographic usage of pairings on abelian varieties

- The Weil pairing was first used to transfer the DLP from an elliptic curve to $\mathbb{F}_{q^d}^*$ (the MOV attack [MOV91]);
- The moduli space of abelian varieties of dimension g is a space of dimension $g(g+1)/2$. We have more liberty to find optimal abelian varieties in function of the security parameters.
- Supersingular abelian varieties can have larger embedding degree than supersingular elliptic curves.
- Over a Jacobian, we can use twists even if they are not coming from twists of the underlying curve.
- If A is an abelian variety of dimension g, $A[\ell]$ is a $(\mathbb{Z}/\ell\mathbb{Z})$-module of dimension $2g \Rightarrow$ the structure of pairings on abelian varieties is richer.

Polarised abelian varieties over $\mathbb{C}$

Definition

A complex abelian variety A of dimension g is isomorphic to a compact Lie group V/Λ with

- A complex vector space V of dimension g;
- A $\mathbb{Z}$-lattice Λ in V (of rank $2g$);

such that there exists an Hermitian form H on V with $E(\Lambda,\Lambda) \subset \mathbb{Z}$ where $E = \operatorname{Im} H$ is symplectic.

- Such an Hermitian form H is called a polarisation on A. Conversely, any symplectic form E on V such that $E(\Lambda,\Lambda) \subset \mathbb{Z}$ and $E(ix,iy) = E(x,y)$ for all $x,y \in V$ gives a polarisation H with $E = \operatorname{Im} H$.
- Over a symplectic basis of Λ, E is of the form.

$$\begin{pmatrix} 0 & D_\delta \\ -D_\delta & 0 \end{pmatrix}$$

where D_δ is a diagonal positive integer matrix $\delta = (\delta_1, \delta_2, \ldots, \delta_g)$, with $\delta_1 \mid \delta_2 | \cdots | \delta_g$.
- The product $\prod \delta_i$ is the degree of the polarisation; H is a principal polarisation if this degree is 1.

Projective embeddings

Proposition

Let $\Phi : A = V/\Lambda \mapsto \mathbb{P}^{m-1}$ be a projective embedding. Then the linear functions f associated to this embedding are Λ-automorphics:

$$f(x+\lambda) = a(\lambda,x)f(x) \quad x \in V, \lambda \in \Lambda;$$

for a fixed automorphy factor a:

$$a(\lambda+\lambda',x) = a(\lambda,x+\lambda')a(\lambda',x).$$

Theorem (Appell-Humbert)

All automorphy factors are of the form

$$a(\lambda,x) = \pm e^{\pi(H(x,\lambda)+\frac{1}{2}H(\lambda,\lambda))}$$

for a polarisation H on A.

Theta functions

- Let (A, H_0) be a principally polarised abelian variety over $\mathbb{C}$: $A = \mathbb{C}^g / (\Omega \mathbb{Z}^g + \mathbb{Z}^g)$ with $\Omega \in \mathfrak{H}_g$.
- The associated Riemann form on A is then given by $E_1(\Omega x_1 + x_2, \Omega y_1 + y_2) = {}^t x_1 \cdot y_2 - {}^t y_1 \cdot x_2$; equivalently the matrix of H_0 is $\operatorname{Im} \Omega^{-1}$.
- The Weil pairing on $A[\ell]$ corresponds to the symplectic form E on $\frac{1}{\ell}\Lambda/\Lambda$.
- All automorphic forms corresponding to a multiple $H = nH_0$ of H_0 come from the theta functions with characteristics:

$$\vartheta \left[\begin{smallmatrix} a \\ b \end{smallmatrix} \right] (z, \Omega) = \sum_{n \in \mathbb{Z}^g} e^{\pi i \, {}^t(n+a)\Omega(n+a) + 2\pi i \, {}^t(n+a)(z+b)} \qquad a, b \in \mathbb{Q}^g$$

- Automorphic property:

$$\vartheta \left[\begin{smallmatrix} a \\ b \end{smallmatrix} \right] (z + m_1 \Omega + m_2, \Omega) = e^{2\pi i ({}^t a \cdot m_2 - {}^t b \cdot m_1) - \pi i \, {}^t m_1 \Omega m_1 - 2\pi i \, {}^t m_1 \cdot z} \vartheta \left[\begin{smallmatrix} a \\ b \end{smallmatrix} \right] (z, \Omega).$$

Remark

Working on level n mean we take a n-th power of the principal polarization. So in the following we will compute the n-th power of the usual Weil and Tate pairings.

Theta functions of level n

- Define $\vartheta_i = \vartheta\left[\begin{smallmatrix} 0 \\ \frac{i}{n} \end{smallmatrix}\right](., \frac{\Omega}{n})$ for $i \in Z(\overline{n}) = \mathbb{Z}^g/n\mathbb{Z}^g$ and
- This is a basis of the automorphic functions for $H = nH_0$ (theta functions of level n);
- This is the unique basis such that in the projective coordinates:

$$\begin{array}{rcl} A & \longrightarrow & \mathbb{P}^{n^g-1}_{\mathbb{C}} \\ z & \longmapsto & (\vartheta_i(z))_{i\in Z(\overline{n})} \end{array}$$

  the translation by a point of n-torsion is normalized by

$$\vartheta_i(z + \frac{m_1}{n}\Omega + \frac{m_2}{n}) = e^{-\frac{2\pi i}{n}\, {}^t i \cdot m_1}\vartheta_{i+m_2}(z).$$

- $(\vartheta_i)_{i\in Z(\overline{n})} = \begin{cases} \text{coordinates system} & n \geqslant 3 \\ \text{coordinates on the Kummer variety } A/\pm 1 & n = 2 \end{cases}$
- $(\vartheta_i)_{i\in Z(\overline{n})}$: basis of the theta functions of level n
  $\Leftrightarrow A[n] = A_1[n] \oplus A_2[n]$: symplectic decomposition.
- Theta null point: $\vartheta_i(0)_{i\in Z(\overline{n})} =$ modular invariant.

Jacobians

- Let C be a curve of genus g;
- Let V be the dual of the space $V^* = \Omega^1(C,\mathbb{C})$ of holomorphic differentials of the first kind on C;
- Let $\Lambda \simeq H^1(C,\mathbb{Z}) \subset V$ be the set of periods (integration of differentials on loops);
- The intersection pairing gives a symplectic form E on Λ;
- Let H be the associated hermitian form on V;

$$H^*(w_1,w_2) = \int_C w_1 \wedge w_2;$$

- Then $(V/\Lambda, H)$ is a principally polarised abelian variety: the Jacobian of C.

Theorem (Torelli)

$\operatorname{Jac} C$ with the associated principal polarisation uniquely determines C.

Remark (Weil pairing)

In this setting, the Weil pairing can be seen as the intersection pairing on

$$\operatorname{Jac} C[\ell] \simeq \frac{1}{\ell} H_1(C,\mathbb{Z})/H_1(C,\mathbb{Z}) \simeq H_1(C,\mathbb{Z}/\ell\mathbb{Z}).$$

The differential addition law ($k=\mathbb{C}$)

$$\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{i+t}(x+y)\vartheta_{j+t}(x-y)\Big).\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{k+t}(0)\vartheta_{l+t}(0)\Big)=$$

$$\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{-i'+t}(y)\vartheta_{j'+t}(y)\Big).\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{k'+t}(x)\vartheta_{l'+t}(x)\Big).$$

where $\chi\in\hat{Z}(\overline{2}), i,j,k,l\in Z(\overline{n})$

$$(i',j',k',l')=A(i,j,k,l)$$

$$A=\frac{1}{2}\begin{pmatrix}1&1&1&1\\1&1&-1&-1\\1&-1&1&-1\\1&-1&-1&1\end{pmatrix}$$

Example: differential addition in dimension 1 and in level 2

Algorithm

Input $z_P = (x_0, x_1)$, $z_Q = (y_0, y_1)$ and $z_{P-Q} = (z_0, z_1)$ with $z_0 z_1 \neq 0$;
$z_0 = (a, b)$ and $A = 2(a^2 + b^2)$, $B = 2(a^2 - b^2)$.

Output $z_{P+Q} = (t_0, t_1)$.

1. $t'_0 = (x_0^2 + x_1^2)(y_0^2 + y_2^2)/A$
2. $t'_1 = (x_0^2 - x_1^2)(y_0^2 - y_1^2)/B$
3. $t_0 = (t'_0 + t'_1)/z_0$
4. $t_1 = (t'_0 - t'_1)/z_1$

Return (t_0, t_1)

Miller functions with theta coordinates

Proposition (Lubicz-R. [LR14])

- *For $P \in A$ we note z_P a lift to $\mathbb{C}^g$. We call P a projective point and z_P an affine point (because we describe them via their projective, resp affine, theta coordinates);*
- *We have (up to a constant)*

$$f_{\lambda,P}(z) = \frac{\vartheta(z)}{\vartheta(z+\lambda z_P)} \left(\frac{\vartheta(z+z_P)}{\vartheta(z)} \right)^{\lambda};$$

- *So (up to a constant)*

$$\mathfrak{f}_{\lambda,\mu,P}(z) = \frac{\vartheta(z+\lambda z_P)\vartheta(z+\mu z_P)}{\vartheta(z)\vartheta(z+(\lambda+\mu)z_P)}.$$

Three way addition

Proposition (Lubicz-R. [LR14])

From the affine points z_P, z_Q, z_R, z_{P+Q}, z_{P+R} and z_{Q+R} one can compute the affine point z_{P+Q+R}.

Proof.

We can compute the three way addition using a generalised version of Riemann's relations:

$$\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{i+t}(z_{P+Q+R})\vartheta_{j+t}(z_P)\Big).\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{k+t}(z_Q)\vartheta_{l+t}(z_R)\Big)=$$

$$\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{-i'+t}(z_0)\vartheta_{j'+t}(z_{Q+R})\Big).\Big(\sum_{t\in Z(\overline{2})}\chi(t)\vartheta_{k'+t}(z_{P+R})\vartheta_{l'+t}(z_{P+Q})\Big).$$

$\square$

Three way addition in dimension 1 level 2

Algorithm

Input *The points* $x, y, z, X = y + z, Y = x + z, Z = x + y$*;*

Output $T = x + y + z$.

Return

$$T_0 = \frac{(aX_0 + bX_1)(Y_0Z_0 + Y_1Z_1)}{x_0(y_0z_0 + y_1z_1)} + \frac{(aX_0 - bX_1)(Y_0Z_0 - Y_1Z_1)}{x_0(y_0z_0 - y_1z_1)}$$

$$T_1 = \frac{(aX_0 + bX_1)(Y_0Z_0 + Y_1Z_1)}{x_1(y_0z_0 + y_1z_1)} - \frac{(aX_0 - bX_1)(Y_0Z_0 - Y_1Z_1)}{x_1(y_0z_0 - y_1z_1)}$$

Computing the Miller function $f_{\lambda,\mu,P}((Q)-(0))$

Algorithm

Input λP, μP and Q;

Output $f_{\lambda,\mu,P}((Q)-(0))$

1. *Compute $(\lambda+\mu)P$, $Q+\lambda P$, $Q+\mu P$ using normal additions and take any affine lifts $z_{(\lambda+\mu)P}$, $z_{Q+\lambda P}$ and $z_{Q+\mu P}$;*
2. *Use a three way addition to compute $z_{Q+(\lambda+\mu)P}$;*

Return

$$f_{\lambda,\mu,P}((Q)-(0)) = \frac{\vartheta(z_Q+\lambda z_P)\vartheta(z_Q+\mu z_P)}{\vartheta(z_Q)\vartheta(z_Q+(\lambda+\mu)z_P)} \cdot \frac{\vartheta((\lambda+\mu)z_P)\vartheta(z_P)}{\vartheta(\lambda z_P)\vartheta(\mu z_P)}.$$

Lemma

The result does not depend on the choice of affine lifts in Step 2.

- ☺ This allows us to evaluate the Weil and Tate pairings and derived pairings;
- ☹ Not possible *a priori* to apply this algorithm in level 2.

The Tate pairing with Miller's functions and theta coordinates

- Let $P \in A[\ell](\mathbb{F}_{q^d})$ and $Q \in A(\mathbb{F}_{q^d})$; choose any lift z_P, z_Q and z_{P+Q}.
- The algorithm loop over the binary expansion of ℓ, and at each step does a doubling step, and if necessary an addition step.

Given	$z_{\lambda P}$, $z_{\lambda P+Q}$;
Doubling	Compute $z_{2\lambda P}$, $z_{2\lambda P+Q}$ using two differential additions;
Addition	Compute $(2\lambda+1)P$ and take an arbitrary lift $z_{(2\lambda+1)P}$. Use a three way addition to compute $z_{(2\lambda+1)P+Q}$.

- At the end we have computed affine points $z_{\ell P}$ and $z_{\ell P+Q}$. Evaluating the Miller function then gives exactly the quotient of the projective factors between $z_{\ell P}$, z_0 and $z_{\ell P+Q}$, z_Q.

☺ Described this way can be extended to level 2 by using compatible additions;

☹ Three way additions and normal (or compatible) additions are quite cumbersome, is there a way to only use differential additions?

The Weil and Tate pairing with theta coordinates (Lubicz-R. [LR10])

Using directly the formula for $f_{\ell,P}(z)$ we get that the Weil and Tate pairings are given by

$$e_{W,\ell}(P,Q) = \frac{\vartheta(z_Q + \ell z_P)\vartheta(0)}{\vartheta(z_Q)\vartheta(\ell z_P)} \frac{\vartheta(z_P)\vartheta(\ell z_Q)}{\vartheta(z_P + \ell z_Q)\vartheta(0)}$$

$$e_{T,\ell}(P,Q) = \frac{\vartheta(z_Q + \ell z_P)\vartheta(0)}{\vartheta(z_Q)\vartheta(\ell z_P)}$$

The Weil and Tate pairing with theta coordinates (Lubicz-R. [LR10])

P and Q points of ℓ-torsion.

$$
\begin{array}{ccccc}
z_0 & z_P & 2z_P & \ldots & \ell z_P = \lambda_P^0 z_0 \\
z_Q & z_P \oplus z_Q & 2z_P + z_Q & \ldots & \ell z_P + z_Q = \lambda_P^1 z_Q \\
2z_Q & z_P + 2z_Q & & & \\
\ldots & \ldots & & & \\
\ell Q = \lambda_Q^0 0_A & z_P + \ell z_Q = \lambda_Q^1 z_P & & &
\end{array}
$$

- $e_{W,\ell}(P,Q) = \frac{\lambda_P^1 \lambda_Q^0}{\lambda_P^0 \lambda_Q^1}$.
- $e_{T,\ell}(P,Q) = \frac{\lambda_P^1}{\lambda_P^0}$.

Why does it work?

$$
\begin{array}{ccccc}
z_0 & \alpha z_P & \alpha^4(2z_P) & \dots & \alpha^{\ell^2}(\ell z_P) = \lambda'^0_P z_0 \\
\beta z_Q & \gamma(z_P \oplus z_Q) & \frac{\gamma^2\alpha^2}{\beta}(2z_P+z_Q) & \dots & \frac{\gamma^\ell \alpha^{\ell(\ell-1)}}{\beta^{\ell-1}}(\ell z_P+z_Q) = \lambda'^1_P \beta z_Q \\
\beta^4(2z_Q) & \frac{\gamma^2\beta^2}{\alpha}(z_P+2z_Q) & & & \\
\dots & \dots & & & \\
\beta^{\ell^2}(\ell z_Q) = \lambda'^0_Q z_0 & \frac{\gamma^\ell \beta^{\ell(\ell-1)}}{\alpha^{\ell-1}}(z_P+\ell z_Q) = \lambda'^1_Q \alpha z_P & & &
\end{array}
$$

We then have

$$
\lambda'^0_P = \alpha^{\ell^2}\lambda^0_P, \quad \lambda'^0_Q = \beta^{\ell^2}\lambda^0_Q, \quad \lambda'^1_P = \frac{\gamma^\ell \alpha^{(\ell(\ell-1))}}{\beta^\ell}\lambda^1_P, \quad \lambda'^1_Q = \frac{\gamma^\ell \beta^{(\ell(\ell-1))}}{\alpha^\ell}\lambda^1_Q,
$$

$$
e'_{W,\ell}(P,Q) = \frac{\lambda'^1_P \lambda'^0_Q}{\lambda'^0_P \lambda'^1_Q} = \frac{\lambda^1_P \lambda^0_Q}{\lambda^0_P \lambda^1_Q} = e_{W,\ell}(P,Q),
$$

$$
e'_{T,\ell}(P,Q) = \frac{\lambda'^1_P}{\lambda'^0_P} = \frac{\gamma^\ell}{\alpha^\ell \beta^\ell}\frac{\lambda^1_P}{\lambda^0_P} = \frac{\gamma^\ell}{\alpha^\ell \beta^\ell} e_{T,\ell}(P,Q).
$$

Ate pairing

- Let $P \in G_2 = A[\ell] \bigcap \mathrm{Ker}(\pi_q - [q])$ and $Q \in G_1 = A[\ell] \bigcap \mathrm{Ker}(\pi_q - 1)$; $\lambda \equiv q \mod \ell$.
- In projective coordinates, we have $\pi_q^d(P+Q) = \lambda^d P + Q = P + Q$;
- Of course, in affine coordinates, $\pi_q^d(z_{P+Q}) \neq \lambda^d z_P + z_Q$.
- But if $\pi_q(z_{P+Q}) = C * (\lambda z_P + z_Q)$, then C is exactly the (non reduced) ate pairing (up to a renormalisation)!

Algorithm (Computing the ate pairing)

Input $P \in G_2$, $Q \in G_1$;

1. *Compute $z_Q + \lambda z_P$, λz_P using differential additions;*
2. *Find the projective factors C_1 and C_0 such that $z_Q + \lambda z_P = C_1 * \pi(z_{P+Q})$ and $\lambda z_P = C_0 * \pi(z_P)$ respectively;*

Return $(C_1/C_0)^{\frac{q^d-1}{\ell}}$.

Optimal ate pairing

- Let $\lambda = m\ell = \sum c_i q^i$ be a multiple of ℓ with small coefficients c_i. ($\ell \nmid m$)
- The pairing

$$\begin{aligned} a_\lambda : G_2 \times G_1 &\longrightarrow \mu_\ell \\ (P,Q) &\longmapsto \left(\prod_i f_{c_i,P}(Q)^{q^i} \prod_i f_{\sum_{j>i} c_j q^j, c_i q^i, P}(Q) \right)^{(q^d-1)/\ell} \end{aligned}$$

  is non degenerate when $mdq^{d-1} \not\equiv (q^d-1)/r \sum_i i c_i q^{i-1} \mod \ell$.
- Since $\varphi_d(q) = 0 \mod \ell$ we look at powers $q, q^2, \ldots, q^{\varphi(d)-1}$.
- We can expect to find λ such that $c_i \approx \ell^{1/\varphi(d)}$.

Optimal ate pairing with theta functions

Algorithm (Computing the optimal ate pairing)

Input $\pi_q(P) = [q]P$, $\pi_q(Q) = Q$, $\lambda = m\ell = \sum c_i q^i$;

1. *Compute the* $z_Q + c_i z_P$ *and* $c_i z_P$*;*
2. *Apply Frobeniuses to obtain the* $z_Q + c_i q^i z_P$, $c_i q^i z_P$*;*
3. *Compute* $c_i q^i z_P \oplus \sum_j c_j q^j z_P$ *(up to a constant) and then do a three way addition to compute* $z_Q + c_i q^i z_P + \sum_j c_j q^j z_P$ *(up to the same constant);*
4. *Recurse until we get* $\lambda z_P = C_0 * z_P$ *and* $z_Q + \lambda z_P = C_1 * z_Q$*;*

Return $(C_1/C_0)^{\frac{q^d-1}{\ell}}$.

The case $n=2$

- If $n=2$ we work over the Kummer variety K over k, so $e(P,Q) \in \overline{k}^{*,\pm 1}$.
- We represent a class $x \in \overline{k}^{*,\pm 1}$ by $x + 1/x \in \overline{k}^{*}$. We want to compute the symmetric pairing

$$e_s(P,Q) = e(P,Q) + e(-P,Q).$$

- From $\pm P$ and $\pm Q$ we can compute $\{\pm(P+Q), \pm(P-Q)\}$ (need a square root), and from these points the symmetric pairing.
- e_s is compatible with the $\mathbb{Z}$-structure on K and $\overline{k}^{*,\pm 1}$.
- The $\mathbb{Z}$-structure on $\overline{k}^{*,\pm}$ can be computed as follow:

$$(x^{\ell_1+\ell_2} + \frac{1}{x^{\ell_1+\ell_2}}) + (x^{\ell_1-\ell_2} + \frac{1}{x^{\ell_1-\ell_2}}) = (x^{\ell_1} + \frac{1}{x^{\ell_1}})(x^{\ell_2} + \frac{1}{x^{\ell_2}})$$

Optimal pairings on Kummer varieties

- Computing $c_i q^i z_P \pm \sum_j c_j q^j z_P$ requires a square root (very costly);
- And we need to recognize $c_i q^i z_P + \sum_j c_j q^j z_P$ from $c_i q^i z_P - \sum_j c_j q^j z_P$.
- We will use compatible additions: if we know x, y, z and $x+z$, $y+z$, we can compute $x+y$ without a square root;
- We apply the compatible additions with $x = c_i q^i z_P$, $y = \sum_j c_j q^j z_P$ and $z = z_Q$.

Compatible additions

- Recall that we know x, y, z and $x+z$, $y+z$;
- From it we can compute $(x+z)\pm(y+z)=\{x+y+2z, x-y\}$ and of course $\{x+y, x-y\}$;
- Then $x+y$ is the element in $\{x+y, x-y\}$ not appearing in the preceding set;
- Since $x-y$ is a common point, we can recover it without computing a square root.

The compatible addition algorithm in dimension 1

Algorithm

Input $x, y, Y = x+z, X = y+z$;

1. *Computing* $x \pm y$:

$$\alpha = (x_0^2 + x_1^2)(y_0^2 + y_1^2)/A$$
$$\beta = (x_0^2 - x_1^2)(y_0^2 - y_1^2)/B$$
$$\kappa_{00} = (\alpha + \beta), \kappa_{11} = (\alpha - \beta)$$
$$\kappa_{10} := x_0 x_1 y_0 y_1 / ab$$

2. *Computing* $(x+z) \pm (y+z)$:

$$\alpha' = (Y_0^2 + Y_1^2)(X_0^2 + X_1^2)/A$$
$$\beta' = (Y_0^2 - Y_1^2)(X_0^2 - X_1^2)/B$$
$$\kappa'_{00} = \alpha' + \beta', \kappa'_{11} = \alpha' - \beta'$$
$$\kappa'_{10} = Y_1 Y_2 X_1 X_2 / ab$$

Return $x + y = [\kappa_{00}(\kappa_{10}\kappa'_{00} - \kappa'_{10}\kappa_{00}), \kappa_{10}(\kappa_{10}\kappa'_{00} - \kappa'_{10}\kappa_{00}) + \kappa_{00}(\kappa_{11}\kappa'_{00} - \kappa'_{11}\kappa_{00})]$

One step of the pairing computation

Algorithm (A step of the Miller loop with differential additions)

Input $nP=(x_n,z_n)$; $(n+1)P=(x_{n+1},z_{n+1})$, $(n+1)P+Q=(x'_{n+1},z'_{n+1})$.

Output $2nP=(x_{2n},z_{2n})$; $(2n+1)P=(x_{2n+1},z_{2n+1})$; $(2n+1)P+Q=(x'_{2n+1},z'_{2n+1})$.

1. $\alpha=(x_n^2+z_n^2)$; $\beta=\frac{A}{B}(x_n^2-z_n^2)$.
2. $X_n=\alpha^2$; $X_{n+1}=\alpha(x_{n+1}^2+z_{n+1}^2)$; $X'_{n+1}=\alpha({x'}_{n+1}^2+{z'}_{n+1}^2)$;
3. $Z_n=\beta(x_n^2-z_n^2)$; $Z_{n+1}=\beta(x_{n+1}^2-z_{n+1}^2)$; $Z'_{n+1}=\beta({x'}_{n+1}^2+{z'}_{n+1}^2)$;
4. $x_{2n}=X_n+Z_n$; $x_{2n+1}=(X_{n+1}+Z_{n+1})/x_P$; $x'_{2n+1}=(X'_{n+1}+Z'_{n+1})/x_Q$;
5. $z_{2n}=\frac{a}{b}(X_n-Z_n)$; $z_{2n+1}=(X_{n+1}-Z_{n+1})/z_p$; $z'_{2n+1}=(X'_{n+1}-Z'_{n+1})/z_Q$;

Return (x_{2n},z_{2n}); (x_{2n+1},z_{2n+1}); (x'_{2n+1},z'_{2n+1}).

Weil and Tate pairing over $\mathbb{F}_{q^d}$

$g=1$	$4\mathbf{M}+2\mathbf{m}+8\mathbf{S}+3\mathrm{m}_0$
$g=2$	$8\mathbf{M}+6\mathbf{m}+16\mathbf{S}+9\mathrm{m}_0$

Table: Tate pairing with theta coordinates, $P,Q \in A[\ell](\mathbb{F}_{q^d})$ (one step)

Operations in $\mathbb{F}_q$: M: multiplication, S: square, m multiplication by a coordinate of P or Q, m_0 multiplication by a theta constant;

Mixed operations in $\mathbb{F}_q$ and $\mathbb{F}_{q^d}$: M, m and m_0;

Operations in $\mathbb{F}_{q^d}$: **M**, **m** and **S**.

Remark

- *Doubling step for a Miller loop with Edwards coordinates:* $9\mathbf{M}+7\mathbf{S}+2\mathrm{m}_0$;
- *Just doubling a point in Mumford projective coordinates using the fastest algorithm [HC]:* $21\mathbf{M}+12\mathbf{S}+2\mathbf{m}_0$.
- *Asymptotically the final exponentiation is more expensive than Miller's loop, so the Weil's pairing is faster than the Tate's pairing!*

Tate pairing

$g=1$	$1\mathbf{m}+2\mathbf{S}+2\mathrm{M}+2M+1m+6S+3m_0$
$g=2$	$3\mathbf{m}+4\mathbf{S}+4\mathrm{M}+4M+3m+12S+9m_0$

Table: Tate pairing with theta coordinates, $P \in A[\ell](\mathbb{F}_q), Q \in A[\ell](\mathbb{F}_{q^d})$ (one step)

		Miller		Theta coordinates
		Doubling	Addition	One step
$g=1$	d even	$1\mathbf{M}+1\mathbf{S}+1\mathrm{M}$	$1\mathbf{M}+1\mathrm{M}$	$1\mathbf{M}+2\mathbf{S}+2\mathrm{M}$
	d odd	$2\mathbf{M}+2\mathbf{S}+1\mathrm{M}$	$2\mathbf{M}+1\mathrm{M}$	
$g=2$	Q degenerate + d even	$1\mathbf{M}+1\mathbf{S}+3\mathrm{M}$	$1\mathbf{M}+3\mathrm{M}$	$3\mathbf{M}+4\mathbf{S}+4\mathrm{M}$
	General case	$2\mathbf{M}+2\mathbf{S}+18\mathrm{M}$	$2\mathbf{M}+18\mathrm{M}$	

Table: $P \in A[\ell](\mathbb{F}_q)$, $Q \in A[\ell](\mathbb{F}_{q^d})$ (counting only operations in $\mathbb{F}_{q^d}$).

Ate and optimal ate pairings

$g = 1$	$4\mathbf{M} + 1\mathbf{m} + 8\mathbf{S} + 1\mathrm{m} + 3\mathrm{m}_0$
$g = 2$	$8\mathbf{M} + 3\mathbf{m} + 16\mathbf{S} + 3\mathrm{m} + 9\mathrm{m}_0$

Table: Ate pairing with theta coordinates, $P \in G_2, Q \in G_1$ (one step)

Remark

Using affine Mumford coordinates in dimension 2, the hyperelliptic ate pairing costs [GHO+07]:

Doubling $1\mathbf{I} + 29\mathbf{M} + 9\mathbf{S} + 7\mathrm{M}$

Addition $1\mathbf{I} + 29\mathbf{M} + 5\mathbf{S} + 7\mathrm{M}$

(where $\mathbf{I}$ *denotes the cost of an affine inversion in* $\mathbb{F}_{q^d}$*).*

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