Weil Conjectures

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1 Notes from Daniel's Office Hours

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    3. Medium example: E/k an elliptic curve.
    4. Work out a harder example as in Weil

1.1 Definition of Zeta Function

Fix q a prime and $\mathbb{F} := \mathbb{F}_q$ the finite field with q elements, along with its unique degree n extensions

$$\mathbb{F}_n := \mathbb{F}_{q^n} = \left\{ x \in \bar{\mathbb{F}}_p \ \middle|\ x^{q^n} - x = 0 \right\} \quad \forall\ n \in \mathbb{Z}^{\geq 2}$$

> **Definition 1.0.1.**
> Let
>
> $$J = \langle f_1, \cdots, f_N \rangle \trianglelefteq k[x_0, \cdots, x_n]$$
>
> be an ideal, then a *projective algebraic* variety $X \hookrightarrow \mathbb{P}^\infty_{\mathbb{F}}$ can be given by
>
> $$X = V(J) = \left\{ \mathbf{x} \in \mathbb{P}^\infty_{\mathbb{F}} \ \middle|\ f_1(\mathbf{x}) = \cdots = f_N(\mathbf{x}) = \mathbf{0} \right\}$$
>
> where an ideal generated by *homogeneous* polynomials in $n + 1$ variables, i.e. there is some fixed $d \in \mathbb{Z}^{\geq 1}$ such that

$$f(\mathbf{x}) = \sum_{\substack{\mathbf{I}=(i_1,\cdots,i_n) \\ \sum_j i_j = d}} \alpha_{\mathbf{I}} \cdot x_0^{i_1} \cdots x_n^{i_n} \quad \text{and} \quad f(\lambda \cdot \mathbf{x}) = \lambda^d f(\mathbf{x}).$$

Examples:

- Dimension 1: Curves
- Dimension 2: Surfaces
- Codimension 1: Hypersurfaces

Example: Take $f_1(x) = x \in \mathbb{F}[x]$, consider $V(\langle f_1 \rangle) \subset \mathbb{P}^1_{\mathbb{F}_n}$. This is given by the single point $x = \mathbf{0}$.

Fix $X/\mathbb{F}$ an N-dimensional projective algebraic variety. Note that it then has points in any finite extension L/K.

Definition 1.0.2.
Define the *local zeta function* of X as follows:

$$\zeta_X : \mathbb{C} \longrightarrow \mathbb{C}$$

$$\zeta_X(z) = \exp\left(\sum_{n=1}^{\infty} \frac{\alpha_n}{n} z^n\right) \quad \text{where} \quad \alpha_n := \#X(\mathbb{F}_n).$$

Note the following two properties:

$$\zeta_X(0) = 1$$

$$z\left(\frac{\partial}{\partial z}\right) \log \zeta_X(z) = t\left(\frac{\zeta_X'(z)}{\zeta_X(z)}\right) = \sum_{n=1}^{\infty} \alpha_n z^n = \alpha_1 z + \alpha_2 z^2 + \cdots,$$

which is an *ordinary generating function* for the sequence (α_n).

Thus if we define $G(x)$ to be the OGF for (α_n), we have $\zeta_X(t) = \exp$

> Todo: why not an OGF.

Remark: Note that for an OGF $F(x) = \sum_{n=0}^{\infty} f_n x^n$, we can extract coefficients in the following way:

$$[x^n]F(x) = [x^n]T_{F,0}(x) = \frac{1}{n!}\left(\frac{\partial}{\partial x}\right)^n F(x)\,\Big|_{x=0}.$$

Using the Residue theorem, we can also extract in the following way:

$$[x^n]F(x) = \frac{1}{2\pi i} \oint_{\mathbb{S}^1} \frac{F(z)}{z^{n+1}}.$$

Example (Point): $X = \{x = 0\}/\mathbb{F}$ a single point over $\mathbb{F}$, then

$$\#X(\mathbb{F}) := \alpha_1 = 1$$
$$\#X(\mathbb{F}_2) := \alpha_2 = 1$$
$$\vdots$$
$$\#X(\mathbb{F}_n) := \alpha_n = 1$$
$$\vdots$$

Recall that by integrating a geometric series we can derive

$$\log(1+t) = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{t^n}{n}$$
$$\implies \log(1-t) = -\sum_{n=1}^{\infty} \frac{t^n}{n}$$
$$\implies -\log(1-t) = \sum_{n=1}^{\infty} \frac{t^n}{n}$$
$$= 1 \cdot t + 1 \cdot t^2 + 1 \cdots t^3 + \cdots .$$

and so

$$\zeta_X(t) = \exp\left(-\log\left(1-t\right)\right) = \frac{1}{1-t}.$$

Example (Affine Line): $X = \mathbb{A}^1/\mathbb{F}$ the affine line over $\mathbb{F}$, then

$$X(\mathbb{F}) = q$$
$$X(\mathbb{F}_2) = q^2$$
$$\vdots$$
$$X(\mathbb{F}_n) = q^n$$
$$.$$

where we just note that we can write $\mathbb{A}^1(\mathbb{F}_n) = \left\{(x_1) \mid x_1 \in \mathbb{F}_n\right\}$.

Example (Projective Line): $X = \mathbb{P}^1/\mathbb{F}$ the projective line over $\mathbb{F}$, then

$$X(\mathbb{F}) = q + 1$$
$$X(\mathbb{F}_2) = q^2 + 1$$
$$\vdots$$
$$X(\mathbb{F}_n) = q^n + 1$$
$$.$$

where we write $\mathbb{P}^1_{\mathbb{F}} = \mathbb{A}^1_{\mathbb{F}} \coprod \{\infty\}$ is the affine line with a point at infinity. We can also count by coordinates:

$$\mathbb{P}^1(\mathbb{F}^n) = \left\{ [x_1, x_2] \mid x_1, x_2 \neq 0 \in \mathbb{F}^n \right\} / \sim \qquad = \left\{ [x_1, 1] \mid x_1 \in \mathbb{F}^n \right\} \coprod \{[1, 0]\}.$$

Example (Affine Space): Take $X = \mathbb{A}^n/\mathbb{F}$, then $\alpha_n = q^m + 1$ for a point at infinity, so

$$X(\mathbb{F}) = .$$

Thus

$$\zeta_X(t) = \frac{1}{(1 - q^{-t})(1 - q^{1-t})}$$

.

Example (Projective Space): Take $X = \mathbb{P}^n_{\mathbb{F}}$, then $\alpha_n = 1 + q^m + (q^m)^2 + \cdots + (q^m)^n$, so

$$\zeta_X(t) = \left(\frac{1}{1 - q^{-t}} \right) \left(\frac{1}{1 - q^{1-t}} \right) \left(\frac{1}{1 - q^{2-t}} \right) \cdots \left(\frac{1}{q^{n-t}} \right)$$

,

or equivalently, take your favorite curve $\gamma \in \mathbb{C}$ homotopic to $\mathbb{S}^1$.

> Note: this is extremely amenable to numerical approximation if you have a closed form for F or even just a black-box numerical version of F! I.e. easy to throw at a computer.

> Todo: how to manually count points in $\mathbb{P}^n$!

Example: Take $X = \mathrm{Gr}_{\mathbb{F}}(k, n)$, then ????? so

$$\zeta_X(t) = ?.$$

Questions about properties

- $\zeta_{X \coprod Y}(t) =_? \zeta_X(t)\zeta_Y(t)$?
- $\zeta_{X \times Y} = ?$

1.2 Statement of Weil Conjectures

1. (Rationality)

$$\zeta_X(t) = \frac{p_1(t)p_3(t) \cdots p_{2N-1}(t)}{p_0(t)p_2(t) \cdots p_N(t)} \in \mathbb{Z}(t), \quad \text{i.e.} \quad p_i(t) \in \mathbb{Z}[t]$$

$$P_0(t) = 1 - t$$
$$P_{2n}(t) = 1 - q^n t$$
$$P_i(t) = \prod_j (1 - a_{ij}t), \quad a_{ij} \in \mathbb{C}.$$

2. (Functional Equation and Poincare Duality)

$$\zeta_X(n - t) = \pm q^{\frac{1}{2}(nE) - Et}\zeta(x, t).$$

3. (Riemann Hypothesis)
4. (Betti Numbers)

1.3 Hard Example: An Elliptic Curve

Take $X = E/\mathbb{F}$, then $\alpha_n = q^n - (a^n + \bar{a}^n - 1)$ where $|a|_{\mathbb{C}} = |\bar{\alpha}|_{\mathbb{C}} = \sqrt{q}$. Then

$$\zeta_X(t) = \frac{(1 - aq^{-t})(1 - \bar{a}q^{-t})}{(1 - q^{-t})(1 - q^{1-s})}.$$