

Motivic Zeta Function

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1 Introduction

In 1949 André Weil, in the paper "Number of solutions of equations in finite fields", formulated his famous Weil-Conjectures which predicted certain deep properties of the Hasse-Weil zeta function for a Variety X over a finite field $k = \mathbb{F}_q$ defined as

$$Z(X, t) = \exp\left(\sum_{m=0}^{\infty} \frac{|X(\mathbb{F}_{q^m})|}{m} t^m\right)$$

The rationality of the zeta function, the most basic of the three conjectures, was first established by Dwork. Grothendieck later gave another proof using his new scheme-theoretic approach to algebraic geometry. Grothendieck's revolutionary new perspective was fundamental for the work of Deligne, who used these new methods to finally establish the last part of the conjectures, an analogue of the Riemann hypothesis, in 1974. In [Kap00] Kapranov generalized the Hasse-Weil zeta function, defining it not only for varieties over finite fields but varieties in general. It turns out that in this more general setting the zeta function isn't as well behaved in terms of rationality as the "classical" Hasse-Weil zetafunction and we will investigate this phenomenon more closely in the case of complex surfaces, following the work of Larsen and Lunts in [LL03].

Definition 1. In the following the term *k-variety* always means a separated, integral scheme of finite type over a field k . We will write \mathcal{V}_k for the category of k -varieties.

We now want to motivate what the "right" generalization of the Hasse-Weil zeta function for varieties over an arbitrary field k should be. This part therefore, in some places, sacrifices mathematical precision for the sake of brevity. We still give citations for most of the results and will of course develop everything that is important for the presentation and proof of our main result in later sections in full detail.

Two things don't generalize easily: the passing to bigger and bigger extensions of the ground field k (what if k is algebraically closed, for example?), and counting k -rational points (again, if $k = \bar{k}$ there are, in general, a lot of k -rational points).

To see what could be generalizations for these phenomena, we give another equivalent definition of the Hasse-Weil zeta function in terms of effective 0-cycles. Recall that a 0-cycle on a Variety X is an element of the free abelian group over the closed points of X . Such a cycle $\alpha = \sum_i n_i x_i$ is called *effective* if the n_i are greater than or equal to zero. The *degree* of α is given by $\deg(\alpha) = \sum_i n_i \deg(x_i)$ ($\deg(x_i)$ being the degree of the field extension $k(x_i)/k$).

Using this notation we can rewrite the zeta function as follows

$$Z(X, t) = \sum_{\alpha} t^{\deg(\alpha)} \quad (1)$$

Where the sum ranges over all 0-cycles on X . (For a proof of this (elementary) identity see for example Mustaș's great notes on zeta functions in algebraic geometry [Mus, Remark 2.9])

This definition still does not easily generalize, since for example $\mathbb{A}_{\mathbb{C}}^1$ has infinitely many 0-cycles of degree n .

But counting degree zero cycles of a given degree n , is the same as counting k -rational points of the n -fold symmetric product of the variety X (denoted by $Sym^n(X)$). We won't formally introduce the symmetric product until later, but thinking of it as the quotient of the n -fold product of X with itself by the natural action of the symmetric group in n letters gives the right intuition. For k algebraically closed, the bijection is obvious, since then the k -rational points are exactly the closed points. Dividing out by the action of the symmetric product hence introduces the commutativity-relations we have if we consider formal sums of such closed points. This intuition carries over for the case of finite fields, hence we get

$$Z(X, t) = \sum_n |Sym^n(X)(k)| t^n \quad (2)$$

So, in some rough sense, we are "measuring" the size of bigger and bigger symmetric products of X , so we expect the symmetric product to make an appearance in our generalized zeta function, taking the role of counting solutions over bigger and bigger field-extensions.

We now collect some properties of counting rational points of a variety over a finite field, that will guide our definition for "measures" of the symmetric product.

Remark 2. For a finite field k , consider the function ¹

$$\begin{aligned} \psi : \mathcal{V}_k &\rightarrow \mathbb{Z} \\ X &\mapsto |X(k)| \end{aligned}$$

1. If X and Y are isomorphic k -varieties, then $\psi(X) = \psi(Y)$
2. If $Y \subset X$ is closed subvariety, then $\psi(X \setminus Y) = \psi(X) - \psi(Y)$ (This essentially gives the equation $Z(X \setminus Y, t) = \frac{Z(X, t)}{Z(Y, t)}$)
3. If X and Y are two varieties, then $\psi(X \times Y) = \psi(X)\psi(Y)$ (This gives, for example, the identity $Z(X \times \mathbb{A}_k^n, t) = Z(X, q^n t)$)

¹not bothering with any set-theoretic issues

2 The Grothendieck Ring of Varieties and Motivic Measures

We now construct the Grothendieck ring of varieties as the universal ring over which any map with these properties factors as a ring homomorphism. Then our generalized measures will simply be ring homomorphisms out of this universal ring.

Definition 3. Let k be a perfect field.² Consider the abelian group of formal linear combinations of isomorphism classes of varieties, subject to relations of the form

$$[X \setminus Y] = [X] - [Y]$$

where Y is closed in X . With multiplication given by

$$[X][Y] = [X \times Y]$$

this forms a ring, called the *Grothendieck ring of varieties* and denoted by $K_0[\mathcal{V}_k]$.

A *motivic measure* with values in a ring A is a ring homomorphism $\mu : K_0[\mathcal{V}_k] \rightarrow A$. The identity function $id : K_0[\mathcal{V}_k] \rightarrow K_0[\mathcal{V}_k]$ is called the *universal motivic measure*.

Since the product is commutative up to isomorphism this is a commutative ring with 1 (equal to $[\text{Spec}(k)]$). The cut and paste relation furthermore gives us

$$0 = [\emptyset] - [\emptyset] = [\emptyset \setminus \emptyset] = [\emptyset]$$

Example 4. Using the decomposition $\mathbb{P}_k^n = \mathbb{P}_k^{n-1} \coprod \mathbb{A}_k^n$ where \mathbb{P}_k^{n-1} is a (closed) hyperplane in \mathbb{P}_k^n we get $[\mathbb{P}_k^n] = [\mathbb{P}_k^{n-1}] + [\mathbb{A}_k^n]$ in the Grothendieck ring. Inductively this yields the identity

$$[\mathbb{P}_k^n] = \sum_{m=0}^n [\mathbb{A}_k^1]^m$$

We also denote the isomorphism class of the affine line as \mathbb{L} .

Remark 5. By [Har77, Proposition 10.1 (d)] the product of two smooth varieties over k is again smooth. Hence the isomorphism classes of smooth irreducible complete varieties form a multiplicative monoid, in the following denoted by \mathcal{M} .

²The definition can be altered to make sense even if k isn't perfect, in this case we just have to account for the fact that the product of two varieties need not be reduced. But since all our applications are either over finite fields or in characteristic zero this slight loss of generality won't affect us.

3 Symmetric Products and the Motivic Zeta Function

Definiton 6. Let $\mu : K_0[\mathcal{V}_k] \rightarrow A$ be a motivic measure and X a variety. Then we define the *motivic zeta function* $\zeta_\mu(X, t) \in A[[t]]$ as

$$\zeta_\mu(X, t) := \sum_{n=0}^{\infty} \mu([Sym^n(X)]) t^n$$

Example 7. We can now compute a first zeta function, namely $\zeta_{id}(\mathbb{P}_k^1, t)$. Using the identity and notation from example 4 we calculate

$$\begin{aligned} \zeta_{id}(\mathbb{P}_k^1, t) &= \sum_{n=0}^{\infty} [Sym^n(\mathbb{P}_k^1)] t^n \\ &= \sum_{n=0}^{\infty} \left(\sum_{k=0}^n \mathbb{L}^k \right) t^n \\ &= \sum_{n=0}^{\infty} \sum_{k=0}^n (\mathbb{L}t)^k t^{n-k} \\ &= \left(\sum_{n=0}^{\infty} t^n \right) \left(\sum_{n=0}^{\infty} (\mathbb{L}t)^n \right) \\ &= \frac{1}{(1-t)(1-\mathbb{L}t)} \end{aligned}$$

Hence $\zeta_{id}(\mathbb{P}_k^1, t)$ is in fact a rational function.

Kapranov proves in [Kap00] that the zeta function of a curve with coefficients in a field is in fact always rational. In their paper [LL03] Larsen and Lunts prove that in the case of surfaces this is false in general. Later the same authors gave a more precise characterisation when the zeta function of a complex surface is rational (namely if and only if the Kodaira dimension is $-\infty$. See [LL04]).

We will prove the following statement from [LL03]

Theorem 8. Assume that $k = \mathbb{C}$. There exists a field \mathcal{H} and a motivic measure $\mu : K_0[\mathcal{V}_k] \rightarrow \mathcal{H}$ with the following property: if X is a smooth complex projective surface such that $P_g(X) = h^{2,0}(X) \geq 2$, then the zeta-function $\zeta_\mu(X, t)$ is not rational.

4 Constructing Motivic Measures

The first important result on the way to prove this is a structure theorem for $K_0[\mathcal{V}_{\mathbb{C}}]$.

Theorem 9. Set $k = \mathbb{C}$. Let G be an abelian commutative monoid and $\mathbb{Z}[G]$ be the corresponding monoid ring. As above, denote by \mathcal{M} the multiplicative monoid of irreducible smooth complete varieties. Let

$$\psi : \mathcal{M} \rightarrow G$$

be a homomorphism of monoids such that

(i) $\psi([X]) = \psi([Y])$ if X and Y are birational;

(ii) $\psi([\mathbb{P}^n]) = 1$ for all $n \geq 0$.

Then ψ can be uniquely extended to a ring homomorphism

$$\phi : K_0[\mathcal{V}_{\mathbb{C}}] \rightarrow \mathbb{Z}[G]$$

To prove this result we will use a result by Bittner.

Theorem 10 (Bittner, [Bit04, Theorem 3.1]). *The Grothendieck group $K_0[\mathcal{V}_{\mathbb{C}}]$ is generated by classes of smooth complete varieties subject to relations of the form*

$$[X] - [f^{-1}(Z)] = [Y] - [Z]$$

where X, Y are smooth complete varieties and $f : X \rightarrow Y$ is a morphism which is a blowup with a smooth center $Z \subset Y$.

Proof of theorem 9. We have to check that ψ preserves the above relations, i.e. that $\psi([X]) - \psi([f^{-1}(Z)]) = \psi([Y]) - \psi([Z])$. But $[X]$ and $[Y]$ are birational since f is a blowup. (WHY?) Now $f^{-1}(Z)$ is birational to $Z \times \mathbb{P}^n$ (WHY??) and thus

$$\psi([f^{-1}(Z)]) = \psi([Z \times \mathbb{P}^n]) = \psi([Z][\mathbb{P}^n]) = \psi([Z])\psi([\mathbb{P}^n]) = \psi([Z])$$

Hence we can linearly extend ψ to define the morphism $\phi : K_0[\mathcal{V}_{\mathbb{C}}] \rightarrow \mathbb{Z}[G]$ \square

5 Irrationality

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