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Some Consequences of the Riemann Hypothesis for Varieties over Finite Fields

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Abstract. We deduce from Deligne's form of the Riemann hypothesis and the hard Lefschetz theorem in ℓ-adic cohomology the corresponding facts for any "reasonable" cohomology theory, in particular for crystalline cohomology, and give some applications to algebraic cycles.

I.

Let X be a projective smooth absolutely irreducible variety of dimension n over $\mathbb{F}_q$. Fix a prime number $\ell \neq p = \operatorname{char}(\mathbb{F}_q)$, and denote by $H^i(X)$ the étale cohomology groups $H^i(\bar{X}, \mathbb{Q}_\ell)$, and by F the Frobenius relative to $\mathbb{F}_q$. For any polynomial $g(T) = \Pi(1-\alpha_i T)$, and any integer $r \geqq 1$, we denote by $g(T)^{(r)}$ the polynomial $\Pi(1-(\alpha_i)^r T)$.

Deligne has proven that:

D1. For every integer $i \geqq 0$, the polynomial

$$P^i(X/\mathbb{F}_q, T) = \det(1 - TF \mid H^i(X))$$

lies in $\mathbb{Z}[T]$, and its reciprocal zeroes all have complex absolute value $q^{i/2}$.

D2. For every integer $d \geqq 2$, and every Lefschetz pencil $\{X_t\}_{t \in \mathbb{P}^1}$ of hypersurface sections of degree d of X, the polynomial $P^{n-1}(X/\mathbb{F}_q, T)$ may be reconstructed as the least common multiple of all complex polynomials $f(T)$ such that whenever $t \in \mathbb{F}_{q^r}$ is a parameter value such that X_t is smooth, the polynomial $f(T)^{(r)}$ divides $P^{n-1}(X_t/\mathbb{F}_{q^r}, T)$.

D3. Let $L \in H^2(X)$ denote the class of a hyperplane. Then for $i \leqq n$, $L^i\colon H^{n-i}(X) \to H^{n+i}(X)$ is an isomorphism.

We should point out that although D3 is a *consequence* of D2 in any "reasonable" theory (as we shall see), Deligne *deduced* D2 from D3 via his monodromy techniques.

II.

Now let $\mathscr{H}$ be any cohomology theory defined for projective smooth absolutely irreducible varieties over finite extensions of $\mathbb{F}_p$ with values in finite-dimensional graded anticommutative algebras over a coefficient field K of characteristic zero, which satisfies

Poincaré Duality. Let $X/\mathbb{F}_q$ be as above, $n = \dim X$. Then $\mathscr{H}^{2n}(X)$ is one-dimensional, $\mathscr{H}^i(X) \otimes \mathscr{H}^{2n-i} \to \mathscr{H}^{2n}(X)$ is a perfect pairing, and

Frobenius F relative to $\mathbb{F}_q$ acts as multiplication by q^n [this implies that F is an *automorphism* of each $\mathscr{H}^i(X)$].

Weak Lefschetz. Given X, there is an integer $d_0 = d_0(X)$ such that if $f\colon Y \hookrightarrow X$ is any smooth hypersurface section of X of degree $d \geqq d_0$, then $f^*\colon \mathscr{H}^i(X) \to \mathscr{H}^i(Y)$ is an *isomorphism* for $i \leqq n-2$, and is injective for $i = n-1$.

Zeta-Function Formula. For X as above, let

$$\mathscr{P}^i(X/\mathbb{F}_q, T) = \det\bigl(1 - TF \mid \mathscr{H}^i(X)\bigr).$$

Then the zeta function $Z(X/\mathbb{F}_q, T)$ is given by the formula

$$Z(X/\mathbb{F}_q, T) = \prod_{i=0}^{2n} \bigl(\mathscr{P}^i(X/\mathbb{F}_q, T)\bigr)^{(-1)^{i+1}}.$$

We should remark that ℓ-adic cohomology, $\ell \neq p$, and crystalline cohomology are such theories!

Theorem 1. *For any theory $\mathscr{H}$ as above, for every $X/\mathbb{F}_q$ as above, we have*

$$\mathscr{P}^i(X/\mathbb{F}_q, T) = P^i(X/\mathbb{F}_q, T) \quad \textit{for every } i.$$

Proof. It suffices to prove the equality after an arbitrary extension of scalars from $\mathbb{F}_q$ to $\mathbb{F}_{q^d}$, i.e. to prove that $\mathscr{P}^{i(d)} = P^{i(d)}$ for some $d \geqq 1$. For then the reciprocal zeroes of each $\mathscr{P}^i$ will be algebraic integers all of whose conjugates have complex absolute value $q^{i/2}$, and the cohomological expression of the zeta function in the theory $\mathscr{H}$ shows that for i odd (resp. for i even), the reciprocal roots of $\mathscr{P}^i$ are precisely those reciprocal zeroes (resp. poles) of the zeta function of $X/\mathbb{F}_q$ all of whose conjugates have complex absolute value $q^{i/2}$. As the reciprocal roots of P^i admit the same description, we have $\mathscr{P}^i = P^i$.

The proof proceeds by induction on $n = \dim X$. At the expense of an extension of scalars, we may choose a Lefschetz pencil $\{X_t\}$ of hypersurface sections of high $\bigl(\geqq d_0(X)\bigr)$ degree defined over $\mathbb{F}_q$, such that at least one of the sections X_{t_0}, $t_0 \in \mathbb{F}_q$, is smooth. Using the weak Lefschetz theorem in *both* theories (for $X_{t_0} \hookrightarrow X$), and induction, we have the equality $\mathscr{P}^i = P^i$ for $i \leqq n-2$, from which it follows for $i \geqq n+2$ by Poincaré duality. Again by the weak Lefschetz theorem, for every parameter value $t \in \mathbb{F}_{q^r}$ such that X_t is smooth, we have

$$\begin{array}{ccc} \mathscr{P}^{n-1}(X/\mathbb{F}_q, T)^{(r)} & \text{divides} & \mathscr{P}^{n-1}(X_t/\mathbb{F}_{q^r}, T) \\ & & \Big\| \; \text{by induction} \\ & & P^{n-1}(X_t/\mathbb{F}_{q^r}, T). \end{array}$$

Hence by D2, it follows that $\mathscr{P}^{n-1}(X/\mathbb{F}_q, T)$ divides $P^{n-1}(X/\mathbb{F}_q, T)$. By Poincaré Duality, this implies that $\mathscr{P}^{n+1}(X/\mathbb{F}_q, T)$ *divides* $P^{n+1}(X/\mathbb{F}_q, T)$.

If we equate the cohomological expressions of the zeta function of $X/\mathbb{F}_q$:

$$\Pi\left(P^i(X/\mathbb{F}_q, T)\right)^{(-1)^{i+1}} = \Pi\left(\mathscr{P}^i(X/\mathbb{F}_q, T)\right)^{(-1)^{i+1}}$$

then we may cancel the terms with $i \leqq n-2$ and $i \geqq n+2$, cross-multiply and get

$$R^{n-1} \cdot R^{n+1} = R^n \quad \text{where} \quad R^i = \frac{P^i}{\mathscr{P}^i}.$$

This shows that $\mathscr{P}^n$ *divides* P^n. By the Riemann hypothesis D1, the absolute values of the reciprocal zeroes of these three polynomials R^{n-1}, R^{n+1}, R^n are respectively $q^{\frac{n-1}{2}}$, $q^{\frac{n+1}{2}}$, $q^{\frac{n}{2}}$. Thus the equality $R^{n-1} \cdot R^{n+1} = R^n$ is impossible unless $R^{n-1} = R^{n+1} = R^n = 1$, whence $\mathscr{P}^i = P^i$ for every i. QED

Corollary 1. 1) $\dim_K \mathscr{H}^i(X) = \dim_{\mathbb{Q}_\ell} H^i(X)$.

2) *Deligne's theorems* D1, D2, D3 *hold with* H^i *and* P^i *replaced by* $\mathscr{H}^i$ *and* $\mathscr{P}^i$.

Proof. The first statement follows from the theorem by equating the *degrees* of P^i and $\mathscr{P}^i$. As D1 and D2 are statements about the P^i, they are also true for the $\mathscr{P}^i$. To conclude, we must explain how D3 follows from D2 in *any* theory $\mathscr{H}$. Let $f\colon Y \to X$ be the inclusion of a smooth hypersurface section of high degree, defined over $\mathbb{F}_{q^r}$. We must show that for $1 \leqq i \leqq n$, the bilinear form $(a, b) \mapsto a\,b\,L^i$ on $\mathscr{H}^{n-i}(X)$ is non-degenerate. For $2 \leqq i \leqq n$ this follows from D3 on Y by weak Lefschetz and the projection formula $a\,b\,L^i = f_*\left(f^*(a)\, f^*(b)\, L^{i-1}\right)$, valid because $L = f_*(1)$. Let $I = \operatorname{image}\left(f^*\colon \mathscr{H}^{n-1}(X) \to \mathscr{H}^{n-1}(Y)\right)$, and let $I^\perp \subset \mathscr{H}^{n-1}(Y)$ be its orthogonal. It remains to show that $I \cap I^\perp = 0$, i.e. that cup-product is non-degenerate on I. Consider the exact sequence

$$0 \to I \cap I^\perp \to I \oplus I^\perp \to \mathscr{H}^{n-1}(Y) \to \mathscr{H}^{n-1}(Y)/I + I^\perp \to 0.$$

Denoting by $Z(\;)$ the characteristic polynomial of Frobenius relative to $\mathbb{F}_{q^r}$, we obtain the polynomial identity

$$Z\left(\mathscr{H}^{n-1}(Y)\right) \cdot Z(I \cap I^\perp) = Z(I) \cdot Z(I^\perp) \cdot Z\left(\mathscr{H}^{n-1}(Y)/I + I^\perp\right),$$

or more conveniently.

$$(*)\quad \mathscr{P}^{n-1}(Y/\mathbb{F}_{q^r}, T) \overset{\text{dfn}}{=} Z\left(\mathscr{H}^{n-1}(Y)\right) = Z(I) \cdot Z(I^\perp/I \cap I^\perp) \cdot Z\left(\mathscr{H}^{n-1}(Y)/I + I^\perp\right).$$

Notice that $\mathscr{H}^{n-1}(Y)/I + I^\perp$ is *dual* to $I \cap I^\perp$, and $I \cap I^\perp$ is isomorphic by f^* with $\operatorname{Ker}\left(L\colon \mathscr{H}^{n-1}(X) \to \mathscr{H}^{n+1}(X)\right)$. Thus if we write

$$\det(1 - TF \mid \operatorname{Ker} L) = \Pi(1 - \alpha_i T),$$

and *define* $g(T)=\Pi(1-(q^{n-1}/\alpha_i)\,T)$, then (recalling that we are over $\mathbb{F}_{q^r}$) we obtain the formula

$$Z(\mathscr{H}^{n-1}(Y)/I+I^{\perp})=g(T)^{(r)}.$$

Again because we are over $\mathbb{F}_{q^r}$, we have

$$Z(I)=\mathscr{P}^{n-1}(X/\mathbb{F}_q,T)^{(r)}.$$

Using these last two formulas to substitute into (*), we see that $\mathscr{P}^{n-1}(Y/\mathbb{F}_{q^r},T)$ is divisible by $g(T)^{(r)}\cdot\mathscr{P}^{n-1}(X/\mathbb{F}_q,T)^{(r)}$. Replacing if necessary q by q^d, and letting Y vary in a Lefschetz pencil defined over $\mathbb{F}_{q^d}$, this contradicts D2 unless $g(T)^{(d)}=1$, i.e., unless

$$\operatorname{Ker}(L\colon \mathscr{H}^{n-1}(X)\to\mathscr{H}^{n+1}(X))$$

is *zero*. QED

Corollary (Ogus). *If $f\colon Y\hookrightarrow X$ is the inclusion of a smooth hypersurface section of any degree, then $f^*\colon \mathscr{H}^i(X)\to\mathscr{H}^i(Y)$ is an isomorphism if $i\leqq n-2$, and injective for $i=n-1$.*

Proof. By the weak Lefschetz theorem in ℓ-adic cohomology and Corollary I, 1), we know that for $i\leqq n-2$, $\dim\mathscr{H}^i(X)=\dim\mathscr{H}^i(Y)$, so it suffices to show that for $i\leqq n-1$, $f^*\colon\mathscr{H}^i(X)\to\mathscr{H}^i(Y)$ is injective. This follows from the commutative diagram

$$\begin{tikzcd} \mathscr{H}^i(X) \arrow[r, "f^*"] \arrow[drr, "L^{n-i}"'] & \mathscr{H}^i(Y) \arrow[r, "f_*"] & \mathscr{H}^{i+2}(X) \arrow[d, "L^{n-1-i}"] \\ & & \mathscr{H}^{2n-i}(X) \end{tikzcd}$$

in which the oblique arrow is an isomorphism by D3.

III. Application to Cycles

Theorem 2. 1) *Assume further that $\mathscr{H}$ is either a "Weil cohomology" in the sense of* [3], *or is crystalline cohomology tensored with the fraction field of the Witt vectors of the algebraic closure of $\mathbb{F}_q$ (in the crystalline theory, the "class of an algebraic cycle" is presently defined only for smooth subvarieties). Let X be a projective smooth absolutely irreducible variety over $\mathbb{F}_q$ of dimension n. Then the Künneth components of the diagonal Δ on $X\times X$ are rationally algebraic cycles independent of the theory $\mathscr{H}$; in fact they are $\mathbb{Q}$-linear combination of the graphs of Frobenius and its iterates.*

2) *If $\mathscr{H}$ is a Weil cohomology, then for any integrally algebraic cycle Z on $X\times X$ of codimension n, the induced endomorphism of each $\mathscr{H}^i(X)$ has a characteristic polynomial which lies in $\mathbb{Z}[T]$ and is independent*

of the theory $\mathscr{H}$. *For any integrally algebraic cycle* Z *on* $X \times X$, *the characteristic polynomial of the induced total endomorphism of* $\oplus_i \mathscr{H}^i(X)$ *lies in* $\mathbb{Z}[T]$ *and is independent of the theory* $\mathscr{H}$.

Proof. 1) By D1 and Theorem 1, it follows that the polynomials $G^i(T) = \det(T\,1 - F|\mathscr{H}^i(X))$ are pairwise relatively prime in $\mathbb{Q}[T]$. Hence for each i we can find a polynomial $\Pi^i(T) \in \mathbb{Q}[T]$ which is divisible by $G^j(T)$ for $j \neq i$, and which is congruent to 1 modulo $G^i(T)$. Letting F denote the graph of Frobenius, it follows from the Cayley-Hamilton theorem that the rationally algebraic cycle $\Pi^i(F)$ defines the endomorphism "projection onto $\mathscr{H}^i(X)$" of $\oplus_j \mathscr{H}^j(X)$. The second assertion 2) follows from 1) for any Weil cohomology, cf. [3, Prop. 2.6]. QED

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