Zeta Functions as Knot Invariants

Minh-Tâm Quang Trinh

Howard University

O. Kivinen, M. Trinh. The Hilb-vs-Quot conjecture.
Crelle's Journal (2025), 44 pp.

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2 Weil's Rosetta Stone

3 From Curves to Knots

4 Cherednik's New Hypothesis

Also featuring:

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1 The Riemann Hypothesis

(Euler ~1730s) Proof of the infinitude of primes:

If there were finitely many, then we'd have

$$\prod_{\text{prime } p > 0} \left(1 + \frac{1}{p} + \frac{1}{p^2} + \cdots\right) = \sum_{n=1}^{\infty} \frac{1}{n}.$$

But the series diverges—a contradiction.

He also implicitly studied the *zeta function*

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}.$$

For $s > 1$, we have $\zeta(s) = \prod_p \left(1 + \frac{1}{p^s} + \frac{1}{p^{2s}} + \cdots\right)$.

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What if we allow s to be complex?

(Riemann 1859) A unique $\mathbf{C}$-valued function ζ that is

- *holomorphic* (complex-differentiable) when $s \neq 1$.
- given by $\displaystyle\sum_{n=1}^{\infty} \frac{1}{n^s}$ when $\mathrm{Re}(s) > 1$.

He checked that $\zeta(s) = 0$ for $s = -2, -4, -6, \ldots$ by relating these zeros to poles of the *gamma function*.

He speculated from examples that all other zeros of ζ live on the *critical line* $\mathrm{Re}(s) = \frac{1}{2}$.

Location of zeros $\leftrightsquigarrow$ distribution of prime numbers.

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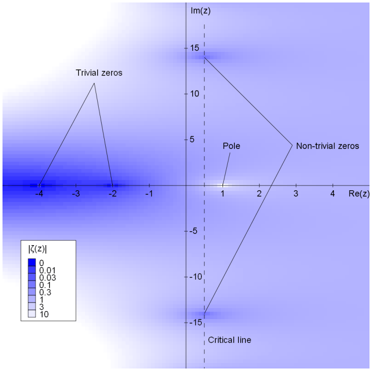

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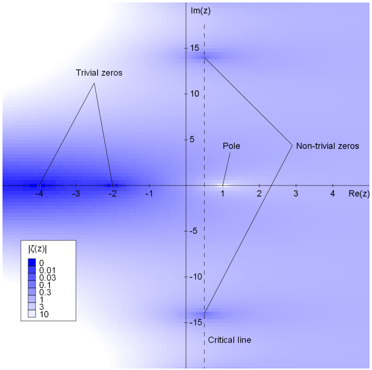

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$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$$

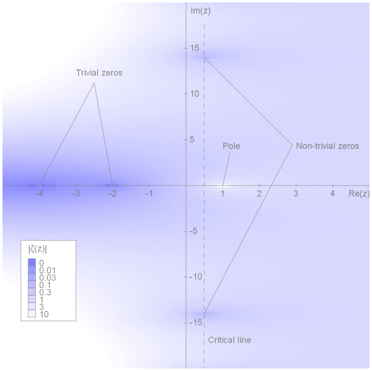
by replacing $\mathbf{Z}$ with other *rings* R.

Thus R is a set with operations resembling addition and multiplication.

$$\zeta_R(s) = \sum_{\substack{\text{ideals } I \subseteq R \\ |R/I| < \infty}} \frac{1}{|R/I|^s}$$

An *ideal* $I \subseteq R$ is the set of all linear combinations $c_{\alpha_1} x_{\alpha_1} + \cdots + c_{\alpha_k} x_{\alpha_k}$ for some given $\{x_\alpha\}_\alpha \subseteq R$.

The *quotient* R/I is the set of translates $y + I \subseteq R$.



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Note Requires that for each $n > 0$, there are finitely many I such that $|R/I| = n$.

Ex Every ideal of $\mathbf{Z}$ takes the form

$$n\mathbf{Z} = \{\text{multiples of } n\} \quad \text{for some integer } n \geq 0.$$

For instance, the ideal generated by 30 and 2025 is

$$\{c_1 30 + c_2 2025 \mid c_1, c_2 \in \mathbf{Z}\} = 15\mathbf{Z}.$$

Check that $\mathbf{Z}/0\mathbf{Z} = \mathbf{Z}$, while $|\mathbf{Z}/n\mathbf{Z}| = n$ for $n > 0$.

$$\zeta_{\mathbf{Z}}(s) = \sum_{\substack{n\mathbf{Z} \subseteq \mathbf{Z} \\ n > 0}} \frac{1}{|\mathbf{Z}/n\mathbf{Z}|^s} = \sum_{n=1}^{\infty} \frac{1}{n^s}.$$

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Why care?

(Hilbert–Pólya ~1910s) To prove RH, prove that

$$\{e^{i\gamma} \mid \tfrac{1}{2} + i\gamma \text{ is a nontrivial zero of } \zeta\}$$

is the set of eigenvalues of an infinite *unitary* matrix.

($\implies$ $e^{i\gamma}$ on the unit circle of $\mathbf{C}$ $\implies$ γ real.)

(Weil ~1940s) Fix a particular prime p.

Can we prove an analogue for ζ_R, for certain rings R appearing in *algebraic geometry* modulo p?

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2 Weil's Rosetta Stone

Algebraic geometry studies *varieties*: shapes cut out by polynomial equations.

For simplicity, we'll stick to *(affine) hypersurfaces*

$$V_f = \{\vec{a} = (a_0, a_1, \ldots, a_d) \mid f(\vec{a}) = 0\},$$

cut out by a single polynomial $f \in \mathbf{Z}[x_0, x_1, \ldots, x_d]$.

V_f is *smooth* at $\vec{a}$ mod p when $\frac{\partial f}{\partial x_j}(\vec{a}) \not\equiv 0 \pmod{p}$ for some j. Else, *singular*.

Ex For $d = 1$, hypersurfaces are plane curves.

$$f(x, y) = y^2 - x^3 - c \implies V_f = \{y^2 = x^3 + c\}$$

For which c is V_f smooth everywhere mod p?

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The *ring of polynomial functions* on V_f mod p is

$$R_{f,p} := \mathbf{F}_p[x_0, \ldots, x_d]/\bar{f}\mathbf{F}_p[x_0, \ldots, x_d],$$

where $\mathbf{F}_p := \mathbf{Z}/p\mathbf{Z}$ and $\bar{f} := f$ mod p.

In a letter to his sister, Weil described a dictionary:

$\mathbf{Z}$	$R_{f,p}$	V_f mod p
$n\mathbf{Z}$	ideals	subvarieties
$p\mathbf{Z}$	maximal ideals	points

The first and last columns = Rosetta stone between number theory and algebraic geometry.

Conj (Weil 1948) Assume V_f is smooth everywhere. Then zeros of $\zeta_{R_{f,p}}(s)$ have $\mathrm{Re}(s) \in \{\frac{1}{2}, \frac{3}{2}, \ldots, \frac{2d-1}{2}\}$.

Weil proved it for many cases.

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Recall: $\zeta_{R_{f,p}}(s) = \sum_I \frac{1}{|R_{f,p}/I|^s}$.

(Grothendieck ~1964) Introduce the variable

$$\mathsf{q} := p^{-s}.$$

There are polynomials $\phi_0, \phi_1, \ldots, \phi_{2d-1}$ such that

$$\zeta_{R_{f,p}}(s) = \frac{\phi_1(\mathsf{q}) \cdot \phi_3(\mathsf{q}) \cdots \phi_{2d-1}(\mathsf{q})}{\phi_0(\mathsf{q}) \cdot \phi_2(\mathsf{q}) \cdots \phi_{2d-2}(\mathsf{q})}.$$

ϕ_k is the charpoly of a certain operator on a certain vector space, describing the *étale topology* of V_f.

Conj For all k, the roots of $\phi_k(\mathsf{q})$ live on the <u>circle</u>

$$|\mathsf{q}| = p^{-k/2}.$$

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Ex Taking $d = 1$ and $f(x, y) = y^2 - x^3 - c$:

$$\phi_0(t) = 1 - p\mathsf{q}$$

$$\phi_1(t) = 1 - a_p\mathsf{q} + p\mathsf{q}^2 \quad \text{for some integer } a_p,$$

giving $\zeta_{R_{f,p}}(s) = \dfrac{1 - a_p p^{-s} + p^{1-2s}}{1 - p^{1-s}}$. It turns out:

- $-2p^{1/2} \leq a_p \leq 2p^{1/2}$.
- So the two roots of $\phi_1(\mathsf{q})$ satisfy $|\mathsf{q}| = p^{-1/2}$.
- So the zeros of $\zeta_{R_{f,p}}(s)$ satisfy $\mathrm{Re}(s) = \frac{1}{2}$.

In fact, Weil conjectured—and Deligne proved—results for all varieties, not just hypersurfaces.

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What if V_f has singularities?

Simplest case: $f(x, y)$ with unique singularity at $(0, 0)$. It turns out that here,

$$\zeta_{R_{f,p}}(s) = \zeta^\star_{R_{f,p}}(s) \cdot \zeta_{R^0_{f,p}}(s),$$

where:

- $\zeta^\star_{R_{f,p}}$ satisfies Weil's Riemann Hypothesis.
- $\zeta_{R^0_{f,p}}$ is analogous to $\zeta_{R_{f,p}}$, with

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in place of $R_{f,p}$. Above, $[\![\quad]\!]$ means power series.

Does $\zeta_{R^0_{f,p}}(s) = \displaystyle\sum_I \frac{1}{|R^0_{f,p}/I|^s}$ satisfy a RH?

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$$\zeta_{R^0_{f,p}}(s) = \frac{1 - p^{1-2s}}{1 - p^{-s}} = \frac{1 + p\mathsf{q}^2}{1 - \mathsf{q}}.$$

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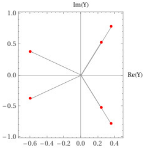
Here, not all roots satisfy $|\mathsf{q}| = p^{-1/2}$.



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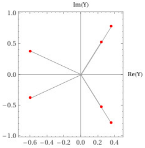

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Ex For $f = y^2 - x^3$,

$$\zeta_{R^0_{f,p}}(s) = \frac{1 - p^{1-2s}}{1 - p^{-s}} = \frac{1 + p\mathsf{q}^2}{1 - \mathsf{q}}.$$

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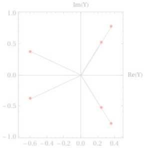

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3 From Curves to Knots

For general $f(x, y)$, it turns out there's $\Psi_f(\mathsf{t}, \mathsf{q}) \in \mathbf{Z}\left[\mathsf{t}, \mathsf{q}, \frac{1}{1-\mathsf{q}}\right]$ such that

$$\zeta_{R^0_{f,p}}(s) = \frac{\Psi_f(p, p^{-s})}{1 - p^{-s}} \quad \text{for almost all } p.$$

These polynomials have many surprising features.

(Piontkowski 2007) Take $f = y^n - x^{n+1}$.

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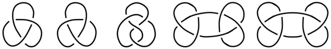
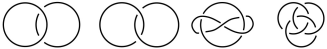
The Ψ_f also arise from *knot/link invariants*.

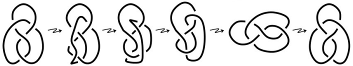
A *knot* is an embedding of a circle into $\mathbf{R}^3$ or S^3.



A *link* is a generalization allowing multiple circles.



Two links are *isotopic* when we can deform one into the other without self-intersections.



Chmutov–Duzhin–Mostovoy

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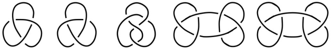

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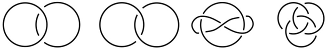

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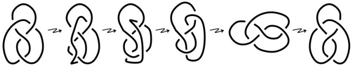

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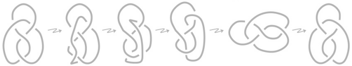

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Let $S^3_\epsilon = \{(x, y) \in \mathbf{C}^2 \mid |x|^2 + |y|^2 = \epsilon\}$. The subset

$$L_f = \{(x, y) \in S^3_\epsilon \mid f(x, y) = 0\}$$

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Wolfram Language

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Conj (Oblomkov–Shende ~2010)

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where $\mu \in \mathbf{Z}$ and $\mathbb{P}$ is the *HOMFLYPT invariant*, discovered in 1986 and defined by the *skein rules*:

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Full statement incorporates a, by upgrading Ψ_f.

(Maulik 2012) True for all plane curves.

Proof sketch Blow up the singularity repeatedly.

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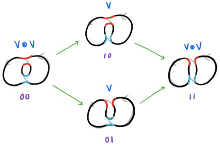

Melissa Zhang

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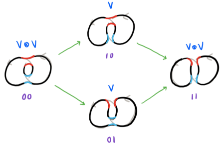

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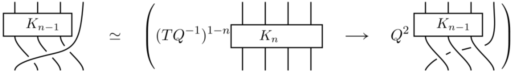

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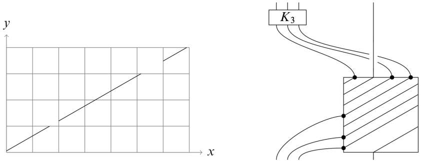

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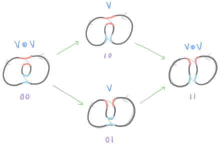

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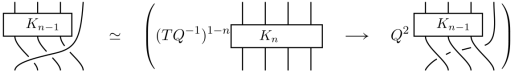

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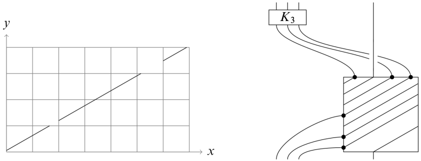

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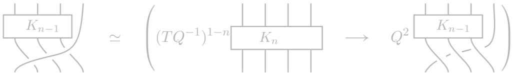

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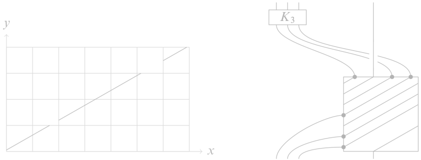

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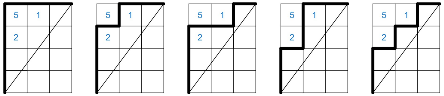

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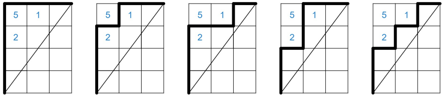

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- *algebraic geometry*
- *knot theory*
- *combinatorics*

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The Dyck-path decomposition of Ψ_f comes from the representation theory of *symmetric groups*.

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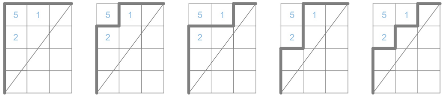

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Recall: For $f = y^3 - x^4$ and prime p, the roots of

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Conj (Cherednik 2018) For any plane curve f:

$$0 < t \leq \tfrac{1}{2} \implies \text{all roots of } \Psi_f(t, \mathsf{q}) \text{ satisfy } |\mathsf{q}| = t^{-1/2}.$$

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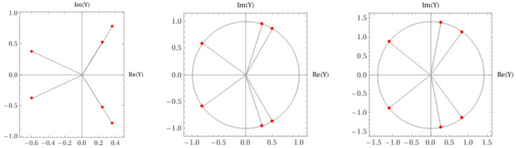

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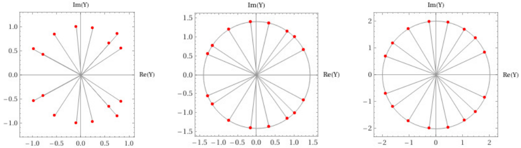

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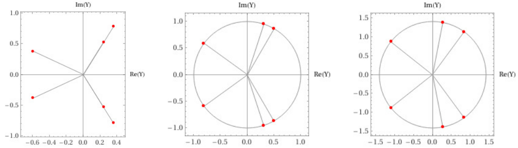
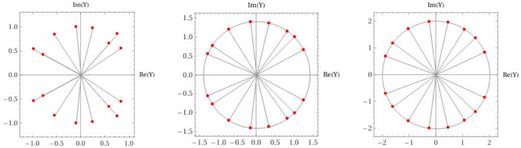
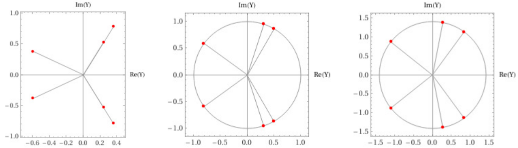


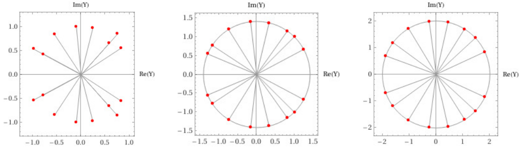
$f = y^4 - 2x^3y^2 - 4x^5y + x^6 - x^7, \qquad t = 1, \frac{1}{2}, \frac{1}{4}$



$f = y^3 - x^4, \qquad t = 2, 1, \frac{1}{2}$



$f = y^4 - 2x^3y^2 - 4x^5y + x^6 - x^7, \qquad t = 1, \frac{1}{2}, \frac{1}{4}$



Thank you for listening.