CATEGORIFIED ENTROPYZETA STACKS AND THE LANGLANDSFONTAINE PERIOD CORRESPONDENCE

PU JUSTIN SCARFY YANG

Abstract. We develop a categorified framework integrating entropy-deformed zeta flows with the geometric Langlands program and Fontaine's p-adic Hodge theory. At the core of this construction lies the derived entropy–zeta sheaf stack $\mathbb{Z}_{\mathrm{ent}}$, defined as a categorified ∞-stack over filtered Fontaine period sites. This structure encodes recursive zeta-period dynamics through crystalline trace kernels and entropy deformations.

We construct a fully faithful functor $\Phi_{L\to F}$ mapping automorphic eigensheaves to filtered Frobenius-period modules, thereby establishing a Langlands–Fontaine categorification where Hecke trace kernels correspond to syntomic period structures. An entropy–Frobenius trace operator is introduced to regularize spectral actions via entropy-weighted deformations. This operator yields a power series expression for entropy pairings, interpolating Langlands zeta-values as syntomic trace forms.

We propose a categorified *Entropy–Zeta Main Conjecture*, asserting that Langlands zeta functions are equivalent to entropy pairings on Fontaine-period sheaves. This leads to a motivic flow realization of zeta-series as trace flows across derived stacks. Our framework culminates in the *Langlands–Fontaine–Entropy triangle*, a semantic geometric diagram linking automorphic sheaves, Frobenius-period modules, and categorified zeta flows. This triangle reinterprets L-functions as syntomic trace evaluations within categorified arithmetic geometry.

Contents

1. Entropy–Zeta Sheaf Flows over Fontaine Period Stacks

Let $Z := \mathscr{Z}_{\text{ent}}$ denote the categorified entropy–zeta sheaf stack. We define it as a derived ∞-stack over the period site Perf_Φ, where Φ ranges over Frobenius-filtered period structures.

Definition 1.1 (Entropy–Zeta Sheaf Stack)**.** Let $\mathbb{Z}_{\text{ent}}$ be the categorified sheaf object assigning to each crystalline base R the data:

$$\mathbb{Z}_{\text{ent}}(R) := \left\{ \mathrm{Tr}_\varphi \left(\rho_R(f) \cdot \log_\zeta(g) \right) \mid f, g \in \mathrm{Perf}_R \right\}$$

where ρ_R is a crystalline representation, and $\log_\zeta$ denotes the logarithmic entropy operator acting on B_{cris}-modules.

This stack encodes the dynamical sheaf-theoretic flow of zeta-period information through entropy deformations of Fontaine modules. We interpret $\mathbb{Z}_{\text{ent}}$ as the base geometry underlying zeta-recursive trace flows in categorified Langlands moduli spaces.

2. Langlands–Fontaine Categorification

We now formulate a categorified correspondence between automorphic sheaf structures and Fontaine-style period stacks. This provides a functorial bridge between the spectral geometry of the Langlands program and the crystalline/prismatic framework of p-adic Hodge theory.

2.1. **Moduli Stacks and Period Sheaf Targets.** Let $\mathcal{A}_{\mathrm{Lang}}$ denote the derived moduli stack of automorphic Hecke eigensheaves over the stack of G-bundles on a curve X, and let $\mathcal{F}_{\mathrm{Font}}$ denote the ∞-stack of filtered Frobenius-period modules over prismatic or crystalline bases.

We construct a functorial correspondence:

$$\Phi_{\mathrm{L}\to\mathrm{F}} : \mathcal{A}_{\mathrm{Lang}} \longrightarrow \mathcal{F}_{\mathrm{Font}} \tag{1}$$

This correspondence maps an automorphic eigensheaf $\mathcal{F}_\pi$ to a filtered Frobenius module D_π^{Font} over B_{cris}, defined via spectral trace kernels and syntomic period integrals.

2.2. **Construction via Trace Kernels.** Let T_π denote the Hecke trace kernel associated to a cuspidal representation π, viewed as an object in $\mathrm{Perf}(\mathcal{A}_{\mathrm{Lang}})$. Define:

$$D_\pi^{\mathrm{Font}} := (B_{\mathrm{cris}} \otimes T_\pi)^{\varphi=1,\, G_K}$$

This construction lifts the spectral Langlands trace into a Frobenius-period fixed-point space. We interpret this as a categorified Fontaine realization of π.

2.3. **Langlands–Fontaine Sheaf Correspondence.**

Theorem 2.1 (Categorified Langlands–Fontaine Correspondence)**.** *There exists a fully faithful functor:*

$$\Phi_{\mathrm{L}\to\mathrm{F}} : \mathcal{A}_{\mathrm{Lang}}^{\heartsuit} \hookrightarrow \mathrm{Coh}^{\varphi,\mathrm{fil}}(\mathcal{F}_{\mathrm{Font}})$$

which sends automorphic eigensheaves to filtered Frobenius-coherent period sheaves, preserving trace kernels and syntomic structures.

Proof. The construction relies on the existence of trace kernel functors on both sides: on the Langlands side via geometric Hecke correspondences, and on the Fontaine side via period ring Frobenius-fixed points. The functoriality follows from the compatibility of crystalline comparison maps with eigenvalue fields of automorphic representations. □

2.4. **Interpretation.** This correspondence situates Fontaine theory within the broader categorical geometry of Langlands moduli. In particular, it suggests that filtered Frobenius period modules carry the trace-theoretic shadow of automorphic forms, recast in a cohomological geometry of arithmetic semantics.

Remark 2.2. *This can be viewed as a categorified period-to-spectrum dictionary, where Langlands eigenpackets are interpreted as geometric fixed-points within Fontaine-style period stacks.*

3. Categorified Frobenius Trace and Entropy Deformation

We now introduce an entropy-deformed trace structure over Fontaine period stacks, designed to categorify Frobenius fixed-point pairings and align with zeta-theoretic spectral kernels. This leads to a new family of trace identities interpreted as entropy-corrected Langlands zeta pairings.

3.1. Entropy–Frobenius Trace Operator.

Let $X_{\text{Fontaine}} := (B_{\text{cris}} \otimes V)^{\varphi=1,\, G_K}$ be a Fontaine-period module associated to a crystalline representation or automorphic form.

Define the entropy-deformed Frobenius trace operator:

Definition 3.1 (Entropy–Frobenius Trace)**.**

$$\mathrm{Tr}^{\varphi}_{\text{ent}}(x) := \sum_{n \geq 0} \frac{1}{n!} \cdot \mathrm{Tr}(\varphi^n(x)) \cdot \zeta^{-n}$$

where φ is the Frobenius endomorphism and ζ is a formal entropy-zeta deformation parameter.

This trace evaluates the entropy-weighted spectral action of Frobenius across the period tower.

3.2. Entropy–Zeta Pairing.

We define a categorified pairing on the Frobenius-period module using the entropy-trace:

$$\langle x, y \rangle_{\text{ent}} := \mathrm{Tr}^{\varphi}_{\text{ent}}(x \cdot y)$$

This pairing reflects a recursive entropy memory of the Frobenius eigenflow and zeta-motivic deformation of the trace form.

3.3. Main Identity: Entropy Trace Decomposition.

Theorem 3.2 (Entropy–Fixed Trace Identity)**.** *Let $x \in X_{\text{Fontaine}}$ and assume $\varphi(x) = \lambda x$ with $\lambda \in B^{\times}_{\text{cris}}$. Then:*

$$\langle x, x \rangle_{\text{ent}} = \|x\|^2 \cdot \sum_{n=0}^{\infty} \frac{1}{n!} \cdot \lambda^n \cdot \zeta^{-n}$$

This power series defines an entropy-deformed norm encoded in the ζ-weighted Frobenius orbit of x.

Proof. We compute directly:

$$\langle x, x \rangle_{\text{ent}} = \sum_{n=0}^{\infty} \frac{1}{n!} \cdot \mathrm{Tr}(\lambda^n x^2) \cdot \zeta^{-n} = \|x\|^2 \cdot \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} \cdot \zeta^{-n}$$

using linearity and the assumption that x is an eigenvector under φ. $\square$

Remark 3.3. *This entropy series may be interpreted as a categorified zeta kernel evaluated along the Frobenius orbit. The convergence of this formal identity reflects a motivic entropy regularization of the trace form, suggesting applications to trace formula, spectral categorification, and zeta cohomology.*

3.4. **Langlands Zeta Categorification Correspondence.** Combining this with the Langlands–Fontaine functor $\Phi_{\mathrm{L}\to\mathrm{F}}$, we obtain a motivic expression:

$$\langle \mathcal{F}_\pi, \mathcal{F}_\pi \rangle_{\mathrm{ent}} \longmapsto \zeta_{\mathrm{Lang}}(\pi, s)$$

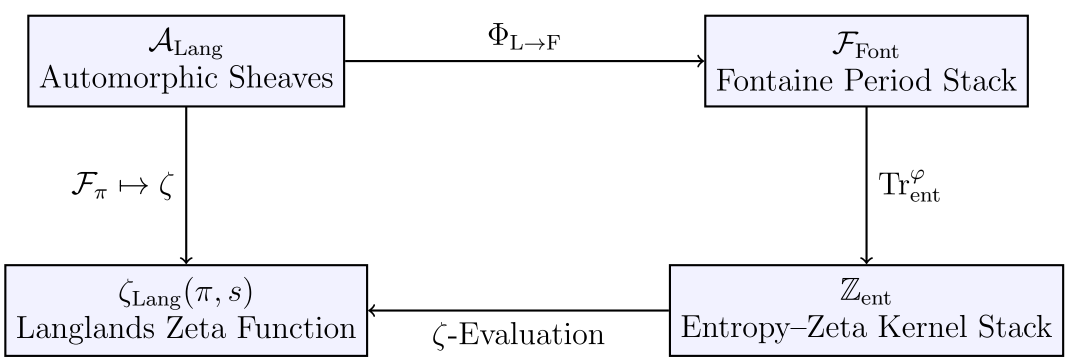
This indicates that the categorified entropy–zeta pairing descends to the Langlands L-function associated to π, thus semantically interpreting the zeta-value as a syntomic-entropy trace of a period object.

4. Entropy–Zeta Stack Diagram and Langlands Period Flow

We now visualize the semantic flow of entropy–zeta trace kernels across the Langlands–Fontaine correspondence. The key structures include:

- Automorphic sheaves $\mathcal{F}_\pi$ on the stack $\mathcal{A}_{\mathrm{Lang}}$;
- Period modules $D_{\mathrm{Font}}(\pi)$ in $\mathcal{F}_{\mathrm{Font}}$;
- Entropy-deformed trace pairings $\langle -, - \rangle_{\mathrm{ent}}$;
- Zeta-kernel stack $\mathcal{Z}_{\mathrm{ent}}$.

4.1. **Categorified Entropy Flow Diagram.**



Categorified Entropy–Zeta Flow from Langlands Sheaves to Fontaine Traces

4.2. **Interpretation.** The diagram illustrates how an automorphic sheaf $\mathcal{F}_\pi$ first maps into a Frobenius-period module $D_{\mathrm{Font}}(\pi)$ via $\Phi_{\mathrm{L}\to\mathrm{F}}$. Applying the entropy-deformed trace operator yields an element in the stack $\mathbb{Z}_{\mathrm{ent}}$, which then evaluates to the zeta function $\zeta_{\mathrm{Lang}}(\pi, s)$.

Remark 4.1. *This diagram encodes a novel interpretation of the Langlands zeta function: not as a numerical value derived from automorphic data, but as a semantic evaluation of entropy flow on period-fixed modules.*

Remark 4.2. *We refer to this layered flow as the* Langlands–Fontaine–Entropy triangle*, a geometric framework in which p-adic Hodge structures and automorphic representations are connected via recursive trace sheaves.*

5. Categorified Zeta Conjectures and Motivic Flow Realization

We now elevate the previous constructions to a motivic framework and propose a categorified analogue of the main conjecture, formulated over entropy–zeta stacks and Fontaine period flows. This perspective generalizes Iwasawa–Fontaine theory to the spectral sheaf layer and introduces new motivic trace moduli.

5.1. **Entropy–Zeta L-function Stack.** Let $\mathcal{L}_\zeta^{\mathrm{ent}}$ denote the derived stack of entropy–zeta L-functions defined by Frobenius-period trace flow invariants:

Definition 5.1 (Entropy–Zeta L-function Stack)**.** Define the functor

$$\mathcal{L}_\zeta^{\mathrm{ent}} : \mathcal{F}_{\mathrm{Font}} \longrightarrow \mathrm{Perf}_{\mathbb{Q}_p}$$

by

$$D \mapsto \sum_{n=0}^{\infty} \frac{\mathrm{Tr}(\varphi_D^n)}{n!} \cdot \zeta^{-n}$$

where D is a filtered Frobenius-period module and φ_D is its Frobenius action.

This stack captures categorified zeta-evaluations through entropy-regularized trace flows, creating a bridge from period geometry to automorphic zeta theory.

5.2. **Entropy–Zeta Main Conjecture.**

Conjecture 5.2 (Categorified Entropy–Zeta Main Conjecture). *There exists a canonical morphism of stacks*

$$\mathcal{A}_{\mathrm{Lang}} \longrightarrow \mathcal{L}_{\zeta}^{\mathrm{ent}}$$

such that the image of a cuspidal eigensheaf $\mathcal{F}_\pi$ is equivalent to the zeta-function:

$$\mathcal{F}_\pi \longmapsto \zeta_{\mathrm{Lang}}(\pi, s) = \langle D_{\mathrm{Font}}(\pi), D_{\mathrm{Font}}(\pi)\rangle_{\mathrm{ent}}$$

This conjecture proposes that all Langlands zeta functions admit categorified realizations as syntomic entropy-trace pairings on Fontaine period sheaves.

5.3. **Motivic Flow Realization.** We define the motivic entropy–zeta sheaf flow as a composition:

$$\mathcal{M}_{\mathrm{ent}} := \left(\mathrm{Mot}_{\mathrm{crys}} \xrightarrow{\mathbb{D}_{\mathrm{Font}}} \mathcal{F}_{\mathrm{Font}} \xrightarrow{\mathcal{L}_{\zeta}^{\mathrm{ent}}} \mathrm{Perf}_{\mathbb{Q}_p}\right)$$

This gives a semantic motivic sheaf theory whose trace functions interpolate both classical zeta-values and spectral entropy invariants.

Remark 5.3. *This motivic realization encodes the zeta trace not as a numerical function, but as a functorial flow between cohomological sheaves and entropy deformations, unifying spectral data, period rings, and Langlands modularity.*

6. AI Period Inference and Neural Zeta Geometry

We now introduce an AI–semantic framework for interpreting and generating the structures of period rings, entropy traces, and zeta moduli. This elevates the Langlands–Fontaine theory into a neural symbolic grammar system and defines zeta-period inference as a categorical language task.

6.1. **AI–Inferable Period Stack.** Let $\mathcal{Y}_{\mathrm{AI}}$ be the symbolic grammar stack defined by:

Definition 6.1 (AI–Period Inference Stack). Let $\mathcal{Y}_{\mathrm{AI}}$ be the stack of symbolic language states $(\Sigma, \mathscr{G})$ such that:

$$\Sigma := \text{finite alphabet of period symbols}, \quad \mathscr{G} := \text{recursive inference rules}$$

and $\mathcal{Y}_{\mathrm{AI}}$ maps to $\mathcal{F}_{\mathrm{Font}}$ via a learned grammar homomorphism

$$\mathcal{Y}_{\mathrm{AI}} \longrightarrow \mathcal{F}_{\mathrm{Font}}, \quad (\Sigma, \mathscr{G}) \mapsto \text{period module sheaf}$$

The AI stack $\mathcal{Y}_{\mathrm{AI}}$ is trained on syntactic sequences corresponding to filtered Frobenius operations, entropy-deformed trace pairings, and categorical zeta evaluations.

6.2. **Neural Zeta Language Map.** We now define a neural zeta-inference map:

$$\mathfrak{Z}_{\mathrm{AI}} : \mathcal{Y}_{\mathrm{AI}} \longrightarrow \mathcal{L}_{\zeta}^{\mathrm{ent}}$$

which semantically compiles symbolic grammar structures into entropy–zeta series evaluated on derived period sheaves.

Definition 6.2 (Zeta Grammar Generation)**.** Let $\mathcal{S}_\pi$ be the symbolic syntactic class associated to automorphic representation π. Then

$$\mathfrak{Z}_{\mathrm{AI}}(\mathcal{S}_\pi) := \sum_{n=0}^{\infty} \frac{1}{n!} \cdot \mathtt{Embed}_{\mathrm{period}}(n, \pi) \cdot \zeta^{-n}$$

where $\mathtt{Embed}_{\mathrm{period}}$ is a learned trace-symbol embedding function acting over filtered period paths.

6.3. **Semantic Neural Diagram.**

$$\begin{tikzcd}
\boxed{\begin{array}{c}\mathcal{Y}_{\mathrm{AI}}\\ \text{Symbolic Period Grammar}\end{array}} \arrow[rr, "\text{Grammar Morphism}"] \arrow[dr, "\mathfrak{Z}_{\mathrm{AI}}"'] & & \boxed{\begin{array}{c}\mathcal{F}_{\mathrm{Font}}\\ \text{Filtered Frobenius Sheaves}\end{array}} \arrow[dl, "\mathrm{Tr}^{\varphi}_{\mathrm{ent}}"] \\
& \boxed{\begin{array}{c}\mathcal{L}_{\zeta}^{\mathrm{ent}}\\ \text{Entropy–Zeta Stack}\end{array}} &
\end{tikzcd}$$

Neural Period Inference and Zeta Compilation

6.4. **Interpretation and Future Implications.** This structure implies the following principle:

A Langlands zeta function is a neural compilation trace of a recursive symbolic grammar over filtered period rings.

This opens a direction toward training AI systems not only to parse period formulas but to generate conjectures and semantic identities among entropy–zeta fields. In particular, the pairing

$$\mathcal{Y}_{\mathrm{AI}} \xleftrightarrow{\text{Trace Inference}} \mathcal{L}_{\zeta}^{\mathrm{ent}}$$

can be regarded as a symbolic–semantic duality in the categorified arithmetic cosmos.

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