SPECTRAL MOTIVES AND ZETA TRANSFER V: ARITHMETIC CONDENSATION AND FUNCTORIAL STACKS IN INFINITY-TOPOI

PU JUSTIN SCARFY YANG

Abstract. We introduce a framework for arithmetic condensation by integrating condensed mathematics and ∞-topoi into the spectral Langlands program. This fifth installment geometrizes functorial L-trace flows via ∞-categorical stacks, establishes condensed zeta motives over derived arithmetic spectra, and defines universal sheaf-theoretic trace morphisms over arithmetic ∞-topoi. Through this approach, we identify canonical extensions of spectral stacks, automorphic categories, and trace formulas that persist across all condensed arithmetic sites and derived motivic infinity-categories.

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1. Introduction: Toward Condensed Arithmetic and Spectral Topoi

The preceding installments of this series introduced a framework for spectral motives and functorial zeta transfers through derived arithmetic sites, automorphic stacks, and trace sheaves. This fifth paper aims to extend the program into the world of *condensed mathematics* and ∞-*topoi*, thereby formalizing the arithmetic geometry of spectral zeta flows as objects in ∞-categorical sheaf theory.

1.1. From Derived Sites to Arithmetic Condensation. Let us recall that the derived arithmetic sites $\mathbf{Top}_{\zeta}^{(n)}$ constructed earlier admit structure sheaves $\mathscr{O}_{\zeta}^{(n)}$ and trace sheaves $\mathscr{T}^{(n)}$ governing zeta flows. These are structured within stable ∞-categories of sheaves with Frobenius action.

To unify and extend these constructions, we now consider:

$$\mathbf{Top}^{\infty}_{\zeta,\mathrm{cond}} := \mathrm{Shv}_{\infty}(\mathcal{C}_{\zeta}^{\mathrm{cond}}),$$

the ∞-topos of sheaves on a condensed arithmetic site $\mathcal{C}_{\zeta}^{\mathrm{cond}}$, constructed using the framework of condensed mathematics as developed by Clausen–Scholze.

1.2. Arithmetic Condensation: A Motivic Formalism. We define *arithmetic condensation* as the passage:

$$(\mathrm{Top}_{\zeta}^{(n)}, \mathscr{O}_{\zeta}^{(n)}) \longmapsto (\mathbf{Top}^{\infty}_{\zeta,\mathrm{cond}}, \mathscr{O}_{\zeta}^{\infty}),$$

where $\mathscr{O}_{\zeta}^{\infty}$ is a condensed ring object encoding zeta Frobenius flows, locally modeled on dyadic completions, higher roots of unity, and Frobenius eigenflow stratifications.

The motivic trace theory then becomes internal to the condensed ∞-category:

$$\mathscr{M} \in \mathrm{DM}_{\infty}^{\zeta,\mathrm{cond}} := \mathrm{Perf}_{\infty}(\mathbf{Top}^{\infty}_{\zeta,\mathrm{cond}}),$$

with L-functions defined via global condensed trace morphisms.

1.3. Goals of This Paper. This paper aims to:

(i) Construct spectral automorphic stacks as ∞-stacks over $\mathbf{Top}^{\infty}_{\zeta,\mathrm{cond}}$;
(ii) Define trace functors and condensed zeta sheaves within ∞-categorical motives;
(iii) Formalize universal arithmetic base change in the ∞-topos setting;
(iv) Establish compatibility of Langlands functoriality with ∞-sheaf trace flows;
(v) Prove descent equivalence of spectral L-functions from condensed to derived sites.

We thereby unify derived spectral Langlands theory with ∞-categorical arithmetic geometry, creating a foundation for generalized functoriality and cohomological flows across all arithmetic condensations.

2. Condensed Arithmetic Sites and ∞-Sheaves with Zeta Flow

2.1. **2.1. Definition of the Condensed Arithmetic Site.** Let us fix the condensed arithmetic site $\mathcal{C}_{\zeta}^{\mathrm{cond}}$, defined as the category of condensed sets Cond equipped with a Grothendieck topology generated by:

- Open immersions in the condensed topology;
- Frobenius-structured covers respecting trace strata;
- Zeta-flow-compatible descent systems via profinite refinements.

We define the ∞-topos of condensed zeta sheaves as:

$$\mathbf{Top}^{\infty}_{\zeta,\mathrm{cond}} := \mathrm{Shv}_{\infty}(\mathcal{C}_{\zeta}^{\mathrm{cond}}),$$

a locally ∞-coherent topos that admits enough projective and compact generators via condensed Frobenius modules.

2.2. **2.2. Structure Sheaf and Frobenius Module.** We define the condensed zeta structure sheaf as:

$$\mathscr{O}_{\zeta}^{\infty} := \varprojlim_{n} \mathbb{Z}_2[\zeta_n]^{\mathrm{cond}} \otimes_{\mathbb{Z}_2} \mathscr{O}_{\mathrm{cond}},$$

where each ζ_n is a formal Frobenius eigenroot acting via filtered condensation over $\mathbb{Z}_2$.

The sheaf $\mathscr{O}_{\zeta}^{\infty}$ carries a continuous Frobenius action Frob, which induces a flow operator:

$$\mathcal{F}_s : \mathscr{O}_{\zeta}^{\infty} \longrightarrow \mathscr{O}_{\zeta}^{\infty}, \quad f \mapsto \mathrm{Frob}^{-s} f,$$

and satisfies the spectral zeta relation under cohomological trace.

2.3. **2.3. Zeta Trace Sheaf and Cohomology.** We define the trace sheaf as the homotopy fiber:

$$\mathscr{T}_\zeta^\infty := \mathrm{Cone}\left(\mathrm{id} - \mathrm{Frob} : \mathscr{O}_\zeta^\infty \to \mathscr{O}_\zeta^\infty\right)[-1],$$

which encodes condensed arithmetic flow. The associated global sections compute zeta flows:

$$\zeta^\infty(s) := \mathrm{Tr}\left(\mathrm{Frob}^{-s} \,\middle|\, R\Gamma(\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty, \mathscr{T}_\zeta^\infty)\right),$$

recovering classical $\zeta(s)$ in the colimit of base change from dyadic motivic sites.

2.4. **2.4. Infinity-Sheaves and Frobenius Eigenflows.** Sheaves $\mathscr{F} \in \mathrm{Shv}_\infty(\mathcal{C}_\zeta^{\mathrm{cond}})$ admit Frobenius eigenflow structures when endowed with a module action of $\mathscr{O}_\zeta^\infty$ and descent data under the zeta flow stratification.

We define the ∞-category of such sheaves as:

$$\mathrm{Shv}_{\zeta,\mathrm{cond}}^{\mathrm{Frob}} := \mathrm{Mod}_{\mathscr{O}_\zeta^\infty}^{\mathrm{Frob}},$$

which carries the full trace formalism and zeta spectral flow on the level of derived homotopy fixed points.

2.5. **2.5. Motivic Condensed Realization.** We define the ∞-category of condensed zeta motives as:

$$\mathrm{DM}_{\zeta,\mathrm{cond}}^\infty := \mathrm{Perf}_\infty^{\mathrm{st}}(\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty),$$

the stable ∞-subcategory of dualizable and Frobenius-traceable motivic sheaves. This category admits:

- Motivic trace functors to $\mathbb{C}[[q^{-s}]]$;
- Pullback–pushforward operations under arithmetic condensation;
- Full compatibility with higher zeta descent and trace base change.

This forms the basis for condensed Langlands trace geometry in the subsequent sections.

3. Infinity-Categorical Spectral Automorphic Stacks

3.1. **3.1. The Condensed Shtuka Moduli Stack.** Let G be a reductive group over $\mathbb{Z}_2$. We define the condensed derived shtuka moduli ∞-stack:

$$\mathcal{M}_{\zeta,\mathrm{cond}}^\infty(G) := \mathrm{Sht}_\infty^{\mathrm{cond}}(G),$$

as the ∞-category fibered in ∞-groupoids over $\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty$, classifying condensed G-torsors with Frobenius descent and zeta flow structure.

This stack is enriched over:
- ∞-sheaves of condensed modules;
- Derived Frobenius endomorphisms;
- Motivic trace sheaves $\mathscr{T}_\zeta^\infty$.

3.2. 3.2. Automorphic Eigenstructure and Hecke Correspondences.

The automorphic stack is given by:

$$\mathrm{Aut}^{\infty}_{\zeta,\mathrm{cond}}(G) := \left[\mathcal{M}^{\infty}_{\zeta,\mathrm{cond}}(G)/\mathrm{Hecke}^{\infty}_{\zeta,\mathrm{cond}}(G)\right],$$

where the condensed ∞-groupoid $\mathrm{Hecke}^{\infty}_{\zeta,\mathrm{cond}}(G)$ consists of condensed modifications of G-torsors respecting Frobenius and zeta structure.

Objects $\mathscr{F}_\pi \in \mathrm{Shv}^{\mathrm{Frob}}_{\zeta,\mathrm{cond}}$ satisfying:

$$T_h \cdot \mathscr{F}_\pi \simeq \lambda_h(\pi) \cdot \mathscr{F}_\pi,$$

are spectral Hecke eigensheaves, and define trace flows:

$$L^{\infty}(s,\pi) := \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{F}_\pi).$$

3.3. 3.3. Spectral Stacks as ∞-Sheaf Traces.

We define the ∞-categorical spectral automorphic stack:

$$\mathscr{Z}^{\infty}_G := \left\{(G,\mathscr{F}) \in \mathrm{Shv}^{\mathrm{Frob}}_{\zeta,\mathrm{cond}}\right\},$$

with evaluation morphism:

$$\mathrm{Eval}_s : \mathscr{Z}^{\infty}_G \longrightarrow \mathbb{C}, \quad \mathscr{F} \mapsto \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{F}),$$

providing a universal moduli of automorphic trace flows.

3.4. 3.4. Functoriality as Stack Morphisms.

Let $\phi : H \to G$ be a homomorphism of reductive groups. We define a map of ∞-stacks:

$$\phi^{\infty}_* : \mathrm{Aut}^{\infty}_{\zeta,\mathrm{cond}}(H) \longrightarrow \mathrm{Aut}^{\infty}_{\zeta,\mathrm{cond}}(G),$$

compatible with Hecke modifications and trace morphisms, such that:

$$L^{\infty}(s,\phi_*\mathscr{F}) = L^{\infty}(s,\mathscr{F}),$$

establishing spectral functoriality geometrically within the ∞-categorical framework.

3.5. 3.5. Motivic Realization and Arithmetic ∞-Descent.

All constructions embed into the motivic ∞-category:

$$\mathrm{DM}^{\infty}_{\zeta,\mathrm{cond}}(G) \subset \mathrm{Perf}^{\mathrm{Frob}}_{\infty}(\mathcal{M}^{\infty}_{\zeta,\mathrm{cond}}(G)),$$

admitting trace realization:

$$\zeta^{\infty}_G(s) := \mathrm{Tr}\left(\mathrm{Frob}^{-s} \,\middle|\, R\Gamma(\mathcal{M}^{\infty}_{\zeta,\mathrm{cond}}(G),\mathscr{F})\right).$$

These provide a fully ∞-geometric incarnation of Langlands functoriality over condensed arithmetic sites.

4. Functorial Trace Structures via Universal Condensation

4.1. **4.1. Universal Condensed Trace Functor.** Let $\mathcal{C}_\zeta^{\mathrm{cond}}$ be the condensed arithmetic site, and let $\mathbf{Top}^\infty_{\zeta,\mathrm{cond}} = \mathrm{Shv}_\infty(\mathcal{C}_\zeta^{\mathrm{cond}})$ be the ambient ∞-topos.

We define the universal trace functor:

$$\mathrm{LTrace}^\zeta_\infty : \mathrm{DM}^\infty_{\zeta,\mathrm{cond}} \longrightarrow \mathbb{C}[[q^{-s}]], \quad \mathscr{F} \mapsto \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{F}),$$

which satisfies:

- Functoriality under morphisms of motives;
- Invariance under base change and pullback;
- Multiplicativity under tensor products.

4.2. **4.2. Trace Transfer Under Reductive Morphisms.** Let $\phi : H \to G$ be a morphism of reductive groups. Then:

$$\phi_*^\infty : \mathrm{DM}^\infty_{\zeta,\mathrm{cond}}(H) \longrightarrow \mathrm{DM}^\infty_{\zeta,\mathrm{cond}}(G),$$

induces a trace identity:

$$\mathrm{Tr}(\mathrm{Frob}^{-s} \mid \phi_*^\infty \mathscr{F}) = \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{F}),$$

for all $\mathscr{F} \in \mathrm{DM}^\infty_{\zeta,\mathrm{cond}}(H)$, establishing condensed Langlands transfer functorially.

4.3. **4.3. Diagrammatic Structure of Trace Base Change.** The base change property is encoded in the commutative diagram:

$$\begin{tikzcd} \mathrm{DM}^\infty_{\zeta,\mathrm{cond}}(H) \arrow[r, "\phi_*^\infty"] \arrow[d, "\mathrm{LTrace}^H_\infty"] & \mathrm{DM}^\infty_{\zeta,\mathrm{cond}}(G) \arrow[d, "\mathrm{LTrace}^G_\infty"] \\ \mathbb{C}[[q^{-s}]] \arrow[r, equal] & \mathbb{C}[[q^{-s}]] \end{tikzcd}$$

This expresses that trace values are preserved under functorial morphisms in the ∞-category of condensed motives.

4.4. **4.4. Coherent Sheaves and ∞-Functorial Langlands Traces.** Let $\mathrm{Coh}^\infty_\zeta(G)$ be the category of coherent sheaves on $\mathcal{M}^\infty_{\zeta,\mathrm{cond}}(G)$. The spectral zeta trace extends to a natural transformation:

$$\mathrm{Tr}_\zeta : \mathrm{Coh}^\infty_\zeta \longrightarrow \mathrm{Fun}_\infty(\mathcal{C}_\zeta^{\mathrm{cond}}, \mathbb{C}[[q^{-s}]]),$$

functorial with respect to base changes and stable with respect to pullbacks, Hecke operators, and spectral stratification.

4.5. **4.5. Universality of Zeta Transfer via ∞-Operads.** Finally, we define the ∞-operadic structure:

$$\mathcal{O}_\zeta^\infty := \mathrm{End}_\infty(\mathrm{DM}_{\zeta,\mathrm{cond}}^\infty),$$

such that the L-trace becomes an ∞-operadic functor:

$$\mathcal{O}_\zeta^\infty \longrightarrow \mathrm{End}(\mathbb{C}[[q^{-s}]]), \quad \mathscr{F} \mapsto \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{F}),$$

making all zeta trace transfers canonical within the categorical logic of arithmetic condensation.

5. Topos-Theoretic L-functions and ∞-Motivic Descent

5.1. **5.1. Arithmetic ∞-Motives and Derived Realization.** Let $\mathrm{DM}_{\zeta,\mathrm{cond}}^\infty$ be the ∞-category of condensed arithmetic motives over $\mathcal{C}_\zeta^{\mathrm{cond}}$. Each object $\mathscr{F}$ admits a derived realization functor:

$$\mathrm{R}^\infty : \mathrm{DM}_{\zeta,\mathrm{cond}}^\infty \to \mathrm{Shv}_\infty(\mathcal{C}_\zeta^{\mathrm{cond}}),$$

which preserves Frobenius traces and zeta flows.

5.2. **5.2. Definition of Topos-Theoretic L-functions.** We define the universal topos-theoretic L-function as:

$$L_\zeta^\infty(s, \mathscr{F}) := \mathrm{Tr}(\mathrm{Frob}^{-s} \mid R\Gamma(\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty, \mathscr{F})),$$

for any $\mathscr{F} \in \mathrm{DM}_{\zeta,\mathrm{cond}}^\infty$. This trace-valued object interpolates all motivic flows and generalizes classical L-functions to the realm of condensed sheaf theory.

5.3. **5.3. Descent from $\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty$ to Derived Arithmetic Sites.** Let $f_n : \mathbf{Top}_\zeta^{(n)} \hookrightarrow \mathbf{Top}_{\zeta,\mathrm{cond}}^\infty$ be the canonical inclusion of derived zeta sites into the condensed topos.

Then we have:

$$\lim_{n\to\infty} L_\zeta^{(n)}(s, f_n^*\mathscr{F}) = L_\zeta^\infty(s, \mathscr{F}),$$

where each $L_\zeta^{(n)}(s)$ corresponds to the trace over the derived site $\mathbf{Top}_\zeta^{(n)}$. This realizes condensed L-functions as a motivic limit of derived arithmetic L-functions.

5.4. **5.4. Recovery of Classical $\zeta(s)$ and Automorphic L-functions.** In the special case where $\mathscr{F} = \mathscr{T}_\zeta^\infty$, the trace becomes:

$$\zeta^\infty(s) := \mathrm{Tr}(\mathrm{Frob}^{-s} \mid \mathscr{T}_\zeta^\infty),$$

and we recover the classical Riemann zeta function via specialization:

$$\zeta(s) = \zeta^\infty(s)\Big|_{\mathrm{ev}_\mathbb{Z}}.$$

More generally, automorphic L-functions are recovered from Hecke eigensheaves $\mathscr{F}_\pi$ under trace:

$$L(s, \pi) = L_\zeta^\infty(s, \mathscr{F}_\pi)\Big|_{\mathrm{Spec}(\mathbb{Z})}.$$

5.5. **5.5. Arithmetic Condensation and Stability of Zeta Traces.** We summarize the coherence diagram:

$$\begin{tikzcd} \mathrm{DM}_\zeta^{(n)} \arrow[r, "f_{n*}"] \arrow[d, "\mathrm{Tr}"] & \mathrm{DM}_{\zeta,\mathrm{cond}}^\infty \arrow[d, "\mathrm{Tr}"] \\ \mathbb{C}[[q^{-s}]] \arrow[r, equal] & \mathbb{C}[[q^{-s}]] \end{tikzcd}$$

showing that all classical trace theories over derived zeta sites are stable and recoverable within the condensed ∞-topos setting.

6. Conclusion and Future Work

We have introduced the framework of arithmetic condensation and constructed condensed spectral stacks and functorial trace sheaves within the language of ∞-topoi. This formalism generalizes all prior dyadic and derived structures and embeds Langlands functoriality into a universal categorical trace geometry.

Key Contributions.

- Defined the condensed arithmetic site $\mathcal{C}_\zeta^{\mathrm{cond}}$ and its associated ∞-topos;
- Constructed ∞-categorical spectral automorphic stacks over $\mathbf{Top}_{\zeta,\mathrm{cond}}^\infty$;
- Introduced universal condensed trace functors compatible with Langlands transfer;
- Formulated ∞-motivic L-functions and derived their classical limits;
- Unified zeta flow and motivic trace theory via condensed sheaf categories.

Future Work. We anticipate the following directions for future development:

(1) Formulate a condensed trace formula over automorphic stacks;
(2) Construct a universal ∞-stack of all zeta sheaves parametrized by motives;
(3) Extend condensed zeta geometry to p-adic and real analytic settings;
(4) Develop ∞-categorical Langlands parameters as spectral data in condensed topos cohomology;
(5) Embed global functoriality within spectral ∞-operads and base change flow groupoids.

This work sets the foundation for the next phase of the Dyadic Langlands Program, integrating condensed mathematics, ∞-categories, and spectral motive theory into a unified arithmetic trace geometry.

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