SEMINAR 2025: GEOMETRIZATION OF COHOMOLOGY THEORIES

The aim of this seminar is to become familiar with the techniques of "geometrization" of cohomology theories, such as de Rham cohomology, prismatic cohomology, and syntomic cohomology, and to discuss applications. The basic idea goes back to Simpson [Sim96] on the de Rham space in characteristic zero. Then, in the last few years, the geometrization of p-adic cohomology theories has been actively developed by Drinfeld [Dri22, Dri24] and Bhatt–Lurie [BL22b, BL∞], and it is the main focus of this seminar.

By geometrization of a cohomology theory E, we mean a natural assignment of a stack X^E to a scheme X such that the cohomology $\mathrm{H}^*(X^E, \mathcal{O})$ of the structure sheaf $\mathcal{O}$ on X^E recovers the E-cohomology $E^*(X)$ of X. We would like to highlight two advantages of this perspective:

— The coefficient system for E is obtained for free as quasi-coherent modules over X^E, e.g., D-modules over X are identified with quasi-coherent modules over the de Rham stack X^{dR}.

— Various structures of such a cohomology theory E and its coefficient system are understood via the geometry of the associated stack X^E (or rather the ring stack behind it, which is independent of X).

As applications, we cover Drinfeld's refinement of the Deligne–Illusie theorem as well as recent work by Petrov [Pet25], and hopefully more in due course.

We will mostly follow Bhatt's notes [Bha22] in this seminar, and the numbering below is as in his notes.

Talk 1 (Introduction, and preliminaries on filtered modules [§2.2.1])**.** In addition to the introduction, this talk covers some preliminaries on filtered modules. Explain that filtered modules are identified with quasi-coherent modules over $\mathbb{A}^1/\mathbb{G}_m$ (Proposition 2.2.6, see also [Mou21]). This allows us to interpret stacks over $\mathbb{A}^1/\mathbb{G}_m$ as "filtered stacks" (Remark 2.2.10).

Talk 2 (de Rham cohomology in characteristic zero [§2.2.2, §2.3])**.** The goal of this talk is to introduce the filtered de Rham stack in characteristic zero and to prove that it recovers the de Rham cohomology with the Hodge filtration (Theorem 2.3.6). The key input for the proof is the following: for a finite locally free sheaf $\mathcal{E}$ on an (affine?) $\mathbb{Q}$-scheme, there is an equivalence $\mathrm{QCoh}(\mathrm{B}\widehat{\mathbb{V}(\mathcal{E})}) \simeq \mathrm{QCoh}(\mathbb{V}(\mathcal{E}^\vee))$ (Proposition 2.2.13), where $\widehat{\mathbb{V}(\mathcal{E})}$ is the formal completion of $\mathbb{V}(\mathcal{E})$ along the zero section, and it gives a recipe for computing the cohomology of quasi-coherent modules over $\mathrm{B}\widehat{\mathbb{V}(\mathcal{E})}$ (Remark 2.2.14).

Introduce the ring stack $\mathbb{G}_a^{\mathrm{dR}}$; for a commutative ring R, we have $\mathbb{G}_a^{\mathrm{dR}}(R) = R_{\mathrm{red}}$ by Lemma 2.2.17. As its filtered refinement, introduce the filtered ring stack $\mathbb{G}_a^{\mathrm{dR},+}$ with the associated graded stack denoted by $\mathbb{G}_a^{\mathrm{Hodge}}$ (Construction 2.3.4); here the notion of *quasi-ideal* should be explained in due course (see [Dri21]).

Let k be a field of characteristic zero. For a k-scheme X, define the *filtered de Rham stack* $X^{\mathrm{dR},+}$ as a filtered k-stack (Definition 2.3.5) via "transmutation" from $\mathbb{G}_a^{\mathrm{dR},+}$ (Remark 2.3.8). Prove that, for a smooth qcqs k-scheme X, the direct image of the structure sheaf under the structure map $X^{\mathrm{dR},+} \to \mathbb{A}^1/\mathbb{G}_m$ recovers the Hodge-filtered de Rham cohomology of X (Theorem 2.3.6). Explain that quasi-coherent modules over $X^{\mathrm{dR},+}$ correspond to "filtered D-modules" over X (Remark 2.3.7, see also [GR14]).

Talk 3 (de Rham cohomology of p-adic formal schemes [§2.4, §2.5])**.** This talk explains the p-adic analogue of Talk 2. Things are mostly parallel to the characteristic zero case, but the computational input is slightly different: for a finite locally free sheaf $\mathcal{E}$ on a scheme, consider the PD-hull $\mathbb{V}(\mathcal{E})^\#$ of the zero section in $\mathbb{V}(\mathcal{E})$, and then there is an equivalence $\mathrm{QCoh}(\mathrm{B}\mathbb{V}(\mathcal{E})^\#) \simeq \mathrm{QCoh}(\widehat{\mathbb{V}(\mathcal{E}^\vee)})$ (Proposition 2.4.5). Explain this by sketching the proof of the case $\mathcal{E} = \mathcal{O}$ as in Proposition 2.4.4.

Introduce the filtered formal ring stack $\mathbb{G}_a^{\mathrm{dR},+}$ and its variants (Definition 2.5.1), and explain the formula for their R-points for a p-nilpotent ring R by Lemma 2.4.7. Let V be a p-complete commutative ring with bounded p-power torsion. For a p-adic formal V-scheme X, define the *filtered de Rham stack* $X^{\mathrm{dR},+}$ as a filtered formal V-stack (Definition 2.5.3) via transmutation from $\mathbb{G}_a^{\mathrm{dR},+}$. Prove that, for a smooth qcqs p-adic formal V-scheme X, the direct image of the structure sheaf under the structure map $X^{\mathrm{dR},+} \to \mathbb{A}^1/\mathbb{G}_m$ recovers the Hodge-filtered de Rham cohomology of X (Theorem 2.5.6). Discuss the coefficient system for the filtered

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de Rham cohomology thus obtained (Remark 2.5.8 and 2.5.9). As an application of Theorem 2.5.6, prove the "crystalline miracle" (Corollary 2.5.10), and mention the crystalline Frobenius thus obtained (Remark 2.5.11).

Talk 4 (The conjugate filtration on de Rham cohomology [§2.6, §2.7.1])**.** The goal of this talk is to "geometrize" what lies behind the conjugate filtration of de Rham cohomology in characteristic p. The Witt vector model for the ring stack $\mathbb{G}_a^{\mathrm{dR}}$ will naturally lead to this.

Recall Witt vectors briefly, and describe $\mathbb{G}_a^{\#}$ in terms of Witt vectors as in Lemma 2.6.1. Using this description, give the Witt vector model for $\mathbb{G}_a^{\mathrm{dR}}$ (Corollary 2.6.8). It follows that, over a ring k of characteristic p, the ring stack $\mathbb{G}_a^{\mathrm{dR}}$ is a square-zero extension of $F_*\mathbb{G}_a$ by $\mathrm{B}F_*\mathbb{G}_a^{\#}$ (Corollary 2.6.11). Via transmutation, we see a map $\nu\colon (X/k)^{\mathrm{dR}} \to X^{(1)}$ that realizes the source as a $\mathrm{T}^{\#}_{X^{(1)}/k}$-gerbe (Proposition 2.7.1). Then the conjugate filtration of the de Rham cohomology of X is understood as that induced by the canonical filtration of $\nu_*\mathcal{O}$; in fact there is a natural isomorphism $\nu_*\mathcal{O} \simeq F_{X/k,*}\Omega^{\bullet}_{X/k}$ over $X^{(1)}$, which is an $\mathcal{O}_{X^{(1)}}$-linear refinement of the isomorphism proved in Talk 3. Prove an isomorphism $\mathrm{H}^*(\nu_*\mathcal{O}) \simeq \Omega^*_{X^{(1)}/k}$ of graded algebras over $X^{(1)}$ (Corollary 2.7.2), which explains the classical Cartier isomorphism.

Talk 5 (Deligne–Illusie theorem [§2.7.2])**.** This talk begins with a conjugate-filtered refinement of the Witt vector model for $\mathbb{G}_a^{\mathrm{dR}}$ explained in Talk 4. We work over a ring k of characteristic p. Introduce the filtered ring stack $\mathbb{G}_a^{\mathrm{dR},c}$ with the underlying ring stack $\mathbb{G}_a^{\mathrm{dR}}$ (Construction 2.7.8). Explain that, for a smooth qcqs k-scheme X, the cohomology of the filtered stack $(X/k)^{\mathrm{dR},c}$ defined via transmutation from $\mathbb{G}_a^{\mathrm{dR},c}$ recovers the conjugate-filtered de Rham cohomology of X (Theorem 2.7.9). Give the Witt vector model for $\mathbb{G}_a^{\mathrm{dR},c}$ (Construction 2.7.11 and Proposition 2.7.12). Through this model, we see a $\mathbb{G}_m^{\#}$-action on the filtered ring stack $\mathbb{G}_a^{\mathrm{dR},c}$, in fact, an action as a filtered W/p^2-algebra stack (Remark 2.7.13).

Prove the Deligne–Illusie theorem using this $\mathbb{G}_m^{\#}$-action as in Corollary 2.7.14. Discuss other recent developments around Deligne–Illusie, such as [Pet23, Pet25]. In particular, the ring stack $\mathbb{G}_a^{\mathrm{dR}}$ plays an essential role in the proof of the main theorem in [Pet25] (see also Remark 2.7.5 and Corollary 2.7.6).

Talk 6 (Filtered prismatization in characteristic p [§3.1, §3.2, §3.3])**.** We work over a perfect filed k of characteristic $p > 0$. Recall the crystallization which is (implicitly) discussed in Talk 3 (Remark 2.5.12). The *prismatization* is its Frobenius twist, and the underlying formal ring stack is simply W/p (Construction 3.1.1).

The aim of this talk is to present the Nygaard filtration on the prismatic cohomology from the stacky point of view. The Nygaard filtration on W is the p-adic filtration by definition, and note that it corresponds to the graded $W[t]$-algebra $W[u,t]/(ut-p)$ under the Rees equivalence. The formal stack $k^{\mathcal{N}}$ is defined to be $\mathrm{Spf}(W[u,t]/(ut-p))/\mathbb{G}_m$ and is called the *filtered prismatization* of k (Construction 3.3.1). Introduce the ring stack $\mathbb{G}_a^{\mathcal{N}}$ over $k^{\mathcal{N}}$ and note that it naturally has a W/p-algebra structure (Construction 3.3.2). Hence, given a k-scheme X, its filtered prismatization $X^{\mathcal{N}}$ is well-defined as a stack over $k^{\mathcal{N}}$ via transmutation from $\mathbb{G}_a^{\mathcal{N}}$. Prove that this lifts the Hodge and conjugate filtered de Rhamification, as well as the crystallization and prismatization (Theorem 3.3.5).

The direct image of the structure sheaf under $X^{\mathcal{N}} \to k^{\mathcal{N}}$ is regarded as a p^*W-module in the p-complete filtered W-modules whose underlying W-module is the (Frobenius-twisted) prismatic cohomology of X; which is called the *Nygaard filtration*. Via transmutation, the W/p-algebra structure on $\mathbb{G}_a^{\mathcal{N}}$ gives the prismatic Frobenius map from the Nygaard filtration to the p-adic filtration on the prismatic cohomology. Explain that the Nygaard graded pieces are identified with the conjugate filtrations of the de Rham cohomology under the prismatic Frobenius and that it characterizes the Nygaard filtration (Theorem 3.2.1 and Remark 3.2.3).

To be continued in the fall.

Talk 7 (Recollection, and syntomification in characteristic p [§4.1, §4.2])**.** Start with an extended recollection with focus on filtered prismatization and gauges over a perfect field k of characteristic $p > 0$. Then define the *syntomification* X^{syn} of a smooth k-scheme X (Definition 4.1.1) and discuss its geometry. Remark that the syntomification is also obtained via transmutation from the k-algebra stack $\mathbb{G}_a^{\mathrm{syn}}$ (Remark 4.1.6).

The category of *prismatic F-gauges* on X is defined as the category of quasi-coherent sheaves on X^{syn}. Discuss its basic features. Explain that lisse $\mathbb{Z}_p$-sheaves are F-gauges of weight zero (Remark 4.2.6 and 4.2.7). Describe F-gauges on k explicitly as in Remark 4.2.8.

Talk 8 (Syntomic cohomology in characteristic p [§4.3, §4.4]). This talk aims to discuss syntomic cohomology in higher weights for schemes in characteristic $p > 0$. Let k be a perfect field of characteristic p. First, explain that finite locally free sheaves on k^{syn} are identified with F-crystals (Proposition 4.3.1); you don't need to go into detail about the proof, but you could mention that this equivalence is obtained through the purity of vector bundles and that it is not exact (cf. Warning 3.4.13). Use this equivalence to determine the Picard stack of k^{syn} (Example 4.3.3). Then introduce the *Breuil–Kisin twist* as a line bundle on k^{syn} (Definition 4.3.4). Remark that the Breuil–Kisin twist is recovered as the syntomic cohomology of the projective line (Remark 4.3.6).

Using the Breuil–Kisin twist, the *syntomic cohomology* of a smooth k-scheme X is defined as in Definition 4.4.1. Explain the fiber sequence relating syntomic cohomology and Nygaard-filtered prismatic cohomology (Proposition 4.4.2). Explain that the weights of the syntomic cohomology of X are only distributed in $[0, \dim X]$ (Corollary 4.4.4). Explain that the syntomic cohomology in weight 1 is the p-completed étale cohomology of $\mathbb{G}_m$ (Proposition 4.4.7).

Talk 9 (Prisms and Cartier–Witt divisors). This talk covers the preliminaries of prisms to prepare for the discussion of mixed characteristic geometry. Basic references are [BS22, BL22a, BL22b, AKN23]. Introduce the notion of prisms and give some examples as in [BS22, §3]. Explain the rigidity of prism maps ([BS22, Lemma 3.5]). Explain the relation between perfect prisms and perfectoid rings ([BS22, Theorem 3.10]); or rather, our take is to understand perfectoid rings as perfect prisms. Discuss animated prisms ([BL22b, §2]).

A *Cartier–Witt divisor* on a p-nilpotent ring R is an animated prism $(W(R), I)$ such that the composition $I \to W(R) \to R$ is nilpotent ([BL22b, Example 2.11]). This leads us to the stack $\mathbb{Z}_p^{\Delta}$ which classifies the prism structures of rings.[1] Make this heuristic more precise by explaining [BL22a, Construction 3.2.4]. Use this construction to give a model of $\mathbb{Z}_p^{\Delta}$ as a quotient stack ([BL22a, Example 3.2.5, Proposition 3.2.3], see also [Bha22, Example 5.1.8]). Explain [BL22a, Corollary 3.2.10], which provides a more conceptual source of a flat cover of $\mathbb{Z}_p^{\Delta}$.

Talk 10 (Prismatization [§5.1]). The purpose of this talk is to comprehend the prismatization of p-adic formal schemes, particularly through the Hodge–Tate locus. Introduce the ring stack $\mathbb{G}_a^{\Delta}$ over $\mathbb{Z}_p^{\Delta}$ (Remark 5.1.7). For a bounded p-adic formal scheme X, the *prismatization* X^{Δ} is defined via transmutation from $\mathbb{G}_a^{\Delta}$. Explain that the prismatization of a perfectoid ring R is $\mathrm{Spf}(\Delta_R)$, where (Δ_R, I) is the unique perfect prism corresponding to R (Example 5.1.9, see also [BL22b, Example 3.12]). Explain that for a scheme X over a perfect field k of characteristic p the prismatization X^{Δ} over $k^{\Delta} = \mathrm{Spf}(W(k))$ agrees with the previously introduced notion (Example 5.1.12).

Introduce the *Hodge–Tate locus* $\mathbb{Z}_p^{\mathrm{HT}} \subset \mathbb{Z}_p^{\Delta}$ (Construction 5.1.13) and prove an isomorphism $\mathbb{Z}_p^{\mathrm{HT}} \simeq \mathrm{B}\mathbb{G}_m^{\#}$ (Proposition 5.1.14). The conormal line bundle $\mathcal{N}_{\mathbb{Z}_p^{\mathrm{HT}}}$ plays the role of Tate twists over the Hodge–Tate locus (Remark 5.1.16), and it lifts to a line bundle $\mathcal{O}\{1\}$ on $\mathbb{Z}_p^{\Delta}$, the *Breuil–Kisin twist* (Remark 5.1.19). For a bounded p-adic formal scheme X, the Hodge–Tate locus $X^{\mathrm{HT}} \subset X^{\Delta}$ is defined as the pullback of $\mathbb{Z}_p^{\mathrm{HT}} \subset \mathbb{Z}_p^{\Delta}$. Elaborate on its structure by discussing the Hodge–Tate structure map and the Hodge–Tate gerbe (Construction 5.1.18). Notably, the description of the Hodge–Tate stack as a $\mathrm{T}_X\{1\}^{\#}$-gerbe provides a straightforward way to understand the Hodge–Tate comparison theorem (cf. [BL22b, Remark 1.1]).

If time permits, explain the explicit description of quasi-coherent sheaves on $\mathbb{Z}_p^{\mathrm{HT}}$ as in [BL22a, §3.5].

Talk 11 (Filtered prismatization [§5.2, §5.3]). This talk aims to present the filtered prismatization in mixed characteristic. We focus on the filtered prismatization $\mathbb{Z}_p^{\mathcal{N}}$ of $\mathbb{Z}_p$.

Introduce the notion of an *admissible W-module* over a p-nilpotent ring (Definition 5.2.4). It is defined as a W-module that is locally an extension of F_*W by $\mathbb{G}_a^{\#}$; but such an extension is necessarily unique and thus globalized (Remark 5.2.5). Explain that every invertible W-module is admissible and that every admissible module is locally a pushout of an invertible module (Lemma 5.2.8). A *filtered Cartier–Witt divisor* consists of an admissible W-module M and a W-linear map $M \to W$ that is an extension of a Cartier–Witt divisor (Definition 5.3.1). Then $\mathbb{Z}_p^{\mathcal{N}}$ is defined as the moduli stack of filtered Cartier–Witt divisors. Elaborate on its geometry by discussing an open immersion $j_{\mathrm{HT}} : \mathbb{Z}_p^{\Delta} \to \mathbb{Z}_p^{\mathcal{N}}$ (Construction 5.3.2), the structure map $\pi : \mathbb{Z}_p^{\mathcal{N}} \to \mathbb{Z}_p^{\Delta}$, and the Rees map $t : \mathbb{Z}_p^{\mathcal{N}} \to \mathbb{A}^1/\mathbb{G}_m$ (Construction 5.3.3). The open locus $(\mathbb{Z}_p^{\mathcal{N}})_{t \neq 0}$ is identified with $\mathbb{Z}_p^{\Delta}$, yielding an open immersion $j_{\mathrm{dR}} : \mathbb{Z}_p^{\Delta} \to \mathbb{Z}_p^{\mathcal{N}}$ (Construction 5.3.5). Explain that the closed locus $(\mathbb{Z}_p^{\mathcal{N}})_{t=0}$ is identified with $\mathbb{G}_a^{\mathrm{dR}}/\mathbb{G}_m$ (Proposition 5.3.7).

[1] $\mathbb{Z}_p^{\Delta}$ is called the Cartier–Witt stack in [BL22a, BL22b].

Introduce the ring stack $\mathbb{G}_a^{\mathcal{N}}$ over $\mathbb{Z}_p^{\mathcal{N}}$, and define the *filtered prismatization* $X^{\mathcal{N}}$ of a bounded p-adic formal scheme X by transmutation from $\mathbb{G}_a^{\mathcal{N}}$ (Definition 5.3.10). State that it recovers the previously introduced notion when X is smooth over a perfect field (Theorem 5.4.1).

Talk 12 (Filtered prismatization of qrsp rings [§5.5])**.** The goal of this talk is to give a concrete description of the filtered prismatization of qrsp rings. Start with an overview of quasi-regular semiperfectoid (qrsp) rings R and their prismatic cohomology Δ_R as in §5.5.1. Introduce the Rees stack $\mathcal{R}(\mathrm{Fil}^*_{\mathcal{N}}\Delta_R)$ (Definition 5.5.2) and elaborate on its geometry.

Explain that the prismatization of a qrsp ring R is identified with $\mathrm{Spf}(\Delta_R)$ (Theorem 5.5.7). Explain that the filtered prismatization of a qrsp ring R is identified with $\mathcal{R}(\mathrm{Fil}^*_{\mathcal{N}}\Delta_R)$ (Theorem 5.5.10 and Corollary 5.5.11). Remark that it leads to another description of the filtered prismatization of arbitrary quasi-syntomic p-adic formal schemes by descent (Remark 5.5.18).

Talk 13 (Syntomification [§6.1, §6.2, §6.3])**.** Define the *syntomification* X^{syn} of a bounded p-adic formal scheme X and define *prismatic F-gauges* on X as quasi-coherent sheaves on X^{syn} (Definition 6.1.1). This is exactly same as the characteristic p case. Discuss F-gauges of qrsp rings (Example 6.1.6). Construct the Breuil–Kisin twist $\mathcal{O}\{1\}$ as a line bundle on $\mathbb{Z}_p^{\mathrm{syn}}$ (Example 6.1.8).

One of the purposes of this talk is to explicitly describe the *reduced locus* of $\mathbb{Z}_p^{\mathrm{syn}}$. Construct the section $v_1 \in H^0(\mathbb{Z}_p^{\mathrm{syn}}, \mathcal{O}\{p-1\}/p)$ (Construction 6.2.1) and define the reduced locus $\mathbb{Z}_{p,\mathrm{red}}^{\mathrm{syn}} \subset \mathbb{Z}_p^{\mathrm{syn}}$ as the zero locus of (p, v_1) (Definition 6.2.4). Describe its geometry in terms of its explicit components: the *Hodge–Tate component* and the *de Rham component* (Remark 6.2.5).

Another topic that will be covered in this talk is the *étale realization* $\mathrm{Perf}(X^{\mathrm{syn}}) \to \mathrm{D}^b_{\mathrm{lisse}}(X_\eta, \mathbb{Z}_p)$, where X_η denotes the rigid generic fiber of X. First, construct it when $X = \mathrm{Spf}(R)$ for a qrsp ring R (Construction 6.3.1). Then explain how this is extended to the étale realization in general (Construction 6.3.2).

Talk 14 (Filtered Tate duality [§6.4, §6.5])**.** This talk aims to explain a filtered refinement of Tate duality. For a mod p perfect F-gauge E on $\mathbb{Z}_p$, the *syntomic filtration* on E is defined as the v_1-adic filtration. State the filtered Tate duality theorem, Theorem 6.4.4, which is a filtered duality for syntomic-filtered F-gauges. Explain that the mod p local Tate duality follows from this (Corollary 6.4.5), as well as its Lagrangian refinement (Corollary 6.4.6, see also Corollary 6.5.22).

Outline the proof of filtered Tate duality, as set out in §6.5.

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