

V5A2 – RIGID ANALYTIC GEOMETRY

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PRELIMINARIES

These notes roughly correspond to the course **V5A2 - Rigid Analytic Geometry** taught by Prof. Jens Franke at the Universität Bonn in the Summer 2025 semester. These notes are L^AT_EX-ed after the fact with significant alteration and are subject to misinterpretation and mistranscription. Use with caution. Any errors are undoubtedly my own and any virtues that could be ascribed to these notes ought be attributed to the instructor and not the typist. These notes assume knowledge of the course on the same topic held in the Winter 2024-25 semester.

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1. LECTURE 1 – 17TH APRIL 2025

We fix the following notation.

Notation 1.1. (i) K is a field complete with respect to a non-Archimedean norm.

(ii) We denote the Tate algebra

$$\mathbb{T}_n = \left\{ f \in \sum_{\alpha \in \mathbb{N}^n} f_\alpha X^\alpha : \forall \varepsilon > 0, |\{\alpha : |f_\alpha|_K \geq \varepsilon\}| < \infty \right\} \subseteq K[[X_1, \dots, X_n]]$$

the subring of convergent power series, with norm $\|f\|_{\mathbb{T}_n} = \max_{\alpha \in \mathbb{N}^n} |f_\alpha|$.

Remark 1.2. (i) The norm $|\cdot|_K$ extends uniquely to any algebraic extension of K .

(ii) The Tate algebra \mathbb{T}_n is Noetherian, hence all ideals are closed.

Affinoid algebras are quotients of Tate algebras.

Definition 1.3 (Affinoid Algebra). A K -algebra A is an affinoid K -algebra if it is of the form \mathbb{T}_n/I .

There is an induced norm on the Tate algebra known as the residual norm.

Definition 1.4 (Residual Norm). Let A be an affinoid K -algebra. The residue norm of $a \in A$ is

$$\|a\| = \inf\{\|f\|_{\mathbb{T}_n} : \bar{f} = a\}.$$

Remark 1.5. Definition 1.4 is independent of the choice of representative.

As in algebraic geometry, affinoid algebras give rise to ringed spaces via the Tate spectrum. We discuss the construction by first defining the space, and the sheaf of rings on it.

Definition 1.6 (Tate Spectrum – Set). Let A be an affinoid K -algebra. The set underlying the Tate spectrum $\mathrm{Sp}(A)$ is $\mathrm{mSpec}(A)$.

Remark 1.7. The Tate spectrum is endowed with the property that $[\kappa(x) : K] < \infty$, where $\kappa(x) = A/\mathfrak{m}_x$ is a field as the ideal \mathfrak{m}_x corresponding to x is maximal.

The topology on the set is defined by rational sieves.

Definition 1.8 (Rational Open Set). Let $\langle f_0, \dots, f_n \rangle_A = A$. The rational open associated to the generators $R_A(f_0|f_1, \dots, f_n)$ is given by

$$R_A(f_0|f_1, \dots, f_n) = \{x \in \mathrm{Sp}(A) : |f_0(x)| < |f_i(x)|, 1 \leq i \leq n\}.$$

Remark 1.9. Rational open subsets are preserved under finite intersection. For $\langle f_0, \dots, f_n \rangle_A, \langle g_0, \dots, g_m \rangle_A$ generators of A , the intersection

$$R_A(f_0|f_1, \dots, f_n) \cap R_A(g_0|g_1, \dots, g_m) = R_A(f_0g_0|f_ig_j, 1 \leq i \leq n, 1 \leq j \leq m).$$

These rational open sets form the basis for the topology on the Tate spectrum $\mathrm{Sp}(A)$.

Definition 1.10 (Tate Spectrum – Topology). Let A be an affinoid K -algebra. The set underlying the Tate spectrum $\mathrm{Sp}(A)$ has a topology with basis consisting of the rational open sets $R_A(f_0|f_1, \dots, f_n)$ and with Grothendieck topology obtained by enforcing quasicompactness of the rational open sets.

In some simple cases, the underlying space of the Tate spectrum admits a description.

Example 1.11. Let $K = \overline{K}$. $\mathrm{Sp}(\mathbb{T}_n) = (K^\circ)^n$, where K° is the subring of power-bounded elements of K . Each point $x \in \mathrm{Sp}(A)$ is taken to $(\xi_i)_{i=1}^n$ where ξ_i is the image of X_i in $K \cong \kappa(x)$ and an n -tuple of powerbounded elements of K is taken to the ideal of \mathbb{T}_n consisting of functions vanishing at that tuple. In this case, the basis for the ordinary topology on the Tate spectrum is identified with non-Archimedean balls $d(\xi, \nu) = \max_{1 \leq i \leq n} |\xi_i - \nu_i|$.

We now want to define the structure sheaf on $\mathrm{Sp}(A)$ which will be valued in the category affinoid K -algebras Aff_K . This is a full subcategory of the category of K -algebras as all maps between affinoid K -algebras are automatically continuous.

The structure sheaf is defined as follows.

Definition 1.12 (Tate Spectrum – Structure Sheaf). Let A be an affinoid K -algebra. The functor

$$R_A(f_0|f_1, \dots, f_n) \mapsto A \left\langle \frac{\varepsilon}{f_0} \right\rangle \left\langle \frac{f_1}{f_0}, \dots, \frac{f_n}{f_0} \right\rangle$$

where $\varepsilon \in K^\times$ such that $\max_{0 \leq i \leq n} |f_i(x)| \geq |\varepsilon|$ for all $x \in \mathrm{Sp}(A)$ represents the functor $\mathrm{Rat}_A^{\mathrm{Opp}} \rightarrow \mathrm{Aff}_K$

$$F_\Omega(B) = \{\varphi \in \mathrm{Hom}_{\mathrm{Aff}_K}(A, B) : \mathrm{Sp}(\varphi)(\mathrm{Sp}(B)) \subseteq \Omega\}.$$

Summing up the preceding constructions, we have:

Definition 1.13 (Tate Spectrum – Ringed Space). Let A be an affinoid K -algebra. The Tate spectrum is given by:

- Topological space $\mathrm{mSpec}(A)$ with basis for the topology given by rational open subsets $R_A(f_0|f_1, \dots, f_n)$ with $\langle f_0, \dots, f_n \rangle_A = A$.
- Sheaf of rings given by $R_A(f_0|f_1, \dots, f_n) \mapsto A \left\langle \frac{\varepsilon}{f_0} \right\rangle \left\langle \frac{f_1}{f_0}, \dots, \frac{f_n}{f_0} \right\rangle$.

Here we used the fact that any sheaf on the base extends to a sheaf on the space.

Remark 1.14. (i) There are identifications $\mathcal{O}_{\mathrm{Sp}(\mathcal{O}_{\mathrm{Sp}(A)}(\Omega))} \cong \mathcal{O}_{\mathrm{Sp}(A)}|_\Omega$.
(ii) By Tate acyclicity, the higher cohomology of $\mathcal{O}_{\mathrm{Sp}(A)}$ vanishes.

We state some additional results surrounding Tate acyclicity.

Definition 1.15 (Laurent Order). Let \mathcal{S} be a sieve on $\mathrm{Sp}(A)$. We define the Laurent order $\mathfrak{o}_L(\mathcal{S})$ inductively as follows:

- $\mathfrak{o}_L(\mathcal{S}) = 0$ if and only if \mathcal{S} is the all sieve.
- $\mathfrak{o}_L(\mathcal{S}) \leq k$ if there is $g \in \mathcal{O}_X(\Omega)$ such that the restriction sieves $\mathcal{S}|_{R_\Omega(g|1)}$ and $\mathcal{S}|_{R_\Omega(1|g)}$ have Laurent order at most k .

- \mathcal{S} is of Laurent order k if k is the smallest number such that \mathcal{S} is of Laurent order at most k

Finiteness of the Laurent order characterizes covering sieves.

Proposition 1.16. Let \mathcal{S} be a sieve on $\mathrm{Sp}(A)$ for A an affinoid K -algebra. \mathcal{S} is a covering sieve if and only if $\mathfrak{o}_L(\mathcal{S}) < \infty$.

This immediately gives a simple sufficient condition for Tate acyclicity.

Corollary 1.17. Let \mathcal{F} be a sheaf of Abelian groups on $\mathrm{Sp}(A)$. If

$$0 \rightarrow \mathcal{F}(\Omega) \rightarrow \mathcal{F}(R_\Omega(g|1)) \oplus \mathcal{F}(R_\Omega(1|g)) \rightarrow \mathcal{F}(R_\Omega(g|1) \cap R_\Omega(1|g)) \rightarrow 0$$

is exact for all $\Omega \subseteq \mathrm{Sp}(A)$ rational and $g \in \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ then \mathcal{F} is acyclic.

We state two additional results concerning the unviersality of certain affinoid K -algebras. We first recall the following definitions.

Definition 1.18 (nat Ring). Let A be a topological ring. A is a nat ring if it has a basis of neighborhoods of zero consisting of open subgroups.

Definition 1.19 (Tate Ring). A nat ring A is Tate if it has a powerbounded neighborhood of zero and has a topologically nilpotent unit known as a quasi-uniformizer.

In turn:

Proposition 1.20. Let A be a Tate ring and

$$A\langle f_1, \dots, f_n \rangle = A\langle X_1, \dots, X_n \rangle / \langle X_1 - f_1, \dots, X_n - f_n \rangle.$$

$A\langle f_1, \dots, f_n \rangle$ is initial among nat A -algebras B where f_1, \dots, f_n are powerbounded. Furthermore, $A\langle f_1, \dots, f_n \rangle$ contains A as a dense subring.

Proposition 1.21. Let A be a Tate ring and

$$A\left\langle \frac{1}{f_1}, \dots, \frac{1}{f_n} \right\rangle = A\langle X_1, \dots, X_n \rangle / \left\langle X_1 - \frac{1}{f_1}, \dots, X_n - \frac{1}{f_n} \right\rangle.$$

$A\langle \frac{1}{f_1}, \dots, \frac{1}{f_n} \rangle$ is initial among nat A -algebras B where f_1, \dots, f_n are units with $\frac{1}{f_1}, \dots, \frac{1}{f_n}$ powerbounded. Furthermore, $A\langle \frac{1}{f_1}, \dots, \frac{1}{f_n} \rangle$ contains $A[\frac{1}{f_1}, \dots, \frac{1}{f_n}]$ as a dense subring.

We are now ready to define coherent sheaves.

We begin with the following preparatory result.

Proposition 1.22. Let A be an affinoid algebra and $\Omega \subseteq \mathrm{Sp}(A)$ a rational subset. Then:

- (i) For $B = \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ and $\mathfrak{m} \in \mathrm{Sp}(B)$, there is an isomorphism of K -algebras $B_{\mathfrak{m}}^\wedge \cong A_{\tilde{\mathfrak{m}}}^\wedge$ where $\tilde{\mathfrak{m}}$ is the preimage of \mathfrak{m} under the map $A \rightarrow B$ and $(-)^\wedge_I$ is the completion of a ring with respect to the ideal I .
- (ii) B is flat as an A -algebra.

Proof of (i). We first show a claim:

We now begin marginal labeling, which follows the lecture.

Proposition 2.1

(†) For all $n \in \mathbb{N}$, $A/\tilde{\mathfrak{m}}^n \rightarrow B/\mathfrak{m}^n$ is an isomorphism.

Note that B/\mathfrak{m}^n is initial amongst affinoid B -algebras C such that $\mathfrak{m}^n C = 0$, while A/\mathfrak{m}^n is initial amongst affinoid A -algebras C' such that $\tilde{\mathfrak{m}}^n C' = 0$. For C as above, the image of $\mathrm{Sp}(C)$ in $\mathrm{Sp}(B)$ is \mathfrak{m} , while the image of $\mathrm{Sp}(C')$ in $\mathrm{Sp}(A)$ is $\tilde{\mathfrak{m}} \in \Omega$. Applying the universal property twice, C' can be endowed uniquely with the structure of a B -algebra, and by $\kappa(\mathfrak{m}) \cong \kappa(\tilde{\mathfrak{m}})$ it follows that C' is generated by $\tilde{\mathfrak{m}}$. Thus both $A/\tilde{\mathfrak{m}}^n, B/\mathfrak{m}^n$ satisfy the same universal property, hence isomorphic.

The desired claim follows from (†) by passage to the limit. ■

Proof of (ii). By a standard result in commutative algebra, it suffices to show $B_{\mathfrak{m}}$ is A -flat for all $\mathfrak{m} \in \mathrm{mSpec}(B)$. B being Noetherian, $B_{\mathfrak{m}}^{\wedge}$ is a faithfully flat $B_{\mathfrak{m}}$ -algebra, whereby it is sufficient to show that $B_{\mathfrak{m}}^{\wedge}$ is flat over A . But $B_{\mathfrak{m}}^{\wedge} \cong A_{\mathfrak{m}}^{\wedge}$ by (i), which is a flat A -module as A is Noetherian, giving the claim. ■

As in the case of algebraic geometry, coherent sheaves are defined as $\widetilde{(-)}$ -ifications of finitely generated modules.

Definition 2.1

Definition 1.23 ($\widetilde{(-)}$). Let A be an affinoid K -algebra and M a finitely generated A -module. The sheaf \widetilde{M} is the sheafification of the presheaf $\Omega \mapsto M \otimes_A \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ on rational open subsets.

Exactness of the sequence

$0 \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega) \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(R_{\Omega}(1|g)) \oplus \mathcal{O}_{\mathrm{Sp}(A)}(R_{\Omega}(g|1)) \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(R_{\Omega}(g|1, g^2)) \rightarrow 0$
is preserved under $- \otimes_A M$ by Corollary 1.17. In particular, we have:

Proposition 2.2

Proposition 1.24. Let A be an affinoid K -algebra and M a finitely generated A -module with associated sheaf \widetilde{M} . Then $\widetilde{M}(\Omega) = \mathcal{O}_{\mathrm{Sp}(A)}(\Omega) \otimes_A M$ and $H^p(\Omega, \widetilde{M}) = 0$ for all $p > 0$ and for all rational Ω .

Proof. By flatness of $\mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ as an A -algebra, exactness of the sequence for Ω rational, we have a short exact sequence

$$0 \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega) \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1) \oplus \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_2) \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1 \cap \Omega_2) \rightarrow 0$$

and by flatness of $\mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ (vis. [Stacks, Tag 00M5]), we get that

$$0 \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega) \otimes_A M \rightarrow (\mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1) \oplus \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_2)) \otimes_A M \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1 \cap \Omega_2) \otimes_A M \rightarrow 0$$

is exact, so by noting that $M \otimes_A \mathcal{O}_{\mathrm{Sp}(A)}(\Omega) \cong \widetilde{M}(\Omega)$, we have that \widetilde{M} is acyclic. ■

2. LECTURE 2 – 24TH APRIL 2025

We define coherent sheaves.

Definition 2.2

Definition 2.1 (Coherent Sheaves). Let A be an affinoid K -algebra and \mathcal{F} an $\mathcal{O}_{\mathrm{Sp}(A)}$ -module. \mathcal{F} is coherent if it is of the form \widetilde{M} for some finitely generated A -module M .

The coherence condition can be shown to be local in the sense that any sheaf of modules for which there exists a covering sieve consisting of a trivialization by a cover by rational opens on which the modules are finitely generated is coherent. We show this as a consequence of a sequence of results.

Proposition 2.3

Proposition 2.2. Let A be an affinoid K -algebra and Ω_1, Ω_2 a rational cover of $\mathrm{Sp}(A)$ with intersection Ω_{12} . If $f_{12} \in \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_{12})$ then $f_{12} = f_1|_{\Omega_{12}} + f_2|_{\Omega_{12}}$ for $f_i \in \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_i)$ with $\|f_i\| = O(\|f_{12}\|)$.

Proof. Omitted. ■

Lemma 2.1

Lemma 2.3. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and Ω_1, Ω_2 a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. If $m_{12} \in \mathcal{M}(\Omega_{12})$ then there are $m_i \in \mathcal{M}(\Omega_i)$ with $\|m_i|_{\mathcal{M}(\Omega_i)}\| = O(\|m_{12}\|)$ (the constant independent of m_{12}) and such that

$$\|m_{12} - m_1|_{\Omega_{12}} - m_2|_{\Omega_{12}}\| \leq \frac{1}{2} \|m_{12}\|.$$

Finish proof. ↩

Lemma 2.2

Lemma 2.4. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and Ω_1, Ω_2 a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. If $m_{12} \in \mathcal{M}(\Omega_{12})$ then

$$m_{12} = m_1|_{\Omega_{12}} + m_2|_{\Omega_{12}}$$

where $m_i \in \mathcal{M}(\Omega_i)$ and $\|m_i|_{\mathcal{M}(\Omega_i)}\| = O(\|m_{12}|_{\mathcal{M}(\Omega_{12})}\|)$ with the implied constant independent of m_{12} .

Proof. Let C be the implied constant of Lemma 2.3. We can define recursively

$$\begin{aligned} m_{12} &= m_{12}^{(0)} = m_1^{(0)}|_{\Omega_{12}} + m_2^{(0)}|_{\Omega_{12}} + m_{12}^{(1)} \\ m_{12}^{(1)} &= m_1^{(1)}|_{\Omega_{12}} + m_2^{(0)}|_{\Omega_{12}} + m_{12}^{(2)} \\ &\vdots \qquad \qquad \qquad \vdots \end{aligned}$$

where $\|m_{12}^{(i+2)}|_{\mathcal{M}(\Omega_{12})}\| \leq \frac{1}{2} \|m_{12}^{(i)}|_{\mathcal{M}(\Omega_{12})}\|$ and $\|m_j^{(i)}|_{\mathcal{M}(\Omega_j)}\| \leq C \|m_{12}^{(i)}|_{\mathcal{M}(\Omega_{12})}\|$, hence $\|m_{12}^{(i)}|_{\mathcal{M}(\Omega_{12})}\| \leq \frac{1}{2^i} \|m_{12}|_{\mathcal{M}(\Omega_{12})}\|$ and $\|m_j^{(i)}|_{\mathcal{M}(\Omega_j)}\| \leq \frac{C}{2^i} \|m_{12}|_{\mathcal{M}(\Omega_{12})}\|$ and the assertion follows with $m_j = \sum_{i=0}^{\infty} m_j^{(i)} \in \mathcal{M}(\Omega_j)$ with the implied constant C . ■

From this we deduce:

Corollary 2.1

Corollary 2.5. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and Ω_1, Ω_2 a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. If $m_{12} \in \mathcal{M}(\Omega_{12})$ and $\varepsilon > 0$ then there are $m_i \in \mathcal{M}(\Omega_i)$ such that $m_{12} = m_1|_{\Omega_{12}} + m_2|_{\Omega_{12}}$ and $\|m_2|_{\mathcal{M}(\Omega_2)}\| < \varepsilon$.

Proof. Choose $m'_2 \in \mathcal{M}(\Omega_2)$ such that $\|m_{12} - m_2|_{\Omega_{12}}|_{\mathcal{M}(\Omega_{12})}\| < \delta$ then $m_{12} - m'_2 = m_1 + m''_2$ with $\|m_1|_{\mathcal{M}(\Omega_1)}\| + \|m''_2|_{\mathcal{M}(\Omega_2)}\| \leq C \cdot \delta$ with C as in Lemma 2.4. Then choose δ such that $C \cdot \delta < \varepsilon$. ■

Corollary 2.2

Corollary 2.6. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and Ω_1, Ω_2 a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. There are $(\mu_j)_{j=1}^{N_1} \in \mathcal{M}(\Omega)$ such that the $\mu_j|_{\Omega_1}$ generate $\mathcal{M}(\Omega_1)$.

Proof. By Corollary 2.5, $m_j^{(1)}|_{\Omega_{12}} = \mu_j^{(1)}|_{\Omega_{12}} + \mu_j^{(2)}|_{\Omega_{12}}$ where $\mu_j^{(k)} \in \mathcal{M}(\Omega_k)$ and $\|\mu_j^{(1)}|_{\mathcal{M}(\Omega)}\| \leq \varepsilon$ for any ε . Let

$$\begin{aligned}\mu_j|_{\Omega_1} &= m_j^{(1)} - \mu_j^{(1)} \\ \mu_j|_{\Omega_2} &= \mu_j^{(2)}\end{aligned}$$

then $\|\mu_j|_{\Omega_1} - m_j^{(1)}|_{\mathcal{M}(\Omega_j)}\| \leq \varepsilon$ and when $\varepsilon = \frac{1}{2}$ the assertion follows. ■

It follows that the set

$$\{g^{-k} \cdot m_1|_{\Omega_{12}} | m_1 \in \mathcal{M}(\Omega_1)\}$$

is dense in $\mathcal{M}(\Omega_{12})$, recalling here that $\Omega_1 = R_A(1|g)$.

Corollary 2.3

Corollary 2.7. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and $\Omega_1 = R_A(1|g), \Omega_2 = R_A(g|1)$ for $g \in A$ a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. If $m_{12} \in \mathcal{M}(\Omega_{12})$ and $\varepsilon > 0$ then

$$m_{12} = g^{-k} \cdot m_1|_{\Omega_{12}} + m_2|_{\Omega_{12}}$$

where $m_i \in \mathcal{M}(\Omega_i)$ and $\|m_2|_{\mathcal{M}(\Omega_2)}\| \leq \varepsilon$.

Proof. One need only repeat the arguments of Corollary 2.5 ■

Corollary 2.4

Corollary 2.8. Let \mathcal{M} be a sheaf of $\mathcal{O}_{\mathrm{Sp}(A)}$ -modules on $\mathrm{Sp}(A)$ and $\Omega_1 = R_A(1|g), \Omega_2 = R_A(g|1)$ for $g \in A$ a rational cover of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_i} = M_i$ with M_i finitely generated. There are $(\mu_j^{(2)})_{j=1}^{N_2} \in \mathcal{M}(\Omega)$ such that $\mu_j|_{\Omega_2}$ generate $\mathcal{M}(\Omega_2)$.

Proof. Write

$$\begin{aligned}m_j^{(2)}|_{\Omega_{12}} &= g^{-k} \mu_j^{(1)}|_{\Omega_{12}} + \mu_j^{(2)}|_{\Omega_{12}} \\ \mu_j|_{\Omega_2} &= \mu_j^{(1)} \\ \mu_j|_{\Omega_2} &= g^k (m_j^{(2)} - \mu_j^{(2)})\end{aligned}$$

and the assertion follows when $\varepsilon \leq \frac{1}{2}$ in which case $\|m_j^{(2)} - g^k \cdot \mu_j|_{\mathcal{M}(\Omega_2)}\| \leq \frac{1}{2}$. ■

3. LECTURE 3 – 8TH MAY 2025

We prove the locality statement earlier alluded to.

Proposition 3.1. Let \mathcal{S} be a covering sieve of $\mathrm{Sp}(A)$ where \mathcal{S} is generated by \widetilde{M}_Ω where M_Ω is a finitely generated $\mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ -module. Then \widetilde{M} is coherent.

Proof. By induction on Laurent order, it suffices to show that for $g \in A$ and $\Omega_1 = R_A(1|g), \Omega_2 = R_A(g|1)$ rational opens of $\mathrm{Sp}(A)$ on which $\mathcal{M}|_{\Omega_1} = M_1, \mathcal{M}|_{\Omega_2} = M_2$ are finitely generated $\mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1), \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_2)$ -modules, that \mathcal{M} is finitely generated too.

By Corollaries 2.6 and 2.8 there are sections $(m_i)_{i=1}^n$ generating \mathcal{M} as an $\mathcal{O}_{\mathrm{Sp}(A)}$ -module such that their restrictions to Ω_1, Ω_2 generate $\mathcal{M}|_{\Omega_1}, \mathcal{M}|_{\Omega_2}$. Consider

$$\mathcal{K} = \ker \left(\mathcal{O}_{\mathrm{Sp}(A)}^n \xrightarrow{(m_i)_{i=1}^n} \mathcal{M} \right).$$

We have $\mathcal{K}|_{\Omega_j} = \widetilde{K}_j$ where

$$K_j = \ker \left(\mathcal{O}_{\mathrm{Sp}(A)}(\Omega_j)^n \xrightarrow{(m_i|_{\Omega_j})_{i=1}^n} M_j \right).$$

Applying the same reasoning, we have that there are $(k_i)_{i=1}^m$ that generate \mathcal{K} as an $\mathcal{O}_{\mathrm{Sp}(A)}$ -module. It follows that \mathcal{M} is the cokernel of

$$\mathcal{O}_{\mathrm{Sp}(A)}^m \xrightarrow{(k_i)_{i=1}^m} \mathcal{O}_{\mathrm{Sp}(A)}^n.$$

The universal property shows that \mathcal{M} is isomorphic to the cokernel as it is an isomorphism of each Ω_j . Since $\widetilde{(-)}$ is exact, we obtain $\mathcal{M} = \widetilde{M}$ where M is the cokernel of $A^{\oplus m} \rightarrow A^{\oplus n}$ by the k_i 's. ■

Remark 3.2. In general if \mathcal{R} is a sheaf of rings on a site, we say an \mathcal{R} -module is finitely generated if there are finitely many global sections such that $\mathcal{R}^n \rightarrow \mathcal{M}$ is an epimorphism of sheaves. We say \mathcal{M} is locally finitely generated if the objects on which \mathcal{M} is finitely generated form a covering sieve, and \mathcal{M} is coherent if it is locally finitely generated and the kernels of the local maps $\mathcal{R}|_X^n \rightarrow \mathcal{M}|_X$ have finitely generated kernels.

Remark 3.3. On a one point space, this is the condition of the kernel being finitely generated. That is, that the ring is a coherent ring.

Example 3.4. Let us consider Remark 3.2 in the setting of $X = \mathrm{Sp}(A), \mathcal{R} = \mathcal{O}_X, \mathcal{M} = \widetilde{M}$ for M a finitely generated A -module. In this case, the kernel of the map $A^{\oplus n} \rightarrow M$ generate the kernel sheaf $\mathcal{O}_{\mathrm{Sp}(A)}^n \rightarrow \mathcal{M}$ so sheaves coherent in the sense of Definition 2.1 are coherent in the sense of Remark 3.2.

Dually, if \mathcal{M} is coherent in the sense of Remark 3.2, we can use locality of coherence Proposition 3.1 to observe that the global sections generating \mathcal{M} and the kernel sheaf \mathcal{K} give rise to A -modules M, K such that M is the cokernel of $K \rightarrow A^n$.

This concludes our discussion of coherent sheaves.

Recall that $\mathrm{Sp}(\mathbb{T}_1)$ for K algebraically closed has van der Put points ξ given by the balls of radius $\leq R$ for $R \in |K| \subseteq \mathbb{R}_{\geq 0}$. Denote $\mathfrak{K}_{\leq R}$ of all balls $K_{\leq R}(X)$ for $x \in \mathrm{Sp}(A)$. For a van der Put point ξ of $\mathrm{Sp}(A)$, we can define M_ξ to be the set of all $r \in [0, 1) \cap |K^\times|$ for which there exists an $x \in \mathfrak{K}_{\leq r} \cap \xi$ – that is, ξ contains a ball of radius r . Denote $K_{\leq R}(\xi)$ be set of rational open sets of radius at most R in the van der Put point ξ .

Example 3.5. If R is arbitrarily small, then $K_{\leq R}(\xi) = \{x\}$. In this case, $x \in \Omega$ if and only if $R(f_0|f_1, \dots, f_n) = \Omega \in \xi$ if and only if $\nu(f_0) \geq \nu(f_i)$ where $\nu(f) = |f(x)|$ for all $1 \leq i \leq n$.

4. LECTURE 4 – 15TH MAY 2025

We consider the van der Put points of a Tate spectrum in terms of the adic spectrum.

The construction of the adic spectrum begins with Huber pairs.

Definition 4.1 (Huber Pair). A Huber pair is a pair (A, A^+) where:

- A is a nat ring with an open bounded subring whose topology is I -adic for some finitely generated ideal I .
- $A^+ \subseteq A^\circ$ is an open integrally closed subring.

Definition 4.2 (Morphism of Huber Pairs). A morphism of Huber pairs $\varphi : (A, A^+) \rightarrow (B, B^+)$ is a continuous homomorphism of rings $\varphi : A \rightarrow B$ such that $\varphi(A^+) \subseteq B^+$.

Remark 4.3. The subring of powerbounded elements A° is always an integrally closed subring of A . In particular, if A is Huber, (A, A°) is a Huber pair. If further A is Tate, then for any morphism of Huber pairs $\varphi : (A, A^\circ) \rightarrow (B, B^\circ)$ the condition that $\varphi(A^\circ) \subseteq B^\circ$ is automatic and B is also Tate.

The adic spectrum is defined as a certain subspace of the space of valuations.

Definition 4.4 (Valuation). A valuation on a ring A is a map $\nu : A \rightarrow \Gamma \cup \{0\}$, where Γ is written multiplicatively, such that:

- (i) $0 < \gamma$ for all $\gamma \in \Gamma$.
- (ii) $\nu(ab) = \nu(a) \cdot \nu(b)$.
- (iii) $\nu(a + b) \leq \max\{\nu(a), \nu(b)\}$.
- (iv) $\nu(1) = 1$.

Definition 4.5 (Support of Valuation). Let ν be a valuation on a ring A . The support $\text{supp}(\nu)$ of ν is the prime ideal $\{a \in A : \nu(a) = 0\} \subseteq A$.

Remark 4.6. We assume that Γ is generated by the image of $R \setminus \text{supp}(\nu)$. In this case, $\nu \simeq \tilde{\nu}$ if and only if there is a unique isomorphism of groups $\tau : \Gamma \rightarrow \tilde{\Gamma}$ of groups $\tilde{\nu} = \tau \circ \nu$.

We consider some additional constructions related to valuations.

Definition 4.7 (Convex Subset). A subset X of Γ is convex if and only if for all $\gamma, \gamma' \in X$, $[\gamma, \gamma']_\Gamma \subseteq X$.

Definition 4.8 (Rank of Valuation). Let ν be a valuation on a ring A . The rank of ν is the number of convex subgroups.

Remark 4.9. The set of convex subgroups is linearly ordered by inclusion.

We can define continuous valuations by topologizing $\Gamma \cup \{0\}$ with the topology that all elements of Γ are open points and the collection of half-open intervals $\{[0, \gamma)_\Gamma : \gamma \in \Gamma\}$ form a neighborhood basis of 0.

Definition 4.10 (Continuous Valuation). Let ν be a valuation on a ring A . ν is a continuous valuation if it is continuous as a map where $\Gamma \cup \{0\}$ is equipped with the topology where all elements of Γ are open points and the collection of half-open intervals $\{[0, \gamma)_\Gamma : \gamma \in \Gamma\}$ form a neighborhood basis of 0.

Remark 4.11. The following conditions are equivalent to a valuation being continuous:

- If $\nu(a) \neq 0$ then $\{a' \in A : \nu(a') < \nu(a)\}$ is open.
- The set $\{a \in A : \nu(a) < \gamma\}$ is open for $\gamma \in \Gamma$.

Definition 4.12 (Space of Continuous Valuations). Let A be a nat ring and let $\text{Cont}(A)$ be the set of continuous valuations equipped with the topology that the rational open subsets

$$R_{\text{Cont}(A)}(a_0|a_1, \dots, a_n) = \{\nu / \sim, \nu \text{ cts.} : \nu(a_0) \neq 0, \nu(a_i) \leq \nu(a_0) \forall 1 \leq i \leq n\}$$

such that (a_0, \dots, a_n) is an open ideal in A .

Remark 4.13. In particular if A is Tate then the only open ideal is the ring itself, and $(a_0, \dots, a_n) = A$.

Remark 4.14. For general topological rings, these rational open subsets may fail to be closed under finite intersection, but this always holds for Huber rings.

We recall the following result.

Proposition 4.15. Let A be a nat ring and let $\text{Cont}(A)$ be the space of continuous valuations of A . $\text{Cont}(A)$ is a spectral space with quasicompact basis given by the rational open subsets.

This allows us to construct the adic spectrum.

Corollary 4.16. Let A^+ be an integrally closed subring of a nat ring A . The subspace

$$\bigcap_{a \in A^+} R_{\text{Cont}(A)}(1|a) = \{\nu / \sim, \nu \text{ cts.} : \nu(a) \leq 1 \forall a \in A^+\}$$

is spectral.

Proof. This is a proconstructible subset of a spectral space, hence spectral. ■

We can finally define the adic spectrum.

Definition 4.17 (Affinoid Adic Space). Let (A, A^+) be a Huber pair. The adic spectrum $\text{Spa}(A, A^+)$ of (A, A^+) is the subspace

$$\bigcap_{a \in A^+} R_{\text{Cont}(A)}(1|a) = \{\nu / \sim, \nu \text{ cts.} : \nu(a) \leq 1 \forall a \in A^+\}.$$

Remark 4.18. When A is a Tate ring,

$$R_{\text{Cont}(A)}(f_0|f_1, \dots, f_n) = \{\nu / \sim, \nu \text{ cts.} : \nu(f_i) \leq \nu(f_0) \forall 1 \leq i \leq n\}.$$

Henceforth we take A to be an affinoid K -algebra.

Example 4.19. If $\kappa \in K$ and $|\kappa| = 1$ then $K^\circ \subseteq A^\circ$ and $1/\kappa \in K^\circ \subseteq A^\circ$ so $\nu(\kappa) \leq 1, \nu(1/\kappa) \leq 1$ showing $\nu(\kappa) = 1$ and K^\times is a subgroup of Γ .

Up to replacing ν by an equivalent valuation as in Remark 4.6, we can assume that $|K^\times| \subseteq \Gamma$ which is typically not convex. If $t \in \mathbb{R}$ such that $t^n \in |K^\times|$ for some $n \in \mathbb{N}$, say $\gamma \leq t$ (resp. $\gamma < t$) if and only if $\gamma^n \leq t^n$ (resp. $\gamma^n < t^n$). If $t \in \mathbb{R}_{>0}$ and there is no positive integer n with $t^n \in |K^\times|$ exists, say $\gamma \leq t$ if and only if $\gamma < t$ if and only if there exists $n \in \mathbb{N}$ and $\kappa \in K^\times$ such that $\gamma^n \leq |\kappa|^n < t^n$. For general real numbers t, γ , the inequality $t < \gamma$ is dealt with in the same way.

In what follows, we will use the following fact.

Lemma 4.20. Let A be an affinoid K -algebra. If $\|\cdot\|$ is a residual norm, then a valuation ν on A such that $\nu((K^\circ)^\times) \subseteq \{1\}$. ν is continuous if and only if there exists $c \in \mathbb{R}$ such that $\nu(a) \leq c\|a\|$ and $|K^\times|$ is cofinal in Γ – for all $\gamma \in \Gamma$, there is $\varepsilon \in K^\times$ such that $|\varepsilon| \leq \gamma$.

We will soon show that the van der Put points of the Tate $\mathrm{Sp}(A)$ is homeomorphic as a G_+ -space to $\mathrm{Spa}(A, A^\circ)$ by constructing a specific bijection, and show that $\mathrm{Spa}(A, A^\circ)$ has Krull dimension is that of A .

Example 4.21. Let $A = \mathbb{T}_1$ and $A^+ = K^\circ + A^{\circ\circ}$. (A, A^+) is a Huber pair and $\mathrm{Spa}(A, A^\circ) \setminus \mathrm{Spa}(A, A^+)$ has exactly one element ν where $\nu(f) = (\|f\|_{\mathbb{T}_1} - \kappa_f)$ where for $f = \sum_{j \geq 0} f_j T^j \in \mathbb{T}_1 \setminus \{0\}$, $\kappa_f = \max\{j : |f_j| = \|f\|_{\mathbb{T}_1}\}$.

Remark 4.22. The pair (A, A^+) is not necessarily topologically of finite type over (K, K°) .

The proofs of the abovementioned result will require a careful treatment of power-bounded elements and the proof of the result on Krull dimension is also fairly subtle.

5. LECTURE 5 – 22ND MAY 2025

We make preparations towards showing the result of van der Put-Schneider and Huber [vdPS95, Thm. 4] showing that the space of van der Put points on $\mathrm{Sp}(A)$ for A affinoid is homeomorphic to the adic spectrum $\mathrm{Spa}(A, A^\circ)$ of the correct Krull dimension.

Proposition 5.1. Let $A \rightarrow B$ be a morphism of affinoid K -algebras.

- (i) If B is finite over A , then B° is integral – but not necessarily finite – over A° .
- (ii) $\tilde{A} = A^\circ/A^{\circ\circ}$ is finite type over $K^\circ/K^{\circ\circ}$ with Krull dimension equal to that of A . Moreover, \tilde{B} is finite over \tilde{A} .

Example 5.2. If $A = \mathbb{T}_n$, then $\tilde{A} = A^\circ/A^{\circ\circ} \cong K[X_1, \dots, X_n]$ the ordinary polynomial ring in n variables.

Proposition 5.3. Let A be a nat ring. Then $A\langle X_1, \dots, X_n \rangle^\circ \cong A^\circ\langle X_1, \dots, X_n \rangle$.

Lemma 5.4. Let A be an affinoid K -algebra, $\Omega = R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n)$, and $B = \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$. Consider the following conditions:

Lemma 3.1

- (a) $\nu \in R_{\mathrm{Spa}(A, A^\circ)}(f_0|f_1, \dots, f_n)$.
- (b) ν can be extended to an element of $\mathrm{Spa}(B, B^\circ)$.
- (c) ν admits a unique continuous extension to B .

then the following implications hold:

- (i) (a) and (b) are equivalent.
- (ii) (a) and (b) imply (c).

The statement of Lemma 5.4 reduces to showing this for Weierstrass domains (where $f_0 = 1$) and Laurent domains (where $f_1 = 1$).

Lemma 5.5. The statement of Lemma 5.4 holds for $f_0 = 1$.

Proof ok?

Proof. Note that in this case $f_0 = 1$ so $\mathcal{O}_{\mathrm{Sp}(A)}(R_{\mathrm{Sp}(A)}(1|f_1, \dots, f_n))$ is of the form $A\langle f_1, \dots, f_n \rangle$.

(a) \Rightarrow (b) Suppose $\nu \in R_{\mathrm{Spa}(A, A^\circ)}(1|f_1, \dots, f_n)$ so $\nu(f_i) \leq 1$ for all i . For $g \in A\langle X_1, \dots, X_n \rangle$, we set $\nu_1(g) = \lim_{n \rightarrow \infty} v_n$ where $v_n = \nu(a_n)$ and

$$(5.1) \quad a_n = \sum_{|\alpha| \leq n} g_\alpha f^\alpha.$$

We observe that the limit $\nu_1(g)$ converges as by definition of the Tate algebra $A\langle X_1, \dots, X_n \rangle$ there is an $N \in \mathbb{N}$ such that for each $\varepsilon \in \mathbb{R}_{>0}$ we have $|g_\alpha| < \varepsilon$ for $|\alpha| \geq N$. This implies that

$$(5.2) \quad \nu \left(\sum_{k < |\alpha| \leq l} g_\alpha f^\alpha \right) \leq \varepsilon$$

when $\min\{k, l\} \geq N$. If $\liminf_{n \rightarrow \infty} v_n = 0$ in (5.1) then $\lim_{n \rightarrow \infty} v_n = 0$. For any $\varepsilon > 0$, we can find N such that (5.2) holds, and the assertion follows. However, if

$\varepsilon = \liminf_{n \rightarrow \infty} |v_n|$ is positive, then we can find N such that (5.2) holds and $k > N$ with $|v_k| \geq \varepsilon$. For $l \geq k$ we have $\nu(a_l - a_k) < v_k = \nu(a_k)$ so $v_l = v_k$ and the sequence converges. This gives a continuous extension of ν to a continuous valuation which is bounded by Proposition 5.3.

(b) \Rightarrow (a),(c) Denote $B = \mathcal{O}_{\mathrm{Sp}(A)}(R_{\mathrm{Sp}(A)}(1|f_1, \dots, f_n))$ and suppose that we have $\mu : A \rightarrow \Gamma_\mu$ a continuous extension of ν to an element of $\mathrm{Spa}(B, B^\circ)$. By Proposition 1.20, A is dense in B so for any $b \in B$ there is a convergent $(a_n)_{n=1}^\infty$ converging to b . By continuity of μ , we have

$$\mu(b) = \lim_{n \rightarrow \infty} \mu(a_n) = \lim_{n \rightarrow \infty} \nu(a_n)$$

as sequences in $\Gamma_\mu \cup \{0\}$. The topology of $\Gamma_\nu \subseteq \Gamma_\mu$ is discrete we have in the case when $\mu(b) \neq 0$ that the sequence $\nu(a_n)$ stabilize for n large. So the values of ν and μ coincide giving $\Gamma_\mu = \Gamma_\nu$. Alternatively, viewing the convergence in $\Gamma_\nu \cup \{0\}$, we have that μ is uniquely determined by ν . This shows that (b) implies (c). Now observe that since the images of f_i lie in B° , $\nu(f_i) = \mu(f_i) \leq 1$ so ν is indeed in $R_{\mathrm{Sp}(A, A^\circ)}(1|f_1, \dots, f_n)$. ■

Lemma 5.6. The statement of Lemma 5.4 holds for $f_1 = 1$.

Proof. This is essentially the same as Lemma 5.5, using the universal property of the localization Proposition 1.21 instead. ■

Proof of Lemma 5.4. By induction on the Laurent order on the sieve, it suffices to prove the statement in the case of Weierstrass and Laurent domains, which are precisely the cases treated in Lemmas 5.5 and 5.6. ■

6. LECTURE 6 – 27TH MAY 2025

We continue with the proof of the result of van der Put-Schneider and Huber stating that the space of van der Put points on $\mathrm{Sp}(A)$ is homeomorphic to $\mathrm{Spa}(A, A^\circ)$.

We can define a morphism $\mathrm{Spa}(A, A^\circ) \rightarrow \mathrm{Sp}(A)^*$ by

$$(6.1) \quad (\nu / \sim) \mapsto \xi_\nu = \{R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n) : \nu(f_i) \leq \nu(f_0), \forall 1 \leq i \leq n\}.$$

This can be shown to be well-defined.

Proposition 6.1. Let A be an affinoid K -algebra, $\Omega = R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n)$, and $B = \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$. Then the map (6.1) exists and is well-defined.

Proof. We first show that ξ_ν is a van der Put point. If $\Omega \subseteq \Theta \subseteq X$ and $\Omega \in \xi_\nu$ then $\nu \in R_{\mathrm{Spa}(A, A^\circ)}(f_0|f_1, \dots, f_n)$ extends to $\nu_\Omega \in \mathrm{Spa}(\mathcal{O}_{\mathrm{Sp}(A)}(\Omega), \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)^\circ)$. Consider the restriction map $\mathcal{O}_{\mathrm{Sp}(A)}(\Theta) \rightarrow \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$. The map is continuous and the image of $\mathcal{O}_{\mathrm{Sp}(A)}(\Theta)^\circ$ is in $\mathcal{O}_{\mathrm{Sp}(A)}(\Omega)^\circ$. By Lemma 5.4, there is a unique extension to $\nu_\Theta \in \mathrm{Spa}(\mathcal{O}_{\mathrm{Sp}(A)}(\Theta), \mathcal{O}_{\mathrm{Sp}(A)}(\Theta)^\circ)$ so $\Theta \in \xi_\nu$.

Having shown the upwards closure property, it remains to show the sieve properties. Let $\Omega = R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n), \Theta = R_{\mathrm{Sp}(A)}(g_0|g_1, \dots, g_m) \in \xi_\nu$. We have $\nu(f_0g_0) \geq \nu(f_ig_j)$ for all $1 \leq i \leq n, 1 \leq j \leq m$ so $\Omega \cap \Theta = R_{\mathrm{Sp}(A)}(f_0g_0|f_ig_j) \in \xi_\nu$. This shows verifies the second van der Put point condition. Now for $\Omega \in \xi_\nu$, let \mathcal{S} be a covering sieve of Ω . We need to show that $\mathcal{S} \cap \xi_\nu$ is nonempty. We proceed by induction on the (necessarily finite) Laurent order of the sieve. If $\mathfrak{o}_L(\mathcal{S}) = 0$ then $\Omega \in \mathcal{S}$ and the assertion follows. Observe that there is $g \in \mathcal{O}_{\mathrm{Sp}(A)}(\Omega)$ such that $\mathfrak{o}_L(\mathcal{S}|_{\Omega_1}) < \mathfrak{o}_L(\mathcal{S})$ or $\mathfrak{o}_L(\mathcal{S}|_{\Omega_2}) < \mathfrak{o}_L(\mathcal{S})$ where $\Omega_1 = R_\Omega(g|1), \Omega_2 = R_\Omega(1|g)$. If $\nu_\Omega(g) \leq 1$ then by Lemma 5.4 replacing $\mathrm{Sp}(A)$ by Ω and ν by ν_Ω we get an extension to an element of $\mathrm{Spa}(\mathcal{O}_{\mathrm{Sp}(A)}(\Omega_2), \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_2)^\circ)$. Arguing similarly in the case of $\nu_\Omega(g) > 1$ we get an extension to an element of $\mathrm{Spa}(\mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1), \mathcal{O}_{\mathrm{Sp}(A)}(\Omega_1)^\circ)$. The Ω_i are rational open subsets and by the induction assumption $\emptyset \neq (\mathcal{S}|_{\Omega_i}) \cap \xi_\nu \subseteq \mathcal{S} \cap \xi_\nu$. The former is nonempty, and thus so is the latter. This too shows the well-definedness of the map. \blacksquare

Proposition 6.1 does the bulk of the work of proving the theorem of Huber and van der Put-Schneider. We first show that this map is a bijection.

Definition 6.2 (ξ -Infinitesimal). Let A be an affinoid K -algebra and $\xi \in \mathrm{Sp}(A)^*$ be a van der Put point. An element $a \in A$ is ξ -infinitesimal if and only if $R_{\mathrm{Sp}(A)}(\varepsilon|a) \in \xi$ for all $\varepsilon \in K^\times$.

Definition 6.3 (ξ -Ordering). Let A be an affinoid K -algebra and $\xi \in \mathrm{Sp}(A)^*$ be a van der Put point. If a is not ξ -infinitesimal, then we say $b \preceq_\xi a$ if and only if the following equivalent conditions hold:

- (i) $R_{\mathrm{Sp}(A)}(a|b, \varepsilon) \in \xi$ for some $\varepsilon \in K^\times$.
- (ii) $R_{\mathrm{Sp}(A)}(a|b, \varepsilon) \in \xi$ for all $\varepsilon \in K^\times$ with $|\varepsilon|$ small enough.

Remark 6.4. We have for a ξ -infinitesimal, $b \preceq_\xi a$ if and only if b is ξ -infinitesimal and we say $a \simeq_\xi b$ if and only if $b \preceq_\xi a$ and $a \preceq_\xi b$.

We can show that the ordering of Definition 6.3 defines a linear partial order on the non- ξ -infinitesimal elements of A .

Proposition 6.5. Let ξ be a van der Put point on $\mathrm{Sp}(A)$. The ξ -ordering is a linear partial order on the monoid $\{a \in A : a \text{ not } \xi\text{-infinitesimal}\}$.

Proof. If a, b are not ξ -infinitesimal then $R_{\mathrm{Sp}(A)}(a|\varepsilon), R_{\mathrm{Sp}(A)}(b|\varepsilon) \in \xi$ for some $\varepsilon \in K^\times$. Their intersection $R_{\mathrm{Sp}(A)}(a|\varepsilon) \cap R_{\mathrm{Sp}(A)}(b|\varepsilon) = R_{\mathrm{Sp}(A)}(fg|\varepsilon^2)$ is in ξ and the covering $R_{\mathrm{Sp}(A)}(a|b, \varepsilon) \cup R_{\mathrm{Sp}(A)}(b|a, \varepsilon)$ is admissible as it is finite, hence one of $R_{\mathrm{Sp}(A)}(a|b, \varepsilon), R_{\mathrm{Sp}(A)}(b|a, \varepsilon)$ lie in ξ giving one of $b \preceq_\xi a$ or $a \preceq_\xi b$.

To show this partial order is linear, suppose we have a, b, c non-infinitesimal and $ac \preceq_\xi bc$. Then $R_{\mathrm{Sp}(A)}(bc|ac, \varepsilon) \in \xi$ and $R_{\mathrm{Sp}(A)}(c|\delta) \in \xi$ for $\varepsilon, \delta \in K^\times$. When $\tilde{\varepsilon} \in K^\times$ such that $|\tilde{\varepsilon}| \cdot \|c|A\|_{\max} \leq \varepsilon$ we have $R_{\mathrm{Sp}(A)}(c|\delta) \cap R_{\mathrm{Sp}(A)}(bc|ac, \varepsilon) \subseteq R_{\mathrm{Sp}(A)}(b|a, \tilde{\varepsilon})$ so $a \preceq_\xi b$, that is, the monoid is cancellative. ■

The data of the linear order allows us to define a map to a linearly ordered group, and in fact prescribes a point of the adic spectrum.

Proposition 6.6. Let ξ be a van der Put point on $\mathrm{Sp}(A)$ and Γ denote the quotient of the linearly ordered monoid $\{a \in A : a \text{ not } \xi\text{-infinitesimal}\}$ by the equivalence \simeq_ξ . There is a continuous map

$$(6.2) \quad \nu_\xi : A \rightarrow \Gamma \cup \{0\} \text{ by } \nu_\xi(a) = \begin{cases} 0 & a \text{ is } \xi\text{-infinitesimal} \\ [a]_\xi & \text{otherwise} \end{cases}$$

with $\nu_\xi \in \mathrm{Spa}(A, A^\circ)$.

Proof. It is clear that ν_ξ is a valuation. If $\gamma \in \Gamma$ with $\gamma = \frac{[a]_\xi}{[b]_\xi}$ then for $R(a|\varepsilon) \cap R(b|\varepsilon) \in \xi$ and δ such that $\delta \cdot \|b|A\|_{\max} < \varepsilon$ then $\|f|A\|_{\max} < \varepsilon\delta$ implies that $\nu_\xi(f) < \gamma$ showing continuity. ν_ξ satisfies the correct compatibility condition with respect to A° as powerbounded elements are ξ -infinitesimal. ■

This is inverse to the construction (6.1).

Proposition 6.7. Let A be an affinoid K -algebra. The constructions (6.1) and (6.2) are mutually inverse.

Proof. Suppose $\Omega = R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n) \in \xi$ then

$$R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n, \varepsilon) = R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n) \in \xi$$

when ε is small enough, showing $\nu_\xi(f_i) \leq \nu_\xi(f_0)$ and $\Omega \in \xi_{\nu_\xi}$. Suppose that $\nu \in \xi_\nu$, that is, $\nu_\xi(f_i) \leq \nu_\xi(f_0)$. Since not all $f_i \in \mathrm{supp}(\nu_\xi) = \{f \in A : f \text{ is } \xi\text{-infinitesimal}\}$ we have $f_0 \in \mathrm{supp}(\nu_\xi)$ hence f_0 is not ξ -infinitesimal. Taking $\varepsilon \in K^\times$ small, all $R_{\mathrm{Sp}(A)}(f_0|f_i, \varepsilon) \in \xi$ hence

$$\bigcap_{i=1}^n R_{\mathrm{Sp}(A)}(f_0|f_i, \varepsilon) \subseteq R_{\mathrm{Sp}(A)}(f_0|f_1, \dots, f_n)$$

and $\bigcap_{i=1}^n R_{\mathrm{Sp}(A)}(f_0|f_i, \varepsilon) \in \xi$. This shows $\xi = \xi_{\nu_\xi}$.

Dually suppose ν is given. It follows from the definitions and continuity that $a \in A$ is ξ -infinitesimal if and only if $\nu(a) = 0$ and $a \geq b$ if and only if $\nu(a) \geq \nu(b)$ so indeed $\nu_\xi = \nu$. ■

This proves the bijection in full. It remains to show the assertion regarding the Krull dimension.

For the statement on Krull dimension, we consider some general properties of specializations in $\mathrm{Spa}(A, A^+)$ for A Tate.

Lemma 6.8. Let (A, A^+) be a Huber pair with A Tate. There is a continuous morphism $S : \mathrm{Spa}(A, A^+) \rightarrow \mathrm{Spec}(A)$ by $\nu \mapsto \mathrm{supp}(\nu)$

Proof. We have $S^{-1}(\mathrm{Spec}(A_f)) = \bigcup_{m \geq 0} R_{\mathrm{Spa}(A, A^+)}(f|s^m)$ for a topologically nilpotent unit $s \in A^\times \cap A^{\circ\circ}$. ■

The map S detects when points have disjoint neighborhoods in $\mathrm{Spa}(A, A^+)$.

Lemma 6.9. Let (A, A^+) be a Huber pair with A Tate. Then $S(x) \neq S(y)$ if and only if $x, y \in \mathrm{Spa}(A, A^+)$ have disjoint open neighborhoods.

Proof. Without loss of generality, let $a \in A$ be such that $|a|_x > 0$ but $|a|_y = 0$. By continuity of $|\cdot|_x$ and $\lim_{m \rightarrow \infty} s^m = 0$, $|a|_x \geq |s^m|_x$ when m is sufficiently large. Thus $x \in R_{\mathrm{Spa}(A, A^+)}(a|s^m)$, $y \in R_{\mathrm{Spa}(A, A^+)}(s^{m+1}|a)$ and these rational open subsets are disjoint. ■

Recall that for X a space, a point $y \in X$ is a generification of $x \in X$ if $x \in \overline{\{y\}}$.

Remark 6.10. Since $\mathrm{Spa}(A, A^+)$ is spectral, each irreducible component has a unique generic point so each point of $\mathrm{Spa}(A, A^+)$ has a maximal generification.

Definition 6.11 (Vertical generification). Let $(\nu/\sim) \in \mathrm{Spa}(A, A^\circ)$, Γ the group of values of ν , and $\Lambda \subseteq \Gamma$ a convex subgroup. We define a valuation

$$(\nu/\Lambda)(a) = \begin{cases} 0 & \nu(a) = 0 \\ \nu(a)\Lambda & \text{otherwise.} \end{cases}$$

These generifications are vertical in the sense that they occur within a single fiber of the map $S : \mathrm{Spa}(A, A^\circ) \rightarrow \mathrm{Spec}(A)$ of Lemma 6.8

7. LECTURE 7 – 5TH JUNE 2025

We continue with the proofs of results relating to vertical generifications in adic spaces.

Lemma 7.1. Let A be a Tate ring with topologically nilpotent unit s and $(\nu/\sim) \in \text{Spa}(A, A^\circ)$.

- (i) $\Lambda_{\max} = \{\gamma \in \Gamma : \nu(s) \leq \gamma^n \leq \nu(s)^{-1}, \forall n \in \mathbb{N}\}$ is the largest proper convex subgroup of Γ_ν .
- (ii) The most vertical generification of (ν/\sim) is $((\nu/\Lambda_{\max})/\sim)$.
- (iii) All generifications of ν are vertical.

Proof of (i). By continuity $\Gamma = \bigcup_{m \in \mathbb{N}} [\nu(s)^m, \nu(s)^{-m}]_\Gamma$ so $\Gamma = \bigcup_{m \in \mathbb{N}} [\gamma^m, \gamma^{-m}]_\Gamma$ when $\gamma \in \Gamma/\Lambda_{\max}$. Let $\tilde{\nu}$ be a generification of ν . By Lemma 6.9 their supports coincide, and ν/Λ where $\Lambda = \bigcup_{a, b \in A \setminus \mathfrak{p}} \left[\frac{\nu(a)}{\nu(b)}, \frac{\nu(b)}{\nu(a)} \right]_\Gamma$ so $\tilde{\nu} \in R_{\text{Spa}(A, A^\circ)}(a|b, s^m)$. ■

Proof of (ii). This is immediate from maximality of Λ_{\max} . ■

Proof of (iii). Let μ/\sim be a generification of ν/\sim . By Lemma 6.9, the two valuations have identical supports. We claim that if $\nu(a) \leq \nu(b)$ then $\mu(a) \leq \mu(b)$. If $\nu(a) = 0$ then the statement is trivial as it follows from equality of supports. Otherwise $\nu(b) \neq 0$ and by continuity there is some natural number n such that $\nu(s^n) \leq \nu(b)$. Then $(\nu/\sim) \in R_{\text{Spa}(A, A^\circ)}(b|a, s^n)$. Since μ/\sim is a generification, it lies in $R_{\text{Spa}(A, A^\circ)}(b|a, s^n)$ as well. So $\mu(a) \leq \mu(b)$ as desired. It then follows that $\mu \simeq \nu/\Lambda$ where $\Lambda \subseteq \Gamma_\nu$ is the convex subgroup generated by $\{\nu(a) : a \in A, \mu(a) = 1\}$. ■

Remark 7.2. Note that Lemma 6.9 implying that generifications have identical supports only holds in the Tate case.

Proposition 7.3. Let (A, A^+) be a Huber pair with A Tate and $x, y \in \text{Spa}(A, A^+)$. Then x, y have disjoint open neighborhoods if and only if their most generic vertical generifications differ.

Proof. Suppose that x, y have disjoint open neighborhoods. Then they obviously cannot have a common vertical generification.

Conversely suppose ξ, ν are the most generic vertical generifications of x, y , respectively. By Lemma 6.8 their supports agree which we denote $\mathfrak{p} \subseteq A$. Without loss of generality, there are $a, b \in A \setminus \mathfrak{p}$ such that $|a|_\xi \leq |b|_\xi$ but $|b|_\nu \leq |a|_\nu$. Then $\frac{|a|_\nu}{|b|_\nu}$ is not an element of the largest proper convex subgroup of Γ_y . Hence by Lemma 7.1 there is $m \in \mathbb{N}$ such that $|b|_y^m \leq |s|_y \cdot |a|_y^m$. Since $|a|_\xi \geq |b|_\xi$ but this cannot happen for ξ : since $|a|_\xi \geq |b|_\xi$ we have $|b|_x^{2m} \geq |s|_x |a|_x^{2m}$. Since $a, b \notin \mathfrak{p}$ there is $\ell \in \mathbb{N}$ such that $|a|_z \geq |s|_z^\ell$ when $z \in \{x, y\}$ and $\ell \in \{a, b\}$. Then $x \in R_{\text{Spa}(A, A^\circ)}(b^{2m}|sa^{2m}, s^{2\ell m})$ and $y \in R_{\text{Spa}(A, A^\circ)}(sa^m|b^m, s^{\ell m+1})$ and these open subsets are disjoint as $|b^{2m}|_z \geq |sa^{2m}|_z$ and $|sa^m|_z \geq |b^m|_z$ imply $|s^2 a^{2m}|_z \geq |b^{2m}|_z$ hence $|a| = |b| = 0$ and $0 < s < 1$. ■

We now recollect some additional results from the theory of affinoid algebras.

Proposition 7.4. If $A \rightarrow B$ is a morphism of affinoid K -algebras such that B is finite over A then there is $D_{B/A} \in \mathbb{N}$ such that for all $b \in B$ there is a polynomial $P(T) = T^d + \sum_{i=0}^{d-1} p_i T^i$ with $p_i \in A$ such that $P(b) = 0$ and $\|p_i|A\|_{\max} \leq \|b|B\|_{\max}^{d-i}$ and $d < D_{B/A}$.

Corollary 7.5. Let A be an affinoid K -algebra. Then

$$A^\circ = \{a \in A : \|a|A\|_{\max} \leq 1\}$$

$$A^\circ = \{a \in A : \|a|A\|_{\max} \leq 1\}.$$

In what follows, we denote $\mathfrak{K} = K^\circ/K^{\circ\circ}$ and for any affinoid algebra A , $\tilde{A} = A^\circ/A^{\circ\circ}$ considered as an algebra over \mathfrak{K} .

Proposition 7.6. Let $A \rightarrow B$ be a morphism of affinoid K -algebras such that B is finitely generated as an A -module. Then B° is integral over A° .

Proposition 7.7. Let $A \rightarrow B$ be a morphism of affinoid K -algebras such that B is finitely generated as an A -module. Then \tilde{B} is integral over \tilde{A} .

Proof. This is merely the observation that the property of being integral over persists under quotients. ■

Remark 7.8. B° may fail to be finite over A° , even when $A = K$ and B is a finite field extension of A .

Corollary 7.9. Let A be an affinoid K -algebra of dimension d . There is a homomorphism $\mathfrak{K}[X_1, \dots, X_d] \rightarrow \tilde{A}$ of \mathfrak{K} -algebras such that \tilde{A} is integral over $\mathfrak{K}[X_1, \dots, X_d]$. In particular, if \mathfrak{p} is a prime ideal of \tilde{A} then the transcendence degree of $\kappa(\mathfrak{p})/\mathfrak{K}$ is d .

Proof. Apply Proposition 7.7 in the case of the map $\mathbb{T}_d \rightarrow A$ which exists by Noether normalization. ■

For a valuation ν , let $\text{supp}(\nu) = \mathfrak{p} \subseteq A$ be its support. Denote $\mathfrak{p}_0 = \{a \in A^\circ : \exists \varepsilon \in K^{\circ\circ} \text{ s.t. } \nu(a) < \nu(\varepsilon)\}$. The quotient $\tilde{\mathfrak{p}} = \mathfrak{p}_0/A^{\circ\circ}$ is prime in \tilde{A} .

Proposition 7.10. Let ν be a valuation and $0 = \Gamma_0 \subsetneq \Gamma_1 \subsetneq \Gamma_2 \subsetneq \dots \subsetneq \Gamma_d \subsetneq \Gamma$ a tower of convex subgroups. Then $\dim(A) \leq d$.

Proof. Without loss of generality, we can assume there is $b_i \in A^\times$ and $\alpha_i = \frac{a_i}{b_i} \in A^\circ$. Using that $\nu(\alpha_i) \in \Gamma_i \setminus \Gamma_{i-1}$, it follows that for $P \in K^\circ[X_1, \dots, X_d]/K^{\circ\circ}[X_1, \dots, X_d]$ we have $\nu(P(\alpha_1, \dots, \alpha_d)) \in \Gamma_d$ a proper convex subgroup. It follows that $P(\alpha_1, \dots, \alpha_d) \notin \mathfrak{p}_0 \subseteq A^\circ$. Thus the images in \tilde{A} are algebraically independent over \mathfrak{K} . When $d > \dim(A)$ this contradicts a corollary from the Winter semester course. ■

In sum, we have shown the following.

Theorem 7.11 (Huber-Schneider-van der Put). Let A be an affinoid K -algebra. There is a bijection between the van der Put points of $\text{Sp}(A)$ and $\text{Spa}(A, A^\circ)$ via (6.1):

$$(\nu / \sim) \mapsto \xi_\nu = \{R_{\text{Sp}(A)}(f_0|f_1, \dots, f_n) : \nu(f_i) \leq \nu(f_0), \forall 1 \leq i \leq n\}.$$

In particular, $\mathrm{Spa}(A, A^\circ)$ is a spectral space with Krull dimension at most that of A .

Proof. The map was shown to be well-defined in Proposition 6.1 and was shown to be a bijection in Proposition 6.7. Spectrality of $\mathrm{Spa}(A, A^\circ)$ is immediate from Corollary 4.16. Finally the statement of the Krull dimension is Proposition 7.10. ■

8. LECTURE 8 – 17TH JUNE 2025

Herein, we let K be a field with non-Archimedean absolute value (not necessarily complete). We say $f \gg g$ if there is C finite such that $|g| \leq C \cdot |f|$.

Proposition 8.1. Let V be a finite dimensional K -vector space and $\|\cdot\|_V$ satisfying $\|\lambda v\|_V = |\lambda| \cdot \|v\|_V$, $\|v + w\|_V \leq \max\{\|v\|, \|w\|\}$. The following conditions are equivalent:

- (i) If $(b_i)_{i=1}^n$ is any basis then $\|\sum_{i=1}^n \lambda_i b_i\|_V \gg \max_{1 \leq i \leq n} |\lambda_i|$.
- (ii) For every $v \in V \setminus \{0\}$ there is a bounded linear functional $\ell : V \rightarrow K$ such that $\ell(v) \neq 0$.

Proof. (a) \Rightarrow (b) Suppose there is some basis where (i) holds. Let $\ell_i \in V^\vee$ such that $\ell_i\left(\sum_{j=1}^n \lambda_j b_j\right) = \lambda_i$. These are bounded.

(b) \Rightarrow (a) We proceed by induction on the dimension of V . The cases where $\dim(V) \leq 1$ are clear. Let $n > 1$ and suppose the assertion is shown for $\dim(V') < n$ and $v \in V \setminus \{0\}$ such that $V = V' \oplus Kv$. Let $\ell \in V^\vee$ be such that $\ell(v) \neq 0$ with $\|(v', \lambda v)\|_V = \max\{|\lambda|, \|v'\|_V\}$ and the induction assumption applies. ■

Remark 8.2. This does not hold in general when K is not complete. In this case, a K -linear functional is bounded if and only if it is continuous.

We now consider the general case without the condition on multiplicativity of the norm.

Proposition 8.3. Let V be a normed K -vector space. The following are equivalent:

- (a) Every finite-dimensional subspace of V satisfies the equivalent conditions of Proposition 8.1.
- (b) Every finite dimensional subspace of V is closed in V .

Proof. (a) \Rightarrow (b) Suppose $W \subseteq V$ is a finite dimensional subspace and $v \in \overline{W} \setminus W$. Let $\widetilde{W} = W \oplus Kv$ equipped with a norm $\|\cdot\|_{\widetilde{W}}$ the restriction of the one on V . For v in the closure of W in \widetilde{W} the norms $\|\cdot\|_V$ and $\sum_{i=1}^n \lambda_i b_i \mapsto \lambda_i$ for a basis $(b_i)_{i=1}^n$ fails to be equivalent to

(b) \Rightarrow (a) Let $W \subseteq V$ be finite dimensional, $w \in W \setminus \{0\}$, and W' a subspace of W such that $W = W' \oplus Kw$ algebraically. If $\ell : W \rightarrow K$ is a linear functional, set $\ell(\lambda w - w') = \lambda$ when $w \in W'$ and all $\lambda \in K$. This produces a linear functional nonvanishing at w' . ■

This leads to the notion of weakly Cartesian norms.

Definition 8.4 (Weakly Cartesian Norm). Let V be a normed K -vector space. V is weakly Cartesian if either (and thus both) of the conditions of Proposition 8.3 hold.

Remark 8.5. By Proposition 8.1, two weakly Cartesian norms on any finite-dimensional vector space are equivalent.

Lemma 8.6. Let $|\cdot|$ be an ultrametric absolute value on L and K a subfield such that L is weakly Cartesian as a K -vector space. Every weakly Cartesian L -norm on an L -vector space V is weakly Cartesian as a K -norm.

This shows that there are many bounded K -linear functionals on L .

Proposition 8.7. Let $|\cdot|$ be an ultrametric absolute value on K and L/K a finite field extension. Then:

- (i) $\|\ell\|_s = \lim_{n \rightarrow \infty} \sqrt[n]{\|\ell\|^n}$ does not depend on the choice of a weakly Cartesian K -norm $\|\cdot\|$ on L and is a power multiplicative ring norm and a K -vector space norm on L .
- (ii) Every power multiplicative norm on L is bounded by the spectral norm $\|\cdot\|_s$.
- (iii) If the minimal polynomial of s is of the form $T^d + \sum_{i=0}^{d-1} p_i T^i$ then $\|\ell\| = \max_{0 \leq i < d} \sqrt[d-i]{|p_i|}$.

Proof of (i). If $\|\cdot\|$ is given by a basis $(b_i)_{i=1}^n$ as in Proposition 8.1 and $b_i b_j = m_{ij}^k b_k$, then $\|xy\| \leq C\|x\| \cdot \|y\|$ with $C = \max\{m_{ij}^k\}$. Such a C exists by being weakly Cartesian. We have that $\|x^n\| \leq C^k \|x\|^n$ and applying this iteratively by induction we have k depends on n sublinearly so $n \leq 2^k$ and we have $\lim_{n \rightarrow \infty} \sqrt[n]{\|x\|^n} \leq \sqrt[n]{\|x^m\|}$ when $m > 0$ showing convergence. Checking that the axioms of the norm hold shows that $\|x\|_s \neq 0$ when $x \neq 0$. ■

Proof of (ii). If N is any norm and $\|\cdot\|$ is a weakly Cartesian norm, then $N(\ell) \leq \|\ell\|$ – every norm is bounded by a weakly Cartesian one, but not conversely. ■

Proof of (iii). Let $M = \max_{0 \leq i < d} \sqrt[d-i]{|p_i|}$ then $\|x\|_s^n = \|x^n\| \leq M^{n+1-d}$ where $n \geq d$ by induction on n . Hence $\|\cdot\|_s \leq M$. For the reverse inequality, the arguments of (i) give that without loss of generality we can take L/K to be normal. If $(x_i)_{i=1}^m$ are the images of x under the elements of $\text{Aut}(L/K)$ then the minimal polynomial of x over K is of the form $(\prod_{i=1}^a (T - x_i))^q$ for some positive integer q as $\|x_i\|_s = \|x\|_s$ by (i) so $M \leq \|x\|_s$ giving the equality. ■

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