
Berkovich Space

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Berkovich Space

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Source code: github.com/MonkeyUnderMountain/Berkovich_Space

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Preface

This document provides an introduction to Berkovich spaces, a fundamental concept in non-archimedean analytic geometry. The theory of Berkovich spaces offers a powerful framework for studying analytic varieties over non-archimedean valued fields, providing a geometric approach that bridges algebraic and analytic methods.

The main references are [[Ber90](#); [BGR84](#)].

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Chapter 1

Non-archimedean analysis

1.1 Valuation fields

1.1.1 Absolute values and completion

Definition 1.1.1. Let \mathbf{k} be a field. An *absolute value* on \mathbf{k} is a function $\|\cdot\| : \mathbf{k} \rightarrow \mathbb{R}_{\geq 0}$ satisfying the following properties for all $x, y \in \mathbf{k}$:

- (a) $\|x\| = 0$ if and only if $x = 0$;
- (b) $\|xy\| = \|x\| \cdot \|y\|$;
- (c) $\|x + y\| \leq \|x\| + \|y\|$.

A field \mathbf{k} equipped with an absolute value $\|\cdot\|$ is called a *valuation field*.

Remark 1.1.2. Let \mathbf{k} be a field. Recall that a *valuation* on \mathbf{k} is a function $v : \mathbf{k}^\times \rightarrow \mathbb{R}$ such that

- $\forall x, y \in \mathbf{k}^\times, v(xy) = v(x) + v(y)$;
- $\forall x, y \in \mathbf{k}^\times, v(x + y) \geq \min\{v(x), v(y)\}$.

We can extend v to the whole field \mathbf{k} by defining $v(0) = +\infty$. Fix a real number $\varepsilon \in (0, 1)$. Then v induces an absolute value $|\cdot|_v : \mathbf{k} \rightarrow \mathbb{R}_+$ defined by $|x|_v = \varepsilon^{v(x)}$ for each $x \in \mathbf{k}$.

In some literature, the valuation v is called an *additive valuation* and the induced absolute value $|\cdot|_v$ is called a *multiplicative valuation*. In this note, the term *valuation* always refers to the additive valuation.

Example 1.1.3. Let \mathbf{k} be a field. The *trivial absolute value* on \mathbf{k} is defined as

$$\|x\| := \begin{cases} 0, & x = 0; \\ 1, & x \neq 0. \end{cases}$$

Definition 1.1.4. The *(multiplicative) valuation group* of a valuation field $(\mathbf{k}, \|\cdot\|)$ is defined as the

subgroup of $\mathbb{R}_{>0}$ given by

$$|\mathbf{k}^\times| := \{\|x\| : x \in \mathbf{k}^\times\}.$$

Definition 1.1.5. Let \mathbf{k} be a field. Two absolute values $\|\cdot\|_1$ and $\|\cdot\|_2$ on \mathbf{k} are said to be *equivalent* if there exists a real number $c \in (0, 1)$ such that

$$\|x\|_1 = \|x\|_2^c, \quad \forall x \in \mathbf{k}.$$

Note that equivalent absolute values induce the same topology on the field \mathbf{k} . Moreover, the following lemma shows that the converse is also true.

Lemma 1.1.6. Let \mathbf{k} be a field and $\|\cdot\|_1, \|\cdot\|_2$ be two absolute values on \mathbf{k} . Then the following statements are equivalent:

- (a) $\|\cdot\|_1$ and $\|\cdot\|_2$ are equivalent;
- (b) $\|\cdot\|_1$ and $\|\cdot\|_2$ induce the same topology on \mathbf{k} ;
- (c) The unit disks $D_1 = \{x \in \mathbf{k} : \|x\|_1 < 1\}$ and $D_2 = \{x \in \mathbf{k} : \|x\|_2 < 1\}$ are the same.

Proof. The implications (a) \Rightarrow (b) is obvious. Now we prove (b) \Rightarrow (c). For any $x \in D_1$, we have $x^n \rightarrow 0$ as $n \rightarrow \infty$ under the absolute value $\|\cdot\|_1$ and thus under $\|\cdot\|_2$. Therefore, $\|x\|_2^n \rightarrow 0$ as $n \rightarrow \infty$, which implies that $\|x\|_2 < 1$, i.e., $x \in D_2$. Similarly, we can prove that $D_2 \subseteq D_1$.

Finally, we prove (c) \Rightarrow (a). If $\|\cdot\|_1$ is trivial, then $D_1 = \{0\}$ and thus $\|\cdot\|_2$ is also trivial. In this case, they are equivalent. Suppose that both $\|\cdot\|_1$ and $\|\cdot\|_2$ are non-trivial. Pick any $x, y \notin D_1 = D_2$. Then there exist real numbers $\alpha, \beta > 0$ such that $\|x\|_1 = \|x\|_2^\alpha$ and $\|y\|_1 = \|y\|_2^\beta$. Suppose the contrary that $\alpha \neq \beta$. Consider the domain $\Omega \subseteq \mathbb{Z}^2$ defined by

$$\begin{cases} n \log \|x\|_2 < m \log \|y\|_2; \\ n\alpha \log \|x\|_2 > m\beta \log \|y\|_2. \end{cases}$$

Since $\alpha \neq \beta$, the two lines defined by the equalities are not parallel. Thus Ω is non-empty. Pick $(n, m) \in \Omega$ and set $z := x^n y^{-m}$. Then we have $\|z\|_2 < 1$ and $\|z\|_1 > 1$, a contradiction. \square

Definition 1.1.7. Let $(\mathbf{k}, \|\cdot\|)$ be a valuation field. We say that \mathbf{k} is *complete* if the metric $d(x, y) := \|x - y\|$ makes \mathbf{k} a complete metric space.

Lemma 1.1.8. Let $(\mathbf{k}, \|\cdot\|)$ be a valuation field and $(\hat{\mathbf{k}}, \|\cdot\|)$ its completion as a metric space. Then the operations of addition and multiplication on \mathbf{k} can be extended to $\hat{\mathbf{k}}$ uniquely, making $(\hat{\mathbf{k}}, \|\cdot\|)$ a complete valuation field containing \mathbf{k} as a dense subfield.

Proof. Simple analysis. \square

Example 1.1.9. Let $|\cdot|_\infty$ be the usual absolute value on the field \mathbb{Q} of rational numbers. Then $(\mathbb{Q}, |\cdot|_\infty)$ is a valuation field. Its completion is the field \mathbb{R} of real numbers equipped with the usual absolute value.

Example 1.1.10. Let p be a prime number. For any non-zero rational number $x \in \mathbb{Q}$, we can write it as $x = p^n \frac{a}{b}$, where $n \in \mathbb{Z}$ and $a, b \in \mathbb{Z}$ are integers not divisible by p . The *p-adic absolute value*

on \mathbb{Q} is defined as

$$|x|_p := \begin{cases} 0, & x = 0; \\ p^{-n}, & x = p^n \frac{a}{b} \text{ as above.} \end{cases}$$

Then $(\mathbb{Q}, |\cdot|_p)$ is a valuation field. Its completion is the field

$$\mathbb{Q}_p = \left\{ \sum_{n=k}^{+\infty} a_n p^n : k \in \mathbb{Z}, a_n \in \{0, 1, \dots, p-1\} \right\}$$

of p -adic numbers equipped with the p -adic absolute value; see [Yang: to be added.](#)

Unlike the real number field \mathbb{R} , even a valuation field is complete, we can not expect the theorem of nested intervals to hold.

Definition 1.1.11. A valuation field $(\mathbf{k}, \|\cdot\|)$ is called *spherically complete* if every decreasing sequence of closed balls in \mathbf{k} has a non-empty intersection.

Example 1.1.12. The field \mathbb{C}_p of p -adic complex numbers is not spherically complete, see [Yang: to be added.](#)

1.1.2 Non-archimedean fields

Definition 1.1.13. Let $(\mathbf{k}, \|\cdot\|)$ be a valuation field. We say that \mathbf{k} is *non-archimedean* if its absolute value $\|\cdot\|$ satisfies the *strong triangle inequality*:

$$\|x + y\| \leq \max\{\|x\|, \|y\|\}, \quad \forall x, y \in \mathbf{k}.$$

Otherwise, we say that \mathbf{k} is *archimedean*.

Let \mathbf{k} be a non-archimedean field. Then easily see that $\{x \in \mathbf{k} : \|x\| \leq 1\}$ is a subring of \mathbf{k} . Moreover, it is a local ring whose maximal ideal is $\{x \in \mathbf{k} : \|x\| < 1\}$.

Definition 1.1.14. Let \mathbf{k} be a non-archimedean field. The *ring of integers* of \mathbf{k} is defined as

$$\mathbf{k}^\circ := \{x \in \mathbf{k} : \|x\| \leq 1\}.$$

Its maximal ideal is

$$\mathbf{k}^{\circ\circ} := \{x \in \mathbf{k} : \|x\| < 1\}.$$

The *residue field* of \mathbf{k} is defined as

$$\mathcal{K}_{\mathbf{k}} := \tilde{\mathbf{k}} := \mathbf{k}^\circ / \mathbf{k}^{\circ\circ}.$$

Definition 1.1.15. Let \mathbf{k} be a non-archimedean field. The *residue absolute value* on the residue field $\mathcal{K}_{\mathbf{k}}$ is defined as

$$|x| := \inf_{y \in \varphi^{-1}(x)} \|y\|, \quad \forall x \in \mathcal{K}_{\mathbf{k}},$$

where $\varphi : \mathbf{k}^\circ \rightarrow \mathcal{K}_{\mathbf{k}}$ is the canonical projection.

Proposition 1.1.16. Let \mathbf{k} be a non-archimedean field. Then the residue absolute value on the residue field $\mathcal{K}_{\mathbf{k}}$ is trivial.

Proof. For any $x \in \mathcal{K}_{\mathbf{k}}$, if $x = 0$, then by definition $|x| = 0$. If $x \neq 0$, then $\forall y \in \varphi^{-1}(x)$, we have $y \in \mathbf{k}^\circ \setminus \mathbf{k}^{\circ\circ}$, i.e., $\|y\| = 1$. Thus by definition $|x| = 1$. \square

1.2 Ultra-metric spaces

We will use $B(x, r)$ (resp. $E(x, r)$) to denote the open ball (resp. closed ball) with center x and radius r .

Definition 1.2.1. A metric space (X, d) is called an *ultra-metric space* if its metric d satisfies the *strong triangle inequality*:

$$d(x, z) \leq \max\{d(x, y), d(y, z)\}, \quad \forall x, y, z \in X.$$

If $(\mathbf{k}, \|\cdot\|)$ is a non-archimedean field, then the metric $d(x, y) := \|x - y\|$ on \mathbf{k} makes (\mathbf{k}, d) an ultra-metric space.

Proposition 1.2.2. Let (X, d) be an ultra-metric space. Then for any $x, y, z \in X$, at least two of the three distances $d(x, y), d(y, z), d(z, x)$ are equal. And the third distance is less than or equal to the common value of the other two.

Proof. Suppose that $d(x, y) \geq d(y, z)$. By the strong triangle inequality, we have

$$d(x, z) \leq \max\{d(x, y), d(y, z)\} = d(x, y).$$

On the other hand, by the strong triangle inequality again, we have

$$d(x, y) \leq \max\{d(x, z), d(z, y)\} = \max\{d(x, z), d(y, z)\} \leq d(x, y).$$

This shows that $d(x, y) = \max\{d(x, z), d(y, z)\}$. Thus either $d(x, z) = d(x, y) \geq d(y, z)$ or $d(y, z) = d(x, y) \geq d(x, z)$. \square

Proposition 1.2.3. Let (X, d) be an ultra-metric space. Let D_i be (open or closed) ball in X for $i = 1, 2$. If $D_1 \cap D_2 \neq \emptyset$, then either $D_1 \subseteq D_2$ or $D_2 \subseteq D_1$.

Proof. Suppose that D_i has center x_i and radius r_i for $i = 1, 2$. Let $y \in D_1 \cap D_2$. We have

$$d(x_1, x_2) \leq \max\{d(x_1, y), d(y, x_2)\}.$$

Without loss of generality, we may assume that $d(x_1, x_2) \leq d(x_1, y)$. It follows that $x_2 \in D_1$ since $d(x_1, y) < r_1$ (or $\leq r_1$).

If there exists $z \in D_2 \setminus D_1$, we claim that $D_1 \subseteq D_2$. We have $d(x_1, z) > d(x_1, x_2)$. Then by ??,

$$r_1 \leq d(x_1, z) = d(x_2, z) \leq r_2.$$

In particular, if D_2 is an open ball, then we have strict inequality $r_1 < r_2$. For any $w \in D_1$, we have

$$d(x_2, w) \leq \max\{d(x_2, x_1), d(x_1, w)\} \leq r_1 \leq r_2.$$

Thus $w \in D_2$ whatever D_2 is open or closed, and it shows that $D_1 \subseteq D_2$. \square

Proposition 1.2.4. Let (X, d) be an ultra-metric space. Then both $B(x, r)$ and $E(x, r)$ are closed and open subsets of X for any $x \in X$ and $r > 0$.

Proof. We show that the sphere $S(x, r) := \{y \in X \mid d(x, y) = r\}$ is open in X . Note that if $y \in S(x, r)$, then for any $r' < r$, we have $B(y, r') \cap E(x, r) \neq \emptyset$ and $x \in E(x, r) \setminus B(y, r')$. Thus by ??, we have $B(y, r') \subseteq E(x, r)$. If $B(y, r') \cap B(x, r) \neq \emptyset$, then by ?? again, we have $B(y, r') \subseteq B(x, r)$. However, $y \in B(y, r') \setminus B(x, r)$, a contradiction. Thus $B(y, r') \subseteq E(x, r) \setminus B(x, r) = S(x, r)$. It yields that $S(x, r) = \bigcup_{y \in S(x, r)} B(y, r/2)$ is open in X .

Since $E(x, r) = B(x, r) \cup S(x, r)$ and $B(x, r) = E(x, r) \setminus S(x, r)$, both $B(x, r)$ and $E(x, r)$ are open and closed in X . \square

Corollary 1.2.5. Let (X, d) be an ultra-metric space. Then X is totally disconnected, i.e., the only connected subsets of X are the set with at most one point.

Proof. Suppose that $S \subset X$ has at least two distinct points $x, y \in S$. Let $r := d(x, y) > 0$. Consider the open ball $B(x, r/2)$. By ??, $B(x, r/2)$ is both open and closed in X . Thus $B(x, r/2) \cap S$ is both open and closed in S , however, it is non-empty and not equal to S since it contains x but not y . This shows that S is disconnected. \square

Proposition 1.2.6. Let (X, d) be an ultra-metric space. A sequence $\{x_n\}$ in X is cauchy if and only if $d(x_n, x_{n+1}) \rightarrow 0$ as $n \rightarrow \infty$.

Proof. The necessity is true for all metric spaces. Suppose that $d(x_n, x) \rightarrow 0$ as $n \rightarrow \infty$. For any $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $d(x_n, x_{n+1}) < \varepsilon$ for all $n \geq N$. For any $m, n \geq N$ with $m < n$, by the strong triangle inequality, we have

$$d(x_n, x_m) \leq \max\{d(x_n, x_{n-1}), d(x_{n-1}, x_m)\} \leq \max\{d(x_n, x_{n-1}), d(x_{n-1}, x_{n-2}), \dots, d(x_{m+1}, x_m)\} < \varepsilon.$$

This shows that $\{x_n\}$ is a cauchy sequence. \square

1.3 Algebraic structures of non-archimedean fields

1.3.1 Recover non-archimedean complete fields algebraically

In this subsection, let \mathbf{k} be a non-archimedean field. Set $I_{r, <} := B(0, r)$ and $I_{r, \leq} := E(0, r)$ for each $r \in [0, 1]$.

Proposition 1.3.1. The sets $I_{r, <}$ and $I_{r, \leq}$ are ideals of the ring of integers \mathbf{k}° . Conversely, any ideal of \mathbf{k}° is of the form $I_{r, <}$ or $I_{r, \leq}$ for some $r \in (0, 1)$.

Proof. Let I be an ideal of \mathbf{k}° . Set $r = \sup\{|a| : a \in I\}$ (resp. $r = \max\{|a| : a \in I\}$ when the maximum exists). Then, by definition, we have $I \subset I_{r, <}$ (resp. $I \subset I_{r, \leq}$). For every $x \in \mathbf{k}^\circ$ with $|x| < r$ (resp. $|x| \leq r$), there exists $a \in I$ such that $|x| \leq |a|$. Thus, $|x/a| \leq 1$ and so $x/a \in \mathbf{k}^\circ$. Since I is an ideal, we have $x = (x/a)a \in I$. Therefore, $I_{r, <} \subset I$ (resp. $I_{r, \leq} \subset I$). \square

Proposition 1.3.2. Let I_r be either $I_{r,<}$ or $I_{r,\leq}$ for each $r \in (0, 1)$. Suppose $\{r_n \in (0, 1)\}_{n \in \mathbb{N}}$ is a decreasing sequence converging to 0. Then the completion $\widehat{\mathbf{k}}$ of \mathbf{k} is isomorphic to the projective limit

$$\widehat{\mathbf{k}}^\circ \cong \varprojlim_{n \in \mathbb{N}} \mathbf{k}^\circ / I_{r_n}.$$

Proof. For every $x \in \widehat{\mathbf{k}}^\circ$, there exists a cauchy sequence $\{x_m\}_{m \in \mathbb{N}}$ in \mathbf{k}° converging to x . Since $\{r_n\}_{n \in \mathbb{N}}$ converges to 0, for each $n \in \mathbb{N}$, there exists $M_n \in \mathbb{N}$ such that for all $m, m' \geq M_n$, we have $|x_m - x_{m'}| < r_n$. Thus, the sequence $\{x_m + I_{r_n}\}_{m \in \mathbb{N}}$ is eventually constant in $\mathbf{k}^\circ / I_{r_n}$. Define a map

$$\Phi : \widehat{\mathbf{k}}^\circ \rightarrow \varprojlim_{n \in \mathbb{N}} \mathbf{k}^\circ / I_{r_n}, \quad x \mapsto \left(\lim_{m \rightarrow \infty} x_m + I_{r_n} \right)_{n \in \mathbb{N}}.$$

It is straightforward to verify that Φ is a well-defined ring homomorphism.

Conversely, for every $(a_n + I_{r_n})_{n \in \mathbb{N}} \in \varprojlim_{n \in \mathbb{N}} \mathbf{k}^\circ / I_{r_n}$, we can choose a representative $a_n \in \mathbf{k}^\circ$ for each n . We claim that the sequence $\{a_n\}_{n \in \mathbb{N}}$ is a cauchy sequence in \mathbf{k}° . Indeed, for every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that $r_N < \varepsilon$. For all $m, n \geq N$, since $a_n + I_{r_n}$ maps to $a_m + I_{r_m}$ under the natural projection, we have $|a_n - a_m| < r_N < \varepsilon$. Thus, $\{a_n\}_{n \in \mathbb{N}}$ converges to some $x \in \widehat{\mathbf{k}}^\circ$. Easily see that the limit x is independent of the choice of representatives $\{a_n\}_{n \in \mathbb{N}}$. This gives a map

$$\Psi : \varprojlim_{n \in \mathbb{N}} \mathbf{k}^\circ / I_{r_n} \rightarrow \widehat{\mathbf{k}}^\circ, \quad (a_n + I_{r_n})_{n \in \mathbb{N}} \mapsto \lim_{n \rightarrow \infty} a_n.$$

Direct verification shows that $\Psi = \Phi^{-1}$. □

Corollary 1.3.3. Let \mathbf{k} be a non-archimedean field and $\widehat{\mathbf{k}}$ its completion. Then the residue field $\widehat{\kappa}_{\widehat{\mathbf{k}}} \cong \kappa_{\mathbf{k}}$ under the natural embedding $\mathbf{k}^\circ \hookrightarrow \widehat{\mathbf{k}}^\circ$.

Corollary 1.3.4. Let \mathbf{k} be a non-archimedean field and $\widehat{\mathbf{k}}$ its completion. Then the valuation group $|\widehat{\mathbf{k}}^\times|$ of $\widehat{\mathbf{k}}$ is equal to the valuation group $|\mathbf{k}^\times|$ of \mathbf{k} .

Proof. Note that

$$\begin{aligned} r \in |\widehat{\mathbf{k}}^\times| &\iff I_{r,<} \subsetneq I_{r,\leq} \text{ in } \widehat{\mathbf{k}}^\circ \\ &\iff \widehat{\mathbf{k}}^\circ / I_{r,<} \rightarrow \widehat{\mathbf{k}}^\circ / I_{r,\leq} \text{ is not an isomorphism} \\ &\iff \mathbf{k}^\circ / I_{r,<} \rightarrow \mathbf{k}^\circ / I_{r,\leq} \text{ is not an isomorphism} \\ &\iff I_{r,<} \subsetneq I_{r,\leq} \text{ in } \mathbf{k}^\circ \\ &\iff r \in |\mathbf{k}^\times|. \end{aligned}$$

□

Proposition 1.3.5. Let \mathbf{k} be a non-archimedean field with non-trivial valuation. Then \mathbf{k}° is totally bounded iff $\mathbf{k}^\circ / I_{r,<}$ and $\mathbf{k}^\circ / I_{r,\leq}$ are finite for each $r \in [0, 1]$. Moreover, if \mathbf{k} is complete, then it is locally compact iff \mathbf{k}° / I_r is finite for each $r \in (0, 1)$.

Slogan “Locally compact \iff pro-finite.”

Proof. We just prove the case for $I_r = I_{r,<}$. The case for $I_r = I_{r,\leq}$ is similar.

Suppose that \mathbf{k}°/I_r is finite for each $r \in [0, 1]$. Then for every $\varepsilon > 0$, there exists $r \in (0, 1)$ such that $r < \varepsilon$ and \mathbf{k}°/I_r is finite. Let $\{a_1 + I_r, \dots, a_n + I_r\}$ be the complete set of representatives of \mathbf{k}°/I_r . Then the balls $B(a_i, r)$ for $i = 1, \dots, n$ cover \mathbf{k}° .

Conversely, suppose that \mathbf{k}°/I_r is infinite for some $r \in [0, 1]$. Then there exists an infinite set $\{a_n\}$ with $|a_n| \in [r, 1]$ such that their images in \mathbf{k}°/I_r are distinct. In particular, for every $m \neq n$, we have $|a_n - a_m| \geq r$. Any subsequence of $\{a_n\}$ is not cauchy. Thus, \mathbf{k}° is not totally bounded. \square

Proposition 1.3.6. The ring \mathbf{k}° is noetherian iff \mathbf{k} is a discrete valuation field.

Proof. Note that $|\mathbf{k}^\times| \subset \mathbb{R}_{>0}$ is a multiplicative subgroup. If \mathbf{k} is not a discrete valuation field, then $|\mathbf{k}^\times|$ is dense in $\mathbb{R}_{>0}$. In particular, there exists a strictly ascending sequence $r_n \in |\mathbf{k}^\times| \cap (0, 1)$. Then the ideals $I_{r_n, \leq}$ form a strictly ascending chain of ideals in \mathbf{k}° .

The converse is standard since now \mathbf{k}° is a discrete valuation ring. \square

Proposition 1.3.7. Let \mathbf{k} be a complete non-archimedean field. Then \mathbf{k} is locally compact iff \mathbf{k} is a discrete valuation field and its residue field $\hat{\mathbf{k}}$ is finite.

Proof. The necessity follows from ???. For the sufficiency, suppose that \mathbf{k} is a discrete valuation field whose residue field $\hat{\mathbf{k}}$ is finite. Let $\pi \in \mathbf{k}^\circ$ be a uniformizer. We only need to show that $\mathbf{k}^\circ/\pi^n \mathbf{k}^\circ$ is finite for each $n \in \mathbb{N}$. Note that there is an isomorphism

$$\pi^{n-1} \mathbf{k}^\circ / \pi^n \mathbf{k}^\circ \cong \hat{\mathbf{k}}, \quad x + \pi^n \mathbf{k}^\circ \mapsto \overline{x/\pi^{n-1}}.$$

Thus, by induction on n , we conclude that $\mathbf{k}^\circ/\pi^n \mathbf{k}^\circ$ is finite. \square

1.3.2 Hensel's Lemma

Theorem 1.3.8 (Hensel's lemma). Let \mathbf{k} be a complete non-archimedean field and $F(T) \in \mathbf{k}^\circ[T]$ a monic polynomial. Suppose that the reduction $f(T) \in \hat{\mathbf{k}}[T]$ of $F(T)$ factors as

$$f(T) = g(T)h(T),$$

where $g(T), h(T) \in \hat{\mathbf{k}}[T]$ are monic polynomials that are coprime in $\hat{\mathbf{k}}[T]$. Then there exist monic polynomials $G(T), H(T) \in \mathbf{k}^\circ[T]$ such that

$$F(T) = G(T)H(T),$$

and the reductions of $G(T), H(T)$ in $\hat{\mathbf{k}}[T]$ are $g(T), h(T)$ respectively.

Proof. Since $\gcd(g, h) = 1$ in $\hat{\mathbf{k}}[T]$, there exist polynomials $u(T), v(T) \in \hat{\mathbf{k}}[T]$ such that $ug + vh = 1$ and $\deg u < \deg h, \deg v < \deg g$. Choose lifts $G_0(T), H_0(T), U(T), V(T) \in \mathbf{k}^\circ[T]$ of $g(T), h(T), u(T), v(T)$ respectively preserving their degrees such that G_0 and H_0 are monic. Then there exist $r < 1$ such that

$$U(T)G_0(T) + V(T)H_0(T) \equiv 1 \pmod{I_r}, \quad F(T) - G_0(T)H_0(T) \equiv 0 \pmod{I_r},$$

where $I_r = \{a \in \mathbf{k}^\circ : |a| < r\}$.

We will construct a sequence of monic polynomials $\{G_n(T)\}_{n \in \mathbb{N}}$ and $\{H_n(T)\}_{n \in \mathbb{N}}$ in $\mathbf{k}^\circ[T]$ such

that for each $n \in \mathbb{N}$,

$$G_n(T) \equiv G_{n-1}(T) \pmod{I_{r^n}}, \quad H_n(T) \equiv H_{n-1}(T) \pmod{I_{r^n}},$$

and

$$F(T) - G_n(T)H_n(T) \equiv 0 \pmod{I_{r^{n+1}}}.$$

If we have such sequences, then their coefficients converge in the complete ring \mathbf{k}° . Let $G(T)$ and $H(T)$ be the limits of $\{G_n(T)\}$ and $\{H_n(T)\}$ respectively. Then we have $F(T) = G(T)H(T)$ and the reductions of $G(T), H(T)$ in $\mathcal{K}_{\mathbf{k}}[T]$ are $g(T), h(T)$ respectively.

The case $n = 0$ is done by the above construction. Now suppose that we have constructed $G_n(T)$ and $H_n(T)$ for some $n \geq 0$. Since $G_n - G_0 \equiv 0 \pmod{I_r}$ and $H_n - H_0 \equiv 0 \pmod{I_r}$, we have

$$UG_n + VH_n = UG_0 + VH_0 + U(G_n - G_0) + V(H_n - H_0) \equiv 1 \pmod{I_r}.$$

Set $\Delta_n(T) = F(T) - G_n(T)H_n(T) \in I_{r^{n+1}}[T]$ and $\epsilon_n = U\Delta_n, \delta_n = V\Delta_n \in I_{r^{n+1}}[T]$. Then we have

$$\begin{aligned} (G_n + \epsilon_n)(H_n + \delta_n) - F_n &= G_nH_n + G_n\delta_n + H_n\epsilon_n + \epsilon_n\delta_n - F_n \\ &= (UG_n + VH_n - 1)\Delta_n + \epsilon_n\delta_n \in I_{r^{n+2}}[T]. \end{aligned}$$

Thus, we can set

$$G_{n+1}(T) = G_n(T) + \epsilon_n(T), \quad H_{n+1}(T) = H_n(T) + \delta_n(T).$$

□

Corollary 1.3.9. Let \mathbf{k} be a complete non-archimedean field and $F(T) \in \mathbf{k}^\circ[T]$ a monic polynomial. Suppose that the reduction $f(T) \in \mathcal{K}_{\mathbf{k}}[T]$ of $F(T)$ has a simple root $a \in \mathcal{K}_{\mathbf{k}}$. Then there exists a root $\alpha \in \mathbf{k}^\circ$ of $F(T)$ whose reduction is a .

Proof. Since a is a simple root of $f(T)$, we have the factorization $f(T) = (T - a)h(T)$ for some monic polynomial $h(T) \in \mathcal{K}_{\mathbf{k}}[T]$ with $h(a) \neq 0$. Then the result follows from ??.

□

1.3.3 Newton polygons

Yang: To be filled.

1.4 Finite field extensions

1.4.1 Finite-dimensional vector space

Definition 1.4.1. Let \mathbf{k} be a valuation field and V a vector space over \mathbf{k} . A *norm* on V is a function $\|\cdot\| : V \rightarrow \mathbb{R}_{\geq 0}$ satisfying the following properties for all $x, y \in V$ and $a \in \mathbf{k}$:

- (a) $\|x\| = 0$ if and only if $x = 0$;
- (b) $\|ax\| = |a| \cdot \|x\|$;
- (c) $\|x + y\| \leq \|x\| + \|y\|$.

Example 1.4.2. Let \mathbf{k} be a valuation field and V a finite-dimensional vector space over \mathbf{k} with basis $\{e_1, e_2, \dots, e_n\}$. For any $x = a_1e_1 + a_2e_2 + \dots + a_ne_n \in V$, define

$$\|x\|_{\max} := \max_{1 \leq i \leq n} |a_i|.$$

Then $\|\cdot\|_{\max}$ is a norm on V , called the *maximal norm* with respect to the basis $\{e_1, e_2, \dots, e_n\}$.

Example 1.4.3. Setting as in ??, for any $x = a_1e_1 + a_2e_2 + \dots + a_ne_n \in V$, define

$$\|x\|_1 := |a_1| + |a_2| + \dots + |a_n|.$$

Then $\|\cdot\|_1$ is also a norm on V .

Definition 1.4.4. Let \mathbf{k} be a valuation field and V a vector space over \mathbf{k} . Two norms $\|\cdot\|_1$ and $\|\cdot\|_2$ on V are said to be *equivalent* if there exist positive constants $C_1, C_2 > 0$ such that for all $x \in V$,

$$C_1\|x\|_1 \leq \|x\|_2 \leq C_2\|x\|_1.$$

Lemma 1.4.5. Let \mathbf{k} be a valuation field and V a vector space over \mathbf{k} . Two norms $\|\cdot\|_1$ and $\|\cdot\|_2$ on V are equivalent if and only if they induce the same topology on V .

Proof. The sufficiency is clear. Now suppose that $\|\cdot\|_1$ and $\|\cdot\|_2$ induce the same topology on V . Hence the unit open ball with respect to $\|\cdot\|_1$ contains a unit open ball with respect to $\|\cdot\|_2$. That is,

$$\{x \in V : \|x\|_1 < 1\} \supseteq \{x \in V : \|x\|_2 < C\}.$$

Then for every $x \in V$ with $\|x\|_1 = 1$, we have $\|x\|_2 \geq C = C\|x\|_1$. By scaling, we get that for every $x \in V$,

$$\|x\|_2 \geq C\|x\|_1.$$

Similar for the other direction, we conclude that $\|\cdot\|_1$ and $\|\cdot\|_2$ are equivalent. \square

Proposition 1.4.6. Let V be a normed finite-dimensional vector space over a complete valuation field \mathbf{k} . Then V is complete.

Proof. Yang: To be added. \square

Theorem 1.4.7. Let V be a finite-dimensional vector space over a complete field \mathbf{k} . Then all norms on V are equivalent.

Proof. Fix a basis $\{e_1, e_2, \dots, e_n\}$ of V and let $\|\cdot\|_{\max}$ be the maximal norm with respect to this basis as in ??. Let $\|\cdot\|$ be any norm on V . It suffices to show that $\|\cdot\|$ and $\|\cdot\|_{\max}$ are equivalent. First

we have

$$\|y\| \leq \sum_{i=1}^n |a_i| \|e_i\| \leq \left(\sum_{i=1}^n \|e_i\| \right) \|y\|_{\max}$$

for any $y = a_1 e_1 + a_2 e_2 + \cdots + a_n e_n \in V$. It remains to show that there exists a constant $C > 0$ such that for any $y \in V$,

$$\|y\|_{\max} \leq C \|y\|.$$

Yang: To be added. □

Remark 1.4.8. If the base field \mathbf{k} is not complete, then ?? may fail. For example, let $\mathbf{k} = \mathbb{Q}$ with the usual absolute value, and let $V = \mathbb{Q}[\alpha]$ with $\alpha^2 - \alpha - 1 = 0$. There are two embeddings of V into \mathbb{R} :

$$\iota_1 : a + b\alpha \mapsto a + b \frac{1 + \sqrt{5}}{2}, \quad \iota_2 : a + b\alpha \mapsto a + b \frac{1 - \sqrt{5}}{2}.$$

Define two norms on V by

$$\|x\|_1 := |\iota_1(x)|, \quad \|x\|_2 := |\iota_2(x)|,$$

where $|\cdot|$ is the usual absolute value on \mathbb{R} . Then $\|\cdot\|_1$ and $\|\cdot\|_2$ are not equivalent since $\iota_2(\alpha^n) \rightarrow 0$ as $n \rightarrow \infty$ while $\iota_1(\alpha^n) \rightarrow \infty$.

The following lemma is a classical result in functional analysis, which will be used in the next subsection.

Lemma 1.4.9. Let \mathbf{k} be a complete field and V a normed finite-dimensional vector space over \mathbf{k} . Then

$$\|\cdot\| : \text{End}_{\mathbf{k}}(V) \rightarrow \mathbb{R}_{\geq 0}, \quad T \mapsto \sup_{x \in V \setminus \{0\}} \frac{\|T(x)\|}{\|x\|}$$

defines a norm on the \mathbf{k} -vector space $\text{End}_{\mathbf{k}}(V)$ satisfying

$$\|AB\| \leq \|A\| \cdot \|B\|, \quad \forall A, B \in \text{End}_{\mathbf{k}}(V).$$

Proof. First we show the existence of the supremum, i.e., there exists $C > 0$ such that for all $x \in V \setminus \{0\}$, $\|T(x)\| \leq C \|x\|$. Fix a basis $\{e_1, e_2, \dots, e_n\}$ of V and let $\|\cdot\|_{\max}$ be the maximal norm with respect to this basis. Since all norms on V are bounded by each other by ??, we only need to show that there exists $C > 0$ such that for all $x \in V \setminus \{0\}$, $\|T(x)\|_1 \leq C \|x\|_{\max}$. Write $T(e_i) = \sum_{j=1}^n a_{ij} e_j$ for $1 \leq i \leq n$. For any $x = \sum_{i=1}^n x_i e_i \in V$, we have

$$\|T(x)\|_1 = \left\| \sum_{j=1}^n \left(\sum_{i=1}^n a_{ij} x_i \right) e_j \right\|_1 = \sum_{j=1}^n \left| \sum_{i=1}^n a_{ij} x_i \right| \leq \left(\sum_{1 \leq i, j \leq n} |a_{ij}| \right) \|x\|_{\max}.$$

Thus the supremum is finite.

The linearity and positive-definiteness of $\|\cdot\|$ are clear. It remains to show the triangle inequality and sub-multiplicativity. For any $A, B \in \text{End}_{\mathbf{k}}(V)$, we have

$$\frac{\|(A+B)(x)\|}{\|x\|} = \frac{\|A(x)\|}{\|x\|} + \frac{\|B(x)\|}{\|x\|} \leq \|A\| + \|B\|.$$

Taking supremum over all $x \in V \setminus \{0\}$ gives $\|A+B\| \leq \|A\| + \|B\|$. We have

$$\|AB(x)\| \leq \|A\| \cdot \|B(x)\| \leq \|A\| \cdot \|B\| \cdot \|x\|$$

and hence $\|AB(x)\|/\|x\| \leq \|A\| \cdot \|B\|$. Taking supremum we get $\|AB\| \leq \|A\| \cdot \|B\|$. □

1.4.2 Finite field extensions

Lemma 1.4.10. Let \mathbf{k} be a complete field and \mathbf{l} a finite extension of \mathbf{k} . Then there exists an absolute value on \mathbf{l} extending the absolute value on \mathbf{k} .

Proof. Fix a norm $\|\cdot\|_V$ on the \mathbf{k} -vector space $V = \mathbf{l}$. The norm $\|\cdot\|_V$ induces an operator norm $\|\cdot\|_{\text{op}}$ on the \mathbf{k} -vector space $\text{End}_{\mathbf{k}}(V)$ as in ???. For any $a \in \mathbf{l}$, let $\mu_a \in \text{End}_{\mathbf{k}}(V)$ be the \mathbf{k} -linear map defined by multiplication by a . Note that $a \mapsto \mu_a$ gives an embedding of \mathbf{k} -algebras and if $a \in \mathbf{k}$, $\|\mu_a\|_{\text{op}} = \|a\|_{\mathbf{k}}$. Thus the restriction of $\|\cdot\|_{\text{op}}$ to \mathbf{l} gives an norm on \mathbf{l} extending that on \mathbf{k} . The normed ring $(\mathbf{l}, \|\cdot\|_{\text{op}})$ is a Banach ring since it is a finite-dimensional vector space over the complete field \mathbf{k} . By ??, there exists a multiplicative seminorm $\|\cdot\|_{\mathbf{l}}$ on \mathbf{l} bounded by $\|\cdot\|_{\text{op}}$. In particular, $\|\cdot\|_{\mathbf{l}}$ is bounded by $\|\cdot\|_{\mathbf{k}}$ on \mathbf{k} . On a field, if one norm is bounded by another norm, then they must be equal (consider the inverse elements). Thus $\|\cdot\|_{\mathbf{l}}$ extends the absolute value on \mathbf{k} . \square

Theorem 1.4.11. Let \mathbf{k} be a complete field and \mathbf{l} a finite extension of \mathbf{k} . Then the absolute value on \mathbf{l} which extends the absolute value on \mathbf{k} is uniquely determined by the absolute value on \mathbf{k} . Furthermore, we have

$$\|\cdot\|_{\mathbf{l}} = \|N_{\mathbf{l}/\mathbf{k}}(\cdot)\|_{\mathbf{k}}^{1/n},$$

where $n = [\mathbf{l} : \mathbf{k}]$ and $N_{\mathbf{l}/\mathbf{k}}$ is the norm map from \mathbf{l} to \mathbf{k} .

Proof. Let $\|\cdot\|_{\mathbf{l}}$ be arbitrary absolute value on \mathbf{l} extending that on \mathbf{k} . We will show that $\|\cdot\|_{\mathbf{l}}$ must be equal to $\|N_{\mathbf{l}/\mathbf{k}}(\cdot)\|_{\mathbf{k}}^{1/n}$. For any $a \in \mathbf{l}$, set $b = a^n / N_{\mathbf{l}/\mathbf{k}}(a) \in \mathbf{l}$. Then $N_{\mathbf{l}/\mathbf{k}}(b) = 1$ and

$$\|b\|_{\mathbf{l}} = \frac{\|a\|_{\mathbf{l}}^n}{\|N_{\mathbf{l}/\mathbf{k}}(a)\|_{\mathbf{k}}}.$$

Thus it suffices to show that $\|b\|_{\mathbf{l}} = 1$ whenever $N_{\mathbf{l}/\mathbf{k}}(b) = 1$.

Note that the norm map $N_{\mathbf{l}/\mathbf{k}} : \mathbf{l} \rightarrow \mathbf{k}$ is the determinant of the \mathbf{k} -linear map $\mu_b \in \text{End}_{\mathbf{k}}(V)$ defined by multiplication by b . Hence it is continuous on \mathbf{l} (since it is a polynomial in the entries of the matrix representation). If $\|b\|_{\mathbf{l}} < 1$, then $\|b^m\|_{\mathbf{l}} \rightarrow 0$ as $m \rightarrow \infty$. Thus $N_{\mathbf{l}/\mathbf{k}}(b^m) = \det(\mu_{b^m}) \rightarrow 0$ as $m \rightarrow \infty$, contradicting the fact that $N_{\mathbf{l}/\mathbf{k}}(b^m) = 1$ for all m . Similarly, if $\|b\|_{\mathbf{l}} > 1$, then just consider b^{-1} . \square

Proposition 1.4.12. Let \mathbf{k} be an algebraically closed non-archimedean field. Then its completion $\widehat{\mathbf{k}}$ is also algebraically closed.

Proof. Let $f \in \widehat{\mathbf{k}}[X]$ be a non-constant polynomial. We will show that f has a root in $\widehat{\mathbf{k}}$. Take a sequence of polynomials $\{f_n\}_{n \in \mathbb{N}}$ in $\mathbf{k}[X]$ converging to f coefficient-wisely. Since \mathbf{k} is algebraically closed, each f_n splits completely in \mathbf{k} and hence in $\widehat{\mathbf{k}}$. Write $f_n(X) = \prod_{i=1}^d (X - \alpha_{n,i})$ with $\alpha_{n,i} \in \widehat{\mathbf{k}}$.

Let \mathbf{l} be a finite extension of $\widehat{\mathbf{k}}$ such that f has a root α in \mathbf{l} . For every $\varepsilon > 0$, if there are infinitely many n such that $\alpha_{n,i} \notin B(\alpha, \varepsilon)$ for all $1 \leq i \leq d$, then we have $|f_n(\alpha)| \geq \varepsilon^d$ for infinitely many n , contradicting the fact that $f_n(\alpha) \rightarrow f(\alpha) = 0$. Thus for every $\varepsilon > 0$, there exists $N > 0$ such that for all $n \geq N$, there exists $1 \leq i \leq d$ with $\alpha_{n,i} \in B(\alpha, \varepsilon)$. That is, we can find a sequence $\alpha_{n,i_n} \in \mathbf{k}$ converging to α . Since $\widehat{\mathbf{k}}$ is complete, we have $\alpha \in \widehat{\mathbf{k}}$. \square

1.5 Analytic functions

Example 1.5.1. Let \mathbf{k} be a non-archimedean field with non-trivial valuation. Then there exists a function $f : \mathbf{k} \rightarrow \mathbf{k}$ that is differentiable everywhere with $f'(x) = 0$ for all $x \in \mathbf{k}$, but f is not locally constant.

Fix $r \in (0, 1)$. Consider a descending sequence of open ball $\{B(0, r^n)\}$ and $a_n \in \mathbf{k}$ with $\|a_n\| = r^{2n}$. Define

$$f : \mathbf{k} \rightarrow \mathbf{k}, \quad x \mapsto \begin{cases} a_n, & x \in B(0, r^n) \setminus B(0, r^{n+1}) \\ 0, & x = 0 \end{cases}$$

Then

$$f'(0) = \lim_{x \rightarrow 0} \frac{f(x) - f(0)}{x - 0} = \lim_{n \rightarrow \infty} \frac{a_n - 0}{x_n - 0}$$

for any sequence $x_n \rightarrow 0$ with $x_n \in B(0, r^n) \setminus B(0, r^{n+1})$. Since $\|x_n\| \geq r^{n+1}$, we have

$$\left\| \frac{a_n}{x_n} \right\| \leq \frac{r^{2n}}{r^{n+1}} = r^{n-1} \rightarrow 0$$

as $n \rightarrow \infty$. Thus $f'(0) = 0$ and then $f'(x) = 0$ for all $x \in \mathbf{k}$. However, f is not locally constant near 0.

1.5.1 Restricted power series

1.5.2 Tate algebras

Notation 1.5.2. Let $T = (T_1, \dots, T_n)$ be a tuple of n indeterminates, $r = (r_1, \dots, r_n)$ be a tuple of n positive real numbers, and $\alpha = (\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n$ be a multi-index. We use the following notations:

- $T^\alpha := T_1^{\alpha_1} T_2^{\alpha_2} \dots T_n^{\alpha_n}$ and $r^\alpha := r_1^{\alpha_1} r_2^{\alpha_2} \dots r_n^{\alpha_n}$;
- $\underline{T}/\underline{r} := (T_1/r_1, T_2/r_2, \dots, T_n/r_n)$;
- $|\alpha| := \alpha_1 + \alpha_2 + \dots + \alpha_n$;
- $E(x, \underline{r}) = \{y \in \mathbf{k}^n \mid \|y_i - x_i\| \leq r_i, i = 1, \dots, n\}$ and $B(x, \underline{r}) = \{y \in \mathbf{k}^n \mid \|y_i - x_i\| < r_i, i = 1, \dots, n\}$ for $x = (x_1, \dots, x_n) \in \mathbf{k}^n$.
- Let $\{x_\alpha\}_{\alpha \in \mathbb{N}^n}$ be a set of elements in a metric space X indexed by multi-indices $\alpha \in \mathbb{N}^n$. We say that $\lim_{|\alpha| \rightarrow +\infty} x_\alpha = x \in X$ if for every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for all $\alpha \in \mathbb{N}^n$ with $|\alpha| > N$, we have $d(x_\alpha, x) < \varepsilon$.

Definition 1.5.3. Let \mathbf{k} be a complete non-archimedean field. Let $T = (T_1, \dots, T_n)$ be a tuple of n indeterminates and $r = (r_1, \dots, r_n)$ be a tuple of n positive real numbers. The *Tate algebra* (or *ring of restricted power series*) is defined as

$$\mathbf{k}\langle \underline{r}^{-1}T \rangle := \mathbf{k}\{\underline{r}^{-1}T\} := \left\{ \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha \mid a_\alpha \in \mathbf{k}, \lim_{|\alpha| \rightarrow +\infty} \|a_\alpha\| r^\alpha = 0 \right\}.$$

Proposition 1.5.4. Let \mathbf{k} be a complete non-archimedean field. Then the Tate algebra $\mathbf{k}\{\underline{T}/r\}$ is a non-archimedean multiplicative banach \mathbf{k} -algebra with respect to the *gauss norm*

$$\left\| \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha \right\| := \sup_{\alpha \in \mathbb{N}^n} \|a_\alpha\| r^\alpha = \max_{\alpha \in \mathbb{N}^n} \|a_\alpha\| r^\alpha.$$

Yang: For the definition of banach ring, see

Proof. The proof splits into several parts. Every parts is straightforward and standard.

Step 1. We first show that $\mathbf{k}\{\underline{T}/r\}$ is a \mathbf{k} -algebra.

Easily to see that it is closed under addition and scalar multiplication. Suppose that $f = \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha$ and $g = \sum_{\alpha \in \mathbb{N}^n} b_\alpha T^\alpha$ are two elements in $\mathbf{k}\{\underline{T}/r\}$. Given $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for all $|\alpha| > N$, we have $\|a_\alpha\| r^\alpha < \varepsilon/\|g\|$ and $\|b_\alpha\| r^\alpha < \varepsilon/\|f\|$. For any $|\gamma| > 2N$, we have

$$\left\| \sum_{\alpha+\beta=\gamma} a_\alpha b_\beta \right\| r^\gamma \leq \max_{\alpha+\beta=\gamma} \|a_\alpha\| r^\alpha \cdot \|b_\beta\| r^\beta < \max \left\{ \frac{\varepsilon}{\|g\|} \|b_\beta\| r^\beta, \frac{\varepsilon}{\|f\|} \|a_\alpha\| r^\alpha \right\} \leq \varepsilon.$$

Hence $f \cdot g \in \mathbf{k}\{\underline{T}/r\}$ and it shows that $\mathbf{k}\{\underline{T}/r\}$ is a \mathbf{k} -algebra.

Step 2. Show that the gauss norm is a non-archimedean norm on $\mathbf{k}\{\underline{T}/r\}$.

The linearity and positive-definiteness of the gauss norm are direct from the definition. We have

$$\|f + g\| = \sup_{\alpha \in \mathbb{N}^n} \|a_\alpha + b_\alpha\| r^\alpha \leq \sup_{\alpha \in \mathbb{N}^n} \max\{\|a_\alpha\| + \|b_\alpha\|\} r^\alpha \leq \max\{\|f\|, \|g\|\}$$

and

$$\begin{aligned} \|f \cdot g\| &= \left\| \sum_{\gamma \in \mathbb{N}^n} \left(\sum_{\alpha+\beta=\gamma} a_\alpha b_\beta \right) T^\gamma \right\| = \sup_{\gamma \in \mathbb{N}^n} \left\| \sum_{\alpha+\beta=\gamma} a_\alpha b_\beta \right\| r^\gamma \\ &\leq \sup_{\gamma \in \mathbb{N}^n} \max_{\alpha+\beta=\gamma} \|a_\alpha\| \|b_\beta\| r^\alpha r^\beta = \|a_{\alpha_0}\| r^{\alpha_0} \cdot \|b_{\beta_0}\| r^{\beta_0} \leq \|f\| \cdot \|g\|. \end{aligned}$$

These show that Tate algebra with the gauss norm is a non-archimedean normed \mathbf{k} -algebra.

Step 3. Show that the gauss norm is multiplicative.

Suppose that $\|f\| = \|a_{\alpha_1}\| r^{\alpha_1}$ and $\|a_\alpha\| r^\alpha < \|f\|$ for all $\alpha <_{\text{total}} \alpha_1$. Similar to $\|b_{\beta_1}\| r^{\beta_1}$. Then we have

$$\|f\| \cdot \|g\| = \|a_{\alpha_1}\| r^{\alpha_1} \cdot \|b_{\beta_1}\| r^{\beta_1} = \max_{\alpha+\beta=\alpha_1+\beta_1} \|a_\alpha\| \|b_\beta\| r^\alpha r^\beta = \left\| \sum_{\alpha+\beta=\alpha_1+\beta_1} a_\alpha b_\beta \right\| r^{\alpha_1+\beta_1} \leq \|f \cdot g\|,$$

where the third equality holds since (α_1, β_1) is the unique pair such that $\|a_{\alpha_1}\| r^{\alpha_1} \cdot \|b_{\beta_1}\| r^{\beta_1}$ is maximized and by ???. Thus the gauss norm is multiplicative.

Step 4. Finally show that $\mathbf{k}\{\underline{T}/r\}$ is complete with respect to the gauss norm.

Let $\{f_m = \sum a_{\alpha,m} T^\alpha\}$ be a cauchy sequence in $\mathbf{k}\{\underline{T}/r\}$. We have

$$\|a_{\alpha,m} - a_{\alpha,l}\| r^\alpha \leq \|f_m - f_l\|.$$

Thus for each $\alpha \in \mathbb{N}^n$, the sequence $\{a_{\alpha,m}\}$ is a cauchy sequence in \mathbf{k} . Since \mathbf{k} is complete, set $a_\alpha := \lim_{m \rightarrow +\infty} a_{\alpha,m}$ and $f = \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha$. Given $\varepsilon > 0$, there exists $M \in \mathbb{N}$ such that for all

$m, l > M$, we have $\|f_m - f_l\| < \varepsilon$. Fixing $m > M$, there exists $N \in \mathbb{N}$ such that for all $|\alpha| > N$, we have $\|a_{\alpha, m}\| r^\alpha < \varepsilon$. Hence for all $|\alpha| > N$ and $l > M$, we have

$$\|a_{\alpha, l}\| r^\alpha \leq \|a_{\alpha, l} - a_{\alpha, m}\| r^\alpha + \|a_{\alpha, m}\| r^\alpha < 2\varepsilon.$$

Taking $l \rightarrow +\infty$, we have $\|a_\alpha\| r^\alpha \leq 2\varepsilon$ for all $|\alpha| > N$. It follows that $f \in \mathbf{k}\{\underline{T}/r\}$.

For every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for all $m, l > N$, we have $\|f_m - f_l\| < \varepsilon$. Thus for all $\alpha \in \mathbb{N}^n$ and $m, l > N$, we have

$$\|a_{\alpha, m} - a_{\alpha, l}\| r^\alpha \leq \|f_m - f_l\| < \varepsilon.$$

Taking $l \rightarrow +\infty$, we have $\|a_{\alpha, m} - a_\alpha\| r^\alpha \leq \varepsilon$ for all $m > N$. It follows that

$$\|f - f_m\| = \sup_{\alpha \in \mathbb{N}^n} \|a_\alpha - a_{\alpha, m}\| r^\alpha \leq \varepsilon$$

for all $m > N$. □

Proposition 1.5.5. Let \mathbf{k} be a complete non-archimedean field. Then the Tate algebra $\mathbf{k}\{\underline{T}/r\}$ can be identified with a subring of the ring of all functions from the closed polydisc $E(0, \underline{r}) \subset \mathbf{k}^n$ to \mathbf{k} .

Proof. Given $f = \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha \in \mathbf{k}\{\underline{T}/r\}$ and $x = (x_1, \dots, x_n) \in E(0, \underline{r})$, we have

$$\left\| \sum_{|\alpha|=n} a_\alpha x^\alpha \right\| \leq \max_{|\alpha|=n} \|a_\alpha\| r^\alpha \rightarrow 0 \quad \text{as } n \rightarrow +\infty.$$

Hence by ??, the series $f(x) := \sum_{\alpha \in \mathbb{N}^n} a_\alpha x^\alpha$ converges in \mathbf{k} . This defines a function $f : E(0, \underline{r}) \rightarrow \mathbf{k}$.

Let $g = \sum_{\alpha \in \mathbb{N}^n} b_\alpha T^\alpha \in \mathbf{k}\{\underline{T}/r\}$. Set

$$A_n = \sum_{|\alpha| < n} a_\alpha x^\alpha, \quad B_n = \sum_{|\beta| < n} b_\beta x^\beta, \quad C_n = \sum_{|\gamma| < n} \left(\sum_{\alpha+\beta=\gamma} a_\alpha b_\beta \right) x^\gamma.$$

We need to show that $f(x)g(x) = \lim A_n B_n = \lim C_n = (fg)(x)$. Note that

$$A_n B_n - C_n = \sum_{\substack{|\alpha| < n, |\beta| < n \\ |\alpha+\beta| \geq n}} a_\alpha b_\beta x^{\alpha+\beta}.$$

Given $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that for all $|\alpha| > N$, we have $\|a_\alpha\| r^\alpha < \varepsilon/\|g\|$ and $\|b_\alpha\| r^\alpha < \varepsilon/\|f\|$. For any $n > 2N$, we have

$$\|A_n B_n - C_n\| \leq \max_{\substack{|\alpha| < n, |\beta| < n \\ |\alpha+\beta| \geq n}} \|a_\alpha\| \|b_\beta\| \|x^{\alpha+\beta}\| < \max \left\{ \frac{\varepsilon}{\|g\|} \|b_\beta\| r^\beta, \frac{\varepsilon}{\|f\|} \|a_\alpha\| r^\alpha \right\} \leq \varepsilon.$$

Thus $f(x)g(x) = (fg)(x)$. The addition and scalar multiplication can be verified directly. Hence above assignments define a homomorphism of \mathbf{k} -algebras from $\mathbf{k}\{\underline{T}/r\}$ to the ring of all functions from $E(0, \underline{r})$ to \mathbf{k} .

Finally, suppose that $f = \sum_{\alpha \in \mathbb{N}^n} a_\alpha T^\alpha \in \mathbf{k}\{\underline{T}/r\}$ is mapped to the zero function. □

Proposition 1.5.6. Let \mathbf{k} be a complete non-archimedean field. Then the gauss norm on the Tate algebra $\mathbf{k}\{\underline{T}/\underline{r}\}$ coincides with the supremum norm

$$\|f\|_{\sup} := \sup_{x \in E(0, \underline{r})} \|f(x)\|_{\mathbf{k}}.$$

Proof. Yang: To be added. □

1.5.3 Fundamental properties

Then following shows that analytic functions over non-archimedean fields share some nice properties as in the case of complex analysis. Yang: To be revised.

Theorem 1.5.7. Let $(\mathbf{k}, \|\cdot\|)$ be a complete non-archimedean field and $U \subset \mathbf{k}$ be an open subset. If $f : U \rightarrow \mathbf{k}$ is an analytic function, then f is locally Lipschitz continuous on U . Yang: To be checked.

Theorem 1.5.8 (Strassman). Let \mathbf{k} be a complete non-archimedean field and $f(x) = \sum_{n=0}^{+\infty} a_n x^n$ be an analytic function on the closed unit disc in \mathbf{k} . Then f has only finitely many zeros in the closed unit disc unless f is identically zero. Yang: To be checked.

1.6 Example: p -adic fields

1.6.1 p -adic fields

Construction 1.6.1. Let K be a number field and \mathfrak{p} be a prime ideal of the ring of integers \mathcal{O}_K of K . Considering the localization $(\mathcal{O}_K)_{\mathfrak{p}}$ of \mathcal{O}_K at \mathfrak{p} , which is a discrete valuation ring, denote by $v_{\mathfrak{p}} : K^{\times} \rightarrow \mathbb{Z}$ the corresponding discrete valuation. The p -adic absolute value on K associated to \mathfrak{p} is defined as

$$|x|_{\mathfrak{p}} := N(\mathfrak{p})^{-v_{\mathfrak{p}}(x)}, \quad \forall x \in K,$$

where $N(\mathfrak{p}) := \#(\mathcal{O}_K/\mathfrak{p})$ is the norm of \mathfrak{p} .

The completion of K with respect to the p -adic absolute value $|\cdot|_{\mathfrak{p}}$ is denoted by $K_{\mathfrak{p}}$, called the p -adic field.

One can just focus on the case $K = \mathbb{Q}$ and $\mathfrak{p} = (p)$ for a prime number p .

Example 1.6.2. Let p be a prime number. For every $r \in \mathbb{Q}$, we can write r as $r = p^n \frac{a}{b}$, where $n \in \mathbb{Z}$ and $a, b \in \mathbb{Z}$ are integers not divisible by p . The p -adic absolute value on \mathbb{Q} is defined as

$$|r|_p := p^{-n}.$$

The p -adic field \mathbb{Q}_p can be described concretely as follows:

$$\mathbb{Q}_p = \left\{ \sum_{i=n}^{+\infty} a_i p^i \mid n \in \mathbb{Z}, a_i \in \{0, 1, \dots, p-1\} \right\}.$$

For $x = \sum_{i=n}^{+\infty} a_i p^i \in \mathbb{Q}_p$ with $a_n \neq 0$, its p -adic absolute value is given by $|x|_p = p^{-n}$. The operations of addition and multiplication on \mathbb{Q}_p are defined similarly as those on decimal expansions.

Proposition 1.6.3. The multiplicative group \mathbb{Q}_p^\times of the p -adic field \mathbb{Q}_p admits the following decomposition:

$$\mathbb{Q}_p^\times \cong p^{\mathbb{Z}} \times \mathbb{Z}_p^\times,$$

where $p^{\mathbb{Z}} := \{p^n \mid n \in \mathbb{Z}\}$ and $\mathbb{Z}_p^\times := \{x \in \mathbb{Q}_p \mid |x|_p = 1\}$ is the group of units of the ring of p -adic integers \mathbb{Z}_p . *Yang: To be checked.*

Yang: What is the relation between the finite extension of \mathbb{Q}_p and K_p ?

1.6.2 Completion

Proposition 1.6.4. The algebraic closure $\overline{\mathbb{Q}_p}$ of \mathbb{Q}_p is not complete with respect to the extension of the p -adic absolute value $|\cdot|_p$.

Construction 1.6.5. Let p be a prime number. The field \mathbb{C}_p of p -adic complex numbers is defined as the completion of the algebraic closure of \mathbb{Q}_p with respect to the unique extension of the p -adic absolute value $|\cdot|_p$ on \mathbb{Q}_p . The field \mathbb{C}_p is algebraically closed and complete with respect to $|\cdot|_p$.

Yang: To be completed.

Proposition 1.6.6. The field \mathbb{C}_p of p -adic complex numbers is not spherically complete.

Construction 1.6.7. Let p be a prime number. *Yang: We construct the spherically complete p -adic field Ω_p .* *Yang: To be completed.*

1.6.3 Elementary functions

Exponential, logarithmic, and the interpolation functions.

Chapter 2

Affinoid algebras

2.1 Semi-normed Rings and Modules

2.1.1 Semi-normed algebraic structures

Definition 2.1.1. Let M be an abelian group. A *semi-norm* on M is a function $\|\cdot\| : M \rightarrow \mathbb{R}_+$ such that

- $\|0\| = 0$;
- $\forall x, y \in M, \|x + y\| \leq \|x\| + \|y\|$.

If we further have $\|x\| = 0 \iff x = 0$, then we say $\|\cdot\|$ is a *norm*. A *semi-normed abelian group* (resp. *normed abelian group*) is an abelian group equipped with a semi-norm (resp. norm).

Definition 2.1.2. Let $\|\cdot\|_1$ and $\|\cdot\|_2$ be two semi-norms on an abelian group M . We say $\|\cdot\|_1$ is *bounded* by $\|\cdot\|_2$ if there exists a constant $C > 0$ such that $\forall x \in M, \|x\|_1 \leq C\|x\|_2$.

Remark 2.1.3. If two semi-norms (resp. norms) on an abelian group M are bounded by each other, then they induce the same topology on M .

Definition 2.1.4. Let M be a semi-normed abelian group and $N \subseteq M$ be a subgroup. The *residue semi-norm* on the quotient group M/N is defined as

$$\|x + N\|_{M/N} = \inf_{y \in N} \|x + y\|_M.$$

Remark 2.1.5. The residue semi-norm is a norm if and only if N is closed in M .

Definition 2.1.6. Let M and N be two semi-normed abelian groups. A group homomorphism $f : M \rightarrow N$ is called *bounded* if there exists a constant $C > 0$ such that $\forall x \in M, \|f(x)\|_N \leq C\|x\|_M$. A bounded homomorphism $f : M \rightarrow N$ is called *admissible* if the induced isomorphism $M/\ker f \rightarrow \operatorname{Im} f$ is an isometry, i.e., $\forall x \in M, \|f(x)\|_N = \inf_{y \in \ker f} \|x + y\|_M$.

Definition 2.1.7. Let R be a ring (commutative with unity). A *semi-norm* on R is a semi-norm $\|\cdot\|$ on the underlying abelian group of R such that $\forall x, y \in R, \|xy\| \leq \|x\|\|y\|$ and $\|1\| = 1$. A *semi-normed ring* is a ring equipped with a semi-norm.

Definition 2.1.8. A semi-norm $\|\cdot\|$ on a ring R is called *multiplicative* if $\forall x, y \in R, \|xy\| = \|x\|\|y\|$. It is called *power-multiplicative* if $\forall x \in R, \|x^n\| = \|x\|^n$ for all integers $n \geq 1$.

Definition 2.1.9. Let $(R, \|\cdot\|_R)$ be a normed ring. A *semi-normed R -module* is a pair $(M, \|\cdot\|_M)$ where M is an R -module and $\|\cdot\|_M$ is a semi-norm on the underlying abelian group of M such that there exists $C > 0$ with $\forall a \in R, x \in M, \|ax\|_M \leq C\|a\|_R\|x\|_M$.

One can talk about boundedness, admissibility and residue semi-norms in the contexts of semi-normed rings and semi-normed modules similar to those in semi-normed abelian groups.

2.1.2 banach rings

Definition 2.1.10. A (semi-)norm on an abelian group M induces a (pseudo-)metric $d(x, y) = \|x - y\|$ on M . A (semi-)normed abelian group M is called *complete* if it is complete as a (pseudo-)metric space.

Definition 2.1.11. A *banach ring* is a complete normed ring.

Definition 2.1.12. Let $(A, \|\cdot\|_A)$ be a (semi-)normed algebraic structure, e.g., a (semi-)normed abelian group, a (semi-)normed ring, or a (semi-)normed module. The *completion* of A , denoted by \hat{A} , is the completion of A as a (pseudo-)metric space. Since A is dense in its completion, the algebraic operations and (semi-)norms on A can be uniquely extended to the completion.

Let R be a normed ring and M, N be semi-normed R -modules. There is a natural semi-norm on the tensor product $M \otimes_R N$ defined as

$$\|z\|_{M \otimes_R N} = \inf \left\{ \sum_i \|x_i\|_M \|y_i\|_N : z = \sum_i x_i \otimes y_i, x_i \in M, y_i \in N \right\}.$$

Definition 2.1.13. Let R be a complete normed ring and M, N complete semi-normed R -modules. The *complete tensor product* $M \hat{\otimes}_R N$ is defined as the completion of the semi-normed R -module $M \otimes_R N$.

Definition 2.1.14. Let R be a banach ring. For each $f \in R$, the *spectral radius* of f is defined as

$$\rho(f) = \lim_{n \rightarrow \infty} \|f^n\|^{1/n}.$$

Yang: Since , $\rho(f)$ exists.

Definition 2.1.15. A banach ring R is called *uniform* if its norm is power-multiplicative.

Proposition 2.1.16. Let $(R, \|\cdot\|)$ be a banach ring. The spectral radius $\rho(\cdot)$ defines a power-multiplicative semi-norm on R that is bounded by $\|\cdot\|$.

Proof. Yang: To be continued. □

Definition 2.1.17. Let R be a banach ring. An element $f \in R$ is called *quasi-nilpotent* if $\rho(f) = 0$. All quasi-nilpotent elements of R form an ideal, denoted by $\text{Qnil}(R)$.

Definition 2.1.18. Let R be a banach ring. The *uniformization* of R , denoted by $R \rightarrow R^u$, is the banach ring with the universal property among all bounded homomorphisms from R to uniform banach rings. Yang: To be continued.

Proposition 2.1.19. Let R be a banach ring. The completion of $R/\text{Qnil}(R)$ with respect to the spectral radius $\rho(\cdot)$ is the uniformization of R .

Proof. Yang: To be continued. □

2.1.3 Examples

Example 2.1.20. Let R be arbitrary ring. The *trivial norm* on R is defined as $\|x\| = 0$ if $x = 0$ and $\|x\| = 1$ if $x \neq 0$. The ring R equipped with the trivial norm is a normed ring.

Example 2.1.21. The fields \mathbb{C} and \mathbb{R} equipped with the usual absolute value are complete fields.

Example 2.1.22. The field \mathbb{Q}_p of p -adic numbers equipped with the p -adic norm is a complete non-Archimedean field.

Example 2.1.23. Let R be a banach ring and $r > 0$ be a real number. We define the ring of absolutely convergent power series over \mathbf{k} with radius r as

$$R\langle T/r \rangle := \left\{ \sum_{n=0}^{\infty} a_n T^n \in R[[T]] : \sum_{n=0}^{\infty} \|a_n\| r^n < \infty \right\}.$$

Equipped with the norm $\|\sum_{n=0}^{\infty} a_n T^n\| = \sum_{n=0}^{\infty} \|a_n\| r^n$, the ring $R\langle T/r \rangle$ is a banach ring.

When $R = \mathbf{k}$ is a Yang: To be checked.

Example 2.1.24. Let \mathbf{k} be a non-Archimedean complete field. We define

$$\mathbf{k}\{T_1/r_1, \dots, T_n/r_n\} := \left\{ \sum_{I \in \mathbb{N}^n} a_I T^I \in \mathbf{k}[[T_1, \dots, T_n]] : \lim_{|I| \rightarrow \infty} |a_I| r^I = 0 \right\},$$

where $r = (r_1, \dots, r_n)$ is an n -tuple of positive real numbers, $T^I = T_1^{i_1} \dots T_n^{i_n}$ for $I = (i_1, \dots, i_n)$, and $|I| = i_1 + \dots + i_n$. Equipped with the norm $\|\sum_{I \in \mathbb{N}^n} a_I T^I\| = \sup_{I \in \mathbb{N}^n} |a_I| r^I$, the affinoid \mathbf{k} -algebra $\mathbf{k}\{T_1/r_1, \dots, T_n/r_n\}$ is a banach \mathbf{k} -algebra. This is called the *Tate algebra* over \mathbf{k} with polyradius r equipped with the *Gauss norm*. We will denote $\mathbf{k}\{\underline{T}/r\} = \mathbf{k}\{T_1/r_1, \dots, T_n/r_n\}$ for simplicity.

Yang: To be continued...

2.2 Affinoid algebras

2.2.1 The first properties

Definition 2.2.1. Let \mathbf{k} be a non-archimedean field. A banach \mathbf{k} -algebra A is called a *affinoid \mathbf{k} -algebra* if there exists an admissible surjective homomorphism

$$\varphi : \mathbf{k}\{r_1^{-1}T_1, \dots, r_n^{-1}T_n\} \twoheadrightarrow A$$

for some $n \in \mathbb{N}$ and $r_1, \dots, r_n \in \mathbb{R}_{>0}$.

If one can choose $r_1 = \dots = r_n = 1$, then we say that A is a *strict affinoid \mathbf{k} -algebra*.

Definition 2.2.2. Let \mathbf{k} be a non-archimedean field. We define the *ring of restricted Laurent series* over \mathbf{k} as

$$\mathbf{K}_r = \mathbf{L}_{\mathbf{k},r} = \left\{ \sum_{n \in \mathbb{Z}} a_n T^n : a_n \in \mathbf{k}, \lim_{|n| \rightarrow \infty} |a_n| r^n = 0 \right\}$$

equipped with the norm

$$\|f\| = \sup_{n \in \mathbb{Z}} |a_n| r^n.$$

Yang: Is \mathbf{K}_r always a field? Yang: Do we have $\mathbf{L}_{\mathbf{k},r} = \text{Frac}(\mathbf{k}\{T/r\})$?

Proposition 2.2.3. Let \mathbf{k} be a non-archimedean field. If $r \notin \sqrt{|\mathbf{k}^\times|}$, then \mathbf{K}_r is a complete non-archimedean field with non-trivial absolute value extending that of \mathbf{k} .

Proposition 2.2.4. Let A be an affinoid \mathbf{k} -algebra. Then A is noetherian, and every ideal of A is closed.

Proposition 2.2.5. Let A be an affinoid \mathbf{k} -algebra. Then there exists a constant $C > 0$ and $N > 0$ such that for all $f \in A$ and $n \geq N$, we have

$$\|f^n\| \leq C \rho(f)^n.$$

Proposition 2.2.6. Let A be an affinoid \mathbf{k} -algebra. If and only if $\rho(f) \in \sqrt{|\mathbf{k}|}$ for all $f \in A$, then A is strict. Yang: To be complete.

2.3 Finite modules

2.3.1 Finite banach module

There are three different categories of finite modules over an affinoid algebra A :

- The category \mathbf{Banmod}_A of finite banach A -modules with A -linear maps as morphisms.
- The category \mathbf{Banmod}_A^b of finite banach A -modules with bounded A -linear maps as morphisms.

- The category \mathbf{mod}_A of finite A -modules with all A -linear maps as morphisms.

Theorem 2.3.1. Let A be an affinoid \mathbf{k} -algebra. Then the category of finite banach A -modules with bounded A -linear maps as morphisms is equivalent to the category of finite A -modules with A -linear maps as morphisms. *Yang: To be revised.*

For simplicity, we will just write \mathbf{mod}_A to denote the category of finite banach A -modules with bounded A -linear maps as morphisms.

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Chapter 3

Affinoid spaces

3.1 Spectrum

Let \mathbf{k} be a spherically complete non-archimedean field which is algebraically closed and $A = \mathbf{k}[T]$. We want to consider the “analytic structure” on $\mathbf{mSpec} A$. However, unlike the complex case, the set $\mathbf{mSpec} A$ is totally disconnected with respect to the topology induced by the absolute value on \mathbf{k} (?). To overcome this difficulty, Berkovich uses multiplicative semi-norms to “fill in the gaps” between the points in $\mathbf{mSpec} A$, leading to the notion of the spectrum of a Banach ring.

We first consider the local model. Hence we should consider the Tate algebra $\mathbf{k}\{T\}$ instead of the polynomial ring $\mathbf{k}[T]$. Yang: The maximal ideal of $\mathbf{k}\{T\}$ corresponding to the point in the disk $\{a \in \mathbf{k} : |a| \leq 1\}$. Yang: Closed or open disk?

3.1.1 Definition

Definition 3.1.1. Let R be a Banach ring. The *spectrum* $\mathcal{M}(R)$ of R is defined as the set of all multiplicative semi-norms on R that are bounded with respect to the given norm on R . For every point $x \in \mathcal{M}(R)$, we denote the corresponding multiplicative semi-norm by $|\cdot|_x$. We equip $\mathcal{M}(R)$ with the weakest topology such that for each $f \in R$, the evaluation map $\mathcal{M}(R) \rightarrow \mathbb{R}_{\geq 0}$, defined by $x \mapsto |f|_x =: f(x)$, is continuous.

Definition 3.1.2. Let $\varphi : R \rightarrow S$ be a bounded ring homomorphism of Banach rings. The *pullback* map $\mathcal{M}(\varphi) : \mathcal{M}(S) \rightarrow \mathcal{M}(R)$ is defined by $\mathcal{M}(\varphi)(x) = x \circ \varphi : f \mapsto |\varphi(f)|_x$ for each $x \in \mathcal{M}(S)$.

Proposition 3.1.3. Let R be a Banach ring. For each $x \in \mathcal{M}(R)$, let \wp_x be the kernel of the multiplicative semi-norm $|\cdot|_x$. Then \wp_x is a closed prime ideal of R , and $x \mapsto \wp_x$ defines a continuous map from $\mathcal{M}(R)$ to $\text{Spec}(R)$ equipped with the Zariski topology.

| *Proof.* Yang: To be completed □

Definition 3.1.4. Let R be a Banach ring. For each $x \in \mathcal{M}(R)$, the *completed residue field* at the point x is defined as the completion of the residue field $\kappa(x) = \text{Frac}(R/\wp_x)$ with respect to the multiplicative norm induced by the semi-norm $|\cdot|_x$, denoted by $\mathcal{H}(x)$.

Definition 3.1.5. Let R be a Banach ring. The *Gel'fand transform* of R is the bounded ring homomorphism

$$\Gamma : R \rightarrow \prod_{x \in \mathcal{M}(R)} \mathcal{H}(x), \quad f \mapsto (f(x))_{x \in \mathcal{M}(R)},$$

where the norm on the product $\prod_{x \in \mathcal{M}(R)} \mathcal{H}(x)$ is given by the supremum norm.

Proposition 3.1.6. The Gel'fand transform $\Gamma : R \rightarrow \prod_{x \in \mathcal{M}(R)} \mathcal{H}(x)$ of a Banach ring R factors through the uniformization R^u of R , and the induced map $R^u \rightarrow \prod_{x \in \mathcal{M}(R)} \mathcal{H}(x)$ is an isometric embedding. **Yang: To be checked.**

Theorem 3.1.7. Let R be a Banach ring. The spectrum $\mathcal{M}(R)$ is nonempty.

Proof. **Yang: To be continued.** □

Lemma 3.1.8. Let $\{K_i\}_{i \in I}$ be a family of completed fields. Consider the Banach ring $R = \prod_{i \in I} K_i$ equipped with the product norm. The spectrum $\mathcal{M}(R)$ is homeomorphic to the Stone-Čech compactification of the discrete space I .

Remark 3.1.9. The Stone-Čech compactification of a discrete space is the largest compact Hausdorff space in which the original space can be densely embedded. **Yang: To be checked.**

Theorem 3.1.10. Let R be a Banach ring. The spectrum $\mathcal{M}(R)$ is a compact Hausdorff space.

Proof. **Yang: To be added.** □

Proposition 3.1.11. Let K/k be a Galois extension of complete fields, and let R be a Banach k -algebra. The Galois group $\text{Gal}(K/k)$ acts on the spectrum $\mathcal{M}(R \hat{\otimes}_k K)$ via

$$g \cdot x : f \mapsto |(1 \otimes g^{-1})(f)|_x$$

for each $g \in \text{Gal}(K/k)$, $x \in \mathcal{M}(R \hat{\otimes}_k K)$ and $f \in R \hat{\otimes}_k K$. Moreover, the natural map $\mathcal{M}(R \hat{\otimes}_k K) \rightarrow \mathcal{M}(R)$ induces a homeomorphism

$$\mathcal{M}(R \hat{\otimes}_k K) / \text{Gal}(K/k) \xrightarrow{\sim} \mathcal{M}(R).$$

Yang: To be checked.

3.1.2 Examples

Example 3.1.12. Let $(\mathbf{k}, |\cdot|)$ be a complete valuation field. The spectrum $\mathcal{M}(\mathbf{k})$ consists of a single point corresponding to the given absolute value $|\cdot|$ on \mathbf{k} . **Yang: To be checked.**

Example 3.1.13. Consider the Banach ring $(\mathbb{Z}, \|\cdot\|)$ with $\|\cdot\| = |\cdot|_\infty$ is the usual absolute value norm on \mathbb{Z} . Let $|\cdot|_p$ denote the p -adic norm for each prime number p , i.e., $|n|_p = p^{-v_p(n)}$ for each $n \in \mathbb{Z}$, where $v_p(n)$ is the p -adic valuation of n . The spectrum

$$\mathcal{M}(\mathbb{Z}) = \{|\cdot|_\infty^\varepsilon : \varepsilon \in (0, 1]\} \cup \{|\cdot|_p^\alpha : p \text{ is prime}, \alpha \in (0, \infty]\} \cup \{|\cdot|_0\},$$

where $|a|_p^\infty := \lim_{\alpha \rightarrow \infty} |a|_p^\alpha$ for each $a \in \mathbb{Z}$ and $|\cdot|_0$ is the trivial norm on \mathbb{Z} . **Yang: To be checked.**

Spectrum of Tate algebra in one variable Let \mathbf{k} be a complete non-archimedean field, and let $A = \mathbf{k}\{T/r\}$. We list some types of points in the spectrum $\mathcal{M}(A)$.

For each $a \in \mathbf{k}$ with $|a| \leq r$, we have the *type I* point x_a corresponding to the evaluation at a , i.e., $|f|_{x_a} := |f(a)|$ for each $f \in A$. For each closed disk $E = E(a, s) := \{b \in \mathbf{k} : |b - a| \leq s\}$ with center $a \in \mathbf{k}$ and radius $s \leq r$, we have the point $x_{a,s}$ corresponding to the multiplicative semi-norm defined by

$$|f|_{x_E} := \sup_{b \in E(a,s)} |f(b)|$$

for each $f \in A$. If $s \in |\mathbf{k}^\times|$, then the point x_E is called a *type II* point; otherwise, it is called a *type III* point.

Let $\{E^{(s)}\}_s$ be a family of closed disks in \mathbf{k} such that $E^{(s)}$ is of radius s , $E^{(s_1)} \subsetneq E^{(s_2)}$ for any $s_1 < s_2$ and $\bigcap_s E^{(s)} = \emptyset$. Then we have the point $x_{\{E^{(s)}\}}$ corresponding to the multiplicative semi-norm defined by

$$|f|_{x_{\{E^{(s)}\}}} := \inf_s |f|_{x_{E^{(s)}}}$$

for each $f \in A$. Such a point is called a *type IV* point.

Yang: To be completed.

Proposition 3.1.14. Let \mathbf{k} be a complete non-archimedean field, and let $r > 0$ be a positive real number. Consider the Tate algebra $\mathbf{k}\{r^{-1}T\}$ equipped with the Gauss norm. The points in the spectrum $\mathcal{M}(\mathbf{k}\{r^{-1}T\})$ can be classified into four types as described above. Yang: To be checked

Proof. Yang: To be completed. □

Proposition 3.1.15. Let \mathbf{k} be a complete non-archimedean field, and let $r > 0$ be a positive real number. Consider the Tate algebra $\mathbf{k}\{r^{-1}T\}$ equipped with the Gauss norm. The completed residue fields of the four types of points in the spectrum $\mathcal{M}(\mathbf{k}\{r^{-1}T\})$ are described as follows:

- For a type I point x_a with $a \in \mathbf{k}$ and $|a| \leq r$, the completed residue field $\mathcal{H}(x_a)$ is isomorphic to \mathbf{k} .
- For a type II point $x_{a,s}$ with $a \in \mathbf{k}$ and $s \in |\mathbf{k}^\times|$, the completed residue field $\mathcal{H}(x_{a,s})$ is isomorphic to the field of Laurent series over the residue field $\mathcal{K}_{\mathbf{k}}$, i.e., $\mathcal{K}_{\mathbf{k}}((t))$.
- For a type III point $x_{a,s}$ with $a \in \mathbf{k}$ and $s \notin |\mathbf{k}^\times|$, the completed residue field $\mathcal{H}(x_{a,s})$ is isomorphic to a transcendental extension of $\mathcal{K}_{\mathbf{k}}$ of degree one.
- For a type IV point $x_{\{E^{(s)}\}}$, the completed residue field $\mathcal{H}(x_{\{E^{(s)}\}})$ is isomorphic to a transcendental extension of $\mathcal{K}_{\mathbf{k}}$ of infinite degree.

Yang: To be checked.

Example 3.1.16. The completed residue field $\mathcal{H}(x_a)$ for a type I point x_a with $a \in \mathbf{k}$ and $|a| \leq r$ is isomorphic to \mathbf{k} . Yang: To be complete.

Spectrum of Tate algebra in several variables Let \mathbf{k} be a complete non-archimedean field, and let $A = \mathbf{k}\{r_1^{-1}T_1, \dots, r_n^{-1}T_n\}$. We can consider the spectrum $\mathcal{M}(A)$ similarly.

3.2 Affinoid domains

Consider $X = \mathcal{M}(A)$ with $A = \mathbf{k}\{T_1, \dots, T_n\}$. Yang: Not every open subset of X gives an affinoid space, that is, the completion of the ring of analytic functions on that open subset is not necessarily an affinoid algebra. Yang: Right? example?

3.2.1 Definition

Definition 3.2.1. Let A be a \mathbf{k} -affinoid algebra, and let $X = \mathcal{M}(A)$ be the associated affinoid space. A closed subset $V \subseteq X$ is called an *affinoid domain* if there exists a \mathbf{k} -affinoid algebra A_V and a morphism of \mathbf{k} -affinoid algebras $\varphi : A \rightarrow A_V$ satisfying the following universal property: for every bounded homomorphism of \mathbf{k} -affinoid algebras $\psi : A \rightarrow B$ such that the induced map on spectra $\mathcal{M}(\psi) : \mathcal{M}(B) \rightarrow X$ has its image contained in V , there exists a unique bounded homomorphism $\theta : A_V \rightarrow B$ such that the following diagram commutes:

$$\begin{array}{ccc} & A_V & \\ \varphi \nearrow & & \searrow \theta \\ A & \xrightarrow{\psi} & B \end{array}$$

In this case, we say that V is represented by the affinoid algebra A_V .

Slogan A closed subset $V \subset X$ is an affinoid domain if the functor “ $\text{Mor}(-, V)$ ” is representable.

Yang: Why we consider closed subset rather than open subset?

Construction 3.2.2. Let $f = (f_1, \dots, f_n)$ be a tuple of elements in A and $r = (r_1, \dots, r_n)$ be a tuple of positive real numbers. Consider the closed subset of X :

$$X(\underline{f/r}) := \{x \in X : |f_i(x)| \leq r_i, 1 \leq i \leq n\}.$$

Such a closed subset is called a *Weierstrass domain* of X . Moreover, we can define a \mathbf{k} -affinoid algebra

$$A\{\underline{f/r}\} := A\{f_1/r_1, \dots, f_n/r_n\}.$$

Yang: The domain $X(\underline{f/r})$ is represented by $A\{\underline{f/r}\}$.

Construction 3.2.3. Let $f = (f_1, \dots, f_n), g = (g_1, \dots, g_m)$ be two tuples of elements in A and $r = (r_1, \dots, r_n), s = (s_1, \dots, s_m)$ be two tuples of positive real numbers. Consider the following closed subset of X :

$$X(\underline{f/r}; \underline{g/s}^{-1}) := \{x \in X : |f_i(x)| \leq r_i, |g_j(x)| \geq s_j, 1 \leq i \leq n, 1 \leq j \leq m\}.$$

Such a closed subset is called a *Laurent domain* of X . Moreover, we can define a \mathbf{k} -affinoid algebra

$$A\{\underline{f/r}; \underline{g/s}^{-1}\} := A\{f_1/r_1, \dots, f_n/r_n, g_1^{-1}/s_1, \dots, g_m^{-1}/s_m\}.$$

Yang: The domain $X(\underline{f/r}; \underline{g/s}^{-1})$ is represented by $A\{\underline{f/r}; \underline{g/s}^{-1}\}$.

Construction 3.2.4. Let $f = (f_1, \dots, f_n), g$ be elements in A such that the ideal generated by them is the whole algebra A . Set $p = (p_1, \dots, p_n)$ be a tuple of positive real numbers. We define the following closed subset of X :

$$X(\underline{f/p}, g) := \{x \in X : |f_i(x)| \leq p_i |g(x)|, 1 \leq i \leq n\}.$$

Such a closed subset is called a *rational domain* of X . Moreover, we can define a \mathbf{k} -affinoid algebra

$$A\langle \underline{f/p}, g^{-1} \rangle := A\left\langle \frac{f_1}{p_1 g}, \dots, \frac{f_n}{p_n g} \right\rangle,$$

which is the quotient of the Tate algebra

$$A\langle T_1, \dots, T_n \rangle$$

by the ideal generated by the elements $p_i g T_i - f_i$ for $1 \leq i \leq n$. There is a natural bounded homomorphism $\varphi : A \rightarrow A\langle \underline{f/p}, g^{-1} \rangle$ induced by the inclusion. It can be shown that the closed subset $X(\underline{f/p}, g)$ is an affinoid domain represented by the affinoid algebra $A\langle \underline{f/p}, g^{-1} \rangle$. **Yang: To be checked**

Yang: We have a sequence of inclusion:

$$\{\text{Weierstrass domains}\} \subseteq \{\text{Laurent domains}\} \subseteq \{\text{Rational domains}\} \subseteq \{\text{Affinoid domains}\}.$$

Proposition 3.2.5. Let A be a \mathbf{k} -affinoid algebra, and let $X = \mathcal{M}(A)$ be the associated affinoid space. Let $V \subseteq X$ be an affinoid domain represented by the \mathbf{k} -affinoid algebra A_V . Then the natural bounded homomorphism $\varphi : A \rightarrow A_V$ is flat.

We have $\mathcal{M}(A_V) \cong V$.

3.2.2 The Grothendieck topology of affinoid domains

3.3

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Chapter 4

Analytic spaces

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