On ramification filtrations and $p$-adic differential modules I: the equal characteristic case

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Let $k$ be a complete discretely valued field of equal characteristic $p > 0$ with possibly imperfect residue field, and let $G_k$ be its Galois group. We prove that the conductors computed by the arithmetic ramification filtrations on $G_k$ defined by Abbes and Saito (Amer. J. Math 124:5, 879–920) coincide with the differential Artin conductors and Swan conductors of Galois representations of $G_k$ defined by Kedlaya (Algebra Number Theory 1:3, 269–300). As a consequence, we obtain a Hasse–Arf theorem for arithmetic ramification filtrations in this case. As applications, we obtain a Hasse–Arf theorem for finite flat group schemes; we also give a comparison theorem between the differential Artin conductors and Borger’s conductors (Math. Ann. 329:1, 1–30).

Introduction

Let $k$ be a complete discretely valued field and let $G_k$ be the Galois group of a fixed separable closure $k^{sep}$ over $k$. When the residue field $\kappa_k$ of $k$ is perfect, classical ramification theory gives Artin conductors and Swan conductors, which measure the ramification of representations of $G_k$ of finite local monodromy (i.e., the image of the inertia group being finite). A fundamental result, the Hasse–Arf theorem, states that Artin and Swan conductors are nonnegative integers. However, when the residue field $\kappa_k$ is not perfect, classical ramification theory is no longer applicable.

Keywords: ramification, $p$-adic differential equation, Swan conductors, Artin conductors, Hasse–Arf theorem.
For one thing, the transition functions \( \phi \) and \( \psi \) in [Serre 1979, §IV.3] fail the basic properties; for another, the extension of the rings of integers may not be generated by a single element (compare [Serre 1979, §III.6, Proposition 12]).

Kato [1989] defined Swan conductors for one-dimensional representations when the residue field is not perfect. Later, Abbes and Saito [2002; 2003] defined an arithmetic (nonlogarithmic) filtration and a logarithmic variant on \( G_k \) by counting geometric connected components of certain rigid spaces \( as_{l/k}^a \) and \( as_{l/k, \log}^a \) over \( k \), which we refer to as Abbes–Saito spaces. The filtrations give the arithmetic Artin conductors and Swan conductors naturally.

Abbes and Saito [2009] showed that their definition of Swan conductors coincides with Kato’s when \( k \) is of equal characteristic \( p > 0 \). Moreover, they proved that the subquotients of both filtrations are abelian groups [Abbes and Saito 2003]. (See also Saito’s proof [2009] that the subquotients of the logarithmic filtration on wild inertia are elementary abelian \( p \)-groups.) However, they were not able to establish an integrality result analogous to the classical Hasse–Arf theorem.

Through a completely different path, when \( k \) is of equal characteristic \( p > 0 \) and has perfect residue field, Christol, Cook, Matsuda, Mebkhout, and Tsuzuki (see [Matsuda 2002]) gave a completely new interpretation of the classical Swan conductors using the theory of \( p \)-adic differential modules. Given a \( p \)-adic Galois representation of finite local monodromy, they associated a \( p \)-adic differential module over the Robba ring and proved that the Swan conductor of the representation can be retrieved from the irregularity of the differential module, or equivalently, the spectral norms of the differential operator.

Partly inspired by [Matsuda 2004], Kedlaya generalized this framework to the case when the residue field \( \kappa_k \) is not perfect. In [Kedlaya 2007], he adopted the same construction and counted in the effects of other differential operators corresponding to elements in a \( p \)-basis of \( \kappa_k \). He defined the differential Swan conductor to be, vaguely speaking, the maximum of the numbers computed by each of the differential operators, under certain normalization; he was aware of a definition for differential Artin conductors using a slightly different normalization. Most importantly, he was able to prove a Hasse–Arf theorem for differential Swan conductors [Kedlaya 2007, Theorem 3.5.8]; his argument can easily be adapted to prove a Hasse–Arf theorem for differential Artin conductors. For a precise statement, see Theorem 2.4.1.

Kedlaya [2007] asked, as Matsuda suggested, whether the differential conductors are the same as the arithmetic ones, in which case the Hasse–Arf theorem for the arithmetic filtrations in the equal characteristic case would follow from that for the differential conductors. Chiarellotto and Pulita [2009] gave an affirmative answer to this question when the representations are one-dimensional, using the setting of Kato’s conductors [Kato 1989].
There is a third story of defining conductors. Borger [2004] introduced the notation of generic perfection of a complete discretely valued field and defined the Artin conductors to be the ones obtained by base change to the generic residual perfection of $k$, which is a complete discretely valued field with perfect residue field satisfying certain universal properties. The Hasse–Arf theorem of these conductors will follow immediately from that of the classical ones. Kedlaya [2007, p. 297] asked if this also coincides with the two definitions above.

This paper answers these questions in the affirmative for all representations of finite local monodromy. Our precise result is the following.

**Theorem.** Let $k$ be a complete discretely valued field of equal characteristic $p > 0$ and let $G_k$ be its absolute Galois group.

1. (Hasse–Arf Theorem) Let $\rho : G_k \to \text{GL}(V_\rho)$ be a $p$-adic representation of finite local monodromy. Then the arithmetic Artin conductor $\text{Art}_{\text{ar}}(\rho)$, the differential Artin conductor $\text{Art}_{\text{dif}}(\rho)$, and the Borger’s conductor $\text{Art}_{B}(\rho)$ are the same. Similarly, the arithmetic Swan conductor $\text{Swan}_{\text{ar}}(\rho)$ is the same as the differential Swan conductor $\text{Swan}_{\text{dif}}(\rho)$. As a consequence, they are all nonnegative integers.

2. The subquotients $\text{Fil}^a G_k / \text{Fil}^{a+} G_k$ of the arithmetic ramification filtrations are trivial if $a \notin \mathbb{Q}$ and are elementary $p$-abelian groups if $a \in \mathbb{Q}_{>1}$; the subquotients $\text{Fil}^{a}_{\text{log}} G_k / \text{Fil}^{a+}_{\text{log}} G_k$ of the arithmetic logarithmic ramification filtrations are trivial if $a \notin \mathbb{Q}$ and are elementary $p$-abelian groups if $a \in \mathbb{Q}_{>0}$.

This theorem consists of Theorems 4.4.1 and 5.4.3 and Corollary 4.4.3.

We now explain the main idea of the proof, which shows that arithmetic conductors and differential conductors coincide in a natural way. (We will use the comparison of Artin conductors as an example; that of Swan conductors is proved similarly.)

Let $k$ be a complete discretely valued field of equal characteristic $p$, with residue field $\kappa_k$. Let $l$ be a finite Galois extension of $k$ with residue field $\kappa_l$. One immediately reduces the comparison to proving that the arithmetic highest ramification break of $l/k$ is the same as the differential one. There are three main ingredients.

(a) A useful way of visualizing spectral norms is to consider the convergence loci or radii at a generic point; see for example [Kedlaya 2005, §5]. However, the convergence loci cannot be defined on the rigid annulus because one cannot separate $m+1$ differential operators on a one-dimensional space. Matsuda [2004] made a pioneering attempt to obtain an $(m+1)$-dimensional space on which we may discuss convergence loci. Our approach, which is independently developed and looks very similar to Matsuda’s work, uses a thickening technique. (Alas, we do not know how to relate the two methods.) If the field $k$ can be realized as
the field of rational functions on a smooth variety over certain perfect field, the thickening space is just a subspace of the generic fiber of the tube corresponding to the diagonal embedding in a formal lifting (see Section 3.1). This thickening space, after a certain base change, “looks the same” as the Abbes–Saito space $\text{as}_{l/k}^a$, whose geometric connected components give the ramification information. However, we have the following technical issue.

(b) The thickening space is a rigid space over $K$, the fraction field of a Cohen ring of $\kappa_k$, which in particular is a field of characteristic zero. In contrast, the Abbes–Saito space $\text{as}_{l/k}^a$ is a rigid space over $k$, which is of characteristic $p$. In order to relate the two spaces, we need a lifting technique (see Section 1) to lift the Abbes–Saito space to characteristic zero and compare the geometric connected components before and after the lifting process. A similar idea is also alluded to as a conjecture in [Matsuda 2004]. (Again, we do not know whether our result answers Matsuda’s conjecture.)

(c) The lifted Abbes–Saito space is isomorphic to the thickening space after a certain base change (Theorem 4.3.6), but not in the naïve way. Very vaguely speaking, if the extension $l/k$ is generated by a series of equations, then the Abbes–Saito space consists of the points which are close to the solutions to those equations; in contrast, the (base change of the) thickening space consists of points which are solutions to some equations whose coefficients are close to the original equations. These two types of points coincide when $l/k$ is totally and wildly ramified.

Combining these three ingredients, we can prove the comparison between the arithmetic conductors and the differential ones. The following diagram may be helpful to illustrate the process:

\[
\begin{array}{c}
Y = A^1_K[\eta_0, 1] \quad \text{TS}^a \times \tilde{\pi}, Z \quad Y \quad \text{AS}^a_{l/k} \quad \text{as}_{l/k}^a \\
\downarrow \quad \downarrow \quad \downarrow \quad \downarrow \quad \downarrow \\
Z = A^1_K[\eta_0, 1] \quad \tilde{\pi} \quad \text{TS}^a = \left( \bigcup_{\eta \in [\eta_0, 1]} A^1_K[\eta, 1] \times A^{m+1}_K[0, \eta^a] \right).
\end{array}
\]

Here $K$ and $L$ are the fraction fields of Cohen rings of $\kappa_k$ and $\kappa_l$, respectively; $A^1_K[\eta_0, 1]$ is the half-open annulus over $K$ (centered at the origin) with inner radius $\eta_0$ and outer radius 1, for some $\eta_0 \in (0, 1)$; $A^{m+1}_K[0, \eta^a]$ is the open polydisc (centered at the origin) of dimension $m+1$ and radius $\eta^a$ for some $a \in \mathbb{Q}_{>1}$ (for the quotation marks on $\bigcup_{\eta \in [\eta_0, 1]} A^1_K[\eta, 1] \times A^{m+1}_K[0, \eta^a]$), see Caution 3.2.4); $\text{TS}^a$ denotes the space obtained by the thickening process (a); $\text{as}_{l/k}^a$ is the rigid analytic space over $k$ defined by Abbes and Saito with respect to a set of distinguished generators; and $\text{AS}^a_{l/k}$ is the lifting space given by lifting process (b); the argument in (c) links the two spaces as shown in the diagram.
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Part (a) is carried out throughout Section 3 (see Theorem 3.4.12). Part (b) is developed in Section 1 (see Corollary 1.2.12 and Example 1.3.4). Part (c) occupies Section 4 (see Theorem 4.3.6). We finally wrap up the proof in Theorem 4.4.1.

We also obtain a comparison theorem between Borger’s Artin conductors and the differential Artin conductors, or equivalently the arithmetic Artin conductors. The key is to show that the differential Artin conductors are invariant under the operation of adding generic $p^\infty$-th roots (see Definition 5.2.2). This fact follows easily from the study of differential operators.

**Plan of the paper.** In Section 1, we make a construction to lift a rigid space over $k$ to a rigid space over an annulus over $K$. We prove that the connected components of the original rigid space are in one-to-one correspondence with the connected components of the lifting space, when the annulus is “thin” enough. This part is written in a relatively independent and self-contained manner, since we feel that it is interesting on its own.

In Section 2, we discuss how to associate a differential module $\mathcal{E}_\rho$ on the Robba ring over $K$ with a representation $\rho$ of $G_k$ of finite local monodromy. Then we review the definition of differential Swan conductors following [Kedlaya 2007]. We also introduce differential Artin conductors and discuss their properties.

Section 3 introduces a thickening construction. In Section 3.1, as an intuitive example, we construct the thickening space when $k$ can be realized geometrically. In Section 3.2, we define thickening spaces for general $k$ and discuss spectral properties of the differential module obtained by pulling back $\mathcal{E}_\rho$ to the thickening spaces. In Sections 3.3 and 3.4, we link the (highest) differential breaks and spectral norms with the connected components of a certain base change of the thickening spaces.

In Section 4, we first quickly review the definition of arithmetic ramification filtrations, following [Abbes and Saito 2002]. Then, in Section 4.2, we define the standard Abbes–Saito spaces $aS^a_{l/k}$ and their lifts $AS^a_{l/k}$. Next, we prove in Section 4.3 that the lifted Abbes–Saito spaces and (the base change of) the thickening spaces are isomorphic (Theorem 4.3.6). From this, in Section 4.4, we deduce our main result, Theorem 4.4.1: differential conductors coincide with arithmetic conductors.

Section 5 gives two applications. In Section 5.1 we deduce a Hasse–Arf theorem for finite flat group schemes; in Sections 5.2–5.4 we compare the arithmetic and differential Artin conductors with Borger’s Artin conductors [Borger 2004].

1. **Lifting rigid spaces**

In this section, which is largely self-contained, we introduce a construction to lift a rigid space over a field of characteristic $p > 0$ to a rigid space over an annulus over a field of characteristic zero. The notation will not be carried over to later
sections unless explicitly noted.\footnote{Most of the proofs in this section should be credited to Kedlaya, to whom I am thankful for allowing their inclusion.}

**Remark 1.0.1.** For most of this paper, we implicitly use rigid analytic spaces in the sense of Berkovich spaces [1990] by allowing discs or annuli with irrational radii. This is mostly for notational convenience. Only in two places (see Remarks 1.2.13 and 4.2.5) will we have to shift back to the classical rigid analytic setting to talk about connected components by assuming some rationality on the radii of discs or annuli.

1.1. A Gröbner basis argument. In this subsection, we introduce a division algorithm using a Gröbner basis, which enables us to find a representative in the quotient ring achieving the quotient norm.

**Notation 1.1.1.** Let $K$ be a complete discretely valued field of mixed characteristic $(0, p)$, with ring of integers $\mathcal{O}_K$ and residue field $\kappa$. Fix a uniformizer $\pi_K$ and normalize the valuation $v_K(\cdot)$ on $K$ so that $v_K(\pi_K) = 1$. We also normalize the norm on $K$ so that $|p| = p^{-1}$.

**Notation 1.1.2.** For a nonarchimedean ring $R$, we use $R\langle u_1, \ldots, u_n \rangle$ to denote the Tate algebra, consisting of formal power series $\sum_{i_1, \ldots, i_n \in \mathbb{Z}_{\geq 0}} f_{i_1, \ldots, i_n} u_1^{i_1} \cdots u_n^{i_n}$ with $f_{i_1, \ldots, i_n} \in R$ and $|f_{i_1, \ldots, i_n}| \rightarrow 0$ as $i_1 + \cdots + i_n \rightarrow +\infty$. For $\eta_1, \ldots, \eta_n \in (0, 1]$, the ring admits a $(\eta_1, \ldots, \eta_n)$-Gauss norm given by

$$\left| \sum_{i_1, \ldots, i_n \in \mathbb{Z}_{\geq 0}} f_{i_1, \ldots, i_n} u_1^{i_1} \cdots u_n^{i_n} \right|_{\eta_1, \ldots, \eta_n} = \max \{ |f_{i_1, \ldots, i_n}| \eta_1^{i_1} \cdots \eta_n^{i_n} \}.$$

**Notation 1.1.3.** Fix a positive integer $n$, and put

$$R^{\text{int}} = \mathcal{O}_K\langle u_1, \ldots, u_n \rangle((S)), \quad R = R^{\text{int}} \otimes_{\mathcal{O}_K} K,$$  

$$R_\kappa = R^{\text{int}} \otimes_{\mathcal{O}_K} \kappa \cong \kappa[u_1, \ldots, u_n](S) = \kappa((S))(u_1, \ldots, u_n).$$

For $\eta \in (0, 1]$, let $|\cdot|_{\eta}$ (for short) denote the $(1, \ldots, 1, \eta)$-Gauss norm on $R$.

**Notation 1.1.4.** The *lexicographic order* on $\mathbb{Z}^n$ is: for $(i_1, \ldots, i_n)$ and $(i'_1, \ldots, i'_n)$ both in $\mathbb{Z}^n$, we have $(i_1, \ldots, i_n) > (i'_1, \ldots, i'_n)$ if there exists some $j \in \{1, \ldots, n\}$ such that $i_1 = i'_1, \ldots, i_{j-1} = i'_{j-1}$ and $i_j > i'_j$.

**Definition 1.1.5.** We equip $R_\kappa$ with the lexicographic term ordering induced by the correspondence $u_1^{i_1} \cdots u_n^{i_n} S^j \mapsto (j, i_1, \ldots, i_n)$, i.e., we write $\tilde{\alpha} u_1^{i_1} \cdots u_n^{i_n} S^j \geq \tilde{\beta} u_1^{i'_1} \cdots u_n^{i'_n} S^{j'}$ if $(-j, i_1, \ldots, i_n) \geq (-j', i'_1, \ldots, i'_n)$ under the lexicographic order, where $\tilde{\alpha}, \tilde{\beta} \in \kappa^\times$.

Using this ordering, we define the *leading term* $\text{lead}(\tilde{f})$ of a nonzero element $\tilde{f} \in R_\kappa$ to be its largest term under the ordering. In particular, for $\tilde{f}, \tilde{g} \in R_\kappa \setminus \{0\}$, $\text{lead}(\tilde{f} \tilde{g}) = \text{lead}(\tilde{f}) \text{lead}(\tilde{g})$. 
For an ideal \( I_\kappa \) of \( R_\kappa \), a Gröbner basis of \( I_\kappa \) is a finite subset \( \{ \bar{r}_1, \ldots, \bar{r}_m \} \subset I_\kappa \) such that no leading term of an \( r_j \) has exponents in \( S \) and such that the ideal consisting of the leading terms of all elements of \( I_\kappa \) is generated by \( \text{lead}(\bar{r}_1), \ldots, \text{lead}(\bar{r}_m) \). Such a basis exists because \( R_\kappa \) is Noetherian. By [Eisenbud 1995, Lemma 15.5], \( \bar{r}_1, \ldots, \bar{r}_m \) also generate \( I_\kappa \).

**Proposition 1.1.6.** For any \( \bar{f} \in R_\kappa \), there exists \( \bar{g}_1, \ldots, \bar{g}_m, \bar{f}' \in R_\kappa \) such that

\[
\bar{f} = \bar{g}_1 \bar{r}_1 + \cdots + \bar{g}_m \bar{r}_m + \bar{f}',
\]

(1.1.7)

where any term of \( \bar{f}' \) is not divisible by any \( \text{lead}(\bar{r}_h) \), and \( \text{lead}(\bar{f}) \geq \text{lead}(\bar{g}_h \bar{r}_h) \) for all \( h \).

**Proof.** Let \( j \) be the exponent of \( S \) in \( \text{lead}(\bar{f}) \) and let \( S^j \bar{f}_{(j)} \) be the sum of terms in \( \bar{f} \) for which the exponents of \( S \) are \( j \). Applying [Eisenbud 1995, Proposition-Definition 15.6] to \( \bar{f}_{(j)} \), we can write

\[
\bar{f}_{(j)} \equiv \tilde{g}_{1,(j)} \bar{r}_1 + \cdots + \tilde{g}_{m,(j)} \bar{r}_m + \bar{f}'_{(j)} \pmod{S \cdot \kappa[u_1, \ldots, u_m][S]}.
\]

where \( \tilde{g}_{h,(j)} \in \kappa[u_1, \ldots, u_m] \) and \( \text{lead}(\tilde{g}_{h,(j)} \bar{r}_h) \leq \text{lead}(\bar{f}_{(j)}) \) for \( h = 1, \ldots, m \) and any term in \( \bar{f}'_{(j)} \in \kappa[u_1, \ldots, u_m] \) is not divisible by any lead(\( \bar{r}_h \)).

If we repeat the above argument for \( \bar{f}_{(j)} - S^j (\tilde{g}_{1,(j)} \bar{r}_1 + \cdots + \tilde{g}_{m,(j)} \bar{r}_m + \bar{f}'_{(j)}) \in S^{j+1} \cdot \kappa[u_1, \ldots, u_m][S] \) in place of \( \bar{f} \), we will obtain \( \bar{f}'_{(j')} \) and \( \tilde{g}_{h,(j')} \) for \( h = 1, \ldots, m \) and for some \( j' \geq j + 1 \). We can then iterate this process.

For \( h = 1, \ldots, m \), put \( \bar{g}_h = S^j \tilde{g}_{h,(j)} + S^{j+1} \tilde{g}_{h,(j+1)} + \cdots \) and \( \bar{f}' = S^j \bar{f}'_{(j)} + S^{j+1} \bar{f}'_{(j+1)} + \cdots \); the power series converge to the elements in \( R_\kappa \) we seek. \( \square \)

**Definition 1.1.8.** For \( f \in R \), write

\[
f = \sum_{i_1, \ldots, i_n} f_{i_1, \ldots, i_n} u_1^{i_1} \cdots u_n^{i_n} S^j.
\]

(1.1.9)

Of the monomials for which \( |f_{i_1, \ldots, i_n}| = |f|_1 \), there must be one which is lexicographically largest; we call the corresponding term \( f_{i_1, \ldots, i_n} u_1^{i_1} \cdots u_n^{i_n} S^j \) the 1-leading term of \( f \), denoted by \( \text{Lead}(f) \).

**Hypothesis 1.1.10.** Let \( I^{\text{int}} \) be an ideal of \( R^{\text{int}} \) such that \( R^{\text{int}}/I^{\text{int}} \) is flat over \( \sigma_\kappa \).

**Notation 1.1.11.** Define \( I = I^{\text{int}} \otimes_{\sigma_\kappa} K \) and \( I_\kappa = I^{\text{int}} \otimes_{\sigma_\kappa} \kappa \); the latter is an ideal in \( R_\kappa \) by the flatness hypothesis above. Choose \( r_1, \ldots, r_m \in I^{\text{int}} \) which project to elements of a Gröbner basis \( \bar{r}_1, \ldots, \bar{r}_m \) of \( I_\kappa \).

For \( f \in R \), let \( j_f \) denote the minimal exponents of \( S \) in the expression (1.1.9) of \( f \). Set \( j_1 = \min\{ j_{r_h}; h = 1, \ldots, m \} \); it is a nonpositive integer.

**Notation 1.1.12.** In this subsection, fix \( \eta_0 \in (|\pi_\kappa|^{-1/j_1}, 1) \). We have \( |\pi_\kappa|^{j_1} \eta_0 < 1 \).
Notation 1.1.13. Let \( \mathcal{R} \) be the Fréchet completion of \( R \) for \( \| \cdot \|_\eta \) for \( \eta \in [\eta_0, 1) \). Let \( R^{\text{int}}_\eta \) denote \( \{ f \in \mathcal{R} : \| f \|_1 \leq 1 \} \) and put \( R_{\eta} = R_{\eta_0}^{\text{int}} \otimes_k \mathcal{K} \) and \( I_\eta = I \otimes_R R_{\eta_0}^{\text{int}} \).

Notation 1.1.14. For an element \( f \in \mathcal{R}_\eta \) written as in (1.1.9) and \( l \in \mathbb{Z} \), let \( \pi_l f(l) \) be the sum of all terms \( f_{i_1, \ldots, i_n} u_1^{i_1} \cdots u_n^{i_n} S_j \) for which \( v_K(f_{i_1, \ldots, i_n}) = l \). Thus, \( f(l) \in R^{\text{int}} \); we use \( \tilde{f}_l(l) \) denote its reduction in \( R_k \).

Lemma 1.1.15. For \( h = 1, \ldots, m \) and \( \eta \in [\eta_0, 1) \),
\[
| r_h \eta | = 1, \quad | r_{h,l(l)} \eta | \leq \eta^{j_l} \quad \text{for } l \in \mathbb{Z}_{\geq 0}.
\]

Proof. The equality follows from the choice of \( \eta_0 \) in Notation 1.1.12. The rest follows from the definition of \( j_l \) in Notation 1.1.11.

Construction 1.1.16. For \( f \in \mathcal{R}_\eta \) with \( \| f \|_1 = \| \pi_K \|_l \), the division algorithm is the following procedure. Put \( f_{l_0} = f \). Given \( f_l \) for \( l \geq l_0 \), we apply Proposition 1.1.6 to write
\[
\tilde{f}_{l(l)} = \tilde{g}_{l_1} + \cdots + \tilde{g}_{l,m} + \tilde{f}_{l(l)},
\]
where \( \tilde{g}_{l_1,h} \in R_k \) and \( \text{lead}(\tilde{g}_{l_1,h} \tilde{r}_h) \leq \text{lead}(\tilde{f}_{l(l)}) \) for \( h = 1, \ldots, m \) and any term of \( \tilde{f}_{l(l)} \in R_k \) is not divisible by any lead \( \tilde{r}_h \). For each \( h \), pick lifts \( g_{l,h} \) of \( \tilde{g}_{l,h} \) in \( R^{\text{int}} \) so that \( g_{l,h} = g_{l,h}(0) \), that is, we only lift nonzero terms. Put
\[
f_{l+1} = f_l - \pi_{K}^{j_l}(g_{l_1,1} r_1 + \cdots + g_{l,m} r_m).
\]

Remark 1.1.17. The division algorithm depends on many choices, but we prove in Proposition 1.1.21 that the outcome \( \lim_{l \to +\infty} f_l \) is uniquely determined by \( f \).

Lemma 1.1.18. At each step of the division algorithm, for \( h \in [\eta_0, 1) \), \( h = 1, \ldots, m \), we have
\[
| g_{l,h} \eta | \leq | f_{l,h} \eta |, \quad | f_{l+1,h} \eta - f_{l,h} \eta | \leq | f_{l,h} \eta | \begin{cases} \leq \eta^{j_l} | f_{l,l(l)} \eta | & \text{if } l' > l, \\ \leq | f_{l, l(l)} \eta | & \text{if } l' = l, \\ = 0 & \text{if } l' < l. \end{cases}
\]

Proof. The inequality on the left holds because \( \text{lead}(\tilde{g}_{l,h} \tilde{r}_h) \leq \text{lead}(\tilde{f}_{l,(l)}) \). The rest follows using Lemma 1.1.15.

Corollary 1.1.20. For \( h = 1, \ldots, m \), the series \( g_h = \pi_K^{l_0} g_{l_0,h} + \pi_K^{l_0+1} g_{l_0+1,h} + \cdots \) converges under \( \| \cdot \|_\eta \) for \( \eta \in [\eta_0, 1) \). Consequently, \( g_h \in \mathcal{R}_\eta \) for \( h = 1, \ldots, m \).

Proof. By Lemma 1.1.18,
\[
| \pi_K^{l_0} g_{l,h} \eta | \leq | \pi_K^{l_0} f_{l,h} \eta | \leq | \pi_K^{l_0} | \max \{ \eta^{j_l} | f_{l-1,l-l} \eta |, | f_{l-1,l(l)} \eta | \}
\]
\[
\leq | \pi_K^{l_0} | \max \{ \eta^{2j_l} | f_{l-2,l-2} \eta |, \eta^{j_l} | f_{l-2,l-l} \eta |, \eta^{j_l} | f_{l-2,l-2} \eta |, | f_{l-2,l(l)} \eta | \}
\]
\[
\leq \cdots
\]
\[
\leq | \pi_K^{l_0} | \max \{ (\eta^{l-l'}) j_l | f_{l(l)} \eta | \} \leq \max \{ (\pi_K^{l_0} j_l | f_{l(l)} \eta | \}.
\]
This goes to zero as \( l \to +\infty \).
Proposition 1.1.21. Keep the notation as above. The quantity \( f - g_1 r_1 - \ldots - g_m r_m \) is the unique element of \( f + I_{\eta_0} \) for which none of its terms is divisible by any \( \text{Lead}(r_h) \).

Proof. It follows from the definition of \( g_1, \ldots, g_m \) that no term of \( f - \sum_{i=1}^{m} g_i r_i \) is divisible by any \( \text{Lead}(r_h) \).

Assume that \( f \in R_{\eta_0} \) does not contain any term divisible by any of \( \text{Lead}(r_h) \), then we need to show that for any nonzero \( g \in I_{\eta_0} \), there is a term in \( f + g \) divisible by some \( \text{Lead}(r_h) \). Assume the contrary. Let \( n = \log_{|\pi_K|} |g|_1 \). Then \( \bar{g}(n) \in I_k \) does not contain any term which divides any of \( \text{lead}(\bar{r}_h) \). This forces \( \bar{g}(n) = 0 \) because the leading term of any nonzero element in \( I_k \) is divisible by some \( \text{lead}(\bar{r}_h) \). This is a contradiction. The lemma follows.

Lemma 1.1.22. For \( \eta \in [\eta_0, 1] \), \( |f - \sum_{i=1}^{m} g_i r_i|_{\eta} \) equals the minimum \( \eta \)-norm of any element of \( f + I_{\eta_0} \). Moreover, this continues to hold if we pass from \( R_{\eta_0} \) to its completion \( R_{\eta_0}^{\wedge, \eta} \) under \( |\cdot|_{\eta} \).

Proof. For \( \eta \in [\eta_0, 1] \), by Lemma 1.1.18, \( |f_{i+1}|_{\eta} \leq |f_i|_{\eta} \), so \( |f - \sum_{i=1}^{m} g_i r_i|_{\eta} \leq |f|_{\eta} \). By Proposition 1.1.21, starting with any element in \( f + I_{\eta_0} \), the division algorithm will eventually lead to a unique element \( f - \sum_{i=1}^{m} g_i r_i \); hence the first statement follows.

The second statement follows from the fact that any element in \( f + I_{\eta_0} R_{\eta_0}^{\wedge, \eta} \) is a limit of elements in \( f + I_{\eta_0} \).

Proposition 1.1.23. Let \( f \) be a rigid analytic function on the space \( X_{\eta_0} = \{(u_1, \ldots, u_n, S) \in A_K^{n+1} \mid \eta_0 \leq |S| < 1; |u_1|, \ldots, |u_n| \leq 1; r_1, \ldots, r_m = 0\} \).

Then the following are equivalent:

(a) \( f \) is induced by an element of \( R_{\eta_0}^{\text{int}} \).

(b) There exists a function \( r : [\eta_0, 1) \rightarrow \mathbb{R} \) with \( \lim_{\eta \rightarrow 1^-} r(\eta) \leq 1 \), such that for each \( \eta \in [\eta_0, 1) \), \( f \) lifts to an element of the \( |\cdot|_{\eta} \)-completion of \( R_{\eta_0} \) having \( \eta \)-norm less than or equal to \( r(\eta) \).

Proof. It is clear that (a) implies (b), so assume (b). We can write \( f \) as a Fréchet limit of the projections of some sequence of elements \( f_1, f_2, \ldots \) of \( R \), under the quotient norms associated with \( |\cdot|_{\eta} \) for \( \eta \in [\eta_0, 1) \). Use the division algorithm to write \( f_i = g_{i,1} r_1 + \cdots + g_{i,m} r_m + h_i \) with \( g_{i,1}, \ldots, g_{i,m}, h_i \in R_{\eta_0} \). Moreover, as \( f_i - f_{i+1} \) tends to zero under the Fréchet topology, so does \( h_i - h_{i+1} \) since it can be obtained from the division algorithm of \( f_i - f_{i+1} \) and Lemma 1.1.18 ensures that \( |f_i - f_{i+1}|_{\eta} \geq |h_i - h_{i+1}|_{\eta} \). Hence, the \( h_i \) form a Fréchet convergent sequence; denote the limit by \( h \), which is a lift of \( f \). Note that for a fixed \( \eta \), \( |h|_{\eta} \) equals the \( \eta \)-quotient norm of \( f_i \), which in turn equals the \( \eta \)-quotient norm of \( f \) when \( l \) is large enough. Thus, \( |h|_{\eta} \leq r(\eta) \) for all \( \eta \in [\eta_0, 1) \). Hence it lies in \( R_{\eta_0}^{\text{int}} \).
Notation 1.1.24. Define
\[ A^{\text{int}} = R^{\text{int}}/I^{\text{int}}, \quad A = R/I, \quad A_{\eta_0} = R_{\eta_0}/I_{\eta_0}, \quad A_\kappa = A^{\text{int}} \otimes_{\kappa} \kappa \cong R_{\kappa}/I_{\kappa}. \]

We may view \( A_\kappa \) as an affinoid algebra over \( \kappa((S)) \), whose corresponding rigid analytic space is denoted by \( X \).

1.2. Quotient norms versus spectral norms. In this subsection, we compare spectral norms with the quotient norms discussed in previous section. As an application, we deduce that the connected components of \( X_{\eta_0} \) when \( \eta_0 \to 1^- \) as a rigid space over \( K \) are the same as the connected components of \( X \) as a rigid space over \( \kappa((S)) \).

Hypothesis 1.2.1. In this subsection, we assume that \( A_\kappa \) is reduced.

Notation 1.2.2. Let \( | \cdot |_{\kappa, \text{quot}} \) denote the quotient norm on \( A_\kappa \) induced by the Gauss norm on \( R_\kappa \). Let \( | \cdot |_{\kappa, \text{sp}} = \lim_{n \to +\infty} | \cdot |_{\kappa, \text{quot}}^{1/n} \) be the spectral norm; it is a norm because \( A_\kappa \) is reduced. By [Bosch et al. 1984, Theorem 6.2.4/1], there exists \( c > 0 \) such that \( | \cdot |_{\kappa, \text{sp}} \leq | \cdot |_{\kappa, \text{quot}} \leq | S |_{\kappa}^{-c} | \cdot |_{\kappa, \text{sp}}, \) where \( | S |_{\kappa} \) is the norm of \( S \) in \( \kappa((S)) \).

Notation 1.2.3. In this subsection, we fix \( \eta_0 \) in the interval \( (|\pi_\kappa|^{1/-j+p_{c}}, 1) \). In particular, \( |\pi_\kappa|_{\eta_0}^{-j} < \eta_0^{p_{c}} \) and \( \eta_0 > p^{-1/p_{c}} \).

Notation 1.2.4. For \( \eta \in [\eta_0, 1) \), let \( | \cdot |_{\eta, \text{quot}} \) denote the quotient norm on \( A_{\eta_0} \) or \( A \) induced by the \( \eta \)-Gauss norm on \( R_{\eta_0} \) or \( R \). Similarly, we have the \( \eta \)-spectral seminorm \( | \cdot |_{\eta, \text{sp}} = \lim_{n \to +\infty} | \cdot |_{\eta, \text{quot}}^{1/n} \); we will see in Lemma 1.2.6 that it is a norm.

Proposition 1.2.5. The quotient norm \( | \cdot |_{\eta, \text{quot}} \) on \( A \) is the same as the spectral (semi)norm \( | \cdot |_{\eta, \text{sp}} \). As a consequence, the map \( A^{\text{int}} \to A_\kappa \) induces an isomorphism \( A^{\circ}/A^{\circ 0} \cong A_\kappa \), where \( A^{\circ} = \{ f \in A \mid |f|_{1, \text{sp}} \leq 1 \} \) and \( A^{\circ 0} = \{ f \in A \mid |f|_{1, \text{sp}} < 1 \} \).

Proof. Since \( A^{\text{int}}/m_{\kappa} A^{\text{int}} = A_\kappa \) is reduced, by [Bosch et al. 1984, 6.2.1/4(iii)], the quotient norm on \( A \) is equal to the spectral seminorm, \( A^0 = A^{\text{int}}, \) and \( A^{\circ 0} = m_{\kappa} A^{\text{int}} \).

This proves the claim. \( \square \)

Lemma 1.2.6. For \( \eta \in [\eta_0, 1) \), we have \( | \cdot |_{\eta, \text{sp}} \leq | \cdot |_{\eta, \text{quot}} \leq \eta^{-pc/(p-1)} | \cdot |_{\eta, \text{sp}} \) on \( A_{\eta_0} \). The same is true when extending both norms to the completion of \( A_{\eta_0} \) with respect to \( | \cdot |_{\eta, \text{quot}} \) (which is the same as the completion with respect to the spectral norm). In particular, this shows that \( | \cdot |_{\eta, \text{sp}} \) is a norm on \( A_{\eta_0} \).

Proof. It suffices to show that for any \( f \in A_{\eta_0} \), \( |f^p|_{\eta, \text{quot}} \geq \eta^{pc} |f|_{\eta, \text{quot}}^p \); then it would follow that \( |f^{pn}|_{\eta, \text{quot}} \geq \eta^{pc/(p-1)} |f|_{\eta, \text{quot}}^n \) for all \( n \in \mathbb{N} \) by iteration, and hence the statement follows by taking the limit.

Pick a representative \( \tilde{f} \) of \( f \) in \( R_{\eta_0} \) containing no terms divisible by any \( \text{Lead}(r_h) \) (hence by Proposition 1.1.21, \( |\tilde{f}|_\eta = |f|_{\eta, \text{quot}} \)). Fixing \( \eta \in [\eta_0, 1) \), we will show that
\[
|\tilde{f}|_{\eta, \text{quot}} = \left( \sum_l \left( \frac{\tau_{K, i}^{l} f(|l|)}{\eta, \text{quot}} \right)^p \right)^\frac{1}{p} \geq \eta^{pc} |\tilde{f}|^p_\eta = \eta^{pc} |f|^p_{\eta, \text{quot}}. \tag{1.2.7}
\]
First, we remark that, given the middle inequality, the former equality follows; this is because \( \tilde{f}^p - \sum_l (\pi_l^p \tilde{f}_l)^p \) consists of products of \( \pi_l^p \tilde{f}_l \) with an extra factor \( p \) from the multinomial coefficients. Then
\[
|\tilde{f}^p - \sum_l (\pi_l^p \tilde{f}_l)^p|_{\eta, \text{quot}} \leq |\tilde{f}^p - \sum_l (\pi_l^p \tilde{f}_l)^p|_{\eta} \leq p^{-1} |\tilde{f}|^p_{\eta} < \eta^{pc} |\tilde{f}|^p_{\eta},
\]
for \( \eta \in [\eta_0, 1) \). So it suffices to prove the middle inequality in (1.2.7). For any \( l \), we have
\[
|\tilde{f}^p|_{\eta, \text{quot}} \geq |\tilde{f}^p|_{\eta, \text{sp}} = |\tilde{f}^p|_{\eta, \text{sp}} \geq |S|^{pc} \cdot |\tilde{f}^p|_{\eta, \text{quot}}.
\]

Let \( (\tilde{f}_l)^p = g_l, r_1 + \cdots + g_l m r_m + h_l \) be the result of the first step of applying the division algorithm to \((\tilde{f}_l)^p\). Then \( \log|\eta h_{l,(0)}|_{\eta} = \log|S|^l |(\tilde{f}_l)^p|_{\eta, \text{quot}} \) and hence
\[
|h_{l,(0)}|_{\eta} \geq \eta^{pc} |\tilde{f}_l|^p_{\eta}. \quad \text{Moreover, by Lemma 1.1.18, } |h_l - h_{l,(0)}|_{\eta} \leq \eta^j |\pi_k| |\tilde{f}_l|^p_{\eta} < \eta^{pc} |\pi_k|^{-pl} |\tilde{f}_l|^p_{\eta}; \quad \text{this implies that } |h_{l,(0)}|_{\eta, \text{quot}} = |h_{l,(0)}|_{\eta}.
\]

Now, we can write
\[
\sum_l (\pi_l^p \tilde{f}_l)^p = \sum_l \pi_k^p h_{l,(0)} + \sum_l \pi_k^p (h_l - h_{l,(0)}) \tag{1.2.8}
\]
in the quotient ring. The first term on the right-hand side of (1.2.8) has (quotient) norm at least \( \eta^{pc} |\tilde{f}|^p_{\eta} \) because none of the summands is divisible by any \( \text{Lead}(r_l) \). In contrast, the latter term on the right-hand side of (1.2.8) has norm strictly less than \( \eta^{pc} |\tilde{f}|^p_{\eta} \). Thus, the inequality in (1.2.7) holds. \( \square \)

**Remark 1.2.9.** It is attractive to think that \( |\cdot|_{\eta, \text{sp}} \leq |\cdot|_{\eta, \text{quot}} \leq \eta^{-c} |\cdot|_{\eta, \text{sp}} \) when \( \eta \to 1^{-} \). However, the best we know is that for any \( c' > c \), we have an \( \varepsilon \) depending on \( c' \), for which \( |\cdot|_{\eta, \text{sp}} \leq |\cdot|_{\eta, \text{quot}} \leq \eta^{-c'} |\cdot|_{\eta, \text{sp}} \) for all \( \eta \in [\varepsilon, 1) \).

**Corollary 1.2.10.** For a rigid analytic function \( f \) on \( X_{\eta_0} \), the following are equivalent.

(a) \( f \) is an element in \( A^\text{int}_{\eta_0} \).

(b) There exists a function \( r : [\eta_0, 1) \to \mathbb{R} \) with \( \lim_{\eta \to 1} r(\eta) \leq 1 \), such that for each \( \eta \in [\eta_0, 1) \), \( |f|_{\eta, \text{sp}} \leq r(\eta) \).

**Proof.** It follows from combining Lemma 1.2.6 with Proposition 1.1.23. \( \square \)

**Theorem 1.2.11.** There are one-to-one correspondences among the following sets:

(a) the idempotent elements of \( A_{\varepsilon} \); (b) the idempotent elements of \( A^\text{int}_{\eta_0} \); (c) the idempotent elements of \( A_{\eta_0} \); and (d) the idempotent elements on \( X_{\eta_0} \).
implies that idempotents whose reductions modulo $\pi_K$ of $\int_{\eta} A_{n_0}$ and of $\int_{\eta} A_{\gamma}$ are the same, i.e., $\bar{f} = \bar{g} \in A_\kappa$. This implies that $\bar{t}^{-1} \bar{f} = \bar{f}^{-1} g = 0$ in $A_\kappa$. Since $f - g = f^{-1} g = (f - g)(f^{-1} + g^{-1} + \cdots + g^{p-1})$, we have

$$|f - g|_{1, \text{quot}} = |(f - g)(f^{-1} + g^{-1} + \cdots + g^{p-1})|_{1, \text{quot}} \leq |f - g|_{1, \text{quot}} f^{-1} + g^{-1} + \cdots + g^{p-1} \leq |f - g|_{1, \text{quot}} |\pi_K|.$$  

This forces $|f - g|_{1, \text{quot}} = 0$ and hence $f = g$.

To prove surjectivity, we start with an idempotent $\bar{f} \in A_\kappa$, viewed as an element in $\int_{\eta} R_{\kappa}$ with none of its terms divisible by any of $\text{Lead}(\bar{f})$; pick a lift $\bar{f}^* \in \int_{\eta} A_{\gamma}$ of $\bar{f}$ which only contains terms present in $\bar{f}$, and let $f_0 \in A_{\gamma}$ denote its image in $A_{\gamma}$. If we set $\bar{h}_0$ to be the result of applying the division algorithm to $f_0^2 - \bar{f}$ and $h_0 = f_0^2 - f_0$, then $|h_0|_{1, \text{quot}} = |\bar{h}_0|_{1, \text{quot}} \leq |\pi_K|$ and $|h_0|_{\eta, \text{quot}} = |\bar{h}_0|_{\eta, \text{quot}} \leq p^{-1} \eta^{-2c} < 1$ for all $\eta \in [\eta_0, 1)$, where the latter inequality holds because all terms in $f_0$ come from terms in $\bar{f}$ having norms at most $|\bar{f}|_{\kappa, \text{quot}} \leq |S|_{\kappa}^{-c} |\bar{f}|_{\kappa, \text{sp}} = |S|_{\kappa}^{-c}$. As in the proof of Hensel's lemma, we iteratively modify $f_0$ as follows. For $\alpha \geq 0$, we set $f_{\alpha + 1} = f_{\alpha} + h_{\alpha} - 2 h_{\alpha} f_{\alpha}$ and

$$h_{\alpha + 1} := f_{\alpha + 1}^2 - f_{\alpha + 1} = (f_{\alpha} + h_{\alpha} - 2 h_{\alpha} f_{\alpha})^2 - (f_{\alpha} + h_{\alpha} - 2 h_{\alpha} f_{\alpha}) = h_{\alpha}^2 (4 h_{\alpha} - 3).$$

Hence, $|h_{\alpha + 1}|_{\eta, \text{quot}} \leq |h_{\alpha}|_{\eta, \text{quot}}^2$ for all $\eta \in [\eta_0, 1)$. Thus $|h_{\alpha}|_{\eta, \text{quot}} \to 0$ as $\alpha \to +\infty$; hence $f_{\alpha}$ converges to an element $f \in \int_{\eta} A_{\gamma}$ which is idempotent. It is clear from the construction that the reduction of $f$ modulo $\pi_K$ is the same as $\bar{f}$. This proves the surjectivity. □

**Corollary 1.2.12.** When $\eta_0 \in p^2$, there is a one-to-one correspondence between the connected components of $X$ and those of $X_{\eta_0}$.

**Remark 1.2.13.** This is the first place where we need the rationality of $\log p$, $\eta_0$ to ensure that we are in the classical rigid analytic space setting to talk about connected components [Bosch et al. 1984, 9.1.4/8].

### 1.3. Lifting construction

In order to apply the results from the previous two subsections later in the paper, we, reversing the picture, start with a rigid analytic space $X$ and try to construct $X_{\eta_0}$ from it.

Let $\kappa$ and $K$ be as before.

**Definition 1.3.1.** Let $X$ be a reduced affinoid rigid space over $\kappa((S))$ with ring of analytic functions $A_\kappa = R_\kappa / I_\kappa$ where $R_\kappa = \kappa((S))(u_1, \ldots, u_n)$ and $I_\kappa$ is some ideal. The *lifting construction* refers to the following.
(1) Find an ideal \( I^{\text{int}} \) in \( R^{\text{int}} = K(u_1, \ldots, u_n)((S)) \) so that \( R^{\text{int}} / I^{\text{int}} \) is flat over \( \mathcal{O}_K \) and \( I^{\text{int}} \otimes_{\mathcal{O}_K} \kappa = I_\kappa \).

(2) Choose a Gröbner basis of \( I_\kappa \), lift its elements to \( r_1, \ldots, r_m \in I^{\text{int}} \) as in Notation 1.1.11, and define \( \eta_0 \) as in Notation 1.2.3.

(3) We call the rigid analytic space

\[
X_{\eta_0} = \{(u_1, \ldots, u_n, S) \in \mathbb{A}_K^{n+1} \mid \eta_0 \leq |S| < 1; |u_1|, \ldots, |u_n| \leq 1; r_1, \ldots, r_m = 0\}
\]

the lifting space of \( X \); it depends only on the choice of \( I^{\text{int}} \) and \( \eta_0 \).

Remark 1.3.2. We do not know if such a lifting space exists in general. The only obstruction is finding an ideal \( I^{\text{int}} \) lifting \( I_\kappa \) such that \( R^{\text{int}} / I^{\text{int}} \) is flat over \( \mathcal{O}_K \).

Question 1.3.3. It would be interesting to know if this lifting construction can be globalized for arbitrary rigid spaces over \( \kappa((S)) \). In particular, given a morphism between two rigid spaces over \( \kappa((S)) \), can we lift the morphism (noncanonically) to a morphism between (some strict neighborhood of) their lifting spaces? Can we “glue” the lifting spaces up to homotopy? This situation is very similar to Berthelot’s construction [1996] of rigid cohomology.

For an affinoid subdomain of a polydisc, we explicate this lifting process.

Example 1.3.4. Let \( p_1, \ldots, p_m \in \kappa[[S]][u_1, \ldots, u_n] \) be polynomials and take \( a_1, \ldots, a_m \in \mathbb{N} \). Consider the following affinoid subdomain of the unit polydisc:

\[
X = \{(u_1, \ldots, u_n) \in \mathbb{A}_K^n \mid |u_1|, \ldots, |u_n| \leq 1; |p_1| \leq |S|^{a_1}, \ldots, |p_m| \leq |S|^{a_m}\}
\]

The ring of analytic functions on \( X \) is

\[
\kappa((S))(u_1, \ldots, u_n, v_1, \ldots, v_m) / (v_1 S^{a_1} - p_1, \ldots, v_m S^{a_m} - p_m).
\]

For each \( i \), let \( P_i \) be a lift of \( p_i \) in \( \mathcal{O}_K[[S]][u_1, \ldots, u_n] \) (here we allow \( P_i \) to have new terms other than the terms of \( p_i \)). We claim that the ring

\[
\mathcal{O}_K(u_1, \ldots, u_n, v_1, \ldots, v_m)((S)) / (v_1 S^{a_1} - P_1, \ldots, v_m S^{a_m} - P_m) \quad (1.3.5)
\]

is flat over \( \mathcal{O}_K \). This is because the ring

\[
\mathcal{O}_K((S))[u_1, \ldots, u_n, v_1, \ldots, v_m] / (v_1 S^{a_1} - P_1, \ldots, v_m S^{a_m} - P_m),
\]

being isomorphic to \( \mathcal{O}_K((S))[u_1, \ldots, u_n] \), is flat and hence torsion-free over \( \mathcal{O}_K \), and (1.3.5) is its completion with respect to the topology induced by the various \( (p, S)'(\mathcal{O}_K[[S]][u_1, \ldots, u_n, v_1, \ldots, v_m], \) for \( r \in \mathbb{N} \). Therefore, by Definition 1.3.1,

\[
X_{\eta_0} = \{(u_1, \ldots, u_n, S) \in \mathbb{A}_K^{n+1} \mid \eta_0 \leq |S| < 1, |u_1|, \ldots, |u_n| \leq 1, |P_1| \leq |S|^{a_1}, \ldots, |P_m| \leq |S|^{a_m}\}
\]

is a lifting space for \( X \), for some \( \eta_0 \in (0, 1) \).
2. Differential conductors

In this section, we recall the definition of differential Swan conductors following [Kedlaya 2007]. Along the way, we define the differential Artin conductors using a slightly different normalization.

2.1. Setup. Recall that we do not use any notation from the previous section.

Convention 2.1.1. Let $J$ be an index set. We write $e_J$ for a tuple $(e_j)_{j \in J}$. For an element $x$, we use $x^{e_J}$ to denote $(x^{e_j})_{j \in J}$. For another tuple $b_J$, we set $b_J^{e_J} = \prod_{j \in J} b_j^{e_j}$ if only a finite number of $e_j$ are nonzero. We also use $\sum_{e_j=0}^n$ to mean the sum over $e_j \in \{0, 1, \ldots, n\}$ for each $j \in J$, only allowing finitely many summands to be nonzero.

Definition 2.1.2. For a finite field extension $l/k$ of characteristic $p > 0$, a $p$-basis of $l$ over $k$ is a set $(c_j)_{j \in J} \subset l$ such that $c_{e_J}$, where $e_j \in \{0, 1, \ldots, p-1\}$ for all $j \in J$ and $e_j = 0$ for all but a finite number of $j$, form a basis of the vector space $l$ over $k^p$. By a $p$-basis of $l$ we mean a $p$-basis of $l$ over $l^p$; it is an empty set if and only if $l$ is perfect. (For more details, see [Eisenbud 1995, p. 565] or [Grothendieck 1964, Ch. 0, §21].)

Remark 2.1.3. For a $p$-basis $c_J \subset l$, the $dc_J$ form a basis for the differentials $\Omega^1_l$ as an $l$-vector space.

Convention 2.1.4. Throughout this paper, all differentials are $p$-adically continuous. In other words, for a continuous homomorphism $A \to B$ of $p$-adic rings, $\Omega^1_{B/A}$ is the relative $p$-adically continuous differentials. Sometimes, we may use in the notation the corresponding geometric objects, such as the rigid space $\text{Max}(B)$, instead of $A$ or $B$. When $A = \mathbb{Z}_p$, we may suppress it from the notation, writing simply $\Omega^1_B$.

For a homomorphism $A \to B$ between rings, a $\nabla$-module or a differential module over $B$ relative to $A$ is a finite projective $B$-module $M$ equipped with an integrable connection $\nabla : M \to M \otimes \Omega^1_{B/A}$. Sometimes, we may use the corresponding geometric objects instead of $A$ or $B$ in the notation. When $A = \mathbb{Z}_p$, we may omit the reference to the base ring.

Notation 2.1.5. Let $k$ be a complete discretely valued field of equal characteristic $p > 0$. Denote its ring of integers, maximal ideal, and residue field by $\mathcal{O}_k$, $m_k$, and $\kappa_k$, respectively. Fix a uniformizer $s$ and a noncanonical isomorphism $\kappa_k((s)) \cong k$.

Let $v_k(\cdot)$ denote the valuation, normalized so that $v_k(s) = 1$. Let $(\bar{b}_j)_{j \in J}$ be a $p$-basis of $\kappa_k$, where $J$ is an index set. Let $b_j$ be the image of $\bar{b}_j$ in $k$ under the isomorphism (2.1.6). Hence, $(db_j)_{j \in J}$ and $ds$ form a basis of $\Omega^1_{\mathcal{O}_k/k}$. We set $\kappa_0 = \bigcap_{n>0} k^{p^n} \cong \bigcap_{n>0} \kappa_k^{p^n}$; it is a perfect field.
Notation 2.1.7. Let $\mathcal{O}_K$ denote the Cohen ring of $\kappa_k$ with respect to $(\bar{b}_j)_{j \in J}$ and let $(B_j)_{j \in J} \subset \mathcal{O}_K$ be the canonical lifts of the $p$-basis. (For more about Cohen rings, see [Kedlaya 2007, §3.1] or [Whitney 2002].) Let $K = \text{Frac} \mathcal{O}_K$. We use $\mathcal{O}_{K_0}$ to denote the ring of Witt vectors $W(\kappa_0)$ of $\kappa_0$, as a subring of $\mathcal{O}_K$. Let $K_0 = \text{Frac} \mathcal{O}_{K_0}$.

We insert here a proposition discussing the functoriality of Cohen rings. For a more detailed study of functoriality of Cohen rings, see [Whitney 2002].

Proposition 2.1.8. Keep the notation as above and let $R$ be a complete Noetherian local ring with the maximal ideal $m$ containing $p$. Assume that we have a homomorphism $\overline{\psi} : \kappa_k \twoheadrightarrow R/m$. Then, for any $B'_j \subseteq R$ lifting $\overline{\psi}(\bar{b}_j)$, there exists a unique continuous homomorphism $\psi : \mathcal{O}_K \rightarrow R$ lifting $\overline{\psi}$ and sending $B_j$ to $B'_j$ for all $j \in J$.

Proof: For any $n \in \mathbb{N}$, a level-$n$ expression of an element $g \in \mathcal{O}_K$ is a (noncanonical) way of writing $g$ as

$$g = \sum_{i,i' \geq 0 \atop e_j = 0} \sum_{i,i' \geq 0 \atop e_j = 0} p^i A_{i,i',e_j}^n B_j^{e_j}$$

(2.1.9)

for some $A_{i,i',e_j} \in \mathcal{O}_K$ and for a fixed $i$, $A_{i,i',e_j} = 0$ when $i' \gg 0$ for all $e_j$. Then we set

$$\psi_n(g) = \sum_{i,i' \geq 0 \atop e_j = 0} \sum_{i,i' \geq 0 \atop e_j = 0} p^i \tilde{A}_{i,i',e_j}^n B_j^{e_j}$$

where $\tilde{A}_{i,i',e_j}$ is some lift of $\overline{\psi}(a_{i,i',e_j})$ in $R$ with $a_{i,i',e_j}$ being the reduction of $A_{i,i',e_j}$ in $\kappa_k$. Different choices of lifts $\tilde{A}_{i,i',e_j}$ may change the definition of $\psi_n(g)$ by an element in $m^n$; a different level-$n$ expression as in (2.1.9) may also vary $\psi_n(g)$ by some element in $m^n$. If $n \geq 1$, we can rewrite a level-$n$ expression of $g$ as in (2.1.9) in the form

$$g = \sum_{i,i' \geq 0 \atop e_j = 0} \sum_{i,i' \geq 0 \atop e_j = 0} p^i (A_{i,i',e_j}^p B_j^{e_j}) p^{n-1} B_j^{e_j},$$

lowering the level by 1. From this we conclude that $\psi_n(g) \equiv \psi_{n-1}(g) \mod m^{n-1}$. Taking $n \to \infty$, we get our map $\psi(g) = \lim_{n \to \infty} \psi_n(g)$. It is not hard to check that $\psi$ is actually a homomorphism; this is because for $g, h \in \mathcal{O}_K$, the formal sum and product of level-$n$ expressions of $g$ and $h$ are level-$n$ expressions of $g + h$ and $gh$, respectively.

To prove the uniqueness, take another continuous homomorphism $\psi' : \mathcal{O}_K \rightarrow R$ satisfying all the conditions. Then, for a level-$n$ expression of $g$ as in (2.1.9),

$$\psi' \left( \sum_{i,i' \geq 0 \atop e_j = 0} \sum_{i,i' \geq 0 \atop e_j = 0} p^i A_{i,i',e_j}^n B_j^{e_j} \right) = \sum_{i,i' \geq 0 \atop e_j = 0} \sum_{i,i' \geq 0 \atop e_j = 0} p^i \psi'(A_{i,i',e_j}) p^n B_j^{e_j}$$
is exactly one possible definition for $\psi_n$. As we proved above, $\psi'(g) \equiv \psi_n(g) \equiv \psi(g) \mod m^n$. Let $n \to \infty$ and we have $\psi = \psi'$.

**Corollary 2.1.10.** Suppose $J = \{1, \ldots, m\}$. There exists a unique continuous homomorphism $\psi : \mathcal{O}_K \to \mathcal{O}_K[\delta_1, \ldots, \delta_m]$ such that for all $j \in J$, $\psi(B_j) = B_j + \delta_j$ and for any $g \in \mathcal{O}_K$, $\psi(g) - g$ lies in the ideal generated by $\delta_1, \ldots, \delta_m$. Moreover, $\psi$ is an $\mathcal{O}_K$-homomorphism.

**Proof.** The first statement follows from previous proposition. By the functoriality of Witt vectors, $\psi$ has to be identity when restricted to $\mathcal{O}_K$ because $\kappa_0$ is perfect. Hence, $\psi$ is an $\mathcal{O}_K$-homomorphism.

**Corollary 2.1.11.** Assume that $\kappa_k$ has a finite $p$-basis $b_J$. Fix $j \in J$ and let $b'_j \in \mathcal{O}_k$ be an element such that $b'_j \equiv b_j \pmod{m_k}$. Then there exists an automorphism $g^* : k \to k$ such that $g^*(s) = s$, $g^*(b_j) = b'_j$, and $g^*(b_{J \setminus j}) = b_{J \setminus j}$.

**Proof.** Applying Proposition 2.1.8 to $R = \kappa_k[\![s]\!]$ and $m = (s)$ gives us a homomorphism $g^* : \mathcal{O}_K/(p) = \kappa_k \to k[\![s]\!]$ such that $g^*(b_j) = b'_j$, and $g^*(b_{J \setminus j}) = b_{J \setminus j}$. One can extend this to an automorphism $g^* : k \to k$ by setting $g^*(s) = s$.

### 2.2. Construction of differential modules.

In this subsection we review Tsuzuki’s construction [2002] of differential modules over the Robba ring associated with $p$-adic Galois representations. For a systematic treatment, one may consult, for example, [Kedlaya 2007, §3].

**Notation 2.2.1.** Keep the notation as in the previous subsection. Fix a separable closure $k^{sep}$ of $k$ and let $G_k = \text{Gal}(k^{sep}/k)$ be the absolute Galois group of $k$.

For a (not necessarily algebraic) separable extension $l/k$ of complete discretely valued fields, the naïve ramification degree $e$ is the index of the valuation group of $k$ in that of $l$; note that this might not be the same as the usual ramification degree because the inseparable part of the residue field extension $k_l/k_k$ is not counted in. We say $l/k$ is tamely ramified if $p \nmid e$ and the residue field extension is algebraic and separable. Moreover, if $e = 1$, we say that $l/k$ is unramified.

**Notation 2.2.2.** By a representation of $G_k$, we mean a continuous homomorphism $\rho : G_k \to \text{GL}(V_\rho)$, where $V_\rho$ is a vector space over a (topological) field $F$ of characteristic zero. We say that $\rho$ is a $p$-adic representation if $F$ is a finite extension of $\mathbb{Q}_p$.

Let $F$ be a finite extension of $\mathbb{Q}_p$. Let $\mathcal{O}$ and $\mathbb{F}_q$ denote its ring of integers and residue field, respectively, where $q$ is a power of $p$. Write $\mathbb{Z}_q$ for the Witt vectors $W(\mathbb{F}_q)$ and $\mathbb{Q}_q$ for its fraction field. By an $\mathcal{O}$-representation of $G_k$, we mean a continuous homomorphism $\rho : G_k \to \text{GL}(V_\rho)$ with $V_\rho$ a finite free $\mathcal{O}$-module.

We always assume that $\mathbb{F}_q \subseteq \kappa_0$ (see Remark 2.4.2). Let $K' = K F$. Since $F/\mathbb{Q}_q$ is totally ramified, we have the ring of integers $\mathcal{O}_{K'} \cong \mathcal{O}_K \otimes_{\mathbb{Z}_q} \mathcal{O}$. Let $v_{K'}$ denote the valuation on $K'$ normalized so that $v_{K'}(p) = 1$. 
Notation 2.2.3. Let \( C_k \) be the Cohen ring of \( k \) relative to the \( p \)-basis \( \{(b_j)_{j \in J}, s\} \).
By the functoriality of Cohen rings (Proposition 2.1.8), \( C_k \) has a natural structure as an \( \mathcal{O}_K \)-algebra, via the isomorphism \( (2.1.6) \). In particular, the (canonical) lifts of \( (b_j)_{j \in J} \) in \( C_k \) are \( (B_j)_{j \in J} \). We denote the canonical lift of \( s \) in \( C_k \) by \( S \).

Put \( \Gamma = C_k \otimes_{\mathbb{Z}_q} \mathcal{O} \); it is a complete discrete valuation ring since \( \mathcal{O} \) is totally ramified over \( \mathbb{Z}_q \). It carries a Frobenius structure \( \phi \) lifting the \( q \)-th power Frobenius on \( k \) which acts trivially on \( \mathcal{O} \).

Definition 2.2.4. Let \( \sigma : R \rightarrow R \) be an endomorphism. A \( (\sigma, \nabla) \)-module over \( R \) is a \( \nabla \)-module over \( R \) (relative to \( \mathbb{Z}_p \)) equipped with an isomorphism \( \sigma^*M \rightarrow M \) of \( \nabla \)-modules.

Definition 2.2.5. For every \( \mathcal{O} \)-representation \( \rho : G_k \rightarrow \text{GL}(V_{\rho}) \), define its associated \( (\phi, \nabla) \)-module over \( \Gamma \) by

\[
D(\rho) = (V_{\rho} \otimes_{\mathcal{O}} \widehat{\Gamma_{\text{unr}}})^{G_k},
\]

where \( \widehat{\Gamma_{\text{unr}}} \) is the \( p \)-adic completion of the maximal unramified extension of \( \Gamma \). All \( \nabla \)-modules we encounter in this section are relative to \( \mathbb{Z}_p \), so we omit the reference to the base ring \( \mathbb{Z}_p \) in the notation.

Proposition 2.2.6. For any Frobenius lift \( \phi \) on \( \Gamma \), the functor \( D \) from \( \mathcal{O} \)-representations of \( G_k \) to \( (\phi, \nabla) \)-modules over \( \Gamma \) is an equivalence of categories.

Proof. For the convenience of the reader, we briefly describe the functor here; for more details, one may consult [Kedlaya 2007, Propositions 3.2.7 and 3.2.8]. It is well-known that \( D \) establishes an equivalence between the category of representations and the category of \( \phi \)-modules over \( \Gamma \) (finite free \( \Gamma \)-modules with semilinear \( \phi \)-actions), with \( V(M) = (M \otimes_{\Gamma} \widehat{\Gamma_{\text{unr}}})^{\phi=1} \) as the inverse. The nontrivial part is that every \( \phi \)-module over \( \Gamma \) admits a unique structure of \( (\phi, \nabla) \)-module; this involves a standard approximation argument. \( \square \)

Definition 2.2.7. Let \( I_k = \text{Gal}(k_{\text{sep}}/k_{\text{unr}}) \) be the inertia subgroup of \( G_k \), where \( k_{\text{unr}} \) is the maximal unramified extension of \( k \) in \( k_{\text{sep}} \). We say that an \( (\mathcal{O}) \)-representation \( \rho \) has finite local monodromy if the image \( \rho(I_k) \) is finite.

For an \( \mathcal{O} \)-representation \( \rho \) of finite monodromy, one can refine the \( (\phi, \nabla) \)-module associated with \( \rho \) as follows.

Construction 2.2.8. Since \( C_k \) has an \( \mathcal{O}_K \)-algebra structure, any element \( x \in \Gamma \) can be uniquely written in the form of \( \sum_{i \in \mathbb{Z}} x_i S^i \) for \( x_i \in \mathcal{O}_K \otimes_{\mathbb{Z}_q} \mathcal{O} = \mathcal{O}_K' \) such that the indices \( i \) for which \( v_{K'}(x_i) \leq n \) are bounded below.

For \( r > 0 \), put \( \Gamma^r = \{ x \in \Gamma \mid \lim_{n \rightarrow -\infty} v_{K'}(x_n) + rn = \infty \} \) and \( \Gamma^\dagger = \bigcup_{r > 0} \Gamma^r \); the latter is commonly known as the integral Robba ring over \( K' \). It is not hard to show that the Frobenius \( \phi \) preserves \( \Gamma^\dagger \) and that \( \Omega^\dagger_{\mathcal{O}/\mathcal{O}} = \bigoplus_{j \in J} \Gamma^\dagger dB_j \oplus \Gamma^\dagger dS \). Also, \( \Gamma^\dagger \) is a Henselian discrete valuation ring as cited in Lemma 2.2.10.
Since $\mathcal{O}_{K'} \hookrightarrow \Gamma^\dagger$, we can identify $\hat{\mathcal{C}}_{K'}^{\text{unr}} \hookrightarrow (\Gamma^\dagger)^{\text{unr}}$, where the superscript unr means taking the maximal unramified extensions of discrete valuation rings. Put
\[ \hat{\Gamma}^\dagger = \hat{\mathcal{C}}_{K}^{\text{unr}} \otimes_{\mathcal{C}_{K}} (\Gamma^\dagger)^{\text{unr}} \subset \Gamma^{\text{unr}}, \]
where we take the $p$-adic completion. For a $p$-adic representation $\rho$ with finite local monodromy, define
\[ D^\dagger(\rho) = D(\rho) \cap (V_\rho \otimes \hat{\Gamma}^\dagger) = (V_\rho \otimes \hat{\Gamma}^\dagger)^{G_k}. \quad (2.2.9) \]

**Lemma 2.2.10** [Kedlaya 2005, Proposition 3.20]. The integral Robba ring $\Gamma^\dagger$ is a henselian discrete valuation ring.

**Theorem 2.2.11** [Kedlaya 2007, Theorem 3.3.6]. Let $\phi$ be a Frobenius lift on $\Gamma$ acting on $\Gamma^\dagger$. Then $D^\dagger$ induces an equivalence between the category of $G$-representations with finite local monodromy and the category of $(\phi, \nabla)$-modules over $\Gamma^\dagger$.

**Notation 2.2.12.** For $I \subset [0, +\infty)$ an interval, let $A_K^I(I)$ denote the annulus (centered at the origin) with radii in $I$. We do not impose any rationality condition on the endpoints of $I$, so this space should be viewed as an analytic space in the sense of [Berkovich 1990]. If $I = [\alpha, \beta]$, we write $A_K^1(\alpha, \beta)$ for $A_K^1([\alpha, \beta])$.

For $0 \leq \alpha \leq \beta < \infty$, let $K\langle \alpha/t, t/\beta \rangle$ denote the ring of analytic functions on $A_K^1(\alpha, \beta)$. (If $\alpha = 0$, we write $K\langle t/\beta \rangle$ instead.) For $\eta \in (\alpha, \beta]\setminus\{0\}$, the ring $K\langle \alpha/t, t/\beta \rangle$ admits an $\eta$-Gauss norm: for $f = \sum_{i \in \mathbb{Z}} a_i x_i \in K\langle \alpha/t, t/\beta \rangle$,
\[ |f|_\eta = \max_{i \in \mathbb{Z}} \{|a_i| \eta^i\}. \]

**Notation 2.2.13.** For $\eta_0 \in (0, 1)$, we use $Z_K^{\geq \eta_0}$ as a shorthand for $A_K^1[\eta_0, 1)$. Denote the ring of analytic functions on it by $\mathcal{R}_K^{\eta_0}$. We define the Robba ring over $K$ to be $\mathcal{R}_K = \bigcup_{\eta \in (\eta_0, 1)} \mathcal{R}_K^\eta$. Also let $\mathcal{R}_K^{\eta_0} = \mathcal{R}_K^{\eta_0} \otimes_{\mathbb{Q}_q} F$ and $\mathcal{R}_K' = \mathcal{R}_K \otimes_{\mathbb{Q}_q} F$. We will only be interested in the behavior when $\eta_0$ is close to 1.

**Remark 2.2.14.** We use $k$ in the subscript of $Z_K^{\geq \eta_0}$ because the space is functorial in $k$ but not in $K$, as we made a noncanonical choice in (2.1.6).

Now, we restrict the $(\phi, \nabla)$-module $D^\dagger(\rho)$ to the Robba ring over $K$ as follows.

**Construction 2.2.15.** Consider the natural injection $\Gamma^\dagger \hookrightarrow \mathcal{R}_{K'}$. Note that the Frobenius $\phi$ extends by continuity to $\mathcal{R}_{K'}$. Thus, from an $\mathcal{O}$-representation $\rho$ with finite local monodromy, we obtain a differential module $\mathcal{E}_\rho = D^\dagger(\rho) \otimes \mathcal{R}_{K'}$ over $\mathcal{R}_{K'}$.

Moreover, if we start with a $p$-adic representation $\rho : G_k \to \text{GL}(V_\rho)$ of finite local monodromy, we can choose an $\mathcal{O}$-lattice $V_\rho^{\text{int}}$ of $V_\rho$ stable under the action of $G_k$. Then we associate a differential module $\mathcal{E}_\rho$ with the $\mathcal{O}$-representation given by $V_\rho^{\text{int}}$. It is clear that $\mathcal{E}_\rho$ does not depend on the choice of the lattice $V_\rho^{\text{int}}$. We call $\mathcal{E}_\rho$ the differential module associated to $\rho$. 

Proposition 2.2.16 [Kedlaya 2007, Proposition 3.5.1]. The $\mathcal{O}_K$-module $\mathcal{E}_\rho$ over $\mathcal{R}_K$ does not depend on the choice of the $p$-basis (up to a canonical isomorphism).

Proposition 2.2.17. The differential module $\mathcal{E}_\rho$ descends to a differential module over $\mathcal{R}_K^{\eta_0}$ for some $\eta_0 \in (0, 1)$.

Proof: Defining a differential module requires only a finite amount of data. So, we can realize it on a certain annulus. See [Kedlaya 2007, Remark 3.4.1]. □

Remark 2.2.18. We will often make $\eta_0$ closer to $1^-$ in proving the main theorems. We will see later that all we care about is the asymptotic behavior of $\mathcal{E}_\rho$ as $\eta_0 \to 1^-$. 

Remark 2.2.19. The current construction of associating a differential module with a representation (Constructions 2.2.8 and 2.2.15) is not functorial with respect to the base field $F$ of the representation. If $F'$ is a finite extension of $F$, for a $p$-adic representation $\rho$ over $F$ of finite local monodromy, one can naturally obtain $\rho \otimes_F F'$ as a $p$-adic representation over $F'$. Assume that $\kappa_k$ contains the residue field $\mathbb{F}_q'$ of $F'$. Then the differential modules associated with $\rho$ and $\rho \otimes_F F'$ are the same if $F'/F$ is unramified and $\mathcal{E}_\rho \otimes_F F' = \mathcal{E}_\rho \otimes_F F'$ if $F'/F$ is totally ramified.

There are two reasons for keeping this nonfunctorial flaw. For one, the differential conductors we define later will be the same if we change $\rho$ to $\rho \otimes_F F'$. For the other, if we define $\mathcal{E}_\rho$ using the tensor over $\mathbb{Z}_p$ instead of $\mathbb{Z}_q$ in Notation 2.2.3, in which case we do have the functoriality, we will get the direct sum of $[\mathbb{F}_q : \mathbb{F}_p]$ copies of $\mathcal{E}_\rho$ as differential modules. When proving the integrality of Swan conductors, we have to come back to study $\mathcal{E}_\rho$ because $K \otimes_{\mathbb{Z}_p} \mathcal{O} \simeq K^{\mathfrak{p}} \otimes_{[\mathbb{F}_q : \mathbb{F}_p]}$ is not a field if $q > p$.

2.3. Differential conductors. Given a $p$-adic representation $\rho$ of finite local monodromy, Kedlaya [2007, §3.5] showed that one can define a differential Swan conductor for $\rho$, using the $p$-adic differential module associated with $\rho$. In this subsection, we review this definition and give an analogous definition for the differential Artin conductor.

Remark 2.3.1. Starting from this subsection, the Frobenius $\phi$ plays almost no role in our theory; most of the arguments work for solvable differential modules [Kedlaya 2007, Definition 2.5.1], and since all the decompositions for differential modules we encounter are canonical, they automatically respect the Frobenius structure. The only place we need Frobenius is to link back with representations; see Proposition 2.3.22.

Hypothesis 2.3.2. In this subsection, we make an auxiliary hypothesis that $k$ admits a finite $p$-basis $\{b_1, \ldots, b_m, s\}$.

Notation 2.3.3. Let $J = \{1, \ldots, m\}$ for notational convenience. We save the letters $j$ and $m$ for indexing the $p$-basis, except in Section 4.1 (see Notation 4.1.2). We also use $J^+$ to denote $J \cup \{0\}$, where 0 refers to the uniformizer $s$ in the $p$-basis.
Definition 2.3.4. Let $E$ be a differential field of order 1 and characteristic zero, i.e., a field of characteristic zero equipped with a derivation $\partial$. Assume that $E$ is complete for a nonarchimedean norm $|\cdot|$. Let $M$ be a finite differential module over $E$, i.e., a finite dimensional $E$-vector space equipped with an action of $\partial$ satisfying the Leibniz rule. The spectral norm of $\partial$ on $M$ is defined to be

$$|\partial|_{M,sp} = \lim_{n \to \infty} |\partial^n|_M^{1/n}$$

for any norm $|\cdot|_M$ on $M$; it does not depend on the choice of $|\cdot|_M$. One can prove that $|\partial|_{M,sp} \geq |\partial|_{E,sp}$ [Kedlaya 2010, Lemma 6.2.4].

Remark 2.3.5. For a complete extension $E'$ of $E$, to which the derivation $\partial$ extends, $M \otimes_E E'$ can be viewed as a differential module over $E'$ with spectral norm $|\partial|_{M \otimes_E E',sp} = \max\{|\partial|_{M,sp}, |\partial|_{E',sp}\}$.

Notation 2.3.6. Let $\partial_0 = \partial/\partial S$, $\partial_1 = \partial/\partial B_1$, $\ldots$, $\partial_m = \partial/\partial B_m$ denote the elements of a dual basis of $\Omega^1_{\mathbb{C}K[\mathbb{S}]/\mathbb{C}K_0}$ with respect to $dS, dB_1, \ldots, dB_m$; they also give a dual basis of $\Omega^1_{\mathbb{R}^{\eta_0}/\mathbb{K}_0}$ for all $\eta_0 \in (0, 1)$. For a $(\phi, \nabla)$-module $\mathcal{E}$ over $\mathbb{R}^{\eta_0}_{\mathbb{K}}$, these differential operators act on $\mathcal{E}$, commuting with each other and commuting with the Frobenius action.

Notation 2.3.7. For $\eta \in [\alpha, \beta] \subset (0, +\infty)$, we denote by $F_\eta'$ the completion of $\text{Frac}(\mathbb{K}'(\alpha/t, t/\beta))$ with respect to the $\eta$-Gauss norm; this does not depend on the choices of $\alpha$ and $\beta$.

Example 2.3.8. For $\eta \in \mathbb{R}_{>0}$, the operator norms of $\partial_j$ and spectral norms on $F_\eta'$ are as follows.

$$|\partial_j|_{F_\eta'} = \begin{cases} \eta^{-1} & \text{for } j = 0, \\ 1 & \text{for } j \in J; \end{cases}$$

$$|\partial_j|_{F_\eta',sp} = \begin{cases} p^{-1/(p-1)}\eta^{-1} & \text{for } j = 0, \\ p^{-1/(p-1)} & \text{for } j \in J. \end{cases}$$

Definition 2.3.9. Let $\mathcal{E}$ be a $\nabla$-module over $\mathbb{R}^{\eta_0}_{\mathbb{K}}$. For $\eta \in (\eta_0, 1)$, we set $\mathcal{E}_\eta = \mathcal{E} \otimes_{\mathbb{R}^{\eta_0}_{\mathbb{K}}} F_\eta'$, which inherits differential operators $\partial_j$. Define the (nonlogarithmic) generic radius (of convergence) $T(\mathcal{E}, \eta)$ of $\mathcal{E}_\eta$ to be

$$\min \left\{ \frac{p^{-1/(p-1)}}{|\partial_j|_{\mathcal{E}_\eta,sp}} : j \in J^+ \right\}. \quad (2.3.10)$$

If $\mathcal{E}_{\eta,i}$ ($i = 1, \ldots, n$) are the Jordan–Hölder factors of $\mathcal{E}_\eta$ as a $\nabla$-module over $F_\eta'$, we define the (nonlogarithmic) radius multiset $S(\mathcal{E}, \eta)$ to be the set consisting of the generic radius of $\mathcal{E}_{\eta,i}$ with multiplicity $\dim F_\eta' \mathcal{E}_{\eta,i}$ for each $i$.

We define the logarithmic generic radius (of convergence) $T_{\log}(\mathcal{E}, \eta)$ to be

$$\min \left\{ \frac{p^{-1/(p-1)}\eta^{-1}}{|\partial_0|_{\mathcal{E}_\eta,sp}}, \frac{p^{-1/(p-1)}}{|\partial_j|_{\mathcal{E}_\eta,sp}} : j \in J \right\}. \quad (2.3.11)$$

Similarly, we define the logarithmic radius multiset $S_{\log}(\mathcal{E}, \eta)$ of $\mathcal{E}$.
Remark 2.3.12. We have $T(\mathcal{E}, \eta) \leq \eta$; more generally, every element in $S(\mathcal{E}, \eta)$ is less than or equal to $\eta$.

Remark 2.3.13. The logarithmic generic radius and logarithmic radius multiset are the same as the notions of the generic radius of convergence and radius multiset in [Kedlaya 2007].

Definition 2.3.14. For $j \in J^+$, we call $\partial_j$ dominant for $\mathcal{E}_\eta$ if the minimum of $T(\mathcal{E}, \eta)$ in (2.3.10) is achieved by the term involving the spectral norm of $\partial_j$. The term log-dominant is defined likewise, with reference to $T_{\text{log}}(\mathcal{E}, \eta)$ in (2.3.11).

Lemma 2.3.15. For a $(\phi, \nabla)$-module $\mathcal{E}$ over $\mathcal{O}_K^{\eta_0}$, and $j \in J^+$, there exists $\eta'_0 \in (0, 1)$ such that one of the following two statements is true:

- For all $\eta \in [\eta'_0, 1)$, $\partial_j$ is (log-)dominant for $\mathcal{E}_\eta$.
- For all $\eta \in [\eta'_0, 1)$, $\partial_j$ is not (log-)dominant for $\mathcal{E}_\eta$.

Proof. The logarithmic case is proved in [Kedlaya 2007, Lemma 2.7.5]. The proof for nonlogarithmic case is very similar.

Definition 2.3.16. Keep the notation as in previous lemma. For $j \in J^+$, $\partial_j$ is called eventually (log-)dominant for $\mathcal{E}$ if it is (log-)dominant for $\mathcal{E}_\eta$ for $\eta \to 1^-$.

Lemma 2.3.17. Keep the notation as in Lemma 2.3.15. Assume that $\partial_0$ is not eventually dominant and $\partial_j$ is. Consider the rotation $g^* : B_j \mapsto B_j + S$, $B_{J\setminus j} \mapsto B_{J\setminus j}$, and $S \mapsto S$ given by Proposition 2.1.8. Then $\partial_0 = \partial / \partial S$ is eventually dominant in $g^*\mathcal{E}$.

Proof. Use the fact that the action of $\partial_0$ on $g^*\mathcal{E}$ is the pull-back of the action of $\partial_0 + \partial_j$ on $\mathcal{E}$. For details, see the proof of [Kedlaya 2007, Lemma 2.7.9].

Remark 2.3.18. The rotation $g$ in the lemma corresponds to changing the isomorphism (2.1.6) so that $\bar{b}_j$ is sent to $b_j + s$ instead; such an isomorphism can be obtained by Corollary 2.1.11. In particular, if $\mathcal{E}_\rho$ comes from a $p$-adic representation $\rho$ of finite local monodromy by Constructions 2.2.8 and 2.2.15, $g^*\mathcal{E}_\rho$ is the differential module associated with the same $\rho$ using the aforementioned alternative isomorphism in place of (2.1.6).

Proposition 2.3.19. The functions

$$f(r) = \log T(\mathcal{E}, e^{-r}) \quad \text{and} \quad f_{\text{log}}(r) = \log T_{\text{log}}(\mathcal{E}, e^{-r})$$

on $(0, -\log \eta_0]$ are piecewise linear, concave functions with slopes in $\frac{1}{(\text{rank } \mathcal{E})!} \mathbb{Z}$. They are linear in a neighborhood of 0.

Proof. The logarithmic case is proved in [Kedlaya 2007, §2.5]. For the nonlogarithmic case, the only difference is a factor $\eta^{-1}$ in the spectral norm of $\partial_0$, which gives an extra linear term $r$. 

□
Definition 2.3.20. As a consequence of the previous proposition, there exists $b_{\text{dif}}(\mathcal{E}) \in \mathbb{Q}_{\geq 0}$ and $\eta_0 \in (0, 1)$ such that $T(\mathcal{E}, \eta) = \eta^{b_{\text{dif}}(\mathcal{E})}$ for all $\eta \in [\eta_0, 1)$. This $b_{\text{dif}}(\mathcal{E})$ is called the (nonlogarithmic) differential ramification break of $\mathcal{E}$. We say that $\mathcal{E}$ has uniform slope $b$ if the radius multiset $S_0(\mathcal{E}, \eta)$ consists only of $\eta^b$ when $\eta \to 1$. The notions of logarithmic differential ramification break $b_{\text{dif, log}}(\mathcal{E})$ and uniform log-slope $b$ are defined likewise, with reference to $T_{\log}(\mathcal{E}, \eta)$ and $S_{\log}(\mathcal{E}, \eta)$.

The ramification breaks give rise to the break decomposition.

Theorem 2.3.21. Let $\mathcal{E}$ be a $(\phi, \nabla)$-module over $\mathcal{R}_K^{\eta_0}$, for some $\eta_0 \in (0, 1)$. Then after making $\eta_0$ sufficiently close to 1, there exists a unique decomposition of $(\phi, \nabla)$-modules $\mathcal{E} = \bigoplus_{b \in \mathbb{Q}_{\geq 1}} \mathcal{E}_b$ (resp. $\mathcal{E} = \bigoplus_{b \in \mathbb{Q}_{\geq 0}} \mathcal{E}_{b, \text{log}}$) over $\mathcal{R}_K^{\eta_0}$, where each of $\mathcal{E}_b$ (resp. $\mathcal{E}_{b, \text{log}}$) has uniform slope (resp. log-slope) $b$.

Proof. Since the differential operators act trivially on $\mathcal{O}$ and commute with $\phi$, it suffices to obtain the decomposition of $\mathcal{E}$ as a $\nabla$-module over $A_{K'}^1[\eta_0, 1)$; the uniqueness of the decomposition of $\mathcal{E}$ follows from the uniqueness of that over $F_{\eta}'$ for $\eta \in [\eta_0, 1)$. The logarithmic part of this theorem is proved in [Kedlaya 2007, Theorem 2.7.2]. We will give the proof of the nonlogarithmic decomposition by applying several lemmas from the same paper.

We need to show that if $\mathcal{E}$ does not have uniform slope at least 1, then $\mathcal{E}$ is decomposable when $\eta_0$ is taken sufficiently close to 1. (See Remark 2.3.12 for the reason for having 1 instead of 0.) If $\partial_0$ is eventually dominant, the decomposition theorem of Christol and Mebkhout [Kedlaya 2007, Lemma 2.7.3] gives the decomposition. If $\partial_0$ is not eventually dominant, Lemma 2.3.15 implies that $\partial_j$ is eventually dominant for some $j \in J$. By Lemma 2.3.17, $\partial_0$ is eventually dominant for $g^\ast \mathcal{E}$. Applying the decomposition theorem [Kedlaya 2007, Lemma 2.7.3] to $g^\ast \mathcal{E}$ and pulling back the decomposition along $g^{-1}$, we obtain a nontrivial decomposition of $\mathcal{E}$ on $\mathcal{R}_K^{\eta_0}$ for some $\eta_0 \in (0, 1)$. □

Proposition 2.3.22. In Theorem 2.3.21, if the $(\phi, \nabla)$-module $\mathcal{E}_\rho$ is associated with a $p$-adic representation $\rho$ of finite local monodromy, then the decomposition of $(\phi, \nabla)$-modules induces a direct sum decomposition of the representation $\rho$ so that each direct summand of $\mathcal{E}_\rho$ is the differential module associated with a direct summand of $\rho$.

Proof. By slope filtration [Kedlaya 2007, Theorem 3.4.6], the Frobenius action on each direct summand of $\mathcal{E}$ is of unit-root; the decomposition of the representation follows by [Kedlaya 2007, Proposition 3.4.4]. □

Definition 2.3.23. Let $\rho : G_k \to \text{GL}(V_\rho)$ be a $p$-adic representation with finite local monodromy. Let $\mathcal{E}$ be the differential module corresponding to $V_\rho / V_\rho^k$ by Constructions 2.2.8 and 2.2.15, where $V_\rho^k$ is the unramified piece of $V_\rho$ consisting of the elements in $V_\rho$ which are fixed by $I_k$. By Theorem 2.3.21 above, there
exists a multiset \( \{a_1, \ldots, a_d\} \) such that for all \( \eta \) sufficiently close to 1, \( S(\mathcal{E}, \eta) = \{\eta^{a_1}, \ldots, \eta^{a_d}\} \). Define the differential Artin conductor of \( \mathcal{E} \) (or \( \rho \)) by

\[
\text{Art}_{\text{diff}}(\mathcal{E}) = \text{Art}_{\text{diff}}(\rho) = a_1 + \cdots + a_d.
\]

The differential Swan conductor of \( \mathcal{E} \) (or \( \rho \)), denoted by \( \text{Swan}_{\text{diff}}(\mathcal{E}) \) or \( \text{Swan}_{\text{diff}}(\rho) \), is defined similarly, by adding the subscript \( \log \) everywhere.

**Remark 2.3.24.** In this definition, we split off the unramified part, because it has both conductors 0. We need to do so because the convergence radius multiset cannot distinguish between the unramified and the tame parts, which give different contributions to the Artin conductor. This does not matter for Swan conductors, and we may define the Swan conductor without first taking out the unramified piece.

**Remark 2.3.25.** By [Kedlaya 2007, Proposition 2.6.6], the definition of differential Swan conductors does not depend on the choice of a uniformizer \( s \) and a \( p \)-basis \( \{b_1, \ldots, b_m, s\} \). We are also free to remove Hypothesis 2.3.2 and define the differential Swan conductors for arbitrary complete discretely valued fields of equal characteristic \( p \) [Kedlaya 2007, Corollary 3.5.7]. A similar statement holds for differential Artin conductors; the proof is the same as for Swan conductors.

### 2.4. Basic properties

We do not impose any hypothesis on \( k \).

**Theorem 2.4.1.** Differential conductors satisfy the following properties:

1. When the residue field \( k_{\kappa} \) is perfect, the differential Artin and Swan conductors are the same as the classical ones defined in [Serre 1979].

2. For any representation \( \rho \) of finite local monodromy, \( \text{Swan}_{\text{diff}}(\rho) \in \mathbb{Z}_{\geq 0} \) and \( \text{Art}_{\text{diff}}(\rho) \in \mathbb{Z}_{\geq 0} \).

3. Let \( k'/k \) be a tamely ramified extension of ramification degree \( e' \). Let \( \rho \) be a representation of \( G_k \) of finite local monodromy and let \( \rho' \) denote the restriction of \( \rho \) to \( G_{k'} \). Then \( \text{Swan}_{\text{diff}}(\rho') = e' \cdot \text{Swan}_{\text{diff}}(\rho) \). If \( e' = 1 \), i.e., \( k'/k \) is unramified, then \( \text{Art}_{\text{diff}}(\rho') = \text{Art}_{\text{diff}}(\rho) \).

4. Let \( \rho \) be a faithful \( p \)-adic representation of the Galois group of a Galois extension \( l/k \). If \( l/k \) is tamely ramified and not unramified, then \( b_{\text{diff}}(\rho) = 1 \) and \( b_{\text{diff}, \log}(\rho) = 0 \). If \( l/k \) is unramified, \( b_{\text{diff}}(\rho) = b_{\text{diff}, \log}(\rho) = 0 \).

5. Put \( G_k^0 = G_k \) and \( G_k^a = I_k \) for \( a \in (0, 1] \). For \( a > 1 \), let \( R_a \) be the set of finite image representations \( \rho \) with differential ramification breaks less than \( a \). Define \( G_k^a = \bigcap_{\rho \in R_a} (I_k \cap \ker \rho) \) and write \( G_k^{a+} \) for the closure of \( \bigcup_{b > a} G_k^b \). This defines a differential filtration on \( G_k \) such that for all finite image representations \( \rho \), \( \rho(G_k^a) \) is trivial if and only if \( \rho \in R_a \).
Similarly, put $G_{k, \text{log}}^0 = G_k$. For $a > 0$, let $R_{a, \text{log}}$ be the set of finite image representations $\rho$ with logarithmic differential ramification breaks less than $a$. Define $G_{k, \text{log}}^a = \bigcap_{\rho \in R_{a, \text{log}}} (I_k \cap \ker \rho)$ and write $G_{k, \text{log}}^{a+}$ for the closure of $\bigcup_{b > a} G_{k, \text{log}}^b$. This defines a differential logarithmic filtration on $G_k$ such that for all finite image representations $\rho$, $\rho(G_{k, \text{log}}^a)$ is trivial if and only if $\rho \in R_{a, \text{log}}$.

For $a > 0$, the group $G_{k, \text{log}}^a / G_{k, \text{log}}^{a+}$ is abelian and killed by $p$ (and trivial if $a \not\in \mathbb{Q}$).

For $a > 1$, the group $G_{k, \text{log}}^a / G_{k, \text{log}}^{a+}$ is abelian and killed by $p$ (and trivial if $a \not\in \mathbb{Q}$).

Proof. For (0), see [Kedlaya 2005, Theorem 5.23]. For the rest of the statements, the proof for Swan conductors can be found in [Kedlaya 2007, §3.5]; we will only prove the corresponding properties for differential Artin conductors. As in the proof for differential Swan conductors, we may first reduce to the case where Hypothesis 2.3.2 holds.

(1) We can follow the proof of [Kedlaya 2007, Theorem 2.8.2], because of the decomposition Theorem 2.3.21. An alternative proof is to apply Lemma 2.3.17, and reduce to the case where $\partial_0$ is dominant (see also Remark 2.3.18); then one can forget about $\partial_1, \ldots, \partial_m$ and hence reduce to the perfect residue field case, which is statement (0) of the theorem.

(2) Since an unramified extension $l/k$ only changes the field $K$ but not the uniformizer $s$, we can use the same $s$ as the uniformizer of $l$. The corresponding differential module $\mathcal{E}_{\rho'}$ of $\rho'$ is just a simple extension of scalars. Since the calculation of spectral norms does not depend on the base field (see Remark 2.3.5), we compute the same result on spectral norms and hence have the same Artin conductor.

(3) is an immediate consequence of the Swan case. Attention: differential ramification breaks cannot distinguish unramified extensions from tamely ramified ones. (See also Remark 2.3.24.)

(4) The proof for the nonlogarithmic differential filtration is much simpler than the logarithmic case because of the different normalization in Definition 2.3.9. By virtue of the proof of [Kedlaya 2007, Theorem 3.5.13], it suffices to show that we can rotate so that $\partial_0$ becomes dominant; this is the content of Lemma 2.3.17. □

Remark 2.4.2. The invariance of the differential conductors under unramified base changes enables us to assume that $k_0$ is algebraically closed. This justifies the assumption we made in Notation 2.2.2.

3. The thickening technique

In this section, we introduce a thickening technique. Loosely speaking, it consists in constructing what can be thought of as a tubular neighborhood of the diagonal
embedding of $A^1_K[\eta_0, 1]$ into $A^1_K[\eta_0, 1] \times K_0 A^1_K[\eta_0, 1]$, but note that the latter rigid space is not really well-defined.

We start with a geometric interpretation of this construction and then move on to the abstract definition of the thickening space.

We keep Hypothesis 2.3.2 throughout this section.

**Notation 3.0.1.** For $\alpha \in (0, +\infty)$, denote by $A^m_K[0, \alpha]$ and $A^m_K(0, \alpha)$ the closed and open polydiscs with radius $\alpha$ and center at the origin. Let $K(u_1/\alpha, \ldots, u_m/\alpha)$ denote the ring of analytic functions on the disc $A^m_K[0, \alpha]$.

Later, we will see many homomorphisms between rings of functions on $K$-rigid spaces, which are only $K_0$-linear. It is unfair to say that they induce morphisms of rigid spaces; however, we prefer to keep some geometric flavor of the whole construction. On the other hand, these rigid spaces are all quasi-Stein or affinoid; knowing the ring of analytic functions is equivalent to knowing the rigid spaces.

**Notation 3.0.2.** For a continuous homomorphism $f^* : A \to B$ between affinoid or Fréchet algebras (not necessarily respecting the ground field $K$), we write formally $f : \text{Max}(B) \to \text{Max}(A)$, as the geometric incarnation of the homomorphism. Pullbacks along maps and Cartesian diagrams are thought of as (completed) tensor products. (In fact, in all cases we encounter, we do not need to take the completion for the tensor products.) In short, whenever such a map is given, strictly speaking, we should view it as a continuous ring homomorphism.

### 3.1. Geometric thickening.

In this subsection, we describe the thickening technique when the residue field $\kappa_k$ can be realized as the field of rational functions on a smooth $\kappa_0$-variety. The purpose of this subsection is solely to provide some geometric intuition for the thickening construction in the next subsection; the content in this subsection will not be used in the rest of this paper.

**Hypothesis 3.1.1.** Only in this subsection, we assume that the field $\kappa_k$ is a finite separable extension of $\kappa_0(\bar{b}_1, \ldots, \bar{b}_m)$.

**Construction 3.1.2.** Let $\bar{X}$ be a smooth variety over $\kappa_0$ whose field of rational functions is $\kappa_k$; such an $\bar{X}$ exists because we may realize it as an affine scheme étale over $\text{Spec} \kappa_0[\bar{b}_1, \ldots, \bar{b}_m]$ which induces the extension $\kappa_k/\kappa_0(\bar{b}_1, \ldots, \bar{b}_m)$. We may further shrink $\bar{X}$ so that it is the special fiber of an affine smooth formal scheme $\mathfrak{X}$ over $\mathcal{O}_{K_0}$ of topological finite type, i.e., $\mathfrak{X} \times_{\text{Spf} \mathcal{O}_{K_0}} \text{Spec} \kappa_0 = \bar{X}$. We may further shrink $\mathfrak{X}$ and $\bar{X}$ so that we have lifts $B_1, \ldots, B_m$ of $\bar{b}_1, \ldots, \bar{b}_m$ on $\mathfrak{X}$ and $d B_1, \ldots, d B_m$ form a basis of the sheaf of relative differentials $\Omega^1_{\mathfrak{X}/\mathcal{O}_{K_0}}$. We use $X$ to denote the “generic fiber” of $\mathfrak{X}$ as a rigid space over $\text{Sp}(K_0)$, in the sense of Raynaud; it is affinoid.
Consider the commutative diagram

\[
\begin{array}{ccc}
\tilde{X} & \xrightarrow{\Delta_P} & \mathcal{P} = \tilde{X} \times_{\text{Spf } \mathcal{O}_K} \mathcal{A}_{K_0}^1 \\
\downarrow & & \downarrow \\
\text{Spec } \mathcal{O}_0 & \xrightarrow{\text{Spf } \mathcal{O}_K} & \text{Spf } \mathcal{O}_K \\
\end{array}
\]

where the vertical arrows from the first row to the second are all embeddings of zero sections and the coordinates of $\mathcal{A}_{K_0}^1$ and $\mathcal{A}_{\mathcal{O}_K}^1$ are denoted by $s$ and $S$, respectively.

The tube of $\tilde{X}$ in $\mathcal{P}$, denoted by $|\tilde{X}|_{\mathcal{P}}$, is isomorphic to $X \times A_{K_0}^1[0, 1]$. Let $\mathcal{O}_X$ be the ring of rigid analytic functions on $X$; then $K$ is exactly the $p$-adic completion of $\text{Frac } \mathcal{O}_X$. If we base-change the tube $|\tilde{X}|_{\mathcal{P}}$ from $X$ over to $K$, we get $A_{K}^1[0, 1]$. We are interested in the annulus $A_{K}^1(\eta_0, 1)$ for some $\eta_0 \in (0, 1)$, which can be obtained by base-changing $X \times A_{K_0}^1(\eta_0, 1)$ from $X$ to $K$.

Now, we consider the thickening space of this annulus $A_{K}^1(\eta_0, 1)$.

**Construction 3.1.3.** Consider the commutative diagram

\[
\begin{array}{ccc}
\tilde{X} & \xrightarrow{\Delta_P} & \mathcal{P} = \tilde{X} \times_{\text{Spf } \mathcal{O}_K} \mathcal{A}_{K_0}^1 \\
\downarrow & & \downarrow \\
\text{Spec } \mathcal{O}_0 & \xrightarrow{\text{Spf } \mathcal{O}_K} & \text{Spf } \mathcal{O}_K \\
\end{array}
\]

where we use $\text{pr}_i : \mathcal{P} \times_{\mathcal{O}_K} \mathcal{P} \rightarrow \mathcal{P}$ to denote the projection to the $i$-th factor for $i = 1, 2$. Then $\mathcal{P} \times_{\mathcal{O}_K} \mathcal{P}$ has a set of local parameters given by $B_1 = \text{pr}_1^*(B_1), \ldots, B_m = \text{pr}_1^*(B_m)$, $S = \text{pr}_1^*(S)$, $B_1' = \text{pr}_2^*(B_1), \ldots, B_m' = \text{pr}_2^*(B_m)$, and $S' = \text{pr}_2^*(S)$. By Berthelot’s fibration theorem [1996, théorème 1.3.2], we have an isomorphism

\[
|\tilde{X}|_{\mathcal{P} \times_{\mathcal{O}_K} \mathcal{P}} \simeq |\tilde{X}|_{\mathcal{P} \times_{\mathcal{O}_K} \mathcal{P}}
\]

where the factor $|\tilde{X}|_{\mathcal{P}}$ respects the projection $\text{pr}_1$ and the coordinates on the right-hand side are given by $\delta_0 = S - S'$, $\delta_1 = B_1 - B_1'$, $\ldots$, $\delta_m = B_m - B_m'$. The geometric thickening space is the subspace of $|\tilde{X}|_{\mathcal{P} \times_{\mathcal{O}_K} \mathcal{P}}$ where $|\delta_0| = |S - S'| < |S|$, or, more precisely,

\[
X \times_{K_0} \{(S, \delta_0) \in A_{K_0}^2[0, 1] \mid |\delta_0| < |S|\} \times_{K_0} A_{K_0}^m[0, 1).
\]

Thus, the **thickening space**, denoted by $TS_{K}^{\geq \eta_0}$, of $A_{K}^1(\eta_0, 1)$ is the space obtained by base-changing

\[
X \times_{K_0} \{(S, \delta_0) \in A_{K_0}^2[0, 1] \mid |S| \geq \eta_0, |\delta_0| < |S|\} \times_{K_0} A_{K_0}^m[0, 1).
\]

from $X$ to $K$. 


The projection $\text{pr}_1 : P \times_{K_0} P \to P$ gives a $K$-morphism of rigid spaces
\[ \pi : TS_k^{\geq \eta_0} \to A_K^1[\eta_0, 1]; \]
the projection $\text{pr}_2 : P \times_{K_0} P \to P$ gives a $K_0$-morphism of rigid spaces
\[ \tilde{\pi} : TS_k^{\geq \eta_0} \to A_K^1[\eta_0, 1]. \]

The morphism $\tilde{\pi}$ does not respect the $K$-rigid space structure; one should always think of $\tilde{\pi}$ as the ring homomorphism between the corresponding ring of analytic functions. In our earlier notation, this is just the geometric incarnation of the map on the ring of global sections.

### 3.2. General thickening construction.

We now introduce thickening spaces and study basic properties of differential modules over them.

We keep Hypothesis 2.3.2 in this subsection. However, Hypothesis 3.1.1 is no longer in force from now on.

**Definition 3.2.1.** For $\eta \in (0, 1)$, we write $Z_k^\eta = A_K^1[\eta, \eta]$. For $a \in \mathbb{Q}_{>1}$ and $\eta_0 \in (0, 1)$, we define the *thickening space* of $A_K^1[\eta_0, 1]$ and level $a$ to be the rigid space over $K$ of the form
\[ TS_k^{a, \geq \eta_0} = \{(S, \delta_{j^+}) \in A_K^{m+2}[0, 1] \mid |S| \geq \eta_0; |\delta_j| \leq |S|^a for j \in J^+\}. \] 
(3.2.2)

For $\eta \in [\eta_0, 1)$, we put
\[ TS_k^{a, \eta} = A_K^1[\eta, \eta] \times_K A_K^{m+1}[0, \eta^a]. \]

Similarly, for $a \in \mathbb{Q}_{>0}$ and $\eta_0 \in (0, 1)$, we define the *log-thickening space* of $A_K^1[\eta_0, 1]$ and level $a$ to be
\[ TS_k^{a, \eta, \log} = \{(S, \delta_{j^+}) \in A_K^{m+2}[0, 1] \mid |S| \geq \eta_0; |\delta_0| \leq |S|^a; |\delta_j| \leq |S|^a for j \in J\}. \] 
(3.2.3)

For $\eta \in [\eta_0, 1)$, we set
\[ TS_k^{a, \eta, \log} = A_K^1[\eta, \eta] \times_K A_K^1[0, \eta^{a+1}] \times_K A_K^{m}[0, \eta^a]. \]

We denote by $\mathcal{O}_{TS_k^{a, \geq \eta_0}}, \mathcal{O}_{TS_k^{a, \eta, \log}},$ and $\mathcal{O}_{TS_k^{a, \eta, \log}}$ the rings of analytic functions on these spaces.

Let $| \cdot |_{Z_k^\eta}$ denote the $\eta$-Gauss norm on $Z_k^\eta$. For $a \in \mathbb{Q}_{>1}$, let $| \cdot |_{TS_k^{a, \eta}}$ denote the Gauss norm on $TS_k^{a, \eta}$; for $a > 0$, let $| \cdot |_{TS_k^{a, \eta}}$ denote the Gauss norm on $TS_k^{a, \eta}$.

The union of all $TS_k^{a, \geq \eta_0}$ is the $TS_k^{\geq \eta_0}$ we discussed in Construction 3.1.3.

**Caution 3.2.4.** One may want to write $TS_k^{a, \geq \eta_0} = \bigcup_{\eta \in [\eta_0, 1)} A_K^1[\eta, 1] \times_K A_K^{m+1}[0, \eta^a]$ for simplicity, as in the introduction. However, this will not define the same rigid space as in (3.2.2), because the union does not give an admissible cover of $TS_k^{a, \geq \eta_0}$. 
A similar expression for log-thickening space is not valid either. Nevertheless, it might be helpful to think the space and picture the geometry this way.

On the other hand, it is true that an element of $K \llbracket S, \delta_0, \ldots, \delta_m \rrbracket$ lies in $\mathcal{O}_{TS_{a,\eta}^{\geq \eta_0}}$ (resp. $\mathcal{O}_{TS_{k,\log}^{a,\eta_0}}$) if and only if it has bounded norms for all $| \cdot |_{TS_{a,\eta}^0}$ (resp. $| \cdot |_{TS_{k,\log}^{a,\eta}}$) for all $\eta \in [\eta_0, 1)$.

**Remark 3.2.5.** We need $a \in \mathbb{Q}$ in Definition 3.2.1 to make sure that (3.2.2) and (3.2.3) actually define a (Berkovich) rigid analytic space. For individual spaces $TS_{a,\eta}^{\geq \eta_0}$ and $TS_{k,\log}^{a,\eta}$, one can allow $a \in \mathbb{R}$.

**Notation 3.2.6.** For $a \in \mathbb{Q}_{>1}$ and $\eta_0 \in (0, 1)$, denote by $\Delta : Z_{k,\log}^{\geq \eta_0} \hookrightarrow TS_{a,\eta}^{\geq \eta_0}$ the natural embedding of $Z_{k,\log}^{\geq \eta_0}$ into the locus where $\delta_j = 0$ for $j \in J^+$. Also, we have the naïve projection $\pi : TS_{k,\log}^{a,\eta_0} \to Z_{k,\log}^{\geq \eta_0}$ to the first factor.

For $a \in \mathbb{Q}_{>0}$, we define likewise $\Delta : Z_{k,\log}^{< \eta_0} \hookrightarrow TS_{a,\eta}^{< \eta_0}$ and $\pi : TS_{k,\log}^{a,\eta_0} \to Z_{k,\log}^{< \eta_0}$.

All these morphisms remain compatible under changes in $a$ and $\eta_0$, and under the replacement of $\geq \eta_0$ by $\eta$ for some $\eta \in (\eta_0, 1)$.

To simplify notation, for $a$ and $\eta_0$ as above, we identify $\mathcal{O}_{Z_{k,\log}^{\geq \eta_0}}$ with a subring of $\mathcal{O}_{TS_{k,\log}^{a,\eta_0}}$ and of $\mathcal{O}_{TS_{k,\log}^{a,\eta_0}}$ via $\pi^*$, and likewise for $\eta$ instead of $\geq \eta_0$. Note that $\pi^*$ is an isometry; hence the identification will not change any calculation on norms.

Corollary 2.1.10 has this immediate consequence:

**Proposition 3.2.7.** There is a unique continuous $\mathcal{O}_{K_0}$-homomorphism

$$\tilde{\pi}^* : \mathcal{O}_K \llbracket S \rrbracket \to \mathcal{O}_K \llbracket S, \delta_J \rrbracket$$

such that $\tilde{\pi}^*(S) = S + \delta_0$ and $\tilde{\pi}^*(B_j) = B_j + \delta_j$ for all $j \in J$. Moreover, for $g \in \mathcal{O}_K$, $\tilde{\pi}^*(g) - g \in (\delta_1, \ldots, \delta_m)(g)\mathcal{O}_K [\delta_1, \ldots, \delta_m]$.

**Theorem 3.2.8.** For $a \in \mathbb{Q}_{>1}$ (resp. $a \in \mathbb{Q}_{>0}$) and $\eta_0 \in (0, 1)$, the homomorphism $\tilde{\pi}^*$ induces a $\mathcal{O}_{K_0}$-homomorphism $\tilde{\pi}^* : \mathcal{O}_{Z_{k,\log}^{\eta_0}} \to \mathcal{O}_{TS_{k,\log}^{a,\eta_0}}$ (resp. $\tilde{\pi}^* : \mathcal{O}_{Z_{k,\log}^{\eta_0}} \to \mathcal{O}_{TS_{k,\log}^{a,\eta_0}}$) such that $\Delta^* \circ \tilde{\pi}^* = \text{id}$; the same if replacing $\geq \eta_0$ by $\eta$ for some $\eta \in [\eta_0, 1)$.

For any $g \in \mathcal{O}_{Z_{k,\log}^{\eta_0}}$ and for $a > 1$ (resp. $a > 0$),

$$|\tilde{\pi}^*(g) - g|_{TS_{a,\eta}} \leq \eta^{a-1} \cdot |g|_{Z_{k,\log}^{\eta}} \quad (\text{resp. } |\tilde{\pi}^*(g) - g|_{TS_{k,\log}^{a,\eta}} \leq \eta^{a} \cdot |g|_{Z_{k,\log}^{\eta}}). \quad (3.2.9)$$

In particular, $|\tilde{\pi}^*(g)|_{TS_{a,\eta}} = |\tilde{\pi}^*(g)|_{TS_{k,\log}^{a,\eta}} = |g|_{Z_{k,\log}^{\eta}}$. Moreover, we have the following bound for $TS_{a,\eta}^{\geq \eta}$. If $g \in \mathcal{O}_{Z_{k,\log}^{\eta}} \cap \mathcal{O}_K \llbracket S \rrbracket$, then

$$|\tilde{\pi}^*(g) - g|_{TS_{k,\log}^{a,\eta}} \leq \eta^{a}. \quad (3.2.10)$$

**Proof.** We need only to establish the bound on the norms. Take

$$g = \sum_{i \in \mathbb{Z}} a_i S^i \in K \llbracket S \rrbracket$$
such that \(|g|Z_k^\eta < +\infty\). We have

\[
\tilde{\pi}^*(g) - g = \sum_{i \in \mathbb{Z}} (\tilde{\pi}^*(a_i)(S + \delta_0)^i - a_i S^i)
\]

\[
= \sum_{i \in \mathbb{Z}} ((\tilde{\pi}^*(a_i) - a_i)(S + \delta_0)^i + a_i((S + \delta_0)^i - S^i)).
\] (3.2.11)

Since \(\tilde{\pi}^*(a_i) - a_i \in (\delta_1, \ldots, \delta_m)(a_i) \cap K[\delta_1, \ldots, \delta_m]\), we have

\[
|\tilde{\pi}(a_i) - a_i|_{TS^{a,\eta}} \leq |a_i|\eta^a, \quad |\tilde{\pi}(a_i) - a_i|_{TS^{a,\log}} \leq |a_i|\eta^a.
\] (3.2.12)

We can bound \((S + \delta_0)^i - S^i\) by

\[
|(S + \delta_0)^i - S^i|_{TS^{a,\eta}} \leq \eta^{a+i-1}, \quad |(S + \delta_0)^i - S^i|_{TS^{a,\log}} \leq \eta^{a+i}.
\] (3.2.13)

Plugging the estimates (3.2.12) and (3.2.13) into (3.2.11), we obtain (3.2.9). When \(g \in \mathcal{O}_K[S]\), (3.2.13) always gives \(|(S + \delta_0)^i - S^i|_{TS^{a,\log}} \leq \eta^d\) for \(i \geq 0\) (when \(i = 0\), we have zero). Equation (3.2.10) follows.

Finally, the equalities \(|\tilde{\pi}^*(g)|_{TS^{a,\eta}} = |\tilde{\pi}^*(g)|_{TS^{a,\log}} = |g|Z_k^\eta\) ensure that we have well-defined continuous homomorphisms \(\tilde{\pi}^*: \mathcal{O}(Z_k^{\geq \eta_0}) \to \mathcal{O}(TS^{a,\log})\) or \(\mathcal{O}(TS^{a,\log})\).

**Notation 3.2.14.** We use \(\tilde{\pi}: TS^{a,\geq \eta_0}_k \to Z_k^{\geq \eta_0}\) and \(\tilde{\pi}: TS^{a,\geq \eta_0}_{k,\log} \to Z_k^{\geq \eta_0}\) to denote the geometric incarnations of the homomorphisms \(\tilde{\pi}^*\) constructed in Theorem 3.2.8; the same for \(\eta\) in place of \(\geq \eta_0\) when \(\eta \in [\eta_0, 1)\). To emphasize again, whenever we refer to \(\tilde{\pi}\), strictly speaking, we are referring to the corresponding homomorphism \(\tilde{\pi}^*\) on rings.

**Remark 3.2.15.** For \(a > 0\), one can factor the map \(\tilde{\pi}\) for a nonlog thickening space as \(TS^{a,1,\geq \eta_0}_k \to TS^{a,\geq \eta_0}_{k,\log} \to Z_k^{\geq \eta_0}\), where the second map is the \(\tilde{\pi}\) for the log-thickening space. Again, this should be thought of as factorization for ring homomorphisms.

**Notation 3.2.16.** For a \(\nabla\)-module \((\mathcal{E}, \nabla_{\mathcal{E}})\) over \(Z_k^{\geq \eta_0}\) relative to \(K_0\), we call \(\tilde{\pi}^*\mathcal{E}\) the **thickened differential module** of \(\mathcal{E}\), denoted by \(\mathcal{F}\). We view \(\mathcal{F}\) as a differential module over \(TS^{a,\geq \eta_0}_k\) or \(TS^{a,\geq \eta_0}_{k,\log}\) relative to \(Z_k^{\geq \eta_0}\), with respect to the differential operators \(\partial/\partial \delta_0, \ldots, \partial/\partial \delta_m\). In precise terms, the connection is given by

\[
\mathcal{F} = \mathcal{E} \otimes_{\mathcal{O}_K^{\eta_0}} \tilde{\pi}^* \subset \Omega^1_{TS^{a,\geq \eta_0}_k/K_0} \otimes_{\mathcal{O}_K^{\eta_0}} \tilde{\pi}^* \mathcal{E}_{TS^{a,\geq \eta_0}_k/K_0}
\]

in the nonlog case. The log case is obtained similarly, with subscript log at the appropriate places. This construction is compatible for different \(a\)'s and \(\eta_0\)'s.
We next link the spectral norms on \( E \) and the spectral norms on its thickening \( \mathcal{F} \).

**Proposition 3.2.17.** Let \( \eta \in [\eta_0, 1) \). The spectral norms of \( \partial_{J^+} \) on \( E_\eta \) over \( \mathbb{Z}^\eta_k \) and the spectral norms of \( \partial/\partial \delta_{J^+} \) on \( \mathcal{F}_{a, \eta} = \mathcal{F} \otimes \text{Frac}(\mathcal{O}_{T_{S_k}^a, \eta}^\wedge) \) and \( \mathcal{F}_{a, \eta, \log} = \mathcal{F} \otimes \text{Frac}(\mathcal{O}_{T_{S_k}^a, \eta}^\wedge) \) are related as follows:

\[
\begin{align*}
|\partial/\partial \delta_j|_{\mathcal{F}_{a, \eta, \log}, \sp} &= \max\{|\partial_j|_{\mathcal{E}_\eta, \sp}, p^{-1/(p-1)} \eta^{-a}\} \quad &\text{for } j \in J^+, \\
|\partial/\partial \delta_0|_{\mathcal{F}_{a, \eta, \log}, \sp} &= \max\{|\partial_0|_{\mathcal{E}_\eta, \sp}, p^{-1/(p-1)} \eta^{-a-1}\}, \\
|\partial/\partial \delta_j|_{\mathcal{F}_{a, \eta, \log}, \sp} &= \max\{|\partial_j|_{\mathcal{E}_\eta, \sp}, p^{-1/(p-1)} \eta^{-a}\} \quad &\text{for } j \in J.
\end{align*}
\]

**Proof.** Note that \( \tilde{\pi}^*(d B_j) = d B_j + d \delta_j \) for \( j \in J \) and \( \tilde{\pi}^*(d S) = d S + d \delta_0 \). The actions of \( \partial/\partial \delta_j \), \( j \in J \) (resp. \( j = 0 \)), on \( \mathcal{F}_{a, \eta} \) and \( \mathcal{F}_{a, \eta, \log} \) are the same as the action of \( \partial/\partial B_j \) (resp. \( \partial/\partial S \)) on \( \mathcal{E}_\eta \). More precisely, we have \( \tilde{\pi}^*(\partial/\partial S(x)) = \partial/\partial \delta_0(\tilde{\pi}^*(x)) \) and \( \tilde{\pi}^*(\partial/\partial B_j(x)) = \partial/\partial \delta_j(\tilde{\pi}^*(x)) \) for any \( j \in J \) and \( x \in \mathbb{R}^\eta_k \) or \( \mathcal{E}_\eta \).

The statement follows, because that \( \delta_j \) are transcendental over \( \mathcal{O}_{Z_k}^\eta \) and the homomorphism \( \tilde{\pi}^* \) is isometric (by Theorem 3.2.8). \( \square \)

### 3.3. Good generators of the extension

We now show that when \( l/k \) is totally and wildly ramified, we can choose nice generators of \( \mathcal{O}_l \) as an \( \mathcal{O}_k \)-algebra, so that the corresponding extension on the Robba rings takes a simple form. Then we give a more explicit construction of the differential module associated with a \( p \)-adic representation.

We keep Hypothesis 2.3.2 for this subsection.

**Hypothesis 3.3.1.** For the rest of this section, we assume that \( l/k \) is a finite totally and wildly ramified Galois extension.

**Remark 3.3.2.** This is a mild hypothesis, since both arithmetic and differential conductors behave well under unramified extensions and the tamely ramified case is well-known: see Theorem 2.4.1(3) and Proposition 4.1.7(6).

**Notation 3.3.3.** Let \( l \) be as above, and let \( G_{l/k} \) denote the Galois group of \( l/k \). Denote the ring of integers and the residue field of \( l \) by \( \mathcal{O}_l \) and \( k_l \), respectively. Given a uniformizer \( t \) of \( l \), we fix a noncanonical isomorphism \( k_l((t)) \simeq l \). For a \( p \)-basis \( \bar{c}_j \) of \( k_l \), we use \( c_j \) to denote the image of \( \bar{c}_j \) under this isomorphism; we may use the same index set \( J \) because \( k_l/k_k \) is a finite extension.

Let \( \mathcal{O}_L \) be the Cohen ring of \( k_l \) with respect to \( \bar{c}_j \) and let \( C_J \) be the canonical lifts of \( \bar{c}_J \). Set \( L = \text{Frac} \mathcal{O}_L \).

**Caution 3.3.4.** The residue field extension \( k_l/k_k \) is typically not separable and hence cannot be embedded into the extension \( l = k_l((t)) \) over \( k = k_k((s)) \).

The reader may skip the next construction and remark on first reading. Their gist is to provide “good” generators and relations of \( \mathcal{O}_l \) as an \( \mathcal{O}_k \)-algebra.
Construction 3.3.5. We temporarily drop the finiteness Hypothesis 2.3.2 on the \(p\)-basis for this construction. Let \(k_0 = \kappa_k\) with \(p\)-basis \((\tilde{b}_j)_{j \in J}\). By possibly rearranging the indexing in \(\tilde{b}_J\), we will inductively construct a "good" \(p\)-basis \((\tilde{c}_j)_{j \in J}\) of \(\kappa_l\) and \(k_j = \kappa_k(\tilde{c}_1, \ldots, \tilde{c}_j)\) with \(p\)-basis \{\(\tilde{c}_1, \ldots, \tilde{c}_j, \tilde{b}_{J\setminus\{1, \ldots, j\}}\)\} so that \(k_m = \kappa_l\) for \(m\) sufficiently large.

Assume that we have constructed \(k_{j-1}\). Let \(r_j\) be the unique integer such that \(\kappa_l \subseteq k_{j-1}^{p^{-r_j}}\) but \(\kappa_l \not\subseteq k_{j-1}^{p^{-r_j+1}}\). If \(r_j = 0\), we must have \(k_{j-1} = \kappa_l\); in this case, we set \(\tilde{c}_\alpha = \tilde{b}_\alpha\) and \(r_\alpha = 0\) for all \(\alpha \in J\setminus\{1, \ldots, j-1\}\) and stop the induction. Otherwise we assume that \(r_j > 0\). Take \(\tilde{c}_j\) to be any element in \(\kappa_l \setminus k_{j-1}^{p^{-r_j+1}}\) and let \(k_j = k_{j-1}(\tilde{c}_j)\). Then \(\tilde{c}_j^{p^{r_j}} \in k_{j-1}\) and \([k_j : k_{j-1}] = p^{r_j}\). There must exist one element in \(\tilde{b}_{J\setminus\{1, \ldots, j-1\}}\) such that the rest together with \(\tilde{c}_1, \ldots, \tilde{c}_j\) form a \(p\)-basis of \(k_j\). We assume that this element is \(\tilde{b}_j\) by reindexing \(\tilde{b}_{J\setminus\{1, \ldots, j-1\}}\). This finishes the induction.

From the induction, one can see that the \(r_j\) form a decreasing sequence of nonnegative integers; but we do not need this fact.

Since \(\kappa_l/\kappa_k\) is finite, the construction ensures that \(\tilde{c}_j \in \kappa_k^\times\) for \(j \in J\setminus J_0\) with \(J_0 = \{1, \ldots, m\}\) a finite subset. By the functoriality of \(p\)-bases (Corollary 2.1.11), we may change the isomorphism \(\kappa_l((t)) \simeq l\) so that \(\tilde{c}_{J\setminus J_0}\) are sent to elements in \(\mathcal{O}_l^\times\). Let \(c_J\) denote the images of \(\tilde{c}_J\) under the above isomorphism.

As a consequence, \(c_1, \ldots, c_m\) and \(t\) generate \(\mathcal{O}_l\) over \(\mathcal{O}_k\). More precisely,

\[
\{ c_j^{p^i} t^j \mid i \in \{0, \ldots, e-1\}; \; j \in \{0, \ldots, p^{r_j} - 1\} \text{ for } j = 1, \ldots, m \}
\]

is a basis of \(\mathcal{O}_l\) as a finite free \(\mathcal{O}_k\)-module. It is also a basis of \(l\) as a \(k\)-vector space.

Remark 3.3.6. It is attractive to hope that we can find a \(p\)-basis \((\tilde{b}_j)_{j \in J}\) of \(\kappa_k\) such that \(\kappa_l = \kappa_k(\tilde{b}_j^{p^{-r_j}})\) for some \(r_j \in \mathbb{Z}_{\geq 0}\). But this is false in general, as pointed out to us by Shun Ohkubo; a counterexample is provided by [Sweedler 1968, Example 1.1]. Sweedler called the case where such a basis can be found modular.

Let \(\kappa_0\) be a perfect field of characteristic \(p\) and let \(X, Y, Z\) be indeterminates. Set \(\kappa_k = \kappa_0(X^p, Y^p, Z^p)\) and \(\kappa_l = \kappa_k(Z, XY + Z)\). Then \([\kappa_l : \kappa_l \cap \kappa_k^{p^{-r}}] = p^2\) and \([\kappa_l \cap \kappa_k^{p^{-r}} : \kappa_k] = p\). Hence, \(\kappa_l/\kappa_k\) cannot be modular.

Now we go back to assuming Hypothesis 2.3.2.

Notation 3.3.7. For a nonarchimedean ring \(R\), we use \(R\{u_0, \ldots, u_m\}\) to denote the completion of \(R[u_0, \ldots, u_m]\) with respect to the natural topology induced from \(R\). When \(R = F\) is a complete nonarchimedean field, \(F\{u_0, \ldots, u_m\}\) is the ring of analytic functions on the unit polydisc \(A_{F,1}^{m+1}[0, 1]\).

Notation 3.3.8. Let \(\mathcal{O}_k\{u_0, \ldots, u_m\}/\mathfrak{F} \xrightarrow{\sim} \mathcal{O}_l\) be the homomorphism that sends \(u_0\) to \(t\) and \(u_j\) to \(c_j\), for each \(j \in J\). We choose a set of generators \(p_0, \ldots, p_m\) of \(\mathfrak{F}\) as follows: each \(c_j^{p^{r_j}}\) or \(t^c\) can be written in terms of the basis of \(\mathcal{O}_l\) over \(\mathcal{O}_k\) listed in
Construction 3.3.5. This gives us an element $p_j$ in $\mathcal{H}$ (the index $j = 0$ being used for $t^e$). Obviously, the $p_i$ generate $\mathcal{H}$. Moreover,

\[ p_0 \in u_0^e - ds + (u_0s, s^2) \cdot \mathcal{O}_k[u_0, \ldots, u_m], \]
\[ p_j \in u_j^{p^f_j} - b_j + (u_0, s) \cdot \mathcal{O}_k[u_0, \ldots, u_m] \quad \text{for } j = 1, \ldots, m, \]

where $b_j$ is a polynomial in $u_1, \ldots, u_{j-1}$ with coefficients in $\mathcal{O}_k$ and with degree on $u_j$ strictly smaller than $p^f_j$ for $j' = 1, \ldots, j - 1$, and $d \in \mathcal{O}_k[u_J]$ such that $d(c_1, \ldots, c_m) \in \mathcal{O}_k^s$. Let $\bar{b}_j$ be the reduction of $b_j$ in $\kappa_k[u_1, \ldots, u_{j-1}]$.

Remark 3.3.9. The need for introducing $d$ was pointed out to us by Shun Ohkubo: in general, one may not be able to find uniformizers $s$ and $t$ of $k$ and $l$, respectively, such that $t^e \equiv s \mod t^{e+1}\mathcal{O}_l$. This is shown by the next example, provided by Ohkubo. (We do not know if there is a counterexample for which $L/K$ is Galois.)

Example 3.3.10. Let $k$ be a complete discretely valued field with nonperfect residue field $\kappa_k$. Let $b \in \mathcal{O}_k$ be such that $\bar{b} \in \kappa_k \setminus \kappa_k^p$. Choose $\alpha, \beta \in \bar{K}$ as follows: let $\alpha$ be a root of polynomial $X^p + sX + b \in k[X]$ and $\beta$ a root of polynomial $Y^p + sY + sa \in k(\alpha)[Y]$. Let $l = k(\alpha, \beta)$. Then $l/k$ is a separable extension of degree $p^2$ with naïve ramification degree $p$. The rings of integers of $k(\alpha)$ and $k(\alpha, \beta)$ are $\mathcal{O}_l(\alpha)$ and $\mathcal{O}_l(\alpha, \beta)$, respectively. We claim that we cannot choose uniformizers $t$ and $s$ so that $t^p/s = 1 \mod m_l$.

It is clear that $\beta$ is a uniformizer of $l$. For any uniformizer $t$ of $l$,

\[ \frac{t^p}{s} = \frac{\beta^p}{s} \left( \frac{1}{\beta} \right)^p \in (\alpha - \beta)(\mathcal{O}_l^\times)^p \xrightarrow{(\mod m_l)} (-\alpha)\kappa_l^p \subset \kappa_l. \]

In particular, $t^p/s$ is not congruent to $1$ modulo $m_l$.

Remark 3.3.11. Generally, the kernel of $\mathcal{O}_k[u_0, \ldots, u_m] \to \mathcal{O}_l$ is not generated by $p_0, \ldots, p_m$. This will not matter since we take $a > 0$ and $a > 1$ in Definition 3.2.1.

Construction 3.3.12. For each $j \in J$, fix an element in $\mathcal{O}_l[T]$ lifting $b_j \in \mathcal{O}_k \subset \kappa_l[T]$; also fix an element in $T^e + T^{e+1}\mathcal{O}_l[T]$ lifting $s \in \mathcal{O}_k \subset \kappa_l[T]$. By Proposition 2.1.8, there exists a continuous homomorphism $f^* : C_k \hookrightarrow C_l$ sending $B_J$ and $S$ to the elements chosen above; it naturally restricts to $f^* : \mathcal{O}_k[S] \hookrightarrow \mathcal{O}_l[T]$.

The proof of the following lemma is not enlightening. The reader may skip it on a first reading. The upshot is that we can turn the good generators and relations of $\mathcal{O}_l$ as an $\mathcal{O}_k$-algebra into good generators and relations of $\mathcal{R}_K^{0^e}$ as an $\mathcal{R}_K^{0^e}$-algebra.

Lemma 3.3.13. Keep the notation as above.

1. The homomorphism $f^*$ is finite, and $C_1, \ldots, C_m$ and $T$ generate $\mathcal{O}_l[T]$ over $\mathcal{O}_K[S]$. Hence, $f^*$ induces a surjective map $\mathcal{O}_K[S](U_0, \ldots, U_m) \twoheadrightarrow \mathcal{O}_l[T]$ sending $U_0$ to $T$ and $U_j$ to $C_j$ for $j \in J$. Moreover, one can choose generators
$P_0, \ldots, P_m$ of the kernel so that, modulo $p$, they are exactly $p_{j^*}$ in Notation 3.3.8. In particular,

$$P_0 \in U_0^e - \mathfrak{B} S + (p, U_0 S, S^2) \cdot \mathcal{O}_K[[S]](U_0, \ldots, U_m),$$

$$P_j \in U_j^{p_{j^*}} - \mathfrak{B}_j + (p, U_0, S) \cdot \mathcal{O}_K[[S]](U_0, \ldots, U_m),$$

where $\mathfrak{B}_j$ is a polynomial in $U_1, \ldots, U_{j-1}$ with coefficients in $\mathcal{O}_K$ and with degree on $U_{j'}$ strictly smaller than $p^{j'}$ for $j' = 1, \ldots, j - 1$, and $\mathfrak{B} \in \mathcal{O}_K[U_j]$ lifts $\mathfrak{a}$. Moreover, $\{U_{j^*}^{e_{j^*}^+} \mid 0 \leq e_0 < e; 0 \leq e_j < p^{j'}, j \in J\}$ form a basis of $\mathcal{O}_K[[S]](U_0, \ldots, U_m)/(P_{j^*})$ over $\mathcal{O}_K[[S]]$.

(2) The map $f^*$ extends to a map $f^*_n : K(\eta/S, S/\eta) \to L(\eta^{1/e}/T, T/\eta^{1/e})$ for $\eta \in [0, 1)$. Thus $f^*$ extends by continuity to a homomorphism $f^* : \mathcal{R}_K^{0/e} \to \mathcal{R}_L^{0/e}$, or in geometric notation, $f : A_K^\dagger[\eta_0, 1) \to A_L^\dagger[\eta_0^{1/e}, 1)$ for $\eta_0 \in (0, 1)$.

(3) Let $\Gamma_K^\dagger$ and $\Gamma_L^\dagger$ be the integral Robba rings over $K$ and $L$, respectively, similarly constructed as in Construction 2.2.8 but without tensoring with $F$. Let $\mathcal{R}_L$ be the Robba ring over $L$ as in Notation 2.2.13. Then $\Gamma_L^\dagger$ is a finite étale extension of $\Gamma_K^\dagger$ with Galois group $G_{l/k}$. Moreover, $\mathcal{R}_L \simeq \Gamma_L^\dagger \otimes_{\Gamma_K^\dagger} \mathcal{R}_K$.

(4) For some $\eta_0 \in (0, 1)$, $A_L^\dagger[\eta_0^{1/e}, 1)$ is Galois étale over $\eta \in [\eta_0, 1)$ via $f^*$ with Galois group $G_{l/k}$. Hence, $\mathcal{R}_L^{0/e}$ becomes a regular $G_{l/k}$-representation over $\mathcal{R}_K^{0/e}$ via $f^*$.

**Proof.** (1) is equivalent to its mod $p$ version, which is exactly Construction 3.3.5.

(2) It suffices to prove that $f^*$ is continuous with respect to the norms $|\cdot|_{Z_{l/k}^{0/e}}$ on $C_k$ and $|\cdot|_{Z_{l/k}^{1/e}}$ on $C_l$, for all $\eta \in [\eta_0, 1)$. Since $f^*(\mathcal{O}_K) \subset \mathcal{O}_L[[T]]$ and $f^*(\mathfrak{S}) \subset T^{e} + T^{e+1}\mathcal{O}_L[[T]]$, we have $|g|_{Z_{l/k}^{0/e}} = |f^*(g)|_{Z_{l/k}^{1/e}}$ for any $g \in C_k$. Hence the map $f^*$ extends continuously to $f^*_n : K(\eta/S, S/\eta) \to L(\eta^{1/e}/T, T/\eta^{1/e})$.

(3) The first statement follows from Lemma 2.2.10. The second statement is true because $\Gamma_L^\dagger \otimes_{\Gamma_K^\dagger} \mathcal{R}_K$ is complete and dense in $\mathcal{R}_L$.

(4) follows from (2) and (3) since $\mathcal{R}_K$ and $\mathcal{R}_L$ are limits of $\mathcal{R}_K^{0/e}$ and $\mathcal{R}_L^{0/e}$, respectively. \hfill $\square$

**Remark 3.3.14.** The homomorphism $f^*$ does not respect the naïve $K$-algebra structure on $\mathcal{R}_K^{0/e}$; this is precisely because of Caution 3.3.4. But it respects the $K$-algebra structure on $\mathcal{R}_K^{0/e}$ induced by $\mathcal{O}_K \hookrightarrow \mathcal{O}_K[[S]] \twoheadrightarrow \mathcal{O}_L[[T]]$. So, it might be better not to view $Z_{l/K}^{0/e} \to Z_K^{0/e}$ as a morphism between rigid spaces, but rather as the geometric incarnation of $f^*$.

**Construction 3.3.15.** Keep the notation as in Construction 2.2.15. Let $\rho : G_{l/k} \to \text{GL}(V_\rho)$ be a $p$-adic representation, where $V_\rho$ is a finite dimensional vector space
over $F$. We have
\[
\mathcal{E}_\rho = D^\dagger(\rho) \otimes_{\Gamma_K} \mathcal{R}_K = (V_\rho \otimes_{\mathcal{O}} \tilde{\Gamma}^\dagger)G_k \otimes_{\Gamma_k} \mathcal{R}_K \\
= (V_\rho \otimes_{\mathbb{Z}_q} \Gamma_k^\dagger)G_{l/k} \otimes_{\Gamma_k} \mathcal{R}_K = (V_\rho \otimes_{\mathbb{Z}_q} \mathcal{R}_L)G_{l/k}.
\]
Hence, for some $\eta_0 \in (0, 1)$, the differential module $\mathcal{E}_\rho$ descends to
\[
\mathcal{E}_\rho = \left( V_\rho \otimes_{\mathbb{Z}_q} f_* \mathcal{O}_{\mathbb{Z}_l^{1/\eta_0}} \right)G_{l/k},
\]
this is a differential module over $\mathcal{R}_{K_0}^{0} \otimes_{\mathbb{Q}_d} F = \mathcal{R}_{K_0}^{0}$ relative to $K_0$. This construction respects tensor products, i.e., given another $p$-adic representation $\rho'$ of $G_{l/k}$ over $F$, we have
\[
\mathcal{E}_{\rho \otimes \rho'} = \mathcal{E}_\rho \otimes_{\mathcal{R}_K^{0}} \mathcal{E}_{\rho'}.
\]

**Hypothesis 3.3.16.** From now on, we always assume that $\eta_0 \in (0, 1)$ is close enough to $1^{-}$ that all statements in Lemma 3.3.13 hold and $\mathcal{E}_\rho$ descends to $\mathcal{R}_K^{0}$.

### 3.4. Spectral norms and connected components of thickening spaces.

We now relate the spectral norms of differential operators on $\mathcal{E}$ to the connected components of certain rigid spaces. We keep Hypotheses 2.3.2, 3.3.1, and 3.3.16 in this subsection.

**Definition 3.4.1.** Let $a \in \mathbb{Q}_{>0}$. We define
\[
\mathcal{O}_{TS_{l/k}^{a, \geq \eta_0}} = \mathcal{R}_{l/k}^{0} \otimes_{f^*, \mathcal{R}_{l/k}^{0}, \pi^*} \mathcal{O}_{TS_{l/k}^{a, \geq \eta_0}}, \\
\mathcal{C}_{TS_{l/k}^{a, \geq \eta_0}} = \mathcal{C}_{TS_{l/k}^{a, \geq \eta_0}} \otimes_{f^*, \mathcal{R}_{l/k}^{0}, \pi^*} \mathcal{C}_{TS_{l/k}^{a, \geq \eta_0}}, \\
\mathcal{C}_{TS_{l/k}^{a, \geq \eta_0}} = \mathcal{R}_{l/k}^{0} \otimes_{f^*, \mathcal{R}_{l/k}^{0}, \pi^*} \mathcal{C}_{TS_{l/k}^{a, \geq \eta_0}} \otimes_{f^*, \mathcal{R}_{l/k}^{0}, \pi^*} \mathcal{R}_{l/k}^{0}.
\]

Here we do not have to complete the tensor products because $f^*$ is finite. (We intentionally put the tensor products on different sides so that it is easy to distinguish the two base changes by $f^*$ through $\pi^*$ and $\tilde{\pi}^*$ respectively.) Let $TS_{l/k}^{a, \geq \eta_0}$, $TS_{k/l}^{a, \geq \eta_0}$, and $TS_{l/k/l}^{a, \geq \eta_0}$, respectively, denote the geometric incarnations of these rings. We have formally the following Cartesian diagram:

\[
\begin{array}{cccc}
Z^{1/\eta_0} & TS_{l/k}^{a, \geq \eta_0} & TS_{l/k/l}^{a, \geq \eta_0} \\
\downarrow f & \downarrow \bar{f} & \\
Z^{\geq \eta_0} & TS_{k/l}^{a, \geq \eta_0} & TS_{k/l}^{a, \geq \eta_0} \\
\end{array}
\]

(3.4.2)

We make similar constructions for the logarithmic version of all spaces if $a \in \mathbb{Q}_{>0}$.
Remark 3.4.3. The morphisms π and 1 × f are genuine morphisms between rigid spaces over $Z_{≥1/0}$, and $\tilde{f}$ and 1 × π are genuine morphisms between rigid spaces over $Z_{≥1/0}$. This is because the rigid space structures on thickening spaces are given by the projections π and 1 × π, respectively. In contrast, all the vertical arrows in (3.4.2) should all be thought of as just geometric incarnations of the corresponding ring homomorphisms.

Remark 3.4.4. The naïve base change $f \times 1$ helps to realize geometric connected components as connected components (see Theorem 3.4.12). The base change $\tilde{f}$ (and also $1 \times f$) encodes the ramification information, which is what we are interested in.

Remark 3.4.5. One may want to relate $TS_{≥1/0}$ to the thickening space of $Z_{≥1/0}$. However, it is not clear how to compare the levels or radii of the two spaces. We will not need this result.

Corollary 3.4.6. The space $TS_{≥1/0}$ admits an action of $G_{1/k}$ by morphisms between $K$-rigid spaces, obtained by pulling back the action on $Z_{≥1/0}$ over $Z_{≥1/0}$ via $\tilde{\pi} \circ (f \times 1)$. Under this action, $\tilde{f}_* \otimes_{TS_{≥1/0}}$ is a regular representation of $G_{1/k}$ over $\mathcal{O}_{TS_{≥1/0}}$. For a $p$-adic representation $\rho$ of $G_{1/k}$ over $F$, define

$$\tilde{\mathcal{F}}_\rho = (V_\rho \otimes_{\mathcal{O}_q} \tilde{f}_* \otimes_{TS_{≥1/0}})^{G_{1/k}};$$

this is a differential module over $TS_{≥1/0} \times_{\mathcal{O}_q} F$ relative to $Z_{≥1/0} \times_{\mathcal{O}_q} F$. Moreover, $\tilde{\mathcal{F}}_\rho \simeq (f \times 1)^* \tilde{\pi}^* \mathcal{E}_\rho$.

The same statement also holds for log-space.

Proof. The differential module structure on $\tilde{f}_* \otimes_{TS_{≥1/0}}$ is given by the composition of natural homomorphisms

$$\tilde{f}_* \otimes_{TS_{≥1/0}} \longrightarrow \tilde{f}_*(\Omega^1_{TS_{≥1/0}} / Z_{≥1/0}) \simeq \tilde{f}_*(\Omega^1_{TS_{≥1/0}} / Z_{≥1/0}) \simeq \tilde{f}_* \otimes_{TS_{≥1/0}} \Omega^1_{TS_{≥1/0}} / Z_{≥1/0}.$$

(In fact this construction works for any finite étale morphisms.) The statement of the corollary is an easy consequence of flat base change for the two Cartesian squares on the right in (3.4.2).

Notation 3.4.7. We may view $1 \times \pi : TS_{≥0} \rightarrow Z_{≥0}^{1/0}$ as bundles, whose fibers are polydiscs (of different radii) with parameters $\delta_0, \ldots, \delta_m$; again this morphism is a genuine morphism between rigid spaces. By the zero section $Z$, we mean the natural closed subspace of this bundle defined by $\delta_0 = 0, \ldots, \delta_m = 0$.

Notation 3.4.8. Let $M$ be a differential module over a differential ring $R$ with derivatives $\partial_1, \ldots, \partial_n$. For $x \in M$ and $r_1, \ldots, r_n \in R$, we define the Taylor series
\[ \mathbb{T}(x; \partial_1, \ldots, \partial_n; r_1, \ldots, r_n) = \sum_{\alpha_1, \ldots, \alpha_n \in \mathbb{Z}_{\geq 0}} \frac{r_1^{\alpha_1} \cdots r_n^{\alpha_n} \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n}}{n!}(x), \]

if it converges. If \( x \in R \), we have \( \mathbb{T}(ax; \partial_1, \ldots, \partial_n; r_1, \ldots, r_n) = \mathbb{T}(a; \partial_1, \ldots, \partial_n; r_1, \ldots, r_n) \cdot \mathbb{T}(x; \partial_1, \ldots, \partial_n; r_1, \ldots, r_n) \) if all terms converge.

**Notation 3.4.9.** Let \( M \) be a differential module over a differential ring \( R \) with derivatives \( \partial_1, \ldots, \partial_n \). Let \( H^0_\nabla(R, M) = \{ x \in M \mid \partial_i(x) = 0, i = 1, \ldots, n \} \) be the set of horizontal sections of \( M \) over \( R \). In particular, if \( r_1, \ldots, r_n \in R \) are elements such that \( \partial_i(r_j) = 1 \) if \( i = j \) and 0 otherwise, then an elementary calculation shows that the Taylor series \( \mathbb{T}(x; \partial_1, \ldots, \partial_n; r_1, \ldots, r_n) \) is an element in \( H^0_\nabla(R, M) \) for any \( x \in M \) such that the Taylor series converges.

We usually use the geometric counterparts in places of \( R \) and \( M \) in the notation. For example, we write \( H^0_\nabla(\text{Max}(R), M) \) if \( R \) is an affinoid algebra.

The following lemma will be frequently used in proving the theorem below. It works in greater generality, but we content ourselves with this special case.

**Lemma 3.4.10 (Dwork’s transfer theorem).** Let \( a > 1 \). Let \( \tilde{\mathcal{F}} \) be a differential module over \( TS_{l/k}^{c, \leq \eta_0} \) relative to \( Z_l^{\geq \eta_0^{1/c}} \). Assume \( |\partial/\partial \delta_i|_{\tilde{\mathcal{F}}_{l/k}} \leq p^{-1/(p-1)} \eta^{-a} \) for all \( j \in J \) and \( \eta \in [\eta_0, 1) \). Then, for any rational number \( c > a \), the natural homomorphism of finite \( \tilde{\mathcal{O}}_{l/k}^{0,c,\eta} \)-modules

\[ \Theta : H^0_\nabla(TS_{l/k}^{c, \geq \eta_0}, \tilde{\mathcal{F}}) \rightarrow \Gamma(Z, \tilde{\mathcal{F}}|_Z) \] (3.4.11)

is an isomorphism. In particular, \( \tilde{\mathcal{F}} \) is a trivial \( \nabla \)-module relative to \( Z_l^{\geq \eta_0^{1/c}} \). The same statement is also true if we base-change everything to \( F \) over \( \mathbb{Q}_q \). When \( \tilde{\mathcal{F}} = f_*\mathcal{O}_{TS_{l/k}^{c, \geq \eta_0}} \), \( \Theta \) induces a ring homomorphism for any rational number \( c > a \):

\[ \Gamma(Z, f_*\mathcal{O}_{TS_{l/k}^{c, \geq \eta_0}}|_Z) \xrightarrow{\Theta} H^0_\nabla(TS_{l/k}^{c, \geq \eta_0}, f_*\mathcal{O}_{TS_{l/k}^{c, \geq \eta_0}}) \hookrightarrow \Gamma(TS_{l/k}^{c, \geq \eta_0}, f_*\mathcal{O}_{TS_{l/k}^{c, \geq \eta_0}}). \]

The same statements hold for the log version with \( a > 0 \), inserting the subscript \( \log \) appropriately.

**Proof.** We prove the lemma for the nonlog case over \( \mathbb{Q}_q \). The proof for the log case differs only by inserting subscript \( \log \) appropriately, using the \( \delta_0 \) coordinate, and increasing the exponents on \( \eta \) by 1. The proof for the tensor \( F \) version is also the same, except we need to tensor \( F \) everywhere.

We may define an inverse of the map \( \Theta \) using Taylor series:

\[ \Theta^{-1}(x) = \mathbb{T}(\hat{x}; \partial/\partial \delta_0, \ldots, \partial/\partial \delta_m; \delta_0, \ldots, \delta_m) \]

for \( x \in \Gamma(Z, \tilde{\mathcal{F}}|_Z) \), where \( \hat{x} \) is a lift of \( x \) in \( \Gamma(TS_{l/k}^{c, \geq \eta_0}, \tilde{\mathcal{F}}) \). The Taylor series converges over \( TS_{l/k}^{c, \geq \eta_0} \) by the condition \( |\partial/\partial \delta_i|_{\tilde{\mathcal{F}}_{l/k}} \leq p^{-1/(p-1)} \eta^{-a} < p^{-1/(p-1)} \eta^{-c} \) for all \( j \in J \) and \( \eta \in [\eta_0, 1) \). Moreover, the Taylor series converges to a horizontal section in \( H^0_\nabla(TS_{l/k}^{c, \geq \eta_0}, \tilde{\mathcal{F}}) \).
When \( \tilde{\mathcal{F}} = f_* \mathcal{T}_{S_{I,k}}^{c, \geq n_0} \), \( \Theta \) is a homomorphism, which can also be seen from the fact that the Taylor series gives a ring homomorphism (see Notation 3.4.8).

The following theorem is one of the key steps of the proof of the Hasse–Arf theorem. This is the main ingredient (a) described in the introduction. It allows us to compare the differential ramification breaks with the geometric connected components of the thickening spaces; we will later identify the thickening spaces with the lifts of the Abbes–Saito spaces (Theorem 4.3.6).

**Theorem 3.4.12.** Let \( \rho : G_{l/k} \to \text{GL}(V_\rho) \) be a faithful \( p \)-adic representation over \( F \) with \( l/k \) satisfying Hypotheses 2.3.2 and 3.3.1. Then, for \( b > 1 \), the following conditions are equivalent:

(a) \( \rho \) has differential ramification break \( \leq b \).

(b) For any rational number \( c > b \), when \( \eta_0 \to 1^- \), \( \tilde{\mathcal{F}} = \mathcal{F}_\rho \) is a trivial \( \nabla \)-module over \( TS_{I,k}^{c, \geq n_0} \times_{\mathbb{Q}_q} F \) relative to \( Z_{I,k}^{\geq n_0/e, \eta} \times_{\mathbb{Q}_q} F \).

(c) For any rational number \( c > b \), when \( \eta_0 \to 1^- \), \( TS_{I,k}^{c, \geq n_0} \) has exactly \( [l : k] \) connected components.

(d) For any rational number \( c > b \), when \( \eta_0 \to 1^- \), \( Z_{p}^{\geq n_0/e, \eta} \times_{\mathbb{Z}_p} \pi, TS_{I,k}^{c, \geq n_0} \) has exactly \( [l : k] \) connected components for some finite extension \( l'/l \), where \( e' \) is the naïve ramification degree of \( l'/k \).

For \( b > 0 \), the corresponding conditions for logarithmic spaces are equivalent.

**Proof.** We prove the statement for nonlogarithmic spaces; in the logarithmic case we just need to add the subscript log and change the scales on \( \partial_0 \) and \( \partial/\partial\delta_0 \) from \( \eta^b \) to \( \eta^{b+1} \) and \( \eta^e \) to \( \eta^{e+1} \).

Further, Proposition 3.2.17 is unchanged if we replace \( \mathcal{F} \) by \( \tilde{\mathcal{F}} \), since the spectral norms are invariant under scalar extensions.

We first that (a) implies (b). Assume \( \rho \) has differential ramification break at most \( b \). By Definition 2.3.20, for \( \eta_0 \) sufficiently close to \( 1^- \), the generic radius of \( \mathcal{E}_\rho \) satisfies \( T(E_\rho, \eta) \geq \eta^b \) for \( \eta \in [\eta_0, 1) \), or equivalently \( |\partial_j|_{\mathcal{E}_{p, a, sp}} \leq p^{-1/(p-1)} \eta^{-b} \) for any \( j \in J^+ \) and \( \eta \in [\eta_0, 1) \). Then Proposition 3.2.17 and Remark 2.3.5 imply that for all \( \eta \in [\eta_0, 1) \), \( |\partial/\partial\delta_j|_{\tilde{\mathcal{F}}_{c, n, sp}} \leq p^{-1/(p-1)} \eta^{-b} \), and hence \( \tilde{\mathcal{F}}_\rho \) is a trivial differential module over \( TS_{I,k}^{c, \geq n_0} \times_{\mathbb{Q}_q} F \) relative to \( Z_{I,k}^{\geq n_0/e, \eta} \times_{\mathbb{Q}_q} F \) for any rational number \( c > b \) by Dwork’s transfer theorem (Lemma 3.4.10). This proves (b).

Now assume (b), i.e., \( \tilde{\mathcal{F}}_\rho \) is trivial over \( TS_{I,k}^{c, \geq n_0} \times_{\mathbb{Q}_q} F \) relative to \( Z_{I,k}^{\geq n_0/e, \eta} \times_{\mathbb{Q}_q} F \) for any rational number \( c > b \) and some \( \eta_0 \in (0, 1) \). It follows that

\[
|\partial/\partial\delta_j|_{\tilde{\mathcal{F}}_{c, n, sp}} = |\partial/\partial\delta_j|_{\text{Frac}(O_{\mathcal{E}_{p, a, sp}}^{c, n})^{c, sp}} = p^{-1/(p-1)} \eta^{-c}.
\]

By Proposition 3.2.17, \( |\partial|_{sp, \mathcal{E}_{\eta}} \leq p^{-1/(p-1)} \eta^{-c} \), for any \( j \in J^+, \eta \in [\eta_0, 1) \), and \( c \in \mathbb{Q}_{> b} \). By Definition 2.3.20, this implies that the differential ramification break is at most \( b \), since the rationals are dense in the real numbers.
Obviously, (c) implies (b). To see the converse, note first claim that if \( c > b \) is rational, \( f_\rho \circ T_{S_k^{c, \geq n_0}} \) is a trivial differential module over \( TS_{l/k}^{c, \geq n_0} \) relative to \( Z_{l/k}^{\geq n_0} \). Indeed, for a rational number \( c' \in (b, c) \), we know \( \tilde{T}_\rho \) is a trivial differential module over \( TS_{l/k}^{c', \geq n_0} \times \mathbb{Q}_q F \) relative to \( Z_{l/k}^{\geq n_0} \times \mathbb{Q}_q F \), then for any \( n \in \mathbb{N} \), \( \tilde{T}_\rho \otimes _\mathbb{Q}^n \) is also a trivial differential module (relative to \( Z_{l/k}^{\geq n_0} \times \mathbb{Q}_q F \)), which corresponds to \( V_{\rho}^n \) by functoriality (Construction 3.3.15). By Lemma 3.4.16 below from the theory of representations of finite groups (or standard Tannakian arguments), the differential module

\[ (F[G_{l/k}] \otimes \mathbb{Q}_q f_\rho \circ T_{S_k^{c', \geq n_0}})^{G_{l/k}} \xrightarrow{\cong} F \otimes \mathbb{Q}_q f_\rho \circ T_{S_k^{c', \geq n_0}} \]  

(3.4.13)

corresponding to the regular representation is a direct summand of a direct sum of some \( \tilde{T}_\rho \otimes _\mathbb{Q}^n \)'s and hence is a trivial differential module (relative to \( Z_{l/k}^{\geq n_0} \times \mathbb{Q}_q F \)). To make it perfectly rigorous, here the isomorphism (3.4.13) of differential modules is given by \( \sum \mathbb{g} \in G_{l/k} f_\mathbb{g} \otimes \mathbb{g} \mathbf{v} \mapsto f \cdot \mathbf{v} \), where \( f \in F \) and \( \mathbf{v} \in f_\rho \circ T_{S_k^{c', \geq n_0}} \); this map does not respect the \( F[G_{l/k}] \)-module structures.

We have finished the proof of the claim in the case \( F = \mathbb{Q}_p \). If \( F \neq \mathbb{Q}_p \), we know that, for all \( j \in J^+ \), the spectral norms of \( \partial / \partial \delta_j \) at radius \( \eta \) on the right-hand side of (3.4.13) are \( p^{-1/(p-1)} \eta^{-c'} \), which equal the spectral norms of \( \partial / \partial \delta_j \) on \( f_\rho \circ T_{S_k^{c', \geq n_0}} \) at radius \( \eta \). By Dwork's transfer theorem (Lemma 3.4.10), the claim is proved.

We now apply the second part of Lemma 3.4.10 and obtain, for any rational numbers \( c' > c \), a ring homomorphism

\[ \Gamma(Z, f_\rho \circ T_{S_k^{c', \geq n_0}} \big| Z) \xrightarrow{\cong} H_0^0(TS_{l/k}^{c', \geq n_0}, f_\rho \circ T_{S_k^{c', \geq n_0}}) \xrightarrow{\cong} \Gamma(TS_{l/k}^{c', \geq n_0}, \mathcal{O}_{TS_{l/k}^{c', \geq n_0}}). \]  

(3.4.14)

The key is that the left-hand side of (3.4.14) is isomorphic to the ring functions on \( Z_{l/k}^{\geq n_0} \times \mathbb{Q} \) because the restrictions of \( \tilde{\pi} \) and \( \pi \) to \( Z \) are both the same as \( f \). Moreover, since \( Z_{l/k}^{\geq n_0} \) is finite étale Galois over \( Z_{k}^{\geq n_0} \) (Lemma 3.3.13), \( Z_{l/k}^{\geq n_0} \times \mathbb{Q} \) is finite étale Galois over \( Z_{l/k}^{\geq n_0} \). In particular, we have fundamental idempotent elements in \( \Gamma(Z, f_\rho \circ T_{S_k^{c', \geq n_0}} \big| Z) \) corresponding to each connected component. Via the composition of the homomorphisms in (3.4.14), we can “lift” the idempotent elements on \( Z_{l/k}^{\geq n_0} \times \mathbb{Q} \) to idempotent elements in \( \mathcal{O}_{TS_{l/k}^{c', \geq n_0}} \). This shows that \( TS_{l/k}^{c', \geq n_0} \) has at least \([l : k]\) connected components. But this space is finite and flat of degree \([l : k]\) over an irreducible rigid space \( TS_{l/k}^{c', \geq n_0} \); it can have at most \([l : k]\) connected components. Therefore, (c) holds.

The equivalence between (b) and (d) can be proved similarly, using a version of Lemma 3.4.10 over \( Z_{l/k}^{\geq n_0} \). The upshot here is that we need a base change to at least \( Z_{l/k}^{\geq n_0} \) in (c) so that we can split the fiber over \( Z \); this is why we did not state the theorem for \( TS_{l/k}^{c', \geq n_0} \) and \( \tilde{T}_\rho \) themselves.

QED
Remark 3.4.15. The faithfulness condition on $\rho$ in the theorem is harmless: we will very easily reduce to this case later in the proof of Theorem 4.4.1.

Lemma 3.4.16. Let $G$ be a finite group and $F$ be a field of characteristic $0$. Let $\rho : G \rightarrow \text{GL}(V_\rho)$ be a faithful representation over $F$. Then the regular representation $F[G]$ is a direct summand of a direct sum of some self-tensor products of $V_\rho$.

This is an easy exercise of finite group representations but we do not know a good reference. The author thanks Xuhua He for providing the following proof.

Proof. Let $\chi$ be the character of $V_\rho$ and let $d$ be the dimension of $V_\rho$. Since the representation is injective, $\chi(1) = d$ and $\chi(g) \not= d$ for all $g \in G$ nontrivial. (This is because all the eigenvalues of $\rho(g)$ are roots of unity and cannot all be 1.)

Therefore, for each $g \not= 1$ there exists a polynomial $P_g$ in $\chi$ with integer coefficients such that $P_g(\chi(g)) = 0$ but $P_g(d) \not= 0$. Let $P = \prod_{1 \not= g \in G} P_g$; then $P(d) \not= 0$ but $P(\chi(g)) = 0$ for all $g \not= 1$. Multiplying by a constant, we may assume that $\#G$ divides $P(d)$ and $P(d) > 0$. If $P(X) = a_n X^n + \cdots + a_0 \in \mathbb{Z}[X]$, then $(V \otimes a_n \oplus \cdots \oplus V \otimes a_1 \oplus 1)_{F} = F[G]^{P(d)/\#G}$ in the Grothendieck group of the representations of $G$, where $1_F$ denotes the trivial representation. Consequently, if we take the direct sum of the terms on the left-hand side with positive $a_i$, the regular representation will be a natural direct summand of it. \hfill \Box

4. Arithmetic ramification filtrations

4.1. Review of Abbes and Saito’s definition. We briefly review the definition of arithmetic ramification filtrations on the Galois group of a complete discretely valued field $k$. For more details, consult [Abbes and Saito 2002; 2003]. The filtrations can be defined for a $k$ of mixed characteristic; however, for the purpose of this paper, we focus on the case where $k$ is of equal characteristic $p > 0$.

In this subsection, we do not make any of the hypothesis we have been using in previous sections.

Notation 4.1.1. Keep the notation as in previous sections. Fix uniformizers $s$ and $t$ for $k$ and $l$, respectively. Let $\nu_l(\cdot)$ be the valuation on $l$ normalized so that $\nu_l(t) = 1$. Let $\theta = |s|$.

Notation 4.1.2. In this subsection, we temporarily free $j$ and $J$ from the restraint introduced in Notation 2.3.3. But in later applications, we will specialize to the case in which $j$ and $J$ actually index $p$-bases.

Definition 4.1.3. Take $Z = (z_j)_{j \in J} \subset \mathcal{O}_l$ to be a finite set of elements generating $\mathcal{O}_l$ as an $\mathcal{O}_k$-algebra, i.e., $\mathcal{O}_k[(u_j)_{j \in J}]/\mathcal{J} \xrightarrow{\sim} \mathcal{O}_l$ mapping $u_j$ to $z_j$ for $j \in J = \{1, \ldots, m\}$ and for some appropriate ideal $\mathcal{J}$. Let $(f_i)_{i=1,\ldots,n}$ be a finite set of generators of $\mathcal{J}$. For $a \in \mathbb{Q}_{>0}$, define the (nonlogarithmic) Abbes–Saito space to be

$$a_{s^{\theta}_{f_i}}_{l/k,Z} = \{(u_1, \ldots, u_m) \in A^m_k[0, 1] \mid |f_i(u_j)| \leq \theta^a, 1 \leq i \leq n\}. \quad (4.1.4)$$
The geometric connected components (see [Bosch et al. 1984, 9.1.4/8] for the definition) of \(a_{l/k,Z}^a\) are \(\pi_0^\text{geom}(a_{l/k,Z}^a)\). The arithmetic ramification break \(b_{ar}(l/k)\) is defined as the minimal number \(b\) such that \(\#\pi_0^\text{geom}(a_{l/k,Z}^a) = [l : k]\) for any \(a > b\).

**Definition 4.1.5.** Keep the notation as above. We single out a subset \(P \subset Z\) and assume that \(P\) and hence \(Z\) contain the uniformizer \(l\). For each \(j \in J\), let \(e_j = v_l(z_j)\). Take a lift \(g_j \in \mathbb{C}_k[(u_j)_{j \in J}]\) of \(z_j^{e_j}/s^{e_j}\) for each \(z_j \in P\), and take a lift \(h_{i,j} \in \mathbb{C}_k[(u_j)_{j \in J}]\) of \(z_i^{e_j}/z_i^{e_j}\) for each pair \((z_i, z_j) \in P \times P\). For \(a \in \mathbb{Q}_{>0}\), define the logarithmic Abbes–Saito space to be

\[
as_{l/k,\log,Z,P}^a = \begin{cases} (u_j) \in A_k^n[0, 1] & |f_i(u_j)| \leq \theta^a, \\ |u_i^e - s^{e_i}g_j| \leq \theta^{a+e_i}, & \text{for all } z_j \in P, \\ |u_j^{e_j} - u_i^{e_j}h_{i,j}| \leq \theta^{a+e_i/(e_j)} & \text{for all } (z_i, z_j) \in P \times P. \end{cases}
\]

Similarly, the logarithmic arithmetic ramification break \(b_{ar,\log}(l/k)\) is defined to be the minimal number \(b\) such that for any \(a > b\), \(\#\pi_0^\text{geom}(a_{l/k,\log,Z,P}^a) = [l : k]\).

**Remark 4.1.6.** To ease the readers who are not familiar with Abbes and Saito’s definition, we give an intuitive way to understand the definition following [Abbes and Saito 2002].

First, if \(a \to \infty\), the conditions on \(f_1, \ldots, f_n\) in (4.1.4) basically restrict the possible \(u_j\) to be very close to \(z_j\) or other solutions to the equations \(f_1 = 0, \ldots, f_n = 0\), which are exactly Galois conjugates of \(z_j\). Thus, one may believe that \(a_{l/k,Z}^a\) has exactly \([l : k]\) geometric connected components, each of which looks like a small polydisc centered at one of the solutions. In contrast, if \(a \to 0^+\), the conditions on \(f_1, \ldots, f_n\) are almost vacuum and \(a_{l/k,Z}^a\) is almost the whole unit polydisc. In particular, the space is likely to be geometrically connected. From the two extreme cases, we know that, when we increase \(a\), the Abbes–Saito space shrinks from a whole unit polydisc to smaller polydiscs and, at some \(a\), a bigger polydisc breaks apart into several smaller polydiscs. The arithmetic ramification break captures the last break point.

We reproduce several statements from [Abbes and Saito 2002; 2003].

**Proposition 4.1.7.** Abbes–Saito spaces have the following properties.

(1) For \(a > 0\), the spaces \(a_{l/k,Z}^a\) and \(a_{l/k,\log,Z,P}^a\) do not depend on the choice of generators \((f_i)_{i=1,\ldots,n}\) of \(\mathcal{F}\) and lifts \(g_j\) and \(h_{i,j}\) for \(i, j \in P\) [Abbes and Saito 2002, §3].

(1’) If, in the definition of both spaces, we choose polynomials \((f_i)_{i=1,\ldots,n}\) as a set of generators of \(\text{Ker}(\mathbb{C}_k[(u_j)_{j \in J}] \to \mathbb{C}_l)\) instead of \(\text{Ker}(\mathbb{C}_k[(u_j)_{j \in J}] \to \mathbb{C}_l)\), the spaces will not change.
(2) If we substitute in another pair of generating sets $Z$ and $P$ satisfying the same properties, then we have a canonical bijection on the sets of the geometric connected components $\pi_0^{\text{geom}}(\text{as}^p_{l/k,Z})$ and $\pi_0^{\text{geom}}(\text{as}^p_{l/k,\log,Z,P})$ for different generating sets, where $a > 0$. In particular, both highest arithmetic ramification breaks are well-defined [Abbes and Saito 2002, §3].

(3) The highest arithmetic ramification break (resp. highest logarithmic arithmetic ramification break) gives rise to a filtration on the Galois group $G_k$ consisting of normal subgroups $\text{Fil}^a G_k$ (resp. $\text{Fil}^a_{\log} G_k$) for $a > 0$ such that $b_{\text{ar}}(l/k) = \inf \{a \mid \text{Fil}^a G_k \subseteq G_l\}$ (resp. $b_{\text{ar,log}}(l/k) = \inf \{a \mid \text{Fil}^a_{\log} G_k \subseteq G_l\}$) [Abbes and Saito 2002, Theorems 3.3 and 3.11]. Moreover, for $l/k$ a finite Galois extension, both arithmetic ramification breaks are rational numbers [Abbes and Saito 2002, Theorems 3.8 and 3.16].

(4) Let $k'/k$ be an algebraic extension of complete discretely valued fields or the completion of such an extension. If $k'/k$ is unramified, then $\text{Fil}^a G_{k'} = \text{Fil}^a G_k$ for $a > 0$ [Abbes and Saito 2002, Proposition 3.7]. If $k'/k$ is tamely ramified with ramification index $e'$, then $\text{Fil}^a_{\log} G_{k'} = \text{Fil}^a_{\log} G_k$ for $a > 0$ [Abbes and Saito 2002, Proposition 3.15]. More generally, for a (not necessarily algebraic) extension $k'/k$ of complete discretely valued fields with the same valued group and linearly independent from $l/k$ such that $\mathcal{O}_{k'} = \mathcal{O}_k \otimes_{\mathcal{O}_k} \mathcal{O}_l$, we have $b_{\text{ar}}(lk'/k') = b_{\text{ar}}(l/k)$ and $b_{\text{ar,log}}(lk'/k') = b_{\text{ar,log}}(l/k)$ [Abbes and Mokrane 2004, lemme 2.1.5].

(5) For $a > 0$, define $\text{Fil}^a + G_k = \bigcup_{b > a} \text{Fil}^b G_k$ and $\text{Fil}^{a+}_{\log} G_k = \bigcup_{b > a} \text{Fil}^b_{\log} G_k$. Then, the subquotients $\text{Fil}^a G_k / \text{Fil}^{a+}_{\log} G_k$ are abelian $p$-groups if $a \in \mathbb{Q}_{>1}$ and are 0 if $a \not\in \mathbb{Q}$ ([Abbes and Saito 2002, Theorem 3.8] and [Abbes and Saito 2003, Theorem 1]); the subquotients $\text{Fil}^a_{\log} G_k / \text{Fil}^{a+}_{\log} G_k$ are elementary abelian $p$-groups if $a \in \mathbb{Q}_{>0}$ and are 0 if $a \not\in \mathbb{Q}$ ([Abbes and Saito 2002, Theorem 3.16] and [Saito 2009, Theorem 1.3.3]).

(6) The inertia subgroup is $\text{Fil}^a G_k$ if $a \in (0, 1]$ and the wild inertia subgroup is $\text{Fil}^{1+} G_k = \text{Fil}^{0+}_{\log} G_k$ [Abbes and Saito 2002, Theorems 3.7 and 3.15].

(7) When the residue field $\kappa_k$ is perfect, the arithmetic ramification filtrations agree with the classical upper numbered filtrations in the following way: $\text{Fil}^a G_k = \text{Fil}^{a-1}_{\log} G_k = \text{Gal}^{a-1}_k$ for $a \geq 1$ [Abbes and Saito 2002, §6.1], where $\text{Gal}^a_k$ is the classical upper numbered filtration on $G_k$.

Proof. For the convenience of readers, we point out some ingredients of the proof. For details, one can consult the original papers.

(1) is straightforward by matching up points.

(1’) is not in the literature. However, it can be proved identically to (1).
(2) One can show that if we add a new (dummy) generator in $Z$ or $P$, the new Abbes–Saito space admits a fibration over the original Abbes–Saito space whose fibers are closed discs of radius $\theta^a$.

(3) The first statement is just abstract nonsense. The second is true essentially because Abbes–Saito spaces are defined over $k$ and the geometric connect components can be detected over the algebraic closure $k^{\text{alg}}$, which has valued group $|k^\times|^Q$. However, realizing this principle requires formal models of rigid spaces. As we will reprove this result in Theorem 4.4.1, we refer to the original paper for the formal model proof.

(4) When $\mathcal{O}_{l'} \simeq \mathcal{O}_l \otimes_{\mathcal{O}_k} \mathcal{O}_{k'}$, one can match up the nonlogarithmic Abbes–Saito space for $lk'/k'$ and the extension of the scalar of that for $lk'/k'$ in a natural way. Actually, the logarithmic ramification break is not considered in [Abbes and Mokrane 2004, lemme 2.1.5], but the proof carries over similarly. In the tamely ramified and logarithmic cases, one can also identify two logarithmic Abbes–Saito spaces [2002, Proposition 9.8]; this is slightly more complicated.

(5) The proof used the formal models of the Abbes–Saito spaces and their stable reductions, which is in an orthogonal direction from the present paper. One may consult [Abbes and Saito 2003; Saito 2009] for a complete treatment.

(6) is an easy fact.

(7) follows from an explicit calculation in the monogenic case. □

**Remark 4.1.8.** In fact, in the proof of the main theorem (Theorem 4.4.1), we do not need (5) or the second statement of (3) on the rationality of the breaks in the proposition above. Therefore, we can obtain these properties from the properties of differential conductors in Theorem 2.4.1 via the comparison in Theorem 4.4.1.

**Definition 4.1.9.** Let $\rho : G_k \to \text{GL}(V_\rho)$ be a representation of finite local monodromy. Define the **arithmetic Artin and Swan conductors** as

$$\text{Art}_{\text{ar}}(\rho) \overset{\text{def}}{=} \sum_{a \in \mathbb{Q}_{\geq 0}} a \cdot \dim(V_{\rho}^{\text{Fil}^a} G_k / V_{\rho}^{\text{Fil}^a} G_k),$$

$$\text{Swan}_{\text{ar}}(\rho) \overset{\text{def}}{=} \sum_{a \in \mathbb{Q}_{\geq 0}} a \cdot \dim(V_{\rho}^{\text{Fil}^a_{\log}} G_k / V_{\rho}^{\text{Fil}^a_{\log}} G_k).$$

(4.1.10)

(4.1.11)

They are actually finite sums.

**Conjecture 4.1.12 (Hasse–Arf Theorem).** Let $k$ be a complete discretely valued field of equal characteristic $p$. For any representation $\rho$ of $G_k$ of finite local monodromy, the arithmetic conductors are nonnegative integers, namely, $\text{Art}_{\text{ar}}(\rho) \in \mathbb{Z}_{\geq 0}$ and $\text{Swan}_{\text{ar}}(\rho) \in \mathbb{Z}_{\geq 0}$.

**Proposition 4.1.13.** Conjecture 4.1.12 is true if the residue field $\kappa_k$ is perfect.
Proof. By Proposition 4.1.7(7), we are reduced to the classical Hasse–Arf theorem [Serre 1979, §VI.2, Theorem 1’ and §IV.2, Corollary 3]. Note that in this case, \( \text{Swan}_\pi(\rho) = \text{Art}_\pi(\rho) - \dim V_\rho/V_\rho^l \).

We will prove Conjecture 4.1.12 in Corollary 4.4.3.

4.2. Standard Abbes–Saito spaces and their lifts. In practice, we will only study Abbes–Saito spaces that are given by some particular generators. We explicitly write down spaces and their lifts in the sense of Section 1.

In this subsection, we retrieve Hypotheses 2.3.2 and 3.3.1, assuming that \( k \) has finite \( p \)-basis and the extension \( l/k \) is totally and wildly ramified. Also, we retrieve Notation 2.3.3 on indexing \( p \)-basis.

Construction 4.2.1. We take \( Z = \{c_1, \ldots, c_m, t\} \) to be the set of generators of \( \mathcal{O}_l/\mathcal{O}_k \) given by Construction 3.3.5. (Maybe some of them are already in the field \( k \), but we still keep those.) We take \( P = \{t\} \). By Proposition 4.1.7(1’), we can take the relations to be \( p_0, \ldots, p_m \) from Notation 3.3.8. For \( a \in \mathbb{Q}_{>0} \), we define the standard Abbes–Saito spaces as

\[
\begin{align*}
\mathcal{A}^{a, \geq \eta_0}_{l/k} &= \left\{ (u_0, \ldots, u_m) \in A^{m+1}_k [0, 1] \mid |p_0(u_{J+})| \leq \theta^a, \ldots, |p_m(u_{J+})| \leq \theta^a \right\},
\mathcal{A}^{a, \geq \eta_0}_{l/k, \log} &= \left\{ (u_0, \ldots, u_m) \in A^{m+1}_k [0, 1] \mid |p_0(u_{J+})| \leq \theta_0^{a+1}, |p_1(u_{J+})| \leq \theta^a, \ldots, |p_m(u_{J+})| \leq \theta^a \right\}.
\end{align*}
\]

Let \( P_{J+} \) be the lifts of \( p_{J+} \) as in Lemma 3.3.13. For \( a \in \mathbb{Q}_{>0} \) and \( \eta_0 \in (0, 1) \), we define the lifting Abbes–Saito spaces to be

\[
\begin{align*}
\mathcal{A}^{a, \geq \eta_0}_{l/k} &= \left\{ (U_{J+}, S) \in A^{m+2}_K [0, 1] \mid \eta_0 \leq |S| < 1, \quad \eta_0 \leq |S| < 1, \right. \\
&= \left. |P_0(U_{J+}, S)| \leq |S|^a, \ldots, |P_m(U_{J+}, S)| \leq |S|^a \right\},
\mathcal{A}^{a, \geq \eta_0}_{l/k, \log} &= \left\{ (U_{J+}, S) \in A^{m+2}_K [0, 1] \mid \eta_0 \leq |S| < 1, \quad \eta_0 \leq |S| < 1, \right. \\
&= \left. \eta_0 \leq |S| < 1, \quad |P_0(U_{J+}, S)| \leq |S|^a, \ldots, |P_m(U_{J+}, S)| \leq |S|^a \right\};
\end{align*}
\]

they are viewed as rigid spaces over \( Z_k^{\geq \eta_0} \).

Lemma 4.2.2. Let \( k'/k \) be a finite Galois extension of naïve ramification degree \( e' \). If we identify \( C_k \) as a subring of \( C_{k'} \) as in Construction 3.3.12, we may view \( P_{J+} \) as polynomials in \( U_{J+} \) with coefficients in \( \mathcal{O}_{K'}[\llbracket S'\rrbracket] \), where \( K' \) is the fraction field of the Cohen ring of \( \kappa_{k'} \) and \( S' \) is a lift of the uniformizer \( s \) in \( k' \). Then, for \( \eta_0 \in (0, 1) \) and \( a \in \mathbb{Q}_{>0} \), we have

\[
\begin{align*}
Z_k^{\geq \eta_0/e'} \times Z_k^{\geq \eta_0} \mathcal{A}^{a, \geq \eta_0}_{l/k} &\sim \left\{ (U_{J+}, S') \in A^{m+2}_K [0, 1] \mid \eta^{1/e'} \leq |S'| < 1, \right. \\
&= \left. \eta^{1/e'} \leq |S'| < 1, \right. \\
&= \left. |P_0| \leq |S'|^{e'a}, \ldots, |P_m| \leq |S'|^{e'a} \right\},
Z_k^{\geq \eta_0/e'} \times Z_k^{\geq \eta_0} \mathcal{A}^{a, \geq \eta_0}_{l/k, \log} &\sim \left\{ (U_{J+}, S') \in A^{m+2}_K [0, 1] \mid \eta^{1/e'} \leq |S'| < 1, \right. \\
&= \left. \eta^{1/e'} \leq |S'| < 1, \right. \\
&= \left. |P_0| \leq |S'|^{e'a}, \ldots, |P_m| \leq |S'|^{e'a} \right\};
\end{align*}
\]
**Proof.** The only thing not obvious is that we replace $|P_j| \leq |S|^a(1 + 1)$ by $|P_j| \leq |S'_{\ell \alpha} + 1|$; this is because $|S| = |S'|_{\ell \alpha}$ as proved in Lemma 3.3.13(2). □

**Remark 4.2.3.** Note that $\mathbb{Z}_k^{n_0} \to \mathbb{Z}_k^{n_0}$ is not a morphism between rigid spaces for the reason explained in Remark 3.3.14. So, strictly speaking, $\mathbb{Z}_k^{n_0} \cdot \mathbb{Z}_k^{n_0} A_{\delta_{l/k}^{(\log)}}$ and the log counterpart should be thought of as the geometric incarnations of the tensor products of the corresponding ring of analytic functions. The new spaces are, however, well-defined rigid analytic spaces over $\mathbb{Z}_k^{n_0}$. 

**Theorem 4.2.4.** For $a \in \mathbb{Q}_{>0}$, there is a one-to-one correspondence between the geometric connected components of $a_{\delta_{l/k}^{(\log)}}$ and the following limit of connected components:

$$\lim_{k'/k \to \eta_0} \lim_{\eta_0 \to 1} \pi_0^{\text{geom}}(\mathbb{Z}_k^{n_0} \times \mathbb{Z}_k^{n_0} A_{\delta_{l/k}^{\log}}),$$

where $e'$ is the naive ramification degree of $k'/k$ and the second limit only takes $\eta_0 \in p^{\mathbb{Q}} \cap (0, 1)$.

**Proof.** By Lemma 4.2.2 and Example 1.3.4, when $e' a \in \mathbb{Z}$, $\mathbb{Z}_k^{n_0} \times \mathbb{Z}_k^{n_0} A_{\delta_{l/k}^{\log}}$ is a lifting space of $a_{\delta_{l/k}^{(\log)}}$. The theorem then follows from Corollary 1.2.12. □

**Remark 4.2.5.** Here, we need $\eta_0 \in p^{\mathbb{Q}} \cap (0, 1)$ since Corollary 1.2.12 requires it.

**Remark 4.2.6.** Introducing this ramified extension $k'/k$ to make $e' a \in \mathbb{Z}$ may not be essential, but it eases the proof.

### 4.3. Comparison of rigid spaces.

In this subsection, we will prove that the lifting Abbes–Saito spaces are isomorphic to some thickening spaces we constructed in Section 3.4. In this subsection, we continue to assume Hypotheses 2.3.2 and 3.3.1.

Before proving the comparison theorem, we need to analyze Construction 3.3.5 closely and give a new view of $\tilde{\pi}^*$ using differentials. However, the proofs of the following two lemmas are not so enlightening in this generality; the reader may skip them when reading the paper for the first time, but see Remark 4.3.5.

**Lemma 4.3.1.** Modulo $p$, the homomorphism $\tilde{\pi}^*$ gives a continuous homomorphism $\tilde{\pi}^*: \kappa_k \to \kappa_k[[\delta_j]]$. For $\tilde{g} \in \kappa_k$, we can write $d \tilde{g} = \tilde{g}_1 d\tilde{b}_1 + \cdots + \tilde{g}_m d\tilde{b}_m$ in $\Omega_{1, k/F_p}$. Then $\tilde{\pi}^*(\tilde{g}) = \tilde{g} + \tilde{g}_1 \delta_1 + \cdots + \tilde{g}_m \delta_m$ modulo $(\delta_j)^2 \cdot \kappa_K[[\delta_j]]$.

**Proof.** Use the $p$-basis to express $\tilde{g}$ (uniquely) as $\tilde{g} = \sum_{e_j = 0}^{p-1} \tilde{a}_{e_j} \tilde{b}_j^{e_j}$ for some $\tilde{a}_{e_j} \in \kappa_k$. Thus, $d \tilde{g} = \sum_{e_j = 0}^{p-1} \tilde{a}_{e_j} d(\tilde{b}_j^{e_j})$. On the other hand, we have

$$\tilde{\pi}^*(\tilde{g}) \equiv \sum_{e_j = 0}^{p-1} \tilde{a}_{e_j} \tilde{b}_j^{e_j} \delta_j$$

modulo $(\delta_j)^p \cdot \kappa_K[[\delta_j]]$. The statement follows by comparing the two formulas. □
Remark 4.3.2. The analogous result for $\tilde{\pi}^*$ is true. Actually, $\tilde{\pi}^*$ is the Taylor expansion homomorphism [Kedlaya 2007, Definition 2.2.2].

Lemma 4.3.3. Keep the notation as in Section 3.3. We have

$$\det\left(\frac{\partial (\tilde{\pi}^* (P_i) - P_j)}{\partial \delta_j}\right)_{i,j \in J^+} \bigg|_{\delta_j^+ = 0} \in \left( \mathcal{O}_k[[S]](U_j^+)/(P_j^+) \right)^{\times} = \left( \mathcal{O}_L[[T]] \right)^{\times}.$$

In particular, the corresponding matrix is invertible.

Proof. It is enough to prove that the matrix is of full rank modulo $(p, T)$. First, modulo $(p, T)$, the first row will be all zero except the first element which is $\partial(\tilde{c}_1, \ldots, \tilde{c}_m) \in \kappa_1^\times$. Hence, we need only to look at

$$\left(\frac{\partial (\tilde{\pi}^* (P_i) - P_j)}{\partial \delta_j}\right)_{i,j \in J^+} \pmod{(p, T, \delta_j^+)} = \left(\frac{\partial (\tilde{\pi}^* (b_i) - b_i)}{\partial \delta_j}\right)_{i,j \in J^+} \pmod{(t, \delta_j^+)} \tag{4.3.4}$$

Let $\tilde{a}_{ij} \in \kappa_i$ denote the entries in the matrix on the right-hand side of (4.3.4), where we identify $\mathcal{O}_k(u_j^+)/\langle p, u_0 \rangle \to \kappa_i$. Under this identification, $\tilde{b}_i$ will become $\tilde{c}_{1}^{p^i}$ for all $i \in J$. It suffices to show that the $i$-th row is $\kappa_1$-linearly independent from the first $i - 1$ rows for all $i$. Write

$$\tilde{b}_i = \sum_{e_{i-1} = 0}^{p^{0-1}} \cdots \sum_{e_1 = 0}^{p^{i-1-1}} \tilde{\lambda}_{e_1, \ldots, e_{i-1}} u_{i-1}^{e_{i-1}} u_{i-1}^{e_1},$$

where $\tilde{\lambda}_{e_1, \ldots, e_{i-1}} \in \kappa_k$ for which $d\tilde{\lambda}_{e_1, \ldots, e_{i-1}} = \tilde{\mu}_{e_1, \ldots, e_{i-1}, 1} d\tilde{b}_1 + \cdots + \tilde{\mu}_{e_1, \ldots, e_{i-1}, m} d\tilde{b}_m$. Then, by Lemma 4.3.1, we can write

$$\tilde{a}_{i1} d\tilde{b}_1 + \cdots + \tilde{a}_{im} d\tilde{b}_m$$

$$= \sum_{e_1 = 0}^{p^{0-1}} \cdots \sum_{e_{i-1} = 0}^{p^{i-1-1}} \tilde{c}_1^{e_1} \cdots \tilde{c}_{i-1}^{e_{i-1}} (\tilde{\mu}_{e_1, \ldots, e_{i-1}, 1} d\tilde{b}_1 + \cdots + \tilde{\mu}_{e_1, \ldots, e_{i-1}, m} d\tilde{b}_m)$$

$$\equiv d(\tilde{c}_1^{p^i}) \pmod{(d\tilde{c}_1, \ldots, d\tilde{c}_{i-1})}$$

in $\Omega^1_{k_{i-1}/F_p}$; it is in fact nontrivial because $d\tilde{c}_1, \ldots, d\tilde{c}_m$ form a basis of $\Omega^1_{k_1/k}$ and hence there should not be any auxiliary relation among $d\tilde{c}_i, d\tilde{c}_l$ in $\Omega^1_{k_1/k_{i-1}}$. But we know that the sums $\tilde{a}_{i1} d\tilde{b}_1 + \cdots + \tilde{a}_{i'm} d\tilde{b}_m$ for $i' < i$ all lie in the submodule of $\Omega^1_{k_{i-1}/F_p}$ generated by $d\tilde{c}_1, \ldots, d\tilde{c}_{i-1}$. Hence the $i$-th row of the matrix in (4.3.4) is $\kappa_{i-1}$-linearly independent from the first $i - 1$ rows. The lemma follows. \qed

Remark 4.3.5. When $\kappa_l/\kappa_k$ is modular in the sense of [Sweedler 1968], we can choose the $p$-basis of $\kappa_k$ so that $\tilde{c}_j^{p^i} = \tilde{b}_j$; in that case, the above lemma is much easier to prove because the matrix, modulo $(p, T)$, is lower triangular with 1 on the diagonal. However, this may not be the case in general; see also Remark 3.3.6.
Theorem 4.3.6. There exists $\eta_0' \in (0, 1)$ such that for any $a \in \mathbb{Q}_{>1}$ and any $\eta_0 \in (\max\{p^{-1/a}, \eta_0'\}, 1)$, there exists an isomorphism of rigid spaces over $Z_{k}^{a, \geq \eta_0}$.

$$TS_{k/l}^{a, \geq \eta_0} \simeq AS_{l/k}^{a, \geq \eta_0}.$$

(4.3.7)

Similarly, there exists $\eta_0' \in (0, 1)$ such that for any $a \in \mathbb{Q}_{>0}$ and any $\eta_0 \in (\max\{p^{-1/a}, \eta_0'\}, 1)$, there exists an isomorphism of rigid spaces over $Z_{k}^{a, \geq \eta_0}$.

$$TS_{k/l, \log}^{a, \geq \eta_0} \simeq AS_{l/k, \log}^{a, \geq \eta_0}.$$

(4.3.8)

Proof. We give the proof for the case of log-spaces and indicate the changes needed for the nonlog case. The only significant difference between the two is that when constructing the morphism $\chi_2$, we have slightly different approximations. We will match up the ring of functions on the two rigid spaces in (4.3.8) in the log case and (4.3.7) in the nonlog case.

Fix an $\eta_0 \in (p^{-1/a}, 1)$ satisfying Hypothesis 3.3.16.

Recall that $\mathcal{O}_{TS_{k}^{a, \geq \eta_0}} = \mathcal{O}_{K}^{0} \langle S^{-a-1} \delta_0, S^{-a} \delta_j \rangle$ (resp. $\mathcal{O}_{TS_{k}^{a, \geq \eta_0}} = \mathcal{O}_{K}^{0} \langle S^{-a} \delta_j+ \rangle$). For each $j \in J^+$, $\tilde{\pi}^*(P_j)$ is the polynomial $P_j$ with coefficients replaced by their pull-backs to $\mathcal{O}_{TS_{k}^{a, \geq \eta_0}}$ (resp. $\mathcal{O}_{TS_{k}^{a, \geq \eta_0}}(\mathcal{D})$) via $\tilde{\pi}^*$. So the rings of functions on $TS_{k/l, \log}^{a, \geq \eta_0}$ and $TS_{k/l}^{a, \geq \eta_0}$ are, respectively.

$$R_{1, \log} = \mathcal{O}_{K}^{0} \langle S^{-a-1} \delta_0, S^{-a} \delta_j \rangle \langle U^+, \tilde{\pi}^*(P_j) \rangle,$$

$$R_1 = \mathcal{O}_{K}^{0} \langle S^{-a} \delta_j+ \rangle \langle U^+, \tilde{\pi}^*(P_j) \rangle.$$
which are clearly finite free modules over $W_{\log} = \mathcal{R}_K^\eta(V_0/\eta^{a+1}, V_j/\eta^a)$ and $W = \mathcal{R}_K^\eta(V_j/\eta^a)$, respectively, with basis $(U_j)_{j = 0}^{e}$; $0 \leq e < e'; 0 \leq e_j < p^{r_j}, j \in J$.

Similarly, for $\eta \in [\eta_0, 1)$, we norm $\mathcal{R}_{2, \log}$ and $\mathcal{R}_2$ as follows: for $g = \sum \lambda_{e+} U_j^{e+}$ with $\lambda_{e+} \in W_{\log}$ or $\lambda_{e+} \in W$, summed over $e = 0, \ldots, e' - 1$ and $e_j = 0, \ldots, p^{r_j} - 1$ for $j \in J$, we define

$$|g|_{\mathcal{R}_{2, \log}, \eta} = \max_{e \in J} (|\lambda_{e+} W_{\log} \cdot \eta^{\alpha/e})$$

and

$$|g|_{\mathcal{R}_2, \eta} = \max_{e \in J} (|\lambda_{e+} W \cdot \eta^{\alpha/e}).$$

It is clear that $\mathcal{R}_{2, \log}$ and $\mathcal{R}_2$ are the Fréchet completions for the norms $| \cdot |_{\mathcal{R}_{2, \log}, \eta}$ and $| \cdot |_{\mathcal{R}_2, \eta}$, for all $\eta \in [\eta_0, 1)$.

We will identify the $U_{j+}$ in different rings, but $V_{j+}$ will not be same as $\delta_{j+}$. Be cautioned that the two norms will not be the same under the identification; but they will give the same topology.

Now, we define a continuous $K$-homomorphism $\chi_1 : \mathcal{R}_{2, \log} \to \mathcal{R}_1, \log$ (resp. $\chi_2 : \mathcal{R}_2 \to \mathcal{R}_1$) so that $\chi_1(S) = S, \chi_1(U_j) = U_j, \chi_1(V_j) = P_j (U_{j+})$ for all $j \in J^+$. We need only to check that for any $\eta \in [\eta_0, 1)$,

$$|\chi_1(V_j)|_{\mathcal{R}_1, \eta} \leq \left\{ \begin{array} {ll} \eta^{a+1} & \text{if } j = 0, \\ \eta^{a} & \text{if } j \in J, \end{array} \right.$$  \hspace{1cm} (4.3.10)

$$|\chi_1(V_j)|_{\mathcal{R}_1, \eta} \leq \eta^{a}$$

for all $j \in J^+$. Here we need separate arguments for the logarithmic and nonlogarithmic cases. In the former case, inequality (3.2.9) says that

$$|P_j - \pi^*(P_j)|_{\mathcal{R}_1, \log, \eta} \leq \eta^{a} |P_j|_{\mathcal{R}_2, \log, \eta}$$

for $j \in J^+$, which gives exactly the bound in (4.3.10) because $|P_0|_{\mathcal{R}_2, \log, \eta} \leq \eta$ and $|P_j|_{\mathcal{R}_2, \log, \eta} \leq 1$ for $j \in J$ by Lemma 3.3.13(1).

In the nonlogarithmic case, combining Lemma 3.3.13(1) and inequality (3.2.10), one has $|P_j - \pi^*(P_j)|_{\mathcal{R}_1, \eta} \leq \eta^{a}$ for $j \in J^+$; inequality (4.3.10) follows.

Conversely, we will define a continuous $K$-homomorphism $\chi_2 : \mathcal{R}_1, \log \to \mathcal{R}_2, \log$ or $\chi_2 : \mathcal{R}_1 \to \mathcal{R}_2$ as the inverse to $\chi_1$. Obviously, we need $\chi_2(S) = S, \chi_2(U_j) = U_j$ for all $j \in J^+$. The only thing not clear is $\chi_2(\delta_j)$ for all $j \in J^+$.

By Lemma 3.3.3, let

$$A := \left( \partial (\pi^*(P_j) - P_j) / \partial \delta_j \right)_{i, j \in J^+} \mid \delta_{j+} = 0 \in GL_{m+1}(\mathcal{O}_K \llbracket T \rrbracket) \cong GL_{m+1}(\mathcal{O}_K \llbracket S \rrbracket \langle U_{j+} \rangle / (P_{j+})).$$

Let $B$ be the $(m + 1) \times (m + 1)$ matrix whose entries are in the free $\mathcal{O}_K \llbracket S \rrbracket$-module generated by the basis in Lemma 3.3.13(1) and which has image $A^{-1}$ in $M_{m+1}(\mathcal{O}_K \llbracket S \rrbracket \langle U_{j+} \rangle / (P_{j+}))$. Then, if $I$ denotes the $(m + 1) \times (m + 1)$ identity matrix, we have

$$BA - I \in Mat_{m+1}(\delta_{j+} : \mathcal{O}_K \llbracket S \rrbracket \langle U_{j+} \rangle),$$  \hspace{1cm} (4.3.11)
Now, we write
\[
\begin{pmatrix}
\delta_0 \\
\vdots \\
\delta_m
\end{pmatrix} = (I - BA) \begin{pmatrix}
\delta_0 \\
\vdots \\
\delta_m
\end{pmatrix} - B \left( \begin{pmatrix}
\bar{\pi}^*(P_0) - P_0 \\
\vdots \\
\bar{\pi}^*(P_m) - P_m
\end{pmatrix} - A \begin{pmatrix}
\delta_0 \\
\vdots \\
\delta_m
\end{pmatrix} \right) - B \begin{pmatrix}
P_0 \\
\vdots \\
P_m
\end{pmatrix},
\] (4.3.12)

the last term being just \(-B \chi_1(V_{J^+})\). We need to bound the first two terms.

By (4.3.11), \(I - BA\) has norm \(\leq \eta^a\). Hence, in the nonlogarithmic case, the first term in (4.3.12) has norm \(\leq \eta^{2a}\); in the logarithmic case the first term in (4.3.12) has norm \(\leq \eta^{2a}\), except for the first row, which has norm \(\leq \eta^{2a+1}\). By the definition of \(A\) and Theorem 3.2.8, the second term in (4.3.12) has norm \(\leq \eta^{2a}\) in the nonlogarithmic case; it has norm \(\leq \eta^{2a}\) in the logarithmic case, except for the first row, which has norm \(\leq \eta^{2a+1}\).

Since we want \(\chi_2\) to be the inverse of \(\chi_1\), we define recursively
\[
\begin{pmatrix}
\delta_0 \\
\vdots \\
\delta_m
\end{pmatrix} = -B \begin{pmatrix}
V_0 \\
\vdots \\
V_m
\end{pmatrix} + \chi_2 \begin{pmatrix}
\Lambda_0 \\
\vdots \\
\Lambda_m
\end{pmatrix},
\] (4.3.13)

where \(\Lambda_{J^+}\) denotes the sum of the first two terms in (4.3.12). Since \(\Lambda_{J^+}\) has strictly smaller norm than \(\delta_{J^+}\) and is in the ideal \((\delta_{J^+})\), one can plug the image of \(\chi_2(\delta_{J^+})\) back into \(\chi_2(\Lambda_{J^+})\) and iterate this substitution. This iteration will converge to the value of \(\chi(\delta_{J^+})\) as an element in \(R_{2, \log}\) or \(R_2\). Moreover, from the construction, one can see that
\[
\begin{align*}
|\chi_2(\delta_j)|_{\bar{R}_{1, \eta}} &\leq \eta^a & \text{for all } \eta \in [\eta_0, 1) \text{ and } j \in J^+, \\
|\chi_2(\delta_0)|_{\bar{R}_{1, \log, \eta}} &\leq \eta^{a+1} & \text{for all } \eta \in [\eta_0, 1) \text{ and } j \in J, \\
|\chi_2(\delta_j)|_{\bar{R}_{1, \log, \eta}} &\leq \eta^a & \text{for all } \eta \in [\eta_0, 1) \text{ and } j \in J.
\end{align*}
\]

Hence, if we define
\[
\chi_2 : \mathcal{R}_K^{\mathfrak{m}}(S^{-a-1}\delta_0, S^{-a}\delta_J)(U_{J^+}) \rightarrow R_{2, \log} \quad \text{and} \quad \chi_2 : \mathcal{R}_K^{\mathfrak{m}}(S^{-a}\delta_{J^+})(U_{J^+}) \rightarrow R_2
\]
by \(\chi_2(u_{J^+}) = u_{J^+}\), then \(\chi_2(\delta_{J^+})\) is the limit we obtained above; this gives a continuous homomorphism. We will check that this homomorphism factors through \(R_{1, \log}\) or \(R_1\). Indeed, by the recursive formula (4.3.13), which is (4.3.12) after applying \(\chi_2\), we see that
\[
-B \chi_2 \begin{pmatrix}
\bar{\pi}^*(P_0) - P_0 \\
\vdots \\
\bar{\pi}^*(P_m) - P_m
\end{pmatrix} - B \begin{pmatrix}
V_0 \\
\vdots \\
V_m
\end{pmatrix} = \begin{pmatrix}
0 \\
\vdots \\
0
\end{pmatrix}.
\]

We know that \(B\) has an invertible image in \(GL_{m+1}(\mathcal{O}_K[S](U_{J^+}/(P_{J^+}))\), and so is invertible over \(R_{1, \log}\) or \(R_1\). We must have \(0 = \chi_2(\bar{\pi}^*(P_j) - P_j) + V_j = \)
On ramification filtrations and p-adic differential modules, I

\[ \chi_2(\tilde{\pi}^*(P_j)) + V_j - P_j = \chi_2(\tilde{\pi}^*(P_j)) \] for all \( j \in J^+ \). This proves that \( \chi_2 \) factors through \( \mathcal{R}_{1, \log} \) or \( \mathcal{R}_1 \).

Finally, we claim that \( \chi_2 \) and \( \chi_1 \) are inverse to each other. One may check this from the definition directly. Alternatively, we observe that, by our definition, they are inverse to one another on a dense subset \( K[S, u_{J^+}] \), the polynomial ring inside the Fréchet algebras; therefore, they have to be inverse to one another and give an isomorphism between the ring of functions on Abbes–Saito space and the ring of functions on thickening space. \( \square \)

**Remark 4.3.14.** The isomorphisms constructed in Theorem 4.3.6 are canonical in the sense that they match up \( U_{J^+} \) on both sides. However, slight perturbations of the isomorphisms will continue to be isomorphic. This point will be important when studying the mixed characteristic case.

4.4. **Comparison of conductors.** In this subsection, we will prove the comparison between the arithmetic conductors and the differential conductors. As a reminder, we do not impose Hypotheses 2.3.2 and 3.3.1 in this subsection.

**Theorem 4.4.1.** Let \( k \) be a complete discretely valued field of equal characteristic \( p > 0 \) and let \( G_k \) be its absolute Galois group. For a \( p \)-adic representation \( \rho : G_k \to \text{GL}(V_\rho) \) of finite local monodromy, the arithmetic Artin conductor \( \text{Art}_{\text{ar}}(\rho) \) of \( \rho \) coincides with the differential Artin conductor \( \text{Art}_{\text{dif}}(\rho) \); the arithmetic Swan conductor \( \text{Swan}_{\text{ar}}(\rho) \) coincides with the differential Swan conductor \( \text{Swan}_{\text{dif}}(\rho) \).

**Proof.** It suffices to prove this for irreducible representations, as all the conductors are additive. All the conductors remain the same if we pass to the completion of the unramified closure of \( k \), by Proposition 4.1.7(4) and Theorem 2.4.1(2). Thus we may assume that the residue field \( \kappa_k \) is separably closed; hence \( \rho \) factors through the Galois group of a finite totally ramified extension \( l/k \) as \( \rho : G_k \to \text{Gal}(l/k) \hookrightarrow \text{GL}(V_\rho) \) with the second map injective. Moreover, we may assume that \( l/k \) is wildly ramified because the theorem is known when \( l/k \) is tamely ramified, by Proposition 4.1.7(6) and Theorem 2.4.1(3). To sum up, we may assume Hypothesis 3.3.1. In particular, \( b_{\text{ar}}(l/k) > 1 \) and \( b_{\text{ar, log}}(l/k) > 0 \).

Next, we want to reduce to the case when the \( p \)-basis of \( k \) is finite. In view of Construction 3.3.5, one can choose a \( p \)-basis of \( l \) so that all but a finite number of elements are actually in \( k \). Let \( (c_l)_{i \in I} \) be a subset of those elements in the \( p \)-basis which lie in \( k \). Set \( \tilde{k} = k(c_l^{1/p^n} \mid i \in I, n \in \mathbb{N})^\wedge \) and \( \tilde{l} = l\tilde{k} \). We claim that \( \tilde{c}_l = c_l \otimes c_l \otimes c_{\tilde{k}} \). Indeed, after base change to \( \tilde{k} \), the valued groups do not change: \( |\tilde{k}^\wedge| = |k^\wedge| \). Thus, \( |\tilde{l}^\wedge : \tilde{k}^\wedge| \geq |l^\wedge : k^\wedge| \). On the other hand, the residue field extension of \( \tilde{l}/\tilde{k} \) has degree at least the same as \( \kappa_l/\kappa_k \) because \( \tilde{c}_{I^+} \) are not in the residue field of \( \tilde{k} \). But we know that the degree of the extension does not increase. Therefore, we have equality on both naïve ramification degrees and degrees of
Remark 4.4.2. In an early version of this paper, Theorem 4.4.1 is stated for representations with finite image. Andrea Pulita pointed out that this could be extended only a finite number of elements in the $p$-basis and the differential conductors are unchanged after taking an inseparable field extension with respect to other elements in the $p$-basis.

To sum up, we can make an inseparable extension so that all conductors do not change, and we are reduced to the case where Hypothesis 2.3.2 holds.

Now, we will prove the comparison theorem for the Swan conductors and the proof for the Artin conductors follows verbatim, except replacing Swan by Art, replacing $a > 0$ by $a > 1$, and dropping all the logs in the subscripts.

Since $\rho$ is irreducible, $\text{Swan}_{\text{ar}}(\rho) = b_{\text{ar,log}}(l/k) \cdot \dim V_\rho$. Recall from Section 2.3, we can associate with $\rho$ a differential module $\mathcal{E}_\rho$ over $\mathcal{H}_K^{\eta_0} \otimes_{\mathbb{Q}_p} F$ for some $\eta_0 \in (0, 1)$. As the representation $\rho$ is irreducible, $\mathcal{E}_\rho$ has a unique ramification break $b_{\text{dif,log}}(\mathcal{E}_\rho)$. So the differential Swan conductor of $\rho$ is $\text{Swan}_{\text{dif}}(\rho) = b_{\text{dif,log}}(\mathcal{E}_\rho) \cdot \dim V_\rho$. Therefore, to conclude, it suffices to show that $b_{\text{ar,log}}(l/k) = b_{\text{dif,log}}(\mathcal{E}_\rho)$.

We do this by means of a chain of equivalences. By the equivalence (a) $\iff$ (d) in Theorem 3.4.12, the inequality $a > b_{\text{dif,log}}(\mathcal{E}_\rho)$ is equivalent to this condition:

For any (or some) extension $l'/l$ with naive ramification degree $e'$,

$$\pi_0^{\text{geom}}(Z_{l'}^{\geq \eta_0/e'} \times Z_l^{\geq \eta_0/e'} T_{\eta_0}^{d_l \geq \eta_0}) = [l : k], \text{ when } \eta_0 \to 1^{-}. \quad (*)$$

By Theorem 4.2.4, the condition (*) is equivalent to $\pi_0^{\text{geom}}(a S_{l/k, \log}^d) = [l : k]$, where $a$ is a rational number. But this is the same as $a > b_{\text{ar,log}}(l/k)$.

Remark 4.4.2. In an early version of this paper, Theorem 4.4.1 is stated for representations with finite image. Andrea Pulita pointed out that this could be extended to the finite local monodromy case by a standard argument as in the proof.

Corollary 4.4.3. (a) (Hasse–Arf Theorem) Let $k$ be a complete discretely valued field of equal characteristic $p > 0$, let $G_k$ be its absolute Galois group, and let $\rho : G_k \to \text{GL}(V_\rho)$ be a $p$-adic representation of finite local monodromy. Then the arithmetic Artin conductor $\text{Art}_{\text{ar}}(\rho)$ and the arithmetic Swan conductor $\text{Swan}_{\text{ar}}(\rho)$ are integers.

(b) Let $k$ be a complete discretely valued field of equal characteristic $p > 0$. Then the subquotients $\text{Fil}_a G_k/\text{Fil}_a^{a+1} G_k$ (resp. $\text{Fil}_0^a G_k/\text{Fil}_0^{a+1} G_k$) of the arithmetic ramification filtrations are elementary $p$-abelian groups if $a \in \mathbb{Q}_{>1}$ (resp. $a \in \mathbb{Q}_{>0}$) and are trivial if $a \notin \mathbb{Q}$.

Proof. This follows from Theorems 2.4.1 and 4.4.1.
5. Applications

In this section, we give two applications of the comparison Theorem 4.4.1. The first is to deduce an integrality result concerning the ramification filtration of finite flat group schemes, introduced in [Abbes and Mokrane 2004]. The other is to compare the arithmetic and differential Artin conductors to the Artin conductor defined by Borger [2004].

Remark 5.0.4. All applications in this section can be carried over to the mixed characteristic case if there is a good theory of differential conductors. For the application to finite flat group schemes, one needs the Hasse–Arf theorem of arithmetic Artin conductors; for the comparison with Borger’s Artin conductor, one needs a mixed characteristic version of Proposition 5.4.1. In the absence of these statements, we only focus on the equal characteristic \( p \) case throughout this section.

5.1. Hasse–Arf theorem for finite flat group schemes. We first recall some definitions and basic properties from [Abbes and Mokrane 2004; Hattori 2008]. Then, we use a theorem by Raynaud [Berthelot et al. 1982, théorème 3.1.1] to reduce the integrality result to the case of finite Galois extension of complete discretely valued fields.

Keep the notation as in previous sections. We do not assume any hypothesis on \( k \) (and there will be no \( l \) in this subsection).

Convention 5.1.1. All finite flat groups schemes are commutative.

The construction of the canonical filtration on a generically étale finite flat group scheme is similar to that of the arithmetic ramification filtration.

Definition 5.1.2. Let \( A \) be a finite flat \( \mathcal{O}_k \)-algebra. Write \( A = \mathcal{O}_k[x_1, \ldots, x_n]/\mathfrak{I} \) with \( \mathfrak{I} \) an ideal generated by \( f_1, \ldots, f_r \). For \( a \in \mathbb{Q}_{>0} \), define the rigid space

\[
X^a = \{ (x_1, \ldots, x_n) \in A^n_K[0, 1] \mid |f_\alpha(x_1, \ldots, x_n)| \leq \theta^a, \alpha = 1, \ldots, r \},
\]

where \( \theta = |s| \) as in Notation 4.1.1. The highest break \( b(A/\mathcal{O}_k) \) is the smallest number such that \( \pi_0^{\text{geom}}(X^a) = \text{rank}_{\mathcal{O}_k} A \) for all \( a > b(A/\mathcal{O}_k) \). This is the same as Definition 4.1.3 if \( A = \mathcal{O}_l \), except here we use the ring of integers instead of the fields in the notation.

Notation 5.1.3. A finite flat group scheme \( G = \text{Spec} A \) is generically étale if \( G \times_{\mathcal{O}_k} k \) is étale over \( k \); it is generically trivial if \( G \times_{\mathcal{O}_k} k \) is a disjoint union of copies of \( \text{Spec} k \).

Definition 5.1.4. For a geometrically étale finite flat group scheme \( G = \text{Spec} A \), we have a natural map of points \( G(k^{\text{alg}}) \hookrightarrow X^a(k^{\text{alg}}) \); further composing with the map for geometric connected components, we obtain a map

\[
\sigma^a : G(k^{\text{alg}}) \hookrightarrow X^a(k^{\text{alg}}) \to \pi_0^{\text{geom}}(X^a).
\]
Define $G^a$ to be the closure of ker $\sigma^a$. We use $b(G/\mathcal{O}_k)$ to denote the highest break $b(A/\mathcal{O}_k)$; then for $a > b(G/\mathcal{O}_k)$, $G^a = \text{Spec} \mathcal{O}_k$.

**Proposition 5.1.5** [Abbes and Mokrane 2004, lemme 2.3.2]. Let

$$0 \to G' \to G \to G'' \to 0$$

be an exact sequence of finite flat group schemes. For $a > 0$,

$$0 \to G'^a \to G^a \to G''^a \to 0$$

is exact.

**Caution 5.1.6.** For a subgroup scheme $H \subset G$ and $a \geq 0$, we do not know how to link $H^a$ with $H \times_G G^a$.

The following question was first raised in [Hattori 2008], and the result is essentially due to Hattori. The author thanks him for clarifying this and for permission to include the proof here.

**Theorem 5.1.7.** Let $\mathcal{O}_k$ be a complete discrete valuation ring of equal characteristic $p$. For any generically trivial finite flat groups scheme $G$ over $\mathcal{O}_k$, $b(G/\mathcal{O}_k)$ is a nonnegative integer.

**Proof.** We may assume that $G$ is connected by taking the connected component of the identity. By a theorem of Raynaud [Berthelot et al. 1982, thèorème 3.1.1], we may realize $G$ as the kernel of an isogeny $f : \mathfrak{B} \to \mathfrak{A}$ of two abelian schemes over $\text{Spec} \mathcal{O}_k$. Let $\alpha$ and $\beta$ be generic points of the special fibers of $\mathfrak{A}$ and $\mathfrak{B}$, respectively. Then by [Abbes and Mokrane 2004, lemme 2.1.6],

$$b(\mathcal{O}_{\mathfrak{B},\beta}/\mathcal{O}_{\mathfrak{A},\alpha}) = b(G/\mathcal{O}_k).$$

Since the generic fiber of $G$ is a disjoint union of copies of $\text{Spec} k$, we know that $\mathcal{O}_{\mathfrak{B},\beta}/\mathcal{O}_{\mathfrak{A},\alpha}$ is a generically étale finite Galois extension of complete discrete valuation rings, with Galois group $G(k)$; in particular, all irreducible representations of this Galois group over an algebraically closed field are one-dimensional. By Hasse–Arf Theorem 4.4.1,

$$b(\mathcal{O}_{\mathfrak{B},\beta}/\mathcal{O}_{\mathfrak{A},\alpha}) = b(G/\mathcal{O}_k)$$

is an integer. \qed

### 5.2. Generic $p^\infty$-th roots

In this subsection, we introduce the notation of generic $p^\infty$-th roots. This idea was first introduced in [Borger 2004] as a key ingredient of Borger’s Artin conductor.

Keep the notation as in previous sections. We assume Hypothesis 2.3.2, that $k$ has a finite $p$-basis $b_f$.

**Notation 5.2.1.** Let $x_1, \ldots, x_m$ be transcendental over $k$. Define $k'$ to be the completion of $k(x_1, \ldots, x_m)$ with respect to the $(1, \ldots, 1)$-Gauss norm. Set $l' = k'l$. Clearly, $l'$ is the completion of $l(x_1, \ldots, x_m)$ with respect to the $(1, \ldots, 1)$-Gauss norm. We call $x_1, \ldots, x_m$ dummy variables.
**Definition 5.2.2.** We use *adding generic* $p^\infty$-*th roots* to refer to the following procedure. Consider
\[ k \hookrightarrow \tilde{k} = k'((b_j + x_j s)^{1/p^n}; j \in J, n \in \mathbb{N})^\wedge, \]
instead of $k$; namely, put all $p$-power roots of $b_j + x_j s$ for all $j \in J$ into $k'$ and then take the completion. We provide $\tilde{k}$ with the $p$-basis $x_J$, i.e., replacing $b_j$ by $x_j$ for all $j \in J$. For a finite field extension $l/k$, we replace it by the extension of the composite $\tilde{l} = l\tilde{k}/\tilde{k}$. Note that $\text{Gal}(\tilde{l}/\tilde{k}) = \text{Gal}(l/k)$ as $\tilde{k}$ is linearly independent from $l$.

The proof of the following proposition is essentially the same as [Kedlaya 2007, Lemma 3.5.4]. It is also implicitly contained in Borger’s construction of Artin conductors (Section 5.3).

**Proposition 5.2.3.** Let $l/k$ be a finite Galois extension of complete discretely valued fields of equal characteristic $p$ and with finite $p$-basis. Then, after a finite number of operations of adding generic $p^\infty$-th roots, the field extension has separable residue field extension.

**Proof.** First, the tamely ramified part is always preserved under these operations. So, we can assume that $l/k$ is totally wildly ramified and hence the Galois group $G_{l/k}$ is a $p$-group. We can filter the extension $l/k$ as $k = k_0 \subset \cdots \subset k_n = l$, where $k_i/k_{i-1}$ is a (wildly ramified) $\mathbb{Z}/p\mathbb{Z}$-Galois extension and $k_i/k$ is Galois for each $i = 1, \ldots, n$. Each of these subextensions

(a) either has inseparable residue field extension (and so has naive ramification degree 1), or

(b) has separable residue field extension (and so has naive ramification degree $p$).

Let $i_0$ be the maximal number such that $k_i/k_{i-1}$ has separable residual extension for $i = 1, \ldots, i_0$. Obviously adding generic $p^\infty$-th roots does not decrease $i_0$ because after adding generic $p^\infty$-th roots, the naive ramification degree of $\tilde{k}_{i_0}/\tilde{k}$ still equals the degree $p^{i_0}$. It then suffices to show that after a finite number of operations of adding generic $p^\infty$-th roots, $k_{i_0+1}/k_{i_0}$ has separable residue field extension. Suppose the contrary.

Let $g \in G_{k_{i_0+1}/k_{i_0}} \simeq \mathbb{Z}/p\mathbb{Z}$ be a generator. We claim that
\[ \gamma = \min_{w \in \mathcal{O}_{k_{i_0+1}}} (v_{k_{i_0+1}}(g(w) - w)) \]
decreases by at least 1 after adding $p^\infty$-th roots. This would conclude the proposition, as $\gamma$ is always a nonnegative integer, which would lead to a contradiction.

Let $z$ be a generator of $\mathcal{O}_{k_{i_0+1}}$ as an $\mathcal{O}_{k_{i_0}}$-algebra. It satisfies an equation
\[ z^p + a_1 z^{p-1} + \cdots + a_p = 0, \quad (5.2.4) \]
where \( a_1, \ldots, a_{p-1} \in m_{k_0} \) and \( a_p \in \mathcal{O}^\times_{k_0} \) with \( \tilde{a}_p \in \kappa^\times_{k_0} \backslash (\kappa^\times_k)^p = \kappa^\times_k \backslash (\kappa^\times_k)^p \). It is easy to see that \( \gamma = v_{k_0}(g(z) - z) \).

Adding generic \( p^\infty \)-th roots to \( k \) gives us the field \( \tilde{k} \). Now, the field extension \( \tilde{k}k_{i_0+1}/\tilde{k}k_{i_0} \) is also generated by \( z \) as above. But we can write \( a_p = \alpha^p + \beta \) for \( \alpha \in \mathcal{O}_{k_0} \) and \( \beta \in m_{k_0} \). Hence if we substitute \( z' = z + \alpha \) into (5.2.4), we get \( z'^p + a'_1z'^{p-1} + \cdots + a'_p = 0 \), with \( a'_1, \ldots, a'_p \in m_{k_0} \). Hence, \( v_{k_{i_0+1}}(z') > 0 \).

By assumption that the extension \( \tilde{k}k_{i_0+1}/\tilde{k}k_{i_0} \) has naïve ramification degree 1, a uniformizer \( \pi_{k_0} \) of \( k_{i_0} \) is also a uniformizer for \( \tilde{k}k_{i_0+1} \) and hence \( z'/\pi_{k_0} \) lies in \( \mathcal{O}_{k_{i_0+1}} \). Thus,

\[
\gamma' = \min_{w \in \mathcal{O}_{k_{i_0+1}}} \left( w_{k_{i_0+1}}(g(w) - w) \right) \\
\leq v_{k_{i_0+1}}(g(z'/\pi_{k_0}) - z'/\pi_{k_0}) = v_{k_{i_0+1}}(g(z) - z) - 1 = \gamma - 1.
\]

This proves the claim and hence the proposition.

\[ \square \]

5.3. Borger’s Artin conductors. We start with reviewing Borger’s definition of Artin conductors following [Borger 2004]. Then, we prove the comparison theorem linking this to arithmetic and differential conductors.

Keep the notation as above. Let \( k \) be a complete discretely valued field of equal characteristic \( p \), with no further hypothesis added. In fact, Borger’s construction works in the mixed characteristic case, but we only focus on the equal characteristic case (see Remark 5.0.4).

Definition 5.3.1. An \( \mathbb{F}_p \)-algebra \( R \) is called perfect if \( F : x \mapsto x^p \) is an isomorphism. For an \( \mathbb{F}_p \)-algebra \( R \), we use \( R^\text{perf} = \bigcup_{n \in \mathbb{N}} R^{1/p^n} \) to denote its perfection. Let CRP\( \mathcal{O}_k \) be the subcategory of the category of \( \mathcal{O}_k \)-algebras consisting of flat \( \mathcal{O}_k \)-algebras \( A \), complete with respect to the \( m_k \)-adic topology and for which \( A/m_k A \) is perfect.

Proposition 5.3.2 [Borger 2004, Theorem 1.4]. This category CRP\( \mathcal{O}_k \) has an initial object \( \mathcal{O}^u_k \), the universal residual perfection of \( \mathcal{O}_k \). We have an equivalence of categories

\[
\text{CRP}_{\mathcal{O}_k} \rightarrow \text{PerfAlg}_{\mathcal{O}_k^u}, \quad A \mapsto A/m_k A,
\]

where PerfAlg\( \mathcal{O}_k^u \) is the category of perfect \( \mathcal{O}^u_k/m_k \mathcal{O}^u_k \)-algebras.

Definition 5.3.4. Let \( \mathcal{O}^g_k \) be the inverse image of Frac(\( \mathcal{O}^u_k/m_k \mathcal{O}^u_k \)) under (5.3.3), called the generic residual perfection of \( \mathcal{O}_k \). Let

\[
k^g = \text{Frac}(\mathcal{O}^g_k).
\]

By Proposition 5.3.2, \( \mathcal{O}^g_k \) is a complete discrete valuation ring with perfect residue field.
We have a homomorphism of Galois groups $G_{k^s} \to G_k$. Given a representation $\rho$ of $G_k$ with finite image, we define the \textit{Borger’s Artin conductor} $\text{Art}_B(\rho)$ to be $\text{Art}(\rho_{G_{k^s}})$, where the latter term is as in the classical definition [Serre 1979].

**Remark 5.3.5.** Borger [2004] only defined Artin conductors for representations of finite image. We expect his definition can be extended to representations of finite local monodromy. However, this additional freedom is not essential, so we stick to the finite image case to ease the argument.

Obviously, Borger’s Artin conductors have a Hasse–Arf property naturally inherited from that of $k^s$, a complete discretely valued field with perfect residue field.

**Proposition 5.3.6** [Borger 2004, Theorem A]. Borger’s Artin conductor $\text{Art}_B(\rho)$ is a nonnegative integer and it coincides with the classical definition when the residue field $\kappa_k$ is perfect.

[Borger 2004, Proposition 2.3] Furthermore, $\text{Art}_B(\rho)$ is unchanged after a finite unramified extension of $k$.

Moreover, Borger proved that his definition coincides with a variant of arithmetic Artin conductor $\text{Art}_K$ for characters using the definition of Kato [1989]. (As we will not use Kato’s definition, we just mention the following proposition as a fact.)

**Proposition 5.3.7** [Borger 2004, Theorem B]. Let $\chi$ be a class in $H^1(G_k, \mathbb{Q}/\mathbb{Z})$ and $\chi'$ its image in $H^1(G_{k^s}, \mathbb{Q}/\mathbb{Z})$. Then $\text{Art}_K(\chi) = \text{Art}_K(\chi')$. In particular, for a rank-one representation $\rho$ of $G_k$ with finite image, $\text{Art}_K(\rho) = \text{Art}_B(\rho)$.

Borger gave the following explicit descriptions of $k^u$ and $k^s$.

**Proposition 5.3.8.** We have $k^u = (\kappa_k[v_{i,j} \mid j \in J, i \in \mathbb{N}])^{pf}((\pi_{k^u}))$. The homomorphism $k \hookrightarrow k^u$ is determined by $s \mapsto \pi_{k^u}$ and $b_j \mapsto b_j + \sum_{i>0} v_{i,j} \pi_{k^u}^i$. Also, $k^s = \text{Frac}(\kappa_k[v_{i,j} \mid j \in J, i \in \mathbb{N}])^{pf}((\pi_{k^s}))$ and the homomorphism $k \to k^s$ is given by composing $k \hookrightarrow k^u$ with the natural morphism $k^u \hookrightarrow k^s$.

### 5.4. Comparison with Borger’s conductors.

The key to proving the comparison between Borger’s Artin conductors and the arithmetic Artin conductors is to study how the arithmetic Artin conductors behave under the operations of adding generic $p^\infty$-th roots.

In this subsection, we do not impose any hypothesis on $k$.

**Proposition 5.4.1.** Assume Hypothesis 2.3.2. For representations of finite image, the differential Artin conductor for a representation of finite image is unchanged after adding generic $p^\infty$-th roots.
Proof. Since the operation of adding $p^\infty$-th roots does not change the Galois group of the finite Galois extension, we may assume that the representation is irreducible and totally and wildly ramified. Hence it suffices to consider the differential ramification break of a totally and wildly ramified finite Galois extension $l/k$.

Recall that we have a differential module $\mathcal{E}$ over $\mathbb{Z}_k^{\geq 0}$ for some $\eta_0 \in (0, 1)$ with differential operators $\partial_{B_j}$ and $\partial_S$, associated with the regular representation of $\text{Gal}(l/k)$ over $\mathbb{Q}_p$. The base change $k \leftrightarrow k' = k(x_j)^\wedge$ is translated into the base change of $\mathcal{E}$ into $\mathcal{E}'$, from $\mathbb{Z}_k^{\geq 0}$ to $\mathbb{Z}_k^{\geq 0} = A^1_{K(X)}[\eta_0, 1]$, where $K' = K(x_j)^\wedge$ is the completion of $K(x_j)$ with respect to the $(1, \ldots, 1)$-Gauss norm; $\mathcal{E}'$ has differential operators $\partial_{B_j}, \partial_{X_j}$, and $\partial_S$.

Consider the rotation $f : Z_k^{\geq 0} \rightarrow Z_k^{\geq 0}$ by $f^*(B_j) = B_j + X_j S$, $f^*(X_j) = X_j$, and $f^*(S) = S$; write $\partial'_{B_j}, \partial'_{X_j}$, and $\partial'_S$ for the action of differential operators on $f^*\mathcal{E}'$. Then
\[
\partial'_{B_j} = \partial_{B_j}, \quad \partial'_{X_j} = S \cdot \partial_{B_j} + \partial_{X_j}, \quad \partial'_S = \sum_{j \in J} X_j \cdot \partial_{B_j} + \partial_S.
\]
Since $X_j$ are transcendental over $K$, we have
\[
\max\{|\partial_{B_j}|_{\varepsilon_\eta, \text{sp}}, |\partial_S|_{\varepsilon_\eta, \text{sp}}, |\partial_{X_j}|_{\varepsilon_\eta, \text{sp}}\} = |\partial'_S|_{\varepsilon'_\eta, \text{sp}} = \max\{|\partial'_{X_j}|_{\varepsilon'_\eta, \text{sp}}, |\partial'_S|_{\varepsilon'_\eta, \text{sp}}\} \quad (5.4.2)
\]
for all $\eta \in [\eta_0, 1)$. Note that adding generic $p^\infty$-th roots to $k$ corresponds exactly to replacing $\mathcal{E}$ by $f^*\mathcal{E}'$ and forgetting the differential operators $B_j$. By (5.4.2), the differential nonlogarithmic ramification break of $\tilde{l}/\tilde{k}$ is the same as that of $l/k$. \square

Theorem 5.4.3. For a complete discretely valued field $k$ of equal characteristic $p$ and a representation $\rho$ of its Galois group $G_k$ with finite image, the arithmetic Artin conductors $\text{Art}_{\text{ar}}(\rho)$ as well as the differential Artin conductors $\text{Art}_{\text{dif}}(\rho)$ are the same as Borger’s Artin conductors $\text{Art}_B(\rho)$.

Proof. First we may assume that $\rho$ is irreducible and it factors exactly through the Galois group $G_{l/k}$ of a totally ramified Galois extension $l/k$ because all conductors are additive and remain the same under a (finite) unramified extension (Theorem 2.4.1(c) and Propositions 4.1.7(d) and 5.3.6). As $k^8$ has a perfect residue field, $\text{Art}_B(\rho) = \text{Art}_B(\rho|_{G_{k^8}}) = \text{Art}_{\text{dif}}(\rho|_{G_{k^8}})$ are the same as in the classical definition. It suffices to show $\text{Art}_{\text{dif}}(\rho) = \text{Art}_{\text{dif}}(\rho|_{G_{k^8}})$.

Similarly to the proof of Theorem 4.4.1, one may add the $p^\infty$-th roots of all but a finite number of elements of the $p$-basis into $k$ without changing the differential Artin conductors. In other words, there exists $k \leftrightarrow k_1 = k(b_j^{-n} \mid j \in J \backslash J_0, n \in \mathbb{N})^\wedge$ for some finite set $J_0 \subset J$, such that $\text{Art}_{\text{dif}}(\rho) = \text{Art}_{\text{dif}}(\rho|_{\text{Gal}_{k_1}^1})$. Since the residue field of $k^8$ is perfect, there exists $k_1 \leftrightarrow k^8$ extending $k \leftrightarrow k^8$. Hence, we may assume Hypothesis 2.3.2, i.e., $k$ has a finite $p$-basis.
By Proposition 5.2.3, we can do a finite number of operations of adding generic $p^\infty$-th roots and make the resulting field extension $k_2L/k_2$ not fiercely ramified and $\text{Art}_{\text{dif}}(\rho|_{G_{k_1}}) = \text{Art}_{\text{dif}}(\rho|_{G_{k_2}})$. In order to link $k_2$ with $k^g$, we need to show that we have a homomorphism $k_2 \hookrightarrow k^g$ extending $k_1 \hookrightarrow k^g$, for which we return to the proof of Proposition 5.2.3 and construct the homomorphism step by step.

The $r$-th (1 ≤ $r$ ≤ $r_0$) step of adding generic $p^\infty$-th roots is to construct

$$k_1^{(r)} = \left(k_1^{(r-1)}(x_{r,j})(x_{r-1,j} + x_{r,j} \pi_k)^{1/p^n}; j \in J, n \in \mathbb{N}\right)^\wedge,$$

where $x_{0,j} = b_j$ for $j \in J$ and $k_1^{(0)} = k_1$. One checks that the map given by

$$x_{r,j} \mapsto \sum_{r' \geq r} v_{r',j} \pi_k^{r'-r}$$

for all $j \in J$ and $r = 1, \ldots, r_0$, gives the desired homomorphism $k_2 \hookrightarrow k^g$.

Now, $k_2L/k_2$ has naïve ramification degree $[k_2L:k_2]$, so $\mathcal{O}_{k^g} = \mathcal{O}_{k^g} \otimes_{\mathcal{O}_{k_2}} \mathcal{O}_{k_2}$. Hence we have

$$\text{Art}_{\text{dif}}(\rho|_{G_{k_2}}) = \text{Art}_{\text{ar}}(\rho|_{G_{k_2}}) = \text{Art}_{\text{ar}}(\rho|_{G_{k^g}}) = \text{Art}_{\text{dif}}(\rho|_{G_{k^g}})$$

via Theorem 4.4.1 and Proposition 4.1.7(d).

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