Reflexive ideals in Iwasawa algebras

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Abstract

Let G be a torsionfree compact p-adic analytic group. We give sufficient conditions on p and G which ensure that the Iwasawa algebra ΩG of G has no non-trivial two-sided reflexive ideals. Consequently, these conditions imply that every non-zero normal element in ΩG is a unit. We show that these conditions hold in the case when G is an open subgroup of SL2(Zp) and p is arbitrary. Using a previous result of the first author, we show that there are only two prime ideals in ΩG when G is a congruence subgroup of SL2(Zp): the zero ideal and the unique maximal ideal. These statements partially answer some questions asked by the first author and Brown.

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0. Introduction

0.1. Motivation

In arithmetic geometry, basic questions about the Iwasawa theory of elliptic curves and other motives over p-adic Lie extensions of number fields provide the main motivation for the study
of Iwasawa algebras $\Lambda_G$, for example when $G$ is an open subgroup of $\text{GL}_2(\mathbb{Z}_p)$ [10, §8]. Specifically, homological and ring-theoretic properties of these Iwasawa algebras are useful for understanding the structure of the Pontryagin dual of Selmer groups [20,23] and other modules over the Iwasawa algebras. Several recent papers [1,3,4,21,22] are devoted to ring-theoretic properties of the Iwasawa algebras. One central question in this research direction is whether there are any non-trivial prime ideals in $\Omega_G = \Lambda_G/p\Lambda_G$, when $G$ is an open subgroup of $\text{SL}_2(\mathbb{Z}_p)$, see [1, Question, p. 197]. The aim of this paper is to answer this question and a few other related open questions.

An Iwasawa algebra over any open torsionfree subgroup of $\text{SL}_2(\mathbb{Z}_p)$ is local and extremely non-commutative since the only non-zero prime ideal is the maximal ideal by one of our main results, Theorem C. These algebras give rise to a class of so-called just infinite-dimensional algebras. On the other hand, their associated graded rings are commutative polynomial rings and hence Iwasawa algebras share many good properties with commutative rings. This class of algebras is very interesting from the ring-theoretic point of view and deserves further investigation.

0.2. Definitions

Throughout we fix a prime integer $p$. Let $\mathbb{Z}_p$ be the ring of $p$-adic integers and let $\mathbb{F}_p$ be the field $\mathbb{Z}/(p)$. We refer to the book [12] for the definition and basic properties of a $p$-adic analytic group and related material. Let $G$ be a compact $p$-adic analytic group. The Iwasawa algebra of $G$ (or the completed group algebra of $G$ over $\mathbb{Z}_p$) is defined to be

$$ \Lambda_G := \lim_{\longleftarrow} \mathbb{Z}_p[G/N], $$

where the inverse limit is taken over the open normal subgroups $N$ of $G$ [15, p. 443], [12, p. 155]. A closely related algebra is $\Omega_G := \Lambda_G/p\Lambda_G$, whose alternative definition is

$$ \Omega_G := \lim_{\longleftarrow} \mathbb{F}_p[G/N]. $$

For simplicity, the algebra $\Omega_G$ is also called the Iwasawa algebra of $G$ (or the completed group algebra of $G$ over $\mathbb{F}_p$). We refer to [3] for some basic properties of $\Lambda_G$ and $\Omega_G$ and to the articles [10,11,21,22] for general readings about Iwasawa algebras and their modules.

In this paper, we deal entirely with $\Omega_G$. For a treatment of the implications of our results for the Iwasawa algebra $\Lambda_G$, see [2].

0.3. Reflexive ideals

Let $A$ be any algebra and $M$ be a left $A$-module. We call $M$ reflexive if the canonical map

$$ M \rightarrow \text{Hom}_{A^{op}}(\text{Hom}_A(M, A), A) $$

is an isomorphism. A reflexive right $A$-module is defined similarly. We will call a two-sided ideal $I$ of $A$ reflexive if it is reflexive as a right and as a left $A$-module.

For the rest of the introduction we assume that $G$ is torsionfree, in which case $\Omega_G$ is an Auslander regular domain. Here is our first main result.
Theorem A. Let \( G \) be a torsionfree compact \( p \)-adic analytic group whose \( \mathbb{Q}_p \)-Lie algebra \( \mathcal{L}(G) \) is split semisimple over \( \mathbb{Q}_p \). Suppose that \( p \geq 5 \) and that \( p \nmid n \) in the case when \( \text{sl}_n(\mathbb{Q}_p) \) occurs as a direct summand of \( \mathcal{L}(G) \). Then \( \Omega_G \) has no non-trivial two-sided reflexive ideals.

The proof of Theorem A is based on a result from [5]. For a few small \( p \), there are some extra difficulties to be dealt with; hence we exclude these primes from consideration. We believe that these restrictions on \( p \) are not really necessary.

0.4. Normal elements

Recall that an element \( w \) of a ring \( A \) is said to be normal if \( w A = A w \). Ken Brown and the first author asked [3, Question K] whether under hypotheses on \( G \) similar to the ones in Theorem A any non-zero normal element of \( \Omega_G \) must be a unit. Because every non-zero normal element \( w \in \Omega_G \) gives rise to a non-zero reflexive two-sided ideal \( w\Omega_G \), Theorem A implies

Theorem B. Under the same hypotheses as in Theorem A, every non-zero normal element of \( \Omega_G \) is a unit.

Theorem B partially answers the open question [3, Question K].

0.5. Iwasawa algebras over subgroups of \( \text{SL}_2(\mathbb{Z}_p) \)

Another open question [3, Question J] is, under hypotheses similar to those in Theorem A, whether there are any non-trivial prime ideals in \( \Omega_G \)? This question is particularly interesting when \( G \) an open subgroup of \( \text{SL}_2(\mathbb{Z}_p) \). Using [1, Theorem A] we can prove

Theorem C. Let \( G \) be an open torsionfree subgroup of \( \text{SL}_2(\mathbb{Z}_p) \). Then every prime ideal in \( \Omega_G \) is either zero or maximal.

The proof of Theorem C is independent of [5].

0.6. A key step in proof

To prove the theorems above we have to overcome several technical difficulties which seem unrelated to the main theorems. The proof is divided into several steps and we only mention one key step: a control theorem for reflexive ideals.

Theorem 5.3. Let \((A, A_1)\) be a Frobenius pair satisfying the derivation hypothesis, such that \( \text{gr} \ A \) and \( \text{gr} \ A_1 \) are UFDs. Let \( I \) be a reflexive two-sided ideal of \( A \). Then \( I \cap A_1 \) is a reflexive two-sided ideal of \( A_1 \) and \( I \) is controlled by \( A_1 \):

\[
I = (I \cap A_1) \cdot A.
\]

All undefined terms will be explained later. As an example we may take \((A, A_1)\) to be \((\Omega_G, \Omega_{G_1})\). We will verify that the derivation hypothesis holds for certain groups \( G \), and the main theorems then follow from the control theorem and induction. This control theorem is in fact the heart of the paper, on which all our main results are dependent. The control theorem
should be useful for studying Iwasawa algebras over other classes of groups, such as the nilpotent or solvable groups.

0.7. A field extension

An algebra $A$ over a field is called just infinite-dimensional if it is infinite-dimensional and every non-zero ideal in $A$ is finite codimensional. This is analogous to the notion of just infinite groups, also known as the almost simple groups. Theorem C assures us of a large class of just infinite-dimensional algebras with good homological properties.

Several researchers are interested in just infinite-dimensional algebras over an algebraically closed field (or an infinite field in general) [8,13]. For ring-theoretic considerations we introduce another algebra closely related to $\Omega G$. Let $K$ be a field of characteristic $p$ (in particular, $K$ could be the algebraic closure of $\mathbb{F}_p$). Define

$$K[G] := \lim_{\leftarrow} K[G/N],$$

where the inverse limit is taken over the open normal subgroups $N$ of $G$. This algebra can be obtained by taking a completion of the algebra $\Omega G \otimes_{\mathbb{F}_p} K$ with respect to the filtration $\{m^n \otimes_{\mathbb{F}_p} K \ | \ n \geq 0\}$ where $m$ is the Jacobson radical of $\Omega G$. Under the same hypotheses, Theorems A, B and C hold for $K[G]$.

1. Preliminaries

1.1. Fractional ideals

Let $R$ be a noetherian domain. It is well known that $R$ has a skewfield of fractions $Q$. Recall that a right $R$-submodule $I$ of $Q$ is said to be a fractional right $R$-ideal if $I$ is non-zero and $I \subseteq uR$ for some non-zero $u \in Q$. When the ring $R$ is understood, we simply say that $I$ is a fractional right ideal. Fractional left $R$-ideals are defined similarly. If $I$ is a fractional right ideal, then

$$I^{-1} := \{q \in Q : qI \subseteq R\}$$

is a fractional left ideal and there is a similar definition of $I^{-1}$ for fractional left ideals $I$. Let $I^* := \text{Hom}_R(I, R)$. This is a left $R$-module and there is a natural isomorphism $\eta_I : I^{-1} \rightarrow I^*$ that sends $q \in I^{-1}$ to the right $R$-module homomorphism induced by left multiplication by $q$.

1.2. Reflexive right ideals

Let $I$ be a fractional right ideal and let $\bar{I} := (I^{-1})^{-1}$ be the reflexive closure of $I$. This is also a fractional right ideal which contains $I$. Recall that $I$ is said to be reflexive if $I = \bar{I}$, or equivalently if the canonical map $I \rightarrow I^{**}$ is an isomorphism.

**Proposition.** Let $R \hookrightarrow S$ be a ring extension such that $R$ is noetherian and $S$ is flat as a left and right $R$-module. Then there is a natural isomorphism

$$\psi_i^*: S \otimes_R \text{Ext}^i_R(M, R) \xrightarrow{\cong} \text{Ext}^i_S(M \otimes_R S, S)$$
for all finitely generated right $R$-modules $M$ and all $i \geq 0$. A similar statement holds for left $R$-modules. If in addition $S$ is a noetherian domain, then

(a) $\overline{J} \cdot S = J \cdot S$ for all right ideals $J$ of $R$,
(b) $I \cap R$ is a reflexive right ideal of $R$ for all reflexive right ideals $I$ of $S$.

**Proof.** Let $M$ be a finitely generated right $R$-module and define

$$\psi_M : S \otimes_R \text{Hom}_R(M, R) \to \text{Hom}_S(M \otimes_R S, S)$$

by the rule $\psi_M(s \otimes f)(m \otimes t) = sf(m)t$ for all $s \in S$, $f \in \text{Hom}_R(M, R)$, $m \in M$ and $t \in R$. This gives a natural transformation

$$\psi : S \otimes_R \text{Hom}_R(\cdot, R) \to \text{Hom}_S(\cdot \otimes_R S, S)$$

such that $\psi_{R^n}$ is an isomorphism for all $n \geq 0$. Now let $P_\bullet \to M \to 0$ be a projective resolution of $M$ consisting of finitely generated free $R$-modules. Using the flatness assumptions on $S$, we see that

$$\text{Ext}_S^i(M \otimes_R S, S) = H^i(\text{Hom}_S(P_\bullet \otimes_R S, S)) \cong H^i(S \otimes_R \text{Hom}_R(P_\bullet, R)) = S \otimes_R H^i(\text{Hom}_R(P_\bullet, R)) = S \otimes_R \text{Ext}_R^i(M, R),$$

for all $i$, as required.

(a) The division ring of fractions $Q$ of $R$ embeds naturally into the division ring of fractions of $S$. Let $I$ be a fractional right $R$-ideal, so that $I \subseteq uR$ for some $u \in Q \setminus 0$. Then $IS \subseteq uS$, so $IS$ is a fractional right $S$-ideal. Now $I^{-1}$ is a fractional left $R$-ideal and $I^{-1}I \subseteq R$, so

$$(SI^{-1})(IS) \subseteq SRS \subseteq S$$

and hence $SI^{-1} \subseteq (IS)^{-1}$. Consider the following diagram of left $S$-modules:

$$
\begin{array}{ccc}
S \otimes_R I^{-1} & \xrightarrow{\alpha} & SI^{-1} & \xrightarrow{i} & (IS)^{-1} \\
1 \otimes \eta_I & \downarrow & & \downarrow \eta_{IS} & \\
S \otimes_R I^* & \xrightarrow{\psi_I} & (I \otimes_R S)^* & \xleftarrow{\beta} & (IS)^*. \\
\end{array}
$$

Here $i$ denotes the inclusion of $SI^{-1}$ into $(IS)^{-1}$ and $\alpha$ and $\beta$ are the obvious maps. A straightforward check shows that this diagram commutes. By the remarks made in Section 1.1 the maps $\eta_I$ and $\eta_{IS}$ are isomorphisms. Since $S$ is a flat left $R$-module, $\alpha$ is an isomorphism and similarly $\beta$ is an isomorphism. Now $\psi_I$ is an isomorphism by the first part, so $i$ must also be an isomorphism. We deduce that $SI^{-1} = (IS)^{-1}$ for all fractional right $R$-ideals $I$. By symmetry, $I^{-1}S = (SI)^{-1}$ for all fractional left $R$-ideals $I$.

We may assume that $J$ is non-zero, so that $J$ is a fractional right ideal, and hence

$$\overline{J} \cdot S = ((JS)^{-1})^{-1} = (SJ^{-1})^{-1} = (J^{-1})^{-1}S = \overline{J} \cdot S.$$
(b) Again, we may assume that $I \cap R$ is a non-zero, so that $I \cap R$ is a fractional right ideal. Clearly $I \cap R \subseteq \overline{I} \cap \overline{R}$. Using part (a) we have

$$\overline{I} \cap \overline{R} \subseteq (I \cap R) \cdot S \subseteq \overline{I} = I,$$

but $\overline{I} \cap \overline{R} \subseteq \overline{R} = R$ and hence $\overline{I} \cap \overline{R} \subseteq I \cap R$. The result follows. $\square$

1.3. Pseudo-null modules

Let $R$ be an arbitrary ring and $M$ be an $R$-module. We denote $\text{Ext}^j_R(M, R)$ by $E^j(M)$. Recall [10, Lemma 2.1 and Definition 2.5] that an $R$-module $M$ is said to be pseudo-null if $E^0(N) = E^1(N) = 0$ for any submodule $N$ of $M$. Part (b) of the proposition below shows that this extends the notion of pseudo-zero modules in the sense of [7, Chapter VII, §4.4, Definition 2].

Lemma. Let $0 \rightarrow X \rightarrow Y \rightarrow Z \rightarrow 0$ be an exact sequence of $R$-modules. Then $Y$ is pseudo-null if and only if $X$ and $Z$ are pseudo-null.

Proof. This appears in [10, §2] and follows easily from the long exact sequence of cohomology. $\square$

The following alternative characterisation of pseudo-null modules over noetherian domains is well known, but we include a proof for the convenience of the reader.

Proposition. Let $R$ be a noetherian domain and let $M$ be a finitely generated $R$-module.

(a) $M$ is pseudo-null if and only if $\text{ann}(x)^{-1} = R$ for all $x \in M$.
(b) If $R$ is commutative then $M$ is pseudo-null if and only if $\text{Ann}_R(M)^{-1} = R$.

Proof. (a) Suppose $M$ is pseudo-null and let $x \in M$. The short exact sequence $0 \rightarrow \text{ann}(x) \rightarrow R \rightarrow xR \rightarrow 0$ induces the long exact sequence

$$0 \rightarrow E^0(xR) \rightarrow E^0(R) \rightarrow E^0(\text{ann}(x)) \rightarrow E^1(xR) \rightarrow 0$$

and $E^0(xR) = E^1(xR) = 0$ since $M$ is pseudo-null. Hence $\text{ann}(x)^{-1} = R^{-1} = R$ by the remarks made in Section 1.1.

Conversely, suppose that $\text{ann}(x)^{-1} = R$ for all $x \in M$. It will be enough to show that $E^0(M) = E^1(M) = 0$. Let $N = yR$ be a quotient of a cyclic submodule $xR$ of $M$. Then $\text{ann}(x) \subseteq \text{ann}(y)$, so $R \subseteq \text{ann}(y)^{-1} \subseteq \text{ann}(x)^{-1} = R$. Hence $\text{ann}(y)^{-1} = R$ and the above long exact sequence shows that $E^0(N) = E^1(N) = 0$.

Because $M$ is finitely generated, $M$ is an extension of finitely many modules $M_1, \ldots, M_k$ such that each $M_i$ is isomorphic to a quotient of a cyclic submodule of $M$. The result now follows from a long exact sequence.

(b) Suppose that $\text{Ann}_R(M)^{-1} = R$. Since $\text{Ann}_R(M) \subseteq \text{ann}(x)$ for all $x \in M$, part (a) implies that $M$ must be pseudo-null.

Conversely, suppose that $M$ is pseudo-null and let $x_1, \ldots, x_k$ be a generating set for $M$. Since $M$ is pseudo-null, $\text{ann}(x_i)^{-1} = R$ for all $i$. Since $R$ is commutative, $\text{Ann}_R(M)$ contains the product $\text{ann}(x_1) \cdot \cdots \cdot \text{ann}(x_k)$ and it follows easily that $\text{Ann}_R(M)^{-1} = R$. $\square$
1.4. Unique factorisation domains

**Lemma.** Let $R$ be a commutative noetherian unique factorisation domain (UFD) and $I$ be a non-zero ideal of $R$. Then $\bar{I} = xR$ for some $x \in R$ and $xR/I$ is pseudo-null. Moreover, if $R$ is a graded ring and $I$ is a graded ideal, then $x$ is homogeneous.

**Proof.** By [7, Chapter VII, §4.2, Example 2 and §3.1, Definition 1], every reflexive ideal of $R$ is necessarily principal. Hence $I = xR$ for some $x \in R$.

Now let $J = \text{Ann}_R(xR/I) = x - 1 I$ and suppose that $q \in J^{-1}$. Then $qJ = qx - 1 I \subseteq R$ and so $qx - 1 \in I^{-1} = \bar{I}^{-1} = x^{-1} R$. Therefore $q \in R$ and $J^{-1} = R$. Hence $xR/I$ is pseudo-null by Proposition 1.3(b).

Suppose finally that $R$ and $I$ are graded. Then we can find a non-zero homogeneous element $y \in I$. Since $I \subseteq xR$ we see that $x$ is a factor of $y$. Because $R$ is a domain, homogeneous elements can only have homogeneous factors, so $x$ is necessarily homogeneous. \Box

1.5. Filtered rings

A **filtered ring** is a ring $R$ with a filtration $FR = \{F_n R: n \in \mathbb{Z}\}$ consisting of additive subgroups of $R$ such that $R = \bigcup_{n \in \mathbb{Z}} F_n R$, $1 \in F_0 R$, $F_n R \subseteq F_{n+1} R$ and $F_n R \cdot F_m R \subseteq F_{n+m} R$ for all $n, m \in \mathbb{Z}$. Our filtrations will always be separated, meaning that $\bigcap_{n \in \mathbb{Z}} F_n R = 0$. If $x$ is a non-zero element of $R$, there exists a unique $n \in \mathbb{Z}$, which is called the *degree* of $x$ and written $n = \deg x$, such that $x \in F_n R - F_{n-1} R$.

The abelian group $\text{gr} R := \bigoplus_{n \in \mathbb{Z}} F_n R / F_{n-1} R$ becomes a graded ring with multiplication induced by that of $R$ and is called the *associated graded ring* of $R$ with respect to $FR$. The **principal symbol** of a non-zero element $x$ of $R$ of degree $n$ is

$$\text{gr} x := x + F_{n-1} R \in F_n R / F_{n-1} R \subseteq \text{gr} R.$$ 

If $\text{gr} R$ is a domain then $\text{gr}(xy) = \text{gr}(x) \cdot \text{gr}(y)$ for any non-zero $x, y \in R$.

The **Rees ring** of $R$ (with respect to the filtration $FR$) is the following subring of the Laurent polynomial ring $R[t, t^{-1}]$:

$$\tilde{R} := \bigoplus_{n \in \mathbb{Z}} t^n F_n R.$$ 

The Rees ring comes equipped with two natural surjective ring homomorphisms $\pi_1 : \tilde{R} \to R$ and $\pi_2 : \tilde{R} \to \text{gr} R$ which send the indeterminate $t$ to one and zero, respectively. The map $\pi_1$ is sometimes called *dehomogenisation*.

2. Frobenius pairs

2.1. The classical Frobenius map

Let $K$ be a field of characteristic $p$ and let $B$ be a commutative $K$-algebra. Then the Frobenius map $x \mapsto x^p$ is a ring endomorphism of $B$ and gives an isomorphism of $B$ onto its image $B^{[p]} := \{ b^p : b \in B \}$.
in $B$ provided $B$ is reduced. We remark at this point that any derivation $d : B \to B$ is $B^{[p]}$-linear:

$$d(a^p b) = a^p d(b) + p a^{p-1} d(a) b = a^p d(b)$$

for all $a, b \in B$.

2.2. Frobenius pairs

Let $t$ be a positive integer. Whenever $\{y_1, \ldots, y_t\}$ is a $t$-tuple of elements of $B$ and $\alpha = (\alpha_1, \ldots, \alpha_t)$ is a $t$-tuple of non-negative integers, we define

$$y^\alpha = y_1^{\alpha_1} \cdots y_t^{\alpha_t}.$$  

Let $[p - 1]$ denote the set $\{0, 1, \ldots, p - 1\}$ and let $[p - 1]^t$ be the product of $t$ copies of $[p - 1]$.

**Definition.** Let $A$ be a complete filtered $K$-algebra and let $A_1$ be a subalgebra of $A$. We always view $A_1$ as a filtered subalgebra of $A$, equipped with the subspace filtration $F_n A_1 := F_n A \cap A_1$. We say that $(A, A_1)$ is a *Frobenius pair* if the following axioms are satisfied:

(i) $A_1$ is closed in $A$,
(ii) gr $A$ is a commutative noetherian domain, and we write $B = \text{gr } A$,
(iii) the image $B_1$ of gr $A_1$ in $B$ contains $B^{[p]}$, and
(iv) there exist homogeneous elements $y_1, \ldots, y_t \in B$ such that $B = \bigoplus_{\alpha \in [p-1]^t} B_1 y^\alpha$.

**Remark.** It is easy to see that $A_1$ is closed in $A$ if and only if the subspace filtration $\{F_n A_1\}_{n \in \mathbb{Z}}$ on $A_1$ is complete.

The canonical example to keep in mind is given by Iwasawa algebras of uniform pro-$p$ groups $G$. We will show in Section 6.6 that $(K[G], K[G^p])$ is always a Frobenius pair.

We will now deduce some consequences of the axioms.

2.3. The structure of $A$ as an $A_1$-module

Let $(A, A_1)$ be a Frobenius pair. We can view $A$ as an $A_1$-bimodule. Let us choose elements $u_1, \ldots, u_t \in A$ such that gr $u_i = y_i$ for all $i$ and set $u^\alpha := u_1^{\alpha_1} \cdots u_t^{\alpha_t}$ for all $\alpha \in \mathbb{N}^t$.

**Lemma.** $A$ is a free left and right $A_1$-module with basis $\{u^\alpha: \alpha \in [p-1]^t\}$:

$$A = \bigoplus_{\alpha \in [p-1]^t} A_1 \cdot u^\alpha = \bigoplus_{\alpha \in [p-1]^t} u^\alpha \cdot A_1.$$  

**Proof.** By symmetry it is sufficient to prove the statement about left modules, say. Suppose for a contradiction that $\sum_{\alpha \in T} a_\alpha u^\alpha = 0$, where $\{a_\alpha \in A_1: \alpha \in T\}$ is some collection of non-zero elements and $T \subseteq [p-1]^t$ is a non-empty indexing set. Let $n$ denote the maximum of the degrees
of the $a_\alpha u^\alpha$ and let $S$ denote the subset of $T$ consisting of those indices $\alpha$ where this maximum is attained. Then

$$\left( \sum_{\alpha \in T} a_\alpha u^\alpha \right) + F_{n-1} A = \sum_{\alpha \in S} \text{gr} a_\alpha \cdot y^\alpha = 0,$$

which is contradictory to Definition 2.2(iv). Thus the sum $M := \sum_{\alpha \in \{p-1\}'} A_1 \cdot u^\alpha$ is direct.

Now $M$ is a filtered $A_1$-submodule of $A$ and $\text{gr} M$ coincides with $\text{gr} A$. Since $A_1$ is complete, $M$ is equal to $A$ and the result follows. \hfill \square

2.4. Derivations

Let $B_1 \subseteq B$ be commutative rings of characteristic $p$, such that $B^{\{p\}} \subseteq B_1$ and

$$B = \bigoplus_{\alpha \in \{p-1\}'} B_1 y^\alpha$$

for some elements $y_1, \ldots, y_t$ of $B$.

Fix $j = 1, \ldots, t$ and let $\epsilon_j$ denote the $t$-tuple of integers having a 1 in the $j$th position and zeros elsewhere. We define a $B_1$-linear map $\partial_j : B \rightarrow B$ by setting

$$\partial_j \left( \sum_{\alpha \in \{p-1\}'} u_\alpha y^\alpha \right) := \sum_{\alpha \in \{p-1\}'} \alpha_j u_\alpha y^\alpha - \epsilon_j.$$

Let $\mathcal{D} := \text{Der}_{B_1}(B)$ denote the set of all $B_1$-linear derivations of $B$. We now collect some very useful results about $\mathcal{D}$ and its natural action on $B$. In particular, we can give a complete characterisation of the $\mathcal{D}$-stable ideals of $B$.

Proposition.

(a) The map $\partial_j$ is a $B_1$-linear derivation of $B$ for each $j$.

(b) $\mathcal{D} = \bigoplus_{j=1}^t B \partial_j$.

(c) For any $x \in B$, $\mathcal{D}(x) = 0$ if and only if $x \in B_1$.

(d) An ideal $I \subseteq B$ is $\mathcal{D}$-stable if and only if it is controlled by $B_1$:

$$I = (I \cap B_1) B.$$

Proof. (a) Because the $y_i$’s generate $B$ as a $B_1$-algebra and $\partial_j$ is $B_1$-linear by definition, to show that $\partial_j$ is a derivation it is sufficient to check that

$$\partial_j (y^\alpha \cdot y_i) = \partial_j (y^\alpha) y_i + y^\alpha \cdot \partial_j (y_i)$$

for all $\alpha \in \{p-1\}'$ and all $i = 1, \ldots, t$. This can be easily verified, using the fact that $y_k^p \in B_1$ for all $k = 1, \ldots, t$. 


(b) If $b_j \in B$ are such that $\sum_{j=1}^{t} b_j \partial_j = 0$, then $b_i = (\sum_{j=1}^{t} b_j \partial_j)(y_i) = 0$ for all $i$, so the sum above is direct. Finally, if $f \in D$, then it is easy to see that $f$ and $\sum_{j=1}^{t} f(y_j) \partial_j$ agree on every element of $B$ with the form $u \cdot y^\alpha$ for $u \in B_1$, so $f = \sum_{j=1}^{t} f(y_j) \partial_j$ and the result follows.

(c) Suppose $x \notin B_1$ and write $x = \sum_{\alpha \in [p-1]} t x_{\alpha} y^\alpha$. Then $x_{\alpha} \neq 0$ for some $\alpha \neq 0$ and so $a_j \neq 0$ for some $j$. Hence $\partial_j(x) \neq 0$. The converse is trivial.

(d) $(\Leftarrow)$ Let $J = I \cap B_1$. For any $f \in D$ we have

$$f(I) = f(JB) = Jf(B) \subseteq JB = I$$

so $I$ is $D$-stable.

$(\Rightarrow)$ Let $I$ be a $D$-stable ideal and let $J = I \cap B_1$. Note that the extension $B_1/J \subseteq B/JB$ satisfies the same conditions as $B_1 \subseteq B$, and the image of $I$ in $B/JB$ is stable under every $B_1/J$-linear derivation of $B/JB$ by part (b). Without loss of generality we may therefore assume that $I \cap B_1 = 0$, and it will be enough to show that $I = 0$.

Suppose for a contradiction that $I \neq 0$. If $u = \sum_{\alpha \in [p-1]} t u_{\alpha} y^\alpha \in B$ is a non-zero element, define

$$m(u) := \max\{\alpha_1 + \cdots + \alpha_t : u_{\alpha} \neq 0\}$$

and choose $u \in I \setminus 0$ such that $m(u)$ is minimal. If $\partial_j(u) \neq 0$ for some $j$ then $m(\partial_j(u)) < m(u)$ and $\partial_j(u) \in I \setminus 0$ contradicting the minimality of $m(u)$. Hence $\partial_j(u) = 0$ for all $j$ and therefore $u \in B_1$ by parts (b) and (c). But then $I \cap B_1 \neq 0$, a contradiction. Hence $I = 0$ as required. 

3. A control theorem for normal elements

3.1. Main result

The purpose of this section is to prove the following

**Theorem.** Let $(A, A_1)$ be a Frobenius pair satisfying the derivation hypothesis, suppose that $B_1$ is a UFD and let $w \in A$ be a normal element. Then the two-sided ideal $wA$ of $A$ is controlled by $A_1$: 

$$wA = (wA \cap A_1) \cdot A.$$

The derivation hypothesis is explained below in Section 3.5 and the proof is given in Section 3.6.

3.2. Inducing derivations on $gr A$

Let $A$ be a filtered ring with associated graded ring $B$ and let $a \in A$. Suppose that there is an integer $n \geq 0$ such that

$$[a, F_k A] \subseteq F_{k-n} A$$

for all $k \in \mathbb{Z}$. This induces linear maps
\[ \{a, -\}_n : \frac{F_k A}{F_{k-1} A} \rightarrow \frac{F_{k-n} A}{F_{k-n-1} A}, \]
\[ b + F_{k-1} A \mapsto [a, b] + F_{k-n-1} A, \]

for each \( k \in \mathbb{Z} \) which piece together to give a graded derivation
\[ \{a, -\}_n : B \rightarrow B. \]

The idea of inducing derivations of \( \text{gr} A \) in this way was first suggested to the first author by Chris Brookes and later independently by Ken Brown.

**Definition.** A source of derivations for a Frobenius pair \((A, A_1)\) is a subset \( a = \{a_0, a_1, a_2, \ldots \} \) of \( A \) such that there exist functions \( \theta, \theta_1 : a \rightarrow \mathbb{N} \) satisfying the following conditions:

(i) \( [a_r, F_k A] \subseteq F_{k-\theta(a_r)} A \) for all \( r \geq 0 \) and all \( k \in \mathbb{Z} \),

(ii) \( [a_r, F_k A_1] \subseteq F_{k-\theta_1(a_r)} A \) for all \( r \geq 0 \) and all \( k \in \mathbb{Z} \),

(iii) \( \theta_1(a_r) - \theta(a_r) \rightarrow \infty \) as \( r \rightarrow \infty \).

Let \( S(A, A_1) \) denote the set of all sources of derivations for \((A, A_1)\).

The reason behind this definition will hopefully become clear after Proposition 3.4 below. By (i), any source of derivations \( a \) generates a sequence of graded derivations \( \{a_r, -\}_\theta(a_r) \) of \( B = \text{gr} A \). These derivations are \( B_1 \)-linear for sufficiently large \( r \) by parts (ii), (iii).

The subset \( \{0\} \) is clearly an example of a source of derivations. Somewhat less trivially, we will show in Corollary 6.7 that if \( G \) is a uniform pro-\( p \) group and \( g \in G \), then \( \{g, g^p, g^{p^2}, \ldots \} \) is a source of derivations for the Frobenius pair \((K[G], K[G^p])\).

### 3.3. The delta function

Let \((A, A_1)\) be a Frobenius pair and \( n \) be an integer. Each filtered part \( F_n A_1 \) is closed in \( A_1 \) by definition of the filtration topology, and \( A_1 \) is closed in \( A \) by assumption. Hence \( F_n A_1 \) is closed in \( A \), which can be expressed as follows:

\[ F_n A_1 = \bigcap_{k \geq 0} (F_n A_1 + F_{n-k} A). \]

We can now define a key invariant of elements of \( A \).

**Definition.** For any \( w \in A \), let \( n = \text{deg} w \). Define

\[ \delta(w) = \begin{cases} \max \{k : w \in F_n A_1 + F_{n-k} A\} & \text{if } w \notin A_1, \\ \infty & \text{if } w \in A_1. \end{cases} \]

Clearly \( \delta(w) \geq 0 \). Note that if \( w \in F_n A \setminus A_1 \), then \( w \notin F_n A_1 + F_{n-k} A \) for some \( k \geq 0 \) by the above remarks, so the definition makes sense and \( \delta(w) \) is finite. The number \( \delta(w) \) measures how closely the element \( w \) can be approximated by elements of \( A_1 \). It should be remarked that \( \delta(w) > 0 \) if and only if \( \text{gr} w \in B_1 \), since both conditions are equivalent to \( w \in F_n A_1 + F_{n-1} A \).
Now suppose that \( w \in A \setminus A_1 \). By the definition of \( \delta \), we can find elements \( x \in F_n A_1 \) and \( y \in F_{n-\delta} A \) such that \( w = x + y \); if \( \delta = 0 \) we take \( x \) to be zero. Note that \( y \notin F_{n-\delta-1} A \) by the maximality of \( \delta \) and hence

\[
Y_w := \text{gr } y = y + F_{n-\delta-1} A
\]

is a non-zero homogeneous element of \( B \) of degree \( n - \delta \). In view of our assumption on \( x \), we have \( Y_w = \text{gr } w \) when \( \delta = 0 \).

### 3.4. \( \mathfrak{a} \)-closures

If \( w \) is an element of a right ideal \( I \) of \( A \), then the symbol of \( w \), \( \text{gr } w \) always lies in the associated graded ideal \( \text{gr } I \) of \( B \). Naturally there are many elements \( w \) having the same symbol, so some information is lost when one passes to the symbol of \( w \). It turns out that if the ideal \( I \) is two-sided, there is a way to save some of this information.

**Definition.** Let \( \mathfrak{a} \) be a source of derivations for a Frobenius pair \((A, A_1)\) and \( I \) be a graded ideal of \( B \). We say that the homogeneous element \( Y \) of \( B \) lies in the \( \mathfrak{a} \)-closure of \( \text{gr } I \) if \( \{a_r, Y\}_{\theta(a_r)} \) lies in \( I \) for all \( r \gg 0 \).

**Proposition.** Let \((A, A_1)\) be a Frobenius pair, let \( I \) be a two-sided ideal of \( A \), let \( w \in I \setminus A_1 \) and let \( \mathfrak{a} \in \mathcal{S}(A, A_1) \). Then \( Y_w \) lies in the \( \mathfrak{a} \)-closure of \( \text{gr } I \).

**Proof.** Let us write \( \delta = \delta(w) \) and \( w = x + y \) as in the previous subsection. Since \( \mathfrak{a} \) is a source of derivations, we can find an integer \( r_0 \geq 1 \) such that \( \theta_1(a_r) - \theta(a_r) > \delta \) for all \( r \geq r_0 \). Therefore

\[
[a_r, x] \in F_{n-\theta_1(a_r)} A \subseteq F_{n-\delta-\theta(a_r)-1} A \quad \text{and}
\]

\[
[a_r, y] \in F_{n-\delta-\theta(a_r)} A,
\]

for all \( r \geq r_0 \). Hence

\[
[a_r, w] \in F_{n-\delta-\theta(a_r)} A, \quad \text{and}
\]

\[
[a_r, w] \equiv [a_r, y] \mod F_{n-\delta-\theta(a_r)-1} A
\]

for all \( r \geq r_0 \). We can rewrite the above as follows:

\[
[a_r, w] + F_{n-\delta-\theta(a_r)-1} A = [a_r, y] + F_{n-\delta-\theta(a_r)-1} A = \{a_r, Y_w\}_{\theta(a_r)}
\]

for \( r \geq r_0 \). Since \( w \in I \) and \( I \) is a two-sided ideal, this element must always lie in the ideal \( \text{gr } I \) of \( B \), and hence \( Y_w \) lies in the \( \mathfrak{a} \)-closure of \( \text{gr } I \) as required.

Each source of derivations \( \mathfrak{a} \) gives rise to a sequence of derivations \( \{a_r, -\}_{\theta(a_r)} \) of \( B \), and some or all of these could well be zero. To ensure that we get an interesting supply of derivations of \( B \), we now introduce a condition which holds for Iwasawa algebras of only rather special uniform pro-\( p \) groups.
3.5. The derivation hypothesis

Recall that $D$ denotes the set of all $B_1$-linear derivations of $B$ and $S(A, A_1)$ denotes the set of all sources of derivations for $(A, A_1)$. Our derivation hypothesis is really concerned with the action of the derivations induced by $S(A, A_1)$ on the graded ring $B$.

**Definition.** Let $(A, A_1)$ be a Frobenius pair and $X \in B$ be an arbitrary homogeneous element. We say that $(A, A_1)$ satisfies the derivation hypothesis if whenever a homogeneous element $Y \in B$ lies in the $a$-closure of $XB$ for all $a \in S(A, A_1)$, we must have $D(Y) \subseteq XB$.

Assuming the derivation hypothesis, it is possible to “clean” a normal element by multiplying it by a unit. The following proposition forms the inductive step in the proof of Theorem 3.1.

**Proposition.** Let $(A, A_1)$ be a Frobenius pair satisfying the derivation hypothesis and let $w \in A \setminus A_1$ be a normal element. Then there exists a unit $u \in A$ such that $\delta(wu) > \delta(w)$. Moreover, if $\delta(w) > 0$ then $u = 1 - c$ for some $c \in F^{-\delta(w)}A$.

**Proof.** Write $w = x + y$ as in Section 3.3, let $X = \text{gr} w$ and $Y = Y_w = \text{gr} y$. By Proposition 3.4, $Y$ lies in the $a$-closure of $\text{gr} w A = XB$ for all $a \in S(A, A_1)$ and hence $D(Y) \subseteq XB$ because $(A, A_1)$ satisfies the derivation hypothesis.

Suppose first that $\delta := \delta(w) = 0$, so that $Y = X$. Then the ideal $XB$ of $B$ is $D$-stable and is hence controlled by $B_1$ by Proposition 2.4(d):

$$XB = (XB \cap B_1) \cdot B.$$  

Because $B$ is a free $B_1$-module, $XB \cap B_1$ is a reflexive ideal of $B_1$ by Proposition 1.2(b). Since $B_1$ is a UFD by assumption, $XB \cap B_1 = X_1B_1$ for some homogeneous element $X_1 \in B_1$ by Lemma 1.4.

Hence $XB = X_1B$ and we can therefore find a homogeneous unit $U \in B$ such that $X_1 = XU$. Choose $u, v \in A$ such that $\text{gr} u = U$ and $\text{gr} v = U^{-1}$; then $uv \equiv 1 \mod F_{-1}A$. But $A$ is complete so $1 + F_{-1}A$ consists of units in $A$ and hence $u$ is a unit. Since $\text{gr}(wu) = XU = X_1 \in B_1$, it follows that $\delta(wu) > 0 = \delta(w)$ as required.

Now suppose that $\delta > 0$; then $X$ must lie in $B_1$. Applying Proposition 2.4(c) to the image of $Y$ in $B/XB$ yields that

$$Y \in XB + B_1.$$  

Since $X$ and $Y$ are homogeneous, we can find homogeneous elements $C \in B$ and $Z \in B_1$ such that

$$Y = XC + Z;$$

moreover $\deg Y = \deg XC$ if $XC \neq 0$ and $\deg Y = \deg Z$ if $Z \neq 0$.

Suppose for a contradiction that $C = 0$. Then $Y = Z \in B_1$. Hence we can find $x' \in F_{n-\delta}A_1$ such that

$$x' \equiv y \mod F_{n-\delta-1}A.$$  

Thus \( w - (x + x') \in F_{n-\delta-1}A \), which is contradictory to the maximality of \( \delta \). So \( C \neq 0 \) and hence \( \deg C = \deg Y - \deg X = -\delta \). Note that \( \deg C < 0 \).

We can find \( c \in A \) such that \( \text{gr } c = C \). Then

\[
 w(1 - c) = (x + y)(1 - c) \equiv x + y - xc \pmod{F_{n-\delta-1}A}
\]

since \( \deg(yc) < n - \delta \). But\( y - xc + F_{n-\delta-1}A = Y - XC = Z \in B_1 \), so we can find \( z \in A_1 \) such that \( y - xc \equiv z \pmod{F_{n-\delta-1}A} \) and hence

\[
 w(1 - c) - (x + z) \in F_{n-\delta-1}A.
\]

Since \( \deg Z = \deg Y \) if \( Z \neq 0 \), \( z \in F_{n-\delta}A \) and hence \( x + Z \in F_nA_1 \). This implies that \( \delta(w(1 - c)) > \delta = \delta(w) \).

Finally, since \( c \in F_{-\delta}A \subseteq F_{-1}A \) and \( A \) is complete, \( u := 1 - c \) is a unit in \( A \) and \( \delta(wu) > \delta(w) \) by construction. \( \square \)

### 3.6. Proof of Theorem 3.1

**Proof.** It will be enough to construct a unit \( u \in A \) such that \( wu \in A_1 \).

If \( w \) already happens to lie in \( A_1 \) then we can take \( u = 1 \), so assume that \( w \notin A_1 \). By Proposition 3.5 there exists a unit \( u_0 \in A \) such that \( \delta(wu_0) > 0 \).

Let \( w_0 := wu_0 \). Using Proposition 3.5 we can inductively construct a sequence of normal elements \( w_1, w_2, \ldots \) of \( A \) and a sequence of elements \( c_1, c_2, \ldots \) of \( A \), such that for all \( i \geq 0 \),

\begin{itemize}
  \item \( c_{i+1} \in F_{-\delta(w_i)}A \),
  \item \( w_{i+1} = w_i(1 - c_{i+1}) \),
  \item \( \delta(w_{i+1}) > \delta(w_i) \) if \( w_i \notin A_1 \).
\end{itemize}

Here we interpret \( F_{-\infty}A \) as the zero subspace of \( A \). With this convention, the sequence \( c_i \) converges to zero as \( i \to \infty \) by construction, so the limit

\[
 u := \lim_{i \to \infty} u_0(1 - c_1) \cdots (1 - c_i)
\]

exists in \( A \) by the completeness of \( A \). Note that \( u \) is unit because we can write down an inverse having the same form as \( u \), and that \( wu = \lim_{i \to \infty} w_i \).

We will now show that \( wu \) lies in \( A_1 \). Since \( A_1 \) is closed in \( A \), it will be sufficient to show that \( wu \in A_1 + F_kA \) for all \( k \in \mathbb{Z} \). Let \( n = \deg w_0 \) and note that \( \deg w_i = n \) for all \( i \geq 0 \) by construction. Since \( w_i \to wu \) and \( \delta(w_i) \to \infty \) as \( i \to \infty \), we see that for \( i \gg 0 \), \( wu - w_i \in F_kA \) and \( w_i \in F_nA_1 + F_kA \). Hence \( wu \in F_nA_1 + F_kA \subseteq A_1 + F_kA \), as required. \( \square \)
4. Microlocalisation

4.1. Notation

We briefly recall some basic facts about the theory of algebraic microlocalisation, following [16] and [6]. Our notation will be slightly non-standard. Throughout Section 4 we will make the following assumptions:

- $R$ is a filtered ring whose Rees ring $\tilde{R}$ is noetherian,
- $T$ is a right Ore subset of $gr R$ consisting of homogeneous regular elements.

Since $R$ and $gr R$ are homomorphic images of $\tilde{R}$ by Section 1.5, these rings must also be noetherian. We should remark at this point that if the filtration on $R$ is complete and $gr R$ is noetherian, then the filtration on $R$ is zariskian: see [17, Chapter II, §2.1, Definition 1 and §2.2, Proposition 1]. In particular $\tilde{R}$ is necessarily noetherian.

4.2. Lifting Ore sets

Let $\tilde{T}$ denote the homogeneous inverse image of $T$ in $\tilde{R}$:

$$\tilde{T} := \{ r \in \tilde{R}: r \text{ is homogeneous and } \pi_2(r) \in T \}.$$

It can be shown that $\tilde{T}$ is a right Ore set in $\tilde{R}$ [16, Corollary 2.2], so we may form the Ore localisation $\tilde{R}_{\tilde{T}}$. This is still a $\mathbb{Z}$-graded ring.

Let $S := \pi_1(\tilde{T}) \subseteq R$. This is a right Ore set in $R$ and in fact

$$S = \{ r \in R: gr r \in T \}.$$

Note that $S$ consists of regular elements in $R$, since every element of $T$ is assumed to be regular. It follows that $R$ embeds into the Ore localisation $R_S$.

The surjection $\pi_1: \tilde{R} \twoheadrightarrow R$ extends to surjection $\pi_1: \tilde{R}_{\tilde{T}} \twoheadrightarrow R_S$. The grading on $\tilde{R}_{\tilde{T}}$ induces a filtration on $R_S$, as in [16, Proposition 2.3(1)]:

$$F_n R_S := \pi_1((\tilde{R}_{\tilde{T}})_n).$$

Here $(\tilde{R}_{\tilde{T}})_n$ denotes the $n$th-graded part of $\tilde{R}_{\tilde{T}}$.

**Lemma.** The filtration on $R_S$ is given explicitly by the formula

$$F_n R_S = \{ rs^{-1}: r \in R, s \in S \text{ and } \deg r - \deg s \leq n \}$$

for all integers $n$. This filtration is zariskian.

**Proof.** Before we begin the proof, let us observe that if $x \in R$ is non-zero and $y \in S$ then $(gr x)(gr y) \neq 0$ (because $gr x \neq 0$ and $gr y \in T$ is regular) and hence $\deg(xy) = \deg x + \deg y$.

Let $L_n = \{ rs^{-1}: r \in R, s \in S \text{ and } \deg r - \deg s \leq n \}$. Decoding the definition of $F_n R_S$, we see that $F_n R_S$ is in fact the additive subgroup of $R_S$ generated by $L_n$. It will therefore be sufficient to show that $L_n$ is closed under addition.
So let \( r_1 s_1^{-1} \) and \( r_2 s_2^{-1} \) be elements of \( L_n \) for some \( r_i \in R \) and \( s_i \in S \). We can find \( u_1 \in S \) and \( u_2 \in R \) such that \( s_1 u_1 = s_2 u_2 = s \) say; then \( r_1 s_1^{-1} + r_2 s_2^{-1} = (r_1 u_1 + r_2 u_2) s^{-1} \). Since \( s_1, s_2 \in S \), we have \( \deg s = \deg s_1 + \deg u_1 = \deg s_2 + \deg u_2 \) by the first paragraph. Now

\[
\deg(r_1 u_1 + r_2 u_2) - \deg s \leq \max\{\deg r_1 + \deg u_1, \deg r_2 + \deg u_2\} - \deg s
\]

so \((r_1 u_1 + r_2 u_2)s^{-1} \in L_n\), as required.

The last assertion follows from [16, Proposition 2.8]. □

4.3. Microlocalisation of rings

**Definition.** The microlocalisation of \( R \) at \( T \) is the completion \( Q_T(R) \) of \( R_S \) with respect to the filtration on \( R_S \) described in Section 4.2.

We record some useful properties enjoyed by microlocalisation.

**Proposition.**

(a) \( Q_T(R) \) is a complete filtered ring,
(b) \( F_n Q_T(R) \) is the closure of \( F_n R_S \) in \( Q_T(R) \),
(c) \( R \) embeds into \( Q_T(R) \),
(d) \( Q_T(R) \) is a flat right \( R \)-module,
(e) there are natural isomorphisms

\[
gr Q_T(R) \cong gr(R_S) \cong (gr R)_T.
\]

**Proof.** Parts (a) and (b) are clear from the definition. We have seen in Section 4.2 that \( R \) embeds into \( R_S \), and the filtration on \( R_S \) is separated by Lemma 4.2 and [17, Chapter II, §2.1, Theorem 2]. Hence \( R_S \) embeds into \( Q_T(R) \) and part (c) follows. Parts (d) and (e) follow from [6, Corollary 3.20(1) and Proposition 3.10]. □

4.4. Microlocalisation of modules

Let \( M \) be a finitely generated right \( R \)-module. We define the microlocalisation of \( M \) at \( T \) to be

\[ Q_T(M) := M \otimes_R Q_T(R). \]

This is naturally a right \( Q_T(R) \)-module. Recall that a filtration on \( M \) is said to be good if the associated Rees module is finitely generated over \( \tilde{R} \).

**Lemma.** Let \( M \) be a finitely generated \( R \)-module equipped with some good filtration, and \( N \) be a submodule of \( M \). Then

(a) \( gr Q_T(M) \cong (gr M)_T \).
the Ore localisation $M_S$ is a dense $R_S$-submodule of $Q_T(M)$,
(c) $Q_T(N)$ can be identified with a $Q_T(R)$-submodule of $Q_T(M)$,
(d) the tensor filtration on $Q_T(N)$ coincides with the subspace filtration induced from $Q_T(M)$,
(e) if $L$ is another submodule of $M$, then $Q_T(N) \cap Q_T(L) = Q_T(N \cap L)$.

Proof. We should remark that the filtration on $Q_T(M) = M \otimes_R Q_T(R)$ is the tensor filtration in the sense of [17, Chapter I, §6]. Part (a) follows from [6, Proposition 3.10 and Corollary 3.20(2)] and part (b) follows from [16, Corollary 2.5(3)], whereas parts (c) and (d) follow from [6, Corollary 3.16(3)].

Finally, $Q_T(R)$ is a flat $R$-module by Proposition 4.3(d), so the microlocalisation functor $M \mapsto M \otimes_R Q_T(R)$ preserves pullbacks, and in particular, intersections. Part (e) follows.

4.5. Constructing normal elements

Let $I$ be a right ideal of $R$. Using Lemma 4.4(c), we can and will identify $Q_T(I)$ with a right ideal of $Q_T(R)$. By Lemma 4.4(d) this identification respects filtrations, and by Lemma 4.4(a) the associated graded ideal $\text{gr} Q_T(I)$ is just the localised right ideal $(\text{gr} I)_T$ of $(\text{gr} R)_T$.

Proposition. Let $I$ be a two-sided of $R$ and suppose that there exists a central regular homogeneous element $X \in \text{gr} R$ such that the localised ideal $(\text{gr} I)_T$ of $(\text{gr} R)_T$ is generated by $X$:

$$(\text{gr} I)_T = X \cdot (\text{gr} R)_T.$$ 

Then there exists a normal element $w \in Q_T(R)$ such that $Q_T(I) = w \cdot Q_T(R)$.

Proof. Choose any $w \in Q_T(I)$ such that $\text{gr} w = X$. Then the right ideal $w \cdot Q_T(R)$ is contained in $Q_T(I)$ and their graded ideals are equal by assumption. Because the filtration on $Q_T(R)$ is complete, it follows that $Q_T(I) = w \cdot Q_T(R)$.

The Ore localisation $I_S$ is a two-sided ideal of $R_S$ because $R$ is noetherian [19, Proposition 2.1.16]. By Lemma 4.4(b), $Q_T(I)$ is the closure of $I_S$ inside $Q_T(R)$ and is hence a two-sided ideal of $Q_T(R)$.

Since $X = \text{gr} w$ is central and regular in $(\text{gr} R)_T$, and the filtration on $Q_T(R)$ is complete, the fact that $w$ is a normal element in $R$ will follow from the following rather general lemma.

Lemma. Let $R$ be a complete filtered ring and $w \in R$. Suppose that $wR$ is a two-sided ideal of $R$ and that $\text{gr} w$ is a central regular element of $\text{gr} R$. Then $w$ is a regular normal element in $R$.

Proof. Because $\text{gr} w$ is a regular element of $\text{gr} R$, $w$ must be a regular element of $R$. Since $Rw \subseteq wR$, for every $r \in R$ there exists $\sigma(r) \in R$ such that $rw = w\sigma(r)$. Since $w$ is regular, $r \mapsto \sigma(r)$ is an injective ring endomorphism of $R$. We will show that $\sigma$ is surjective, which will complete the proof.

Let $r \in R$ be non-zero, so that $\sigma(r)$ is non-zero. Since $\text{gr} w$ is central and regular,

$$\text{gr} r \text{gr} w = \text{gr}(rw) = \text{gr}(w\sigma(r)) = \text{gr} w \text{gr} \sigma(r) = \text{gr} \sigma(r) \text{gr} w$$
and therefore $\text{gr}\, \sigma(r) = \text{gr}\, r$ for any non-zero $r \in R$. Now let $s \in R$ be a non-zero element of degree $n$. Set $r_n := s$, so that

$$s \equiv \sigma(r_n) \mod F_{n-1}R.$$ 

Set $r_{n-1} = s - \sigma(r_n) \in F_{n-1}R$, so that

$$s - \sigma(r_n) \equiv \sigma(r_{n-1}) \mod F_{n-2}R.$$ 

Continuing this process, we can construct a sequence $r_n, r_{n-1}, r_{n-2}, \ldots$ of elements of $R$ such that $r_i \in F_i R$ for all $i \leq n$. Because $R$ is complete, the infinite sum $\sum_{k=0}^{\infty} r_{n-k}$ converges to an element $r$ of $R$ and $\sigma(r) = s$ by construction. The result follows. \qed

5. A control theorem for reflexive ideals

In this section we state and prove our main result.

5.1. Microlocalisation of Frobenius pairs

Let $(A, A_1)$ be a Frobenius pair. Because $B = \text{gr}\, A$ is noetherian and the filtration on $A$ is complete, the remarks made in Section 4.1 show that we may apply the theory developed in Section 4.

If $Z$ is a non-zero homogeneous element of $B$, then $T := \{1, Z, Z^2, \ldots\}$ is an Ore set in $B$ consisting of regular homogeneous elements, since $B$ is a commutative domain by assumption. By abuse of notation, we will denote the corresponding microlocalisation $Q_T(A)$ by $Q_Z(A)$.

It turns out that Frobenius pairs are stable under microlocalisation.

**Proposition.** Let $(A, A_1)$ be a Frobenius pair and $Z \in B$ be a non-zero homogeneous element.

(a) $(Q_Z(A), Q_{Z^p}(A_1))$ is also a Frobenius pair.
(b) If $a$ is a source of derivations for $(A, A_1)$, then it is also a source of derivations for $(Q_Z(A), Q_{Z^p}(A_1))$.
(c) Suppose $B$ is a UFD. If $(A, A_1)$ satisfies the derivation hypothesis, then so does $(Q_Z(A), Q_{Z^p}(A_1))$.

**Proof.** (a) By Proposition 4.3(c), we can identify $A$ with its image in $Q_Z(A)$. We will also identify $\text{gr}\, A_1$ with its image $B_1$ in $B$. By Definition 2.2(iii), $Z^p$ lies in $B_1$ so the microlocalisation $Q_{Z^p}(A_1)$ makes sense.

Let $T$ and $T_1$ denote the multiplicatively closed sets in $B$ and $B_1$ generated by $Z$ and $Z^p$ and let $S$ and $S_1$ be the corresponding right Ore sets in $A$ and $A_1$. Clearly $S_1 \subseteq S$, so the Ore localisation $(A_1)_{S_1}$ naturally embeds into $A_S$. Moreover, using Lemma 4.2 we see that

$$(F_n A_S) \cap (A_1)_{S_1} = F_n (A_1)_{S_1}$$
for all \( n \in \mathbb{Z} \), which means that the filtration on \((A_1)_S\) induced from \( A_1 \) coincides with the subspace filtration induced from \( A_S \). Passing to completions we see that \( Q_{ZP}(A_1) \) can be identified with a closed subalgebra of \( Q_Z(A) \). Moreover, one can easily check that
\[
(F_n Q_Z A) \cap Q_{ZP}(A_1) = F_n Q_{ZP}(A_1)
\]
for all \( n \). Hence Definition 2.2(i) is satisfied for the new pair \( (Q_Z(A), Q_{ZP}(A_1)) \).

Next, \( gr Q_Z(A) \cong B_Z \) and \( gr Q_{ZP}(A_1) \cong (B_1)_Z \) by Proposition 4.3(e). Since \( B_Z \) is a commutative noetherian domain and \( (B_Z)^{[p]} = (B_1)^{[p]} \subseteq (B_1)_{ZP} \), Definitions 2.2(ii), (iii) are satisfied.

Finally, \( B_Z = B_{ZP} \) because \( Z \) is becomes a unit when \( ZP \) gets inverted. Hence
\[
(B_Z)_{1}^{[p]} = (B_{ZP})_{1}^{[p]},
\]
which shows that Definition 2.2(iv) is inherited by \( B_Z \).

(b) Let \( a \in A \) and let the integers \( k, n \) be such that \([a, F_k A] \subseteq F_{k-n} A\). For any \( y \in A \) and \( s \in S \) we have
\[
[a, y s^{-1}] = [a, y] s^{-1} - y s^{-1} [a, s] s^{-1},
\]
which together with Lemma 4.2 implies that
\[
[a, F_k A_S] \subseteq F_{k-n} A_S.
\]

Now \( F_k Q_Z(A) \) is the closure of \( F_k A_S \) in \( Q_Z(A) \) by Proposition 4.3(b) and the bracket operation \([a, -]\) is continuous, so
\[
[a, F_k Q_Z(A)] \subseteq F_{k-n} Q_Z(A).
\]
A similar argument shows that if \([a, F_k A_1] \subseteq F_{k-n} A\), then
\[
[a, F_k Q_{ZP}(A_1)] \subseteq F_{k-n} Q_{ZP}(A_1).
\]
Part (b) follows.

(c) Let \( X, Y \) be homogeneous elements of \( B_Z \) and suppose that \( Y \) lies in the \( a \)-closure of \( X B_Z \) for all \( a \in S(Q_Z(A), Q_{ZP}(A_1)) \).

Let \( a \) be a source of derivations for \((A, A_1)\). Note that the derivation \( D_r \) of \( gr Q_Z(A) \cong B_Z \) induced by the element \( a_r \in Q_Z(A) \) coincides with the extension to \( B_Z \) of the derivation \( \{a_r, -\}_{\theta(a_r)} \) of \( B \) induced by \( a_r \in A \).

Because \( Y \) lies in the \( a \)-closure of \( X B_Z \), \( D_r(Y) \in X B_Z \) for all \( r \gg 0 \). We can find an integer \( n \) such that \( Z^{p^n} Y \in B \). Then
\[
D_r(Z^{p^n} Y) \in X B_Z \cap B
\]
for all \( r \gg 0 \). Since \( B_Z \) is a flat \( B \)-module, \( X B_Z \cap B \) is a reflexive ideal of \( B \) by Proposition 1.2(b). Since \( B \) is a UFD, Lemma 1.4 implies that \( X B_Z \cap B = X' B \) for some homogeneous element \( X' \in B \). Hence
\[
D_r(Z^{p^n} Y) \in X' B
\]
for all \( \epsilon > 0 \) and therefore \( Z_{p^\epsilon} Y \) lies in the \( a \)-closure of \( X' B \) for any source of derivations \( a \) for \( (A, A_1) \). Because \( (A, A_1) \) satisfies the derivation hypothesis, it follows that \( D(Z_{p^\epsilon} Y) \subseteq X' B \). By Proposition 2.4(b), the localised \( B_\epsilon \)-module \( D \) can be identified with the set of all \( (B_1)_{p^\epsilon} \)-linear derivations of \( B_\epsilon \). But \( D(Y) \subseteq XB_\epsilon \) and part (c) follows.

5.2. Applying Theorem 3.1

We can now use the Control Theorem for normal elements to deduce some information about arbitrary two-sided ideals. Recall the definition of pseudo-null modules from Section 1.3.

**Theorem.** Let \( (A, A_1) \) be a Frobenius pair satisfying the derivation hypothesis, such that \( B \) and \( B_1 \) are UFDs. Let \( I \) be a two-sided ideal of \( A \) and \( J = (I \cap A) \cdot A_1 \). Then \( \text{gr} I / \text{gr} J \) is pseudo-null.

**Proof.** The right ideal \( J \) is clearly contained in \( I \), and we have the following chain of inclusions of graded ideals in \( B \):

\[
\text{gr} J \subseteq \text{gr} I \subseteq \overline{\text{gr} I} \subseteq \text{gr} R,
\]

where \( \overline{\text{gr} I} \) denotes the reflexive closure of \( \text{gr} I \) in \( B \) defined in Section 1.2. Since \( B \) is a UFD, \( \text{gr} I = XB \) for some homogeneous element \( X \in B \) by Lemma 1.4.

Let \( Z \) be a non-zero homogeneous element of \( B \) such that \( ZX \in \text{gr} I \), and consider the microlocalisations \( A' := QZ(A) \) and \( A_1' := QZ_1(A_1) \). By construction, \( (\text{gr} I)_Z = X \cdot B_Z \), so the two-sided ideal \( I' := QZ(I) \) of \( A' \) is generated by a normal element \( w \) of \( A' \) by Proposition 4.5. Because the Frobenius pair \( (A', A_1') \) satisfies the derivation hypothesis by Proposition 5.1(c), the ideal \( I' = wA' \) is controlled by \( A_1' \) by Theorem 3.1:

\[
I' = (I' \cap A_1') \cdot A'.
\]

By Lemma 2.3, \( A = \bigoplus_{\alpha \in [p-1]} u^\alpha A_1 \) and \( A' = \bigoplus_{\alpha \in [p-1]} u^\alpha A_1' \); note that the same generators occur in both expressions. Hence

\[
A' = A \cdot A_1' \quad \text{and} \quad I' = I \cdot A' = I \cdot A \cdot A_1' = I \cdot A_1'.
\]

Because \( A \) is a finitely generated \( A_1 \)-module, Lemma 4.4(e) implies that

\[
Q_{Z_1}(I) \cap Q_{Z_1}(A_1) = Q_{Z_1}(I \cap A_1)
\]

or equivalently, \( (I \cdot A_1') \cap A_1' = (I \cap A_1) \cdot A_1' \). Hence

\[
I' = (I' \cap A_1') \cdot A' = (I \cap A_1) \cdot A_1' \cdot A' = (I \cap A_1) A \cdot A'
\]

and hence \( I \cdot A' = J \cdot A' \). Passing to the graded ideals and using Lemma 4.4(a), we obtain \( (\text{gr} I)_Z = (\text{gr} J)_Z \), which means that \( Z^n \text{gr} I \subseteq \text{gr} J \) for some integer \( n \).

This holds for any \( Z \in X^{-1} \text{gr} I \), a finitely generated ideal in \( B \). Hence

\[
(X^{-1} \text{gr} I)^m \subseteq \text{Ann}_B(\text{gr} I / \text{gr} J)
\]
for some integer \( m \). But \( B/X^{-1} \text{gr} I \cong X B/I \) is pseudo-null by Lemma 1.4, so \( C := B/(X^{-1} \text{gr} I)^m \) is also pseudo-null by Lemma 1.3. Since \( \text{gr} I/\text{gr} J \) is a finitely generated \( B \)-module, it must be a quotient of a direct sum of finitely many copies of \( C \) and is therefore pseudo-null, again by Lemma 1.3. \( \square \)

5.3. A control theorem for reflexive ideals

We can now prove our main result. Recall from Section 0.3 that a reflexive two-sided ideal is a two-sided ideal which is reflexive as a right and left ideal. See also the remark below.

**Theorem.** Let \((A, A_1)\) be a Frobenius pair satisfying the derivation hypothesis, such that \( B \) and \( B_1 \) are UFDs. Let \( I \) be a reflexive two-sided ideal of \( A \). Then \( I \cap A_1 \) is a reflexive two-sided ideal of \( A_1 \) and \( I \) is controlled by \( A_1 \):

\[
I = (I \cap A_1) \cdot A.
\]

**Proof.** Retain the notation of Section 5.2. Note that \( A \) is a free right and left \( A_1 \)-module by Lemma 2.3. It follows from Proposition 1.2 that \( I \cap A_1 \) is a reflexive ideal of \( A_1 \) and \( J = (I \cap A_1)A \) is a reflexive right ideal of \( A \). It will clearly be enough to show that \( I \subseteq J \).

Let \( N \) be a right submodule of \( I/J \). If we equip \( N \) with the subquotient filtration, then \( \text{gr} N \) is a submodule of \( \text{gr} I/\text{gr} J \) and is hence pseudo-null by Theorem 5.2 and Lemma 1.3. In particular, \( E^0(\text{gr} N) = E^1(\text{gr} N) = 0 \).

Since the filtration on \( A \) is zariskian by the remarks made in Section 4.1, there is a good filtration on \( E^1(N) \) such that \( \text{gr} E^1(N) \) is a subquotient of \( E^1(\text{gr} N) \) by [9, Proposition 3.1]. Hence \( \text{gr} E^1(N) = 0 \). It now follows from [17, Chapter II, §1.2, Lemma 9] that \( E^1(N) = 0 \). Similarly \( E^0(N) = 0 \), and so \( I/J \) is a pseudo-null right \( A \)-module.

Let \( x \in I \) and \((J : x) := \{a \in A : xa \in J\}\) be the annihilator of the image of \( x \) in \( I/J \). By Proposition 1.3(a) we know that \((J : x)^{-1} = A\). Now \( J^{-1}x(J : x) \subseteq J^{-1}J \subseteq A \) so \( J^{-1}x \subseteq (J : x)^{-1} = A \). Hence \( x \in J = J \), as required. \( \square \)

**Remark.** If \( B \) is a UFD, then \( B \) is completely integrally closed. In other words, \( B \) is a maximal order [19, Proposition 5.1.3]. It follows from [18, X.2.1] that \( A \) is also a maximal order. Now it is well known that a two-sided ideal \( I \) of a maximal order \( A \) is reflexive as a right ideal if and only if it is reflexive as a left ideal [19, Proposition 5.1.8].

6. Iwasawa algebras

6.1. The Campbell–Hausdorff series

Following [12], we define

\[
\epsilon := \begin{cases} 2 & \text{if } p = 2, \\ 1 & \text{otherwise.} \end{cases}
\]

Recall [12, §9.4] that a \( \mathbb{Z}_p \)-Lie algebra \( L \) is said to be powerful if \( L \) is free of finite rank as a module over \( \mathbb{Z}_p \) and \([L, L] \subseteq p^n L\).

Let \( \Phi(X, Y) \) be the Campbell–Hausdorff series [12, Definition 6.26].
**Lemma.** Let $L$ be a powerful $\mathbb{Z}_p$-Lie algebra, $v, w \in L$ and $k \geq 0$. Then

$$\Phi(-v + p^k w, v) \equiv p^k w \mod p^{k+1} L.$$

**Proof.** By the definition of the Campbell–Hausdorff series,

$$\Phi(X, Y) = X + Y + \frac{1}{2} [X, Y] + \sum_{n \geq 3} \sum_{\langle e \rangle = n-1} q_e (X, Y)_e$$

where $e = (e_1, \ldots, e_s)$ ranges over all possible sequences of positive integers such that $\langle e \rangle := e_1 + \cdots + e_s = n - 1$, $q_e$ is a certain rational number and

$$(X, Y)_e = \left[ \cdots \left[ [X, Y], \ldots, Y \right], X \right], \ldots, X \ldots$$

is a repeated Lie commutator depending on $e$ of length $n$. Fix the integer $n \geq 3$ and the sequence $e$ for the time being.

Substitute $X = -v + p^k w$ and $Y = v$ into this repeated commutator and expand: this gives a $\mathbb{Z}_p$-linear combination of repeated commutators of $v$ and $p^k w$ of length $n$. With the exception of $[v, v, \ldots, v] = 0$, each one of these involves at least one $p^k w$ and hence is contained in $p^k L^n$, where $L^1 = L, L^2 = [L, L], L^3 = [[L, L], L], \ldots$ is the lower central series of $L$.

Using the fact that $L$ is powerful, we deduce that

$$(-v + p^k w, v)_e \in p^k L^n \subseteq p^{k+\epsilon(n-1)} L.$$

Now as $n \geq 3$, $p^{\epsilon(n-1)} q_e \in p^\epsilon \mathbb{Z}_p$ by [12, Theorem 6.28], so

$$q_e (-v + p^k w, v)_e \in p^k q_e p^{\epsilon(n-1)} L \subseteq p^{k+\epsilon} L$$

for all $n \geq 3$ and all $e$ such that $\langle e \rangle = n - 1$. Hence

$$\Phi(-v + p^k w, v) \equiv p^k w + \frac{p^k}{2} [w, v] \mod p^{k+\epsilon} L.$$

Now $\frac{p^k}{2} [w, v] \in p^{k+1} L$ since $[w, v] \in p^\epsilon L$ and the result follows. □

**6.2. The exponential map**

We recall the definition of a *uniform pro-$p$ group* from [12, §4.1, §3.1] for the convenience of the reader. Let $G$ be a pro-$p$ group. Define $P_1(G) = G$ and $P_{i+1}(G) = P_i(G) P_i(P_i(G), G)$ for $i \geq 1$. The decreasing chain of characteristic subgroups

$$G = P_1(G) \supseteq P_2(G) \supseteq \cdots \supseteq P_i(G) \supseteq \cdots$$

is called the *lower $p$-series* of $G$, and the group $G$ is said to be *powerful* if $G/P_i^{p^\epsilon}$ is abelian. Finally, $G$ is *uniform* if it is powerful, finitely generated, and

$$|G : P_2(G)| = |P_1(G) : P_{i+1}(G)|$$
for all \( i \geq 1 \).

By [12, Theorem 9.10], there is an isomorphism between the category of uniform pro- \( p \) groups and group homomorphisms and the category of powerful \( \mathbb{Z}_p \)-Lie algebras and Lie homomorphisms.

If \( L \) is a powerful \( \mathbb{Z}_p \)-Lie algebra and \( G \) is the corresponding uniform pro- \( p \) group, then there is a bijection

\[
\exp : L \to G
\]

which allows us to write every element of \( G \) in the form \( \exp(u) \) for some \( u \in L \). The Campbell–Hausdorff series allows us to recover the group multiplication in \( G \) from the Lie structure on \( L \) [12, Proposition 6.27]:

\[
\exp(u) \cdot \exp(v) = \exp(\Phi(u, v))
\]

for all \( u, v \in L \). We collect together some useful properties of \( \exp \) in the following

**Lemma.** Let \( L \) be a powerful \( \mathbb{Z}_p \)-Lie algebra, \( u, v \in L \) and \( G \) be the corresponding uniform pro- \( p \) group. Then

(a) \( \exp(mu) = \exp(u)^m \) for all \( m \in \mathbb{Z} \),
(b) \( \exp(p^k L) = G^{p^k} \) for all \( k \geq 0 \),
(c) if \( u \equiv v \mod p^k L \) for some \( k \geq 0 \), then \( \exp(u) \equiv \exp(v) \mod G^{p^k} \),
(d) \( \exp \) induces an \( \mathbb{F}_p \)-linear isomorphism \( L/pL \to G/G^p \):

\[
\exp(u + v) \equiv \exp(u) \exp(v) \mod G^p.
\]

**Proof.** For parts (a), (b) and (d) see the proof of [12, Theorem 9.8]. Now Lemma 6.1 implies that \( \Phi(-u, v) \in p^k L \), so

\[
\exp(u)^{-1} \exp(v) = \exp(-u) \exp(v) = \exp(\Phi(-u, v)) \in \exp(p^k L) = G^{p^k}
\]

and part (c) follows. \( \square \)

Let \( (g, h) = g^{-1} h^{-1} gh \) denote the group commutator of \( g, h \in G \).

**Proposition.** Let \( u \in L \) be such that \( [u, L] \subseteq p^k L \) for some \( k \geq \epsilon \). Then

\[
(\exp(u), \exp(v)) \equiv \exp([u, v]) \mod G^{p^{k+1}}
\]

for all \( v \in L \). In particular, \( (\exp(u), G) \subseteq G^{p^k} \).

**Proof.** We can compute the conjugate \( \exp(-u) \exp(-v) \exp(u) \) in \( G \) using [12, Exercise 6.12]:

\[
\exp(-u) \exp(-v) \exp(u) = \exp(-z),
\]

where

\[
z := v \exp(\text{ad}(u)) = v + [v, u] + \frac{1}{2} [[v, u], u] + \frac{1}{6} [[[v, u], u], u] + \cdots \in L.
\]
Now \( \exp(p^k) = 1 + p^k + \frac{1}{2}p^{2k} + \cdots \equiv 1 + p^k \) mod \( p^{k+1}\mathbb{Z}_p \) and \( L \cdot \text{ad}(u) \subseteq p^k L \), so

\[
\frac{v \cdot \text{ad}(u)^n}{n!} \in \frac{p^{kn}}{n!} L \subseteq p^{k+1} L
\]

for all \( n \geq 2 \). Hence \( z = v + p^k w \) for some \( w \in L \) such that \( p^k w \equiv [v, u] \) mod \( p^{k+1} L \).

Applying Lemma 6.1, we deduce that

\[
\Phi(-z, v) = \Phi(-v - p^k w, v) \equiv -p^k w \equiv [u, v] \mod p^{k+1} L.
\]

Using Lemma 6.2(c), we finally obtain

\[
(\exp(u), \exp(v)) = \exp(-z) \cdot \exp(v) = \exp \Phi(-z, v) \equiv \exp([u, v]) \mod G^{p^{k+1}},
\]

as required. \( \square \)

### 6.3. Subalgebras and subgroups

From now on, we will assume that \( L \) is a powerful \( \mathbb{Z}_p \)-Lie algebra of rank \( d \) and we will fix a subalgebra \( L_1 \) of \( L \) which contains \( pL \). We can find a subset \( \{v_1, \ldots, v_d\} \) of \( L \) such that

- \( \{v_i + pL: 1 \leq i \leq d\} \) is an \( \mathbb{F}_p \)-basis for \( L/pL \), and
- \( \{v_i + L_1: 1 \leq i \leq t\} \) is an \( \mathbb{F}_p \)-basis for \( L/L_1 \) for some \( t \).

In many interesting cases, \( L_1 \) will in fact be equal to \( pL \).

**Lemma.** Let \( G = \exp(L) \) be the uniform pro-\( p \) group corresponding to \( L \), let \( G_1 = \exp(L_1) \) and let \( g_i = \exp(v_i) \) for all \( i \). Then

(a) \( G_1 \) is a subgroup of \( G \),

(b) \( \{g_1, \ldots, g_d\} \) is a topological generating set for \( G \), and

(c) \( \{g_1^p, \ldots, g_t^p, g_{t+1}, \ldots, g_d\} \) is a topological generating set for \( G_1 \).

**Proof.** (a) This is not entirely trivial, since \( \exp(M) \) does not have to be a subgroup of \( G \) for arbitrary subalgebras \( M \) of \( L \)—see [14]. However, since \( \exp(u) \exp(v) \equiv \exp(u + v) \mod G^p \) for all \( u, v \in L \) by Lemma 6.2 and \( G^p = \exp(pL) \subseteq \exp(L_1) = G_1 \), we have \( xy \in G_1 \) for all \( x, y \in G_1 \) and \( G_1 \) is a subgroup.

(b) Let \( M \) be the \( \mathbb{Z}_p \)-submodule of \( L \) generated by \( \{v_1, \ldots, v_d\} \). As \( M + pL = L \) by assumption, \( M = L \) by Nakayama’s Lemma and hence \( \{v_1, \ldots, v_d\} \) is a \( \mathbb{Z}_p \)-basis for \( L \) since \( L \) has rank \( d \). Part (b) now follows from [12, Theorem 9.8].

(c) By [12, Theorem 3.6(iii)] and part (b), \( \{g_1^p, \ldots, g_d^p\} \) is a topological generating set for \( G^p \). Since \( \{g_{t+1}G^p, \ldots, g_dG^p\} \) is a basis for \( G_1/G^p \) by Lemma 6.2(d), \( \{g_1^p, \ldots, g_t^p, g_{t+1}, \ldots, g_d\} \) must be a topological generating set for \( G_1 \), as required. \( \square \)
6.4. The group algebra of a uniform pro-$p$ group

Let $G$ be a uniform pro-$p$ group and let $K$ be a field of characteristic $p$. Let $J$ be the augmentation ideal of the group algebra $K[G]$ of $G$. If $\{g_1, \ldots, g_d\}$ is a topological generating set for $G$ and $b_i := g_i - 1$ for all $i = 1, \ldots, d$, then these elements all lie in $J$.

**Proposition.** The associated graded ring of $K[G]$ with respect to the $J$-adic filtration is isomorphic to the polynomial algebra $K[y_1, \ldots, y_d]$.

**Proof.** As in the proof of [12, Theorem 7.22], the $b_i$'s commute modulo $J^3$. We can therefore define a $K$-algebra homomorphism $\varphi : K[y_1, \ldots, y_d] \to \text{gr} K[G]$ by setting $\varphi(y_i) = b_i + J^2$. When the field $K$ is $\mathbb{F}_p$, [12, Theorem 7.24] implies that $\varphi$ is an isomorphism. The general case now follows, using a simple “extension of scalars” argument. □

From now on we will identify $K[y_1, \ldots, y_d]$ with $\text{gr} K[G]$ via the map $\varphi$. For each $\alpha \in \mathbb{N}^d$, let $b^\alpha := b_1^{\alpha_1} \cdots b_d^{\alpha_d} \in K[G]$ and define

$$\mathcal{M} := \{b^\alpha : \alpha \in \mathbb{N}^d\}. $$

Writing $|\alpha| := \alpha_1 + \cdots + \alpha_d$, we can define

$$\mathcal{M}_{<n} := \{b^\alpha \in \mathcal{M} : |\alpha| < n\}$$

for each $n \geq 0$, the subsets $\mathcal{M}_{=n}$ and $\mathcal{M}_{\geq n}$ being defined similarly.

**Corollary.** $K[G] = J^n \oplus K[\mathcal{M}_{<n}]$ for all $n \geq 0$.

**Proof.** The above proposition implies that $J^{n+1} = J^n \oplus K[\mathcal{M}_{=n}]$ for all $n \geq 0$. The corollary follows from this by an easy induction. □

6.5. Subgroups

Recall the notation of Section 6.3, so that $\{g_1^p, \ldots, g_t^p, g_{t+1}, \ldots, g_d\}$ is a topological generating set for $G_1$. Now define

$$\mathcal{N} := \{b^\alpha \in \mathcal{M} : p|\alpha_i \text{ for all } i \leq t\}$$

and note that the $K$-linear span $K[\mathcal{N}]$ of $\mathcal{N}$ is contained in $K[G_1]$.

**Lemma.**

(a) $K[\mathcal{N}]$ is dense in $K[G_1]$ with respect to the $J$-adic topology.
(b) $K[\mathcal{N}] \cap J^n = K[\mathcal{N} \cap \mathcal{M}_{\geq n}]$, for all $n \geq 0$.
(c) The image of $\text{gr} K[\mathcal{N}]$ inside $\text{gr} K[G]$ is equal to $K[y_1^p, \ldots, y_t^p, y_{t+1}, \ldots, y_d]$. 
Proof. (a) Let \( x \in G_1 \) and \( n \geq 0 \). It will be enough to show that \( x \equiv y \mod J^n \) for some \( y \in K[N] \). Since \( G/G^p \) is a finite powerful \( p \)-group, by [12, Corollary 2.8] we can find non-negative integers \( \lambda_1, \ldots, \lambda_d \) such that
\[
x = g_1^{\lambda_1} \cdots g_d^{\lambda_d} u
\]
for some \( u \in G^p \). Considering the image of \( x \) in \( G/G_p \) and using the fact that \( x \in G_1 \), we see that \( \lambda_i \) is divisible by \( p \) for all \( i \leq t \). Write \( \lambda_i = p \mu_i \) for some \( \mu_i \in \mathbb{N} \), for each \( i \leq t \). Let \( y := g_1^{\lambda_1} \cdots g_d^{\lambda_d} \); then
\[
y = (1 + b_1^p)^{\mu_1} \cdots (1 + b_t^p)^{\mu_t} (1 + b_{t+1})^{\lambda_{t+1}} \cdots (1 + b_d)^{\lambda_d} \in K[N].
\]
Because \( G^p - 1 \subseteq J^n \), the element \( u \) is congruent to 1 modulo \( J^n \), and hence
\[
x = yu \equiv y \mod J^n
\]
as required.

(b) It will be enough to show that \( K[N] \cap J^n \subseteq K[N \cap M_{\geq n}] \), so let \( a \in K[N] \cap J^n \). We can decompose \( a \) uniquely as \( a = b + c \), where \( b \in K[N \cap M_{< n}] \) and \( c \in K[N \cap M_{\geq n}] \). Now \( c \in K[M_{\geq n}] \subseteq J^n \) so \( b = a - c \in J^n \cap K[M_{< n}] = 0 \) by Corollary 6.4. Hence \( a = c \in K[N \cap M_{\geq n}] \), as required.

(c) This follows immediately from part (b). \( \square \)

6.6. Completed group algebras

Let \( H \) be a compact \( p \)-adic analytic group. The completed group algebra \( K[H] \) is by definition the inverse limit
\[
K[H] := \lim_{\leftarrow} K[H/N],
\]
as \( N \) runs over all the open normal subgroups of \( H \). When the field \( K \) is finite, this algebra is sometimes called the Iwasawa algebra of \( H \).

Proposition. Let \( A := K[G] \) and \( A_1 := K[G_1] \). Then \( (A, A_1) \) is a Frobenius pair.

Proof. For each open normal subgroup \( N \) of \( G \), let \( w_{N,G} \) be the kernel of the natural map from \( K[G] \) to \( K[G/N] \). By the proof of [12, Lemma 7.1], this family of ideals of \( K[G] \) is cofinal with the powers of the augmentation ideal \( J = w_{G,G} \). Therefore \( A \) is isomorphic to the completion of \( K[G] \) with respect to the \( J \)-adic filtration on \( K[G] \). Let \( (F_n A) \) be the associated filtration on \( A \); explicitly, if \( J^{-n} \) denotes the closure of \( J^{-n} \) in the topology of \( A \) then
\[
F_n A := \begin{cases} J^{-n} & \text{if } n \leq 0, \\ A & \text{otherwise.} \end{cases}
\]
In this way, \( A \) becomes a complete filtered \( K \)-algebra, and
\[
B := \text{gr } A \cong \text{gr } K[G] \cong K[y_1, \ldots, y_d]
\]
is a commutative noetherian domain, by Proposition 6.4.

Now if $N$ is an open normal subgroup of $G$, then $N \cap G_1$ is an open normal subgroup of $G_1$ and

$$w_{N,G} \cap K[G_1] = w_{N \cap G_1,G_1}.$$ 

Conversely, if $N_1$ is an open normal subgroup of $G_1$, then we can find an open normal subgroup $N$ of $G$ such that $N \cap G_1 \subseteq N_1$, so that

$$w_{N_1,G_1} \supseteq w_{N \cap G_1,G_1} = w_{N,G} \cap K[G_1].$$

Hence the subspace topology on $K[G_1]$, induced from the $J$-adic topology on $K[G]$, coincides with the natural topology on $K[G_1]$ used in the definition of $A_1$. We may therefore identify $A_1$ with the closure of $K[G_1]$ inside $A$. In this way $A_1$ becomes a closed subalgebra of $A$.

Finally, Lemma 6.5 implies that the image of $\text{gr } A_1 \cong K[N]$ inside $\text{gr } A$ can be identified with the subalgebra $B_1 := K[y_1^p, \ldots, y_t^p, y_{t+1}, \ldots, y_d]$ of $B$. This clearly contains $B^p$ and moreover

$$B = \bigoplus_{\alpha \in [p-1]^t} B_1 y^\alpha,$$

as required. □

6.7. Sources of derivations for Iwasawa algebras

**Proposition.** Let $u \in L$ be such that $[u, L] \subseteq p^k L$ and $[u, L_1] \subseteq p^{k+1} L$ for some $k \geq \epsilon$, and let $a = \exp(u)$. Then

(a) $(a, G) \subseteq G^p$
(b) $(a, G_1) \subseteq G^{p+1}$
(c) $[a, F_n A] \subseteq F_{n-p^k+1} A$ for all $n \in \mathbb{Z}$, and
(d) $[a, F_n A_1] \subseteq F_{n-p^{k+1}+p} A$ for all $n \in \mathbb{Z}$.

**Proof.** Parts (a) and (b) follow from Proposition 6.2:

$$(a, G) = (\exp(u), \exp(L)) \subseteq \exp([u, L]) G^p \subseteq G^p$$

and

$$(a, G_1) = (\exp(u), \exp(L_1)) \subseteq \exp([u, L_1]) G^{p+1} = G^{p+1}.$$ 

(c) It is sufficient to prove this for non-positive values of $n$, since then

$$[a, F_n A] = [a, F_0 A] \subseteq F_{-p^k+1} A \subseteq F_{-p^{k+1}+1} A$$

for all $n \geq 0$. Let $h \in G$ and set $b := h - 1$. Then

$$[a, b] = [a, h] = ha((a, h) - 1) \in K[G](G^p - 1) \subseteq J^p.$$
by (a), so by induction we have
\[ [a, b^m] = b[a, b^{m-1}] + [a, b]b^{m-1} \in J^{p^k + m - 1} \]
for all \( m \geq 0 \). Therefore
\[ [a, b^\alpha] = a^\alpha_1 \cdots b^\alpha_d \cdots b^\alpha_d + \cdots + b^\alpha_1 \cdots b^\alpha_d \cdots b^\alpha_d [a, b]^{m-1} \in J^{[a|+p^k-1} \]
for all \( b^\alpha \in M \). Now \( K[\mathcal{M}_{
rightarrow -n}] \) is dense in \( F_{nA} \), so
\[ [a, F_{nA}] = [a, K[\mathcal{M}_{
rightarrow -n}]] \subseteq J^{-n+p^k-1} = F_{n-p^k+1} \]
as required.

(d) Again, we may assume that \( n \leq 0 \). Let \( h \in G_1 \) and set \( b = h - 1 \). Then
\[ [a, b] = [a, h] = ha((a, h) - 1) \in K[G](G^{p^k+1} - 1) \subseteq J^{p^k+1} \]
by (b). Hence in the notation of Section 6.4, \([a, b_i^{pm}] \in J^{pm+p^k+1-p} \) for all \( i \leq t \) and \([a, b_i^m] \in J^{m+p^k+1-1} \subseteq J^{m+p^k+1-p} \) for all \( i > t \), whenever \( m \geq 0 \). We can now deduce as in part (a) that
\[ [a, b^\alpha] \in J^{[a|+p^k+1-p} \]
for all \( b^\alpha \in N \), or equivalently, \([a, N \cap \mathcal{M}_{
rightarrow -n}] \subseteq J^{-n+p^k+1-p} \). Part (d) now follows because \( K[N \cap \mathcal{M}_{
rightarrow -n}] \) is dense in \( F_{nA} \) by Lemma 6.5. \( \square \)

**Corollary.** Let \( u \in L \) be such that \([u, L] \subseteq p^k L \) and \([u, L_1] \subseteq p^{k+1} L \) for some \( k \geq \epsilon \), and let \( a = \exp(u) \in G \). Then \( \mathbf{a} = \{a, a^p, a^{p^2}, \ldots\} \) is a source of derivations for the Frobenius pair \((A, A_1)\).

**Proof.** For all \( r \geq 0 \), \([p^r u, L] \subseteq p^{r+k} L \) and \([p^r u, L_1] \subseteq p^{r+k+1} L \). Now let \( \theta(a^{p^r}) = p^{r+k} - 1 \) and \( \theta_1(a^{p^r}) = p\theta(a^{p^r}) \) and apply the proposition. \( \square \)

In particular, if \( G \) is a uniform pro-\( p \) group and \( g \in G \), then \( g = \exp(u) \) for some \( u \in L \). Since \( L \) is powerful, \([u, L] \subseteq p^\epsilon L \) and \([u, pL] \subseteq p^{\epsilon+1} L \) Hence \((g, g^p, g^{p^2}, \ldots)\) is always a source of derivations for \((K[G], K[G^p])\).

### 6.8. Computing the corresponding derivations

Let \( u \in L \) be such that for some \( k \geq \epsilon \), we have
1. \([u, L] \subseteq p^k L \),
2. \([u, L] \nsubseteq p^{k+1} L \), and
3. \([u, L_1] \subseteq p^{k+1} L \).


Note that if such a $k$ exists, then it is uniquely determined by $u$. Moreover, if $L_1 = pL$, then the third condition automatically follows from the first, and in this case such an integer $k$ always exists for any non-central element $u$ of $L$.

We can now define a well-defined non-zero $\mathbb{F}_p$-linear map

$$
\rho_u : L/L_1 \rightarrow L/pL
$$

$$
v + L_1 \mapsto \frac{1}{p^k}[u, v] + pL.
$$

Let $a = \exp(u)$. Since $[a, F_n A] \subseteq F_{n-p^k+1} A$ for all $n \in \mathbb{Z}$ by Proposition 6.7(c), $u$ induces a derivation

$$
D_u := \{a, -\}_{p^k-1}
$$

of $B = K[y_1, \ldots, y_d]$ as in Section 3.2. It turns out that there is a very close connection between $D_u$ and $\rho_u$. Recall from Section 6.3 that $\{v_i + L_1 : 1 \leq i \leq t\}$ is an $\mathbb{F}_p$-basis for $L/L_1$, and $\{v_i + pL : 1 \leq i \leq d\}$ is an $\mathbb{F}_p$-basis for $L/pL$.

**Theorem.** Let $(c_{ij})$ be the matrix of $\rho_u$ with respect to these bases. Then

$$
D_u(y_j) = \sum_{i=1}^{d} c_{ij} y_i^{p^k}
$$

for all $j = 1, \ldots, t$.

**Proof.** Choose $\lambda_{ij} \in [p-1]$ such that $c_{ij}$ is the reduction of $\lambda_{ij}$ modulo $p$. By the definition of $c_{ij}$,

$$
\frac{1}{p^k}[u, v_j] \equiv \sum_{i=1}^{d} \lambda_{ij} v_i \mod pL
$$

for all $j = 1, \ldots, t$. Recall from Section 6.3 that $g_i = \exp(v_i)$ for all $i$. By Lemma 6.2(d),

$$
\exp\left(\frac{1}{p^k}[u, v_j]\right) \equiv \prod_{i=1}^{d} g_i^{\lambda_{ij}} \mod G^p.
$$

Now by [12, Theorem 3.6(iv)], $g \mapsto g^{p^k}$ induces an isomorphism between $G/G^p$ and $G^{p^k}/G^{p^k+1}$. Using Lemma 6.2(a), we see that

$$
\exp([u, v_j]) = \exp\left(\frac{1}{p^k}[u, v_j]\right)^{p^k} \equiv \prod_{i=1}^{d} g_i^{p^k \lambda_{ij}} \mod G^{p^k+1}.
$$
We can now apply Proposition 6.2 and deduce that
\[(a, g_j) \equiv \exp([u, v_j]) \equiv \prod_{i=1}^{d} g_i^{p^k \lambda_{ij}} \mod G^{p^{k+1}}.\]

Next, recall that \(b_j = g_j - 1\) and consider the commutator \([a, b_j]\) inside \(K[G]\):
\[[a, b_j] = [a, g_j] = g_j a ((a, g_j) - 1) = g_j a \left( h_j \prod_{i=1}^{d} g_i^{p^k \lambda_{ij}} - 1 \right)\]
for some \(h_j \in G^{p^{k+1}}\). Since we are interested in \(\{a, \{-\}^{p^k-1}_p\}\), we only need to compute \([a, b_j]\) modulo \(J^{p^{k+1}}\). Now \(h_j - 1 \subseteq G^{p^{k+1}} - 1 \subseteq J^{p^{k+1}} \subseteq J^{p^{k+1+1}}\), so
\[h_j \equiv 1 \mod J^{p^{k+1}}.\]
Because \(g_j a \equiv 1 \mod J\), we can deduce that
\[[a, b_j] \equiv \prod_{i=1}^{d} \left( 1 + b_i^{p^k} \right)^{\lambda_{ij}} - 1 \equiv \sum_{i=1}^{d} c_{ij} b_i^{p^k} \mod J^{p^{k+1}}\]
for all \(j = 1, \ldots, t\). The result follows. \(\square\)

6.9. Verifying the derivation hypothesis

In a forthcoming paper [5], we will prove the following result.

**Theorem.** (See [5, Theorem A]) Let \(\Phi(\mathbb{Z}_p)\) be the Chevalley \(\mathbb{Z}_p\)-Lie algebra associated to a root system \(\Phi\). Let \(L\) be the Lie algebra \(p^t \Phi(\mathbb{Z}_p)\) for some \(t \geq 1\) and \(G\) be the corresponding uniform pro-\(p\) group \(\exp(L)\). Suppose that \(p \geq 5\) and that \(p \nmid n + 1\) if \(\Phi\) has an indecomposable component of type \(A_n\). Then \((K[G], K[G^p])\) satisfies the derivation hypothesis.

For the time being, we only verify that the derivation hypothesis holds in the special case when \(G\) is a congruence subgroup of \(SL_2(\mathbb{Z}_p)\).

6.10. Congruence subgroups of \(SL_2(\mathbb{Z}_p)\), \(p \geq 3\)

Fix an integer \(l \geq 1\) and let \(L\) be the powerful Lie algebra \(sl_2(p^l \mathbb{Z}_p)\). Thus \(L\) has a basis
\[
\left\{\begin{array}{c}
eq \left(\begin{array}{cc}0 & p^l \\ 0 & 0\end{array}\right), f = \left(\begin{array}{cc}0 & 0 \\ p^l & 0\end{array}\right), h = \left(\begin{array}{cc}p^l & 0 \\ 0 & -p^l\end{array}\right)\end{array}\right\}
\]
satisfying the following relations:
- \([h, e] = 2 p^l e,\]
- \([h, f] = -2 p^l f,\]
\[ e, f = p^l h. \]

Let \( \Gamma_l(\text{SL}_2(\mathbb{Z}_p)) \) denote the \( l \)th congruence subgroup of \( \text{SL}_2(\mathbb{Z}_p) \):

\[ \Gamma_l(\text{SL}_2(\mathbb{Z}_p)) := \ker(\text{SL}_2(\mathbb{Z}_p) \to \text{SL}_2(\mathbb{Z}/p^l\mathbb{Z})). \]

It is well known that \( G := \exp(L) \) is isomorphic to \( \Gamma_l(\text{SL}_2(\mathbb{Z}_p)) \). We let \( L_1 = pL \), so that the corresponding subgroup \( G_1 \) is just \( G_1 \cong \Gamma_{l+1}(\text{SL}_2(\mathbb{Z}_p)) \).

We use the same variables \( \{ e, f, h \} \) for the generators of the associated graded ring \( B = \text{gr } K[G] \) and hope that this will cause no confusion. Thus

\[ B = K[e, f, h] \quad \text{and} \quad B_1 = K[e^p, f^p, h^p]. \]

Let \( \{ \partial / \partial e, \partial / \partial f, \partial / \partial h \} \) be the corresponding derivations, which were constructed in Section 2.4. Using Theorem 6.8 and Proposition 2.4(b), we can write down the derivations

\[ D_{p^r u} = \{ \exp(p^r u), - \}^{p^r+l-1} : B \to B \]

generated by \( u \) explicitly, for each \( u \in \{ e, f, h \} \):

\[
\begin{align*}
D_{p^r e} &= h^{p^{r+l}} \frac{\partial}{\partial f} - 2e^{p^{r+l}} \frac{\partial}{\partial h}, \\
D_{p^r f} &= -h^{p^{r+l}} \frac{\partial}{\partial e} + 2f^{p^{r+l}} \frac{\partial}{\partial h}, \\
D_{p^r h} &= 2e^{p^{r+l}} \frac{\partial}{\partial e} - 2f^{p^{r+l}} \frac{\partial}{\partial f}.
\end{align*}
\]

**Proposition.** Let \( l \geq 1 \) and let \( G = \exp(\text{sl}_2(p^l\mathbb{Z}_p)) \) as above. Then the Frobenius pair \((K[G], K[G^p])\) satisfies the derivation hypothesis.

**Proof.** Let \( X, Y \) be homogeneous elements of \( B \) and suppose that \( Y \) lies in the \( a \)-closure of \( XB \) for all \( a \in S(K[G], K[G^p]) \). By Corollary 6.7, \((g, g^p, g^{p^2}, \ldots) \in S(K[G], K[G^p]) \) for all \( g \in G \), so we can find an integer \( s \) such that

\[ D_{p^r u}(Y) \in XB \]

for all \( u \in \{ e, f, h \} \) and all \( r \geq s \). Consider the \( D_{p^r e} \)-equations for \( r = s \) and \( r = s + 1 \). Eliminating the terms involving \( \partial Y / \partial f \) yields that

\[ 2e^{p^{s+l}} (h^{p^{s+l}(p-1)} - e^{p^{s+l}(p-1)}) \frac{\partial Y}{\partial h} \in XB, \]

and using similar operations with the \( D_{p^r f} \)-equations we have

\[ 2f^{p^{s+l}} (h^{p^{s+l}(p-1)} - f^{p^{s+l}(p-1)}) \frac{\partial Y}{\partial h} \in XB. \]
The coefficients of $\partial Y/\partial h$ appearing in the above two equations are coprime, which allows us to deduce

$$\frac{\partial Y}{\partial h} \in XB.$$

Similar manipulations with the other equations show that $\partial Y/\partial e$ and $\partial Y/\partial f$ also lie in $XB$. Hence $D(Y) \subseteq XB$, by Proposition 2.4(b). □

7. Ideals in Iwasawa algebras

7.1. Canonical dimension function

Let $A$ be a noetherian ring. We say that $A$ is Gorenstein if it has finite injective dimension on both sides. For any finitely generated left (or right) $A$-module $M$, the $j$-number or grade of $M$ is defined to be

$$j(M) := \inf \{ n \mid \text{Ext}^n_A(M, A) \neq 0 \}.$$

The ring $A$ is called Auslander–Gorenstein if it is Gorenstein and it satisfies the Auslander condition:

For every finitely generated left (respectively, right) $A$-module $M$ and every positive integer $q$, one has $j(N) \geq q$ for every finitely generated right (respectively, left) $A$-submodule $N \subseteq \text{Ext}^q_A(M, A)$.

An Auslander-regular ring is a noetherian, Auslander–Gorenstein ring which has finite global dimension. See [9] for some details. Note that a noetherian commutative regular algebra is always Auslander-regular. For any Auslander–Gorenstein ring $A$, there is a canonical dimension function defined by

$$\text{Cdim}(M) = \text{injdim}(A) - j(M)$$

for all finitely generated left (or right) $A$-modules $M$ [3, §5.3]. This is a dimension function in the sense of [19, §6.8.4]. Recall that a finitely generated $A$-module is said to be pure if $\text{Cdim}(N) = \text{Cdim}(M)$ for all non-zero submodules $N$ of $M$. We will use the following nice observation of Venjakob [10, Lemma 4.12]:

**Lemma.** Let $A$ be an Auslander-regular domain and $I$ be a proper non-zero right ideal of $A$. Then $I$ is reflexive if and only if $A/I$ is pure of grade 1.

It is well known that the completed group algebra $K \llbracket G \rrbracket$ is always Auslander–Gorenstein, and that it is Auslander-regular if and only if $G$ has no elements of order $p$; see for example [3, §5].
7.2. Crossed products

Let $R$ be an Auslander–Gorenstein ring, $G$ be a finite group and $S = R \ast G$ be a crossed product. We know by [4, Lemma 5.4] that the restriction $M|_R$ to $R$ of any finitely generated $S$-module $M$ satisfies

$$Cdim_S(M) = Cdim_R(M|_R).$$

Hence $S$ is also Auslander–Gorenstein.

**Proposition.** $R$ has a two-sided ideal $I$ with $Cdim_R(R/I) = n$ if and only if $S$ has a two-sided ideal $J$ with $Cdim_S(S/J) = n$.

**Proof.** ($\Rightarrow$) Choose a set of units $\{g : g \in G\}$ in $S$ such that $Rg = gR$ inside $S$ and $S = \bigoplus_{g \in G} Rg$. Then $\alpha_g : r \mapsto g^{-1}rg$ is an algebra automorphism of $R$. Hence $Cdim_R(R/\alpha_g(I)) = Cdim_R(R/I)$ for all $g \in G$. We set $I_0 := \bigcap_{g \in G} \alpha_g(I)$, which is a $G$-invariant ideal in $R$. It follows from the fact $I_0 \subseteq I$ that $Cdim_R(R/I_0) \geq Cdim_R(R/I)$. Since

$$R/I_0 \hookrightarrow \bigoplus_{g \in G} R/\alpha_g(I),$$

we actually have equality. Let us set $J = I_0 \cdot S$; because $I_0$ is $G$-invariant, $J$ is a two-sided ideal in $S$ and by construction


($\Leftarrow$) We set $I := J \cap R$, which is a $G$-invariant ideal in $R$. Then $S/IS = \bigoplus_{g \in G} (Rg/Ig)$ and hence $(S/IS)|_R \cong (R/I)^{|G|}$. Since $S/IS \hookrightarrow S/J$, we have


On the other hand, $R/I \hookrightarrow (S/J)|_R$, so we have equality and the result follows. □

7.3. Proof of Theorem A

We present a slightly more general version of Theorem A this section. Let $\mathcal{L}(G)$ denote the $\mathbb{Q}_p$-Lie algebra of $G$.

**Theorem.** Let $K$ be a field of characteristic $p$. Suppose $G$ is a compact $p$-adic analytic group of dimension $d$ such that $\mathcal{L}(G)$ is split semisimple over $\mathbb{Q}_p$. Suppose that $p \geq 5$, and that $p \nmid n$ in the case when $\mathfrak{sl}_n(\mathbb{Q}_p)$ occurs as a direct summand of $\mathcal{L}(G)$. Then $K[G]$ has no two-sided ideals $I$ such that

$$Cdim_{K[G]}(K[G]/I) = d - 1.$$
Proof. Note that $K[G]$ is a crossed product of the Auslander–Gorenstein ring $K[N]$ with the finite group $G/N$, for any open normal uniform subgroup $N$ of $G$. By Proposition 7.2, we may replace $G$ by any uniform pro-$p$ group $N$ having the same $\mathbb{Q}_p$-Lie algebra without affecting the conclusion of the theorem.

By considering a suitable Chevalley basis, we can find a sub $\mathbb{Z}_p$-Lie algebra $L \subset \mathcal{L}(G)$ such that $L \cong p^t \Phi(\mathbb{Z}_p)$ where $\Phi$ is the root system associated to $\mathcal{L}(G)$. Now take $N$ to be the corresponding uniform pro-$p$ group $\exp(L)$. The $\mathbb{Z}_p$-Lie algebra of $N^{p^k}$ is $p^k L$, so the Frobenius pair $(K[N^{p^k}], K[N^{p^k+1}])$ satisfies the derivation hypothesis for all $k \geq 0$ by Theorem 6.9.

Suppose for a contradiction that $I$ is a two-sided ideal of $K[N]$ such that

$$\text{Cdim}_{K[N]}(K[N]/I) = d - 1.$$ 

By replacing $I$ by the inverse image of the largest pseudo-null submodule of $K[N]/I$ in $K[N]$ we may assume that $K[N]/I$ is pure. Note that $I$ is proper and non-zero, since otherwise $d = \text{Cdim}_{K[N]}(K[N]) = d - 1$. It follows from Lemma 7.1 that $I$ is a reflexive ideal of $K[N]$. Applying Theorem 5.3 repeatedly, we see that $I$ is controlled by $K[N^{p^k}]$ for each $k$:

$$I = (I \cap K[N^{p^k}]) \cdot K[N].$$

Since $I$ is a proper ideal of $K[N]$, we see that $I \cap K[N^{p^k}]$ must be contained in the maximal ideal $(N^{p^k} - 1) \cdot K[N^{p^k}]$ of $K[N^{p^k}]$ for all $k \geq 0$. Hence

$$I \subseteq \bigcap_{k=0}^{\infty} ((N^{p^k} - 1) \cdot K[N]) = 0,$$

a contradiction. \qed

8. The case when $p = 2$

8.1. Congruence subgroups of $\text{SL}_2(\mathbb{Z}_p)$, $p = 2$

The reader might have wondered why we did not just assume that $L_1 = pL$ from Section 6.3 onwards. The reason is that the extra generality allows us to be more flexible when choosing the particular open subgroup of $G$ that we should try to “descend” towards. The case of open subgroups in $\text{SL}_2(\mathbb{Z}_p)$ when $p = 2$ should illustrate this flexibility: if $G = \Gamma_1(\text{SL}_2(\mathbb{Z}_p))$ and $p = 2$, then $(K[G], K[G^P])$ does not satisfy the derivation hypothesis, but we can circumvent this problem by going down to $G^p$ from $G$ in two steps.

So assume that $p = 2$ and fix $l \geq 2$. We choose the same basis $\{e, f, h\}$ for $L_0 := \mathfrak{sl}_2(p^l \mathbb{Z}_p)$ as in Section 6.10, so that the following relations are satisfied:

- $[h, e] = p^l + 1 e$,
- $[h, f] = -p^l + 1 f$,
- $[e, f] = p^l h$.

Let $L_1 = pe\mathbb{Z}_p \oplus pf\mathbb{Z}_p \oplus h\mathbb{Z}_p$ and let $L_2 = pL$. The relations in $L_1$
• \([h, pe] = p^{l+1}(pe),\]
• \([h, pf] = -p^{l+1}(pf),\]
• \([pe, pf] = p^{l+2}h\]

show that \(L_1\) is a powerful \(\mathbb{Z}_p\)-subalgebra of \(L_0\) which contains \(L_2\). Moreover, \(pL_1 \subseteq L_2\), so the pairs \((L_0, L_1)\) and \((L_1, L_2)\) both satisfy the assumptions made in Section 6.3, and hence \((K[G_0], K[G_1])\) and \((K[G_1], K[G_2])\) are Frobenius pairs, by Proposition 6.6. However the parameter \(t\) equals 2 in the first case and 1 in the second case.

**Proposition.** Let \(G_i = \exp(L_i)\) for each \(i = 0, 1, 2\). Then the Frobenius pairs \((K[G_0], K[G_1])\) and \((K[G_1], K[G_2])\) both satisfy the derivation hypothesis.

**Proof.** We first deal with the case \((K[G_0], K[G_1])\); in this case, \(B = \mathbb{K}[e, f, h]\) and \(B_1 = \mathbb{K}[e^p, f^p, h]\). We observe that

\[
\begin{align*}
[e, L_0] &\subseteq p^l L_0, & [e, L_0] &\nsubseteq p^{l+1} L_0, & [e, L_1] &\subseteq p^{l+1} L_0, \\
[f, L_0] &\subseteq p^l L_0, & [f, L_0] &\nsubseteq p^{l+1} L_0, & [f, L_1] &\subseteq p^{l+1} L_0, \\
h, L_0] &\subseteq p^{l+1} L_0, & [h, L_0] &\nsubseteq p^{l+2} L_0, & [h, L_1] &\subseteq p^{l+2} L_0.
\end{align*}
\]

By Theorem 6.8, we obtain three sets of derivations of \(B = \text{gr} K[G_0]\) arising from sources of derivations of \((K[G_0], K[G_1]):\)

\[
\begin{align*}
D_p^r e &= h^{p^r} \frac{\partial}{\partial f}, \\
D_p^r f &= h^{p^r} \frac{\partial}{\partial e}, \\
D_p^r h &= e^{p^{r+1}} \frac{\partial}{\partial e} - f^{p^{r+1}} \frac{\partial}{\partial f}.
\end{align*}
\]

Let \(X, Y\) be homogeneous elements of \(B\) and suppose that \(Y\) lies in the \(a\)-closure of \(XB\) for all \(a \in S(K[G_0], K[G_1])\); we can thus find an integer \(s\) such that

\[
D_p^r u(Y) \in XB
\]

for all \(u \in \{e, f, h\}\) and all \(r \geq s\). Eliminating the terms involving \(\partial Y/\partial f\) from the \(D_p^r h\) equations for \(r = s\) and \(r = s + 1\) shows that

\[
f^{p^{r+1}} \left( f^{p^{r+1}} (p-1) + e^{p^{r+1}} (p-1) \right) \frac{\partial Y}{\partial f} \in XB.
\]

Since \(D_p^r e(Y) = h^{p^{r+l}} \frac{\partial Y}{\partial f} \in XB\) and the coefficients of \(\partial Y/\partial f\) are coprime,

\[
\frac{\partial Y}{\partial f} \in XB.
\]

Similarly \(\partial Y/\partial e \in XB\), so the derivation hypothesis holds by Proposition 2.4(b).

Now consider the case \((K[G_1], K[G_2])\). Recycling notation, let \(\{e, f, h\}\) be the basis for \(L_1\) considered above, so that \(\{e, f, ph\}\) is a basis for \(L_2\), and the relations
• \([h, e] = p^{l+1} e\),
• \([h, f] = -p^{l+1} f\),
• \([e, f] = p^{l+2} h\)

hold in \(L_1\). The corresponding graded rings are \(B = K[e, f, h]\) and \(B_1 = K[e, f, h^p]\). Since

\[
[e, L_1] \subseteq p^{l+1} L_1, \quad [e, L_1] \nsubseteq p^{l+2} L_1, \quad [e, L_2] \subseteq p^{l+2} L_1.
\]

Theorem 6.8 gives us two sets of derivations of \(B\) arising from sources of derivations of \((K[G_1], K[G_2])\):

\[
D_{p^r e} = e p^{l+r+1} \frac{\partial}{\partial h},
D_{p^r f} = f p^{l+r+1} \frac{\partial}{\partial h}.
\]

Let \(X, Y\) be homogeneous elements of \(B\) and suppose that \(Y\) lies in the \(a\)-closure of \(XB\) for all \(a \in S(K[G_1], K[G_2])\); we can thus find an integer \(s\) such that

\[
D_{p^r u}(Y) \in XB
\]

for all \(u \in \{e, f\}\) and all \(r \geq s\). In particular, \(D_{p^r e}(Y) = e p^{l+r+1} Y/\partial h\) and \(D_{p^r f}(Y) = f p^{l+r+1} Y/\partial h\) both lie in \(XB\). Since the coefficients of \(Y/\partial h\) are coprime, \(Y/\partial h \in XB\), so the derivation hypothesis holds. \(\square\)

**Corollary.** Let \(K\) be a field of characteristic 2 and suppose that \(G\) is an open subgroup of \(SL_2(\mathbb{Z}_2)\). Then \(K[G]\) has no two-sided ideals \(I\) such that

\[
\text{Cdim}_{K[G]}(K[G]/I) = 2.
\]

**Proof.** Follow the proof of Theorem A. \(\square\)

### 8.2. Proof of Theorem C

Let \(I\) be a prime ideal of \(K[G]\). The dimension of \(G\) is three, so the possible values for \(c = \text{Cdim}_{K[G]}(K[G]/I)\) when \(I\) is a two-sided ideal of \(K[G]\) are 0, 1, 2 or 3. By Theorem 7.3 and Corollary 8.1, \(c\) cannot be equal to 2 and by [1, Theorem A], \(c\) cannot be equal to 1. Hence \(c = 0\), in which case \(I\) is the maximal ideal of \(K[G]\) since \(K[G]\) is local, or \(c = 3\) in which case \(I = 0\). \(\square\)

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