VALUATION SEMIGROUPS OF TWO DIMENSIONAL LOCAL RINGS

STEVEN DALE CUTKOSKY AND PHAM AN VINH

ABSTRACT. We consider the question of when a semigroup is the semigroup of a valuation dominating a two dimensional noetherian domain, giving some surprising examples. We give a necessary and sufficient condition for the pair of a semigroup \( S \) and a field extension \( L/\mathfrak{k} \) to be the semigroup and residue field of a valuation dominating a regular local ring \( R \) of dimension two with residue field \( \mathfrak{k} \), generalizing the theorem of Spivakovsky for the case when there is no residue field extension.

1. INTRODUCTION

Suppose that \((R, \mathfrak{m}_R)\) is a Noetherian local ring which is dominated by a valuation \( \nu \). The semigroup of \( \nu \) in \( R \) is

\[
S^R(\nu) = \{ \nu(f) \mid f \in R \setminus \{0\} \}.
\]

\( S^R(\nu) \) generates the value group of \( \nu \).

In this paper we give a classification of the semigroups and residue field extensions that may be obtained by a valuation dominating a regular local ring of dimension two. Our results are completely general, as we make no further assumptions on the ring or on the residue field extension of the valuation ring. This classification (given in Theorems 1.1 and 1.2) is very simple. The classification does not extend to more general rings.

We give an example showing that the semigroup of a valuation dominating a normal local ring of dimension two can be quite different from the semigroup of a regular local ring, even on an \( A_2 \) singularity (Example 9.2). In [17], [18] and [11], we give examples showing that the semigroups of valuations dominating regular local rings of dimension \( \geq 3 \) can be very complicated. For instance, in Proposition 6.3 of [11], we show that there exists a regular local ring \( R \) of dimension 3 dominated by a rational rank 1 valuation \( \nu \) which has the property that given \( \varepsilon > 0 \), there exists an \( i \) such that \( \beta_{i+1} - \beta_i < \varepsilon \), where \( \beta_0 < \beta_1 < \cdots \) is the minimal set of generators of \( S^R(\nu) \). In [17] and [18] we give examples showing that spectacularly strange behavior of the semigroup can occur for a higher rank valuation. The growth of valuation semigroups is however bounded by a polynomial whose coefficients are computed from the multiplicities of the centers of the composite valuations on \( R \). This is proven in [18].

The possible value groups \( \Gamma \) of a valuation \( \nu \) dominating a Noetherian local ring have been extensively studied and classified, including in the papers MacLane [35], MacLane and Schilling [36], Zariski and Samuel [48], and Kuhlmann [32]. \( \Gamma \) can be any ordered abelian group of finite rational rank (Theorem 1.1 [32]). The semigroup \( S^R(\nu) \) is however not well understood, although it is known to encode important information about the topology and resolution of singularities of \( \text{Spec}(R) \) [5], [6], [44], [45], [7], [16], [19], [31], [24], [37], [42], [27] to mention a few references, and the ideal theory of \( R \) [46], [47], [48] and its development in many subsequent papers.

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In Sections 3 through 8 of this paper we analyze valuations dominating a regular local ring $R$ of dimension two. Our analysis is constructive, being based on an algorithm which finds a generating sequence for the valuation. A generating sequence of $\nu$ in $R$ is a set of elements of $R$ whose initial forms are generators of the graded $\mathfrak{g} = R/\mathfrak{m}_R$-algebra $\text{gr}_\nu(R)$ (Section 2). The characteristic of the residue field of $R$ does not appear at all in the proofs, although the proof may be simplified significantly if the assumption that $R$ has equal characteristic is added; in this case we may reduce to the case where $R$ is a polynomial ring over a field (Section 8). A construction of a generating sequence, and the subsequent classification of the semigroups, is classical in the case when the residue field of $R$ is algebraically closed; this was proven by Spivakovsky in [41]. Besides the complete generality of our results, our proofs differ from those of Spivakovsky in that we only use elementary techniques, using nothing more sophisticated than the definition of linear independence in a vector space, and the definition of the minimal polynomial of an element in a field extension. In our proof we construct the residue field of the valuation ring as a tower of primitive extensions; the minimal polynomials of the primitive elements are used to construct the generating sequence for the valuation. It is not necessary for $R$ to be excellent in our analysis; the only place in this paper where excellence manifests itself is in the possibility of ramification in the extension of a valuation to the completion of a non excellent regular local ring (Proposition 3.4).

In a finite field extension, the quotient of the valuation group of an extension of a valuation by the value group is always a finite group (2nd corollary on page 52 of [48]). This raises the following question: Suppose that $R \to T$ is a finite extension of regular local rings, and $\nu$ is a valuation which dominates $R$. Is $S^T(\nu)$ a finitely generated module over the semigroup $S^R(\nu)$? We give a counterexample to this question in Example 9.4. This example is especially interesting in light of the results on relative finite generation in the papers [22] of Ghezzi, Hà and Kashcheyeva, and [23] of Ghezzi and Kashcheyeva.

We now turn to a discussion of our results on regular local rings of dimension two. We obtain the following necessary and sufficient condition for a semigroup and field extension to be the semigroup and residue field extension of a valuation dominating a complete regular local ring of dimension two in the following theorem (proven in Section 5):

**Theorem 1.1.** Suppose that $R$ is a complete regular local ring of dimension two with residue field $R/\mathfrak{m}_R = \mathfrak{k}$. Let $S$ be a subsemigroup of the positive elements of a totally ordered abelian group and $L$ be a field extension of $\mathfrak{k}$. Then $S$ is the semigroup of a valuation $\nu$ dominating $R$ with residue field $V_\nu/\mathfrak{m}_\nu = L$ if and only if there exists a finite or countable index set $I$, of cardinality $\Lambda = |I| - 1 \geq 1$ and elements $\beta_i \in S$ for $i \in I$ and $\alpha_i \in L$ for $i \in I_+$, where $I_+ = \{i \in I \mid i > 0\}$, such that

1) The semigroup $S$ is generated by $\{\beta_i\}_{i \in I}$ and the field $L$ is generated over $\mathfrak{k}$ by $\{\alpha_i\}_{i \in I_+}$.

2) Let

$$\overline{\pi}_i = [G(\beta_0, \ldots, \beta_i) : G(\beta_0, \ldots, \beta_{i-1})]$$

and

$$d_i = [\mathfrak{k}(\alpha_1, \ldots, \alpha_i) : \mathfrak{k}(\alpha_1, \ldots, \alpha_{i-1})].$$

Then there are inequalities

$$\beta_{i+1} > \overline{\pi}_i d_i \beta_i > \beta_i$$

with $\overline{\pi}_i < \infty$ and $d_i < \infty$ for $1 \leq i < \Lambda$ and if $\Lambda < \infty$, then either $\overline{\pi}_\Lambda = \infty$ and $d_\Lambda = 1$ or $\overline{\pi}_\Lambda < \infty$ and $d_\Lambda = \infty$. 

2
Here $G(\beta_0, \ldots, \beta_i)$ is the subgroup generated by $\beta_0, \ldots, \beta_i$.

The case when $R$ is not complete is more subtle, because of the possibility, when $R$ is not complete, of the existence of a rank 1 discrete valuation which dominates $R$ and such that the residue field extension $V_\nu/m_\nu$ of $k = R/m_R$ is finite. For all other valuations $\nu$ which dominate $R$ (so that $\nu$ is not rank 1 discrete with $V_\nu/m_\nu$ finite over $k$) the analysis is the same as for the complete case, as there is then a unique extension of $\nu$ to a valuation dominating the completion of $R$ which is an immediate extension; that is, there is no extension of the valuation semigroups or of the residue fields of the valuations. The differences between the complete and non complete cases are explained in more detail by Theorem 3.1, Corollary 3.2, Example 3.3, Proposition 3.4 and Corollary 5.1 to Theorem 1.1.

We give a necessary and sufficient condition for a semigroup to be the semigroup of a valuation dominating a regular local ring of dimension two in the following theorem, which is proven in Section 6:

**Theorem 1.2.** Suppose that $R$ is a regular local ring of dimension two. Let $S$ be a subsemigroup of the positive elements of a totally ordered abelian group. Then $S$ is the semigroup of a valuation $\nu$ dominating $R$ if and only if there exists a finite or countable index set $I$, of cardinality $\Lambda = |I| - 1 \geq 1$ and elements $\beta_i \in S$ for $i \in I$ such that

1) The semigroup $S$ is generated by $\{\beta_i\}_{i \in I}$.

2) Let

$$\pi_i = [G(\beta_0, \ldots, \beta_i) : G(\beta_0, \ldots, \beta_{i-1})].$$

There are inequalities

$$\beta_{i+1} > \pi_i \beta_i$$

with $\pi_i < \infty$ for $1 \leq i < \Lambda$. If $\Lambda < \infty$ then $\pi_\Lambda \leq \infty$.

Theorem 1.2 is proven by Spivakovsky when $R$ has algebraically closed residue field in [41].

The proof in Section 5 of [11], given for the case when the residue field of $R$ is algebraically closed, now extends to arbitrary regular local rings of dimension two, using the conclusions of Theorem 1.2, to prove the following:

**Corollary 1.3.** Suppose that $R$ is a regular local ring of dimension two and $\nu$ is a rank 1 valuation dominating $R$. Embed the value group of $\nu$ in $\mathbb{R}_+$ so that 1 is the smallest nonzero element of $S^R(\nu)$. Let $\varphi(n) = |S^R(\nu) \cap (0, n)|$ for $n \in \mathbb{Z}_+$. Then

$$\lim_{n \to \infty} \frac{\varphi(n)}{n^2}$$

exists. The set of limits which are obtained by such valuations $\nu$ dominating $R$ is the real half open interval $[0, \frac{1}{2})$.

As a consequence of Theorem 1.1, we obtain the following example, which we prove in Section 6, showing the subtlety of the criteria of Theorem 1.1.

**Example 1.4.** There exists a semigroup $S$ which satisfies the sufficient conditions 1) and 2) of Theorem 1.2, such that if $(R, m_R)$ is a 2-dimensional regular local ring dominated by a valuation $\nu$ such that $S^R(\nu) = S$, then $R/m_R = V_\nu/m_\nu$; that is, there can be no residue field extension.

The main technique we use in the proofs of the above theorems is the algorithm of Theorem 4.2, which constructs a sequence of elements $\{P_i\}$ in $R$, starting with a given
regular system of parameters $P_0 = x, P_1 = y$ of $R$, which gives a generating sequence of $\nu$ in $R$. This fact is proven in Theorems 4.11 and 4.12.

In Section 7, we develop the birational theory of the generating sequence $\{P_i\}$, generalizing to the case when $R$ has arbitrary residue field the results of [41].

Suppose that $R$ is a regular local ring of dimension two which is dominated by a valuation $\nu$. Let $\mathfrak{k} = R/m_R$ and

$$R \rightarrow T_1 \rightarrow T_2 \rightarrow \cdots$$

be the sequence of quadratic transforms along $\nu$, so that $V_\nu = \bigcup T_i$, and $L = V_\nu/m_\nu = \bigcup T_i/m_{T_i}$. Suppose that $x, y$ are regular parameters in $R$, and let $P_0 = x, P_1 = y$ and $\{P_i\}$ be the sequence of elements of $R$ constructed in Theorem 4.2. Suppose there exists some smallest value $i$ in the sequence (1) such that the divisor of $xy$ in $\text{Spec}(T_i)$ has only one component. Let $R_1 = T_i$. By Theorem 7.1, a local equation of the exceptional divisor and a strict transform of $P_2$ in $R_1$ are a regular system of parameters in $R_2$, and a local equation of the exceptional divisor and a strict transform of $P_i$ in $R_1$ for $i \geq 2$ satisfy the conclusions of Theorem 4.2 on $R_2$.

We can repeat this construction, for this new sequence, to construct a sequence of quadratic transforms $R_1 \rightarrow R_2$ such that a local equation of the exceptional divisor and a strict transform of $P_3$ in $R_2$ is a regular system of parameters in $R_2$, and a local equation of the exceptional divisor and a strict transform of $P_i$ for $i \geq 3$ satisfy the conclusions of Theorem 4.2 on $R_2$.

We thus have a sequence of iterated quadratic transforms

$$R \rightarrow R_1 \rightarrow R_2 \rightarrow \cdots$$

such that $V_\nu = \bigcup R_i$ and where a local equation of the exceptional divisor of $R_i \rightarrow R_{i+1}$ and the strict transform of $P_{i+1}$ are a regular system of parameters in $R_i$ for all $i$.

The notion of a generating sequence of a valuation already can be recognized in the famous algorithm of Newton to find the branches of a (characteristic zero) plane curve singularity. In more modern times, it has been developed by Maclane [35] (“key polynomials”), Zariski [46], Abhyankar [3], [4] (“approximate roots”), and Spivakovsky [41].

Most recently, the construction and application of generating sequences of a valuation have appeared in many papers, including [13], [9], [15], [20], [21], [25], [22], [23], [34], [38], [43]. The theory of generating sequences in regular local rings of dimension two is closely related to the configuration of exceptional curves appearing in the sequence of quadratic transforms along the center of the valuation. This subject has been explored in many papers, including [7] and [33]. The extension of valuations to the completion of a local ring, which becomes extremely difficult in higher dimension and rank, is studied in [41], [28], [12], [10], [14], [8], [12] and [30]. There is an extensive literature on the theory of complete ideals in local rings, beginning with Zariski’s articles [46] and [48].

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2. Preliminaries

Suppose that $(R, m_R)$ is a Noetherian local domain and $\nu$ is valuation of the quotient field which dominates $R$. Let $V_\nu$ be the valuation ring of $\nu$, and $m_\nu$ be its maximal ideal. Let $\Gamma_\nu$ be the value group of $\nu$. Let $\mathfrak{k} = R/m_R$. The semigroup of $\nu$ on $R$ is

$$S^R(\nu) = \{\nu(f) \mid f \in R \setminus \{0\}\}.$$
For \( \varphi \in \Gamma \), define valuation ideals
\[
\mathcal{P}_\varphi(R) = \{ f \in R \mid \nu(f) \geq \varphi \},
\]
and
\[
\mathcal{P}_\varphi^+(R) = \{ f \in R \mid \nu(f) > \varphi \}.
\]
We have that \( \mathcal{P}_\varphi^+(R) = \mathcal{P}_\varphi(R) \) if and only if \( \varphi \notin S^R(\nu) \). The associated graded ring of \( \nu \) on \( R \) is
\[
gr_\nu(R) = \bigoplus_{\varphi \in \Gamma} \mathcal{P}_\varphi(R)/\mathcal{P}_\varphi^+(R).
\]
Suppose that \( f \in R \) and \( \nu(f) = \varphi \). Then the initial form of \( f \) in \( gr_\nu(R) \) is
\[
in_\nu(f) = f + \mathcal{P}_\varphi^+(R) \in [\mathcal{P}_\varphi(R)]_\varphi = \mathcal{P}_\varphi(R)/\mathcal{P}_\varphi^+(R).
\]
A set of elements \( \{ F_i \}_{i \in I} \) such that \( \{ in_\nu(F_i) \} \) generates \( gr_\nu(R) \) as a \( \mathfrak{t} \)-algebra is called a generating sequence of \( \nu \) in \( R \).

We have that the vector space dimension
\[
dim_{R/mR} \mathcal{P}_\varphi(R)/\mathcal{P}_\varphi^+(R) < \infty
\]
and
\[
dim_{R/mR} \mathcal{P}_\varphi(R)/\mathcal{P}_\varphi^+(R) \leq [V_\nu/m_\nu : R/mR]
\]
for all \( \varphi \in \Gamma \).

\( S^R(\nu) \) is countable and is well ordered of ordinal type \( \leq \omega^2 \) by Proposition 2, Appendix 3 [48]. Further, \( V_\nu/m_\nu \) is a countably generated field extension of \( \mathfrak{t} = R/mR \), since \( gr_\nu(R) \) is a countably generated vector space over \( R/mR \), and if \( 0 \neq \alpha \in V_\nu/m_\nu \), then \( \alpha \) is the residue of \( \frac{f}{g} \) for some \( f, g \in R \) with \( \nu(f) = \nu(g) \).

We will make use of Abhyankar’s Inequality ([1], Appendix 2 [48]):
\[
(2) \quad \text{rat rank } \nu + \text{trdeg}_{R/mR} V_\nu/m_\nu \leq \dim R
\]
If equality holds then \( \Gamma \nu \cong \mathbb{Z}^m \) as an unordered group, where \( m = \text{rat rank } \nu \), and \( V_\nu/m_\nu \) is a finitely generated field extension of \( R/mR \).

We have that
\[
\text{rank } \nu \leq \text{rat rank } \nu \leq \dim R.
\]
Let \( n = \text{rank } \nu \). Then we have an order preserving embedding
\[
\Gamma \nu \subset \Gamma \nu \mathbb{R} \cong (\mathbb{R}^n)_{\text{lex}}
\]
(Proposition 2.10 [2]). We say that \( \nu \) is discrete if \( \Gamma \nu \) is discrete in the Euclidean topology.

If \( I \) is an ideal in \( R \), we may define \( \nu(I) = \min \{ \nu(f) \mid f \in I \setminus \{0\} \} \), since \( S^R(\nu) \) is well ordered.

\( \mathbb{N} \) denotes the natural numbers \( \{0, 1, 2, \ldots \} \) and \( \mathbb{Z}_+ \) denotes the positive integers \( \{1, 2, 3, \ldots \} \).

Given elements \( z_1, \ldots, z_n \) in a group \( G \), let \( G(z_1, \ldots, z_n) \) be the subgroup generated by \( z_1, \ldots, z_n \). Let \( S(z_1, \ldots, z_n) \) be the semigroup generated by \( z_1, \ldots, z_n \).

**Lemma 2.1.** Suppose that \( \Gamma \) is a totally ordered abelian group, \( I \) is a finite or countable index set of cardinality \( \geq 2 \) and \( \beta_i \in \Gamma \) are positive elements for \( i \in I \). Let \( \Lambda = |I| - 1 \).

Let
\[
\pi_i = [G(\beta_0, \ldots, \beta_i) : G(\beta_0, \ldots, \beta_{i-1})] \in \mathbb{Z}_+ \cup \{\infty\}
\]
for \( \geq 1 \). Assume that \( \pi_i \in \mathbb{Z}_+ \) if \( i < \Lambda \). Let \( s_i \) be the smallest positive integer \( t \) such that \( t\beta_i \in S_{i-1} \) (or \( s_i = \infty \) if \( i = \Lambda \) and no such \( t \) exists).

Suppose that \( 1 \leq k < \Lambda \) and \( \pi_i \beta_i < \beta_{i+1} \) for \( 1 \leq i \leq k - 1 \). Then
Thus using the inequalities isomorphism, the value groups $\Gamma$.

Proof. We first prove 2). By repeated Euclidean division, we obtain an expansion $\gamma = a_0\beta_0 + a_1\beta_1 + \cdots + a_k\beta_k$ with $a_0 \in \mathbb{Z}$ and $0 \leq a_i < \pi_i$ for $1 \leq i \leq k$. Now we calculate, using the inequalities $\pi_i\beta_i < \beta_{i+1}$,

$$a_1\beta_1 + \cdots + a_k\beta_k < \pi_k\beta_k.$$ 

Thus $a_0 > 0$ and $\gamma \in S(\beta_0, \ldots, \beta_k)$.

Now 1) follows from 2) and induction on $k$. □

A Laurent monomial in $H_0, H_1, \ldots, H_l$ is a product $H_0^{a_0}H_1^{a_1}\cdots H_l^{a_l}$ with $a_0, a_1, \ldots, a_l \in \mathbb{Z}$.

Suppose that $R$ is a regular local ring with maximal ideal $m_R$. Suppose that $f \in R$. Then we define

$$\text{ord}(f) = \max\{n \in \mathbb{N} | f \in m_R^n\}.$$

3. Regular local rings of dimension two

Suppose that $(R, m_R)$ is a Noetherian local domain of dimension two. Up to order isomorphism, the value groups $\Gamma_\nu$ of a valuation $\nu$ which dominates $R$ are by Abhyankar’s inequality and Example 3, Section 15, Chapter VI [48]:

1. $\alpha\mathbb{Z} + \beta\mathbb{Z}$ with $\alpha, \beta \in \mathbb{R}$ rationally independent.
2. $(\mathbb{Z}^d)_{\text{lex}}$.
3. Any subgroup of $\mathbb{Q}$.

Suppose that $N$ is a field, and $V$ is a valuation ring of $N$. We say that the rank of $V$ increases under completion if there exists an analytically normal local domain $T$ with quotient field $N$ such that $V$ dominates $T$ and there exists an extension of $V$ to a valuation ring of the quotient field of $T$ which dominates $T$ and which has higher rank than the rank of $V$.

Theorem 3.1. (Theorem 4.2, [14]; [41] in the case when $R/m_R$ is algebraically closed) Suppose that $V$ dominates an excellent two dimensional local ring $R$. Then the rank of $V$ increases under completion if and only if $V/mV$ is finite over $R/m_R$ and $V$ is discrete of rank 1.

Corollary 3.2. If $R$ is complete and $\nu$ is a discrete rank one valuation which dominates $R$ then $[V_\nu/m_\nu : R/m_R] = \infty$.

The following example shows an important distinction between the case when $R$ is complete and when $R$ is not.

Example 3.3. Suppose that $\mathfrak{k}$ is a field and $R = \mathfrak{k}[x, y]_{(x, y)}$ is a localization of a polynomial ring in two variables. Then there exists a rank one discrete valuation $\nu$ dominating $R$ such that $V_\nu/m_\nu = \mathfrak{k}$.

Proof. Let $f(t) \in \mathfrak{k}[[t]]$ be a transcendental element over $\mathfrak{k}(t)$. Embed $R$ into $\mathfrak{k}[[t]]$ by substituting $t$ for $x$ and $f(t)$ for $y$. The valuation $\nu$ on $R$ obtained by restriction of the $t$-adic valuation to $R$ has the desired properties. □

Suppose that $\nu$ is a valuation which dominates $R$. Let $a$ be the smallest positive element in $S^R(\nu)$. Suppose that $\{f_i\}$ is a Cauchy sequence in $R$ (for the $m_R$-adic topology). Then
either there exist \( n_0 \in \mathbb{Z}_+ \), \( m \in \mathbb{Z}_+ \) and \( \gamma \in S^R(\nu) \) such that \( \gamma < ma \) and \( \nu(f_i) = \gamma \) for \( i \geq n_0 \), or

(4) Given \( m \in \mathbb{Z}_+ \), there exists \( n_0 \in \mathbb{Z}_+ \) such that \( \nu(f_i) > ma \) for \( i > n_0 \)

Let \( \hat{I}_R \) be the set of limits of Cauchy sequences \( \{f_i\} \) satisfying (4). Then \( \hat{I}_R \) is a prime ideal in \( \hat{R} \) ([10], [13], [12], [41], [42]). The following proposition is well known.

**Proposition 3.4.** Suppose that \( R \) is a regular local ring of dimension two, and let \( \nu \) be a valuation which dominates \( R \). Then there exists an extension of \( \nu \) to a valuation \( \hat{\nu} \) which dominates the completion \( \hat{R} \) of \( R \) with respect to \( \mathfrak{m}_R \), which has one of the following semigroups:

1. \( \text{rank} \ \nu = \text{rank} \ \hat{\nu} = 1 \) and

   \[
   S^R(\nu) = S^{\hat{R}}(\hat{\nu}).
   \]

2. \( \nu \) is discrete of rank 1, \( \hat{\nu} \) is discrete of rank 2 and

   \[
   S^{\hat{R}}(\hat{\nu}) \text{ is generated by } S^R(\nu) \text{ and an element } \alpha \text{ such that } \alpha > \gamma \text{ for all } \gamma \in S^R(\nu).
   \]

3. \( \nu \) and \( \hat{\nu} \) are discrete of rank 2, there exists a height one prime \( I_R \) in \( R \), and a discrete rank 1 valuation \( \overline{\nu} \) which dominates the maximal ideal \( \mathfrak{m}_R(R/I_R) \) of \( R/I_R \) such that

   \[
   S^R(\nu) \text{ is generated by } S^{R/I_R}(\overline{\nu}) \text{ and an element } \alpha \text{ such that } \alpha > \gamma
   \]

   for all \( \gamma \in S^{R/I_R}(\overline{\nu}) \).

4. \( \nu \) and \( \hat{\nu} \) are discrete of rank 2, \( I_R = (0) \) and \( S^R(\nu) = S^{\hat{R}}(\hat{\nu}) \).

**Proof.** First suppose that \( \nu \) has rank 1. Then \( I_R \cap R = (0) \), so we have an embedding \( R \subset \hat{R}/I_R \). We can then extend \( \nu \) to a valuation \( \overline{\nu} \) which dominates \( \hat{R}/I_R \) by defining for \( f \not\in I_R \), \( \overline{\nu}(f + I_R) = \lim_{i\to\infty} \nu(f_i) \), where \( \{f_i\} \) is a Cauchy sequence in \( \hat{R} \) representing \( f \).

We have that \( S^R(\nu) = S^{\hat{R}/I_R}(\overline{\nu}) \).

If \( I_R = (0) \) then we have constructed the desired extension \( \hat{\nu} = \overline{\nu} \) of \( \nu \) to \( \hat{R} \). Suppose that \( I_R \neq (0) \). Then \( \hat{R}/I_R \) has dimension 1, so \( \overline{\nu} \) is discrete of rank 1. We have that \( I_R = (v) \) is a height one prime ideal. We can extend \( \overline{\nu} \) to a rank 2 valuation \( \hat{\nu} \) which dominates \( \hat{R} \) by defining \( \hat{\nu}(f) = (n, \overline{\nu}(g)) \in (\mathbb{Z} \oplus \Gamma_{\overline{\nu}})_{\text{lex}} \) if \( f \in \hat{R} \) has a factorization \( f = v^n g \) where \( n \in \mathbb{N} \) and \( v \nmid g \).

Now assume that \( \nu \) has rank 2. Further assume that \( I_R \cap R \neq (0) \). Then \( \nu \) has rank 2, and \( I_R = I_R \cap R \) is a height one prime ideal in \( R \). Thus there exists an irreducible \( g \in R \) such that \( I_R = (g) \). We then have that \( I_R \) is a height one prime ideal in \( \hat{R} \), so there exists an irreducible \( v \in \hat{R} \) such that \( I_R = (v) \).

There exists a valuation \( \overline{\nu} \) dominating \( R/I_R \) such that if \( f \in R \) has a factorization \( f = g^n h \) where \( g \nmid h \), then

\[
\nu(f) = n \nu(g) + \overline{\nu}(h).
\]

Write \( g = v^n \varphi \) where \( t \in \mathbb{Z}_+ \) and \( v \nmid \varphi \). Thus \( \varphi \notin I_R \). If \( R \) is excellent, then \( g \) is reduced in \( \hat{R} \) (by Schol II 7.8.3 (vii) [26]), so \( t = 1 \). We have an inclusion \( R/I_R \subset \hat{R}/I_{\hat{R}} \) and \( \overline{\nu} \) extends to a valuation \( \hat{\nu} \) which dominates \( \hat{R}/I_{\hat{R}} \). We then extend \( \nu \) to a valuation \( \hat{\nu} \) which dominates \( \hat{R} \) by setting

\[
t\hat{\nu}(v) = \nu(g) - \overline{\nu}(\varphi)
\]
Theorem 4.2.\[\text{(8)}\]

\[\mathcal{P}_1\text{ and for } L \text{ with } h \in \mathcal{P}_1\text{, denote the class of } \Omega \in \mathcal{Z}_{\nu}\text{ such that } n\nu(\mathcal{P}_1) > \gamma \text{ and there exists } n \in \mathbb{Z}_+ \text{ such that } n\nu(\mathcal{P}_1) > \gamma \text{ and there exists } f \in R \text{ such that if } \mathcal{T} \text{ is the image of } f \text{ in } R/I_R, \text{ then } \mathcal{T} - h \in \mathcal{m}^n(R/I_R). \text{ Thus } \nu(f) = \nu(\mathcal{T}) = \nu(h) = \gamma.\]

Suppose that \(0 \neq h \in \mathcal{R}/I_R\), and that \(\nu(h) = \gamma\). There exists \(n \in \mathbb{Z}_+\) such that \(n\nu(\mathcal{R}/I_R)) > \gamma\) and there exists \(f \in R\) such that if \(\mathcal{T}\) is the image of \(f\) in \(R/I_R\), then \(\mathcal{T} - h \in \mathcal{m}^n(\mathcal{R}/I_R)\). Thus \(\nu(f) = \nu(\mathcal{T}) = \nu(h) = \gamma\).

Suppose that rank \(\nu = 2\) and \(I_{\hat{R}} \cap R = (0)\). We can extend \(\nu\) to a valuation \(\mathcal{V}\) dominating \(R/I_{\hat{R}}\) by defining for \(f \notin I_{\hat{R}}, \mathcal{V}(f + I_{\hat{R}}) = \lim_{n \to \infty} \nu(f_i)\) if \(\{f_i\}\) is a Cauchy sequence in \(R\) converging to \(f\). We must have that \(I_{\hat{R}} = (0)\), since otherwise we would be able to extend \(\mathcal{V}\) to a valuation \(\nu\) dominating \(\hat{R}\) which is composite with the rank 2 extension \(\mathcal{V}\) of \(\nu\) to \(R/I_{\hat{R}}\); this extension would have rank \(\geq 3\) which is impossible by Abhyankar’s inequality. Thus \(I_{\hat{R}} = (0)\).

\(\square\)

Remark 3.5. Nagata gives an example in the Appendix to [39] of a regular local ring \(R\) of dimension two with an irreducible element \(f \in R\) such that \(f\) is not reduced in \(\hat{R}\).

4. The Algorithm

In this section, we will suppose that \(R\) is a regular local ring of dimension two, with maximal ideal \(\mathcal{m}_R\) and residue field \(\mathfrak{t} = R/\mathcal{m}_R\). For \(f \in R\), let \(\mathcal{F}\) or \([f]\) denote the residue of \(f\) in \(\mathfrak{t}\). Suppose that \(CS\) is a coefficient set of \(R\). A coefficient set of \(R\) is a subset \(CS\) of \(R\) such that the mapping \(CS \to \mathfrak{t}\) defined by \(s \mapsto \mathfrak{t}\) is a bijection. We further require that \(0 \in CS\) and \(1 \in CS\).

Remark 4.1. Suppose that \(x, y\) are regular parameters in \(R\), \(a, b \in CS\) and \(n \in \mathbb{Z}_+.\) Let \(c \in CS\) be defined by \(a + b = \mathfrak{t}\). Then there exist \(e_{ij} \in CS\) such that

\[a + b = c + \sum_{i+j=1}^{n-1} e_{ij} x^i y^j + h\]

with \(h \in \mathcal{m}_R^n\). Let \(d \in CS\) be defined by \(ab = \mathcal{d}\). Then there exist \(g_{ij} \in CS\) such that

\[ab = d + \sum_{i+j=1}^{n-1} g_{ij} x^i y^j + h'\]

with \(h' \in \mathcal{m}_R^n\).

Theorem 4.2. Suppose that \(\nu\) is a valuation of the quotient field of \(R\) dominating \(R\). Let \(L = V_{\nu}/m_{\nu}\) be the residue field of the valuation ring \(V_{\nu}\) of \(\nu\). For \(f \in V_{\nu}\), let \([f]\) denote the class of \(f\) in \(L\). Suppose that \(x, y\) are regular parameters in \(R\). Then there exist \(\Omega \in \mathbb{Z}_+ \cup \{\infty\}\) and \(P_i \in \mathcal{m}_R\) for \(i \in \mathbb{Z}_+\) with \(i < \min(\Omega + 1, \infty)\) such that \(P_0 = x, P_1 = y\) and for \(1 \leq i < \Omega\), there is an expression

\[P_{i+1} = P_{i+1}^{\nu_i} + \sum_{k=1}^{\nu_i} c_k P_0^{\nu_{i,0}(k)} P_1^{\nu_{i,1}(k)} \ldots P_i^{\nu_{i,i}(k)}\]

with \(n_i \geq 1, \lambda_i \geq 1,\)

\[0 \neq c_k \in CS\]
for \(1 \leq k \leq \lambda_i\), \(\sigma_{i,s}(k) \in \mathbb{N}\) for all \(s, k\), \(0 \leq \sigma_{i,s}(k) < n_s\) for \(s \geq 1\). Further,
\[
n_i \nu(P_i) = \nu(P_0^{\sigma_{i,0}(k)} P_1^{\sigma_{i,1}(k)} \ldots P_i^{\sigma_{i,i}(k)})
\]
for all \(k\).

For all \(i \in \mathbb{Z}_+\) with \(i < \Omega\), the following are true:

1) \(\nu(P_{i+1}) > n_i \nu(P_i)\).

2) Suppose that \(r \in \mathbb{N}\), \(m \in \mathbb{Z}_+, j_k(l) \in \mathbb{N}\) for \(1 \leq l \leq m\) and \(0 \leq j_k(l) < n_k\) for \(1 \leq k \leq r\) are such that \((j_0(l), j_1(l), \ldots, j_r(l))\) are distinct for \(1 \leq l \leq m\), and
\[
\nu(P_0^{j_0(l)} P_1^{j_1(l)} \ldots P_r^{j_r(l)}) = \nu(P_0^{j_0(1)} \ldots P_r^{j_r(1)})
\]
for \(1 \leq l \leq m\). Then
\[
1, \left[ \frac{P_0^{j_0(2)} P_1^{j_1(2)} \ldots P_r^{j_r(2)}}{P_0^{j_0(1)} P_1^{j_1(1)} \ldots P_r^{j_r(1)}} \right], \ldots, \left[ \frac{P_0^{j_0(m)} P_1^{j_1(m)} \ldots P_r^{j_r(m)} N}{P_0^{j_0(1)} P_1^{j_1(1)} \ldots P_r^{j_r(1)}} \right]
\]
are linearly independent over \(\mathcal{K}\).

3) Let
\[
\pi_i = \left[ G(\nu(P_0), \ldots, \nu(P_i)) : G(\nu(P_0), \ldots, \nu(P_{i-1})) \right].
\]
Then \(\pi_i\) divides \(\sigma_{i,k}(k)\) for all \(k\) in (8). In particular, \(n_i = \pi_i d_i\) with \(d_i \in \mathbb{Z}_+\).

4) There exists \(U_i = P_0^{w_0(i)} P_1^{w_1(i)} P_{i-1}^{w_{i-1}(i)}\) for \(i \geq 1\) with \(w_0(i), \ldots, w_{i-1}(i) \in \mathbb{N}\) and \(0 \leq w_j(i) < n_j\) for \(1 \leq j \leq i - 1\) such that \(\nu(P_i^{\pi_i}) = \nu(U_i)\) and if
\[
\alpha_i = \left[ \frac{P_i^{\pi_i}}{U_i} \right]
\]
then
\[
b_{i,t} = \left[ \sum_{\sigma_{i,(k)} = \pi_i} c_k \frac{P_0^{\sigma_{i,0}(k)} P_1^{\sigma_{i,1}(k)} \ldots P_{i-1}^{\sigma_{i,i-1}(k)}}{U_i^{(d_i-t)}} \right] \in \mathcal{K}(\alpha_1, \ldots, \alpha_{i-1})
\]
for \(0 \leq t \leq d_i - 1\) and
\[
f_t(u) = u^{d_t} + b_{i,d_i-1} u^{d_i-1} + \ldots + b_{i,0}
\]
is the minimal polynomial of \(\alpha_i\) over \(\mathcal{K}(\alpha_1, \ldots, \alpha_{i-1})\).

The algorithm terminates with \(\Omega < \infty\) if and only if either
\[
\pi_\Omega = [G(\nu(P_0), \ldots, \nu(P_\Omega)) : G(\nu(P_0), \ldots, \nu(P_{\Omega-1}))] = \infty
\]
or
\[
\pi_\Omega < \infty \quad (so\ that\ \alpha_\Omega\ is\ defined\ as\ in\ 4)\)\ and \(d_\Omega = [\mathcal{K}(\alpha_1, \ldots, \alpha_\Omega) : \mathcal{K}(\alpha_1, \ldots, \alpha_{\Omega-1})] = \infty.
\]
If \(\pi_\Omega = \infty\), set \(\alpha_\Omega = 1\).

Proof. Consider the following statements \(A(i), B(i), C(i), D(i)\) for \(1 \leq i < \Omega\):
There exists \( U_i = P_{w_0(i)}^{n_0(i)} P_{w_1(i)}^{n_1(i)} \cdots P_{i-1}^{n_{i-1}(i)} \) for some \( w_j(i) \in \mathbb{N} \) and \( 0 \leq w_j(i) < n_j \) for \( 1 \leq j \leq i - 1 \).

Such that \( \pi_i \nu(P_i) = \nu(U_i) \). Let \( \alpha_i = \left[ \frac{P_i^{n_i}}{\nu_i} \right] \in L \) and

\[
A(i) \quad f_i(u) = u^{d_i} + b_{i,d_i-1} u^{d_i-1} + \cdots + b_{i,0} \in \mathfrak{f}(\alpha_1, \ldots, \alpha_{i-1})[u]
\]

be the minimal polynomial of \( \alpha_i \).

Let \( d_i \) be the degree of \( f_i(u) \), and \( n_i = \pi_i d_i \). Then there exist \( a_{s,t} \in CS \) and \( j_0(s,t), j_1(s,t), \ldots, j_{i-1}(s,t) \in \mathbb{N} \) with \( 0 \leq j_k(s,t) < n_k \) for \( k \geq 1 \) and \( 0 \leq t < d_i \) such that

\[

\nu(P_0^{j_0(s,t)} P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)} P_i^{n_i}) = \pi_i d_i \nu(P_i)

\]

for all \( s,t \) and

\[
P_{i+1} := P_i^{n_i d_i} + \sum_{l=0}^{d_i-1} \left( \sum_{s,t=1}^{\lambda_i} a_{s,t} P_0^{j_0(s,t)} P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)} \right) P_i^{n_i}
\]

satisfies

\[

b_{i,t} = \left[ \sum_{s,t=1}^{\lambda_i} a_{s,t} \frac{P_0^{j_0(s,t)} P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)}}{U_i^{j_{i-1}(s,t)}} \right]
\]

for \( 0 \leq t \leq d_i - 1 \). In particular,

\[

\nu(P_{i+1}) > n_i \nu(P_i).
\]

\[
B(i) \quad \text{Suppose that } M \text{ is a Laurent monomial in } P_0, P_1, \ldots, P_i \text{ and } \nu(M) = 0. \text{ Then there exist } s_i \in \mathbb{Z} \text{ such that}
\]

\[
M = \prod_{j=1}^{i} \left[ \frac{u_j^{s_j}}{U_j} \right]^{s_j}
\]

so that

\[
[M] \in \mathfrak{f}(\alpha_1, \ldots, \alpha_i).
\]

Suppose that \( \lambda \in \mathfrak{f}(\alpha_1, \ldots, \alpha_i) \) and \( N \) is a Laurent monomial in \( P_0, P_1, \ldots, P_i \) such that \( \gamma = \nu(N) \geq n_i \nu(P_i) \). Then there exists

\[
G = \sum_{j} c_j P_0^{\tau_0(j)} P_1^{\tau_1(j)} \cdots P_i^{\tau_i(j)}
\]

with \( \tau_0(j), \ldots, \tau_i(j) \in \mathbb{N} \), \( 0 \leq \tau_k(j) < n_k \) for \( 1 \leq k \leq i \) and \( c_j \in CS \) such that

\[
\nu(P_0^{\tau_0(j)} P_1^{\tau_1(j)} \cdots P_i^{\tau_i(j)}) = \gamma \text{ for all } j
\]

and

\[
\left[ \frac{G}{N} \right] = \lambda.
\]
Suppose that \( m \in \mathbb{Z}_+ \), \( j_k(l) \in \mathbb{N} \) for \( 1 \leq l \leq m \) and \( 0 \leq j_k(l) < n_k \) for \( 1 \leq k \leq i \) are such that the \( j_0(l), j_1(l), \ldots, j_i(l) \) are distinct for \( 1 \leq l \leq m \), and
\[
(14) \quad \nu(P_0^{j_0(l)}P_1^{j_1(l)} \cdots P_i^{j_i(l)}) = \nu(P_0^{j_0(1)} \cdots P_i^{j_i(1)})
\]
are linearly independent over \( \mathbb{F} \).

D(i) for \( 1 \leq l \leq m \). Then
\[
(15) \quad \left[ P_0^{j_0(0)}P_1^{j_1(0)} \cdots P_i^{j_i(0)} \right], \ldots, \left[ P_0^{j_0(m)}P_1^{j_1(m)} \cdots P_i^{j_i(m)} \right]
\]
are linearly independent over \( \mathbb{F} \).

We will leave the proofs of \( A(1), B(1), C(1) \) and \( D(1) \) to the reader, as they are an easier variation of the following inductive statement, which we will prove.

Assume that \( i \geq 1 \) and \( A(i), B(i), C(i) \) and \( D(i) \) are true. We will prove that \( A(i+1), B(i+1) \) and \( C(i+1) \) and \( D(i+1) \) are true. Let \( \beta_j = \nu(P_j) \) for \( 0 \leq j \leq i+1 \). By Lemma 2.1, there exists \( U_{i+1} = P_0^{\nu_0(i)}P_1^{\nu_1(i)} \cdots P_i^{\nu_i(i)} \) for some \( \nu_j(i) \in \mathbb{N} \) such that \( 0 \leq \nu_j(i) < n_j \) for \( 1 \leq j \leq i \) and \( \nu(U_{i+1}) = \nu_{i+1}(\beta_{i+1}) \) (where \( \nu_{i+1} = \nu_0(\beta_0, \ldots, \beta_{i+1}) : G(\beta_0, \ldots, \beta_{i+1}) \)).

Let \( f_{i+1}(u) \) be the minimal polynomial of \( u^{d+1} \) over \( \mathbb{F}(\alpha_1, \ldots, \alpha_i) \). Let \( d = d_{i+1} = \deg f_{i+1} \). Expand
\[
f_{i+1}(u) = u^d + b_{d-1}u^{d-1} + \cdots + b_0
\]
with \( b_j \in \mathbb{F}(\alpha_1, \ldots, \alpha_i) \). For \( j \geq 1 \),
\[
\nu(U_{i+1}^j) = j\nu_{i+1}(\beta_{i+1}) \geq \beta_{i+1} > n_i \beta_i.
\]
In the inductive statement \( C(i) \), take \( N = U_{i+1}^{d-t} \) for \( 0 \leq t < d = d_{i+1} \), to obtain for \( 0 \leq t < d_{i+1} \),
\[
(16) \quad G_t = \sum_{s=1}^{\lambda_t} a_{s,t}P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_i^{j_i(s,t)}
\]
with \( a_{s,t} \in CS, j_k(s,t) \in \mathbb{N} \) and \( 0 \leq j_k(s,t) < n_k \) for \( 1 \leq k \leq i \) such that
\[
\nu(G_t) = \nu(P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_i^{j_i(s,t)}) = (d-t)\nu_{i+1}(\beta_{i+1})
\]
for all \( s, t \) and
\[
(15) \quad \left[ G_t \right]_t = b_t.
\]

Set
\[
P_{i+2} = P_{i+1}^{d_{i+1}} + G_{d-1}P_{i+1}^{d_{i+1}+1} + \cdots + G_0
\]
\[
= P_{i+1}^{d_{i+1}} + \sum_{t=0}^{d-t} \sum_{s=1}^{\lambda_t} a_{s,t}P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_i^{j_i(s,t)}
\]
We have established \( A(i+1) \).

Suppose \( M \) is a Laurent polynomial in \( P_0, P_1, \ldots, P_i+1 \) and \( \nu(M) = 0 \). We have a factorization
\[
M = P_0^{\nu_0}P_1^{\nu_1} \cdots P_i^{\nu_i}P_{i+1}^{\nu_{i+1}}
\]
with all $a_j \in \mathbb{Z}$. Thus $a_{i+1} \beta_{i+1} \in G(\beta_0, \ldots, \beta_i)$, so that $\pi_{i+1}$ divides $a_{i+1}$. Let $s = \frac{a_{i+1}}{\pi_{i+1}}$. Then

$$M = U_{i+1}^s(P_0^{a_0} P_1^{a_1} \cdots P_i^{a_i}) \left( \frac{P_{i+1}^{\pi_{i+1}}}{U_{i+1}} \right)^s.$$ 

Now $U_{i+1}^s P_0^{a_0} \cdots P_i^{a_i}$ is a Laurent monomial in $P_0, \ldots, P_i$ of value zero, so the validity of $B(i + 1)$ follows from the inductive assumption $B(i)$.

We now establish $C(i + 1)$. Suppose $\lambda \in \mathfrak{f}(\alpha_1, \ldots, \alpha_{i+1})$ and $N$ is a Laurent monomial in $P_0, P_1, \ldots, P_i$ such that $\gamma = \nu(N) \geq n_{i+1} \nu(P_{i+1})$. We have

$$\gamma \geq n_{i+1} \beta_{i+1} = \pi_{i+1} d_{i+1} \beta_{i+1} \geq \pi_{i+1} \beta_{i+1}.$$ 

By Lemma 2.1 there exist $r_0, r_1, \ldots, r_i, k \in \mathbb{N}$ such that $0 \leq r_j < n_j$ for $1 \leq j \leq i$ and $0 \leq k < \pi_{i+1}$ such that

$$\bar{N} = P_0^{r_0} P_1^{r_1} \cdots P_i^{r_i} P_i^{k}$$

satisfies $\nu(\bar{N}) = \gamma$. Let $\bar{N} = P_0^{\alpha_0} P_1^{\alpha_1} \cdots P_i^{\alpha_i}$, so that $\bar{N} = \tilde{N} P_i^{k}$. Let $\tau = \lfloor \frac{N}{\bar{N}} \rfloor$. We have that $0 \neq \tau \in \mathfrak{f}(\alpha_1, \ldots, \alpha_{i+1})$ by $B(i + 1)$.

Suppose $0 \leq j \leq d_{i+1} - 1$. Then

$$\nu \left( \frac{\bar{N}}{U_{i+1}^{d_{i+1}}} \right) = \nu(\bar{N}) - j \nu(U_{i+1})$$

(17)

$$\geq \gamma - (\pi_{i+1} - 1) \beta_{i+1} - (d_{i+1} - 1) \pi_{i+1} \beta_{i+1}$$

$$\geq \pi_{i+1} d_{i+1} \beta_{i+1} - \pi_{i+1} \beta_{i+1} + \beta_{i+1} - d_{i+1} \pi_{i+1} \beta_{i+1} + \pi_{i+1} \beta_{i+1}$$

$$\geq \beta_{i+1} > n_{i+1} \beta_{i+1}.$$ 

Write

$$\tau \lambda = e_0 + e_1 \alpha_{i+1} + \cdots + e_{d_{i+1} - 1} \alpha_{i+1}$$

with $e_j \in \mathfrak{f}(\alpha_1, \ldots, \alpha_i)$. By the inductive statement $C(i)$ and (17), there exist for $0 \leq j \leq d_{i+1} - 1$

$$H_j = \sum_k c_{k,j} P_0^{\delta_0(k,j)} P_1^{\delta_1(k,j)} \cdots P_i^{\delta_i(k,j)}$$

with $\delta_0(k,j), \delta_1(k,j), \ldots, \delta_i(k,j) \in \mathbb{N}$, $0 \leq \delta_i(k,j) < n_i$ for $1 \leq l$ and $c_{k,j} \in CS$ for all $k, j$ such that

$$\nu(P_0^{\delta_0(k,j)} P_1^{\delta_1(k,j)} \cdots P_i^{\delta_i(k,j)}) = \nu \left( \frac{\bar{N}}{U_{i+1}^{d_{i+1}}} \right)$$

for all $j, k$ and

$$\left[ \frac{H_j}{\bar{N}} \frac{U_{i+1}^{d_{i+1}}} \right] = e_j$$

for all $j$. Set

$$G = H_0 P_i^{d_{i+1}} + H_1 P_i^{\pi_{i+1} + k} + \cdots + H_{d_{i+1} - 1} P_i^{\pi_{i+1} (d_{i+1} - 1) + k}.$$ 

We have

$$\pi_{i+1} (d_{i+1} - 1) + k < \pi_{i+1} (d_{i+1} - 1) + \pi_{i+1} \leq \pi_{i+1} d_{i+1} = n_{i+1},$$
and
\[ G \frac{N}{N} = H_0 \frac{N}{N} + \left( \frac{H_1 U_{i+1}}{N} \right) \left( P_{i+1} \frac{N}{U_{i+1}} \right) + \cdots + \left( \frac{H_{d+1-1} U_{i+1}}{N} \right) \left( P_{i+1} \frac{N}{U_{i+1}} \right)^{d+1-1} \]

We have
\[ \left[ G \frac{N}{N} \right] = e_0 + e_1 \alpha_{i+1} + \cdots + e_{d+1-1} \alpha_{i+1}^{d+1-1} = \tau \lambda. \]

Thus
\[ \left[ G \frac{N}{N} \right] = \left[ G \frac{N}{N} \right] \frac{N}{N} = \tau \lambda \tau^{-1} = \lambda. \]

We have established \( C(i+1). \)

Suppose that \( D(i+1) \) is not true. We will obtain a contradiction. Under the assumption that \( D(i+1) \) is not true, there exists \( m \in \mathbb{Z}_+, j_k(l) \in \mathbb{N} \) for \( 1 \leq l \leq m \) with \( 0 \leq j_k(l) < n_k \) for \( 1 \leq k \leq i+1 \) such that \( (j_0(l), j_1(l), \ldots, j_{i+1}(l)) \) are distinct for \( 1 \leq l \leq m, \) and
\[ \nu(P_0^j(l) P_1^{j_1(l)} \cdots P_{i+1}^{j_{i+1}(l)}) = \nu(P_0^j(1) P_1^{j_1(1)} \cdots P_{i+1}^{j_{i+1}(1)}) \]
for \( 1 \leq l \leq m \) and \( \bar{a}_l \in \mathfrak{p} \) for \( 1 \leq l \leq m \) not all zero such that
\[ \bar{a}_1 + \bar{a}_2 \left[ P_0^{j_0(2)} P_1^{j_1(2)} \cdots P_{i+1}^{j_{i+1}(2)} \right] + \cdots + \bar{a}_m \left[ P_0^{j_0(m)} P_1^{j_1(m)} \cdots P_{i+1}^{j_{i+1}(m)} \right] = 0. \]

\((j_{i+1}(l) - j_{i+1}(1)) \beta_{i+1} \in G(\beta_0, \ldots, \beta_i) \) for \( 1 \leq l \leq m, \) so \( \pi_{i+1} \) divides \( (j_{i+1}(l) - j_{i+1}(1)) \) for all \( l. \) Thus after possibly dividing all monomials \( P_0^{j_0(l)} P_1^{j_1(l)} \cdots P_{i+1}^{j_{i+1}(l)} \) by a common power of \( P_{i+1}, \) we may assume that
\[(18) \quad \pi_{i+1} \text{ divides } j_{i+1}(l) \text{ for all } l.
\]

After possibly reindexing the \( P_0^{j_0(l)} P_1^{j_1(l)} \cdots P_{i+1}^{j_{i+1}(l)}, \) we may assume that \( j_{i+1}(1) = \pi_{i+1} \varphi \) is the largest value of \( j_{i+1}(l). \)

For \( 1 \leq l \leq m, \) define \( a_l \in CS \) by \( \pi_l = \bar{a}_l. \) Let
\[ Q = \sum_{l=1}^{m} a_l P_0^{j_0(l)} P_1^{j_1(l)} \cdots P_{i+1}^{j_{i+1}(l)}. \]

Let
\[ Q_s = \sum_{j_{i+1}(l) = s \pi_i} a_l P_0^{j_0(l)} P_1^{j_1(l)} \cdots P_i^{j_i(l)} \]
for \( 0 \leq s \leq \varphi. \) Then
\[ Q = \sum_{s=0}^{\varphi} Q_s P_{i+1}^{s \pi_i}. \]

Let
\[ c_s = \left[ \frac{Q_s}{P_0^{j_0(1)} P_1^{j_1(1)} \cdots P_i^{j_i(1)} U_{i+1}^{\varphi-s}} \right] \in \mathfrak{p}(\alpha_1, \ldots, \alpha_i) \]
by \( B(i). \) We further have that \( c_{\varphi} \neq 0 \) by \( D(i) \) since the monomials are all distinct.
Dividing $Q$ by $P_0^{b_0(1)}P_1^{b_1(1)}\ldots P_i^{b_i(1)}U_i^{\varphi}$, we have

$$0 = \sum_{s=0}^{\varphi} c_s \alpha_{i+1}^s.$$ 

Thus the minimal polynomial $f_{i+1}(u)$ of $\alpha_{i+1}$ divides $g(u) = \sum_{s=0}^{\varphi} c_s u^s$ in $\mathfrak{t}(\alpha_1, \ldots, \alpha_i)[u]$. But then $\varphi \geq \delta_{i+1}$, so that $j_{i+1}(1) = \pi_{i+1}^\varphi \geq \eta_{i+1}$, a contradiction. $\square$ 

**Remark 4.3.** Theorem 4.2 can be stated without recourse to a coefficient set. To give this statement (which has the same proof) (9) must be replaced with “$c_k$ are units in $R$ for $1 \leq k \leq \lambda_i$”. In the proof, the statement “$a_{s,t} \in CS$” in $A(i)$ must be replaced with “$a_{s,t}$ units in $R$ or $a_{s,t} = 0$”. The statement “$c_j \in CS$” in $C(i)$ must be replaced with “$c_j$ is a unit in $R$ or $c_j = 0$”.

**Remark 4.4.** For $i > 0$, there is an expression

$$P_{i+1} = y^{n_i-n_i} + x \Theta_{i+1}$$

with $\Theta_{i+1} \in R$. This follows by considering the expression (8) and the various constraints on the values of the terms of the monomials in this expression.

**Remark 4.5.** The algorithm of Theorem 4.2 concludes with $\Omega < \infty$ if and only if $\nu(P_0) \not\in \mathbb{Q}\nu(x)$ (so that $\text{rank}(\nu) = 2$) or $\nu$ is discrete of rank 1 with $\text{trdeg}_{R/m_R} V_\nu/m_\nu = 1$ (so that $\nu$ is divisorial).

**Proof.** From Theorem 4.2, we see that the algorithm terminates with $\Omega < \infty$ if and only if either

$$[G(\nu(P_0), \ldots, \nu(P_i)) : G(\nu(P_0), \ldots, \nu(P_{\Omega-1}))] = \infty$$

or

$$[G(\nu(P_0), \ldots, \nu(P_i)) : G(\nu(P_0), \ldots, \nu(P_{\Omega-1}))] < \infty$$

and $|\mathfrak{t}(\alpha_1, \ldots, \alpha_\Omega) : \mathfrak{t}(\alpha_1, \ldots, \alpha_{\Omega-1})| = \infty$. $\square$

**Remark 4.6.** Suppose that $\Omega = \infty$ and $n_i = 1$ for $i \gg 0$ in the conclusions of Theorem 4.2. Then $\nu$ is discrete, and $V_\nu/m_\nu$ is finite over $\mathfrak{t}$.

**Proof.** We first deduce a consequence of the assumption that $\Omega = \infty$ and $n_i = 1$ for $i \gg 0$. There exists $i_0 \in \mathbb{Z}_+$ such that $n_i = 1$ for all $i \geq i_0$. Thus for $i \geq i_0$, $P_{i+1}$ is the sum of $P_i$ and a $\mathfrak{t}$-linear combination of monomials $M$ in $x$ and the finitely many $P_j$ with $j < i_0$, and with $\nu(M) = \nu(P_i)$. We see that the $P_i$ form a Cauchy sequence in $\hat{R}$ whose limit $f$ in $\hat{R}$ is nonzero (by Remark 4.4), and such that $\lim_{i \to \infty} \nu(P_i) = \infty$.

Thus $I_{\hat{R}} \neq (0)$, $\nu$ is discrete and $V_\nu/m_\nu$ is finite over $\mathfrak{t}$ by the proof of Proposition 3.4. $\square$

**Remark 4.7.** Suppose that $V_\nu/m_\nu = R/m_R$ in the hypotheses of Theorem 4.2 (so that there is no residue field extension). Then the $P_i$ constructed by the algorithm are binomials for $i \geq 2$; (8) becomes

$$P_{i+1} = P_{i+1}^{\mathfrak{t}i} + cU_i = P_{i+1}^{\mathfrak{t}i} + cP_0^{\mathfrak{t}0(i)} \ldots P_{i-1}^{\mathfrak{t}0(i)}$$

for some $0 \neq c \in CS$. 

14
Example 4.8. There exists a rank 2 valuation $\nu$ dominating $R = \mathfrak{f}[x,y]_{(x,y)}$ such that the set

$$\{\nu(P_0), \nu(P_1), \nu(P_2), \ldots\}$$

does not generate the semigroup $S^R(\nu)$.

Proof. Suppose that $\mathfrak{f}$ is a field of characteristic zero. We define a rank 2 valuation $\hat{\nu}$ on $\mathfrak{f}[[x,y]]$. Let $g(x,y) = y - x\sqrt{1+x}$. For $0 \neq f(x,y) \in \mathfrak{f}[[x,y]]$, we have a factorization $f = g^nh$ where $n \in \mathbb{N}$ and $g \not{|} h$. The rule

$$\hat{\nu}(f) = (n, \text{ord}(h(x, x\sqrt{1+x}))) \in (\mathbb{Z}^2)_{\text{lex}}$$

then defines a rank 2 valuation dominating $\mathfrak{f}[[x,y]]$ with value group $(\mathbb{Z}^2)_{\text{lex}}$.

We have that $(g) \cap \mathfrak{f}[x,y] = (y^2 - x^2 - x^3)$. Thus $\hat{\nu}$ restricts to a rank 2 valuation $\nu$ which dominates the maximal ideal $\mathfrak{m} = (x,y)$ of $\mathfrak{f}[x,y]$. Expand

$$x\sqrt{1+x} = \sum_{j \geq 1} a_j x^j = x + \frac{1}{2}x^2 - \frac{1}{8}x^3 + \cdots$$

as a series with all $a_j \in \mathfrak{f}$ non zero. Applying the algorithm of Theorem 4.2, we construct the infinite sequence of polynomials $P_1, P_2, \ldots$ where $P_0 = x$, $P_1 = y$ and $P_i = y - \sum_{j=1}^{i-1} a_j x^j$ for $i \geq 2$. We have that $\nu(P_i) = (0,i)$ for $i \geq 0$. However, $\nu(y^2 - x^2 - x^3) = (1,1)$.

Thus the set $\{\nu(x), \nu(P_1), \nu(P_2), \ldots\}$ does not generate the semigroup $S^R(\nu)$.

\[ \square \]

Lemma 4.9. Suppose that $\nu$ is a valuation dominating $R$. Let

$$P_0 = x, P_1 = y, P_2, \ldots$$

be the sequence of elements of $R$ constructed by Theorem 4.2. Set $\beta_i = \nu(P_i)$ for $i \geq 0$.

Suppose that $P_0^{m_0} P_1^{m_1} \cdots P_r^{m_r}$ is a monomial in $P_0, \ldots, P_r$ and $m_i \geq n_i$ for some $i \geq 1$.

Let $\rho = \nu(P_0^{m_0} P_1^{m_1} \cdots P_r^{m_r})$. Then with the notation of (12),

$$P_0^{m_0} \cdots P_r^{m_r} = - \sum_{i=0}^{r} \lambda_i \sum_{s,t} \nu(P_{0+s+t}^{m_{0+s+t}}) \cdots P_{i-1}^{m_{i-1}} P_i^{m_i-n_i+t \lambda_i} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r}\nu(P_{i-1}^{m_{i-1}} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r})\nu(P_{i-1}^{m_{i-1}} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r}) \cdots P_r^{m_r}.$$  

All terms in the first sum of (20) have value $\rho$ and $\nu(P_0^{m_0} \cdots P_{i-1}^{m_{i-1}} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r}) > \rho$.

Suppose that $W$ is a Laurent monomial in $P_0, \ldots, P_r$ such that $\nu(W) = \rho$. Then

$$\left[\frac{P_0^{m_0} P_1^{m_1} \cdots P_r^{m_r}}{W}\right] = - \sum_{i=0}^{r} \lambda_i \sum_{s,t} \nu(P_{0+s+t}^{m_{0+s+t}}) \cdots P_{i-1}^{m_{i-1}} P_i^{m_i-n_i+t \lambda_i} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r}.$$

and

$$m_0 + j_0(s,t) + \cdots + (m_i-1 + j_{i-1}(s,t)) + (m_i - n_i + t \lambda_i) + m_{i+1} + \cdots + m_r
$$

for all terms in the first sum of (20).

Proof. We have

$$P_0^{m_0} \cdots P_r^{m_r} = P_0^{m_0} P_1^{m_1} P_{i-1}^{m_{i-1}} P_{i+1}^{m_{i+1}} \cdots P_r^{m_r}.$$
where \( m_i - n_i \geq 0 \). Substituting (12) for \( P_i^n \), we obtain equation (20). We compute, from the first term of (20),

\[
- \sum_{t=1}^{d_i-1} \sum_{s=1}^{\lambda_t} \alpha_{s,t} \left[ \frac{P_i^{r_0 + j_0(s,t)} \cdots P_i^{m_r}}{W} \right] = - \left[ \frac{P_i^{m_0} \cdots P_i^{m_{i-n_i}} \cdots P_i^{m_r}}{W} \right] \left( \sum_{t=0}^{d_i-1} \sum_{s=1}^{\lambda_t} \alpha_{s,t} \left[ \frac{P_i^{j_0(s,t)} \cdots P_i^{j_i(s,t)+\bar{\pi}_i(t)} \cdots P_i^{m_r}}{U_1^{n_i-1}} \right] \left[ \frac{P_i^{\bar{\pi}_r}}{U_r} \right] \right)
\]

\[
= - \left[ \frac{P_i^{m_0} \cdots P_i^{m_{i-n_i}} \cdots P_i^{m_r}}{W} \right] \sum_{t=0}^{d_i-1} b_i(t) \alpha_i^t
\]

\[
= \sum_{t=0}^{d_i-1} b_i(t) \alpha_i^t \left[ \frac{P_i^{m_0} \cdots P_i^{m_{i-n_i}} \cdots P_i^{m_r}}{W} \right]
\]

giving (21). For all \( s, t \) (with \( 0 \leq t \leq d_i - 1 \),

\[
n_i \beta_i = j_0(s,t) \beta_0 + j_1(s,t) \beta_1 + \cdots + j_{i-1}(s,t) \beta_{i-1} + \bar{\pi}_i(t) \beta_i < (j_0(s,t) + j_1(s,t) + \cdots + j_{i-1}(s,t) + \bar{\pi}_i(t)) \beta_i
\]

so

\[
n_i < j_0(s,t) + j_1(s,t) + \cdots + j_{i-1}(s,t) + \bar{\pi}_i(t).
\]

(22) follows. \( \square \)

**Theorem 4.10.** Suppose that \( \nu \) is a valuation dominating \( R \). Let

\[
P_0 = x, P_1 = y, P_2, \ldots
\]

be the sequence of elements of \( R \) constructed by Theorem 4.2. Set \( \beta_i = \nu(P_i) \) for \( i \geq 0 \). Suppose that \( f \in R \) and there exists \( n \in \mathbb{Z}_+ \) such that \( \nu(f) < n \nu(\mathfrak{m}_R) \). Then there exists an expansion

\[
f = \sum_{I} a_I P_0^{i_0} P_1^{i_1} \cdots P_r^{i_r} \sum_{J} \varphi_J P_0^{j_0} \cdots P_r^{j_r} + h
\]

where \( r \in \mathbb{N}, a_I \in CS, i, j \in \mathbb{N}^{r+1}, \nu(P_0^{i_0} P_1^{i_1} \cdots P_r^{i_r}) = \nu(f) \) for all \( I \) in the first sum, \( 0 \leq i_k < n_k \) for \( 1 \leq k \leq r \), \( \nu(P_0^{j_0} \cdots P_r^{j_r}) > \nu(f) \) for all terms in the second sum, \( \varphi_J \in R \) and \( h \in \mathfrak{m}_R^n \).

The first sum is uniquely determined by these conditions.

**Proof.** We first prove existence. We have an expansion

\[
f = \sum_{I} a_{i_0,i_1} x^{i_0} y^{i_1} + h_0
\]

with \( a_{i_0,i_1} \in CS \) and \( h_0 \in \mathfrak{m}_R^n \). More generally, suppose that we have an expansion

(23)

\[
f = \sum a_I P_0^{i_0} P_1^{i_1} \cdots P_r^{i_r} + h
\]

for some \( r \in \mathbb{Z}_+, I = (i_0, \ldots, i_r) \in \mathbb{N}^{r+1}, a_I \in CS \) and \( h \in \mathfrak{m}_R^n \). Let

\[
\rho = \min \{ \nu(P_0^{i_0} P_1^{i_1} \cdots P_r^{i_r}) \mid a_I \neq 0 \}.
\]
Proof. Theorem 4.10 implies that the set 
\[
\text{gr}_\nu(R) \quad \text{as a } \mathfrak{g}\text{-algebra.}
\]

We can rewrite (23) as
\[
(24) \quad f = \sum_J a_J P_0^{j_0} P_1^{j_1} \cdots P_r^{j_r} + \sum_J a_J' P_0^{j_0'} P_1^{j_1'} \cdots P_r^{j_r'} + h
\]

where the terms in the first sum have minimal value \(\nu(P_0^{j_0} P_1^{j_1} \cdots P_r^{j_r}) = \rho\) and the nonzero terms in the second sum have value \(\nu(P_0^{j_0'} P_1^{j_1'} \cdots P_r^{j_r'}) > \rho\).

If we have that the first sum is nonzero and \(0 \leq j_k < n_k\) for \(1 \leq k \leq r\) for all terms in the first sum of (24) then \(\rho = \nu(f)\) and we have achieved the conclusions of the theorem. So suppose that one of these conditions fails.

First suppose that \(\sum_J a_J P_0^{j_0} \cdots P_r^{j_r} \neq 0\) and for some \(J, j_0 \geq n_i\) for some \(i \geq 1\). Let
\[
a = \min \{j_0 + \cdots + j_r \mid j_i \geq n_i \text{ for some } i \geq 1\}
\]

and let \(b\) be the numbers of terms in \(\sum_J a_J P_0^{j_0} \cdots P_r^{j_r}\) such that \(j_i \geq n_i\) for some \(i \geq 1\) and \(j_0 + \cdots + j_r = a\). Let \(\sigma = (a, b) \in (\mathbb{Z}^2)_{\text{lex}}\). Let \(J_0 = (\overline{j_0}, \ldots, \overline{j_r})\) be such that \(a_{J_0} \neq 0\) and \(\overline{j_0} + \cdots + \overline{j_r} = a\). Write
\[
P_0^{\overline{j_0}} \cdots P_r^{\overline{j_r}} = P_0^{j_0} \cdots P_r^{j_r} = P_i^{\overline{\sigma}}
\]

and substitute (12) for \(P_i^{\overline{\sigma}}\), to obtain an expression of the form (20) of Lemma 4.9.

Substitute this expression (20) for \(P_0^{\overline{j_0}} \cdots P_r^{\overline{j_r}}\) in (24) and apply Remark 4.1, to obtain an expression of the form (24) such that either the first sum is zero or the first sum is nonzero and all terms in the first sum satisfy \(j_i < n_i\) for \(1 \leq i \leq r\) so that \(\nu(f) = \rho\) and we have achieved the conclusions of the theorem, or the first sum has a nonzero term which satisfies \(j_i \geq n_i\) for some \(i \geq 1\). By (22), we have an increase in \(\sigma\) if this last case holds.

Since there are only finitely many monomials \(M\) in \(P_0, \ldots, P_r\) which have the value \(\rho\), after a finite number of iterations of this step we must either find an expression (24) where the first sum is zero, or attain an expression (24) satisfying the conclusions of the theorem.

If we obtain an expression (24) where the first sum is zero, then we have an expression (23) with an increase in \(\rho\) (and possibly an increase in \(r\)), and we repeat the last step, either attaining the conclusions of the theorem or obtaining another increase in \(\rho\). Since there are only a finite number of monomials in the \(\{P_i\}\) which have value \(\leq \nu(f)\), we must achieve the conclusions of the theorem in a finite number of steps.

Uniqueness of the first sum follows from 2) of Theorem 4.2.

Theorem 4.11. Suppose that \(\nu\) is a rank 1 valuation which dominates \(R\) and \(\nu(x) = \nu(m_R)\). Then

a) The set \(\{\text{in}_\nu(x)\} \cup \{\text{in}_\nu(P_i) \mid n_i > 1\}\) minimally generates \(\text{gr}_\nu(R)\) as a \(\mathfrak{g}\)\text{-algebra.}

b) The set
\[
\{\nu(x)\} \cup \{\nu(P_i) \mid \pi_i > 1\}
\]

minimally generates the semigroup \(S^R(\nu)\).

c) \(V_\nu / m_\nu = \mathfrak{g}(\alpha_i \mid d_i > 1)\) where \(\alpha_i\) is defined by 4) (and possibly (11)) of Theorem 4.2.

Proof. Theorem 4.10 implies that the set \(\{\text{in}_\nu(x)\} \cup \{\text{in}_\nu(P_i) \mid n_i > 1\}\) generates \(\text{gr}_\nu(R)\) as a \(\mathfrak{g}\)\text{-algebra. We will show that the set generates \(\text{gr}_\nu(R)\) minimally. Suppose that it doesn’t. Then there exists an \(i \in \mathbb{N}\) such that \(n_i > 1\) if \(i > 0\) and a sum
\[
H = \sum_J c_J P_0^{j_0} \cdots P_r^{j_r}
\]
for some $r \in \mathbb{N}$ with $c_J \in CS$ such that the monomials $P_0^{j_0} \cdots P_r^{j_r}$ have value $\nu(P_0^{j_0} \cdots P_r^{j_r}) = \nu(P_i)$ with $j_i = 0$ and $j_k = 0$ if $n_k = 1$ for $1 \leq k \leq r$ for all $J$, and

$$\nu\left(\sum_J c_J P_0^{j_0} \cdots P_r^{j_r} - P_i\right) > \nu(P_i).$$

We thus have by 1) of Theorem 4.2 and since $\nu(P_0) = \nu(m_R)$, that $r \leq i - 1$. Thus $i \geq 1$. By Theorem 4.10 applied to (26) we have an expression

$$(26) \quad P_i = \sum_K d_K P_0^{k_0} \cdots P_s^{k_s} + f$$

where $s \in \mathbb{N}$, $d_K \in CS$, $0 \leq k_l < m_l$ for $1 \leq l$, some $d_K \neq 0$, $f \in R$ is such that $\nu(f) > \nu(P_i)$, and

$$\nu(P_0^{k_0} \cdots P_s^{k_s}) = \nu(H) = \nu(P_i)$$

for all monomials in the first sum of (26). Since the minimal value terms of the expression of $H$ in (25) only involve $P_0, \ldots, P_{i-1}$ and all these monomials have the same value $\rho = \nu(H)$, the algorithm of Theorem 4.10 ends with $s \leq i - 1$ in (26). But then we obtain from (26) a contradiction to 2) of Theorem 4.2.

Now a) and 3) of Theorem 4.2 imply statement b).

Suppose that $\lambda \in L = V_\nu/m_\nu$. Then $\lambda = \left[\frac{f}{f'}\right]$ for some $f, f' \in R$ with $\nu(f) = \nu(f')$. By Theorem 4.10, there exist $r \in \mathbb{Z}_+$ and expressions

$$f = \sum_{i=1}^m a_i P_0^{\sigma_0(i)} P_1^{\sigma_1(i)} \cdots P_r^{\sigma_r(i)} + h,$$

$$f' = \sum_{j=1}^n b_j P_0^{\tau_0(j)} P_1^{\tau_1(j)} \cdots P_r^{\tau_r(j)} + h'$$

with $a_i, b_j \in CS$, $0 \leq \sigma_k(i) < n_k$ for $1 \leq k$ and $0 \leq \tau_k(j) < n_k$ for $1 \leq k$, the $P_0^{\sigma_0(i)} P_1^{\sigma_1(i)} \cdots P_r^{\sigma_r(i)}$, $P_0^{\tau_0(j)} P_1^{\tau_1(j)} \cdots P_r^{\tau_r(j)}$ all have the common value

$$\rho := \nu(f) = \nu(f'),$$

$h, h' \in R$ and $\nu(h) > \rho$, $\nu(h') > \rho$.

$$\lambda = \left(\prod_i \bar{a}_i P_0^{\sigma_0(i)-\sigma_0(1)} \cdots P_r^{\sigma_r(i)-\sigma_r(1)}\right) \left(\prod_j \bar{b}_j P_0^{\tau_0(j)-\tau_0(1)} \cdots P_r^{\tau_r(j)-\tau_r(1)}\right)^{-1} \in \mathfrak{p}(\alpha_1, \ldots, \alpha_r)$$

by $B(r)$ of the proof of Theorem 4.2. \qed

If $V_\nu/m_\nu$ is transcendental over $\mathfrak{p}$ then $\Gamma_\nu \cong \mathbb{Z}$ by Abhyankar’s inequality. Zariski called such a valuation a “prime divisor of the second kind”. By c) of Theorem 4.11, $V_\nu/m_\nu = \mathfrak{p}(\alpha_i \mid d_i > 1)$. There thus exists an index $i$ such that $\mathfrak{p}(\alpha_1, \ldots, \alpha_{i-1})$ is algebraic over $\mathfrak{p}$ and $\alpha_i$ is transcendental over $\mathfrak{p}(\alpha_1, \ldots, \alpha_{i-1})$. Thus $\Omega = i$ in the algorithm of Theorem 4.2, since $\alpha_i$ does not have a minimal polynomial over $\mathfrak{p}(\alpha_1, \ldots, \alpha_{i-1})$.

**Theorem 4.12.** Suppose that $\nu$ is a rank 2 valuation which dominates $R$ and $\nu(x) = \nu(m_R)$. Let $I_\nu$ be the height one prime ideal in $V_\nu$. Then one of the following three cases hold:

1. $I_\nu \cap R = m_R$. Then
a) the finite set
\[ \{i_{\nu}(x) \cup \{i_{\nu}(P_i) \mid n_i > 1\} \]
minimally generates \( \text{gr}_{\nu}(R) \) as an \( \mathfrak{f} \)-algebra and

b) the finite set
\[ \{\nu(x) \cup \{\nu(P_i) \mid n_i > 1\} \]
minimally generates the semigroup \( S^R(\nu) \).

c) \( V_\nu / m_\nu = \mathfrak{f}(\alpha_i \mid d_i > 1) \).

2. \( I_\nu \cap R = (P_\Omega) \) is a height one prime ideal in \( R \) and

a) the finite set
\[ \{i_{\nu}(x) \cup \{i_{\nu}(P_i) \mid n_i > 1\} \]
minimally generates \( \text{gr}_{\nu}(R) \) as a \( \mathfrak{f} \)-algebra, and

b) The finite set
\[ \{\nu(x) \cup \{\nu(P_i) \mid n_i > 1\} \]
minimally generates the semigroup \( S^R(\nu) \).

c) \( V_\nu / m_\nu = \mathfrak{f}(\alpha_i \mid d_i > 1) \).

3. \( I_\nu \cap R = (g) \) is a height one prime ideal in \( R \) and

a) the finite set
\[ \{i_{\nu}(x) \cup \{i_{\nu}(P_i) \mid n_i > 1\} \cup \{i_{\nu}(g)\} \]
minimally generates \( \text{gr}_{\nu}(R) \) as a \( \mathfrak{f} \)-algebra, and

b) The finite set
\[ \{\nu(x) \cup \{\nu(P_i) \mid n_i > 1\} \cup \{\nu(g)\} \]
minimally generates the semigroup \( S^R(\nu) \).

c) \( V_\nu / m_\nu = \mathfrak{f}(\alpha_i \mid d_i > 1) \).

Proof. Since \( \nu \) has rank 2, the set \( \{P_i \mid n_i > 1\} \) is a finite set since otherwise either \( \Gamma_\nu \) is not a finitely generated group or \( V_\nu / m_\nu \) is not a finitely generated field extension of \( \mathfrak{f} \), by 3) and 4) of Theorem 4.2, which is a contradiction to Abhyankar’s inequality.

The case when \( I_\nu \cap R = m_R \) now follows from Theorem 4.10 and 2), 3) of Theorem 4.2; the proof of c) is the same as the proof of c) of Theorem 4.11.

Suppose that \( I_\nu \cap R = (g) \) is a height one prime ideal in \( R \). Suppose that \( f \in R \). Then there exists \( n \in \mathbb{N} \) and \( u \in R \) such that \( f = g^nu \) with \( u \not\in (g) \). Thus
\[ \nu(f) = n\nu(g) + \nu(u) \tag{27} \]
Assume that \( \Omega < \infty \). Then \( \nu(P_1) \not\in \mathbb{Q}\nu(m_R) \) by Remark 4.5. Then \( P_\Omega = gf \) for some \( f \in R \). We will show that \( f \) is a unit in \( R \). Suppose not. Then \( \nu(g) < \nu(P_\Omega) \).

Let \( t = \text{ord}(g) \). There exists \( c \in \mathbb{Z}_+ \) such that if \( j_0, j_1, \ldots, j_{\Omega-1} \in \mathbb{N} \) are such that \( \nu(P_0^{j_0} P_1^{j_1} \cdots P_{\Omega-1}^{j_{\Omega-1}}) \geq \nu(m_R) \) then \( \text{ord}(P_0^{j_0} P_1^{j_1} \cdots P_{\Omega-1}^{j_{\Omega-1}}) > t \). We may assume that \( c \) is larger than \( t \). Write
\[ g = \sum_{i,j=1}^c a_{ij} x^i y^j + \Lambda \]
with \( \Lambda \in m_R' \) and \( a_{ij} \in CS \). \( g \) has an expression of the form
\[ g = \sum_J a_J P_0^{j_0} \cdots P_{\Omega}^{j_\Omega} + \sum_{J'} a_{J'} P_0^{j'_0} \cdots P_{\Omega}^{j'_{\Omega}} + h \tag{28} \]
with \( a_J, a_{J'} \in CS \) and \( h \in m_R' \), and the terms in the first sum all have a common value \( \rho \), which is smaller than the values of the terms in the second sum.
Now we draw some conclusions which must hold for an expression of the form (28). We must have that

\[(29) \quad \rho < cv(m_R),\]

since otherwise, by our choice of \( c \) and our assumption that \( \text{ord}(f) > 0 \), so that \( \text{ord}(P_\Omega) > \text{ord}(g) = t \), we would have that the right hand side of (28) has order larger than \( t \), which is impossible. In particular, we have

\[(30) \quad j_\Omega = 0\]

in all terms in the first sum.

We also must have that

\[(31) \quad j_i \geq n_i \text{ for some } i \text{ with } 1 \leq i < \Omega \text{ for all terms in the first sum.}\]

This follows since otherwise we would have \( \nu(g) = \rho < cv(m_R) \), which is impossible.

We apply the algorithm of Theorem 4.9 to (28), and apply a substitution of the form (20) to a monomial in the first sum. As shown in the proof of Theorem 4.9, we must obtain an expression (28) with an increase in \( \rho \) after a finite number of iterations, since (31) must continue to hold. Since there are only finitely many values in the semigroup \( S^R(\nu) \) between 0 and \( cv(m_R) \), after finitely many iterations of the algorithm we obtain an expression (28) with \( \rho \geq cv(m_R) \), which is a contradiction to (29). This contradiction shows that \( P_\Omega \) is a unit times \( g \), so we may replace \( g \) with \( P_\Omega \), and we are in Case 2 of the conclusions of the corollary.

If \( \Omega = \infty \) then \( \nu(P_i) \in \mathbb{Q} \nu(m_R) \) for all \( i \) (by Remark 4.5) and we are in Case 3 of the conclusions of the corollary.

The conclusions of a) and b) of Cases 2 and 3 of the corollary now follow from applying Theorem 4.10 and 2), 3) of Theorem 4.2 to \( u \) in (27).

5. Valuation semigroups and residue field extension on a two dimensional regular local ring

In this section, we prove Theorem 1.1 which is stated in the introduction. Theorem 1.1 gives necessary and sufficient conditions for a semigroup and field extension to be the valuation semigroup and residue field of a valuation dominating a regular local ring of dimension two.

Suppose that \( \nu \) is a valuation dominating \( R \). Let \( S = S^r(\nu) \) and \( L = V_\nu/m_\nu \). Let \( x, y \) be regular parameters in \( R \) such that \( \nu(x) = \nu(m_R) \). Set \( P_0 = x \) and \( P_1 = y \). Let \( \{P_i\} \) be the sequence of elements of \( R \) defined by the algorithm of Theorem 4.2. We have by Remark 4.6 and its proof, that if

\[ \Omega = \infty \text{ and } n_i = 1 \text{ for } i \gg 0, \]

then \( I_R \neq (0) \) (where \( I_R \) is the prime ideal in \( \hat{R} \) of Cauchy sequences in \( R \) satisfying (4)). Thus \( \nu \) has rank 2 since \( R \) is complete, and \( \nu \) must satisfy Case 3 of Theorem 4.12.

Set \( \sigma(0) = 0 \) and inductively define

\[ \sigma(i) = \min\{j \mid j > \sigma(i - 1) \text{ and } n_j > 1\}. \]
This defines an index set $I$ of finite or infinite cardinality $\Lambda = |I| - 1 \geq 1$. Suppose that either $\nu$ has rank 1 or $\nu$ has rank 2 and one of the first two cases of Theorem 4.12 hold for the $P_i$. Let

$$\beta_i = \nu(P_{\sigma(i)}) \in S^R(\nu)$$

for $i \in I$ and

$$\gamma_i = \left[ \frac{P_{\sigma(i)}^{\sigma(i)}}{U_{\sigma(i)}} \right] \in V_{\nu}/m_{\nu}$$

if $i > 0$ and $\sigma(i) < \Omega$ or $\sigma(i) = \Omega$ and $\pi\Omega < \infty$. Set $\gamma_{\Lambda} = 1$ if $\sigma(\Lambda) = \Omega$ and $\pi\Omega = \infty$.

By Theorem 4.2 and Theorem 4.11 or 4.12, $\{\beta_i\}$ and $\{\gamma_i\}$ satisfy the conditions 1) and 2) of Theorem 1.1.

Suppose that $\nu$ has rank 2 and the third case of Theorem 4.12 holds for the $P_i$. Then $\Lambda < \infty$. Let $I_\nu \cap R = (g)$ (where $I_\nu$ is the height one prime ideal of $V_{\nu}$). Let $\Lambda = \Lambda + 1$.

Define $\beta_i = \nu(P_{\sigma(i)})$ for $i < \Lambda$ and $\beta_{\Lambda} = \nu(g)$. Define

$$\gamma_i = \left[ \frac{P_{\sigma(i)}^{\sigma(i)}}{U_{\sigma(i)}} \right] \in V_{\nu}/m_{\nu}$$

for $0 < i < \Lambda$ and define $\gamma_{\Lambda} = 1$. By Theorem 4.2 and Case 3 of Theorem 4.12, $\{\beta_i\}$ and $\{\gamma_i\}$ satisfy conditions 1) and 2) of Theorem 1.1.

Suppose that $S$ and $L$ and the given sets $\{\beta_i\}$ and $\{\alpha_i\}$ satisfy conditions 1) and 2) of the theorem. We will construct a valuation $\nu$ which dominates $R$ with $S^R(\nu) = S$ and $V_{\nu}/m_{\nu} = L$.

Define $f_i(u) = u^{d_i} + b_{i,d_i-1}u^{d_i-1} + \ldots + b_{i,0}$ be the minimal polynomial of $\alpha_i$ over $\mathbb{K}(\alpha_1, \ldots, \alpha_{i-1})$, and let $n_i = \pi_i d_i$.

We will inductively define $P_i \in R$, a function $\nu$ on Laurent monomials in $P_0, \ldots, P_i$ such that

$$\nu(P_0^{a_0} P_1^{a_1} \cdots P_i^{a_i}) = a_0 \beta_0 + a_1 \beta_1 + \cdots + a_i \beta_i$$

for $a_0, \ldots, a_i \in \mathbb{Z}$ and monomials $U_i$ in $P_0, \ldots, P_{i-1}$, such that

$$\nu(U_i) = \pi_i \beta_i,$$

a function res on the Laurent monomials $P_0^{a_0} P_1^{a_1} \cdots P_i^{a_i}$ which satisfy $\nu(P_0^{a_0} P_1^{a_1} \cdots P_i^{a_i}) = 0$, such that

$$\text{res} \left( \frac{P_{\pi j}}{U_j} \right) = \alpha_j$$

for $1 \leq j \leq i$.

Let $x, y$ be regular parameters in $R$. Define $P_0 = x$, $P_1 = y$, $\beta_0 = \nu(P_0)$, and $\beta_1 = \nu(P_1)$. We inductively construct the $P_i$ by the procedure of the algorithm of Theorem 4.2. We must modify the inductive statement $A(i)$ of the proof of Theorem 4.2 as follows:
There exists $U_i = P_0^{w_0(i)}P_1^{w_1(i)} \cdots P_{i-1}^{w_{i-1}(i)}$ for some $w_j(i) \in \mathbb{N}$ and $0 \leq w_j(i) < n_j$ for $1 \leq j \leq i-1$

Then

$$\bar{A}(i) \text{ such that } \nu(U_i) = \nu(P_i).$$

There exist $a_{s,t} \in CS$ and $j_0(s,t), j_1(s,t), \ldots, j_{i-1}(s,t) \in \mathbb{N}$ with $0 \leq j_k(s,t) < n_k$

for $k \geq 1$ and $0 \leq t < d_i$ such that

$$\nu(P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)}) = \nu(U_i)$$

for all $s,t$ and

$$P_{i+1} := P_i^{d_i} + \sum_{t=0}^{d_i-1} \left( \sum_{s=1}^{\lambda_i} a_{s,t} P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)} \right) P_i^{d_i}$$

satisfies

$$b_{i,t} = \sum_{s=1}^{\lambda_i} a_{s,t} \text{res} \left( \frac{P_0^{j_0(s,t)}P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)}}{U_i^{j_0(s,t)} \cdots U_i^{j_{i-1}(s,t)}} \right)$$

for $0 \leq t < d_i - 1$.

We inductively verify $\bar{A}(i)$ for $1 \leq i < \lambda$ and the statements $B(i), C(i)$ and $D(i)$ (with the residues $[M]$ replaced with $\text{res}(M)$). We observe from $B(i)$ that the function $\text{res}$ is determined by (32). The inequality in 2) of the assumptions of the theorem is necessary to allow us to apply Lemma 2.1.

We now show that if $\lambda = \infty$, then given $\sigma \in \mathbb{Z}_+$, there exists $\tau \in \mathbb{Z}_+$ such that

$$\text{ord}(P_i) > \sigma \text{ if } i > \tau.$$ (34)

We establish (34) by induction on $\sigma$. Suppose that $\text{ord}(P_i) > \sigma$ if $i > \tau$. There exists $\lambda$ such that $\beta_0 < \beta_i$ if $i \geq \lambda$. Let $\tau' = \max\{\sigma + \tau + 1, \tau + 1, \lambda\}$. We will show that $\text{ord}(P_i) > \sigma + 1$ if $i > \tau'$. From (33), we must show that if $i > \tau'$ and $(a_0, \ldots, a_{i-1}) \in \mathbb{N}^i$ are such that

$$a_0\beta_0 + a_1\beta_1 + \cdots + a_{i-1}\beta_{i-1} = n_{i-1}\beta_{i-1}$$

then

$$a_0\text{ord}(P_0) + a_1\text{ord}(P_1) + \cdots + a_{i-1}\text{ord}(P_{i-1}) > \sigma + 1.$$ (35)

If $a_{r+1} + \cdots + a_{i-1} \geq 2$ then (35) follows from induction. If $a_{r+1} + \cdots + a_{i-1} = 1$ then some $a_j \neq 0$ with $0 \leq j \leq \tau$ since $n_{i-1} > 1$, so (35) follows from induction. If $a_j = 0$ for $j \geq \tau + 1$ then

$$n_{i-1}\beta_{i-1} = a_0\beta_0 + \cdots + a_{r}\beta_r < (a_0 + \cdots + a_r)\beta_r.$$ (a) + \cdots + a_r > \frac{n_{i-1}\beta_{i-1}}{\beta_r} \geq 2^{i-\tau} > \sigma + 1.$$(b) Thus (35) holds in this case.

We first suppose that for all $P_i$, there exists $m_i \in \mathbb{Z}_+$ such that $m_i\nu(P_i) > \min\{\beta_0, \beta_1\}$.

We now establish the following:

Suppose that $f \in R$. Then there exists an expansion

$$f = \sum_I a_I P_0^{i_0} P_1^{i_1} \cdots P_r^{i_r} + \sum_J \varphi_J P_0^{j_0} \cdots P_r^{j_r} (36)$$
for some $r \in \mathbb{N}$ where $\nu(P_1^{i_1} \cdots P_r^{i_r})$ have a common value $\rho$ for all terms in the first sum, all $a_I \in C S$, $I, J \in N^{r+1}$ and some $a_I \neq 0$, $0 \leq i_k < n_k$ for $1 \leq k \leq r$ $\nu(P_0^{i_0} \cdots P_r^{i_r}) > \rho$ for all terms in the second sum, and $\varphi_j \in R$ for all terms in the second sum. The first sum $\sum_I a_IP_0^{i_0} P_1^{i_1} \cdots P_r^{i_r}$ is uniquely determined by these conditions.

The proof of (36) follows from the proofs of Lemma 4.9 and Theorem 4.10, observing that all properties of a valuation which $\nu$ is required to satisfy in these proofs hold for the function $\nu$ on Laurent monomials in the $P_i$ which we have defined above, and replacing $[M]$ in Lemma 4.9 with the function $\text{res}(M)$ for Laurent monomials $M$ with $\nu(M) = 0$.

The $n$ in the statement of Theorem 4.10 is chosen so that if $M$ is a monomial in the $P_i$ with $\text{ord}(M) = \text{ord}(f)$, then $\nu(M) < n \min\{\beta_0, \beta_1\}$ (such an $n$ exists trivially if $\Lambda < \infty$ and by (34) if $\Lambda = \infty$).

We can thus extend $\nu$ to $R$ by defining $\nu(f) = \rho$ if $f$ has an expansion (36).

Now we will show that $\nu$ is a valuation. Suppose that $f, g \in R$. We have expansions

$$f = \sum_I a_IP_0^{i_0} P_1^{i_1} \cdots P_r^{i_r} + \sum_J \varphi_J P_0^{j_0} \cdots P_r^{j_r}$$

and

$$g = \sum_K b_KP_0^{k_0} P_1^{k_1} \cdots P_r^{k_r} + \sum_L \varphi_KP_0^{l_0} \cdots P_r^{l_r}$$

of the form (36). Let $\rho = \nu(f)$ and $\rho' = \nu(g)$. The statement that $\nu(f + g) \geq \min\{\nu(f), \nu(g)\}$ follows from Remark 4.1 and the algorithm of Theorem 4.10.

Let $V$ be a monomial in $P_0, \ldots, P_r$ such that $\nu(V) = \nu(P_0^{i_0} \cdots P_r^{i_r})$ for all $I$ in the first sum of $f$ in (37) and let $W$ be a monomial in $P_0, \ldots, P_r$ such that $\nu(W) = \nu(P_0^{k_0} \cdots P_r^{k_r})$ for all $K$ in the first sum of $g$ in (38). We have that

$$\sum_I \alpha_I \text{res} \left( \frac{P_0^{i_0} \cdots P_r^{i_r}}{V} \right) \neq 0 \text{ in } L$$

and

$$\sum_K \beta_K \text{res} \left( \frac{P_0^{k_0} \cdots P_r^{k_r}}{W} \right) \neq 0 \text{ in } L$$

by $D(r)$.

We have (applying Remark 4.1) an expansion

$$fg = \sum_M d_MP_0^{m_0} P_1^{m_1} \cdots P_r^{m_r} + \sum_Q \psi_Q P_0^{q_0} \cdots P_r^{q_r}$$

with $d_M \in S$ for all $M$, $\psi_Q \in R$ for all $Q$, $\nu(P_0^{m_0} P_1^{m_1} \cdots P_r^{m_r}) = \rho + \rho'$ for all terms in the first sum, and some $d_M \neq 0$ and $\nu(P_0^{q_0} \cdots P_r^{q_r}) > \rho + \rho'$ for all terms in the second sum, which satisfies all conditions of (36) except that we only have that $m_0, m_1, \ldots, m_r \in \mathbb{N}$. We have

$$\sum_M \alpha_M \text{res} \left( \frac{P_0^{i_0} \cdots P_r^{i_r}}{V} \right) = \left( \sum_I \alpha_I \text{res} \left( \frac{P_0^{i_0} \cdots P_r^{i_r}}{V} \right) \right) \left( \sum_K \beta_K \text{res} \left( \frac{P_0^{k_0} \cdots P_r^{k_r}}{W} \right) \right) \neq 0.$$
the form (36) converges to an expression (36) where the terms in the first sum all have 
\( \nu(P_0^{i_0} \cdots P_r^{i_r}) = \rho + \rho' \) with
\[
\sum_I \pi_I \res \left( \frac{P_0^{i_0} \cdots P_r^{i_r}}{VW} \right) = \sum_M d_M \res \left( \frac{P_0^{m_0} \cdots P_r^{m_r}}{VW} \right) \neq 0.
\]
Thus \( \nu(fg) = \nu(f) + \nu(g) \). We have established that \( \nu \) is a valuation.

By Theorem 4.11 or Case 1 of Theorem 4.12, we have that \( S = S^R(\nu) \) and \( L = V_\nu / m_\nu \).

Finally, we suppose that \( \Lambda \) is finite and \( \pi_\Lambda = \infty \). Given \( g \in R \), write
\[
g = P_\Lambda^f
\]
where \( P_\Lambda \nmid f \). Choose \( n \in \mathbb{Z}_+ \) so that if \( M \) is a monomial in \( P_0, \ldots, P_{\Lambda-1} \) with \( \ord(M) = \ord(f) \) then \( \nu(M) < n \min\{\beta_0, \beta_1\} \).

The argument giving the expansion (36) now provides an expansion
\[
f = \sum_I a_I P_0^{i_0} \cdots P_\Lambda^{i_\Lambda} + \sum_J \varphi_J P_0^{j_0} \cdots P_\Lambda^{j_\Lambda} + h_1
\]
where \( \nu(P_0^{i_0} \cdots P_\Lambda^{i_\Lambda}) \) has a common value \( \rho \) for all monomials in the first sum, \( a_I \in CS \) for all \( I \), \( \nu(P_0^{j_0} \cdots P_\Lambda^{j_\Lambda}) > \rho \) for all monomials in the second sum, \( \varphi_J \in R \) for all \( J \) and \( h_1 \in m_R^f \).

If \( i_\Lambda = 0 \) for all monomials in the first sum, then we obtain an expansion of \( f \) of the form (36). Suppose that \( i_\Lambda \neq 0 \) for some monomial in the first sum. Then \( i_\Lambda \neq 0 \) for all terms in the first sum, \( j_\Lambda \neq 0 \) for all terms in the second sum, and we have an expression
\[
f = P_\Lambda t_\Lambda + h_1
\]
for some \( t_\Lambda \in R \). Repeating this argument for increasingly large values of \( n \), we either obtain an \( n \) giving an expression (36) for \( f \), or we obtain the statement that
\[
f \in \cap_{n=1}^{\infty} (P_\Lambda + m_R^n) = (P_\Lambda)
\]
which is impossible. Thus we can extend \( \nu \) to \( R \) by defining \( \nu(g) = t\beta_\Lambda + \rho \) if \( g = P_\Lambda^f \) where \( P_\Lambda \nmid f \) and \( f \) has an expansion (36).

It follows that \( \nu \) is a valuation, by an extension of the proof of the previous case. By
Case 2 of Theorem 4.12, we have that \( S = S^R(\nu) \) and \( L = V_\nu / m_\nu \).

**Corollary 5.1.** Suppose that \( R \) is a regular local ring of dimension two and \( \nu \) is a valuation dominating \( R \). Then the semigroup \( S^R(\nu) \) has a generating set \( \{\beta_i\}_{i \in I} \) and \( V_\nu / m_\nu \) is generated over \( \mathfrak{t} = R / m_R \) by a set \( \{\alpha_i\}_{i \in I_+} \) such that 1) and 2) of Theorem 1.1 hold, but the additional case that \( \pi_\Lambda < \infty \) and \( d_\Lambda < \infty \) if \( \Lambda < \infty \) may hold if \( R \) is not complete.

**Proof.** The only case we have not considered in Theorem 1.1 is the analysis in the case when \( \Omega = \infty \), \( n_i = 1 \) for \( i \gg 0 \), \( I_R \neq 0 \) and \( I_R \cap R = (0) \) (so that \( R \) is not complete). In this case \( \nu \) is discrete of rank 1, \( \Lambda < \infty \), \( \pi_\Lambda < \infty \) and \( d_\Lambda < \infty \) by Remark 4.6, giving the additional possibility stated in the Corollary.

6. **Valuation Semigroups on a Regular Local Ring of Dimension Two**

In this section we prove Theorem 1.2 which is stated in the introduction. Theorem 1.2 gives necessary and sufficient conditions for a semigroup to be the valuation semigroup of a valuation dominating a regular local ring of dimension two.

If \( S = S^R(\nu) \) for some valuation \( \nu \) dominating \( R \), then 1) and 2) of Theorem 1.2 hold by Corollary 5.1. Observe that the construction in the proof of Theorem 1.1 of a valuation
ν with a prescribed semigroup S and residue field L satisfying the conditions 1) and 2) of Theorem 1.1 is valid for any regular local ring R of dimension 2 (with residue field ℱ).

Taking L = ℱ (or L = ℱ(t) where t is an indeterminate), we may thus construct a valuation ν dominating R with semigroup S^R(ν) = S whenever S satisfies the conditions 1) and 2) of Theorem 1.2.

**Definition 6.1.** Suppose that S is a semigroup such that the group G generated by S is isomorphic to ℤ. S is symmetric if there exists m ∈ G such that s ∈ S if and only if m − s ∉ S for all s ∈ G.

We deduce from Theorem 1.2 a generalization of a result of Noh [40].

**Corollary 6.2.** Suppose that R is a regular local ring of dimension two and ν is a valuation dominating R such that ν is discrete of rank 1. Then S^R(ν) is symmetric.

**Proof.** By Theorem 1.2, and since ν is discrete of rank 1, there exists a finite set
\[ \beta_0 < \beta_1 < \cdots < \beta_\Lambda \]
such that S^ν(R) = S(β_0, β_1, ..., β_\Lambda) and β_{i+1} > \pi_i β_i for 1 ≤ i < \Lambda, where π_i = \([G(β_0, ..., β_i) : G(β_0, ..., β_{i−1})]\). We identify the value group Γ_ν with ℤ. Then we calculate that
\[ \text{lcm}(\text{gcd}(β_0, ..., β_{i−1}), β_i) = π_i β_i \]
for 1 ≤ i ≤ \Lambda. We have that π_i β_i ≥ β_i > π_{i−1} β_{i−1} for 2 ≤ i ≤ \Lambda. By Lemma 2.1, we have that π_i β_i ∈ S(β_0, ..., β_{i−1}) for 2 ≤ i ≤ \Lambda. Since β_0 and β_1 are both positive, we have that π_1 β_1 ∈ S(β_0). Thus the criteria of Proposition 2.1 [29] is satisfied, so that S^R(ν) is symmetric. □

**Example 6.3.** There exists a semigroup S which satisfies the sufficient conditions 1) and 2) of Theorem 1.2, such that (R, m_R) is a 2-dimensional regular local ring dominated by a valuation ν such that S^R(ν) = S, then R/m_R = V_ν/m_ν; that is, there can be no residue field extension.

**Proof.** Define β_i ∈ ℤ by
\[ \beta_0 = 1, \beta_1 = \frac{3}{2}, \text{ and } \beta_i = 2\beta_{i−1} + \frac{1}{2}i \text{ for } i ≥ 2. \]

Let S = S(β_0, β_1, ...) be the semigroup generated by β_0, β_1, .... Observe that π_i = 2, ∀i ≥ 1, β_0 < β_1 < ... is the minimal sequence of generators of S and S satisfies conditions 1) and 2) of Theorem 1.2. The group Γ = G(β_0, β_1, ...) generated by S is
\[ Γ = \frac{1}{2}πZ = \bigcup_{i=0}^{\infty} \frac{1}{2^i}Z. \]

Now suppose that (R, m_R) is a regular local ring of dimension 2, with residue field ℱ and ν is a valuation of the quotient field of R which dominates R such that S^R(ν) = S. Since Γ_ν = \frac{1}{2}π is not discrete, we have by Proposition 3.4 that ν extends uniquely to a valuation ν of the quotient field of R which dominates R and S^R(ν) = S.

We will now show that V_ν/m_ν = V_ν/m_ν. Suppose that f ∈ R. Since ν has rank 1, there exists a positive integer n such that ν(f) < ν(m). There exists f' ∈ R such that f'' = f - f' ∈ m_R^nR. Thus ν(f) = ν(f'). Suppose that h ∈ V_ν/m_ν. Then h = \left[ \frac{f}{g} \right] where f, g ∈ R and ν(f) = ν(g). Write f = f' + f'' and g = g' + g'' where f', g' ∈ R and f'', g'' ∈ R satisfy ν(f'') > ν(f) and ν(g'') > ν(g). Then \left[ \frac{f}{g} \right] = \left[ \frac{f'}{g'} \right] ∈ V_ν/m_ν.
We also have \( t = R/m_R = \hat{R}/m_{\hat{R}} \). By Theorem 1.1, there exists \( \alpha_i \in V_\nu/M_\nu \) for \( i \geq 1 \) such that \( V_\nu/M_\nu = \{ t(\alpha_1, \alpha_2, \ldots) \} \) and if \( d_i = \| t(\alpha_1, \ldots, \alpha_i) : t(\alpha_1, \ldots, \alpha_{i-1}) \| \) then
\[
\beta_{i+1} \geq \pi_i d_i \beta_i, \forall i \geq 1,
\]
so that
\[
[V_\nu/m_\nu : t] = \prod_{i=1}^{\infty} \| t(\alpha_1, \ldots, \alpha_i) : t(\alpha_1, \ldots, \alpha_{i-1}) \| = \prod_{i=1}^{\infty} d_i.
\]
On the other hand, since \( \beta_i \geq \beta_1 = \frac{3}{2}, \forall i \geq 1 \), we have
\[
\beta_{i+1} = 2 \beta_i + \frac{1}{2^{i+1}} \leq 4 \beta_i + \frac{1}{2^{i+1}} - 3 < 4 \beta_i.
\]
From (43), (44) and (45) we have \( d_i = 1, \forall i \geq 1 \) so that \([V_\nu/m_\nu : t] = 1\).

\[\Box\]

7. Birational extensions

Suppose that \( R \) is a regular local ring of dimension two which is dominated by a valuation \( \nu \). Let \( t = R/m_R \). The quadratic transform \( R_1 \) of \( R \) along \( \nu \) is defined as follows. Let \( u, v \) be a system of regular parameters in \( R \), where we may assume that \( \nu(u) \leq \nu(v) \). Then \( R[\frac{u}{v}] \subset V_\nu \). Let
\[
R_1 = R[\frac{u}{v}] / \hat{R}[\frac{u}{v}] \cap m_\nu.
\]
\( R_1 \) is a two dimensional regular local ring which is dominated by \( \nu \). Let
\[
R \rightarrow T_1 \rightarrow T_2 \rightarrow \cdots
\]
be the sequence of quadratic transforms along \( \nu \), so that \( V_\nu = \cup T_i ([1]) \), and \( L = V_\nu/m_\nu = \cup T_i/m_{T_i} \). Suppose that \( x, y \) are regular parameters in \( R \).

**Theorem 7.1.** Let \( P_0 = x, P_1 = y \) and \( \{ P_i \} \) be the sequence of elements of \( R \) constructed in Theorem 4.2. Suppose that \( \Omega \geq 2 \). Then there exists some smallest value \( i \) in the sequence (46) such that the divisor of \( xy \) in \( \text{Spec}(T_i) \) has only one component. Let \( R_1 = T_i \). Then \( R_1/m_{R_1} \cong t(\alpha_1) \), and there exists \( x_1 \in R_1 \) and \( w \in \mathbb{Z}_+ \) such that \( x_1 = 0 \) is a local equation of the exceptional divisor of \( \text{Spec}(R_1) \rightarrow \text{Spec}(R) \), and \( Q_0 = x_1 \), \( Q_1 = \frac{P_i}{x_1} \) are regular parameters in \( R_1 \). We have that
\[
Q_i = \frac{P_i}{Q_0^{m_i - n_i}}
\]
for \( 1 \leq i < \max\{\Omega, \infty\} \) satisfy the conclusions of Theorem 4.2 (as interpreted by Remark 4.3) for the ring \( R_1 \).

**Proof.** We use the notation of Theorem 4.2 and its proof for \( R \) and the \( \{ P_i \} \). Recall that \( U_1 = U^{w_0(1)} \). Let \( w = w_0(1) \). Since \( \pi_1 \) and \( w \) are relatively prime, there exist \( a, b \in \mathbb{N} \) such that
\[
\varepsilon := \pi_1 b - wa = \pm 1.
\]
Define elements of the quotient field of \( R \) by
\[
x_1 = (x^by^{-a})^\varepsilon, y_1 = (x^{-w}y^{\pi_1})^\varepsilon.
\]
We have that
\[
x = x_1^{\pi_1}y_1^a, y = x_1^{w}y_1^b.
\]
Since \( n_1 \nu(y) = w \nu(x) \), it follows that
\[
\overline{n}_1 \nu(x_1) = \nu(x), \overline{\nu}(y_1) = 0.
\]
We further have that
\[
\alpha_1 = [y_1] \in L.
\]
Let \( A = R[x_1, y_1] \subset V_\nu \) and \( \mathfrak{m}_A = \mathfrak{m}_\nu \cap A \). \( R \to A_{\mathfrak{m}_A} \) factors as a product of quadratic transforms such that \( xy \) has two distinct irreducible factors in all intermediate rings. Thus \( A = R_1 \). Recall that
\[
f_1(u) = u^{d_1} + b_{1,d_1-1} u^{d_1-1} + \cdots + b_{1,0}
\]
is the minimal polynomial of \( \alpha_1 = \left[ \frac{\nu_1}{\nu} \right] \) over \( \mathfrak{f} \), and from (12) of (A1),
\[
P_2 = y^{\nu_1 d_1} + a_{1,d_1-1} x y^{\nu_1(d_1-1)} + \cdots + a_{1,0} x^{d_1}.
\]
Substituting (47) into (49), we find that
\[
P_2 = x_1^{\nu n_1}(y_1^{\nu_1 d_1} + a_{1,d_1-1} x y^{\nu_1(d_1-1)} + \cdots + a_{1,0} x^{d_1}).
\]
Thus
\[
Q_1 = \frac{P_2}{x_1^{\nu n_1}} \in R_1.
\]
We calculate
\[
\nu(Q_1) = \nu(P_2) - w n_1 \nu(x_1) = \nu(P_2) - n_1 \nu(P_1) > 0.
\]
Thus \( x_1, Q_1 \in \mathfrak{m}_{R_1} \).

Suppose that \( \varepsilon = 1 \). Then since
\[
Q_1 = y_1^{\nu_1 d_1} \left( y_1^{d_1} + a_{1,d_1-1} y_1^{d_1-1} + \cdots + a_{1,0} \right)
\]
and \( y_1 \) is a unit in \( R_1 \), we have that
\[
R_1/(x_1, Q_1) \cong \mathfrak{f}[y_1]/(f(y_1)) \cong \mathfrak{f}(\alpha_1).
\]

Suppose that \( \varepsilon = -1 \). Let
\[
h(u) = y_1^{d_1} + \frac{b_{1,1}}{b_{1,0}} y_1^{d_1-1} + \cdots + \frac{1}{b_{1,0}},
\]
which is the minimal polynomial of \( \alpha_1^{-1} \) over \( \mathfrak{f} \). Since
\[
Q_1 = y_1^{\nu_1 d_1} \left( 1 + a_{1,d_1-1} y_1 + \cdots + a_{1,0} y_1^{d_1} \right)
\]
and \( y_1 \) is a unit in \( R_1 \), we have that
\[
R_1/(x_1, Q_1) \cong \mathfrak{f}[y_1]/(h(y_1)) \cong \mathfrak{f}(\alpha_1^{-1}) \cong \mathfrak{f}(\alpha_1).
\]

Now define \( \beta_i = \nu(P_i) \) and \( \hat{\beta}_i = \nu(Q_i) \) for \( i \geq 0 \). We have
\[
\hat{\beta}_i = \nu(P_{i+1}) - w n_1 \cdots n_i \hat{\beta}_0
\]
for \( i \geq 1 \).

Since \( \gcd(w, \overline{n}_1) = 1 \), we have that \( G(\hat{\beta}_0) = G(\hat{\beta}_0, \hat{\beta}_1). \) Thus
\[
\overline{n}_{i+1} = \left[ G(\hat{\beta}_0, \ldots, \hat{\beta}_i) : G(\hat{\beta}_0, \ldots, \hat{\beta}_{i-1}) \right]
\]
for \( i \geq 1 \).
We will leave the proof that the analogue of $A(1)$ of Theorem 4.2 holds for $Q_1$ in $R_1$ for the reader, as is an easier variation of the following inductive statement, which we will prove.

Assume that $2 \leq i < \Omega - 1$ and the analogue of $A(j)$ of Theorem 4.2 holds for $Q_j$ in $R_1$ for $j < i$. We will prove that the analogue of $A(i)$ of Theorem 4.2 holds for $Q_i$ in $R_1$.

In particular, we assume that

\begin{equation}
\hat{\beta}_j > n_{j+1} \hat{\beta}_j
\end{equation}

for $1 \leq j \leq i - 1$.

Define

\begin{equation}
V_j = U_{i+1} Q_0^{-w_{n_1 n_2 \cdots n_{i+1}}} y_1
= Q_0^w_{i+1} Q_1^{w_2(i+1)} \cdots Q_{i-1}^{w_{n_1(i+1)}}
\end{equation}

where

\begin{equation}
\hat{w}_0(i+1) = \pi_1 w_0(i+1) + w_{n_1(i+1)} + w_{n_2(i+1)} + \cdots + w_{n_{i-1}(i+1)} - w_{n_1 n_2 \cdots n_{i+1}}.
\end{equation}

We have that

\begin{equation}
\nu(Q_i^{\pi_{i+1}}) = \pi_{i+1} \hat{\beta}_i = \pi_{i+1} \nu(P_{i+1}) - w_{n_1 n_2 \cdots n_{i+1}} \beta_i = \nu(V_i).
\end{equation}

Thus

\begin{equation}
\pi_{i+1} \hat{\beta}_i = \hat{w}_0(i+1) \hat{\beta}_0 + \hat{w}_2(i+1) \hat{\beta}_1 + \hat{w}_3(i+1) \hat{\beta}_2 + \cdots + \hat{w}_i(i+1) \hat{\beta}_{i-1}.
\end{equation}

Recall that $0 \leq w_j(i+1) < n_j$ for $1 \leq j \leq i$ and apply (51) to obtain

\begin{equation}
\hat{w}_0(i+1) \hat{\beta}_0 = \pi_{i+1} \hat{\beta}_0 - w_i(i+1) \hat{\beta}_i - \cdots - w_3(i+1) \hat{\beta}_2 - w_2(i+1) \hat{\beta}_1 \geq \hat{\beta}_i - (n_{i-1} - 1) \hat{\beta}_{i-1} - \cdots - (n_3 - 1) \hat{\beta}_2 - (n_2 - 1) \hat{\beta}_1 \geq \hat{\beta}_i - n_i \hat{\beta}_{i-1} > 0.
\end{equation}

Thus $V_i \in R_1$. We have

\begin{equation}
Q_i^{\pi_{i+1}} / V_i = \left( \frac{P_{i+1}^{\pi_{i+1}}}{U_{i+1}} \right) y_1^{\hat{\beta}_0(i+1) + \hat{w}_1(i+1)}
\end{equation}

Let

\begin{equation}
\hat{\alpha}_i = \left[ \frac{Q_i^{\pi_{i+1}}}{V_i} \right] = \alpha_{i+1} \alpha_1^{e(\hat{w}_0(i+1) + \hat{w}_1(i+1))} \in L
\end{equation}

From the minimal polynomial $f_{i+1}(u)$ of $\alpha_{i+1}$, we see that

\begin{equation}
g_i(u) = u^{d_{i+1}} + b_{i+1,i} d_{i+1} + \cdots + b_1 d_1 + \cdots + b_1 \alpha_1^{e(\hat{w}_0(i+1) + \hat{w}_1(i+1))} d_{i+1}
\end{equation}

is the minimal polynomial of $\hat{\alpha}_i$ over $\hat{f}(\alpha_1)(\hat{\alpha}_1, \ldots, \hat{\alpha}_{i-1})$.

Now from equation (12) of $A(i+1)$ determining $P_{i+1}$, we obtain

\begin{equation}
Q_{i+1} = Q_i^{\pi_{i+1}} d_{i+1} + \sum_{t=0}^{d_{i+1}-1} \left( \sum_{s=0}^{d_{i+1}} a_{s,t} y_1^{a_{j_0(s,t)} + b_{j_0(s,t)} Q_0^{j_0(s,t)} Q_1^{j_1(s,t)} \cdots Q_{i-1}^{j_{i-1}(s,t)}} \right)
\end{equation}

where

\begin{equation}
\hat{j}_0(s, t) = \pi_1 j_0(s, t) + w_{j_1(s, t)} + w_{n_1 j_2(s, t)} + \cdots + w_{n_1 n_2} + n_{i-1 j_i(s, t)} - (d_{i+1} - t) w_{n_1 n_2} + n_i \pi_{i+1}.
\end{equation}
Recall that $0 \leq j_k(s, t) < n_k$ for $1 \leq k \leq i$. We further have that

$$
\nu(Q_0^{j_0(s, t)} Q_1^{j_1(s, t)} \cdots Q_{i-1}^{j_{i-1}(s, t)}) = (d_{i+1} - t) \bar{\beta}_i \geq \hat{\beta}_i.
$$

By a similar argument to (53), we obtain that $\hat{\beta}_0(s, t) > 0$ for all $s, t$.

By the definition of $Q_{i+1}$, (52) and (56), we have

$$(57) \quad \frac{y_1}{d_{i+1}} = \left(\frac{Q_i^{\hat{\beta}_i}}{V_i^{d_{i+1}}}ight)^{d_{i+1}} + \sum_{t=0}^{d_{i+1}-1} \left(\sum_{s=1}^{n_t} a_{j_0(s, t) + b_j(s, t)} Q_0^{j_0(s, t)} Q_1^{j_1(s, t)} \cdots Q_{i-1}^{j_{i-1}(s, t)} \right) \left(\frac{Q_i^{\hat{\beta}_i}}{V_i^{d_{i+1}-t}}\right)
$$

We have

$$
\left[\frac{\sum_{s=1}^{n_t} a_{s, t} y_1}{d_{i+1}}\right] = \left[\frac{\sum_{s=1}^{n_t} a_{s, t} y_1}{d_{i+1}}\right] = [n_t y_1]
$$

for $0 \leq t \leq d_{i+1} - 1$ and

$$
\frac{Q_i^{\hat{\beta}_i}}{V_i^{d_{i+1}}} = g_i(\hat{\beta}_i) = 0.
$$

Thus

$$
\hat{\beta}_i = \nu(Q_i) > d_{i+1} \nu(V_i) = d_{i+1} \nu(U_{i+1}) = wn_1 n_2 \cdots n_i \beta_0.
$$

We have thus established that $\lambda(i)$ holds for $Q_i$ in $R_1$. By induction on $i$, we have that $\lambda(i)$ of Theorem 4.2 holds for $Q_i$ in $R_1$ for $1 \leq i < \Omega - 1$.

We now will show that $D(r)$ of Theorem 4.2 holds for the $Q_i$ in $R_1$ for all $r$. We begin by establishing the following statement:

**Suppose that $\lambda \geq n_1 w$ is an integer. Then there exist $\delta_0, \delta_1 \in \mathbb{N}$ with $0 \leq \delta_1 < n_1$ such that**

$$(58) \quad x^{\delta_0 + i w} y^{\delta_1 + (d_i - 1 - i) n_1} = x t^b y_1^{z - i e}
$$

for $0 \leq i \leq d_i - 1$ where $z = a \delta_0 + b (\delta_1 + (d_i - 1 - i) n_1$.

We first prove (58). We have that

$$(\lambda \delta b - r w) n_1 + (r n_1 - \lambda \delta) w = \lambda
$$

for all $r \in \mathbb{Z}$. Choose $r$ so that $\delta_1 = r n_1 - \lambda \delta$ satisfies $0 \leq \delta_1 < n_1$. Set

$$
\delta_0 = (\lambda \delta b - r w) - (d_i - 1) w.
$$

Then

$$(\lambda \delta b - r w) n_1 = \lambda - \delta_1 w \geq n_1 w - (n_1 - 1) w = (n_1 - n_1 + 1) w
$$

so

$$
\delta_0 \geq (n_1 - n_1 - d_i + 2) w = ((n_1 - 1)(d_i - 1) + 1) w \geq w.
$$

Substituting (47) in $x^{\delta_0 + i w} y^{\delta_1 + (d_i - 1 - i) n_1}$, we obtain the formula (58).
We now will prove that statement $D(r)$ of Theorem 4.2 holds for the $Q_i$ in $R_1$ for all $r$. Suppose that we have monomials $Q_0^{j_0(l)}Q_1^{j_1(l)}\cdots Q_r^{j_r(l)}$ for $1 \leq l \leq m$ such that

$$\nu(Q_0^{j_0(l)}Q_1^{j_1(l)}\cdots Q_r^{j_r(l)}) = \nu(Q_0^{j_0(1)}Q_1^{j_1(1)}\cdots Q_r^{j_r(1)})$$

for $1 \leq l \leq m$, and that we have a dependence relation in $L = V_0/m_0$.

$$0 = e_1 + e_2 \left[ \frac{Q_0^{j_0(2)}Q_1^{j_1(2)}\cdots Q_r^{j_r(2)}}{Q_0^{j_0(1)}Q_1^{j_1(1)}\cdots Q_r^{j_r(1)}} \right] + \cdots + e_m \left[ \frac{Q_0^{j_0(m)}Q_1^{j_1(m)}\cdots Q_r^{j_r(m)}}{Q_0^{j_0(1)}Q_1^{j_1(1)}\cdots Q_r^{j_r(1)}} \right]$$

with $e_i \in \mathfrak{t}(\alpha_1)$ (and some $e_i \neq 0$). Multiplying the $Q_0^{j_0(l)}Q_1^{j_1(l)}\cdots Q_r^{j_r(l)}$ for $1 \leq l \leq m$ by a common term $Q_0^j$ with $t$ a sufficiently large positive integer, we may assume that

$$\hat{j}_0(l) = j_0(l) - j_1(l)wn_1 - j_2(l)wn_2 - \cdots - j_r(l)wn_1n_2\cdots n_r \geq n_1w$$

for $1 \leq l \leq m$. We have that

$$Q_0^{j_0(l)}Q_1^{j_1(l)}\cdots Q_r^{j_r(l)} = Q_0^{j_0(l)}P_1^{j_1(l)}\cdots P_r^{j_r(l)}.$$ 

Since $\hat{j}_0(l) \geq wn_1$, (58) implies that for each $l$ with $1 \leq l \leq w$, there exist $\delta_0(l), \delta_1(l)$ with $\delta_0(l), \delta_1(l) \in \mathbb{N}$ and $0 \leq \delta_1(l) < \overline{\pi}_1$ such that

$$I_0^{\delta_0(l)+iw}P_1^{\delta_1(l)+(d_1-1-i)\overline{\pi}_1} = y_1^{\varepsilon(z(l)-z(1))-i}Q_0^{j_0(l)}$$

for $0 \leq i \leq d_1-1$. The ordered set

$$\{ e_1^{\varepsilon(z(l)-z(1))}, e_1^{\varepsilon(z(l)-z(1))-1}, \cdots, e_1^{\varepsilon(z(l)-z(1))-(d_1-1)} \}$$

is a $\mathfrak{t}$-basis of $\mathfrak{t}(\alpha_1)$ for all $l$ (since multiplication by $\alpha_1^{\varepsilon(z(l)-z(1))+(d_1-1)}$ is a $\mathfrak{t}$-vector space isomorphism of $\mathfrak{t}(\alpha_1)$, and thus takes a basis to a basis). Thus there exists $e_{l,i} \in \mathfrak{t}$ such that

$$e_l = \sum_{i=0}^{d_1-1} e_{l,i} e_1^{\varepsilon(z(l)-z(1))-i}.$$ 

Since some $e_{l,i} \neq 0$, we have a dependence relation

$$0 = \sum_{l=1}^{m} \sum_{i=0}^{d_1-1} e_{l,i} \left[ \frac{I_0^{\delta_0(l)+iw}P_1^{\delta_1(l)+(d_1-1-i)\overline{\pi}_1}P_2^{j_1(l)}\cdots P_r^{j_r(l)}}{I_0^{\delta_0(1)}P_1^{\delta_1(1)+(d_1-1)\overline{\pi}_1}P_2^{j_1(1)}\cdots P_r^{j_r(1)}} \right],$$

a contradiction to $D(r+1)$ of Theorem 4.2 for the $P_i$ in $R$. Thus we have established $D(r)$ of Theorem 4.2 for the $Q_i$ in $R_1$. 

8. Polynomial rings in two variables

The algorithm of Theorem 4.2 is applicable when $R = \mathfrak{t}[x, y]$ is a polynomial ring over a field and $\nu$ is a valuation which dominates the maximal ideal $(x, y)$ of $R$. In this case many of the calculations in this paper become much simpler, as we now indicate (of course we take the coefficient set $CF$ to be the field $\mathfrak{t}$). In the case when $R$ is equicharacteristic, we can establish from the polynomial case the results of this paper using Cohen’s structure theorem and Proposition 3.4 to reduce to the case of a polynomial ring in two variables.

If $f \in R = \mathfrak{t}[x, y]$ is a nonzero polynomial, then we have an expansion $f = a_0(x) + a_1(x)y + \cdots + a_r(x)y^r$ where $a_i(x) \in \mathfrak{t}[x]$ for all $i$ and $a_r(x) \neq 0$. We define $\text{ord}_y(f) = r$, and say that $f$ is monic in $y$ if $a_r(x) \in \mathfrak{t}$. We first establish the following formula.

$$P_i \text{ is monic in } y \text{ with } \deg_y P_i = n_1n_2\cdots n_{i-1} \text{ for } i \geq 2.$$
We establish (59) by induction. In the expansion (12) of $P_{i+1}$, we have for $0 \leq t \leq d_i - 1$ and whenever $a_{s,t} \neq 0$, that $0 \leq j_k(s,t) < n_k$ for $1 \leq k \leq i - 1$. Thus

$$\deg_y(p_{j_0}^{(s,t)} P_1^{j_1(s,t)} \cdots P_{i-1}^{j_{i-1}(s,t)} a_{i}) = j_1(s,t) + j_2(s,t)n_1 + j_3(s,t)n_1n_2 + \cdots + j_{i-1}n_1n_2 \cdots n_i + \sum_{r} n_1n_2 \cdots n_i.$$ 

Thus $\deg_y p_{i+1} = \deg_y p_{i}^{n_i} = n_1n_2 \cdots n_i$. We further see that $P_{i+1}$ is monic in $y$.

Set $\sigma(0) = 0$ and for $i \geq 1$ let

$$\sigma(i) = \min\{j \mid j > \sigma(i-1) \text{ and } n_j > 1\}.$$ 

Let $Q_i = P_{\sigma(i)}$. We calculate (as long as we are not in the case $\Omega = \infty$ and $n_i = 1$ for $i \gg 0$) that for $d \in \mathbb{Z}_+$, there exists a unique $r \in \mathbb{Z}_+$ and $j_1, \ldots, j_r \in \mathbb{Z}_+$ such that $0 \leq j_k < n_k$ for $1 \leq k \leq r$ and $\deg_y Q_1^{j_1} \cdots Q_r^{j_r} = d$. Let $M_d$ be this monomial. Since the monomials $M_d$ are monic in $y$, we see (continuing to assume that we are not in the case $\Omega = \infty$ and $n_i = 1$ for $i \gg 0$) that if $f \in R = \mathfrak{t}[x,y]$ is nonzero with $\deg_y(f) = d$, then there is a unique expression

$$f = \sum_{i=0}^{d} A_i(x) M_i$$

where $A_i(x) \in \mathfrak{t}[x]$, and

$$\nu(f) = \min_{i} \{\text{ord}(A_i) \nu(Q_0) + \nu(M_i)\}.$$ 

In the case when $\Omega = \infty$ and $n_i = 1$ for $i \gg 0$ we have a similar statement, but we may need to introduce a new polynomial $g$ of “infinite value” as in Case 3 of Theorem 4.12.

9. The $A_2$ Singularity

**Lemma 9.1.** Let $\mathfrak{t}$ be an algebraically closed field, and let $A = \mathfrak{t}[x^2, xy, y^2]$, a subring of the polynomial ring $B = \mathfrak{t}[x,y]$. Let $m = (x^2, xy, y^2)A$ and $n = (x,y)B$. Suppose that $\nu$ is a rational nondiscrete valuation dominating $B_n$, such that $\nu$ has a generating sequence $P_0 = x, P_1 = y, P_2, \ldots$ in $\mathfrak{t}[x,y]$ of the form of the conclusions of Theorem 4.2, such that each $P_i$ is a $\mathfrak{t}$-linear combinations of monomials in $x$ and $y$ of odd degree, and

$$\beta_0 = \nu(x), \beta_1 = \nu(y), \beta_2 = \nu(P_2), \ldots$$

is the increasing sequence of minimal generators of $S^B_n(\nu)$, with $\beta_{i+1} > \pi_i \beta_i$ for $i \geq 1$, where

$$\pi_i = [G(\beta_0, \ldots, \beta_i) : G(\beta_0, \ldots, \beta_{i-1})].$$

Then

$$S^{A_n}(\nu) = \left\{ a_0 \beta_0 + a_1 \beta_1 + \cdots + a_i \beta_i \mid i \in \mathbb{N}, a_0, \ldots, a_i \in \mathbb{N} \right\}.$$ 

**Proof.** For $f \in \mathfrak{t}[x,y]$, let $t = \deg_y(f)$. By (60), $f$ has a unique expansion

$$f = \sum_{i=0}^{t} \left( \sum_{k} b_{k,i} x^k \right) P_1^{j_1(i)} \cdots P_r^{j_r(i)}$$

where $b_{k,i} \in \mathfrak{t}$, $0 \leq j_k(i) < \pi_k$ for $1 \leq k$ and

$$\deg_y P_1^{j_1(i)} \cdots P_r^{j_r(i)} = i.$$
for all \( i \). Looking first at the \( t = \text{deg}_y(f) \) term, and then at lower order terms, we see that 
\[ f \in \mathfrak{t}[x^2, xy, y^2] \]
if and only if \( k + j_1(i) + \cdots + j_r(i) \equiv 0 \mod 2 \) whenever \( b_{k,i} \neq 0 \). \( \square \)

**Example 9.2.** Suppose that \( \mathfrak{t} \) is a field and \( R \) is the localization of \( \mathfrak{t}[u, v, w]/uw-w^2 \) at the maximal ideal \( (u, v, w) \). Then there exists a rational nondiscrete valuation \( \nu \) dominating \( R \) such that if 
\[ \gamma_0 < \gamma_1 < \cdots \]
is the increasing sequence of minimal generators of the semigroup \( S_R(\nu) \), then given \( n \in \mathbb{Z}_+ \), there exists \( i > n \) such that \( \gamma_{i+1} = \gamma_i + \frac{5}{3} \) and \( \gamma_{i+1} \) is in the group generated by \( \gamma_0, \ldots, \gamma_i \).

**Proof.** Let \( A = \mathfrak{t}[x, y] \) be a polynomial ring with maximal ideal \( n = (x, y)\mathfrak{t}[x, y] \). We will use the criterion of Theorem 1.2 to construct a rational nondiscrete valuation \( \nu \) dominating \( T = A_n \), with a generating sequence 
\[ P_0 = x, P_0 = y, P_2, \ldots \]
such that 
\[ \beta_0 = \nu(x), \beta_1 = \nu(y), \beta_2 = \nu(P_2), \ldots \]
is the increasing set of minimal generators of the semigroup \( S^T(\nu) \). We will construct the \( P_i \) so that each \( P_i \) is a \( \mathfrak{t} \)-linear combination of monomials in \( x \) and \( y \) of odd degree.

We define the first part of a generating sequence by setting 
\[ P_0 = x, P_1 = y, P_2 = y^3 - x^5, \]
with \( \beta_0 = \nu(x) = 1, \beta_1 = \nu(y) = \frac{5}{3} \). Set \( b_1 = 0 \).

We now inductively define 
\[ P_{i+1} = P_i^3 - x^{a_i}P_{i-1} \]
with \( a_i \) an even positive integer, and \( \beta_i = \nu(P_i) = b_i + \frac{5}{3} \) with \( b_i \in \mathbb{Z}_+ \), for \( i \geq 2 \), by requiring that \( 3 \) divides \( a_i + b_{i-1} \) and 
\[ b_i = \frac{a_i + b_{i-1}}{3} > 3b_{i-1} + 5 \]
for \( i \geq 2 \). \( a_i, b_i \) satisfying these relations can be constructed inductively from \( b_{i-1} \).

Now let \( B = \mathfrak{t}[x^2, xy, y^2], \ m = (x^2, xy, y^2)B \), so that \( R \cong B_m \). With this identification, the semigroup \( S^R(\nu) \) is generated by \( \{ \beta_i + \beta_j \mid i, j \in \mathbb{N} \} \). From \( 3\beta_i < \beta_{i+1} \) for \( i \geq 1 \) and \( \beta_i < \beta_j \) if \( j > i \), we conclude that if \( i \leq j, k \leq l \) and \( j < l \), then 
\[ (62) \quad \beta_i + \beta_j < \beta_k + \beta_l. \]

Let 
\[ \gamma_0 = 2 < \gamma_1 < \cdots \]
be the sequence of minimal generators of the semigroup \( S^R(\nu) \). By (62), for \( n \in \mathbb{Z}_+ \), there exists an index \( l \) such that \( \gamma_l = \beta_0 + \beta_n \). We have \( l \geq n \). The semigroup \( S(\gamma_0, \gamma_1, \ldots, \gamma_l) \) is generated by 
\[ \{ \beta_i + \beta_j \mid i \leq j \text{ and } j \leq n - 1 \} \]
and \( \beta_0 + \beta_n \).

Suppose \( \beta_1 + \beta_n \in S(\gamma_0, \gamma_1, \ldots, \gamma_l) \). Since \( S(\gamma_0, \ldots, \gamma_{l-1}) \subset \frac{1}{3^{l-1}} \mathbb{Z} \), we have an expression \( \beta_1 + \beta_n = r\gamma_l + \tau \) with \( r \) a positive integer, and \( \tau \in S(\gamma_0, \ldots, \gamma_{l-1}) \). Now 
\[ \gamma_l = \beta_0 + \beta_n = 1 + b_n + \frac{5}{3^n} \]
for all \( n \).
\[ \beta_1 + \beta_n = \frac{5}{3} + b_n + \frac{5}{3^n} \]

implies \( \tau \leq \frac{5}{3} - 1 = \frac{2}{3} \), which is impossible, since \( \gamma_0 = \beta_0 + \beta_0 = 2 \). Thus \( \beta_1 + \beta_n \notin S(\gamma_0, \gamma_1, \ldots, \gamma_l) \) and \( \beta_1 + \beta_n = \gamma_{l+1} \) is the next largest minimal generator of \( S^R(\nu) \).

We have that \( \gamma_{l+1} = \beta_1 + \beta_n = (\beta_0 + \beta_1) + (\beta_0 + \beta_n) - 2\beta_0 \) is in the group generated by \( \gamma_0, \ldots, \gamma_l \).

**Example 9.3.** Let notation be as in Example 9.2 and its proof. Then \( R \to T \) is finite, but \( S^T(\nu) \) is not a finitely generated \( S^R(\nu) \) module.

**Proof.** Suppose \( S^T(\nu) \) is a finitely generated \( S^R(\nu) \) module. Then there exists \( n > 0 \) such that \( S^T(\nu) \) is generated by \( \beta_0, \ldots, \beta_n \) and \( \{ \beta_i + \beta_j \mid i, j \in \mathbb{N} \} \). For \( l > n \), \( \beta_l \) cannot be in this semigroup. \( \square \)

**Example 9.4.** Let \( A = \mathfrak{t}[u, v]_{(u, v)} \). Then \( A \to T \) is a finite extension of regular local rings, but \( S^T(\nu) \) is not a finitely generated \( S^A(\nu) \) module.

**Proof.** Since \( A \) is a subring of \( R \), \( S^A(\nu) \) is a subsemigroup of \( S^R(\nu) \). Since \( S^T(\nu) \) is not a finitely generated \( S^R(\nu) \)-module, by Example 9.3, \( S^T(\nu) \) cannot be a finitely generated \( S^A(\nu) \)-module. \( \square \)

**References**

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Steven Dale Cutkosky, Department of Mathematics, University of Missouri, Columbia, MO 65211, USA
E-mail address: cutkoskys@missouri.edu

Pham An Vinh, Department of Mathematics, University of Missouri, Columbia, MO 65211, USA
E-mail address: vapnnc@mizzou.edu