

Rank two Artin–Schelter regular algebras from noncommuting derivations

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Abstract. If Δ and Γ are two derivations of a commutative algebra A such that $\Delta\Gamma - \Gamma\Delta = \Delta$ is locally nilpotent, one can endow A with a new product $*$ whose filtered semiclassical limit is the Poisson structure $\Delta \wedge \Gamma$. In this article, we first study these (Poisson) algebras from an algebraic point of view, and when A is a polynomial algebra, we investigate their homological properties. In particular, when the derivations Δ and Γ are linear, the algebras $(A, *)$ provide, in each dimension at least four, new examples of multiparameter families of Artin–Schelter regular algebras. These algebras are deformations of Poisson algebras $(A, \Delta \wedge \Gamma)$ of rank two, thus explaining the title of the article. Assuming furthermore a technical condition on Γ , we show that the algebra $(A, *)$ is Calabi–Yau if and only if the trace of Γ is equal to 1 if and only if the Poisson algebra $(A, \Delta \wedge \Gamma)$ is unimodular. Since the trace of Γ is a linear function of the parameters, the algebras $(A, *)$ also provide, in each dimension at least four, new examples of multiparameter families of Calabi–Yau algebras.

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Introduction

The philosophy behind noncommutative projective algebraic geometry [24] is to study noncommutative version of the projective spaces $\mathbb{P}^n$ by describing suitable noncommutative algebras that would be thought of as their homogeneous coordinates rings: the so-called Artin–Schelter regular algebras (AS regular algebras for short) [2]. Numerous examples of AS regular algebras are known, but a complete classification is achieved only up to projective dimension 2. The work of Pym [22] provides a partial answer in dimension 3 by focusing on a classification of graded Calabi–Yau algebras [10] that are flat deformations of $\mathbb{C}[x_0, x_1, x_2, x_3]$. In [16], Sierra and the second author introduced a family of AS regular algebras $R(n, a)$ of Gel’fand–Kirillov dimension $n + 1$ indexed by a scalar a . The authors proved that for any integer $n \geq 0$, there exists a unique scalar a such that the algebra $R(n, a)$ is Calabi–Yau. This is of particular interest since it explains a specific choice of parameter made in the exceptional component $E(3)$ of Pym’s classification [22].

Back to the algebra $R(n, a)$, the parameter $n + 1$ can be interpreted as the index of nilpotency of a maximal Jordan block seen as the restriction to degree one polynomials of a locally nilpotent derivation Δ of a polynomial algebra in $n + 1$ variables. The construction of $R(n, a)$ relies on a second derivation Γ such that $\Delta\Gamma - \Gamma\Delta = \Delta$ together with a deformation formula of Coll, Gerstenhaber, and Giaquinto [5]. The aim of this article is to investigate the following natural generalization: what are the possible algebras arising from this construction by relaxing the conditions on Δ ? The case of homogeneous locally nilpotent derivations Δ of a polynomial ring whose canonical Jordan normal form acting on the set of degree one polynomials is not a maximal block will be of particular interest. In this situation, we obtain a wide family of non-isomorphic AS regular algebras in each dimension since the Jordan type of Δ must be preserved by isomorphism (Theorem 5.9). Among them, we describe a family of Calabi–Yau algebras indexed by $r - 1$ scalar parameters, where r is the number of blocks in the canonical Jordan normal form of Δ (the algebras studied in [16] correspond to the case $r = 1$).

This article is divided into eight sections. In Section 1, we present the general construction of a Poisson algebra $A_{(\Delta, \Gamma)}$ and an associative algebra $R_{(\Delta, \Gamma)}$ associated with a pair of derivations (Δ, Γ) of a commutative algebra A such that $\Delta\Gamma - \Gamma\Delta = \Delta$ is locally nilpotent. Such a pair of derivations will be called a *solvable pair*. Section 2 is devoted to the study of general algebraic properties of $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$. A lot of examples of solvable pairs are given. Moreover, we compute the (Poisson) center in many cases (Lemma 2.9) and exhibit examples of important Poisson derivations of $A_{(\Delta, \Gamma)}$ and automorphisms of $R_{(\Delta, \Gamma)}$ (see Lemma 2.15 and Theorem 2.17). Furthermore, we remark that the natural filtration associated with the locally nilpotent derivation Δ is compatible with both the Poisson structure of $A_{(\Delta, \Gamma)}$ and the associative structure of $R_{(\Delta, \Gamma)}$. This filtration is presented and studied in Section 2.4; it will be one of our main tools to prove a lot of results in this article. In the general situation, not much can be said about normal elements.

However, among them, we identify and study a significant subset consisting of the so-called strongly normal elements (Definition 2.30) which will be of particular interest later in this article. To end Section 2, we observe that up to localization, the Poisson algebra $A_{(\Delta, \Gamma)}$ and the algebra $R_{(\Delta, \Gamma)}$ are particularly nice: they are isomorphic to (Poisson) Ore extensions over (a localization of) the kernel of Δ , thanks to the local slice construction.

The rest of the article is devoted to the case where the solvable pair is defined on a polynomial algebra A . In Section 3, the rank of a non-abelian Poisson algebra $A_{(\Delta, \Gamma)}$ is shown to be equal to two. Section 4 deals with the case of homogeneous derivations Δ and Γ . In this situation, both the Poisson center of $A_{(\Delta, \Gamma)}$ and the center of $R_{(\Delta, \Gamma)}$ are characterized (Corollary 4.8). Moreover, we construct a finer filtration than the previous one, having the benefit that the associated graded algebra is a polynomial algebra. In Section 5, we show that the algebra $R_{(\Delta, \Gamma)}$ is AS regular, and we characterize the (Poisson) normal elements: they are precisely the strongly normal elements introduced in Section 2. Moreover, we prove that the Jordan type of Δ is an invariant of both $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$. In Sections 6 and 7, we focus on the case where Γ is diagonalizable. In this situation, we are able to determine the linear Poisson derivations when Γ is generic. We also provide a presentation of $R_{(\Delta, \Gamma)}$ by generators and relations. In the last section, we study when our algebras (resp. Poisson algebras) are Calabi–Yau (resp. unimodular); see Corollary 8.12. Finally, the article ends with appendices which recap some of the results frequently used in the article, in particular it explains the structure of the graded ring for the finer of the filtrations we study. In this article, we always assume that $\mathbb{k}$ is a field of characteristic zero.

1. A deformation formula for noncommuting derivations

Let A be a commutative $\mathbb{k}$ -algebra and Δ, Γ be two derivations of A such that $[\Delta, \Gamma] = \Delta\Gamma - \Gamma\Delta = \Delta$. It is easily verified that the biderivation $\{-, -\} = \Delta \wedge \Gamma$ satisfies the Jacobi identity and hence is a Poisson bracket on A . More precisely, we have

$$\{f, g\} = \Delta(f)\Gamma(g) - \Delta(g)\Gamma(f) \quad (1.1)$$

for any $f, g \in A$. Moreover, if Δ is locally nilpotent, by setting for any $f, g \in A$,

$$f * g = \sum_{i \geq 0} \Delta^i(f) \binom{\Gamma}{i}(g) = fg + \Delta(f)\Gamma(g) + \sum_{i \geq 2} \Delta^i(f) \binom{\Gamma}{i}(g), \quad (1.2)$$

where $\binom{\Gamma}{i} = \frac{1}{i!} \Gamma \circ (\Gamma - \text{id}) \circ \dots \circ (\Gamma - (i-1)\text{id})$, we define an associative product on A ; see [5] for the formal version and [22, Lemma 3.3] for the algebraic version. We set

- $A = A_{(\Delta, \Gamma)} = (A, \{-, -\})$,
- $R = R_{(\Delta, \Gamma)} = (A, *)$.

The algebra R is a deformation of the Poisson algebra A in the following sense. Consider $A[t]$ as an algebra over $\mathbb{k}[t]$ and define

$$f *_t g = \sum_{i \geq 0} t^i \Delta^i(f) \binom{\Gamma}{i}(g).$$

Then $A_t = (A[t], *_t)$ is an associative algebra over $\mathbb{k}[t]$ such that

- $A_t/(t-1)A_t \cong R$,
- A_t/tA_t is commutative and can be endowed with a Poisson structure given by

$$\{f + tA_t, g + tA_t\} = \frac{f *_t g - g *_t f}{t} + tA_t,$$

- A_t/tA_t and A are isomorphic as Poisson algebras.

Therefore, the Poisson algebra $A_{(\Delta, \Gamma)}$ is the commutative fiber version of the semiclassical limit of $R_{(\Delta, \Gamma)}$ in the sense of [11, Section 2.1].

Example 1.3. For $A = \mathbb{k}[X_0, \dots, X_n]$ and the derivations $\Delta(X_i) = X_{i-1}$ ($X_{-1} = 0$) and $\Gamma(X_i) = (a+i)X_i$ ($a \in \mathbb{k}$), the (Poisson) algebras obtained by formulae (1.1) and (1.2) have been studied in [16] where they are denoted by $A(n, a)$ and $R(n, a)$. In this article, our aim is to generalize the results of [16] to other pairs of derivations.

2. Solvable pairs

2.1. Generalities

A pair (Δ, Γ) of derivations of A such that $[\Delta, \Gamma] = \Delta$ is locally nilpotent will be called a *solvable pair*. Since $[\Delta, \Gamma] = \Delta$, we observe, thanks to equations (1.1) and (1.2), that

$$\Gamma = 0 \implies \Delta = 0 \implies \begin{cases} A_{(\Delta, \Gamma)} \text{ is Poisson commutative,} \\ R_{(\Delta, \Gamma)} \text{ is commutative.} \end{cases}$$

The aim of this section is to study general facts about solvable pairs. The following result studies the influence of a change of generators of A on the algebras $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$.

Lemma 2.1. *Let (Δ, Γ) be a solvable pair on A and σ an automorphism of the algebra A . Then*

- (i) $(\tilde{\Delta}, \tilde{\Gamma}) := (\sigma\Delta\sigma^{-1}, \sigma\Gamma\sigma^{-1})$ is a solvable pair on A ,
- (ii) the Poisson algebras $A_{(\Delta, \Gamma)}$ and $A_{(\tilde{\Delta}, \tilde{\Gamma})}$ are isomorphic,
- (iii) the algebras $R_{(\Delta, \Gamma)}$ and $R_{(\tilde{\Delta}, \tilde{\Gamma})}$ are isomorphic.

Proof. Assertion (i) is a straightforward computation.

For assertions (ii) and (iii) we show that σ is an isomorphism between the appropriate algebras. Since $\sigma\Delta = \tilde{\Delta}\sigma$ and $\sigma\Gamma = \tilde{\Gamma}\sigma$, we have for all $f, g \in A$

$$\begin{aligned}\sigma(\{f, g\}_{(\Delta, \Gamma)}) &= \sigma\Delta(f)\sigma\Gamma(g) - \sigma\Delta(g)\sigma\Gamma(f) \\ &= \tilde{\Delta}\sigma(f)\tilde{\Gamma}\sigma(g) - \tilde{\Delta}\sigma(g)\tilde{\Gamma}\sigma(f) = \{\sigma(f), \sigma(g)\}_{(\tilde{\Delta}, \tilde{\Gamma})}.\end{aligned}$$

By induction, we obtain easily that $\sigma\Delta^\ell = \tilde{\Delta}^\ell\sigma$ and $\sigma(\Gamma_\ell) = (\tilde{\Gamma}_\ell)\sigma$ for all $\ell \in \mathbb{N}$. The equality $\sigma(f *_{(\Delta, \Gamma)} g) = \sigma(f) *_{(\tilde{\Delta}, \tilde{\Gamma})} \sigma(g)$ follows from the definition of the product $*$ given by (1.2). ■

Remark 2.2. When $\Delta = 0$, the Poisson algebra A is Poisson commutative, and the algebra R is commutative for every choice of derivation Γ . Therefore, there is no hope in general that a Poisson isomorphism between $A_{(\Delta, \Gamma)}$ and $A_{(\Delta', \Gamma')}$ implies that there exists $\sigma \in \text{Aut}(A)$ such that $(\Delta', \Gamma') = (\sigma\Delta\sigma^{-1}, \sigma\Gamma\sigma^{-1})$ (the same remark also applies to $R_{(\Delta, \Gamma)}$). In other words, the Poisson isomorphism class of $A_{(\Delta, \Gamma)}$ or the $\mathbb{k}$ -algebra isomorphism class of $R_{(\Delta, \Gamma)}$ does not determine the isomorphism class of the representation of the two-dimensional solvable Lie algebra.

For a less trivial example showing that even the conjugacy class of Δ is not determined, see Example 2.13.

We conclude this section with some examples. If $A = \mathbb{k}[X_0, \dots, X_n]$ is a polynomial algebra, then we denote by ∂_{X_i} the usual derivative with respect to the indeterminate X_i . Recall that the set of derivations of A is a free A -module with basis $(\partial_{X_0}, \dots, \partial_{X_n})$.

Proposition 2.3. *Let $A = \mathbb{k}[X_0, X_1]$. Up to isomorphism, any solvable pair (Δ, Γ) on A with $\Delta \neq 0$ is of the form*

$$\Delta = P\partial_{X_1}, \quad \Gamma = Q\partial_{X_0} + R\partial_{X_1},$$

where $P, Q \in \mathbb{k}[X_0]$, $P \neq 0$ and $R = R_0 + R_1X_1$ for some $R_0, R_1 \in \mathbb{k}[X_0]$ are such that

- (1) if $P \in \mathbb{k}^*$ or $Q = 0$, then $R = R_0 + X_1$ (i.e., $R_1 = 1$),
- (2) if $\deg_{X_0}(P) > 0$ and $Q \neq 0$, then $R_1 \neq 1$, and we have $P(R_1 - 1) = Q\partial_{X_0}(P)$.

In particular, if $\deg_{X_0}(P) > 0$, $Q \neq 0$ and $R_1 \in \mathbb{k} \setminus \{1\}$, then there exist $\Lambda \in \mathbb{k}^*$, $\alpha \in \mathbb{k}$ and an integer $n > 0$ such that $Q = \frac{R_1-1}{n}(X_0 - \alpha)$ and $P = \Lambda(X_0 - \alpha)^n$.

Proof. Let (δ, γ) be a solvable pair on A with $\delta \neq 0$. Thanks to Rentschler's theorem, see [9, Theorem 4.1], there exists $\alpha \in \text{Aut}(A)$ such that $\Delta := \alpha\delta\alpha^{-1} = P\partial_{X_1}$ for some nonzero polynomial $P \in \mathbb{k}[X_0]$. Note that $\ker \Delta = \mathbb{k}[X_0]$ since $P \neq 0$. Set $\Gamma := \alpha\gamma\alpha^{-1} = Q\partial_{X_0} + R\partial_{X_1}$ for some $Q, R \in A$. Then $[\Delta, \Gamma] = \Delta$ implies that

$$0 = \Delta(X_0) = \Delta\Gamma(X_0) - \Gamma\Delta(X_0) = \Delta(Q)$$

so that $Q \in \ker \Delta = \mathbb{k}[X_0]$. Moreover, we have

$$P = \Delta(X_1) = \Delta\Gamma(X_1) - \Gamma\Delta(X_1) = \Delta(R) - \Gamma(P) = P\partial_{X_1}(R) - Q\partial_{X_0}(P)$$

so that $P(\partial_{X_1}(R) - 1) = Q\partial_{X_0}(P)$. Two cases can happen:

- (1) $Q\partial_{X_0}(P) = 0$, that is, $Q = 0$ or $P \in \mathbb{k}^*$,
- (2) $Q\partial_{X_0}(P) \neq 0$, that is, $\deg_{X_0}(P) > 0$ and $Q \neq 0$.

Since $P \neq 0$, the first case implies that $\partial_{X_1}(R) = 1$; hence $R = R_0 + X_1$ with $R_0 \in \mathbb{k}[X_0]$. This proves the proposition in case (1). In the second case, every factor in $P(\partial_{X_1}(R) - 1) = Q\partial_{X_0}(P)$ is nonzero. Therefore, the degree in X_1 of $\partial_{X_1}(R) - 1$ is equal to 0. Hence $R = R_0 + R_1X_1$ with $R_0, R_1 \in \mathbb{k}[X_0]$ and $R_1 \neq 1$. This proves the proposition in case (2). For the final assertion, assume that $R_1 = \mu \in \mathbb{k} \setminus \{1\}$. In $\mathbb{k}[X_0]$, we have $(\mu - 1)P = QP' \neq 0$. This implies that $\deg_{X_0}(Q) = 1$. Thus $Q = \lambda(X_0 - \alpha)$ for some $\lambda \in \mathbb{k}^*$ and some $\alpha \in \mathbb{k}$. Classically, we obtain $P = \Lambda(X_0 - \alpha)^n$ for some $\Lambda \in \mathbb{k}^*$ and some integer $n > 0$. Finally, the relation $(\mu - 1)P = QP'$ gives $\lambda = \frac{\mu-1}{n}$. ■

Corollary 2.4. *Every Poisson structure on $A = \mathbb{k}[X_0, X_1]$ arising from a solvable pair is, up to isomorphism, of the form $\{X_0, X_1\} = S$, where $S \in \mathbb{k}[X_0]$. The algebra $(R, *)$ is given by two generators X_0, X_1 and one relation $X_0 * X_1 - X_1 * X_0 = S$. In particular, the Poisson field $\text{Frac } A$ is either Poisson commutative or a Poisson Weyl field. Similarly, the skewfield $\text{Frac } R$ is either commutative or a Weyl skewfield.*

Proof. We have the result for A with $S = -PQ$, thanks to Proposition 2.3 and by setting, if $S \neq 0$, $X'_1 = X_1S^{-1}$ so that $\{X_0, X'_1\} = 1$. We denote by X_1^{*i} the i th power of X_1 with respect to the product $*$. Observe that the powers X_1^{*i} for $i \geq 0$ form a basis of $R = (A, *)$ over $\mathbb{k}[X_0]$ so that R is isomorphic to the Ore extension $\mathbb{k}[X_0][X_1; S\partial_{X_0}]$ (see Proposition 2.33 for a proof in a more general situation). In particular, R is a Noetherian domain and hence admits a skewfield of fraction denoted by $\text{Frac } R$. If $S \neq 0$, set $X'_1 = X_1 * S^{-1}$ so that $X_0 * X'_1 - X'_1 * X_0 = 1$ and $\text{Frac } R$ is isomorphic to a Weyl skewfield. ■

Example 2.5. The Poisson structure on $A = \mathbb{k}[X_0, X_1]$ given by $\{X_0, X_1\} = X_0X_1$ cannot be obtained by a solvable pair. It follows from Corollary 2.4 since $\text{Frac } A$ (resp. $\text{Frac } R$) cannot contain any Poisson bracket (resp. commutator) equal to 1; see [12] (resp. [1]).

Example 2.6. Let $A = \mathbb{k}[X_0, X_1]$ and set $(\Delta, \Gamma) = (\partial_{X_0}, X_0\partial_{X_0} + X_1^i\partial_{X_1})$ for some integer $i \in \mathbb{N}$. One easily verifies that (Δ, Γ) is a solvable pair on A and that

$$\{X_0, X_1\} = X_1^i \quad \text{and} \quad X_0 * X_1 - X_1 * X_0 = X_1^i = X_1^{*i},$$

where X_1^{*i} denotes the i th power of X_1 with respect to the product $*$. We retrieve the following classical (Poisson) algebras:

$i = 0$, the (Poisson) Weyl algebra,

$i = 1$, the (symmetric) enveloping algebra of the two-dimensional non-abelian Lie algebra,

$i = 2$, the (Poisson) Jordan plane.

Note that the (Poisson) Weyl algebra is classically obtained via the commuting pair of derivations $(\partial_{X_0}, \partial_{X_1})$.

Example 2.7. Let $A = \mathbb{k}[X, Y_1, \dots, Y_n]$ and set $\Delta = \partial_X$ and $\Gamma = X\partial_X + \lambda_1 Y_1 \partial_{Y_1} + \dots + \lambda_n Y_n \partial_{Y_n}$ for some scalars $\lambda_1, \dots, \lambda_n$. Then (Δ, Γ) is a solvable pair on A , and $A_{(\Delta, \Gamma)}$ (resp. $R_{(\Delta, \Gamma)}$) is isomorphic to the symmetric (resp. enveloping) algebra of the solvable Lie algebra $\mathfrak{g}$ with basis $\{x, y_1, \dots, y_n\}$ and Lie brackets

$$[x, y_i] = \lambda_i y_i, \quad [y_i, y_j] = 0, \quad i, j = 1, \dots, n.$$

2.2. Center

In this section, we study the elementary and general properties of solvable pairs related to the center of $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$. As invariant subspaces will often appear in proofs from now on, we recall their definition. For a subspace V of the algebra A and a linear map $f : A \rightarrow A$, we say that V is f -invariant, or that V is invariant under f , if $f(v) \in V$ for any $v \in V$.

Definition 2.8. Let A be a Poisson algebra. The Poisson center of A is the set

$$Z_P(A) = \{z \in A \mid \{z, a\} = 0 \text{ for all } a \in A\}$$

of Poisson central elements. It is a Poisson-commutative subalgebra of A .

Lemma 2.9. Assume that $\Delta \neq 0$ and that $A = A_{(\Delta, \Gamma)}$ is a domain. Set $R = R_{(\Delta, \Gamma)}$.

- (1) Then $\ker \Delta \cap \ker \Gamma \subseteq Z_P(A)$ with equality if $\ker \Delta \neq \ker \Gamma$.
- (2) We have $\ker \Delta \cap \ker \Gamma \subseteq Z(R)$. Moreover, $Z(R) \cap \ker \Delta \subseteq \ker \Gamma$.
- (3) Assume that $\ker \Delta \neq \ker \Gamma$. Then $Z(R) = \ker \Delta \cap \ker \Gamma$.

Proof. (1) The inclusion $\ker \Delta \cap \ker \Gamma \subseteq Z_P(A)$ is clear. Let $z \in Z_P(A)$. First assume that there exists $x \in \ker \Delta \setminus \ker \Gamma$. Then $0 = \{z, x\} = \Delta(z)\Gamma(x)$, which implies $z \in \ker \Delta$. For $y \notin \ker \Delta$, we have $0 = \{y, z\} = \Delta(y)\Gamma(z)$ and so $z \in \ker \Gamma$. Now assume that there exists $x \in \ker \Gamma \setminus \ker \Delta$. Then $0 = \{x, z\} = \Delta(x)\Gamma(z)$ so that $z \in \ker \Gamma$. Since $\ker \Gamma \neq A$ (otherwise $\Gamma = 0$ which implies $\Delta = 0$), we have for any $y \notin \ker \Gamma$ that $0 = \{z, y\} = \Delta(z)\Gamma(y)$ and so $z \in \ker \Delta$.

(2) The inclusion $\ker \Delta \cap \ker \Gamma \subseteq Z(R)$ is clear. Let us now consider $z \in Z(R) \cap \ker \Delta$. Since $\Delta \neq 0$ and Δ is locally nilpotent, there exists $x \in \ker \Delta^2 \setminus \ker \Delta$. We then have $z * x = zx$ since $z \in \ker \Delta$ and $x * z = zx + \Delta(x)\Gamma(z)$ since $x \in \ker \Delta^2$. But $z \in Z(R)$; hence $\Delta(x)\Gamma(z) = 0$ and $\Delta(x) \neq 0$. Thus $\Gamma(z) = 0$.

(3) We first show that $\ker \Delta \not\subseteq \ker \Gamma$. To the contrary, if $\ker \Delta \subseteq \ker \Gamma$, then $\ker \Delta \subsetneq \ker \Gamma$ since $\ker \Delta \neq \ker \Gamma$. Consider $x \in \ker \Gamma \setminus \ker \Delta$ and $n \geq 0$ such that $\Delta^n(x) \neq 0$ and $\Delta^{n+1}(x) = 0$. In particular, $\Delta^n(x) \in \ker \Delta \subseteq \ker \Gamma$. Thus $[\Delta^n, \Gamma](x) = n\Delta^n(x)$ (see Lemma 2.20) implies $\Delta^n(\Gamma(x)) = n\Delta^n(x)$. But $x \in \ker \Gamma$; thus $n\Delta^n(x) = 0$, that is,

$n = 0$ or $\Delta^n(x) = 0$. Since $\Delta^n(x) \neq 0$ by the choice of n , we must have $n = 0$. But then $\Delta(x) = \Delta^{n+1}(x) = 0$, which is absurd. Hence we have $\ker \Delta \not\subseteq \ker \Gamma$ as desired.

Let $x \in \ker \Delta$ be such that $\Gamma(x) \neq 0$ and choose $z \in Z(R)$. Then $x * z = xz$ since $x \in \ker \Delta$. Moreover,

$$0 = z * x - x * z = \sum_{i \geq 1} \Delta^i(z) \binom{\Gamma}{i}(x). \quad (2.10)$$

But $[\Delta, \Gamma] = \Delta$ implies that $\ker \Delta$ is Γ -invariant and hence $\binom{\Gamma}{i}$ -invariant for all $i \geq 1$ (see Lemma A.3). Therefore, we have $\binom{\Gamma}{i}(x) \in \ker \Delta$ for all $i \geq 1$. Let $N \geq 1$ be the smallest positive integer such that $\Delta^N(z) = 0$. Assume that $N \geq 2$. By applying Δ^{N-2} to equation (2.10), we obtain that $\Gamma(x)\Delta^{N-1}(z) = 0$. Since $\Gamma(x) \neq 0$, we get a contradiction. Hence $N = 1$, that is, $z \in \ker \Delta$, and assertion (2) provides us with $z \in \ker \Gamma$. ■

Example 2.11. Recall the derivations $\Delta = \partial_{X_0}$ and $\Gamma = X_0 \partial_{X_0} + X_1^i \partial_{X_1}$ from Example 2.6. One easily demonstrates that $\ker \Delta = \mathbb{k}[X_1]$ and $\ker \Gamma = \mathbb{k}$ so that $Z_P(A) = Z(R) = \mathbb{k}$.

Example 2.12. Recall the derivations $\Delta = \partial_X$ and $\Gamma = X \partial_X + \lambda_1 Y_1 \partial_{Y_1} + \cdots + \lambda_n Y_n \partial_{Y_n}$ from Example 2.7. Then $\ker \Delta = \mathbb{k}[Y_1, \dots, Y_n] \neq \ker \Gamma$ (as long as not all the λ_i are zeros) so that $Z_P(A) = Z(R) = \ker \Delta \cap \ker \Gamma$. Note that to understand

$$\ker \Delta \cap \ker \Gamma = \ker \Gamma|_{\mathbb{k}[Y_1, \dots, Y_n]} = \text{Vect}\{Y_1^{\alpha_1} \cdots Y_n^{\alpha_n} \mid \lambda_1 \alpha_1 + \cdots + \lambda_n \alpha_n = 0, \alpha_i \in \mathbb{N}\},$$

one needs to study the structure of the submonoid $\sum_{i=1}^n \lambda_i \mathbb{N}$ of $(\mathbb{k}, +)$. For instance, if the λ_i are $\mathbb{N}$ -linearly independent, then $Z_P(A) = Z(R) = \mathbb{k}$.

The following example illustrates the fact that when $\ker \Delta = \ker \Gamma$, the inclusion $\ker \Delta \cap \ker \Gamma \subseteq Z_P(A)$ can be strict.

Example 2.13. Let $A = \mathbb{k}[X_0, \dots, X_n]$. For the solvable pair $(\Delta, \Gamma) = (X_0 \partial_{X_1}, X_1 \partial_{X_1})$, we have $A = Z_P(A)$, but $\ker \Delta = \ker \Gamma = \mathbb{k}[X_0, X_2, X_3, \dots, X_n] \subsetneq A$ (see also Corollary 4.8). Similarly, we have $Z(R) = R$, so $Z(R)$ contains strictly $\ker \Delta = \ker \Gamma$.

2.3. Derivation and automorphism

Definition 2.14. Let A be a Poisson algebra.

- (1) A *Poisson derivation* is a derivation δ of A such that for all $a, b \in A$,

$$\delta(\{a, b\}) = \{\delta(a), b\} + \{a, \delta(b)\}.$$

- (2) The set $\text{PDer}(A)$ of Poisson derivations of A is a Lie subalgebra of the Lie algebra of derivations of the associative commutative algebra A .

Let $A = A_{(\Delta, \Gamma)}$. When $\Delta \neq 0$, the Lie algebra $\text{PDer}(A)$ is not reduced to 0, thanks to the following easy lemma.

Lemma 2.15. *The derivation Δ is a Poisson derivation of A .*

Remark 2.16. Poisson center and Poisson derivation are compatible in the following sense. The Poisson center of A is δ -invariant for any Poisson derivation δ .

Note that the map Δ is not a derivation of $R_{(\Delta, \Gamma)}$ in general. The following proposition can be seen as a deformation formula for the Poisson derivation Δ .

Theorem 2.17. *Let (Δ, Γ) be a solvable pair. For $a \in \mathbb{k}$, the map $\phi_a := (\text{id} + \Delta)^a = \sum_{k \geq 0} \binom{a}{k} \Delta^k$ is a (graded if Δ is graded) $\mathbb{k}$ -algebra automorphism of $R = R_{(\Delta, \Gamma)}$. The linear map*

$$\delta = \sum_{r \geq 1} \frac{(-1)^{r-1}}{r} \Delta^r$$

is a (graded if Δ is graded) derivation of R .

Strictly speaking, δ is an element of the formal power series ring $\mathbb{k}[[\Delta]]$. However, since Δ is locally nilpotent, $\delta(f)$ is a well-defined element of R for any $f \in R$.

Proof. We first prove that the map $\phi_1 = \text{id} + \Delta$ is an automorphism of R . For any $f, g \in R$, we obtain, thanks to Lemma A.3 (from line 3 to line 4),

$$\begin{aligned} \phi_1(f) * \phi_1(g) &= \sum_{i \geq 0} \Delta^i(\phi_1(f)) \binom{\Gamma}{i}(\phi_1(g)) \\ &= \sum_{i \geq 0} (\Delta^i(f) + \Delta^{i+1}(f)) \left(\binom{\Gamma}{i}(g) + \binom{\Gamma}{i} \Delta(g) \right) \\ &= f * g + \sum_{i \geq 0} \Delta^{i+1}(f) \binom{\Gamma}{i}(g) + \Delta^i(f) \binom{\Gamma}{i} \Delta(g) \\ &\quad + \Delta^{i+1}(f) \binom{\Gamma}{i} \Delta(g) \\ &= f * g + \sum_{i \geq 0} \Delta^{i+1}(f) \binom{\Gamma}{i}(g) + f * \Delta(g) \\ &\quad + \sum_{i \geq 0} \Delta^{i+1}(f) \left[\Delta, \binom{\Gamma}{i+1} \right](g) \\ &= f * g + \sum_{i \geq 0} \Delta^{i+1}(f) \binom{\Gamma}{i}(g) + f * \Delta(g) \\ &\quad + \sum_{i \geq 0} \Delta^i(f) \left[\Delta, \binom{\Gamma}{i} \right](g) \end{aligned}$$

$$\begin{aligned}
&= f * g + \sum_{i \geq 0} \Delta^{i+1}(f) \binom{\Gamma}{i}(g) + \sum_{i \geq 0} \Delta^i(f) \Delta \binom{\Gamma}{i}(g) \\
&= f * g + \Delta(f * g) \\
&= \phi_1(f * g).
\end{aligned}$$

Therefore, ϕ_1 is a ring endomorphism of R . Moreover, since Δ is locally nilpotent, $\text{id} + \Delta$ is bijective as desired. Consequently, [30, Proposition 2] allows us to conclude that δ is a derivation of R . Hence $a\delta$ is a locally nilpotent derivation of R for any $a \in \mathbb{k}$. So $\exp(a\delta) = (\text{id} + \Delta)^a$ is an automorphism of R .

This last property can also be obtained by a direct computation using the combinatorial relation

$$\begin{aligned}
\sum_{i=0}^u \binom{a}{v+i} \binom{v+i}{i} \binom{v}{u-i} &= \sum_{i=0}^u \frac{a(a-1) \cdots (a-v-i+1)}{i!(v-u+i)!(u-i)!} \\
&= \binom{a}{v} \sum_{i=0}^u \frac{(a-v) \cdots (a-v-i+1)v!}{i!(v-u+i)!(u-i)!} \\
&= \binom{a}{v} \sum_{i=0}^u \binom{a-v}{i} \binom{v}{u-i} = \binom{a}{v} \binom{a}{u},
\end{aligned}$$

where the last equality is the Chu–Vandermonde identity, see Lemma A.1. ■

Lemma 2.18. *For any $a, b \in \mathbb{k}$, we have $\phi_a \circ \phi_b = \phi_{a+b}$. Moreover, if $\Delta \neq 0$, then $\phi_a = \text{id}$ if and only if $a = 0$. When $a \neq 0$, we have $\ker(\phi_a - \text{id})^n = \ker \Delta^n$ for every $n \in \mathbb{N}$.*

Proof. Let $f \in R$. By Lemma A.1 we have

$$\begin{aligned}
\phi_a \circ \phi_b(f) &= \sum_{k, \ell \geq 0} \binom{a}{k} \binom{b}{\ell} \Delta^{k+\ell}(f) = \sum_{u \geq 0} \left(\sum_{k+\ell=u} \binom{a}{k} \binom{b}{\ell} \right) \Delta^u(f) \\
&= \sum_{u \geq 0} \binom{a+b}{u} \Delta^u(f).
\end{aligned}$$

Hence $\phi_a \circ \phi_b(f) = \phi_{a+b}(f)$. When $\Delta \neq 0$, there exists $f \in R$ such that $\Delta^2(f) = 0$ and $\Delta(f) \neq 0$. Then $\phi_a(f) = f + a\Delta(f)$, hence the second assertion is proved.

To prove the last assertion, observe that since Δ is a locally nilpotent derivation, the map $\mathbb{k}[[T]] \rightarrow \text{End}_{\mathbb{k}}(A)$ sending T to Δ is a well-defined $\mathbb{k}$ -algebra homomorphism. In particular, every element of the form $\sum_{k \in \mathbb{N}} a_k \Delta^k$, where $a_k \in \mathbb{k}$ for $k \in \mathbb{N}$, is invertible if $a_0 \neq 0$. Since $(\phi_a - \text{id})^n = (a^n + \sum_{k \geq 1} b_k \Delta^k) \Delta^n$ for some $b_k \in \mathbb{k}$ for all $k \geq 1$, we obtain the result. ■

2.4. A filtration on $R_{(\Delta, \Gamma)}$

It is a classical fact that locally nilpotent derivations induce filtrations on commutative algebras. In this section, we show that the sequence $(\ker \Delta^{i+1})_{i \in \mathbb{N}}$ provides us with a filtration of both the Poisson algebra $A_{(\Delta, \Gamma)}$ and the algebra $R_{(\Delta, \Gamma)}$.

Definition 2.19. Let Δ be a locally nilpotent derivation on A . Set $\varepsilon(0) = -\infty$, and for any nonzero element $f \in A$, define $\varepsilon(f) = \min\{i \in \mathbb{N}, \Delta^{i+1}(f) = 0\}$ and set $A^{\leq i} = \{f \in A, \varepsilon(f) \leq i\} = \ker \Delta^{i+1}$. By convention, set $A^{\leq -1} = \{0\}$.

Note that $\varepsilon = \deg_{\Delta}$ in the notation of [9, Section 1.1.8] which is a degree function, thanks to [19, Proposition 6.1.1], since Δ is locally nilpotent.

Lemma 2.20. For any polynomial $P \in \mathbb{k}[T]$, we have $[P(\Delta), \Gamma] = Q(\Delta)$, where $Q = TP'$. In particular, for any integer $i \geq 0$, we have $\Delta^i \Gamma = \Gamma \Delta^i + i \Delta^i$.

Proof. By linearity, it is enough to prove the relation for $P = T^i$, where $i \in \mathbb{N}$, which is easily obtained by induction. ■

Lemma 2.21. Let (Δ, Γ) be a solvable pair on A and fix integers $i, j \geq 0$.

- (1) We have $\Delta(A^{\leq i}) \subseteq A^{\leq i-1}$, that is, $\varepsilon(\Delta(f)) \leq \varepsilon(f) - 1$ for every $f \in A$, with equality for $f \in A \setminus \ker \Delta$.
- (2) We have $\Gamma(A^{\leq i}) \subseteq A^{\leq i}$. Hence $\varepsilon(P(\Gamma)(f)) \leq \varepsilon(f)$ for every $f \in A$ and $P \in \mathbb{k}[T]$.
- (3) For any $f, g \in A$, we have

$$f * g - g * f = \Delta(f)\Gamma(g) - \Delta(g)\Gamma(f) + \sum_{i \geq 2} \left(\Delta^i(f) \binom{\Gamma}{i}(g) - \Delta^i(g) \binom{\Gamma}{i}(f) \right).$$

In particular, if $\varepsilon(f) = i$ and $\varepsilon(g) = j$, then $\varepsilon(f * g - g * f) \leq i + j - 1$.

- (4) Assume that A is a domain. If $f, g \in A$ are such that $\varepsilon(f) = i$ and $\varepsilon(g) = j$, then $\varepsilon(fg) = i + j$.

Proof. Assertion (1) is obvious since $\Delta(f) \in \ker \Delta^{i-1}$ if and only if $f \in \ker \Delta^i$; also see [9, Proposition 1.10(a)]. Assertion (2) follows from Lemma 2.20 which shows that $\ker \Delta^i$ is Γ -invariant, hence $P(\Gamma)$ -invariant for every polynomial $P \in \mathbb{k}[T]$. Assertion (3) follows from (1.2) and assertions (1) and (2). Assertion (4) is true since from Leibniz formula, we get $\Delta^{i+j+1}(fg) = 0$ and $\Delta^{i+j}(fg) = \binom{i+j}{i} \Delta^i(f) \Delta^j(g) \neq 0$ because A is a domain and $\text{char } \mathbb{k} = 0$. ■

Let $(T^{\leq i})_{i \in \mathbb{N}}$ be a filtration of an algebra T . The associated graded algebra $\text{gr}(T) = \bigoplus T^{\leq i} / T^{\leq i-1}$ is an $\mathbb{N}$ -graded algebra whose homogeneous elements of degree i are denoted by $x + T^{\leq i-1}$ for an element $x \in T^{\leq i} \setminus T^{\leq i-1}$. By convention set $T^{\leq -1} = \{0\}$

whenever $i < 0$. Let $k \geq 0$ be an integer. A linear map $u : T \rightarrow T$ satisfying $u(T^{\leq i}) \subset T^{\leq i-k}$ for all $i \geq 0$ induces a well-defined linear map $\bar{u} : \text{gr}(T) \rightarrow \text{gr}(T)$ as follows. Define $\bar{u}$ on homogeneous elements by $\bar{u}(x + T^{\leq i-1}) = u(x) + T^{\leq i-k-1}$ and extend by linearity to $\text{gr}(T)$. Since $\bar{u}(T^{\leq i} / T^{\leq i-1}) \subset T^{\leq i-k} / T^{\leq i-k-1}$, we say that $\bar{u}$ is a homogeneous map of degree $-k$. Note that $\bar{u}$ is a derivation of $\text{gr}(T)$ when u is a derivation of T ; see, for instance, [9, Section 1.1.6].

Proposition 2.22. *Assume that A is a domain.*

- (1) *The family $(A^{\leq i})_{i \geq 0}$ is a Poisson algebra filtration of $A_{(\Delta, \Gamma)}$ of degree -1 , meaning that it is an algebra filtration of A together with $\{A^{\leq i}, A^{\leq j}\} \subseteq A^{\leq i+j-1}$ for all integers $i, j \geq 0$. Moreover, the associated graded algebra $\text{gr}(A)$ is a domain.*
- (2) *The family $(A^{\leq i})_{i \geq 0}$ is an algebra filtration of $R_{(\Delta, \Gamma)}$. Moreover, the associated graded algebra $\text{gr}(R)$ is equal to $\text{gr}(A)$.*
- (3) *The commutative algebra $\text{gr}(R) = \text{gr}(A)$ can be endowed with the following three Poisson brackets:*

- (a) $\{\bar{f}, \bar{g}\}' := (f * g - g * f) + A^{\leq i+j-2}$,
- (b) $\{\bar{f}, \bar{g}\}'' := \{f, g\} + A^{\leq i+j-2}$,
- (c) $\{\bar{f}, \bar{g}\}''' := \bar{\Delta}(\bar{f})\bar{\Gamma}(\bar{g}) - \bar{\Gamma}(\bar{f})\bar{\Delta}(\bar{g}) \in A^{\leq i+j-1} / A^{\leq i+j-2}$

for homogeneous elements $\bar{f}$ and $\bar{g}$ of respective ε -degree i and j . In (c), the pair of maps $(\bar{\Delta}, \bar{\Gamma})$ is the solvable pair of homogeneous derivations of $\text{gr}(A)$ of respective degree -1 and 0 which is induced by the solvable pair (Δ, Γ) of A .

- (4) *The Poisson structures defined in (3) are all equal and make $\text{gr}(A) = \text{gr}(R)$ into a graded Poisson algebra of degree -1 .*

Proof. (1) The fact that $(A^{\leq i})_{i \geq 0}$ is an algebra filtration of A is an easy consequence of Leibniz formula; see [9, Section 1.1.8] for instance. It is a Poisson filtration of degree -1 , thanks to equation (1.1) and assertions (1) and (2) of Lemma 2.21. Moreover, $\text{gr}(A)$ is a domain, thanks to assertion (4) of Lemma 2.21.

(2) The fact that $(A^{\leq i})_{i \geq 0}$ is an algebra filtration of $R_{(\Delta, \Gamma)}$ follows from equation (1.2) since the degree ε is decreased by Δ and preserved by Γ , thanks to Lemma 2.21. More precisely, if $f, g \in A$ are such that $\varepsilon(f) = i$ and $\varepsilon(g) = j$, then $f * g = fg + u$ for some $u \in A^{\leq i+j-1}$. This also implies that the associated graded algebras $\text{gr}(A)$ and $\text{gr}(R)$ have the same multiplication so that they are indeed equal.

(3) The fact that $\{-, -\}'$ is a Poisson bracket on $\text{gr}(R)$ follows from the filtered version of the semiclassical limit construction; see [11, Section 2.4]. The fact that $\{-, -\}''$ is a well-defined biderivation satisfying the Jacobi identity on $\text{gr}(A)$ follows by tedious but straightforward computation from the fact that $\{-, -\}$ is a filtered Poisson bracket on A . Finally, $\{-, -\}'''$ is a Poisson bracket since it is easily verified that $(\bar{\Delta}, \bar{\Gamma})$ is a solvable pair of derivations of $\text{gr}(A)$.

(4) The Poisson brackets $\{-, -\}'$ and $\{-, -\}''$ are the same since both $f * g - g * f$ and $\{f, g\}$ belong to $A^{\leq i+j-1}$ combined with $f * g - g * f - \{f, g\} \in A^{\leq i+j-2}$ thanks to assertion (4) of Lemma 2.21. Finally, for homogeneous elements $\bar{f}$ and $\bar{g}$ of ε -degree i and j , we have

$$\begin{aligned} \{\bar{f}, \bar{g}\}''' &= \bar{\Delta}(\bar{f})\bar{\Gamma}(\bar{g}) - \bar{\Gamma}(\bar{f})\bar{\Delta}(\bar{g}) \\ &= (\Delta(f) + A^{\leq i-2})(\Gamma(g) + A^{\leq i-1}) - (\Delta(g) + A^{\leq i-2})(\Gamma(f) + A^{\leq i-1}) \\ &= (\Delta(f)\Gamma(g) + A^{\leq i+j-2}) - (\Delta(g)\Gamma(f) + A^{\leq i+j-2}) \\ &= (\Delta(f)\Gamma(g) - \Delta(g)\Gamma(f)) + A^{\leq i+j-2} \\ &= \{f, g\} + A^{\leq i+j-2} \\ &= \{\bar{f}, \bar{g}\}'' . \end{aligned}$$

Hence $\{-, -\}''$ and $\{-, -\}'''$ are the same. ■

In fact, it is enough to assume that $\ker \Delta$ is a domain to obtain that R is a domain. More precisely, we have the following corollary.

Corollary 2.23. *The following assertions are equivalent:*

- (1) $\ker \Delta$ is a domain,
- (2) A is a domain,
- (3) $\text{gr}(A) = \text{gr}(R)$ is a domain,
- (4) R is a domain.

Proof. (2) $\Rightarrow$ (3) is part of assertion (1) of Proposition 2.22.

(3) $\Rightarrow$ (4) is classical.

(4) $\Rightarrow$ (1) since $\ker \Delta$ is a subring of R .

(1) $\Rightarrow$ (2) With the notation of the proof of assertion (4) of Lemma 2.21, we have $\Delta^i(f) \in \ker \Delta$ and $\Delta^j(g) \in \ker \Delta$. So $\binom{i+j}{i} \Delta^i(f) \Delta^j(g) \neq 0$ implies that $\Delta^{i+j}(fg) \neq 0$, hence $fg \neq 0$. ■

Example 2.24. Consider the solvable pair on $A = \mathbb{k}[X_0, X_1]$ given by $\Delta = X_0 \partial_{X_1}$ and $\Gamma = a X_0 \partial_{X_0} + (a+1) X_1 \partial_{X_1}$ for $a \in \mathbb{k}$. We have $A^{\leq i} = \ker \Delta^{i+1} = \bigoplus_{\ell \leq i} \mathbb{k}[X_0] X_1^\ell$. Then $\text{gr}(A) = \bigoplus_{i \geq 0} A^{\leq i} / A^{\leq i-1} \cong \bigoplus_{i \geq 0} \mathbb{k}[X_0] X_1^i \cong A$. Observe that $X_0 \in A^{\leq 0}$ and $X_1 \in A^{\leq 1}$ and

$$X_0 * X_1 - X_1 * X_0 = -a X_0 * X_0 \in A^{\leq 0}$$

so that the induced Poisson bracket on $\text{gr}(A)$ is given by

$$\{X_0 + A^{\leq -1}, X_1 + A^{\leq 0}\} = -a X_0 * X_0 + A^{\leq -1}.$$

In the previous example, $\text{gr}(A)$ is isomorphic to A as a Poisson algebra. This is not always the case as the following example demonstrates.

Example 2.25. Consider the solvable pair on $A = \mathbb{k}[X_0, X_1, X_2]$ given by $\Delta = X_0\partial_{X_1}$ and $\Gamma = aX_0\partial_{X_0} + (a+1)X_1\partial_{X_1} + (aX_2 + X_0)\partial_{X_2}$. Since $\ker \Delta = \mathbb{k}[X_0, X_2]$, it is clear that $\text{gr}(A) \cong A$. The induced solvable pair on $\text{gr}(A)$ is given by $\overline{\Delta} = X_0\partial_{X_1}$ and $\overline{\Gamma} = aX_0\partial_{X_0} + (a+1)X_1\partial_{X_1} + aX_2\partial_{X_2}$. Despite being isomorphic as associative algebras, $\text{gr}(A)$ and A are not isomorphic as Poisson algebras, thanks to Corollary 6.14.

The following example focuses on the associative structure of $\text{gr}(A)$. To lighten notation, we denote by $\text{gr}(f) = f + A^{\leq i-1}$ the image in $\text{gr}(A)$ of any element $f \in A$ with $\varepsilon(f) = i \in \mathbb{N}$.

Example 2.26. Consider the derivation $\Delta = X_0\partial_{X_1} + X_1\partial_{X_2}$ of $A = \mathbb{k}[X_0, X_1, X_2]$. It is classical that $A^{\leq 0} = \ker \Delta = \mathbb{k}[X_0, F_2]$, where $F_2 = 2X_0X_2 - X_1^2$; see, for instance, [19, Example 6.7.1]. Recall that $\varepsilon(fg) = \varepsilon(f) + \varepsilon(g)$ and that $\varepsilon(X_k) = k$ for $k \in \{0, 1, 2\}$. Therefore, for all $i \geq 1$, we have $\varepsilon(X_1X_2^{i-1}) = 2i - 1$ and $\varepsilon(X_2^i) = 2i$. Hence the family $\mathcal{B} = (1, X_1X_2^{i-1}, X_2^{2i})_{i \geq 1}$ is free over $A^{\leq 0}$. Moreover, observe that the Hilbert series of $A^{\leq 0} \bigoplus_{i \geq 1} (A^{\leq 0}X_1X_2^{i-1} \oplus A^{\leq 0}X_2^i)$ is the same as that of $\mathbb{k}[X_0, X_1, X_2]$. Hence $\mathcal{B}$ is a basis of $\mathbb{k}[X_0, X_1, X_2]$ over $A^{\leq 0}$. This implies that $\text{gr}(A) = A^{\leq 0} \oplus \bigoplus_{i \geq 1} A^{\leq 0} \text{gr}(X_1X_2^{i-1}) \oplus A^{\leq 0} \text{gr}(X_2^i)$. Observe that $\text{gr}(X_2) \in \text{gr}(A)$ generates a polynomial ring over $A^{\leq 0}$ and that we have the relation $X_1^2 = 2X_0X_2 - F_2$. Therefore, $\text{gr}(A) \cong k[X_0, F_2, X_2][T]/(T^2 - (2X_0X_2 - F_2)) \cong k[X_0, X_2, T] \cong A$ since $T^2 - (2X_0X_2 - F_2)$ is a degree one polynomial in F_2 .

Although this is true in the three preceding examples, it is unclear to us whether or not $\text{gr}(A) \cong A$ in general. We will define in Section 4.3 a finer filtration for which it is always true.

2.5. Normal elements

The filtration introduced in the previous section allows us to study Poisson automorphisms and Poisson derivations of $\text{gr}(R) = \text{gr}(A)$ induced by (strongly) normal elements of R . This will be useful in Section 8. Recall that if σ and τ are endomorphisms of a ring T , a (σ, τ) -derivation of T is an endomorphism δ of T such that $\delta(rs) = \sigma(r)\delta(s) + \delta(r)\tau(s)$ for all $r, s \in T$.

Lemma 2.27. *Let (Δ, Γ) be a solvable pair on A and consider an automorphism Φ of $R = (A, *)$ that is compatible with the filtration ε , that is, such that $\varepsilon(\Phi(f)) = \varepsilon(f)$ for all $f \in R$. Then Φ induces a Poisson automorphism $\overline{\Phi}$ of $\text{gr}(R) = \text{gr}(A)$ given by $\overline{\Phi}(f + A^{\leq i-1}) = \Phi(f) + A^{\leq i-1}$ for all $f \in R$ with $\varepsilon(f) = i$. Moreover, if $\overline{\Phi} = \text{id}$, then $\Phi - \text{id}$ induces a Poisson derivation of $\text{gr}(R) = \text{gr}(A)$ of degree -1 .*

Proof. Since $\varepsilon(\Phi(f)) = \varepsilon(f)$ for all $f \in R$, it is clear that $\overline{\Phi}$ is a well-defined automorphism of $\text{gr}(R)$. Consider $f, g \in R$ such that $\varepsilon(f) = i$ and $\varepsilon(g) = j$ and denote by $\overline{f}, \overline{g}$

their images in $\text{gr}(R)$. We have

$$\begin{aligned}\overline{\Phi}(\{\overline{f}, \overline{g}\}) &= \overline{\Phi}(f * g - g * f + A^{\leq i+j-2}) \\ &= \Phi(f) * \Phi(g) - \Phi(g) * \Phi(f) + A^{\leq i+j-2} \\ &= \{\overline{\Phi}(\overline{f}), \overline{\Phi}(\overline{g})\},\end{aligned}$$

hence $\overline{\Phi}$ is a Poisson automorphism of $\text{gr}(A)$.

The equality $\overline{\Phi} = \text{id}$ means that if $\varepsilon(f) = i$, then $\varepsilon(\Phi(f) - f) \leq i - 1$. Hence $\Phi - \text{id}$ induces a well-defined vector space endomorphism $\overline{\Phi - \text{id}}$ of $\text{gr}(R)$ of degree -1 by setting $\overline{(\Phi - \text{id})(f)} = \Phi(f) - f + A^{\leq i-2}$ for all $\overline{f} \in \text{gr}(R)$, where $f \in R$ is such that $\varepsilon(f) = i$. By definition, we have $\overline{(\Phi - \text{id})(\{\overline{f}, \overline{g}\})} = (\Phi - \text{id})(f * g - g * f) + A^{\leq i+j-3}$. Since $\Phi - \text{id}$ is both a (Φ, id) -derivation and a (id, Φ) -derivation of R , we obtain

$$\begin{aligned}(\Phi - \text{id})(f * g - g * f) &= (\Phi(f) * (\Phi(g) - g) - (\Phi(g) - g) * \Phi(f)) \\ &\quad + ((\Phi(f) - f) * g - g * (\Phi(f) - f)).\end{aligned}$$

Hence $\overline{(\Phi - \text{id})(\{\overline{f}, \overline{g}\})} = \{\overline{\Phi}(\overline{f}), \overline{(\Phi - \text{id})(\overline{g})}\} + \{(\overline{\Phi - \text{id}})(\overline{f}), \overline{g}\}$, and we get the result using the fact that $\overline{\Phi} = \text{id}$. ■

Definition 2.28. Let T be a $\mathbb{k}$ -algebra that is a domain, and let $N \in T$ be a normal element. For every $u \in T$, there exists a unique element $\Phi(u) \in T$ such that $uN = N\Phi(u)$. Then Φ is a $\mathbb{k}$ -algebra automorphism of T and is called the automorphism associated with N and denoted by Φ_N .

Lemma 2.29. Let (Δ, Γ) be a solvable pair on a domain A and consider $R = (A, *)$. Let N be a normal element in R and consider Φ_N its associated automorphism. We denote by $\overline{N}$ the image of N in $\text{gr}(R)$. Then Φ_N is compatible with ε . Moreover, $\overline{\Phi_N} = \text{id}$, and $\overline{(\Phi_N - \text{id})}$ verifies that $\overline{N} \overline{(\Phi_N - \text{id})} = \{\cdot, \overline{N}\}$. In particular, $\overline{N}$ is Poisson normal in $\text{gr}(R)$.

Proof. Let $f \in R$ and set $i = \varepsilon(f)$ and $j = \varepsilon(N)$. Since $f * N = N * \Phi_N(f)$ and A is a domain, we have $i + j = \varepsilon(\Phi_N(f)) + j$. Therefore, Φ_N is compatible with ε .

The definition of the product $*$ implies that $f * N = fN + u$, where $u \in A^{\leq i+j-1}$. Similarly, $N * \Phi_N(f) = N\Phi_N(f) + v$, where $v \in A^{\leq i+j-1}$. Hence $N(\Phi_N(f) - f) \in A^{\leq i+j-1}$. Since A is a domain, we obtain that $\Phi_N(f) - f \in A^{\leq i-1}$, that is, $\overline{\Phi_N} = \text{id}$. Moreover, we have the following equalities:

$$0 = N * \Phi_N(f) - f * N = N(\Phi_N(f) - f) + \Delta(N)\Gamma(\Phi_N(f)) - \Delta(f)\Gamma(N) + u$$

for some $u \in A^{\leq i+j-2}$. Hence $N(\Phi_N(f) - f) = \Delta(f)\Gamma(N) - \Delta(N)\Gamma(\Phi_N(f)) - u$ with $\Delta(f)\Gamma(N) - \Delta(N)\Gamma(\Phi_N(f)) \in A^{\leq i+j-1}$ since Φ_N is compatible with ε . This implies the desired equality since $\overline{\Phi_N} = \text{id}$. ■

Definition 2.30 (Strongly normal element). Let (Δ, Γ) be a solvable pair on A . An element $f \in A$ is said to be strongly normal if $\Delta(f) = 0$ and there exists $\alpha \in \mathbb{k}$ such that $\Gamma(f) = \alpha f$.

Lemma 2.31. *Let (Δ, Γ) be a solvable pair on A . If f is strongly normal in A , then f is normal in R as well as Poisson normal in A . Set $\Gamma(f) = \alpha f$, where $\alpha \in \mathbb{k}$. If A is a domain, then the automorphism of R associated with f is ϕ_α (see Theorem 2.17), the Poisson derivation $\{-, f\}$ associated with f is $\alpha\Delta$ and we have $\overline{(\phi_\alpha - \text{id})} = \alpha\overline{\Delta}$ as derivations of $\text{gr}(A)$.*

Proof. Since $f \in \ker \Delta$, we have $f * g = fg$ for all $g \in R$, hence $f * R = fA$. Also we have

$$g * f = \sum_{k \geq 0} \Delta^k(g) \binom{\Gamma}{k}(f) = \sum_{k \geq 0} \Delta^k(g) \binom{\alpha}{k} f = f \sum_{k \geq 0} \binom{\alpha}{k} \Delta^k(g) = f \phi_\alpha(g).$$

Recall from Theorem 2.17 that ϕ_α is an automorphism of R . Hence the equality $g * f = f \phi_\alpha(g)$ implies that $R * f = Af$. Therefore, we have $f * R = fA = R * f$ and f is normal in R . Moreover, for every $g \in A$, we have $\{g, f\} = \Delta(g)\Gamma(f) - \Gamma(g)\Delta(f) = \alpha f \Delta(g) \in fA$, and we conclude that f is Poisson normal and that the Poisson derivation associated with f is $\alpha\Delta$.

Assume that A is a domain. Since $f \in \ker \Delta$ and $\Gamma(f) = \alpha f$, we have $\overline{\Delta}(f) = 0$ and $\overline{\Gamma}(f) = \alpha \overline{f}$. Hence we obtain $\{\overline{g}, \overline{f}\} = \alpha \overline{\Delta}(\overline{g}) \overline{f}$. Thanks to Lemma 2.29, we have $\{\overline{g}, \overline{f}\} = \overline{(\phi_\alpha - \text{id})}(\overline{g}) \overline{f}$. Since $\text{gr}(A)$ is a domain, we obtain the relation $\overline{(\phi_\alpha - \text{id})} = \alpha \overline{\Delta}$. ■

The converse of Lemma 2.31 will be proved in Section 5: in the case of a linear solvable pair, every normal element in R or Poisson normal element in A is strongly normal (Proposition 5.7).

2.6. A canonical form up to localization

It is well known that locally nilpotent derivations with slices feature very interesting properties. For instance, if A is a $\mathbb{k}$ -algebra that is a domain and Δ is a locally nilpotent derivation of A admitting an element $s \in A$ such that $\Delta(s) = 1$ (s is called a slice for Δ), then A is a polynomial ring in the variable s over the base ring $A^\Delta = \ker \Delta$; see [6, 27]. In this section, we exploit this fact to show that, up to localization, the algebras $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$ are (Poisson-) Ore extensions of the (localized) kernel of Δ by the (Poisson) derivation Γ .

Let (Δ, Γ) be a solvable pair on A with $\Delta \neq 0$ and choose $r \in A$ such that $\Delta(r) \neq 0$ and $\Delta^2(r) = 0$ (any element of $A^{\leq 1} \setminus A^{\leq 0}$). We consider the localization $A^\circ = S_r^{-1}A$, where $S_r = \{\Delta(r)^i \mid i \geq 0\}$. The pair of derivations (Δ, Γ) extends uniquely by localization into a solvable pair of derivations on A° , again denoted by (Δ, Γ) . Note that Δ is

locally nilpotent on A° since $\Delta(r) \in A^\Delta$. Observe that the element $s := r\Delta(r)^{-1} \in A^\circ$ is a slice for Δ since

$$\Delta(s) = \Delta(r)\Delta(r)^{-1} - r\Delta(r)^{-2}\Delta^2(r) = 1.$$

2.6.1. The Poisson case. We consider the Poisson algebra $(A^\circ)_{(\Delta, \Gamma)}$ arising from the solvable pair (Δ, Γ) on A° . Note that the kernel $(A^\circ)^\Delta$ is a Poisson-commutative subalgebra of A° that is Γ -invariant since for any $a \in (A^\circ)^\Delta$, $\Delta\Gamma(a) = \Gamma\Delta(a) + \Delta(a) = 0$. Hence Γ induces a Poisson derivation of $(A^\circ)^\Delta$. This allows us to define the so-called Poisson–Ore extension $(A^\circ)^\Delta[X; \Gamma]_P$ which is equal to the polynomial ring $(A^\circ)^\Delta[X]$ as a commutative algebra and whose Poisson bracket is defined to be the unique extension of the Poisson bracket of $(A^\circ)^\Delta$ such that $\{X, a\} = \Gamma(a)$ for all $a \in (A^\circ)^\Delta$; see [20].

Proposition 2.32. *The map $\phi : (A^\circ)^\Delta[X; \Gamma]_P \rightarrow (A^\circ)_{(\Delta, \Gamma)}$ given by*

$$\phi\left(\sum_{i=0}^n a_i X^i\right) = \sum_{i=0}^n a_i s^i,$$

where $a_i \in (A^\circ)^\Delta$ for all i , is a Poisson algebra isomorphism.

Proof. The inclusion $(A^\circ)^\Delta \rightarrow A^\circ$ is a Poisson algebra homomorphism. Moreover, for $a \in (A^\circ)^\Delta$, we have $\{s, a\} = \Delta(s)\Gamma(a) - \Gamma(s)\Delta(a) = \Gamma(a)$ since $\Delta(s) = 1$. Thanks to the universal property of the Poisson–Ore extension $((A^\circ)^\Delta)[X; \Gamma]_P$ (see [15, Proposition 1.1.15]), there exists a unique Poisson algebra homomorphism from $((A^\circ)^\Delta)[X; \Gamma]_P$ to $(A^\circ)_{(\Delta, \Gamma)}$ sending $a \in (A^\circ)^\Delta$ to a and X to s . It is given by ϕ . Since $A^\circ = (A^\circ)^\Delta[s]$ is a polynomial ring in the slice s over $(A^\circ)^\Delta$ [27, Corollary 1.2], it is clear that ϕ is an isomorphism. ■

2.6.2. The noncommutative case. We consider the algebra $R^\circ = (R^\circ)_{(\Delta, \Gamma)} = (A^\circ, *)$ arising from the solvable pair (Δ, Γ) on A° . Recall that

$$a * b = ab + \sum_{i \geq 1} \Delta^i(a) \binom{\Gamma}{i}(b)$$

for all $a, b \in A^\circ$. In particular, $(A^\circ)^\Delta$ is a commutative subalgebra of R° . Since Γ leaves $(A^\circ)^\Delta$ invariant, we can consider the Ore extension $(A^\circ)^\Delta[X; \Gamma]$ which is, by definition [13, Chapter 2], a free left $(A^\circ)^\Delta$ -module with basis $\{X^i \mid i \geq 0\}$ and whose multiplication extends the multiplication of $(A^\circ)^\Delta$ by the rule $Xa = aX + \Gamma(a)$ for all $a \in (A^\circ)^\Delta$. For all integers $i \geq 0$, let us denote by s^{*i} the i th power of s with respect to the product $*$.

Proposition 2.33. *The map $\phi : (A^\circ)^\Delta[X; \Gamma] \rightarrow R^\circ$ given by*

$$\phi\left(\sum_{i=0}^n a_i X^i\right) = \sum_{i=0}^n a_i s^{*i},$$

where $a_i \in (A^\circ)^\Delta$ for all i , is an algebra isomorphism.

Proof. The inclusion map $(A^\circ)^\Delta \subseteq R^\circ$ is an algebra homomorphism. Moreover, for $a \in (A^\circ)^\Delta$, we have $a * s = as$ and $s * a = sa + \Gamma(a)$ since $\Delta(s) = 1$ and $\Delta^2(s) = 0$. Hence from the universal property (see [13, Exercise 2.F]) of $(A^\circ)^\Delta[X; \Gamma]$, there exists a unique algebra homomorphism from $(A^\circ)^\Delta[X; \Gamma]$ to R° sending $a \in (A^\circ)^\Delta$ to $a \in R^\circ$ and X to s . It is given by ϕ . So it remains to show that ϕ is bijective. For this, we will show by induction on $i \geq 0$ that there exist elements $a_{j,i} \in (A^\circ)^\Delta$ with $0 \leq j < i$ such that $s^{*i} = s^i + \sum_{j=0}^{i-1} a_{j,i} s^j$. Cases $i = 0$ and $i = 1$ are trivial. Recall that $\Delta(s) = 1$ and $\Delta^2(s) = 0$ in order to compute $s^{*(i+1)}$:

$$\begin{aligned}
 s^{*(i+1)} &= s * s^{*i} \\
 &= s * s^i + s * \sum_{j=0}^{i-1} a_{j,i} s^j = s^{i+1} + \Gamma(s^i) + \sum_{j=0}^{i-1} a_{j,i} s^{j+1} + \sum_{j=0}^{i-1} \Gamma(a_{j,i} s^j) \\
 &= s^{i+1} + i(\Gamma(s) - s)s^{i-1} + i s^i + \sum_{j=1}^i a_{j-1,i} s^j + \sum_{j=0}^{i-1} \Gamma(a_{j,i}) s^j \\
 &\quad + \sum_{j=0}^{i-1} a_{j,i} \Gamma(s^j) \\
 &= s^{i+1} + i(\Gamma(s) - s)s^{i-1} + \sum_{j=0}^i b_{j,i} s^j + \sum_{j=0}^{i-1} j a_{j,i} (\Gamma(s) - s) s^{j-1} \\
 &\quad + \sum_{j=0}^{i-1} j a_{j,i} s^j,
 \end{aligned}$$

where the $b_{j,i}$ for $0 \leq j \leq i$ are elements of $(A^\circ)^\Delta$ expressed in terms of i , $a_{j-1,i}$ and $\Gamma(a_{j,i})$. Moreover, we have $\Delta(\Gamma(s) - s) = \Gamma\Delta(s) = \Gamma(1) = 0$. Hence $\Gamma(s) - s \in (A^\circ)^\Delta$ and $s^{*(i+1)}$ has the desired form. We then deduce that $(s^{*i})_{i \geq 0}$ is a basis of R° over $(A^\circ)^\Delta$ since $(s^i)_{i \geq 0}$ is [27, Corollary 1.2], and we conclude that ϕ is bijective. ■

2.7. Skewfield of fractions

When A is a polynomial ring and the action of Γ is diagonal, the results of the previous section allow us to relate R° to a particular Lie algebra and to describe the skewfield of fractions of $R_{(\Delta, \Gamma)}$. Recall that, given a field F , the Weyl skewfield $D_1(F)$ is the skewfield of fractions of the algebra generated over F by two elements u and v such that $uv - vu = 1$. Linear diagonalizable solvable pairs will be defined in Section 6.

Proposition 2.34. *Assume that A is a polynomial ring and that (Δ, Γ) is a nonzero linear diagonalizable solvable pair on A . Then $R_{(\Delta, \Gamma)}$ is, up to localization, isomorphic to the enveloping algebra of a completely solvable Lie algebra $\mathfrak{g}$. In particular, if $\mathfrak{g}$ is algebraic and non-abelian, the skewfield of fractions of $R_{(\Delta, \Gamma)}$ is isomorphic to the Weyl skewfield $D_1(F)$ for a purely transcendental extension F of $\mathbb{k}$.*

Proof. Since $\Delta(X_1) = X_0$ and $\Delta(X_0) = 0$, we can apply the slice construction with the element $s = X_1 X_0^{-1}$ of $A^\circ = A[X_0^{-1}]$. In particular, the map $\pi : A^\circ \rightarrow A^\circ$ given by $\pi(a) = \sum_{p \geq 0} \frac{(-s)^p}{p!} \Delta^p(a)$ is an algebra homomorphism such that $(A^\circ)^\Delta = \pi(A^\circ)$; see [27]. Therefore, the algebra $(A^\circ)^\Delta$ is generated by elements $Y_0^{\pm 1}, Y_2, \dots, Y_n$, where Y_i denotes the image of X_i by π (note that $\pi(X_0) = X_0$ and $\pi(X_1) = 0$). Observe that $\{Y_0, Y_2, \dots, Y_n\}$ is a set of algebraically independent elements of A° since, for $i \geq 2$, we can write $Y_i = \pi(X_i) = X_i + F_i$, where $F_i \in \mathbb{k}[X_0^{\pm 1}, X_1, \dots, X_{i-1}]$. Moreover, each Y_i is an eigenvector for Γ because one can verify that Γ and π commute, thanks to the equality $\Delta\Gamma - \Gamma\Delta = \Delta$.

Denote by $\mathfrak{g}$ the completely solvable Lie algebra with basis $\{y_0, y_2, \dots, y_n, x\}$ and nonzero brackets $[x, y_i] = \lambda_i y_i$ for all i , where $\lambda_i \in \mathbb{k}$ is the eigenvalue of Y_i (equivalently X_i) for Γ . The element y_0 is normal in $U(\mathfrak{g})$, and it is clear that $(A^\circ)^\Delta[X; \Gamma]$ is isomorphic to the localization $U(\mathfrak{g})[y_0^{-1}]$. The first part of the proof is now complete since $R^\circ \cong (A^\circ)^\Delta[X; \Gamma]$, thanks to Proposition 2.33.

The second assertion follows first from [18]: skewfields of fractions of enveloping algebras of algebraic completely solvable Lie algebras are isomorphic to Weyl skewfields. Moreover, the transcendence degree of the center of the enveloping skewfield of $\mathfrak{g}$ is equal to the index of $\mathfrak{g}$ whose value can be easily computed to be $n - 1$, thanks to [21]. The result follows. ■

Remark 2.35. With similar arguments (using [26]), the following Poisson version can be obtained: under the assumption of Proposition 2.34, the Poisson field of $A_{(\Delta, \Gamma)}$ is isomorphic to a Poisson Weyl field over a purely transcendental extension F of $\mathbb{k}$, that is, a rational function field $F(U, V)$ with $\{U, V\} = 1$.

3. The rank of $A_{(\Delta, \Gamma)}$

We recall the notion of rank of an affine Poisson variety following [29]. Let $V = \mathbb{k}^{n+1}$ be a Poisson variety, that is, an affine variety V whose coordinate ring $A = \mathcal{O}(\mathbb{k}^{n+1}) = \mathbb{k}[X_0, \dots, X_n]$ is endowed with a Poisson structure. The Poisson matrix of A is the skew-symmetric matrix $\Pi(A) = (\{X_i, X_j\})_{0 \leq i, j \leq n}$. For any $p \in V$, the rank $\text{Rk}_p(A)$ of the Poisson bracket at p is the rank of the Poisson matrix $\Pi(A)$ evaluated at p . Finally, we define the rank of A to be the maximum of the $\text{Rk}_p(A)$ for $p \in V$. Note that A is Poisson commutative if and only if its rank is zero. If (Δ, Γ) is a solvable pair on A , we have

$$\Pi(A_{(\Delta, \Gamma)}) = \begin{pmatrix} \Delta(X_0) \\ \Delta(X_1) \\ \vdots \\ \Delta(X_n) \end{pmatrix} \begin{pmatrix} \Gamma(X_0) \\ \Gamma(X_1) \\ \vdots \\ \Gamma(X_n) \end{pmatrix}^T - \begin{pmatrix} \Gamma(X_0) \\ \Gamma(X_1) \\ \vdots \\ \Gamma(X_n) \end{pmatrix} \begin{pmatrix} \Delta(X_0) \\ \Delta(X_1) \\ \vdots \\ \Delta(X_n) \end{pmatrix}^T.$$

Therefore, when $A_{(\Delta, \Gamma)}$ is not Poisson commutative, its rank is equal to two. When Δ and Γ are linear, the algebra $A_{(\Delta, \Gamma)}$ is the semiclassical limit of the AS regular algebra $R_{(\Delta, \Gamma)}$ (see Corollary 5.6), which explains the title of the article.

Note that, since the rank of a Poisson algebra A is invariant under isomorphism, thanks to [29, Proposition 2.17], there exist Poisson brackets that cannot be obtained from solvable pairs since Poisson structures with higher ranks do exist. Moreover, even in rank two, it is not possible to obtain every Poisson structure, not even homogeneous ones, from a solvable pair; see Example 2.5.

4. Linear solvable pairs

From this section onward until the end of this article, we focus on the case of linear solvable pairs on polynomial algebras. Recall that the polynomial algebra $A = \mathbb{k}[X_0, \dots, X_n] = \bigoplus_{i \geq 0} A_i$ is a connected graded algebra, where A_i denotes the vector space of homogeneous polynomials of degree i . A derivation of A is called linear if it is homogeneous of degree 0. Note that linear derivations are in one-to-one correspondence with endomorphisms of A_1 or equivalently with square matrices of order $n + 1$ (acting on A_1 by left multiplication). Moreover, locally nilpotent derivations of A correspond to nilpotent endomorphisms/matrices. When dealing with a linear derivation of A , typically Δ , its rank will always mean the rank of its restriction as an endomorphism of (a subspace of) A_1 .

A Poisson structure on A is called homogeneous if $\{A_i, A_j\} \subseteq A_{i+j}$, and in that case A is said to be a homogeneous polynomial Poisson algebra. We provide a couple of invariants for homogeneous polynomial Poisson algebras. Denote by $\text{PDer}_{\text{gr}}(A)$ the Lie algebra of linear Poisson derivations of A .

Proposition 4.1. *Let A and B be two isomorphic homogeneous polynomial Poisson algebras.*

- (1) *There exists a Lie algebra isomorphism between $\text{PDer}_{\text{gr}}(A)$ and $\text{PDer}_{\text{gr}}(B)$ that sends locally nilpotent derivations to locally nilpotent derivations.*
- (2) *There exists a vector space isomorphism between $Z_P(A) \cap A_1$ and $Z_P(B) \cap B_1$.*

Proof. Thanks to [14, Proposition 8.8], a Poisson isomorphism between homogeneous polynomial Poisson structures can always be realized by a linear isomorphism. We denote by $\phi : A \rightarrow B$ such an isomorphism. For (1), the map $\Psi : \text{PDer}_{\text{gr}}(A) \rightarrow \text{PDer}_{\text{gr}}(B)$ given by $\Psi(\delta) = \phi \delta \phi^{-1}$ is the desired isomorphism, and for (2), the restriction of ϕ to $A_1 \cap Z_P(A)$ provides us with the desired isomorphism since $\phi(A_1) = B_1$ and $\phi(Z_P(A)) = Z_P(B)$. ■

Definition 4.2. A solvable pair (Δ, Γ) is said to be linear if Δ and Γ are linear derivations of A .

Remark 4.3. In a solvable pair, the derivation Δ is locally nilpotent. It implies, when the solvable pair is linear, that Δ is a nilpotent endomorphism of A_1 . We remark that when Δ and Γ are linear derivations of A verifying $[\Delta, \Gamma] = \Delta$, then Δ is automatically locally nilpotent. The proof goes as follows. We have $[P(\Delta), \Gamma] = (TP')[\Delta]$ for every polynomial $P \in \mathbb{k}[T]$ by assertion (2) of Lemma 2.21. If P is the minimal polynomial of Δ acting on the finite-dimensional space A_1 , we obtain that $TP'(T)$ is collinear to P . Hence $P = T^\ell$ for some ℓ and Δ acting on A_1 is nilpotent. Therefore, Δ is locally nilpotent on A , and (Δ, Γ) is a linear solvable pair.

The article [16] considers the case where Δ is the maximal Jordan block. In the following, we will investigate algebras $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$ arising from linear derivations Δ with more than one Jordan block. Let (Δ, Γ) be a linear solvable pair on A . Thanks to Lemma 2.1, one can always assume that Δ is in canonical Jordan form, up to a linear automorphism of A . Recall that in canonical Jordan form, a nilpotent matrix is made of diagonal blocks of the form $J_{n_i}(0)$, that is, blocks of size n_i with 0's everywhere except on the upper diagonal, where the entries are 1. It can be assumed that the size of the diagonal blocks $J_{n_i}(0)$ is decreasing. So, given such a Δ , what are the possible choices for Γ ?

Lemma 4.4. *The set of endomorphisms $\Gamma \in \text{End}_{\mathbb{k}}(A_1)$ such that $[\Delta, \Gamma] = \Delta$ is given by*

$$\Gamma_0 + \mathcal{C}(\Delta),$$

where $\mathcal{C}(\Delta) = \{f \in \text{End}_{\mathbb{k}}(A_1) \mid [f, \Delta] = 0\}$ is the commutant of Δ in $\text{End}_{\mathbb{k}}(A_1)$ and where $\Gamma_0 \in \text{End}_{\mathbb{k}}(A_1)$ is such that $[\Delta, \Gamma_0] = \Delta$.

Proof. The result follows from the fact that for solvable pairs (Δ, Γ) and $(\Delta, \tilde{\Gamma})$, we have $[\Delta, \Gamma - \tilde{\Gamma}] = 0$. ■

4.1. The case of Δ maximal

When Δ is a maximal Jordan block, one can choose $\Gamma_0 = \text{diag}(0, 1, \dots, n)$. Recall the algebras $A(n, a)$ and $R(n, a)$ from Example 1.3.

Theorem 4.5. *Given a solvable pair (Δ, Γ) with Δ a maximal Jordan block, there exists $u \in \text{GL}(A_1) \cap \mathcal{C}(\Delta)$ such that $u\Gamma u^{-1} = a \text{Id}_{A_1} + \Gamma_0$, where $a \in \mathbb{k}$ is such that $\text{tr}(\Gamma) = (n+1)(a + \frac{n}{2})$. In particular, $A_{(\Delta, \Gamma)} \cong A(n, a)$ and $R_{(\Delta, \Gamma)} \cong R(n, a)$.*

The proof relies on the following classical facts. Recall that $A_1 = \mathbb{k}X_0 \oplus \dots \oplus \mathbb{k}X_n$ is a $\mathbb{k}$ -vector space of dimension $n+1$.

- (1) We have $\mathcal{C}(\Delta) = \mathbb{k}[\Delta] = \text{Span}(\text{id}, \Delta, \Delta^2, \dots, \Delta^n)$ as a subalgebra of $\text{End}_{\mathbb{k}}(A_1)$.
- (2) Let $u \in \mathcal{C}(\Delta)$ and $P \in \mathbb{k}[X]$ such that $u = P(\Delta)$. Then $u \in \text{GL}(A_1)$ if and only if $P(0) \neq 0$.

Proof. The relation $[\Delta^i, \Gamma] = i\Delta^i$ shows that $\ker \Delta^i$ is Γ -invariant. So let us consider a basis $(e_0, \dots, e_n)$ of A_1 in which Δ has canonical Jordan form. In such a basis, Γ is upper triangular. Let us denote by $(\lambda_0, \dots, \lambda_n)$ the diagonal part of Γ . We have

$$\Gamma(e_i) = \Gamma(\Delta^{n-i}(e_n)) = \Delta^{n-i}\Gamma(e_n) - (n-i)\Delta^{n-i}(e_n).$$

Thus by computing modulo $\text{vect}(e_0, \dots, e_{i-1})$, we get that $\lambda_i = \lambda_n - (n-i)$ for all $0 \leq i < n$. In particular, Γ has $n+1$ distinct eigenvalues and thus a basis of eigenvectors. We then deduce that there exists an eigenvector e'_n of Γ which is not in $\ker \Delta^n$. Using the relation $[\Delta^i, \Gamma] = i\Delta^i$, we obtain that $(\Delta^n(e'_n), \Delta^{n-1}(e'_n), \dots, e'_n)$ is a basis of A_1 in which Δ has canonical Jordan form and $\Gamma = \text{diag}(a, a+1, \dots, a+n)$, where $a = \lambda_0 = \lambda_n - n$. Finally, we get

$$\text{tr}(\Gamma) = a(n+1) + \frac{n(n+1)}{2},$$

showing that a is uniquely determined by Γ . ■

Example 4.6. Let $n = 1$. There exist only two isomorphism classes for the algebras $A = A_{(\Delta, \Gamma)}$ and $R = R_{(\Delta, \Gamma)}$ with not necessarily maximal linear solvable pairs. If $\Delta = 0$, then $A = R = \mathbb{k}[X_0, X_1]$ is a (Poisson) commutative algebra. If $\Delta \neq 0$, then it is necessarily a maximal Jordan block since $n = 1$. Therefore, thanks to Theorem 4.5, we have $A \cong A(1, a)$ and $R \cong R(1, a)$ with $a \in \mathbb{k}$. If $a = 0$, we retrieve the commutative case (this is Example 2.13 for $n = 1$), and when $a \neq 0$, A is isomorphic to the Poisson algebra $\mathbb{k}[x, y]$ with Poisson bracket $\{x, y\} = x^2$ and R is isomorphic to the Jordan plane, that is, the algebra given by two generators x, y and the relation $xy - yx = x^2$.

4.2. Center in the linear case

The following result is a generalization of Lemma 2.9 in the linear case. We describe the Poisson center of A and the center of R which allow us to determine exactly when A is Poisson commutative and R is commutative. The results of this section will be improved by Proposition 5.7, but they are stated here since they will be needed in the proof of Proposition 5.7.

Proposition 4.7. *Let (Δ, Γ) be a linear solvable pair on A . Assume that the rank of Δ is at least two. Then we have $A_1 \cap Z_P(A) = \ker \Delta \cap \ker \Gamma \cap A_1$ and $A_1 \cap Z(R) = \ker \Delta \cap \ker \Gamma \cap A_1$.*

Proof. Since in this proof we only consider restrictions of Δ and Γ to A_1 , we simply denote by $\ker \Delta$ the set $\ker \Delta \cap A_1$ and similarly for Γ . Since we have $\ker \Gamma \cap \ker \Delta \subseteq Z_P(A)$ and $\ker \Gamma \cap \ker \Delta \subseteq Z(R)$ with equality if $\ker \Gamma \neq \ker \Delta$, thanks to Lemma 2.9, it only remains to study the case $\ker \Gamma = \ker \Delta$.

Consider $z \in Z_P(A) \cap A_1$. Let us first show that $z \in \ker \Delta^2$. If not, $z, \Delta(z)$ and $\Delta^2(z)$ are linearly independent over $\mathbb{k}$. Then $0 = \{z, \Delta(z)\} = \Delta(z)\Gamma\Delta(z) - \Delta^2(z)\Gamma(z)$. Since

$\ker \Delta = \ker \Gamma$ and $z \notin \ker \Delta^2$, we get that $\Gamma \Delta(z) \neq 0$. Moreover, $\Delta(z), \Gamma \Delta(z), \Delta^2(z)$ and $\Gamma(z)$ are homogeneous elements of A of degree 1 and hence are irreducible elements of the unique factorization domain A . Since $\Delta(z)$ and $\Delta^2(z)$ are not collinear, they are irreducible elements of A that are not associate. The unique factorization of $\Delta(z)\Gamma \Delta(z) = \Delta^2(z)\Gamma(z)$ ensures us that there exists $\alpha \in \mathbb{k}$ such that $\Gamma \Delta(z) = \alpha \Delta^2(z)$ and $\Gamma(z) = \alpha \Delta(z)$. Computing $\Delta(z) = [\Delta, \Gamma](z) = \alpha \Delta^2(z) - \alpha \Gamma \Delta(z) = 0$, we get a contradiction. Hence $z \in \ker \Delta^2$.

Before pursuing the computation of the Poisson center of A , we switch to the study of the center of R . Consider $z \in Z(R) \cap A_1$. As in the Poisson case, we first show that $z \in \ker \Delta^2$. If not, the integer such that $\Delta^n(z) \neq 0$ and $\Delta^{n+1}(z) = 0$ is greater than 1. We now compute $z * \Delta^{n-1}(z) = \Delta^{n-1}(z) * z$. For $\Delta((\Gamma - \text{id})(\Delta^{n-1}(z))) = \Gamma \Delta^n(z) + \Delta^n(z) - \Delta^n(z) = 0$. Indeed, $\Delta^n(z) \in \ker \Delta = \ker \Gamma$. So $(\Gamma - \text{id})(\Delta^{n-1}(z)) \in \ker \Delta = \ker \Gamma$. Hence $\Delta^{n-1}(z) \in \ker \binom{\Gamma}{2}$. Hence the relation $z * \Delta^{n-1}(z) = \Delta^{n-1}(z) * z$ becomes $\Delta(z)\Gamma(\Delta^{n-1}(z)) = \Gamma(z)\Delta^n(z)$. Since $n > 1$, the elements $\Delta(z)$ and $\Delta^n(z)$ are linearly independent. As in the preceding paragraph, we deduce that there exists $\alpha \in \mathbb{k}$ such that $\alpha \Delta(z) = \Gamma(z)$ and $\alpha \Delta^n(z) = \Gamma(\Delta^{n-1}(z))$. The relation $[\Delta^{n-1}, \Gamma](z) = (n-1)\Delta^{n-1}(z)$ can then be written as $\alpha \Delta^n(z) - \alpha \Delta^n(z) = (n-1)\Delta^{n-1}(z)$. Hence $(n-1)\Delta^{n-1}(z) = 0$, which is absurd since $n > 1$ and $\Delta^{n-1}(z) \neq 0$. We deduce that $z \in \ker \Delta^2$ and therefore that $z = \Delta^{n-1}(z) \in \ker \binom{\Gamma}{2}$.

We now finish the proof by showing that in both cases $z \in \ker \Delta$ when the rank of Δ is at least equal to two. If $z \notin \ker \Delta$, then there exists y such that $\Delta(y)$ is not collinear to $\Delta(z)$. For the Poisson case, we have $0 = \{z, y\} = \Delta(z)\Gamma(y) - \Delta(y)\Gamma(z)$. For the case of R , we have $z * y = zy + \Delta(z)\Gamma(y)$ since $z \in \ker \Delta^2$. But $y * z = yz + \Delta(y)\Gamma(z)$ since $z \in \ker \binom{\Gamma}{2}$. Finally, we also have the equality $\Delta(z)\Gamma(y) = \Delta(y)\Gamma(z)$. Since $\ker \Delta = \ker \Gamma$, we get that $\Gamma(y) \neq 0$ and $\Gamma(z) \neq 0$. Using the fact that $\Delta(y)$ and $\Delta(z)$ are not collinear, we can mimic the argument of the two preceding paragraphs to get the relation $\Gamma(z) = \alpha \Delta(z)$ for some $\alpha \in \mathbb{k}$. We then obtain $\Delta(z) = [\Delta, \Gamma](z) = \alpha \Delta^2(z) - \Gamma \Delta(z)$. But $z \in \ker \Delta^2$, and hence $\Delta(z) \in \ker \Delta = \ker \Gamma$. Therefore, $\Delta(z) = 0$ and $z \in \ker \Delta \cap \ker \Gamma$. ■

Corollary 4.8. *Let (Δ, Γ) be a linear solvable pair on A . Then $A_1 \cap Z_P(A) \neq \ker \Delta \cap \ker \Gamma \cap A_1$ implies that A is Poisson commutative and $A_1 \cap Z(R) \neq \ker \Delta \cap \ker \Gamma \cap A_1$ implies that R is commutative.*

Moreover, A is Poisson commutative if and only if R is commutative if and only if $\Delta = 0$ or (Δ, Γ) is conjugated to $(X_0 \partial_{X_1}, X_1 \partial_{X_1})$.

Proof. Assume that $A_1 \cap Z_P(A) \neq \ker \Delta \cap \ker \Gamma \cap A_1$ or $A_1 \cap Z(R) \neq \ker \Delta \cap \ker \Gamma \cap A_1$; Lemma 2.9 and Proposition 4.7 show that $\Delta = 0$ (and $\Gamma \neq 0$) or Δ is of Jordan type $(2, 1, \dots, 1)$ and $\ker \Gamma = \ker \Delta$.

In the first case, A is Poisson commutative and R is commutative. In the second case, up to a change of basis, we have $\Delta = X_0 \partial_{X_1}$ and $(X_0, X_2, \dots, X_n)$ is a basis of $\ker \Delta = \ker \Gamma$. Hence $\Gamma = (\alpha_0 X_0 + \alpha_1 X_1 + \dots + \alpha_n X_n) \partial_{X_1}$. The relation $[\Delta, \Gamma] = \Delta$

ensures that $\alpha_1 = 1$. Replacing X_1 by $X_1 + \alpha_0 X_0 + \alpha_2 X_2 + \dots + \alpha_n X_n$ in the basis, we obtain $\Gamma = X_1 \partial_{X_1}$ as desired. Since $\ker \Gamma = \ker \Delta$, we have $\{X_i, X_j\} = 0$ and $X_i * X_j = X_i X_j$ as soon as i or j belongs to $\{0, 2, \dots, n\}$. In particular, R is commutative and A is Poisson commutative.

It remains to show that if A is Poisson commutative or R is commutative, then $\Delta = 0$ or (Δ, Γ) is conjugated to $(X_0 \partial_{X_1}, X_1 \partial_{X_1})$. If $A_1 \cap Z_P(A) \neq \ker \Delta \cap \ker \Gamma \cap A_1$ or $A_1 \cap Z(R) \neq \ker \Delta \cap \ker \Gamma \cap A_1$, then the first part of the proof allows us to conclude. If $A_1 \cap Z_P(A) = \ker \Delta \cap \ker \Gamma \cap A_1$ or $A_1 \cap Z(R) = \ker \Delta \cap \ker \Gamma \cap A_1$, then $A_1 = \ker \Delta \cap \ker \Gamma \cap A_1$ and $\Delta = 0$. ■

4.3. A finer filtration for the linear case

In Section 2.4, we defined a filtration ε on any commutative $\mathbb{k}$ -algebra A endowed with a solvable pair (Δ, Γ) . When A is a polynomial ring and Δ, Γ are linear, we can define a finer filtration $\tilde{\varepsilon}$ on A . The new filtration is defined as the extension to A of the restriction to A_1 of the filtration ε . Recall that A_1 denotes the set of homogeneous polynomials of degree one, which is both Δ -invariant and Γ -invariant since the pair (Δ, Γ) is linear. Appendix C is devoted to the construction of this filtration $\tilde{\varepsilon}$ and the study of its properties; see in particular Example C.3. When Δ is a maximal Jordan block, then $\tilde{\varepsilon}$ is the filtration used in [16, Section 3].

For this filtration $\tilde{\varepsilon}$, analogues of Lemma 2.21 and Proposition 2.22 are valid. Precisely, we have the following proposition.

Proposition 4.9. *Let (Δ, Γ) be a linear solvable pair on $A = \mathbb{k}[X_0, \dots, X_n]$ and fix integers $i, j \geq 0$. Set $A^{\leq i, \tilde{\varepsilon}} = \{x \in A, \tilde{\varepsilon}(x) \leq i\}$.*

- (1) *We have $\Delta(A^{\leq i, \tilde{\varepsilon}}) \subseteq A^{\leq i-1, \tilde{\varepsilon}}$ and so $\tilde{\varepsilon}(\Delta(f)) \leq \tilde{\varepsilon}(f) - 1$ for every $f \in A$.*
- (2) *We have $\Gamma(A^{\leq i, \tilde{\varepsilon}}) \subseteq A^{\leq i, \tilde{\varepsilon}}$. Hence $\tilde{\varepsilon}(P(\Gamma)(f)) \leq \tilde{\varepsilon}(f)$ for every $P \in \mathbb{k}[T]$ and $f \in A$.*
- (3) *If $f, g \in A$ are such that $\tilde{\varepsilon}(f) = i$ and $\tilde{\varepsilon}(g) = j$, then $\tilde{\varepsilon}(fg) = i + j$.*
- (4) *The family $(A^{\leq i, \tilde{\varepsilon}})_{i \in \mathbb{N}}$ is a Poisson algebra filtration of $A_{(\Delta, \Gamma)}$ of degree -1 , meaning that it is an algebra filtration of A together with $\{A^{\leq i, \tilde{\varepsilon}}, A^{\leq j, \tilde{\varepsilon}}\} \subseteq A^{\leq i+j-1, \tilde{\varepsilon}}$ for all $i, j \geq 0$.*
- (5) *The family $(A^{\leq i, \tilde{\varepsilon}})_{i \in \mathbb{N}}$ is an algebra filtration of $R_{(\Delta, \Gamma)}$. Moreover, the associated graded algebra $\text{gr}^{\tilde{\varepsilon}}(R)$ is equal to $\text{gr}^{\tilde{\varepsilon}}(A)$.*
- (6) *For any $f, g \in A$, we have*

$$f * g - g * f = \Delta(f)\Gamma(g) - \Delta(g)\Gamma(f) + \sum_{k \geq 2} \left(\Delta^k(f) \binom{\Gamma}{k}(g) - \Delta^k(g) \binom{\Gamma}{k}(f) \right),$$

In particular, if $\tilde{\varepsilon}(f) = i$ and $\tilde{\varepsilon}(g) = j$, then $\tilde{\varepsilon}(f * g - g * f) \leq i + j - 1$.

- (7) *The commutative algebra $\text{gr}^{\tilde{\varepsilon}}(R) = \text{gr}^{\tilde{\varepsilon}}(A)$ can be endowed with the following three Poisson brackets:*

- (a) $\{\bar{f}, \bar{g}\}' := (f * g - g * f) + A^{\leq i+j-2, \tilde{\varepsilon}},$
- (b) $\{\bar{f}, \bar{g}\}'' := \{f, g\} + A^{\leq i+j-2, \tilde{\varepsilon}},$
- (c) $\{\bar{f}, \bar{g}\}''' := \bar{\Delta}(\bar{f})\bar{\Gamma}(\bar{g}) - \bar{\Gamma}(\bar{f})\bar{\Delta}(\bar{g}) \in A^{\leq i+j-1, \tilde{\varepsilon}}/A^{\leq i+j-2, \tilde{\varepsilon}}$

for homogeneous elements $\bar{f}$ and $\bar{g}$ of respective $\tilde{\varepsilon}$ -degree i and j . In (c), the pair of maps $(\bar{\Delta}, \bar{\Gamma})$ is the solvable pair of homogeneous derivations of $\text{gr}^{\tilde{\varepsilon}}(A)$ of respective degree -1 and 0 which is induced by the solvable pair (Δ, Γ) of A (see Proposition C.2).

- (8) The Poisson structures defined in (3) are all equal and make $\text{gr}^{\tilde{\varepsilon}}(A) = \text{gr}^{\tilde{\varepsilon}}(R)$ into a graded Poisson algebra of degree -1 .

Proof. The proof is similar to those of Lemma 2.21 and Proposition 2.22. However, the arguments should be given in a somewhat different order since the construction of the filtration is more complicated. We start with assertion (3). Proposition C.1 shows that $\text{gr}^{\tilde{\varepsilon}}(A)$ is a domain. This establishes (3). To prove (1) and (2), we start with $x \in A_1$. By definition of $\tilde{\varepsilon}$, we have $\tilde{\varepsilon}(\Delta(x)) \leq \tilde{\varepsilon}(x) - 1$. Moreover, Lemma 2.20 shows that $\ker \Delta^i \cap A_1$ is Γ -invariant, hence $P(\Gamma)$ -invariant, showing that $\tilde{\varepsilon}(P(\Gamma)(x)) \leq \tilde{\varepsilon}(x)$. We write now $f \in A$ as a sum of products of elements of A_1 , and (1) and (2) follow from (3) and the fact that Δ and Γ are derivations. Assertion (4) follows from (1.1) and then by applying (1), (2) and (3). Assertions (5) and (6) follow from (1.2) and then by applying (1), (2) and (3).

(7) The fact that $\{-, -\}'$ is a Poisson bracket on $\text{gr}(R)$ follows from the filtered version of the semiclassical limit construction; see [11, Section 2.4]. The fact that $\{-, -\}''$ is a well-defined biderivation satisfying the Jacobi identity on $\text{gr}(A)$ follows by tedious but straightforward computation from the fact that $\{-, -\}$ is a filtered Poisson bracket on A . Finally, $\{-, -\}'''$ is a Poisson bracket since $(\bar{\Delta}, \bar{\Gamma})$ is a solvable pair of derivations of $\text{gr}^{\tilde{\varepsilon}}(A)$.

(8) The Poisson brackets $\{-, -\}'$ and $\{-, -\}''$ are the same since both $f * g - g * f$ and $\{f, g\}$ belong to $A^{\leq i+j-1, \tilde{\varepsilon}}$ combined with $f * g - g * f - \{f, g\} \in A^{\leq i+j-2, \tilde{\varepsilon}}$, thanks to assertions (1), (2), (3) and (6). Finally, for homogeneous elements $\bar{f}$ and $\bar{g}$ of $\tilde{\varepsilon}$ -degree i and j , we have

$$\begin{aligned} \{\bar{f}, \bar{g}\}''' &= \bar{\Delta}(\bar{f})\bar{\Gamma}(\bar{g}) - \bar{\Gamma}(\bar{f})\bar{\Delta}(\bar{g}) \\ &= (\Delta(f) + A^{\leq i-2, \tilde{\varepsilon}})(\Gamma(g) + A^{\leq j-1, \tilde{\varepsilon}}) \\ &\quad - (\Delta(g) + A^{\leq j-2, \tilde{\varepsilon}})(\Gamma(f) + A^{\leq i-1, \tilde{\varepsilon}}) \\ &= (\Delta(f)\Gamma(g) + A^{\leq i+j-2, \tilde{\varepsilon}}) - (\Delta(g)\Gamma(f) + A^{\leq i+j-2, \tilde{\varepsilon}}) \\ &= (\Delta(f)\Gamma(g) - \Delta(g)\Gamma(f)) + A^{\leq i+j-2, \tilde{\varepsilon}} \\ &= \{f, g\} + A^{\leq i+j-2, \tilde{\varepsilon}} \\ &= \{\bar{f}, \bar{g}\}'' . \end{aligned}$$

Hence $\{-, -\}''$ and $\{-, -\}'''$ are the same. ■

Remark 4.10 (Matrix version). Assertion (8) says that the Poisson structure on $\text{gr}^{\tilde{\varepsilon}}(A)$ is associated with the solvable pair $(\overline{\Delta}, \overline{\Gamma})$. On A_1 , the filtrations $\tilde{\varepsilon}$ and ε coincide; hence by an appropriate choice of basis of A_1 and by using the Jordan reduction theorem adapted to this filtration, we obtain the following block decompositions:

$$\Delta = \begin{pmatrix} 0 & I_{m_0, m_1} & & \\ & \ddots & \ddots & \\ & & \ddots & I_{m_{r-2}, m_{r-1}} \\ & & & 0 \end{pmatrix} \quad \text{and} \quad \Gamma = \begin{pmatrix} \Gamma_1 & \Gamma_{1,2} & \cdots & \Gamma_{1,r} \\ & \ddots & \ddots & \vdots \\ & & \ddots & \Gamma_{r-1,r} \\ & & & \Gamma_r \end{pmatrix},$$

where, for $p \geq r$, we set

$$I_{p,r} = \begin{pmatrix} 1 & & \\ & \ddots & \\ 0 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & 0 \end{pmatrix} \in M_{p,r}(\mathbb{k}).$$

The corresponding $\overline{\Delta}$ and $\overline{\Gamma}$ are then given by

$$\overline{\Delta} = \begin{pmatrix} 0 & I_{m_0, m_1} & & \\ & \ddots & \ddots & \\ & & \ddots & I_{m_{r-2}, m_{r-1}} \\ & & & 0 \end{pmatrix} \quad \text{and} \quad \overline{\Gamma} = \begin{pmatrix} \Gamma_1 & & \\ & \ddots & \\ & & \Gamma_r \end{pmatrix}.$$

Example 4.11. Let (Δ, Γ) be a linear solvable pair on $A = \mathbb{k}[X_0, \dots, X_n]$ and assume that Δ is of rank one. Then R (resp. A) is isomorphic to an Ore extension (resp. a Poisson–Ore extension) over a commutative (resp. Poisson-commutative) polynomial ring in n variables.

Indeed, after a suitable change of basis of A_1 , by Remark 4.10 and the relation $[\Delta, \Gamma] = \Delta$, we have $\Delta = X_0 \partial_{X_n}$ and $\Gamma = \alpha X_0 \partial_{X_0} + \sum_{i=1}^{n-1} P_i \partial_{X_i} + ((\alpha + 1)X_n + P_n) \partial_{X_n}$, where $P_i \in \mathbb{k}[X_0, \dots, X_{n-1}]$ for $1 \leq i \leq n$. We have $\ker \Delta = \mathbb{k}[X_0, \dots, X_{n-1}]$, and we observe that Γ induces a derivation of $\ker \Delta$. For any $Q \in \ker \Delta$, we have $\{X_n, Q\} = X_0 \Gamma(Q)$. Therefore, $A_{(\Delta, \Gamma)}$ is isomorphic to the Poisson–Ore extension $(\ker \Delta)[X_n; X_0 \Gamma]_P$. Also, for any $Q \in \ker \Delta$, we have

$$X_n * Q - Q * X_n = QX_n + X_0 \Gamma(Q) - QX_n = X_0 \Gamma(Q) = X_0 * \Gamma(Q).$$

For any $i \in \mathbb{N}$, we denote by X_n^{*i} the i th power of X_n for the product $*$. By an easy induction, we obtain that for any $i \in \mathbb{N}$, there exist $P_{ij} \in \mathbb{k}[X_0, \dots, X_{n-1}]$ such that $X_n^{*i} = X_n^i + \sum_{j=0}^{i-1} P_{ij} X_n^j$. Hence $(X_n^{*i})_{i \in \mathbb{N}}$ is a basis of A over $\ker \Delta = \mathbb{k}[X_0, \dots, X_{n-1}]$ and $R_{(\Delta, \Gamma)}$ is isomorphic to the Ore extension $(\ker \Delta)[X_n; X_0 \Gamma]$.

5. Trigonalizable linear solvable pair

We continue with the notations of Section 4: $A = \mathbb{k}[X_0, \dots, X_n]$ is a polynomial algebra with standard grading, and, for all $k \geq 0$, we denote by A_k the vector space of degree k homogeneous polynomials.

Definition 5.1. A linear solvable pair (Δ, Γ) is said to be trigonalizable if the linear map induced by Γ on A_1 is.

Proposition 5.2. *Let (Δ, Γ) be a linear solvable pair. Then it is trigonalizable if and only if the linear map Γ_1 induced by Γ on $A_1 \cap \ker \Delta$ is.*

Proof. Using notations of Remark 4.10, the linear map induced by Γ on $A_1 \cap \ker \Delta$ is Γ_1 . Hence if Γ is trigonalizable, then Γ_1 is trigonalizable. Reciprocally, by computing the superdiagonal blocks of the relation $\Delta\Gamma - \Gamma\Delta = \Delta$, we have for every $1 \leq i \leq r-1$ the following triangular block decomposition:

$$\Gamma_i = \begin{pmatrix} \Gamma_{i+1} - I & C_i \\ & B_i \end{pmatrix},$$

where I denotes the identity matrix of the appropriate size. Hence $\chi_{\Gamma_{i+1}}(X+1)$ divides $\chi_{\Gamma_i}(X)$, where χ_M denote the characteristic polynomial of the square matrix M . We then deduce that when χ_{Γ_1} is trigonalizable, every χ_{Γ_i} is. Hence Γ acts on A_1 as a trigonalizable linear map. ■

5.1. The Artin–Schelter regular property

In this section, we prove that the algebra $R = R_{(\Delta, \Gamma)}$ is Artin–Schelter regular when (Δ, Γ) is a linear solvable pair. Artin–Schelter regular algebras [2] are thought to be noncommutative analogue of commutative polynomial rings in the following sense.

Definition 5.3. A connected $\mathbb{N}$ -graded $\mathbb{k}$ -algebra R is called *Artin–Schelter regular* or *AS regular* if

- (1) $\text{gldim } R < \infty$,
- (2) R has finite Gel'fand–Kirillov dimension,
- (3) $\text{Ext}_R^i(\mathbb{k}_R, R_R) \cong \begin{cases} 0 & \text{if } i \neq \text{gldim } R, \\ {}_R\mathbb{k}[\ell] & \text{if } i = \text{gldim } R, \end{cases}$

where $\mathbb{k}[\ell]$ means that the module is degree-shifted by some amount $\ell \in \mathbb{Z}$.

Since both Δ and Γ are linear derivations, we have $\Delta(A_k) \subseteq A_k$ and $\Gamma(A_k) \subseteq A_k$ for all integers $k \geq 0$. Therefore, $A_k * A_\ell \subseteq A_{k+\ell}$ for any $k, \ell \geq 0$, thanks to equation (1.2). Thus the algebra $R = (A, *)$ is $\mathbb{N}$ -graded, generated in degree 1 and with Hilbert series given by

$$\text{hilb}(R) = \text{hilb}(A) = \frac{1}{(1-t)^{n+1}}.$$

The following result is the key argument for our inductive proof of Theorem 5.5. Since this result relates algebras $R_{(\Delta, \Gamma)}$ (resp. $A_{(\Delta, \Gamma)}$) of different dimensions, we will specify the (projective) dimension of the underlying polynomial ring by using the notation $R_{(\Delta, \Gamma)}^n$ (resp. $A_{(\Delta, \Gamma)}^n$).

Proposition 5.4. *Let (Δ, Γ) be a linear solvable pair on $A = \mathbb{k}[X_0, \dots, X_n]$ such that $\Delta(X_0) = 0$ and there exists $\alpha \in \mathbb{k}$ verifying $\Gamma(X_0) = \alpha X_0$. Set $A = A_{(\Delta, \Gamma)}^n$ and $R = R_{(\Delta, \Gamma)}^n$ and denote by Δ and Γ the matrices of Δ and Γ acting on A_1 with respect to a basis starting with X_0 .*

- (1) *The quotient algebra $R/\langle X_0 \rangle$ is isomorphic to $R_{(\Delta', \Gamma')}^{n-1}$ for the solvable pair (Δ', Γ') of $A^{n-1} = \mathbb{k}[Y_0, \dots, Y_{n-1}]$ obtained from the solvable pair (Δ, Γ) by deleting the first row and first column.*
- (2) *X_0 is Poisson normal in A , and the Poisson algebra $A/\langle X_0 \rangle$ is isomorphic to $A_{(\Delta', \Gamma')}^{n-1}$ for the same solvable pair (Δ', Γ') of A^{n-1} .*

In particular, $R/\langle X_0 \rangle$ is a deformation of the Poisson algebra $A/\langle X_0 \rangle$.

Proof. (1) First note that X_0 is strongly normal in R and Poisson normal in A . The algebras $R/\langle X_0 \rangle$, A/X_0A and $R_{(\Delta', \Gamma')}^{n-1}$ can all be identified as graded vector spaces. Let $\pi : R \rightarrow R/\langle X_0 \rangle$ be the quotient map and set $\bar{X}_i = \pi(X_i)$ for all $0 \leq i \leq n$. Then the product in $R/\langle X_0 \rangle$ is given by

$$\bar{X}_i * \bar{X}_j = \sum_{\ell \geq 0} \bar{\Delta}^\ell(\bar{X}_i) \binom{\bar{\Gamma}}{\ell}(\bar{X}_j),$$

where $\bar{\Delta}$ and $\bar{\Gamma}$ denote the derivations induced by $\bar{\Delta}$ and $\bar{\Gamma}$ on the quotient $A/\langle X_0 \rangle \cong \mathbb{k}[Y_0, \dots, Y_{n-1}]$. It is now a simple verification to check that $(\bar{\Delta}, \bar{\Gamma})$ is a solvable pair on $A/\langle X_0 \rangle$ that agrees with the solvable pair (Δ', Γ') of $\mathbb{k}[Y_0, \dots, Y_{n-1}]$ under the identification $\bar{X}_{i+1} \mapsto Y_i$ for all $0 \leq i < n$.

(2) X_0 is Poisson normal since it is in the kernel of Δ and is an eigenvector of Γ . It is direct that the Poisson bracket on A/X_0A is given by the solvable pair $(\bar{\Delta}, \bar{\Gamma})$, and we conclude as in (1). ■

We now prove that $R_{(\Delta, \Gamma)}$ is Artin–Schelter regular for any solvable pair (Δ, Γ) . The result follows from the trigonalizable case.

Theorem 5.5. *Let (Δ, Γ) be a linear solvable trigonalizable pair. The algebra $R = R_{(\Delta, \Gamma)}^n$ is Artin–Schelter regular of global dimension $n + 1$.*

Proof. The proof follows by induction on n , exactly as in the proof of [16, Theorem 3.8] since the only hypotheses used by the authors are that R is connected graded generated in degree 1 with polynomial growth and admits a normal sequence $\Omega = (r_0, \dots, r_n)$ of homogeneous regular elements $r_i \in R$ such that $R/(r_0, \dots, r_n)R \cong \mathbb{k}$. Here, we can

also use the sequence $\Omega = (X_0, X_1, \dots, X_n)$, where $(X_0, \dots, X_n)$ is a basis of A_1 as in Remark 4.10 and Γ is triangular (Proposition 5.2). ■

Corollary 5.6. *Let (Δ, Γ) be a linear solvable pair. The algebra $R = R^n_{(\Delta, \Gamma)}$ is Artin–Schelter regular of global dimension $n + 1$.*

Proof. Consider $\tilde{\mathbb{k}}$ a finite field extension of $\mathbb{k}$ such that the characteristic polynomial of Γ acting on A_1 splits over $\tilde{\mathbb{k}}$. Thanks to Theorem 5.5, the algebra $\tilde{R} = \tilde{\mathbb{k}} \otimes R$ is Artin–Schelter regular since the unique extension of (Δ, Γ) to $\tilde{R}$ is a trigonalizable solvable pair.

Since $\tilde{\mathbb{k}} \otimes -$ is an exact functor which sends projective modules over R to projective modules over $\tilde{R}$, for any R -modules M, N , we have

$$\mathrm{Ext}^*_{\tilde{R}}(\tilde{\mathbb{k}} \otimes M, \tilde{\mathbb{k}} \otimes N) \cong \mathrm{Ext}^*_R(M, \tilde{\mathbb{k}} \otimes N) \cong \mathrm{Ext}^*_R(M, N)^{[\tilde{\mathbb{k}}:\mathbb{k}]}.$$

Therefore, we have $\mathrm{gldim} R \leq \mathrm{gldim} \tilde{R} < \infty$. Since R and $\tilde{R}$ are $\mathbb{N}$ -graded connected algebras, the case $M = N = k$ and [8, Theorem 11, Theorem 13 and Proposition 15] show that $\mathrm{gldim} R = \mathrm{gldim} \tilde{R}$. By considering the case $M = k$ and $N = R$, we obtain that $\mathrm{Ext}^*_{\tilde{R}}(\tilde{\mathbb{k}}, \tilde{R}) \cong \mathrm{Ext}^*_R(k, R)^{[\tilde{\mathbb{k}}:\mathbb{k}]}$. In particular, if $\mathrm{Ext}^*_{\tilde{R}}(\tilde{\mathbb{k}}, \tilde{R}) \cong \tilde{k}$, then $\mathrm{Ext}^*_R(k, R) \cong k$ since the field extension is finite. It follows that the algebra R is Artin–Schelter regular. ■

5.2. Normal elements

The next proposition describes normal elements of R and Poisson normal elements in A in the case of a linear solvable pair: they are the strongly normal elements (see Definition 2.30). This generalizes the results of Lemma 2.9 and Proposition 4.7 and is a converse of Lemma 2.31 in the linear case.

Proposition 5.7. *Let (Δ, Γ) be a linear solvable pair. Assume that A is not Poisson commutative (see Corollary 4.8). Then*

- (1) *N is normal in R if and only if N is strongly normal if and only if N is Poisson normal in A ,*
- (2) *N is central in R if and only if $N \in \ker \Delta \cap \ker \Gamma$ if and only if N is Poisson central in A .*

Proof. The case where Δ is a maximal Jordan block is exactly [16, Proposition 3.21], thanks to Theorem 4.5. We observe that the proof of [16, Proposition 3.21] carries over without modification to the case of any linear solvable pair under the assumption that there exists an $\tilde{\varepsilon}$ -homogeneous, irreducible, strongly normal element G in A which is not in $\ker \Gamma$. Note that for such an element G , the ideal $G * R = R * G$ of R is completely prime since G is an irreducible element of the unique factorization domain A .

Let (Δ, Γ) be a trigonalizable solvable pair such that A is not Poisson commutative. We will prove that we can almost always exhibit such an element G in A . More precisely,

the only situation in which this will not be possible is when the rank r of Δ acting on A_1 is equal to 1, and we will deal with this situation later.

Assume that $r > 1$. In the following, we only consider actions of (Δ, Γ) on A_1 and its subspaces. Using the notations of Remark 4.10 and Proposition 5.2, we see that Γ_1 is trigonalizable. If Γ_1 has a nonzero eigenvalue λ , then an eigenvector G of Γ_1 with respect to λ satisfies the desired properties. Hence we can assume that Γ_1 is nilpotent. As in the proof of Proposition 5.2, the relation $\Delta\Gamma - \Gamma\Delta = \Delta$ shows that for every $1 \leq i \leq r-1$, we have the following triangular block decomposition:

$$\Gamma_i = \begin{pmatrix} \Gamma_{i+1} - I & C_i \\ & B_i \end{pmatrix},$$

where I denotes the identity matrix of the appropriate size. Hence $i-1$ is the only eigenvalue of Γ_i and thus $\Gamma_i - (i-1)\text{id}$ is nilpotent. The triangular shape of the block decomposition of Γ then shows that $\ker \Delta^i = \bigoplus_{j=0}^{i-1} N_j$, where N_j is the generalized eigenspace of Γ with respect to j . The relation $\Delta\Gamma - \Gamma\Delta = \Delta$ can be rewritten as $\Delta(\Gamma - j\text{id}) = (\Gamma - (j-1)\text{id})\Delta$ and then $\Delta(\Gamma - j\text{id})^k = (\Gamma - (j-1)\text{id})^k \Delta$ for all integers $k \geq 0$. Hence Δ maps N_j into N_{j-1} . Moreover, the relation $\ker \Delta^i = \bigoplus_{j=0}^{i-1} N_j$ shows that for all integers $j \geq 1$, Δ maps injectively N_j into N_{j-1} .

Assume now that Δ admits a Jordan block of size at least 3. Then 2 is an eigenvalue of Γ . If we consider X_2 such that $\Gamma(X_2) = 2X_2$, then $X_1 = \Delta(X_2) \in \ker(\Gamma - \text{id})$, $X_0 = \Delta(X_1) \in \ker(\Gamma)$, the family (X_0, X_1, X_2) is linearly independent and then $G = 2X_2X_0 - X_1^2 \neq 0$ verifies $\Delta(G) = 0$ and $\Gamma(G) = 2G$ as desired.

Hence we can now assume that Δ admits only Jordan blocks of size 2. If Δ admits at least two such blocks, then $\dim(\ker \Delta^2 / \ker \Delta) \geq 2$. Hence $\dim N_1 \geq 2$. If $\dim \ker(\Gamma - \text{id}) \geq 2$, we can choose linearly independent elements X_1 and Y_1 in $\ker(\Gamma - \text{id})$. Note that both $\Delta(Y_1)$ and $\Delta(X_1)$ belong to $\ker \Delta \cap \ker \Gamma$. Then the element $G = X_1\Delta(Y_1) - Y_1\Delta(X_1) \neq 0$ verifies $\Delta(G) = 0$ and $\Gamma(G) = G$. If $\dim \ker(\Gamma - \text{id}) = 1$, since $\dim N_1 \geq 2$, there exists $(X_1, Y_1) \in N_1^2$ such that $\Gamma(X_1) = X_1$ and $\Gamma(Y_1) = Y_1 + X_1$ (apply canonical Jordan form to Γ acting on N_1). Set then $X_0 = \Delta(X_1)$ and $Y_0 = \Delta(Y_1)$. We have $X_0, Y_0 \in \ker \Delta$ and $\Gamma(X_0) = 0$ and $\Gamma(Y_0) = X_0$. Hence $G = X_1Y_0 - X_0Y_1 \neq 0$ verifies $\Gamma(G) = G$ and $\Delta(G) = 0$.

It remains to consider the case where Δ admits only one Jordan block which is of size 2, that is to say the rank of Δ is one. In this case, we have

$$\Delta = \begin{pmatrix} 0 & 0 & 1 \\ & 0 & 0 \\ & & 0 \end{pmatrix} \quad \text{and} \quad \Gamma = \begin{pmatrix} 0 & L_1 & 0 \\ & \widetilde{\Gamma}_1 & 0 \\ & & 1 \end{pmatrix},$$

where the second column of the matrices Δ and Γ corresponds to matrices with $(n-1)$ columns. By choosing the corresponding basis $(X_0, \dots, X_n)$ for A_1 , we have $\Delta = X_0\partial_{X_n}$ and $\Gamma(X_0) = 0$, $\Gamma(X_j) \in \mathbb{k}[X_0, \dots, X_{n-1}]$ for $j \in \{1, \dots, n-1\}$ and $\Gamma(X_n) = X_n$. We will show that every Poisson normal element Q lies in $\ker \Delta \cap \ker \Gamma$ and that

every normal element Q in R also lies in $\ker \Delta \cap \ker \Gamma$. Write $Q = \sum_{i=0}^s P_i X_n^i$ with $P_i \in \mathbb{k}[X_0, \dots, X_{n-1}]$ and an integer $s \geq 0$. We have

$$\Delta(Q) = \sum_{i=0}^s i P_i X_0 X_n^{i-1} \quad \text{and} \quad \Gamma(Q) = \sum_{i=0}^s (\Gamma(P_i) + i P_i) X_n^i.$$

Moreover, there exists $j_0 \in \{1, \dots, n-1\}$ such that $\Gamma(X_{j_0}) \neq 0$; otherwise, from Corollary 4.8, we have that A is Poisson commutative. Assume that Q is Poisson normal and compute $\{Q, X_{j_0}\} = \Delta(Q)\Gamma(X_{j_0})$. Since Q is Poisson normal, there exists $F \in A$ such that $\Delta(Q)\Gamma(X_{j_0}) = FQ$. If $F \neq 0$, then comparing the degree in X_n of the two sides of the equality leads to something impossible. Hence $F = 0$ and $\Delta(Q) = 0$ since $\Gamma(X_{j_0}) \neq 0$. So $Q = P_0 \in k[X_0, \dots, X_{n-1}]$. By computing $\{Q, X_n\} = -\Gamma(Q)X_0 = -\Gamma(P_0)X_0$, from the Poisson normality of Q , we obtain that there exists $F \in A$ such that $\Gamma(P_0)X_0 = FP_0$. We then write $P_0 = X_0^\ell R$ with $X_0 \nmid R$. Since $X_0 \in \ker \Gamma$, we obtain the relation $\Gamma(R)X_0 = FR$. Hence $X_0 \mid F$, so $\Gamma(R) = F_1 R$ for some $F_1 \in A$. By comparing the total degree, we obtain that $F_1 \in \mathbb{k}$, and by multiplying by X_0^ℓ , we obtain that $Q = P_0$ verifies $\Gamma(P_0) = F_1 P_0$. But Γ is locally nilpotent on $\mathbb{k}[X_0, \dots, X_{n-1}]$ since it acts as a nilpotent linear map on the span of $X_0, \dots, X_{n-1}$; hence $F_1 = 0$ and $Q = P_0 \in \ker \Gamma \cap \ker \Delta$ is strongly normal.

Let us now consider that $Q \neq 0$ is normal in R and compute $X_{j_0} * Q = X_{j_0} Q$. Since Q is normal, there exists $f \in R$ such that $X_{j_0} * Q = Q * f$. By applying the ε -degree, we deduce that $\varepsilon(f) = \varepsilon(X_{j_0}) = 0$, that is to say $f \in \ker \Delta$. By sending the preceding equality in $\text{gr}(R)$ which is a domain, thanks to Corollary 2.23, we obtain that $\overline{X_{j_0}} = \overline{f} \in \ker(A^{\leq 0}/\{0\})$ and then $X_{j_0} = f$. The relation $X_{j_0} * Q = Q * f$ can then be rewritten as

$$\sum_{i \geq 1} \Delta^i(Q) \binom{\Gamma}{i} (X_{j_0}) = 0 \quad \text{with} \quad \binom{\Gamma}{i} (X_{j_0}) \in \ker \Delta.$$

By considering the smallest integer $N \geq 1$ such that $\Delta^N(Q) = 0$ and by composing the preceding relation with Δ^{N-2} , we obtain that $\Delta^{N-1}(Q)\Gamma(X_{j_0}) = 0$. But $\Gamma(X_{j_0}) \neq 0$; hence $N = 1$ and $Q \in \ker \Delta = k[X_0, \dots, X_{n-1}]$. We now compute $X_n * Q = X_n Q + X_0 \Gamma(Q)$. Since Q is normal, there exists f such that $X_n * Q = Q * f = Qf$. Hence $Qf = X_n Q + X_0 \Gamma(Q)$, and we deduce that the total degree of f is not greater than 1 and that $\deg_{X_n}(f) = 1$. By writing $f = aX_n + f_1$ with $f_1 \in \mathbb{k}[X_0, \dots, X_{n-1}]$ and $a \in \mathbb{k}$, we obtain $a = 1$ and then $Qf_1 = X_0 \Gamma(Q)$. By applying the same argument as in the Poisson normal case, we obtain that $\Gamma(Q) = 0$. Therefore, $Q \in \ker \Gamma \cap \ker \Delta$ is strongly normal.

To conclude, it remains to consider the case where the pair (Δ, Γ) is not trigonalizable. Consider an element Q that is either Poisson normal in A or normal in R . Let $\overline{\mathbb{k}}$ be the algebraic closure of $\mathbb{k}$ and consider the scalar extensions $\overline{A} = \overline{\mathbb{k}} \otimes A$ and $\overline{R} = \overline{\mathbb{k}} \otimes R$ of A and R , respectively. The pair (Δ, Γ) is a trigonalizable linear pair on $\overline{A}$ and $1 \otimes Q$ is Poisson normal in $\overline{A}$ or normal in $\overline{R}$. Hence $1 \otimes Q$ is strongly normal. Hence $1 \otimes \Delta(Q) = 0$ and $1 \otimes \Gamma(Q) = \lambda \otimes Q$ for some $\lambda \in \overline{\mathbb{k}}$. But $1 \otimes \Gamma(Q) \in 1 \otimes A$, so $\lambda \in \mathbb{k}$ and $\Gamma(Q) = \lambda Q$. So Q is strongly normal. ■

Remark 5.8. Let (Δ, Γ) be a linear trigonalizable solvable pair. According to the previous proof, we have the following three disjoint cases:

- The rank of Δ is one, and the restriction of Γ to $\ker \Delta$ is zero. In this case, A is Poisson commutative and R is commutative.
- The rank of Δ is one, and the restriction of Γ to $\ker \Delta$ is nonzero and nilpotent. In this case, every normal element in R is central and every Poisson normal element in A is Poisson central. Moreover, A is not Poisson commutative and R is not commutative.
- Otherwise, there exists a strongly normal element with a nonzero Γ -eigenvalue, that is to say, there exists an element that is Poisson normal but not Poisson central in A , as well as normal in R but not central in R .

Moreover, in the third case, we can assume that this normal element which is not central belongs to the image $\operatorname{im} \Delta$ of Δ . Indeed, by the relation $\Gamma\Delta = \Delta(\Gamma - \operatorname{id})$, we obtain that $\operatorname{im} \Delta$ is Γ -invariant. Hence $\ker \Delta \cap \operatorname{im} \Delta$ is by Γ -invariant. Since Γ is trigonalizable, its restriction to $\ker \Delta \cap \operatorname{im} \Delta$ is too. In particular, this restriction has an eigenvector. Hence there exists $x \in \ker \Delta \cap \operatorname{im} \Delta$ and $\lambda \in \mathbb{k}$ such that $\Gamma(x) = \lambda x$. If $\lambda \neq 0$, we are done. If $\lambda = 0$, consider y such that $\Delta(y) = x$. Let z be a strongly normal element whose eigenvalue for Γ , denoted by μ , is nonzero (z may not be in A_1). Then $xz \in \ker \Delta$ and xz is an eigenvector for Γ with eigenvalue $\mu + \lambda = \mu \neq 0$. Finally, we have $\Delta(yz) = z\Delta(y) = zx \in \operatorname{im} \Delta$ as desired.

5.3. On the isomorphism problem

In this section, we show that for a linear solvable pair (Δ, Γ) , the Jordan type of Δ is determined by the isomorphism class of R or the Poisson isomorphism class of A . The Jordan type of a linear derivation of a polynomial algebra A means the Jordan type of its restriction to A_1 .

Theorem 5.9. Let (Δ, Γ) and (Δ', Γ') be linear solvable pairs on $\mathbb{k}[X_0, \dots, X_n]$ with $\Delta \neq 0$ and $\Delta' \neq 0$. We set $A = A_{(\Delta, \Gamma)}$, $A' = A_{(\Delta', \Gamma')}$, $R = R_{(\Delta, \Gamma)}$ and $R' = R_{(\Delta', \Gamma')}$.

- If A and A' are Poisson isomorphic, then Δ and Δ' have the same Jordan type.
- If R and R' are isomorphic, then Δ and Δ' have the same Jordan type.

Lemma 5.10. Assume that there exists a strongly normal element in A with nonzero Γ -eigenvalue and that A is not Poisson commutative.

- (1) If $\phi : A \rightarrow A'$ is a Poisson isomorphism, then there exists $\alpha \in \mathbb{k}^*$ such that $\phi\Delta\phi^{-1} = \alpha\Delta'$.
- (2) If $\phi : R \rightarrow R'$ is an isomorphism, then $\phi(\ker \Delta^n) = \ker(\phi\Delta^n\phi^{-1}) = \ker \Delta'^n$ for every $n \in \mathbb{N}$.

Proof. We denote by x the strongly normal element of A whose Γ -eigenvalue λ is nonzero.

(1) By Lemma 2.31, the element x is Poisson normal in A and the associated Poisson derivation is $\lambda\Delta$. Since ϕ is a Poisson isomorphism, $\phi(x)$ is Poisson normal in A' , hence strongly normal by Proposition 5.7. Therefore, there exists $\mu \in \mathbb{k}$ such that $\Gamma'(\phi(x)) = \mu\phi(x)$, and the Poisson derivation of A' associated with $\phi(x)$ is $\mu\Delta'$. Because this derivation is also equal to $\phi(\lambda\Delta)\phi^{-1}$, we obtain the result since $\mu \neq 0$.

(2) Thanks to Lemma 2.31, since x is strongly normal, it is also normal in R , and the automorphism of R associated with x is ϕ_λ . We then deduce that $\phi(x)$ is normal in R' , and, from Proposition 5.7, that it is strongly normal in R' . Hence there exists $\mu \in \mathbb{k}$ such that $\Gamma'(\phi(x)) = \mu\phi(x)$. Since the automorphism of R' associated with $\phi(x)$ is $\phi\phi_\lambda\phi^{-1}$, we deduce that $\phi\phi_\lambda\phi^{-1} = \phi_\mu$, and hence $\mu \neq 0$. By the last part of Lemma 2.18, we have $\ker \Delta^n = \ker(\phi_\mu - \text{id})^n = \ker(\phi(\phi_\lambda - \text{id})^n\phi^{-1}) = \phi(\ker(\Delta^n))$ for every $n \in \mathbb{N}$. ■

Proof of Theorem 5.9. If R is commutative (resp. A is Poisson commutative), then so is R' (resp. A'). By Corollary 4.8, both Δ and Δ' are of rank one, hence of the same Jordan type. Assume now that R is not commutative (resp. A is not Poisson commutative).

If every normal element in R (resp. Poisson normal element in A) is central (resp. Poisson central), then the same is true for R' (resp. A'). Thanks to Remark 5.8, the rank of both Δ and Δ' is one. Hence Δ and Δ' have the same Jordan type.

Otherwise, there exists a normal element in R that is not central (resp. a Poisson normal element in A that is not Poisson central). Let $\phi : R \rightarrow R'$ be a $\mathbb{k}$ -algebra isomorphism (resp. $\phi : A \rightarrow A'$ be a Poisson isomorphism). By [3, Theorem 1] (resp. [14, Proposition 8.8]), we may assume that ϕ is graded. By extending the scalars to an algebraic closure of $\mathbb{k}$, we can furthermore assume that (Δ, Γ) and (Δ', Γ') are trigonalizable solvable pairs.

We start with the Poisson case. By assertion (1) of Lemma 5.10, we have $\phi\Delta\phi^{-1} = \alpha\Delta'$ with $\alpha \in \mathbb{k}^*$. The derivations $\alpha\Delta'$ and Δ' have the same Jordan type. And since ϕ is graded, the derivation $\phi\Delta\phi^{-1}$ and Δ have the same Jordan type. The result follows.

In the case of R , thanks to assertion (2) of Lemma 5.10, the isomorphism ϕ preserves the filtration ε . Since moreover ϕ is graded, it must also preserve the filtration $\tilde{\varepsilon}$. Hence ϕ induces a graded Poisson isomorphism between $\text{gr}^{\tilde{\varepsilon}}(R) = \text{gr}^{\tilde{\varepsilon}}(A)$ and $\text{gr}^{\tilde{\varepsilon}}(R') = \text{gr}^{\tilde{\varepsilon}}(A')$. From Remark 4.10, the Jordan type of Δ (resp. Δ') is the same as that of $\bar{\Delta}$ (resp. $\bar{\Delta}'$). Then the Poisson isomorphism case allows us to conclude. ■

6. Diagonalizable linear solvable pair: Poisson derivations

In this section, we show that under a generic condition on Γ the derivation Δ may be recovered from the Poisson algebra A as, up to a nonzero scalar, the only locally nilpotent derivation in the center of $\text{PDer}_{\text{gr}}(A)$.

Definition 6.1. A linear solvable pair (Δ, Γ) is said to be diagonalizable if there exists a basis of A consisting of eigenvectors for Γ .

Lemma 6.2. *The existence of a basis of A consisting of eigenvectors for Γ is equivalent to the fact that the restriction of Γ to A_1 is diagonalizable.*

Proof. Indeed, if we consider a basis of eigenvectors of Γ acting on A_1 , then the set of monomials formed with elements of this basis of A_1 is a basis of A consisting of eigenvectors for Γ .

Reciprocally, assume that $\mathcal{B}$ is a basis of A consisting of eigenvectors for Γ . Let us show that the eigenvectors of Γ contained in A_1 generate A_1 . Consider $v \in A_1$ and express it as a linear combination of elements of $\mathcal{B}$. Gather the eigenvectors associated with the same eigenvalue to write $v = w_1 + \cdots + w_r$, where w_i is an eigenvector for Γ associated with the eigenvalue $\lambda_i \in \mathbb{k}$ and where $\lambda_i \neq \lambda_j$ when $i \neq j$. By considering the family $(v, \Gamma(v), \dots, \Gamma^{r-1}(v)) \in A_1^r$ and inverting the Vandermonde matrix associated with $(\lambda_1, \dots, \lambda_r)$, we get that $w_i \in A_1$ for all i . This concludes the proof. ■

For a diagonalizable linear solvable pair (Δ, Γ) , we denote by $n_1 \geq n_2 \geq \cdots \geq n_r$ the sizes of the Jordan blocks of Δ acting on A_1 . Such a Δ is said to be of Jordan type $\bar{n} = (n_1, \dots, n_r)$, where we set $n + 1 = n_1 + \cdots + n_r$.

Proposition 6.3. *Let (Δ, Γ) be a diagonalizable linear solvable pair. Assume that Δ is of Jordan type $\bar{n} = (n_1, \dots, n_r)$. Then there exists a basis of A_1 and $\bar{a} = (a_1, \dots, a_r) \in \mathbb{k}^r$ such that Δ is in canonical Jordan form and Γ is a diagonal matrix of the form $\Gamma = \text{diag}(a_1, \dots, a_1 + n_1 - 1, a_2, \dots, a_2 + n_2 - 1, \dots, a_r, \dots, a_r + n_r - 1)$.*

Proof. This is an adaptation of the proof of the existence of the canonical Jordan form. For any integer $i \geq 0$, we get that $F_i := \ker \Delta^i$ is Γ -invariant by using the relation $[\Delta^i, \Gamma] = i \Delta^i$. There exists $s \geq 0$ such that $F_s = A_1$ since Δ is nilpotent on A_1 . We construct subspaces $(G_i)_{1 \leq i \leq s}$ by decreasing induction such that

- (1) $F_{i-1} \oplus G_i = F_i$,
- (2) Δ maps injectively G_{i+1} into G_i ,
- (3) G_i is Γ -invariant.

Since F_{s-1} is Γ -invariant and Γ is diagonalizable, there exists a Γ -invariant subspace G_s such that $F_s = A_1 = F_{s-1} \oplus G_s$. Assume that $G_s, \dots, G_{s+1}$ have been constructed satisfying (1), (2) and (3). Then clearly, Δ maps G_{i+1} into F_i . Moreover, since $G_{i+1} \cap F_i = \{0\}$, we obtain $\Delta(G_{i+1}) \cap F_{i-1} = \{0\}$ and $G_{i+1} \cap \ker \Delta = \{0\}$. Moreover, $\Delta(G_{i+1})$ is Γ -invariant; hence $F_{i-1} \oplus \Delta(G_{i+1})$ is Γ -invariant. Therefore, there exists a Γ -invariant subspace W_i of F_i (since Γ is diagonalizable) such that $F_{i-1} \oplus \Delta(G_{i+1}) \oplus W_i = F_i$. It suffices now to consider $G_i = \Delta(G_{i+1}) \oplus W_i$ to get the result.

Remark that if x is an eigenvector for Γ (associated with λ) and $\Delta(x) \neq 0$, then $\Delta(x)$ is an eigenvector for Γ (associated with $\lambda - 1$). Thus if we consider a basis of G_s composed of eigenvectors of Γ , then we consider the image of this basis by Δ that we complete into

a basis of G_{s-1} (adding eigenvectors of Γ belonging to W_{s-1}). We proceed by induction to produce the desired basis. ■

Definition 6.4. Thanks to Lemma 2.1 and Proposition 6.3, one can assume without loss of generality that for any diagonalizable solvable pair (Δ, Γ) , the Poisson algebra $A_{(\Delta, \Gamma)}$ is presented in the basis, denoted by $(X_0, \dots, X_n)$, given by Proposition 6.3. We denote by $A(\bar{n}, \bar{a})$ this Poisson algebra $A_{(\Delta, \Gamma)}$.

Remark 6.5. It will sometimes be convenient to denote by λ_ℓ the eigenvalue for Γ of X_ℓ in $A(\bar{n}, \bar{a})$. The Poisson bracket of $A(\bar{n}, \bar{a})$ is then given by

$$\{X_i, X_j\} = \lambda_j \Delta(X_i)X_j - \lambda_i \Delta(X_j)X_i$$

for all $0 \leq i, j \leq n$.

Remark 6.6. Note that when (Δ, Γ) is a linear solvable pair with Δ maximal, then (Δ, Γ) is automatically a diagonalizable linear solvable pair by Theorem 4.5.

6.1. Poisson derivations for diagonalizable linear solvable pairs

In this section, we study Poisson derivations for diagonalizable linear solvable pairs. We have seen in Lemma 2.15 that Δ is always a Poisson derivation. In the linear case, the so-called *Eulerian derivation* $\mathcal{E}$ sending X_i to itself for all $0 \leq i \leq n$ is also a Poisson derivation. Our aim is to recover Δ , or more precisely its conjugacy class, from the algebraic structure of A . We first study the case of the maximal Jordan block since the proof of the general case will rely on it.

6.1.1. Poisson derivations for maximal Jordan block. In this section, thanks to Section 4.1, we may assume that $A = A(n, a)$ (see Example 1.3). We show that there are no other linear Poisson derivations apart from those in the $\mathbb{k}$ -linear span of Δ and $\mathcal{E}$. We note that essentially the same observation is made in [25, Remark 5.4], where the computation is omitted.

Lemma 6.7. Assume that $n \geq 2$ or that $n = 1$ and $a \neq 0$. For any $\delta \in \text{PDer}_{\text{gr}}(A)$, there exists a scalar λ such that $\delta(X_0) = \lambda X_0 \in \langle X_0 \rangle$.

Proof. First if $a = 0$ (so $n \geq 2$), then X_0 is, up to scalar multiple, the unique Poisson central element in A_1 , thanks to [16, Proposition 3.1 (2)]. The result follows since $\delta(X_0)$ is also a Poisson central element in A_1 ; see Remark 2.16.

Assume now $a \neq 0$. Using the fact that $\{X_0, X_n\} = -aX_0X_{n-1}$ and comparing for $0 < i \leq n$ the coefficients of X_iX_{n-1} in the relation $\delta(\{X_0, X_n\}) = \{\delta(X_0), X_n\} + \{X_0, \delta(X_n)\}$, we obtain that $\delta(X_0) = \lambda X_0$ for some $\lambda \in \mathbb{k}$. ■

Theorem 6.8. Assume that $n \geq 2$ or that $n = 1$ and $a \neq 0$. Then $\text{PDer}_{\text{gr}}(A) = \mathbb{k}\mathcal{E} \oplus \mathbb{k}\Delta$. In particular, the set of locally nilpotent derivations of $\text{PDer}_{\text{gr}}(A)$ is the one-dimensional subspace spanned by Δ .

Proof. We proceed by induction on $n \geq 1$. First assume that $a \neq -(n-1)$. Let $n = 1$ (so that $a \neq 0$) and $\delta \in \text{PDer}_{\text{gr}}(A)$. By Lemma 6.7, we know that $\delta(X_0) = \lambda X_0$ for a scalar λ . If $\delta(X_1) = \mu X_0 + \nu X_1$ for some scalars $\mu, \nu \in \mathbb{k}$, we have $\delta(\{X_0, X_1\}) = -2a\lambda X_0^2$ and $\{\delta(X_0), X_1\} + \{X_0, \delta(X_1)\} = -2a(\lambda + \nu)X_0^2$ so that $\lambda = \nu$. The result is proved since we have $\delta = \lambda \mathcal{E} + \mu \Delta$.

Let $n > 1$ and assume that the statement of the theorem is true for all algebras $A(n-1, b)$ with $b \neq -(n-2)$. Thanks to Lemma 6.7, there exists $\lambda \in \mathbb{k}$ such that $\delta(X_0) = \lambda X_0 \in \langle X_0 \rangle$. Therefore, δ induces a graded Poisson derivation of the Poisson algebra $A/\langle X_0 \rangle \cong A(n-1, a+1)$; see [16, Proposition 3.7 (1)] for the isomorphism. Since $a+1 \neq -(n-2)$, we can apply the induction hypothesis to get that there exist $\mu, \mu', v_i \in \mathbb{k}$ such that

$$\delta(X_i) = \begin{cases} \mu X_i + \mu' X_{i-1} + v_i X_0, & 2 \leq i \leq n, \\ \mu X_1 + v_1 X_0, & i = 1. \end{cases}$$

To conclude the proof, it remains to show that $\mu = \lambda$, $v_1 = \mu'$ and $v_i = 0$ for all $2 \leq i \leq n$ since then $\delta = \mu \mathcal{E} + \mu' \Delta$. If $a \neq 0$ then by applying δ to the Poisson brackets $\{X_0, X_1\}$ (resp. $\{X_0, X_2\}$) a straightforward computation yields $\mu = \lambda$ (resp. $v_1 = \mu'$). If $a = 0$, then by applying δ to the Poisson brackets $\{X_1, X_2\}$, a straightforward computation yields $\mu = \lambda$ and $v_1 = \mu'$. Let $2 \leq i \leq n$. By comparing the coefficient of X_0^2 in the relation $\delta(\{X_1, X_i\}) = \{\delta(X_1), X_i\} + \{X_1, \delta(X_i)\}$, we obtain that $v_i = 0$.

It remains to deal with the case $a = -(n-1)$. We proceed again by induction on $n \geq 2$. It is only necessary to prove the initialization (for $A(2, -1)$) because the induction step proceeds exactly as in the case $a \neq -(n-1)$. Direct computations from the Poisson brackets $\{X_0, X_1\} = X_0^2$, $\{X_0, X_2\} = X_0 X_1$ and $\{X_1, X_2\} = X_0 X_2$ yield $\delta = \mu \mathcal{E} + \mu' \Delta$. ■

6.1.2. When Δ is not necessarily maximal. We now assume that (Δ, Γ) is a diagonalizable linear solvable pair, but we do not assume that Δ is a maximal Jordan block. This situation is more complicated as the following example illustrates.

Example 6.9. Let Δ be of Jordan type $(2, 2)$ and $\Gamma = \text{diag}(a, a+1, b, b+1)$. We obtain the Poisson brackets

$$\begin{aligned} \{X_0, X_1\} &= -aX_0^2, & \{X_0, X_2\} &= 0, \\ \{X_0, X_3\} &= -aX_0X_2, & \{X_1, X_2\} &= bX_0X_2, \\ \{X_1, X_3\} &= (b+1)X_0X_3 - (a+1)X_1X_2, & \{X_2, X_3\} &= -bX_2^2. \end{aligned}$$

It is easy to verify that $\text{PDer}_{\text{gr}}(A_{(\Delta, \Gamma)}) = \mathbb{k}\Delta \oplus \mathbb{k}\mathcal{E}_{01} \oplus \mathbb{k}\mathcal{E}_{23}$, where $\mathcal{E}_{01}$ is the derivation sending X_0 to X_0 and X_1 to X_1 and both X_2, X_3 to 0 (a similar definition applies to $\mathcal{E}_{23}$). Therefore, $\dim \text{PDer}_{\text{gr}}(A_{(\Delta, \Gamma)}) = 3$ which is one more than the number of blocks of Δ .

Definition 6.10. Let (Δ, Γ) be a linear solvable pair. We say that (Δ, Γ) is generic or that Γ is generic if all the eigenvalues of Γ acting on A_1 are distinct and nonzero. In particular, a generic linear solvable pair is a diagonalizable linear solvable pair.

Recall from Definition 6.4 that without loss of generality, we have $A_{(\Delta, \Gamma)} = A(\bar{n}, \bar{a})$, where the derivation Δ can be chosen to be in canonical Jordan form (with $n_1 \geq n_2 \geq \dots \geq n_r$ denoting the sizes of the blocks of Δ) and that Γ can be chosen to be diagonal (with the notation of Remark 6.5 for its eigenvalues).

Theorem 6.11. Assume that (Δ, Γ) is a generic linear solvable pair with $r \geq 2$.

- (1) If $n_1 = 1$ (i.e., $\Delta = 0$), then $\text{PDer}_{\text{gr}} A(\bar{n}, \bar{a}) = \mathfrak{gl}_{n+1}(\mathbb{k})$.
- (2) If $\bar{n} = (2, 1, \dots, 1)$, then $\text{PDer}_{\text{gr}} A(\bar{n}, \bar{a})$ is the solvable non-nilpotent Lie algebra $\mathcal{L}$ of dimension $2n$ given by

$$\mathcal{L} = \{\delta_{u,v,c_2,\dots,c_n,d_2,\dots,d_n}, u, v, c_2, \dots, c_n, d_2, \dots, d_n \in \mathbb{k}\},$$

where

$$\delta_{u,v,c_2,\dots,c_n,d_2,\dots,d_n} := \begin{pmatrix} u & v & & \\ 0 & u & & \\ 0 & c_2 & d_2 & \\ \vdots & \vdots & & \ddots \\ 0 & c_n & & & d_n \end{pmatrix}.$$

Moreover, we have $Z(\mathcal{L}) = \mathbb{k} \text{id} \oplus \mathbb{k} \Delta$ and

$$[\mathcal{L}, \mathcal{L}] = \{\delta_{0,0,c_2,\dots,c_n,0,\dots,0}, c_2, \dots, c_n \in \mathbb{k}\}.$$

The ascending and descending central series of $\mathcal{L}$ are stationary from rank one.

- (3) Otherwise, $\text{PDer}_{\text{gr}} A(\bar{n}, \bar{a})$ is the $(r+1)$ -dimensional abelian Lie algebra given by

$$\mathbb{k} \Delta \oplus \bigoplus_{i=1}^r \mathbb{k} \mathcal{E}_i,$$

where $\mathcal{E}_i$ is the block diagonal matrix where the diagonal blocks are 0 except the i th which is id_{n_i} .

In particular, up to a scalar factor, Δ is the only locally nilpotent derivation in the center of $\text{PDer}_{\text{gr}} A$, except when $\Delta = 0$.

Proof. (1) The case where $\Delta = 0$ is trivial.

(2) and (3) Let $\delta \in \text{PDer}_{\text{gr}} A(\bar{n}, \bar{a})$. We first prove the following claim: if $n_i \geq 2$ for some i , then δ stabilizes all the blocks except possibly the i th.

It is enough to consider the case $i = 1$, that is, $n_1 \geq 2$. It clearly suffices to consider the case of the second block. We proceed by induction on $j \in \{n_1, \dots, n_1 + n_2 - 1\}$ to prove that $\delta(X_j) \in \bigoplus_{i=n_1}^{n_1+n_2-1} \mathbb{k} X_i$. It suffices, for $n_1 \leq j < n_1 + n_2$, to compare the

coefficients of X_0X_ℓ for $\ell \neq n_1$ if $j = n_1$ and $\ell \notin \{n_1, \dots, n_1 + n_2 - 1\}$ otherwise in the relation $\delta(\{X_1, X_j\}) = \{\delta(X_1), X_{n_1}\} + \{X_1, \delta(X_{n_1})\}$.

We now split the argument into two cases:

- (i) There are at least two blocks of size larger than or equal to 2.
- (ii) $n_i = 1$ for all $i > 1$ and $n_1 \geq 2$.

In case (i), by applying the claim to two different blocks of sizes larger than or equal to 2, we see that δ must stabilize every block. In particular, δ induces a Poisson derivation on each Poisson subalgebra B_i generated by the variables X_j corresponding to a block. It is clear that $B_i \cong A(n_i - 1, a_i)$ for each $1 \leq i \leq r$ so that the induced derivation has a form $\delta|_{B_i} = u_i \mathcal{E}_{n_i} + v_i \Delta|_{B_i}$, thanks to Theorem 6.8. Hence $\delta = \sum_{i=1}^r u_i \mathcal{E}_{n_i} + v_i \Delta|_{B_i}$ for some $u_i, v_i \in \mathbb{k}$. We will show that the v_i are all equal, thus proving assertion (3) in case (i). First note that there is nothing to check if the corresponding block is of size 1 since in that case $\Delta|_{B_i}$ is the zero map. Now if $n_i \geq 2$, then we compare the coefficients of $X_0X_{n_i}$ in the relation $\delta(\{X_1, X_{n_i+1}\}) = \{\delta(X_1), X_{n_i+1}\} + \{X_1, \delta(X_{n_i+1})\}$ to obtain that $v_i = v_1$, as desired.

In case (ii), we first show that $\delta(X_i) \in \bigoplus_{j=0}^{n_1-1} \mathbb{k}X_j$ for all $0 \leq i \leq n_1 - 2$. For this, let $0 < i < n_1 \leq \ell \leq n$. We obtain the result by identifying the coefficients of X_kX_ℓ for all $k \geq n_1 - 1$ in the relation $\delta(\{X_i, X_\ell\}) = \{\delta(X_i), X_\ell\} + \{X_i, \delta(X_\ell)\}$, using that $\Delta(X_\ell) = 0$ and $\delta(X_\ell) = u_\ell X_\ell$ for some $u_\ell \in \mathbb{k}$.

When $n_1 = 2$, we conclude by applying δ to the Poisson bracket $\{X_0, X_1\}$. This provides us with the form for δ given in (2). The final assertions of (2) follow from simple computations.

When $n_1 \geq 3$, we can moreover prove that $\delta(X_{n_1-1}) \in \bigoplus_{j=0}^{n_1-1} \mathbb{k}X_j$ by comparing, in the relation $\delta(\{X_1, X_{n_1-1}\}) = \{\delta(X_1), X_{n_1-1}\} + \{X_1, \delta(X_{n_1-1})\}$, the coefficients of X_0X_k for all $k \geq n_1$ and by using the fact that δ sends the Poisson subalgebra generated by $X_0, \dots, X_{n_1-2}$ into the Poisson subalgebra generated by $X_0, \dots, X_{n_1-1}$. In conclusion, δ stabilizes the subalgebra generated by $X_0, \dots, X_{n_1-1}$ which is isomorphic to $A(n_1 - 1, a_1)$, and the result follows from Theorem 6.8. This concludes the proof of (3). ■

Recall from Theorem 5.9 that the derivation Δ can be recovered from the Poisson structure of A . Theorem 6.11 is a means to do so in practice. More precisely, we have the following corollary.

Corollary 6.12. *Let (Δ, Γ) be a diagonalizable linear solvable pair with Γ generic and $\Delta \neq 0$. Then Δ may be recovered from the algebraic structure of A since it is, up to a scalar, the only locally nilpotent derivation contained in the center of $\text{PDer}_{\text{gr}} A$.*

6.1.3. When Γ is not diagonal. In this section, we show that the conclusion of Corollary 6.12 does not hold in general when Γ is not diagonalizable, or when Γ is diagonalizable but not generic. Our counterexamples, cases (1) and (2) from Lemma 6.13, will arise

from the study of the case where Δ has Jordan type $(2, 1)$. The general form for Γ is

$$\begin{pmatrix} a & b & c \\ 0 & a+1 & 0 \\ 0 & d & e \end{pmatrix}.$$

In $A_{(\Delta, \Gamma)}$ and $R_{(\Delta, \Gamma)}$, we have

$$\begin{aligned} \{X_0, X_1\} &= -aX_0^2, & [X_0, X_1] &= -aX_0 * X_0, \\ \{X_0, X_2\} &= 0, & [X_0, X_2] &= 0, \\ \{X_1, X_2\} &= eX_0X_2 + cX_0^2, & [X_1, X_2] &= eX_0 * X_2 + cX_0 * X_0. \end{aligned}$$

Since both X_0 and X_2 are in the kernel of Δ , we remark that $\Gamma(X_1)$ does not appear in the formulae of the Poisson bracket and of the product $*$. Therefore, without loss of generality, we can assume that $b = d = 0$. In particular, Γ is triangular, and its eigenvalues are $a, a+1$ and e .

Case 1. If $e \neq a$ and $e \neq a+1$, then Γ is diagonalizable, and one can assume $c = 0$ by Proposition 6.3.

Case 2. Assume that $e = a+1$. The solvable pair (Δ, Γ) is conjugate to the diagonal solvable pair $(\Delta, \text{diag}(a, a+1, a+1))$ via the automorphism of A fixing X_0 and X_1 and sending X_2 to $X_2 + cX_0$. Again, we can assume Γ is diagonalizable.

Case 3. Assume that $e = a$. If $c \neq 0$, then Γ is not diagonalizable so that the solvable pair (Δ, Γ) is not diagonalizable (Lemma 6.2). Note that the case $c \neq 0$ is isomorphic to the case $c = 1$ via the change of variable $X'_1 = \frac{1}{c}X_1$.

Lemma 6.13. *Consider the Poisson algebra $A = A_{(\Delta, \Gamma)}$ from Case 3 with $a, c \in \mathbb{k}$.*

- (1) *If $a \neq 0$ and $c \neq 0$, then $\text{PDer}_{\text{gr}}(A) = \left\{ \begin{pmatrix} u_{00} & u_{01} & u_{02} \\ 0 & u_{00} & 0 \\ 0 & u_{21} & u_{00} \end{pmatrix} \right\}$ is of dimension 4. In particular, $\text{PDer}_{\text{gr}}(A)$ contains a 3-dimensional subspace of locally nilpotent derivations.*
- (2) *If $a \neq 0$ and $c = 0$, then $\text{PDer}_{\text{gr}}(A) = \left\{ \begin{pmatrix} u_{00} & u_{01} & u_{02} \\ 0 & u_{00} & 0 \\ 0 & u_{21} & u_{22} \end{pmatrix} \right\}$ is of dimension 5. In particular, $\text{PDer}_{\text{gr}}(A)$ contains a 3-dimensional subspace of locally nilpotent derivations.*
- (3) *If $a = 0$ and $c \neq 0$, then $\text{PDer}_{\text{gr}}(A) = \left\{ \begin{pmatrix} u_{00} & u_{01} & u_{02} \\ 0 & u_{11} & u_{12} \\ 0 & u_{21} & 2u_{00}-u_{11} \end{pmatrix} \right\}$ is of dimension 6.*
- (4) *If $a = c = 0$, then A is Poisson commutative and the dimension of $\text{PDer}_{\text{gr}}(A)$ is 9.*

Proof. The computational proof is omitted. ■

Lemma 6.13 shows that in general, the derivation Δ cannot be recovered from the linear Poisson derivations $\text{PDer}_{\text{gr}}(A)$ when Γ is not diagonalizable, see case (1), or when Γ is diagonalizable but not generic, see case (2).

The following corollary is used in Example 2.25. Recall that the Lie algebra of linear Poisson derivations and its subset of locally nilpotent derivations are both invariants of homogeneous Poisson polynomial algebras by Proposition 4.1.

Corollary 6.14. *The Poisson algebra $A = A_{(\Delta, \Gamma)}$ from Case 3 with $c \neq 0$ cannot be realized by a diagonalizable solvable pair.*

Proof. Assume to the contrary that $A_{(\Delta, \Gamma)}$ is isomorphic to $A_{(\Delta', \Gamma')}$ for a diagonalizable solvable pair (Δ', Γ') . By Theorem 5.9, the Jordan type of Δ' is $(2, 1)$; hence we must have $\Gamma' = \text{diag}(\alpha, \alpha + 1, \varepsilon)$ for $\alpha, \varepsilon \in \mathbb{k}$. We have $\alpha \neq 0$ or $\varepsilon \neq 0$ since otherwise $A_{(\Delta, \Gamma)} \cong A_{(\Delta', \Gamma')}$ would be Poisson commutative, which is impossible since $c \neq 0$. We compute

$$\text{PDer}_{\text{gr}}(A_{(\Delta', \Gamma')}) = \left\{ \begin{pmatrix} u_{00} & u_{01} & \delta_{\alpha, \varepsilon} u_{02} \\ 0 & u_{00} & 0 \\ 0 & u_{21} & u_{22} \end{pmatrix} \right\},$$

where $\delta_{\alpha, \varepsilon}$ is the Kronecker delta symbol. When $\alpha \neq \varepsilon$, the dimension of the space of linear Poisson derivations $\text{PDer}_{\text{gr}}(A_{(\Delta', \Gamma')})$ is 4, and $\text{PDer}_{\text{gr}}(A_{(\Delta', \Gamma')})$ contains a two-dimensional subspace of locally nilpotent derivations. This cannot happen by the lemma. When $\alpha = \varepsilon$, the dimension of $\text{PDer}_{\text{gr}}(A_{(\Delta', \Gamma')})$ is 5. Since $c \neq 0$, this cannot happen by the lemma. ■

Remark 6.15. The fact that the case $\Gamma = \begin{pmatrix} a & 0 & 0 \\ 0 & a+1 & 0 \\ 0 & d & a+1 \end{pmatrix}$ with $d \neq 0$ can be realized by a diagonal solvable pair is a consequence of the fact that $\Gamma(X_1)$ never appears in the formulae. This is because all the other variables are in the kernel of Δ . Therefore, we should expect more non-diagonalizable cases when the rank of Δ is at least two.

7. Diagonalizable linear solvable pair: The algebra $R_{(\Delta, \Gamma)}$

The aim of this section is to give a presentation of the algebra R in the case of a diagonalizable linear solvable pair (Δ, Γ) . According to Proposition 6.3, we can choose a basis $(X_0, \dots, X_n)$ of A_1 such that Δ is in canonical Jordan form (we denote its Jordan type by $\bar{n} = (n_1, \dots, n_r)$ with $n_1 \geq n_2 \geq \dots \geq n_r$ and $n + 1 = \sum_{i=1}^r n_i$) and Γ is diagonal of the form $\Gamma = \text{diag}(a_1, \dots, a_1 + n_1 - 1, a_2, \dots, a_2 + n_2 - 1, \dots, a_r, \dots, a_r + n_r - 1)$.

For any $k \in \{1, \dots, r\}$ and $0 \leq j < n_k$, we denote by $Y_{j,k} = X_{n_1 + \dots + n_{k-1} + j}$ the j th variable of the k th block. Fix $k \in \{1, \dots, r\}$ and $0 \leq j < n_k$. Thanks to equation (1.2), we have for any $f \in R$ that

$$f * Y_{j,k} = \sum_{\ell \geq 0} \Delta^\ell(f) \binom{\Gamma}{\ell} (Y_{j,k}) = \sum_{\ell \geq 0} \Delta^\ell(f) \binom{a_k + j}{\ell} Y_{j,k} = \phi_{a_k + j}(f) Y_{j,k}.$$

In particular, for any $k' \in \{1, \dots, r\}$ and $0 \leq j' < n_{k'}$, we obtain the relations

$$\phi_{-a_k - j}(Y_{j',k'}) * Y_{j,k} = Y_{j',k'} Y_{j,k} = \phi_{-a_{k'} - j'}(Y_{j,k}) * Y_{j',k'}.$$

These relations may be rewritten as

$$\sum_{\ell=0}^{j'} \binom{-a_k - j}{\ell} Y_{j'-\ell, k'} * Y_{j, k} = \sum_{\ell=0}^j \binom{-a_{k'} - j'}{\ell} Y_{j-\ell, k} * Y_{j', k'}, \quad (7.1)$$

and we have the following proposition.

Proposition 7.2. *The algebra R is given by generators $Y_{j, k}$ for $1 \leq k \leq r$ and $1 \leq j \leq n_k$, and the homogeneous relations (7.1).*

Proof. We first show that the set $\mathcal{G} = \{Y_{j, k} \mid 1 \leq k \leq r, 1 \leq j \leq n_k\}$ is a generating set for R . From Proposition C.1, $\text{gr}^{\tilde{\epsilon}}(A)$ is generated by the image of the $Y_{j, k}$ in $\text{gr}^{\tilde{\epsilon}}(A)$. But from Proposition 4.9, $\text{gr}^{\tilde{\epsilon}}(A) = \text{gr}^{\tilde{\epsilon}}(R)$. Hence $\mathcal{G}$ is a set of generators for R as desired.

Denote by T the algebra given by generators $Y_{j, k}$ for $1 \leq k \leq r$ and $1 \leq j \leq n_k$, and relations (7.1). From the preceding argument, R is a quotient of T . Moreover, note that relations (7.1) are homogeneous with respect to the degree $\deg(Y_{j, k}) = 1$ for all j, k . Hence the natural map from T onto R is graded. We endow the set $\mathcal{G}$ with the order given by $Y_{j, k} \leq Y_{j', k'}$ if $k < k'$, or if $k = k'$ and $j \leq j'$. This induces an order on the monomials in the $Y_{j, k}$'s. The relations (7.1) may be rewritten as

$$Y_{j, k} * Y_{j', k'} = Y_{j', k'} * Y_{j, k} + \text{lower monomials}$$

for all $(j, k), (j', k')$. Hence every element of T is a linear combination of monomials $Y_{j_1, k_1} \cdots Y_{j_s, k_s}$ in the $Y_{j, k}$'s where $Y_{j_\ell, k_\ell} \leq Y_{j_{\ell+1}, k_{\ell+1}}$ for all $\ell \in \{1, \dots, s-1\}$. In particular, the dimension of the homogeneous component of degree d of T is smaller than that of R . But since R is a graded quotient of T , the canonical map from T onto R must be one-to-one. ■

Example 7.3. Let Δ be of Jordan type $(2, 2)$, and let $\Gamma = \text{diag}(a, a+1, b, b+1)$ be as in Example 6.9. Thanks to Proposition 7.2, we obtain the following complete set of relations between the generators of $R = R_{(\Delta, \Gamma)}$:

$$\begin{aligned} X_0 * X_1 - X_1 * X_0 &= -aX_0 * X_0, & X_2 * X_3 - X_3 * X_2 &= -bX_2 * X_2, \\ X_0 * X_2 - X_2 * X_0 &= 0, \\ X_0 * X_3 - X_3 * X_0 &= -aX_0 * X_2, & X_1 * X_2 - X_2 * X_1 &= bX_0 * X_2, \\ X_1 * X_3 - X_3 * X_1 &= (b+1)X_0 * X_3 - (a+1)X_2 * X_1 \\ &= (b+1)X_0 * X_3 - (a+1)X_1 * X_2 + (a+1)bX_0 * X_2. \end{aligned}$$

8. Unimodularity and Calabi–Yau property

In this section, we study the unimodularity of the Poisson algebra $A = A_{(\Delta, \Gamma)}$ in the polynomial case and determine when the algebra $R = R_{(\Delta, \Gamma)}$ is Calabi–Yau. Whereas the

unimodularity of A is completely characterized by Proposition 8.1, we only compute the Nakayama automorphism of R in the case of a generic diagonalizable linear solvable pair (Theorem 8.9). This result generalizes [16, Theorem 4.16].

8.1. Unimodularity of $A_{(\Delta, \Gamma)}$ in the polynomial case

Unimodular Poisson algebras are thought to be Poisson analogues of Calabi–Yau algebras; see [7]. Recall that a polynomial Poisson algebra $A = \mathbb{k}[X_0, \dots, X_n]$ is called unimodular if its modular derivation is zero, where the modular derivation m of A is given in the polynomial case by

$$m(f) = \sum_{k=0}^n \frac{\partial \{X_k, f\}}{\partial X_k}$$

for all $f \in A$; see [17, Lemma 2.4].

Proposition 8.1. *Let $A = \mathbb{k}[X_0, \dots, X_n]$ and (Δ, Γ) be a solvable pair on A . The modular derivation m of the Poisson algebra $A_{(\Delta, \Gamma)}$ is equal to $m = (1 - \operatorname{div}(\Gamma))\Delta$. In particular, as long as $\Delta \neq 0$, the Poisson algebra $A_{(\Delta, \Gamma)}$ is unimodular if and only if $\operatorname{div}(\Gamma) = 1$. When Γ is linear, this is equivalent to saying that $\operatorname{tr}(\Gamma) = 1$.*

Proof. Thanks to [14, Equality 4.22, p. 108], the modular derivation m of $A_{(\Delta, \Gamma)}$ is equal to minus the divergence of the Poisson bivector field $\pi = \Delta \wedge \Gamma$ of $A_{(\Delta, \Gamma)}$. Thanks to [14, Proposition 4.16] and the fact that the divergence of a locally nilpotent derivation is zero [28, Proposition 1.3.51], we have

$$\begin{aligned} m &= -\operatorname{div}(\pi) \\ &= -\operatorname{div}(\Delta \wedge \Gamma) \\ &= -(\operatorname{div}(\Gamma)\Delta - \operatorname{div}(\Delta)\Gamma - [\Delta, \Gamma]) \\ &= -\operatorname{div}(\Gamma)\Delta + \Delta \\ &= (1 - \operatorname{div}(\Gamma))\Delta \end{aligned}$$

as desired. For the assertion in the linear case, recall that $\operatorname{div}(\Gamma) = \sum_{i=0}^n \frac{\partial \Gamma(X_i)}{\partial X_i}$. ■

We illustrate this result with several examples in the linear case.

Example 8.2. Let (Δ, Γ) be a diagonalizable linear solvable pair and recall that

- (1) its Jordan type is $\bar{n} = (n_1, \dots, n_r)$, where $n_1 \geq n_2 \geq \dots \geq n_r$ are the sizes of the Jordan blocks of Δ acting on A_1 ,
- (2) there exists a basis of A_1 , and $\bar{a} = (a_1, \dots, a_r) \in \mathbb{k}^r$ such that Δ is in canonical Jordan form and Γ is diagonal of the form $\Gamma = \operatorname{diag}(a_1, \dots, a_1 + n_1 - 1, a_2, \dots, a_2 + n_2 - 1, \dots, a_r, \dots, a_r + n_r - 1)$,
- (3) we denote by $A(\bar{n}, \bar{a})$ the corresponding $A_{(\Delta, \Gamma)}$,

(4) we set $n + 1 = n_1 + \cdots + n_r$.

The parameter space of unimodular Poisson algebras $A(\bar{n}, \bar{a})$ is a $(r - 1)$ -dimensional affine subspace of $\mathbb{k}^r$ since the Poisson algebra $A(\bar{n}, \bar{a})$ is unimodular if and only if $\text{tr}(\Gamma) = 1$ if and only if

$$\sum_{t=0}^{r-1} n_{t+1} a_{t+1} + \binom{n_{t+1}}{2} = 1.$$

Example 8.3. If $r = 1$ (a single Jordan block), then A is unimodular if and only if

$$(n + 1)a + \binom{n + 1}{2} - 1 = 0 \iff a = \frac{-(n + 2)(n - 1)}{2(n + 1)}$$

as expected from [16], since $n + 1 = n_1 + \cdots + n_r = n_1$. We note that this value of a is also given in [25, Remark 5.4].

Example 8.4. Let Δ be of Jordan type $(2, 1)$. The general form for Γ is $\begin{pmatrix} a & b & c \\ 0 & a+1 & 0 \\ 0 & d & e \end{pmatrix}$, and hence the Poisson algebra $A_{(\Delta, \Gamma)}$ is unimodular if and only if $2a + e = 0$.

8.2. Calabi–Yau property for $R_{(\Delta, \Gamma)}$ in the generic diagonalizable case

The aim of this section is to compute the Nakayama automorphism of R in order to determine when R is a Calabi–Yau algebra. We denote by $R^e = R \otimes_{\mathbb{k}} R^{\text{op}}$ the enveloping algebra of R .

Definition 8.5. We say that R is *skew Calabi–Yau* (or *skew CY*) if

- (i) R is *homologically smooth*: R has a finite projective resolution as a left R^e -module such that each term is finitely generated,
- (ii) there are an algebra automorphism μ of R and an integer d such that

$$\text{Ext}_{R^e}^i(R, R^e) \cong \begin{cases} 0 & \text{if } i \neq 0, \\ {}^1R^\mu & \text{if } i = d, \end{cases}$$

where ${}^1R^\mu$ is the R -bimodule which is isomorphic to R as a $\mathbb{k}$ -vector space and such that $r \cdot s \cdot t = rs\mu(t)$.

If R is skew CY, the automorphism μ is called the *Nakayama automorphism* of R . If μ is inner, then R is *Calabi–Yau* or *CY*.

By [23, Lemma 1.2], any AS regular connected graded algebra is skew CY. In particular, the algebras $R_{(\Delta, \Gamma)}$ are skew CY in the linear case, thanks to Theorem 5.5.

Proposition 8.6. Let (Δ, Γ) be a linear solvable pair such that A is not Poisson commutative (see Corollary 4.8). Let Φ be an automorphism of R compatible with $\tilde{\epsilon}$ such that $\Phi = \text{id}$ (see Lemma 2.27). Assume that there exists a strongly normal element N of R whose eigenvalue with respect to Γ is nonzero. Then Φ commutes with Δ and ϕ_c for every $c \in \mathbb{k}$.

Proof. The proof decomposes into three steps. The first step is to show that Φ commutes with one ϕ_λ by considering the normal element $N \in R$. In the second step, we deduce from the first that Φ commutes with Δ by considering that Φ commutes with $\phi_{k\lambda}$ for $k \in \mathbb{N}$. The third step is easy: since Φ commutes with Δ , it commutes with every formal power series in Δ , hence with ϕ_c for every $c \in \mathbb{k}$.

First step. Consider $N \in \ker \Delta \cap \ker(\Gamma - \lambda \text{id})$ with $\lambda \neq 0$. Then N is a normal element, hence $\Phi(N)$ is too. Since every normal element in R is strongly normal, thanks to Proposition 5.7, there exists $\mu \in \mathbb{k}$ such that $\Gamma(\Phi(N)) = \mu\Phi(N)$. Since Lemmas 2.29 and 2.31 extend with the same proof to the filtration $\tilde{\varepsilon}$ and since the automorphism associated with the normal element $\Phi(N)$ is $\Phi \circ \phi_\lambda \circ \Phi^{-1} = \phi_\mu$, we deduce that the Poisson derivation of $\text{gr}^{\tilde{\varepsilon}}(R)$ associated with N is $\mu\overline{\Delta} = \overline{\Phi} \circ (\lambda\overline{\Delta}) \circ \overline{\Phi}^{-1}$, where the notation $\overline{\cdot}$ represents the induced map in $\text{gr}^{\tilde{\varepsilon}}(R)$. However, we have $\overline{\Phi} = \text{id}$, hence $\mu\overline{\Delta} = \lambda\overline{\Delta}$. Since $\Delta \neq 0$, we have $\overline{\Delta} \neq 0$. Thus we obtain $\mu = \lambda$ and therefore that Φ and ϕ_λ commute.

Second step. For $f \in R$, choose an integer n such that $\Delta^{n+1}(f) = \Delta^{n+1}(\Phi(f)) = 0$. The aim is to express $\Delta(f)$ as a linear combination of $(\phi_{k\lambda}(f))_{0 \leq k \leq n}$. Since $\lambda \neq 0$, the matrix of generalized binomial coefficients

$$A = \left(\binom{\lambda k}{\ell} \right)_{0 \leq k, \ell \leq n}$$

is invertible (see Lemma A.5). Hence there exists $(\alpha_0, \dots, \alpha_n) \in \mathbb{k}^{n+1}$ such that

$$A \begin{pmatrix} \alpha_0 \\ \vdots \\ \alpha_n \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}.$$

We then deduce that $\Delta(f) = \sum_{k=0}^n \alpha_k \phi_{k\lambda}(f)$ and $\Delta(\Phi(f)) = \sum_{k=0}^n \alpha_k \phi_{k\lambda}(\Phi(f))$. But Φ commutes with ϕ_λ ; therefore, it commutes with $\phi_{k\lambda} = (\phi_\lambda)^k$ for any $k \in \{0, \dots, n\}$ (Lemma 2.18). From the preceding equalities, we obtain that $\Phi(\Delta(f)) = \Delta(\Phi(f))$. ■

Remark 8.7. When the solvable pair (Δ, Γ) is not necessarily linear, the preceding proposition can be adapted with the following statement. Let Φ be an automorphism of R compatible with ε and such that $\overline{\Phi} = \text{id}$. Assume that every normal element of R is strongly normal and that there exists a strongly normal element N of R whose eigenvalue with respect to Γ is nonzero. Then Φ commutes with Δ and ϕ_c for every $c \in \mathbb{k}$.

The preceding proposition applies in particular to the Nakayama automorphism of R as detailed in the next example.

Example 8.8. Let (Δ, Γ) be a linear solvable pair. From Proposition C.1, $\text{gr}^{\tilde{\varepsilon}}(A)$ is a polynomial algebra; hence we can apply [31, Theorem 5.7] to get that the Nakayama automorphism μ of R is compatible with $\tilde{\varepsilon}$ and verifies $\overline{\mu} = \text{id}$ and $\overline{(\mu - \text{id})} = (1 - \text{tr}(\overline{\Gamma}))\overline{\Delta} = (1 - \text{tr}(\Gamma))\overline{\Delta}$.

Theorem 8.9. Assume that (Δ, Γ) is a generic diagonalizable linear solvable pair on $A = k[X_0, \dots, X_n]$ (see Definition 6.10). Then the Nakayama automorphism of R is $\phi_{1-\text{tr}(\Gamma)}$.

Proof. Let μ be the Nakayama automorphism of R . It is a graded automorphism for the standard degree. Since $\ker \Delta$ is Γ -invariant and Γ is diagonalizable, it induces a diagonalizable endomorphism of $\ker \Delta$. Hence there exists a strongly normal element N whose eigenvalue with respect to Γ is nonzero since 0 is not an eigenvalue of Γ . From Proposition 8.6 and Example 8.8, μ commutes with Δ and with ϕ_c for all $c \in \mathbb{k}$. In particular, Proposition 5.7 shows that every strongly normal element of A_1 is sent by μ to a strongly normal element of A_1 with the same eigenvalue with respect to Γ .

Consider a basis $(X_0, \dots, X_n)$ of A such that Δ is in canonical Jordan form of type $\bar{n} = (n_1, \dots, n_r)$ and Γ is diagonal (see Proposition 6.3). For $1 \leq k \leq r$ and $0 \leq i \leq n_r - 1$, we denote by $Y_{i,k} = X_{i+n_1+\dots+n_{k-1}}$ the i th element of the k th block. In particular, $\ker \Delta$ is the linear span of the $Y_{0,k}$ for $1 \leq k \leq r$.

Since the family $\mathcal{G} = \{Y_{j,k} \mid 1 \leq k \leq r, 1 \leq j \leq n_k\}$ is a generating set of R , it is enough to prove that μ and $\phi_{1-\text{tr}(\Gamma)}$ coincide on $\mathcal{G}$. Since $\overline{\mu} = \text{id}$ (Example 8.8) and $\tilde{\varepsilon}(Y_{0,k}) = 0$, we obtain $\mu(Y_{0,k}) = Y_{0,k} = \phi_{1-\text{tr}(\Gamma)}(Y_{0,k})$. Since $\varepsilon(Y_{1,k}) = 1$, [31, Theorem 5.7] and Proposition 8.1 show that $\mu(Y_{1,k}) = Y_{1,k} + (1 - \text{tr}(\Gamma))\Delta(Y_{1,k}) = \phi_{1-\text{tr}(\Gamma)}(Y_{1,k})$.

Therefore, we have the desired equalities for every k such that $n_k \leq 2$. Assume now that $n_k \geq 3$. We prove by induction on $i \geq 2$ that $\mu(Y_{i,k}) = \phi_{1-\text{tr}(\Gamma)}(Y_{i,k})$. Assume that $i \geq 1$ and $\mu(Y_{j,k}) = \phi_{1-\text{tr}(\Gamma)}(Y_{j,k})$ for $j \leq i$. Since both μ and $\phi_{1-\text{tr}(\Gamma)}$ commute with Δ , we have

$$\Delta((\mu - \phi_{1-\text{tr}(\Gamma)})(Y_{i+1,k})) = (\mu - \phi_{1-\text{tr}(\Gamma)})(\Delta(Y_{i+1,k})) = (\mu - \phi_{1-\text{tr}(\Gamma)})(Y_{i,k}) = 0.$$

Hence there exist scalars $\alpha_0, \dots, \alpha_r$ such that

$$\mu(Y_{i+1,k}) = \phi_{1-\text{tr}(\Gamma)}(Y_{i+1,k}) + \sum_{\ell=0}^r \alpha_\ell Y_{0,\ell}. \quad (8.10)$$

If $f \in R$ is an eigenvector for Γ associated with the eigenvalue λ , then for every $g \in R$, we have $g * f = \phi_\lambda(g)f$. Set $\Gamma(Y_{0,k}) = \lambda Y_{0,k}$, where $\lambda \in \mathbb{k}$. Then $\Gamma(Y_{1,k}) = (\lambda + 1)Y_{1,k}$, and we obtain $\Gamma(Y_{i+1,k}) = (\lambda + i + 1)Y_{i+1,k}$ by an easy induction on $i \in \{0, \dots, n_k - 1\}$. Hence we obtain that

$$\phi_{-\lambda-1}(Y_{i+1,k}) * Y_{1,k} = Y_{i+1,k} Y_{1,k} = \phi_{-\lambda-i-1}(Y_{1,k}) * Y_{i+1,k}. \quad (8.11)$$

For the sake of simplicity, we set $c = 1 - \text{tr}(\Gamma)$ and $\Upsilon = \sum_{\ell=0}^r \alpha_\ell Y_{0,\ell}$. By applying μ and ϕ_c to the relation (8.11) and by using the commutation of μ with ϕ_α , of ϕ_β with ϕ_α for every $\alpha, \beta \in \mathbb{k}$, and the relation (8.10), we obtain

$$\begin{aligned} 0 &= \phi_{-\lambda-1}(\mu(Y_{i+1,k})) * \mu(Y_{1,k}) - \phi_{-\lambda-i-1}(\mu(Y_{1,k})) * \mu(Y_{i+1,k}) \\ &= \phi_{-\lambda-1}(\phi_c(Y_{i+1,k}) + \Upsilon) * \phi_c(Y_{1,k}) - \phi_{-\lambda-i-1}(\phi_c(Y_{1,k})) * (\phi_c(Y_{i+1,k}) + \Upsilon) \\ &= \phi_{-\lambda-1}(\Upsilon) * \phi_c(Y_{1,k}) - \phi_{-\lambda-i-1}(\phi_c(Y_{1,k})) * \Upsilon. \end{aligned}$$

By applying ϕ_{-c} to the last equality, we obtain the relation

$$\left(\sum_{\ell=0}^r \alpha_\ell Y_{0,\ell} \right) * Y_{1,k} = \phi_{-\lambda-i-1}(Y_{1,k}) * \sum_{\ell=0}^r \alpha_\ell Y_{0,\ell}$$

since $f = \sum_{\ell=0}^r \alpha_\ell Y_{0,\ell} \in \ker \Delta$ and so $\phi_\alpha(f) = f$ for all $\alpha \in \mathbb{k}$. By using the expression of the product $*$, this last relation can be rewritten as $Y_{0,k} \sum_{\ell=0}^r \alpha_\ell (\lambda_\ell - (\lambda + i + 1)) Y_{0,\ell} = 0$, where λ_ℓ is the eigenvalue for Γ associated with the eigenvector $Y_{0,\ell}$. Since Γ has distinct eigenvalues, we obtain that $\alpha_\ell = 0$ for all ℓ and $\mu(Y_{i+1,k}) = \phi_{1-\text{tr}(\Gamma)}(Y_{i+1,k})$. This concludes the proof. ■

Corollary 8.12. *Let (Δ, Γ) be a generic diagonalizable linear solvable pair on the algebra $A = k[X_0, \dots, X_n]$. Then $A_{(\Delta, \Gamma)}$ is unimodular if and only if $R_{(\Delta, \Gamma)}$ is Calabi–Yau if and only if $\text{tr}(\Gamma) = 1$.*

Proof. Since R is a connected graded algebra, every inner automorphism is trivial. Hence R is Calabi–Yau if and only if its Nakayama automorphism is trivial. The result follows from Proposition 8.1 and Theorem 8.9 since $\Phi_c = \text{id}$ if and only if $c = 0$. ■

A. Combinatorial relations

Let B be an associative $\mathbb{k}$ -algebra and $b \in B$. Recall that for any $k \in \mathbb{N}$, the generalized binomial coefficient $\binom{b}{k}$ is defined by $\binom{b}{k} = \frac{b(b-1)\cdots(b-k+1)}{k!}$. For $k \in \mathbb{Z}$ with $k < 0$, we set $\binom{b}{k} = 0$.

Lemma A.1. *Let $a, b \in B$ and assume that $ab = ba$. For any $n \geq 0$, we have*

$$\sum_{\ell=0}^n \binom{a}{\ell} \binom{b}{n-\ell} = \binom{a+b}{n} \quad (\text{Chu–Vandermonde identity}), \quad (\text{A.2})$$

We need a better understanding of commutation relations in the enveloping algebra of the two-dimensional solvable Lie algebra spanned by Δ and Γ .

Lemma A.3. *Let $\Delta, \Gamma \in B$ and assume that $[\Delta, \Gamma] = \Delta\Gamma - \Gamma\Delta = \Delta$. For any $i \geq 0$ and $k \geq 0$ we have*

$$\left[\Delta, \binom{\Gamma}{k}\right] = \binom{\Gamma}{k-1}\Delta \quad \text{and} \quad \left[\Delta^i, \binom{\Gamma}{k}\right] = \sum_{\ell=1}^i \binom{i}{\ell} \binom{\Gamma}{k-\ell} \Delta^\ell.$$

Proof. The first assertion is clear for $k = 0$. Let $k \geq 1$. Since $\Delta(\Gamma - u) = (\Gamma - (u - 1))\Delta$ for any $u \in \mathbb{k}$, we have

$$\begin{aligned} k! \left[\Delta, \binom{\Gamma}{k}\right] &= (\Delta\Gamma(\Gamma - 1) \cdots (\Gamma - (k - 1)) - \Gamma(\Gamma - 1) \cdots (\Gamma - (k - 1))\Delta) \\ &= ((\Gamma + 1)\Gamma \cdots (\Gamma - (k - 2))\Delta - \Gamma(\Gamma - 1) \cdots (\Gamma - (k - 1))\Delta) \\ &= \Gamma \cdots (\Gamma - (k - 2))(\Gamma + 1 - (\Gamma - (k - 1)))\Delta \\ &= k\Gamma \cdots (\Gamma - (k - 2))\Delta \\ &= k(k - 1)! \binom{\Gamma}{k-1} \Delta \\ &= k! \binom{\Gamma}{k-1} \Delta, \end{aligned}$$

and the result is proved. We prove the second assertion by induction on $i \geq 0$. The case $i = 0$ is clear. The initialization $i = 1$ has just been proved. Assume that the result is true for some $i \geq 1$ and all $k \geq 0$. Then

$$\begin{aligned} \left[\Delta^{i+1}, \binom{\Gamma}{k}\right] &= \Delta^i \Delta \binom{\Gamma}{k} - \binom{\Gamma}{k} \Delta^{i+1} \\ &= \Delta^i \left(\binom{\Gamma}{k} \Delta + \binom{\Gamma}{k-1} \Delta \right) - \binom{\Gamma}{k} \Delta^{i+1} \\ &= \left[\Delta^i, \binom{\Gamma}{k}\right] \Delta + \Delta^i \binom{\Gamma}{k-1} \Delta \\ &= \left(\sum_{\ell=1}^i \binom{i}{\ell} \binom{\Gamma}{k-\ell} \right) \Delta + \sum_{\ell=0}^i \binom{i}{\ell} \binom{\Gamma}{k-\ell-1} \Delta \\ &= \sum_{\ell=1}^{i+1} \binom{i+1}{\ell} \binom{\Gamma}{k-\ell} \Delta^{\ell}. \end{aligned}$$

Remark A.4. The second relation of Lemma A.3 can be rewritten as

$$\begin{aligned} \Delta^i \binom{\Gamma}{k} &= \sum_{\ell=0}^i \binom{i}{\ell} \binom{\Gamma}{k-\ell} \Delta^\ell = \sum_{\ell=0}^{\min(i,k)} \binom{i}{\ell} \binom{\Gamma}{k-\ell} \Delta^\ell \\ &= \sum_{\ell=0}^k \binom{i}{\ell} \binom{\Gamma}{k-\ell} \Delta^\ell = \sum_{\ell=0}^k \binom{i}{k-\ell} \binom{\Gamma}{\ell} \Delta^\ell. \end{aligned}$$

Indeed, for $\ell > k$, $\binom{\Gamma}{k-\ell} = 0$, and for $\ell > i$, $\binom{i}{\ell} = 0$.

We finish this combinatorial appendix with the computation of the following determinant which will be useful for the determination of the Nakayama automorphism of R .

Lemma A.5. *Let $\mathbb{k}$ be a field of characteristic 0 and A be a $\mathbb{k}$ -algebra. For $a \in A$ and $n \in \mathbb{N}$, set*

$$M(a) = \left(\binom{ka}{\ell} \right)_{0 \leq k, \ell \leq n} \in M_{n+1}(A)$$

and $m(a) = \det(M(a))$. Then

$$m(a) = a^{\frac{n(n+1)}{2}}.$$

Proof. We can write $\binom{ka}{\ell} = \sum_{i=0}^{\ell} c_{i\ell} (ka)^i$ with $c_{i\ell} \in \mathbb{Q}$. Set $c_{i\ell} = 0$ for $\ell < i \leq n$. We have $M(a) = V(a)C$, where $C = (c_{k\ell})_{0 \leq k, \ell \leq n} \in M_{n+1}(\mathbb{Q})$ and $V(a) = ((ka)^{\ell})_{0 \leq k, \ell \leq n} \in M_{n+1}(A)$. Since C is an upper triangular matrix with diagonal coefficients $c_{\ell\ell} = \frac{1}{\ell!}$ and $V(a)$ is a Vandermonde matrix, we obtain the desired equality. ■

B. Tensor product of Poisson algebras

Let A and B be Poisson algebras. The tensor product $A \otimes B$ is a Poisson algebra for the Poisson bracket given by

$$\{a \otimes b, a' \otimes b'\}_{A \otimes B} = \{a, a'\}_A \otimes bb' + aa' \otimes \{b, b'\}_B$$

for $a, a' \in A$ and $b, b' \in B$. A derivation δ of A extends to a derivation $\hat{\delta}$ of $A \otimes B$ by setting

$$\hat{\delta}(a \otimes b) = \delta(a) \otimes b$$

for $a \in A$ and $b \in B$. Moreover, if δ is a Poisson derivation of A , then $\hat{\delta}$ is a Poisson derivation of $A \otimes B$. The same is true for a (Poisson) derivation of B with the obvious modification.

C. Symmetric algebra of a filtered vector space

Let us consider $V = \bigcup_{i \in \mathbb{N}} V_i$ a filtration of the vector space V , that is to say, for every $i \in \mathbb{N}$, V_i is a subspace of V and $V_i \subseteq V_{i+1}$. This filtration on V induces algebra filtrations on the tensor algebra $T(V)$ of V and on the symmetric algebra $S(V)$ of V that are given by

$$T_{\alpha}^n = \sum_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n = \alpha}} V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n} = \sum_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n \leq \alpha}} V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n} \subseteq V^{\otimes n}$$

and $S_{\alpha}^n = \sigma(T_{\alpha}^n)$, where $\sigma: T(V) \rightarrow S(V)$ is the canonical map.

Set $M_0 = V_0$, and for $i \geq 1$, consider a supplementary subspace M_i of V_{i-1} inside V_i . We thus get that $V_i = \bigoplus_{j \leq i} M_j$ and $V = \bigoplus_{i \in \mathbb{N}} M_i$ can be seen as a graded vector space which we denote by $\text{gr}(V)$. Using this graduation, we get a bigraduation on $T(V) = \bigoplus_{(n, \alpha) \in \mathbb{N}^2} T^{n, \alpha}$ and $S(V) = \bigoplus_{(n, \alpha) \in \mathbb{N}^2} S^{n, \alpha}$ given by

$$T^{n, \alpha} = \bigoplus_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n = \alpha}} M_{\alpha_1} \otimes \dots \otimes M_{\alpha_n}$$

and

$$S^{n, \alpha} = \bigoplus_{\substack{r \in \mathbb{N}, (n_1, \dots, n_r) \in \mathbb{N}^r \\ n_1 + \dots + n_r = n \\ n_1 \alpha_1 + \dots + n_r \alpha_r = \alpha}} S^{n_1}(M_{\alpha_1}) \otimes \dots \otimes S^{n_r}(M_{\alpha_r}).$$

See [4, Algèbre, Chapitre III, Section 5.5, Proposition 7, Section 6.6, Proposition 10]. We then set $T_\alpha = \bigoplus_{n \in \mathbb{N}} T_\alpha^n$ and $S_\alpha = \bigoplus_{n \in \mathbb{N}} S_\alpha^n$.

Proposition C.1. *The associated graded rings of the filtrations $T(V) = \bigcup_{\alpha \in \mathbb{N}} T_\alpha$ and $S(V) = \bigcup_{\alpha \in \mathbb{N}} S_\alpha$ are isomorphic to $T(\text{gr}(V))$ and $S(\text{gr}(V))$, respectively.*

Proof. For $(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n$, let us define $\pi_{\alpha_1, \dots, \alpha_n}^{\beta_1, \dots, \beta_n} : V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n} \rightarrow M_{\beta_1} \otimes \dots \otimes M_{\beta_n}$ the map associated with the decomposition of $V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n}$ as a direct sum

$$V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n} = \bigoplus_{\substack{(\beta_1, \dots, \beta_n) \in \mathbb{N}^n \\ \forall i, 0 \leq \beta_i \leq \alpha_i}} M_{\beta_1} \otimes \dots \otimes M_{\beta_n}.$$

Note that if there exists i such that $\beta_i > \alpha_i$, then $\pi_{\alpha_1, \dots, \alpha_n}^{\beta_1, \dots, \beta_n} = 0$. When $(\alpha_1, \dots, \alpha_n) = (\beta_1, \dots, \beta_n)$, we simply denote $\pi_{\alpha_1, \dots, \alpha_n}$ instead of $\pi_{\alpha_1, \dots, \alpha_n}^{\alpha_1, \dots, \alpha_n}$.

Let us now define

$$\pi = \bigoplus_{\alpha_1, \dots, \alpha_n} \pi_{\alpha_1, \dots, \alpha_n} : \bigoplus_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n = \alpha}} V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n} \longrightarrow \bigoplus_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n = \alpha}} M_{\alpha_1} \otimes \dots \otimes M_{\alpha_n}.$$

We want to show that π induces a map from T_α^n to $T^{n, \alpha}$. It suffices to show that if

$$w = (w_{\alpha_1, \dots, \alpha_n})_{(\alpha_1, \dots, \alpha_n)} \in \bigoplus_{\substack{(\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n \\ \alpha_1 + \dots + \alpha_n = \alpha}} V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n}$$

verifies $\sum_{(\alpha_1, \dots, \alpha_n)} w_{\alpha_1, \dots, \alpha_n} = 0 \in T^n(V)$, then $\pi(w) = 0$. But using the direct sum decomposition of the V_i , we get that

$$T_\alpha^n = \bigoplus_{\substack{(\beta_1, \dots, \beta_n) \in \mathbb{N}^n \\ \beta_1 + \dots + \beta_n \leq \alpha}} M_{\beta_1} \otimes \dots \otimes M_{\beta_n}.$$

Hence the equality $\sum_{(\alpha_1, \dots, \alpha_n)} w_{\alpha_1, \dots, \alpha_n} = 0 \in T^n(V)$ may be written as

$$\sum_{(\alpha_1, \dots, \alpha_n)} \pi_{\alpha_1, \dots, \alpha_n}^{\beta_1, \dots, \beta_n}(w_{\alpha_1, \dots, \alpha_n}) = 0$$

for all $(\beta_1, \dots, \beta_n)$ such that $\beta_1 + \dots + \beta_n \leq \alpha$.

In particular, when $\beta_1 + \dots + \beta_n = \alpha$ and $(\alpha_1, \dots, \alpha_n) \neq (\beta_1, \dots, \beta_n)$, there exists i such that $\beta_i > \alpha_i$. Hence $0 = \sum_{(\alpha_1, \dots, \alpha_n)} \pi_{\alpha_1, \dots, \alpha_n}^{\beta_1, \dots, \beta_n}(w_{\alpha_1, \dots, \alpha_n}) = \pi_{\alpha_1, \dots, \alpha_n}(w_{\alpha_1, \dots, \alpha_n})$ as wanted. We still denote by $\pi: T_\alpha^n \rightarrow T^{n, \alpha}$ the induced map. We clearly have $\ker \pi = T_{\alpha-1}^n$ showing the first result since the kernel of $\pi_{\alpha_1, \dots, \alpha_n}$ is included in $T_{\alpha-1}^n$ (see [4, Algèbre, Chapter 2, Section 3, Proposition 6]).

Let us now consider the case of the symmetric algebra. We denote by $\sigma_\alpha^n: T_\alpha^n \rightarrow S_\alpha^n$ and by $\sigma^{n, \alpha}: T^{n, \alpha} \rightarrow S^{n, \alpha}$ the maps induced by $\sigma: T(V) \rightarrow S(V)$.

The surjective map $\pi: T_\alpha^n \rightarrow T^{n, \alpha}$ sends $\ker \sigma_\alpha^n$ onto $\ker \sigma^{n, \alpha}$. Hence π induces a surjective map, also denoted by $\pi: S_\alpha^n \rightarrow S^{n, \alpha}$. To conclude, it remains to show that $\ker \pi = S_{\alpha-1}^n$. It is clear that $S_{\alpha-1}^n \subseteq \ker \pi$. The reverse inclusion follows from diagram chasing in the following diagram (where the columns are exact as well as the second row).

$$\begin{array}{ccccc} & & \ker \sigma_\alpha^n & \xrightarrow{\pi} & \ker \sigma^{n, \alpha} \\ & & \downarrow & & \downarrow \\ T_{\alpha-1}^n & \hookrightarrow & T_\alpha^n & \xrightarrow{\pi} & T^{n, \alpha} \\ & & \downarrow \sigma_\alpha^n & & \downarrow \sigma^{n, \alpha} \\ S_{\alpha-1}^n & \hookrightarrow & S_\alpha^n & \xrightarrow{\pi} & S^{n, \alpha} \end{array}$$

This concludes the proof. ■

Proposition C.2. Assume that there exist linear maps $\Delta: V \rightarrow V$ and $\Gamma: V \rightarrow V$ such that $\Delta(V_i) \subseteq V_{i-1}$ and $\Gamma(V_i) \subseteq V_i$ for every $i \in \mathbb{N}$ and such that $[\Delta, \Gamma] = \Delta$. The extension of Δ as a derivation of $T(V)$, respectively $S(V)$, verifies $\Delta(T_\alpha^n) \subseteq \Delta(T_{\alpha-1}^n)$, respectively $\Delta(S_\alpha^n) \subseteq \Delta(S_{\alpha-1}^n)$. The extension of Γ as a derivation of $T(V)$, respectively $S(V)$, stabilizes the preceding filtration on $T(V)$, respectively $S(V)$. Hence Δ and Γ induce graded derivations $\overline{\Delta}$ of degree -1 and $\overline{\Gamma}$ of degree 0 on $T(\text{gr}(V))$ and $S(\text{gr}(V))$. Moreover, we have $[\overline{\Delta}, \overline{\Gamma}] = \overline{\Delta}$.

In addition, Δ induces a degree -1 map on $\text{gr}(V)$, and Γ induces a degree 0 map on $\text{gr}(V)$, and their extensions as derivations on $T(\text{gr}(V))$ and $S(\text{gr}(V))$ coincide with $\overline{\Delta}$ and $\overline{\Gamma}$.

Proof. The extension of a linear map $f: V \rightarrow V$ as a derivation of $T(V)$ acts on $V_{\alpha_1} \otimes \dots \otimes V_{\alpha_n}$ as $f \otimes \text{id} \otimes \dots \otimes \text{id} + \dots + \text{id} \otimes \dots \otimes \text{id} \otimes f$. Hence if $f = \Delta$, then T_α^n is mapped into $T_{\alpha-1}^n$, and if $f = \Gamma$, then T_α^n is mapped into T_α^n , showing that they induce graded endomorphisms $\overline{\Delta}$ of degree -1 and $\overline{\Gamma}$ of degree 0 of $T(\text{gr}(V))$ and $S(\text{gr}(V))$.

Moreover, these endomorphisms are derivations of the associated graded rings and verify $[\overline{\Delta}, \overline{\Gamma}] = \overline{\Delta}$.

For the last part of the proof, since the maps considered are derivations of $T(\text{gr}(V))$ and $S(\text{gr}(V))$, it suffices to show that they coincide on $\text{gr}(V)$. This follows readily from the following commutative diagrams.

$$\begin{array}{ccc}
 V_\alpha & \xrightarrow{\Delta} & V_{\alpha-1} \\
 \downarrow & & \downarrow \\
 V_\alpha / V_{\alpha-1} \cong M_\alpha & \xrightarrow{\overline{\Delta}} & V_{\alpha-1} / V_{\alpha-2} \cong M_{\alpha-1} \\
 \\
 V_\alpha & \xrightarrow{\Gamma} & V_\alpha \\
 \downarrow & & \downarrow \\
 V_\alpha / V_{\alpha-1} \cong M_\alpha & \xrightarrow{\overline{\Gamma}} & V_\alpha / V_{\alpha-1} \cong M_\alpha
 \end{array}$$

This concludes the proof. ■

Example C.3. Consider V a finite-dimensional vector space and Δ and Γ two linear endomorphisms of V verifying $[\Delta, \Gamma] = \Delta$. Since Δ is nilpotent and $\ker \Delta^i$ is Γ -invariant (see the proof of Theorem 4.5), the family of subspaces $V_i = \ker \Delta^i$ is a filtration of V satisfying the hypothesis of Proposition C.2.

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