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DERIVATIONS OF LIE ALGEBRA EXTENSIONS AND NON-SINGULAR DERIVATIONS OF LIE ALGEBRAS IN PRIME CHARACTERISTIC

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1. Introduction

Let L be a Lie algebra and d be a derivation of L. The derivation d is non-singular if it is injective as linear transformation. We are interested in studying what information we can obtain about a Lie algebra if it has a nonsingular derivation. Jacobson's famous theorem [7] states that a finite-dimensional Lie algebra over a field of characteristic zero that admits a non-singular derivation must be nilpotent. It is well-known that this theorem is not valid when the characteristic is non-zero. Non-nilpotent and solvable examples were constructed by Shalev [12] and Mattarei [10], whereas the simple Lie algebras with non-singular derivations were classified by Benkart and her collaborators in [4]. A significant application of Lie algebras with non-singular derivation in characteristic p was presented by Shalev [11]. In his proof of the coclass conjectures of Leddham-Green and Newman for pro-p groups, Shalev uses the fact that finite-dimensional Lie algebras over a field of characteristic $p > 0$ with non-singular derivation d such that $d^{p-1} = 1$, must be nilpotent.

Despite the existing examples, little is known about non-nilpotent Lie algebras with non-singular derivations. In these project we propose to explore the structure of solvable, non-nilpotent Lie algebras with non-singular derivations. In order to study these algebras we develop a theory of derivations of Lie algebra extensions. We adopt the concept of a compatible pair of automorphisms introduced in [3] for derivations of Lie algebras.

Let K and I be Lie algebras such that K acts on I, then we can define the subalgebra $\mathsf{Comp}(K, I)$ of $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$ as the set of derivations of $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$ that are derivations of semi-direct sum $K \oplus I$. Formally,

$$\mathsf{Comp}(K, I) = \{\alpha + \beta \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I) \mid \alpha + \beta \in \mathsf{Der}(K \oplus I)\}.$$

The algebra $\mathsf{Der}(K)$ carries information about the multiplicative structure of K. Analogously, the algebra $\mathsf{Comp}(K, I)$ carries information about the action of K on I. In section 3.4 we present an example of this by exploring the proof of Jacobson's Theorem and we prove a version for Lie algebras representations over a field of characteristic $p > 0$.

Theorem 3.14 *Let K and I be finite dimensional Lie algebras over a field of characteristic p where $p \geqslant 0$ such that K is nilpotent. Suppose that K act on I by representation $\psi : K \to \mathsf{Der}(I)$. Let $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ such that α has no eigenvalue 0. If either $p = 0$*

or $p > 0$ and $\dim I < p$ then $Tr(\psi^n(k)) = 0$, for all $k \in K$ and $n > 0$. In these two cases, $\psi(k), k \in K$ is nilpotent.

We also adapt an algorithm presented by Bettina Eick [3] for calculating the automorphism group of solvable Lie algebras. A key step in the algorithm is the following. Let L be a Lie algebra and I an abelian ideal of L such that I is invariant by $\mathsf{Aut}(L)$. Then there exists a homomorphism $\phi : \mathsf{Aut}(L) \to \mathsf{Aut}(L)/I \times \mathsf{Aut}(I)$ induced by the actions of $\mathsf{Aut}(L)$ on L/I and I. The image of ϕ can be calculated using $Aut(L/I)$, while $\mathsf{Ker}(\phi)$ is equal to $\mathsf{Z}^1(K, I)$. Then the group $\mathsf{Aut}(L)$ can be obtained applying the first isomorphism theorem to ϕ. It is possible to use this process to derivations.

We can define a Lie algebra homomorphism similar to ψ in the previous paragraph. Let L be a Lie algebra and $I \trianglelefteq L$ an ideal such that I is invariant under $\mathsf{Der}(L)$. Then if $d \in \mathsf{Der}(L)$, d induces derivations α and β of L/I and I, respectively. Hence we obtain a Lie algebra homomorphism

$$\psi : \mathsf{Der}(L) \to \mathsf{Der}(L/I) \oplus \mathsf{Der}(I).$$

Let K be a Lie algebra and I be a K-module. Let $\mathsf{Z}^2(K, I)$ be the vector space of cocycles and $\mathsf{Comp}(K, I)$ the Lie algebra of compatible pairs. Let $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ and $\vartheta \in \mathsf{Z}^2(K, I)$. Define an action of $\mathsf{Comp}(K, I)$ over $\mathsf{Z}^2(K, I)$ by

$$(\alpha, \beta) \cdot \vartheta(h, k) = \beta(\vartheta(h, k)) - \vartheta(\alpha(k), h) - \vartheta(k, \alpha(h)), \qquad \text{for all } h, k \in K.$$

The elements of the annihilator of this action will be called induced pairs and we denote the set of induced pairs by $\mathsf{Indu}(K, I, \vartheta)$. Let $\vartheta \in \mathsf{Z}^2(K, I)$ a cocycle and K_θ be the Lie algebra extension obtained from K by ϑ. Then we can lift the derivation of $\mathsf{Indu}(K, I, \vartheta)$ to $Der(K_\theta)$. Thus we obtained the following theorem.

Theorem 3.8 *Let K be a Lie algebra and I a K-module. Let $\vartheta \in \mathsf{H}^2(K, I)$ and suppose that I, as ideal of K_ϑ, invariant under derivations of K_ϑ. Let $\phi : \mathsf{Der}(K_\vartheta) \to \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ given by $\phi(d) = (\alpha, \beta)$. Then:*

(1) $\mathsf{Im}(\phi) = \mathsf{Indu}(K, I, \vartheta)$
(2) $\mathsf{Ker}(\phi) \cong \mathsf{Z}^1(K, I)$

The details of this construction can be seen in Section 3. There is a significant difference between the application of this approach to automorphisms and to derivations: calculating the automorphism groups of Lie algebras is usually a difficult task that may involve a large orbit-stabilizer calculation, while calculating the algebra $\mathsf{Der}(K_\vartheta)$ can be done by solving a system of linear equations. Thus, to understand the importance of Theorem 3.8 we must discover what additional information of $\mathsf{Der}(K_\vartheta)$ we are able to obtain through information concerning the algebras $\mathsf{Der}(K)$ and $\mathsf{Der}(I)$.

In order facilitate the reading of the text and the references, we added a section with results on the primary decomposition of vector spaces in relation to subalgebras of linear operators and a brief description of the main articles used.

This text is organized as follows: Section 2 is dedicated to literature review. In Section 3, we present compatible pairs and the lifting process of derivations of a Lie algebra K to the Lie algebras K_ϑ such that ϑ is a cocycle. We end this section by applying the compatible pairs to Jacobson's Theorem. Section 4 is composed of some examples and conjectures about modular solvable non-nilpotent Lie algebras with non-singular derivations.

2. Non-singular derivations: known results

This section is composed by description of a decomposition of a Lie algebra L relative to a subalgebra K of $\mathfrak{gl}(L)$ and its application in Jacobson's Theorem. Next, we have the calculations presented in Shalev's article [12] about conditions on the order of derivation which guarantee nilpotency of a Lie algebra. The section ends with Mattarei's Theorem that relates the order of non-singular derivations of solvable modular Lie algebras to roots of certain types of polynomials.

2.1. **Basic concepts.** The symbol '$\oplus$' will be used to denote the direct sum of algebras, while the direct sum of vector spaces will be denoted by '$\dot{+}$'.

Let V be a finite-dimensional vector space over a field $\mathbb{F}$ and $a \in \mathsf{End}(V)$. Let $p \in \mathbb{F}[X]$ be a univariate polynomial and define

$$V_0(p(a)) = \{v \in V \mid \text{ there is an } m > 0 \text{ such that } p(a)^m v = 0\}.$$

$V_0(p(a))$ is a vector subspace of V invariant under a. Now let A be the associative sualgebra of $\mathsf{End}(V)$ with 1 generated by a. Let p_a be the minimum polynomial of a and suppose that

$$p_a = p_1^{k_1} \cdots p_r^{k_r}$$

is the factorization of p_a into irreducible factors, such that p_i has leading coefficient 1 and $p_i \neq p_j$ for $1 \leqslant i, j \leqslant r$. Then V decomposes as a direct sum of subspaces

$$V = V_0(p_1(a)) \dot{+} \cdots \dot{+} V_0(p_r(a)),$$

each space $V_0(p_i(a))$ being invariant under A. Furthermore, the minimum polynomial of the restriction of a to $V_0(p_i(a))$ is $p_i^{k_i}$. A proof of this result can be found in [2] Lemma A.2.2.

We can generalize this decomposition to subalgebras of $\mathfrak{gl}(V)$ generated by more than one element. Let K be a subalgebra of $\mathfrak{gl}(V)$. A decomposition $V = V_1 \oplus \cdots \oplus V_s$ of V into K-modules V_i is said to be *primary* if the minimum polynomial of the restriction of a to V_i is a power of an irreducible polynomial for all $a \in K$ and $1 \leqslant i \leqslant s$. The subspaces V_i are called primary components. If for any two components V_i and V_j ($i \neq j$), there is an $x \in K$ such that the minimum polynomials of the restrictions of x to V_i and V_j are powers of different irreducible polynomial, then the decomposition is called *collected*. In general V will not have a primary (or primary collected) decomposition into K-modules but such a decomposition is guaranteed to exist if the base field of V is algebraically closed and $K \leqslant \mathfrak{gl}(V)$ is nilpotent.

Proposition 2.1 ([2], Theorem 3.1.10). *Let V be finite-dimensional vector space. Let $K \leqslant \mathfrak{gl}(V)$ be a nilpotent subalgebra. Then V has a unique collected primary decomposition relative to K*

If the vector space V has a collected primary decomposition $V = V_1 \dotplus \cdots \dotplus V_s$ then we can characterize the components V_i. For $x \in K$ and $1 \leqslant i \leqslant s$ define $p_{x,i}$ to be the irreducible polynomial such that the minimum polynomial of x restricted to V_i is a power of $p_{x,i}$. Then we obtain the equality

$$V_i = \{v \in V \mid \text{ for all } x \in K \text{ there is an } m > 0 \text{ such that } p_{x,i}(x)^m v = 0\}.$$

It is worth noting that if the base field of V is algebraically closed, then all irreducible polynomials are of the form $p(X) = (X - \lambda)$, for some $\lambda \in \mathbb{F}$, and hence $p_{x,i} = (X - \lambda_i(x)), \lambda_i \in \mathbb{F}^*$. Further, in this case, primary components are of the form

$$V_i = \{v \in V \mid \text{ for all } x \in K \text{ there is an } m > 0 \text{ such that } (x - \lambda_i(x)I)^m v = 0\},$$

with $\lambda_i \in K^*$. Its natural to give a name for this case. Let V be a finite-dimensional vector space over a field $\mathbb{F}$ and $K \leqslant \mathfrak{gl}(V)$ a subalgebra. Let $\lambda \in K^*$. Then

$$V_\lambda = \{v \in V \mid \text{ for all } x \in K \text{ there is an } m > 0 \text{ such that } (x - \lambda(x).I)^m v = 0\}.$$

If $V_\lambda \neq 0$ then V_λ is called a *generalized eigenspace* of V associated to the *generalized eigenvalue* $\lambda \in K^*$.

Now we consider a Lie algebra L and a nilpotent subalgebra $K \leqslant \mathsf{Der}(L)$. Then the decomposition to generalized eigenspaces of D can provide us some information of the multiplicative structure of L.

Proposition 2.2 ([8], Proposition 5 of Chapter III). *Let L be a Lie algebra over an algebraically closed field. Let K be a subalgebra of $\mathsf{Der}(L)$. If $\lambda, \mu : K \to \mathbb{F}^*$ are generalized eigenvalues of K then $[L_\lambda, L_\mu] \subseteq L_{\lambda+\mu}$ if $\lambda + \mu$ is a generalized eigenvalue of K. Otherwise $[L_\mu, L_\lambda] = 0$.*

Following we present some general results about Lie algebras that will be used in the this text.

Proposition 2.3. *Let L be a Lie algebra, let I be an ideal of L such that L/I is nilpotent and such that $\mathsf{ad}_x^I : I \to I$ is nilpotent for all $x \in L$. Then L is nilpotent.*

Proof. As L/I is nilpotent then for each $x \in L$, $(\mathsf{ad}_{x+I})^n$ is a nilpotent endomorphism in $\mathsf{End}(L/I)$, i.e., there is $n > 0$ such that $(\mathsf{ad}_x)^n(a) \in I$, for all $x \in L, a \in I$. On the other hand, ad_x^I is nilpotent, so we have a m such that $(\mathsf{ad}_x^I)^m(\mathsf{ad}_x)^n = 0$, i.e., $(\mathsf{ad}_x)^{m+n} = 0$. So ad_x is a nilpotent endomorphism in $\mathfrak{gl}(L)$. By Engel's theorem, L is nilpotent. $\square$

Theorem 2.4 ([5], Theorem 4.1). *Let L be a solvable subalgebra of $\mathfrak{gl}(V)$, V finite dimensional. If $V \neq 0$, then V contains a common eigenvector for all the endomorphism in L.*

Theorem 2.5 ([5], Corollary A of Theorem 4.1)**.** *(Lie) Let L be a finite-dimensional solvable Lie algebra over an algebraically closed field $\mathbb{F}$ of characteristic 0. Let $\psi : L \to \mathfrak{gl}(V)$ be a finite-dimensional representation of L. Then there is a basis of V relative to which then matrix of all $\psi(x)$ for all $x \in L$ are all upper triangular.*

The Theorems 2.4 and 2.5 still valid in characteristic $p > 0$ if $\dim V < p$. The proof of Theorem 2.4 in prime characteristic goes through as in the Humphreys' book except for the last sentence. In the book's version, we have $n\lambda([x, y]) = 0$ and conclude $\lambda([x, y]) = 0$ because the characteristic of $\mathbb{F}$ is 0. In this case, since $p > \dim V = n$, we can still make the same conclusion since n will not be a zero divisor. The proof of Theorem 2.5 goes through exactly as in the book. For future reference in the text we will report a version of the Lie's Theorem in positive characteristic.

Theorem 2.6. *Let L be a finite-dimensional solvable Lie algebra over an algebraically closed field $\mathbb{F}$ of characteristic $p > 0$. Let V be a finite-dimensional vector space of dimension $n < p$. Let $\psi : L \to \mathfrak{gl}(V)$ be a finite-dimensional representation of L. Then there is a basis of V relative to which then matrix of all $\psi(x)$ for all $x \in L$ are all upper triangular.*

2.2. **Jacobson's Theorem.** In the article *A note on automorphism and derivations of Lie algebras* [7], Jacobson used a variation of Engel's Theorem for weakly closed sets to get sufficient conditions for a Lie algebra to be nilpotent. We recommend the reading of Sections 1 and 2 of Chapter 2 of Jacobson's book [8] as reference for examples and proofs.

Suppose that K and I are Lie algebras and $\psi : K \to \mathsf{Der}(I)$ is a given Lie algebra homomorphism. Then we say that K *acts* on I or that I is a K*-module*. In this case, the image $\psi(k)(a)$ of $a \in I$ under $k \in K$ will be written simply as $[k, a]$. If I is an ideal of a Lie algebra K, then K acts on I. If $k \in K$, then the image of k under this action will be denoted by ad_k^I or simply by ad_k when the domain of the representation is clear from the context. Thus, for $a \in I$ and for $k \in K$, $\mathsf{ad}_k^I(a) = \mathsf{ad}_k(a) = [k, a]$. The homomorphism $K \to \mathsf{Der}(I)$ that takes $k \mapsto \mathsf{ad}_k^I$, will be denoted by ad^I.

Example 2.7. Let L be a Lie algebra with an abelian ideal I and set $K = L/I$. Define the Lie algebra representation $\mathsf{ad}^I : K \to \mathsf{Der}(I)$ by $\mathsf{ad}_{x+I}^I(a) = [x, a]$ for all $x \in L$ and $a \in I$. This is well defined, since I is abelian. Then I is a K-module. In this case, we say that the action is *induced by the adjoint representation.*

Let A be an associative algebra with 1 over a field $\mathbb{F}$. A subset S of A is called *weakly closed* if for every ordered pair $(a, b) \in S \times S$, there is an element $\gamma(a, b) \in \mathbb{F}$ such that $ab + \gamma(a, b)ba \in S$. If S is a subset of an Lie or associative algebra X, then $\langle S\rangle$ denotes the Lie or associative, respectively, subalgebra of X generated by S. In the case of associative algebras we assume that $1 \in \langle S\rangle$. This notation may cause confusion when X is an associative and Lie algebra in the same time, in such cases we will indicate clearly if $\langle S\rangle$ denotes associative or Lie subalgebra.

Proposition 2.8 ([8], Theorem 1 of Chapter II)**.** *Let V be a finite-dimensional vector space over a field $\mathbb{F}$. Let $S \subseteq \mathsf{End}(V)$ be a weakly closed subset such that every $s \in S$ is* *associative nilpotent, that is, $s^k = 0$, for some positive integer k. Then the associative subalgebra $\langle S\rangle \leqslant \mathsf{End}(V)$ is nilpotent.*

With this result we can prove Jacobson's Theorem.

Theorem 2.9 ([7], Theorem 3)**.** *Let L be a finite-dimensional Lie algebra over a field of characteristic 0 and suppose that there exists a subalgebra D of the algebra of derivations of L such that*

(1) *D is nilpotent;*
(2) *if there is $c \in L$ such that $d(c) = 0$ for all $d \in D$ then $c = 0$.*

Then L is nilpotent.

Proof. Let $\overline{\mathbb{F}}$ be the algebraic closure of the base field. We can extend all derivations of L to $\overline{L} = L \otimes \overline{\mathbb{F}}$. If we prove that $\overline{L}$ is nilpotent then L is nilpotent. So we will assume that $\mathbb{F}$ is algebraically closed. In this case the extension of D is nilpotent and without 0 as common eigenvalue, i.e. if there is $c \in L$ such that $d(c) = 0$ for all $d \in D$ then $c = 0$. Let $L = L_{\gamma_1} \dotplus \cdots \dotplus L_{\gamma_t}$ be the decomposition of L into generalized eigenspaces of D. By Proposition 2.2 we have $[L_{\gamma_i}, L_{\gamma_j}] \subseteq L_{\gamma_i+\gamma_j}$ if $\gamma_i + \gamma_j$ is a eigenvalue of D and $[L_{\gamma_i}, L_{\gamma_j}] = 0$ otherwise. For a subset $Y \subseteq L$, we let ad_Y denote the set of adjoint mappings induced by elements of Y. Then the inclusion just noted shows that the set $S = \bigcup \mathsf{ad}_{L_{\gamma_j}}$ is a weakly closed set of linear transformations. Let $a \in L_{\gamma_j}$ and $b \in L_{\gamma_i}$. Then $(\mathsf{ad}_a)^s(b) \in L_{\gamma_i+s\gamma_j}$, for all $s \geqslant 0$.(*)

The generalized eigenvalue $\gamma_j \neq 0$ and $\mathbb{F}$ has characteristic 0 then $\gamma_i + s\gamma_j$, for $s > 0$, are pairwise distinct. Then for some r large enough $(\gamma_i + r\gamma_j)$ is not an eigenvalue and $\mathsf{ad}_a(b) = 0$. Follow that ad_a is nilpotent linear transformation. Thus every element of S is nilpotent. By Proposition 2.8 the associative subalgebra $\langle S\rangle \leqslant \mathsf{End}(V)$ is nilpotent. Observe that the Lie subalgebra $\langle S\rangle$ is subset of the associative subalgebra $\langle S\rangle$, then $\langle S\rangle$ is nilpotent as Lie subalgebra. But $\langle S\rangle = \mathsf{ad}_L$ implies that L is a nilpotent Lie algebra. ☐

A review of the proof of Theorem 2.9 shows that the hypothesis of zero characteristic is essential to prove that every element in a homogeneous component is nilpotent. As the following examples shows, Theorem 2.9 fails to hold in characteristic $p > 0$.

Example 2.10. Let $\mathbb{F}$ be the field of 2^m elements and L be the vector space over $\mathbb{F}$ such that

$$L = \langle x_\alpha \mid \alpha \in \mathbb{F}, \alpha \neq 0\rangle$$

with a basis labeled by nonzero elements of the field $\mathbb{F}$ and with multiplication $[x_\alpha, x_\beta] = (\beta - \alpha)x_{\alpha+\beta}$. Then L is a simple Lie algebra and the map $d \in \mathsf{End}(L)$ given by $d(e_\alpha) = \alpha e_\alpha$ is a non-singular derivation. The calculations of this example and a systematic investigation of simple Lie algebras with nonsingular derivations can be found in [4].

Example 2.11. Let V be a vector space over a field $\mathbb{F}$ of characteristic $p > 0$. Let $B = \{a_1, a_2, \cdots, a_p\}$ be a basis of V. Define the linear map $x \in \mathfrak{gl}(V)$ by

$$x(a_i) = a_{i+1 \mod p}, 1 \leqslant i \leqslant 0.$$

Let K be the abelian Lie algebra generated by $\{x, x^2, \cdots, x^{p-1}\}$. Then V can be considered as K-module with the standard action of $\mathfrak{gl}(V)$ on V. Let L be the semi-direct sum $L = K \bigoplus V$ then L is an Solvable non-nilpotent Lie algebra of derived length 2. Let $\lambda, \delta \in \mathbb{F}$ both non-zero and $\lambda \neq s\delta$, for all $s \in \mathbb{F}_p$. The linear map $d : L \to L$ defined by

$$d : \begin{cases} x^j \mapsto j\lambda x^j, & 1 \leqslant j \leqslant p-1; \\ a_i \mapsto (\delta + (i-1)\lambda)a_i, & 1 \leqslant i \leqslant p, \end{cases}$$

is a non-singular derivation of L.

For Lie algebras over fields of characteristic $p > 3$ we could not find an example of derived length greater than 3 but in characteristic 2 we have the following example.

Example 2.12. Let L be a vector space of dimension 6 over $\mathbb{F}_4$. Let $\lambda \in \mathbb{F}_4$ such that $\lambda^2 = \lambda + 1$ and $\{a_1, a_2, a_3, a_4, a_5, a_6\}$ a basis of L over $\mathbb{F}_4$. Define the products

$$\begin{array}{llll} [a_1, a_3] = \lambda a_5 + a_6, & [a_1, a_4] = \lambda a_6, & [a_1, a_5] = \lambda^2 a_3 + a_4, & [a_3, a_5] = \lambda a_2, \\ [a_1, a_6] = \lambda^2 a_4, & [a_2, a_3] = \lambda a_6, & \text{and } [a_2, a_5] = \lambda^2 a_4. & \end{array}$$

L is a solvable non-nilpotent Lie algebra of derived length 3. The linear map $d : L \to L$ defined by

$$d : \begin{cases} a_1 \mapsto a_1 & a_3 \mapsto \lambda a_3 & a_5 \mapsto \lambda^2 a_5 \\ a_2 \mapsto a_2 & a_4 \mapsto \lambda a_4 & a_6 \mapsto \lambda^2 a_6 \end{cases}$$

is a non-singular derivation of L.

Another question is whether the converse of Jacobson's Theorem is true, that is, is it true that all finite-dimensional nilpotent Lie algebras admit non-singular derivation. By Dixmier and Lister [6], there are nilpotent Lie algebras admitting only nilpotent derivations. Bellow we present Dixmier and Lister example of such an algebra.

Example 2.13. Let $\mathbb{F}$ be a field of characteristic 0 and $L = \langle x_1, x_2, \cdots, x_8 \rangle$ be a Lie algebra over $\mathbb{F}$ with dimension 8 and multiplication table

$$\begin{array}{llllll} [e_1, e_2] = e_5 & [e_1, e_3] = e_6 & [e_1, e_4] = e_7 & [e_1, e_5] = -e_8 & [e_2, e_3] = e_8 & [e_2, e_4] = e_6 \\ [e_2, e_6] = -e_7 & [e_3, e_4] = -e_5 & [e_3, e_5] = -e_7 & [e_4, e_6] = -e_8 & [e_i, e_j] = -[e_j, e_i]. & \end{array}$$

Moreover, $[e_i, e_j] = 0$ if it is not in table above. Then L is nilpotent with $L^3 \neq 0$, $L^4 = 0$ and every derivation of L is nilpotent.

2.3. **Jacobson's Theorem in characteristic** $p > 0$**.** As the examples above shows, Jacobson's Theorem is in general not true in characteristic $p > 0$. However, we have the follow weaker result.

Theorem 2.14. *Let L be a Lie algebra over a field of characteristic $p > 0$ and suppose that there exists a subalgebra $D \leqslant \mathsf{Der}(L)$ such that*

(1) *D is nilpotent;*
(2) *if there is $c \in L$ such that $d(c) = 0$ for all $d \in D$ then $c = 0$.*

If D has at most $p-1$ generalized eigenvalues then L is nilpotent.

Proof. The proof of this theorem is identical to proof of Theorem 2.9 up to point marked by (*). The generalized eigenvalue $\gamma_j \neq 0$ then the set $\{\gamma_i, \gamma_i + \gamma_j, \cdots, \gamma_i + (p-1)\gamma_j\}$ has p distinct elements. As D has at most $p-1$ generalized eigenvalues then for some r, $0 < r \leqslant p-1$, $(\gamma_i + r\gamma_j)$ is not an eigenvalue. Follow that ad_a is nilpotent linear transformation, for every $a \in L_{\gamma_i}$. Thus every element of S is nilpotent. By Proposition 2.8 the associative subalgebra $\langle S \rangle \leqslant \mathsf{End}(V)$ is nilpotent and hence ad_L is nilpotent. Therefore L is a nilpotent Lie algebra. ☐

2.4. **The orders of non-singular derivations.** An interesting approach by Shalev in article [12] is to study the order of nonsingular derivations, establishing conditions for a Lie algebra over a field of characteristic p with non-singular derivations to be nilpotent. More precisely, Shalev studied the set of orders of nonsingular derivations of non-nilpotent Lie algebras of characteristic p. Later, Mattarei in [10] showed that this set of numbers corresponds to the set of solutions of some polynomial equation over a field of characteristic p. Below we present some results of these articles.

Let L be a Lie algebra over an algebraically closed field of characteristic p. We can characterize the matrix of a non-singular derivation of L. We need a result for derivations in Lie algebras over a field of characteristic p.

Lemma 2.15. *Let L be a Lie algebra over a field $\mathbb{F}$ of characteristic $p > 0$. If $d \in \mathsf{Der}(L)$ then $d^{p^m} \in \mathsf{Der}(L)$, for all $m \geqslant 1$.*

Proof. If we prove this result for $m = 1$ then the general case when $m \geqslant 1$ will follow by induction. Let us hence prove the statement only for $m = 1$. Let $d \in \mathsf{Der}(L)$ and $x, y \in L$. First we prove the Leibniz's formula by induction:

$$d^n([x,y]) = \sum_{k=0}^{n} \binom{n}{k} [d^k(x), d^{n-k}(y)], \text{ for all } n > 0.$$

The case $n = 1$ follow from derivation's definition. Suppose that Leibniz's formula is valid for n. Then

$$d^n([x,y]) = \sum_{k=0}^{n} \binom{n}{k} [d^k(x), d^{n-k}(y)]. \tag{1}$$

Calculating d in both sides of equation (1) we have

$$d^{n+1}([x,y]) = \sum_{k=0}^{n} \binom{n}{k} [d^{k+1}(x), d^{n-k}(y)] + \sum_{k=0}^{n} \binom{n}{k} [d^k(x), d^{n-k+1}(y)]. \tag{2}$$

Rearranging the index, the right side of equation (2) can be write as

$$[d^{n+1}(x), y] + \sum_{k=1}^{n} \left(\binom{n}{k-1} + \binom{n}{k} \right) [d^k(x), d^{n+1-k}(y)] + [x, d^{n+1}(y)].$$

As $\binom{n}{k-1} + \binom{n}{k} = \binom{n+1}{k}$ then

$$d^{n+1}([x,y]) = \sum_{k=0}^{n+1} \binom{n+1}{k} [d^k(x), d^{n+1-k}(y)].$$

Then by induction Leibniz's formula is proved. As the field $\mathbb{F}$ has characteristic p then setting $n = p^m$ the Leibniz's formula is reduced to

$$d^{p^m}([x,y]) = [d^{p^m}(x), y] + [x, d^{p^m}(y)].$$

□

Proposition 2.16. *Let V be a finite-dimensional vector space over an algebraically closed field of characteristic $p > 0$ and $f \in \mathsf{End}(V)$ non-singular with order r coprime to p. Then f is diagonalizable.*

Proof. Let A be the matrix of the endomorphism f in Jordan normal form and write $A = S + N$ such that S is diagonal, N is nilpotent upper triangular and S, N commute. Denote by M_{ij} the element of a matrix M of the i^{th} line and the j^{th} column. It follows that

- If $S_{ii} = \lambda_i$ then $(S^k)_{ii} = \lambda_i^k$, for all $k > 0$;
- $N^k_{i(i+j)} = 0$, for all $0 \leqslant j < k$.

As the order of A is r we have $A^r = Id$. Then

$$I = A^r = (S+N)^r = S^r + \binom{r}{1} S^{r-1}N + \binom{r}{2} S^{r-2}N^2 + \cdots + \binom{r}{r-1} SN^{r-1} + N^r.$$

The identity matrix on the left-hand side of the last equation is diagonal, while the summands, with the exception of the first summand, on the right-hand side are nilpotent. Further, if $N \neq 0$, then the second summand rS^{r-1}N in non-zero, and it is the only summand that contains a non-zero entry in a positions $(i, i+1)$ with $i > 0$. However, this implies that if $N \neq 0$, then A^r must contain a non-zero entry in a position $(i, i+1)$, which is a contradiction, as $A^r = I$. Hence $N = 0$ as claimed. Then f is diagonalizable. □

Let L be a Lie algebra over the field $\mathbb{F}$ of characteristic $p > 0$ such that L has a non-singular derivation d. Let r be the order of d such that $r = sp^t$, with $\gcd(s,p) = 1$. Then by Lemma 2.15 d^{p^t} is a derivation whose order is prime to p and, by Proposition 2.16, d^{p^t} is diagonalizable. So if L is a Lie algebra over an algebraically closed field $\mathbb{F}$ of characteristic $p > 0$ with non-singular derivation then L has a diagonalizable derivation d without eigenvalue 0.

Proposition 2.17 ([12], Lemma 2.2)**.** *Let L be a finite-dimensional Lie algebra in characteristic $p > 0$ which admits a non-singular derivation d whose order n is coprime to p. Suppose that L is not nilpotent. Then there exist $\lambda \in \overline{\mathbb{F}}_p$ such that $(\lambda + \delta)^n = 1$ for all $\delta \in \mathbb{F}_p$.*

Proof. Let $\overline{\mathbb{F}}$ be a algebraic closure of $\mathbb{F}$ and $R = \{\alpha \in \overline{\mathbb{F}}_p \mid \alpha^n = 1\}$. If R is not contained in base field of L then we consider d for the extension $L \otimes \overline{\mathbb{F}}$. By Proposition 2.16, d is diagonalizable. Let $L = L_{\lambda 1} \dotplus \cdots \dotplus L_{\lambda_r}$ the decomposition of L to eigenspaces of d. The set $S = \bigcup \mathsf{ad}_{L_{\lambda_j}}$ is weakly closed with $\gamma(\mathsf{ad}_a, \mathsf{ad}_b) = -1$ for all $a \in L_{\lambda_i}, b \in L_{\lambda_j}$. If each ad_a is nilpotent then the associative subalgebra $\langle S \rangle \leqslant \mathfrak{gl}(L)$ is nilpotent by Proposition 2.8. Hence ad_L is a nilpotent Lie algebra and L is nilpotent. As L is non-nilpotent by hypothesis then there is $a \in L_{\lambda_j}$ and $b \in L_{\lambda_i}$ such that $(\mathsf{ad}_a)^n(b) \neq 0$, $1 \leqslant n \leqslant p$. However this implies $(\lambda_i + \delta\lambda_j)$ are eigenvalues of d for $1 \leqslant \delta \leqslant p$. Since $|d| = n$ each eigenvalue of d has order n. Thus $(\lambda_i + \delta\lambda_j)^n = 1$, for all $\delta \in \mathbb{F}_p$. As λ_j is an eigenvalue of d, $\lambda_j^n = \lambda_j^{-n} = 1$. Thus $1 = (\lambda_i + \delta\lambda_j)^n \lambda^{-n} = (\lambda_i\lambda_j^{-1} + \delta)^n$. Therefore setting $\lambda = \lambda_i\lambda_j^{-1}$, $(\lambda + \delta)^n = 1$ for all $\delta \in \mathbb{F}_p$. □

Usying the same notation as in the proof of Proposition 2.17 and observing that the set R contains precisely the n-th roots of unity in $\overline{\mathbb{F}}$, we write $x^n - 1 = \prod_{\alpha \in R}(x - \alpha)$. As for all $\delta \in \mathbb{F}_p$, $\lambda + \delta \in R$, $\prod_{\delta \in \mathbb{F}_p}(x - \lambda - \delta)$ divides $x^n - 1$. But

$$\prod_{\delta \in \mathbb{F}_p}(x - \lambda - \delta) = (x - \lambda)^p - (x - \lambda) = x^p - x - c,$$

where $c = \lambda^p - \lambda$. The first equation of last display can be seen by observing that the elements $\lambda + \delta$ with $\delta \in \mathbb{F}_p$ are exacty the p roots of the polynomial $(x - \lambda)^p - (x - \lambda)$. Let $g(x) = x^p - x - c$. Then $g(x)$ divides $x^n - 1$, which implies that x^n is congruent to 1 modulo $g(x)$. In this case, Lemma 2.4 of [12] shows that $n \geqslant p^2 - 1$. Now we can prove the theorem.

Theorem 2.18 ([12], Theorem 1.1)**.** *Let L be a finite dimensional Lie algebra in characteristic $p > 0$ which admits non-singular derivation of order n. Write $n = p^s m$ where m is coprime to p. Suppose $m < p^2 - 1$. Then L is nilpotent.*

Proof. The derivation d^{p^s} has order m. Suppose that L is not nilpotent. Then by the comment above we have $m \geqslant p^2 - 1$. □

Mattarei in [10] presented an example of non-nilpotent solvable modular Lie algebra.

Example 2.19. Let $\alpha, \beta \in \overline{\mathbb{F}}_p$ with $\alpha\beta^{-1} \notin \mathbb{F}_p$. Let M be a p-dimensional vector space over $\overline{\mathbb{F}}_p$ with basis $e_1, \cdots, e_p$, and let E, F be the linear transformations of M defined by $E(e_i) = e_{i+1}$(indices modulo p), and $F(e_i) = (\alpha + i\beta)e_i$. The transformations E and F span a two-dimensional solvable Lie algebra, which admits M as a left module. Let L be the semidirect sum of $\{E\}$ and M with respect to this action. Then F acts on L as a non-singular derivation, with eigenvalues β on $\{E\}$, and $\alpha + \lambda\beta$ for $\lambda \in \mathbb{F}_p$ on M.

The next result links the orders non-singular derivations of Lie algebras of characteristic p to some polynomial equations.

Proposition 2.20. *Let p be a prime number and let n be a positive integer, prime to p. The following statements are equivalent:*

(1) *there exists a non-nilpotent Lie algebra of characteristic p with a non-singular derivations of order n;*
(2) *there exists an element $\alpha \in \overline{\mathbb{F}}_p$ such that $(\alpha + \lambda)^n = 1$ for all $\lambda \in \mathbb{F}_p$*
(3) *there exist an element $c \in \overline{\mathbb{F}}_p^*$ such that $x^p - x - c$ divides $x^n - 1$ as elements of the polynomial ring $\overline{\mathbb{F}}_p[x]$.*

Mattarei in [10] defines the set N_p of the possible orders of non-singular derivations of non-nilpotent Lie algebras of characteristic p and determine all elements of N_p which are smaller than p^3, for $p > 3$.

2.5. **Objectives of the project.** In this section we will present some questions about solvable non-nilpotent modular Lie algebras L with a non-singular derivation d. This questions are based in the examples and results showed in the previous sections. These issues will serve as a reference for further work.

Problem 1. Is there a solvable, non-nilpotent Lie algebra over a field of characteristic $p \geqslant 3$ with non-singular derivation and derived length greater than 2?

Suppose that the answer to Problem 1 is yes and let L be such Lie algebra. Let $I = L^{(2)}$ and $K = L/I$. As $L^{(3)} = 0$ then I is abelian and so K acts on I by adjoint representation. In this case, K is a solvable Lie algebra of derived length 2 with non-singular derivation. By Proposition 3.1, there is a cocycle $\vartheta \in \mathsf{Z}^2(K, I)$ such that $L \cong K_\vartheta$. This calculation show us that every Lie algebra that answer Problem 1 can be obtained by an extension of a solvable Lie algebra of derived length 2 with non-singular derivation. So we need to understand this Lie algebras of derived length 2 to search for an answer of Problem 1. We will study a variation of this question.

Problem 2. Let K be one of the known solvable, non-nilpotent Lie algebra over a field of characteristic $p \geqslant 3$ with non-singular derivation and derived length 2. Is there a non-trivial K-module I and a cocycle $\vartheta \in \mathsf{Z}^2(K, I)$ such that K_ϑ has a non-singular derivation?

As first step to study Problem 2 we will try to describe some cases of abelian Lie algebras K acting over vector spaces. This study defines our next objectives in this project.

Objectives

- To characterize solvable non-nilpotent modular Lie algebras of the form $L = \langle x \rangle \bigoplus I$ where I is a finite dimensional abelian Lie algebra such that L admits a non-singular derivation; study the extensions of such algebras and obtain ones that admits non-singular derivations; By Corollary 3.15, there is a quotient $Q = L^{(i)}/L^{i+1}$ with $\dim Q \geqslant p$. Study the number of such quotients.

- How the existence of non-singular derivations affect the structure of $\mathsf{Der}(L)$? Can we define some algebra structure over non-singular derivations of L?
- Stydy the general structure of solvable non-nilpotent Lie algebras with non-singular derivations

3. Derivations and Lie algebra extensions

3.1. **Lie algebra extensions.** An *extension* of a Lie algebra K by a Lie algebra I is an exact sequence

$$0 \to I \xrightarrow{i} L \xrightarrow{s} K \to 0 \tag{3}$$

of Lie algebras. The Lie algebra L in the middle of the exact sequence contains an ideal $\mathsf{Ker}(s) = \operatorname{Im} i \cong I$ such that $L/I \cong K$. We will write informally that 'L is an extension of K by I'. The extension (3) *splits* if L has a subalgebra S such that $L = S \dotplus \mathsf{Ker}(s)$. The extension (3) is *trivial* if there exists an ideal S of L such that $L = S \oplus \mathsf{Ker}(s)$. The extension (3) is central if $\mathsf{Ker}(s)$ lies in the center $Z(L)$ of L.

Let K be a Lie algebra over a field $\mathbb{F}$ and let I be a vector space over $\mathbb{F}$. Denote by $\mathsf{C}^2(K, I)$ the vector space of alternating bilinear maps $\vartheta : K \times K \to I$. If I is a K-module and $\vartheta \in \mathsf{C}^2(K, I)$ has the property that

$$\vartheta(x, [y, z]) + \vartheta(y, [z, x]) + \vartheta(z, [x, y]) + [x, \vartheta(y, z)] + [y, \vartheta(z, x)] + [z, \vartheta(x, y)] = 0, \tag{4}$$

for all $x,\ y,\ z \in K$, then ϑ is said to be a *cocycle* and the vector space of coclycles is denoted by $\mathsf{Z}^2(K, I)$. Let $T : K \to I$ be a linear transformation and define, $\vartheta_T : K \times K \to I$ by

$$\vartheta_T(h, k) = T([h, k]) + [k, T(h)] - [h, T(k)] \quad \text{for all} \quad h,\ k \in K. \tag{5}$$

Then $\vartheta_T \in \mathsf{Z}^2(K, I)$ and such a cocycle ϑ_T is said to be a *coboundary.* The set of coboundaries is denoted by $\mathsf{B}^2(K, I)$. The set $\mathsf{B}^2(K, I)$ is a subspace of $\mathsf{Z}^2(K, I)$, and we set $\mathsf{H}^2(K, I) = \mathsf{Z}^2(K, I)/\mathsf{B}^2(K, I)$ to be the quotient space. The first cohomology group of K and I is defined as

$$\mathsf{Z}^1(K, I) = \{\nu \in \mathsf{Hom}(K, I) \mid \nu([h, k]) = [h, \nu(k)] - [k, \nu(h)] \text{ for all } h,\ k \in K\}.$$

The next result, whose proof can be found, for instance, in [9, Section 4.2], links Lie algebra extensions to cohomology. Let K be a Lie algebra and let I be a K-module. Let $\vartheta \in \mathsf{Z}^2(K, I)$ and define the Lie algebra $K_\vartheta = K \dotplus I$ with the product

$$[x + a, y + b] = [x, y] + \vartheta(x, y) + [a, y] - [b, x] \text{ for all } x,\ y \in K \text{ and } a,\ b \in I. \tag{6}$$

Proposition 3.1. *The following hold for the Lie algebra K_ϑ:*

(1) *K_ϑ is a Lie algebra extension of K by I;*
(2) *if $\nu \in \mathsf{B}^2(K, I)$, then K_ϑ is isomorphic to $K_{\vartheta+\nu}$;*
(3) *if $\vartheta \in \mathsf{B}^2(K, I)$, then K_ϑ is a split extension of K by I.*

Conversely, let L be a Lie algebra and J be an abelian ideal of L. Then there exists $\vartheta \in \mathsf{Z}^2(L/J, J)$ such that $L \cong (L/J)_\vartheta$.

The cocycle ϑ in last the statement of Proposition 3.1 can be constructed as follows. Let $\pi : L \to L/I$ denote the natural projection, and let $\sigma : L/I \to L$ be a right inverse of π; that is, $\pi\sigma = \mathrm{id}_{L/I}$. Then, for $k + I,\ h + I \in L/I$, set

$$\vartheta(k + I, h + I) = \sigma([k + I, h + I]) - [\sigma(k + I), \sigma(h + I)].$$

Routine calculation shows that $\vartheta \in \mathsf{Z}^2(L/I, I)$ and that $L \cong L_\vartheta$.

3.2. **Compatible pairs and derivations of semidirect sums.** Compatible pairs were introduced in [3] to compute automorphisms of solvable groups and solvable Lie algebras. We adopt the concept for derivations of Lie algebras. Let K and I be Lie algebras such that K acts on I via the homomorphism $\psi : K \to \mathsf{Der}(I)$. We define the *semidirect sum* $K \oplus_\psi I$ as the vector space $K \dotplus I$ with the product operation given as

$$[(k_1, a_1), (k_2, a_2)] = ([k_1, k_2], [k_1, a_2] - [k_2, a_1] + [a_1, a_2]).$$

When the K-action on I is clear from the context, then we usually suppress the homomorphism 'ψ' from the notation and write simply $K \oplus I$. If L is a Lie algebra such that L has an ideal I and a subalgebra K in such a way that $L = K \dotplus I$, then $L \cong K \oplus_\psi I$ where ψ is the restriction of ad_I to K. In a semidirect sum $K \oplus I$, an element $(k, a) \in K \dotplus I$ will usually be written as $k + a$.

Suppose that K and I are as in the previous paragraph. The direct sum $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$ of the derivation Lie algebras is a Lie algebra. An element $(\alpha, \beta) \in \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ is said to be a *compatible pair* if

$$\beta([k, a]) = [\alpha(k), a] + [k, \beta(a)] \quad \text{for all} \quad k \in K,\ a \in I. \tag{7}$$

We let $\mathsf{Comp}(K, I)$ denote the set of compatible pairs in $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$. Using the homomorphism $\psi : K \to \mathsf{Der}(I)$ associated to the K-action on I, we can write equation (7) in another form as follows. Writing $[k, a]$ as $\psi(k)(a)$, we have that $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ if and only if the equation

$$\beta\psi(k) = \psi(\alpha(k)) + \psi(k)\beta.$$

holds in $\mathsf{Der}(I)$ for all $k \in K$. Using commutator, this is equivalent to

$$[\beta, \psi(k)] = \psi(\alpha(k)) \quad \text{for all} \quad k \in K. \tag{8}$$

Letting $\mathsf{ad} : \mathsf{Der}(I) \to \mathsf{Der}(I)$ denote the adjoint representation, equation (8) can be rewritten as

$$\mathsf{ad}_\beta \psi(k) = \psi(\alpha(k)) \quad \text{for all} \quad k \in K. \tag{9}$$

Therefore, $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ if and only if the following diagram commutes:

$$\begin{tikzcd} K \arrow[r, "\psi"] \arrow[d, "\alpha"] \arrow[dr, phantom, "\circlearrowright"] & \mathsf{Der}(I) \arrow[d, "\mathsf{ad}_\beta"] \\ K \arrow[r, "\psi"] & \mathsf{Der}(I). \end{tikzcd}$$

A compatible pair $(\alpha, \beta) \in \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ will usually be written as $\alpha + \beta$. If $\alpha + \beta \in \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ as above, then $\alpha + \beta$ can be considered a element of $\mathfrak{gl}(I \oplus K)$ by letting $(\alpha + \beta)(a + k) = \alpha(a) + \beta(k)$ for all $a \in I$ and $k \in K$.

Proposition 3.2. *Using the notation above, we have that*

$$\mathsf{Comp}(K, I) = \{\alpha + \beta \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I) \mid \alpha + \beta \in \mathsf{Der}(K \oplus I)\}.$$

In particular $\mathsf{Comp}(K, I)$ *is a Lie subalgebra of* $\mathsf{Der}(K \oplus I)$.

Proof. Suppose that $\alpha + \beta \in \mathsf{Comp}(K, I)$ is a compatible pair and let $k + a,\ k' + a' \in K \oplus I$. Then

$$\begin{aligned}(\alpha + \beta)[k + a, k' + a'] &= (\alpha + \beta)([k, k'] + ([k, a'] - [k', a] + [a, a'])) \\ &= \alpha([k, k']) + \beta([k, a'] - [k', a] + [a, a']) \\ &= [\alpha(k), k'] + [k, \alpha(k')] + [\alpha(k), a'] - [\alpha(k'), a] \\ &\quad + [\beta(a), a'] + [k, \beta(a')] - [k', \beta(a)] + [a, \beta(a')].\end{aligned}$$

On the other hand

$$\begin{aligned}&[(\alpha + \beta)(k + a), k' + a'] + [k + a, (\alpha + \beta)(k' + a')] = \\ &\qquad [\alpha(k), k'] + [\alpha(k), a'] + [\beta(a), k'] + [\beta(a), a'] \\ &\qquad\quad + [k, \alpha(k')] + [k, \beta(a')] + [a, \alpha(k')] + [a, \beta(a')].\end{aligned}$$

Thus $\alpha + \beta \in \mathsf{Der}(K \oplus I)$.

Conversely, let $\alpha + \beta \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$ such that $\alpha + \beta$ is a derivation of $K \oplus I$. Then $(\alpha + \beta)|_K = \alpha$ and $(\alpha + \beta)|_I = \beta$, and so $\alpha \in \mathsf{Der}(K)$ and $\beta \in \mathsf{Der}(I)$. Further, if $k \in K$ and $a \in I$, then $[k, a] \in I$, and so

$$\beta([k, a]) = (\alpha + \beta)[k, a] = [(\alpha + \beta)(k), a] + [k, (\alpha + \beta)(a)] = [\alpha(k), a] + [k, \beta(a)].$$

Thus $\alpha + \beta \in \mathsf{Comp}(K, I)$, as required.

The fact that $\mathsf{Comp}(K, I)$ is a Lie subalgebra of $\mathsf{Der}(K \oplus I)$ follows from the fact that $\mathsf{Comp}(K, I)$ is the intersection of two Lie algebras; namely, $\mathsf{Comp}(K, I) = (\mathfrak{gl}(K) \oplus \mathfrak{gl}(I)) \cap \mathsf{Der}(K \oplus I)$. $\square$

Lemma 3.3. *Let K and I be Lie algebras over a field $\mathbb{F}$ of characteristic $p > 0$. If $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ then $(\alpha, \beta)^{p^t} \in \mathsf{Comp}(K, I)$ for all $t \geqslant 0$.*

Proof. Let $L = K \oplus I$ be the semi-direct sum of K and I. By Proposition 3.2, $(\alpha, \beta) \in \mathsf{Der}(L)$. Then by Lemma 2.15, $(\alpha, \beta)^{p^t} \in \mathsf{Der}(L)$, for all $t \geqslant 0$. Hence, by Proposition 3.2, $(\alpha, \beta)^{p^t} \in \mathsf{Comp}(K, I)$. $\square$

Let K and I be vector spaces. Consider the Lie algebra $\mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$ and define an action of $\mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$ on the vector space $\mathsf{Hom}(K, \mathfrak{gl}(I))$ as follows. Let ad denote the adjoint representation of $\mathfrak{gl}(I)$. Thus, for $\beta,\ \beta' \in \mathfrak{gl}(I)$ and $\mathsf{ad}_\beta(\beta') = [\beta, \beta']$. For $(\alpha, \beta) \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$ and for $T \in \mathsf{Hom}(K, \mathfrak{gl}(I))$, set

$$(\alpha, \beta) \cdot T = \mathsf{ad}_\beta T - T\alpha. \tag{10}$$

Let us show that this in fact defines a Lie algebra action. First notice that $(\alpha, \beta) \cdot T \in \mathsf{Hom}(K, \mathfrak{gl}(I))$ because it is linear combination of compositions of linear maps. Let us check that the action is compatible with Lie brackets. Let $(\alpha, \beta),\ (\alpha', \beta') \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$. By definition

$$(\alpha', \beta') \cdot T = \mathsf{ad}_{\beta'} T - T\alpha'.$$

Thus

$$(\alpha, \beta) \cdot ((\alpha', \beta') \cdot T) = \mathsf{ad}_\beta \mathsf{ad}_{\beta'} T - \mathsf{ad}_{\beta'} T\alpha - \mathsf{ad}_\beta T\alpha' + T\alpha'\alpha.$$

In the same way,

$$(\alpha', \beta') \cdot ((\alpha, \beta) \cdot T) = \mathsf{ad}_{\beta'} \mathsf{ad}_\beta T - \mathsf{ad}_\beta T\alpha' - \mathsf{ad}_{\beta'} T\alpha + T\alpha\alpha'.$$

Hence,

$$\begin{aligned}(\alpha, \beta) \cdot ((\alpha', \beta') \cdot T) - (\alpha', \beta') \cdot ((\alpha, \beta) \cdot T) &= \mathsf{ad}_\beta \mathsf{ad}_{\beta'} T - \mathsf{ad}_{\beta'} \mathsf{ad}_\beta T - T\alpha\alpha' + T\alpha'\alpha \\ &= [\mathsf{ad}_\beta, \mathsf{ad}_{\beta'}]T - T[\alpha, \alpha'].\end{aligned}$$

Therefore,

$$[(\alpha, \beta), (\alpha', \beta')] \cdot T = ([\alpha, \alpha'], [\beta, \beta']) \cdot T.$$

Now, if K and I are Lie algebras and I is a K-module, then there is a corresponding homomorphism $\psi \in \mathsf{Hom}(K, \mathsf{Der}(I))$. Now suppose that $\alpha + \beta \in \mathfrak{gl}(K) \oplus \mathfrak{gl}(I)$ such that $\alpha + \beta \in \mathsf{Der}(K) \oplus \mathsf{Der}(I)$. Then, for $k \in K$, we have $\mathsf{ad}_\beta T(k) + T\alpha(k)$ is a derivation of I since $\mathsf{ad}_\beta T(k),\ T\alpha(k) \in \mathsf{Der}(I)$.

If X is a subalgebra of $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$, then the annihilator $\mathsf{Ann}_X(\psi)$ of ψ in X is defined as

$$\mathsf{Ann}_X(\psi) = \{(\alpha, \beta) \in X \mid (\alpha, \beta) \cdot \psi = 0\}.$$

Computing the annihilator of ψ in $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$ explicitly, we obtain

$$\begin{aligned}\mathsf{Ann}_{\mathsf{Der}(K)\oplus\mathsf{Der}(I)}(\psi) &= \{(\alpha, \beta) \in \mathsf{Der}(K) \oplus \mathsf{Der}(I) \mid (\alpha, \beta) \cdot \psi = 0\} \\ &= \{(\alpha, \beta) \in \mathsf{Der}(K) \oplus \mathsf{Der}(I) \mid \mathsf{ad}_\beta \psi - \psi\alpha = 0\} = \mathsf{Comp}(K, I).\end{aligned}$$

The last equality follows from (9). Hence we have proved the following proposition.

Proposition 3.4. *Let K and I be Lie algebras such that I is also a K-module via the representation $\psi \in \mathsf{Hom}(K, \mathsf{Der}(I))$. Then $\mathsf{Comp}(K, I) = \mathsf{Ann}_{\mathsf{Der}(K)\oplus\mathsf{Der}(I)}(\psi)$, where the action of $\mathsf{Der}(K) \oplus \mathsf{Der}(I)$ on $\mathsf{Hom}(K, \mathsf{Der}(I))$ is given by (10).*

3.3. **Derivations of K_ϑ.** In this section we present a method to describe the derivations of an extension K_ϑ presented in Proposition 3.1 from the derivations of the Lie algebra K. By an adaptation of the process used by Eick in [3], we set conditions which guarantee that a derivation of K can be lifted to a derivation of K_ϑ. It is first necessary to define an action of $\mathfrak{gl}(K)\oplus\mathfrak{gl}(I)$ on the vector space of alternating bilinear maps.

Let K and I be vector spaces. Let (α,β) be an element of the Lie algebra $\mathfrak{gl}(K)\oplus\mathfrak{gl}(I)$ and $\vartheta\in\mathsf{C}^2(K,I)$. Define an action of $\mathfrak{gl}(K)\oplus\mathfrak{gl}(I)$ on $\mathsf{C}^2(K,I)$ by setting for $\vartheta\in\mathsf{C}^2(K,I)$

$$(\alpha,\beta)\cdot\vartheta(h,k)=\beta(\vartheta(h,k))-\vartheta(\alpha(h),k)-\vartheta(h,\alpha(k)),\quad \text{for all } h,k\in K. \tag{11}$$

Let $(\alpha',\beta')\in\mathfrak{gl}(K)\oplus\mathfrak{gl}(I)$, then

$$(\alpha,\beta)\cdot((\alpha',\beta')\cdot\vartheta(h,k)) = (\alpha,\beta)\cdot(\beta'(\vartheta(h,k))-\vartheta(\alpha'(h),k)-\vartheta(h,\alpha'(k))). \tag{12}$$

Applying the action in each summand of the right-hand of equation (12) we have

$$(\alpha,\beta)\cdot\beta'(\vartheta(h,k)=\beta\beta'\vartheta(h,k))-\beta'\vartheta(\alpha(h),k)-\beta'\vartheta(h,\alpha(k)),$$

$$(\alpha,\beta)\cdot\vartheta(\alpha'(h),k)=\beta\vartheta(\alpha'(h),k))-\vartheta(\alpha'\alpha(h),k)-\vartheta(\alpha'(h),\alpha(k)),$$

$$(\alpha,\beta)\cdot\vartheta(h,\alpha'(k))=\beta\vartheta(h,\alpha'(k))-\vartheta(\alpha(h),\alpha'(k))-\vartheta(h,\alpha'\alpha(k)).$$

Then

$$\begin{aligned}(\alpha,\beta)\cdot((\alpha',\beta')\cdot\vartheta(h,k)) = \beta\beta'\vartheta(h,k)) &- \beta'\vartheta(\alpha(h),k)-\beta'\vartheta(h,\alpha(k))\\ &-\beta\vartheta(\alpha'(h),k))+\vartheta(\alpha'\alpha(h),k)+\vartheta(\alpha'(h),\alpha(k))\\ &-\beta\vartheta(h,\alpha'(k))+\vartheta(\alpha(h),\alpha'(k))+\vartheta(h,\alpha'\alpha(k)).\end{aligned}$$

It follows

$$\begin{aligned}[(\alpha,\beta),(\alpha',\beta')]\cdot\vartheta(h,k) &= [\beta,\beta']\vartheta(h,k)-\vartheta([\alpha,\alpha'](h),k)-\vartheta(h,[\alpha,\alpha'](k))\\ &= ([\alpha,\alpha'],[\beta,\beta'])\cdot\vartheta(h,k).\end{aligned}$$

Therefore, the action presented in (11) is well defined.

Our goal now is to study the action of compatible pairs $\mathsf{Comp}(K,I)$ on subspaces $\mathsf{Z}^2(K,I)$ and $\mathsf{B}^2(K,I)$ of $\mathsf{C}^2(K,I)$. For this, assume that K is a Lie algebra and I is a K-module. Then for all $h,k,l\in K$, $(\alpha,\beta)\in\mathsf{Comp}(K,I)$ and $\vartheta\in Z^2(K,I)$ we have

$$\begin{aligned}(\alpha,\beta)\cdot\vartheta(k,[h,l]) &= \beta(\vartheta(k,[h,l]))-\vartheta(\alpha(k),[h,l])-\vartheta(k,\alpha([h,l]))\\ &= \beta(\vartheta(k,[h,l]))-\vartheta(\alpha(k),[h,l])-\vartheta(k,[\alpha(h),l])-\vartheta(k,[h,\alpha(l)]).\end{aligned}$$

If

$$X=(\alpha,\beta)\cdot\vartheta(k,[h,l])+(\alpha,\beta)\cdot\vartheta(h,[l,k])+(\alpha,\beta)\cdot\vartheta(l,[k,h]),$$

then

$$\begin{aligned}X = \beta(\vartheta(k,[h,l])) + \beta(\vartheta(h,[l,k])) + \beta(\vartheta(l,[k,h]))\\ - \vartheta(\alpha(k),[h,l]) - \vartheta(\alpha(h),[l,k]) - \vartheta(\alpha(l),[k,h])\\ - \vartheta(k,[\alpha(h),l]) - \vartheta(h,[\alpha(l),k]) - \vartheta(l,[\alpha(k),h])\\ - \vartheta(k,[h,\alpha(l)]) - \vartheta(h,[l,\alpha(k)]) - \vartheta(l,[k,\alpha(h)]).\end{aligned}$$

Using that β is linear and the definition of cocycles (4)

$$\begin{aligned}X = -\beta([k,\vartheta(h,l)]) - \beta([h,\vartheta(l,k)]) - \beta([l,\vartheta(k,h)])\\ + [\alpha(k),\vartheta(h,l)] + [\alpha(h),\vartheta(l,k)] + [\alpha(l),\vartheta(k,h)]\\ + [k,\vartheta(\alpha(h),l)] + [h,\vartheta(\alpha(l),k)] + [l,\vartheta(\alpha(k),h)]\\ + [k,\vartheta(h,\alpha(l))] + [h,\vartheta(l,\alpha(k))] + [l,\vartheta(k,\alpha(h))].\end{aligned}$$

Since (α,β) is a compatible pair we have by (7)

$$\begin{aligned}\beta([k,\vartheta(h,l)]) &= [\alpha(k),\vartheta(h,l)] + [k,\beta(\vartheta(h,l))];\\ \beta([h,\vartheta(l,k)]) &= [\alpha(h),\vartheta(l,k)] + [h,\beta(\vartheta(l,k))];\\ \beta([l,\vartheta(k,h)]) &= [\alpha(l),\vartheta(k,h)] + [l,\beta(\vartheta(k,h))].\end{aligned}$$

Hence we obtain combining the last two displayed systems of equations

$$\begin{aligned}X = -[k,\beta(\vartheta(h,l))] - [h,\beta(\vartheta(l,k))] - [l,\beta(\vartheta(k,h))]\\ + [k,\vartheta(\alpha(h),l)] + [h,\vartheta(\alpha(l),k)] + [l,\vartheta(\alpha(k),h)]\\ + [k,\vartheta(h,\alpha(l))] + [h,\vartheta(l,\alpha(k))] + [l,\vartheta(k,\alpha(h))].\end{aligned}$$

Again, by the definition of the action in (11)

$$X = -[k,(\alpha,\beta)\cdot\vartheta(h,l)] - [h,(\alpha,\beta)\cdot\vartheta(l,k)] - [l,(\alpha,\beta)\cdot\vartheta(k,h)].$$

So $(\alpha,\beta)\cdot\vartheta \in \mathsf{Z}^2(K,I)$.

Now suppose that $\vartheta \in \mathsf{B}^2(K,I)$. By definition (5) there is a linear map $T : K \to I$ such that $\vartheta = \vartheta_T$. Hence

$$\vartheta_T(h,k) = T([h,k]) + [k,T(h)] - [h,T(k)]. \tag{13}$$

Let $Y = (\alpha,\beta)\cdot\vartheta_T(h,k)$. By (13) we have

$$Y = \beta(\vartheta_T(h,k)) - \vartheta_T(\alpha(h),k) - \vartheta_T(h,\alpha(k)). \tag{14}$$

Using the definition of ϑ_T we have

$$\begin{aligned} \beta(\vartheta_T(h,k)) &= \beta T([h,k]) + \beta[k,T(h)] - \beta[h,T(k)], \\ \vartheta_T(\alpha(h),k) &= T([\alpha(h),k]) + [k,T\alpha(h)] - [\alpha(h),T(k)], \\ \vartheta_T(h,\alpha(k)) &= T([h,\alpha(k)]) + [\alpha(k),T(h)] - [h,T\alpha(k)]. \end{aligned} \tag{15}$$

We can use that (α,β) is a compatible pair in equation (15) to write

$$\beta(\vartheta_T(h,k)) = \beta T([h,k]) + [\alpha(k),T(h)] + [k,\beta T(h)] - [\alpha(h),T(k)] - [h,\beta T(k)].$$

Then

$$\begin{aligned} Y = \beta T([h,k]) + [\alpha(k),T(h)] + [k,\beta T(h)] - [\alpha(h),T(k)] - [h,\beta T(k)] \\ - T([\alpha(h),k]) - [k,T\alpha(h)] + [\alpha(h),T(k)] \\ - T([h,\alpha(k)]) - [\alpha(k),T(h)] + [h,T\alpha(k)]. \end{aligned}$$

Making the cancellations, Y can be written as

$$\begin{aligned} Y = \beta T([h,k]) - T([\alpha(h),k]) - T([h,\alpha(k)]) \\ + [k,\beta T(h)] - [k,T\alpha(h)] + [h,T\alpha(k)] - [h,\beta T(k)]. \end{aligned}$$

Now we use that T and the action are linear to obtain

$$Y = \beta T([h,k]) - T([\alpha(h),k] + [h,\alpha(k)]) + [k,\beta T(h) - T\alpha(h)] - [h,\beta T(k) - T\alpha(k)].$$

Hence,

$$Y = (\beta T - T\alpha)([h,k]) + [k,(\beta T - T\alpha)(h)] - [h,(\beta T - T\alpha)(k)].$$

If $U = \beta T - T\alpha : K \to I$ then

$$(\alpha,\beta)\cdot\vartheta(h,k) = U([h,k]) - [k,U(h)] - [h,U(k)].$$

Therefore, $(\alpha,\beta)\cdot\vartheta \in \mathsf{B}^2(K,I)$. We just proof

Proposition 3.5. *Let K be a Lie algebra and let I be a K-module. Consider the action of $\mathsf{Comp}(K,I)$ on $\mathsf{C}^2(K,I)$ defined in (11). Then the vector spaces $\mathsf{Z}^2(K,I)$ and $\mathsf{B}^2(K,I)$ are invariants by this action.*

This result allows us to define an action of $\mathsf{Comp}(K,I)$ on $\mathsf{H}^2(K,I)$: let $\vartheta \in \mathsf{Z}^2(K,I)$ and $(\alpha,\beta) \in \mathsf{Comp}(K,I)$. Define the action

$$(\alpha,\beta)\cdot(\vartheta + \mathsf{B}^2(K,I)) = ((\alpha,\beta)\cdot\vartheta) + \mathsf{B}^2(K,I). \tag{16}$$

This is well defined by Proposition 3.5.

Definition 3.6. Let K be a Lie algebra and I a K-module. Let $\vartheta \in \mathsf{Z}^2(K,I)$ and consider the action of $\mathsf{Comp}(K,I)$ on $\mathsf{H}^2(K,I)$ defined in (16). Define the set of induced pairs of $\mathsf{Comp}(K,I)$ by

$$\mathsf{Indu}(K,I,\vartheta) = \mathsf{Ann}_{\mathsf{Comp}(K,I)}(\vartheta + \mathsf{B}^2(K,I)).$$

Now we have the tools needed to describe the Lie algebra $\mathsf{Der}(K_\vartheta)$ from the Lie algebra $\mathsf{Der}(K)$. We will define a homomorphism $\phi : \mathsf{Der}(K_\vartheta) \to \mathsf{Der}(K)$, whose kernel is known and the image coincides with the induced pairs defined above. So, using the First Isomorphism Theorem for Lie algebras we have $\mathsf{Der}(K_\vartheta)$ is isomorphic to $\mathsf{Ker}(\phi) \oplus \mathsf{Im}(\phi)$ but these subspaces correspond to structures: $\mathsf{Ker}(\phi) \cong \mathsf{Z}^1(\mathsf{K}, \mathsf{I})$ and $\mathsf{Im}(\phi) \cong \mathsf{Indu}(\mathsf{K}, \mathsf{I}, \vartheta)$. One application of this type of construction is using known information about the algebra $\mathsf{Der}(K)$ to obtain information about the algebra $\mathsf{Der}(K_\vartheta)$ as the existence of non-singular derivations. Therefore, this method will allow us to study some properties of Lie algebra extensions by cocycles. First we define ϕ.

Let K be a Lie algebra and I a K-module. Let $\vartheta \in \mathsf{H}^2(K, I)$ and $d \in \mathsf{Der}(K_\vartheta)$. Suppose that I, as ideal of K_ϑ, it is invariant under d. Recall that $K_\vartheta = K \bigoplus I$ and let $\pi_K : K_\vartheta \to K$ and $\pi_I : K_\vartheta \to I$ to be the natural vector space projections of K_ϑ onto K and K_ϑ onto I. Then define the maps

- $\alpha : K \to K$ by $\alpha(h) = \pi_K d(h)$, for all $h \in K$;
- $\beta : I \to I$ by $\beta(a) = d(a)$, for all $a \in I$;
- $\eta : K \to I$ by $\eta(h) = \pi_I d(h)$, for all $h \in K$.

For each $h + a \in K_\vartheta$ we have

$$d(h + a) = \alpha(h) + \eta(h) + \beta(a) \text{ for all } h \in K \text{ and } a \in I. \tag{17}$$

We can see that β is a derivation of I because it is restriction of d to I. To see that $\alpha \in \mathsf{Der}(K)$ let $x, y \in K$. To make our calculation more clear, we will denote $[\cdot, \cdot]_K$ the product in K, and by $[\cdot, \cdot]_\vartheta$ the product in K_ϑ. Then by product definition on K_ϑ

$$d([h, k]_\vartheta) = d([h, k]_K + \vartheta(h, k)).$$

By the decomposition showed in (17)

$$d([h, k]_\vartheta) = \alpha([h, k]_K) + \eta([h, k]_K) + \beta(\vartheta(h, k)). \tag{18}$$

We can calculate

$$[d(h), k]_\vartheta + [h, d(k)]_\vartheta = [\alpha(h) + \eta(h), k]_\vartheta + [h, \alpha(k) + \eta(k)]_\vartheta, \tag{19}$$

and use the definition of the product in equation (19) to get

$$\begin{aligned}[d(h), k]_\vartheta + [h, d(k)]_\vartheta = {} & [\alpha(h), k]_K + \vartheta(\alpha(h), k) - [k, \eta(h)]_\vartheta \\ & + [h, \alpha(k)]_K + \vartheta(h, \alpha(k)) + [h, \eta(k)]_\vartheta.\end{aligned} \tag{20}$$

Comparing the components of K in (18) and (20) we have

$$\alpha([h, k]_K) = [\alpha(h), k]_K + [h, \alpha(k)]_K,$$

and $\alpha \in \mathsf{Der}(K)$.

Now it is possible define our homomorphism ϕ. Let K be a Lie algebra and I a K-module. Let $\vartheta \in \mathsf{H}^2(K, I)$ and suppose that I, as an ideal of K_ϑ, is invariant under derivations. For all $x + a \in K_\vartheta$ and $d \in \mathsf{Der}(K)_\vartheta$ write $d(h + a) = \alpha(h) + \eta(h) + \beta(a)$ with $\alpha \in \mathsf{Der}(K)$ and $\beta \in \mathsf{Der}(I)$. Then define $\phi : \mathsf{Der}(K_\vartheta) \to \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ by

$$\phi(d) = (\alpha, \beta). \tag{21}$$

The following calculation will check that ϕ is a Lie algebra morphism. Let $d, d' \in \mathsf{Der}(K_\vartheta)$ such that

$$\begin{aligned} d(h + a) &= \alpha(h) + \eta(h) + \beta(a) \\ d'(h + a) &= \alpha'(h) + \eta'(h) + \beta'(a), \end{aligned}$$

Then

$$\begin{aligned} dd'(h) &= d(\alpha'(h) + \eta'(h) + \beta'(a)) \\ &= \alpha\alpha'(h) + \eta(\alpha'(h)) + \beta(\eta'(h) + \beta'(a)). \end{aligned}$$

Hence, $\pi_K dd'(h) = \alpha\alpha'(h)$. Analogously, $\pi_K d'd(h) = \alpha'\alpha(h)$. So $\pi_K[d, d'] = [\alpha, \alpha']$. As β and β' are defined by restriction of d and d' to I, respectively, then $\pi_I[d, d'] = [\beta, \beta']$. Therefore,

$$\phi([d, d']) = ([\alpha, \alpha'], [\beta, \beta']) = [(\alpha, \beta), (\alpha', \beta')] = [\phi(d), \phi(d')],$$

and ϕ is indeed a Lie algebra homomorphism.

The next result presents the first connection between compatible pairs and the homomorphism ϕ.

Lemma 3.7. *Let K be a Lie algebra and I a K-module. Let $\vartheta \in \mathsf{H}^2(K, I)$ and suppose that I, as an ideal of K_ϑ, is invariant under derivations. Let $\phi : \mathsf{Der}(K_\vartheta) \to \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ given by $\phi(d) = (\alpha, \beta)$, defined in* (21)*. Then $\mathsf{Im}(\phi) \leqslant \mathsf{Comp}(K, I)$.*

Proof. Let $(\alpha, \beta) \in \mathsf{Im}(\phi)$. Then there is $d \in \mathsf{Der}(K_\vartheta)$ such that $\phi(d) = (\alpha, \beta)$. If $h \in K$ and $a \in I$ then

$$\begin{aligned} \beta([h, a]_\vartheta) &= d([h, a]_\vartheta) && \text{(since } [h, a] \in I) \\ &= [d(h), a]_\vartheta + [h, d(a)]_\vartheta && (d \in \mathsf{Der}(K_\vartheta)) \\ &= [\alpha(h) + \eta(h), a]_\vartheta + [h, \beta(a)]_\vartheta \\ &= [\alpha(h), a]_\vartheta + [h, \beta(a)]_\vartheta && \text{(since } I \text{ is abelian).} \end{aligned}$$

□

Now we present the main theorem of this section. Recall that for a Lie algebra K, for a K-module I, and for $\vartheta \in \mathsf{Z}^2(K, I)$, $\mathsf{Indu}(K, I, \vartheta)$ was defined in Definition 3.6.

Theorem 3.8. *Let K be a Lie algebra and let I be a K-module. Let $\vartheta \in \mathsf{H}^2(K, I)$ and suppose that I, as ideal of K_ϑ, is invariant by derivations. Let $\phi : \mathsf{Der}(K_\vartheta) \to \mathsf{Der}(K) \oplus \mathsf{Der}(I)$ be defined as above. Then:*

(1) $\mathsf{Im}(\phi) = \mathsf{Indu}(K, I, \vartheta)$
(2) $\mathsf{Ker}(\phi) \cong \mathsf{Z^1(K, I)}$

Proof. In this proof we will denote the product in K_ϑ of $h \in K$ and $a \in I$ just by the action $[h,a]$ of K on I, since $[h,a]_\vartheta = [h,a]$.

1) Let $(\alpha,\beta) \in \mathsf{Indu(K,I,\vartheta)}$. By definition

$$(\alpha,\beta)\cdot\vartheta = 0 \bmod \mathsf{B}^2(K,I).$$

Then there is a linear map $T : K \to I$ such that, for all $h,k \in K$,

$$\beta(\vartheta(h,k)) - \vartheta(\alpha(h),k) - \vartheta(h,\alpha(k)) = T([h,k]) + [k,T(h)] - [h,T(k)]. \tag{22}$$

Let $h \in K$, $a \in I$ and define the linear map $(\alpha,\beta)^* : K_\vartheta \to K_\vartheta$ by

$$(\alpha,\beta)^*(h+a) = \alpha(h) - T(h) + \beta(a). \tag{23}$$

Let's check that $(\alpha,\beta)^*$ is a derivation of K_ϑ. Let $k+b \in K_\vartheta$. If

$$X = (\alpha,\beta)^*([h+a,k+b]_\vartheta)$$

then

$$\begin{aligned} X &= (\alpha,\beta)^*([h,k]_K + \vartheta(h,k) + [h,b] - [k,a]) \\ &= \alpha([h,k]_K) - T([h,k]_K) + \beta(\vartheta(h,k)) + \beta([h,b]) - \beta([k,a]). \end{aligned}$$

Now, let

$$Y = [(\alpha+\beta)^*(h+a),k+b]_\vartheta + [h+a,(\alpha+\beta)^*(k+b)]_\vartheta.$$

By definition (23)

$$[(\alpha+\beta)^*(h+a),k+b]_\vartheta = [\alpha(h) - T(h) + \beta(a),k+b]_\vartheta.$$

Hence, by product definition in (6)

$$[\alpha(h) - T(h) + \beta(a),k+b]_\vartheta = [\alpha(h),k]_K + \vartheta(\alpha(h),k) + [\alpha(h),b] - [k,-T(h)+\beta(a)]$$

and

$$[(\alpha+\beta)^*(h+a),k+b]_\vartheta = [\alpha(h),k]_K + \vartheta(\alpha(h),k) + [\alpha(h),b] - [k,-T(h)+\beta(a)].$$

Analogously,

$$[h+a,(\alpha+\beta)^*(k+b)]_\vartheta = [h,\alpha(k)]_K + \vartheta(h,\alpha(h)) + [h,-T(k)+\beta(b)] - [\alpha(k),a].$$

It follows

$$\begin{aligned} Y = {} & [\alpha(h),k]_K + [h,\alpha(k)]_K + \vartheta(\alpha(h),k) + \vartheta(h,\alpha(h)) \\ & + [\alpha(h),b] + [h,\beta(b)] - [k,\beta(a)] - [\alpha(k),a] - [h,T(k)] + [k,T(h)]. \end{aligned}$$

We can use that $(\alpha,\beta) \in \mathsf{Comp}(K,I)$ to write Y as

$$\begin{aligned} Y = {} & \alpha([h,k]_K) + \vartheta(\alpha(h),k) + \vartheta(h,\alpha(h)) \\ & + \beta([h,b]) - \beta([k,a]) - [h,T(k)] + [k,T(h)]. \end{aligned}$$

By equation (22)

$$\vartheta(\alpha(h),k) + \vartheta(h,\alpha(k)) = \beta(\vartheta(h,k)) - T([h,k]) - [k,T(h)] + [h,T(k)].$$

Then

$$Y = [\alpha(h), k]_K + [h, \alpha(k)]_K + \beta(\vartheta(h,k)) - T([h,k]) - [k, T(h)] + [h, T(k)] \\ + \beta([h,b]) - \beta([k,a]) - [h, T(k)] + [k, T(h)].$$

As $X = Y$ then $(\alpha, \beta)^*$ is a derivation.

Besides, observe that $\pi_K(\alpha,\beta)^* = \alpha$ and $\pi_I(\alpha,\beta)^* = \beta$. Hence $\phi((\alpha+\beta)^*) = (\alpha,\beta)$, that is, $\mathsf{Indu}(K, I, \vartheta) \subseteq \mathsf{Im}(\phi)$.

Now, suppose that $(\alpha, \beta) \in \mathsf{Im}(\phi)$. Then there is $d \in \mathsf{Der}(K_\vartheta)$ such that

$$\phi(d) = (\alpha, \beta).$$

By Theorem 3.7 we have $\mathsf{Im}(\phi) \subseteq \mathsf{Comp}(K, I)$. Then it is enough to show that there is a linear map $T : K \to I$ such that the equation (22) is satisfied.

For each $h + a \in K_\vartheta$ we can use the decomposition defined in (17) to write

$$d(h+a) = \alpha(h) + \eta(h) + \beta(a).$$

Then

$$[d(h+a), k+b]_\vartheta = [\alpha(h) + \eta(h) + \beta(a), k+b]_\vartheta.$$

By product definition in (6) we get

$$[\alpha(h) + \eta(h) + \beta(a), k+b]_\vartheta = [\alpha(h), k]_K + \vartheta(\alpha(h), k) + [\alpha(h), b] - [k, \eta(h) + \beta(a)].$$

Hence

$$[d(h+a), k+b]_\vartheta = [\alpha(h), k]_K + \vartheta(\alpha(h), k) + [\alpha(h), b] - [k, \eta(h) + \beta(a)].$$

Analogously,

$$[h+a, d(k+b)]_\vartheta = [h, \alpha(k)]_K + \vartheta(h, \alpha(k)) + [h, \eta(k) + \beta(b)] - [\alpha(k), a].$$

Therefore

$$[d(h+a), k+b]_\vartheta + [h+a, d(k+b)]_\vartheta = [\alpha(h), k]_K + [h, \alpha(k)]_K + \vartheta(\alpha(h), k) + \vartheta(h, \alpha(k)) \\ + [\alpha(h), b] + [h, \beta(b)] - [\alpha(k), a] - [k, \beta(a)] - [k, \eta(h)] + [h, \eta(k)]. \tag{24}$$

We can use that $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ in the last displayed equation to write

$$[d(h+a), k+b]_\vartheta + [h+a, d(k+b)]_\vartheta = \alpha([h,k]_K) + \vartheta(\alpha(h), k) + \vartheta(h, \alpha(k)) \\ + \beta([h,b]) - \beta([k,a]) - [k, \eta(h)] + [h, \eta(k)].$$

Now we will calculate $d([k+a, h+b]_\vartheta)$. By product definition

$$d([h+a, k+b]_\vartheta) = d([h,k]_K + \vartheta(h,k) + [h,b] - [k,a]).$$

Hence

$$d([h,k]_K + \vartheta(h,k) + [h,b] - [k,a]) = \alpha([h,k]_K) + \eta([h,k]_K) + \beta(\vartheta(h,k)) + \beta([h,b]) - \beta([k,a]).$$

As d is a derivation then we have equality

$$d([h+a,k+b]_\vartheta) = [d(h+a),k+b]_\vartheta + [h+a,d(k+b)]_\vartheta.$$

It follows

$$\vartheta(\alpha(h),k) + \vartheta(h,\alpha(k)) - [k,\eta(h)] + [h,\eta(k)] = \eta([h,k]_K) + \beta(\vartheta(h,k)).$$

We can rearrange the last displayed equation to get

$$-(\eta([h,k]_K) + [k,\eta(h)] - [h,\eta(k)]) = \beta(\vartheta(h,k)) - \vartheta(\alpha(h),k) - \vartheta(h,\alpha(k)).$$

Therefore $T = -\eta$ satisfies the equation (22) e $\mathsf{Im}(\phi) \subseteq \mathsf{Indu}(\mathsf{K},\mathsf{I},\vartheta)$.

2) Let $d \in \mathsf{Ker}(\phi)$. The decomposition showed in (17) provide us

$$d(h) = \eta(h), h \in K.$$

Let $h,k \in K$. By definition of derivation

$$d([h,k]_\vartheta) = [d(h),k]_\vartheta + [h,d(k)]_\vartheta. \tag{25}$$

We can use product definition in K_ϑ to write

$$d([h,k]_\vartheta) = d([h,k]_K + \vartheta(h,k)).$$

Since $d \in \mathsf{Ker}(\phi)$ then

$$d([h,k]_\vartheta) = \eta([h,k]_K).$$

By other hand,

$$[d(h),k]_\vartheta + [h,d(k)]_\vartheta = [\eta(h),k]_\vartheta + [h,\eta(k)]_\vartheta.$$

Then (25) it is equal to

$$\eta([k,h]_K) = [k,\eta(k)] - [h,\eta(k)],$$

and $\eta \in \mathsf{Z}^1(\mathsf{K},\mathsf{I})$. Observe that η is the restriction of d to K. Denote the restriction of d to K by $d|_K$. Therefore, if $d \in \mathsf{Ker}(\phi)$ then $d|_K \in \mathsf{Z}^1(K,I)$.

Let $d \in \mathsf{Ker}(\phi)$ and define $\sigma : \mathsf{Ker}(\phi) \to (\mathsf{Z}^1(K,I),+)$ by $\sigma(d) = d|_K$. Then $\sigma(\mathsf{Ker}(\phi)) \subseteq \mathsf{Z}^1(\mathsf{K},\mathsf{I})$. Let $d' \in \mathsf{Ker}(\phi)$. Then

$$\sigma(d+d') = (d+d')|_K = d|_K + d'|_K = \sigma(d) + \sigma(d').$$

So σ it is group homomorphism.

First we will show that σ is injective. Let $d,d' \in \mathsf{Ker}(\phi)$ such that $\sigma(d) = \sigma(d')$. Let $h+a \in K_\vartheta$. Then

$$d(h+a) = d(h) = d|_K(h) = d'|_K(h) = d'(h) = d(h+a).$$

Hence $d = d'$. Now, to prove that σ is onto, let $\eta \in \mathsf{Z}^1(K,I)$ and define a linear map $d : K_\vartheta \to K_\vartheta$ by

$$d(h+a) = T(x), h \in K, a \in I.$$

We will show that d is a derivation. Observe that, for all $h+a,k+b \in K_\vartheta$ we have

$$d([h+a,k+b]_\vartheta) = d([h,k]_K + \vartheta(h,k) + [h,b] - [k,a]) = \eta([h,k]_K).$$

By other hand,

$$\begin{aligned}[d(h+a), k+b]_\vartheta + [h+a, d(k+b)]_\vartheta &= [\eta(h), k+b]_\vartheta + [h+a, \eta(k)]_\vartheta \\ &= -[k, \eta(h)] + [h, \eta(k)].\end{aligned}$$

Since $\eta \in \mathsf{Z}^1(K, I)$ then $d([h+a, k+b]_\vartheta) = [d(h+a), k+b]_\vartheta + [h+a, d(k+b)]_\vartheta$, hence $d \in \mathsf{Der}(K_\vartheta)$. It is immediate that $\phi(d) = 0$. So $d \in \mathsf{Ker}(\phi)$. As by definition, $\sigma(d) = \eta$ then σ is onto and, therefore, is an isomorphism. □

Example 3.9. Let L be a Lie algebra with an abelian ideal I invariant by derivations. Set $K = L/I$. By Proposition 3.1, there is a $\vartheta \in \mathsf{Z}^2(K, I)$ such that $L \cong K_\vartheta$. Then we can apply the map $\phi : \mathsf{Der}(L) \to \mathsf{Der}(L/I) \oplus \mathsf{Der}(I)$ defined in Theorem 3.8. Further, if $d \in \mathsf{Der}(L)$ then $\phi(d) = (\alpha, \beta) \in \mathsf{Comp}(L/I, I)$. Hence, each derivation of L gives rise to a pair of derivations $\alpha \in \mathsf{Der}(L/I)$ and $\beta \in I$. In particular, if d is non-singular then α and β are non-singulars.

3.4. **Compatible pairs and Jacobson Theorem.** In this section we show some examples of the use of compatible pairs in the study of non-singular derivations.

Example 3.10. Let K and I be finite-dimensional Lie algebras over an algebraically closed field $\mathbb{F}$. Suppose that K acts on I by representation $\psi : K \to \mathsf{Der}(I)$. Let $D \leqslant \mathsf{Comp}(K, I)$ be a subalgebra. Define $L = K \oplus I$. By Proposition 3.2, $D \leqslant \mathsf{Der}(L)$. If D is nilpotent then L has a decomposition into generalized eigenspaces of D. This decomposition induces decompositions in K and I, since as K and I are invariants under D. Hence,

$$L = K_{\lambda_1} \oplus \cdots \oplus K_{\lambda_r} \oplus I_{\mu_1} \cdots \oplus I_{\mu_s}.$$

In particular, we have $[K_{\lambda_i}, I_{\mu_j}] \subseteq I_{\lambda_i + \mu_j}$ if $\lambda_i + \mu_j$ is eigenvalue of D in I. Otherwise $[K_{\lambda_i}, I_{\mu_j}] = 0$.

From this example we can state a result:

Proposition 3.11. *Let K and I be finite-dimensional Lie algebras over an algebraically closed field $\mathbb{F}$. Suppose that K acts on I by representation $\psi : K \to \mathsf{Der}(I)$. Let $D \leqslant \mathsf{Comp}(K, I)$ be a subalgebra. Suppose that 0 is not generalized eigenvalue of D. Then if either the characteristic of $\mathbb{F}$ is zero or the characteristic of $\mathbb{F}$ is p and D has at most $p-1$ generalized eigenvalues, then the Lie subalgebra $\psi(K) \leqslant \mathfrak{gl}(I)$ is nilpotent.*

Proof. Let $L = K_{\lambda_1} \dotplus \cdots \dotplus K_{\lambda_r} \dotplus I_{\mu_1} \cdots \dotplus I_{\mu_s}$ the generalized eigenspace decomposition presented in Example 3.10. Suppose that 0 is not generalized eigenvalues of D. Let $E_K = \{\lambda_1, \cdots, \lambda_r\}$ and $E_I = \{\mu_1, \cdots, \mu_s\}$ be the generalized eigenvalues of D in K and I, respectively. Let $k \in K_{\alpha_j}, a \in I_{\mu_i}$ then

$$\begin{cases} \psi^n(k)(a) \in I_{\mu_i + n\lambda_j} & if \quad \mu_i + n\lambda_j \in E_I \\ \psi^n(k)(a) = 0 & if \quad \mu_i + n\lambda_j \notin E_I. \end{cases}$$

- If the characteristic of $\mathbb{F}$ is 0 then the linear functions $\mu_i + \lambda_j, \mu_i + 2\lambda_j, \cdots, \mu_i + n\lambda_j \cdots$ are all distinct since $\lambda_j \neq 0$. Since $\dim I$ is finite, so $\mu_i + n\lambda_j \notin E_I$ for some $n > 0$. Hence $\psi(k)^n = 0$.
- If the characteristic of $\mathbb{F}$ is $p > 0$ and $s < p$ then the linear forms $\{\mu_i + \lambda_j, \mu_i + 2\lambda_j, \cdots, \mu_i + (p-1)\lambda_j, \mu_i\}$ cannot be all non-trivial, and so $\mu_i + n\lambda_j = 0$ for some $1 \leqslant n \leqslant p$, and so $\psi^n(k) = 0$ for some n, $1 \leqslant n \leqslant p$.

In both cases $\psi(k)$ is nilpotent for all $k \in K_{\lambda_j}$, $1 \leqslant j \leqslant r$. Let $S = \bigcup \psi(K_{\lambda_j})$. Since S is a weakly closed set such that each element is nilpotent. Then the associative subalgebra $\langle S \rangle \leqslant \mathsf{End}(I)$ is nilpotent. We conclude that the Lie algebra $\langle S \rangle = \psi(K) \leqslant \mathfrak{gl}(I)$ is nilpotent. □

For our next example we need some result about traces of matrices.

Proposition 3.12. *Let $\mathbb{F}$ be a field of characteristic $p \geqslant 0$. Suppose that $A \in \mathsf{M}(n, \mathbb{F})$ with $n < p$ or $p = 0$. Then A is nilpotent if, and only if, the trace of matrices A^r is zero, for $1 \leqslant r \leqslant n$.*

Proof. Let $\overline{\mathbb{F}}$ be the algebraic closure of $\mathbb{F}$ and assume without loss of generality that A is in Jordan normal form. We will use that a matrix is nilpotent if, and only if, zero is the only eigenvalue of A.

Hence A is as a diagonal block matrix where each block is formed by grouping the Jordan blocks associated to same eigenvalue. Let $\lambda_1, \cdots, \lambda_k$ be the non-zero eigenvalues of A. Denote by A_t the diagonal block in A associated with eigenvalue λ_t and let assume that A_t is an $n_j \times n_j$-matrix. Then

$$tr(A^r) = n_1\lambda_1^n + \cdots + n_k\lambda_k^n. \tag{26}$$

Suppose that A is nilpotent. Then zero is the only eigenvalue of A, and also of A^r for all $r \geqslant 1$, and by equation (26) we have $tr(A^r) = 0$ for $1 \leqslant r \leqslant n$.

Conversely, suppose that $tr(A^r) = 0$ for $1 \leqslant r \leqslant n$. From equation (26) we can extract the system

$$n_1\lambda_1^r + \cdots + n_k\lambda_k^r = 0, \qquad 1 \leqslant r \leqslant k, \tag{27}$$

of linear equations in the variables $n_1, \cdots, n_k$ over $\mathbb{F}$ considering each n_j as the element $n_j \cdot 1$ in $\mathbb{F}$, whose matrix of coefficients is

$$C = \begin{bmatrix} \lambda_1 & \lambda_2 & \cdots & \lambda_k \\ \lambda_1^2 & \lambda_2^2 & \cdots & \lambda_k^2 \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_1^k & \lambda_2^k & \cdots & \lambda_k^k \end{bmatrix}.$$

Denote by $m_i(\lambda)$ the operation that multiplies line i of a matrix by λ and A^t the transposed matrix of A. So we can write

$$C = m_1(\lambda_1).m_2(\lambda_2)\cdots m_k(\lambda_k).V^t,$$

where

$$V = \begin{bmatrix} 1 & \lambda_1 & \lambda_1^2 \cdots & \lambda_1^{k-1} \\ 1 & \lambda_2 & \lambda_2^2 \cdots & \lambda_2^{k-1} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \lambda_k & \lambda_k^2 \cdots & \lambda_k^{k-1} \end{bmatrix}$$

is the Vandermonde matrix in the variables $\lambda_1, \lambda_2, \cdots, \lambda_k$ whose determinant is $\det V = \prod_{1 \leqslant i < j \leqslant n}(\lambda_j - \lambda_i)$. As the λ_i are pairwise distinct we have that $\det V$ is non-zero. Then the determinant of C is $\lambda_1.\lambda_2 \cdots \lambda_k. \det V$. As we assume that $\lambda_i \neq 0$ for $1, \cdot, k$, C is non-singular. It follows that the system (27) has only trivial solution. Therefore, considered as an element of $\mathbb{F}$, each n_j is zero. If $p = 0$ then zero is the only eigenvector of A. If $p > 0$, then, since we assume that $n < p$, we also have that $n_j < p$ for all j. Hence the fact that $n_j = 0$ in $\mathbb{F}$, implies that $n_j = 0$ as a natural number. Conclude that zero is the only eigenvalue of A. □

Proposition 3.13 ([1], Fact 3.17.13). *Let $\mathbb{F}$ be a field of characteristic $p > 0$. Let $A, B, C \in \mathsf{M}(n, \mathbb{F})$ with $p = 0$ or $n < p$. If $[A, B] = C + \lambda B$, for some $\lambda \in \mathbb{F}$ and $[B, C] = 0$ then $[A, B^r] = rB^{r-1}C + \lambda r B^r$ for all $r \geqslant 1$. In particular, if $\lambda \neq 0$ and C is nilpotent then B is nilpotent.*

Proof. We prove this result by induction on r. The case $r = 1$ follows from the conditions. Suppose that result is valid for $(r-1)$. Then,

$$[A, B^{r-1}] = (r-1)B^{r-2}C + \lambda(r-1)B^{r-1}.$$

We can rewrite this equation as

$$\lambda(r-1)B^{r-1} = AB^{r-1} - B^{r-1}A - (r-1)B^{r-2}C.$$

Multiplying the the last equation on the right by B we have

$$\lambda(r-1)B^r = AB^r - B^{r-1}(AB) - (r-1)B^{r-2}(CB).$$

By the conditions we can write $AB = BA + C + \lambda B$ and $CB = BC$. Replacing these terms above we obtain

$$\lambda(r-1)B^r = AB^r - B^rA - B^{r-1}C - \lambda B^r - (r-1)B^{r-1}C.$$

Therefore,

$$AB^r - B^rA = \lambda r B^r + rB^{r-1}C.$$

For the second statement suppose $\lambda \neq 0$ and C is nilpotent with nilpotency index m. Using the first assertion we have

$$B^r = (1/\lambda r)[A, B^r] - (1/\lambda)B^{r-1}C, \text{ for all } r \geqslant 1.$$

Since, B and C commute, $(B^{r-1}C)^m = (B^{r-1})^m(C)^m = 0$, Hence, for all $r \geqslant 1$ $B^{r-1}C$ is nilpotent and has trace zero by Proposition 3.12. As the trace of commutators is always zero then $tr([A, B^r]) = 0$ for all $r \geqslant 1$. It follows that $tr(B^r) = 0$ for all $r \geqslant 1$ and again by Proposition 3.12 we conclude that B is nilpotent. □

Now we can present a result similar to the Proposition 3.11 but with a new proof using compatible pairs.

Theorem 3.14. *Let K and I be finite dimensional Lie algebras over a field of characteristic $p \geqslant 0$ such that K is solvable. Suppose that K acts on I by representation $\psi : K \to \mathsf{Der}(I)$. Let $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ such that α has no eigenvalue 0. If either $p = 0$ or $p > 0$ and dimension of I is less than p then $Tr(\psi^n(k)) = 0$, for all $k \in K$. In these two cases, $\psi(k)$ is nilpotent for all $k \in K$.*

Proof. As α has no eigenvalue 0, it is non-singular. Suppose that the order of α, considered as an endomorphism of I, is $p^t m$. Then by Lemma 3.3, $(\alpha, \beta)^{p^t} = (\alpha^{p^t}, \beta^{p^t})$ is a compatible pair and by Proposition 2.16, α^{p^t} is diagonalizable. Hence by possibly replacing (α, β) by $(\alpha, \beta)^{p^t}$, we may assume without loss of generality that α is diagonalizable. Let $x_1, ..., x_s$ be a basis of K such that $\alpha(x_i) = \lambda_i x_i$. For all $a \in \mathfrak{gl}(I)$ denote by $[a]$ the matrix of a in this basis. Then, by equation (8),

$$[[\beta], [\psi(x_i)]] = \lambda_i [\psi(x_i)].$$

We can apply Proposition 3.13 to this last equation for $A = [\beta]$, $B = [\psi(x_i)]$, $C = 0$ and $\lambda = \lambda_i \neq 0$ to conclude that $\psi(x_i)$ is nilpotent for $1 \leqslant i \leqslant s$. Now we observe that if K is a nilpotent Lie algebra in either characteristic is 0 or characteristic p with dimension of L less than p then Lie's Theorem (Theorem 2.6) is valid. Lie's Theorem grants that there is a basis of I such that the image of ψ lies in the subalgebra of $\mathfrak{gl}(I)$ formed by upper triangular matrices. Since $[\psi(x_i)]$ is nilpotent and upper triangular, it must be strictly upper triangular (that is, it contains zeros in the diagonal). Then all $\psi(k)$, for all $k \in K$, are also strictly upper triangular matrices, since they are linear combinations of the $\psi(x_i)$. Hence every $\psi(k)$ is nilpotent. □

Corollary 3.15. *Let L be a solvable Lie algebra over a field $\mathbb{F}$ of characteristic $p \geqslant 0$. Suppose that L has a nonsingular derivation. If either $p = 0$ or $p > 0$ and dimension of $L^{(i)}/L^{(i+1)} < p$, for all i, then L is nilpotent.*

Proof. Suppose that $L > L^{(1)} > \cdots > L^{(k)} > L^{(k+1)} = 0$ is the derived series of L. We prove this result by induction on k. When $k = 0$, then L is clearly nilpotent, as it is actually abelian. Suppose that the result holds for Lie algebras of derived length $k - 1$ and assume that L has derived length k. Then $I = L^{(k)}$ is an abelian ideal of L. Setting $K = L/I$, we have that K acts on I (see Example 2.7) and let us call the corresponding representation ψ. Further, since the terms of the derived series are invariant under derivations, a non-singular derivation $\delta \in \mathsf{Der}(L)$ gives rise to a compatible pair $(\alpha, \beta) \in \mathsf{Comp}(K, I)$ as explained in Example 3.9. Since δ is non-singular, so are $\alpha \in \mathsf{Der}(K)$ and $\beta \in \mathsf{Der}(I)$. Note that K is solvable of solvable length $k - 1$ and $K^{(i)}/K^{(i+1)} \cong L^{(i)}/L^{(i+1)}$ for all $i \leqslant k - 1$. Hence the induction hypothesis is valid for K and we obtain that K is nilpotent. Further, since

$\dim I < p$, we have that $\psi(k)$ is nilpotent for all k. Now Proposition 2.3 implies that L is nilpotent. $\square$

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