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Math XXXX – Independent Study: Manifolds– Summer 2025  
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*An Introduction to Lie Algebras*– August, 2025

# Chapter 1

## Introduction

**Definition 1.0.1** (Lie Bracket). We define the Lie Bracket,  $[\cdot, \cdot]$  as a bilinear operation

$$[\cdot, \cdot] : L \times L \rightarrow L$$

with the following properties

$$[x, x] = 0 \tag{L1}$$

$$[x, [y, z]] + [y, [z, x]] + [z, [x, y]] = 0 \tag{L2}$$

**Definition 1.0.2** (Derivation of  $A$ ). Given an algebra  $A$  over a field  $F$ , a **derivation**  $D : A \rightarrow A$  is defined by

$$D(ab) = aD(b) + D(A)b, \forall a, b, \in A$$

We denote  $\text{Der } A$  as the set of all derivations of  $A$ .

We define the **inner derivation** of the Lie Algebra  $L$ , denoted as  $\text{IDer } L$  as the set of all  $\text{ad } x : L \rightarrow L$  which are derivations.

## 1.1 Exercises

1.1 (Pg 2.)

(a) Show that  $[v, 0] = 0 = [0, v]$  for all  $v \in L$ .

$$\begin{aligned} [v, v] &= 0 \\ [v, v] - [v, 0] &= 0 - [v, 0] \\ [v - v, v - 0] &= [0, v] \\ [0, v] &= [v, 0] \end{aligned}$$

but  $[0, v] = -[v, 0]$  for all  $v$  therefore  $[0, v] = 0$ .

(b) Suppose that  $x, y \in L$  satisfy  $[x, y] \neq 0$ . Show that  $x$  and  $y$  are linearly independent on  $F$ .  
Want to show that  $ax + by = 0$  implies that  $a, b = 0$ .

$$\begin{aligned} \text{Let } ax + by &= 0 \\ by &= -ax \implies y = cx, \text{ for some } c \\ [x, y] &= [x, cx] = c[x, x] = 0 \end{aligned}$$

but  $[x, y] \neq 0$  therefore  $c = 0$  and  $x, y$  are linearly independent.

- 1.2 (Pg 2.) Convince yourself that  $\wedge$  is bilinear. Then check that the Jacobi Identity holds. *Hint:* if  $x \cdot y$  denotes the dot product of  $x, y \in \mathbb{R}^3$ , then

$$x \wedge (y \wedge z) = (x \cdot z)y - (x \cdot y)z, \forall x, y, z \in \mathbb{R}^3.$$

*wedge is bilinear.*

Given  $x = (x_1, x_2, x_3)$  and  $y = (y_1, y_2, y_3)$  we have

$$\begin{aligned} x \wedge y &= (x_2y_3 - x_3y_2, x_3y_1 - x_1y_3, x_1y_2 - x_2y_1) \\ (x + (0, b, 0)) \wedge y &= ((x_2 + b)y_3 - (x_3 + 0)y_2, (x_3 + 0)y_1 - (x_1 + 0)y_3, (x_1 + 0)y_2 - (x_2 + b)y_1) \\ &= (x_2y_3 - x_3y_2, x_3y_1 - x_1y_3, x_1y_2 - x_2y_1) + (by_3, 0, -by_1) \\ &= x \wedge y + (0, b, 0) \wedge y \end{aligned}$$

Therefore additive on the left for the middle coordinate. Each argument is independent of coordinate so is true for  $(a, 0, 0)$  and  $(0, 0, c)$  and can be easily seen when used on the write (e.g.,  $x \wedge (y + (0, b, 0))$ ).

### The Jacobi Identity

Want to show

$$x \wedge (y \wedge z) + y \wedge (z \wedge x) + z \wedge (y \wedge x) = 0 \quad (1.1)$$

from the hint

$$x \wedge (y \wedge z) = (x \cdot z)y - (x \cdot y)z$$

and from (1)

$$\begin{aligned} x \wedge (y \wedge z) + y \wedge (z \wedge x) + z \wedge (y \wedge x) &= (x \cdot z)y - (x \cdot y)z \\ &\quad + (y \cdot x)z - (y \cdot z)x \\ &\quad + (z \cdot y)x - (z \cdot x)y \\ &= ((x \cdot z) - (z \cdot x))y \\ &\quad + (-(x \cdot y) + (y \cdot x))z \\ &\quad + (-(y \cdot z) + (z \cdot y))x \\ &= 0 \end{aligned}$$

- 1.3 (Pg 2.) Suppose that  $V$  is a finite-dimensional vector space over  $F$ . Write  $\text{gl}(V)$  for the set of all linear maps from  $V$  to  $V$ . This is again a vector space over  $F$ , and it becomes a Lie algebra, known as the *general linear algebra*, if we define the Lie bracket  $[-, -]$  by

$$[x, y] := x \circ y - y \circ x, \forall x, y \in \text{gl}(V),$$

where  $\circ$  denotes the composition of maps. Check that the Jacobi Identity holds.

Given  $R, S, T \in \text{gl}(V)$  there exists matrix  $A, B, C \in \mathcal{M}_{n \times n}(F)$  where  $n = \dim V$  and  $Rx = Ax$ ,  $Sx = Bx$ ,  $Tx = Cx$ ,  $\forall x \in V$ . Further remember that  $R \circ S = AB$  (similar for the other two transformations) for all  $x \in v$ . Then

$$\begin{aligned} [R, [S, T]] + [S, [T, R]] + [T, [R, S]] &= (R \circ (S \circ T - T \circ S) - (S \circ T - T \circ S) \circ R) \\ &\quad + (S \circ (T \circ R - R \circ T) - (T \circ R - R \circ T) \circ S) \\ &\quad + (T \circ (R \circ S - S \circ R) - (R \circ S - S \circ R) \circ T) \\ &= (A(BC - CB) - (BC - CB)A) \\ &\quad + (B(CA - AC) - (CA - AC)B) \\ &\quad + (C(AB - BC) - (AB - BA)C) \end{aligned}$$

by rearranging the terms we can see that they all cancel out. Most notably this is done *without commuting*. It is important to remember that, in general,  $R \circ S \neq S \circ R$ .

- 1.4 Let  $b(n, F)$  be the upper triangular matrices in  $\mathfrak{gl}(n, F)$ . (A matrix  $x$  is said to be upper triangular if  $x_{ij} = 0$  whenever  $i > j$ .) This is a Lie algebra with the same Lie bracket as  $\mathfrak{gl}(n, F)$ .

Similarly, let  $n(n, F)$  be the strictly upper triangular matrices in  $\mathfrak{gl}(n, F)$ . (A matrix  $x$  is said to be strictly upper triangular if  $x_{ij} = 0$  whenever  $i \geq j$ .) Again this is a Lie algebra with the same Lie bracket as  $\mathfrak{gl}(n, F)$ .

Verify these assertions.

Let  $b(n, F) = \{A \in \mathfrak{gl}(n, F) \mid A = [x_{ij}], i > j \rightarrow x_{ij} = 0\}$ . Define

$$[x, y] := x \circ y - y \circ x, \forall x, y \in b(n, F),$$

The only question that needs to be answered is ... Given  $S, T \in b(n, F)$  is  $S \circ T \in b(n, F)$ . Let  $A, B \in \mathcal{M}_{n \times n}(F)$  and  $T(x) = Ax, S(x) = Bx, \forall x \in F$ . Then  $(T \circ S)(x) = ABx$ . Is  $AB \in b(n, F)$ .

Let  $A = [a_{ij}]$  and  $B = [b_{ij}]$

$$AB = \left[ x_{ij} = \sum_{k=1}^n a_{ik} b_{kj} \right]$$

If  $i > j$  then  $x_{ij}$

- 1.5 (Pg 4) Find  $Z(L)$  when  $L = \mathfrak{sl}(2, F)$ . You should find the answer depends on the characteristic of  $F$ .

Let  $\mathfrak{sl}(n, F)$  be the subspace of  $GL(n, F)$  consisting of all matrices whose trace is zero, i.e.,  $\mathfrak{sl}(n, F) = \left\{ A \in \mathcal{M}_{n \times n}(F) \mid \sum_{i=1}^n a_{ii} = 0 \right\}$ . This is known as *Special Linear Algebra* on square matrices.

**When is  $\sum_{i=1}^n a_{ii} = 0$  for all  $a_{ii} \in F$ ? OR  $a_{11} + a_{22} = 0$ ?**

Notice, for example, that on the discrete field  $F = \mathbb{Z}/\mathbb{Z}5$ ,  $2 + 3 = 0$ . Thus, when  $L = \mathfrak{sl}(2, \mathbb{Z}/\mathbb{Z}p)$  where  $p$  is prime,  $Z(L)$  will have elements where  $a_{11} + a_{22} = p$ .

- 1.6 (Pg 5.) Show that if  $\varphi : L_1 \rightarrow L_2$  is a homomorphism, then the kernel of  $\varphi$ ,  $\ker \varphi$ , is an ideal of  $L_1$ , and the image of  $\varphi$ ,  $\text{im } \varphi$ , is a Lie subalgebra of  $L_2$ .

**Show that the kernel is an ideal.** Let  $h, k \in \ker \varphi$  such that  $h \neq k$ . Then  $\varphi(k) = \varphi(h) = 0$ .

$$\varphi(a - b) = \varphi(a) - \varphi(b) = 0$$

$$\therefore a - b \in \ker \varphi$$

which makes it a group under addition. Now we need to show that it is closed under multiplication, that is,  $ra \in \ker \varphi$  for all  $r \in L$ . Let  $r \in L$  then

$$\varphi(ra) = \varphi(r)\varphi(a) = 0$$

$$\therefore ra \in \ker \varphi$$

**Show that the image is a subalgebra.** We need to show three things:

**Closed under addition (group condition).**

Let  $u, v \in \text{im } \varphi$  then there exists  $x, y \in L_1$  such that  $\varphi(x) = u, \varphi(y) = v$ .

Then  $\varphi(x + y) = \varphi(x) + \varphi(y) = u + v \in \text{im } \varphi$ .

Therefore closed under addition.

**closed under scalar multiplication (ring condition).**

Let  $r, a \in \text{im } \varphi$ . Then there exists  $x, y \in L_1$  such that  $\varphi(x) = r, \varphi(y) = x$ .

Then  $\varphi(xy) = \varphi(x)\varphi(y) = ra \in \text{im } \varphi$

Therefore closed under scalar multiplication.

**closed under Lie bracket (subalgebra condition).**

Let  $u, v \in \text{im } \varphi$  then there exists  $x, y \in L_1$  such that  $\varphi(x) = u, \varphi(y) = v$ .

Then

$$\begin{aligned}\varphi([x + y, x + y]) &= \varphi([x, x] + [x, y] + [y, x] + [y, y]) \\ &= \varphi([x, y] + [y, x]) \\ &= \varphi([x, y]) + \varphi([y, x]) \\ \varphi([x, y]) &= -\varphi([y, x]) \\ [\varphi(x + y), \varphi(x + y)] &= [\varphi(x) + \varphi(y), \varphi(x) + \varphi(y)] \\ &= [u + v, u + v] \\ &= [u, u] + [u, v] + [v, u] + [v, v] \\ &= [u, v] + [v, u] \\ [u, v] &= -[v, u]\end{aligned}$$

therefore closed under Lie Bracket.

1.7 (Pg 6.) Let  $L$  be a Lie algebra. Show that the Lie bracket is associative, this is  $[x, [y, z]] = [[x, y], z]$  for all  $x, y, z \in L$ , if and only if for all  $a, b \in L$  the commutator  $[a, b]$  lies in  $Z(L)$ .

1.8 (Pg 6) Let  $D$  and  $E$  be derivations on algebra  $A$ .

(i) Show that  $[D, E] = D \circ E - E \circ D$  is also a derivation.

$$\begin{aligned}(D \circ E)(ab) &= D(aE(b) - E(a)b) \\ &= D(aE(b)) - D(E(a)b) \\ &= aD(E(b)) - D(a)E(b) - E(a)D(b) + D(E(a))b \\ &= aD(E(b)) + D(E(a))b - D(a)E(b) - E(a)D(b)\end{aligned}$$

We can switch  $D$  and  $E$  to compute  $E \circ D$

$$(E \circ D)(ab) = aE(D(b)) + E(D(a))b - E(a)D(b) - D(a)E(b)$$

taking the difference

$$\begin{aligned}(D \circ E)(ab) - (E \circ D)(ab) &= aD(E(b)) + D(E(a))b - D(a)E(b) - E(a)D(b) \\ &\quad - (aE(D(b)) + E(D(a))b - E(a)D(b) - D(a)E(b))\end{aligned}$$

$$\begin{aligned}[D, E](ab) &= a[D, E](b) - [D, E](a)b \\ &= a(D \circ E)(b) - ((D \circ E)(a))b - (a(E \circ D)(b) - (E \circ D)(a)b) \\ [D, E](ab) &= (D \circ E)(ab) - (E \circ D)(ab) \\ &= D(E(ab)) - E(D(ab)) \\ &= D(aE(b) - E(a)b) - E(aD(b) - D(a)b) \\ &= D(aE(b)) - D(E(a)b) - E(aD(b)) + E(D(a)b) \\ &= aD(E(b)) - E(b)D(a) \\ &\quad - E(a)D(b) + D(E(a))b \\ &\quad - aE(D(b)) + E(a)D(b) \\ &\quad + D(a)E(b) - E(D(a))b \\ &= a(D(E(b)) - E(D(b)) - (E(b))D(a)\end{aligned}$$

(ii) Show that  $D \circ E$  need not be a derivation. (see example).

1.9 (Pg 7.) Let  $L_1$  and  $L_2$  be Lie algebras. Show that  $L_1$  is isomorphic to  $L_2$  if and only if there is a basis  $B_1$  of  $L_1$  and a basis  $B_2$  of  $L_2$  such that the structure constants of  $L_1$  with respect to  $B_1$  are equal to the structure constants of  $L_2$  with respect to  $B_2$ .

( $\Rightarrow$ ) Assuming that  $L_1 \xrightarrow{\text{iso}} L_2$ . Define  $f : L_1 \rightarrow L_2$  to be that isomorphism. Let  $B_1 = (x_1, \dots, x_n)$  be the basis vectors for  $L_1$ . Then,

$$\begin{aligned} f([x_i, x_j]) &= f\left(\sum_{k=1}^n a_{ij}^k x_k\right) \\ &= \sum_{k=1}^n a_{ij}^k f(x_k) \end{aligned} \quad (1.6)$$

since  $f$  is isomorphic, it is also injective and surjective. Thus, each  $f(x_k)$  is unique. Further, given any  $i, j \in [1, \dots, n]$  we know that  $x_i, x_j$  are linearly independent. Thus,

$$\begin{aligned} 0 &= Ax_i + Bx_j \implies A = B = 0 \text{ and} \\ f(0) &= 0 = f(Ax_i + Bx_j) = Af(x_i) + Bf(x_j) \end{aligned}$$

therefore,  $f(x_i), f(x_j)$  are linearly independent and thus, form a basis. From (1.6) we see that it has the same Structure Constants.

1.10 (Pg 7.) Let  $L$  be a Lie algebra with basis  $(x_1, \dots, x_n)$ . What condition does the Jacobi identity impose on the structure constants  $a_{ij}^k$ ?

We have three brackets for the Jacobi Identity that start with

$$\begin{aligned} [x_i, x_j] &= \sum_{k=1}^n a_{ij}^k x_k \\ [x_e, x_f] &= \sum_{k=1}^n a_{ef}^k x_k \\ [x_b, x_c] &= \sum_{k=1}^n a_{bc}^k x_k \\ [x_i, [x_e, x_f]] &= \left[ x_i, \sum_{k=1}^n a_{ef}^k x_k \right] \\ &= \sum_{k=1}^n a_{ef}^k [x_i, x_k] \\ &= \sum_{k=1}^n a_{ef}^k \sum_{l=1}^n a_{ik}^l x_l \end{aligned}$$

Since, the  $x_i$  are linearly independent we can examine each element  $l$  independently that is

$$[x_i, [x_e, x_f]]_l = \sum_{k=1}^n a_{ef}^k a_{ik}^l x_l$$

cycling through the other terms of the Jacobi identity we get

$$\begin{aligned} [x_e, [x_f, x_i]]_l &= \sum_{k=1}^n a_{fi}^k a_{ek}^l x_l \\ [x_f, [x_i, x_e]]_l &= \sum_{k=1}^n a_{ei}^k a_{fk}^l x_l \end{aligned}$$

The Jacobi Identity means that the sum of the coefficients of these terms must be zero that is

$$0 = \sum_{k=1}^n a_{ef}^k a_{ik}^l + \sum_{k=1}^n a_{fi}^k a_{ek}^l g + \sum_{k=1}^n a_{ei}^k a_{fk}^l$$

1.11 (Pg 8.) Let  $L_1$  and  $L_2$  be two abelian Lie algebras. Show that  $L_1$  and  $L_2$  are isomorphic if and only if they have the same dimension.

If  $L_1$  and  $L_2$  are abelian then since  $[x, y] = -[y, x]$  then  $[x, y] = 0$  for all  $x, y \in L_1$  or  $L_2$ . Consequently, these are vector spaces that are isomorphic to each other and, hence, have the same dimension.

1.12 Find the structure constants of  $\mathfrak{sl}(2, F)$  with respect to the basis given by the matrices

$$e = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, f = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The Lie Bracket for  $\mathfrak{sl}(2, F)$  is  $[X, Y] = XY - YX$ . Thus,

$$\begin{aligned} [e, f] &= \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\ &= h \\ [f, h] &= \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} - \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ -1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 \\ 2 & 0 \end{pmatrix} \\ &= 2f \\ [h, e] &= \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} - \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & -1 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & -2 \\ 0 & 0 \end{pmatrix} \\ &= -2e \end{aligned}$$

Thus,

$$\begin{aligned} a_{ii}^k &= 0, \forall k = 1, 2, 3 \\ [e, f] &= a_{12}^1 e + a_{12}^2 f + a_{12}^3 h = h \rightarrow a_{12}^3 = 1 \\ [f, h] &= a_{23}^1 e + a_{23}^2 f + a_{23}^3 h = 2f \rightarrow a_{23}^2 = 2 \\ [h, e] &= a_{31}^1 e + a_{31}^2 f + a_{31}^3 h = -2e \rightarrow a_{31}^1 = -2 \end{aligned}$$

all else are zero.

1.13 Prove  $\mathfrak{sl}(2, \mathbb{C})$  has no non-trivial ideals.

1.14 Let  $L$  be the 3-dimensional *complex* Lie algebra with basis  $(x, y, z)$  and Lie bracket defined by

$$[x, y] = z, [y, z] = x, [z, x] = y$$

(Here  $L$  is the “complexification” of the 3-dimensional real Lie algebra  $\mathbb{R}_\wedge^3$ .)

- (i) Show that  $L$  is isomorphic to the Lie subalgebra of  $\mathfrak{gl}(3, \mathbb{C})$  consistent for all  $3 \times 3$  antisymmetric matrices with entries in  $\mathbb{C}$ .

Let  $U = \{A \in \mathfrak{gl}(3, \mathbb{C}) : A \text{ is an anti-symmetric matrix}\}$ . Thus for any  $A \in U$  there exists  $a, b, c \in \mathbb{C}$  such that

$$X = \begin{pmatrix} 0 & a & b \\ -a & 0 & c \\ -b & -c & 0 \end{pmatrix}$$

which have three linearly independent elements

$$\begin{aligned} x &= \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ y &= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \\ z &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \end{aligned}$$

Verify

$$\begin{aligned} [x, y] &= xy - yx \\ &= \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \\ &= z \end{aligned}$$

$$\begin{aligned} [y, z] &= yz - zy \\ &= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ &= x \end{aligned}$$



$$\begin{aligned}
[z, x] &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \\
&= y
\end{aligned}$$

(ii) Find an explicit isomorphism  $\mathfrak{sl}(2, \mathbb{C}) \xrightarrow{\text{iso}} L$ .

1.15 Let  $S$  be an  $n \times n$  matrix with entries in a field  $F$ . Define

$$\mathfrak{gl}_S(n, F) = \{x \in \mathfrak{gl}(n, F) : x^t S = -Sx\}.$$

(i) Show that  $\mathfrak{gl}_S(n, F)$  is a Lie subalgebra of  $\mathfrak{gl}(n, F)$ .

Additive Group

Let  $x, y \in \mathfrak{gl}_S(n, F)$ , then

$$(x + y)^t S = x^t S + y^t S = -Sx - Sy = -S(x + y)$$

Multiplicative property.

Let  $x \in \mathfrak{gl}_S(n, F)$  then  $x^t S = -Sx$  and  $rx^t S = -Sxr$  for all  $r \in F$

Lie Bracket

Let  $x, y \in \mathfrak{gl}_S(n, F)$  then

$$\begin{aligned}
[x, y] &= xy - yx \\
[x, y]^t S &= (xy - yx)^t S \\
&= (xy)^t S - (yx)^t S \\
&= y^t x^t S - x^t y^t S \\
&= -y^t Sx + x^t Sy \\
&= Syx - Sxy \\
&= S(yx - xy) \\
&= -S[x, y]
\end{aligned}$$

(ii) Find  $\mathfrak{gl}_S(2, \mathbb{R})$  if  $S = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$ .

Let  $x \in \mathfrak{gl}_S(2, \mathbb{R})$  and

$$\begin{aligned} x &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \\ x^t S &= \begin{pmatrix} a & c \\ b & d \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & a \\ 0 & b \end{pmatrix} \\ Sx &= \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} a & c \\ b & d \end{pmatrix} = \begin{pmatrix} b & d \\ 0 & 0 \end{pmatrix} \\ 0 = x^t S + Sx &= \begin{pmatrix} 0 & a \\ 0 & b \end{pmatrix} + \begin{pmatrix} b & d \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} b & a+d \\ 0 & b \end{pmatrix} \\ x &= \begin{pmatrix} a & 0 \\ c & -a \end{pmatrix} \\ &= a \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + c \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \end{aligned}$$

- (iii) Does there exist a matrix  $S$  such that  $\mathfrak{gl}_S(2, \mathbb{R})$  is equal to the set of all diagonal matrices in  $\mathfrak{gl}(2, \mathbb{R})$ .

Let  $A \in \mathfrak{gl}(2, \mathbb{R})$  be a diagonal matrix.

$$\begin{aligned} \text{Let } A &= \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix} \\ \text{Let } S &= \begin{pmatrix} u & v \\ w & z \end{pmatrix} \\ A^t S + SA &= AS + SA \rightarrow AS = -SA \\ au &= -ua \text{ and } bz = -zb \end{aligned}$$

No, no such  $S$  exists.

- (iv) Find a matrix  $S$  such that  $\mathfrak{gl}_S(3, \mathbb{R})$  is isomorphic to the Lie algebra  $\mathbb{R}_\wedge^3$  defined in §1.2, Example 1.

*Hint:* Part (i) of Exercise 1.14 is relevant.

Let  $x, y, z$  be a basis of  $\mathbb{R}^3$ . We want to find  $\phi : \mathbb{R}^3 \rightarrow \mathbb{R}_\wedge^3$ .

Let  $X, Y \in \mathfrak{gl}_S(3, \mathbb{R})$  and  $\phi : \mathfrak{gl}_S(3, \mathbb{R}) \rightarrow \mathbb{R}_\wedge^3$  such that

$$\begin{aligned} \phi([X, Y]) &= [\phi(X), \phi(Y)] = \phi(X) \wedge \phi(Y) \\ \phi(XY - YX) &= \phi(X) \wedge \phi(Y) \end{aligned}$$

Notice that

$$\begin{aligned} (XY)^t S &= Y^t X^t S = -Y^t S X = S Y X \\ \text{and } [X, Y]^t S &= (XY - YX)^t S \\ &= (XY)^t S - (YX)^t S \\ &= S Y X - S X Y \\ &= S(YX - XY) \\ &= -S[X, Y] \end{aligned}$$

$$\phi(X^t S) = \phi(-SX) = -\phi(S)\phi(X)$$

1.16 Show, by giving an example, that if  $F$  is a field of characteristic 2, there are algebras over  $F$  which satisfy (L1') and (L2) but are not Lie algebras.

- 1.17 Let  $V$  be an  $n$ -dimensional complex vector space and let  $L = \text{gl}(V)$ . Suppose that  $x \in L$  is diagonalisable, with eigenvalues  $\lambda_1, \dots, \lambda_n$ . Show that  $\text{ad } x \in \text{gl}(L)$  is also diagonalisable and that its eigenvalues are  $\lambda_i - \lambda_j$  for  $1 \leq i, j \leq n$ .
- 1.18 Let  $L$  be a Lie algebra. We saw in §1.6, Example 1.2(2) that the maps  $\text{ad } x : L \rightarrow L$  for  $x \in L$  are derivations of  $L$ ; these are known as *inner derivations*. Show that if  $\text{IDER } L$  is the set of inner derivations of  $L$ , then  $\text{IDER } L$  is an ideal of  $\text{DER } L$ .
- 1.19 Let  $A$  be an algebra and let  $\delta : A \rightarrow A$  be a derivation. Prove that  $\delta$  satisfies the Leibniz rule

$$\delta^n(xy) = \sum_{r=0}^n \binom{n}{r} \delta^r(x) \delta^{n-r}(y), \forall x, y \in A.$$

This resembles the binomial theorem

$$(a + b)^n = \sum_{r=0}^n \binom{n}{r} a^r b^{n-r}$$

Consider an inductive proof and consider  $\delta^0(x) = x$   
**Show true for  $n = 1$ .**

$$\begin{aligned} \delta(xy) &= \binom{1}{0} \delta^0(x) \delta^1(y) + \binom{1}{1} \delta^1(x) \delta^0(y) \\ &= x \delta(y) + \delta(x) y \end{aligned}$$

which is the Leibniz rule.

**Show true for  $n + 1$ .** Now, assuming that this is true for some number  $n$ , we must show that it is also true for  $n + 1$ . Thus, starting with  $n$  we'll calculate  $\delta(\delta^n(xy)) = \delta^{n+1}(xy)$ .

$$\begin{aligned} \delta^n(xy) &= \sum_{r=0}^n \binom{n}{r} \delta^r(x) \delta^{n-r}(y), \forall x, y \in A. \\ \delta(\delta^n(xy)) &= \delta \left( \sum_{r=0}^n \binom{n}{r} \delta^r(x) \delta^{n-r}(y) \right) \\ &= \sum_{r=0}^n \binom{n}{r} \delta(\delta^r(x) \delta^{n-r}(y)) \end{aligned} \tag{*}$$

Let us focus on the term in the summation

$$\begin{aligned} \delta(\delta^r(x) \delta^{n-r}(y)) &= \delta^r(x) \delta(\delta^{n-r}(y)) + \delta(\delta^r(x)) \delta^{n-r}(y) \\ &= \delta^r(x) \delta^{n-r+1}(y) + \delta^{r+1}(x) \delta^{n-r}(y). \end{aligned}$$

Thus,

$$\begin{aligned} \sum_{r=0}^n \binom{n}{r} \delta(\delta^r(x) \delta^{n-r}(y)) &= \sum_{r=0}^n \binom{n}{r} (\delta^r(x) \delta^{n-r+1}(y) + \delta^{r+1}(x) \delta^{n-r}(y)) \\ &= \sum_{r=0}^n \left( \binom{n}{r} + \binom{n}{r-1} \right) \delta^r(x) \delta^{n-r+1}(y) \end{aligned}$$

when  $r = 0$  we have

$$\begin{aligned} r = 0 &\rightarrow x \delta^{n+1}(y) + \delta(x) \delta^n(y) \\ r = n &\rightarrow \delta^n(x) \delta(y) + \delta^{n+1}(x) y \end{aligned}$$

From combinatorics we have the identity

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

and we have

$$\begin{aligned} \delta^{n+1}(xy) &= x\delta^{n+1}(y) + \delta(x)\delta^n(y) \\ &\quad + \sum_{r=0}^n \binom{n+1}{r} \delta^r(x)\delta^{n-r+1}(y) \\ &\quad + \delta^n(x)\delta(y) + \delta^{n+1}(x)y \\ &= \sum_{r=0}^{n+1} \binom{n+1}{r} \delta^r(x)\delta^{n-r+1}(y) \end{aligned}$$

Thus, by Mathematical Induction, our assertion is true

□

# Chapter 2

## Ideals and Homomorphisms

### Operations that work on Ideals

Addition:  $I + J = \{x + y : x \in I, y \in J\}$  is an ideal.

Lie Bracket:  $[I, J] = \text{span}\{[x, y] \mid x \in I, y \in J\}$  is an ideal.

Quotient:  $L/I = \{z + I : z \in L\}$  is a quotient algebra.

#### Notes:

Correspondence:  $L \supset J \supset I$ , where  $I, J$  are ideals of  $L$ . Then,  $J/I$  is an ideal of  $L/I$ .

Also, if  $K$  is an ideal of  $L/I$  and  $J = \{z \in L : z + I \in K\}$  (i.e.,  $J$  is the set of cosets of  $K$  in  $I$ ) then  $J$  is an ideal of  $L$  and  $J \supset I$ .

### 2.1 Exercises

2.1 (Pg. 11) Show that  $I + J$  is an ideal of  $L$  where

$$I + J = \{x + y : x \in I, y \in J\}.$$

Let  $z \in L$  and  $x, y \in I + J$  then there exists  $x_I, y_I \in I$  and  $x_J, y_J \in J$  such that  $x = x_I + x_J$  and  $y = y_I + y_J$  then from (L2) we have

$$\underbrace{[[y, x], z]}_{\in I+J} = \underbrace{[x, [y, z]]}_{\in I} + \underbrace{[y, [z, x]]}_{\in J} \in I + J$$

2.2 (Pg. 12) Show that  $\text{sl}(2, \mathbb{C})' = \text{sl}(2, \mathbb{C})$ .

Let  $L = \text{sl}(2, \mathbb{C})$  and  $X \in [L, L]$ . Then, there exist  $A, B \in L$  such that  $[A, B] = X$  thus

$$X = [A, B] = AB - BA$$

$AB \in L$  and  $BA \in L$  therefore  $X \in L$ .

2.3 (Pg. 13)

(i) Show that the Lie Bracket defined in  $L/I$  is bilinear and satisfies the axioms (L1) and (L2).

Define the Lie Bracket of two cosets as

$$[w + I, z + I] = [w, z] + I, \forall w, z \in L$$

where the bracket on the right side is the Lie Bracket defined for  $L$ . Thus, let  $a, b \in L$  then we have

$$\begin{aligned}[a + w + I, b + z + I] &= [a + w, b + z] + I \\ &= [a, b] + [a, z] + [w, b] + [w, z] + I\end{aligned}$$

the four Lie Brackets add up to a single element in  $L$  and is therefore true. Thus, this Lie Bracket is bilinear.

- (ii) Show that the linear transformation  $\pi : L \rightarrow L/I$  which takes an element  $z \in L$  to its coset  $z + I$  is a homomorphism of a Lie Algebras.

Need to show that

$$\pi([x, y]) = [\pi(x), \pi(y)]$$

I prefer to call elements of  $L/I$  equivalence classes. That is  $L/I$  is partitioned into equivalence classes (cosets) and its elements are these subsets. The proper notation for such an element would be  $[x] \in L/I$  where  $x$  is a representative element of the equivalence class containing  $x$ . Thus  $\pi(x) = [x] = \{x + I\}$ .

$$\begin{aligned}\pi(x) &= [x] = \{x + I\} \\ [\pi(x), \pi(y)] &= [[x], [y]] \\ &= [\{x + I\}, \{y + I\}] \\ &= [x, y] + I \\ &= [[x, y]]\end{aligned}$$

or the equivalence class of the Lie Bracket of the left hand side.

- 2.4 (Pg. 14) Show that if  $L$  is a Lie Algebra then  $L/Z(L)$  is isomorphic to a subalgebra of  $\mathfrak{gl}(L)$ .

$Z(L) = \{x \in L : [x, y] = 0 \text{ for all } y \in L\}$ . Therefore,  $[x] \in L/Z(L) = \{y \in L : y = x + z, z \in Z(L)\}$ .  $Z(L)$  is an ideal. Thus,  $[x] = x + Z(L)$ . Let  $\varphi : L/Z(L) \rightarrow \mathfrak{gl}(L)$  be a homomorphism. Then  $x, y \in Z(L)$  implies that  $\varphi([x, y]) = \ker \varphi$ . From the first isomorphism theorem,  $L/\ker \varphi = L/Z(L) \cong \text{Im } \varphi$ .

- 2.5 Show that if  $z \in L'$  then  $\text{tr ad } z = 0$ .

The thing to remember is that every  $z \in L'$  is a linear combination of Lie Brackets. Thus

$$\begin{aligned}z &= \sum_k [x_k, y_k] \\ \text{tr ad } z &= \sum_k \text{tr ad}([x_k, y_k]) \\ \text{or each } \text{tr ad}([x_k, y_k]) &= 0, \forall k\end{aligned}$$

That is,

$$\begin{aligned}\text{ad}([x_k, y_k]) &= \text{ad } x_k \circ \text{ad } y_k - \text{ad } y_k \circ \text{ad } x_k = 0 \\ \therefore \text{tr ad } z &= 0\end{aligned}$$

- 2.6 Suppose  $L_1$  and  $L_2$  are Lie algebras. let  $L := \{(x_1, x_2) : x_i \in L_i\}$  be the direct sum of their underlying vector spaces, e.g.,  $L = L_1 \oplus L_2$ . Show that if we define

$$[(x_1, x_2), (y_1, y_2)] := ([x_1, y_1], [x_2, y_2])$$

then  $L$  becomes a Lie algebra, the *direct sum* of  $L_1$  and  $L_2$ ,  $L = L_1 \oplus L_2$ .

- (i) Prove that  $\mathfrak{gl}(2, \mathbb{C})$  is isomorphic to the direct sum of  $\mathfrak{sl}(2, \mathbb{C}) \oplus \mathbb{C}$ , the 1-dimensional complex abelian Lie algebra.

Let  $\varphi : \mathfrak{gl}(2, \mathbb{C}) \rightarrow \mathfrak{sl}(2, \mathbb{C}) \oplus \mathbb{C}$  be a surjective transformation. Then

$$\begin{aligned}\dim \mathfrak{gl}(2, \mathbb{C}) &= \dim \ker \varphi + \dim \text{range } \varphi \\ \dim \ker \varphi &= \dim \mathfrak{gl}(2, \mathbb{C}) - \dim(\mathfrak{sl}(2, \mathbb{C}) \oplus \mathbb{C}) \\ &= n^2 - n^2 = 0\end{aligned}$$

The dimension of the kernel of  $\varphi$  is 0 therefore  $\varphi$  is a bijection implying an isomorphism.

- (ii) Show that if  $L = L_1 \oplus L_2$  then  $Z(L) = Z(L_1) \oplus Z(L_2)$  and  $L' = L'_1 \oplus L'_2$ . Formulate a general version for a direct sum  $L_1 \oplus \cdots \oplus L_k$ .

**1: Show**  $Z(L) = Z(L_1) \oplus Z(L_2)$ .

For any  $u \in L$  there exists  $u_1 \in L_1$  and  $u_2 \in L_2$  such that  $u = (u_1, u_2)$ . If  $z \in Z(L)$  then  $[z, u] = 0$ .

$$\begin{aligned}[z, u] &= [(z_1, z_2), (u_1, u_2)] \\ &= ([z_1, u_1], [z_2, u_2]) \\ \therefore [z_1, u_1] &= 0 \text{ and } [z_2, u_2] = 0\end{aligned}$$

for any  $u$ . Thus,  $z_1 \in Z(L_1)$  and  $z_2 \in Z(L_2)$ .

**2: Show**  $L' = L'_1 \oplus L'_2$ .

Let  $z \in L$  then there exists a linear combination of commutators  $[x_k, y_k]$  equal to zero

$$z = \sum_k [x_k, y_k]$$

There exist  $a_k, b_k \in L_1$  and  $c_k, d_k \in L_2$  such that  $x_k = (a_k, c_k)$  and  $y_k = (b_k, d_k)$ . then

$$\begin{aligned}z &= \sum_k [(a_k, c_k), (b_k, d_k)] \\ &= \sum_k ([a_k, b_k], [c_k, d_k]) \\ &= \left( \sum_k [a_k, b_k], \sum_k [c_k, d_k] \right) \\ &\in L_1 \oplus L_2\end{aligned}$$

Thus

$$L = \bigoplus_k L_k \implies Z(L) = \bigoplus_k Z(L_k) \text{ and } L' = \bigoplus_k L'_k$$

- (iii) Are the summands in the direct sum decomposition of a Lie Algebra uniquely determined?

*Hint:* If you think that the answer is yes, now might be a good time to read §16.4 in Appendix A on the “diagonal fallacy”. The next question looks at this point in more detail.

2.7 Suppose  $L = L_1 \oplus L_2$  is the direct sum of two Lie algebras.

- (i) Show that  $\{(x_1, 0) : x_1 \in L_1\}$  is an ideal of  $L$  isomorphic to  $L_1$  and that  $\{(0, x_2) : x_2 \in L_2\}$  is an ideal of  $L$  isomorphic to  $L_2$ . Show that the projections  $p_1(x_1, x_2) = x_1$  and  $p_2(x_1, x_2) = x_2$  are Lie algebra homomorphisms.

**Show the  $L_1$  isomorphism.**

Let  $u = (u_1, u_2) \in L$ . Then  $N_1 = \{(x_1, 0) : x_1 \in L_1\}$  and  $x = (x_1, x_2) \in N_1$  then  $[u, x] = [(u_1, u_2), (x_1, 0)] = ([u_1, x_1], [u_2, 0]) = ([u_1, x_1], 0) \in N_1$  and therefore an ideal. Also, allow

$\varphi : N_1 \rightarrow L_1$ . Let  $a, b \in \ker \varphi$ . Then  $\varphi(a + b) = \varphi(a) + \varphi(b) = (0, 0)$  implies that  $a_1 = b_1$  or  $a = b$ . Thus,  $\varphi$  is an isomorphism.

**A similar argument for the  $L_2$  isomorphism.**

**Projections:**

Given any  $x, y \in L$

$$\begin{aligned} p_1([x, y]) &= p_1([x_1, y_1], [x_2, y_2]) \\ &= [x_1, y_1] \end{aligned}$$

thus  $p_1([x, y]) \in L_1$ . A similar argument for  $L_2$ .

Now suppose that  $L_1$  and  $L_2$  do not have any non-trivial proper ideals.

- (ii) Let  $J$  be a proper ideal of  $L$ . Show that  $J \cap L_1 = 0$  and  $J \cap L_2 = 0$ , then the projection  $p_1 : J \rightarrow L_1$  and  $p_2 : J \rightarrow L_2$  are isomorphisms.
- (iii) Deduce that if  $L_1$  and  $L_2$  are not isomorphic as Lie algebras, then  $L_1 \oplus L_2$  has only two non-trivial proper ideals.
- (iv) Assume that the ground field is infinite. Show that if  $L_1 \cong L_2$  and  $L_1$  is 1-dimensional, then  $L_1 \oplus L_2$  has infinitely many different ideals.

2.8 Let  $L_1$  and  $L_2$  be Lie algebras, and let  $\varphi : L_1 \rightarrow L_2$  be a surjective Lie algebra homomorphism. True or False:

- (a)  $\varphi(L'_1) = L'_2$ ;

Let  $x, y \in L_1$  then  $[x, y] \in L'_1$ . Then  $\varphi([x, y]) = [\varphi(x), \varphi(y)] \in L'_2$ . Therefore  $\varphi(L'_1) \subseteq L'_2$ .

Then, we know that given any  $u, v \in L_2$  there is  $[u, v] \in L'_2$  and there exist  $x, y \in L_1$  such that  $\varphi(x) = u, \varphi(y) = v$ . Thus,  $[u, v] = [\varphi(x), \varphi(y)] = \varphi([x, y])$  and  $L'_2 \subseteq \varphi(L'_1)$ .

**TRUE**

- (b)  $\varphi(Z(L_1)) = Z(L_2)$ ;

Let  $u \in Z(L_1)$ . Then for any  $x \in L_1$  we have  $\varphi(0) = 0$  or  $\varphi(u) = 0$  therefore  $\varphi(Z(L_1)) \subseteq Z(L_2)$

Given any  $v \in Z(L_2)$  then any  $y \in L_2$  implies that  $[v, y] = 0$  and there exist  $w, z \in L_1$  such that  $\varphi(w) = v$  and  $\varphi(z) = y$ . Then  $[v, y] = [\varphi(w), \varphi(z)] = \varphi([w, z]) \in Z(L_1)$  because  $w \in Z(L_1)$ . Therefore,  $Z(L_2) \subseteq \varphi(Z(L_1))$ .

- (c)  $h \in L_1$  and  $\text{ad}_h$  is diagonalisable then  $\text{ad}_{\varphi(h)}$  is diagonalisable.

Notice that

$$\begin{aligned} \text{ad}_h(x) &= [h, x] \\ \varphi(\text{ad}_h(x)) &= \varphi([h, x]) \\ &= [\varphi(h), \varphi(x)] \\ &= \text{ad}_{\varphi(h)}(\varphi(x)) \end{aligned}$$

2.9 For each pair of the following Lie algebras over  $\mathbb{R}$ , decide whether or not they are isomorphic:

- (i) the Lie algebra  $R_\wedge^3$  where the Lie bracket is given by the vector product;

In other words, compare the wedge with the cross product. Define a Lie Algebra  $\mathbb{R}_\times^3 = \mathbb{R}^3$  with  $[x, y] = x \times y$  for all  $x, y \in \mathbb{R}_\times^3$ . Let  $\varphi : \mathbb{R}_\vee^3 \rightarrow \mathbb{R}_\times^3$ . Then,  $u, v \in \mathbb{R}_\vee^3$  and  $x, y \in \mathbb{R}_\times^3$  such that  $\varphi(u) = x, \varphi(v) = y$ .

$$\begin{aligned} \varphi([u, v]) &= [\varphi(u), \varphi(v)] = [x, y] \\ \varphi(u_2v_3 - u_3v_2, u_3v_1 - u_1v_3, u_2v_1 - v_1u_2) &= (x_2y_3 - x_3y_2, x_3y_1 - x_1y_3, x_2y_1 - x_1y_2) \end{aligned}$$

which is true if  $\varphi$  is the identity



- (ii) the upper triangular  $2 \times 2$  matrices over  $\mathbb{R}$ ;
- (iii) the strict upper triangular  $3 \times 3$  matrices over  $\mathbb{R}$ ;
- (iv)  $L = \{x \in \mathfrak{gl}(3, \mathbb{R}) : x^t = -x\}$ .

*Hint:* Use Exercises 1.15 and 2.8.

2.10 Let  $F$  be a field. Show that the derived algebra of  $\mathfrak{gl}(n, F)$  is  $\mathfrak{sl}(n, F)$

**Show that**  $\mathfrak{gl}(n, F)' \subseteq \mathfrak{sl}(n, F)$  Let  $u \in \mathfrak{gl}(n, F)'$  then there exist  $x, y \in \mathfrak{gl}(n, F)$  such that  $u = [x, y]$

$$\begin{aligned}\mathrm{tr} u &= \mathrm{tr}[x, y] \\ &= \mathrm{tr}(xy - yx) \\ &= \mathrm{tr}(xy) - \mathrm{tr}(yx) \\ &= 0\end{aligned}$$

$$\therefore u \in \mathfrak{sl}(n, F)$$

**Show that**  $\mathfrak{gl}(n, F)' \supseteq \mathfrak{sl}(n, F)$  Let  $u \in \mathfrak{sl}(n, F)$  then  $\mathrm{tr} u = 0$

2.11 In Exercise 1.15, we defined the Lie Algebra  $\mathfrak{gl}_S(n, F)$  over a field  $F$  where  $S$  is an  $n \times n$  matrix with entries in  $F$ .

Suppose that  $T \in \mathfrak{gl}(n, F)$  is another  $n \times n$  matrix such that  $T = P^t S P$  for some invertible  $n \times n$  matrix  $P \in \mathfrak{gl}(n, F)$  (Equivalently, the bilinear forms defined by  $S$  and  $T$  are congruent.) Show that the Lie algebras  $\mathfrak{gl}_S(n, F)$  and  $\mathfrak{gl}_T(n, F)$  are isomorphic.

2.12 Let  $S$  be an  $n \times n$  invertible matrix with entries in  $\mathbb{C}$ . Show that if  $x \in \mathfrak{gl}_S(n, \mathbb{C})$ , then  $\mathrm{tr} x = 0$

2.13 Let  $I$  be an ideal of a Lie Algebra  $L$ . Let  $B$  be the centraliser of  $I$  in  $L$ ; that is

$$B = C_L(I) = \{x \in L : [x, a] = 0, \forall a \in I\}$$

Show that  $B$  is an ideal of  $L$ . Now suppose that

- (a)  $Z(I) = 0$ , and
- (b) if  $D : I \rightarrow I$  is a derivation, then  $D = \mathrm{ad} x$  for some  $x \in I$ .  
Show that  $L = I \oplus B$ .
- (c) Recall that if  $L$  is Lie algebra, we defined  $L'$  to be the subspace spanned by the commutators  $[x, y]$  for  $x, y \in L$ . The purpose of this exercise, which may safely be skipped on first reading, is to show that the set of commutators may not even be a vector space (and so certainly not an ideal of  $L$ ).

Let  $\mathbb{R}[x, y]$  denote the ring of all real polynomials in two variables. Let  $L$  be the set of all matrices of the form

$$A(f(x), g(y), h(x, y)) = \begin{pmatrix} 0 & f(x) & h(x, y) \\ 0 & 0 & g(y) \\ 0 & 0 & 0 \end{pmatrix}.$$

- (i) Prove  $L$  is a Lie algebra with usual commutator bracket. (In contrast to all the Lie algebras seen so far,  $L$  is infinite-dimensional.)
- (ii) Prove that

$$[A(f_1(x), g_1(y), h_1(x, y)), A(f_2(x), g_2(y), h_2(x, y))] = A(0, 0, f_1(x)g_2(y) - f_2(x)g_1(y)).$$

Hence describe  $L'$ .

- (iii) Show that if  $h(x, y) = s^2 + xy + y^2$ , then  $A(0, 0, h(x, y))$  is not a commutator.

# Chapter 3

## Low Dimensional Lie Algebras

### Dimension 1

Given a single basis vector  $e$  then by definition the Lie bracket must be  $[e, e] = 0$  making the entire 1-dimensional vector space Abelian.

$$\mathfrak{g} \cong \mathbb{R}$$

### Dimension 2

Given a basis  $e_1, e_2$ .

#### 1. Abelian

The Lie Bracket must be  $[e_1, e_2] = 0$  for all elements of the vector space (plane).

#### 2. Non-Abelian (solvable)

The Lie Bracket must be  $[e_1, e_2] = e_2$ . This algebra is solvable but not nilpotent (i.e.,  $A^n = 0$  for some  $n$ ).

### Dimension 3

Given a basis  $e_1, e_2, e_3$ .

#### 1. Abelian

All Lie brackets are zero.

#### 2. Heisenberg Algebra

The Lie bracket is  $[e_1, e_2] = e_3$ . This becomes nilpotent.

#### 3. Solvable (non-nilpotent)

**Type 1:**

$$[e_1, e_2] = e_3 \text{ and } [e_1, e_3] = e_2$$

**Type 2:**

$$[e_1, e_2] = -e_3 \text{ and } [e_1, e_3] = e_2$$

#### 4. Simple Lie Algebras

(a)  $\mathfrak{so}(3)$

$$[e_1, e_2] = e_3, [e_2, e_3] = e_1 \text{ and } [e_3, e_1] = e_2$$

(b)  $\mathfrak{sl}(2, \mathbb{R})$

Consider the basis  $h, e, f$

$$[h, e] = 2e, [h, f] = -2f \text{ and } [e, f] = h$$

### 3.1 Exercises

- 3.1. Let  $V$  be a vector space and let  $\varphi$  be an endomorphism of  $V$ . Let  $L$  have underlying vector space  $V \oplus \text{span}\{x\}$ . Show that if we define the Lie bracket on  $L$  by  $[y, z] = 0$  and  $[x, y] = \varphi(y)$  for  $y, z \in V$ , then  $L$  is a Lie algebra and  $\dim L' = \text{rank } \varphi$ . (For a more general construction, see Exercise 3.9 below.)

If  $u_1, u_2 \in L$  then there exist  $y_1, y_2 \in V$  and  $x_1, x_2 \in \text{Span}(x)$  such that  $u_1 = (y_1, x_1)$  and  $u_2 = (y_2, x_2)$  then

$$\begin{aligned} [u_1, u_2] &= [(y_1, x_1), (y_2, x_2)] \\ &= [y_1, x_1] + [y_1, x_2] + [y_2, x_1] + [y_2, x_2] \\ &= 2\varphi(y_1) + 2\varphi(y_2) \end{aligned}$$

The only elements of  $L$  that are non-zero are the ones indicated by  $x$  and hence  $\varphi$ . Therefore,  $\dim L' = \text{rank } \varphi$ , i.e., the number of linearly independent rows of its matrix of transformation.

- 3.2. With the notation of §3.2.3, show that the Lie algebra  $L_\mu$  is isomorphic to  $L_\nu$  if and only if either  $\mu = \nu$  or  $\mu = \nu^{-1}$ .

From 3.1, let  $V_\mu, V_\nu$  be spanned by  $[y_\mu, z_\mu], [y_\nu, z_\nu]$  and  $x_\mu, x_\nu$  be the such that  $L_\mu = V_\mu \oplus \text{span}\{x\}, L_\nu = V_\nu \oplus \text{span}\{x\}$ . We can see that the Lie bracket for each  $L_\mu$  is  $[x_\mu, y_\nu] = y$  (from the text) and  $[y_\mu u, z_\mu] = 0$ , from the lemma. This Lie Bracket is precisely the Lie bracket from 3.1 for both  $\mu, \nu$ . Their rank must each be 2, therefore an isomorphism exists  $\varphi : L_\mu \rightarrow L_\nu$ .

Let  $\varphi : L_\mu \rightarrow L_\nu$  be this isomorphism. Thus, given any  $u \in L_\mu, v \in L_\nu$

$$\begin{aligned} \varphi(u) &= A_\mu u \text{ and } \varphi^{-1}(v) = A^{-1}v \\ A_\mu &= \begin{pmatrix} 1 & 0 \\ 0 & \mu \end{pmatrix} \\ I &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \mu \end{pmatrix} \\ &= \begin{pmatrix} a & b\mu \\ c & d\mu \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ 0 & d\mu \end{pmatrix} \\ \therefore d &= \mu^{-1} \end{aligned}$$

$A^{-1}$  is the  $\text{ad } x_\nu$ .

- 3.3. Find out where each of the following 3-dimensional complex Lie algebras appears in our classification:

(i)  $\mathfrak{gl}_S(3, \mathbb{C})$ , where  $S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$ ;

Remember that

$$\mathfrak{gl}_S(n, F) = \{u \in \mathfrak{gl}(n, F) : u^t S = -Su\}.$$

Let's determine a basis for  $\mathfrak{gl}_S(3, \mathbb{C})$ . Let  $u \in \mathfrak{gl}_S(3, \mathbb{C})$  then

$$\begin{aligned}
 u^t S &= -Su \\
 \text{Let } u &= \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & k \end{pmatrix} \\
 -Su &= \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & k \end{pmatrix} \\
 &= \begin{pmatrix} -a & -b & -c \\ d & e & f \\ g & h & k \end{pmatrix} \\
 u^t S &= \begin{pmatrix} a & d & g \\ b & e & h \\ c & f & k \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \\
 &= \begin{pmatrix} a & d & -g \\ b & e & -h \\ c & f & -k \end{pmatrix}
 \end{aligned}$$

Which leads us to the following conclusions:

$$\begin{aligned}
 a &= k = 0 \\
 -b &= d \text{ and } b = d \rightarrow b = d = 0 \\
 g &= c \\
 e &= e \\
 f &= -h \text{ and } f = h \rightarrow f = h = 0
 \end{aligned}$$

Thus,

$$\begin{aligned}
 u &= \begin{pmatrix} 0 & 0 & c \\ 0 & e & 0 \\ c & 0 & 0 \end{pmatrix} \\
 &= c \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + e \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}
 \end{aligned}$$

$\mathfrak{gl}_S(3, \mathbb{C})$  is 2 dimensional. This is not Abelian therefore it is non-abelian solvable.

(ii) the Lie subalgebra of  $\mathfrak{gl}(3, \mathbb{C})$  spanned by the matrices

$$u = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \nu \end{pmatrix}, v = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, w = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

where  $\lambda, \mu, \nu$  are fixed complex numbers;

$$\begin{aligned}
uv &= \begin{pmatrix} \lambda & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \nu \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & \lambda \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \lambda v \\
vw &= \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} = 0 \\
uw &= \begin{pmatrix} \lambda & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \nu \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \\
&= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \nu \\ 0 & 0 & 0 \end{pmatrix} = \nu w
\end{aligned}$$

Heisenberg?

$$(iii) \left\{ \begin{pmatrix} 0 & a & b & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} : a, b, c \in \mathbb{C} \right\};$$

$$\text{Let } A = \begin{pmatrix} 0 & a & b & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\text{and } B = \begin{pmatrix} 0 & d & e & 0 \\ 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$AB = \begin{pmatrix} 0 & a & b & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & d & e & 0 \\ 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & bf & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$BA = \begin{pmatrix} 0 & d & e & 0 \\ 0 & 0 & f & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & a & b & 0 \\ 0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & ec & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$AB - BA = \begin{pmatrix} 0 & 0 & bf - ed & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$L' = \{e_{13}\}$$

one dimensional

$$(iv) \left\{ \begin{pmatrix} 0 & 0 & a & b \\ 0 & 0 & 0 & c \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} : a, b, c \in \mathbb{C} \right\}.$$

$$L' = \{e_{14}\}$$

- 3.4. Suppose  $L$  is a vector space with basis  $x, y$  and that a bilinear operation  $[-, -]$  on  $L$  is defined such that  $[u, u] = 0$  for all  $u \in L$ . Show that the Jacobi Identity holds and hence  $L$  is a Lie algebra.

$$\begin{aligned}[u + a, u + a] &= [u, u] + [u, a] + [a, u] + [a, a] \\ &= [u, a] + [a, u] \\ [u, a] &= -[a, u]\end{aligned}$$

to show that the Jacobi Identity

$$\begin{aligned}[x, [y, z]] + [y, [z, x]] + [z, [x, y]] &= [x, yz - zy] + [y, zx - xz] + [z, yx - xy] \\ &= xyz - xzy - yzx + zyx + yzx - yxz - zxy + \\ &\quad xzy + zyx - zxy + yxz - xyz \\ &= 0\end{aligned}$$

- 3.5. Show that over  $\mathbb{R}$  the Lie algebras  $\mathfrak{sl}(2, \mathbb{R})$  and  $\mathbb{R}_\wedge^3$  are not isomorphic. *Hint:* Prove that there is no non-zero  $x \in \mathbb{R}_\wedge^3$  such that the map  $\text{ad } x$  is diagonalisable.

Let  $x, y, z \in \mathbb{R}_\wedge^3$  then

$$z = [x, y] = x \times y$$

and  $z \perp x$  and  $y$ . Thus,  $\text{ad } z(u) = [z, u]$  then  $\text{ad } z(x) \parallel y$  and  $\text{ad } z(y) \parallel x$  and  $\text{ad } z(z) = 0$ . Hence,  $\text{ad } x$

- 3.6. Show that over  $\mathbb{R}$  there are exactly two non-isomorphic 3-dimensional Lie algebras with  $L' = L$ .  
From 3.5 we have two Lie Algebras both whose dimension is 3 and are non-isomorphic.
- 3.7. Let  $L$  be a non-abelian Lie algebra. Show that  $\dim Z(L) \leq \dim L - 2$ .
- 3.8. Let  $L$  be the 3-dimensional Heisenberg Lie algebra defined over field  $F$ . Show that  $\text{Der } L$  is 6-dimensional. Identify the inner derivations (as defined in Exercise 1.18) and show that the quotient  $\text{Der } L / \text{IDer } L$  is isomorphic to  $\mathfrak{gl}(2, F)$ .
- 3.9. Suppose that  $I$  is an ideal of a Lie algebra  $L$  and that there is a subalgebra  $S$  of  $L$  such that  $L = S \oplus I$ .

- (i) Show that the map  $\theta : S \rightarrow \mathfrak{gl}(I)$  defined by  $\theta(s)x = [s, x]$  is a Lie algebra homomorphism from  $S$  into  $\text{Der } I$ .

We say that  $L$  is *semidirect product* of  $I$  by  $S$ . (the reader may have seen the analogous construction for groups.)

- (ii) Show conversely that given Lie algebras  $S$  and  $I$  and a Lie algebra homomorphism  $\theta : S \rightarrow \text{Der } I$ , the vector space  $S \oplus I$  may be made into a Lie algebra by defining

$$[(s_1, x_1), (s_2, x_2)] = ([s_1, s_2], [x_1, x_2] + \theta(s_1)x_2 - \theta(s_2)x_1)$$

for  $s_1, s_2 \in S$ , and  $x_1, x_2 \in I$ , and that this Lie algebra is a semidirect product of  $I$  by  $S$ . (The direct sum construction introduced in Exercise 2.6 is the special case where  $\theta(s) = 0$  for all  $s \in S$ .)

- (iii) Show that the Lie algebras in Exercise 3.1 may be constructed as semidirect products.
- (iv) Investigate necessary and sufficient conditions for two semidirect products to be isomorphic.

- 3.10. Find, up to isomorphism, all Lie algebras with a 1-dimensional derived algebra.

# Chapter 4

## Solvable Lie Algebras

*Remark 4.0.1 (MathGPT: Describe the difference between an Ideal and a derived Lie algebra.). .*

Solution:

### Step 1: Define an ideal of a Lie Algebra.

An ideal of a Lie algebra is a subalgebra that interacts with the Lie bracket in a specific way. For a Lie algebra  $\mathfrak{g}$  over a field  $F$ , a subspace  $\mathfrak{i} \subset \mathfrak{g}$  is an ideal if and only if  $x \in \mathfrak{g}$  and  $y \in \mathfrak{i}$ , the Lie bracket  $[x, y]$  is in  $\mathfrak{i}$ . This condition is expressed as  $[\mathfrak{g}, \mathfrak{i}] \subseteq \mathfrak{i}$ . Ideals are analogous to normal subgroups in group theory and are essential for constructing quotient Lie algebras.

### Step 2: Define a Derived Lie Algebra

The derived Lie algebra, also known as the commutator subalgebra, of a Lie algebra  $\mathfrak{g}$  is denoted  $\mathfrak{g}'$  or  $[\mathfrak{g}, \mathfrak{g}]$ . It is the subspace spanned by all Lie brackets of elements in  $\mathfrak{g}$ , as shown using the Jacobi identity.

### Step 3: Difference in Generality.

An ideal is a type of subspace with a specific property related to the Lie bracket, while the derived Lie algebra is a specific construction that results in an ideal. Every derived Lie algebra is an ideal, but not every ideal is a derived algebra.

Step 4: An ideal  $\mathfrak{i}$  is defined by the property  $[\mathfrak{g}, \mathfrak{i}] \subseteq \mathfrak{i}$  and can be any subspace satisfying this condition. The derived Lie algebra  $\mathfrak{g}'$  is defined as the set of all possible Lie brackets of elements within  $\mathfrak{g}$  and is uniquely determined by  $\mathfrak{g}$ .

### Step 5: Difference in Purpose/Role

Ideals are used to define quotient Lie algebras and help understand the structure of Lie algebras, similar to normal subgroups in group theory. The derived Lie algebra  $\mathfrak{g}'$  measures how "non-abelian" a Lie algebra is. If  $\mathfrak{g}' = \{0\}$ , then  $\mathfrak{g}$  is abelian. The derived series of all Lie algebras is used to define solvable and nilpotent Lie algebras.

### Step 6: Examples

Consider the Lie algebra  $\mathfrak{gl}(n, F)$  of all  $n \times n$  matrices over a field  $F$ , with the Lie bracket  $[A, B] = AB - BA$ .

- **Ideal:** The set of scalar matrices,  $\mathfrak{s} = \{cI \mid c \in F\}$ , forms an ideal of  $\mathfrak{gl}(n, F)$ . This ideal is not the derived Lie algebra.
- **Derived Lie Algebra:** the derived Lie algebra  $\mathfrak{gl}(n, F)$  is  $\mathfrak{sl}(n, F)$ , the Lie algebra of  $n \times n$  matrices with trace zero. This is because the trace of a commutator is always zero, and any matrix with trace zero can be written as a commutator.  $\mathfrak{sl}(n, F)$  is an ideal of  $\mathfrak{gl}(n, F)$ .

**Final Answer** In summary, while the derived Lie algebra is always an ideal, an ideal is a more general concept. The derived Lie algebra is a specific ideal that captures the "commutativity" properties of the Lie algebra itself.

---

*Remark 4.0.2. Simple Algebras:* Special Linear, Special Orthogonal and Symplectic Lie Algebras

### Special Linear, $\mathfrak{sl}(n, \mathbb{C})$

Description:

The Lie algebra  $\mathfrak{sl}(n, \mathbb{C})$  consists of all  $n \times n$  complex matrices with trace zero,  $\text{tr } A = 0$ . The Lie bracket is defined by the commutator  $[A, B] = AB - BA$ .

Dimensions:

The dimensions of  $\mathfrak{sl}(n, \mathbb{C})$  is  $n^2 - 1$ , as the trace condition imposes one linear constraint on the  $n^2$  entries of a matrix.

Importance:

- If  $L = \mathfrak{gl}(n, \mathbb{C})$  then  $L' = \mathfrak{sl}(n, \mathbb{C})$ .
- Fundamental Representation: It is the Lie algebra of the special linear group  $\text{SL}(n, \mathbb{C})$  which acts on  $\mathbb{C}^n$ .
- Simple Lie Algebra: For  $n \geq 2$ , it is a simple Lie algebra, corresponding to the  $A$ -series of the Cartan classification.
- Physics: It appears in quantum mechanics and quantum field theory, describing symmetries.

### The Special Orthogonal Lie Algebra, $\mathfrak{so}(n, \mathbb{C})$

Description:

The Lie Algebra  $\mathfrak{so}(n, \mathbb{C})$  consists of  $n \times n$  complex skew-symmetric matrices. The Lie bracket is the commutator  $[A, B] = AB - BA$ .

Dimension:

The dimension is  $\frac{n(n-1)}{2}$ , as skew-symmetric matrices have zero diagonal entries and  $A_{aj} = -A_{ji}$  for  $i \neq j$ .

Importance:

- Orthogonal Group: It is the Lie algebra of the special orthogonal group  $\text{SO}(n, \mathbb{C})$ , preserving a symmetric bilinear form.
- Simple Lie Algebra: For  $n \geq 3$  and  $n \neq 4$ , it is simple, corresponding to the  $B$ -series and  $D$ -series in the Cartan classification.
- Geometry and Physics: It is crucial in geometry and physics, related to **rotations** and Lorentz transformations.

### The Symplectic Lie Algebra, $\mathfrak{sp}(2n, \mathbb{C})$ .

Description:

The Lie algebra  $\mathfrak{sp}(2n, \mathbb{C})$  consists  $2n \times 2n$  complex matrices  $A$  satisfying  $A^T J + JA = 0$  where  $J$  is a standard skew-symmetric matrix.

Dimension:

The dimension is  $n(2n + 1)$ , derived from the conditions on the matrix blocks  $P, Q, R, S$ .

Importance:



- Symplectic Group: It is the Lie algebra of the symplectic group  $Sp(2n, \mathbb{C})$ , preserving skew-symmetric bilinear form.
- Simple Lie Algebra: For  $n \geq 1$ , it is simple, corresponding to the  $C$ -series in the Cartan classification.
- Hamiltonian Mechanics and Quantum Mechanics: It is fundamental in Hamiltonian mechanics and quantum mechanics, related to symplectic manifolds and canonical transformations.

## 4.1 Exercises

4.1 Suppose that  $\varphi : L_1 \rightarrow L_2$  is a surjective homomorphism of Lie algebras. Show that

$$\varphi \left( L_1^{(k)} \right) = (L_2)^{(k)}.$$

A proof by induction. The initial case

$$\begin{aligned} \varphi(L_1') &= \varphi([L_1, L_1]) \\ &= [\varphi(L_1), \varphi(L_1)] \end{aligned}$$

Since  $\varphi$  is surjective  $\varphi(L_1) = L_2$  hence

$$\varphi(L_1') = [L_2, L_2] = L_2'$$

The inductive case.

$$\begin{aligned} \text{assume } \varphi(L_1^{(k)}) &= (L_2)^{(k)} \\ \varphi(L_1^{(k+1)}) &= \varphi([L_1^{(k)}, L_1^{(k)}]) \\ &= [\varphi(L_1^{(k)}), \varphi(L_1^{(k)})] \\ &= [(L_2)^{(k)}, (L_2)^{(k)}] \\ &= (L_2)^{(k+1)} \end{aligned}$$

4.2 Let  $x \in \mathfrak{gl}(2\ell, \mathbb{C})$ . Show that  $x$  belongs to  $\mathfrak{sp}(2\ell, \mathbb{C})$  if and only if it is of the form

$$x = \begin{pmatrix} m & p \\ q & -m \end{pmatrix}$$

where  $p$  and  $q$  are symmetric. Hence find the dimension of  $\mathfrak{sp}(2\ell, \mathbb{C})$ . (See Exercise 12.1 for the other families)

4.3 Use lemma 4.4 to show that if  $L$  is a Lie algebra then  $L$  is solvable if and only if  $\text{ad } L$  is a solvable subalgebra of  $\mathfrak{gl}(L)$ . Show that this result also holds if we replace "solvable" with "nilpotent".

4.4 Let  $L = \mathfrak{n}(n, F)$ , the Lie algebra of strictly upper triangular  $n \times n$  matrices over a field  $F$ . Show that  $L^k$  has a basis consisting of all the matrix units  $e_{ij}$  with  $j - i > k$ . Hence show that  $L$  is nilpotent. What is the smallest  $m$  such that  $L^m = 0$ ?

Let  $L \in \mathfrak{n}(n, F)$ .

$$L^1 = L' = [L, L]$$

given any  $A, B \in L$ ,  $[A, B] = AB - BA$ . Given any  $i, j < n$ , first we can see that  $A_{ij} = 0$  whenever  $i \geq j$  (the diagonal and lower triangle of the matrix). Further,

$$\begin{aligned} AB &= \left[ \sum_{k=1}^n A_{ik} B_{kj} \right] \\ &= \left[ \sum_{k=j}^n A_{ik} B_{kj} \right] \end{aligned}$$

$$\text{or } i < j + 1 \implies AB_{ij} = BA_{ij} = 0$$

that is, the elements along the diagonal one row up (or one column to the right) are all zero. Similarly, let  $C = AB$  then for some  $D \in L$  we get a similar argument, that is  $i < j + 2$  implies that  $DC_{ij} = CD_{ij} = 0$ .  $C \in [L, L]$  and  $D \in [L, L'] = L^2$ , this process can be repeated as long as  $j - i < k$ , that is  $k = n - 1$ . When  $k = n - 1$  we have a zero indicating that  $L$  is nilpotent at  $m = n - 1$

4.5 Let  $L = \mathfrak{b}(n, F)$  be the Lie algebra of upper triangular  $n \times n$  matrices over a field  $F$ .

(i) Show that  $L' = \mathfrak{n}(n, F)$ .

Let  $A, B \in \mathfrak{b}(n, F)$ . Looking only at the elements on the diagonal, we can see that,

$$\begin{aligned} (AB)_{ii} &= \sum_{k=1}^n A_{ik} B_{ki} = \sum_{k=1}^n B_{ik} A_{ki} = (BA)_{ii} \\ \therefore (AB)_{ii} - (BA)_{ii} &= 0 \implies [A, B] \in \mathfrak{n}(n, F) \end{aligned}$$

(ii) More generally, show that  $L^{(k)}$  has a basis consisting of all the matrix units  $e_{ij}$  with  $j - i \geq 2^{k-1}$ . (the commutator formula for the  $e_{ij}$  given in §1.2 will be helpful.)

(iii) Hence show that  $L$  is solvable. What is the smallest  $m$  such that  $L^{(m)} = 0$ ?

(iv) Show that if  $n \geq 2$  then  $L$  is not nilpotent.

4.6 Show that a Lie algebra is semisimple if and only if it has no non-zero abelian ideals. (this was the original definition of semisimplicity given Wilhelm Killing.)

4.7 Prove directly that  $\mathfrak{sl}(n, \mathbb{C})$  is a simple Lie algebra  $n \geq 2$ .

Let  $I$  be an ideal of the  $\mathfrak{sl}(n, \mathbb{C})$ . If  $\mathfrak{sl}(n, \mathbb{C})$  is not simple then there exists  $x \in \mathfrak{sl}(n, \mathbb{C})$  such  $x \notin I$ . Further,  $x$  will be a linear combination of basis vectors of  $e_i \in \mathfrak{sl}(n, \mathbb{C})$  that is

$$x = \sum_{i=1}^n a_i e_i$$

If a basis vector  $e_i \in I$  then all linear combinations of  $e_i$  are in  $I$ . Let  $f_i, i = 1, \dots, k$  be the basis vectors NOT in  $I$ . Thus, for all  $e_i \in I$ ,  $a_i = 0$ . If  $y = \sum_{i=1}^n b_i e_i$  then

$$\begin{aligned} [x, y] &= \left[ \sum_{i=1}^k a_i f_i, \sum_{j=1}^n b_j e_j \right] \\ &= \sum_{i=1}^k \sum_{j=1}^n a_i b_j [f_i, e_j] \end{aligned}$$

$$[f_i, e_j] \in I$$

$$[f_i, e_j] = f_i e_j - e_j f_i$$

$$\det([f_i, e_j]) = \det(f_i e_j - e_j f_i)$$

$$\det(f_i + e_j)(f_i - e_j) = \det(f_i^2 - f_i e_j + e_j f_i - e_j^2)$$

4.8 Let  $L$  be a Lie algebra over a field  $F$  such that  $[[a, b], b] = 0$  for all  $a, b \in L$ , (or equivalently,  $(\text{ad } b)^2 = 0$  for all  $b \in L$ ).

(i) Suppose the characteristic of  $F$  is not 3. Show that then  $L^3 = 0$ .

(ii) Suppose the characteristic of  $F$  is 3 then  $L^4 = 0$ . *Hint:* Show first that the Lie brackets  $[[x, y], z]$  are alternating; that is,

$$[[x, y], z] = -[[y, x], z], \quad [[x, y], z] = -[[x, z], y]$$

for all  $x, y, z \in L$ .

4.9 The purpose of this exercise is to give some idea why the families of Lie algebra are given the names that we have used. We shall not need to refer to this exercise later; some basic group theory is needed . . .

4.10 Let  $F$  be a field. Exercise 2.11 shows that if  $S, T \in \text{gl}(n, F)$  are congruent matrices (that is, there exists an invertible matrix  $P$  such that  $T = P^t S P$ ), then  $\text{gl}_S(n, F) \cong \text{gl}_T(n, F)$ . Does the converse hold when  $F = \mathbb{C}$ ? For a challenge, think about other fields.

# Chapter 5

## Subalgebras of $\mathfrak{gl}(V)$

### 5.1 Exercises

- 5.1 (i) Check that the eigenspaces  $V_\lambda$  defined above are vector subspaces of  $V$ .  
(ii) Using the notation above, define  $\varepsilon_i : A \rightarrow F$  by  $\varepsilon_i(a) = \alpha_i$ . Show that  $V_{\varepsilon_i} = \text{span}\{e_i\}$  and  $V$  decomposes as a direct sum of the  $V_{\varepsilon_i}$  for  $1 \leq i \leq n$ .
- 5.2 Let  $A = \mathfrak{b}(n, F)$  be the Lie subalgebra of  $\mathfrak{gl}(n, F)$  consisting of upper triangular matrices. Show that  $e_1$  is an eigenvector for  $A$ . Find the corresponding weight and determine its weight space.
- 5.3 Show that Lemma 5.4 really does generalise the result mentioned in the first paragraph of this section.
- 5.4 (i) Let  $L$  be a Lie subalgebra of  $\mathfrak{gl}(V)$ . Suppose that there is a basis of  $V$  such that, with respect to this basis, every  $x \in L$  is represented by a strictly upper triangular matrix. Show that  $L$  is isomorphic to a Lie subalgebra of  $\mathfrak{n}(n, F)$  and hence that  $L$  is nilpotent.  
(ii) Prove a result analogous to (i) in the case where there is a basis of  $V$  such that with respect to this basis every  $x$  in  $L$  is represented by an upper triangular matrix.
- 5.5 This exercise gives an alternative approach to Proposition 5.7. Recall that  $V$  is a complex vector space and  $x, y \in \mathfrak{gl}(V)$  are linear maps such that  $[x, y]$  commutes with both  $x$  and  $y$ .  
(i) Let  $z = [x, y]$ . Show that  $\text{tr } z^m = 0$  for all  $m \geq 1$ .  
(ii) Let  $\lambda_1, \dots, \lambda_n$  be the eigenvalues of  $[x, y]$ . Show that  $\lambda_i = 0$  for all  $i$ , and deduce that  $[x, y]$  is nilpotent. *Hint:* Use the Vandermonde determinant.
- 5.6 Let  $L$  be a Lie algebra and let  $A$  be a subalgebra of  $L$ . The *normaliser* of  $A$ , denoted  $N_L(A)$ , is defined by

$$N_L(A) = \{x \in L : [x, a] \in A \text{ for all } a \in A\}.$$

- (i) Prove that  $N_L(A)$  is a subalgebra of  $L$  and that  $N_L(A)$  contains  $A$ . Show moreover that  $N_L(A)$  is the largest subalgebra of  $L$  in which  $A$  is an ideal.
- (ii) Let  $L = \mathfrak{gl}(n, C)$  and let  $A$  be the subalgebra of  $L$  consisting of all diagonal matrices. Show that  $N_L(A) = A$ .
- 5.7 Show that if  $a, y \in \mathfrak{gl}(V)$  are linear maps, then for any  $m \geq 1$

$$ay^m = y^m a \sum_{k=1}^m \binom{m}{k} y^{m-k} a_k$$

where  $a_1 = [a, y]$ ,  $a_2 = [a_1, y] = [[a, y], y]$ , and generally  $a_k = [a_{k-1}, y]$ . Deduce that In this formula, the power  $y^{m-k}$  acts on  $\mathfrak{gl}(V)$  as the linear map which sends  $x \in \mathfrak{gl}(V)$  to  $y^{m-k}x$ .

$$\mathrm{ad} y^m = \sum_{k=1}^m (-1)^{k+1} \binom{m}{k} y^{m-k} (\mathrm{ad} y)^k$$

In this formula, the power  $y^{m-k}$  acts on  $\mathfrak{gl}(V)$  as the linear map which sends  $x \in \mathfrak{gl}(V)$  to  $y^{m-k}x$ .