

Solutions to Linear Algebra Done Right (4th Ed)  
- Sheldon Axler

Samy Lahlou

March 4, 2025

# Preface

The goal of this document is to share my personal solutions to the exercises in the Fourth Edition of Linear Algebra Done Right by Sheldon Axler during my reading. As a disclaimer, the solutions are not unique and there will probably be better or more optimized solutions than mine. Feel free to correct me or ask me anything about the content of this document at the following address : [samy.lahloukamel@mcgill.ca](mailto:samy.lahloukamel@mcgill.ca)

# Contents

<b>1</b>	<b>Vector Spaces</b>	<b>3</b>
1A	$\mathbf{R}^n$ and $\mathbf{C}^n$ . . . . .	3
1B	Definition of Vector Space . . . . .	10
1C	Subspaces . . . . .	16
<b>2</b>	<b>Finite-Dimensional Vector Spaces</b>	<b>32</b>
2A	Span and Linear Independence . . . . .	32
2B	Bases . . . . .	43
2C	Dimension . . . . .	53
<b>3</b>	<b>Linear Maps</b>	<b>69</b>
3A	Vector Space of Linear Maps . . . . .	69
3B	Null Spaces and Ranges . . . . .	70
3C	Matrices . . . . .	71
3D	Invertibility and Isomorphisms . . . . .	72
3E	Products and Quotients of Vector Spaces . . . . .	73
3F	Duality . . . . .	74

# Chapter 1

## Vector Spaces

### 1A $\mathbf{R}^n$ and $\mathbf{C}^n$

#### Exercise 1

Show that  $\alpha + \beta = \beta + \alpha$  for all  $\alpha, \beta \in \mathbf{C}$ .

#### Solution

First, suppose that

$$\alpha = a + ib \quad \text{and} \quad \beta = c + id$$

where  $a, b, c, d \in \mathbf{R}$ , then

$$\begin{aligned} \alpha + \beta &= (a + ib) + (c + id) \\ &= (a + c) + i(b + d) \\ &= (c + a) + i(d + b) \\ &= (c + id) + (a + ib) \\ &= \beta + \alpha \end{aligned}$$

which proves that addition is commutative in  $\mathbf{C}$  using the fact that it is commutative in  $\mathbf{R}$ .

#### Exercise 2

Show that  $(\alpha + \beta) + \lambda = \alpha + (\beta + \lambda)$  for all  $\alpha, \beta, \lambda \in \mathbf{C}$ .

#### Solution

First, suppose that

$$\alpha = a + ib, \quad \beta = c + id \quad \text{and} \quad \lambda = e + if$$

where  $a, b, c, d, e, f \in \mathbf{R}$ , then

$$\begin{aligned} (\alpha + \beta) + \lambda &= [(a + ib) + (c + id)] + (e + if) \\ &= [(a + c) + i(b + d)] + (e + if) \\ &= ([a + c] + e) + i([b + d] + f) \\ &= (a + [c + e]) + i(b + [d + f]) \\ &= (a + ib) + [(c + e) + i(d + f)] \\ &= (a + ib) + [(c + id) + (e + if)] \\ &= \alpha + (\beta + \lambda) \end{aligned}$$

which proves that addition is associative in  $\mathbf{C}$  using the fact that it is associative in  $\mathbf{R}$ .

### Exercise 3

Show that  $(\alpha\beta)\lambda = \alpha(\beta\lambda)$  for all  $\alpha, \beta, \lambda \in \mathbf{C}$ .

### Solution

First, suppose that

$$\alpha = a + ib, \quad \beta = c + id \quad \text{and} \quad \lambda = e + if$$

where  $a, b, c, d, e, f \in \mathbf{R}$ , then

$$\begin{aligned} (\alpha\beta)\lambda &= [(a + ib)(c + id)](e + if) \\ &= [(ac - bd) + i(ad + bc)](e + if) \\ &= ([ac - bd]e - [ad + bc]f) + i([ac - bd]f + [ad + bc]e) \\ &= (ace - bde - adf - bcf) + i(acf - bdf + ade + bce) \\ &= (a[ce - fd] - b[cf + de]) + i(a[cf + de] + b[ce - fd]) \\ &= (a + ib)[(ce - fd) + i(cf + de)] \\ &= (a + ib)[(c + id)(e + if)] \\ &= \alpha(\beta\lambda) \end{aligned}$$

which proves that multiplication is associative in  $\mathbf{C}$  using the fact that multiplication is associative and addition is commutative in  $\mathbf{R}$ .

### Exercise 4

Show that  $\lambda(\alpha + \beta) = \lambda\alpha + \lambda\beta$  for all  $\lambda, \alpha, \beta \in \mathbf{C}$ .

### Solution

First, suppose that

$$\alpha = a + ib, \quad \beta = c + id \quad \text{and} \quad \lambda = e + if$$

where  $a, b, c, d, e, f \in \mathbf{R}$ , then

$$\begin{aligned} \lambda(\alpha + \beta) &= (e + if)[(a + ib) + (c + id)] \\ &= (e + if)[(a + c) + i(b + d)] \\ &= [e(a + c) - f(b + d)] + i[e(b + d) + f(a + c)] \\ &= (ea + ec - fb - fd) + i(eb + ed + fa + fc) \\ &= [(ea - fb) + i(eb + fa)] + [(ec - fd) + i(ed + fc)] \\ &= [(e + if)(a + ib)] + [(e + if)(c + id)] \\ &= \lambda\alpha + \lambda\beta \end{aligned}$$

which proves the distributivity in  $\mathbf{C}$  using the distributivity in  $\mathbf{R}$ .

### Exercise 5

Show that for every  $\alpha \in \mathbf{C}$ , there exists a unique  $\beta \in \mathbf{C}$  such that  $\alpha + \beta = 0$ .

**Solution**

Let  $\alpha = a + ib$  and consider  $\beta = (-a) + i(-b)$ , then we get

$$\begin{aligned}\alpha + \beta &= (a + ib) + ([-a] + i[-b]) \\ &= (a + [-a]) + i(b + [-b]) \\ &= 0 + i0 \\ &= 0\end{aligned}$$

which proves the existence of such a complex number  $\beta$ . To prove the uniqueness of such a complex number, let  $\beta_1$  and  $\beta_2$  be two complex numbers satisfying  $\alpha + \beta_1 = 0$  and  $\alpha + \beta_2 = 0$ , this implies that  $\alpha + \beta_1 = \alpha + \beta_2$ . If we add  $\beta_1$  on both sides, we get

$$\begin{aligned}\beta_1 + (\alpha + \beta_1) &= \beta_1 + (\alpha + \beta_2) \implies (\beta_1 + \alpha) + \beta_1 = (\beta_1 + \alpha) + \beta_2 \\ &\implies (\alpha + \beta_1) + \beta_1 = (\alpha + \beta_1) + \beta_2 \\ &\implies 0 + \beta_1 = 0 + \beta_2 \\ &\implies \beta_1 = \beta_2\end{aligned}$$

which proves that such a complex number is unique.

**Exercise 6**

Show that for every  $\alpha \in \mathbf{C}$  with  $\alpha \neq 0$ , there exists a unique  $\beta \in \mathbf{C}$  such that  $\alpha\beta = 1$ .

**Solution**

Let  $\alpha = a + ib \neq 0$ , then notice that we must have  $a^2 + b^2 \neq 0$ . Hence, consider

$$\beta = \left( \frac{a}{a^2 + b^2} \right) + i \left( -\frac{b}{a^2 + b^2} \right)$$

Thus, we get

$$\begin{aligned}\alpha\beta &= (a + ib) \left[ \left( \frac{a}{a^2 + b^2} \right) + i \left( -\frac{b}{a^2 + b^2} \right) \right] \\ &= \left( a \left( \frac{a}{a^2 + b^2} \right) - b \left( -\frac{b}{a^2 + b^2} \right) \right) + i \left( a \left( -\frac{b}{a^2 + b^2} \right) + b \left( \frac{a}{a^2 + b^2} \right) \right) \\ &= \frac{a^2 + b^2}{a^2 + b^2} + i \frac{-ab + ba}{a^2 + b^2} \\ &= 1 + i0 \\ &= 1\end{aligned}$$

which proves the existence of such a complex number  $\beta$ . To prove the uniqueness of such a complex number, let  $\beta_1$  and  $\beta_2$  be two complex numbers satisfying  $\alpha\beta_1 = 1$  and  $\alpha\beta_2 = 1$ , this implies that  $\alpha\beta_1 = \alpha\beta_2$ . If we multiply by  $\beta_1$  on both sides, we get

$$\begin{aligned}\beta_1(\alpha\beta_1) &= \beta_1(\alpha\beta_2) \implies (\beta_1\alpha)\beta_1 = (\beta_1\alpha)\beta_2 \\ &\implies (\alpha\beta_1)\beta_1 = (\alpha\beta_1)\beta_2 \\ &\implies 1 \cdot \beta_1 = 1 \cdot \beta_2 \\ &\implies \beta_1 = \beta_2\end{aligned}$$

which proves that such a complex number is unique.

### Exercise 7

Show that

$$\frac{-1 + \sqrt{3}i}{2}$$

is a cube root of 1 (meaning that its cube equals 1).

### Solution

This is pretty straightforward:

$$\begin{aligned} \left( \frac{-1 + \sqrt{3}i}{2} \right)^3 &= \frac{(-1 + \sqrt{3}i)^3}{2^3} \\ &= \frac{(-1)^3 + 3(-1)^2(\sqrt{3}i) + 3(-1)^1(\sqrt{3}i)^2 + (\sqrt{3}i)^3}{8} \\ &= \frac{-1 + 3\sqrt{3}i + 3 \cdot 3 - 3(\sqrt{3}i)}{8} \\ &= \frac{8}{8} \\ &= 1 \end{aligned}$$

### Exercise 8

Find two distinct square roots of  $i$ .

### Solution

Consider  $\alpha = \frac{\sqrt{2}}{2} + i\frac{\sqrt{2}}{2}$  and  $\beta = -\frac{\sqrt{2}}{2} - i\frac{\sqrt{2}}{2}$ . Hence,

$$\begin{aligned} \alpha^2 &= \left( \frac{\sqrt{2}}{2} + i\frac{\sqrt{2}}{2} \right)^2 \\ &= \left( \frac{\sqrt{2}}{2} \right)^2 + 2 \cdot \frac{\sqrt{2}}{2} \cdot i\frac{\sqrt{2}}{2} + \left( i\frac{\sqrt{2}}{2} \right)^2 \\ &= \frac{2}{4} + i - \frac{2}{4} \\ &= i \end{aligned}$$

and

$$\begin{aligned} \beta^2 &= \left( -\frac{\sqrt{2}}{2} - i\frac{\sqrt{2}}{2} \right)^2 \\ &= \left( -\frac{\sqrt{2}}{2} \right)^2 + 2 \cdot \left( -\frac{\sqrt{2}}{2} \right) \cdot \left( -i\frac{\sqrt{2}}{2} \right) + \left( -i\frac{\sqrt{2}}{2} \right)^2 \\ &= \frac{2}{4} + i - \frac{2}{4} \\ &= i \end{aligned}$$

Therefore,  $\alpha$  and  $\beta$  are two distinct square roots of  $i$ .

### Exercise 9

Find  $x \in \mathbf{R}^4$  such that

$$(4, -3, 1, 7) + 2x = (5, 9, -6, 8).$$

### Solution

First, suppose that such an element  $x$  exists, then there exist  $a, b, c, d \in \mathbf{R}$  such that  $x = (a, b, c, d)$  and

$$(4 + 2a, -3 + 2b, 1 + 2c, 7 + 2d) = (5, 9, -6, 8)$$

But notice that this is equivalent to the following system of equations:

$$\begin{cases} 4 + 2a = 5 \\ -3 + 2b = 9 \\ 1 + 2c = -6 \\ 7 + 2d = 8 \end{cases}$$

which implies that

$$\begin{cases} a = \frac{1}{2} \\ b = 6 \\ c = \frac{7}{2} \\ d = \frac{1}{2} \end{cases}$$

Therefore, we get that  $x = (\frac{1}{2}, 6, \frac{7}{2}, \frac{1}{2}) \in \mathbf{R}^4$  is indeed a solution to our original equation.

### Exercise 10

Explain why there is does not exist  $\lambda \in \mathbf{C}$  such that

$$\lambda(2 - 3i, 5 + 4i, -6 + 7i) = (12 - 5i, 7 + 22i, -32 - 9i).$$

### Solution

By contradiction, suppose there exists a complex number  $\lambda = a + ib$  such that

$$\lambda(2 - 3i, 5 + 4i, -6 + 7i) = (12 - 5i, 7 + 22i, -32 - 9i)$$

Then, we would get the following system of equation:

$$\begin{cases} \lambda(2 - 3i) = 12 - 5i \\ \lambda(5 + 4i) = 7 + 22i \\ \lambda(-6 + 7i) = -32 - 9i \end{cases}$$

which is equivalent to

$$\begin{cases} \lambda = 3 + 2i \\ \lambda = 3 + 2i \\ \lambda = \frac{129}{85} + i\frac{278}{85} \end{cases}$$



We clearly have a contradiction since  $3 + 2i \neq \frac{129}{85} + i\frac{278}{85}$ . Therefore, there doesn't exist such a complex number  $\lambda$ .

### Exercise 11

Show that  $(x + y) + z = x + (y + z)$  for all  $x, y, z \in \mathbf{F}^n$ .

### Solution

First, write

$$x = (x_1, \dots, x_n), \quad y = (y_1, \dots, y_n) \quad \text{and} \quad z = (z_1, \dots, z_n)$$

Since addition is commutative in  $\mathbf{F}$ , we get

$$\begin{aligned} (x + y) + z &= [(x_1, \dots, x_n) + (y_1, \dots, y_n)] + (z_1, \dots, z_n) \\ &= (x_1 + y_1, \dots, x_n + y_n) + (z_1, \dots, z_n) \\ &= ([x_1 + y_1] + z_1, \dots, [x_n + y_n] + z_n) \\ &= (x_1 + [y_1 + z_1], \dots, x_n + [y_n + z_n]) \\ &= (x_1, \dots, x_n) + (y_1 + z_1, \dots, y_n + z_n) \\ &= (x_1, \dots, x_n) + [(y_1, \dots, y_n) + (z_1, \dots, z_n)] \\ &= x + (y + z) \end{aligned}$$

which proves that addition is associative in  $\mathbf{F}^n$ .

### Exercise 12

Show that  $(ab)x = a(bx)$  for all  $x \in \mathbf{F}^n$  and all  $a, b \in \mathbf{F}$ .

### Solution

First, write  $x = (x_1, \dots, x_n)$ . Using associativity of multiplication in  $\mathbf{F}$ , we get

$$\begin{aligned} (ab)x &= (ab)(x_1, \dots, x_n) \\ &= ((ab)x_1, \dots, (ab)x_n) \\ &= (a(bx_1), \dots, a(bx_n)) \\ &= a(bx_1, \dots, bx_n) \\ &= a[b(x_1, \dots, x_n)] \\ &= a(bx) \end{aligned}$$

which proves the desired formula for all  $x \in \mathbf{F}^n$  and all  $a, b \in \mathbf{F}$ .

### Exercise 13

Show that  $1x = x$  for all  $x \in \mathbf{F}^n$ .

### Solution

Let  $x = (x_1, \dots, x_n) \in \mathbf{F}^n$ . Hence,

$$\begin{aligned} 1x &= 1(x_1, \dots, x_n) \\ &= (1 \cdot x_1, \dots, 1 \cdot x_n) \\ &= (x_1, \dots, x_n) \\ &= x \end{aligned}$$

which proves the desired formula for all  $x \in \mathbf{F}^n$ .

#### Exercise 14

Show that  $\lambda(x + y) = \lambda x + \lambda y$  for all  $\lambda \in \mathbf{F}$  and  $x, y \in \mathbf{F}^n$ .

#### Solution

Let  $\lambda \in \mathbf{F}$  and  $x, y \in \mathbf{F}^n$  with  $x = (x_1, \dots, x_n)$  and  $y = (y_1, \dots, y_n)$ . Using distributivity in  $\mathbf{F}$ , we get

$$\begin{aligned} \lambda(x + y) &= \lambda[(x_1, \dots, x_n) + (y_1, \dots, y_n)] \\ &= \lambda(x_1 + y_1, \dots, x_n + y_n) \\ &= (\lambda(x_1 + y_1), \dots, \lambda(x_n + y_n)) \\ &= (\lambda x_1 + \lambda y_1, \dots, \lambda x_n + \lambda y_n) \\ &= (\lambda x_1, \dots, \lambda x_n) + (\lambda y_1, \dots, \lambda y_n) \\ &= \lambda(x_1, \dots, x_n) + \lambda(y_1, \dots, y_n) \\ &= \lambda x + \lambda y \end{aligned}$$

which proves the desired formula.

#### Exercise 15

Show that  $(a + b)x = ax + bx$  for all  $a, b \in \mathbf{F}$  and all  $x \in \mathbf{F}^n$ .

#### Solution

Let  $a, b \in \mathbf{F}$  and  $x = (x_1, \dots, x_n) \in \mathbf{F}^n$ . Using distributivity in  $\mathbf{F}$ , we get

$$\begin{aligned} (a + b)x &= (a + b)(x_1, \dots, x_n) &= ((a + b)x_1, \dots, (a + b)x_n) \\ &= (ax_1 + bx_1, \dots, ax_n + bx_n) \\ &= (ax_1, \dots, ax_n) + (bx_1, \dots, bx_n) \\ &= a(x_1, \dots, x_n) + b(x_1, \dots, x_n) \\ &= ax + bx \end{aligned}$$

which proves the desired formula.

## 1B Definition of Vector Space

### Exercise 1

Prove that  $-(-v) = v$  for every  $v \in V$ .

### Solution

Let  $v \in V$ , by definition, we know that by definition,  $-v$  is defined as the only vector in  $V$  satisfying

$$v + (-v) = 0$$

which is equivalent to

$$(-v) + v = 0$$

by commutativity of addition in  $V$ . However, notice that by definition,  $-(-v)$  is the unique vector satisfying

$$(-v) + [-(-v)] = 0$$

But since  $v$  itself also satisfies this equation, we get  $-(-v) = v$  by uniqueness.

### Exercise 2

Suppose  $a \in \mathbf{F}$ ,  $v \in V$ , and  $av = 0$ . Prove that  $a = 0$  or  $v = 0$ .

### Solution

Suppose that  $a \neq 0$ , then by properties of  $\mathbf{F}$ , the inverse  $a^{-1}$  exists. Hence, if we multiply by  $a^{-1}$  on both sides, we get

$$\begin{aligned} av = 0 &\implies a^{-1}(av) = a^{-1}0 \\ &\implies (a^{-1}a)v = 0 \\ &\implies 1v = 0 \\ &\implies v = 0 \end{aligned}$$

Therefore, we either have  $a = 0$  or  $v = 0$ .

### Exercise 3

Suppose  $v, w \in V$ . Explain why there exists a unique  $x \in V$  such that  $v + 3x = w$ .

### Solution

By properties of vector spaces, since  $v \in V$ , then  $-v \in V$ . Similarly, since  $w$  and  $-v$  are in  $V$ , then  $w + (-v) \in V$ . Finally, since  $w + (-v) \in V$ , then  $3^{-1}(w + (-v)) \in V$ . Thus, define  $x_0$  as the vector  $3^{-1}(w + (-v))$  in  $V$ . Notice that

$$\begin{aligned} v + 3x_0 &= v + 3[3^{-1}(w + (-v))] \\ &= v + (3 \cdot 3^{-1})(w + (-v)) \\ &= v + 1(w + (-v)) \\ &= v + (w + (-v)) \\ &= v + ((-v) + w) \\ &= (v + (-v)) + w \\ &= 0 + w \\ &= w \end{aligned}$$

which shows that the equation has at least one solution. To prove uniqueness, let  $x_1 \in V$  be an arbitrary solution to the equation, then we get

$$\begin{aligned}
 v + 3x_1 = w &\implies (-v) + (v + 3x_1) = (-v) + w \\
 &\implies ((-v) + v) + 3x_1 = w + (-v) \\
 &\implies 0 + 3x_1 = w + (-v) \\
 &\implies 3x_1 = w + (-v) \\
 &\implies 3^{-1}(3x_1) = 3^{-1}(w + (-v)) \\
 &\implies (3^{-1}3)x_1 = x_0 \\
 &\implies 1x_1 = x_0 \\
 &\implies x_1 = x_0
 \end{aligned}$$

which proves that  $x_0$  is the unique solution to the equation.

#### Exercise 4

The empty set is not a vector space. The empty set fails to satisfy only one of the requirements listed in the definition of a vector space. Which one?

#### Solution

The empty set doesn't satisfy the axiom that states that there must be an additive identity since the empty set is empty by definition.

#### Exercise 5

Show that in the definition of a vector space, the additive inverse condition can be replaced with the condition that

$$0v = 0 \text{ for all } v \in V.$$

Here, the 0 on the left side is the number 0, and the 0 on the right side is the additive identity of  $V$ .

#### Solution

We already know that the axioms of a vector space imply that  $0v = 0$  for all  $v \in V$ . Hence, it suffices to prove that if we assume the axioms of a vector space without the additive inverse condition, then we can prove the additive inverse condition if we also assume the property that  $0v = 0$  for all  $v \in V$ . Let  $v \in V$ , then by the distributive condition, we get

$$\begin{aligned}
 0v = 0 &\implies (1 + (-1))v = 0 \\
 &\implies 1v + (-1)v = 0 \\
 &\implies v + (-1)v = 0
 \end{aligned}$$

which proves that  $v$  has an additive inverse for all  $v \in V$ .

#### Exercise 6

Let  $\infty$  and  $-\infty$  denote two distinct objects, neither of which is in  $\mathbf{R}$ . Define an addition and scalar multiplication on  $\mathbf{R} \cup \{\infty, -\infty\}$  as you could guess from the

notation. Specifically, the sum and product of two real numbers is as usual, and for  $t \in \mathbf{R}$  define

$$t\infty = \begin{cases} -\infty & \text{if } t < 0, \\ 0 & \text{if } t = 0, \\ \infty & \text{if } t > 0, \end{cases} \quad t(-\infty) = \begin{cases} \infty & \text{if } t < 0, \\ 0 & \text{if } t = 0, \\ -\infty & \text{if } t > 0, \end{cases}$$

and

$$\begin{aligned} t + \infty &= \infty + t = \infty + \infty = \infty \\ t + (-\infty) &= (-\infty) + t = (-\infty) + (-\infty) = -\infty \\ \infty + (-\infty) &= (-\infty) + \infty = 0 \end{aligned}$$

With these operations of addition and scalar multiplication, is  $\mathbf{R} \cup \{\infty, -\infty\}$  a vector space over  $\mathbf{R}$ ? Explain.

### Solution

With these operations of addition and scalar multiplication,  $\mathbf{R} \cup \{\infty, -\infty\}$  cannot be a vector space since

$$((-\infty) + \infty) + \infty = 0 + \infty = \infty$$

and

$$(-\infty) + (\infty + \infty) = (-\infty) + \infty = 0$$

which proves that addition isn't associative under this operation.

### Exercise 7

Suppose  $S$  is a nonempty set. Let  $V^S$  denote the set of functions from  $S$  to  $V$ . Define a natural addition and scalar multiplication on  $V^S$ , and show that  $V^S$  is a vector space with these definitions.

### Solution

For any  $f$  and  $g$  in  $V^S$ , define  $f + g : S \rightarrow V$  by  $s \mapsto f(s) + g(s)$  for all  $s \in S$ . Similarly, for all  $\alpha \in \mathbf{F}$  and  $f \in V^S$ , define  $\alpha f : S \rightarrow V$  by  $s \mapsto \alpha f(s)$  for all  $s \in S$ . With these definitions, let's prove that  $V^S$  is a vector space.

- **(commutativity)** Let  $f, g \in V^S$ , let's show that  $f + g = g + f$ . Let  $s \in S$ , then by commutativity in  $V$ , we obviously have

$$(f + g)(s) = f(s) + g(s) = g(s) + f(s) = (g + f)(s)$$

Since it holds for all  $s$ , then  $f + g = g + f$ .

- **(associativity)** Let  $f, g, h \in V^S$  and  $s \in S$ , then by associativity in  $V$ , we have

$$\begin{aligned} [(f + g) + h](s) &= (f + g)(s) + h(s) \\ &= [f(s) + g(s)] + h(s) \\ &= f(s) + [g(s) + h(s)] \\ &= f(s) + (g + h)(s) \\ &= [f + (g + h)](s) \end{aligned}$$

Since it holds for all  $s \in S$ , then  $(f + g) + h = f + (g + h)$ .

Let now  $f \in V^S$ ,  $a, b \in \mathbf{F}$  and  $s \in S$ , then by associativity in  $V$ , we get:

$$\begin{aligned} [(ab)f](s) &= (ab)f(s) \\ &= a(bf(s)) \\ &= a(bf)(s) \\ &= [a(bf)](s) \end{aligned}$$

Since it holds for all  $s \in S$ , then  $(ab)f = a(bf)$ .

- **(additive identity)** Let's denote by  $0_{V^S}$  the zero function in  $V^S$ , then for all  $f \in V^S$  and  $s \in S$ , we have

$$(f + 0_{V^S})(s) = f(s) + 0_{V^S}(s) = f(s) + 0 = f(s)$$

Since it holds for all  $s \in S$ , then  $f + 0_{V^S} = f$  for all  $f \in V^S$ .

- **(additive inverse)** Again, let's denote by  $0_{V^S}$  the zero function in  $V^S$ , then for all  $f \in V^S$ , we can define the function  $g = (-1)f \in V^S$ . Hence, for all  $s \in S$ , we get

$$\begin{aligned} (f + g)(s) &= f(s) + g(s) \\ &= f(s) + (-1)f(s) \\ &= f(s) + (-f(s)) \\ &= 0 \\ &= 0_{V^S}(s) \end{aligned}$$

Since it holds for all  $s \in S$ , then  $f + g = 0_{V^S}$ .

- **(multiplicative identity)** Let  $f \in V^S$ , then for all  $s \in S$ , we have

$$(1f)(s) = 1f(s) = f(s)$$

Since it holds for all  $s \in S$ , then  $1f = f$ .

- **(distributive property)** Let  $f, g \in V^S$ ,  $a \in \mathbf{F}$  and  $s \in S$ , then

$$\begin{aligned} [a(f + g)](s) &= a(f + g)(s) \\ &= a(f(s) + g(s)) \\ &= af(s) + ag(s) \\ &= (af)(s) + (ag)(s) \\ &= (af + ag)(s) \end{aligned}$$

Since it holds for all  $s \in S$ , then  $a(f + g) = af + ag$ . Similarly, for all  $f \in V^S$ ,  $a, b \in \mathbf{F}$  and  $s \in S$ , we have

$$\begin{aligned} [(a + b)f](s) &= (a + b)f(s) \\ &= af(s) + bf(s) \\ &= (af)(s) + (bf)(s) \\ &= (af + bf)(s) \end{aligned}$$

Since it holds for all  $s \in S$ , then  $(a + b)f = af + bf$ .

Therefore,  $V^S$  is a vector space under these definitions.

### Exercise 8

Suppose  $V$  is a real vector space.

- The *complexification* of  $V$ , denoted by  $V_{\mathbf{C}}$ , equals  $V \times V$ . An element of  $V_{\mathbf{C}}$  is an ordered pair  $(u, v)$ , where  $u, v \in V$ , but we write this as  $u + iv$ .
- Addition on  $V_{\mathbf{C}}$  is defined by

$$(u_1 + iv_1) + (u_2 + iv_2) = (u_1 + u_2) + i(v_1 + v_2)$$

for all  $u_1, v_1, u_2, v_2 \in V$ .

- Complex scalar multiplication on  $V_{\mathbf{C}}$  is defined by

$$(a + ib)(u + iv) = (au - bv) + i(av + bu)$$

for all  $a, b \in \mathbf{R}$  and all  $u, v \in V$ .

Prove that with these definitions of addition and scalar multiplication as above,  $V_{\mathbf{C}}$  is a complex vector space.

### Solution

- **(commutativity)** Let  $u_1, v_1, u_2, v_2 \in V$ , then by commutativity in  $V$ , we have

$$\begin{aligned} (u_1 + iv_1) + (u_2 + iv_2) &= (u_1 + u_2) + i(v_1 + v_2) \\ &= (u_2 + u_1) + i(v_2 + v_1) \\ &= (u_2 + iv_2) + (u_1 + iv_1) \end{aligned}$$

which proves that addition is commutative.

- **(associativity)** Let  $u_1, v_1, u_2, v_2, u_3, v_3 \in V$ , then by associativity in  $V$ , we have

$$\begin{aligned} [(u_1 + iv_1) + (u_2 + iv_2)] + (u_3 + iv_3) &= [(u_1 + u_2) + i(v_1 + v_2)] + (u_3 + iv_3) \\ &= ([u_1 + u_2] + u_3) + i([v_1 + v_2] + v_3) \\ &= (u_1 + [u_2 + u_3]) + i(v_1 + [v_2 + v_3]) \\ &= (u_1 + iv_1) + [(u_2 + u_3) + i(v_2 + v_3)] \\ &= (u_1 + iv_1) + [(u_2 + iv_2) + (u_3 + iv_3)] \end{aligned}$$

Let now  $a, b, c, d \in \mathbf{R}$  and  $u, v \in V$ , then we get:

$$\begin{aligned} [(a + bi)(c + di)](u + iv) &= [(ac - bd) + i(ad + bc)](u + iv) \\ &= [(ac - bd)u - (ad + bc)v] + i[(ac - bd)v + (ad + bc)u] \\ &= [acu - bdu - adv - bcv] + i[acv - bdv + adu + bcu] \\ &= [a(cu - dv) - b(cv + du)] + i[a(cv + du) + b(cu - dv)] \\ &= (a + ib)[(cu - dv) + i(cv + du)] \\ &= (a + ib)[(c + id)(u + iv)] \end{aligned}$$

which proves the associativity condition.

- **(additive identity)** For all  $u, v \in V$ ,

$$(u + iv) + (0 + i0) = (u + 0) + i(v + 0) = u + iv$$

which proves that  $0 + i0$  is an additive identity.

- **(additive inverse)** Let  $u, v \in V$ , then since  $(-u), (-v) \in V$ , we get

$$(u + iv) + ([-u] + i[-v]) = (u + [-u]) + i(v + [-v]) = 0 + i0$$

which proves that every element has an additive inverse.

- **(multiplicative identity)** Let  $u, v \in V$ , then

$$(1 + i0)(u + iv) = (1u - 0v) + i(1v + 0u) = u + iv$$

which proves that  $1 = 1 + i0$  is a multiplicative identity.

- **(distributive property)** Let  $a, b \in \mathbf{R}$  and  $u_1, v_1, u_2, v_2 \in V$ , then

$$\begin{aligned} (a + ib)[(u_1 + iv_1) + (u_2 + iv_2)] &= (a + ib)([u_1 + u_2] + i[v_1 + v_2]) \\ &= (a[u_1 + u_2] - b[v_1 + v_2]) + i(a[v_1 + v_2] + b[u_1 + u_2]) \\ &= (au_1 + au_2 - bv_1 - bv_2) + i(av_1 + av_2 + bu_1 + bu_2) \\ &= ([au_1 - bv_1] + [au_2 - bv_2]) + i([av_1 + bu_1] + [av_2 + bu_2]) \\ &= [(au_1 - bv_1) + i(av_1 + bu_1)] + [(au_2 - bv_2) + i(av_2 + bu_2)] \\ &= [(a + ib)(u_1 + iv_1)] + [(a + ib)(u_2 + iv_2)] \end{aligned}$$

Similarly, for all  $a, b, c, d \in \mathbf{R}$ , and  $u, v \in \mathbf{R}$ , we have

$$\begin{aligned} [(a + ib) + (c + id)](u + iv) &= ([a + c] + i[b + d])(u + iv) \\ &= ([a + c]u - [b + d]v) + i([a + c]v + [b + d]u) \\ &= (au + cu - bv - dv) + i(av + cv + bu + du) \\ &= ([au - bv] + [cu - dv]) + i([av + bu] + [cv + du]) \\ &= [(au - bv) + i(av + bu)] + [(cu - dv) + i(cv + du)] \\ &= (a + ib)(u + iv) + (c + id)(u + iv) \end{aligned}$$

which proves the distributive property.

Therefore,  $V_{\mathbf{C}}$  is a vector space under these definitions.



## 1C Subspaces

### Exercise 1

For each of the following subsets of  $\mathbf{F}^3$ , determine whether it is a subspace of  $\mathbf{F}^3$ .

- (a)  $\{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1 + 2x_2 + 3x_3 = 0\}$
- (b)  $\{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1 + 2x_2 + 3x_3 = 4\}$
- (c)  $\{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1x_2x_3 = 0\}$
- (d)  $\{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1 = 5x_3\}$

### Solution

- (a) First, define

$$U = \{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1 + 2x_2 + 3x_3 = 0\}$$

Let's prove that it is indeed a subspace of  $\mathbf{F}^3$ . Since  $0 + 2 \cdot 0 + 3 \cdot 0 = 0$ , then  $0 = (0, 0, 0) \in U$ . Now, let  $x, y \in U$  be two arbitrary elements where  $x = (x_1, x_2, x_3)$  and  $y = (y_1, y_2, y_3)$ , then by definition:

$$\begin{cases} x_1 + 2x_2 + 3x_3 &= 0 \\ y_1 + 2y_2 + 3y_3 &= 0 \end{cases}$$

Adding the two equations gives us

$$(x_1 + y_1) + 2(x_2 + y_2) + 3(x_3 + y_3) = 0 + 0 = 0$$

which proves that  $x + y = (x_1 + y_1, x_2 + y_2, x_3 + y_3) \in U$ . Similarly, let  $x = (x_1, x_2, x_3)$  be an arbitrary element in  $U$  and  $\alpha$  an arbitrary scalar in  $\mathbf{F}$ , then by definition of  $U$ :

$$x_1 + 2x_2 + 3x_3 = 0$$

Multiplying by  $\alpha$  on both sides gives us

$$(\alpha x_1) + 2(\alpha x_2) + 3(\alpha x_3) = \alpha \cdot 0 = 0$$

which proves that  $\alpha x \in U$ . Therefore,  $U$  is a subspace of  $\mathbf{F}^3$ .

- (b) Since  $0 = (0, 0, 0)$  doesn't satisfy  $x_1 + 2x_2 + 3x_3 = 4$ , then the set of such vectors cannot be a subspace since it doesn't contain the zero vector.
- (c) Let  $U = \{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1x_2x_3 = 0\}$  and notice that that both  $x = (1, 1, 0)$  and  $y = (0, 0, 1)$  are in  $U$ . However,  $x + y$  is obviously not in  $U$  since  $x + y = (1, 1, 1)$  and  $1 \cdot 1 \cdot 1 = 1$ . Therefore,  $U$  is not a subspace of  $\mathbf{F}^3$ .
- (d) Define  $U = \{(x_1, x_2, x_3) \in \mathbf{F}^3 : x_1 = 5x_3\}$  and let's show that it is a subspace of  $\mathbf{F}^3$ . First, since  $0 = 5 \cdot 0$ , then  $0 = (0, 0, 0) \in U$ . To prove that  $U$  is closed under addition, let  $x = (x_1, x_2, x_3)$  and  $y = (y_1, y_2, y_3)$  be two arbitrary elements of  $U$ , then by definition:

$$\begin{cases} x_1 = 5x_3 \\ y_1 = 5y_3 \end{cases}$$

By adding the two equations together, we get

$$x_1 + y_1 = 5(x_3 + y_3)$$

Thus,  $x + y = (x_1 + y_1, x_2 + y_2, x_3 + y_3) \in U$ . Finally, to prove that  $U$  is closed under scalar multiplication, let  $x = (x_1, x_2, x_3)$  be an element of  $U$  and  $\alpha \in \mathbf{F}$ , then

$$\begin{aligned} x_1 = 5x_3 &\implies \alpha x_1 = \alpha(5x_3) \\ &\implies \alpha x_1 = 5(\alpha x_3) \end{aligned}$$

Thus,  $\alpha x = (\alpha x_1, \alpha x_2, \alpha x_3) \in U$ . Therefore,  $U$  is a subspace of  $\mathbf{F}^3$ .

### Exercise 2

Verify all assertions about subspaces in Example 1.35:

- (a) If  $b \in \mathbf{F}$ , then

$$\{(x_1, x_2, x_3, x_4) \in \mathbf{F}^4 : x_3 = 5x_4 + b\}$$

is a subspace of  $\mathbf{F}^4$  if and only if  $b = 0$ .

- (b) The set of continuous real-valued functions on the interval  $[0,1]$  is a subspace of  $\mathbf{R}^{[0,1]}$ .
- (c) The set of differentiable real-valued functions on  $\mathbf{R}$  is a subspace of  $\mathbf{R}^{\mathbf{R}}$ .
- (d) The set of differentiable real-valued functions  $f$  on the interval  $(0,3)$  such that  $f'(2) = b$  is a subspace of  $\mathbf{R}^{(0,3)}$  if and only if  $b = 0$ .
- (e) The set of all sequences of complex numbers with limit 0 is a subspace of  $\mathbf{C}^\infty$ .

### Solution

- (a) Define  $U_b = \{(x_1, x_2, x_3, x_4) \in \mathbf{F}^4 : x_3 = 5x_4 + b\}$  for all  $b \in \mathbf{F}$  and suppose first that  $U$  is a subspace of  $\mathbf{F}^4$ , then it must contain the zero vector. Hence, since  $(0, 0, 0, 0) \in U$ , then by definition:

$$0 = 5 \cdot 0 + b$$

which is equivalent to  $b = 0$ .

For the converse, let's show that  $U_0$  is a subspace of  $\mathbf{F}^4$ . Since  $0 = 5 \cdot 0$ , then  $0 = (0, 0, 0, 0) \in U_0$ . If  $x = (x_1, x_2, x_3, x_4)$  and  $y = (y_1, y_2, y_3, y_4)$  are arbitrary elements of  $U_0$ , then  $x_3 = 5x_4$  and  $y_3 = 5y_4$ . By adding these two equations and by distributivity, we get

$$x_3 + y_3 = 5(x_4 + y_4)$$

which implies that  $x + y \in U_0$ . Similarly, if  $x = (x_1, x_2, x_3, x_4) \in U_0$  and  $\alpha \in \mathbf{F}$ , then we get

$$x_3 = 5x_4 \implies \alpha x_3 = 5(\alpha x_4)$$

which implies that  $\alpha x \in U_0$ . Thus,  $U_0$  is a subspace of  $\mathbf{F}^4$ . Therefore,  $U_b$  is a subspace of  $\mathbf{F}^4$  if and only if  $b = 0$ .

- (b) Let  $C$  denote the set of real-valued continuous functions on the interval  $[0,1]$  and  $0_{\mathbf{R}^{[0,1]}}$  the zero function which acts as the additive identity in  $\mathbf{R}^{[0,1]}$ . Since the constant zero function is continuous, then  $0_{\mathbf{R}^{[0,1]}} \in C$ . Similarly, since the sum of two continuous functions is continuous and the multiplication of a continuous function with a scalar is still continuous, then  $C$  is closed under addition and scalar multiplication. Therefore,  $C$  is a subspace of  $\mathbf{R}^{[0,1]}$ .
- (c) The proof is similar to part (b). The constant zero function is differentiable on  $\mathbf{R}$ . Moreover, differentiable functions are closed under addition and scalar multiplication. Therefore, the set of differentiable real-valued functions on  $\mathbf{R}$  is a subspace of  $\mathbf{R}^{\mathbf{R}}$ .
- (d) Define  $U_b = \{f : (0,3) \rightarrow \mathbf{R} \text{ differentiable} : f'(2) = b\}$  for all  $b \in \mathbf{R}$ . Suppose that  $U_b$  is a subspace of  $\mathbf{R}^{(0,3)}$ , then we must have  $0_{(0,3)} \in U_b$  where  $0_{(0,3)}$  denotes the constant zero function on  $(0,3)$ . By definition of  $U_b$ , it implies that  $0'_{(0,3)}(2) = b$ . However, we know that  $0'_{(0,3)}(2) = 0$ . Thus,  $b = 0$ .  
Conversely, let's show that  $U_0$  is a subspace of  $\mathbf{R}^{(0,3)}$ . First, the constant zero function  $0_{\mathbf{R}^{(0,3)}}$  on  $(0,3)$  which acts as the additive identity in  $\mathbf{R}^{(0,3)}$ , is differentiable on  $(0,3)$  and its derivative at 2 is 0. Hence,  $0_{\mathbf{R}^{(0,3)}} \in U_0$ . Now, let  $f, g \in U_0$ , then  $f + g$  is differentiable on  $(0,3)$  and

$$(f + g)'(2) = f'(2) + g'(2) = 0 + 0 = 0$$

so  $f + g \in U_0$ . Similarly, for any  $f \in U_0$  and  $\alpha \in \mathbf{F}$ , the function  $\alpha f$  is still differentiable on  $(0,3)$  and

$$(\alpha f)'(2) = \alpha f'(2) = \alpha \cdot 0 = 0$$

so  $\alpha f \in U_0$ . Thus,  $U_0$  is a subspace of  $\mathbf{R}^{(0,3)}$ . Therefore,  $U_b$  is a subspace if and only if  $b = 0$ .

- (e) Let  $S$  be the set of sequences of complex numbers with limit 0. Since the additive identity  $(0, 0, \dots)$  of  $C^\infty$  converges to 0, then it is in  $S$ . Let  $(a_n)_n, (b_n)_n \in S$ , then

$$\lim_{n \rightarrow \infty} a_n = 0 \quad \text{and} \quad \lim_{n \rightarrow \infty} b_n = 0$$

which implies

$$\lim_{n \rightarrow \infty} (a_n + b_n) = \lim_{n \rightarrow \infty} a_n + \lim_{n \rightarrow \infty} b_n = 0 + 0 = 0$$

Thus,  $(a_n)_n + (b_n)_n \in S$ . Similarly, for all  $(a_n)_n \in S$  and  $\alpha \in \mathbf{C}$ , we have

$$\lim_{n \rightarrow \infty} \alpha a_n = \alpha \lim_{n \rightarrow \infty} a_n = \alpha \cdot 0 = 0$$

so  $\alpha(a_n)_n \in S$ . Therefore,  $S$  is a subspace of  $\mathbf{C}^\infty$ .

### Exercise 3

Show that the set of differentiable real-valued functions  $f$  on the interval  $(-4, 4)$  such that  $f'(-1) = 3f(2)$  is a subspace of  $\mathbf{R}^{(-4,4)}$ .

**Solution**

Define the set  $U = \{f : (-4, 4) \rightarrow \mathbf{R} \text{ differentiable} : f'(-1) = 3f(2)\}$  and let's show that it is a subspace of  $\mathbf{R}^{(-4,4)}$ . First, denote by  $f_0$  to constant zero function on  $(-4, 4)$  which is also the additive identity in  $\mathbf{R}^{(-4,4)}$ . We know that  $f_0$  is differentiable on  $(-4, 4)$  with  $f'_0 = f_0$ . Hence,  $f'_0(-1) = 0 = 3f_0(2)$  which proves that  $f_0 \in U$ . To show that it is closed under addition, let  $f, g \in U$ , then by definition,  $f$  and  $g$  are differentiable on  $(-4, 4)$  and

$$\begin{cases} f'(-1) = 3f(2) \\ g'(-1) = 3g(2) \end{cases}$$

If we add these two equations, we get

$$(f + g)'(-1) = 3(f + g)(2)$$

which proves that  $f + g \in U$  since  $f + g$  is differentiable on  $(-4, 4)$ .

To prove that it is closed under scalar multiplication, let  $f \in U$  and  $\alpha \in \mathbf{R}$ , then

$$\begin{aligned} f'(-1) = 3f(2) &\implies \alpha f'(-1) = \alpha \cdot 3f(2) \\ &\implies (\alpha f)'(-1) = 3(\alpha f)(2) \end{aligned}$$

which proves that  $\alpha f \in U$  since  $\alpha f$  is differentiable on  $(-4, 4)$ . Therefore,  $U$  is a subspace of  $\mathbf{R}^{(-4,4)}$ .

**Exercise 4**

Suppose  $b \in \mathbf{R}$ . Show that the set of continuous real-valued functions  $f$  on the interval  $[0, 1]$  such that  $\int_0^1 f = b$  is a subspace of  $\mathbf{R}^{[0,1]}$  if and only if  $b = 0$ .

**Solution**

Let  $b \in \mathbf{R}$  and define  $I = \{f : [0, 1] \rightarrow \mathbf{R} \text{ continuous} : \int_0^1 f = b\}$ . Suppose that  $I$  is a subspace of  $\mathbf{R}^{[0,1]}$ , then the additive identity  $0 : x \mapsto 0$  must be in  $I$  so  $\int_0^1 0 = b$ . But we know that  $\int_0^1 0 = 0$  so it follows that  $b = 0$ .

Conversely, let's show that  $I$  is a subspace of  $\mathbf{R}^{[0,1]}$  when  $b = 0$ . First, the additive identity  $0$  is obviously continuous with  $\int_0^1 0 = 0$  so  $0 \in I$ . Now, let  $f, g \in I$ , then  $f$  and  $g$  are continuous and

$$\int_0^1 f = \int_0^1 g = 0$$

It follows that  $f + g$  is a continuous function that satisfies

$$\int_0^1 (f + g) = \int_0^1 f + \int_0^1 g = 0$$

Hence,  $f + g \in I$ . Similarly, if  $f \in I$  and  $\alpha \in \mathbf{R}$ , then  $f$  is continuous and

$$\int_0^1 f = 0$$

which implies that  $\alpha f$  is also continuous and

$$\int_0^1 (\alpha f) = \alpha \int_0^1 f = \alpha \cdot 0 = 0$$

Hence,  $\alpha f \in I$ . Therefore,  $I$  is a subspace of  $\mathbf{R}^{[0,1]}$ .

### Exercise 5

Is  $\mathbf{R}^2$  a subspace of the complex vector space  $\mathbf{C}^2$ ?

### Solution

No, it isn't because it is not closed under scalar multiplication since the scalars are complex numbers. For example,  $(1, 1) \in \mathbf{R}^2$  but  $i(1, 1) = (i, i) \notin \mathbf{R}^2$ . Therefore,  $\mathbf{R}^2$  is not a subspace of the complex vector space  $\mathbf{C}^2$ .

### Exercise 6

(a) Is  $\{(a, b, c) \in \mathbf{R}^3 : a^3 = c^3\}$  a subspace of  $\mathbf{R}^3$ ?

(b) Is  $\{(a, b, c) \in \mathbf{C}^3 : a^3 = c^3\}$  a subspace of  $\mathbf{C}^3$ ?

### Solution

(a) In  $\mathbf{R}$ , the function  $x \mapsto x^3$  is bijective so if we define  $I = \{(a, b, c) \in \mathbf{R}^3 : a^3 = c^3\}$ , then we actually have  $I = \{(a, b, c) \in \mathbf{R}^3 : a = c\}$ . Hence, it is easier now to show that  $I$  is a subspace of  $\mathbf{R}^3$ . Obviously,  $(0, 0, 0) \in I$  since  $0 = 0$ . Moreover, if  $(x_1, x_2, x_3)$  and  $(y_1, y_2, y_3)$  are in  $I$ , then  $x_1 = x_3$  and  $y_1 = y_3$  which implies that  $x_1 + y_1 = x_3 + y_3$ . Hence,  $(x_1 + y_1, x_2 + y_2, x_3 + y_3)$  is in  $I$ . Similarly, for  $(x_1, x_2, x_3) \in I$  and  $\alpha \in \mathbf{R}$ , we must have  $x_1 = x_3$  which implies that  $\alpha x_1 = \alpha x_3$ . Thus,  $(\alpha x_1, \alpha x_2, \alpha x_3) \in I$ . Therefore,  $I$  is a subspace of  $\mathbf{R}^3$ .

(b) If we let  $I = \{(a, b, c) \in \mathbf{R}^3 : a^3 = c^3\}$ , notice that  $(\frac{-1+\sqrt{3}i}{2}, 0, 1)$  and  $(\frac{-1-\sqrt{3}i}{2}, 0, 1)$  are both elements of  $I$ . However, their sum is not in  $I$  since

$$\left(\frac{-1+\sqrt{3}i}{2}, 0, 1\right) + \left(\frac{-1-\sqrt{3}i}{2}, 0, 1\right) = (-1, 0, 2) \notin I$$

Therefore, it is not a subspace of  $\mathbf{C}^3$  since it is not closed under addition.

### Exercise 7

Prove or give a counterexample: If  $U$  is a nonempty subset of  $\mathbf{R}^2$  such that  $U$  is closed under addition and under taking inverses (meaning  $-u \in U$  whenever  $u \in U$ ), then  $U$  is a subspace of  $\mathbf{R}^2$ .

### Solution

Consider the set  $U = \{(k, k) : k \in \mathbf{Z}\}$  which is obviously closed under addition and taking inverses. Notice that  $U$  is not a subspace because it is not closed under scalar multiplication:  $(1, 1) \in U$  and  $\pi \in \mathbf{R}$  but  $\pi(1, 1) = (\pi, \pi) \notin U$ .

### Exercise 8

Give an example of a nonempty subset  $U$  of  $\mathbf{R}^2$  such that  $U$  is closed under scalar

multiplication, but  $U$  is not a subspace of  $\mathbf{R}^2$ .

### Solution

Consider the set  $U = \{(x, y) \in \mathbf{R}^2 : xy \geq 0\}$ , let's first show that it is closed under scalar multiplication. Given  $(x, y) \in U$  and  $\alpha \in \mathbf{R}$ , we know by definition of  $U$  that  $xy \geq 0$ . Moreover, since  $\alpha$  is a real number, then  $\alpha^2 \geq 0$ . Hence,

$$(\alpha x)(\alpha y) = \alpha^2 xy \geq 0$$

Thus,  $(\alpha x, \alpha y) \in U$  so  $U$  is indeed closed under scalar multiplication. To show that  $U$  is not a subspace, consider the elements  $(-1, 0)$  and  $(0, 1)$  in  $U$  and notice that their addition cannot be in  $U$  since  $(-1) \cdot 1 \not\geq 0$ . Thus,  $U$  is not closed under addition which proves that it is not a subspace.

### Exercise 9

A function  $f : \mathbf{R} \rightarrow \mathbf{R}$  is called *periodic* if there exists a positive number  $p$  such that  $f(x + p) = f(x)$  for all  $x \in \mathbf{R}$ . Is the set of periodic functions from  $\mathbf{R}$  to  $\mathbf{R}$  a subspace of  $\mathbf{R}^{\mathbf{R}}$ ? Explain.

### Solution

Let's prove that this set is not a subspace of  $\mathbf{R}^{\mathbf{R}}$  by showing that it is not closed under addition. To do so, consider the functions  $x \mapsto \cos(x)$  and  $x \mapsto \cos(\pi x)$  defined on  $\mathbf{R}$ . Obviously, both are periodic since the first one has period  $2\pi$  and the second one has period 2. Consider their sum  $f : \cos(x) + \cos(\pi x)$  and suppose by contradiction that there exists a  $p > 0$  such that

$$f(x) = f(x + p) \tag{1}$$

for all  $x \in \mathbf{R}$ . Notice that

$$\begin{aligned} f(x) = 2 &\implies \cos(x) + \cos(\pi x) = 2 \\ &\implies \cos(x) = 1 \quad \text{and} \quad \cos(\pi x) = 1 \\ &\implies x \in 2\pi\mathbf{Z} \quad \text{and} \quad x \in 2\mathbf{Z} \\ &\implies x = 0 \end{aligned}$$

Hence,  $f$  is equal to 2 if and only if  $x = 0$ . Thus, if we plug-in  $x = 0$  in equation (1), we get

$$f(p) = f(0) = 2$$

which implies that  $p = 0$ , a contradiction since  $p > 0$ . Therefore,  $f$  is not periodic which proves that periodic functions are not closed under addition. With a similar argument, periodic functions are not closed under multiplication either.

### Exercise 10

Suppose  $V_1$  and  $V_2$  are subspaces of  $V$ . Prove that  $V_1 \cap V_2$  is a subspace of  $V$ .

### Solution

Let's show that  $V_1 \cap V_2$  satisfies the three subspace conditions:

- **(additive identity)** Since  $V_1$  and  $V_2$  are subspaces, then they both contain the additive identity 0 of  $V$ . It follows that  $0 \in V_1 \cap V_2$  since it is contained in both sets.

- **(closed under addition)** Let  $u$  and  $v$  be two vectors in  $V_1 \cap V_2$ , then  $u$  and  $v$  must be contained in  $V_1$ . Since  $V_1$  is a subspace, then it is closed under addition so  $u + v$  must also be an element of  $V_1$ . Similarly,  $u$  and  $v$  are contained in  $V_2$  so for the same reasons,  $u + v$  must be an element of  $V_2$ . Thus,  $u + v \in V_1 \cap V_2$  since  $u + v \in V_1$  and  $u + v \in V_2$ .
- **(closed under scalar multiplication)** Let  $a \in \mathbf{F}$  and  $u \in V_1 \cap V_2$ , then  $u$  must be contained in  $V_1$ . Since  $V_1$  is a subspace, then it is closed under scalar multiplication so  $au$  must also be an element of  $V_1$ . Similarly,  $u$  is contained in  $V_2$  so for the same reasons,  $au$  must be an element of  $V_2$ . Thus,  $au \in V_1 \cap V_2$  since  $au \in V_1$  and  $au \in V_2$ .

Therefore,  $V_1 \cap V_2$  is a subspace of  $V$ .

### Exercise 11

Prove that the intersection of every collection of subspaces of  $V$  is a subspace of  $V$ .

### Solution

Let  $\{V_i\}_{i \in I}$  be an arbitrary collection of subspaces of  $V$ , let's show that  $\cap_{i \in I} V_i$  is also a subspace of  $V$  by proving the three subspace conditions:

- **(additive identity)** Since  $V_i$  is a subspace of  $V$ , then  $0 \in V_i$  for all  $i \in I$ . It follows that  $0 \in \cap_{i \in I} V_i$ .
- **(closed under addition)** Let  $u$  and  $v$  be two vectors in  $\cap_{i \in I} V_i$ , then  $u$  and  $v$  must be contained in  $V_i$  for all  $i \in I$ . For any  $i \in I$ ,  $V_i$  is a subspace so it is closed under addition, hence  $u + v \in V_i$ . It follows that  $u + v \in \cap_{i \in I} V_i$ .
- **(closed under scalar multiplication)** Let  $a \in \mathbf{F}$  and  $v \in \cap_{i \in I} V_i$ . For all  $i \in I$ , since  $u \in V_i$  and  $V_i$  is a subspace, then  $au \in V_i$ . It follows that  $au \in \cap_{i \in I} V_i$  since  $au \in V_i$  for all  $i \in I$ .

Therefore,  $\cap_{i \in I} V_i$  is a subspace of  $V$ .

### Exercise 12

Prove that the union of two subspaces of  $V$  is a subspace of  $V$  if and only if one of the subspaces is contained in the other.

### Solution

Let  $V_1$  and  $V_2$  be subspaces of  $V$ . If  $V_1 \subset V_2$  or  $V_2 \subset V_1$ , then  $V_1 \cup V_2$  must be a subspace of  $V$  as well. To show the converse, suppose now that  $V_1 \cup V_2$  is a subspace of  $V$  and that  $V_1 \not\subset V_2$ . Then there exists a vector  $u_1 \in V_1$  such that  $u_1 \notin V_2$ . Let's prove that  $V_2 \subset V_1$  in that case. Let  $v \in V_2$  be arbitrary, since  $u_1$  and  $v$  are both vectors in  $V_1 \cup V_2$ , then  $u_1 + v \in V_1 \cup V_2$  since it is a subspace. But this implies that  $u_1 + v$  is either in  $V_1$  or in  $V_2$ . If  $u_1 + v \in V_2$ , then we must have

$$u_1 = (u_1 + v) - v \in V_2$$

since  $v \in V_2$  and  $V_2$  is a subspace. A contradiction since  $u_1 \notin V_2$ . It follows that  $u_1 + v \in V_1$ . But again, since  $V_1$  is a subspace and  $u_1 \in V_1$ , then

$$v = (u_1 + v) - u_1 \in V_1$$

which proves that  $V_2 \subset V_1$ . Therefore, if  $V_1 \cup V_2$  is a subspace, then we either have  $V_1 \subset V_2$  or  $V_2 \subset V_1$ .

### Exercise 13

Prove that the union of three subspaces of  $V$  is a subspace of  $V$  if and only if one of the subspaces contains the other two.

### Solution

Let  $V_1$ ,  $V_2$  and  $V_3$  be three subspaces of  $V$ . Obviously, if one contains the other two, then  $V_1 \cup V_2 \cup V_3$  is also a subspace of  $V$  since it is either equal to  $V_1$ ,  $V_2$  or  $V_3$ .

To show the converse, suppose that  $V_1 \cup V_2 \cup V_3$  is a subspace of  $V$ . To prove that one subspace contains the other two, suppose that  $V_1 \not\supset V_2 \cup V_3$  and  $V_2 \not\supset V_1 \cup V_3$ , then it suffices to show that  $V_3$  contains  $V_1 \cup V_2$ . Notice that  $V_1 \not\supset V_2 \cup V_3$  and  $V_2 \not\supset V_1 \cup V_3$  implies the existence of vectors  $v_1, v_2 \in V$  such that

$$\begin{cases} v_1 \in V_1 \cup V_3 \\ v_1 \notin V_2 \end{cases} \quad \text{and} \quad \begin{cases} v_2 \in V_2 \cup V_3 \\ v_2 \notin V_1 \end{cases}$$

To show that  $V_3 \supset V_1 \cup V_2$ , let's proceed by cases:

- Suppose that  $V_1 \cup V_2 \leq V$ , then by the previous exercise, we must have  $V_1 \cup V_2 \subset V_3$  or  $V_3 \leq V_1 \cup V_2$ . By contradiction, suppose that  $V_3 \subset V_1 \cup V_2$ . Since  $V_1 \cup V_2 \leq V$ , then again, by the previous exercise,  $V_1 \subset V_2$  or  $V_2 \subset V_1$ . If  $V_1 \subset V_2$ , then  $v_1 \in V_1 \cup V_3 \subset V_2 \cup V_3$ . But,  $v_1 \notin V_2$  so  $v_1 \in V_3$ . However,  $V_3 \subset V_1 \cup V_2 = V_2$  so  $v_1 \in V_2$ . A contradiction that shows that  $V_1 \not\subset V_2$ . Similarly, we can prove in the same way using  $v_2$  that  $V_2 \not\subset V_1$ . Thus, by contradiction, we get that  $V_3$  is not a subset of  $V_1 \cup V_2$ . It follows that  $V_1 \cup V_2 \subset V_3$ .
- Suppose now that  $V_1 \cup V_2$  is not a subspace of  $V$ , then by the previous exercise,  $V_1 \not\subset V_2$  and  $V_2 \not\subset V_1$ . It follows that there exist vectors  $u_1, u_2 \in V$  such that

$$\begin{cases} u_1 \in V_1 \\ u_1 \notin V_2 \end{cases} \quad \text{and} \quad \begin{cases} u_2 \in V_2 \\ u_2 \notin V_1 \end{cases}$$

Consider now the vector  $\alpha_1 u_1 + \alpha_2 u_2$  where  $\alpha_1$  and  $\alpha_2$  are non-zero scalars. Since  $\alpha_1 u_1 \in V_1 \subset V_1 \cup V_2 \cup V_3$ ,  $\alpha_2 u_2 \in V_2 \subset V_1 \cup V_2 \cup V_3$  and  $V_1 \cup V_2 \cup V_3$  is a subspace of  $V$ , then  $\alpha_1 u_1 + \alpha_2 u_2 \in V_1 \cup V_2 \cup V_3$ . If  $\alpha_1 u_1 + \alpha_2 u_2 \in V_1$ , then using the fact that  $\alpha_1 u_1 \in V_1$  and that  $V_1$  is a subspace gives us

$$\alpha_2 u_2 = (\alpha_1 u_1 + \alpha_2 u_2) - \alpha_1 u_1 \in V_1$$

Multiplying by  $\alpha_2^{-1}$  implies that  $u_2 \in V_1$ , a contradiction. Similarly, if  $\alpha_1 u_1 + \alpha_2 u_2 \in V_2$ , then we can show in the same way that  $u_1 \in V_2$ , another contradiction. Thus, we must have  $\alpha_1 u_1 + \alpha_2 u_2 \in V_3$ .

Using the fact that  $2 \neq 0$ , we get that  $u_1 + u_2$ ,  $2u_1 + u_2$  and  $u_1 + 2u_2$  are in  $V_3$ . Thus,

$$u_1 = (2u_1 + u_2) - (u_1 + u_2) \in V_3$$

and

$$u_2 = (u_1 + 2u_2) - (u_1 + u_2) \in V_3$$

We are now ready to show that  $V_1 \cup V_2 \subset V_3$  in that case. To do so, let  $w \in V_1 \cup V_2$  and proceed again by cases:



- Suppose that  $w \in V_1 \setminus V_2$  and consider the vector  $w + u_2 \in V_1 \cup V_2 \cup V_3$ . If  $w + u_2 \in V_1$ , then  $u_2 \in V_1$ , a contradiction. Similarly, if  $w + u_2 \in V_2$ , then  $w \in V_2$ , a contradiction. Hence,  $w + u_2 \in V_3$ . But since  $u_2 \in V_3$ , then  $w \in V_3$ .
- Suppose that  $w \in V_2 \setminus V_1$  and consider the vector  $w + u_1 \in V_1 \cup V_2 \cup V_3$ . If  $w + u_1 \in V_1$ , then  $w \in V_1$ , a contradiction. Similarly, if  $w + u_1 \in V_2$ , then  $u_1 \in V_2$ , a contradiction. Hence,  $w + u_1 \in V_3$ . But since  $u_1 \in V_3$ , then  $w \in V_3$ .
- Suppose that  $w \in V_1 \cap V_2$  and consider the vector  $w + u_1 + u_2 \in V_1 \cup V_2 \cup V_3$ . If  $w + u_1 + u_2 \in V_1$ , then  $u_2 \in V_1$ , a contradiction. Similarly, if  $w + u_1 + u_2 \in V_2$ , then  $u_1 \in V_2$ , a contradiction. Hence,  $w + u_1 + u_2 \in V_3$ . But since  $u_1 + u_2 \in V_3$ , then  $w \in V_3$ .

Thus,  $V_1 \cup V_2 \subset V_3$ .

Hence, in all possible cases, we get that  $V_1 \cup V_2 \subset V_3$ . Therefore, the union of three subspaces is a subspace if and only if one of the subspaces contains the other two.

#### Exercise 14

Suppose

$$U = \{(x, -x, 2x) \in \mathbf{F}^3 : x \in \mathbf{F}\} \quad \text{and} \quad W = \{(x, x, 2x) \in \mathbf{F}^3 : x \in \mathbf{F}\}$$

Describe  $U + W$  using symbols, and also give a description of  $U + W$  that uses no symbols.

#### Solution

By definition, we have

$$\begin{aligned} U + W &= \{(x, -x, 2x) \in \mathbf{F}^3 : x \in \mathbf{F}\} + \{(x, x, 2x) \in \mathbf{F}^3 : x \in \mathbf{F}\} \\ &= \{(x + y, -x + y, 2x + 2y) \in \mathbf{F}^3 : x, y \in \mathbf{F}\} \\ &= \{(x + y, -x + y, 2(x + y)) \in \mathbf{F}^3 : x, y \in \mathbf{F}\} \end{aligned}$$

From this expression, let's prove that

$$U + W = \{(a, b, 2a) \in \mathbf{F}^3 : a, b \in \mathbf{F}\}$$

Obviously,  $U + W \subset \{(a, b, 2a) \in \mathbf{F}^3 : a, b \in \mathbf{F}\}$  because for any vector  $(x + y, -x + y, 2(x + y)) \in \mathbf{F}^3$ , if we let  $a = x + y$  and  $b = -x + y$ , we can rewrite this vector as  $(a, b, 2a)$  which is in  $\{(a, b, 2a) \in \mathbf{F}^3 : a, b \in \mathbf{F}\}$ . Similarly, given an arbitrary vector  $(a, b, 2a) \in \mathbf{F}^3$ , if we let

$$x = \frac{a - b}{2} \quad \text{and} \quad y = \frac{x + y}{2}$$

then we can rewrite the vector as  $(x + y, -x + y, 2(x + y))$  which is obviously in  $U + W$ . It follows that the sets are equal. Without symbols, this just means that  $U + W$  is precisely the set of vectors in  $V$  such that the third component is twice the first component.

**Exercise 15**

Suppose  $U$  is a subspace of  $V$ . What is  $U + U$ ?

**Solution**

Let's show that  $U = U + U$ . An arbitrary element in  $U + U$  is of the form  $x + y$  where  $x$  and  $y$  are in  $U$ . Since  $U$  is a subspace, then it is closed under addition which implies that  $x + y \in U$ . It follows that  $U + U \subset U$ .

For the reverse inclusion, take an arbitrary  $u \in U$  and notice that we can write  $u = u + 0$ . Again, since  $U$  is a subspace of  $V$ , then  $0 \in U$ . Thus, in the expression  $u + 0$ , both vectors are in  $U$ . It follows that  $u = u + 0 \in U + U$ . Therefore,  $U = U + U$ .

**Exercise 16**

Is the operation of addition on the subspaces of  $V$  commutative? In other words, if  $U$  and  $W$  are subspaces of  $V$ , is  $U + W = W + U$ ?

**Solution**

Let  $U$  and  $W$  be subspaces of  $V$ . Then by commutativity of addition in  $V$ , we get

$$\begin{aligned} U + W &= \{u + w : u \in U \text{ and } w \in W\} \\ &= \{w + u : w \in W \text{ and } u \in U\} \\ &= W + U \end{aligned}$$

Therefore, the operation of addition on subspaces of  $V$  is commutative.

**Exercise 17**

Is the operation of addition on the subspaces of  $V$  associative? In other words, if  $V_1$ ,  $V_2$  and  $V_3$  are subspaces of  $V$ , is

$$(V_1 + V_2) + V_3 = V_1 + (V_2 + V_3)?$$

**Solution**

Let  $V_1$ ,  $V_2$  and  $V_3$  are subspaces of  $V$  and let's show that

$$(V_1 + V_2) + V_3 = V_1 + (V_2 + V_3)$$

First, take an arbitrary  $x + y \in (V_1 + V_2) + V_3$  where  $x \in V_1 + V_2$  and  $y \in V_3$ . Since  $x \in V_1 + V_2$ , then there exist vectors  $a \in V_1$  and  $b \in V_2$  such that  $x = a + b$ . It follows from the associativity of addition in  $V$  that

$$x + y = (a + b) + y = a + (b + y)$$

Since  $b \in V_2$  and  $y \in V_3$ , then  $b + y \in V_2 + V_3$ . Hence,  $a + (b + y) \in V_1 + (V_2 + V_3)$  using the fact that  $a \in V_1$ . Thus, the arbitrary  $x + y \in (V_1 + V_2) + V_3$  is in  $V_1 + (V_2 + V_3)$  as well so

$$(V_1 + V_2) + V_3 \subset V_1 + (V_2 + V_3)$$

The reverse inclusion has the same proof. The desired equality follows.

**Exercise 18**

Does the operation of addition on subspaces of  $V$  have an additive identity? Which subspaces have additive inverses?

**Solution**

First, let's show that indeed, the operation of addition on subspaces of  $V$  has an additive identity. Define  $I = \{0\}$ , the subspace of  $V$  containing the zero vector only. Take an arbitrary subspace  $U$  of  $V$  and notice that

$$\begin{aligned} U + I &= \{u + i : u \in U \text{ and } i \in I\} \\ &= \{u + 0 : u \in U \text{ and } i \in I\} \\ &= \{u : u \in U\} \\ &= U \end{aligned}$$

By commutativity of addition of subspaces of  $V$ , we also have  $I + U = U$ . Therefore,  $I$  is an additive identity for the addition on subspaces of  $V$ .

Concerning additive inverses, let's determine which subspaces of  $V$  have an additive inverse by taking an arbitrary subspace  $U$  of  $V$  and supposing that there is a subspace  $W$  of  $V$  such that  $U + W = I$ . Since  $W$  is a subspace of  $V$ , then  $0 \in W$ . It follows that for all  $u \in U$ ,

$$u = u + 0 \in U + W = I = \{0\}$$

In other words,  $U = \{0\} = I$ . Since  $I$  obviously has an additive inverse (itself), then the unique subspace having an additive inverse is  $I$ .

**Exercise 19**

Prove or give a counterexample: If  $V_1, V_2, U$  are subspaces of  $V$  such that

$$V_1 + U = V_2 + U,$$

then  $V_1 = V_2$ .

**Solution**

Consider the following counterexample. Let  $V_1 = U = V$  and  $V_2 = \{0\}$ . We know from Exercise 15 of this section that

$$V_1 + U = V + V = V$$

Moreover, from Exercise 19, we also have

$$V_2 + U = \{0\} + V = V$$

Thus,

$$V_1 + U = V_2 + U$$

but  $V_1 \neq V_2$ .

**Exercise 20**

Suppose

$$U = \{(x, x, y, y) \in \mathbf{F}^4 : x, y \in \mathbf{F}\}.$$

Find a subspace  $W$  of  $\mathbf{F}^4$  such that  $\mathbf{F}^4 = U \oplus W$ .

**Solution**

Consider the subspace

$$W = \{(0, a, 0, b) \in \mathbf{F}^4 : a, b \in \mathbf{F}\}$$

and the sum  $U + W$ . First, let's show that the sum is direct by proving that  $(0, 0, 0, 0)$  has a unique representation in this sum. Suppose  $(x, x, y, y) \in U$  and  $(0, a, 0, b) \in W$  satisfy

$$(0, 0, 0, 0) = (x, x, y, y) + (0, a, 0, b)$$

This is equivalent to the system of equation

$$\begin{cases} x = 0 \\ a + x = 0 \\ y = 0 \\ b + y = 0 \end{cases}$$

which clearly has the following unique solution

$$\begin{cases} x = 0 \\ a = 0 \\ y = 0 \\ b = 0 \end{cases}$$

Therefore, in  $U + W$ , the zero vector can only be written as the sum of two zero vectors. It follows that the sum is direct.

Let's now show that  $U \oplus W = \mathbf{F}^4$  by taking an arbitrary vector  $(x_1, x_2, x_3, x_4)$ . Consider the vectors

$$u = (x_1, x_1, x_3, x_3) \in U \quad \text{and} \quad w = (0, x_2 - x_1, 0, x_4 - x_3) \in W$$

and notice that

$$\begin{aligned} u + w &= (x_1, x_1, x_3, x_3) + (0, x_2 - x_1, 0, x_4 - x_3) \\ &= (x_1, x_1 + x_2 - x_1, x_3, x_3 + x_4 - x_3) \\ &= (x_1, x_2, x_3, x_4) \end{aligned}$$

which shows that  $(x_1, x_2, x_3, x_4) \in U \oplus W$ . Thus,  $\mathbf{F}^4 \subset U \oplus W$ . Since  $U$  and  $W$  are subspaces of  $\mathbf{F}^4$ , then  $U \oplus W$  must also be a subspace of  $\mathbf{F}^4$ :  $U \oplus W \subset \mathbf{F}^4$ . Therefore, we get  $U \oplus W = \mathbf{F}^4$ .

**Exercise 21**

Suppose

$$U = \{(x, y, x + y, x - y, 2x) \in \mathbf{F}^5 : x, y \in \mathbf{F}\}.$$

Find subspace  $W$  of  $\mathbf{F}^5$  such that  $\mathbf{F}^5 = U \oplus W$ .

**Solution**

Consider the subspace

$$W = \{(0, 0, a, b, c) \in \mathbf{F}^5 : a, b, c \in \mathbf{F}\}$$

and consider the sum  $U + W$ . Let's first prove that it is actually a direct sum by focusing on the vector zero. Let  $(x, y, x + y, x - y, 2x) \in U$  and  $(0, 0, a, b, c) \in W$  be two vectors such that

$$(0, 0, 0, 0) = (x, y, x + y, x - y, 2x) + (0, 0, a, b, c)$$

This translates to the following system of equation:

$$\begin{cases} x = 0 \\ y = 0 \\ x + y + a = 0 \\ x - y + b = 0 \\ 2x + c = 0 \end{cases}$$

which is equivalent to

$$\begin{cases} x = 0 \\ y = 0 \\ a = 0 \\ b = 0 \\ c = 0 \end{cases}$$

Therefore, since the zero vector can only be written as the sum of two zero vectors, the sum is direct.

Let's now show that  $U \oplus W = \mathbf{F}^5$ . Obviously, since  $U \oplus W$  is a subspace of  $\mathbf{F}^5$ , we have  $U \oplus W \subset \mathbf{F}^5$ . Moreover, for any  $(x_1, x_2, x_3, x_4, x_5) \in \mathbf{F}^5$ , we have

$$\begin{aligned} & (x_1, x_2, x_3, x_4, x_5) \\ &= (x_1, x_2, [x_1 + x_2] + [x_3 - x_2 - x_1], [x_1 - x_2] + [x_4 + x_2 - x_1], 2x_1 + [x_5 - 2x_1]) \\ &= (x_1, x_2, x_1 + x_2, x_1 - x_2, 2x_1) + (0, 0, x_3 - x_2 - x_1, x_4 + x_2 - x_1, x_5 - 2x_1) \\ &= (x, y, x + y, x - y, 2x) + (0, 0, a, b, c) \\ &\in U \oplus W \end{aligned}$$

where  $x = x_1$ ,  $y = x_2$ ,  $a = x_3 - x_2 - x_1$ ,  $b = x_4 + x_2 - x_1$  and  $c = x_5 - 2x_1$ . Thus,  $\mathbf{F}^5 \subset U \oplus W$ . Therefore,  $U \oplus W = \mathbf{F}^5$ .

**Exercise 22**

Suppose

$$U = \{(x, y, x + y, x - y, 2x) \in \mathbf{F}^5 : x, y \in \mathbf{F}\}.$$

Find three subspaces  $W_1$ ,  $W_2$ ,  $W_3$  of  $\mathbf{F}^5$ , none of which equals  $\{0\}$ , such that  $\mathbf{F}^5 = U \oplus W_1 \oplus W_2 \oplus W_3$ .

**Solution**

Consider the subspaces

$$W_1 = \{(0, 0, a, 0, 0) \in \mathbf{F}^5 : a \in \mathbf{F}\}$$

$$W_2 = \{(0, 0, 0, b, 0) \in \mathbf{F}^5 : b \in \mathbf{F}\}$$

$$W_3 = \{(0, 0, 0, 0, c) \in \mathbf{F}^5 : c \in \mathbf{F}\}$$

and their sum  $U + W_1 + W_2 + W_3$ . Let's first prove that it is actually a direct sum by focusing on the zero vector. Let

$$u = (x, y, x + y, x - y, 2x) \in U$$

$$w_1 = (0, 0, a, 0, 0) \in W_1$$

$$w_2 = (0, 0, 0, b, 0) \in W_2$$

$$w_3 = (0, 0, 0, 0, c) \in W_3$$

be arbitrary vectors in their respective sets such that

$$(0, 0, 0, 0, 0) = u + w_1 + w_2 + w_3$$

This can be rewritten into the following system of equation:

$$\begin{cases} x = 0 \\ y = 0 \\ x + y + a = 0 \\ x - y + b = 0 \\ 2x + c = 0 \end{cases}$$

which is equivalent to

$$\begin{cases} x = 0 \\ y = 0 \\ a = 0 \\ b = 0 \\ c = 0 \end{cases}$$

Hence,  $u = w_1 = w_2 = w_3 = (0, 0, 0, 0, 0)$ . Therefore, since the zero vector can only be written as the sum of zero vectors, the sum is direct.

Let's now show that  $U \oplus W_1 \oplus W_2 \oplus W_3 = \mathbf{F}^5$ . Obviously, since  $U \oplus W_1 \oplus W_2 \oplus W_3$  is a subspace of  $\mathbf{F}^5$ , we have  $U \oplus W_1 \oplus W_2 \oplus W_3 \subset \mathbf{F}^5$ . Moreover, for any  $(x_1, x_2, x_3, x_4, x_5) \in \mathbf{F}^5$ , we have

$$\begin{aligned} & (x_1, x_2, x_3, x_4, x_5) \\ &= (x_1, x_2, [x_1 + x_2] + [x_3 - x_2 - x_1], [x_1 - x_2] + [x_4 + x_2 - x_1], 2x_1 + [x_5 - 2x_1]) \\ &= (x_1, x_2, x_1 + x_2, x_1 - x_2, 2x_1) + (0, 0, x_3 - x_2 - x_1, x_4 + x_2 - x_1, x_5 - 2x_1) \\ &= (x, y, x + y, x - y, 2x) + (0, 0, a, b, c) \\ &= (x, y, x + y, x - y, 2x) + (0, 0, a, 0, 0) + (0, 0, 0, b, 0) + (0, 0, 0, 0, c) \\ &\in U \oplus W \end{aligned}$$

where  $x = x_1$ ,  $y = x_2$ ,  $a = x_3 - x_2 - x_1$ ,  $b = x_4 + x_2 - x_1$  and  $c = x_5 - 2x_1$ . Thus,  $\mathbf{F}^5 \subset U \oplus W_1 \oplus W_2 \oplus W_3$ . Therefore,  $U \oplus W_1 \oplus W_2 \oplus W_3 = \mathbf{F}^5$ .

**Exercise 23**

Prove or give a counterexample: If  $V_1, V_2, U$  are subspaces of  $V$  such that

$$V = V_1 \oplus U \quad \text{and} \quad V = V_2 \oplus U,$$

then  $V_1 = V_2$ .

**Solution**

Consider the following counterexample:

$$\begin{aligned} V &= \mathbf{R}^2 \\ V_1 &= \{(0, x) : x \in \mathbf{R}\} \\ V_2 &= \{(x, x) : x \in \mathbf{R}\} \\ U &= \{(x, 0) : x \in \mathbf{R}\} \end{aligned}$$

I will not prove that  $V_1, V_2$  and  $U$  are subspaces of  $V$  because it is not goal of this exercise. Notice that

$$V_1 + U = \{(x, y) : x, y \in \mathbf{R}\} = \mathbf{R}^2 = V$$

Moreover, for any arbitrary  $u = (0, y) \in V_1$  and  $v = (x, 0) \in U$ , if

$$(0, 0) = u + v = (x, y)$$

then it follows that  $u = v = (0, 0)$  since  $x = y = 0$ . Hence,  $V_1 \oplus U = V$ . Similarly, let's show that  $V_2 \oplus U = V$ . To do so, let's first prove that  $V_2 + U = V$ . Since  $V_2 + U \subset V$ , it suffices to prove that  $V \subset V_2 + U$ . Let  $(a, b)$  be an arbitrary element in  $V$ , then we have

$$(x, y) = (x - y, 0) + (y, y) \in V_2 + U$$

Hence,  $V_2 + U = V$ . To prove that the sum is direct, let  $(x, x) \in V_2$  and  $(y, 0) \in U$  such that

$$(x + y, x) = (x, x) + (y, 0) = (0, 0)$$

Since it follows that  $x = 0$  and  $y = 0$ , then it follows that the zero vector can only be written as a sum of two zero vectors in  $V_2 + U$ . Thus,  $V_2 \oplus U = V$ . However, notice that  $V_1 \neq V_2$  since  $(1, 1) \in V_2$  but  $(1, 1) \notin V_1$ .

**Exercise 24**

A function  $f : \mathbf{R} \rightarrow \mathbf{R}$  is called *even* if

$$f(-x) = f(x)$$

for all  $x \in \mathbf{R}$ . A function  $f : \mathbf{R} \rightarrow \mathbf{R}$  is called *odd* if

$$f(-x) = -f(x)$$

for all  $x \in \mathbf{R}$ . Let  $V_e$  denote the set of real-valued even functions on  $\mathbf{R}$  and  $V_o$  denote the set of real-valued odd functions on  $\mathbf{R}$ . Show that  $\mathbf{R}^{\mathbf{R}} = V_e \oplus V_o$ .

**Solution**

First, let's show that  $\mathbf{R}^{\mathbf{R}} = V_e \oplus V_o$ . Since  $V_e \oplus V_o \subset \mathbf{R}^{\mathbf{R}}$ , then it suffices to prove that  $\mathbf{R}^{\mathbf{R}} \subset V_e \oplus V_o$ . Given an arbitrary function  $f \in \mathbf{R}^{\mathbf{R}}$ , define

$$f_e(x) = \frac{f(x) + f(-x)}{2} \quad \text{and} \quad f_o(x) = \frac{f(x) - f(-x)}{2}$$

for all  $x \in \mathbf{R}$ . Notice that for all  $x \in \mathbf{R}$ , we have

$$\begin{aligned} f_e(-x) &= \frac{f((-x)) + f(-(-x))}{2} \\ &= \frac{f(-x) + f(x)}{2} \\ &= f_e(x) \end{aligned}$$

and

$$\begin{aligned} f_o(-x) &= \frac{f((-x)) - f(-(-x))}{2} \\ &= \frac{f(-x) - f(x)}{2} \\ &= -\frac{f(x) - f(-x)}{2} \\ &= f_o(x) \end{aligned}$$

which proves that  $f_e \in V_e$  and  $f_o \in V_o$ . Moreover, for all  $x \in \mathbf{R}$

$$f_e(x) + f_o(x) = \frac{f(x) + f(-x)}{2} + \frac{f(x) - f(-x)}{2} = f(x)$$

so  $f = f_e + f_o \in V_e + V_o$ . Therefore,  $\mathbf{R}^{\mathbf{R}} = V_e + V_o$  since we just proved that  $\mathbf{R}^{\mathbf{R}} \subset V_e + V_o$ . Let's now show that the sum is direct by proving that the zero function can be represented as  $f_e + f_o$  where  $f_e \in V_e$  and  $f_o \in V_o$  only when  $f_e = f_o \equiv 0$ . To prove this, consider two arbitrary functions  $f_e \in V_e$  and  $f_o \in V_o$  such that

$$f_e(x) + f_o(x) = 0$$

for all  $x \in \mathbf{R}$ . Then, given any  $y \in \mathbf{R}$ , we have

$$f_e(y) + f_o(y) = 0$$

and

$$f_e(-y) + f_o(-y) = 0 \implies f_e(y) - f_o(y) = 0$$

by plugging-in  $x = y$  and  $x = -y$  into our previous equation. Adding the two equations gives us

$$\begin{aligned} [f_e(y) + f_o(y)] + [f_e(y) - f_o(y)] &= 0 \implies 2f_e(y) = 0 \\ &\implies f_e(y) = 0 \end{aligned}$$

It follows that  $f_o(y) = 0$  as well since  $f_e(y) + f_o(y) = 0$ . Thus, since it holds for all  $y \in \mathbf{R}$ , then  $f_e = f_o \equiv 0$ . Therefore,  $\mathbf{R}^{\mathbf{R}} = V_e \oplus V_o$ .



## Chapter 2

# Finite-Dimensional Vector Spaces

### 2A Span and Linear Independence

#### Exercise 1

Find a list of four distinct vectors in  $\mathbf{F}^3$  whose span equals

$$\{(x, y, z) \in \mathbf{F}^3 : x + y + z = 0\}.$$

#### Solution

Consider the following list of vectors:  $(-1, 0, 1)$ ,  $(0, -1, 1)$ ,  $(1, 1, -2)$  and  $(-1, 1, 0)$ . To prove that it spans the given set, take an arbitrary  $(x, y, z) \in \mathbf{F}^3$  such that  $x + y + z = 0$  and notice that

$$(x, y, z) = (-x)(-1, 0, 1) + (-y)(0, -1, 1) + 0(1, 1, -2) + 0(-1, 1, 0)$$

Hence, the given set is in the span of the four vectors. Moreover, any element in the span of the four vectors is in the given set since the four vectors are in the set and the set is closed under linear combinations.

#### Exercise 2

Prove or give a counterexample: If  $v_1, v_2, v_3, v_4$  spans  $V$ , then the list

$$v_1 - v_2, v_2 - v_3, v_3 - v_4, v_4$$

also spans  $V$ .

#### Solution

Let's prove it. Define the vectors

$$u_1 = v_1 - v_2$$

$$u_2 = v_2 - v_3$$

$$u_3 = v_3 - v_4$$

$$u_4 = v_4$$

and  $B$  as the set containing these four vectors. To show that  $B$  spans  $V$ , we need to prove that for any element  $v \in V$ , there exists a linear combination of the elements

in  $B$  equal to  $v$ . To do so, let  $v \in V$ , since  $v_1, v_2, v_3, v_4$  spans  $V$ , then there exist coefficients  $\alpha_1, \alpha_2, \alpha_3, \alpha_4 \in \mathbf{F}$  such that

$$v = \alpha_1 v_1 + \alpha_2 v_2 + \alpha_3 v_3 + \alpha_4 v_4$$

Now, notice that we can write  $v_1$  as  $u_1 + u_2 + u_3 + u_4$ ,  $v_2$  as  $u_2 + u_3 + u_4$ ,  $v_3$  as  $u_3 + u_4$  and  $v_4$  simply as  $u_4$ . Hence:

$$\begin{aligned} v &= \alpha_1 v_1 + \alpha_2 v_2 + \alpha_3 v_3 + \alpha_4 v_4 \\ &= \alpha_1(u_1 + u_2 + u_3 + u_4) + \alpha_2(u_2 + u_3 + u_4) + \alpha_3(u_3 + u_4) + \alpha_4 u_4 \\ &= \alpha_1 u_1 + (\alpha_1 + \alpha_2)u_2 + (\alpha_1 + \alpha_2 + \alpha_3)u_3 + (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4)u_4 \end{aligned}$$

Thus, we get that  $v$  can be written as a linear combination of the vectors in  $B$ . Therefore,  $B$  spans  $V$ .

### Exercise 3

Suppose  $v_1, \dots, v_m$  is a list of vectors in  $V$ . For  $k \in \{1, \dots, m\}$ , let

$$w_k = v_1 + \dots + v_k.$$

Show that  $\text{span}(v_1, \dots, v_m) = \text{span}(w_1, \dots, w_m)$ .

### Solution

First, notice that for all  $k \in \{2, \dots, m\}$ , we have

$$v_k = w_k - w_{k-1} \in \text{span}(w_1, \dots, w_m)$$

(for  $k = 1$ ,  $v_1 = w_1 \in \text{span}(w_1, \dots, w_m)$ ). Hence, since  $\text{span}(v_1, \dots, v_m)$  is the smallest subspace containing the vectors  $v_1, \dots, v_m$ , and  $\text{span}(w_1, \dots, w_m)$  is a subspace that contains the vectors  $v_1, \dots, v_m$ , then  $\text{span}(v_1, \dots, v_m) \subset \text{span}(w_1, \dots, w_m)$ .

Similarly, by definition, for all  $k \in \{1, \dots, m\}$ , we have

$$w_k = v_1 + \dots + v_k \in \text{span}(v_1, \dots, v_m)$$

Hence, since  $\text{span}(w_1, \dots, w_m)$  is the smallest subspace containing the vectors  $w_1, \dots, w_m$ , and  $\text{span}(v_1, \dots, v_m)$  is a subspace that contains the vectors  $w_1, \dots, w_m$ , then  $\text{span}(w_1, \dots, w_m) \subset \text{span}(v_1, \dots, v_m)$ . Therefore,  $\text{span}(v_1, \dots, v_m) = \text{span}(w_1, \dots, w_m)$ .

### Exercise 4

- (a) Show that a list of length one in a vector space is linearly independent if and only if the vector in the list is not 0.
- (b) Show that a list of length two in a vector space is linearly independent if and only if neither of the two vectors in the list is a scalar multiple of the other.

### Solution

- (a) Consider the list containing the single vector  $v_0$ . By definition, the list is linearly independent if and only if the only choice of scalars in a linear combination of the vectors in the list that is equal to zero is all of the scalars being equal to zero. In our case, this is equivalent to saying that  $\alpha v_0 = 0$  only when  $\alpha = 0$ . However, if it holds, then  $v_0$  cannot be the zero vector since otherwise,  $\alpha v_0 = 0$  even when  $\alpha \neq 0$ . Similarly, if  $v_0$  is not the zero vector then  $\alpha v_0 = 0$  can only happen when  $\alpha = 0$ . Thus,  $\alpha v_0 = 0$  only when  $\alpha = 0$  is equivalent to  $v_0 \neq 0$ . Therefore, the list is linearly independent if and only if  $v_0$  is not the zero vector.
- (b) For this one, let's prove the converse equivalence: the list is linearly dependent if and only if one vector is a scalar multiple of the other. To do so, suppose that the list is linearly dependent, then there exist scalars  $\alpha, \beta \in \mathbf{F}$  such that

$$\alpha v_1 + \beta v_2 = 0$$

but not all scalars are zero. Suppose without loss of generality that  $\alpha \neq 0$ , then we can rewrite the previous equation as

$$v_1 = -\frac{\beta}{\alpha}v_2$$

Thus,  $v_1$  is a scalar multiple of  $v_2$ .

For the reverse implication, suppose that one of the vectors is a multiple of the other. Without loss of generality, suppose that  $v_1$  is a scalar multiple of  $v_2$ , then there exists a scalar  $\alpha \in \mathbf{F}$  such that  $v_1 = \alpha v_2$ . But notice that we can rewrite the previous equation as follows:

$$(1)v_1 + (-\alpha)v_2 = 0$$

Since  $1 \neq 0$ , then there exists a non-trivial linear combination of the vectors in that list that is equal to zero. Thus, the list is linearly dependent.

### Exercise 5

Find a number  $t$  such that

$$(3, 1, 4), (2, -3, 5), (5, 9, t)$$

is not linearly independent in  $\mathbf{R}^3$ .

### Solution

If we take  $t = 55/2$ , then we can write the vector  $(5, 9, t)$  as  $\alpha(3, 1, 4) + \beta(2, -3, 5)$  where  $\alpha = 15/2$  and  $\beta = -1/2$ . Hence,

$$\alpha(3, 1, 4) + \beta(2, -3, 5) + (-1)(5, 9, t) = 0$$

is a non-trivial linear combination. Thus, with such a value of  $t$ , the three vectors are not linearly independent.

### Exercise 6

Show that the list  $(2, 3, 1), (1, -1, 2), (7, 3, c)$  is linearly dependent in  $\mathbf{F}^3$  if and only if

$c = 8$ .

**Solution**

( $\implies$ ) Suppose that the list  $(2,3,1), (1,-1,2), (7,3,c)$  is linearly dependent in  $\mathbf{F}^3$ , then there exist scalars  $\alpha, \beta, \gamma \in \mathbf{F}$  not all zero such that

$$\alpha(2, 3, 1) + \beta(1, -1, 2) + \gamma(7, 3, c) = 0$$

If  $\gamma = 0$ , then we get that  $(2,3,1)$  and  $(1,-1,2)$  are linearly dependent. However, this is impossible since  $(2,3,1)$  is not a scalar multiple of  $(1,-1,2)$  and vice versa. Thus,  $\gamma$  must be non-zero. Thus:

$$\begin{aligned} \alpha(2, 3, 1) + \beta(1, -1, 2) + \gamma(7, 3, c) = 0 &\implies \gamma(7, 3, c) = -\alpha(2, 3, 1) - \beta(1, -1, 2) \\ &\implies (7, 3, c) = -\frac{\alpha}{\gamma}(2, 3, 1) - \frac{\beta}{\gamma}(1, -1, 2) \end{aligned}$$

Hence, if we let  $a = -\alpha/\gamma$  and  $b = -\beta/\gamma$ , then

$$(7, 3, c) = a(2, 3, 1) + b(1, -1, 2)$$

which can be written as the following system of equation:

$$\begin{cases} 2a + b = 7 \\ 3a - b = 3 \\ a + 2b = c \end{cases}$$

To solve the system, we can add equation 1 and 2 to get  $5a = 10$ . It follows that  $a = 2$ . If we plug-in  $a = 2$  in equation 2, we get  $6 - b = 3$  so  $b = 3$ . Thus, we get that  $c = a + 2b = 2 + 2 \cdot 3 = 8$ .

( $\impliedby$ ) Suppose that  $c = 8$ . Using our work from the previous implication gives us

$$(7, 3, c) = 2(2, 3, 1) + 3(1, -1, 2)$$

which can be rearranged as

$$2(2, 3, 1) + 3(1, -1, 2) + (-1)(7, 3, c) = 0$$

Thus, since there exists a non-trivial linear combination that is equal to zero, then the three vectors are linearly dependent.

**Exercise 7**

- (a) Show that if we think of  $\mathbf{C}$  as a vector space over  $\mathbf{R}$ , then the list  $1 + i, 1 - i$  is linearly independent.
- (b) Show that if we think of  $\mathbf{C}$  as a vector space over  $\mathbf{C}$ , then the list  $1 + i, 1 - i$  is linearly dependent.

**Solution**

- (a) By contradiction, suppose that  $1 + i, 1 - i$  is linearly dependent, then using Exercise 4.(b), we know that there is a scalar  $\alpha \in \mathbf{R}$  such that

$$1 + i = \alpha(1 - i) = \alpha + (-\alpha)i$$

But by the unique representation of complex numbers in the form  $a + ib$ , we get that  $\alpha = 1$  and  $-\alpha = 1$ , a contradiction. Thus, the list  $1 + i, 1 - i$  is linearly independent.

- (b) Simply notice that

$$(1 + i) + (-i)(1 - i) = 0$$

even if the scalars are not all zero. Therefore, the list  $1 + i, 1 - i$  is linearly dependent.

### Exercise 8

Suppose  $v_1, v_2, v_3, v_4$  is linearly independent in  $V$ . Prove that

$$v_1 - v_2, v_2 - v_3, v_3 - v_4, v_4$$

is also linearly independent.

### Solution

To prove that  $v_1 - v_2, v_2 - v_3, v_3 - v_4, v_4$  is linearly independent, take arbitrary scalars  $a, b, c, d \in \mathbf{F}$  such that

$$a(v_1 - v_2) + b(v_2 - v_3) + c(v_3 - v_4) + dv_4 = 0$$

and prove that  $a = b = c = d = 0$ . First, notice that we can rearrange the previous equation as follows:

$$\begin{aligned} & a(v_1 - v_2) + b(v_2 - v_3) + c(v_3 - v_4) + dv_4 = 0 \\ \implies & av_1 - av_2 + bv_2 - bv_3 + cv_3 - cv_4 + dv_4 = 0 \\ \implies & av_1 + (b - a)v_2 + (c - b)v_3 + (d - c)v_4 = 0 \end{aligned}$$

But since the list  $v_1, v_2, v_3, v_4$  is linearly independent, then all coefficients in the last equation must be zero. Hence, we get the following system of equation:

$$\begin{cases} a = 0 \\ b - a = 0 \\ c - b = 0 \\ d - c = 0 \end{cases}$$

which is equivalent to

$$\begin{cases} a = 0 \\ a = b = c = d \end{cases}$$

It follows that  $a = b = c = d = 0$ . Therefore, the given list is linearly independent.

**Exercise 9**

Prove or give a counterexample: If  $v_1, v_2, \dots, v_m$  is a linearly independent list of vectors in  $V$ , then

$$5v_1 - 4v_2, v_2, v_3, \dots, v_m$$

is linearly independent.

**Solution**

To prove that  $5v_1 - 4v_2, v_2, v_3, \dots, v_m$  is linearly independent, take arbitrary scalars  $a_1, \dots, a_m \in \mathbf{F}$  such that

$$a_1(5v_1 - 4v_2) + a_2v_2 + a_3v_3 + \dots + a_mv_m = 0$$

and prove that  $a_1 = a_2 = \dots = a_m = 0$ . First, notice that we can rearrange the previous equation as follows:

$$\begin{aligned} & a_1(5v_1 - 4v_2) + a_2v_2 + a_3v_3 + \dots + a_mv_m = 0 \\ \implies & 5a_1v_1 - 4a_1v_2 + a_2v_2 + a_3v_3 + \dots + a_mv_m = 0 \\ \implies & 5a_1v_1 + (a_2 - 4a_1)v_2 + a_3v_3 + \dots + a_mv_m = 0 \end{aligned}$$

But since the list  $v_1, v_2, \dots, v_m$  is linearly independent, then all coefficients in the last equation must be zero. Hence, we get the following system of equation:

$$\begin{cases} 5a_1 = 0 \\ a_2 - 4a_1 = 0 \\ a_3 = 0 \\ \vdots \\ a_m = 0 \end{cases}$$

which is equivalent to  $a_1 = a_2 = \dots = a_m = 0$  by solving the system. Therefore, the given list is linearly independent.

**Exercise 10**

Prove or give a counterexample: If  $v_1, v_2, \dots, v_m$  is a linearly independent list of vectors in  $V$  and  $\lambda \in \mathbf{F}$  with  $\lambda \neq 0$ , then  $\lambda v_1, \lambda v_2, \dots, \lambda v_m$  is linearly independent.

**Solution**

To prove that  $\lambda v_1, \lambda v_2, \dots, \lambda v_m$  is linearly independent, take arbitrary scalars  $a_1, \dots, a_m \in \mathbf{F}$  such that

$$a_1\lambda v_1 + a_2\lambda v_2 + \dots + a_m\lambda v_m = 0$$

and prove that  $a_1 = a_2 = \dots = a_m = 0$ . But since the list  $v_1, v_2, \dots, v_m$  is linearly independent, then all coefficients in front of the  $a_i$ 's the last equation must be zero. Hence, we get the following system of equation:

$$\begin{cases} \lambda a_1 = 0 \\ \lambda a_2 = 0 \\ \vdots \\ \lambda a_m = 0 \end{cases}$$

Using the fact that  $\lambda \neq 0$ , we can divide each equation in the system to get  $a_1 = a_2 = \dots = a_m = 0$ . Therefore, the given list is linearly independent.

### Exercise 11

Prove or give a counterexample: If  $v_1, \dots, v_m$  and  $w_1, \dots, w_m$  are linearly independent lists of vectors in  $V$ , then  $v_1 + w_1, \dots, v_m + w_m$  is linearly independent.

### Solution

Consider the following counterexample: take any list  $v_1, v_2, \dots, v_m$  of linearly independent vectors. We know from Exercise 10 that if we take  $\lambda = -1$ , then  $-v_1, -v_2, \dots, -v_m$  is also linearly independent. However, the list  $v_1 + (-v_1), \dots, v_m + (-v_m)$  is precisely equal to the list containing  $m$  zero vectors. Thus,  $v_1 + (-v_1), \dots, v_m + (-v_m)$  is not linearly independent since any linear combination of the vectors in that list gives the zero vector, even if some scalars are non-zero.

### Exercise 12

Suppose  $v_1, \dots, v_m$  is linearly independent in  $V$  and  $w \in V$ . Prove that if  $v_1 + w, \dots, v_m + w$  is linearly dependent, then  $w \in \text{span}(v_1, \dots, v_m)$ .

### Solution

Suppose that  $v_1 + w, \dots, v_m + w$  is linearly dependent, then there must be some scalars  $a_1, \dots, a_m \in \mathbf{F}$  not all zero such that

$$a_1(v_1 + w) + a_2(v_2 + w) + \dots + a_m(v_m + w) = 0$$

But notice that we can rewrite the previous equation as follows:

$$(a_1 + a_2 + \dots + a_m)w = a_1(-v_1) + a_2(-v_2) + \dots + a_m(-v_m)$$

Define  $\alpha = a_1 + a_2 + \dots + a_m$  so we can rewrite again the equation as

$$\alpha w = a_1(-v_1) + a_2(-v_2) + \dots + a_m(-v_m)$$

and suppose by contradiction that  $\alpha = 0$ . If  $\alpha = 0$ , then the previous equation becomes:

$$a_1(-v_1) + a_2(-v_2) + \dots + a_m(-v_m) = 0$$

Using Exercise 10, by linear independence of  $v_1, \dots, v_m$  and by taking  $\lambda = -1$ , we get that the list  $-v_1, \dots, -v_m$  is linearly independent as well. Hence, the previous equation implies that  $a_1 = a_2 = \dots = a_m = 0$ . But this is a contradiction with the fact that the scalars  $a_1, \dots, a_m$  are not all zero. Thus, by contradiction,  $\alpha \neq 0$ . Hence:

$$\begin{aligned} \alpha w &= a_1(-v_1) + a_2(-v_2) + \dots + a_m(-v_m) \\ \implies w &= \left(-\frac{a_1}{\alpha}\right)v_1 + \left(-\frac{a_2}{\alpha}\right)v_2 + \dots + \left(-\frac{a_m}{\alpha}\right)v_m \end{aligned}$$

which proves that  $w \in \text{span}(v_1, \dots, v_m)$ .

### Exercise 13

Suppose  $v_1, \dots, v_m$  is linearly independent in  $V$  and  $w \in V$ . Show that

$$v_1, \dots, v_m, w \text{ is linearly independent} \iff w \notin \text{span}(v_1, \dots, v_m).$$

**Solution**

( $\implies$ ) By contrapositive, suppose that  $w \in \text{span}(v_1, \dots, v_m)$ , then there exist coefficients  $a_1, \dots, a_m \in \mathbf{F}$  such that

$$w = a_1v_1 + \dots + a_mv_m$$

which can be rewritten as

$$a_1v_1 + \dots + a_mv_m + (-1)w = 0$$

Notice that not all scalars in this linear combination are zero. It follows that the list  $v_1, \dots, v_m, w$  is linearly dependent.

( $\impliedby$ ) Again, by contrapositive, suppose that  $v_1, \dots, v_m, w$  is linearly dependent, then there exist coefficients  $a_1, \dots, a_m, \alpha \in \mathbf{F}$  not all zero such that

$$a_1v_1 + \dots + a_mv_m + \alpha w = 0$$

By contradiction, if  $\alpha = 0$ , then we get

$$a_1v_1 + \dots + a_mv_m = 0$$

which implies, by linear independence of  $v_1, \dots, v_m$  that all coefficients are zero. A contradiction since we know that at least one of them is non-zero. Thus, by contradiction, we have that  $\alpha \neq 0$ :

$$\begin{aligned} & a_1v_1 + \dots + a_mv_m + \alpha w = 0 \\ \implies & -\alpha w = a_1v_1 + \dots + a_mv_m \\ \implies & w = \left(-\frac{a_1}{\alpha}\right)v_1 + \left(-\frac{a_2}{\alpha}\right)v_2 + \dots + \left(-\frac{a_m}{\alpha}\right)v_m \end{aligned}$$

which proves that  $w \in \text{span}(v_1, \dots, v_m)$ .

**Exercise 14**

Suppose  $v_1, \dots, v_m$  is a list of vectors in  $V$ . For  $k \in \{1, \dots, m\}$ , let

$$w_k = v_1 + \dots + v_k.$$

Show that the list  $v_1, \dots, v_m$  is linearly independent if and only if the list  $w_1, \dots, w_m$  is linearly independent.

**Solution**

( $\implies$ ) Suppose that  $v_1, \dots, v_m$  is linearly independent, then for any scalars  $a_1, \dots, a_m \in \mathbf{F}$  such that

$$a_1w_1 + \dots + a_mw_m = 0,$$

we can rewrite the previous equation as

$$\begin{aligned} & a_1w_1 + a_1w_2 + \dots + a_mw_m = 0 \\ \implies & a_1v_1 + a_2(v_1 + v_2) + \dots + a_m(v_1 + \dots + v_m) = 0 \\ \implies & a_1v_1 + a_2v_1 + a_2v_2 + \dots + a_mv_1 + \dots + a_mv_m = 0 \\ \implies & (a_1 + \dots + a_m)v_1 + \dots + a_mv_m = 0 \end{aligned}$$



By linear independence of  $v_1, \dots, v_m$ , this implies

$$\begin{cases} a_1 + \dots + a_m = 0 \\ a_2 + \dots + a_m = 0 \\ \vdots \\ a_{m-1} + a_m = 0 \\ a_m = 0 \end{cases}$$

We can easily solve this system of equation and get  $a_1 = a_2 = \dots = a_m = 0$ . Thus,  $w_1, \dots, w_m$  is linearly independent.

( $\Leftarrow$ ) Suppose that  $w_1, \dots, w_m$  is linearly independent, then for any scalars  $a_1, \dots, a_m \in \mathbf{F}$  such that

$$a_1 v_1 + \dots + a_m v_m = 0,$$

we can rewrite the previous equation as

$$\begin{aligned} & a_1 v_1 + a_1 v_2 + \dots + a_m v_m = 0 \\ \implies & a_1 w_1 + a_2(w_2 - w_1) \dots + a_m(w_m - w_{m-1}) = 0 \\ \implies & a_1 w_1 + a_2 w_2 - a_2 w_1 \dots + a_m w_m - a_m w_{m-1} = 0 \\ \implies & (a_1 - a_2)w_1 + (a_2 - a_3)w_2 + \dots + a_m w_m = 0 \end{aligned}$$

By linear independence of  $v_1, \dots, v_m$ , this implies

$$\begin{cases} a_1 - a_2 = 0 \\ a_2 - a_3 = 0 \\ \vdots \\ a_m = 0 \end{cases}$$

We can easily solve this system of equation and get  $a_1 = a_2 = \dots = a_m = 0$ . Thus,  $v_1, \dots, v_m$  is linearly independent.

### Exercise 15

Explain why there does not exist a list of six polynomials that is linearly independent in  $\mathcal{P}_4(\mathbf{F})$ .

### Solution

We already know a list of size 5 that spans  $\mathcal{P}_4(\mathbf{F})$ :  $1, x, x^2, x^3, x^4$ . Hence, any list of linearly independent polynomials must have a length smaller than 5. In particular, a linearly independent list of 6 polynomials cannot exist in  $\mathcal{P}_4(\mathbf{F})$ .

### Exercise 16

Explain why no list of four polynomials spans  $\mathcal{P}_4(\mathbf{F})$ .

### Solution

We already know a linearly independent list of size 5 in  $\mathcal{P}_4(\mathbf{F})$ :  $1, x, x^2, x^3, x^4$ . Hence, any list of polynomials that spans  $\mathcal{P}_4(\mathbf{F})$  must have a length greater or equal

to 5. In particular, a spanning list of 4 polynomials cannot exist in  $\mathcal{P}_4(\mathbf{F})$ .

### Exercise 17

Prove that  $V$  is infinite-dimensional if and only if there is a sequence  $v_1, v_2, \dots$  of vectors in  $V$  such that  $v_1, \dots, v_m$  is linearly independent for every positive integer  $m$ .

### Solution

( $\implies$ ) Suppose that  $V$  is infinite-dimensional, let's define a sequence  $v_1, v_2, \dots$  of vectors recursively as follows. First,  $V$  cannot be the trivial vector space  $\{0\}$  because the trivial vector space has a list of vectors that spans it: the list containing the zero vector only. Hence,  $\{0\}$  is finite-dimensional so it cannot be equal to  $V$ . Thus, define the vector  $v_1 \in V$  as any non-zero vector. Obviously, the list  $v_1$  of length 1 is linearly independent by Exercise 4.(a).

Recursively, suppose that we have a linearly independent list  $v_1, v_2, \dots, v_k$  of vectors in  $V$  for some natural number  $k$ . Since  $V$  is infinite-dimensional, then the given list don't span  $V$ . It follows that there exists a vector  $v_{k+1}$  such that

$$v_{k+1} \notin \text{span}(v_1, \dots, v_k)$$

Therefore, by Exercise 13, the list  $v_1, v_2, \dots, v_k, v_{k+1}$  is linearly independent as well. Now that we defined our sequence recursively, notice that by construction, for all positive integer  $m$ , the list  $v_1, \dots, v_m$  is linearly independent.

( $\impliedby$ ) Suppose there is a sequence  $v_1, v_2, \dots$  of vectors in  $V$  such that  $v_1, \dots, v_m$  is linearly independent for every positive integer  $m$ . By contradiction, suppose that  $V$  is finite-dimensional, then there is a list  $w_1, \dots, w_N$  that spans  $V$  for some positive integer  $N$ . However, if we let  $m = N + 1$ , then our assumption implies that there is a linearly independent list of length  $N + 1$  in  $V$ . This is in contradiction with Theorem 2.22 so  $V$  must be infinite-dimensional.

### Exercise 18

Prove that  $\mathbf{F}^\infty$  is infinite-dimensional.

### Solution

Consider the sequence  $v_1, v_2, \dots$  of sequences in  $\mathbf{F}^\infty$  defined as follows: for all positive integer  $k$ , define  $v_k \in \mathbf{F}^\infty$  as the sequence with all terms equal to 0, except the  $k$ th term which is equal to 1. For all positive integer  $m$ , consider the list  $v_1, \dots, v_m$ . Notice that by construction, for all scalars  $a_1, \dots, a_m \in \mathbf{F}$ , the linear combination

$$a_1 v_1 + a_2 v_2 + \dots + a_m v_m$$

is simply the sequence with terms  $(a_1, a_2, \dots, a_{m-1}, a_m, 0, 0, 0, \dots)$ . It follows that this linear combination is equal to the zero sequence if and only if all the coefficients  $a_i$  are zero. Thus, the list  $v_1, \dots, v_m$  is linearly independent. Therefore, by Exercise 17,  $\mathbf{F}^\infty$  is infinite-dimensional.

### Exercise 19

Prove that the real vector space of all continuous real-valued functions on the interval  $[0,1]$  is infinite-dimensional.

**Solution**

Consider the sequence  $v_1, v_2, \dots$  of continuous functions on the interval  $[0, 1]$  defined by  $v_k : x \mapsto x^k$  for all positive integer  $k$ . Let  $m$  be a positive integer and consider the list  $v_1, \dots, v_m$ . To show that this list is linearly independent, take arbitrary scalars  $a_1, \dots, a_m \in \mathbf{R}$  such that

$$a_1v_1 + a_2v_2 + \dots + a_mv_m = 0$$

By definition of the  $v_i$ 's, the previous equation implies that

$$a_1x + a_2x^2 + \dots + a_mx^m = 0$$

for all  $x \in [0, 1]$ . If we consider the function  $f : [0, 1] \rightarrow [0, 1]$  defined by  $f(x) = a_1x + a_2x^2 + \dots + a_mx^m$ , then  $f$  is differentiable on  $[0, 1]$ . Thus, differentiating on both sides gives us

$$a_1 + a_2x + \dots + a_mx^{m-1} = 0$$

for all  $x \in [0, 1]$ . By plugging-in  $x = 0$ , we get  $a_1 = 0$ . If we repeat this process  $m$  times, we get  $a_1 = a_2 = \dots = a_m = 0$ . Thus, the list is linearly independent. Therefore, by Exercise 17, the real vector space of all continuous real-valued functions on the interval  $[0, 1]$  is infinite-dimensional.

**Exercise 20**

Suppose  $p_0, p_1, \dots, p_m$  are polynomials in  $\mathcal{P}_m(\mathbf{F})$  such that  $p_k(2) = 0$  for each  $k \in \{0, \dots, m\}$ . Prove that  $p_0, p_1, \dots, p_m$  is not linearly independent in  $\mathcal{P}_m(\mathbf{F})$ .

**Solution**

We already know a list of size  $m + 1$  that spans  $\mathcal{P}_m(\mathbf{F})$ :  $1, x, x^2, \dots, x^m$ . Hence, any list of linearly independent polynomials must have a length smaller than  $m + 1$ . By contradiction, suppose that the given list  $p_0, p_1, \dots, p_m$  is linearly independent and consider the constant polynomial  $p \equiv 1$ . Notice that for all scalars  $a_0, \dots, a_m \in \mathbf{F}$ , the new polynomial

$$a_0p_0 + a_1p_1 + \dots + a_mp_m$$

also vanishes at  $x = 2$ . Hence, for any linear combination of the list  $p_0, p_1, \dots, p_m$ , the polynomial  $p$  must be different from this linear combination they don't evaluate to the same number at  $x = 2$ . It follows that

$$p \notin \text{span}(p_0, p_1, \dots, p_m)$$

Thus, by Exercise 13, the list  $p_0, \dots, p_m, p$  is linearly independent. However, this list has length  $m + 2$  so we get a contradiction. Therefore,  $p_0, p_1, \dots, p_m$  cannot be linearly independent in  $\mathcal{P}_m(\mathbf{F})$ .

## 2B Bases

### Exercise 1

Find all vector spaces that have exactly one basis.

### Solution

Let  $V$  be a vector space over the field  $\mathbf{F}$  that have exactly one basis. First, let's show that the basis must contain only one vector. To do so, suppose that the basis is the following list:  $b_1, b_2, \dots, b_n$  with  $n \geq 2$ . Consider the new list  $b_1, b_1 + b_2, b_3, \dots, b_n$  where  $b_2$  is replaced by  $b_1 + b_2$ . Notice that this new list is also linearly independent because for all scalars  $\alpha_1, \dots, \alpha_n \in \mathbf{F}$ :

$$\begin{aligned} & \alpha_1 b_1 + \alpha_2 (b_1 + b_2) + \alpha_3 b_3 + \dots + \alpha_n b_n = 0 \\ \implies & (\alpha_1 + \alpha_2) b_1 + \alpha_2 b_2 + \alpha_3 b_3 + \dots + \alpha_n b_n = 0 \\ \implies & \alpha_1 + \alpha_2 = 0 \quad \text{and} \quad \alpha_i = 0, \quad i = 2, \dots, n \\ \implies & \alpha_i = 0, \quad i = 1, \dots, n \end{aligned}$$

Moreover, notice that for all  $u \in V$ , since  $b_1, b_2, \dots, b_n$  is a basis for  $V$ , then there exist scalars  $a_1, \dots, a_n \in \mathbf{F}$  such that

$$u = a_1 b_1 + a_2 b_2 + \dots + a_n b_n$$

Hence,

$$u = (a_1 - a_2) b_1 + a_2 (b_1 + b_2) + \dots + a_n b_n \in \text{span}(b_1, b_1 + b_2, \dots, b_n)$$

It follows that the new list also spans  $V$ . Therefore, the new list is a basis. But since  $V$  has a unique basis, then the new list must be equal to the first one. In particular, the vector  $b_1 + b_2$  must be in the list  $b_1, b_2, \dots, b_n$  as well. Hence, there is a  $i \in \{1, \dots, n\}$  such that  $b_1 + b_2 = b_i$ . If  $i = 1$ , then we get  $b_2 = 0$ , a contradiction with the fact that  $b_1, \dots, b_n$  is linearly independent. Similarly,  $i = 2$  would lead to the same contradiction. Now, if  $i > 2$ , then we can rearrange the equation to  $b_1 + b_2 - b_i = 0$ . Again, this is impossible since the  $b_j$ 's are linearly independent. Therefore, by contradiction, the unique basis for  $V$  must contain at most 1 vector. Now, we have two cases, either the basis is a list of length 0 or a list of length 1. If the list has length 0, then  $V$  must be the trivial vector space  $\{0\}$ . Indeed, the trivial vector space over any field has a unique basis, the list of length 0.

Suppose now that the basis for  $V$  is a list of length 1, call  $v_0 \neq 0$  the unique vector in the basis. Let  $\alpha$  be a non-zero scalar and consider the list containing the vector  $\alpha v_0$ . Since neither  $\alpha$  nor  $v_0$  is zero, then  $\alpha v_0$  is non-zero. Thus, this new list is linearly independent. Moreover, for any  $u \in V$ , since the list  $v_0$  spans  $V$ , then there is a  $\lambda \in \mathbf{F}$  such that  $u = \lambda v_0$ . Thus:

$$u = \frac{\lambda}{\alpha} (\alpha v_0) \in \text{span}(\alpha v_0)$$

It follows that the list  $\alpha v_0$  is also a basis for  $V$ . By uniqueness, we must have  $\alpha v_0 = v_0$ . But since  $v_0 \neq 0$ :

$$\begin{aligned} \alpha v_0 = v_0 & \implies \alpha v_0 - v_0 \\ & \implies (\alpha - 1) v_0 = 0 \\ & \implies \alpha = 1 \end{aligned}$$

In conclusion, the only non-zero element in  $\mathbf{F}$  is 1 so  $\mathbf{F}$  must be the field containing two elements.

From these results, we get that the only vector spaces with exactly one basis are either the trivial vector spaces on any field, or the vector spaces over the field with two elements with a basis containing only one element.

### Exercise 2

Verify all assertions in Example 2.27.

### Solution

- (a) Denote by  $e_i \in \mathbf{F}^n$  the vector with all entries equal to zero except the  $i$ th entry which is equal to 1. Let's show that the list  $e_1, \dots, e_n$  is a basis for  $\mathbf{F}^n$ . First, let's show that it spans  $\mathbf{F}^n$ . Take an arbitrary  $(\alpha_1, \dots, \alpha_n) \in \mathbf{F}^n$  and notice that

$$\begin{aligned} (\alpha_1, \dots, \alpha_n) &= \alpha_1(1, \dots, 0) + \dots + \alpha_n(0, \dots, 1) \\ &= \alpha_1 e_1 + \dots + \alpha_n e_n \\ &\in \text{span}(e_1, \dots, e_n) \end{aligned}$$

Hence, the list spans  $\mathbf{F}^n$ . Moreover, for any scalars  $\alpha_1, \dots, \alpha_n \in \mathbf{F}$ , we get

$$\begin{aligned} \alpha_1 e_1 + \dots + \alpha_n e_n &= (0, \dots, 0) \\ \implies \alpha_1(1, \dots, 0) + \dots + \alpha_n(0, \dots, 1) &= (0, \dots, 0) \\ \implies (\alpha_1, \dots, \alpha_n) &= (0, \dots, 0) \\ \implies \alpha_i &= 0 \text{ for all } i = 1, \dots, n \end{aligned}$$

Therefore, the list  $e_1, \dots, e_n$  is a basis for  $\mathbf{F}^n$ .

- (b) Let's show that the list  $(1, 2), (3, 5)$  is a basis of  $\mathbf{F}^2$ . To do so, notice that for all  $(a, b) \in \mathbf{F}^2$ , we have

$$(a, b) = (3b - 5a)(1, 2) + (2a - b)(3, 5) \in \text{span}((1, 2), (3, 5))$$

so the list spans  $\mathbf{F}^2$ . Moreover, for all scalars  $\alpha, \beta \in \mathbf{F}$ ,

$$\begin{aligned} \alpha(1, 2) + \beta(3, 5) = (0, 0) &\implies (\alpha + 3\beta, 2\alpha + 5\beta) = (0, 0) \\ &\implies \begin{cases} \alpha + 3\beta = 0 \\ 2\alpha + 5\beta = 0 \end{cases} \\ &\implies \alpha = \beta = 0 \end{aligned}$$

Thus, the list is linearly independent. Therefore, it is a basis for  $\mathbf{F}^2$ .

- (c) Let's first prove that the list  $(1, 2, -4), (7, -5, 6)$  is linearly independent in  $\mathbf{F}^3$ .

Notice that for all scalars  $\alpha, \beta \in \mathbf{F}$ :

$$\begin{aligned}
 \alpha(1, 2, -4) + \beta(7, -5, 6) = 0 &\implies (\alpha + 7\beta, 2\alpha - 5\beta, -4\alpha + 6\beta) = 0 \\
 &\implies \begin{cases} \alpha + 7\beta = 0 \\ 2\alpha - 5\beta = 0 \\ -4\alpha + 6\beta = 0 \end{cases} \\
 &\implies \begin{cases} \alpha + 7\beta = 0 \\ 4\alpha - 10\beta = 0 \\ -4\alpha + 6\beta = 0 \end{cases} \\
 &\implies \begin{cases} \alpha + 7\beta = 0 \\ 4\beta = 0 \end{cases} \\
 &\implies \begin{cases} \alpha + 7\beta = 0 \\ \beta = 0 \end{cases} \\
 &\implies \alpha = \beta = 0
 \end{aligned}$$

It follows that the list is linearly independent. Now, to show that it doesn't span  $\mathbf{F}^3$ , notice that the standard basis of  $\mathbf{F}^3$  is linearly independent list of length 3. Hence, any spanning list of  $\mathbf{F}^3$  must have length bigger than or equal to 3. Since the given list has length 2, then it cannot span  $\mathbf{F}^3$ .

- (d) First, recall from part (b) of this exercise that the list  $(1, 2), (3, 5)$  spans  $\mathbf{F}^2$ . Hence, for all  $(a, b) \in \mathbf{F}^2$ , there exist scalars  $\alpha, \beta \in \mathbf{F}$  such that

$$\begin{aligned}
 (a, b) &= \alpha(1, 2) + \beta(3, 5) \\
 &= \alpha(1, 2) + \beta(3, 5) + 0(4, 13) \\
 &\in \text{span}((1, 2), (3, 5), (4, 13))
 \end{aligned}$$

It follows that the list  $(1, 2), (3, 5), (4, 13)$  spans  $\mathbf{F}^2$ . However, it is not linearly independent because the standard basis of  $\mathbf{F}^2$  is a spanning list of  $\mathbf{F}^2$  of length 2. Hence, any linearly independent list in  $\mathbf{F}^2$  must have length lesser than 2. Since our given set has length 3, then it cannot be linearly independent.

- (e) Define the set

$$S = \{(x, x, y) \in \mathbf{F}^3 : x, y \in F\}$$

and notice that it is a subspace of  $F^3$ . Let's show that the list  $(1, 1, 0), (0, 0, 1)$  is a basis of  $S$ . First, linear independence follows from the fact that for all  $\alpha, \beta \in \mathbf{F}$ :

$$\begin{aligned}
 \alpha(1, 1, 0) + \beta(0, 0, 1) = 0 &\implies (\alpha, \alpha, \beta) = 0 \\
 &\implies \begin{cases} \alpha = 0 \\ \alpha = 0 \\ \beta = 0 \end{cases} \implies \alpha = \beta = 0
 \end{aligned}$$

To show that the list spans  $S$ , let  $(x, x, y)$  be an arbitrary element of  $S$  where  $x, y \in F$ , then:

$$(x, x, y) = x(1, 1, 0) + y(0, 0, 1) \in \text{span}((1, 1, 0), (0, 0, 1))$$

Therefore, the given list is a basis of  $S$ .

(f) Define the set

$$S = \{(x, y, z) \in \mathbf{F}^3 : x + y + z = 0\}$$

and notice that it is a subspace of  $F^3$ . Let's show that the list  $(1, -1, 0), (1, 0, -1)$  is a basis of  $S$ . First, linear independence follows from the fact that for all  $\alpha, \beta \in \mathbf{F}$ :

$$\begin{aligned} \alpha(1, -1, 0) + \beta(1, 0, -1) = 0 &\implies (\alpha + \beta, -\alpha, -\beta) = 0 \\ &\implies \begin{cases} \alpha + \beta = 0 \\ -\alpha = 0 \\ -\beta = 0 \end{cases} \implies \alpha = \beta = 0 \end{aligned}$$

To show that the list spans  $S$ , let  $(x, y, z)$  be an arbitrary element of  $S$ , then we know that  $x + y + z = 0$  which implies that  $z = -x - y$ . Hence:

$$(x, y, z) = (-y)(1, -1, 0) + (x + y)(1, 0, -1) \in \text{span}((1, -1, 0), (1, 0, -1))$$

Therefore, the given list is a basis of  $S$ .

(g) Consider the list  $1, z, \dots, z^m$  as elements of  $\mathcal{P}_m(\mathbf{F})$ . Notice that for all scalars  $\alpha_0, \alpha_1, \dots, \alpha_m \in \mathbf{F}$ , we have

$$\alpha_0 + \alpha_1 z + \dots + \alpha_m z^m = 0 \implies \alpha_i = 0, \quad i = 0, 1, \dots, m$$

Moreover, given a polynomial  $\alpha_0 + \alpha_1 z + \dots + \alpha_m z^m \in \mathcal{P}_m(\mathbf{F})$ , it directly follows by the way it is written that it is a linear combination of the given list. Therefore, it is a basis of  $\mathcal{P}_m(\mathbf{F})$ .

### Exercise 3

(a) Let  $U$  be the subspace of  $\mathbf{R}^5$  defined by

$$U = \{(x_1, x_2, x_3, x_4, x_5) \in \mathbf{R}^5 : x_1 = 3x_2 \text{ and } x_3 = 7x_4\}.$$

Find a basis of  $U$ .

(b) Extend the basis in (a) to a basis of  $\mathbf{R}^5$ .

(c) Find a subspace  $W$  of  $\mathbf{R}^5$  such that  $\mathbf{R}^5 = U \oplus W$ .

### Solution

(a) Consider the list  $u_1 = (3, 1, 0, 0, 0), u_2 = (0, 0, 7, 1, 0), u_3 = (0, 0, 0, 0, 1)$  and let's prove that it is a basis for  $U$ . First, for any scalars  $\alpha, \beta, \gamma \in \mathbf{R}$ :

$$\begin{aligned} \alpha u_1 + \beta u_2 + \gamma u_3 = 0 &\implies (3\alpha, \alpha, 7\beta, \beta, \gamma) = 0 \\ &\implies \begin{cases} 3\alpha = 0 \\ \alpha = 0 \\ 7\beta = 0 \\ \beta = 0 \\ \gamma = 0 \end{cases} \\ &\implies \alpha = \beta = \gamma = 0 \end{aligned}$$

Moreover, for any  $(x_1, x_2, x_3, x_4, x_5) \in U$ , we now that  $x_1 = 3x_2$  and  $x_3 = 7x_4$ . Hence:

$$\begin{aligned}(x_1, x_2, x_3, x_4, x_5) &= (3x_2, x_2, 7x_4, x_4, x_5) \\ &= x_2u_1 + x_4u_2 + x_5u_3 \\ &\in \text{span}(u_1, u_2, u_3)\end{aligned}$$

Therefore, it is a basis of  $U$ .

- (b) As in the proof of 2.32, consider the list  $(3, 1, 0, 0, 0), (0, 0, 7, 1, 0), (0, 0, 0, 0, 1), e_1, e_2, e_3, e_4, e_5$  where  $e_1, e_2, e_3, e_4, e_5$  is the standard basis for  $\mathbf{R}^5$ . This list is spanning  $\mathbf{R}^5$  but it is not linearly independent. Hence, we can reduce it to a basis as follows. First, remove  $e_5$  because it is already in the list. Keep the first three vectors since we know that they are linearly independent. The vector  $e_1$  cannot be written as a linear combination of the first three vectors so keep it in the list. The vector  $e_2$  can be written as

$$e_2 = (3, 1, 0, 0, 0) - 3e_1$$

so we don't keep it in the list. Similarly,  $e_3$  is not in the span of the first four vectors in the list so we keep it, and  $e_4$  can be written as

$$e_4 = (0, 0, 7, 1, 0) - 7e_3$$

so we remove it. Hence, our original list can be extended to a basis by adding the vectors  $e_1$  and  $e_3$ .

- (c) As in the proof of 2.33, take  $W = \text{span}(e_1, e_3)$ , then it follows that  $\mathbf{R}^5 = U \oplus W$ .

#### Exercise 4

- (a) Let  $U$  be the subspace of  $\mathbf{C}^5$  defined by

$$U = \{(z_1, z_2, z_3, z_4, z_5) \in \mathbf{C}^5 : 6z_1 = z_2 \text{ and } z_3 + 2z_4 + 3z_5 = 0\}.$$

Find a basis of  $U$ .

- (b) Extend the basis in (a) to a basis of  $\mathbf{C}^5$ .  
(c) Find a subspace  $W$  of  $\mathbf{C}^5$  such that  $\mathbf{C}^5 = U \oplus W$ .

#### Solution

- (a) Consider the list  $u_1 = (1, 6, 0, 0, 0), u_2 = (0, 0, -2, 1, 0), u_3 = (0, 0, -3, 0, 1)$  and let's prove that it is a basis for  $U$ . First, for any scalars  $\alpha, \beta, \gamma \in \mathbf{R}$ :

$$\begin{aligned}\alpha u_1 + \beta u_2 + \gamma u_3 = 0 &\implies (\alpha, 6\alpha, -2\beta - 3\gamma, \beta, \gamma) = 0 \\ &\implies \begin{cases} \alpha = 0 \\ 6\alpha = 0 \\ -2\beta - 3\gamma = 0 \\ \beta = 0 \\ \gamma = 0 \end{cases} \\ &\implies \alpha = \beta = \gamma = 0\end{aligned}$$



Moreover, for any  $(z_1, z_2, z_3, z_4, z_5) \in U$ , we now that  $6z_1 = z_2$  and  $z_3 + 2z_4 + 3z_5 = 0$ . Hence:

$$\begin{aligned}(z_1, z_2, z_3, z_4, z_5) &= (z_1, 6z_1, -2z_4 - 3z_5, z_4, z_5) \\ &= z_1 u_1 + z_4 u_2 + z_5 u_3 \\ &\in \text{span}(u_1, u_2, u_3)\end{aligned}$$

Therefore, it is a basis of  $U$ .

- (b) As in the proof of 2.32, consider the list  $u_1, u_2, u_3, e_1, e_2, e_3, e_4, e_5$  where  $e_1, e_2, e_3, e_4, e_5$  is the standard basis for  $\mathbf{C}^5$ . This list is spanning  $\mathbf{C}^5$  but it is not linearly independent. Hence, we can reduce it to a basis as follows. First, keep the first three vectors since we know that they are linearly independent. The vector  $e_1$  cannot be written as a linear combination of the first three vectors so keep it in the list. The vector  $e_2$  can be written as

$$e_2 = \frac{1}{6}(u_1 - e_1)$$

so we don't keep it in the list. Similarly,  $e_3$  is not in the span of the first four vectors in the list so we keep it, and  $e_4$  can be written as

$$e_4 = u_2 + 2e_3$$

so we remove it. Again, we also remove  $e_5$  because

$$e_5 = u_3 + 3e_3$$

Hence, our original list can be extended to a basis by adding the vectors  $e_1$  and  $e_3$ .

- (c) As in the proof of 2.33, take  $W = \text{span}(e_1, e_3)$ , then it follows that  $\mathbf{C}^5 = U \oplus W$ .

### Exercise 5

Suppose  $V$  is finite-dimensional and  $U, W$  are subspaces of  $V$  such that  $V = U + W$ . Prove that there exists a basis of  $V$  consisting of vectors in  $U \cup W$ .

### Solution

Since  $V$  is finite-dimensional, then  $U$  and  $W$  must be finite-dimensional as well by Proposition 2.25. Hence, let  $u_1, \dots, u_n$  be a list of vectors spanning  $U$ , and  $w_1, \dots, w_m$  be a list of vectors spanning  $W$ . Consider the list  $u_1, \dots, u_n, w_1, \dots, w_m$  of vectors in  $U \cup W$ . Notice that for all  $v \in V = U + W$ , there exist vectors  $u \in U$  and  $w \in W$  such that  $v = u + w$ . Moreover, since the lists  $u_1, \dots, u_n$  and  $w_1, \dots, w_m$  are spanning their respective subspaces, then there exist scalars  $\alpha_1, \dots, \alpha_n \in \mathbf{F}$  and  $\beta_1, \dots, \beta_m \in \mathbf{F}$  such that

$$u = \alpha_1 u_1 + \dots + \alpha_n u_n$$

and

$$w = \beta_1 w_1 + \dots + \beta_m w_m$$

It follows that

$$v = \alpha_1 u_1 + \dots + \alpha_n u_n + \beta_1 w_1 + \dots + \beta_m w_m$$

so the list  $u_1, \dots, u_n, w_1, \dots, w_m$  spans  $V$ . By Proposition 2.30, this list must contain a sublist that is a basis of  $V$ . Thus, such a sublist is indeed a basis of  $V$  consisting of vectors in  $U \cup W$  by construction.

### Exercise 6

Prove or give a counterexample: If  $p_0, p_1, p_2, p_3$  is a list in  $\mathcal{P}_3(\mathbf{F})$  such that none of the polynomials  $p_0, p_1, p_2, p_3$  has degree 2, then  $p_0, p_1, p_2, p_3$  is not a basis of  $\mathcal{P}_3(\mathbf{F})$ .

### Solution

Consider the following list of polynomials in  $\mathcal{P}_3(\mathbf{F})$ :

$$\begin{aligned} p_0(x) &= 1 & p_2(x) &= 1 + x + x^2 + x^3 \\ p_1(x) &= x & p_3(x) &= x^3 \end{aligned}$$

and notice that it contains no polynomials of degree 2. Let's show that it is a basis for  $\mathcal{P}_3(\mathbf{F})$ . To do so, consider the fact that  $1, x, x^3 \in \text{span}(p_0, p_1, p_2, p_3)$ . Moreover,

$$x^2 = p_2 - p_0 - p_1 - p_3 \in \text{span}(p_0, p_1, p_2, p_3)$$

Hence,  $\text{span}(p_0, p_1, p_2, p_3)$  is a subspace that contains the standard basis of  $\mathcal{P}_3(\mathbf{F})$ . It follows that  $p_0, p_1, p_2, p_3$  spans  $\mathcal{P}_3(\mathbf{F})$ . To prove the linear independence, simply take scalars  $a_0, a_1, a_2, a_3 \in \mathbf{F}$  and notice that

$$\begin{aligned} a_0 p_0 + a_1 p_1 + a_2 p_2 + a_3 p_3 = 0 &\implies a_0 + a_1 x + a_2(1 + x + x^2 + x^3) + a_3 x^3 = 0 \\ &\implies (a_0 + a_2) + (a_1 + a_2)x + a_2 x^2 + (a_3 + a_2)x^3 = 0 \\ &\implies \begin{cases} a_0 + a_2 = 0 \\ a_1 + a_2 = 0 \\ a_2 = 0 \\ a_3 + a_2 = 0 \end{cases} \\ &\implies a_0 = a_1 = a_2 = a_3 = 0 \end{aligned}$$

Therefore,  $p_0, p_1, p_2, p_3$  is a basis of  $\mathcal{P}_3(\mathbf{F})$  even if it contains no polynomials of degree 2.

### Exercise 7

Suppose  $v_1, v_2, v_3, v_4$  is a basis of  $V$ . Prove that

$$v_1 + v_2, v_2 + v_3, v_3 + v_4, v_4$$

is also a basis of  $V$ .

### Solution

First, let's prove that it is linearly independent. Take scalars  $a_1, a_2, a_3, a_4 \in \mathbf{F}$ , by

linear independence of  $v_1, v_2, v_3, v_4$ :

$$\begin{aligned}
 & a_1(v_1 + v_2) + a_2(v_2 + v_3) + a_3(v_3 + v_4) + a_4v_4 = 0 \\
 \implies & a_1v_1 + (a_1 + a_2)v_2 + (a_2 + a_3)v_3 + (a_3 + a_4)v_4 = 0 \\
 \implies & \begin{cases} a_1 = 0 \\ a_1 + a_2 = 0 \\ a_2 + a_3 = 0 \\ a_3 + a_4 = 0 \end{cases} \\
 \implies & a_1 = a_2 = a_3 = a_4 = 0
 \end{aligned}$$

To prove that it spans  $V$ , take  $v \in V$ . Since  $v_1, v_2, v_3, v_4$  spans  $V$ , then there exist scalars  $a_1, a_2, a_3, a_4 \in \mathbf{F}$  such that

$$u = a_1v_1 + a_2v_2 + a_3v_3 + a_4v_4$$

But since

$$\begin{aligned}
 v_1 &= (v_1 + v_2) - (v_2 + v_3) + (v_3 + v_4) - v_4 \\
 v_2 &= (v_2 + v_3) - (v_3 + v_4) + v_4
 \end{aligned}$$

and

$$v_3 = (v_3 + v_4) - v_4,$$

then

$$\begin{aligned}
 u &= a_1v_1 + a_2v_2 + a_3v_3 + a_4v_4 \\
 &= a_1[(v_1 + v_2) - (v_2 + v_3) + (v_3 + v_4) - v_4] \\
 &\quad + a_2[(v_2 + v_3) - (v_3 + v_4) + v_4] \\
 &\quad + a_3[(v_3 + v_4) - v_4] + a_4v_4 \\
 &= a_1(v_1 + v_2) + (a_2 - a_1)(v_2 + v_3) \\
 &\quad + (a_3 - a_2 + a_1)(v_3 + v_4) + (a_4 - a_3 + a_2 - a_1)v_4
 \end{aligned}$$

which proves that it spans  $V$ . Therefore, the new list of vectors is also a basis of  $V$ .

### Exercise 8

Prove or give a counterexample: If  $v_1, v_2, v_3, v_4$  is a basis of  $V$  and  $U$  is a subspace of  $V$  such that  $v_1, v_2 \in U$  and  $v_3 \notin U$  and  $v_4 \notin U$ , then  $v_1, v_2$  is a basis of  $U$ .

### Solution

Consider the following counterexample: Take  $V = \mathbf{R}^4$ ,  $v_1, v_2, v_3, v_4$  be the standard basis and define

$$U = \text{span}(v_1, v_2, (0, 0, 1, 1))$$

Obviously,  $U$  is a subspace of  $V$  that contains  $v_1$  and  $v_2$ . Moreover, if  $v_3 \in U$ , then there would be scalars  $a, b, c \in \mathbf{R}$  such that

$$(0, 0, 1, 0) = (a, b, c, c) \implies c = 1 \text{ and } c = 0,$$

a contradiction that shows that  $v_3 \notin U$ . Using a similar argument,  $v_4 \notin U$  as well. However,  $v_1, v_2$  is not a basis of  $U$  because it doesn't span it. Take for example

$(0, 0, 1, 1) \in U$  which is not in the span of  $v_1, v_2$ .

### Exercise 9

Suppose  $v_1, \dots, v_m$  is a list of vectors in  $V$ . For  $k \in \{1, \dots, m\}$ , let

$$w_k = v_1 + \dots + v_k.$$

Show that  $v_1, \dots, v_m$  is a basis of  $V$  if and only if  $w_1, \dots, w_m$  is a basis of  $V$ .

### Solution

Suppose that  $v_1, \dots, v_m$  is a basis, then it is linearly independent. By Section 2A Exercise 14,  $w_1, \dots, w_m$  must be linearly independent as well. Moreover, since  $v_1, \dots, v_m$  is a basis, then  $\text{span}(v_1, \dots, v_m) = V$ . Again, using Section 2A Exercise 3, we have that  $\text{span}(w_1, \dots, w_m) = \text{span}(v_1, \dots, v_m) = V$ . It follows that  $w_1, \dots, w_m$  spans  $V$ . Therefore,  $w_1, \dots, w_m$  is a basis of  $V$ . All the arguments presented here prove the reverse implication as well.

### Exercise 10

Suppose  $U$  and  $W$  are subspace of  $V$  such that  $V = U \oplus W$ . Suppose also that  $u_1, \dots, u_m$  is a basis of  $U$  and  $w_1, \dots, w_n$  is basis of  $W$ . Prove that

$$u_1, \dots, u_m, w_1, \dots, w_n$$

is a basis of  $V$ .

### Solution

First, let's prove that  $u_1, \dots, u_m, w_1, \dots, w_n$  spans  $V$ . Take an arbitrary  $v \in V$ , then there exist vectors  $u \in U$  and  $w \in W$  such that  $v = u + w$ . Since  $u_1, \dots, u_m$  is a basis of  $U$  and  $w_1, \dots, w_n$  is basis of  $W$ , then there exist scalars  $\alpha_1, \dots, \alpha_m, \beta_1, \dots, \beta_n \in \mathbf{F}$  such that

$$u = \alpha_1 u_1 + \dots + \alpha_m u_m$$

and

$$w = \beta_1 w_1 + \dots + \beta_n w_n$$

It follows that

$$v = \alpha_1 u_1 + \dots + \alpha_m u_m + \beta_1 w_1 + \dots + \beta_n w_n \in \text{span}(u_1, \dots, u_m, w_1, \dots, w_n)$$

which proves that the list spans  $V$ . Now, to prove the linear independence, take arbitrary scalars  $\alpha_1, \dots, \alpha_m, \beta_1, \dots, \beta_n \in \mathbf{F}$  and recall that  $u + w = 0 \implies u = w = 0$  for all  $u \in U$  and  $w \in W$ . Hence,

$$\alpha_1 u_1 + \dots + \alpha_m u_m + \beta_1 w_1 + \dots + \beta_n w_n = 0$$

implies

$$\begin{cases} \alpha_1 u_1 + \dots + \alpha_m u_m = 0 \\ \beta_1 w_1 + \dots + \beta_n w_n = 0 \end{cases}$$

But since the lists  $u_1, \dots, u_m$  and  $w_1, \dots, w_n$  are linearly independent, then we get

$$\alpha_1 = \dots = \alpha_m = \beta_1 = \dots = \beta_n = 0$$

Therefore, the list  $u_1, \dots, u_m, w_1, \dots, w_m$  is a basis of  $V$ .

### Exercise 11

Suppose  $V$  is a real vector space. Show that if  $v_1, \dots, v_n$  is a basis of  $V$  (as a real vector space), then  $v_1, \dots, v_n$  is also a basis of the complexification  $V_{\mathbf{C}}$  (as a complex vector space).

### Solution

First, let's show that  $v_1, \dots, v_n$  spans  $V_{\mathbf{C}}$ . To do so, let  $u + iv \in V_{\mathbf{C}}$  be an arbitrary vector. Since  $u, v \in V$ , then there exist scalars  $\alpha_1, \dots, \alpha_n, \beta_1, \dots, \beta_n \in \mathbf{R}$  such that

$$u = \alpha_1 v_1 + \dots + \alpha_n v_n$$

and

$$v = \beta_1 v_1 + \dots + \beta_n v_n.$$

It follows that

$$\begin{aligned} u + iv &= \alpha_1 v_1 + \dots + \alpha_n v_n + i\beta_1 v_1 + \dots + i\beta_n v_n \\ &\in \text{span}(v_1, \dots, v_n) \end{aligned}$$

Thus,  $v_1, \dots, v_n$  spans  $V_{\mathbf{C}}$ . To prove the linear independence, let  $\alpha_1 + i\beta_1, \dots, \alpha_n + i\beta_n \in \mathbf{C}$  be complex scalars and notice that

$$\begin{aligned} &(\alpha_1 + i\beta_1)v_1 + \dots + (\alpha_n + i\beta_n)v_n = 0 \\ \implies &[\alpha_1 v_1 + \dots + \alpha_n v_n] + i[\beta_1 v_1 + \dots + \beta_n v_n] = 0 \\ \implies &\begin{cases} \alpha_1 v_1 + \dots + \alpha_n v_n = 0 \\ \beta_1 v_1 + \dots + \beta_n v_n = 0 \end{cases} \\ \implies &\alpha_1 = \dots = \alpha_n = \beta_1 = \dots = \beta_n = 0 \\ \implies &\alpha_1 + i\beta_1 = \dots = \alpha_n + i\beta_n = 0 \end{aligned}$$

Thus, the vectors  $v_1, \dots, v_n$  are linearly independent in  $V_{\mathbf{C}}$ . Therefore, it is a basis of  $V_{\mathbf{C}}$ .

## 2C Dimension

### Exercise 1

Show that the subspaces of  $\mathbf{R}^2$  are precisely  $\{0\}$ , all lines in  $\mathbf{R}^2$  containing the origin, and  $\mathbf{R}^2$ .

### Solution

Let  $V$  be a subspace of  $\mathbf{R}^2$ . Since  $\mathbf{R}^2$  has dimension 2, then  $0 \leq \dim V \leq 2$  by Proposition 2.37. If  $V$  has dimension 0, then its basis must be the empty set. In that case,  $V = \text{span}(\emptyset) = \{0\}$ . If  $V$  has dimension 1, then its basis must contain a single non-zero vector. It follows that

$$V = \text{span}(u) = \{\lambda u : \lambda \in \mathbf{R}\}.$$

But notice that  $\lambda u$  with  $\lambda \in \mathbf{R}$  is simply the equation of a line with direction vector  $u$  passing through the origin (take  $\lambda = 0$ ), hence,  $V$  is a line passing through the origin. Finally, if  $V$  has dimension 2, then by Proposition 2.39,  $V = \mathbf{R}^2$ . Therefore, since  $V$  was an arbitrary subspace, then subspaces of  $\mathbf{R}^2$  are  $\{0\}$ , all lines in  $\mathbf{R}^2$  containing the origin, and  $\mathbf{R}^2$ .

To prove that the subspaces of  $\mathbf{R}^2$  are precisely these subsets, let's show that any of these subsets are subspaces. Trivially,  $\{0\}$  and  $\mathbf{R}^2$  are indeed subspaces of  $\mathbf{R}^2$ . Now, let  $L$  be a line in  $\mathbf{R}^2$  passing through the origin, then  $L$  must have a direction vector  $u$ . Moreover, if  $L$  passes through the point  $P$ , then we can write

$$L = \{P + \lambda u : \lambda\}$$

Since  $L$  contains the origin, then we can take  $P = 0$  which implies that

$$L = \{\lambda u : \lambda\} = \text{span}(u)$$

which is a subspace of  $\mathbf{R}^2$ . Therefore, the subspaces of  $\mathbf{R}^2$  are precisely  $\{0\}$ , all lines in  $\mathbf{R}^2$  containing the origin, and  $\mathbf{R}^2$ .

### Exercise 2

Show that the subspaces of  $\mathbf{R}^3$  are precisely  $\{0\}$ , all lines in  $\mathbf{R}^3$  containing the origin, all planes in  $\mathbf{R}^3$  containing the origin, and  $\mathbf{R}^3$ .

### Solution

Let  $V$  be a subspace of  $\mathbf{R}^3$ . Since  $\mathbf{R}^3$  has dimension 3, then  $0 \leq \dim V \leq 3$  by Proposition 2.37. If  $V$  has dimension 0, then its basis must be the empty set. In that case,  $V = \text{span}(\emptyset) = \{0\}$ . If  $V$  has dimension 1, then its basis must contain a single non-zero vector. It follows that

$$V = \text{span}(u) = \{\lambda u : \lambda \in \mathbf{R}\}.$$

But notice that  $\lambda u$  with  $\lambda \in \mathbf{R}$  is simply the equation of a line with direction vector  $u$  passing through the origin (take  $\lambda = 0$ ), hence,  $V$  is a line passing through the origin. If  $V$  has dimension 2, then there are two linearly independent vectors  $u_1, u_2$  such that

$$V = \text{span}(u_1, u_2) = \{\alpha u_1 + \beta u_2 : \alpha, \beta \in \mathbf{R}\}$$

But notice that  $\alpha u_1 + \beta u_2$  is simply the equation of a plane containing the origin described by the two vectors  $u_1$  and  $u_2$ . Hence,  $V$  is a plane containing the origin. Finally, if  $V$  has dimension 3, then by Proposition 2.39,  $V = \mathbf{R}^3$ . Thus, subspaces of  $\mathbf{R}^3$  are  $\{0\}$ , lines and planes containing the origin and  $\mathbf{R}^3$ .

To prove that the subspaces of  $\mathbf{R}^3$  are precisely these subsets, let's show that any of these subsets are subspaces. Trivially,  $\{0\}$  and  $\mathbf{R}^3$  are indeed subspaces of  $\mathbf{R}^3$ . Now, let  $L$  be a line in  $\mathbf{R}^3$  passing through the origin, then  $L$  must have a direction vector  $u$ . Moreover, if  $L$  passes through the point  $P$ , then we can write

$$L = \{P + \lambda u : \lambda\}$$

Since  $L$  contains the origin, then we can take  $P = 0$  which implies that

$$L = \{\lambda u : \lambda\} = \text{span}(u)$$

which is a subspace of  $\mathbf{R}^3$ . Similarly, if  $P$  is a plane in  $\mathbf{R}^3$  containing the origin, then it must contain two linearly independent vectors  $u_1, u_2$  that describe the orientation of the plane. Moreover, if  $A$  is a point on the plane  $P$ , then the vectors in the  $P$  are described by the equation

$$A + \alpha u_1 + \beta u_2$$

Since  $P$  contains the origin, then take  $A = 0$  to get:

$$P = \{\alpha u_1 + \beta u_2 : \alpha, \beta \in \mathbf{R}\} = \text{span}(u_1, u_2)$$

It follows that  $P$  is a subspace of  $\mathbf{R}^3$ . Therefore, the subspaces of  $\mathbf{R}^2$  are precisely  $\{0\}$ , all lines in  $\mathbf{R}^2$  containing the origin, and  $\mathbf{R}^2$ .

### Exercise 3

- (a) Let  $U = \{p \in \mathcal{P}_4(\mathbf{F}) : p(6) = 0\}$ . Find a basis of  $U$ .
- (b) Extend the basis in (a) to a basis of  $\mathcal{P}_4(\mathbf{F})$ .
- (c) Find a subspace  $W$  of  $\mathcal{P}_4(\mathbf{F})$  such that  $\mathcal{P}_4(\mathbf{F}) = U \oplus W$ .

### Solution

- (a) Consider the list  $p_1, p_2, p_3, p_4$  defined by

$$\begin{aligned} p_1(x) &= x - 6 & p_2(x) &= x^2 - 6x \\ p_3(x) &= x^3 - 6x^2 & p_4(x) &= x^4 - 6x^3 \end{aligned}$$

This list spans  $U$  because given any  $p \in U$ , then  $p$  is a polynomial of degree four that has 6 as a root. Hence, we can factorize  $x - 6$  such that  $p(x) = (x - 6)(ax^3 + bx^2 + cx + d)$  for some  $a, b, c, d \in \mathbf{F}$ . Thus:

$$\begin{aligned} p(x) &= (x - 6)(ax^3 + bx^2 + cx + d) \\ &= a(x^4 - 6x^3) + b(x^3 - 6x^2) + c(x^2 - 6x) + d(x - 6) \\ &= ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) \end{aligned}$$

which shows that the list spans  $U$ . To show that it is linearly independent, take scalars  $a, b, c, d \in \mathbf{F}$  and notice that

$$\begin{aligned}
 & ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) = 0 \\
 \implies & a(x^4 - 6x^3) + b(x^3 - 6x^2) + c(x^2 - 6x) + d(x - 6) = 0 \\
 \implies & ax^4 + (b - 6a)x^3 + (c - 6b)x^2 + (d - 6c)x + (-6d) = 0 \\
 \implies & \begin{cases} a = 0 \\ b - 6a = 0 \\ c - 6b = 0 \\ d - 6c = 0 \\ -6d = 0 \end{cases} \\
 \implies & a = b = c = d = 0
 \end{aligned}$$

Therefore,  $p_1, p_2, p_3, p_4$  is a basis of  $U$ .

- (b) Since the list  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ , then it must be linearly independent in  $\mathcal{P}_4(\mathbf{F})$ . Hence, we can extend it to a basis of  $\mathcal{P}_4(\mathbf{F})$ . To do so, we only need to add one single polynomial to our list because we already know a basis of  $\mathcal{P}_4(\mathbf{F})$  of size 5:  $1, x, x^2, x^3, x^4$ . It is easy to notice that the constant polynomial 1 cannot be written as a linear combination of  $p_1, p_2, p_3, p_4$  because for any scalars  $a, b, c, d \in \mathbf{F}$ :

$$\begin{aligned}
 & ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) = 1 \\
 \implies & a(x^4 - 6x^3) + b(x^3 - 6x^2) + c(x^2 - 6x) + d(x - 6) = 1 \\
 \implies & ax^4 + (b - 6a)x^3 + (c - 6b)x^2 + (d - 6c)x + (-6d) = 1 \\
 \implies & \begin{cases} a = 0 \\ b - 6a = 0 \\ c - 6b = 0 \\ d - 6c = 0 \\ -6d = 1 \end{cases} \\
 \implies & a = b = c = d = 0 \text{ and } d = -\frac{1}{6}
 \end{aligned}$$

A contradiction. Therefore, by Section 2A Exercise 13, the list  $1, p_1, p_2, p_3, p_4$  is linearly independent. Since the list has length 5, then it must be a basis by Proposition 2.38.

- (c) Since  $1, p_1, p_2, p_3, p_4$  is a basis of  $\mathcal{P}_4(\mathbf{F})$ , then we can easily get

$$\mathcal{P}_4(\mathbf{F}) = U \oplus \mathbf{F}$$

where  $\mathbf{F}$  denotes the set of constant polynomials.

#### Exercise 4

- (a) Let  $U = \{p \in \mathcal{P}_4(\mathbf{F}) : p''(6) = 0\}$ . Find a basis of  $U$ .



- (b) Extend the basis in (a) to a basis of  $\mathcal{P}_4(\mathbf{F})$ .
- (c) Find a subspace  $W$  of  $\mathcal{P}_4(\mathbf{F})$  such that  $\mathcal{P}_4(\mathbf{F}) = U \oplus W$ .

**Solution**

- (a) Consider the list  $p_1, p_2, p_3, p_4$  defined by

$$\begin{aligned} p_1(x) &= 1 & p_2(x) &= x \\ p_3(x) &= \frac{1}{6}x^3 - 3x^2 & p_4(x) &= \frac{1}{12}x^4 - x^3 \end{aligned}$$

To show that it is linearly independent, take scalars  $a, b, c, d \in \mathbf{F}$  and notice that

$$\begin{aligned} & ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) = 0 \\ \implies & a\left(\frac{1}{12}x^4 - x^3\right) + b\left(\frac{1}{6}x^3 - 3x^2\right) + cx + d = 0 \\ \implies & \frac{a}{12}x^4 + \left(\frac{b}{6} - a\right)x^3 + (-3b)x^2 + cx + d = 0 \\ \implies & \begin{cases} \frac{a}{12} = 0 \\ \frac{b}{6} - a = 0 \\ -3b = 0 \\ c = 0 \\ d = 0 \end{cases} \\ \implies & a = b = c = d = 0 \end{aligned}$$

Therefore,  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ . To prove that it is a basis, consider its span. If  $p_1, p_2, p_3, p_4$  don't span  $U$ , then we must be able to extend it to a basis of  $U$ . However, since  $\dim U \leq \dim \mathcal{P}_4(\mathbf{F}) = 5$ , then we can add only one polynomial. In this case,  $U$  has a basis of length 5 which implies that  $U = \mathcal{P}_4(\mathbf{F})$  by Proposition 2.39, a contradiction since  $x^2 \notin U$ . It follows that the list  $p_1, p_2, p_3, p_4$  must span  $U$ . Therefore, it is a basis of  $U$ .

- (b) Since the list  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ , then it must be linearly independent in  $\mathcal{P}_4(\mathbf{F})$ . Hence, we can extend it to a basis of  $\mathcal{P}_4(\mathbf{F})$ . To do so, we only need to add one single polynomial to our list because we already know a basis of  $\mathcal{P}_4(\mathbf{F})$  of size 5:  $1, x, x^2, x^3, x^4$ . It is easy to notice that the polynomial  $x^2$  cannot be written as a linear combination of  $p_1, p_2, p_3, p_4$  since  $x^2 \notin U$ . Therefore, by Section 2A Exercise 13, the list  $x^2, p_1, p_2, p_3, p_4$  is linearly independent. Since the list has length 5, then it must be a basis by Proposition 2.38.
- (c) Since  $x^2, p_1, p_2, p_3, p_4$  is a basis of  $\mathcal{P}_4(\mathbf{F})$ , then we can easily get

$$\mathcal{P}_4(\mathbf{F}) = U \oplus \mathbf{F}x^2$$

where  $\mathbf{F}x^2$  denotes the span of the polynomial  $x^2$ .

**Exercise 5**

- (a) Let  $U = \{p \in \mathcal{P}_4(\mathbf{F}) : p(2) = p(5)\}$ . Find a basis of  $U$ .
- (b) Extend the basis in (a) to a basis of  $\mathcal{P}_4(\mathbf{F})$ .
- (c) Find a subspace  $W$  of  $\mathcal{P}_4(\mathbf{F})$  such that  $\mathcal{P}_4(\mathbf{F}) = U \oplus W$ .

**Solution**

- (a) Consider the list  $p_1, p_2, p_3, p_4$  defined by

$$\begin{aligned} p_1(x) &= 1 & p_2(x) &= (x-2)(x-5) \\ p_3(x) &= x(x-2)(x-5) & p_4(x) &= x^2(x-2)(x-5) \end{aligned}$$

To show that it is linearly independent, take scalars  $a, b, c, d \in \mathbf{F}$  and notice that

$$\begin{aligned} & ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) = 0 \\ \implies & a(x^4 - 7x^3 + 10x^2) + b(x^3 - 7x^2 + 10x) + c(x^2 - 7x + 10) + d = 0 \\ \implies & ax^4 + (b - 7a)x^3 + (c - 7b + 10a)x^2 + (10b - 7c)x + (10c + d) = 0 \\ \implies & \begin{cases} a = 0 \\ b - 7a = 0 \\ c - 7b + 10a = 0 \\ 10b - 7c = 0 \\ 10c + d = 0 \end{cases} \\ \implies & a = b = c = d = 0 \end{aligned}$$

Therefore,  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ . To prove that it is a basis, consider its span. If  $p_1, p_2, p_3, p_4$  don't span  $U$ , then we must be able to extend it to a basis of  $U$ . However, since  $\dim U \leq \dim \mathcal{P}_4(\mathbf{F}) = 5$ , then we can add only one polynomial. In this case,  $U$  has a basis of length 5 which implies that  $U = \mathcal{P}_4(\mathbf{F})$  by Proposition 2.39, a contradiction since  $x^2 \notin U$ . It follows that the list  $p_1, p_2, p_3, p_4$  must span  $U$ . Therefore, it is a basis of  $U$ .

- (b) Since the list  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ , then it must be linearly independent in  $\mathcal{P}_4(\mathbf{F})$ . Hence, we can extend it to a basis of  $\mathcal{P}_4(\mathbf{F})$ . To do so, we only need to add one single polynomial to our list because we already know a basis of  $\mathcal{P}_4(\mathbf{F})$  of size 5:  $1, x, x^2, x^3, x^4$ . It is easy to notice that the polynomial  $x^2$  cannot be written as a linear combination of  $p_1, p_2, p_3, p_4$  since  $x^2 \notin U$ . Therefore, by Section 2A Exercise 13, the list  $x^2, p_1, p_2, p_3, p_4$  is linearly independent. Since the list has length 5, then it must be a basis by Proposition 2.38.

- (c) Since  $x^2, p_1, p_2, p_3, p_4$  is a basis of  $\mathcal{P}_4(\mathbf{F})$ , then we can easily get

$$\mathcal{P}_4(\mathbf{F}) = U \oplus \mathbf{F}x^2$$

where  $\mathbf{F}x^2$  denotes the span of the polynomial  $x^2$ .

**Exercise 6**

- (a) Let  $U = \{p \in \mathcal{P}_4(\mathbf{F}) : p(2) = p(5) = p(6)\}$ . Find a basis of  $U$ .
- (b) Extend the basis in (a) to a basis of  $\mathcal{P}_4(\mathbf{F})$ .
- (c) Find a subspace  $W$  of  $\mathcal{P}_4(\mathbf{F})$  such that  $\mathcal{P}_4(\mathbf{F}) = U \oplus W$ .

**Solution**

- (a) Consider the list  $p_1, p_2, p_3$  defined by

$$\begin{aligned} p_1(x) &= 1 \\ p_2(x) &= (x-2)(x-5)(x-6) \\ p_3(x) &= x(x-2)(x-5)(x-6) \end{aligned}$$

To show that it is linearly independent, take scalars  $a, b, c \in \mathbf{F}$  and notice that

$$\begin{aligned} &ap_3(x) + bp_2(x) + cp_1(x) = 0 \\ \implies &a(x^4 - 13x^3 + 52x^2 - 60x) + b(x^3 - 13x^2 + 52x - 60) + c = 0 \\ \implies &ax^4 + (b - 13a)x^3 + (52a - 13b)x^2 + (52b - 60a)x + (c - 60b) = 0 \\ \implies &\begin{cases} a = 0 \\ b - 13a = 0 \\ 52a - 13b = 0 \\ 52b - 60a = 0 \\ c - 60b = 0 \end{cases} \\ \implies &a = b = c = 0 \end{aligned}$$

Therefore,  $p_1, p_2, p_3$  is linearly independent in  $U$ . Let's now show that it spans  $U$ . To do so, let  $p$  be an arbitrary polynomial in  $U$ , then  $p - p(2)$  must have roots at  $x = 2, 5, 6$  which means that

$$p(x) - p(2) = (x-2)(x-5)(x-6)q(x)$$

where  $q$  is a polynomial of degree 1. Thus, there exist scalars  $a, b \in \mathbf{F}$  such that  $q(x) = ax + b$ . Thus,

$$\begin{aligned} p(x) &= (x-2)(x-5)(x-6)q(x) + p(2) \\ &= (x-2)(x-5)(x-6)(ax+b) + p(2) \\ &= ax(x-2)(x-5)(x-6) + b(x-2)(x-5)(x-6) + p(2) \\ &= ap_3(x) + bp_2(x) + p(2)p_1(x) \\ &\in \text{span}(p_1, p_2, p_3) \end{aligned}$$

Therefore,  $p_1, p_2, p_3$  is a basis for  $U$ .

- (b) Since the list  $p_1, p_2, p_3$  is linearly independent in  $U$ , then it must be linearly independent in  $\mathcal{P}_4(\mathbf{F})$ . Hence, we can extend it to a basis of  $\mathcal{P}_4(\mathbf{F})$ . To do so, we need to add two polynomials to our list because  $\dim \mathcal{P}_4(\mathbf{F}) = 5$ . It is

easy to see that the polynomial  $x$  cannot be written as a linear combination of  $p_1, p_2, p_3$  since  $x \notin U$ . Therefore, by Section 2A Exercise 13, the list  $x, p_1, p_2, p_3$  is linearly independent. Let's add one last polynomial to our list to make it a basis of  $U$ . Suppose that  $x^2 \in \text{span}(x, p_1, p_2, p_3)$ , then there exist scalars  $a, b, c, d \in \mathbf{F}$  such that

$$x^2 = ax + bp_1(x) + cp_2(x) + dp_3(x)$$

But notice that  $bp_1 + cp_2 + dp_3 \in U$  so just define it as  $p_U$ , then we have

$$x^2 = ax + p_U(x)$$

where  $p_U(2) = p_U(5) = p_U(6)$ . This, if we plug-in  $x = 2, 5, 6$ , we get the following system of equations:

$$\begin{aligned} & \begin{cases} 4 = 2a + p_U(2) \\ 25 = 5a + p_U(2) \\ 36 = 6a + p_U(2) \end{cases} \\ \implies & \begin{cases} 21 = 3a \\ 11 = a \end{cases} \end{aligned}$$

A contradiction that shows that  $x^2$  is not in the span of  $x, p_1, p_2, p_3$ . Therefore, by Section 2A Exercise 13, the list  $x, x^2, p_1, p_2, p_3$  is linearly independent. Since the list has length 5, then it must be a basis by Proposition 2.38.

(c) Since  $x, x^2, p_1, p_2, p_3$  is a basis of  $\mathcal{P}_4(\mathbf{F})$ , then we can easily get

$$\mathcal{P}_4(\mathbf{F}) = U \oplus \text{span}(x, x^2)$$

### Exercise 7

- (a) Let  $U = \{p \in \mathcal{P}_4(\mathbf{F}) : \int_{-1}^1 p = 0\}$ . Find a basis of  $U$ .
- (b) Extend the basis in (a) to a basis of  $\mathcal{P}_4(\mathbf{F})$ .
- (c) Find a subspace  $W$  of  $\mathcal{P}_4(\mathbf{F})$  such that  $\mathcal{P}_4(\mathbf{F}) = U \oplus W$ .

### Solution

- (a) Consider the list  $p_1, p_2, p_3, p_4$  defined by

$$\begin{aligned} p_1(x) &= x & p_2(x) &= x^2 - \frac{1}{3} \\ p_3(x) &= x^3 & p_4(x) &= x^4 - \frac{1}{5} \end{aligned}$$

To show that it is linearly independent, take scalars  $a, b, c, d \in \mathbf{F}$  and notice that

$$\begin{aligned}
 & ap_4(x) + bp_3(x) + cp_2(x) + dp_1(x) = 0 \\
 \implies & a\left(x^4 - \frac{1}{5}\right) + bx^3 + c\left(x^2 - \frac{1}{3}\right) + dx = 0 \\
 \implies & ax^4 + bx^3 + cx^2 + dx - \left(\frac{a}{5} + \frac{c}{3}\right) = 0 \\
 \implies & \begin{cases} a = 0 \\ b = 0 \\ c = 0 \\ d = 0 \\ \frac{a}{5} + \frac{c}{3} = 0 \end{cases} \\
 \implies & a = b = c = d = 0
 \end{aligned}$$

Therefore,  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ . To prove that it is a basis, consider its span. If  $p_1, p_2, p_3, p_4$  don't span  $U$ , then we must be able to extend it to a basis of  $U$ . However, since  $\dim U \leq \dim \mathcal{P}_4(\mathbf{F}) = 5$ , then we can add only one polynomial. In this case,  $U$  has a basis of length 5 which implies that  $U = \mathcal{P}_4(\mathbf{F})$  by Proposition 2.39, a contradiction since  $1 \notin U$ . It follows that the list  $p_1, p_2, p_3, p_4$  must span  $U$ . Therefore, it is a basis of  $U$ .

- (b) Since the list  $p_1, p_2, p_3, p_4$  is linearly independent in  $U$ , then it must be linearly independent in  $\mathcal{P}_4(\mathbf{F})$ . Hence, we can extend it to a basis of  $\mathcal{P}_4(\mathbf{F})$ . To do so, we only need to add one single polynomial to our list because  $\dim \mathcal{P}_4(\mathbf{F}) = 5$ . It is easy to notice that the polynomial 1 cannot be written as a linear combination of  $p_1, p_2, p_3, p_4$  since  $1 \notin U$ . Therefore, by Section 2A Exercise 13, the list  $1, p_1, p_2, p_3, p_4$  is linearly independent. Since the list has length 5, then it must be a basis by Proposition 2.38.

- (c) Since  $1, p_1, p_2, p_3, p_4$  is a basis of  $\mathcal{P}_4(\mathbf{F})$ , then we can easily get

$$\mathcal{P}_4(\mathbf{F}) = U \oplus \mathbf{F}$$

where  $\mathbf{F}$  denotes the subspace of constant polynomials.

### Exercise 8

Suppose  $v_1, \dots, v_m$  is linearly independent in  $V$  and  $w \in V$ . Prove that

$$\dim \text{span}(v_1 + w, \dots, v_m + w) \geq m - 1.$$

### Solution

Consider the list  $v_1 + w, \dots, v_m + w$  of length  $m$  and suppose by contradiction that

$$\dim \text{span}(v_1 + w, \dots, v_m + w) = d \leq m - 2,$$

then there exists a linearly independent list of vectors  $u_1, \dots, u_d$  in  $V$  such that

$$\text{span}(v_1 + w, \dots, v_m + w) = \text{span}(u_1, \dots, u_d).$$

For each  $i \in \{1, \dots, n\}$ , the previous equation implies that

$$v_i + w = \alpha_1 u_1 + \dots + \alpha_d u_d,$$

which itself implies that

$$v_i = \alpha_1 u_1 + \dots + \alpha_d u_d - w \in \text{span}(u_1, \dots, u_d, w).$$

Since it holds for all  $i \in \{1, \dots, n\}$ , then

$$\{v_1, \dots, v_m\} \subset \text{span}(u_1, \dots, u_d, w) \implies \text{span}(v_1, \dots, v_m) \leq \text{span}(u_1, \dots, u_d, w).$$

Since subspaces have a dimensions less than the vector space they are contained in (Proposition 2.37), then

$$\dim \text{span}(v_1, \dots, v_m) \leq \dim \text{span}(u_1, \dots, u_d, w). \quad (1)$$

The  $v_i$ 's are linearly independent so they form a basis for their span. It follows that

$$\dim \text{span}(v_1, \dots, v_m) = m. \quad (2)$$

Moreover, the list  $u_1, \dots, u_d, w$  is spanning its span (obviously), so it must contain a basis. Since the list has length  $d + 1$ , then the dimension of the span must be less than  $d + 1$ . But since  $d \leq m - 2$ , then

$$\dim \text{span}(u_1, \dots, u_d, w) \leq m - 1. \quad (3)$$

Combining equations (1), (2) and (3) gives us

$$m \leq m - 1$$

which is clearly a contradiction. Therefore,

$$\dim \text{span}(v_1 + w, \dots, v_m + w) \geq m - 1.$$

### Exercise 9

Suppose  $m$  is a positive integer and  $p_0, p_1, \dots, p_m \in \mathcal{P}(\mathbf{F})$  are such that each  $p_k$  has degree  $k$ . Prove that  $p_0, p_1, \dots, p_m$  is a basis of  $\mathcal{P}_m(\mathbf{F})$ .

### Solution

Since the list  $p_0, p_1, \dots, p_m$  has length  $m + 1$  and we already know that  $\dim \mathcal{P}_m(\mathbf{F}) = m + 1$ , then it suffices to show that the list is linearly independent by Proposition 2.38. Let's prove by induction on  $m$  that any list  $p_0, p_1, \dots, p_m$  such that each  $p_k$  has degree  $k$  must be linearly independent.

For the base case, take  $m = 0$  and consider the list  $p_0$  where  $p_0$  is a polynomial of degree 0. Hence  $p_0$  must be a nonzero constant polynomial (since the zero polynomial has degree  $-\infty$ ). But we know from Section 2A Exercise 4(a) that the list containing  $p_0$  only must be linearly independent since it is nonzero. This proves that the statement holds for  $m = 0$ .

Suppose now that it holds for an integer  $m \geq 0$  and consider the list  $p_0, p_1, \dots, p_{m+1}$

such that each  $p_k$  has degree  $k$ . By our assumption, we know that the list  $p_0, p_1, \dots, p_m$  is linearly independent. If we take arbitrary scalars  $\alpha_0, \dots, \alpha_{m+1}$  satisfying

$$\alpha_0 p_0 + \alpha_1 p_1 + \dots + \alpha_{m+1} p_{m+1} = 0,$$

then notice that  $\alpha_{m+1}$  must be equal to zero since  $p_{m+1}$  is only polynomial in the linear combination containing a  $x^{m+1}$  term. Thus, we get that

$$\alpha_0 p_0 + \alpha_1 p_1 + \dots + \alpha_m p_m = 0.$$

But by linear independence of the  $p_i$ 's, we know that  $\alpha_0 = \dots = \alpha_m = 0$ . It follows that the new list is linearly independent as well. Therefore, by induction, all such lists must be linearly independent and hence, a basis for  $\mathcal{P}_m(\mathbf{F})$ .

### Exercise 10

Suppose  $m$  is a positive integer. For  $0 \leq k \leq m$ , let

$$p_k(x) = x^k(1-x)^{m-k}.$$

Show that  $p_0, \dots, p_m$  is a basis of  $\mathcal{P}_m(\mathbf{F})$ .

### Solution

Since the list  $p_0, p_1, \dots, p_m$  has length  $m+1$  and we already know that  $\dim \mathcal{P}_m(\mathbf{F}) = m+1$ , then it suffices to show that the list is linearly independent by Proposition 2.38.

Let  $\alpha_0, \alpha_1, \dots, \alpha_m \in \mathbf{F}$  be scalars such that

$$\alpha_0 p_0 + \alpha_1 p_1 + \dots + \alpha_m p_m = 0.$$

The polynomial on the left hand side is equal to zero, this implies that the coefficients in front of each monomial of the form  $x^k$  are zero. Given a  $k$  between 0 and  $m$ , notice that the polynomial  $p_k$  can be written as

$$p_k(x) = x^k \sum_{i=0}^{m-k} \binom{m-k}{i} (-1)^i x^i = \sum_{i=k}^m \binom{m-k}{i-k} (-1)^{i-k} x^i$$

using the Binomial Formula. It follows that the lowest degree term in  $p_k$  is  $x^k$ . Therefore, in the list  $p_0, \dots, p_m$ ,  $p_0$  is the only polynomial containing a constant term. Hence, the constant term in the polynomial  $\alpha_0 p_0 + \alpha_1 p_1 + \dots + \alpha_m p_m$  is  $\alpha_0$ . It follows that  $\alpha_0 = 0$ . Thus, we now have the equation

$$\alpha_1 p_1 + \dots + \alpha_m p_m = 0.$$

In the list  $p_1, \dots, p_m$ , the polynomial  $p_1$  is the only polynomial containing the term  $x^1$ . Thus, the coefficient in front of the term  $x^1$  in the polynomial  $\alpha_1 p_1 + \dots + \alpha_m p_m$  is  $\alpha_1$ . It follows that  $\alpha_1 = 0$ . If we continue in this manner, we can prove by induction that all the  $\alpha_i$ 's are zero. Therefore, the list is linearly independent and hence, a basis of  $\mathcal{P}_m(\mathbf{F})$ .

### Exercise 11

Suppose  $U$  and  $V$  are both four-dimensional subspaces of  $\mathbf{C}^6$ . Prove that there exist

two vectors in  $U \cap W$  such that neither of these vectors is a scalar multiple of the other.

**Solution**

By Proposition 2.43, we know that

$$\dim(U + W) = \dim U + \dim W - \dim(U \cap W) \quad (1)$$

Since  $U + W \leq V$ , then by Proposition 2.37,  $\dim(U + W) \leq \dim V = 6$ . Thus, if we substitute this inequality and the known values into equation (1), we get:

$$6 \geq 4 + 4 - \dim(U \cap W),$$

which can be rearranged into

$$\dim(U \cap W) \geq 2.$$

Thus, if we denote by  $d$  the dimension of  $U \cap W$ , then there exists a basis  $v_1, \dots, v_d$  of  $U \cap W$ . Since it is a basis and  $d \geq 2$ , then we can take the vectors  $v_1, v_2 \in U \cap W$  and assert that they are linearly independent. Therefore, there exist two vectors in  $U \cap W$  such that neither of these vectors is a scalar multiple of the other (by linear independence).

**Exercise 12**

Suppose that  $U$  and  $V$  are subspaces of  $\mathbf{R}^8$  such that  $\dim U = 3$ ,  $\dim W = 5$ , and  $U + W = \mathbf{R}^8$ . Prove that  $\mathbf{R}^8 = U \oplus W$ .

**Solution**

Since we already know that  $U + W = \mathbf{R}^8$ , it suffices to prove that  $U \cap W = \{0\}$ . To do so, notice that  $U + W = \mathbf{R}^8$  implies  $\dim(U + W) = 8$ . Using the formula in Proposition 2.43, we get

$$\dim U + \dim V - \dim(U \cap W) = 8.$$

If we plug-in the known values, we get

$$4 + 4 - \dim(U \cap W) = 8,$$

which can be rearranged into

$$\dim(U \cap W) = 0.$$

But the only zero-dimensional vector space is the trivial vector space  $\{0\}$ . Hence,  $U \cap W = \{0\}$ . Therefore,  $\mathbf{R}^8 = U \oplus W$ .

**Exercise 13**

Suppose  $U$  and  $W$  are both five-dimensional subspaces of  $\mathbf{R}^9$ . Prove that  $U \cap W \neq \{0\}$ .

**Solution**

Since  $U + W \leq \mathbf{R}^9$ , then by Proposition 2.37,  $\dim(U + W) \leq \dim \mathbf{R}^9 = 9$ . Using the formula in Proposition 2.43, we get

$$\dim U + \dim V - \dim(U \cap W) \leq 9.$$



If we plug-in the known values, we get

$$5 + 5 - \dim(U \cap W) \leq 9,$$

which can be rearranged into

$$\dim(U \cap W) \geq 1.$$

Therefore,  $U \cap W$  cannot be  $\{0\}$  since otherwise, its dimension would be 0.

#### Exercise 14

Suppose  $V$  is a ten-dimensional vector space and  $V_1, V_2, V_3$  are subspaces of  $V$  with  $\dim V_1 = \dim V_2 = \dim V_3 = 7$ . Prove that  $V_1 \cap V_2 \cap V_3 \neq \{0\}$ .

#### Solution

First, consider the subspace  $V_1 \cap V_2$ . Since  $V_1 + V_2 \leq V$ , then  $\dim(V_1 + V_2) \leq 10$ . It follows that

$$\dim(V_1 \cap V_2) = \dim V_1 + \dim V_2 - \dim(V_1 + V_2) \geq 7 + 7 - 10 = 4.$$

Now, consider the subspace  $V_1 \cap V_2 \cap V_3$  as the intersection between  $V_1 \cap V_2$  and  $V_3$ . Since  $(V_1 \cap V_2) + V_3 \leq V$ , then  $\dim((V_1 \cap V_2) + V_3) \leq 10$ . It follows that

$$\begin{aligned} \dim(V_1 \cap V_2 \cap V_3) &= \dim(V_1 \cap V_2) + \dim V_3 - \dim((V_1 \cap V_2) + V_3) \\ &\geq 4 + 7 - 10 \\ &= 1 \end{aligned}$$

Thus,  $V_1 \cap V_2 \cap V_3$  cannot be  $\{0\}$  since otherwise, its dimension would be 0.

#### Exercise 15

Suppose  $V$  is finite-dimensional and  $V_1, V_2, V_3$  are subspaces of  $V$  with  $\dim V_1 + \dim V_2 + \dim V_3 > 2 \dim V$ . Prove that  $V_1 \cap V_2 \cap V_3 \neq \{0\}$ .

#### Solution

First, consider the subspace  $V_1 \cap V_2$ . Since  $V_1 + V_2 \leq V$ , then  $\dim(V_1 + V_2) \leq \dim V$ . It follows that

$$\dim(V_1 \cap V_2) = \dim V_1 + \dim V_2 - \dim(V_1 + V_2) \geq \dim V_1 + \dim V_2 - \dim V.$$

Now, consider the subspace  $V_1 \cap V_2 \cap V_3$  as the intersection between  $V_1 \cap V_2$  and  $V_3$ . Since  $(V_1 \cap V_2) + V_3 \leq V$ , then  $\dim((V_1 \cap V_2) + V_3) \leq \dim V$ . It follows that

$$\begin{aligned} \dim(V_1 \cap V_2 \cap V_3) &= \dim(V_1 \cap V_2) + \dim V_3 - \dim((V_1 \cap V_2) + V_3) \\ &\geq \dim V_1 + \dim V_2 - \dim(V_1 + V_2) + \dim V_3 - \dim V \\ &\geq \dim V_1 + \dim V_2 + \dim V_3 - \dim V - \dim V \\ &> 2 \dim V - 2 \dim V \\ &= 0 \end{aligned}$$

Thus,  $V_1 \cap V_2 \cap V_3$  cannot be  $\{0\}$  since otherwise, its dimension would be 0.

**Exercise 16**

Suppose  $V$  is finite-dimensional and  $U$  is a subspace of  $V$  with  $U \neq V$ . Let  $n = \dim V$  and  $m = \dim U$ . Prove that there exist  $n - m$  subspaces of  $V$ , each of dimension  $n - 1$ , whose intersection equals  $U$ .

**Solution**

Let  $u_1, \dots, u_m$  be a basis of  $U$  and extend it to a basis

$$u_1, \dots, u_m, v_1, \dots, v_{n-m}$$

of  $V$ . For each  $i \in \{1, \dots, n - m\}$ , define the subspace  $V_i$  of  $V$  as the span of the list  $u_1, \dots, u_m, v_1, \dots, v_{n-m}$  except the vector  $v_i$ . Hence,  $V_i$  is the span of  $n - 1$  linearly independent vectors so  $\dim V_i = n - 1$ . Consider now the intersection  $V_1 \cap \dots \cap V_{n-m}$ . Since each  $V_i$  is the span of a list containing a basis of  $U$ , then  $U$  is a subspace of all the  $V_i$ 's. It follows that

$$U \leq \bigcap_{i=1}^{n-m} V_i.$$

Let  $v$  be an arbitrary vector in  $\bigcap_{i=1}^{n-m} V_i$ , since  $\bigcap_{i=1}^{n-m} V_i \leq V$ , then

$$v = \alpha_1 u_1 + \dots + \alpha_m u_m + \beta v_1 + \dots + \beta_{n-m} v_{n-m}$$

for some scalars  $\alpha_1, \dots, \alpha_m, \beta_1, \dots, \beta_{n-m} \in \mathbf{F}$ . Let  $j \in \{1, \dots, n\}$ , since  $v \in \bigcap_{i=1}^{n-m} V_i$ , then  $v \in V_j$  in particular. Since  $V_j$  is the span of the  $u_i$ 's and  $v_i$ 's except  $v_j$ , then  $V_j$  contains

$$v_0 = \alpha_1 u_1 + \dots + \alpha_m u_m + \beta v_1 + \dots + \beta_{n-m} v_{n-m}$$

where  $\beta_j = 0$ . Hence,  $V_j$  is a subspace that contains both  $v$  and  $v_0$ , so it follows that

$$\beta_j v_j = v - v_0 \in V_j.$$

If  $\beta_j$  is non-zero, then  $v_j \in V_j$ . But since  $V_j$  already contains all the vectors in the basis of  $V$  except  $v_j$ , then  $V_j$  contains a basis of  $V$ . It follows that  $V \leq V_j$  so  $n \leq n - 1$ , a contradiction. Therefore,  $\beta_j = 0$ . Since it holds for all  $j \in \{1, \dots, n - m\}$ , then all the possibly non-zero coefficients in the linear combination of  $v$  are the coefficients in front of the  $u_i$ 's. Hence:

$$v = \alpha_1 u_1 + \dots + \alpha_m u_m + 0 + \dots + 0 \in \text{span}(u_1, \dots, u_m) = U.$$

Since it holds for all  $v \in \bigcap_{i=1}^{n-m} V_i$ , then  $\bigcap_{i=1}^{n-m} V_i \leq U$ . Therefore,  $U = \bigcap_{i=1}^{n-m} V_i$ , which proves that there exist  $n - m$  subspaces of  $V$ , each of dimension  $n - 1$ , whose intersection equals  $U$ .

**Exercise 17**

Suppose that  $V_1, \dots, V_m$  are finite-dimensional subspaces of  $V$ . Prove that  $V_1 + \dots + V_m$  is finite-dimensional and

$$\dim(V_1 + \dots + V_m) \leq \dim V_1 + \dots + \dim V_m.$$

**Solution**

Let  $i \in \{1, \dots, m\}$  and define  $d_i$  as the dimension of  $V_i$ . Since  $V_i$  is finite-dimensional,

then it has a finite basis  $v_1^{(i)}, \dots, v_{d_i}^{(i)}$ . Consider now the list which merges all of these bases:

$$v_1^{(1)}, \dots, v_{d_1}^{(1)}, v_1^{(2)}, \dots, v_{d_2}^{(2)}, \dots, v_1^{(m)}, \dots, v_{d_m}^{(m)}$$

This new list has length  $d_1 + d_2 + \dots + d_m < \infty$ . Moreover, it is easy to see that it is spanning  $V_1 + \dots + V_m$  since for all  $u \in V_1 + \dots + V_m$ , we can write  $u$  as  $u_1 + \dots + u_m$  where  $u_i \in V_i$  for all  $i \in \{1, \dots, m\}$ . Hence, for all  $i \in \{1, \dots, m\}$ , since  $v_1^{(i)}, \dots, v_{d_i}^{(i)}$  is a basis of  $V_i$ , then there exist scalars  $\alpha_1^{(i)}, \dots, \alpha_{d_i}^{(i)} \in \mathbf{F}$  such that

$$u_i = \alpha_1^{(i)} v_1^{(i)} + \dots + \alpha_{d_i}^{(i)} v_{d_i}^{(i)}.$$

It follows that

$$u = \alpha_1^{(1)} v_1^{(1)} + \dots + \alpha_{d_1}^{(1)} v_{d_1}^{(1)} + \dots + \alpha_1^{(m)} v_1^{(m)} + \dots + \alpha_{d_m}^{(m)} v_{d_m}^{(m)}$$

which proves that the list

$$v_1^{(1)}, \dots, v_{d_1}^{(1)}, v_1^{(2)}, \dots, v_{d_2}^{(2)}, \dots, v_1^{(m)}, \dots, v_{d_m}^{(m)}$$

spans  $V_1 + \dots + V_m$ . Hence,  $V_1 + \dots + V_m$  is finite dimensional since it contains a finite spanning list. Moreover, any spanning list must contain a basis. It follows that there exists a sublist of the one presented that it a basis of  $V_1 + \dots + V_m$ . This list has a length less than or equal to the length of the presented list (since it is a sublist) which is equal to  $d_1 + \dots + d_m$ . But since it is a basis, then it has length  $\dim(V_1 + \dots + V_m)$ . Therefore:

$$\dim(V_1 + \dots + V_m) \leq d_1 + \dots + d_m = \dim V_1 + \dots + \dim V_m.$$

### Exercise 18

Suppose  $V$  is finite-dimensional, with  $\dim V = n \geq 1$ . Prove that there exist one-dimensional subspaces  $V_1, \dots, V_n$  of  $V$  such that

$$V = V_1 \oplus \dots \oplus V_n.$$

### Solution

Let  $v_1, \dots, v_n$  be a basis of  $V$  and for each  $i \in \{1, \dots, n\}$ , define the subspace  $V_i$  as the span of the vector  $v_i$ . Let's prove that  $V = V_1 \oplus \dots \oplus V_n$ . First, it is clear that  $V_1 + \dots + V_n \leq V$ . Moreover, for all  $v \in V$ , since  $v_1, \dots, v_n$  is a basis of  $V$ , there exist scalars  $\alpha_1, \dots, \alpha_n \in \mathbf{F}$  such that

$$v = \alpha_1 v_1 + \dots + \alpha_n v_n.$$

For all  $i \in \{1, \dots, n\}$ , the term  $\alpha_i v_i \in V_i$ . It follows that  $v \in V_1 + \dots + V_n$ . Therefore,  $V = V_1 + \dots + V_n$ . To prove that the sum is direct, it suffices to show that zero has a unique representation as a sum of elements in the  $V_i$ 's (Proposition 1.45). But this follows from the fact the  $v_i$ 's are linearly independent since it is a basis. Therefore,

$$V = V_1 \oplus \dots \oplus V_n.$$

**Exercise 19**

Explain why you might guess, motivated by analogy with the formula for the number of elements in the union of three finite sets, that if  $V_1, V_2, V_3$  are subspaces of a finite-dimensional vector space, then

$$\begin{aligned}\dim(V_1 + V_2 + V_3) &= \\ &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \dim(V_1 \cap V_2) - \dim(V_1 \cap V_3) - \dim(V_2 \cap V_3) \\ &\quad + \dim(V_1 \cap V_2 \cap V_3).\end{aligned}$$

Then either prove the formula above or give a counterexample.

**Solution**

Given three finite sets  $S_1, S_2, S_3$ , we can easily derive the following formula for the cardinality of the union of the three sets:

$$\begin{aligned}\#(S_1 \cup S_2 \cup S_3) &= \#(S_1 \cup S_2) + \#S_3 - \#((S_1 \cup S_2) \cap S_3) \\ &= \#S_1 + \#S_2 - \#(S_1 \cap S_2) + \#S_3 - \#((S_1 \cap S_3) \cup (S_2 \cap S_3)) \\ &= \#S_1 + \#S_2 + \#S_3 - \#(S_1 \cap S_2) \\ &\quad - \#(S_1 \cap S_3) - \#(S_2 \cap S_3) + \#(S_1 \cap S_2 \cap S_3)\end{aligned}$$

Now, using the correspondence between finite sets and finite-dimensional vector spaces, cardinality and dimension, unions and sums, we could guess that the analogous formula for finite-dimensional vector spaces is

$$\begin{aligned}\dim(V_1 + V_2 + V_3) &= \dim V_1 + \dim V_2 + \dim V_3 - \dim(V_1 \cap V_2) \\ &\quad - \dim(V_1 \cap V_3) - \dim(V_2 \cap V_3) + \dim(V_1 \cap V_2 \cap V_3)\end{aligned}$$

However, this formula is false. To see why, consider the following counterexample: Take  $V_1$  to be the span of the vector  $(1, 0) \in \mathbf{R}^2$ ,  $V_2$  to be the span of  $(0, 1) \in \mathbf{R}^2$  and  $V_3$  to be the span of  $(1, 1) \in \mathbf{R}^2$ . Since the three vectors span  $\mathbf{R}^2$ , then

$$V_1 + V_2 + V_3 = \text{span}((1, 0), (0, 1), (1, 1)) = \mathbf{R}^2.$$

This implies that  $\dim(V_1 + V_2 + V_3) = 2$ . Moreover, we also have

$$\dim V_1 = \dim V_2 = \dim V_3 = 1$$

and

$$V_1 \cap V_2 = V_1 \cap V_3 = V_2 \cap V_3 = V_1 \cap V_2 \cap V_3 = \{0\}.$$

Thus, if the formula for the dimension of the sum of three subspaces was true, we would have:

$$2 = 1 + 1 + 1 - 0 - 0 - 0 + 0$$

which is clearly a contradiction. Therefore, the formula is false.

**Exercise 20**

Prove that if  $V_1, V_2$  and  $V_3$  are subspaces of a finite-dimensional vector space, then

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \\ &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \frac{\dim(V_1 \cap V_2) + \dim(V_1 \cap V_3) + \dim(V_2 \cap V_3)}{3} \\ &\quad - \frac{\dim((V_1 + V_2) \cap V_3) + \dim((V_1 + V_3) \cap V_2) + \dim((V_2 + V_3) \cap V_1)}{3}. \end{aligned}$$

**Solution**

First, recall that  $V_1 + V_2 + V_3 = (V_1 + V_2) + V_3$ . Thus, using the formula in Proposition 2.43, we get

$$\dim(V_1 + V_2 + V_3) = \dim(V_1 + V_2) + \dim V_3 - \dim((V_1 + V_2) \cap V_3).$$

Now, applying the same formula to  $\dim(V_1 + V_2)$  gives us

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \dim(V_1 \cap V_2) - \dim((V_1 + V_2) \cap V_3). \end{aligned} \quad (1)$$

We can repeat this process by writing  $V_1 + V_2 + V_3$  as  $(V_1 + V_3) + V_2$  to get

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \dim(V_1 \cap V_3) - \dim((V_1 + V_3) \cap V_2). \end{aligned} \quad (2)$$

Again, by writing  $V_1 + V_2 + V_3$  as  $(V_2 + V_3) + V_1$ , we get

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \dim(V_2 \cap V_3) - \dim((V_2 + V_3) \cap V_1). \end{aligned} \quad (3)$$

If we add equations (1), (2) and (3) together, we get

$$\begin{aligned} 3 \dim(V_1 + V_2 + V_3) &= \\ &= 3 \dim V_1 + 3 \dim V_2 + 3 \dim V_3 \\ &\quad - \dim(V_1 \cap V_2) - \dim(V_1 \cap V_3) - \dim(V_2 \cap V_3) \\ &\quad - \dim((V_1 + V_2) \cap V_3) - \dim((V_1 + V_3) \cap V_2) - \dim((V_2 + V_3) \cap V_1). \end{aligned}$$

By dividing by 3 on both sides, we obtain

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \\ &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \frac{\dim(V_1 \cap V_2) + \dim(V_1 \cap V_3) + \dim(V_2 \cap V_3)}{3} \\ &\quad - \frac{\dim((V_1 + V_2) \cap V_3) + \dim((V_1 + V_3) \cap V_2) + \dim((V_2 + V_3) \cap V_1)}{3}. \end{aligned}$$

which is the desired formula.

# Chapter 3

## Linear Maps

### 3A Vector Space of Linear Maps

Exercise 1

**TODO**

Solution

**TODO**

## 3B Null Spaces and Ranges

### Exercise 1

**TODO**

### Solution

**TODO**

## 3C Matrices

### Exercise 1

**TODO**

### Solution

**TODO**



## 3D Invertibility and Isomorphisms

Exercise 1

**TODO**

Solution

**TODO**

## 3E Products and Quotients of Vector Spaces

### Exercise 1

**TODO**

### Solution

**TODO**

## 3F Duality

### Exercise 1

**TODO**

### Solution

**TODO**