Linear Algebra Notes

Lance Remigio

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Chapter 1

Vector Spaces

1.1 Vector Spaces

1.1.1 Basics

Definition 1 (Vector Spaces). A **vector space** (or **linear space**) over a field F consists of a set on which two operations (called **addition** and **scalar multiplication**, respectively) are defined so that for each pair of elements x, y, in V there is a unique element ax in V, such that the following conditions hold:

(VS 1) For all $x, y \in V$, $x + y = y + x$ (commutativity of addition).

(VS 2) For all $x, y, z \in V$, $(x + y) + z = x + (y + z)$ (associativity of addition).

(VS 3) There exists an element in V denoted by O such that $x + O = x$ for each $x \in V$

(VS 4) For each element $x \in V$, there exists an element $y \in V$ such that $x + y = O$.

(VS 5) For each element $x \in V$, we have $1x = x$.

(VS 6) For each $a, b \in F$ and each element $x \in V$, then $(ab)x = a(bx)$.

(VS 7) For each element $a \in F$ and each pair $x, y \in V$, we have $a(x + y) = ax + ay$.

(VS 8) For each pair $a, b \in F$ and each $x \in V$, we have $(a + b)x = ax + bx$.

The elements $x + y$ and ax are called the **sum** of x and y and the **product** of a and x, respectively.

- The elements of a field F are called **scalars** and the elements of a vector space V are called **vectors** (these should not be confused!).
- Every vector space will always be defined over a given field, mostly defined over the real numbers $\mathbb{R}$ or the complex numbers $\mathbb{C}$ unless otherwise noted.
- Every vector space should specify the operations of addition and scalar multiplication.

Definition 2 (n-tuples). An object of the form $(a_1, a_2, \ldots, a_n)$, where the entries $a_1, a_2, \ldots, a_n$ are elements of a field F, is called an **n-tuple** with entries from F. The elements $a_1, a_2, \ldots, a_n$ are called **entries** or **components** of the n-tuple.

Definition 3. We say that two n-tuples, $(a_1, a_2, \ldots, a_n)$ and $(b_1, b_2, \ldots, b_n)$, are **equal** if $a_i = b_i$ for $i = 1, 2, \ldots, n$.

Example. The set of all n-tuples with entries from a field F denoted by F_n is a vector space. To see why, suppose $u, v \in F_n$ where $u = (a_1, a_2, \ldots a_n)$ and $v = (b_1, b_2, \ldots, b_n)$. If we take term-by-term addition of the entries in both u and v, then we end up with

$$u + v = (a_1 + b_1, a_2 + b_2, \ldots, a_n + b_n)$$

and likewise,

$$cu = (ca_1, ca_2, \ldots, ca_n).$$

These same set of operations define $\mathbb{R}^3$ as a vector space over $\mathbb{R}$ and likewise, $\mathbb{C}^2$ is a vector space over $\mathbb{C}$.

- Note that vectors in F^n can be written as **column vectors**

$$\begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}$$

  rather than **row vectors** $(a_1, a_2, \ldots, a_n)$.

- 1-tuples are are just scalars or an just an element from F.

Definition 4. An $m \times n$ **matrix** with entries from a field F is a rectangular array of the form

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix}$$

where each entry a_{ij} with $(1 \leq i \leq m, 1 \leq j \leq n)$ is an element of F. We call the entries a_{ij} with $i = j$ the **diagonal entries** of the matrix. The entries $a_{i1}, a_{i2}, \ldots a_{in}$ compose the i**th row**of the matrix, and the entries $a_{1j}, a_{2j}, \ldots a_{mj}$ compose the jth column of the matrix.

- The rows make a vector space which we denote F^n.
- Likewise, the columns make a vector space we denote F^m

Definition 5 (Zero Matrix)**.** The $m \times n$ matrix in which each entry equals zero is called the **zero matrix** and is denoted by O.

Definition 6 (Square Matrix)**.** A matrix is **square** if the number of rows and columns of a matrix are equal.

- Just like our tuple example, the set of all $m \times n$ matrices with entries from a field F form a vector space. Denote this vector space as $M_{m\times n}(F)$ endowed with two operations; that is, **matrix addition** and **scalar multiplication**. Suppose for $A, B \in M_{m\times n}(F)$ and $c \in F$, we have

$$(A + B)_{ij} = A_{ij} + B_{ij}$$

  and

$$(cA)_{ij} = cA_{ij}$$

  for $1 \leq i \leq m$ and $1 \leq j \leq n$. In other words, the two operations can be performed entry-wise.

- The operations from our tuple case extends very naturally to $M_{m\times n}(F)$. In other words, if we add two matrices A_{ij} and B_{ij}, then we would expect to that $A_{ij} + B_{ij} \in M_{m\times n}(F)$ as well and likewise for the scalar multiplication case.

Definition 7 (Set of All Functions). Let S be any nonempty set and F be any field, and let $\mathscr{F}(S,F)$ denote the set of all functions from S to F.

Definition 8. Two functions $f,g \in \mathscr{F}(S,F)$ are called **equal** if $f(s) = g(s)$ for each $s \in S$.

The set of functions above forms a vector space with the operations of addition and scalar multiplication defined for every $f,g \in \mathscr{F}(S,F)$ and $c \in F$ with

$$(f+g)(s) = f(s) + g(s) \text{ and } (cf)(s) = cf(s)$$

Definition 9 (Set of All Polynomials). A **polynomial** with coefficients from a field F is an expression of the form

$$f(x) = a_n x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0,$$

where n is a nonnegative integer and each $a_k \in F$ is called the **coefficient** of x_k.

Definition 10 (Zero Polynomial). We call $f(x) = 0$ the **zero polynomial** if $a_n = a_{n-1} = \cdots = a_0 = 0$.

Definition 11 (Degree). The **degree** of a given polynomial f is defined to be the largest exponent of x that appears in the representation

$$f(x) = a_n x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0.$$

Definition 12 (Equality of Polynomials). We call two polynomials f,g, where

$$f(x) = a_n x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0$$

and

$$g(x) = b_m x^m + b_{m-1}x^{m-1} + \cdots + b_1 x + b_0,$$

are **equal** if $m = n$ and $a_i = b_i$ for all $i = 0,1,\ldots,n$.

Suppose we have $c \in F$ and say we evaluated the polynomial $f \in F$ at c. Then we would have the following

$$f(c) = a_n c^n + a_{n-1}c^{n-1} + \cdots + a_1 c + a_0$$

where $f(c) \in F$.

Definition 13 (Basic Operations of Polynomials). Define polynomial **addition** $f+g$ as the following:

$$f(x) + g(x) = (a_n + b_n)x^n + (a_{n-1} + b_{n-1})x^{n-1} + \cdots + (a_1 + b_1)x + (a_0 + b_0).$$

Let $c \in F$. Let scalar **multiplication** be defined by

$$cf(x) = ca_n x^n + ca_{n-1}x^{n-1} + \cdots + ca_1 x + ca_0.$$

The operations above form a vector space for $P(F)$ (the set of all polynomials).

Definition 14 (Sequences). A **sequence** in F is a function $\sigma : \mathbb{Z}^+ \to F$. A given sequence σ such that $\sigma(n) = a_n$ for $n = 1,2,\ldots$ is denoted (a_n).

Let V be the set of all sequences $\sigma(n) \in F$. For every $(a_n),(b_n) \in V$ with $t \in F$, we have the following operations

$$(a_n) + (b_n) = (a_n + b_n) \text{ and } t(a_n) = (ta_n).$$

1.1.2 Non-examples

Example. Let $S = \{(a_1, a_2) : a_1, a_2 \in R\}$ where R is a field. For every $(a_1, a_2), (b_1, b_2) \in S$ and $c \in R$, define

$$(a_1, a_2) + (b_1, b_2) = (a_1 + b_1, a_2 - b_2) \text{ and } c(a_1, a_2) = (ca_1, ca_2).$$

Note that S is **NOT** a vector space since (VS 1), (VS 2), and (VS 8) fail.

Example. Let S be the same set as in the last example. For $(a_1, a_2), (b_1, b_2) \in S$ and $c \in R$, define

$$(a_1, a_2) + (b_1, b_2) = (a_1 + b_1, 0)$$

and

$$c(a_1, a_2) = (ca_1, 0).$$

Note that S is **NOT** a vector space with these operations since (VS 3), (VS 4), and (VS 5) fail.

1.1.3 Basic Extensions from Definition

Theorem 1 (Cancellation Law for Vector Addtion). If $x, y, z \in V$ such that $x + z = y + z$, then $x = y$.

Proof. There exists a vector $v \in V$ such that $z + v = O$ (VS 4). Thus, we have

$$\begin{aligned} x &= x + O \\ &= x + (z + v) \\ &= (x + z) + v \\ &= (y + z) + v \\ &= y + (z + v) \\ &= y + O \\ &= y. \end{aligned}$$

Hence, we have $x = y$. ■

Corollary. The vector described O described in (VS 3) is unique.

Proof. Let $x \in V$. Suppose there exists two elements $O, O' \in V$ such that

$$x + O = x \tag{1}$$

and

$$x + O' = x. \tag{2}$$

Our objective is to show that $O = O'$. Equating (1) and (2), we find that

$$x + O = x + O' \tag{3}$$

Using the Cancellation Law for Vector Addition, (3) implies that $O = O'$. Hence, O is a unique vector in V. ■

Corollary. The vector y described in (VS 4) is unique.

Proof. Let $x \in V$. Suppose there exists $y, y' \in V$ such that

$$x + y = O \text{ and } x + y' = O.$$

Equating the two equations above, we get that

$$x + y = x + y'.$$

Applying the Cancellation Law for Vector Addition once again, we get that $y = y'$. Hence, y is a unique vector in V. ■

Theorem 2. In any vector space V, the following statements are true:

(a) $0x = O$ for any $x \in V$.

(b) $(-a)x = -(ax) = a(-x)$ for each $a \in F$ and each $x \in V$.

(c) $a0 = 0$ for any $a \in F$.

Proof. (a) Using (VS 8), (VS 3), and (VS 1), it follows that

$$\begin{aligned} 0x + 0x &= (0+0)x \\ &= 0x \\ &= 0x + O \\ &= O + 0x. \end{aligned}$$

Hence, $0x = O$ by Theorem 1.1.

(b) The vector $-(ax)$ is the unique element of V such that $ax+[-(ax)] = O$. If we know that $ax+(-a)x = O$, we can use Corollary 2 to Theorem 1.1 to state that $(-a)x = -(ax)$. But by (VS 8), we have

$$ax + (-ax) = [a + (-a)]x = 0x = O$$

by (a). Hence, we have that $(-a)x = -(ax)$. In particular, we have $(-1)x = -x$. Thus, (VS 6) implies that

$$a(-x) = a[(-1)x] = [a(-1)]x = (-a)x.$$

(c) The proof of (c) is similar to the proof of (a).

■

1.2 Subspaces

Definition 15 (Subspaces)**.** A subset W of a vector space V over a field F is called a **subspace** of V if W is a vector space over F with the operations of addition and scalar multiplication.

The most simple examples of subspaces of V is V itself and the set containing just the zero vector. The latter is denoted as the **zero subspace** of V.

We don't have to check all the vector space properties to prove that a subset W of V is a subspace of V. This is because vectors in any subset of V already satisfy all the properties of a vector space. Hence, we need only check that W is closed under

1. **Addition**: $x + y \in W$ whenever $x \in W$ and $y \in W$.
2. **Scalar Multiplication**: $cx \in W$ whenever $c \in F$ and $x \in W$.
3. W contains a zero vector.
4. Each vector in W has an additive inverse in W.

Theorem 3 (Subspaces)**.** Let V be a vector space and W a subset of V. Then W is a subspace of V if and only if the following three conditions hold for the operations defined in V.

(a) $O \in W$.

(b) $x + y \in W$ whenever $x \in W$ and $y \in W$.

(c) $cx \in W$ whenever $c \in F$ and $x \in W$.

Proof. Suppose W is a subspace of V. Since W is also a vector space with the operations of addition and scalar multiplication defined in V. Hence, we know that W is closed under addition and scalar multiplication. Note that W contains a zero vector $O' \in W$ such that for any $x \in W$, we have $x + 0' = x$. Since x is also in V (since $W \subseteq V$), we know that $x + 0 = x$. Using the cancellation , we can see that $x + 0' = x + 0$ implies $0' = 0$. Hence, properties (a), (b), and (c) are satisfied.

Conversely, suppose conditions (a), (b), and (c) hold. We need to show that W is a subspace. This tells us that W is closed under addition and scalar multiplication in addition to containing the zero vector. Let $x \in W$. Since W is closed under scalar multiplication, we know that $(-1)x \in W$. By part (b) of theorem 2, we know that $1(-x) = -x \in W$. Hence, W contains an additive inverse and we are done. ■

The theorem above provides a simpler way to determine whether a given subset of a vector space is a subspace. Instead of using the definition to show that a give subset is a subspace, it is more common to use the result above.

Definition 16 (Tranpose)**.** The **transpose** of A^t of an $m \times n$ matrix A is the $n \times m$ matrix obtained from A by interchanging the rows with the columns; that is, $(A^t)_{ij} = A_{ji}$.

Example.

$$\begin{pmatrix} 1 & -2 & 3 \\ 0 & 5 & -1 \end{pmatrix}^t = \begin{pmatrix} 1 & 0 \\ -2 & 5 \\ 3 & -1 \end{pmatrix}$$

and

$$\begin{pmatrix} 1 & 2 \\ 2 & 3 \end{pmatrix}^t = \begin{pmatrix} 1 & 2 \\ 2 & 3 \end{pmatrix}.$$

Definition 17 (Symmetric Matrices)**.** A **symmetric matrix** is a matrix A such that $A^t = A$.

- The easiest example of a symmetric matrix would be a square matrix where $i = j$.
- The set W of all symmetric matrices in $M_{n\times n}(F)$ is a subspace of $M_{n\times n}(F)$ since the conditions of Theorem 1.3 hold.

We can show that W is indeed a subspace.

1. The zero matrix is equal to its transpose and hence belongs to W.
2. Suppose $A \in W$ and $B \in W$. Hence, $A^t = A$ and $B^t = B$. Hence, we have

   $$(A+B)^t = A^t + B^t = A + B$$

   which implies that $A + B \in W$.
3. We have $A \in W$ implies $A^t = A$. Now, let $a \in F$. Then we have that $(aA)^t = aA^t = aA$. Hence, $aA \in W$.

Example. Let n be non-negative integer, and let $P_n(F)$ consist of all polynomials in $P(F)$ having degree less than or equal to n. We get that $P_n(F)$ is a subspace because:

1. Zero polynomial has degree -1, it is in $P_n(F)$.
2. The sum of two polynomials with degrees less than or equal to n is another a polynomial less than or equal to n.
3. The product of a scalar and a polynomial of degree less than or equal to n is a polynomial less than or equal to n.

This tells us that $P_n(F)$ is a subspace of the space of all polynomials.

Example. Let $C(\mathbb{R})$ denote the set of all continuous real-valued functions defined on $\mathbb{R}$. We know that $C(\mathbb{R})$ is a subset of the vector space $\mathscr{F}(\mathbb{R},\mathbb{R})$ defined in Example 3. We will show that $C(\mathbb{R})$ is a subspace of $\mathscr{F}(\mathbb{R},\mathbb{R})$.

1. Note that the zero function $f(x) = 0$ for all $x \in \mathbb{R}$ of $\mathscr{F}(\mathbb{R},\mathbb{R})$ is a continuous real-valued function.
2. Let $f, g \in C(\mathbb{R})$. Since the sum of f and g is also continuous for all $x \in \mathbb{R}$, we have that $f + g \in C(\mathbb{R})$.
3. Let $c \in \mathbb{R}$ and $f \in C(\mathbb{R})$. We have that for any $x \in \mathbb{R}$, $(cf)(x) = cf(x)$ is a continuous function. Hence, property (c) is satisfied.

Hence, $C(\mathbb{R})$ is a subspace.

Definition 18 (Upper Triangular). An $m \times n$ matrix A is called **upper triangular** if all its entries below the diagonal entries are zero; that is, if $A_{ij} = 0$ whenever $i > j$.

Example. Let B be an upper triangular 3×4 matrix

$$B = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 0 & 5 & 6 & 7 \\ 0 & 0 & 8 & 9 \end{pmatrix}$$

Definition 19 (Diagonal Matrix). An $n \times n$ matrix M is called a **diagonal matrix** if $M_{ij} = 0$ whenever $i \neq j$; that is, if all its non-diagonal entries are zero.

Example. Let A be diagonal 3×3 matrix.

$$A = \begin{pmatrix} 3 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 8 \end{pmatrix}$$

Example. The set of diagonal matrices is a subspace of $M_{n\times n}(F)$. To see why, we have

1. Let O be the zero matrix of $M_{n\times n}(F)$. Since O is also a diagonal matrix, we know that O must be in the set of diagonal matrices.
2. Let A, B in the set of diagonal matrices. Let $i \neq j$ such that
$$(A+B)_{ij} = A_{ij} + B_{ij} = 0 + 0 = 0.$$
Hence, $A + B$ is a diagonal matrix and so addition is closed.
3. Let A be a diagonal matrix as before and let $c \in F$. Let $i \neq j$ again, and observe that
$$(cA)_{ij} = cA_{ij} = c \cdot 0 = 0.$$
Hence, cA is a diagonal matrix and so scalar multiplication is closed.

Since the set of diagonal matrices satisfies all properties of theorem 3, we conclude that it is indeed a subspace of $M_{n\times n}(F)$.

Definition 20 (Trace). The **trace** of an $n \times n$ matrix M, denoted $\mathrm{tr}(M)$, is the sun of the diagonal entries of M; that is,
$$\mathrm{tr}(M) = M_{11} + M_{22} + \cdots + M_{nn}.$$

The set of all $n \times n$ matrices that have a trace equal to zero is a subspace of $M_{n\times n}(F)$ (proved in Exercise 6).

Example (Non-example). Denote V as the set of matrices in $M_{m\times n}(\mathbb{R})$ having non-negative entries. The subset V is not a subspace because it is not closed under scalar multiplication. We can see this by multiplying any matrix in V be a negative number and observe that the entries of said matrix are no longer all non-negative.

We can create subspaces out of other subspaces.

Theorem 4. Any intersection of subspaces of a vector space V is a subspace of V.

Proof. Let C be a collection of subspaces of V, and let W denote the intersection of the subspaces in C. Since every subspace contains the zero vector and the intersection $W \neq \emptyset$, the zero vector $0 \in W$. Let $a \in F$ and $x, y \in W$. Since each subspace of C is closed under addition and scalar multiplication, it follows that $x + y$ and ax are contained each subspace in C and hence W must be closed under addition and closed under scalar multiplication. Thus, W is a subspace of V by theorem 3. ■

A natural question to ask is whether or not the union of subspaces of a vector space V is a subspace of V too. We can see that indeed the union of subspaces of V satisfy the first first and third property of theorem 3. However, property 2 need not be satisfied all the time. In fact, the union can only be a subspace of V if and only if one the subspaces is a subset of the other.