

MATH 304
Linear Algebra

Lecture 13:
Span. Spanning set.

Subspaces of vector spaces

Definition. A vector space V_0 is a **subspace** of a vector space V if $V_0 \subset V$ and the linear operations on V_0 agree with the linear operations on V .

Proposition A subset S of a vector space V is a subspace of V if and only if S is **nonempty** and **closed under linear operations**, i.e.,

$$\mathbf{x}, \mathbf{y} \in S \implies \mathbf{x} + \mathbf{y} \in S,$$

$$\mathbf{x} \in S \implies r\mathbf{x} \in S \text{ for all } r \in \mathbb{R}.$$

Remarks. The zero vector in a subspace is the same as the zero vector in V . Also, the subtraction in a subspace agrees with that in V .

Examples of subspaces

- $F(\mathbb{R})$: all functions $f : \mathbb{R} \rightarrow \mathbb{R}$
- $C(\mathbb{R})$: all continuous functions $f : \mathbb{R} \rightarrow \mathbb{R}$

$C(\mathbb{R})$ is a subspace of $F(\mathbb{R})$.

- \mathcal{P} : polynomials $p(x) = a_0 + a_1x + \cdots + a_{n-1}x^{n-1}$
- \mathcal{P}_n : polynomials of degree less than n

\mathcal{P}_n is a subspace of \mathcal{P} .

- Any vector space V
- $\{\mathbf{0}\}$, where $\mathbf{0}$ is the zero vector in V

The trivial space $\{\mathbf{0}\}$ is a subspace of V .

System of linear equations:

$$\left\{ \begin{array}{l} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \dots\dots\dots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{array} \right.$$

Any solution (x_1, x_2, \dots, x_n) is an element of \mathbb{R}^n .

Theorem The solution set of the system is a subspace of \mathbb{R}^n if and only if all $b_i = 0$.

Examples of subspaces of $\mathcal{M}_{2,2}(\mathbb{R})$: $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$

- diagonal matrices: $b = c = 0$
- upper triangular matrices: $c = 0$
- lower triangular matrices: $b = 0$
- symmetric matrices ($A^T = A$): $b = c$
- anti-symmetric matrices ($A^T = -A$):
 $a = d = 0$ and $c = -b$
- matrices with zero trace: $a + d = 0$
(trace = the sum of diagonal entries)

Let V be a vector space and $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n \in V$. Consider the set L of all linear combinations $r_1\mathbf{v}_1 + r_2\mathbf{v}_2 + \dots + r_n\mathbf{v}_n$, where $r_1, r_2, \dots, r_n \in \mathbb{R}$.

Theorem L is a subspace of V .

Proof: First of all, L is not empty. For example, $\mathbf{0} = 0\mathbf{v}_1 + 0\mathbf{v}_2 + \dots + 0\mathbf{v}_n$ belongs to L .

The set L is closed under addition since

$$\begin{aligned}(r_1\mathbf{v}_1 + r_2\mathbf{v}_2 + \dots + r_n\mathbf{v}_n) + (s_1\mathbf{v}_1 + s_2\mathbf{v}_2 + \dots + s_n\mathbf{v}_n) &= \\ &= (r_1 + s_1)\mathbf{v}_1 + (r_2 + s_2)\mathbf{v}_2 + \dots + (r_n + s_n)\mathbf{v}_n.\end{aligned}$$

The set L is closed under scalar multiplication since

$$t(r_1\mathbf{v}_1 + r_2\mathbf{v}_2 + \dots + r_n\mathbf{v}_n) = (tr_1)\mathbf{v}_1 + (tr_2)\mathbf{v}_2 + \dots + (tr_n)\mathbf{v}_n.$$

Span: implicit definition

Let S be a subset of a vector space V .

Definition. The **span** of the set S , denoted $\text{Span}(S)$, is the smallest subspace of V that contains S . That is,

- $\text{Span}(S)$ is a subspace of V ;
- for any subspace $W \subset V$ one has
$$S \subset W \implies \text{Span}(S) \subset W.$$

Remark. The span of any set $S \subset V$ is well defined (it is the intersection of all subspaces of V that contain S).

Span: effective description

Let S be a subset of a vector space V .

- If $S = \{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n\}$ then $\text{Span}(S)$ is the set of all linear combinations $r_1\mathbf{v}_1 + r_2\mathbf{v}_2 + \dots + r_n\mathbf{v}_n$, where $r_1, r_2, \dots, r_n \in \mathbb{R}$.
- If S is an infinite set then $\text{Span}(S)$ is the set of all linear combinations $r_1\mathbf{u}_1 + r_2\mathbf{u}_2 + \dots + r_k\mathbf{u}_k$, where $\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_k \in S$ and $r_1, r_2, \dots, r_k \in \mathbb{R}$ ($k \geq 1$).
- If S is the empty set then $\text{Span}(S) = \{\mathbf{0}\}$.

Examples of subspaces of $\mathcal{M}_{2,2}(\mathbb{R})$:

- The span of $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ and $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$ consists of all matrices of the form

$$a \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + b \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}.$$

This is the subspace of diagonal matrices.

- The span of $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$, and $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ consists of all matrices of the form

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

This is the subspace of symmetric matrices.

Examples of subspaces of $\mathcal{M}_{2,2}(\mathbb{R})$:

- The span of $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ is the subspace of anti-symmetric matrices.
- The span of $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$, and $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$ is the subspace of upper triangular matrices.
- The span of $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$, $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$ is the entire space $\mathcal{M}_{2,2}(\mathbb{R})$.

Spanning set

Definition. A subset S of a vector space V is called a **spanning set** for V if $\text{Span}(S) = V$.

Examples.

- Vectors $\mathbf{e}_1 = (1, 0, 0)$, $\mathbf{e}_2 = (0, 1, 0)$, and $\mathbf{e}_3 = (0, 0, 1)$ form a spanning set for \mathbb{R}^3 as

$$(x, y, z) = x\mathbf{e}_1 + y\mathbf{e}_2 + z\mathbf{e}_3.$$

- Matrices $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$

form a spanning set for $\mathcal{M}_{2,2}(\mathbb{R})$ as

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

Problem Let $\mathbf{v}_1 = (1, 2, 0)$, $\mathbf{v}_2 = (3, 1, 1)$, and $\mathbf{w} = (4, -7, 3)$. Determine whether \mathbf{w} belongs to $\text{Span}(\mathbf{v}_1, \mathbf{v}_2)$.

We have to check if there exist $r_1, r_2 \in \mathbb{R}$ such that $\mathbf{w} = r_1\mathbf{v}_1 + r_2\mathbf{v}_2$. This vector equation is equivalent to a system of linear equations:

$$\begin{cases} 4 = r_1 + 3r_2 \\ -7 = 2r_1 + r_2 \\ 3 = 0r_1 + r_2 \end{cases} \iff \begin{cases} r_1 = -5 \\ r_2 = 3 \end{cases}$$

Thus $\mathbf{w} = -5\mathbf{v}_1 + 3\mathbf{v}_2 \in \text{Span}(\mathbf{v}_1, \mathbf{v}_2)$.

Problem Let $\mathbf{v}_1 = (2, 5)$ and $\mathbf{v}_2 = (1, 3)$. Show that $\{\mathbf{v}_1, \mathbf{v}_2\}$ is a spanning set for \mathbb{R}^2 .

Take any vector $\mathbf{w} = (a, b) \in \mathbb{R}^2$. We have to check that there exist $r_1, r_2 \in \mathbb{R}$ such that

$$\mathbf{w} = r_1\mathbf{v}_1 + r_2\mathbf{v}_2 \iff \begin{cases} 2r_1 + r_2 = a \\ 5r_1 + 3r_2 = b \end{cases}$$

Coefficient matrix: $C = \begin{pmatrix} 2 & 1 \\ 5 & 3 \end{pmatrix}$. $\det C = 1 \neq 0$.

Since the matrix C is invertible, the system has a unique solution for any a and b .

Thus $\text{Span}(\mathbf{v}_1, \mathbf{v}_2) = \mathbb{R}^2$.

Problem Let $\mathbf{v}_1 = (2, 5)$ and $\mathbf{v}_2 = (1, 3)$. Show that $\{\mathbf{v}_1, \mathbf{v}_2\}$ is a spanning set for \mathbb{R}^2 .

Alternative solution: First let us show that vectors $\mathbf{e}_1 = (1, 0)$ and $\mathbf{e}_2 = (0, 1)$ belong to $\text{Span}(\mathbf{v}_1, \mathbf{v}_2)$.

$$\mathbf{e}_1 = r_1\mathbf{v}_1 + r_2\mathbf{v}_2 \iff \begin{cases} 2r_1 + r_2 = 1 \\ 5r_1 + 3r_2 = 0 \end{cases} \iff \begin{cases} r_1 = 3 \\ r_2 = -5 \end{cases}$$

$$\mathbf{e}_2 = r_1\mathbf{v}_1 + r_2\mathbf{v}_2 \iff \begin{cases} 2r_1 + r_2 = 0 \\ 5r_1 + 3r_2 = 1 \end{cases} \iff \begin{cases} r_1 = -1 \\ r_2 = 2 \end{cases}$$

Thus $\mathbf{e}_1 = 3\mathbf{v}_1 - 5\mathbf{v}_2$ and $\mathbf{e}_2 = -\mathbf{v}_1 + 2\mathbf{v}_2$.

Then for any vector $\mathbf{w} = (a, b) \in \mathbb{R}^2$ we have

$$\begin{aligned} \mathbf{w} &= a\mathbf{e}_1 + b\mathbf{e}_2 = a(3\mathbf{v}_1 - 5\mathbf{v}_2) + b(-\mathbf{v}_1 + 2\mathbf{v}_2) \\ &= (3a - b)\mathbf{v}_1 + (-5a + 2b)\mathbf{v}_2. \end{aligned}$$

Problem Let $\mathbf{v}_1 = (2, 5)$ and $\mathbf{v}_2 = (1, 3)$. Show that $\{\mathbf{v}_1, \mathbf{v}_2\}$ is a spanning set for \mathbb{R}^2 .

Remarks on the alternative solution:

Notice that \mathbb{R}^2 is spanned by vectors $\mathbf{e}_1 = (1, 0)$ and $\mathbf{e}_2 = (0, 1)$ since $(a, b) = a\mathbf{e}_1 + b\mathbf{e}_2$.

This is why we have checked that vectors \mathbf{e}_1 and \mathbf{e}_2 belong to $\text{Span}(\mathbf{v}_1, \mathbf{v}_2)$. Then

$$\begin{aligned} \mathbf{e}_1, \mathbf{e}_2 \in \text{Span}(\mathbf{v}_1, \mathbf{v}_2) &\implies \text{Span}(\mathbf{e}_1, \mathbf{e}_2) \subset \text{Span}(\mathbf{v}_1, \mathbf{v}_2) \\ &\implies \mathbb{R}^2 \subset \text{Span}(\mathbf{v}_1, \mathbf{v}_2) \implies \text{Span}(\mathbf{v}_1, \mathbf{v}_2) = \mathbb{R}^2. \end{aligned}$$

In general, to show that $\text{Span}(S_1) = \text{Span}(S_2)$, it is enough to check that $S_1 \subset \text{Span}(S_2)$ and $S_2 \subset \text{Span}(S_1)$.