LECTURE 1. VECTOR SPACES

Please consider every proposition in this text as an exercise.

1. Definition of a Vector Space

Definition 1.1. Assume that $\mathbb{F}$ is a field, whose elements we call scalars. A non-empty set V with an operation of addition $+ : V \times V \to V\,((x, y) \mapsto x + y)$ and an operation of scalar multiplication $\mathrm{scal} : \mathbb{F} \times V \to V\,((\lambda, x) \mapsto \lambda x)$ is called a vector space over $\mathbb{F}$ if the following conditions hold:

(1) $(V, +)$ is an abelian group. We denote its identity element by 0 or by 0_V.
(2) $\lambda(x + y) = \lambda x + \lambda y, \quad \forall \lambda \in \mathbb{F}, \forall x, y \in V.$
(3) $(\lambda + \mu)x = \lambda x + \mu x, \quad \forall \lambda, \mu \in \mathbb{F}, \forall x \in V.$
(4) $(\lambda\mu)x = \lambda(\mu x), \quad \forall \lambda, \mu \in \mathbb{F}, \forall x \in V.$
(5) $1_{\mathbb{F}}\, x = x, \quad \forall x \in V.$

The notation here may be a bit confusing. For example, in condition (3), the symbol "+" in the LHS stands for the addition in the field $\mathbb{F}$, and in the RHS, the same symbol stands for the addition in V.

Exercise 1.2. For a vector space V over a field $\mathbb{F}$ show that $0_{\mathbb{F}}\, x = 0_V$, $\forall x \in V$.

Exercise 1.3. For a vector space V over a field $\mathbb{F}$ show that $(-1_{\mathbb{F}})\, x = -x$, $\forall x \in V$.

Definition 1.4. For a field $\mathbb{F}$ denote by

$$\mathbb{F}^n := \left\{ \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} \mid a_j \in \mathbb{F},\ \forall 1 \le j \le n \right\} \tag{1.1}$$

the set of ordered n-tuples of elements of $\mathbb{F}$. We define the component-wise addition on $\mathbb{F}^n$ and the multiplication of elements of $\mathbb{F}^n$ by the elements of $\mathbb{F}$:

$$\begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} + \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix} := \begin{pmatrix} a_1 + b_1 \\ \vdots \\ a_n + b_n \end{pmatrix}, \quad \forall a_j, b_j \in \mathbb{F}; \tag{1.2}$$

$$\lambda \cdot \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix} := \begin{pmatrix} \lambda a_1 \\ \vdots \\ \lambda a_n \end{pmatrix}, \quad \forall a_j, \lambda \in \mathbb{F}. \tag{1.3}$$

Exercise 1.5. Which of the following pairs are vector spaces over corresponding fields:

(1) $\emptyset$ over $\mathbb{R}$;
(2) $\{0\}$ over $\mathbb{R}$;
(3) $\mathbb{Z}$ over $\mathbb{Q}$;
(4) $\mathbb{Q}$ over $\mathbb{Z}$;
(5) $\mathbb{Q}$ over $\mathbb{R}$;
(6) $\mathbb{R}$ over $\mathbb{Q}$;
(7) $\mathbb{C}$ over $\mathbb{R}$;
(8) $\mathbb{C}^n$ over $\mathbb{C}$;
(9) $\mathbb{C}^n$ over $\mathbb{R}$?

2. Subspaces, Direct Sums, Quotient Spaces

Definition 2.1. Assume that V is a vector space over a field $\mathbb{F}$. A non-empty subset U of V is called a subspace (of V) if:

(1) for all elements $x, y \in U$ their sum $x + y \in U$;
(2) for every scalar $\lambda \in \mathbb{F}$ and for every $x \in U$ the product $\lambda x \in U$.

Definition 2.2. Assume that V is a vector space over a field $\mathbb{F}$. A non-empty subset U of V is called a subspace of V if U is a vector space over $\mathbb{F}$ with respect to addition and multiplication by scalars defined in V.

Exercise 2.3. Show that the previous two definitions are equivalent.

It is generally understood that if V is a vector space, then the notation $U \subset V$ means that U is a subspace of V unless specified otherwise.

Exercise 2.4. Is it always true that the intersection of an arbitrary family of subspaces of a vector space V is also a subspace?

Definition 2.5. Assume that $U_1, \dots, U_n$ are subspaces of the vector space V. Define a set

$$\sum_{j=1}^{n} U_j := \{\sum_{j=1}^{n} x_j \mid x_j \in U_j, \forall 1 \le j \le n\}. \tag{2.1}$$

It is called the sum or the join of the subspaces $U_1, \dots, U_n$. Another notation for it is $U_1 + U_2 + \dots + U_n$.

Exercise 2.6. Is it always true that $\sum_{j=1}^{n} U_j$ is also a subspace of the vector space V?

Definition 2.7. Assume that $U_1, \dots, U_n$ are subspaces of the vector space V. We write

$$V = \bigoplus_{j=1}^{n} U_j \tag{2.2}$$

and say that V is a direct sum of $U_1, \dots, U_n$ if and only if $\forall x \in V \; \exists!(x_1, \dots, x_n)$ such that

(1) $x_j \in U_j$, $\forall 1 \le j \le n$;
(2) $x = \sum_{j=1}^{n} x_j$.

Exercise 2.8. Show that $V = U_1 \oplus U_2$ if and only if

(1) $V = U_1 + U_2$;
(2) $U_1 \cap U_2 = \{0\}$.

Definition 2.9. Let U be a subspace of a vector space V. Then we say that $x, y \in V$ are equivalent if and only if $x - y \in U$. We write

$$(x \sim_U y) \iff (x - y \in U). \tag{2.3}$$

Exercise 2.10. Show that $\sim_U$ is indeed an equivalence relation for every subspace U.

Exercise 2.11. Let U be a subspace of a vector space V over $\mathbb{F}$. Consider equivalence classes in V with respect to the relation $\sim_U$. If a class contains an element x we may denote that class by $x + U$. We define the operations of addition and multiplication by scalars on these equivalence classes by

$$(x + U) + (y + U) := (x + y) + U, \quad \lambda(x + U) := (\lambda x) + U. \tag{2.4}$$

. Show that the operations are well-defined. That is, the results do not depend on the choices of representatives. Also, show that these operations turn the set of equivalence classes into a vector space over $\mathbb{F}$. It is called a quotient space and is denoted by V/U.

Chapters from the textbooks relevant to the lecture:

- Friedberg, Insel, Spence, Sections 1.2, 1.3;
- Roman, pp.17-19, 29-30, 35-38, 41-45, 87-89;
- Axler, Ch.1.