

MA22020: Exercise sheet 1

Warmup questions

- Let U be a subset of a vector space V . Show that U is a linear subspace of V if and only if U satisfies the following conditions:
 - $0 \in U$;
 - For all $u_1, u_2 \in U$ and $\lambda \in \mathbb{F}$, $u_1 + \lambda u_2 \in U$.
- Which of the following subsets of \mathbb{R}^3 are linear subspaces? In each case, briefly justify your answer.
 - $U_1 := \{(x_1, x_2, x_3) \mid x_1^2 + x_2^2 + x_3^2 = 1\}$
 - $U_2 := \{(x_1, x_2, x_3) \mid x_1 = x_2\}$
 - $U_3 := \{(x_1, x_2, x_3) \mid x_1 + 2x_2 + 3x_3 = 0\}$
- Which of the following maps $f : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ are linear? In each case, briefly justify your answer.
 - $f(x, y) = (5x + y, 3x - 2y)$
 - $f(x, y) = (5x + 2, 7y)$
 - $f(x, y) = (\cos y, \sin x)$
 - $f(x, y) = (3y^2, x^3)$.
- Let $U, W \leq V$ be subspaces of a vector space V .
When is $U \cup W$ also a subspace of V ?

Homework

- Which of the following subsets of \mathbb{C}^3 are linear subspaces over \mathbb{C} ? In each case, briefly justify your answer.
 - $U_1 := \{(z_1, z_2, z_3) \mid z_1 z_2 = 1\}$
 - $U_2 := \{(z_1, z_2, z_3) \mid z_1 = \bar{z}_2\}$
 - $U_3 := \{(z_1, z_2, z_3) \mid z_1 + \sqrt{-1}z_2 + 3z_3 = 0\}$
- Let V, W be vector spaces, v_1, \dots, v_n a basis of V and w_1, \dots, w_n a list of vectors in W . Let $\phi : V \rightarrow W$ be the unique linear map with

$$\phi(v_i) = w_i,$$

for all $1 \leq i \leq n$. Show:

- ϕ injects if and only if w_1, \dots, w_n is linearly independent.
- ϕ surjects if and only if w_1, \dots, w_n spans W .

Deduce that ϕ is an isomorphism if and only if w_1, \dots, w_n is a basis for W .

Please hand in at 4W level 1 by NOON on Thursday 17th October 2024

MA22020: Exercise sheet 1—Solutions

1. First suppose that $U \leq V$. The U is non-empty so there is some $u \in U$ and then, since U is closed under addition and scalar multiplication, $0 = u + (-1)u \in U$ also and condition (i) is satisfied. Now if $u_1, u_2 \in U$ and $\lambda \in \mathbb{F}$, then $\lambda u_2 \in U$ (U is closed under scalar multiplication) and so $u_1 + \lambda u_2 \in U$ (U is closed under addition). Thus condition (ii) holds also.

For the converse, if conditions (i) and (ii) hold, then, first, $0 \in U$ so U is non-empty and, second, U is closed under addition (take $\lambda = 1$ in condition (ii)) and under scalar multiplication (take $u_1 = 0$ in condition (ii)). Thus $U \leq V$.

2. (a) U_1 is not a subspace as it does not contain 0 !
 (b) U_2 is a subspace: in fact, it is $\ker \phi_A$ where $A = \begin{pmatrix} 1 & -1 & 0 \end{pmatrix}$.
 (c) U_3 is a subspace. It is $\ker \phi_A$ for $A = \begin{pmatrix} 1 & 2 & 3 \end{pmatrix}$.
3. (a) Here f is linear: it is the map ϕ_A corresponding to the matrix

$$A = \begin{pmatrix} 5 & 1 \\ 3 & -2 \end{pmatrix}.$$

(b) This is not linear (because of that $+2$ term). In particular $f(0,0) = (2,0) \neq 0$!

(c) Again $f(0,0) = (1,0) \neq 0$ so this f cannot be linear. Of course, we already **know** this because it is certainly not true that $\cos(y_1 + y_2) = \cos y_1 + \cos y_2$.

(d) Another non-linear map: for example $f(2x, 2y) \neq 2f(x, y)$.

4. If $U \subseteq W$ then $U \cup W = W$ is a subspace and similarly if $W \subseteq U$. In any other case, $U \cup W$ is not a subspace: we can find $u \in U \setminus W$ and $w \in W \setminus U$ and then $u + w \notin U$ (else $w = (u + w) - u \in U$) and similarly $u + w \notin W$. Thus $U \cup W$ is not closed under addition.

5. (a) $0 \notin U_1$ so U_1 is not a subspace.
 (b) U_2 is not a subspace because it is not closed under complex scalar multiplication: $(1, 1, 0) \in U_2$ but $i(1, 1, 0) = (i, i, 0)$ is not (here $i = \sqrt{-1}$). In general, any time you see complex conjugation in the definition of a subset, it is unlikely to be a complex subspace.
 (c) $U_3 = \ker \phi_A$ for $A = \begin{pmatrix} 1 & \sqrt{-1} & 3 \end{pmatrix}$ and so is a subspace.
6. (a) $\lambda_1 w_1 + \dots + \lambda_n w_n = 0$ if and only if $\lambda_1 v_1 + \dots + \lambda_n v_n \in \ker \phi$. Thus w_1, \dots, w_n is linearly independent if and only if ϕ has trivial kernel.
 (b) ϕ surjects if and only if any $w \in W$ can be written $w = \phi(v)$, or equivalently,

$$w = \phi(\lambda_1 v_1 + \dots + \lambda_n v_n) = \lambda_1 w_1 + \dots + \lambda_n w_n,$$

for some λ_i , $1 \leq i \leq n$.