

IB Linear Algebra – Example Sheet 1

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1. Suppose that the vectors $\mathbf{e}_1, \dots, \mathbf{e}_n$ form a basis for a real vector space V . Which of the following are also bases?

- (a) $\mathbf{e}_1 + \mathbf{e}_2, \mathbf{e}_2 + \mathbf{e}_3, \dots, \mathbf{e}_{n-1} + \mathbf{e}_n, \mathbf{e}_n$;
- (b) $\mathbf{e}_1 + \mathbf{e}_2, \mathbf{e}_2 + \mathbf{e}_3, \dots, \mathbf{e}_{n-1} + \mathbf{e}_n, \mathbf{e}_n + \mathbf{e}_1$;
- (c) $\mathbf{e}_1 - \mathbf{e}_n, \mathbf{e}_2 + \mathbf{e}_{n-1}, \dots, \mathbf{e}_n + (-1)^n \mathbf{e}_1$.

2. Let T, U and W be subspaces of V .

(i) Show that $T \cup U$ is a subspace of V only if either $T \leq U$ or $U \leq T$.

(ii) Give explicit counter-examples to the following statements:

$$(a) \quad T + (U \cap W) = (T + U) \cap (T + W); \quad (b) \quad (T + U) \cap W = (T \cap W) + (U \cap W).$$

(iii) Show that each of the equalities in (ii) can be replaced by a valid inclusion of one side in the other.

3. For each of the following pairs of vector spaces (V, W) over $\mathbb{R}$, either give an isomorphism $V \rightarrow W$ or show that no such isomorphism can exist. [Here $P(\mathbb{R})$ denotes the space of polynomial functions $\mathbb{R} \rightarrow \mathbb{R}$, and $C[a, b]$ denotes the space of continuous functions defined on the closed interval $[a, b]$.]

- (a) $V = \mathbb{R}^4$, $W = \{\mathbf{x} \in \mathbb{R}^5 : x_1 + x_2 + x_3 + x_4 + x_5 = 0\}$.
- (b) $V = \mathbb{R}^5$, $W = \{p \in P : \deg p \leq 5\}$.
- (c) $V = C[0, 1]$, $W = C[-1, 1]$.
- (d) $V = C[0, 1]$, $W = \{f \in C[0, 1] : f(0) = 0, f \text{ continuously differentiable}\}$.
- (e) $V = \mathbb{R}^2$, $W = \{\text{real solutions of } \ddot{x}(t) + x(t) = 0\}$.
- (f) $V = \mathbb{R}^4$, $W = C[0, 1]$.
- (g) (Harder:) $V = P(\mathbb{R})$, $W = \mathbb{R}^{\mathbb{N}}$.

4. (i) If α and β are linear maps from U to V show that $\alpha + \beta$ is linear. Give explicit counter-examples to the following statements:

$$(a) \quad \text{im}(\alpha + \beta) = \text{im}(\alpha) + \text{im}(\beta); \quad (b) \quad \text{Ker}(\alpha + \beta) = \text{Ker}(\alpha) \cap \text{Ker}(\beta).$$

Show that in general each of these equalities can be replaced by a valid inclusion of one side in the other.

(ii) Let α be a linear map from V to V . Show that if $\alpha^2 = \alpha$ then $V = \text{Ker}(\alpha) \oplus \text{im}(\alpha)$. Does your proof still work if V is infinite dimensional? Is the result still true?

5. Let

$$U = \{\mathbf{x} \in \mathbb{R}^5 : x_1 + x_3 + x_4 = 0, 2x_1 + 2x_2 + x_5 = 0\}, \quad W = \{\mathbf{x} \in \mathbb{R}^5 : x_1 + x_5 = 0, x_2 = x_3 = x_4\}.$$

Find bases for U and W containing a basis for $U \cap W$ as a subset. Give a basis for $U + W$ and show that

$$U + W = \{\mathbf{x} \in \mathbb{R}^5 : x_1 + 2x_2 + x_5 = x_3 + x_4\}.$$

6. (i) Let $\alpha : V \rightarrow V$ be an endomorphism of a finite dimensional vector space V . Show that

$$V \geq \text{im}(\alpha) \geq \text{im}(\alpha^2) \geq \dots \quad \text{and} \quad \{0\} \leq \text{Ker}(\alpha) \leq \text{Ker}(\alpha^2) \leq \dots$$

If $r_k = \text{rk}(\alpha^k)$, deduce that $r_k \geq r_{k+1}$ and that $r_k - r_{k+1} \geq r_{k+1} - r_{k+2}$. Conclude that if, for some $k \geq 0$, we have $r_k = r_{k+1}$, then $r_k = r_{k+\ell}$ for all $\ell \geq 0$.

(ii) Suppose that $\dim(V) = 5$, $\alpha^3 = 0$, but $\alpha^2 \neq 0$. What possibilities are there for $\text{rk}(\alpha)$ and $\text{rk}(\alpha^2)$?

7. Let $\alpha : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be the linear map given by $\alpha : \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \mapsto \begin{pmatrix} 2 & 1 & 0 \\ 0 & 2 & 1 \\ 0 & 0 & 2 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$. Find the matrix representing α relative to the basis $\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ for both the domain and the range.

Write down bases for the domain and range with respect to which the matrix of α is the identity.

8. Let $U_1, \dots, U_k$ be subspaces of a vector space V and let B_i be a basis for U_i . Show that the following statements are equivalent:

- (i) $U = \sum_i U_i$ is a direct sum, i.e. every element of U can be written uniquely as $\sum_i u_i$ with $u_i \in U_i$.
- (ii) $U_j \cap \sum_{i \neq j} U_i = \{0\}$ for all j .
- (iii) The B_i are pairwise disjoint and their union is a basis for $\sum_i U_i$.

Give an example where $U_i \cap U_j = \{0\}$ for all $i \neq j$, yet $U_1 + \dots + U_k$ is not a direct sum.

9. Show that any two subspaces of the same dimension in a finite dimensional vector space have a common complementary subspace.
10. Let Y and Z be subspaces of the finite dimensional $\mathbb{F}$ -vector spaces V and W , respectively. Suppose that $\alpha : V \rightarrow W$ is a linear map such that $\alpha(Y) \subseteq Z$.

- (i) Show that α induces well-defined linear maps $\alpha|_Y : Y \rightarrow Z$ via $\alpha|_Y(y) = \alpha(y)$ and $\bar{\alpha} : V/Y \rightarrow W/Z$ via $\bar{\alpha}(v + Y) = \alpha(v) + Z$.

Consider a basis $\mathcal{B}_V = \{v_1, \dots, v_n\}$ for V containing a basis $\mathcal{B}_Y = \{v_1, \dots, v_k\}$ for Y and a basis $\mathcal{B}_W = \{w_1, \dots, w_m\}$ for W containing a basis $\mathcal{B}_Z = \{w_1, \dots, w_l\}$ for Z . Recall from lectures that $\mathcal{B}_{V/Y} = \{v_{k+1} + Y, \dots, v_n + Y\}$ is a basis for V/Y and that $\mathcal{B}_{W/Z} = \{w_{l+1} + Z, \dots, w_m + Z\}$ is a basis for W/Z .

- (ii) Describe the relationship between the three matrices:

$$A = [\alpha]_{\mathcal{B}_W}^{\mathcal{B}_V} \in \mathcal{M}_{m \times n}(\mathbb{F}); B = [\alpha|_Y]_{\mathcal{B}_Z}^{\mathcal{B}_Y} \in \mathcal{M}_{l \times k}(\mathbb{F}) \text{ and } C = [\bar{\alpha}]_{\mathcal{B}_{W/Z}}^{\mathcal{B}_{V/Y}} \in \mathcal{M}_{(m-l) \times (n-k)}(\mathbb{F}).$$

- (iii) Show that $R = \{\beta \in \mathcal{L}(V, W) : \beta(Y) \subseteq Z\}$ is a subspace of the space $\mathcal{L}(V, W)$ of all linear maps from V to W . What is the dimension of R ?

11. Let T, U, V, W be vector spaces over $\mathbb{F}$ and let $\alpha : T \rightarrow U, \beta : V \rightarrow W$ be fixed linear maps. Show that the mapping $\Phi : \mathcal{L}(U, V) \rightarrow \mathcal{L}(T, W)$ which sends θ to $\beta \circ \theta \circ \alpha$ is linear. If the spaces are finite-dimensional and α and β have rank r and s respectively, find the rank of Φ .