

Linear Algebra

Notes

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1 Linear Maps

1.1 Vector Spaces of Linear Maps

1.1.1 Definiton and Examples of Linear Maps

Definition 1.1. A *linear map* from V to W is a function $T : V \rightarrow W$ with the following properties.

1. **(Additivity)** $T(u + w) = T(u) + T(w)$ for all $u, v \in V$
2. **(Homogeneity)** $T(\lambda u) = \lambda T(u)$ for all $\lambda \in \mathbf{F}$ and for all $u \in V$

Remark. Some mathematicians use the phrase *linear transformation*, which means the same as linear map.

Definition 1.2. (Notation)

1. The set of linear maps from $V \rightarrow W$ is denoted by $\mathcal{L}(V, W)$.
2. The set of linear maps from $V \rightarrow V$ is denoted by $\mathcal{L}(V)$. In other words, $\mathcal{L}(V, V) = \mathcal{L}(V)$.

Examples:

zero

We will let the symbol 0 denote the liner map that takes every element of some vector space to additive identity of some another vector space. Thus, $0 \in \mathcal{L}(V, W)$ is defined by

$$0(v) = 0$$

identity operator

Let $I \in \mathcal{L}(V)$ be defined by

$$I(v) = v$$

differentiation

Let $D \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ be defined by

$$D(p) = p'$$

integration

Let $T \in \mathcal{L}(\mathcal{P}(\mathbf{R}), \mathbf{R})$ be defined by

$$T(p) = \int_0^1 p$$

composition

Fix a polynomial $q \in \mathcal{P}(\mathbf{R})$. Let $T \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ be defined by

$$T(p) = (p \circ q)$$

Remark. We'll limit the Notation of $T(v)$ to just Tv for convenience.

Theorem 1.1. Suppose v_1, \dots, v_n is a basis of V and $w_1, \dots, w_n \in W$. Then, there exists a unique linear map $T : V \rightarrow W$ such that

$$Tv_k = w_k$$

for $i = 1, 2, 3, \dots, n$.

Proof. First we show the existence of such map. Define $T : V \rightarrow W$ by

$$T(c_1v_1 + \cdots + c_nv_n) = c_1w_1 + \cdots + c_nw_n$$

where $c_i \in \mathbf{F}$. Since, v_1, \dots, v_n is a basis of V , it maps every element of V to W , thus it is a function.

Now, set $c_k = 1$ and all other c 's to be 0 to show that $Tv_k = w_k$. From, here one can show that T is indeed a linear map. To show the uniqueness, suppose $T' \in \mathcal{L}(V, W)$ and $T'v_k = w_k$. Using the properties of linear map,

$$T'(c_1v_1 + \cdots + c_nv_n) = c_1w_1 + \cdots + c_nw_n$$

Thus, T and T' agree on every input, thus $T = T'$. □

1.1.2 Algebraic Operation on $\mathcal{L}(V, W)$

Definition 1.3. Suppose $T, S \in \mathcal{L}(V, W)$ and $\lambda \in \mathbf{F}$ then the *sum* and the *product* of the linear maps from V to W is defined by

$$(S + T)(v) = Sv + Tv \quad \text{and} \quad (\lambda T)(v) = \lambda(Tv)$$

for all $v \in V$.

Proposition 1.1. With the operations defined above, the set $\mathcal{L}(V, W)$ is a vector space.

Proof. The additive identity for $\mathcal{L}(V, W)$ is the zero linear map $0(v) = 0$. The inverse for T is $((-1)T)v = -(Tv)$. And the rest of the axioms are left for readers (future me) to verify. □

Definition 1.4. Suppose $T \in \mathcal{L}(U, V)$ and $S \in \mathcal{L}(V, W)$ then the *product* $ST \in \mathcal{L}(U, W)$ is defined by

$$(ST)(u) = S(Tu)$$

for all $u \in U$.

Remark. Be careful about the domains of S and T . Here, the domain of S must be the co-domain of T .

Proposition 1.2. For the product of linear maps, the following holds

1. (**associativity**) $(T_1T_2)T_3 = T_1(T_2T_3)$ whenever the product makes sense (i.e T_3 must map to domain of T_2 and T_2 must map to the domain of T_1).
2. (**identity**) $TI_{W,V} = I_{V,W}T$ whenever $T \in \mathcal{L}(V, W)$. Here $I_{V,W}, I_{W,V}$ are the identity linear maps from V to W and W to V . We'll just limit the notation to $TI = IT$.
3. (**distributivity**) $(S_1 + S_2)T = S_1T + S_2T$ and $S(T_1 + T_2) = ST_1 + ST_2$ for $T, T_1, T_2 \in \mathcal{L}(U, V)$ and $S, S_1, S_2 \in \mathcal{L}(V, W)$.

Proposition 1.3. Suppose T is a linear map from V to W . Then, $T(0) = 0$.

Proof. From the definition of linear map we have,

$$T(0) = T(0 + 0) = T(0) + T(0) \implies T(0) = 0$$

□

1.1.3 Exercises

Problem : Suppose $b, c \in \mathbf{R}$. Define $T : \mathbf{R}^3 \rightarrow \mathbf{R}^2$ by

$$T(x, y, z) = (2x - 4y + 3z, 6x + cxyz)$$

Show that T is a linear map if and only if $b = c = 0$.

Solution : (\Leftarrow) is pretty simple as you just have to verify the two axioms. For (\Rightarrow), we know that if it is a linear map then $T(0) = 0 \Rightarrow b = 0$. Also, using the first axiom we get

$$T((x, y, z) + (1, 0, 0)) = T((x, y, z)) + T((1, 0, 0)) \Rightarrow c = 0$$

Problem : Suppose $b, c \in \mathbf{R}$. Define $T : \mathcal{P}(\mathbf{R}) \rightarrow \mathbf{R}^2$ by

$$Tp = \left(3p(4) + 5p'(6) + bp(1)p(2), \int_{-1}^2 x^3 p(x) dx + c \sin(p(0)) \right)$$

Show that T is a linear map if and only if $b = c = 0$.

Solution : (\Leftarrow) is pretty simple. For (\Rightarrow), we can use the first axiom

$$T(p + q) = Tp + Tq$$

we'll just look at the first component first,

$$\begin{aligned} \Rightarrow 3(p + q)(4) + 5(p + q)'(6) + b(p + q)(1)(p + q)(2) &= 3p(4) + 5p'(6) + bp(1)p(2) + \\ &3q(4) + 5q'(6) + bq(1)q(2) \end{aligned}$$

Since, $(p + q)(4) = p(4) + q(4)$ and $(p + q)'(6) = p'(6) + q'(6)$, we can simplify is down to,

$$b(p(1)q(2) + p(2)q(1)) = 0$$

Now, if you choose polynomials $p, q > 0$ for $x > 0$ then $b = 0$. A similar argument works for $c = 0$.

Problem : Suppose $T \in \mathcal{L}(V, W)$ and v_1, \dots, v_m is a list of vectors in V such that Tv_1, \dots, Tv_m is a linearly independent list in W . Prove that v_1, \dots, v_m is linearly independent.

Solution : Suppose on the contrary that v_1, \dots, v_m are not linearly independent in V , then there exists $\lambda_1, \dots, \lambda_m$ not all zero such that

$$\lambda_1 v_1 + \dots + \lambda_m v_m = 0$$

But $T(\lambda_1 v_1 + \dots + \lambda_m v_m) = \lambda_1 T(v_1) + \dots + \lambda_m T(v_m)$ which implies

$$\lambda_1 T(v_1) + \dots + \lambda_m T(v_m) = 0 \Rightarrow \lambda_i = 0$$

a contradiction.

Problem : Show that every linear map from a one-dimensional vector space to itself is multiplication by some scalar. More precisely, prove that if $\dim V = 1$ and $T \in \mathcal{L}(V)$, then there exists $\lambda \in \mathbf{F}$ such that $Tv = \lambda v$ for all $v \in V$.

Solution : Since $\dim V = 1$ there exists a $v \in V$ s.t every $v_i \in V$ can be written as $\lambda_i v$ for some $\lambda_i \in \mathbf{F}$. Thus, $v_i = \lambda_i v \implies T(v_i) = \lambda_i T(v)$. Since, $T(v) = v_j \in V$ for some j . Thus, $T(v_i) = \lambda_i \lambda_j v = \lambda_j v_i$.

Problem : Give an example of a function $\varphi : \mathbf{R}^2 \rightarrow \mathbf{R}$ such that

$$\varphi(av) = a\varphi(v)$$

for all $a \in \mathbf{R}$ and $v \in \mathbf{R}^2$ but φ is not linear.

$$\text{Solution : } \varphi(x, y) = \begin{cases} \frac{x^3}{x^2+y^2} & \text{if } (x, y) \neq (0, 0) \\ 0 & \text{if } (x, y) = (0, 0) \end{cases}$$

Problem : Give an example of a function $\varphi : \mathbf{C} \rightarrow \mathbf{C}$ such that

$$\varphi(v + w) = \varphi(v) + \varphi(w)$$

for all $v, w \in \mathbf{C}$ and but φ is not homogeneous.

$$\text{Solution : } \varphi(x) = \operatorname{Re}(x).$$

Problem : Prove or give a counter example: Fix a polynomial $q \in \mathcal{P}(\mathbf{R})$.

Let $T : \mathcal{P}(\mathbf{R}) \rightarrow \mathcal{P}(\mathbf{R})$ be defined by $Tp = q \circ p$ then T is a linear map.

Solution : Assume it was a linear map then $T(0) = q(0) = 0$. Just pick $q(0) \neq 0$.
Example : $q(x) = x + 1$.

Problem : Suppose V is finite-dimensional and $T \in \mathcal{L}(V)$. Prove that T is a scalar multiple of identity if and only if $ST = TS$ for every $S \in \mathcal{L}(V)$.

Solution : I really tried but it seems very hard to prove (\Rightarrow) but will come back later.

Problem : Suppose U is a subspace of V with $U \neq V$. Suppose $S \in \mathcal{L}(U, W)$ and $Su \neq 0$ for some $u \in U$. Define $T : V \rightarrow W$ by

$$Tv = \begin{cases} Sv & \text{if } v \in U \\ 0 & \text{if } v \in V \text{ and } v \notin U \end{cases}$$

Prove that $T \notin \mathcal{L}(V, W)$.

Solution : Suppose it is a linear map, then $T(u + v) = Tu + Tv$ where $u \in U$ and $v \in V$ and $v \notin U$. One can check that $v + u \in V$ but $v + u \notin U$. Thus, $0 = Tu = Su$, but just take u s.t $Su \neq 0$.

Problem : Suppose V is finite-dimensional. Prove that every linear map on a subspace of U can be extended to a linear map on V . In other words, let U be a subspace of V and $S \in \mathcal{L}(U, W)$, then there exists a $T \in \mathcal{L}(V, W)$ such that $Tu = Su$ for all $u \in U$.

Solution : Let u_1, \dots, u_m be the basis of U and let $u_1, \dots, u_m, v_1, \dots, v_k$ be the extended basis of V . Let $x = a_1u_1 + \dots + a_mu_m + b_1v_1 + \dots + b_kv_k$ and define

$$T(x) = a_1Su_1 + \dots + a_mSu_m + b_1v_1 + \dots + b_kv_k$$

From here its easy to see that $Tu = Su$ for all $u \in U$. We just have to prove this is a linear map on V . Let $y = x = c_1u_1 + \dots + c_mu_m + d_1v_1 + \dots + d_kv_k$ then

$$\begin{aligned} T(x+y) &= (a_1+c_1)Su_1 + \dots + (a_m+c_m)Su_m + (b_1+d_1)v_1 + \dots + (b_k+d_k)v_k \\ \implies T(x+y) &= a_1Su_1 + \dots + a_mSu_m + b_1v_1 + \dots + b_kv_k + c_1Su_1 + \dots + c_mSu_m + d_1v_1 + \dots + d_kv_k \\ &\implies T(x+y) = Tx + Ty \end{aligned}$$

Similarly one can prove $T(\lambda x) = \lambda T(x)$.

Problem : Suppose V is finite-dimensional with $\dim V > 0$ and suppose W is infinite-dimensional. Prove that $\mathcal{L}(V, W)$ is infinite-dimensional.

Solution : Let v_1, \dots, v_m be basis of V . Suppose $\mathcal{L}(V, W)$ is finite-dimensional then every $T \in \mathcal{L}(V, W)$ can be written as

$$T(x) = \lambda_1 T_1(x) + \lambda_2 T_2(x) + \dots + \lambda_k T_k(x)$$

for some fixed $T_1, T_2, \dots, T_k \in \mathcal{L}(V, W)$ and $\lambda_i \in \mathbf{F}$.

Since, W is infinite-dimensional, $\exists w \in W$ s.t $w \notin \text{span}\{T_1(x), T_2(x), \dots, T_k(x)\}$ for some fixed $x \in V$.

Now, set $x = v_i$ then $w \neq \lambda_1 T_1(v_i) + \lambda_2 T_2(v_i) + \dots + \lambda_k T_k(v_i)$. One can find $T \in \mathcal{L}(V, W)$ such that $T(v_i) = w$ thus $T(v_i) \neq \lambda_1 T_1(v_i) + \lambda_2 T_2(v_i) + \dots + \lambda_k T_k(v_i)$ contradicting our assumption.

Problem : Let V be finite-dimensional and let $\dim V > 1$. Prove that there exists $S, T \in \mathcal{L}(V)$ such that $ST \neq TS$.

Solution : Let v_1, \dots, v_m be the basis of V and let $x = a_1v_1 + \dots + a_mv_m$. Define $S(x) = a_1v_1$ and $T(x) = a_1v_2 + a_2v_3 + \dots + a_{m-1}v_m + a_mv_1$. So, $T(S(x)) = a_1v_2$ and $S(T(x)) = a_mv_1$, thus

$$ST = TS \iff a_1 = a_m$$

but one can always choose x s.t $a_1 \neq a_m$.

Problem : Suppose V is finite-dimensional. Show that the only two-sided ideals of $\mathcal{L}(V)$ are $\{0\}$ and $\mathcal{L}(V)$. A subspace \mathcal{E} of $\mathcal{L}(V)$ is called a two-sided ideal if for every $E \in \mathcal{E}$ and $T \in \mathcal{L}(V)$, $TE \in \mathcal{E}$ and $ET \in \mathcal{E}$.

Solution : Let \mathcal{E} be a two-sided ideal of $\mathcal{L}(V)$. If $\mathcal{E} = \{0\}$ we are done. Otherwise pick a nonzero operator $A \in \mathcal{E}$. Choose $v \in V$ with $Av \neq 0$. Fix any $y, z \in V$. Choose $R \in \mathcal{L}(V)$ with $R(z) = v$ and choose $S \in \mathcal{L}(V)$ with $S(Av) = y$. Then

$$T := SAR \in \mathcal{E}$$

(since \mathcal{E} is a two-sided ideal), and

$$T(z) = S(A(R(z))) = S(A(v)) = y.$$

Thus \mathcal{E} contains, for every pair y, z , an operator that sends z to y . Taking a basis u_1, \dots, u_n of V and the operators E_{ij} defined by $E_{ij}(u_j) = u_i$ and $E_{ij}(u_k) = 0$ for $k \neq j$, we see each E_{ij} lies in \mathcal{E} . The set $\{E_{ij}\}$ spans $\mathcal{L}(V)$, so $\mathcal{E} = \mathcal{L}(V)$. Hence the only two-sided ideals are $\{0\}$ and $\mathcal{L}(V)$. \square

1.2 Null Spaces and Ranges

1.2.1 Null Space and Injectivity

Definition 1.5. let $T \in \mathcal{L}(V, W)$, the null space of T , written as $\text{null } T$ is the following set

$$\text{null } T = \{v \in V \mid Tv = 0\}$$

Examples

1. The zero map from V to W has a null space V as everything gets mapped to 0.
2. Let $D \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ be the differentiation map defined by $Dp = p'$. The only functions whose derivative is equal to 0 are the constant function. Thus, $\text{null } D$ is the set of constant functions.
3. Let $D \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ be the multiplication by x^2 map i.e $Dp = x^2p$. The only polynomial such that $x^2p = 0$ is $p = 0$. Thus, $\text{null } D = \{0\}$.

Proposition 1.4. Suppose $T \in \mathcal{L}(V, W)$. Then, $\text{null } T$ is a subspace of V .

Proposition 1.5. Let $T \in \mathcal{T}(V, W)$. Then T is injective $\iff \text{null } T = \{0\}$.

Proof. Suppose T is injective. Since it is a linear map $T(0) = 0$, thus by injectivity the only thing that gets map to 0 is 0. Thus, $\text{null } T = \{0\}$. Suppose T is such that $\text{null } T = \{0\}$ then

$$\begin{aligned} T(v) = T(w) &\implies T(v) + (-1)T(w) = 0 \\ \implies T(v) + T(-w) &= 0 \implies T(v - w) = 0 \implies v = w \end{aligned}$$

Thus, the map is injective. □

1.2.2 Range and Surjectivity

Definition 1.6. Let $T \in \mathcal{L}(V, W)$, the *range* of T is the following set,

$$\text{range } T = \{Tv \mid v \in V\}$$

Examples

1. If T is the zero map then the range of T is $\{0\}$.
2. Suppose $D \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ be the differentiation map. Since, for every polynomial q there exists a polynomial p such that $p' = q$, the range is $\mathcal{P}(\mathbf{R})$.

Proposition 1.6. Let $T \in \mathcal{L}(V, W)$ then $\text{range } T$ is a subspace of W .

Proof. Since, $0 \in V$ we know $T(0) = 0 \in \text{range } T$. Now, suppose $x, y \in \text{range } T$ then $x = Tv$ and $y = Tw$. Since, $v + w \in V$, $T(v + w) \in \text{range } T \implies Tv + Tw \in \text{range } T$ which mean $x + y \in \text{range } T$. And $x \in \text{range } T \implies Tv \in \text{range } T$ which means $T(\lambda v) \in \text{range } T$ as $\lambda v \in V$. Thus, $\lambda x = \lambda T(v) = T(\lambda v) \in \text{range } T$. □

1.2.3 Fundamental Theorem of Linear Maps

Theorem 1.2. *Suppose V is finite-dimensional and $T \in \mathcal{L}(V, W)$. Then $\text{range } T$ is finite-dimensional and*

$$\dim V = \dim \text{null } T + \dim \text{range } T$$

Proof. We know that $\text{null } T$ is a subspace of V then since V is finite-dimensional it has a basis. Let u_1, \dots, u_m be the basis of $\text{null } T$. Then we can extend this basis to a basis of V . Let $u_1, \dots, u_m, v_1, \dots, v_n$ be the basis of V . Then,

$$x = a_1 u_1 + \dots + a_m u_m + b_1 v_1 + \dots + b_n v_n$$

$$\implies Tx = b_1 T v_1 + \dots + b_n T v_n$$

Thus, every Tv can be written as a linear combination of Tv_1, \dots, Tv_n . Thus, $\text{range } T$ is finite-dimensional. To prove our main result, we need to show that Tv_1, \dots, Tv_n is a basis of $\text{range } T$. We already proved it spanned $\text{range } T$, now suppose

$$b_1 T v_1 + \dots + b_n T v_n = 0$$

$$\implies T(b_1 v_1 + \dots + b_n v_n) = 0$$

Thus, $b_1 v_1 + \dots + b_n v_n \in \text{null } T$ and we can write it as $b_1 v_1 + \dots + b_n v_n = a_1 u_1 + \dots + a_m u_m$. Since, $u_1, \dots, u_m, v_1, \dots, v_n$ is a basis vector we can say that $b_i = a_i = 0$. Thus, we have proved that Tv_1, \dots, Tv_n is a basis of $\text{range } T$ and our theorem follows. \square

Theorem 1.3. *Suppose V and W are both finite-dimensional vector spaces such that $\dim V > \dim W$. Then, there exists no **injective** linear map from V to W .*

Proof. We know that, for a $T \in \mathcal{L}(V, W)$,

$$\dim V = \dim \text{null } T + \dim \text{range } T$$

Since $\text{range } T$ is a subspace of W , $\dim W \geq \dim \text{range } T$. Thus,

$$\begin{aligned} \dim \text{null } T &= \dim V - \dim \text{range } T \\ &\geq \dim V - \dim W \\ &> 0 \end{aligned}$$

Thus, $\text{null } T$ has more than one vector, so T is not injective by **Proposition 1.5**. \square

Theorem 1.4. *Suppose V and W are both finite-dimensional vector spaces such that $\dim V < \dim W$. Then, there exists no **surjective** linear map from V to W .*

Proof. Similar to the proof above. \square

Definition 1.7. Define $T : \mathbf{F}^n \rightarrow \mathbf{F}^m$ as

$$T(x_1, \dots, x_n) = \left(\sum_{k=1}^n A_{1,k} x_k, \dots, \sum_{k=1}^n A_{m,k} x_k \right)$$

Definition 1.8. A homogeneous system of linear equations defined is as

$$\left(\sum_{k=1}^n A_{1,k}x_k, \dots, \sum_{k=1}^n A_{m,k}x_k \right) = (0, \dots, 0)$$

And a Inhomogeneous system of linear equation is defined as

$$\left(\sum_{k=1}^n A_{1,k}x_k, \dots, \sum_{k=1}^n A_{m,k}x_k \right) = (c_1, \dots, c_m)$$

where not all c_i are zero.

Proposition 1.7. A homogeneous system of linear equations with more variables than equations has nonzero solutions.

Proof. Use **Theorem 1.3** and **Theorem 1.4**. □

Proposition 1.8. An inhomogeneous system of linear equations with more equations than variables has no solution for some choice of the constant terms.

Proof. Use **Theorem 1.3** and **Theorem 1.4**. □

1.2.4 Exercise

Problem : Give an example of a linear map T such that $\dim \text{null } T = 3$ and $\dim \text{range } T = 2$.

Solution : $T(x_1, x_2, x_3, x_4, x_5) = (x_1, x_2)$.

Problem : Suppose $S, T \in \mathcal{L}(V, W)$ are such that $\text{range } S \subseteq \text{null } T$. Prove that $(ST)^2 = 0$.

Solution : Since $\text{range } S \subseteq \text{null } T$, $T(Sv) = 0$. Thus,

$$(ST)^2 = (ST)(ST) = S(T(S(Tv))) = S(0) = 0$$

Problem : Suppose v_1, \dots, v_m is a list of vector in V . Define $T \in \mathcal{L}(\mathbf{F}^m, V)$ by

$$T(z_1, \dots, z_m) = z_1v_1 + \dots + z_mv_m$$

- What property of T corresponds to v_1, \dots, v_m spanning V ?
- What property of T corresponds to v_1, \dots, v_m being linearly independent on V ?

Solution : If v_1, \dots, v_m spans V then $\text{range } T = V$ thus T being surjective corresponds to v_1, \dots, v_m spanning V .

If v_1, \dots, v_m is linearly independent on V then $\text{null } T = \{0\}$, thus T being injective corresponds to v_1, \dots, v_m being linearly independent on V .

Problem: Show that $\{T \in \mathcal{L}(\mathbf{R}^5, \mathbf{R}^4) : \dim \text{null } T > 2\}$ is not a subspace of $\mathcal{L}(\mathbf{R}^5, \mathbf{R}^4)$.

Solution : Let $T(x_1, x_2, x_3, x_4, x_5) = (x_1, x_2, 0, 0)$ and $T'(x_1, x_2, x_3, x_4, x_5) = (0, 0, x_3, 0)$. Both of them are in $\mathcal{L}(\mathbf{R}^5, \mathbf{R}^4)$. Also $\dim \text{null } T = 3$, $\dim \text{null } T' = 4$ but $T + T' = (x_1, x_2, x_3, 0) \implies \dim \text{null}(T + T') = 2 \not> 2$.

Problem : Give an example of $T \in \mathcal{L}(\mathbf{R}^4)$ such that $\text{range } T = \text{null } T$.

Solution : $T(x_1, x_2, x_3, x_4) = (0, 0, x_1, x_2)$.

Problem : Prove that there doesn't exist a $T \in \mathcal{L}(\mathbf{R}^5)$ such that $\text{range } T = \text{null } T$.

Solution : Suppose there exists such T , then $\dim \text{range } T = \dim \text{null } T$ but from the fundamental theorem of linear maps we have

$$\begin{aligned} \dim V &= \dim \text{range } T + \dim \text{null } T \\ \implies \dim \text{range } T &= \dim \text{null } T = \frac{5}{2} \end{aligned}$$

which is impossible.

Problem : Suppose V and W are finite-dimensional with $2 \leq \dim V \leq \dim W$. Show that $\{T \in \mathcal{L}(V, W) \mid T \text{ is not injective}\}$ is not a subspace of $\mathcal{L}(V, W)$.

Solution : Let v_1, \dots, v_m be the basis of V and w_1, \dots, w_n be the basis of W . Then, define $T_i(a_1v_1 + \dots + a_mv_m) = a_iw_i$. One can check that this is not injective thus

$$T(a_1v_1 + \dots + a_mv_m) = \left(\sum_{i=1}^m T_i \right) (a_1v_1 + \dots + a_mv_m) = \sum_{i=1}^m a_iw_i$$

Now, suppose $T(v) = T(v')$ then

$$\begin{aligned} a_1w_1 + \dots + a_mw_m &= a'_1w_1 + \dots + a'_mw_m \\ \implies b_1 &= b'_1 \quad (\text{because of linear independence}) \end{aligned}$$

Thus, $v = v'$.

Problem : Suppose V is finite-dimensional and $T \in \mathcal{L}(V, W)$. Prove that there exists a subspace U and V such that

$$U \cap \text{null } T = \{0\} \quad \text{and} \quad \text{range } T = \{Tu \mid u \in U\}$$

Solution : We know that $\text{null } T$ is the subspace of V . Thus, there exists a U such that $V = U \oplus \text{null } T$ and since it is a direct sum $U \cap \text{null } T = \{0\}$. Now, for the range of T

$$\begin{aligned} \text{range } T &= \{Tv \mid v \in V\} \\ \implies \{T(u + z) \mid u \in U, z \in \text{null } T\} &= \{Tu \mid u \in U\} \end{aligned}$$

Problem : Suppose T is a linear map from \mathbf{F}^4 to \mathbf{F}^2 such that

$$\text{null } T = \{(x_1, x_2, x_3, x_4) \in \mathbf{F}^4 \mid x_1 = 5x_2 \text{ and } x_3 = 7x_4\}$$

Prove that T is a surjective linear map.

Solution : We can write T as

$$\text{null } T = \{(5x_2, x_2, 7x_4, x_4) \mid x_2, x_4 \in \mathbf{F}\}$$

Now, since $(5x_2, x_2, 7x_4, x_4) = x_2(5, 1, 0, 0) + x_4(0, 0, 7, 1) \implies \dim \text{null } T = 2$. Thus,

$$\dim V = \dim \text{null } T + \dim \text{range } T$$

$$\implies 4 = 2 + \dim \text{range } T$$

$$\implies \dim \text{range } T = 2$$

Since, $\dim \mathbf{F}^2 = 2 = \dim \text{range } T \implies \text{range } T = \mathbf{F}^2$. Thus, T is surjective.

Problem : Suppose U is three-dimensional subspace of \mathbf{R}^8 and that T is a linear map from \mathbf{R}^8 to \mathbf{R}^5 such that $\text{null } T = U$. Prove that T is surjective.

Solution : Since, $\text{null } T = U \implies \dim \text{null } T = 3$. Thus,

$$\dim \mathbf{R}^8 = \dim \text{null } T + \dim \text{range } T$$

$$\implies \dim \text{range } T = 5$$

Since, $\text{range } T$ is a subspace of \mathbf{R}^5 and $\dim \text{range } T = \dim \mathbf{R}^5$, $\mathbf{R}^5 = \text{range } T$. Thus, T is surjective.

Problem : Prove that there does not exist a linear map from \mathbf{F}^5 to \mathbf{F}^2 whose null space doesn't equals $\{(x_1, x_2, x_3, x_4, x_5) \in \mathbf{F}^5 \mid x_1 = 3x_2 \text{ and } x_3 = x_4 = x_5\}$.

Solution : Suppose there does exist such a T . Then the null space can be written as

$$\text{null } T = \{(3x_2, x_2, k, k, k) \mid x_2, k \in \mathbf{F}\}$$

One can check that $\dim \text{null } T = 2$ but

$$\dim \mathbf{F}^5 = \dim \text{null } T + \dim \text{range } T$$

$$\implies \dim \text{range } T = 3$$

But $2 = \dim \mathbf{F}^2 \geq \dim \text{range } T = 3$ which is false.

Problem : Suppose there exists a linear map on V such that the null space and range of T is finite dimensional. Prove that V is finite-dimensional.

Solution : Since, the range of T is finite-dimensional it must have a basis. Suppose Tv_1, \dots, Tv_m is the basis then

$$T(x) = \lambda_1 Tv_1 + \dots + \lambda_m Tv_m$$

$$\implies T(x - \lambda_1 v_1 - \dots - \lambda_m v_m) = 0$$

Since, the null space is also finite-dimensional

$$x - \lambda_1 v_1 - \dots - \lambda_m v_m = \lambda'_1 v'_1 + \dots + \lambda'_n v'_n$$

where v'_1, \dots, v'_n is the basis of the null space. Thus,

$$V = \text{span}(v_1, \dots, v_m, v'_1, \dots, v'_n)$$

Problem : Suppose V and W are both finite-dimensional. Prove that there exists an injective linear map from V to W if and only if $\dim V \leq \dim W$.

Solution : Suppose $T \in \mathcal{L}(V, W)$ is an injective map, then

$$\dim V = \dim \text{null } T + \dim \text{range } T$$

$$\implies \dim V = \dim \text{range } T \leq \dim W$$

Now suppose $\dim V \leq \dim W$ then we can construct an injective map from V to W .

$$T(a_1v_1 + \cdots + a_nv_n) = a_1w_1 + \cdots + a_nw_n$$

where v_1, \dots, v_n is the basis of V and w_1, \dots, w_m is the basis of W . One can check this is a linear map and suppose $T(x) = T(y)$ and let $x = a_1v_1 + \cdots + a_nv_n$ and $y = b_1v_1 + \cdots + b_nv_n$ then

$$T(x) = T(y)$$

$$\implies (a_1 - b_1)w_1 + \cdots + (a_n - b_n)w_n = 0$$

$$\implies a_i = b_i$$

Thus, $x = y$.

Problem : Suppose V and W are finite-dimensional vector spaces and U is a subspace of V . Prove that there exists $T \in \mathcal{L}(V, W)$ such that $\text{null } T = U$ if and only if $\dim U \geq \dim V - \dim W$.

Solution : Suppose $\text{null } T = U$ then

$$\dim V - \dim \text{range } T = \dim U$$

$$\implies \dim V - \dim W \leq \dim V - \dim \text{range } T = \dim U$$

Now, suppose $\dim U \geq \dim V - \dim W$ then let u_1, \dots, u_k be the basis of U and

$$u_1, \dots, u_k, v_1, \dots, v_m$$

be the extended basis of V . Let w_1, \dots, w_j be the basis of W . From our condition, we know $k \geq k + m - j \implies j \geq m$. Thus we define

$$T(a_1u_1 + \cdots + a_ku_k + b_1v_1 + \cdots + b_mv_m) = b_1w_1 + \cdots + b_mv_m$$

Here, $\text{null } T = U$.

Problem : Suppose V is finite-dimensional, $T \in \mathcal{L}(V, W)$, and U is a subspace of W . Prove that $X = \{v \in V \mid Tv \in U\}$ is a subspace of V and

$$\dim X = \dim \text{null } T + \dim(U \cap \text{range } T)$$

Solution : The subspace part is pretty simple. Let $S : X \rightarrow U$ be a map such that $S(v) = T(v)$. Here, $\text{range } S = U \cap \text{range } T$ and $\text{null } S = \text{null } T$.

Problem : Suppose U and V are finite-dimensional vector spaces and $S \in \mathcal{L}(V, W)$ and $T \in \mathcal{L}(U, V)$. Prove that

$$\dim \text{null } ST \leq \dim \text{null } T + \dim \text{null } S$$

Solution : One can find that $\text{null } ST = \text{null } T \cup \{x \in U \mid S(T(x)) = 0, T(x) \neq 0\}$.

Note : It seems that these exercises are taking way too long to do. I'll however come back to it and finish

1.3 Matrices

1.3.1 Representing a Linear Map by a Matrix

Definition 1.9. Suppose m and n are two non-negative integers. A $m \times n$ matrix is A is a rectangular array of elements in \mathbf{F} with m rows and n columns

$$A = \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix}$$

The $A_{i,j}$ represents the entry in i -th row and j -th column.

Definition 1.10. Suppose $T \in \mathcal{L}(V, W)$ and v_1, \dots, v_n is the basis of V and w_1, \dots, w_m is a basis of W . The matrix of T with respect to these bases is the $m \times n$ matrix $\mathcal{M}(T)$ whose entries $A_{i,j}$ are defined by

$$Tv_k = A_{1,k}w_1 + \cdots + A_{m,k}w_m$$

Examples :

Suppose $T \in \mathcal{L}(\mathbf{F}^2, \mathbf{F}^3)$ is defined by

$$T(x, y) = (x + 3y, 2x + 5y, 7x + 9y)$$

Then,

$$\mathcal{M}(T) = \begin{pmatrix} 1 & 3 \\ 2 & 5 \\ 7 & 9 \end{pmatrix}$$

As $T(1, 0) = 1(1, 0, 0) + 2(0, 1, 0) + 7(0, 0, 1)$ and $T(0, 1) = 3(1, 0, 0) + 5(0, 1, 0) + 9(0, 0, 1)$.

1.3.2 Addition and Scalar Multiplication of Matrices

Definition 1.11. The sum of two matrices of same size is obtained by adding corresponding entries in the matrices i.e

$$\begin{aligned} & \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} + \begin{pmatrix} B_{1,1} & \cdots & B_{1,n} \\ \vdots & & \vdots \\ B_{m,1} & \cdots & B_{m,n} \end{pmatrix} \\ &= \begin{pmatrix} A_{1,1} + B_{1,1} & \cdots & A_{1,n} + B_{1,n} \\ \vdots & & \vdots \\ A_{m,1} + B_{m,1} & \cdots & A_{m,n} + B_{m,n} \end{pmatrix} \end{aligned}$$

Proposition 1.9. Suppose $S, T \in \mathcal{L}(V, W)$. Then $\mathcal{M}(S + T) = \mathcal{M}(S) + \mathcal{M}(T)$.

Proof. Follows from the definition. □

Definition 1.12. The product of a scalar and a matrix is obtained by multiplying each entry by the scalar i.e

$$\lambda \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} = \begin{pmatrix} \lambda A_{1,1} & \cdots & \lambda A_{1,n} \\ \vdots & & \vdots \\ \lambda A_{m,1} & \cdots & \lambda A_{m,n} \end{pmatrix}$$

Proposition 1.10. Suppose $T \in \mathcal{L}(V, W)$ and $\lambda \in \mathbf{F}$ then $\lambda \mathcal{M}(T) = \mathcal{M}(\lambda T)$.

Proof. Again, just use the definitions. \square

Theorem 1.5. Suppose $\mathbf{F}^{m,n}$ be the set of all the matrices with entries in \mathbf{F} . Then, with addition and scalar multiplication defined above $\mathbf{F}^{m,n}$ is a vector space and $\dim \mathbf{F}^{m,n} = mn$.

Proof. Proving it is a vector space is pretty easy. To verify $\dim \mathbf{F}^{m,n} = mn$ define

$$X_{i,j} = \begin{pmatrix} 0 & \cdots & \cdots & \cdots \\ \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & 1 & \vdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

where every entry is 0 except the $A_{i,j}$ entry which is equal to 1. Now, its easy to see that every $Z \in \mathbf{F}^{m,n}$ can be written as some linear combination of $X_{i,j}$'s. Thus, $\mathbf{F}^{m,n} = \text{span}\{X_{i,j}\}$ where i, j vary with $i = 1, \dots, m$ and $j = 1, \dots, n$. Also, every matrix with only 0 as its entry can only be written as linear combination of $X_{i,j}$ with all of its scalars equal to 0. Since, there are mn entries the dimension of $\mathbf{F}^{m,n}$ is equal to mn . \square

1.3.3 Matrix Multiplication

Definition 1.13. Suppose A is a $m \times n$ matrix and B is $n \times p$ matrix. Then AB is defined as to be an $m \times p$ matrix whose entry in row j and column k is given by

$$(AB)_{j,k} = \sum_{r=1}^n A_{j,r} B_{r,k}$$

Remark. The motivation for us to define the product like this comes from questioning, does $\mathcal{M}(ST) = \mathcal{M}(S)\mathcal{M}(T)$? Suppose v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is the basis of W . Suppose u_1, \dots, u_k is the basis of U then consider the map $T : U \rightarrow V$ and $S : V \rightarrow W$. Suppose $\mathcal{M}(S) = A$ and $\mathcal{M}(T) = B$. Then

$$\begin{aligned} (ST)u_k &= S \left(\sum_{r=1}^n B_{r,k} v_r \right) \\ &= \sum_{r=1}^n B_{r,k} S v_r \\ &= \sum_{r=1}^n B_{r,k} \sum_{j=1}^m A_{j,r} w_j \\ &= \sum_{j=1}^m \left(\sum_{r=1}^n A_{j,r} B_{r,k} \right) w_j \end{aligned}$$

That is how we define $\mathcal{M}(ST)$ and that is why **Definition 1.13.** makes sense.

Proposition 1.11. Suppose $T \in \mathcal{L}(U, V)$ and $S \in \mathcal{L}(V, W)$, then

$$\mathcal{M}(ST) = \mathcal{M}(S) \mathcal{M}(T)$$

Proof. It follows from our remark and how we defined the product of the matrix. \square

Definition 1.14. Suppose A is a $m \times n$ matrix then

1. If $1 \leq j \leq m$ then $A_{j, \cdot}$ denotes the $1 \times n$ matrix consisting of row j of A .
2. If $1 \leq j \leq n$ then $A_{\cdot, j}$ denotes $m \times 1$ matrix consisting of column j of A .

Example :

Suppose $A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$ then

$$A_{1, \cdot} = (1 \quad 2 \quad 3)$$

$$A_{\cdot, 3} = \begin{pmatrix} 3 \\ 6 \end{pmatrix}$$

Theorem 1.6. Suppose A is a $m \times n$ matrix and B is a $n \times p$ matrix. Then

$$(AB)_{j,k} = A_{j, \cdot} B_{\cdot, k}$$

where $1 \leq j \leq m$ and $1 \leq k \leq p$.

Proof. The definition of matrix multiplication states that

$$\begin{aligned} (AB)_{j,k} &= \sum_{r=1}^n A_{j,r} B_{r,k} \\ &= A_{j,1} B_{1,k} + \cdots + A_{j,n} B_{n,k} \end{aligned}$$

Now, if you take $A_{j, \cdot}$ and $B_{\cdot, k}$ and multiply it out you'll get the same thing. \square

Theorem 1.7. Suppose A is a $m \times n$ matrix and B is a $n \times p$ matrix. Then

$$(AB)_{\cdot, k} = AB_{\cdot, k}$$

for $1 \leq k \leq p$.

Proof. Both of the matrix have size $m \times 1$. The j -th row of $(AB)_{\cdot, k}$ has the element $(AB)_{j,k}$ and the j -th row of $AB_{\cdot, k}$ has element $A_{j,1} B_{1,k} + A_{j,2} B_{2,k} + \cdots + A_{j,n} B_{n,k}$. Thus, from our previous theorem they're equal. \square

Theorem 1.8. Suppose A is a $m \times n$ matrix and $b = \begin{pmatrix} b_1 \\ \vdots \\ b_n \end{pmatrix}$ is a $n \times 1$ matrix. Then,

$$Ab = b_1 A_{\cdot, 1} + \cdots + b_n A_{\cdot, n}$$

Proof. They both have same size and the entries of of Ab is the same as of the right side. \square

Theorem 1.9. Suppose C is an $m \times c$ matrix and R is a $c \times n$ matrix

1. The column k of CR is the linear combination of the columns of C , with coefficients of this linear combination coming from column k of R .
2. Then row j of CR is a linear combination of the rows of R , with the coefficients of this linear combination coming from row j of C .

Proof. Use **Theorem 1.7.** and **Theorem 1.8.** for 1. and we'll prove 2. in the exercise section. \square

1.3.4 Column-Row Factorization and Rank of a Matrix

Definition 1.15. Suppose A is a $m \times n$ matrix with entries in \mathbf{F} .

1. The **column rank** of A is the dimension of the span of columns of A in $\mathbf{F}^{1,m}$.
2. The **row rank** of A is the dimension of the span of rows of A in $\mathbf{F}^{n,1}$.

Example : Suppose

$$A = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix}$$

then the column rank is the dimension of

$$\text{span} \left(\begin{pmatrix} 1 \\ 4 \end{pmatrix}, \begin{pmatrix} 2 \\ 5 \end{pmatrix}, \begin{pmatrix} 3 \\ 6 \end{pmatrix} \right)$$

and the row rank is the dimension of

$$\text{span} \left((1 \ 2 \ 3), (4 \ 5 \ 6) \right)$$

Definition 1.16. The *transpose* of a $m \times n$ matrix A , denoted by A^t , is the $n \times m$ matrix whose entries are given by

$$(A^t)_{i,j} = A_{j,i}$$

Theorem 1.10. Suppose A is an $m \times n$ matrix with entries in \mathbf{F} and column rank $c \geq 1$. Then there exists a $m \times c$ matrix C and $c \times n$ matrix R , both with entries in \mathbf{F} , such that $A = CR$.

Proof. The list $A_{\cdot,1}, \dots, A_{\cdot,n}$ of columns of A can be reduced to a basis of the span of the columns of A . This basis has length c by definition of column rank. The c columns can be put together to form $m \times c$.

Now, each column k of A is a linear combination of columns of C . Make the coefficients of this linear combination column k of R . This matrix R has size $c \times n$. Thus, $A = CR$ follows from **Theorem 1.9.(a)**. \square

Theorem 1.11. Suppose $A \in \mathbf{F}^{m,n}$ then the column rank of A equals row rank of A .

Proof. Let c be the column rank of A . Then $A = CR$ by the previous theorem where C and R are the matrix whose size are $m \times c$ and $c \times n$ respectively. Now, from **Theorem 1.9. (b)** each row of A is a linear combination of rows of R . Since, R has c columns this implies that

$$\text{rowrank } A \leq c = \text{columnrank } A$$

Now applying the same thing to A^t we get

$$\begin{aligned} \text{columnrank } A &= \text{rowrank } A^t \\ &\leq \text{columnrank } A^t \\ &= \text{rowrank } A \end{aligned}$$

Thus, we're done. \square

Remark. From now on, we'll limit our use of terminology of “row rank” and “column rank” to just “rank”.

1.3.5 Exercise

Problem : Suppose $T \in \mathcal{L}(V, W)$. Show that with respect to each choice of basis of V and W , the matrix of T has at least $\dim \text{range } T$ nonzero entries.

Solution : Let v_1, \dots, v_n be the basis of V and w_1, \dots, w_m be the basis of W then suppose k of those vectors are 0 under T and let those vectors be v_1, \dots, v_k . Thus,

$$\text{range } T = \text{span}\{Tv_{k+1}, \dots, Tv_n\}$$

Thus, $\dim \text{range } T \leq n - k$. But since $T(v_j) \neq 0$ for each $k+1 \leq j \leq n$, there must be one entry that is not 0 for each $T(v_j)$. Since, the number of $T(v_j) \neq 0$ are exactly $n - k$ and $n - k \geq \dim \text{range } T$ this means there is at least $\dim \text{range } T$ nonzero entries in matrix of T .

Problem : Suppose V and W are finite-dimensional and $T \in \mathcal{L}(V, W)$. Prove that $\dim \text{range } T = 1$ if and only if there exist a basis of V and a basis of W such that with respect to these bases, all the entries of $\mathcal{M}(T)$ is 1.

Solution : Let us first prove (\Leftarrow). Suppose $A_{i,j} = 1$ for all i, j . That means, $T(v_i) = \sum w_j$ where v_1, \dots, v_n is the basis of V and w_1, \dots, w_m is the basis of W . Thus, $Tv_1 = Tv_2 = \dots = Tv_n = \sum w_j$ and $\text{range } T = \text{span}\{Tv_1, \dots, Tv_n\} = \text{span}\{\sum w_j\} \implies \dim \text{range } T = 1$. Now, for the (\Rightarrow) we use the Fundamental theorem of linear maps,

$$\dim V = \dim \text{null } T + \dim \text{range } T$$

$$\implies \dim V = \dim \text{null } T + 1$$

Now, suppose v_2, \dots, v_n be that basis of $\text{null } T$. Then extend this basis to V , suppose v_2, \dots, v_n, v then

$$\begin{aligned} T(v_2) &= T(v_3) = \dots = T(v_n) = 0 \\ \implies T(v) &= T(v_2 + v) = \dots = T(v_n + v) \end{aligned}$$

One can check that $v_2 + v, \dots, v$ is a basis of V (as it is linearly independent and has length n). Now, since $\dim \text{range } T = 1$ we have $T(x) = \lambda T(v)$ and we choose $T(v), w_2, \dots, w_m$ as our basis for W . Now, we use a clever trick and set $w_1 = T(v) - w_2 - w_3 - \dots - w_m$ and notice that w_1, \dots, w_m is a basis of W . Thus,

$$T(v_i) = T(v) = \sum w_j$$

Thus, we're done.

Problem : Suppose that $D \in \mathcal{L}(\mathcal{P}_3(\mathbf{R}), \mathcal{P}_2(\mathbf{R}))$ is the differentiation map defined by $Dp = p'$. Find a basis of $\mathcal{P}_3(\mathbf{R})$ and a basis of $\mathcal{P}_2(\mathbf{R})$ such that the matrix of D with respect to these bases is

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Solution : Take the basis of $\mathcal{P}_3(\mathbf{R})$ to be $z, \frac{z^2}{2}, \frac{z^3}{3}, 1$ and $\mathcal{P}_2(\mathbf{R})$ to be $1, z, z^2$.

Problem : Suppose V and W are finite-dimensional and $T \in \mathcal{L}(V, W)$. Prove that there exist a basis of V and a basis of W such that with respect to these bases, all entries of $\mathcal{M}(T)$ are 0 except that the entries in row k , column k , equal 1 if $1 \leq k \leq \dim \text{range } T$.

Solution : Let $\dim V = n$ and $\dim \text{range } T = m$. Now, let v_{m+1}, \dots, v_n be the basis of $\dim \text{null } T$. Now, extend these basis such in the following way

$$(v_1, \dots, v_m, v_{m+1}, \dots, v_n)$$

Here, $T(v_i) \neq 0$ for $1 \leq i \leq m$. Now, since $(v_1, \dots, v_m, v_{m+1}, \dots, v_n)$ spans V the list (Tv_1, \dots, Tv_m) must span $\text{range } T$ and in fact it is the basis of $\text{range } T$ (one can check that its linearly independent). We can now extend this basis to the basis of W . Suppose $(Tv_1, \dots, Tv_m, w_1, \dots, w_k)$ is the basis of W . Then,

$$T(v_i) = 0 \cdot T(v_1) + \dots + 1 \cdot T(v_i) + \dots + 0 \cdot w_k$$

for $1 \leq i \leq m = \dim \text{range } T$. But for $i > \dim \text{range } T$ we have

$$0 = T(v_i) = 0 \cdot T(v_1) + 0 \cdot T(v_2) + \dots + 0 \cdot w_k$$

Problem : Suppose $\sigma_1, \dots, \sigma_m$ is a basis of V and W is finite-dimensional. Suppose $T \in \mathcal{L}(V, W)$. Prove that there exists a basis w_1, \dots, w_n of W such that all entries in the first column of $\mathcal{M}(T)$ [with respect to the bases $\sigma_1, \dots, \sigma_m$ and w_1, \dots, w_n] are 0 except for possibly a 1 in the first row, first column.

Solution :