



简介

这是我个人用于复习的「*Linear Algebra Done Right 3E/4E, by Sheldon Axler*」笔记，一本习题选答与课文补注。范围覆盖所有第三版和第四版的课文和习题（除了第一章 A 节、极少数结合上下文太过显而易见的习题。没有任何日后反复推敲价值的当堂习题和方法套路过于雷同的习题）。这份笔记尚处于缓慢的编撰进度中。

习题答案中，有我完全独立思考得出的，有抄 <https://linearalgebras.com/> 的，有抄 <https://math.stackexchange.com/> 的，有抄 LADR2eSolutions (By Axler) .pdf，有抄最新的 LADR4eSolutions 经典最全 (By Axler?) .pdf，还有请教别人，乃至请教 AI 得出来的。这些文档的许可证件，除 LADR4eSolutions 经典最全 (By Axler?) .pdf 找不到/没有指明外，都允许复制/引用。

课文补注中，除了我独立思考总结出的易错误区和技巧、难点之外，还（因为我想要兼容那些使用 LADR 第三版纸质书的读者，包括我在内）把 LADR4e 中对课文定理等等的修改也（作了简化和提炼）摘录上去。

题目标为正常数字 N 的，为第三版某章某节第 N 题（有个别题是第四版又删去的，这里，或直接摘录，或合并简化，仍然作保留；还有个别题是第四版增添条件、设问的，也一并写在第 N 题下）。题目标为 ‘•’ 的，为第四版。因为要面向以第三版为主要教材的学习者，所以为了避免混淆，故而将题号（部分题目的实心黑点后有标注具体第四版的数字标号）、甚至章节略去（一些变动过大的章节除外）。题目顺序会有调换，在每章大标题处会交代清楚。除了原书第四版新加入的章节外，均使用原书第三版的索引。这也许对第四版的使用者很不友好，我在此欢迎有心人士将我的作品修改后在同样的 CC BY NC SA 条款下作为衍生作品发布。

因为使用中文会给我编撰这份笔记带来额外的中英文输入法切换的工作成本，况且对于专业学习者，直接使用英文不会造成任何困扰。但英文词句的冗长性拖慢我编撰/复习的效率，所以我对许多常用术语作了简写。

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作者序

我目前还没有能力和资格评论原书好坏以及线性代数课程教材选用的问题。但作为原书的学习者，我可以说：

相较于（其他课程的）其他教材，以 LADR 作为自学读本的精学计划，往往在执行中出现一次又一次的时间误判/超时，比如我最开始计划 $40 \times 8h$ 完成 LADR 的精学，差不多是一天（8h）完成一节，还有额外的复习时间。但在实际学习中，（刨去笔记的功夫）完成到一半时，发现已经耗费了约 $35 \times 8h$ ，于是我不得不重新估计 LADR 精学所需的总时间为 $70 \times 8h$ 。这一点对于有学时/学期限制/应试要求的线性代数初学者来说很不安全。更主观地讲，这是因为 LADR 更像是一本参考手册，而不是一本细致入微的自学读本；如果把 LADR 作为初学线性代数第一教材和自学读本来学习，会面临不小的困难。

以上或许能劝退相当一部分打算入门的线性代数初学者。S.Axler 说这本书作为第二遍学习线性代数的教材更合适。我认为理由就是，在校的科班生第二遍学习线性代数时，也已经学习过了离散数学、抽象代数、数论、数学分析等课程，这些知识储备统统会化作一个叫 “mathematical maturity” 的东西，让他们面对 LADR 的课文和习题不再少见多怪、茫然无措。据此，我进一步认为，对于完全的初学者，想要完成 LADR 的精学，要么有很好的天赋，要么有与之相匹配的 “mathematical maturity”，再要么，拿出足够的耐心和毅力。幸运的是，在坚持学习 LADR 的过程中，这三样会一同增益。就我个人来说：课文一次看不懂，就多看几遍，一天看不懂，就分三天看；习题一个小时做不出来，就隔六个小时再尝试，一天做不出来，就隔天再尝试。这确实让我收获了独特的学习体验和能力，我迄今也无法在别处得到，因此我很珍视 LADR，我愿意为此编撰一份电子辅助书并免费公开于网络中。这本身并不花费什么，因为实际的时间开销包括了很多不相干的额外项目：初学 \LaTeX 、调整代码架构、了解许可证选用，诸如此类的各种波折，也不乏戏剧性。

Goto

1		B	C				6	A	B	C	D	
2	A	B	C				7	A	B	C	D	F*
3	A	B	C	D	E	F	8	A	B	C	D	
4							9	A	B			
5	A	B ^I	B ^{II}	C	E*		10	A	B			

ABBREVIATION TABLE

A

add	addi(tion)(tive)
algo	algorithm
arb	arbitrary
assoc	associa(tive)(tivity)
asum	assum(e)(ption)

B

becs	because
bss	basis
bses	bases
B_V	basis of V

C

ch	characteristic
clsd	closed under
commu	commut(es)(ing)(ativity)
cond	condition
coeff	coefficient
col	column
conveni	convenience
corres	correspond(s)(ing)
ctradic	contradict(s)(ion)
ctrapos	constrapositive

D

def	definition
deg	degree
dep	dependen(t)(ce)
deri	derivative(s)
diag	diagonal(iza- ble/ility/tion)
diff	differentia(l)(ting)(tion)
diffce	difference
dim	dimension(al)
disti	distinct
distr	distributive
	propert(ies)(ty)
div	div(ide)(ision)

E

-ec	-ec(t)(tor)(tion)(tive)
eig-	eigen-
ele	element(s)
ent	entr(y)(ies)
exa	example
exe	exercise
exis	exist(s)(ing)
existns	existence
expr	expression

F

factoriz	factorizaion
fini	finite
finide	finite-dimensional

G

G disk(s)	Gershgorin disk(s)
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H

homo	homogeneity
hypo	hypothesis

I

induc	induct(ion)(ive)
id	identity
infily	infinitely
invar	invariant
invard	invariant under
invarsp	invariant subspace
inje	injectiv(e)(ity)
inv	inver(se)(tib- le/ility)
iso	isomorph(ism)(ic)

J

K

L

liney	linear(ly)
linity	linearity
len	length

M

max	maxi(mal(ity))(mum)
min	mini(mal(ity))(mum)
multi	multipl(e)(icati-on/ve)

N

notat	notation(al)
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O

optor	operator
othws	otherwise

P

poly	polynomial
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Q

quotient	quot
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R

recurly	recursively
rev	revers(e(s))(ed)(ing)
restr	restrict(ion)(ive)(ing)
req	require(s)(d)/requiring
respectly	respectively

S

seq	sequence
simlr	similar(ly)
solus	solution
sp	space
stam	statement
std	standard
sups	suppose
surj	surjectiv(e)(ity)
suth	such that

T

trig	triangular
trslate	translate
trspose	transpose

U

uniq	unique
uniques	uniqueness

V

val	value
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W

wrto	with respect to
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X

Y

Z

1.B

1 Prove $\forall v \in V, -(-v) = v$.

SOLUS: $-(-v) = (-1)((-1)v) = ((-1)(-1))v = 1 \cdot v = v$.

OR. Becs $-(-v) + (-v) = 0$ 又 $v + (-v) = 0$. Now by the uniqueness of add inv. □

2 Sups $a \in \mathbf{F}, v \in V$, and $av = 0$. Prove $a = 0$ or $v = 0$.

SOLUS: Sups $a \neq 0, \exists a^{-1} \in \mathbf{F}, a^{-1}a = 1$, hence $v = 1 \cdot v = (a^{-1}a)v = a^{-1}(av) = a^{-1} \cdot 0 = 0$. □

3 Sups $v, w \in V$. Explain why $\exists! x \in V, v + 3x = w$.

SOLUS: $v + 3x = w \Leftrightarrow 3x = w - v \Leftrightarrow x = \frac{1}{3}(w - v)$. □

OR. [Existence] Let $x = \frac{1}{3}(w - v)$.

[Uniqueness] If $v + 3x_1 = w, (I) v + 3x_2 = w (II)$. Then $(I) - (II) : 3(x_1 - x_2) = 0 \Rightarrow x_1 = x_2$. □

5 Show in the def of a vecsp, the add inv cond can be replaced by [1.29].

Hint: Sups V satisfies all conds in the def, except we've replaced the add inv cond with [1.29].

Prove the add inv is true.

Using [1.31]. $0v = 0$ for all $v \in V \Leftrightarrow (1 + (-1))v = 1 \cdot v + (-1)v = v + (-v) = 0$. □

6 Let ∞ and $-\infty$ denote two distinct objects, neither of which is in \mathbf{R} .

Define an add and scalar multi on $\mathbf{R} \cup \{\infty, -\infty\}$ as you could guess.

The operations of real numbers is as usual. While for $t \in \mathbf{R}$ define

$$t\infty = \begin{cases} -\infty & \text{if } t < 0, \\ 0 & \text{if } t = 0, \\ \infty & \text{if } t > 0, \end{cases} \quad t(-\infty) = \begin{cases} -\infty & \text{if } t > 0, \\ 0 & \text{if } t = 0, \\ \infty & \text{if } t < 0, \end{cases}$$

(I) $t + \infty = \infty + t = \infty + \infty = \infty$,

(II) $t + (-\infty) = (-\infty) + t = (-\infty) + (-\infty) = -\infty$,

(III) $\infty + (-\infty) = (-\infty) + \infty = 0$.

With these operations of add and scalar multi, is $\mathbf{R} \cup \{\infty, -\infty\}$ a vecsp over \mathbf{R} ? Explain.

SOLUS: Not a vecsp, since the add and scalar multi is not assoc and distr.

By Assoc: $(a + \infty) + (-\infty) \neq a + (\infty + (-\infty))$.

OR. By Distr: $\infty = (2 + (-1))\infty \neq 2\infty + (-\infty) = \infty + (-\infty) = 0$. □

• TIPS: About the Field \mathbf{F} : Many choices.

EXA: $\mathbf{F} = \mathbf{Z}_m = \{K_0, K_1, \dots, K_{m-1}\}, \forall m - 1 \in \mathbf{N}^+$. [Using Euler's Theorem.]

ENDED

1.C

7 8 9 11 12 13 15 16 17 18 21 23 24

• NOTE FOR [1.45]: If $\mathbf{F} = \{0, 1\}$. Prove if $U + W$ is a direct sum, then $U \cap W = \{0\}$.

Becs $\forall v \in U \cap W, \exists! (u, w) \in U \times W, v = u + w$.

If $U \cap W \neq \{0\}$, then (u, w) can be $(v, 0)$ or $(0, v)$, contradic the uniqueness. □

• **TIPS 1:** Sups $U, W \subseteq V$. And U, W, V are vecsps $\Rightarrow U, W$ are subsp of V .

Then $U + W$ is also a subsp of V . Becs $\forall u \in U, w \in U, u + w \in V$ since $u, w \in V$.

7 Give a nonempty $U \subseteq \mathbb{R}^2$, U is closed taking add invs and add, but is not a subsp of \mathbb{R}^2 .

SOLUS: ($0 \in U$; $v \in U \Rightarrow -v \in U$. And operations on U are the same as \mathbb{R}^2 .) Let $\mathbb{Z}^2, \mathbb{Q}^2$.

8 Give a nonempty $U \subseteq \mathbb{R}^2$, U is closed scalar multi, but is not a subsp of \mathbb{R}^2 .

SOLUS: Let $U = \{(x, y) \in \mathbb{R}^2 : x = 0 \vee y = 0\}$.

9 A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is called periodic if $\exists p \in \mathbb{N}^+, f(x) = f(x + p)$ for all $x \in \mathbb{R}$.

Is the set of periodic functions $\mathbb{R} \rightarrow \mathbb{R}$ a subsp of $\mathbb{R}^{\mathbb{R}}$? Explain.

SOLUS: Denote the set by S .

Sups $h(x) = \cos x + \sin \sqrt{2}x \in S$, since $\cos x, \sin \sqrt{2}x \in S$.

Asum $\exists p \in \mathbb{N}^+$ such $h(x) = h(x + p), \forall x \in \mathbb{R}$. Let $x = 0 \Rightarrow h(0) = h(\pm p) = 1$.

Thus $1 = \cos p + \sin \sqrt{2}p = \cos p - \sin \sqrt{2}p$

$\Rightarrow \sin \sqrt{2}p = 0, \cos p = 1 \Rightarrow p = 2k\pi, k \in \mathbb{Z}$, while $p = \frac{m\pi}{\sqrt{2}}, m \in \mathbb{Z}$.

Hence $2k = \frac{m}{\sqrt{2}} \Rightarrow \sqrt{2} = \frac{m}{2k} \in \mathbb{Q}$. Ctradic!

□

OR. Becs [I] : $\cos x + \sin \sqrt{2}x = \cos(x + p) + \sin(\sqrt{2}x + \sqrt{2}p)$. By diff twice,

[II] : $\cos x + 2 \sin \sqrt{2}x = \cos(x + p) + 2 \sin(\sqrt{2}x + \sqrt{2}p)$.

[II] - [I] : $\sin \sqrt{2}x = \sin(\sqrt{2}x + \sqrt{2}p)$ } \Rightarrow Let $x = 0, p = \frac{m\pi}{\sqrt{2}} = 2k\pi$. Ctradic.

2[I] - [II] :

$\cos x = \cos(x + p)$

□

24 Let $V_E = \{f \in \mathbb{R}^{\mathbb{R}} : f \text{ is even}\}, V_O = \{f \in \mathbb{R}^{\mathbb{R}} : f \text{ is odd}\}$. Show $V_E \oplus V_O = \mathbb{R}^{\mathbb{R}}$.

SOLUS: (a) $V_E \cap V_O = \{f \in \mathbb{R}^{\mathbb{R}} : f(x) = f(-x) = -f(-x)\} = \{0\}$.

(b) $\left\{ \begin{array}{l} \text{Let } f_e(x) = \frac{1}{2}[g(x) + g(-x)] \Rightarrow f_e \in V_E \\ \text{Let } f_o(x) = \frac{1}{2}[g(x) - g(-x)] \Rightarrow f_o \in V_O \end{array} \right\} \Rightarrow \forall g \in \mathbb{R}^{\mathbb{R}}, g(x) = f_e(x) + f_o(x).$

□

• Sups U, W, V_1, V_2, V_3 are subsp of V .

15 $U + U \ni u + w \in U$. **16** $U + W \ni u + w = w + u \in W + U$.

□

17 $(V_1 + V_2) + V_3 \ni (v_1 + v_2) + v_3 = v_1 + (v_2 + v_3) \in V_1 + (V_2 + V_3)$.

□

• $(U + W)_C \ni (u_1 + w_1) + i(u_2 + w_2) = (u_1 + iu_2) + (w_1 + iw_2) \in U_C + W_C$.

□

18 Does the add on the subsp of V have an add id? Which subsp have add invs?

SOLUS: Sups Ω is the uniq add id.

(a) For any subsp U of V . $\Omega \subseteq U + \Omega = U \Rightarrow \Omega \subseteq U$. Let $U = \{0\}$, then $\Omega = \{0\}$.

(b) Now sups W is an add inv of $U \Rightarrow U + W = \Omega$.

Note that $U + W \supseteq U, W \Rightarrow \Omega \supseteq U, W$. Thus $U = W = \Omega = \{0\}$.

□

11 Prove the intersec of every collec of subsp of V is a subsp of V .

SOLUS: Sups $\{U_\alpha\}_{\alpha \in \Gamma}$ is a collec of subsp of V ; here Γ is an index set.

We show $\bigcap_{\alpha \in \Gamma} U_\alpha$, which equals the set of vecs that are in U_α for each $\alpha \in \Gamma$, is a subsp of V .

(一) $0 \in \bigcap_{\alpha \in \Gamma} U_\alpha$. Nonempty.

(二) $u, v \in \bigcap_{\alpha \in \Gamma} U_\alpha \Rightarrow u + v \in U_\alpha, \forall \alpha \in \Gamma \Rightarrow u + v \in \bigcap_{\alpha \in \Gamma} U_\alpha$. Clsd add.

(三) $u \in \bigcap_{\alpha \in \Gamma} U_\alpha, \lambda \in \mathbf{F} \Rightarrow \lambda u \in U_\alpha, \forall \alpha \in \Gamma \Rightarrow \lambda u \in \bigcap_{\alpha \in \Gamma} U_\alpha$. Clsd scalar multi.

Thus $\bigcap_{\alpha \in \Gamma} U_\alpha$ is nonempty subset of V that is clsd add and scalar multi. □

12 Sups U, W are subsp of V . Prove $U \cup W$ is a subsp of $V \iff U \subseteq W$ or $W \subseteq U$.

SOLUS: (a) Sups $U \subseteq W$. Then $U \cup W = W$ is a subsp of V .

(b) Sups $U \cup W$ is a subsp of V . Asum $U \not\subseteq W, U \not\supseteq W$ ($U \cup W \neq U$ and W).

Then $\forall a \in U \wedge a \notin W, \forall b \in W \wedge b \notin U$, we have $a + b \in U \cup W$.

$a + b \in U \Rightarrow b = (a + b) + (-a) \in U$, ctrad $\Rightarrow W \subseteq U$. | Ctrad asum.

$a + b \in W \Rightarrow a = (a + b) + (-b) \in W$, ctrad $\Rightarrow U \subseteq W$. | □

13 Prove the union of three subsp of V is a subsp of V if and only if one of the subsp contains the other two.

This exe is not true if we replace \mathbf{F} with a field containing only two ele.

SOLUS:

Sups U_1, U_2, U_3 are subsp of V . Denote $U_1 \cup U_2 \cup U_3$ by \mathcal{U} .

(a) Sups that one of the subsp contains the other two.

Then $\mathcal{U} = U_1, U_2$ or U_3 is a subsp of V .

(b) Sups that $U_1 \cup U_2 \cup U_3$ is a subsp of V .

Distinctively notice that $A \cup B \cup C = (A \cup B) \cup (B \cup C) = (A \cup C) \cup (B \cup C) = (A \cup B) \cup (A \cup C)$.

Also note that, if $U \cup W = V$ is a vecsp, then in general U and W are not subsp of V .

Hence this literal trick is invalid.

(I) If any U_j is contained in the union of the other two, say $U_1 \subseteq U_2 \cup U_3$, then $\mathcal{U} = U_2 \cup U_3$.

By applying Exe (12) we conclude that one U_j contains the other two. Thus done.

(II) Asum no U_j is contained in the union of the other two,

and no U_j contains the union of the other two. Say $U_1 \not\subseteq U_2 \cup U_3$ and $U_1 \not\supseteq U_2 \cup U_3$.

$\exists u \in U_1 \wedge u \notin U_2 \cup U_3; v \in U_2 \cup U_3 \wedge v \notin U_1$. Let $W = \{v + \lambda u : \lambda \in \mathbf{F}\} \subseteq \mathcal{U}$.

Note that $W \cap U_1 = \emptyset$, for if any $v + \lambda u \in W \cap U_1$ then $v + \lambda u - \lambda u = v \in U_1$.

Now $W \subseteq U_1 \cup U_2 \cup U_3 \Rightarrow W \subseteq U_2 \cup U_3$. $\forall v + \lambda u \in W, v + \lambda u \in U_i, i = 2, 3$.

If $U_2 \subseteq U_3$ or $U_2 \supseteq U_3$, then $\mathcal{U} = U_1 \cup U_i, i = 2, 3$. By Exe (12) done.

Othws, both $U_2, U_3 \neq \{0\}$. Bcs $W \subseteq U_2 \cup U_3$ has at least three ele.

There must be some U_i that contains at least two ele of W .

\exists disti $\lambda_1, \lambda_2 \in \mathbf{F}, v + \lambda_1 u, v + \lambda_2 u \in U_i, i \in \{2, 3\}$.

Then $u \in U_i$ while $u \notin U_2 \cup U_3$. Ctrad. □

EXA: Let $\mathbf{F} = \mathbf{Z}_2$. $U_1 = \{u, 0\}, U_2 = \{v, 0\}, U_3 = \{v + u, 0\}$. While $\mathcal{U} = \{0, u, v, v + u\}$ is a subsp.

- *Sups* $U = \{(x, x, y, y)\}, W = \{(x, x, x, y)\} \subseteq \mathbf{F}^4$. Prove $U + W = \{(x, x, y, z)\}$.

SOLUS: Let T denote $\{(x, x, y, z)\}$. By def, $U + W \subseteq T$.

And $T \ni (x, x, y, z) \Rightarrow (0, 0, y - x, y - x) + (x, x, x, -y + x + z) \in U + W$. Hence $T \subseteq U + W$. \square

- 21** *Sups* $U = \{(x, y, x + y, x - y, 2x)\}$. Find a W such $\mathbf{F}^5 = U \oplus W$.

SOLUS: Let $W = \{(0, 0, z, w, u)\}$. Then $U \cap W = \{0\}$.

And $\mathbf{F}^5 \ni (x, y, z, w, u) \Rightarrow (x, y, x + y, x - y, 2x) + (0, 0, z - x - y, w - x - y, u - 2x) \in U + W$.

- 23** Give an exa of vecsps V_1, V_2, U such $V_1 \oplus U = V_2 \oplus U$, but $V_1 \neq V_2$.

SOLUS: $V = \mathbf{F}^2, U = \{(x, x)\}, V_1 = \{(x, 0)\}, V_2 = \{(0, x)\}$.

- **TIPS 2:** *Sups* $V_1 \subseteq V_2$ in Exe (23). Prove $V_1 = V_2$.

SOLUS:

Becs the subset V_1 of vecsp V_2 is closed add and scalar multi, V_1 is a subspace of V_2 .

Sups W is such $V_2 = V_1 \oplus W$. Now $V_2 \oplus U = (V_1 \oplus W) \oplus U = (V_1 \oplus U) \oplus W = V_1 \oplus U$.

If $W \neq \{0\}$, then $V_1 \oplus U \subsetneq (V_1 \oplus U) \oplus W$, contradic. Hence $W = \{0\}, V_1 = V_2$. \square

- *Sups* V_1, V_2, U_1, U_2 are vecsps, $V_1 \oplus U_1 = V_2 \oplus U_2, V_1 \subseteq V_2, U_2 \subseteq U_1$.

Prove or give a counterexa: $V_1 = V_2, U_1 = U_2$.

V_1	U_1
V_2	U_2

SOLUS: Let $U_2 = \{0\}$. Give an exa that each of V_1, V_2, U_1 is nonzero. \square

- **TIPS 3:** *Sups* the intersec of any two of the vecsps U, W, X, Y is $\{0\}$.

Give an exa that $(X \oplus U) \cap (Y \oplus W) \neq \{0\}$.

SOLUS: [Using notas in Chapter 2.] Let $B_X = (e_1), B_U = (e_2 - e_1), B_Y = (), B_W = (e_2)$.

- **TIPS 4:** Let $V = U + W, I = U \cap W, U = I \oplus X, W = I \oplus Y$. Prove $V = I \oplus (X \oplus Y)$.

SOLUS: We show $X \cap Y = U \cap Y = W \cap X = \{0\}$ by contradic.

$X \cap Y = \Delta \neq \{0\} \Rightarrow I = U \cap W \supseteq \Delta \Rightarrow I \cap X \neq \{0\}, I \cap Y \neq \{0\}$.

$U \cap Y = \Delta \neq \{0\} \Rightarrow I = U \cap W \supseteq \Delta \Rightarrow I \cap Y \neq \{0\}$. Simlr for $W \cap X$.

Thus $I + (X + Y) = (I \oplus X) \oplus Y = I \oplus (X \oplus Y)$.

Now we show $V = I + (X + Y)$. $\forall v \in V, v = u + w, \exists (u, w) \in U \times W$

$\Rightarrow \exists (i_u, x_u) \in I \times X, (i_w, y_w) \in I \times Y, v = (i_u + i_w) + x_u + y_w \in I + (X + Y)$. \square

ENDED

2.A

1 2 10 11 14 16 17 | 4E: 3,14

1 Prove $[P] (v_1, v_2, v_3, v_4) \text{ spans } V \iff (v_1 - v_2, v_2 - v_3, v_3 - v_4, v_4) \text{ also spans } V [Q]$.

SOLUS: Note that $V = \text{span}(v_1, \dots, v_n) \iff \forall v \in V, \exists a_1, \dots, a_n \in \mathbb{F}, v = a_1 v_1 + \dots + a_n v_n$.

Asum $\forall v \in V, \exists a_1, \dots, a_4, b_1, \dots, b_4 \in \mathbb{F}$, (that is, if $\exists a_i$, then we are to find b_i , vice versa)

$$v = a_1 v_1 + a_2 v_2 + a_3 v_3 + a_4 v_4 = b_1(v_1 - v_2) + b_2(v_2 - v_3) + b_3(v_3 - v_4) + b_4 v_4$$

$$= b_1 v_1 + (b_2 - b_1)v_2 + (b_3 - b_2)v_3 + (b_4 - b_3)v_4$$

$$= a_1(v_1 - v_2) + (a_1 + a_2)(v_2 - v_3) + (a_1 + a_2 + a_3)(v_3 - v_4) + (a_1 + \dots + a_4)v_4. \quad \square$$

• Sups (v_1, \dots, v_m) is a list in V . For each k , let $w_k = v_1 + \dots + v_k$.

(a) Show $\text{span}(v_1, \dots, v_m) = \text{span}(w_1, \dots, w_m)$.

(b) Show $[P] (v_1, \dots, v_m) \text{ is liney indep} \iff (w_1, \dots, w_m) \text{ is liney indep} [Q]$.

SOLUS:

(a) Asum $a_1 v_1 + \dots + a_m v_m = b_1 w_1 + \dots + b_m w_m = b_1 v_1 + \dots + b_k(v_1 + \dots + v_k) + \dots + b_m(v_1 + \dots + v_m)$.

Then $a_k = b_k + \dots + b_m$; $a_{k+1} = b_{k+1} + \dots + b_m \Rightarrow b_k = a_k - a_{k+1}$; $b_m = a_m$. Simlr to Exe (1).

(b) $P \Rightarrow Q$: $b_1 w_1 + \dots + b_m w_m = 0 = a_1 v_1 + \dots + a_m v_m$, where $0 = a_k = b_k + \dots + b_m$.

$Q \Rightarrow P$: $a_1 v_1 + \dots + a_m v_m = 0 = b_1 w_1 + \dots + b_m w_m = 0$, where $0 = b_m = a_m$, $0 = b_k = a_k - a_{k+1}$.

OR. By (a), let $W = \text{span}(v_1, \dots, v_m) = \text{span}(w_1, \dots, w_m)$. Sups (w_1, \dots, w_m) is liney dep.

By [2.21](b), a list of len $(m - 1)$ spans W . 又 By [2.23], (w_1, \dots, w_m) liney indep $\Rightarrow m \leq m - 1$.

Thus (w_1, \dots, w_m) is liney dep. Now rev the roles of v and w . \square

2 (a) $[P] \quad A \text{ list } (v) \text{ of len } 1 \text{ in } V \text{ is liney indep} \iff v \neq 0. \quad [Q]$

(b) $[P] \quad A \text{ list } (v, w) \text{ of len } 2 \text{ in } V \text{ is liney indep} \iff \forall \lambda, \mu \in \mathbb{F}, v \neq \lambda w, w \neq \mu v. \quad [Q]$

SOLUS: (a) $Q \Rightarrow P$: $v \neq 0 \Rightarrow$ if $av = 0$ then $a = 0 \Rightarrow (v)$ liney indep.

$P \Rightarrow Q$: (v) liney indep $\Rightarrow v \neq 0$, for if $v = 0$, then $av = 0 \nRightarrow a = 0$.

$\neg Q \Rightarrow \neg P$: $v = 0 \Rightarrow av = 0$ while we can let $a \neq 0 \Rightarrow (v)$ is liney dep.

$\neg P \Rightarrow \neg Q$: (v) liney dep $\Rightarrow av = 0$ while $a \neq 0 \Rightarrow v = 0$.

(b) $P \Rightarrow Q$: (v, w) liney indep \Rightarrow if $av + bw = 0$, then $a = b = 0 \Rightarrow$ no scalar multi.

$Q \Rightarrow P$: no scalar multi \Rightarrow if $av + bw = 0$, then $a = b = 0 \Rightarrow (v, w)$ liney indep.

$\neg P \Rightarrow \neg Q$: (v, w) liney dep \Rightarrow if $av + bw = 0$, then a or $b \neq 0 \Rightarrow$ scalar multi.

$\neg Q \Rightarrow \neg P$: scalar multi \Rightarrow if $av + bw = 0$, then a or $b \neq 0 \Rightarrow$ liney dep. \square

10 Sups (v_1, \dots, v_m) is liney indep in V and $w \in V$.

Prove if $(v_1 + w, \dots, v_m + w)$ is liney depe, then $w \in \text{span}(v_1, \dots, v_m)$.

SOLUS:

Note that $a_1(v_1 + w) + \dots + a_m(v_m + w) = 0 \Rightarrow a_1 v_1 + \dots + a_m v_m = -(a_1 + \dots + a_m)w$.

Then $a_1 + \dots + a_m \neq 0$, for if not, $a_1 v_1 + \dots + a_m v_m = 0$ while $a_i \neq 0$ for some i , ctradic.

OR. We prove the ctrapos: Sups $w \notin \text{span}(v_1, \dots, v_m)$. Then $a_1 + \dots + a_m = 0$.

Thus $a_1 v_1 + \dots + a_m v_m = 0 \Rightarrow a_1 = \dots = a_m = 0$. Hence $(v_1 + w, \dots, v_m + w)$ is liney indep. \square

OR. $\exists j \in \{1, \dots, m\}, v_j + w \in \text{span}(v_1 + w, \dots, v_{j-1} + w)$. If $j = 1$ then $v_1 + w = 0$ and done.

If $j \geq 2$, then $\exists a_i \in \mathbb{F}, v_j + w = a_1(v_1 + w) + \dots + a_{j-1}(v_{j-1} + w) \iff v_j + \lambda w = a_1 v_1 + \dots + a_{j-1} v_{j-1}$.

Where $\lambda = 1 - (a_1 + \dots + a_{j-1})$. Note that $\lambda \neq 0$, for if not, $v_j + \lambda w = v_j \in \text{span}(v_1, \dots, v_{j-1})$, ctradic.

Now $w = \lambda^{-1}(a_1 v_1 + \dots + a_{j-1} v_{j-1} - v_j) \Rightarrow w \in \text{span}(v_1, \dots, v_m)$. \square

11 Sups (v_1, \dots, v_m) is liney indep in V and $w \in V$.

Show $[P] (v_1, \dots, v_m, w)$ is liney indep $\iff w \notin \text{span}(v_1, \dots, v_m) [Q]$.

SOLUS: $\neg Q \Rightarrow \neg P$: Sups $w \in \text{span}(v_1, \dots, v_m)$. Then (v_1, \dots, v_m, w) is liney depe.

$\neg P \Rightarrow \neg Q$: Sups (v_1, \dots, v_m, w) is liney dep. Then by [2.21](a), $w \in \text{span}(v_1, \dots, v_m)$. □

14 Prove $[P] V$ is infinide $\iff [Q] \left| \begin{array}{l} \text{there is a sequence } (v_1, v_2, \dots) \text{ in } V \text{ suth} \\ (v_1, \dots, v_m) \text{ is liney indep for each } m \in \mathbb{N}^+. \end{array} \right.$

SOLUS:

$P \Rightarrow Q$: Sups V is infinide, so that no list spans V .

Step 1 Pick a $v_1 \neq 0, (v_1)$ liney indep.

Step m Pick a $v_m \notin \text{span}(v_1, \dots, v_{m-1})$, by Exe (11), (v_1, \dots, v_m) is liney indep.

This process recurly defines the desired sequence (v_1, v_2, \dots) .

$\neg P \Rightarrow \neg Q$: Sups V is finide and $V = \text{span}(w_1, \dots, w_m)$.

Let (v_1, v_2, \dots) be a sequence in V , then $(v_1, v_2, \dots, v_{m+1})$ must be liney dep.

OR. $Q \Rightarrow P$: Sups there is such a sequence.

Choose an m . Sups a liney indep list (v_1, \dots, v_m) spans V .

Simlr to [2.16]. $\exists v_{m+1} \in V \setminus \text{span}(v_1, \dots, v_m)$. Hence no list spans V . □

16 Prove the vecsp of all continuous functions in $\mathbb{R}^{[0,1]}$ is infinide.

SOLUS: Denote the vecsp by U .

Choose one $m \in \mathbb{N}^+$. Sups $a_0, \dots, a_m \in \mathbb{R}$ are suth $p(x) = a_0 + a_1x + \dots + a_mx^m = 0, \forall x \in [0, 1]$.

Then p has infily many roots and hence each $a_k = 0$, othws $\deg p \geq 0$, ctradic [4.12].

Thus $(1, x, \dots, x^m)$ is liney indep in $\mathbb{R}^{[0,1]}$. Simlr to [2.16], U is infinide. □

OR. Note that $\frac{1}{1} > \frac{1}{2} > \dots > \frac{1}{m}, \forall m \in \mathbb{N}^+$. Sups $f_m = \begin{cases} x - \frac{1}{m}, & x \in (\frac{1}{m}, 1] \\ 0, & x \in [0, \frac{1}{m}] \end{cases}$

Then $f_1\left(\frac{1}{m}\right) = \dots = f_m\left(\frac{1}{m}\right) = 0 \neq f_{m+1}\left(\frac{1}{m}\right)$. Hence $f_{m+1} \notin \text{span}(f_1, \dots, f_m)$. By Exe (14). □

17 Sups $p_0, p_1, \dots, p_m \in \mathcal{P}_m(\mathbb{F})$ suth $p_k(2) = 0$ for each $k \in \{0, \dots, m\}$.

Prove (p_0, p_1, \dots, p_m) is not liney indep in $\mathcal{P}_m(\mathbb{F})$.

SOLUS:

Sups (p_0, p_1, \dots, p_m) is liney indep. Define $p \in \mathcal{P}_m(\mathbb{F})$ by $p(z) = z$.

NOTICE that $\forall a_i \in \mathbb{F}, z \neq a_0p_0(z) + \dots + a_mp_m(z)$, for if not, let $z = 2$. Thus $z \notin \text{span}(p_0, p_1, \dots, p_m)$.

Then $\text{span}(p_0, p_1, \dots, p_m) \subsetneq \mathcal{P}_m(\mathbb{F})$ while the list (p_0, p_1, \dots, p_m) has len $(m+1)$.

Hence (p_0, p_1, \dots, p_m) is liney depe. For if not, then becs $(1, z, \dots, z^m)$ of len $(m+1)$ spans $\mathcal{P}_m(\mathbb{F})$,

by the steps in [2.23] trivially, (p_0, p_1, \dots, p_m) of len $(m+1)$ spans $\mathcal{P}_m(\mathbb{F})$. Ctrad. □

OR. Note that $\mathcal{P}_m(\mathbb{F}) = \text{span}(\underbrace{1, z, \dots, z^m}_{\text{of len } (m+1)})$. Then $(p_0, p_1, \dots, p_m, z)$ of len $(m+2)$ is liney dep.

As shown above, $z \notin \text{span}(p_0, p_1, \dots, p_m)$. And hence by [2.21](a), (p_0, p_1, \dots, p_m) is liney dep. □

ENDED

7 Prove or give a counterexa: If (v_1, v_2, v_3, v_4) is a bss of V and U is a subsp of V suth $v_1, v_2 \in U$ and $v_3 \notin U$ and $v_4 \notin U$, then (v_1, v_2) is a bss of U .

SOLUS: A counterexa: Let $V = \mathbb{R}^4$ and $B_V = (e_1, e_2, e_3, e_4)$ be std bss.

Let $v_1 = e_1, v_2 = e_2, v_3 = e_3 + e_4, v_4 = e_4$. Then (v_1, \dots, v_4) is a bss of \mathbb{R}^4 .

Let $U = \text{span}(e_1, e_2, e_3) = \text{span}(v_1, v_2, v_3 - v_4)$. Then $v_3 \notin U$ and (v_1, v_2) is not a bss of U . \square

COMMENT: Let $W = \text{span}(v_4 - v_1)$. Then $v_4 \in V = U \oplus W$ but $W \not\subseteq U$.

• NOTE FOR " $\mathbb{C}_V U \cup \{0\}$ ": " $\mathbb{C}_V U \cup \{0\}$ " is supposed to be a subsp W suth $V = U \oplus W$.

But if we let $u \in U \setminus \{0\}$ and $w \in W \setminus \{0\}$, then $\left. \begin{array}{l} w \in \mathbb{C}_V U \cup \{0\} \\ u \pm w \in \mathbb{C}_V U \cup \{0\} \end{array} \right\} \Rightarrow u \in \mathbb{C}_V U \cup \{0\}$. Ctradic.

To fix this, denote the set $\{W_1, W_2, \dots\}$ by $\mathcal{S}_V U$, where for each W_i , $V = U \oplus W_i$. See also in (1.C.23).

• TIPS: Sups V is finide with $\dim V = n$ and U is a subsp of V with $U \neq V$.

Prove $\exists B_V = (v_1, \dots, v_n)$ suth each $v_k \notin U$.

Note that $U \neq V \Rightarrow n \geq 1$. We will construct B_V via the following process.

Step 1. $\exists v_1 \in V \setminus U \Rightarrow v_1 \neq 0$. If $\text{span}(v_1) = V$ then we stop.

Step k. Sups (v_1, \dots, v_{k-1}) is liney indep in V , each of which belongs to $V \setminus U$.

Note that $\text{span}(v_1, \dots, v_{k-1}) \neq V$. And if $\text{span}(v_1, \dots, v_{k-1}) \cup U = V$, then by (1.C.12),

[becs $\text{span}(v_1, \dots, v_{k-1}) \not\subseteq U$,] $U \subseteq \text{span}(v_1, \dots, v_{k-1}) \Rightarrow \text{span}(v_1, \dots, v_{k-1}) = V$.

Hence becs $\text{span}(v_1, \dots, v_{k-1}) \neq V$, it must be case that $\text{span}(v_1, \dots, v_{k-1}) \cup U \neq V$.

Thus $\exists v_k \in V \setminus U$ suth $v_k \notin \text{span}(v_1, \dots, v_{k-1})$.

By (2.A.11), (v_1, \dots, v_k) is liney indep in V . If $\text{span}(v_1, \dots, v_k) = V$, then we stop.

Becs V is finide, this process will stop after n steps. \square

OR. Sups $U \neq \{0\}$. Let $B_U = (u_1, \dots, u_m)$. Extend to a bss (u_1, \dots, u_n) of V .

Then let $B_V = (u_1 - u_k, \dots, u_m - u_k, u_{m+1}, \dots, u_k, \dots, u_n)$. \square

1 Find all vecsps on whatever \mathbf{F} that have exactly one bss.

SOLUS: The trivial vecsp $\{0\}$ will do. Indeed, the only bss of $\{0\}$ is the empty list $()$.

Now consider the field $\{0, 1\}$ containing only the add id and multi id,

with $1 + 1 = 0$. Then the list (1) is the uniq bss. Now the vecsp $\{0, 1\}$ will do.

COMMENT: All vecsp on such \mathbf{F} of dim 1 will do.

And more generally, consider $\mathbf{F} = \mathbb{Z}_m, \forall m - 1 \in \mathbb{N}^+$. For each $s, t \in \{1, \dots, m\}$,

$\mathbf{F} = \text{span}(K_s) = \text{span}(K_t)$. More than one bss. So are $\mathbb{Q}, \mathbb{R}, \mathbb{C}$ and all vecsps on such \mathbf{F} .

Consider other \mathbf{F} . Note that this \mathbf{F} contains at least and strictly more than 0 and 1. Failed. \square

• (4E 9) Sups (v_1, \dots, v_m) is a list in V . For $k \in \{1, \dots, m\}$, let $w_k = v_1 + \dots + v_k$.

Show $[P] B_V = (v_1, \dots, v_m) \iff B_W = (w_1, \dots, w_m)$. $[Q]$

SOLUS: NOTICE that $B_U = (u_1, \dots, u_n) \iff \forall u \in U, \exists! a_i \in \mathbf{F}, u = a_1 u_1 + \dots + a_n u_n$.

$P \Rightarrow Q$: $\forall v \in V, \exists! a_i \in \mathbf{F}, v = a_1 v_1 + \dots + a_m v_m \Rightarrow v = b_1 w_1 + \dots + b_m w_m, \exists! b_k = a_k - a_{k+1}, b_m = a_m$.

$Q \Rightarrow P$: $\forall v \in V, \exists! b_i \in \mathbf{F}, v = b_1 w_1 + \dots + b_m w_m \Rightarrow v = a_1 v_1 + \dots + a_m v_m, \exists! a_k = \sum_{j=k}^m b_j$. \square

COMMENT: See also ??? in (3.F).

- (4E 5) *Sups* U, W are finide, $V = U + W$, $B_U = (u_1, \dots, u_m)$, $B_W = (w_1, \dots, w_n)$.

Prove $\exists B_V$ consisting of vecs in $U \cup W$.

SOLUS: $V = \text{span}(u_1, \dots, u_m) + \text{span}(w_1, \dots, w_n) = \text{span}(\overbrace{u_1, \dots, u_m, w_1, \dots, w_n}^{\text{Reduce}})$. By [2.31]. \square

- 8 *Sups* $V = U \oplus W$, $B_U = (u_1, \dots, u_m)$, $B_W = (w_1, \dots, w_n)$.

Prove $B_V = (u_1, \dots, u_m, w_1, \dots, w_n)$.

SOLUS: $\forall v \in V, \exists! u \in U, w \in W \Rightarrow \exists! a_i, b_i \in \mathbb{F}, v = u + w = \sum_{i=1}^m a_i u_i + \sum_{i=1}^n b_i w_i$.

OR. $V = \text{span}(u_1, \dots, u_m) \oplus \text{span}(w_1, \dots, w_n) = \text{span}(u_1, \dots, u_m, w_1, \dots, w_n)$.

Note that $\sum_{i=1}^m a_i u_i + \sum_{i=1}^n b_i w_i = 0 \Rightarrow \sum_{i=1}^m a_i u_i = -\sum_{i=1}^n b_i w_i \in U \cap W = \{0\}$. \square

- (9.A.3.4 OR 4E 11) *Sups* V is on \mathbb{R} , and $v_1, \dots, v_n \in V$. Let $B = (v_1, \dots, v_n)$.

(a) Show $[P]$ B is liney indep in $V \iff B$ is liney indep in $V_{\mathbb{C}}$. $[Q]$

(b) Show $[P]$ B spans $V \iff B$ spans $V_{\mathbb{C}}$. $[Q]$

(a) $P \Rightarrow Q$: Note that each $v_k \in V_{\mathbb{C}}$. $Q \Rightarrow P$: If $\lambda_k \in \mathbb{R}$ with $\lambda_1 v_1 + \dots + \lambda_n v_n = 0$, then each $\text{Re } \lambda_k = \lambda_k = 0$.

$\neg P \Rightarrow \neg Q$: $\exists v_j = a_{j-1} v_{j-1} + \dots + a_1 v_1 \in V_{\mathbb{C}}$.

$\neg Q \Rightarrow \neg P$: $\exists v_j = \lambda_{j-1} v_{j-1} + \dots + \lambda_1 v_1 \Rightarrow v_j = (\text{Re } \lambda_{j-1}) v_{j-1} + \dots + (\text{Re } \lambda_1) v_1 \in V$.

(b) $P \Rightarrow Q$: $\forall u + iv \in V_{\mathbb{C}}, u, v \in V \Rightarrow \exists a_i, b_i \in \mathbb{R}, u + iv = \sum_{i=1}^n (a_i + ib_i) v_i$.

$Q \Rightarrow P$: $\forall v \in V, \exists a_i + ib_i \in \mathbb{C}, v + i0 = (\sum_{i=1}^n a_i v_i) + i(\sum_{i=1}^n b_i v_i) \Rightarrow v \in \text{span}(v_1, \dots, v_n)$.

$\neg Q \Rightarrow \neg P$: $\exists v \in V, v \notin \text{span}(B) \Rightarrow v + i0 \notin \text{span}(B)$ while $v + i0 \in V_{\mathbb{C}}$.

$\neg Q \Rightarrow \neg P$: $\exists u + iv \in V_{\mathbb{C}}, u + iv \notin \text{span}(B) \Rightarrow u$ or $v \notin \text{span}(B)$. Note that $u, v \in V$. \square

- **NOTE FOR liney indep sequence and [2.34]:** " $V = \text{span}(v_1, \dots, v_n, \dots)$ " is an invalid expr.

If we allow using "infini list", then we must assure that (v_1, \dots, v_n, \dots) is a spanning "list"

suth $\forall v \in V, \exists$ smallest $n \in \mathbb{N}^+, v = a_1 v_1 + \dots + a_n v_n$. Moreover, given a list (w_1, \dots, w_n, \dots) in W , we can prove $\exists! T \in \mathcal{L}(V, W)$ with each $T v_k = w_k$, which has less restr than [3.5].

But the key point is, how can we assure that such a "list" exis. **TODO: More details.**

ENDED

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- 15 *Sups* V is finide and $\dim V = n \geq 1$.

Prove \exists one-dim subspcs V_1, \dots, V_n of V suth $V = V_1 \oplus \dots \oplus V_n$.

SOLUS: *Sups* $B_V = (v_1, \dots, v_n)$. Define V_i by $V_i = \text{span}(v_i)$ for each $i \in \{1, \dots, n\}$.

Then $\forall v \in V, \exists! a_i \in \mathbb{F}, v = a_1 v_1 + \dots + a_n v_n \Rightarrow \exists! u_i \in V_i, v = u_1 + \dots + u_n$ \square

- **NOTE FOR Exe (15):**

Sups $v \in V \setminus \{0\}$, and $\dim V = n \geq 1$. Prove $\exists B_V = (v_1, \dots, v_n), v = v_1 + \dots + v_n$.

SOLUS: If $n = 1$ then let $v_1 = v$ and done. *Sups* $n > 1$.

Extend (v) to a bss (v, v_1, \dots, v_{n-1}) of V . Let $v_n = v - v_1 - \dots - v_{n-1}$.

$\times \text{span}(v, v_1, \dots, v_{n-1}) = \text{span}(v_1, \dots, v_n)$. Hence (v_1, \dots, v_n) is also a bss of V . \square

COMMENT: Let $B_V = (v_1, \dots, v_n)$ and *sups* $v = u_1 + \dots + u_n$, where each $u_i = a_i v_i \in V_i$.

But (u_1, \dots, u_n) might not be a bss, becs there might be some $u_i = 0$.

1 [CORO for [2.38,39]] *Sups* U is a subsp of V suth $\dim V = \dim U$. Then $V = U$.

Let $B_U = (u_1, \dots, u_m)$. Then $m = \dim V$. 又 $u_i \in V$. By [2.39], $B_V = (u_1, \dots, u_m)$. □

- Let $v_1, \dots, v_n \in V$ and $\dim \text{span}(v_1, \dots, v_n) = n$. Then (v_1, \dots, v_n) is a bss of $\text{span}(v_1, \dots, v_n)$.
Notice that (v_1, \dots, v_n) is a spanning list of $\text{span}(v_1, \dots, v_n)$ of len $n = \dim \text{span}(v_1, \dots, v_n)$.

- 7** (a) Let $U = \{p \in \mathcal{P}_4(\mathbf{F}) : p(2) = p(5) = p(6)\}$. Find a bss of U .
 (b) Extend the bss in (b) to a bss of $\mathcal{P}_4(\mathbf{F})$.
 (c) Find a subsp W of $\mathcal{P}_4(\mathbf{F})$ suth $\mathcal{P}_4(\mathbf{F}) = U \oplus W$.

SOLUS: Using Exe (10).

NOTICE that $\nexists p \in \mathcal{P}(\mathbf{F})$ of deg 1 and 2, while $p \in U$. Thus $\dim U \leq \dim \mathcal{P}_4(\mathbf{F}) - 2 = 3$.

(a) Consider $B = (1, (z-2)(z-5)(z-6), z(z-2)(z-5)(z-6))$.

Let $a_0 + a_3(z-2)(z-5)(z-6) + a_4z(z-2)(z-5)(z-6) = 0 \Rightarrow a_0 = a_3 = a_4 = 0$.

Thus the list B is liney indep in U . Now $\dim U \geq 3 \Rightarrow \dim U = 3$. Thus $B_U = B$.

(b) Extend to a bss of $\mathcal{P}_4(\mathbf{F})$ as $(1, z, z^2, (z-2)(z-5)(z-6), z(z-2)(z-5)(z-6))$.

(c) Let $W = \text{span}(z, z^2) = \{az + bz^2 : a, b \in \mathbf{F}\}$, so that $\mathcal{P}_4(\mathbf{F}) = U \oplus W$. □

9 *Sups* (v_1, \dots, v_m) is liney indep in $V, w \in V$. Prove $\dim \text{span}(v_1 + w, \dots, v_m + w) \geq m - 1$.

SOLUS: Using the result of (2.A.10, 11).

Note that $v_i - v_1 = (v_i + w) - (v_1 + w) \in \text{span}(v_1 + w, \dots, v_m + w)$, for each $i = 1, \dots, m$.

(v_1, \dots, v_m) liney indep $\Rightarrow (v_1, v_2 - v_1, \dots, v_m - v_1)$ liney indep $\Rightarrow \underbrace{(v_2 - v_1, \dots, v_m - v_1)}_{\text{of len } (m-1)}$ liney indep.

又 If $w \notin \text{span}(v_1, \dots, v_m)$. Then $(v_1 + w, \dots, v_m + w)$ is liney indep. □

Hence $m \geq \dim \text{span}(v_1 + w, \dots, v_m + w) \geq m - 1$.

- (4E 16) *Sups* V is finide, U is a subsp of V with $U \neq V$. Let $n = \dim V, m = \dim U$.

Prove $\exists (n - m)$ subsps U_1, \dots, U_{n-m} , each of dim $(n - 1)$, suth $\bigcap_{i=1}^{n-m} U_i = U$.

SOLUS: Let $B_U = (v_1, \dots, v_m)$, $B_V = (v_1, \dots, v_m, u_1, \dots, u_{n-m})$.

Define $U_i = \text{span}(v_1, \dots, v_m, u_1, \dots, u_{i-1}, u_{i+1}, \dots, u_{n-m})$ for each i . Then $U \subseteq U_i$ for each i .

And becs $\forall v \in \bigcap_{i=1}^{n-m} U_i, v = v_0 + b_1 u_1 + \dots + b_{n-m} u_{n-m} \in U_i \Rightarrow \text{each } b_i = 0 \Rightarrow v \in U$.

Hence $\bigcap_{i=1}^{n-m} U_i \subseteq U$. □

- **NOTE FOR Exe 10:** For each nonconst $p \in \text{span}(1, z, \dots, z^m)$, \exists smallest $m \in \mathbf{N}^+$, which is $\deg p$.

(a) If p_0, p_1, \dots, p_m are suth all $a_{k,k} \neq 0$, and

$p_0 = a_{0,0}$, each $p_k = a_{0,k} + a_{1,k}z + \dots + a_{k,k}z^k$.

Then the upper-trig $\mathcal{M}(I, (p_0, p_1, \dots, p_m), (1, z, \dots, z^m)) = \begin{pmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,m} \\ 0 & a_{1,1} & \cdots & a_{1,m} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{m,m} \end{pmatrix}$.

(b) If p_0, p_1, \dots, p_m are suth all $a_{k,k} \neq 0$, and

$p_0 = a_{0,0} + \dots + a_{m,0}x^m$, each $p_k = a_{k,k}x^k + \dots + a_{m,k}x^m$.

Then the lower-trig $\mathcal{M}(I, (p_0, p_1, \dots, p_m), (1, z, \dots, z^m)) = \begin{pmatrix} a_{0,0} & 0 & \cdots & 0 \\ a_{1,0} & a_{1,1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ a_{m,0} & a_{m,1} & \cdots & a_{m,m} \end{pmatrix}$.

COMMENT: Define $\xi_k(p)$ by the coeff of z^k in $p \in \mathcal{P}_m(\mathbf{F})$.

Then $\mathcal{M}(\xi_k, (1, z, \dots, z^m), (1)) = \mathcal{E}^{(1,k)} \in \mathbf{F}^{1,m+1}$.

10 Sups $m \in \mathbf{N}^+$, $p_0, p_1, \dots, p_m \in \mathcal{P}(\mathbf{F})$ are suth each p_k has $\deg k$.

Prove (p_0, p_1, \dots, p_m) is a bss of $\mathcal{P}_m(\mathbf{F})$.

SOLUS: Using induc on m .

(i) $k = 1$. $\deg p_0 = 0$; $\deg p_1 = 1 \Rightarrow \text{span}(p_0, p_1) = \text{span}(1, x)$.

(ii) $1 \leq k \leq m-1$. Asum $\text{span}(p_0, p_1, \dots, p_k) = \text{span}(1, x, \dots, x^k)$.

Then $\text{span}(p_0, p_1, \dots, p_k, p_{k+1}) \subseteq \text{span}(1, x, \dots, x^k, x^{k+1})$.

又 $\deg p_{k+1} = k+1$, $p_{k+1}(x) = a_{k+1}x^{k+1} + r_{k+1}(x)$; $a_{k+1} \neq 0$, $\deg r_{k+1} \leq k$.

$$\Rightarrow x^{k+1} = \frac{1}{a_{k+1}}(p_{k+1}(x) - r_{k+1}(x)) \in \text{span}(1, x, \dots, x^k, p_{k+1}) = \text{span}(p_0, p_1, \dots, p_k, p_{k+1}).$$

$$\therefore x^{k+1} \in \text{span}(p_0, p_1, \dots, p_k, p_{k+1}) \Rightarrow \text{span}(1, x, \dots, x^k, x^{k+1}) \subseteq \text{span}(p_0, p_1, \dots, p_k, p_{k+1}).$$

Thus $\mathcal{P}_m(\mathbf{F}) = \text{span}(1, x, \dots, x^m) = \text{span}(p_0, p_1, \dots, p_m)$. □

OR. 用比较系数法. Denote the coeff of x^k in $p \in \mathcal{P}(\mathbf{F})$ by $\xi_k(p)$.

Sups $L = a_m p_m(x) + \dots + a_1 p_1(x) + a_0 p_0(x) = 0 \cdot x^m + \dots + 0 \cdot x + 0 \cdot 1 = R, \forall x \in \mathbf{F}$.

We show $a_m = \dots = a_0 = 0$ via the following process. So that (p_0, p_1, \dots, p_m) is liney indep.

Step 1. For $k = m$, $\xi_m(L) = a_m \xi_m(p_m) = \xi_m(R) = 0$ 又 $\deg p_m = m$, $\xi_m(p_m) \neq 0 \Rightarrow a_m = 0$.

Now $L = a_{m-1} p_{m-1}(x) + \dots + a_0 p_0(x)$.

Step k. For $0 \leq k \leq m$, we have $a_m = \dots = a_{k+1} = 0$.

Now $\xi_k(L) = a_k \xi_k(p_k) = \xi_k(R) = 0$ 又 $\deg p_k = k$, $\xi_k(p_k) \neq 0 \Rightarrow a_k = 0$.

Now if $k = 0$, then done. Othws, we have $L = a_{k-1} p_{k-1}(x) + \dots + a_0 p_0(x)$. □

• **TIPS:** Sups $m \in \mathbf{N}^+$, $p_0, p_1, \dots, p_m \in \mathcal{P}_m(\mathbf{F})$ are suth the lowest term of each p_k is of $\deg k$.

Prove (p_0, p_1, \dots, p_m) is a bss of $\mathcal{P}_m(\mathbf{F})$.

SOLUS: Using induc on m .

Let each p_k be defined by $p_k(x) = a_{k,k}x^k + \dots + a_{m,k}x^m$, where $a_{k,k} \neq 0$.

(i) $k = 1$. $p_m(x) = a_{m,m}x^m$; $p_{m-1}(x) = a_{m-1,m-1}x^{m-1} + a_{m,m-1}x^m \Rightarrow \text{span}(x^m, x^{m-1}) = \text{span}(p_m, p_{m-1})$.

(ii) $1 \leq k \leq m-1$. Asum $\text{span}(x^m, \dots, x^{m-k}) = \text{span}(p_m, \dots, p_{m-k})$.

Then $\text{span}(p_m, \dots, p_{m-(k+1)}) \subseteq \text{span}(x^m, \dots, x^{m-(k+1)})$.

又 $p_{m-(k+1)}$ has the form $a_{m-(k+1),m-(k+1)}x^{m-(k+1)} + r_{m-(k+1)}(x)$;

where the lowest term of $r_{m-(k+1)} \in \mathcal{P}_m(\mathbf{F})$ is of $\deg(m-k)$.

$$\Rightarrow x^{m-(k+1)} = \frac{1}{a_{m-(k+1),m-(k+1)}}(p_{m-(k+1)}(x) - r_{m-(k+1)}(x)) \in \text{span}(x^m, \dots, x^{m-k}, p_{m-(k+1)})$$

$$= \text{span}(p_m, \dots, p_{m-k}, p_{m-(k+1)}).$$

$$\therefore x^{m-(k+1)} \in \text{span}(p_m, \dots, p_{m-k}, p_{m-(k+1)})$$

$$\Rightarrow \text{span}(x^m, \dots, x^{m-k}, x^{m-(k+1)}) \subseteq \text{span}(p_m, \dots, p_{m-k}, p_{m-(k+1)}).$$

Thus $\mathcal{P}_m(\mathbf{F}) = \text{span}(x^m, \dots, x, 1) = \text{span}(p_m, \dots, p_1, p_0)$. □

OR. 用比较系数法. Denote the coeff of x^k in $p \in \mathcal{P}(\mathbf{F})$ by $\xi_k(p)$.

Sups $L = a_m p_m(x) + \dots + a_1 p_1(x) + a_0 p_0(x) = 0 \cdot x^m + \dots + 0 \cdot x + 0 \cdot 1 = R, \forall x \in \mathbf{F}$.

We show $a_m = \dots = a_0 = 0$ via the following process. So that (p_0, p_1, \dots, p_m) is liney indep.

Step 1. For $k = 0$, $\xi_0(L) = a_0 \xi_0(p_0) = \xi_0(R) = 0$ 又 $\deg p_0 = 0$, $\xi_0(p_0) \neq 0 \Rightarrow a_0 = 0$.

Now $L = a_1 p_1(x) + \dots + a_m p_m(x)$.

Step k. For $0 \leq k \leq m$, we have $a_{k-1} = \dots = a_0 = 0$.

Now $\xi_k(L) = a_k \xi_k(p_k) = \xi_k(R) = 0$ 又 $\deg p_k = k$, $\xi_k(p_k) \neq 0 \Rightarrow a_k = 0$.

Now if $k = m$, then done. Othws, we have $L = a_{k+1} p_{k+1}(x) + \dots + a_m p_m(x)$. □

• **NOTE FOR [2.11]:** *Good definition for a general term always avoids undefined behaviours.*

If $\deg p = 0$, then $p(z) = a_0 \neq 0$, but not literally $a_0 z^0$, by which if p is defined, then it comes to 0^0 .

To make it clear, we specify that in $\mathcal{P}(\mathbf{F})$, $a_0 z^0 = a_0$, where z^0 appears just for nota conveni.

Becs by def, the term $a_0 z^0$ in a poly only represents the const term of the poly, which is a_0 .

For conveni, we asum $z^0 = 1$ in formula deduction and poly def. Absolutely without 0^0 .

• (4E 10) *Sups m is a positive integer. For $0 \leq k \leq m$, let $p_k(x) = x^k(1-x)^{m-k}$.*

Show (p_0, \dots, p_m) is a bss of $\mathcal{P}_m(\mathbf{F})$.

SOLUS: We may see $p_0 = 1$ and $p_m(x) = x^m$, from the expansion below, by the NOTE FOR [2.11] above.

Note that each $p_k(x) = \sum_{j=0}^{m-k} C_{m-k}^j (-1)^j \cdot x^{j+k} \cdot 1^j = \underbrace{(-1)^0 \cdot x^k \cdot 1^0}_{\text{of deg } k} + \underbrace{\sum_{j=1}^{m-k} C_{m-k}^j (-1)^j \cdot x^{j+k} \cdot 1^j}_{\text{of deg } m; \text{ denote it by } q_k(x)}$.
And, each $q_k \in \text{span}(x^{k+1}, \dots, x^m)$. Using TIPS above. □

OR. Simlr to the TIPS above. We will recurly prove each $x^{m-k} \in \text{span}(p_m, \dots, p_{m-k})$.

(i) $k = 1$. $p_m(x) = x^m \in \text{span}(p_m)$; $p_{m-1}(x) = x^{m-1} - x^m \Rightarrow x^{m-1} \in \text{span}(p_{m-1}, p_m)$.

(ii) $k \in \{1, \dots, m-1\}$. Sups for each $k \in \{0, \dots, k\}$, we have $x^{m-k} \in \text{span}(p_{m-k}, \dots, p_m)$, $\exists ! a_m \in \mathbf{F}$.

Note that $x^{m-(k+1)} = p_{m-(k+1)}(x) + \sum_{j=1}^{k+1} C_{k+1}^j (-1)^{j+1} x^{m-(k+1)+j} \in \text{span}(p_{m-(k+1)}, x^{m-k}, \dots, x^m)$.

Thus $x^{m-(k+1)} \in \text{span}(p_{m-(k+1)}, p_{m-k}, \dots, p_m)$. □

COMMENT: The base step and the induc step can be indep.

OR. For any $m, k \in \mathbf{N}^+$ suth $k \leq m$. Define $p_{k,m}$ by $p_{k,m}(x) = x^k(1-x)^{m-k}$.

Define the stam $S(m)$ by $S(m) : (p_{0,m}, \dots, p_{m,m})$ is liney indep (and therefore is a bss).

We use induc on to show $S(m)$ holds for all $m \in \mathbf{N}^+$.

(i) $m = 0$. $p_{0,0} = 1$, and $ap_{0,0} = 0 \Rightarrow a = 0$.

$m = 1$. Let $a_0(1-x) + a_1x = 0, \forall x \in \mathbf{F}$. Then take $x = 1, x = 0 \Rightarrow a_1 = a_0 = 0$.

(ii) $1 \leq m$. Asum $S(m)$ and $S(m-1)$ holds. Now we show $S(m+1)$ holds.

Sups $\sum_{k=0}^{m+1} a_k p_{k,m+1}(x) = \sum_{k=0}^{m+1} a_k [x^k(1-x)^{m+1-k}] = 0, \forall x \in \mathbf{F}$.

Now $a_0(1-x)^{m+1} + \sum_{k=1}^m a_k x^k(1-x)^{m+1-k} + a_{m+1}x^{m+1} = 0, \forall x \in \mathbf{F}$.

While $x = 0 \Rightarrow a_0 = 0$; and $x = 1 \Rightarrow a_{m+1} = 0$.

Then $0 = \sum_{k=1}^m a_k x^k(1-x)^{m+1-k}$
 $= x(1-x) \sum_{k=1}^m a_k x^{k-1}(1-x)^{m-k}$, note that $m-k = (m-1) - (k-1)$
 $= x(1-x) \sum_{k=0}^{m-1} a_{k+1} x^k(1-x)^{m-1-k} = x(1-x) \sum_{k=0}^{m-1} a_{k+1} p_{k,m-1}(x)$.

Hence $\sum_{k=0}^{m-1} a_{k+1} p_{k,m-1}(x) = 0, \forall x \in \mathbf{F} \setminus \{0, 1\}$. Which has infily many zeros.

Moreover, $\sum_{k=0}^{m-1} a_{k+1} p_{k,m-1}(x) = 0$. By asum, $a_1 = \dots = a_{m-1} = a_m = 0$.

Thus $(p_{0,m+1}, \dots, p_{m+1,m+1})$ is liney indep and $S(m+1)$ holds. □

14 *Sups V_1, \dots, V_m are finide. Prove $\dim(V_1 + \dots + V_m) \leq \dim V_1 + \dots + \dim V_m$.*

SOLUS: For each V_i , let $B_{V_i} = \mathcal{E}_i$. Then $V_1 + \dots + V_m = \text{span}(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_m)$; $\dim V_i = \text{card } \mathcal{E}_i$.

Now $\dim(V_1 + \dots + V_m) = \dim \text{span}(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_m) \leq \text{card}(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_m) \leq \text{card } \mathcal{E}_1 + \dots + \text{card } \mathcal{E}_m$.

CORO: $V_1 + \dots + V_m$ is direct

\Leftrightarrow For each $k \in \{1, \dots, m-1\}$, $(V_1 \oplus \dots \oplus V_k) \cap V_{k+1} = \{0\}$, $(\mathcal{E}_1 \cap \dots \cap \mathcal{E}_{k-1}) \cap \mathcal{E}_k = \emptyset$

$\Leftrightarrow \dim \text{span}(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_m) = \text{card}(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_m) = \text{card } \mathcal{E}_1 + \dots + \text{card } \mathcal{E}_m$

$\Leftrightarrow \dim(V_1 \oplus \dots \oplus V_m) = \dim V_1 + \dots + \dim V_m$. □

17 Sups V_1, V_2, V_3 are subsp of a finide vecsp, then

$$\dim(V_1 + V_2 + V_3) = \dim V_1 + \dim V_2 + \dim V_3 - \dim(V_1 \cap V_2) - \dim(V_1 \cap V_3) - \dim(V_2 \cap V_3) + \dim(V_1 \cap V_2 \cap V_3).$$

Explain why you might think and prove the formula above or give a counterexa.

SOLUS:

[Simlrr to] Given three sets A, B and C .

Becs $|X \cup Y| = |X| + |Y| - |X \cap Y|$; $(X \cup Y) \cap Z = (X \cap Z) \cup (Y \cap Z)$.

Now $|(A \cup B) \cup C| = |A \cup B| + |C| - |(A \cup B) \cap C|$.

And $|(A \cup B) \cap C| = |(A \cap C) \cup (B \cap C)| = |A \cap C| + |B \cap C| - |A \cap B \cap C|$.

Hence $|(A \cup B) \cup C| = |A| + |B| + |C| + |A \cap B \cap C| - |A \cap B| - |A \cap C| - |B \cap C|$.

Note that $(V_1 + V_2) + V_3 = V_1 + (V_2 + V_3) = (V_1 + V_3) + V_2$.

$$\dim(V_1 + V_2 + V_3) = \dim(V_1 + V_2) + \dim(V_3) - \dim((V_1 + V_2) \cap V_3) \quad (1)$$

$$= \dim(V_2 + V_3) + \dim(V_1) - \dim((V_2 + V_3) \cap V_1) \quad (2)$$

$$= \dim(V_1 + V_3) + \dim(V_2) - \dim((V_1 + V_3) \cap V_2) \quad (3).$$

Notice that in general, $(X + Y) \cap Z \neq (X \cap Z) + (Y \cap Z)$.

For exa, $X = \{(x, 0) \in \mathbb{R}^2 : x \in \mathbb{R}\}, Y = \{(0, y) \in \mathbb{R}^2 : y \in \mathbb{R}\}, Z = \{(z, z) \in \mathbb{R}^2 : z \in \mathbb{R}\}$.

COMMENT: If $X \subseteq Y$, then $(X + Y) \cap Z = Y \cap Z$; $\dim(X + Y + Z) = \dim(Y) + \dim(Z) - \dim(Y \cap Z)$, and the wrong formul holds. Simlrr for $Y \subseteq Z, X \subseteq Z$, and $X, Y \subseteq Z$.

However, $(X + Y) \cap Z \supseteq (X \cap Z) + (Y \cap Z)$ holds. Becs $\forall v \in (X \cap Z) + (Y \cap Z)$,

$\exists u = x_1 = z_1 \in X \cap Z, w = y_2 = z_2 \in Y \cap Z, v = u + w = x_1 + y_2 = z_1 + z_2 \in (X + Y) \cap Z$.

COMMENT: $\dim((X + Y) \cap Z) \geq \dim(X \cap Z) + \dim(Y \cap Z) - \dim(X \cap Y \cap Z)$.

• **CORO:** Sups V_1, V_2, V_3 are finide, then

$$\begin{aligned} \dim(V_1 + V_2 + V_3) &= \dim V_1 + \dim V_2 + \dim V_3 \\ &\quad - \frac{\dim(V_1 \cap V_2) + \dim(V_1 \cap V_3) + \dim(V_2 \cap V_3)}{3} \\ &\quad - \frac{\dim((V_1 + V_2) \cap V_3) + \dim((V_1 + V_3) \cap V_2) + \dim((V_2 + V_3) \cap V_1)}{3}. \end{aligned}$$

• **TIPS:** Becs $\dim(V_1 \cap V_2 \cap V_3) = \dim V_1 + \dim(V_2 \cap V_3) - \dim(V_1 + (V_2 \cap V_3))$.

And $\dim(V_2 \cap V_3) = \dim V_2 + \dim V_3 - \dim(V_2 + V_3)$. We have (1), and (2), (3) simlrr.

$$(1) \dim(V_1 \cap V_2 \cap V_3) = \dim V_1 + \dim V_2 + \dim V_3 - \dim(V_2 + V_3) - \dim(V_1 + (V_2 \cap V_3)).$$

$$(2) \dim(V_1 \cap V_2 \cap V_3) = \dim V_1 + \dim V_2 + \dim V_3 - \dim(V_1 + V_3) - \dim(V_2 + (V_1 \cap V_3)).$$

$$(3) \dim(V_1 \cap V_2 \cap V_3) = \dim V_1 + \dim V_2 + \dim V_3 - \dim(V_1 + V_2) - \dim(V_3 + (V_1 \cap V_2)).$$

• Sups V_1, V_2, V_3 are subsp of V with

(a) $\dim V = 10, \dim V_1 = \dim V_2 = \dim V_3 = 7$. Prove $V_1 \cap V_2 \cap V_3 \neq \{0\}$.

By TIPS, $\dim(V_1 \cap V_2 \cap V_3) \geq \dim V_1 + \dim V_2 + \dim V_3 - 2 \dim V > 0$.

(b) $\dim V_1 + \dim V_2 + \dim V_3 > 2 \dim V$. Prove $V_1 \cap V_2 \cap V_3 \neq \{0\}$.

By TIPS, $\dim(V_1 \cap V_2 \cap V_3) \geq 2 \dim V - \dim(V_2 + V_3) - \dim(V_1 + (V_2 \cap V_3)) \geq 0$. □

ENDED

• **TIPS 1:** $T : V \rightarrow W$ is liney $\iff \left\{ \begin{array}{l} (-) \forall v, u \in V, T(v+u) = Tv + Tu; \\ (二) \forall v, u \in V, \lambda \in \mathbf{F}, T(\lambda v) = \lambda(Tv). \end{array} \right\} \iff T(v + \lambda u) = Tv + \lambda Tu.$

• (9.A.2,6 OR 4E 3.B.33) *Sups that V, W are on \mathbf{R} , and $T \in \mathcal{L}(V, W)$. Show*

(a) $T_C \in \mathcal{L}(V_C, W_C)$. (b) $\text{null}(T_C) = (\text{null } T)_C, \text{range}(T_C) = (\text{range } T)_C$. (c) T_C is inv $\iff T$ is inv.

SOLUS: (a) $T_C((u_1 + iv_1) + (x + iy)(u_2 + iv_2)) = T(u_1 + xu_2 - yv_2) + iT(v_1 + xv_2 + yu_2)$
 $= T_C(u_1 + iv_1) + (x + iy)T_C(u_2 + iv_2).$

(b) $u + iv \in \text{null}(T_C) \iff u, v \in \text{null } T \iff u + iv \in (\text{null } T)_C.$

$w + ix \in \text{range}(T_C) \iff w, x \in \text{range } T \iff w + ix \in (\text{range } T)_C.$

(c) $\forall w, x \in W, \exists! u, v \in V, T_C(u + iv) = w + ix \iff Tu = w, Tv = x.$ OR. By (b). □

• (9.A.5) *Sups V is on \mathbf{R} , and $S, T \in \mathcal{L}(V, W)$. Prove $(S + \lambda T)_C = S_C + \lambda T_C$.*

SOLUS: $(S + \lambda T)_C(u + iv) = (S + \lambda T)(u) + i(S + \lambda T)(v)$
 $= Su + iSv + \lambda(Tu + iTv) = (S_C + \lambda T_C)(u + iv).$ □

• *Sups U, V, W are on \mathbf{R} , $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$. Prove $(ST)_C = S_C T_C$.*

SOLUS: $\forall u + ix \in U_C, (ST)_C(u + ix) = STu + iSTx = S_C(Tu + iTx) = (S_C T_C)(u + ix).$ □

• **NOTE FOR Restr:** U is a subsp of V .

(a) $\forall S, T \in \mathcal{L}(V, W), \lambda \in \mathbf{F}, (T + \lambda S)|_U = T|_U + \lambda S|_U.$

(b) $\forall S \in \mathcal{L}(W, X), T \in \mathcal{L}(V, W), (ST)|_U = ST|_U.$

• (4E 1.B.7) *Sups $V \neq \emptyset$ and W is a vecsp. Let $W^V = \{f : V \rightarrow W\}.$*

(a) *Define a natural add and scalar multi on W^V .*

(b) *Prove W^V is a vecsp with these defs.*

SOLUS:

(a) $W^V \ni f + g : x \rightarrow f(x) + g(x);$ where $f(x) + g(x)$ is the vec add on W .

$W^V \ni \lambda f : x \rightarrow \lambda f(x);$ where $\lambda f(x)$ is the scalar multi on W .

(b) **Commu:** $(f + g)(x) = f(x) + g(x) = g(x) + f(x) = (g + f)(x).$

Assoc: $((f + g) + h)(x) = (f(x) + g(x)) + h(x)$
 $= f(x) + (g(x) + h(x)) = (f + (g + h))(x).$

Add Id: $(f + 0)(x) = f(x) + 0(x) = f(x) + 0 = f(x).$

Add Inv: $(f + g)(x) = f(x) + g(x) = f(x) + (-f(x)) = 0 = 0(x).$

Distr: $(a(f + g))(x) = a(f + g)(x) = a(f(x) + g(x))$
 $= af(x) + ag(x) = (af)(x) + (ag)(x) = (af + ag)(x).$

Simlr, $((a + b)f)(x) = (af + bf)(x).$

So far, we have used the same properties in W .

Which means that *if W^V is a vecsp, then W must be a vecsp.*

Multi Id: $(1f)(x) = 1f(x) = f(x).$ (NOTICE that the smallest \mathbf{F} is $\{0, 1\}.$) □

• **TIPS 2:** $T \in \mathcal{L}(V, W) \iff T \in \mathcal{L}(V, \text{range } T) \iff T \in \mathcal{L}(V, U)$, if $\text{range } T$ is a subsp of U .

CORO: $\{T \in \mathcal{L}(V, W) : \text{range } T \subseteq U\} = \{T \in \mathcal{L}(V, U)\} = \mathcal{L}(V, U)$.

5 Becs $\mathcal{L}(V, W) = \{T : V \rightarrow W \mid T \text{ is liney}\}$ is a subsp of W^V , $\mathcal{L}(V, W)$ is a vecsp.

3 Sups $T \in \mathcal{L}(\mathbf{F}^n, \mathbf{F}^m)$. Prove $\exists A_{j,k} \in \mathbf{F}$ suth for any $(x_1, \dots, x_n) \in \mathbf{F}^n$,

$$T(x_1, \dots, x_n) = \begin{pmatrix} A_{1,1}x_1 + \dots + A_{1,n}x_n \\ \vdots \\ A_{m,1}x_1 + \dots + A_{m,n}x_n \end{pmatrix}$$

SOLUS:

Let $T(1, 0, 0, \dots, 0, 0) = (A_{1,1}, \dots, A_{m,1})$, Note that $(1, 0, \dots, 0, 0), \dots, (0, 0, \dots, 0, 1)$ is a bss of \mathbf{F}^n .

$T(0, 1, 0, \dots, 0, 0) = (A_{1,2}, \dots, A_{m,2})$, Then by [3.5], done. □

$T(0, 0, 0, \dots, 0, 1) = (A_{1,n}, \dots, A_{m,n})$.

4 Sups $T \in \mathcal{L}(V, W)$, and $v_1, \dots, v_m \in V$ suth (Tv_1, \dots, Tv_m) is liney indep in W .

Prove (v_1, \dots, v_m) is liney indep.

SOLUS: Sups $a_1v_1 + \dots + a_mv_m = 0$. Then $a_1Tv_1 + \dots + a_mTv_m = 0$. Thus $a_1 = \dots = a_m = 0$. □

7 Show every liney map from a one-dim vecsp to itself is a multi by some scalar.

More precisely, prove if $\dim V = 1$ and $T \in \mathcal{L}(V)$, then $\exists \lambda \in \mathbf{F}, Tv = \lambda v, \forall v \in V$.

SOLUS: Let u be a nonzero vec in $V \Rightarrow V = \text{span}(u)$. Bcs $Tu \in V \Rightarrow Tu = \lambda u$ for some λ .

Sups $v \in V \Rightarrow v = au, \exists! a \in \mathbf{F}$. Then $Tv = T(au) = \lambda au = \lambda v$. □

8 Give a map $\varphi : \mathbf{R}^2 \rightarrow \mathbf{R}$ suth $\forall a \in \mathbf{R}, v \in \mathbf{R}^2, \varphi(av) = a\varphi(v)$ but φ is not liney.

SOLUS: Define $T(x, y) = \begin{cases} x + y, & \text{if } (x, y) \in \text{span}(3, 1), \\ 0, & \text{othws.} \end{cases}$ OR. Define $T(x, y) = \sqrt[3]{(x^3 + y^3)}$. □

9 Give a map $\varphi : \mathbf{C} \rightarrow \mathbf{C}$ suth $\forall w, z \in \mathbf{C}, \varphi(w + z) = \varphi(w) + \varphi(z)$ but φ is not liney.

SOLUS: Define $\varphi(u + iv) = u = \text{Re}(u + iv)$ OR. Define $\varphi(u + iv) = v = \text{Im}(u + iv)$. □

• Prove if $q \in \mathcal{P}(\mathbf{R})$ and $T : \mathcal{P}(\mathbf{R}) \rightarrow \mathcal{P}(\mathbf{R})$ is defined by $Tp = \underbrace{q \circ p}_{\text{composition}}$, then T is not liney.

SOLUS: **Composition and product are not the same in $\mathcal{P}(\mathbf{F})$.**

NOTICE that $(p \circ q)(x) = p(q(x))$, while $(pq)(x) = p(x)q(x) = q(x)p(x)$.

Bcs in general, $[q \circ (p_1 + \lambda p_2)](x) = q(p_1(x) + \lambda p_2(x)) \neq (qp_1)(x) + \lambda(qp_2)(x)$.

EXA: Let q be defined by $q(x) = x^2$, then $q \circ (1 + (-1)) = 0 \neq q(1) + q(-1) = 2$. □

10 Sups U is a subsp of V with $U \neq V$.

Sups $S \in \mathcal{L}(U, W)$ with $S \neq 0$. Define $T : V \rightarrow W$ by $Tv = \begin{cases} Sv, & \text{if } v \in U, \\ 0, & \text{if } v \in V \setminus U. \end{cases}$

Prove T is not a liney map on V .

SOLUS: Asum T is a liney map. Sups $v \in V \setminus U, u \in U$ suth $Su \neq 0$.

Then $v + u \in V \setminus U$, for if not, $v = (v + u) - u \in U$;

while $T(v + u) = 0 = Tv + Tu = 0 + Su \Rightarrow Su = 0$. Ctradic. □

11 Sups U is a subsp of V and $S \in \mathcal{L}(U, W)$.

Prove $\exists T \in \mathcal{L}(V, W), Tu = Su, \forall u \in U$. (OR. $\exists T \in \mathcal{L}(V, W), T|_U = S$.)

In other words, every liney map on a subsp of V can be **extended** to a liney map on the entire V .

SOLUS: Sups W is suth $V = U \oplus W$. Then $\forall v \in V, \exists ! u_v \in U, w_v \in W, v = u_v + w_v$.

Define $T \in \mathcal{L}(V, W)$ by $T(u_v + w_v) = Su_v$. □

OR. [Finide Req] Define by $T\left(\sum_{i=1}^m a_i u_i\right) = \sum_{i=1}^m a_i Su_i$. Let $B_V = (\overbrace{u_1, \dots, u_n}^{B_U}, \dots, u_m)$. □

12 Sups nonzero V is finide and W is infinide. Prove $\mathcal{L}(V, W)$ is infinide.

SOLUS: Using (2.A.14).

Let $B_V = (v_1, \dots, v_n)$ be a bss of V . Let (w_1, \dots, w_m) be liney indep in W for any $m \in \mathbb{N}^+$.

Define $T_{x,y} : V \rightarrow W$ by $T_{x,y}(v_z) = \delta_{z,x} w_y, \forall x \in \{1, \dots, n\}, y \in \{1, \dots, m\}$, where $\delta_{z,x} = \begin{cases} 0, & z \neq x, \\ 1, & z = x. \end{cases}$

$\forall v = \sum_{i=1}^n a_i v_i, u = \sum_{i=1}^n b_i v_i, \lambda \in \mathbb{F}, T_{x,y}(v + \lambda u) = (a_x + \lambda b_x) w_y = T_{x,y}(v) + \lambda T_{x,y}(u)$.

Linity checked. Now sups $a_1 T_{x,1} + \dots + a_m T_{x,m} = 0$.

Then $(a_1 T_{x,1} + \dots + a_m T_{x,m})(v_x) = 0 = a_1 w_1 + \dots + a_m w_m \Rightarrow a_1 = \dots = a_m = 0$. $\forall m$ arb.

Thus $(T_{x,1}, \dots, T_{x,m})$ is a liney indep list in $\mathcal{L}(V, W)$ for any x and len m . Hence by (2.A.14). □

13 Sups (v_1, \dots, v_m) is linely depe in V and $W \neq \{0\}$.

Prove $\exists w_1, \dots, w_m \in W, \nexists T \in \mathcal{L}(V, W)$ suth $Tv_k = w_k, \forall k = 1, \dots, m$.

SOLUS:

We prove by ctradic. By liney dependence lemma, $\exists j \in \{1, \dots, m\}, v_j \in \text{span}(v_1, \dots, v_{j-1})$.

Sups $a_1 v_1 + \dots + a_m v_m = 0$, where $a_j \neq 0$. Now let $w_j \neq 0$, while $w_1 = \dots = w_{j-1} = w_{j+1} = \dots = w_m = 0$.

Define $T \in \mathcal{L}(V, W)$ by $Tv_k = w_k$ for each k . Then $T(a_1 v_1 + \dots + a_m v_m) = 0 = a_1 w_1 + \dots + a_m w_m$.

And $0 = a_j w_j$ while $a_j \neq 0$ and $w_j \neq 0$. Ctradic. □

OR. We prove the ctrapos: Sups $\forall w_1, \dots, w_m \in W, \exists T \in \mathcal{L}(V, W), Tv_k = w_k$ for each w_k .

Now we show (v_1, \dots, v_n) is liney indep. Sups $\exists a_i \in \mathbb{F}, a_1 v_1 + \dots + a_n v_n = 0$.

Choose one $w \in W \setminus \{0\}$. By asum, for $(\overline{a_1} w, \dots, \overline{a_m} w), \exists T \in \mathcal{L}(V, W), Tv_k = \overline{a_k} w$ for each v_k .

Now we have $0 = T\left(\sum_{k=1}^m a_k v_k\right) = \sum_{k=1}^m a_k Tv_k = \sum_{k=1}^m a_k \overline{a_k} w = \left(\sum_{k=1}^m |a_k|^2\right) w$.

Then $\sum_{k=1}^m |a_k|^2 = 0$. Thus $a_1 = \dots = a_m = 0$. Hence (v_1, \dots, v_n) is liney indep. □

• (4E 17) Sups V is finide. Show all two-sided ideals of $\mathcal{L}(V)$ are $\{0\}$ and $\mathcal{L}(V)$.

A subsp \mathcal{E} of $\mathcal{L}(V)$ is called a two-sided ideal of $\mathcal{L}(V)$ if $TE \in \mathcal{E}, ET \in \mathcal{E}, \forall E \in \mathcal{E}, T \in \mathcal{L}(V)$.

SOLUS: Let $B_V = (v_1, \dots, v_n)$. If $\mathcal{E} = 0$, then done.

Sups $\mathcal{E} \neq 0$ and \mathcal{E} is a two-sided ideal of $\mathcal{L}(V)$. Let $S \in \mathcal{E} \setminus \{0\}$.

Sups $sv_i \neq 0$ and $sv_i = a_1 v_1 + \dots + a_n v_n$, where $a_k \neq 0$.

Define $R_{x,y} \in \mathcal{L}(V)$ by $R_{x,y} : v_x \mapsto v_y, v_z \mapsto 0 (z \neq x)$. OR. $R_{x,y} v_z = \delta_{z,x} v_y$.

Then $(R_{1,1} + \dots + R_{n,n})v_j = v_j \Rightarrow \sum_{r=1}^n R_{r,r} = I$. Asum each $R_{x,y} \in \mathcal{E}$.

Hence $\forall T \in \mathcal{L}(V), I \circ T = T \circ I = T \in \mathcal{E} \Rightarrow \mathcal{E} = \mathcal{L}(V)$. Now we prove the asum.

Notice that $\forall x, y \in \mathbb{N}^+, (R_{k,y} S)(v_i) = a_k v_y \Rightarrow ((R_{k,y} S) \circ R_{x,i})(v_z) = \delta_{z,x} (a_k v_y)$.

Thus $R_{k,y} S R_{x,i} = a_k R_{x,y}$. Now $S \in \mathcal{E} \Rightarrow R_{k,y} S \in \mathcal{E} \Rightarrow R_{x,y} \in \mathcal{E}$. □

- (4E 3.B.32) *Sups V is finide with $n = \dim V > 1$.*

Show if $\varphi : \mathcal{L}(V) \rightarrow \mathbf{F}$ is liney and $\forall S, T \in \mathcal{L}(V), \varphi(ST) = \varphi(S) \cdot \varphi(T)$, then $\varphi = 0$.

SOLUS: Using notas in (4E 3.A.17). Using the result in NOTE FOR [3.60].

Sups $\varphi \neq 0 \Rightarrow \exists i, j \in \{1, \dots, n\}, \varphi(R_{i,j}) \neq 0$. Becs $R_{i,j} = R_{x,j} \circ R_{i,x}, \forall x = 1, \dots, n$
 $\Rightarrow \varphi(R_{i,j}) = \varphi(R_{x,j}) \cdot \varphi(R_{i,x}) \neq 0 \Rightarrow \varphi(R_{x,j}) \neq 0$ and $\varphi(R_{i,x}) \neq 0$.

Again, becs $R_{i,x} = R_{y,x} \circ R_{i,y}, \forall y = 1, \dots, n$. Thus $\varphi(R_{y,x}) \neq 0, \forall x, y = 1, \dots, n$.

Let $k \neq i, j \neq l$ and then $\varphi(R_{i,j} \circ R_{l,k}) = \varphi(R_{l,k} \circ R_{i,j}) = \varphi(0) = 0 = \varphi(R_{l,k}) \cdot \varphi(R_{i,j})$
 $\Rightarrow \varphi(R_{l,k}) = 0$ or $\varphi(R_{i,j}) = 0$. Ctradic. □

OR. Note that by (4E 3.A.17), $\exists S, T \in \mathcal{L}(V), ST - TS \neq 0$.

Then $\varphi(ST - TS) = \varphi(S)\varphi(T) - \varphi(T)\varphi(S) = 0 \Rightarrow ST - TS \in \text{null } \varphi \neq \{0\}$.

Note that $\forall E \in \text{null } \varphi, T \in \mathcal{L}(V), \varphi(ET) = \varphi(TE) = 0 \Rightarrow ET, TE \in \text{null } \varphi$.

Hence $\text{null } \varphi$ is a nonzero two-sided ideal of $\mathcal{L}(V)$. □

- *Sups V is finide. $T \in \mathcal{L}(V)$ is suth $\forall S \in \mathcal{L}(V), ST = TS$.*

Prove $\exists \lambda \in \mathbf{F}, T = \lambda I$.

SOLUS: If $V = \{0\}$, then done. Now sups $V \neq \{0\}$.

Asum $\forall v \in V, (v, Tv)$ is liney depe, then by (2.A.2.(b)), $\exists \lambda_v \in \mathbf{F}, Tv = \lambda_v v$.

To prove λ_v is indep of v , we discuss in two cases:

(-) If (v, w) is liney indep, $\lambda_{v+w}(v+w) = T(v+w) = Tv + Tw = \lambda_v v + \lambda_w w$
 $\Rightarrow (\lambda_{v+w} - \lambda_v)v + (\lambda_{v+w} - \lambda_w)w = 0$
 (=) Othws, sups $w = cv, \lambda_w w = Tw = cTv = c\lambda_v v = \lambda_v w \Rightarrow (\lambda_w - \lambda_v)w = 0$ □

Now we prove the asum. Asum $\exists v \in V, (v, Tv)$ is liney indep. Let $B_V = (v, Tv, u_1, \dots, u_n)$.

Define $S \in \mathcal{L}(V)$ by $S(av + bTv + c_1 u_1 + \dots + c_n u_n) = bv \Rightarrow S(Tv) = v = T(Sv) = 0$. Ctradic. □

OR. Let $B_V = (v_1, \dots, v_m)$. Define $\varphi \in \mathcal{L}(V, \mathbf{F})$ by $\varphi(v_1) = \dots = \varphi(v_m) = 1$.

Sups $v \in V$. Define $S_v \in \mathcal{L}(V)$ by $S_v(u) = \varphi(u)v$.

Then $Tv = T(\varphi(v_1)v) = T(S_v v_1) = S_v(Tv_1) = \varphi(Tv_1)v = \lambda v$. □

OR. For each $k \in \{1, \dots, n\}$, define $S_k \in \mathcal{L}(V)$ by $S_k v_j = \begin{cases} v_k, & j = k, \\ 0, & j \neq k. \end{cases}$ OR. $S_k v_j = \delta_{j,k} v_k$

Note that $S_k \left(\sum_{i=1}^n a_i v_i \right) = a_k v_k$. Then $S_k v = v \iff \exists ! a_k \in \mathbf{F}, v = a_k v_k$.

Hence $S_k(Tv_k) = T(S_k v_k) = Tv_k \Rightarrow Tv_k = a_k v_k$.

Define $A^{(j,k)} \in \mathcal{L}(V)$ by $A^{(j,k)} v_j = v_k, A^{(j,k)} v_k = v_j, A^{(j,k)} v_x = 0, x \neq j, k$.

Then $\left\{ \begin{array}{l} A^{(j,k)} T v_j = T A^{(j,k)} v_j = T v_k = a_k v_k \\ A^{(j,k)} T v_j = A^{(j,k)} a_j v_j = a_j A^{(j,k)} v_j = a_j v_k \end{array} \right\} \Rightarrow a_k = a_j$. Hence a_k is inde of v_k . □

- **TIPS 3:** *Sups $T \in \mathcal{L}(V, W)$. Prove $Tv \neq 0 \Rightarrow v \neq 0$.*

SOLUS: Asum $v = 0$. Then $Tv = T(0) = T(0 \cdot 0) = 0 \cdot T(0) = 0$.

OR. $T(0) = T(0 + 0) = T(0) + T(0) \Rightarrow T(0) = 0$. Ctradic. □

- Given the fact that $\mathcal{L}(V, W)$ is a vecsp. Prove or give a counterexa: V, W are vecsp.

We can assure that $\{0\} \subseteq \mathcal{L}(V, W), \{0\} \subseteq V, \{0\} \subseteq W$.

And by [3.2], the add and homo imply that V is closd add and scalar multi.

(W^V might not be a vecsp.)

SOLUS: **TODO: Too tricky to be answered by AI.**

(I) If $W^V = \{0\}$. Then $\mathcal{L}(V, W) = \{0\}$.

And $W = \{0\}$, for if not, $\exists w \in W \setminus \{0\}$, define a map f by $f(x) = w, \forall x \in V$.

And V might not be a vecsp. Example: ???

(II) If W^V is a nonzero vecsp. Then W is a vecsp.

(a) If $\mathcal{L}(V, W) = \{0\}$, then we cannot guarantee that V is a vecsp. Example: ???

(b) If not, then $\exists T \in \mathcal{L}(V, W), T \neq 0$. Which means $\exists v \in V, Tv \neq 0 \Rightarrow v \neq 0$.

Then both W and V have a nonzero ele.

(i) If \exists inje $T \in \mathcal{L}(V, W)$, then $T(u+v) = T(v+u) \Rightarrow u+v = v+u$. etc. Hence V is a vecsp.

(ii) If not, then we cannot guarantee that V is a vecsp. Exa: ???

(III) If W^V is not a vecsp, then W is not a vecsp. Exa: ???

□

ENDED

3.B 3 7 8 9 10 11 12 16 17 18 19 20 21 22 23 24 25 26 28 29 30 | 4E: 21 24 27 31 32 33

3 Sups (v_1, \dots, v_m) in V . Define $T \in \mathcal{L}(\mathbf{F}^m, V)$ by $T(z_1, \dots, z_m) = z_1v_1 + \dots + z_mv_m$.

(a) The surj of T corres to (v_1, \dots, v_m) spanning V . $\text{range } T = \text{span}(v_1, \dots, v_m) = V$.

(b) The inje of T corres to (v_1, \dots, v_m) being liney indep. (v_1, \dots, v_m) liney indep $\Leftrightarrow T$ inje.

COMMENT: Let (e_1, \dots, e_m) be std bss of \mathbf{F}^m . Then $Te_k = v_k$.

7 Sups V is finide with $2 \leq \dim V$. And $\dim V \leq \dim W = m$, if W is finide.

Show $U = \{T \in \mathcal{L}(V, W) : \text{null } T \neq \{0\}\}$ is not a subsp of $\mathcal{L}(V, W)$.

SOLUS: The set of all inje $T \in \mathcal{L}(V, W)$ is a not subsp either.

Let (v_1, \dots, v_n) be a bss of V , (w_1, \dots, w_m) be liney indep in W . $[2 \leq n \leq m.]$

Define $T_1 \in \mathcal{L}(V, W)$ as $T_1: v_1 \mapsto 0, v_2 \mapsto w_2, v_i \mapsto w_i$.

Define $T_2 \in \mathcal{L}(V, W)$ as $T_2: v_1 \mapsto w_1, v_2 \mapsto 0, v_i \mapsto w_i, i = 3, \dots, n$.

Thus $T_1 + T_2 \notin U$. □

COMMENT: If $\dim V = 0$, then $V = \{0\} = \text{span}(\)$. $\forall T \in \mathcal{L}(V, W), T$ is inje. Hence $U = \emptyset$.

If $\dim V = 1$, then $V = \text{span}(v_0)$. Thus $U = \text{span}(T_0)$, where $\forall v \in V, T_0v = 0 \Rightarrow T_0 = 0$.

8 Sups W is finide with $\dim W \geq 2$. And $n = \dim V \geq \dim W$, if V is finide.

Show $U = \{T \in \mathcal{L}(V, W) : \text{range } T \neq W\}$ is not a subsp of $\mathcal{L}(V, W)$.

SOLUS: The set of all surj $T \in \mathcal{L}(V, W)$ is not a subsp either. **Using the generalized version of [3.5].**

Let (v_1, \dots, v_n) be liney indep in V , (w_1, \dots, w_m) be a bss of W . $[n \in \{m, m+1, \dots\}; 2 \leq m \leq n.]$

Define $T_1 \in \mathcal{L}(V, W)$ as $T_1: v_1 \mapsto 0, v_2 \mapsto w_2, v_j \mapsto w_j, v_{m+i} \mapsto 0$.

Define $T_2 \in \mathcal{L}(V, W)$ as $T_2: v_1 \mapsto w_1, v_2 \mapsto 0, v_j \mapsto w_j, v_{m+i} \mapsto 0$.

(For each $j = 2, \dots, m; i = 1, \dots, n-m$, if V is finide, othws let $i \in \mathbf{N}^+$.) Thus $T_1 + T_2 \notin U$. □

COMMENT: If $\dim W = 0$, then $W = \{0\} = \text{span}(\)$. $\forall T \in \mathcal{L}(V, W), T$ is surj. Hence $U = \emptyset$.

If $\dim W = 1$, then $W = \text{span}(w_0)$. Thus $U = \text{span}(T_0)$, where each $T_0v_i = 0 \Rightarrow T_0 = 0$.

9 Sups (v_1, \dots, v_n) is liney indep. Prove \forall inje $T, (Tv_1, \dots, Tv_n)$ is liney indep.

SOLUS: $a_1Tv_1 + \dots + a_nTv_n = 0 = T\left(\sum_{i=1}^n a_i v_i\right) \iff \sum_{i=1}^n a_i v_i = 0 \iff a_1 = \dots = a_n = 0.$ □

10 Sups $\text{span}(v_1, \dots, v_n) = V$. Show $\text{span}(Tv_1, \dots, Tv_n) = \text{range } T$.

SOLUS: (a) $\text{range } T = \{Tv : v \in \text{span}(v_1, \dots, v_n)\} \Rightarrow Tv_1, \dots, Tv_n \in \text{range } T$. By [2.7].

OR. $\text{span}(Tv_1, \dots, Tv_n) \ni a_1Tv_1 + \dots + a_nTv_n = T(a_1v_1 + \dots + a_nv_n) \in \text{range } T$.

(b) $\forall w \in \text{range } T, w = Tv, \exists v \in V \Rightarrow \exists a_i \in \mathbf{F}, v = \sum_{i=1}^n a_i v_i, w = a_1Tv_1 + \dots + a_nTv_n.$ □

11 Sups $S_1, \dots, S_n \in \mathcal{L}(V)$ and $S = S_1S_2 \dots S_n$ makes sense. Then using induc:

(a) $\text{range } S_1 \supseteq \text{range } (S_1S_2) \supseteq \dots \supseteq \text{range } (S);$ (b) $\text{null } S_n \subseteq \text{null } (S_{n-1}S_n) \subseteq \dots \subseteq \text{null } (S).$

• Define $X_p = \{T \in \mathcal{L}(V) : p(T) \text{ holds}\}; P_p : X_p \text{ is closd vec multi}; Q_p : X_p \text{ is a group}.$

(1) $S \text{ surj} \iff \text{each } S_k \text{ surj. } P_{\text{surj}} \text{ holds.}$ (2) $S \text{ inje} \iff \text{each } S_k \text{ inje. } P_{\text{inje}} \text{ holds.}$

(3) P_{inv} and Q_{inv} hold. Q_p in (1) and (2) holds $\iff V$ is finide.

(4) $P_{\text{inje or surj}}$ holds $\iff V$ is finide $\iff Q_{\text{inje or surj}}$ holds.

• Sups $S, T \in \mathcal{L}(V)$. Prove or give a counterexa:

(a) $\text{null } S \subseteq \text{null } T \Rightarrow \text{range } T \subseteq \text{range } S;$ (b) $\text{range } T \subseteq \text{range } S \Rightarrow \text{null } S \subseteq \text{null } T.$

SOLUS: Let $B_V = (v_1, v_2, v_3)$. Counterexas:

(a) Let $S : v_1 \mapsto 0; v_2 \mapsto 0; v_3 \mapsto v_2.$ | Then $\text{null } S = \text{null } T$, but

$T : v_1 \mapsto 0; v_2 \mapsto 0; v_3 \mapsto v_3.$ | $\text{range } T = \text{span}(v_3) \not\subseteq \text{span}(v_2) = \text{null } T.$

(b) Let $S : v_1 \mapsto v_2; v_2 \mapsto v_2; v_3 \mapsto v_2.$ | Then $\text{range } T = \text{range } S$, but

$T : v_1 \mapsto 0; v_2 \mapsto 0; v_3 \mapsto v_2.$ | $\text{null } S = \text{span}(v_1 - v_2, v_2 - v_3, v_3 - v_1) \not\subseteq \text{span}(v_1, v_2) = \text{null } T.$

16 Sups $T \in \mathcal{L}(V)$ suth $\text{null } T, \text{range } T$ are finide. Prove V is finide.

SOLUS: Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n), B_{\text{null } T} = (u_1, \dots, u_m).$

$\forall v \in V, \exists ! a_i \in \mathbf{F}, T(v - a_1v_1 - \dots - a_nv_n) = 0 \Rightarrow \exists ! b_i \in \mathbf{F}, v - \sum_{i=1}^n a_i v_i = \sum_{i=1}^m b_i u_i.$ □

17 Sups V, W are finide. Prove \exists inje $T \in \mathcal{L}(V, W) \iff \dim V \leq \dim W.$

SOLUS: (a) Sups \exists inje T . Then $\dim V = \dim \text{range } T \leq \dim W.$

(b) Sups $\dim V \leq \dim W$. Let $B_V = (v_1, \dots, v_n), B_W = (w_1, \dots, w_m).$

Define $T \in \mathcal{L}(V, W)$ by $Tv_i = w_i, i = 1, \dots, n (= \dim V).$ □

18 Sups V, W are finide. Prove \exists surj $T \in \mathcal{L}(V, W) \iff \dim V \geq \dim W.$

SOLUS: (a) Sups \exists surj T . Then $\dim V = \dim W + \dim \text{null } T \Rightarrow \dim W \leq \dim V.$

(b) Sups $\dim V \geq \dim W$. Let $B_V = (v_1, \dots, v_n), B_W = (w_1, \dots, w_m).$

Define $T \in \mathcal{L}(V, W)$ by $T(a_1v_1 + \dots + a_mv_m + \dots + a_nv_n) = a_1w_1 + \dots + a_mw_m.$ □

19 Sups V, W are finide, U is a subsp of V .

Prove $\exists T \in \mathcal{L}(V, W), \text{null } T = U \iff \underbrace{\dim U}_m \geq \underbrace{\dim V}_{m+n} - \underbrace{\dim W}_p.$

SOLUS:

(a) Sups $\exists T \in \mathcal{L}(V, W), \text{null } T = U$. Then $\dim U + \dim \text{range } T = \dim V \leq \dim U + \dim W.$

(b) Let $B_U = (u_1, \dots, u_m), B_V = (u_1, \dots, u_m, v_1, \dots, v_n), B_W = (w_1, \dots, w_p).$ Sups that $p \geq n.$

Define $T \in \mathcal{L}(V, W)$ by $T(a_1v_1 + \dots + a_nv_n + b_1u_1 + \dots + b_mu_m) = a_1w_1 + \dots + a_nw_n.$ □

• **TIPS 1:** Sups U is a subsp of V . Then $\forall T \in \mathcal{L}(V, W), U \cap \text{null } T = \text{null } T|_U$.

• **TIPS 2:** Sups $T \in \mathcal{L}(V, W)$ and $T|_U$ is inje. Let $V = M + N, U = X + Y$.

Then $\text{range } T = \text{range } T|_M + \text{range } T|_N = \text{range } T|_X + \text{range } T|_Y$.

(a) Show if $U = X \oplus Y$, then $\text{range } T = \text{range } T|_X \oplus \text{range } T|_Y$.

(b) Give an exa suth $V = M \oplus N, \text{range } T \neq \text{range } T|_M \oplus \text{range } T|_N$.

SOLUS: Asum for some $v \in V$, there exis two disti pairs $(x_1, y_1), (x_2, y_2)$ in $X \times Y$

suth $Tv = Tx_1 + Ty_1 = Tx_2 + Ty_2$. Becs $\forall v \in X \oplus Y, \exists! (x, y) \in X \times Y, v = x + y$.

Now $T(x_1 + y_1) = T(x_2 + y_2) \Rightarrow x_1 + y_1 = x_2 + y_2 \Rightarrow x_1 = x_2, y_1 = y_2$. Ctradic.

Thus $\forall Tv \in \text{range } T, \exists! Tx \in \text{range } T|_X, Ty \in \text{range } T|_Y, Tv = Tx + Ty$. □

EXA: Let $B_V = (v_1, v_2, v_3), B_W = (w_1, w_2), T : v_1 \mapsto 0, v_2 \mapsto w_1, v_3 \mapsto w_2$.

Let $B_M = (v_1 - v_2, v_3), B_N = (v_2)$. Then $\text{range } T|_M = \text{span}(w_1, w_2), \text{range } T|_N = \text{span}(w_1)$

COMMENT: Also $\text{null } T|_M = \text{null } T|_N = \{0\}$. Hence $\text{null } T \neq \text{null } T|_M \oplus \text{null } T|_N$.

12 Prove $\forall T \in \mathcal{L}(V, W), \exists \text{ subsp } U \text{ of } V \text{ suth}$

$U \cap \text{null } T = \text{null } T|_U = \{0\}, \text{range } T = \{Tu : u \in U\} = \text{range } T|_U$.

Which is equiv to $T|_U : U \rightarrow \text{range } T$ being iso.

SOLUS: By [2.34] (note that V can be infinide), $\exists \text{ subsp } U \text{ of } V \text{ suth } V = U \oplus \text{null } T$.

$\forall v \in V, \exists! w \in \text{null } T, u \in U, v = w + u$. Then $Tv = T(w + u) = Tu \in \{Tu : u \in U\}$. □

CORO: $[P] \quad T|_U : U \rightarrow \text{range } T \text{ is iso} \iff U \oplus \text{null } T = V. \quad [Q]$

We have shown $Q \Rightarrow P$. Now we show $P \Rightarrow Q$ to complete the proof.

$\forall v \in V, Tv \in \text{range } T = \text{range } T|_U \Rightarrow \exists! u \in U, Tv = Tu \Rightarrow v - u \in \text{null } T$.

Thus $v = (v - u) + u \in U + \text{null } T$. $\forall u \in U \cap \text{null } T \iff T|_U(u) = 0 \iff u = 0$. □

OR. $\neg Q \Rightarrow \neg P$: Becs $U \oplus \text{null } T \subsetneq V$. We show $\text{range } T \neq \text{range } T|_U$ by ctradic.

Let $X \oplus (U \oplus \text{null } T) = V$. Now $\text{range } T = \text{range } T|_X \oplus \text{range } T|_U$. And X is nonzero.

Asum $\text{range } T = \text{range } T|_U$. Then $\text{range } T|_X = \{0\}$. While $T|_X$ is inje. Ctradic.

OR. $\text{range } T|_X \subseteq \text{range } T|_U \Rightarrow \forall x \in X, Tx \in \text{range } T|_U, \exists u \in U, Tu = Tx \Rightarrow x = 0$.

Also, $\neg P \Rightarrow \neg Q$: (a) $\text{range } T|_U \subsetneq \text{range } T$; OR (b) $U \cap \text{null } T \neq \{0\}$.

For (a), $\exists x \in V \setminus U, Tx \neq 0 \iff x \notin \text{null } T$. Thus $U + \text{null } T \subsetneq V$. For (b), immediately. □

COMMENT: If $T|_U : U \rightarrow \text{range } T$ is iso. Let $R \oplus U = V$. Then R might not be $\text{null } T$.

OR. Extend B_U to $B_V = (u_1, \dots, u_n, r_1, \dots, r_m)$, then (r_1, \dots, r_m) might not be a $B_{\text{null } T}$.

• **TIPS 3:** Sups $T \in \mathcal{L}(V, W)$ and U is a subsp suth $V = U \oplus \text{null } T$. Let $\text{null } T = X \oplus Y$.

Now $\forall v \in V, \exists! u_v \in U, (x_v, y_v) \in X \times Y, v = u_v + x_v + y_v$. Define $i \in \mathcal{L}(V, U \oplus X)$ by $i(v) = u_v + x_v$.

Then $T = T \circ i$. Becs $\forall v \in V, T(v) = T(u_v + x_v + y_v) = T(u_v) = T(u_v + x_v) = T(i(v)) = (T \circ i)(v)$.

• **TIPS 4:** Sups $T \in \mathcal{L}(V, W), T \neq 0$. Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n)$.

By (3.A.4), $R = (v_1, \dots, v_n)$ is liney indep in V . Let $\text{span } R = U$. We will prove $U \oplus \text{null } T = V$.

(a) $T\left(\sum_{i=1}^n a_i v_i\right) = 0 \iff \sum_{i=1}^n a_i Tv_i = 0 \iff a_1 = \dots = a_n = 0$. Thus $U \cap \text{null } T = \{0\}$.

(b) $Tv = \sum_{i=1}^n a_i Tv_i \iff v - \sum_{i=1}^n a_i v_i \in \text{null } T \iff v = \left(v - \sum_{i=1}^n a_i v_i\right) + \left(\sum_{i=1}^n a_i v_i\right)$.

Thus $U + \text{null } T = V$. OR. $\text{range } T = \{Tu : u \in U\} = \text{range } T|_U$. Using Exe (12). □

CORO: Conversely, if $U \oplus \text{null } T = V$ and $B_U = (v_1, \dots, v_n)$, then $B_{\text{range } T} = (Tv_1, \dots, Tv_n)$.

Becs $\text{range } T = \text{range } T|_U = \text{span}(Tv_1, \dots, Tv_n)$, $\forall T$ is inje.

- [4E 27, OR 5.B.4] *Sups $P \in \mathcal{L}(V)$ and $P^2 = P$. Prove $V = \text{null } P \oplus \text{range } P$.*

SOLUS: (a) If $v \in \text{null } P \cap \text{range } P \Rightarrow Pv = 0$, and $\exists u \in V, v = Pu$. Then $v = Pu = P^2u = Pv = 0$.

(b) Note that $\forall v \in V, v = Pv + (v - Pv)$ and $P(v - Pv) = 0 \Rightarrow v - Pv \in \text{null } P$.

OR. Becs $\dim V = \dim \text{null } P + \dim \text{range } P = \dim(\text{null } P \oplus \text{range } P)$. □

OR. [Only in Finite] Let $B_{\text{range } P^2} = (P^2v_1, \dots, P^2v_n)$. Then (Pv_1, \dots, Pv_n) is liney indep.

Let $U = \text{span}(Pv_1, \dots, Pv_n) \Rightarrow V = U \oplus \text{null } P^2$. While $U = \text{range } P = \text{range } P^2$; $\text{null } P = \text{null } P^2$. □

- *Sups $T \in \mathcal{L}(V), v \in V$, and $n \in \mathbf{N}^+$ such $T^{n-1}v \neq 0, T^n v = 0$. [See [5.16]]
Prove $(v, Tv, \dots, T^{n-1}v)$ is liney indep.*

SOLUS: $a_0v + a_1Tv + \dots + a_{n-1}T^{n-1}v = 0 \Rightarrow a_0T^{n-1}v = 0 \Rightarrow a_0 = 0$. Simlr for a_1, \dots, a_{n-1} . □

- (4E 21) *Sups V is finite, $T \in \mathcal{L}(V, W)$, Y is a subsp of W . Let $\{v \in V : Tv \in Y\}$.*

(a) *Prove $\{v \in V : Tv \in Y\}$ is a subsp of V .*

(b) *Prove $\dim\{v \in V : Tv \in Y\} = \dim \text{null } T + \dim(Y \cap \text{range } T)$.*

SOLUS: Let $\mathcal{K}_Y = \{v \in V : Tv \in Y\}$.

(a) $\forall u, w \in \mathcal{K}_Y, [Tu, Tw \in Y], \lambda \in \mathbf{F}, T(u + \lambda w) = Tu + \lambda Tw \in Y \Rightarrow \mathcal{K}_Y$ is a subsp of V .

(b) Define the range-restr map R of T by $R = T|_{\mathcal{K}_Y} \in \mathcal{L}(\mathcal{K}_Y, Y)$. Now $\text{range } R = Y \cap \text{range } T$.

And $v \in \text{null } T \Leftrightarrow Tv = 0 \in Y \Leftrightarrow Rv = 0 \in \text{range } T \Leftrightarrow v \in \text{null } R$. By [3.22]. □

COMMENT: Now $\text{span}(v_1, \dots, v_m) \oplus \text{null } T = \mathcal{K}_Y$. Where $B_{Y \cap \text{range } T} = (Tv_1, \dots, Tv_m)$.

In particular, $\dim \mathcal{K}_{\text{range } T} = \dim \text{null } T + \dim \text{range } T \Rightarrow \mathcal{K}_{\text{range } T} = V$.

- (4E 31) *Sups V is finite, X is a subsp of V , and Y is a finite subsp of W .*

Prove if $\dim X + \dim Y = \dim V$, then $\exists T \in \mathcal{L}(V, W), \text{null } T = X, \text{range } T = Y$.

SOLUS: Let $V = U \oplus X, B_U = (v_1, \dots, v_m)$. Then $\forall v \in V, \exists! a_i \in \mathbf{F}, x \in X, v = \sum_{i=1}^m a_i v_i + x$.

Let $B_Y = (w_1, \dots, w_m)$. Define $T \in \mathcal{L}(V, W)$ by $Tv_i = w_i, Tx = 0$ for each v_i and all $x \in X$.

Now $v \in \text{null } T \Leftrightarrow Tv = a_1w_1 + \dots + a_mw_m = 0 \Leftrightarrow v = x \in X$. Hence $\text{null } T = X$.

And $Y \ni w = a_1w_1 + \dots + a_mw_m = a_1Tv_1 + \dots + a_mTv_m \in \text{range } T$. Hence $\text{range } T = Y$.

OR. NOTICE that $V = U \oplus \text{null } T$. By Exe (12), $\text{range } T = \text{range } T|_U$.

又 $\dim \text{range } T|_U = \dim U = \dim Y$; $\text{range } T \subseteq Y$.

OR. Let $B_X = (x_1, \dots, x_n)$. Now $\text{range } T = \text{span}(Tv_1, \dots, Tv_m, Tx_1, \dots, Tx_n) = \text{span}(w_1, \dots, w_m) = Y$. □

- 22** *Sups U, V are finite, $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$.*

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

SOLUS: We show $\dim \text{null } ST = \dim \text{null } S|_{\text{range } T} + \dim \text{null } T$.

Becs (a) $\text{range } T|_{\text{null } ST} = \text{range } T \cap \text{null } S = \text{null } S|_{\text{range } T}$,

(b) $\text{null } T|_{\text{null } ST} = \text{null } T \cap \text{null } ST = \text{null } T$. By [3.22] □

OR. NOTICE that $u \in \text{null } ST \Leftrightarrow S(Tu) = 0 \Leftrightarrow Tu \in \text{null } S$.

Thus $\{u \in U : Tu \in \text{null } S\} = \mathcal{K}_{\text{null } S \cap \text{range } T} = \text{null } ST$.

By Exe (4E 21), $\dim \text{null } ST = \dim \text{null } T + \dim(\text{null } S \cap \text{range } T)$. □

CORO: (1) T surj $\Rightarrow \dim \text{null } ST = \dim \text{null } S + \dim \text{null } T$.

(2) T inv $\Rightarrow \dim \text{null } ST = \dim \text{null } S, \text{null } ST = \text{null } T$.

(3) S inje $\Rightarrow \dim \text{null } ST = \dim \text{null } T$.

23 Sups V is finide, $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$.

Prove $\dim \text{range } ST \leq \min\{\dim \text{range } S, \dim \text{range } T\}$.

COMMENT: If $\dim V = \dim U$. Then $\dim \text{null } ST \geq \max\{\dim \text{null } S, \dim \text{null } T\}$.

SOLUS: NOTICE that $\text{range } ST = \{Sv : v \in \text{range } T\} = \text{range } S|_{\text{range } T}$.

Let $\text{range } ST = \text{span}(Su_1, \dots, Su_{\dim \text{range } T})$, where $B_{\text{range } T} = (u_1, \dots, u_{\dim \text{range } T})$.

$\dim \text{range } ST \leq \dim \text{range } T$ 又 $\dim \text{range } ST \leq \dim \text{range } S$. □

OR. $\dim \text{range } ST = \dim \text{range } S|_{\text{range } T} = \dim \text{range } T - \dim \text{null } S|_{\text{range } T} \leq \dim \text{range } T$. □

COMMENT: $\dim \text{range } ST = \dim U - \dim \text{null } ST = \dim \text{range } T|_U - \dim \text{range } T|_{\text{null } ST}$.

CORO: (1) $S|_{\text{range } T} \text{ inje} \iff \dim \text{range } ST = \dim \text{range } T$.

(2) Let $X \oplus \text{null } S = V$. Then $X \subseteq \text{range } T \iff \text{range } ST = \text{range } S$.

And T is surj $\Rightarrow \text{range } ST = \text{range } S$.

• (a) Sups $\dim V = n$, $ST = 0$ where $S, T \in \mathcal{L}(V)$. Prove $\dim \text{range } TS \leq \lfloor \frac{n}{2} \rfloor$.

(b) Give an exa of such S, T with $n = 5$ and $\dim \text{range } TS = 2$.

SOLUS: Note that $\dim \text{range } TS \leq \min\{\dim \text{range } T, \dim \text{range } S\}$. We prove by ctradict.

Asum $\dim \text{range } TS \geq \lfloor \frac{n}{2} \rfloor + 1$. Then $\min\{n - \dim \text{null } T, n - \dim \text{null } S\} \geq \lfloor \frac{n}{2} \rfloor + 1$

又 $\dim \text{null } ST = n \leq \dim \text{null } S + \dim \text{null } T \Rightarrow \max\{\dim \text{null } T, \dim \text{null } S\} \leq \lfloor \frac{n}{2} \rfloor - 1$.

Thus $n \leq 2(\lfloor \frac{n}{2} \rfloor - 1) \Rightarrow \frac{n}{2} \leq \lfloor \frac{n}{2} \rfloor - 1$. Ctradict. □

OR. $\dim \text{null } S = n - \dim \text{range } S \leq n - \dim \text{range } TS$. 又 $ST = 0 \Rightarrow \text{range } T \subseteq \text{null } S$.

$\dim \text{range } TS \leq \dim \text{range } T \leq \dim \text{null } S \leq n - \dim \text{range } TS$. Thus $2 \dim \text{range } TS \leq n$. □

OR. Becs $\dim \text{range } TS \leq \lfloor \frac{n}{2} \rfloor$, and $\lfloor \frac{n}{2} \rfloor + \lfloor \frac{n}{2} \rfloor = n$.

We show $\dim \text{null } TS \geq \lfloor \frac{n}{2} \rfloor$. Note that $\dim \text{null } S + \dim \text{null } T \geq n$.

$\dim \text{null } S + \dim \text{null } T|_{\text{range } S} = \dim \text{null } TS$. If $\dim \text{null } S \geq \lfloor \frac{n}{2} \rfloor$. Then done.

Othws, $\dim \text{null } S \leq \lfloor \frac{n}{2} \rfloor - 1 \Rightarrow \dim \text{null } T \geq n - \dim \text{null } S \geq n - \lfloor \frac{n}{2} \rfloor + 1 = \lfloor \frac{n}{2} \rfloor + 1 \geq \lfloor \frac{n}{2} \rfloor$.

Thus $\dim \text{null } TS \geq \max\{\dim \text{null } S, \dim \text{null } T\} = \lfloor \frac{n}{2} \rfloor$. □

EXA: Define $T : v_1 \mapsto 0, v_2 \mapsto 0, v_i \mapsto v_i ; S : v_1 \mapsto v_4, v_2 \mapsto v_5, v_i \mapsto 0 ; i = 3, 4, 5$.

26 Sups $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}))$ and $\forall p, \deg(Dp) = (\deg p) - 1$. Prove $D \in \mathcal{P}(\mathbb{R})$ is surj.

SOLUS: [D might not be $D : p \mapsto p'$.] NOTICE that the following proof is wrong:

Becs $\text{span}(Dx, Dx^2, Dx^3, \dots) \subseteq \text{range } D$, and $\deg Dx^n = n - 1$.

又 By (2.C.10), $\text{span}(Dx, Dx^2, Dx^3, \dots) = \text{span}(1, x, x^2, \dots) = \mathcal{P}(\mathbb{R})$.

Let $D(C) = 0, Dx^k = p_k$ of $\deg(k - 1)$, for all $C \in \mathbb{R} = \mathcal{P}_0(\mathbb{R})$ and for each $k \in \mathbb{N}^+$.

Becs $B_{\mathcal{P}_m(\mathbb{R})} = (p_1, \dots, p_m, p_{m+1})$. And for all $p \in \mathcal{P}(\mathbb{R}), \exists ! m = \deg p \in \mathbb{N}^+$.

So that $\exists ! a_i \in \mathbb{R}, p = \sum_{i=1}^{m+1} a_i p_i \Rightarrow \exists q = \sum_{i=1}^{m+1} a_i x^i, Dq = p$. □

OR. We will recurly define a sequence of polys $(p_k)_{k=0}^\infty$ where $Dp_0 = 1, Dp_k = x^k$ for each $k \in \mathbb{N}^+$.

So that $\forall p = \sum_{k=0}^{\deg p} a_k x^k \in \mathcal{P}(\mathbb{R}), Dq = p, \exists q = \sum_{k=0}^{\deg p} a_k p_k$.

(i) Becs $\deg Dx = (\deg x) - 1 = 0, Dx = C \in \mathbb{F} \setminus \{0\}$. Let $p_0 = C^{-1}x \Rightarrow Dp_0 = C^{-1}Dx = 1$.

(ii) Sups we have defined $Dp_0 = 1, Dp_k = x^k$ for each $k \in \{1, \dots, n\}$. Becs $\deg D(x^{n+2}) = n + 1$.

Let $D(x^{n+2}) = a_{n+1}x^{n+1} + a_n x^n + \dots + a_1 x + a_0$, with $a_{n+1} \neq 0$.

Then $a_{n+1}^{-1} D(x^{n+2}) = x^{n+1} + a_{n+1}^{-1}(a_n Dp_n + \dots + a_1 Dp_1 + a_0 Dp_0)$

$\Rightarrow x^{n+1} = D[a_{n+1}^{-1}(x^{n+2} - a_n p_n - \dots - a_1 p_1 - a_0 p_0)]$. Thus defining p_{n+1} , so that $Dp_{n+1} = x^{n+1}$. □

- 20, 21** (a) Prove if $ST = I \in \mathcal{L}(V)$, then T is inje and S is surj.
 (b) Sups $T \in \mathcal{L}(V, W)$. Prove if T is inje, then $\exists S \in \mathcal{L}(W, V)$, $ST = I$.
 (c) Sups $S \in \mathcal{L}(W, V)$. Prove if S is surj, then $\exists T \in \mathcal{L}(V, W)$, $ST = I$.

SOLUS:

- (a) $Tv = 0 \Rightarrow S(Tv) = 0 = v$. OR. $\text{null } T \subseteq \text{null } ST = \{0\}$.
 $\forall v \in V, ST(v) = v \in \text{range } S$. OR. $V = \text{range } ST \subseteq \text{range } S$.
 (b) Define $S \in \mathcal{L}(\text{range } T, V)$ by $Sw = T^{-1}w$, where T^{-1} is the inv of $T \in \mathcal{L}(V, \text{range } T)$.
 Then extend to $S \in \mathcal{L}(W, V)$ by (3.A.11). Now $\forall v \in V, STv = T^{-1}Tv = v$.
 OR. [Req V Finide] Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n) \Rightarrow B_V = (v_1, \dots, v_n)$. Let $U \oplus \text{range } T = W$.
 Define $S \in \mathcal{L}(W, V)$ by $S(Tv_i) = v_i, Su = 0$ for each v_i and all $u \in U$. Thus $ST = I$.
 (c) By Exe (12), \exists subsp U of $W, W = U \oplus \text{null } S, \text{range } S = \text{range } S|_U = V$.
 Note that $S|_U : U \rightarrow V$ is iso. Define $T = (S|_U)^{-1}$, where $(S|_U)^{-1} : V \rightarrow U$.
 Then $ST = S \circ (S|_U)^{-1} = S|_U \circ (S|_U)^{-1} = I_V$.
 OR. [Req V Finide] Let $B_{\text{range } S} = B_V = (Sw_1, \dots, Sw_n) \Rightarrow \text{span}(w_1, \dots, w_n) \oplus \text{null } S = W$.
 Define $T \in \mathcal{L}(V, W)$ by $T(Sw_i) = w_i$. Now $ST(a_1Sw_1 + \dots + a_nSw_n) = (a_1Sw_1 + \dots + a_nSw_n)$. \square

CORO: For (b), if T is inje and $\exists S, ST = I$, then by (a), this S is surj. Simlr for (c).

- **TIPS 5:** Sups $S \in \mathcal{L}(U, V)$ is surj. Define $\mathcal{B} \in \mathcal{L}(\mathcal{L}(V, W), \mathcal{L}(U, W))$ by $\mathcal{B}(T) = TS$.
 Then \mathcal{B} is inje. Becs $\mathcal{B}(T) = TS = 0 \iff T|_{\text{range } S} = 0$. OR. $\text{range } TS = \text{range } T = \{0\}$.

24 Sups $S, T \in \mathcal{L}(V, W)$, and $\text{null } S \subseteq \text{null } T$. Prove $\exists E \in \mathcal{L}(W), T = ES$.

SOLUS:

Let $V = U \oplus \text{null } S$
 $\Rightarrow S|_U : U \rightarrow \text{range } S$ is iso.
 Extend $T(S|_U)^{-1}$ to $E \in \mathcal{L}(W)$.

$$\begin{array}{ccc} \text{range } T & \xleftarrow{\text{surj } T} & U \\ & \searrow \text{inv } S & \downarrow S \\ & & \text{range } S \end{array}$$

OR. Define $E : \text{range } S \rightarrow W$ by $E : Sv \mapsto Tv$.
 Extend $E \in \mathcal{L}(\text{range } S, W)$ to $E \in \mathcal{L}(W)$. \square

COMMENT: Let $\Delta \oplus \text{null } S = \text{null } T, U_\Delta \oplus (\Delta \oplus \text{null } S) = V = U_\Delta \oplus \text{null } T$. Redefine $U = U_\Delta \oplus \Delta$.

U	$\text{null } S$
U_Δ	$\text{null } T$
Δ	$\text{null } S$

$\text{range } S \xleftarrow{S} U_\Delta \xrightarrow{T} \text{range } T$
 $\Delta \xrightarrow{T} \{0\}$

Becs $\Delta = \text{null } T|_U = \text{null } T \cap \text{range } (S|_U)^{-1}$.
 Thus $E = T(S|_U)^{-1}$ is not inje $\iff \Delta \neq \{0\}$.
 In other words, $\text{range } S|_\Delta = \text{null } E$,
 while $E|_{\dots} : \text{range } S|_{U_\Delta} \rightarrow \text{range } T$ is iso.

COMMENT: Let $E_1 \in \mathcal{L}(U_\Delta \oplus \text{null } T, U_\Delta)$, and E_2 be an iso of $\text{range } S|_{U_\Delta}$ onto $\text{range } T$.

Define $E_1|_{U_\Delta} = I|_{U_\Delta}$, and $E_2 = T(S|_{U_\Delta})^{-1}$. Then $T = E_2SE_1$.

CORO: If $\text{null } S = \text{null } T$. Then $\Delta = \{0\}, U_\Delta = U$.

By (3.D.3), we can extend inje $T(S|_U)^{-1} \in \mathcal{L}(\text{range } S, W)$ to inv $E \in \mathcal{L}(W)$.

OR. [Req $\text{range } S$ Finide] Let $B_{\text{range } S} = (Sv_1, \dots, Sv_n)$. Then $V = \text{span}(v_1, \dots, v_n) \oplus \text{null } S$.

Let $U \oplus \text{range } S = W$. Define $E \in \mathcal{L}(W)$ by $E(Sv_i) = Tv_i, Eu = 0$ for all $u \in U$ and each v_i .

Hence $\forall v \in V, (\exists! a_i \in \mathbb{F}, u \in \text{null } S \subseteq \text{null } T), Tv = a_1Tv_1 + \dots + a_nTv_n = E(a_1Sv_1 + \dots + a_nSv_n) \square$

CORO: [Req W Finide] Sups $\text{null } S = \text{null } T$. We show \exists inv $E \in \mathcal{L}(W), T = ES$.

Redefine $E \in \mathcal{L}(W)$ by $E(Tv_i) = Sv_i, E(w_j) = x_j$, for each Tv_i and w_j . Where:

Let $B_{\text{range } T} = (Tv_1, \dots, Tv_m), B_W = (Tv_1, \dots, Tv_m, w_1, \dots, w_n), B_U = (v_1, \dots, v_m)$.

Now $V = U \oplus \text{null } T = U \oplus \text{null } S \Rightarrow B_{\text{range } S} = (Sv_1, \dots, Sv_m)$. Let $B'_W = (Sv_1, \dots, Sv_m, x_1, \dots, x_n)$. \square

25 Sups $S, T \in \mathcal{L}(V, W)$, and $\text{range } T \subseteq \text{range } S$. Prove $\exists E \in \mathcal{L}(V), T = SE$.

SOLUS:

Let $V = U \oplus \text{null } S \Rightarrow S|_U : U \rightarrow \text{range } S$ is iso. Becs $(S|_U)^{-1} : \text{range } S \rightarrow U$.

Define $E = (S|_U)^{-1}T = (S|_U)^{-1}|_{\text{range } T}T \in \mathcal{L}(V, U) \subseteq \mathcal{L}(V)$. $\overline{\supseteq \text{range } T}$ □

COMMENT: Let $U_1 = U$. Let $U_2 \oplus \text{null } T = V = U_1 \oplus \text{null } S$.

Let $U_{1\Delta} = \text{range } (S|_{U_1})|_{\text{range } T} \subseteq U_1 = \Delta \oplus U_{1\Delta}$.

OR. Let $U_{1\Delta} = \text{range } E|_{U_2}$. Let $\Delta \oplus \text{range } E|_{U_2} = U_1$.

Thus $U_1 \oplus \text{null } S = U_{1\Delta} \oplus \underbrace{(\Delta \oplus \text{null } S)}_{\text{iso, by (3.D.Tips)}} = U_2 \oplus \text{null } T$.

$$\begin{array}{ccc} U_1 & \xrightarrow{\text{inv}_S} & \text{range } S \\ || & & || \\ \Delta & \xrightarrow{\text{inv}_S} & \text{range } S|_\Delta \\ \oplus & & \oplus \\ U_{1\Delta} & \xrightarrow{\text{inv}_S} & \text{range } T \xleftarrow{\text{inv}_T} U_2 \\ \uparrow & & \downarrow \\ & \xrightarrow{\text{inv } E|_{U_2}} & \end{array}$$

If $\Delta \neq \{0\}$, asum $\exists \text{inv } E \in \mathcal{L}(V)$ re-extended from $E|_{U_2}$ still satisfying $T = SE$,

then let $\Delta \xrightarrow{E^{-1}} \Theta$; $\text{null } S \xrightarrow{E^{-1}} \text{null } T_\Theta$. Now $\Theta \oplus \text{null } T_\Theta = \text{null } T$.

Then $\Theta \xrightarrow{E} \Delta \neq \{0\}$, while $\text{null } S \cap \Delta = \{0\}$. Thus $T|_\Theta = SE|_\Theta \neq 0$, ctradic.

CORO: If $\Delta = \{0\}$, then $U_1 = U_{1\Delta} \Rightarrow \text{range } S = \text{range } T$. 又 $\text{null } S, \text{null } T$ are iso.

By (3.D.3), we can re-extend inje $E|_{U_2} \in \mathcal{L}(U_2, U_1 \oplus \text{null } S)$ to $\text{inv } E \in \mathcal{L}(U_2 \oplus \text{null } T, U_1 \oplus \text{null } S)$.

Thus we have $\Delta \neq \{0\} \iff E|_{U_2} \in \mathcal{L}(U_2, V)$ cannot be re-extended to $\text{inv } E \in \mathcal{L}(V)$ freely.

OR. [Req range T Finide] Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n)$. Then $V = \text{span}(v_1, \dots, v_n) \oplus \text{null } T$.

Let $S(u_i) = Tv_i$ for each Tv_i . Define E by $Ev_i = u_i, Ex = 0$ for all $x \in \text{null } T$ and each v_i . □

COMMENT: [Req V Finide] Note that $\dim U_2 \leq \dim U_1 \implies \dim \text{null } T = p \geq q = \dim \text{null } S$.

Let $B_{\text{null } T} = (x_1, \dots, x_p), B_{\text{null } S} = (y_1, \dots, y_q)$. Redefine $E : v_i \mapsto u_i, x_k \mapsto y_k, x_j \mapsto 0$, for each $i \in \{1, \dots, \dim U_2\}, k \in \{1, \dots, \dim \text{null } S\}, j \in \{\dim \text{null } S + 1, \dots, \dim \text{null } T\}$.

Note that (u_1, \dots, u_n) is liney indep. Let $X = \text{span}(x_1, \dots, x_q) \oplus \text{span}(v_1, \dots, v_n)$.

Now $E|_X$ is inje, but cannot be re-extend to $\text{inv } E \in \mathcal{L}(V)$ without loss of functionality.

CORO: [Req V Finide] If $\text{range } T = \text{range } S$, then $\dim \text{null } T = \dim \text{null } S = p$.

Redefine E by $Ev_i = u_i, Ex_j = y_j$ for each v_i and x_j . Then $E \in \mathcal{L}(V)$ is inv. □

28 Sups $T \in \mathcal{L}(V, W)$. Let $B_{\text{range } T} = (w_1, \dots, w_m)$.

(a) Prove $\exists \varphi_1, \dots, \varphi_m \in \mathcal{L}(V, \mathbf{F})$ suth $\forall v \in V, Tv = \varphi_1(v)w_1 + \dots + \varphi_m(v)w_m$.

(b) [4E 3.F.5] $\forall v \in V, \exists! \varphi_i(v) \in \mathbf{F}, Tv = \varphi_1(v)w_1 + \dots + \varphi_m(v)w_m$.

Thus defining each $\varphi_i : V \rightarrow \mathbf{F}$. Show each $\varphi_i \in \mathcal{L}(V, \mathbf{F})$.

SOLUS: (a) Using TIPS (4). Let each $w_i = Tv_i$. Then (v_1, \dots, v_m) is liney indep.

And $\text{span}(v_1, \dots, v_m) \oplus \text{null } T = V$. Now $\forall v \in V, \exists! a_i \in \mathbf{F}, u \in \text{null } T, v = \sum_{i=1}^m a_i v_i + u$.

Define $\varphi_i \in \mathcal{L}(V, \mathbf{F})$ by $\varphi_i(v_j) = \delta_{ij}, \varphi_i(u) = 0$ for all $u \in \text{null } T$.

Linity: $\forall v, w \in V [\exists! a_i, b_i \in \mathbf{F}], \lambda \in \mathbf{F}, \varphi_i(v + \lambda w) = a_i + \lambda b_i = \varphi(v) + \lambda \varphi(w)$. □

(b) $\sum_{i=1}^m \varphi_i(u + \lambda v)w_i = T(u + \lambda v) = Tu + \lambda Tv = \left(\sum_{i=1}^m \varphi_i(u)w_i\right) + \lambda \left(\sum_{i=1}^m \varphi_i(v)w_i\right)$. □

OR. Using (3.F). Let each $w_i = Tv_i \Rightarrow (v_1, \dots, v_m)$ is liney indep.

Now $\forall v \in V, \exists! a_i \in \mathbf{F}, Tv = a_1 Tv_1 + \dots + a_m Tv_m$. Let $B_{(\text{range } T)'} = (\psi_1, \dots, \psi_m)$.

Then $[T'(\psi_i)](v) = (\psi_i \circ T)(v) = a_i$. Where $T : V \rightarrow \text{range } T; T' : (\text{range } T)' \rightarrow V'$.

Thus each $\varphi_i = \psi_i \circ T = T'(\psi_i) \in V'$. □

29 Sups $\varphi \in \mathcal{L}(V, \mathbf{F})$. Sups $\varphi(u) \neq 0$. Prove $V = \text{null } \varphi \oplus \{au : a \in \mathbf{F}\}$.

SOLUS: Let $B_{\text{range } \varphi} = (\varphi(u))$. Then by TIPS (4), $\text{span}(u) \oplus \text{null } \varphi = V$. □

OR. (a) $v = cu \in \text{null } \varphi \cap \text{span}(u) \Rightarrow c\varphi(u) = 0 \Rightarrow v = 0$. Now $\text{null } \varphi \cap \text{span}(u) = \{0\}$.

(b) $\forall v \in V, v = \left(v - \frac{\varphi(v)}{\varphi(u)}u\right) + \frac{\varphi(v)}{\varphi(u)}u$. Now $V = \text{null } \varphi + \text{span}(u)$. □

30 Sups $\varphi, \beta \in \mathcal{L}(V, \mathbf{F})$ and $\text{null } \varphi = \text{null } \beta = \eta$. Prove $\exists c \in \mathbf{F}, \varphi = c\beta$.

SOLUS: If $\eta = V$, then $\varphi = \beta = 0$, done. Now by Exe (29),

$\varphi(u) \neq 0 \iff V = \text{null } \varphi \oplus \text{span}(u) \iff V = \text{null } \beta \oplus \text{span}(u) \iff \beta(u) \neq 0$.

Note that $\forall v \in V, \exists! u_0 \in \eta, a_v \in \mathbf{F}, v = u_0 + a_v u \mid \text{Let } c = \frac{\varphi(u)}{\beta(u)} \in \mathbf{F} \setminus \{0\}.$
 $\Rightarrow \varphi(u_0 + a_v u) = a_v \varphi(u), \beta(u_0 + a_v u) = a_v \beta(u).$ □

• (4E 3.F.6) Sups $\varphi, \beta \in \mathcal{L}(V, \mathbf{F})$. Prove $\text{null } \beta \subseteq \text{null } \varphi \iff \varphi = c\beta, \exists c \in \mathbf{F}$.

CORO: $\text{null } \varphi = \text{null } \beta \iff \varphi = c\beta, \exists c \in \mathbf{F} \setminus \{0\}$.

SOLUS: Using Exe (29) and (30).

(a) If $\varphi = 0$, then done. Othws, $\text{sups } u \notin \text{null } \varphi \supseteq \text{null } \beta$.

Now $V = \text{null } \varphi \oplus \text{span}(u) = \text{null } \beta \oplus \text{span}(u)$. By [1.C TIPS (2)], $\text{null } \varphi = \text{null } \beta$. Let $c = \frac{\varphi(u)}{\beta(u)}$.

OR. We discuss in two cases. If $\text{null } \beta = \text{null } \varphi$, or if $\varphi = 0$, then done. Othws,

$\exists u' \in \text{null } \varphi \setminus \text{null } \beta, \exists u \notin \text{null } \varphi \supsetneq \text{null } \beta \Rightarrow V = \text{null } \beta \oplus \text{span}(u') = \text{null } \beta \oplus \text{span}(u)$.

$\forall v \in V, v = w + au = w' + bu', \exists! w, w' \in \text{null } \beta \mid \text{Let } c = \frac{a\varphi(u)}{b\beta(u')} \in \mathbf{F} \setminus \{0\}$. Done.
Thus $\varphi(w + au) = a\varphi(u), \beta(w' + bu) = b\beta(u')$.

NOTICE that by (b) below, we have $\text{null } \varphi \subseteq \text{null } \beta$, ctradic the asum.

(b) If $c = 0$, then $\text{null } \varphi = V \supseteq \text{null } \beta$, done. Othws, becs $v \in \text{null } \beta \iff v \in \text{null } \varphi$. □

OR. By Exe (24), $\text{null } \beta \subseteq \text{null } \varphi \iff \exists E \in \mathcal{L}(\mathbf{F}), \varphi = E \circ \beta$. [If E is inv. Then $\text{null } \beta = \text{null } \varphi$.]

Now $\exists E \in \mathcal{L}(\mathbf{F}), \varphi = E \circ \beta \iff \exists c = E(1) \in \mathbf{F}, \varphi = c\beta$. [E is inv $\iff E(1) \neq 0 \iff c \neq 0$.] □

ENDED

• **NOTE FOR Trspose:** [3.F.33] Define $\mathcal{T} : A \rightarrow A^t$. By [3.111], \mathcal{T} is liney. Becs $(A^t)^t = A$.

$\mathcal{T}^2 = I$, $\mathcal{T} = \mathcal{T}^{-1} \Rightarrow \mathcal{T}$ is iso of $\mathbf{F}^{m,n}$ onto $\mathbf{F}^{n,m}$. Define $\mathcal{C}_k : A \rightarrow A_{\cdot,k}$, $\mathcal{R}_j : A \rightarrow A_{j,\cdot}$, $\mathcal{E}_{j,k} : A \rightarrow A_{j,k}$.

Now we show (a) $\mathcal{T}\mathcal{R}_j = \mathcal{C}_j\mathcal{T}$, (b) $\mathcal{T}\mathcal{C}_k = \mathcal{R}_k\mathcal{T}$, and (c) $\mathcal{T}\mathcal{E}_{j,k} = \mathcal{E}_{k,j}\mathcal{T}$.

So that furthermore, $\mathcal{T}\mathcal{C}_k\mathcal{T} = \mathcal{R}_k$, $\mathcal{T}\mathcal{R}_j\mathcal{T} = \mathcal{C}_j$, and $\mathcal{T}\mathcal{E}_{j,k}\mathcal{T} = \mathcal{E}_{k,j}$.

Let $A = \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & \ddots & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} \Rightarrow A^t = \begin{pmatrix} A_{1,1} & \cdots & A_{m,1} \\ \vdots & \ddots & \vdots \\ A_{1,n} & \cdots & A_{m,n} \end{pmatrix}$. Note that $(A_{j,k})^t = A_{j,k} = (A^t)_{k,j}$. Thus (c) holds.
And $(A_{\cdot,k})^t = (A_{1,k} \cdots A_{m,k}) = (A_{k,1}^t \cdots A_{k,m}^t) = (A^t)_{k,\cdot}$.
 \Rightarrow (b) holds. Simlr for (a).

• **NOTE FOR [3.48]:**

$$\underbrace{\begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}}_A \underbrace{\begin{pmatrix} 5 & 6 & 7 \\ 8 & 9 & 10 \end{pmatrix}}_B = \begin{pmatrix} \begin{pmatrix} 1 & 2 \end{pmatrix} \begin{pmatrix} 5 \\ 8 \end{pmatrix} & \begin{pmatrix} 1 & 2 \end{pmatrix} \begin{pmatrix} 6 \\ 9 \end{pmatrix} & \begin{pmatrix} 1 & 2 \end{pmatrix} \begin{pmatrix} 7 \\ 10 \end{pmatrix} \\ \begin{pmatrix} 3 & 4 \end{pmatrix} \begin{pmatrix} 5 \\ 8 \end{pmatrix} & \begin{pmatrix} 3 & 4 \end{pmatrix} \begin{pmatrix} 6 \\ 9 \end{pmatrix} & \begin{pmatrix} 3 & 4 \end{pmatrix} \begin{pmatrix} 7 \\ 10 \end{pmatrix} \end{pmatrix} = \begin{pmatrix} 21 & 24 & 27 \\ 47 & 54 & 61 \end{pmatrix}$$

• **NOTE FOR [3.47]:** $(AC)_{j,k} = \sum_{r=1}^n A_{j,r}C_{r,k} = \sum_{r=1}^n (A_{j,\cdot})_{1,r}(C_{\cdot,k})_{r,1} = (A_{j,\cdot}C_{\cdot,k})_{1,1} = A_{j,\cdot}C_{\cdot,k}$ \square

• **NOTE FOR [3.49]:** $[(AC)_{\cdot,k}]_{j,1} = (AC)_{j,k} = \sum_{r=1}^n A_{j,r}C_{r,k} = \sum_{r=1}^n A_{j,r}(C_{\cdot,k})_{r,1} = (AC_{\cdot,k})_{j,1}$ \square

• **EXE 10:** $[(AC)_{j,\cdot}]_{1,k} = (AC)_{j,k} = \sum_{r=1}^n A_{j,r}C_{r,k} = \sum_{r=1}^n (A_{j,\cdot})_{1,r}C_{r,k} = (A_{j,\cdot}C)_{1,k}$ \square

• **COMMENT:** For [3.49], let $B_U = (u_1, \dots, u_p)$, $B_V = (v_1, \dots, v_n)$, $B_W = (w_1, \dots, w_m)$.

And $C = \mathcal{M}(T, B_U, B_V) \in \mathbf{F}^{n,p}$, $A = \mathcal{M}(S, B_V, B_W) \in \mathbf{F}^{m,n}$.

Then $\mathcal{M}(Tu_k, B_V) = C_{\cdot,k} \Rightarrow \mathcal{M}(S(Tu_k), B_W) = AC_{\cdot,k}$, 又 $\mathcal{M}((ST)(u_k), B_W) = (AC)_{\cdot,k}$ \square

By NOTE FOR Transpose, $(AC)_{j,\cdot} = [((AC)^t)_{\cdot,j}]^t = (C^t(A^t)_{\cdot,j})^t = ((A^t)_{\cdot,j})^t C = A_{j,\cdot}C$ \square

• **NOTE FOR [3.52]:** $A \in \mathbf{F}^{m,n}$, $c \in \mathbf{F}^{n,1} \Rightarrow Ac \in \mathbf{F}^{m,1}$. By [4E 3.51(a)], $(Ac)_{\cdot,1} = c_1A_{\cdot,1} + \cdots + c_nA_{\cdot,n}$ \square

OR. $\because (Ac)_{j,1} = \sum_{r=1}^n A_{j,r}c_{r,1} = [\sum_{r=1}^n (A_{j,\cdot}c_{r,1})]_{1,1} = (c_1A_{\cdot,1} + \cdots + c_nA_{\cdot,n})_{j,1}$

$\therefore Ac = A_{\cdot,\cdot}c_{\cdot,1} = \sum_{r=1}^n A_{\cdot,r}c_{r,1} = c_1A_{\cdot,1} + \cdots + c_nA_{\cdot,n}$ OR. $(Ac)_{j,1} = (Ac)_{j,\cdot} = A_{j,\cdot}c \in \mathbf{F}$. \square

OR. Let $B_V = (v_1, \dots, v_n)$. Now $Ac = \mathcal{M}(Tv, B_W) = \mathcal{M}(T(c_1v_1 + \cdots + c_nv_n)) = c_1A_{\cdot,1} + \cdots + c_nA_{\cdot,n}$. \square

• **EXE 11:** $a \in \mathbf{F}^{1,n}$, $C \in \mathbf{F}^{n,p} \Rightarrow aC \in \mathbf{F}^{1,p}$. By [4E 3.51(b)], $(aC)_{1,\cdot} = a_1C_{1,\cdot} + \cdots + a_nC_{n,\cdot}$. \square

OR. $\because (aC)_{1,k} = \sum_{r=1}^n a_{1,r}C_{r,k} = [\sum_{r=1}^n a_{1,r}(C_{r,\cdot})]_{1,k} = (a_1C_{1,\cdot} + \cdots + a_nC_{n,\cdot})_{1,k}$

$\therefore aC = a_{1,\cdot}C_{\cdot,\cdot} = \sum_{r=1}^n a_{1,r}C_{r,\cdot} = a_1C_{1,\cdot} + \cdots + a_nC_{n,\cdot}$ OR. $(aC)_{1,k} = (aC)_{\cdot,k} = aC_{\cdot,k} \in \mathbf{F}$. \square

OR. $aC = ((aC)^t)^t = (C^ta^t)^t = [a_1^t(C^t)_{\cdot,1} + \cdots + a_n^t(C^t)_{\cdot,n}]^t = a_1C_{1,\cdot} + \cdots + a_nC_{n,\cdot}$. \square

• [4E 3.51] Sups $C \in \mathbf{F}^{m,c}$, $R \in \mathbf{F}^{c,p}$.

[See also NOTE FOR [3.49] and Exe (10).]

(a) For $k = 1, \dots, p$, $(CR)_{\cdot,k} = CR_{\cdot,k} = C_{\cdot,\cdot}R_{\cdot,k} = \sum_{r=1}^c C_{\cdot,r}R_{r,k} = R_{1,k}C_{\cdot,1} + \cdots + R_{c,k}C_{\cdot,c}$

(b) For $j = 1, \dots, m$, $(CR)_{j,\cdot} = C_{j,\cdot}R = C_{j,\cdot}R_{\cdot,\cdot} = \sum_{r=1}^c C_{j,r}R_{r,\cdot} = C_{j,1}R_{1,\cdot} + \cdots + C_{j,c}R_{c,\cdot}$.

• **EXA:** $m = 2, c = 2, p = 3$.

$$(AB)_{\cdot,2} = AB_{\cdot,2} = \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} \begin{pmatrix} 6 \\ 9 \end{pmatrix} = A_{\cdot,1}B_{1,2} + A_{\cdot,2}B_{2,2} = 6 \begin{pmatrix} 1 \\ 3 \end{pmatrix} + 9 \begin{pmatrix} 2 \\ 4 \end{pmatrix} = \begin{pmatrix} 24 \\ 54 \end{pmatrix};$$

$$(AB)_{1,\cdot} = A_{1,\cdot}B = \begin{pmatrix} 1 & 2 \end{pmatrix} \begin{pmatrix} 5 & 6 & 7 \\ 8 & 9 & 10 \end{pmatrix} = A_{1,1}B_{1,\cdot} + A_{1,2}B_{2,\cdot} = 1 \begin{pmatrix} 5 & 6 & 7 \end{pmatrix} + 2 \begin{pmatrix} 8 & 9 & 10 \end{pmatrix} = \begin{pmatrix} 21 & 24 & 27 \end{pmatrix};$$

• **COLUMN-ROW FACTORIZATION (CR Factorization)** Sups $A \in \mathbf{F}^{m,n}, A \neq 0$.

Prove, with p specified below, that $\exists C \in \mathbf{F}^{m,p}, R \in \mathbf{F}^{p,n}, A = CR$.

(a) Sups $S_c = \text{span}(A_{\cdot,1}, \dots, A_{\cdot,n}) \subseteq \mathbf{F}^{m,1}, \dim S_c = c$, the col rank. Let $p = c$.

(b) Sups $S_r = \text{span}(A_{1,\cdot}, \dots, A_{m,\cdot}) \subseteq \mathbf{F}^{1,n}, \dim S_r = r$, the row rank. Let $p = r$.

SOLUS: Using [4E 3.51]. Notice that $A \neq 0 \Rightarrow c, r \geq 1$.

(a) Reduce to bss $B_C = (C_{\cdot,1}, \dots, C_{\cdot,c})$, forming $C \in \mathbf{F}^{m,c}$. Then $\forall k \in \{1, \dots, n\}$,

$$A_{\cdot,k} = R_{1,k}C_{\cdot,1} + \dots + R_{c,k}C_{\cdot,c} = (CR)_{\cdot,k}, \exists! R_{1,k}, \dots, R_{c,k} \in \mathbf{F}, \text{ forming } R \in \mathbf{F}^{c,n}. \text{ Thus } A = CR.$$

(b) Reduce to bss $B_R = (R_{1,\cdot}, \dots, R_{r,\cdot})$, forming $R \in \mathbf{F}^{r,n}$. Then $\forall j \in \{1, \dots, m\}$,

$$A_{j,\cdot} = C_{j,1}R_{1,\cdot} + \dots + C_{j,r}R_{r,\cdot} = (CR)_{j,\cdot}, \exists! C_{j,1}, \dots, C_{j,r} \in \mathbf{F}, \text{ forming } C \in \mathbf{F}^{m,r}. \text{ Thus } A = CR. \quad \square$$

$$\text{EXA: } A = \begin{pmatrix} 10 & 7 & 4 & 1 \\ 26 & 19 & 12 & 5 \\ 46 & 33 & 20 & 7 \end{pmatrix} \xrightarrow{\text{(I)}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 10 & 7 & 4 & 1 \\ 26 & 19 & 12 & 5 \end{pmatrix} \xrightarrow{\text{(II)}} \begin{pmatrix} 7 & 4 \\ 19 & 12 \\ 33 & 20 \end{pmatrix} \begin{pmatrix} 2 & -1 \\ 1 & 0 \\ 0 & 1 \\ -1 & 2 \end{pmatrix}$$

$$\text{(I)} \begin{pmatrix} 46 & 33 & 20 & 7 \end{pmatrix} = 2 \begin{pmatrix} 10 & 7 & 4 & 1 \end{pmatrix} + \begin{pmatrix} 26 & 19 & 12 & 5 \end{pmatrix} = \begin{pmatrix} 2 & 1 \end{pmatrix} \begin{pmatrix} 10 & 7 & 4 & 1 \\ 26 & 19 & 12 & 5 \end{pmatrix}, \text{ using [4E 3.51(b)]}.$$

$$\begin{pmatrix} 46 & 33 & 20 & 7 \end{pmatrix} \in \text{span}(A_{1,\cdot}, A_{2,\cdot}), \text{ and } (A_{1,\cdot}, A_{2,\cdot}) \text{ is liney indep. Thus } B_R = (A_{1,\cdot}, A_{2,\cdot}).$$

$$\text{(II)} \begin{pmatrix} 10 \\ 26 \\ 46 \end{pmatrix} = 2 \begin{pmatrix} 7 \\ 19 \\ 33 \end{pmatrix} - \begin{pmatrix} 4 \\ 12 \\ 20 \end{pmatrix}; \quad \begin{pmatrix} 1 \\ 5 \\ 7 \end{pmatrix} = - \begin{pmatrix} 7 \\ 19 \\ 33 \end{pmatrix} + 2 \begin{pmatrix} 4 \\ 12 \\ 20 \end{pmatrix}. \text{ Thus } B_C = (A_{\cdot,2}, A_{\cdot,3}).$$

• **COLUMN RANK EQUALS ROW RANK** Using nota and result above.

$$\text{For each } A_{j,\cdot} \in S_r, A_{j,\cdot} = (CR)_{j,\cdot} = C_{j,\cdot}R = C_{j,1}R_{1,\cdot} + \dots + C_{j,c}R_{c,\cdot}.$$

$$\text{For each } A_{\cdot,k} \in S_c, A_{\cdot,k} = (CR)_{\cdot,k} = CR_{\cdot,k} = R_{1,k}C_{\cdot,1} + \dots + R_{c,k}C_{\cdot,c}$$

$$\Rightarrow \text{span}(A_{1,\cdot}, \dots, A_{m,\cdot}) = S_r = \text{span}(R_{1,\cdot}, \dots, R_{c,\cdot}) \Rightarrow \dim S_r = r \leq c = \dim S_c.$$

$$\Rightarrow \text{span}(A_{\cdot,1}, \dots, A_{\cdot,m}) = S_c = \text{span}(C_{\cdot,1}, \dots, C_{\cdot,r}) \Rightarrow \dim S_c = c \leq r = \dim S_r.$$

$$\text{OR. Apply the result to } A^t \in \mathbf{F}^{n,m} \Rightarrow \dim S_r^t = \dim S_c = c \leq r = \dim S_r = \dim S_c^t. \quad \square$$

• Sups $A \in \mathbf{F}^{m,n} \setminus \{0\}$. Prove $[P] \text{ rank } A = 1 \iff \exists c_j, d_k \in \mathbf{F}, \text{ each } A_{j,k} = c_j \cdot d_k. [Q]$

SOLUS:

[Using CR Factorization]

$P \Rightarrow Q$: Immediately.

$$Q \Rightarrow P: \text{ Becs } A = \begin{pmatrix} c_1 \\ \vdots \\ c_m \end{pmatrix} \begin{pmatrix} d_1 & \dots & d_n \end{pmatrix} = \begin{pmatrix} c_1 d_1 & \dots & c_1 d_n \\ \vdots & \ddots & \vdots \\ c_m d_1 & \dots & c_m d_n \end{pmatrix} \Rightarrow S_r = \text{span} \left\{ \begin{pmatrix} \underline{c_1} d_1 & \dots & \underline{c_1} d_n \\ \vdots \\ \underline{c_m} d_1 & \dots & \underline{c_m} d_n \end{pmatrix} \right\}.$$

$$\text{OR. } S_c = \text{span} \left\{ \begin{pmatrix} \underline{c_1} d_1 \\ \vdots \\ \underline{c_m} d_1 \end{pmatrix}, \dots, \begin{pmatrix} \underline{c_1} d_n \\ \vdots \\ \underline{c_m} d_n \end{pmatrix} \right\} = \text{span} \left\{ \begin{pmatrix} c_1 \\ \vdots \\ c_m \end{pmatrix} \right\}.$$

□

[Not Using CR Factorization]

$$Q \Rightarrow P: \text{ Using [4E 3.51(a)]. Each } A_{\cdot,k} \in \text{span} \left\{ \begin{pmatrix} c_1 \\ \vdots \\ c_m \end{pmatrix} \right\}. \text{ Then rank } A = \dim S_c \leq 1$$

$$\text{又 } A \neq 0 \Rightarrow \dim S_c \geq 1.$$

$$P \Rightarrow Q: \text{ Becs } \dim S_c = \dim S_r = 1.$$

$$\text{Let } c_j = \frac{A_{j,1}}{A_{1,1}} = \frac{A_{j,2}}{A_{1,2}} = \dots = \frac{A_{j,n}}{A_{1,n}}, \quad d'_k = \frac{A_{1,k}}{A_{1,1}} = \frac{A_{2,k}}{A_{2,1}} = \dots = \frac{A_{m,k}}{A_{m,1}}.$$

$$\Rightarrow A_{j,k} = d'_k A_{j,1} = c_j A_{1,k} = c_j d'_k A_{1,1} = c_j d_k, \text{ where } d_k = d'_k A_{1,1}. \quad \square$$

• **TIPS 1:** Sups $T \in \mathcal{L}(V, W)$, $B_V = (v_1, \dots, v_n)$, $B_W = (w_1, \dots, w_m)$.

Let $L = (Tv_{\alpha_1}, \dots, Tv_{\alpha_k})$, $M = (A_{\cdot, \alpha_1}, \dots, A_{\cdot, \alpha_k})$, where each $\alpha_i \in \{1, \dots, n\}$.

(a) Show $[P]$ L is liney indep $\iff M$ is liney indep. $[Q]$

(b) Show $[P]$ $\text{span } L = W \iff \text{span } M = \mathbf{F}^{m,1}$. $[Q]$ [Let $A = \mathcal{M}(T, B_V, B_W)$.]

SOLUS:

(a) Note that $\mathcal{M}: Tv_k \rightarrow A_{\cdot, k}$ is iso of W onto $\mathbf{F}^{m,1}$. (b) Reduce L to B'_W , M to $B_{\mathbf{F}^{m,1}}$. Simlr. \square

$$\begin{aligned} \text{OR. } c_1Tv_{\alpha_1} + \dots + c_kTv_{\alpha_k} &= c_1(A_{1,\alpha_1}w_1 + \dots + A_{m,\alpha_1}w_m) + \dots + c_k(A_{1,\alpha_k}w_1 + \dots + A_{m,\alpha_k}w_m) \\ &= (c_1A_{1,\alpha_1} + \dots + c_kA_{1,\alpha_k})w_1 + \dots + (c_1A_{m,\alpha_1} + \dots + c_kA_{m,\alpha_k})w_m. \end{aligned}$$

$$\text{And } c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k} = c_1 \begin{pmatrix} A_{1,\alpha_1} \\ \vdots \\ A_{m,\alpha_1} \end{pmatrix} + \dots + c_k \begin{pmatrix} A_{1,\alpha_k} \\ \vdots \\ A_{m,\alpha_k} \end{pmatrix} = \begin{pmatrix} c_1A_{1,\alpha_1} + \dots + c_kA_{1,\alpha_k} \\ \vdots \\ c_1A_{m,\alpha_1} + \dots + c_kA_{m,\alpha_k} \end{pmatrix}.$$

(a) $P \Rightarrow Q$: Sups $c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k} = 0$. Let $v = c_1v_{\alpha_1} + \dots + c_kv_{\alpha_k}$.

Then $Tv = (c_1A_{1,\alpha_1} + \dots + c_kA_{1,\alpha_k})w_1 + \dots + (c_1A_{m,\alpha_1} + \dots + c_kA_{m,\alpha_k})w_m = 0w_1 + \dots + 0w_m$.

Now $c_1Tv_{\alpha_1} + \dots + c_kTv_{\alpha_k} = 0$. Then each $c_i = 0 \Rightarrow M$ liney indep.

$Q \Rightarrow P$: Becs $c_1Tv_{\alpha_1} + \dots + c_kTv_{\alpha_k} = 0$. For each $i \in \{1, \dots, m\}$, $c_1A_{i,\alpha_1} + \dots + c_kA_{i,\alpha_k} = 0$.

Which is equi to $c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k} = 0$. Thus each $c_i = 0 \Rightarrow L$ liney indep.

OR. $\exists A_{\cdot, \alpha_j} = c_1A_{\cdot, \alpha_1} + \dots + c_{j-1}A_{\cdot, \alpha_{j-1}}$

\iff For each $i \in \{1, \dots, m\}$, $A_{i,\alpha_j} = c_1A_{i,\alpha_1} + \dots + c_{j-1}A_{i,\alpha_{j-1}}$

$\iff Tv_{\alpha_j} = A_{1,\alpha_j}w_1 + \dots + A_{m,\alpha_j}w_m$

$= (c_1A_{1,\alpha_1} + \dots + c_{j-1}A_{1,\alpha_{j-1}})w_1 + \dots + (c_1A_{m,\alpha_1} + \dots + c_{j-1}A_{m,\alpha_{j-1}})w_m$

$\iff \exists Tv_{\alpha_j} = c_1Tv_{\alpha_1} + \dots + c_{j-1}Tv_{\alpha_{j-1}}$.

(b) Note that each $\mathcal{M}(Tv_{\alpha_i}) = A_{\cdot, \alpha_i}$

$P \Rightarrow Q$: Sups each $w_i = Iw_i = J_{1,i}Tv_{\alpha_1} + \dots + J_{k,i}Tv_{\alpha_k}$.

$\forall a \in \mathbf{F}^{m,1}, \exists w = a_1w_1 + \dots + a_mw_m \in W$, $a = \mathcal{M}(w, B_W)$.

Becs $w = a_1(J_{1,1}Tv_{\alpha_1} + \dots + J_{k,1}Tv_{\alpha_k}) + \dots + a_m(J_{1,m}Tv_{\alpha_1} + \dots + J_{k,m}Tv_{\alpha_k})$

$= (a_1J_{1,1} + \dots + a_mJ_{1,m})Tv_{\alpha_1} + \dots + (a_1J_{k,1} + \dots + a_mJ_{k,m})Tv_{\alpha_k}$.

Apply \mathcal{M} to both sides, $a = c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k}$, where each $c_i = a_1J_{i,1} + \dots + a_mJ_{i,m}$.

$Q \Rightarrow P$: $\forall w \in W, \exists a = c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k} \in \mathbf{F}^{m,1}$, $\mathcal{M}(w, B_W) = a$

$\Rightarrow w = (c_1A_{1,\alpha_1} + \dots + c_kA_{1,\alpha_k})w_1 + \dots + (c_1A_{m,\alpha_1} + \dots + c_kA_{m,\alpha_k})w_m = c_1Tv_{\alpha_1} + \dots + c_kTv_{\alpha_k}$.

$\neg Q \Rightarrow \neg P$: $\exists w \in W, \exists a \in \mathbf{F}^{m,1}, \mathcal{M}(w, B_W) = a$, but $\nexists c_i \in \mathbf{F}, a = c_1A_{\cdot, \alpha_1} + \dots + c_kA_{\cdot, \alpha_k}$

$\Rightarrow \nexists c_i \in \mathbf{F}, w = c_1Tv_{\alpha_1} + \dots + c_kTv_{\alpha_k}$. \square

CORO: Let $L = (Tv_1, \dots, Tv_n)$, $M = (A_{\cdot, 1}, \dots, A_{\cdot, n})$.

Then (a*) By [3.B.9, TIPS (4)], T is inje $\iff L$ is liney indep, so is M .

And (b*) T is surj $\iff \text{span } L = W \iff \text{span } M = \mathbf{F}^{n,1}$.

CORO: $B_{\mathbf{F}^{n,1}} = (A_{\cdot, 1}, \dots, A_{\cdot, n}) \iff T$ is inje and surj $\iff B_{\mathbf{F}^{1,n}} = (A_{1,\cdot}, \dots, A_{n,\cdot})$.

COMMENT: If T is inv. Then by (a*, c) or (b*, d), we have another proof of CORO.

OR. If $m = n$. Then by [3.118] and one of (a*, b*, c, d). Yet another proof.

(c) T surj $\iff T'$ inje $\iff (T'(\psi_1), \dots, T'(\psi_m))$ liney indep

$\stackrel{(a)}{\iff} ((A^t)_{\cdot, 1}, \dots, (A^t)_{\cdot, m})$ liney indep in $\mathbf{F}^{n,1}$, so is $(A_{1,\cdot}, \dots, A_{m,\cdot})$ in $\mathbf{F}^{1,n}$.

(d) T inje $\iff T'$ surj $\iff V' = \text{span}(T'(\psi_1), \dots, T'(\psi_m))$

$\stackrel{(b)}{\iff} \mathbf{F}^{n,1} = \text{span}((A^t)_{\cdot, 1}, \dots, (A^t)_{\cdot, m}) \iff \mathbf{F}^{1,n} = \text{span}(A_{1,\cdot}, \dots, A_{m,\cdot})$.

• **TIPS2:** Sups p is a poly of n variables in \mathbf{F} . Prove $\mathcal{M}(p(T_1, \dots, T_n)) = p(\mathcal{M}(T_1), \dots, \mathcal{M}(T_n))$.

Where the liney maps T_1, \dots, T_n are suth $p(T_1, \dots, T_n)$ makes sense. See [5.16,17,20].

SOLUS: Sups the poly p is defined by $p(x_1, \dots, x_n) = \sum_{k_1, \dots, k_n} \alpha_{k_1, \dots, k_n} \prod_{i=1}^n x_i^{k_i}$.

Note that $\mathcal{M}(T^x S^y) = \mathcal{M}(T)^x \mathcal{M}(S)^y$; $\mathcal{M}(T^x + S^y) = \mathcal{M}(T)^x + \mathcal{M}(S)^y$.

$$\begin{aligned} \text{Then } \mathcal{M}(p(T_1, \dots, T_n)) &= \mathcal{M}\left(\sum_{k_1, \dots, k_n} \alpha_{k_1, \dots, k_n} \prod_{i=1}^n T_i^{k_i}\right) \\ &= \sum_{k_1, \dots, k_n} \alpha_{k_1, \dots, k_n} \prod_{i=1}^n \mathcal{M}(T_i^{k_i}) = p(\mathcal{M}(T_1), \dots, \mathcal{M}(T_n)). \end{aligned} \quad \square$$

• **CORO:** Sups τ is an algebraic property. Then τ holds for liney maps $\iff \tau$ holds for matrices.

Each $\alpha_k \in \{1, \dots, n\}$. Now $p(T_1, \dots, T_n) = p(T_{\alpha_1}, \dots, T_{\alpha_n})$

$$\iff p(\mathcal{M}(T_1), \dots, \mathcal{M}(T_n)) = p(\mathcal{M}(T_{\alpha_1}), \dots, \mathcal{M}(T_{\alpha_n})).$$

13 Prove the distr holds for matrix add and matrix multi.

Sups A, B, C are matrices suth $A(B + C)$ make sense, we prove the left distr.

SOLUS: Sups $A \in \mathbf{F}^{m,n}$ and $B, C \in \mathbf{F}^{n,p}$.

$$\text{Note that } [A(B + C)]_{j,k} = \sum_{r=1}^n A_{j,r}(B + C)_{r,k} = \sum_{r=1}^n (A_{j,r}B_{r,k} + A_{j,r}C_{r,k}) = (AB + AC)_{j,k}.$$

OR. Define T, S, R suth $\mathcal{M}(T) = A, \mathcal{M}(S) = B, \mathcal{M}(R) = C$.

$$A(B + C) = \mathcal{M}(T(S + R)) \stackrel{[3.9]}{=} \mathcal{M}(TS + TR) = AB + AC.$$

$$\text{OR. } T(S + R) = TS + TR \Rightarrow \mathcal{M}(T(S + R)) = \mathcal{M}(TS + TR) \Rightarrow A(B + C) = AB + AC. \quad \square$$

1 Sups $T \in \mathcal{L}(V, W)$. Show for each pair of B_V and B_W ,

$A = \mathcal{M}(T, B_V, B_W)$ has at least $n = \dim \text{range } T$ nonzero ent.

SOLUS:

Using [3.B TIPS (4)]. Let $U \oplus \text{null } T = V$; $B_U = (v_1, \dots, v_n), B_V = (v_1, \dots, v_m)$.

For each $k \in \{1, \dots, n\}, Tv_k \neq 0 \iff A_{\cdot,k} \neq 0$. Hence every such $A_{\cdot,k}$ has at least one nonzero ent. \square

OR. We prove by ctradic. Sups A has at most $(n - 1)$ nonzero ent.

Then by Pigeon Hole Principle, at least one of $A_{\cdot,1}, \dots, A_{\cdot,n}$ equals 0.

Thus there are at most $(n - 1)$ nonzero vecs in Tv_1, \dots, Tv_n .

$$\curlywedge \text{range } T = \text{span}(Tv_1, \dots, Tv_n) \Rightarrow \dim \text{range } T = \dim \text{span}(Tv_1, \dots, Tv_n) \leq n - 1. \text{ Ctradic.} \quad \square$$

6 Sups V and W are finide and $T \in \mathcal{L}(V, W)$.

Prove $\dim \text{range } T = 1 \iff \exists B_V, B_W$, all ent of $A = \mathcal{M}(T, B_V, B_W)$ equal 1.

SOLUS:

(a) Sups $B_V = (v_1, \dots, v_n), B_W = (w_1, \dots, w_m)$ are the bses suth all ent of A equal 1.

Then $Tv_i = w_1 + \dots + w_m$ for all $i = 1, \dots, n$. Becs w_1, \dots, w_m is liney indep, $w_1 + \dots + w_m \neq 0$.

(b) Sups $\dim \text{range } T = 1$. Then $\dim \text{null } T = \dim V - 1$.

Let $B_{\text{null } T} = (u_2, \dots, u_n)$. Extend to a bss (u_1, u_2, \dots, u_n) of V .

Let $w_1 = Tv_1 - w_2 - \dots - w_m$. Extend to B_W . Let $v_1 = u_1, v_i = u_1 + u_i$. Extend to B_V . \square

OR. Sups $B_{\text{range } T} = (w)$. By [2.C NOTE FOR (15)], $\exists B_W = (w_1, \dots, w_m), w = w_1 + \dots + w_m$.

By [2.C TIPS], \exists a bss (u_1, \dots, u_n) of V suth each $u_k \notin \text{null } T$.

Now each $Tu_k \in \text{range } T = \text{span}(w) \Rightarrow Tu_k = \lambda_k w, \exists \lambda_k \in \mathbf{F} \setminus \{0\}$.

Let $v_k = \lambda_k^{-1} u_k \neq 0$, so that each $Tv_k = w = w_1 + \dots + w_m$. Thus $B_V = (v_1, \dots, v_n)$ will do. \square

3 Sups V and W are finide and $T \in \mathcal{L}(V, W)$. Prove $\exists B_V, B_W$ suth

[letting $A = \mathcal{M}(T, B_V, B_W)$] $A_{k,k} = 1, A_{i,j} = 0$, where $1 \leq k \leq \dim \text{range } T, i \neq j$.

SOLUS: Using [3.B TIPS (4)]. Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n), B_V = (v_1, \dots, v_n, u_1, \dots, u_m)$. □

COMMENT: Let each $Tv_k = w_k$. Extend $B_{\text{range } T}$ to $B_W = (w_1, \dots, w_n, \dots, w_p)$. See [3.D NOTE FOR [3.60]].

4 Sups $B_V = (v_1, \dots, v_m)$ and W is finide. Sups $T \in \mathcal{L}(V, W)$.

Prove $\exists B_W = (w_1, \dots, w_n), \mathcal{M}(T, B_V, B_W)_{1,1} = (1 \ 0 \ \dots \ 0)^t$ or $(0 \ \dots \ 0)^t$.

SOLUS: If $Tv_1 = 0$, then done. If not then extend (Tv_1) to B_W . □

5 Sups $B_W = (w_1, \dots, w_n)$ and V is finide. Sups $T \in \mathcal{L}(V, W)$.

Prove $\exists B_V = (v_1, \dots, v_m), \mathcal{M}(T, B_V, B_W)_{1,1} = (0 \ \dots \ 0)$ or $(1 \ 0 \ \dots \ 0)$.

SOLUS:

Let (u_1, \dots, u_n) be a bss of V . Denote $\mathcal{M}(T, (u_1, \dots, u_n), B_W)$ by A .

If $A_{1,1} = 0$, then $B_V = (u_1, \dots, u_n)$ and done. Othws, sups $A_{1,k} \neq 0$.

Let $v_1 = \frac{u_k}{A_{1,k}} \Rightarrow Tv_1 = 1w_1 + \frac{A_{2,k}}{A_{1,k}}w_2 + \dots + \frac{A_{n,k}}{A_{1,k}}w_n$. $\left| \begin{array}{l} \text{Let } v_j = u_{j-1} - A_{1,j-1}v_1 \text{ for each } j \in \{2, \dots, k\}. \\ \text{Let } v_i = u_i - A_{1,i}v_1 \text{ for } i \in \{k+1, \dots, n\}. \end{array} \right.$

NOTICE that $Tu_i = A_{1,i}w_1 + \dots + A_{n,i}w_n$. 又 Each $u_i \in \text{span}(v_1, \dots, v_n) = V$. Let $B_V = (v_1, \dots, v_n)$. □

OR. Using Exe (4). Let B_W be the B_V .

Now $\exists B_V$, suth $\mathcal{M}(T', B_W, B_V)_{1,1} = (1 \ 0 \ \dots \ 0)^t$ or $(0 \ \dots \ 0)^t$.

Which is equiv to $\exists B_V$ [Using (3.F.31)] suth $\mathcal{M}(T, B_V, B_W)_{1,1} = (1 \ 0 \ \dots \ 0)$ or $(0 \ \dots \ 0)$. □

ENDED

3.D

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2 Sups V is finide and $\dim V > 1$.

Prove the set U of non-inv optors on V is not a subsp of $\mathcal{L}(V)$.

The set of inv optors is not either. Although multi id/inv, and commu for vec multi hold.

SOLUS: Let $B_V = (v_1, \dots, v_n)$. [If $\dim V = 1$, then $U = \{0\}$ is a subsp of $\mathcal{L}(V)$.]

Define $S, T \in \mathcal{L}(V)$ by $S(a_1v_1 + \dots + a_nv_n) = a_1v_1, T(a_1v_1 + \dots + a_nv_n) = a_2v_1 + \dots + a_nv_n$.

Hence $S, T \in U$ while $S + T \notin U$. □

• **TIPS:** Sups $U \oplus X = W \oplus Y$, and X, Y are iso. Prove U, W are iso.

SOLUS: Let ζ be an iso of X onto Y . That is, $\forall y \in Y, \exists! x \in X, \zeta(x) = y$.

$\forall u \in U, \exists! w \in W, y \in Y, u = w + y \Rightarrow \exists! x \in X, u = w + \zeta(x)$. Define $\pi : u \mapsto w$.

Now sups $u_1, u_2 \in U$, then each $u_i = w_i + \zeta(x_i), \exists! w_i \in W, x_i \in X$.

Linity: $\forall, \lambda \in \mathbb{F}, \pi(u_1 + \lambda u_2) = w_1 + \lambda w_2 = \pi(u_1) + \lambda \pi(u_2)$.

Inje: $\pi(u_1) = \pi(u_2) \Rightarrow w_1 = w_2 \Rightarrow \zeta(x_1) = \zeta(x_2) \Rightarrow x_1 = x_2 \Rightarrow u_1 = u_2$.

Surj: $\forall w \in W, \pi(w) = w \in \text{range } \pi$. Thus π is iso of U onto W . □

3 Sups V and W are iso, U is a subsp of V , and $S \in \mathcal{L}(U, W)$.

Prove $\exists \text{ inv } T \in \mathcal{L}(V, W), Tu = Su, \forall u \in U \iff S \text{ is inje.}$

[See also (3.A.11).]

SOLUS: (a) $\forall u \in U, u = T^{-1}Su \Rightarrow T^{-1}S = I \in \mathcal{L}(U) \implies S \text{ is inje, by (3.B.20).}$

OR. $\text{null } S = \text{null } T|_U = \text{null } T \cap U = \{0\}.$

(b) Let $X \oplus U = V$. Becs $S : U \rightarrow W$ is inje. By (3.B.12), $S : U \rightarrow \text{range } S$ is iso.

Let $Y \oplus \text{range } S = W$. Then by TIPS, X and Y are iso. Let $E : X \rightarrow Y$ be an iso.

Define $T \in \mathcal{L}(V, W)$ by $Tu = Su, Tw = Ew$ for all $u \in U, w \in X$.

OR. [Req V Finide] Let $B_U = (u_1, \dots, u_m)$. Then $S \text{ inje} \Rightarrow (Su_1, \dots, Su_m)$ liney indep.

Extend to $B_V = (u_1, \dots, u_m, v_1, \dots, v_n), B_W = (Su_1, \dots, Su_m, w_1, \dots, w_n)$.

Define $T \in \mathcal{L}(V, W)$ by $T(u_i) = Su_i, Tv_j = w_j$, for each u_i and v_j . □

8 Sups $T \in \mathcal{L}(V, W)$ is **surj**. Prove $\exists \text{ subsp } U \text{ of } V, T|_U : U \rightarrow W \text{ is iso.}$

SOLUS: By (3.B.12). Note that $\text{range } T = W$. OR. [Req $\text{range } T$ Finide] By [3.B TIPS (4)]. □

18 Show V and $\mathcal{L}(\mathbf{F}, V)$ are iso vecsps.

SOLUS:

Define $\Psi \in \mathcal{L}(V, \mathcal{L}(\mathbf{F}, V))$ by $\Psi(v) = \Psi_v$; where $\Psi_v \in \mathcal{L}(\mathbf{F}, V)$ and $\Psi_v(\lambda) = \lambda v$.

(a) $\Psi(v) = \Psi_v = 0 \Rightarrow \forall \lambda \in \mathbf{F}, \Psi_v(\lambda) = \lambda v = 0 \Rightarrow v = 0$. Hence Ψ is inje.

(b) $\forall T \in \mathcal{L}(\mathbf{F}, V)$, let $v = T(1) \Rightarrow T(\lambda) = \lambda v = \Psi_v(\lambda), \forall \lambda \in \mathbf{F} \Rightarrow T = \Psi(T(1))$. Hence Ψ is surj. □

OR. Define $\Phi \in \mathcal{L}(\mathcal{L}(\mathbf{F}, V), V)$ by $\Phi(T) = T(1)$.

(a) Sups $\Phi(T) = 0 = T(1) = \lambda T(1) = T(\lambda), \forall \lambda \in \mathbf{F} \Rightarrow T = 0$. Thus Φ is inje.

(b) For any $v \in V$, define $T \in \mathcal{L}(\mathbf{F}, V)$ by $T(\lambda) = \lambda v$. Then $\Phi(T) = T(1) = v$. Thus Φ is surj. □

COMMENT: $\Phi = \Psi^{-1}$.

• Sups $S, T \in \mathcal{L}(V, W)$.

[For Exe (4) and (5), see the CORO in (3.B.24, 25).]

6 Sups V and W are finide. $\dim \text{null } S = \dim \text{null } T = n$.

Prove $S = E_2 T E_1, \exists \text{ inv } E_1 \in \mathcal{L}(V), E_2 \in \mathcal{L}(W)$.

SOLUS: Define $E_1 : v_i \mapsto r_i; u_j \mapsto s_j$; for each $i \in \{1, \dots, m\}, j \in \{1, \dots, n\}$.

Define $E_2 : Tv_i \mapsto Sr_i; x_j \mapsto y_j$; for each $i \in \{1, \dots, m\}, j \in \{1, \dots, n\}$. Where:

$$\left| \begin{array}{l} \text{Let } B_{\text{range } T} = (Tv_1, \dots, Tv_m); B_{\text{range } S} = (Sr_1, \dots, Sr_m). \\ \text{Let } B_W = (Tv_1, \dots, Tv_m, x_1, \dots, x_p); B'_W = (Sr_1, \dots, Sr_m, y_1, \dots, y_p). \\ \text{Let } B_{\text{null } T} = (u_1, \dots, u_n); B_{\text{null } S} = (s_1, \dots, s_n). \\ \text{Thus } B_V = (v_1, \dots, v_m, u_1, \dots, u_n); B'_V = (r_1, \dots, r_m, s_1, \dots, s_n). \end{array} \right| \begin{array}{l} \therefore E_1, E_2 \text{ are inv} \\ \text{and } S = E_2 T E_1. \end{array} \quad \square$$

• (a) Sups $T = ES$ and $E \in \mathcal{L}(W)$ is inv. Prove $\text{null } S = \text{null } T$.

(b) Sups $T = SE$ and $E \in \mathcal{L}(V)$ is inv. Prove $\text{range } S = \text{range } T$.

(c) Sups $T = E_2 S E_1$ and $E_1 \in \mathcal{L}(V), E_2 \in \mathcal{L}(W)$ are inv.

Prove $\dim \text{null } S = \dim \text{null } T$.

SOLUS: (a) $v \in \text{null } T \iff Tv = 0 = E(Sv) \iff Sv = 0 \iff v \in \text{null } S$.

(b) $w \in \text{range } T \iff \exists v \in V, Tv = S(Ev) \iff \exists u \in V, w = Su \iff w \in \text{range } S$.

(c) Using (3.B.22). $\dim \text{null } E_2 S E_1 \xrightarrow{E_2}_{\text{inv}} \dim \text{null } S E_1 \xrightarrow{E_1}_{\text{inv}} \dim \text{null } S = \dim \text{null } T$. □

• **NOTE FOR [3.69]:** Sups V, W are finide and iso, $T \in \mathcal{L}(V, W)$. Then $T \text{ inv} \iff \text{inje} \iff \text{surj}$.

9 [OR 1] Sups U, V, W are iso and finide, $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$.

Prove ST is inv $\iff S, T$ are inv.

COMMENT: If any two of U, V, W are not iso or finide, then S, T are inv $\implies ST$ is inv.

SOLUS: Sups S, T are inv. Then $(ST)(T^{-1}S^{-1}) = I_W, (T^{-1}S^{-1})(ST) = I_U$. Hence ST is inv.

Sups ST is inv. Let $R = (ST)^{-1} \Rightarrow R(ST) = I_U, (ST)R = I_W$.

$Tv = 0 \Rightarrow v = R(ST)v = RS(Tv) = 0.$ $\left| \begin{array}{l} T \text{ is inje, } S \text{ is surj.} \\ \forall v \in V, v = (ST)Rv = S(TRv) \in \text{range } S. \end{array} \right. \quad \begin{array}{l} \text{ } \\ \text{ } \end{array}$

$\forall v \in V, v = (ST)Rv = S(TRv) \in \text{range } S.$ $\left| \begin{array}{l} \text{ } \\ \text{ } \end{array} \right. \quad \begin{array}{l} \text{ } \\ \text{ } \end{array}$

OR. By (3.B.23), $\dim W = \dim \text{range } ST \leq \min\{\text{range } S, \text{range } T\} \Rightarrow S, T$ are surj. □

13 Sups U, V, W, X are iso and finide, $R \in \mathcal{L}(W, X), S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$.

Sups RST is surj. Prove S is inje.

SOLUS: Using Exe (9). Notice that U, X are finide, so that RST is inv.

Let $X = (RST)^{-1} \left\{ \begin{array}{l} Tv = 0 \Rightarrow v = X(RSTv) = 0 \Rightarrow T \text{ is inje.} \\ \forall v \in V, v = (RST)Xv \in \text{range } R \Rightarrow R \text{ is surj.} \end{array} \right\} \Rightarrow S = R^{-1}(RST)T^{-1}.$ □

OR. $(RST)^{-1} = ((RS)T)^{-1} = T^{-1}(RS)^{-1} = T^{-1}S^{-1}R^{-1}.$ □

10 Sups V is finide and $S, T \in \mathcal{L}(V)$. Prove $ST = I \iff TS = I$.

SOLUS: (a) Sups $ST = I$.

By (3.B 20, 21)(a), $ST = I \Rightarrow T$ is inje and S is surj. $\text{ } \forall V$ is finide. S, T are inv.

OR. By Exe (9), V is finide and $ST = I$ is inv $\Rightarrow S, T$ are inv.

Then $\forall v \in V, S((TS)v) = ST(Sv) = Sv \Rightarrow (TS)v = v \Rightarrow TS = I$.

OR. $S^{-1} = T \text{ } \forall S = S \Rightarrow TS = S^{-1}S = I$.

(b) Reversing the roles of S and T , we conclude that $TS = I \Rightarrow ST = I$. □

11 Sups V is finide, $S, T, U \in \mathcal{L}(V)$ and $STU = I$. Show T is inv and $T^{-1} = US$.

SOLUS: Using Exe (9) and (10). This result can fail without the hypo that V is finide.

$(ST)U = U(ST) = (US)T = I \Rightarrow T^{-1} = US$.

OR. $(ST)U = S(TU) = I \Rightarrow U, S$ are inv $\Rightarrow TU = S^{-1}$. $\text{ } \forall U^{-1} = U^{-1} \Rightarrow T = S^{-1}U^{-1}.$ □

EXA: $V = \mathbb{R}^\infty, S(a_1, a_2, \dots) = (a_2, \dots); T(a_1, \dots) = (0, a_1, \dots); U = I \Rightarrow STU = I$ but T is not inv.

• (4E 3) $T \in \mathcal{L}(V) \left| \begin{array}{l} (Tv_1, \dots, Tv_n) \text{ is a bss of } V \text{ for some bss } (v_1, \dots, v_n) \text{ of } V \iff T \text{ is surj} \\ (Tv_1, \dots, Tv_n) \text{ is a bss of } V \text{ for every bss } (v_1, \dots, v_n) \text{ of } V \iff T \text{ is inje} \end{array} \right\} \iff T \text{ is inv.}$

• (4E 15) Sups $T \in \mathcal{L}(V)$ and $V = \text{span}(Tv_1, \dots, Tv_m)$. Prove $V = \text{span}(v_1, \dots, v_m)$.

SOLUS: Becs $V = \text{span}(Tv_1, \dots, Tv_m) \Rightarrow T$ is surj, and therefore is inv $\Rightarrow T^{-1}$ is inv.

$\forall v \in V, \exists a_i \in \mathbb{F}, v = \sum_{i=1}^m a_i Tv_i \Rightarrow T^{-1}v = \sum_{i=1}^m a_i v_i \Rightarrow \text{range } T^{-1} \subseteq \text{span}(v_1, \dots, v_m).$

OR. Reduce the spanning list (Tv_1, \dots, Tv_m) of V to a bss $(Tv_{\alpha_1}, \dots, Tv_{\alpha_k})$ of V .

Where $k = \dim V$ and each $\alpha_i \in \{1, \dots, m\}$. Then by Exe (4E 3),

$(v_{\alpha_1}, \dots, v_{\alpha_k})$ is also a bss of V , contained in the list (v_1, \dots, v_m) . □

15 Prove every liney map from $\mathbf{F}^{n,1}$ to $\mathbf{F}^{m,1}$ is given by a matrix multi.

In other words, prove if $T \in \mathcal{L}(\mathbf{F}^{n,1}, \mathbf{F}^{m,1})$, then $\exists A \in \mathbf{F}^{m,n}, Tx = Ax, \forall x \in \mathbf{F}^{n,1}$.

SOLUS: Let $B_1 = (E_1, \dots, E_n), B_2 = (R_1, \dots, R_m)$ be std bses of $\mathbf{F}^{n,1}, \mathbf{F}^{m,1}$.

$$\forall k = 1, \dots, n, T(E_k) = A_{1,k}R_1 + \dots + A_{m,k}R_m, \exists A_{j,k} \in \mathbf{F}, \text{ forming } A = \begin{pmatrix} A_{1,1} & \dots & A_{1,n} \\ \vdots & \ddots & \vdots \\ A_{m,1} & \dots & A_{m,n} \end{pmatrix}.$$

OR. Let $A = \mathcal{M}(T, B_1, B_2)$. Note that $\mathcal{M}(x, B_1) = x, \mathcal{M}(Tx, B_2) = Tx$.

Hence $Tx = \mathcal{M}(Tx, B_2) = \mathcal{M}(T, B_1, B_2)\mathcal{M}(x, B_1) = Ax$, by [3.65]. □

• **NOTE FOR [3.62]:** $\mathcal{M}(v) = \mathcal{M}(I, (v), B_V)$. Where I is the id optor restr to $\text{span}(v)$.

• **NOTE FOR [3.65]:** $\mathcal{M}(Tv) = \mathcal{M}(I, (Tv), B_W) = \mathcal{M}(T, B_V, B_W)\mathcal{M}(I, (v), B_V) = \mathcal{M}(T, (v), B_W)$.

If $v = 0$, then $\text{span}(v) = \text{span}(\)$, we replace (v) by $B = (\)$; simlr for $Tv = 0$.

• (4E 23, OR 10.A.4) Sups that $(\beta_1, \dots, \beta_n)$ and $(\alpha_1, \dots, \alpha_n)$ are bses of V .

Let $T \in \mathcal{L}(V)$ be suth each $T\alpha_k = \beta_k$. Prove $\mathcal{M}(T, \alpha \rightarrow \alpha) = \mathcal{M}(I, \beta \rightarrow \alpha)$.

For ease of nota, let $\mathcal{M}(T, \alpha \rightarrow \beta) = \mathcal{M}(T, (\alpha_1, \dots, \alpha_n), (\beta_1, \dots, \beta_n))$.

SOLUS:

Denote $\mathcal{M}(T, \alpha \rightarrow \alpha)$ by A and $\mathcal{M}(I, \beta \rightarrow \alpha)$ by B .

$$\forall k \in \{1, \dots, n\}, I\beta_k = \beta_k = B_{1,k}\alpha_1 + \dots + B_{n,k}\alpha_n = Tv_k = A_{1,k}\alpha_1 + \dots + A_{n,k}\alpha_n \Rightarrow A = B. \quad \square$$

OR. Note that $\mathcal{M}(T, \alpha \rightarrow \beta) = I$. Hence $\mathcal{M}(T, \alpha \rightarrow \alpha) = \mathcal{M}(I, \beta \rightarrow \alpha) \underbrace{\mathcal{M}(T, \alpha \rightarrow \beta)}_{=\mathcal{M}(I, \beta \rightarrow \beta)} = \mathcal{M}(I, \beta \rightarrow \alpha)$. □

OR. Note that $\mathcal{M}(T, \beta \rightarrow \beta)\mathcal{M}(I, \alpha \rightarrow \beta) = \mathcal{M}(T, \alpha \rightarrow \beta) = I$.

$$\mathcal{M}(T, \alpha \rightarrow \alpha) = \mathcal{M}(I, \alpha \rightarrow \beta)^{-1} \left(\underbrace{\mathcal{M}(T, \beta \rightarrow \beta)\mathcal{M}(I, \alpha \rightarrow \beta)}_{=\mathcal{M}(T, \alpha \rightarrow \beta)} \right) = \mathcal{M}(I, \beta \rightarrow \alpha). \quad \square$$

COMMENT: Let $A' = \mathcal{M}(T, \beta \rightarrow \beta)$.

$$\beta_k = I\beta_k = B_{1,k}\alpha_1 + \dots + B_{n,k}\alpha_n, \forall k \in \{1, \dots, n\}.$$

$$\text{又 } T\beta_k = T(B_{1,k}\alpha_1 + \dots + B_{n,k}\alpha_n) = A'_{1,k}\beta_1 + \dots + A'_{n,k}\beta_n \Rightarrow A' = B.$$

$$\text{OR. } \mathcal{M}(T, \beta \rightarrow \beta) = \mathcal{M}(T, \alpha \rightarrow \beta)\mathcal{M}(I, \beta \rightarrow \alpha) = B.$$

• **TIPS:** When using \mathcal{M}^{-1} , you must first declare bses and the purpose for using \mathcal{M}^{-1} .

That is, to declare $B_U, B_V, B_W, \mathcal{M}: \mathcal{L}(V, W) \mapsto \mathbf{F}^{m,n}$, or $\mathcal{M}: v \mapsto \mathbf{F}^{n,1}$.

So that $\mathcal{M}^{-1}(AC, B_U, B_W) = \mathcal{M}^{-1}(A, B_V, B_W)\mathcal{M}^{-1}(C, B_U, B_V)$;

Or $\mathcal{M}^{-1}(Ax, B_W) = \mathcal{M}^{-1}(A, B_V, B_W)\mathcal{M}^{-1}(x, B_V)$. Where everything is well-defined.

• (4E 22, OR 10.A.1) Sups $T \in \mathcal{L}(V)$. Prove $\mathcal{M}(T, B_V)$ is inv $\iff T$ itself is inv.

SOLUS: Notice that $\mathcal{M}: T \mapsto \mathcal{M}(T, B_V)$ is iso. And that $\mathcal{M}(T)\mathcal{M}(S) = \mathcal{M}(TS)$.

$$(a) T^{-1}T = TT^{-1} = I \Rightarrow \mathcal{M}(T^{-1})\mathcal{M}(T) = \mathcal{M}(I) = \mathcal{M}(T)\mathcal{M}(T^{-1}) \Rightarrow \mathcal{M}(T^{-1}) = \mathcal{M}(T)^{-1}.$$

$$(b) \mathcal{M}(T)\mathcal{M}(T)^{-1} = \mathcal{M}(T)^{-1}\mathcal{M}(T) = I, \exists! S \in \mathcal{L}(V) \text{ suth } \mathcal{M}(T)^{-1} = \mathcal{M}(S)$$

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

$$\Rightarrow \mathcal{M}^{-1}\mathcal{M}(TS) = \mathcal{M}^{-1}\mathcal{M}(ST) = I = TS = ST \Rightarrow S = T^{-1}. \quad \square$$

• (4E 24, OR 10.A.2) Sups $A, B \in \mathbf{F}^{n,n}$. Prove $AB = I \iff BA = I$.

[Using Exe (10, 15).]

SOLUS: Define $T, S \in \mathcal{L}(\mathbf{F}^{n,1})$ by $Tx = Ax, Sx = Bx$ for all $x \in \mathbf{F}^{n,1}$. Now $\mathcal{M}(T) = A, \mathcal{M}(S) = B$.

$$AB = I \iff A(Bx) = x \iff T(Sx) = x \iff TS = I \iff ST = I \iff \mathcal{M}(S)\mathcal{M}(T) = BA = I.$$

$$\text{OR. Becs } \mathcal{M}: \mathcal{L}(\mathbf{F}^{n,1}, \mathbf{F}^{n,1}) \rightarrow \mathbf{F}^{n,n} \text{ is iso. } \mathcal{M}^{-1}(AB) = TS = ST = \mathcal{M}^{-1}(BA) = I. \quad \square$$

• **NOTE FOR [3.60]:** $\text{Sups } B_V = (v_1, \dots, v_n)$, $B_W = (w_1, \dots, w_m)$.

Define $E_{ij} \in \mathcal{L}(V, W)$ by $E_{ij}(v_x) = \delta_{i,x} w_j$. **CORO:** $E_{l,k} E_{i,j} = \delta_{j,l} E_{i,k}$.

Denote $\mathcal{M}(E_{ij})$ by $\mathcal{E}^{(j,i)}$. And $(\mathcal{E}^{(j,i)})_{l,k} = \begin{cases} 1, & \text{if } (i,j) = (l,k); \\ 0, & \text{othws.} \end{cases}$

NOTICE that $\mathcal{M}: \mathcal{L}(V, W) \rightarrow \mathbf{F}^{m,n}$ is iso. And $E_{ij} = \mathcal{M}^{-1} \mathcal{E}^{(j,i)}$.

$$\text{Thus } A = \begin{pmatrix} A_{1,1}\mathcal{E}^{(1,1)} + \dots + A_{1,n}\mathcal{E}^{(1,n)} \\ + & \dots & + \\ \vdots & \ddots & \vdots \\ + & \dots & + \\ A_{m,1}\mathcal{E}^{(m,1)} + \dots + A_{m,n}\mathcal{E}^{(m,n)} \end{pmatrix} \Longleftrightarrow \begin{pmatrix} A_{1,1}E_{1,1} + \dots + A_{1,n}E_{n,1} \\ + & \dots & + \\ \vdots & \ddots & \vdots \\ + & \dots & + \\ A_{m,1}E_{1,m} + \dots + A_{m,n}E_{n,m} \end{pmatrix} = T.$$

$$\text{By [2.42] and [3.61], } B_{\mathcal{L}(V,W)} = \begin{pmatrix} E_{1,1}, & \dots, & E_{n,1}, \\ \vdots & & \vdots \\ E_{1,m}, & \dots, & E_{n,m} \end{pmatrix}; \quad B_{\mathbf{F}^{m,n}} = \begin{pmatrix} \mathcal{E}^{(1,1)}, & \dots, & \mathcal{E}^{(1,n)}, \\ \vdots & & \vdots \\ \mathcal{E}^{(m,1)}, & \dots, & \mathcal{E}^{(m,n)} \end{pmatrix}.$$

• **TIPS:** Let $B_{\text{range } T} = (Tv_1, \dots, Tv_p)$, $B_V = (v_1, \dots, v_p, \dots, v_n)$. Let each $w_k = Tv_k$; $B_W = (w_1, \dots, w_p, \dots, w_m)$.

Then $T = E_{1,1} + \dots + E_{p,p}$, $\mathcal{M}(T, B_V, B_W) = \mathcal{E}^{(1,1)} + \dots + \mathcal{E}^{(p,p)}$.

17 *Sups V is finide. Show the only two-sided ideals of $\mathcal{L}(V)$ are $\{0\}$ and $\mathcal{L}(V)$.*

A subsp \mathcal{E} of $\mathcal{L}(V)$ is called a two-sided ideal of $\mathcal{L}(V)$ if $TE \in \mathcal{E}, ET \in \mathcal{E}, \forall E \in \mathcal{E}, T \in \mathcal{L}(V)$.

SOLUS: [See also in (3.A).] Using NOTE FOR [3.60].

Let $B_V = (v_1, \dots, v_n)$. If $\mathcal{E} = 0$, then done. Sups $\mathcal{E} \neq 0$ and \mathcal{E} is a two-sided ideal of $\mathcal{L}(V)$.

Then $\forall E_{ij} \in \mathcal{E}$, by asum, $\forall x, y \in \{1, \dots, n\}, E_{j,x} E_{i,j} = E_{i,x} \in \mathcal{E}, E_{i,j} E_{y,i} = E_{y,j} \in \mathcal{E}$.

Again, $\forall x, x', y, y' \in \{1, \dots, n\}, E_{y,x'}, E_{y',x} \in \mathcal{E}$. Thus $\mathcal{E} = \mathcal{L}(V)$. □

• (4E 10) *Sups V, W are finide, U is a subsp of V .*

Let $\mathcal{E} = \{T \in \mathcal{L}(V, W) : U \subseteq \text{null } T\} = \{T \in \mathcal{L}(V, W) : T|_U = 0\}$.

(a) Show \mathcal{E} is a subsp of $\mathcal{L}(V, W)$.

(b) Find a formula for $\dim \mathcal{E}$ in terms of $\dim V$, $\dim W$ and $\dim U$.

Hint: Define $\Phi: \mathcal{L}(V, W) \rightarrow \mathcal{L}(U, W)$ by $\Phi(T) = T|_U$. What is $\text{null } \Phi$? What is $\text{range } \Phi$?

SOLUS:

(a) $\forall S, T \in \mathcal{E}, \lambda \in \mathbf{F}, \forall u \in U, Su = \lambda Tu = (S + \lambda T)u = 0 \Rightarrow (S + \lambda T) \in \mathcal{E}$.

(b) Define Φ as in the hint. Φ is liney, by [3.A NOTE FOR Restriction].

$\Phi(T) = 0 \iff \forall u \in U, Tu = 0 \iff T \in \mathcal{E}$. Thus $\text{null } \Phi = \mathcal{E}$.

Extend $S \in \mathcal{L}(U, W)$ to $T \in \mathcal{L}(V, W) \Rightarrow \Phi(T) = S \in \text{range } \Phi$. Thus $\text{range } \Phi = \mathcal{L}(U, W)$.

Thus $\dim \text{null } \Phi = \dim \mathcal{E} = \dim \mathcal{L}(V, W) - \dim \text{range } \Phi = (\dim V - \dim U) \dim W$. □

OR. Let $B_U = (u_1, \dots, u_m)$, $B_V = (u_1, \dots, u_m, v_1, \dots, v_n)$. Let $p = \dim W$. [See NOTE FOR [3.60].]

$$\forall T \in \mathcal{E}, k \in \{1, \dots, m\}, TE_{k,k} = 0 \Rightarrow \text{span} \left\{ \begin{matrix} E_{1,1}, & \dots, & E_{m,1}, \\ \vdots & & \vdots \\ E'_{1,p}, & \dots, & E'_{m,p} \end{matrix} \right\} \cap \mathcal{E} = \{0\}.$$

$$\text{又 } W = \text{span} \left\{ \begin{matrix} E_{m+1,1}, & \dots, & E_{n,1}, \\ \vdots & & \vdots \\ E_{m+1,p}, & \dots, & E_{n,p} \end{matrix} \right\} \subseteq \mathcal{E}.$$

Denote it by R

Where $\mathcal{L}(V, W) = R \oplus W \Rightarrow \mathcal{L}(V, W) = R + \mathcal{E}$.

Then $\dim \mathcal{E} = \dim \mathcal{L}(V, W) - \dim R - \dim(R \cap \mathcal{E}) = (\dim V - \dim U) \dim W$. □

• (4E 17) Sups V is finite and $S \in \mathcal{L}(V)$. Define $\mathcal{A} \in \mathcal{L}(\mathcal{L}(V))$ by $\mathcal{A}(T) = ST$.

(a) Show $\dim \text{null } \mathcal{A} = (\dim V)(\dim \text{null } S)$.

(b) Show $\dim \text{range } \mathcal{A} = (\dim V)(\dim \text{range } S)$.

SOLUS: (a) $\forall T \in \mathcal{L}(V), ST = 0 \iff \text{range } T \subseteq \text{null } S$.

Thus $\text{null } \mathcal{A} = \{T \in \mathcal{L}(V) : \text{range } T \subseteq \text{null } S\} = \mathcal{L}(V, \text{null } S)$.

(b) $\forall R \in \mathcal{L}(V), \text{range } R \subseteq \text{range } S \iff \exists T \in \mathcal{L}(V), R = ST$, by (3.B 25).

Thus $\text{range } \mathcal{A} = \{R \in \mathcal{L}(V) : \text{range } R \subseteq \text{range } S\} = \mathcal{L}(V, \text{range } S)$. \square

OR. Using NOTE FOR [3.60]. Let $B_{\text{range } S} = (\overline{w_1}, \dots, \overline{w_m})$, $B_U = (v_1, \dots, v_m)$.

Let $(w_1, \dots, w_n), (v_1, \dots, v_n)$ be bses of V . Now $S = E_{1,1} + \dots + E_{m,m}$. $\mathcal{M}(S, v \rightarrow w) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$.

Define $R_{i,j} \in \mathcal{L}(V)$ by $R_{i,j} : w_x \mapsto \delta_{i,x} v_i$. Let $E_{j,k} R_{i,j} = Q_{i,k}$, $R_{j,k} E_{i,j} = G_{i,k}$.

Where $E_{i,k} : v_x \mapsto \delta_{i,x} w_k$, $Q_{i,k} : w_x \mapsto \delta_{i,x} w_k$, and $G_{i,k} : v_x \mapsto \delta_{i,x} v_k$.

For any $T \in \mathcal{L}(V)$, $\exists! A_{i,j} \in \mathbb{F}, T = \sum_{i=1}^n \sum_{j=1}^n A_{i,j} R_{j,i} \implies \mathcal{M}(T, w \rightarrow v) = \begin{pmatrix} A_{1,1} & \dots & A_{1,m} & \dots & A_{1,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{m,1} & \dots & A_{m,m} & \dots & A_{m,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{n,1} & \dots & A_{n,m} & \dots & A_{n,n} \end{pmatrix}$.

$\implies \mathcal{A}(T) = ST = \left(\sum_{r=1}^m E_{r,r} \right) \left(\sum_{i=1}^n \sum_{j=1}^n A_{i,j} R_{j,i} \right) = \sum_{i=1}^n \sum_{j=1}^m A_{i,j} Q_{j,i}$. $\mathcal{M}(S, v \rightarrow w) \mathcal{M}(T, w \rightarrow v) = \mathcal{M}(ST, w) = \begin{pmatrix} A_{1,1} & \dots & A_{1,m} & \dots & A_{1,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{m,1} & \dots & A_{m,m} & \dots & A_{m,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \dots & 0 \end{pmatrix}$ $\nexists \mathcal{M}(T, R) = \mathcal{M}(T, w \rightarrow v)$.
 $\mathcal{M}(\mathcal{A}, R \rightarrow Q) \mathcal{M}(T, R) = \mathcal{M}(\mathcal{A}(T), Q) = \begin{pmatrix} A_{1,1} & \dots & A_{1,m} & \dots & A_{1,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{m,1} & \dots & A_{m,m} & \dots & A_{m,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \dots & 0 \end{pmatrix}$ Let $T = I$, we have $\mathcal{M}(\mathcal{A}, R \rightarrow Q) = \mathcal{M}(S, v \rightarrow w)$.

$\text{range } \mathcal{A} = \text{span} \left\{ \begin{pmatrix} Q_{1,1} & \dots & Q_{n,1} \\ \vdots & \ddots & \vdots \\ Q_{1,m} & \dots & Q_{n,m} \end{pmatrix} \right\}$, $\text{null } \mathcal{A} = \text{span} \left\{ \begin{pmatrix} R_{1,m+1} & \dots & R_{n,m+1} \\ \vdots & \ddots & \vdots \\ R_{1,n} & \dots & R_{n,n} \end{pmatrix} \right\}$. (a) $\dim \text{null } \mathcal{A} = n \times (n - m)$;
 (b) $\dim \text{range } \mathcal{A} = n \times m$. \square

• **NOTE FOR Exe (4E 17):** Define $\mathcal{B} \in \mathcal{L}(\mathcal{L}(V))$ by $\mathcal{B}(T) = TS$.

(a) Show $\dim \text{null } \mathcal{B} = (\dim V)(\dim \text{null } S)$.

(b) Show $\dim \text{range } \mathcal{B} = (\dim V)(\dim \text{range } S)$.

SOLUS: (a) $\forall T \in \mathcal{L}(V), TS = 0 \iff \text{range } S \subseteq \text{null } T$.

Thus $\text{null } \mathcal{B} = \{T \in \mathcal{L}(V) : \text{range } S \subseteq \text{null } T\} = \{T \in \mathcal{L}(V) : T|_{\text{range } S} = 0\}$.

(b) $\forall R \in \mathcal{L}(V), \text{null } S \subseteq \text{null } R \iff \exists T \in \mathcal{L}(V), R = TS$, by (3.B.24).

Thus $\text{range } \mathcal{B} = \{R \in \mathcal{L}(V) : \text{null } S \subseteq \text{null } R\} = \{R \in \mathcal{L}(V) : R|_{\text{null } S} = 0\}$.

Using [3.22] and Exe (4E 10). \square

OR. Using NOTE FOR [3.60] and nota in Exe (4E 17).

$\mathcal{B}(T) = TS = \left(\sum_{i=1}^n \sum_{j=1}^n A_{i,j} R_{j,i} \right) \left(\sum_{r=1}^m E_{r,r} \right) = \sum_{i=1}^n \sum_{j=1}^m A_{i,j} G_{j,i} \implies \mathcal{M}(TS, v) = \begin{pmatrix} A_{1,1} & \dots & A_{1,m} & \dots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{m,1} & \dots & A_{m,m} & \dots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{n,1} & \dots & A_{n,m} & \dots & 0 \end{pmatrix}$.

$\text{range } \mathcal{B} = \text{span} \left\{ \begin{pmatrix} G_{1,1} & \dots & G_{m,1} \\ \vdots & \ddots & \vdots \\ G_{1,n} & \dots & G_{m,n} \end{pmatrix} \right\}$, $\text{null } \mathcal{B} = \text{span} \left\{ \begin{pmatrix} R_{m+1,1} & \dots & R_{n,1} \\ \vdots & \ddots & \vdots \\ R_{m+1,n} & \dots & R_{n,n} \end{pmatrix} \right\}$. (a) $\dim \text{null } \mathcal{B} = n \times (n - m)$;
 (b) $\dim \text{range } \mathcal{B} = n \times m$. \square

• (4E 20) Sups $q \in \mathcal{P}(\mathbb{R})$. Prove $\exists p \in \mathcal{P}(\mathbb{R}), q(x) = (x^2 + x)p''(x) + 2xp'(x) + p(3)$.

SOLUS: Note that $\deg[(x^2 + x)p''(x) + 2xp'(x) + p(3)] = \deg p$.

Define $T_n \in \mathcal{L}(\mathcal{P}_n(\mathbb{R}))$ by $T_n(p) = (x^2 + x)p''(x) + 2xp'(x) + p(3)$.

And note that $T_n(p) = 0 \implies \deg T_n(p) = -\infty = \deg p \implies p = 0$. Thus T_n is inv.

$\forall q \in \mathcal{P}(\mathbb{R})$, if $q = 0$, let $n = 0$; if $q \neq 0$, let $n = \deg q$, we have $q \in \mathcal{P}_n(\mathbb{R})$.

Now $\exists p \in \mathcal{P}_n(\mathbb{R}), q(x) = T_n(p) = (x^2 + x)p''(x) + 2xp'(x) + p(3)$ for all $x \in \mathbb{R}$. \square

19 Sups $T \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ is inje. And $\deg Tp \leq \deg p$ for every nonzero $p \in \mathcal{P}(\mathbf{R})$.

(a) Prove T is surj. (b) Prove for every nonzero p , $\deg Tp = \deg p$.

SOLUS: (a) T is inje $\iff \forall n \in \mathbf{N}^+, T|_{\mathcal{P}_n(\mathbf{R})} \in \mathcal{L}(\mathcal{P}_n(\mathbf{R}))$ is inje, so is inv $\iff T$ is surj.

(b) Using induc.

(i) $\deg p = -\infty \geq \deg Tp \iff p = 0 = Tp$. And $\deg p = 0 \geq \deg Tp \iff p = C \neq 0$.

(ii) Asum $\forall s \in \mathcal{P}_n(\mathbf{R}), \deg s = \deg Ts$. We show $\forall p \in \mathcal{P}_{n+1}(\mathbf{R}), \deg Tp = \deg p$ by ctradic.

Sups $\exists r \in \mathcal{P}_{n+1}(\mathbf{R}), \deg Tr \leq n < n+1 = \deg r$. By (a), $\exists s \in \mathcal{P}_n(\mathbf{R}), T(s) = (Tr)$.

$\times T$ is inje $\Rightarrow s = r$. While $\deg s = \deg Ts = \deg Tr < \deg r$. Ctradic. \square

16 Sups V is finide and $S \in \mathcal{L}(V)$ suth $\forall T \in \mathcal{L}(V), ST = TS$. Prove $\exists \lambda \in \mathbf{F}, S = \lambda I$.

SOLUS: If $S = 0$, done. Now sups $S \neq 0$.

[Using nota in Exe (4E 17). See also in (3.A).]

Let $S = E_{1,1} + \dots + E_{m,m} \Rightarrow \mathcal{M}(S, B_U) = \mathcal{M}(I, B_{\text{range } S}, B_U)$. Note that $R_{k,1} : w_x \mapsto \delta_{k,x} v_1$.

Then $\forall k \in \{1, \dots, n\}, 0 \neq SR_{k,1} = R_{k,1}S$. Hence $\dim \text{null } S = 0, \dim \text{range } S = m = n$.

NOTICE that $G_{i,j} = R_{i,j}S = SR_{i,j} = Q_{i,j}$. Where $G_{i,j} : v_x \mapsto \delta_{i,x} v_j$; $Q_{i,j} : w_x \mapsto \delta_{i,x} w_j$.

For each $w_i, \exists ! a_{k,i} \in \mathbf{F}, w_i = a_{1,i} v_1 + \dots + a_{n,i} v_n$. Where $a_{k,i} = \mathcal{M}(I, (w_1, \dots, w_n), (v_1, \dots, v_n))_{k,i}$.

Then fix one i . Now for each $j \in \{1, \dots, n\}, Q_{i,j}(w_i) = w_j = a_{i,i} v_j = G_{i,j}(\sum_{k=1}^n a_{k,i} v_k)$.

Let $\lambda = a_{i,i}$. Hence each $w_j = \lambda v_j$. Now fix one j , we have $a_{1,1} v_j = \dots = a_{n,n} v_j$, then all $a_{i,i}$ are equal.

Thus each $w_j = \lambda v_j \Rightarrow \mathcal{M}(S, B_U) = \mathcal{M}(\lambda I)$. \square

• (10.A.3, OR 4E 19) Sups V is finide and $T \in \mathcal{L}(V)$.

[See also in (3.A).]

Prove $\forall B_V \neq B'_V, \mathcal{M}(T, B_V) = \mathcal{M}(T, B'_V) \implies T = \lambda I, \exists \lambda \in \mathbf{F}$.

SOLUS: Sups $\forall B_V \neq B'_V, \mathcal{M}(T, B_V) = \mathcal{M}(T, B'_V)$. If $T = 0$, then done.

Sups $T \neq 0$, and $v \in V \setminus \{0\}$. Asum (v, Tv) is liney indep.

Extend (v, Tv) to $B_V = (v, Tv, u_3, \dots, u_n)$. Let $B = \mathcal{M}(T, B_V)$.

$\Rightarrow Tv = B_{1,1}v + B_{2,1}(Tv) + B_{3,1}u_3 + \dots + B_{n,1}u_n \Rightarrow B_{2,1} = 1, B_{i,1} = 0, \forall i \neq 2$.

By asum, $A = \mathcal{M}(T, B'_V) = B, \forall B'_V = (v, w_2, \dots, w_n)$. Then $A_{2,1} = 1, A_{i,1} = 0, \forall i \neq 2$.

$\Rightarrow Tv = w_2$, which is not true if $w_2 = u_3, w_3 = Tv, w_j = u_j, \forall j \in \{4, \dots, n\}$. Ctradic.

Hence (v, Tv) is liney depe $\Rightarrow \forall v \in V, \exists \lambda_v \in \mathbf{F}, Tv = \lambda_v v$.

Now we show λ_v is indep of v , that is, for all disti $v, w \in V \setminus \{0\}, \lambda_v = \lambda_w$.

(v, w) liney indep $\Rightarrow T(v+w) = \lambda_{v+w}(v+w) = \lambda_v v + \lambda_w w = Tv + Tw$
 (v, w) liney depe, $w = cv \Rightarrow Tw = \lambda_w w = \lambda_w cv = c\lambda_v v = T(cv)$ $\Rightarrow T = \lambda I$. \square

OR. Let $A = \mathcal{M}(T, B_V)$, where $B_V = (u_1, \dots, u_m)$ is arb.

Fix one $B_V = (v_1, \dots, v_m)$ and then $(v_1, \dots, \frac{1}{2}v_k, \dots, v_m)$ is also a bss for any given $k \in \{1, \dots, m\}$.

Fix one k . Now we have $T(\frac{1}{2}v_k) = A_{1,k}v_1 + \dots + A_{k,k}(\frac{1}{2}v_k) + \dots + A_{m,k}v_m$

$\Rightarrow Tv_k = 2A_{1,k}v_1 + \dots + A_{k,k}v_k + \dots + 2A_{m,k}v_m = A_{1,k}v_1 + \dots + A_{k,k}v_k + \dots + A_{m,k}v_m$.

Then $A_{j,k} = 2A_{j,k} \Rightarrow A_{j,k} = 0$ for all $j \neq k$. Thus $Tv_k = A_{k,k}v_k, \forall k \in \{1, \dots, m\}$.

Now we show $A_{k,k} = A_{j,j}$ for all $j \neq k$. Choose j, k suth $j \neq k$.

Consider $B'_V = (v'_1, \dots, v'_j, \dots, v'_k, \dots, v'_m)$, where $v'_j = v_k, v'_k = v_j$ and $v'_i = v_i$ for all $i \in \{1, \dots, m\} \setminus \{j, k\}$.

Now $T(v'_k) = A_{1,k}v'_1 + \dots + A_{k,k}v'_k + \dots + A_{m,k}v'_m = A_{k,k}v'_k = A_{k,k}v_j$, while $T(v'_k) = T(v_j) = A_{j,j}v_j$. \square

3.E 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 20 | 4E: 8 14

1 A function $T : V \rightarrow W$ is liney \iff The graph of T is a subspace of $V \times W$.

2 Sups $V_1 \times \dots \times V_m$ is finide. Prove each V_j is finide.

SOLUS:

For any $k \in \{1, \dots, m\}$, define $S_k \in \mathcal{L}(V_1 \times \dots \times V_m, V_k)$ by $S_k(v_1, \dots, v_m) = v_k$.

Then S_k is liney map. By [3.22], range $S_k = V_k$ is finide. \square

OR. Denote $V_1 \times \dots \times V_m$ by U . Denote $\{0\} \times \dots \times \{0\} \times V_i \times \{0\} \times \dots \times \{0\}$ by U_i .

We show each U_i is iso to V_i . Then U is finide \implies its subsp U_i is finide, so is V_i .

Let $B_U = (v_1, \dots, v_M) \left\{ \begin{array}{l} \text{Define } R_i \in \mathcal{L}(V_i, U_i) \text{ by } R_i(u_i) = (0, \dots, 0, u_i, 0, \dots, 0) \\ \text{Define } S_i \in \mathcal{L}(U, V_i) \text{ by } S_i(u_1, \dots, u_i, \dots, u_m) = u_i \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} R_i S_j|_{U_j} = \delta_{ij} I_{U_j}, \\ S_i R_j = \delta_{ij} I_{V_j}. \end{array} \right. \square$

4 Prove $\mathcal{L}(V_1 \times \dots \times V_m, W)$ and $\mathcal{L}(V_1, W) \times \dots \times \mathcal{L}(V_m, W)$ are iso.

SOLUS: Using nota in Exe (2): $R_i : u_i \mapsto (0, \dots, u_i, \dots, 0)$; $S_i : (u_1, \dots, u_m) \mapsto u_i$.

Note that $T(u_1, \dots, u_m) = T(u_1, 0, \dots, 0) + \dots + T(0, \dots, u_m)$.

Define $\varphi : T \mapsto (T_1, \dots, T_m)$ by $\varphi(T) = (TR_1, \dots, TR_m)$.

Define $\psi : (T_1, \dots, T_m) \mapsto T$ by $\psi(T_1, \dots, T_m) = T_1 S_1 + \dots + T_m S_m$. $\left. \begin{array}{l} \text{Define } \varphi : T \mapsto (T_1, \dots, T_m) \text{ by } \varphi(T) = (TR_1, \dots, TR_m) \\ \text{Define } \psi : (T_1, \dots, T_m) \mapsto T \text{ by } \psi(T_1, \dots, T_m) = T_1 S_1 + \dots + T_m S_m \end{array} \right\} \Rightarrow \psi = \varphi^{-1}.$ \square

5 Prove $\mathcal{L}(V, W_1 \times \dots \times W_m)$ and $\mathcal{L}(V, W_1) \times \dots \times \mathcal{L}(V, W_m)$ are iso.

SOLUS: Using nota in Exe (2): $R_i : u_i \mapsto (0, \dots, u_i, \dots, 0)$; $S_i : (u_1, \dots, u_m) \mapsto u_i$.

Note that $T_i : v \mapsto w_i$, $\left\{ \begin{array}{l} \text{Define } \varphi : T \mapsto (T_1, \dots, T_m) \text{ by } \varphi(T) = (S_1 T, \dots, S_m T) \\ \text{Define } \psi : (T_1, \dots, T_m) \mapsto T \text{ by } \psi(T_1, \dots, T_m) = R_1 T_1 + \dots + R_m T_m \end{array} \right\} \Rightarrow \psi = \varphi^{-1}.$

$T : v \mapsto (w_1, \dots, w_m)$. $\left. \begin{array}{l} \text{Define } \varphi : T \mapsto (T_1, \dots, T_m) \text{ by } \varphi(T) = (S_1 T, \dots, S_m T) \\ \text{Define } \psi : (T_1, \dots, T_m) \mapsto T \text{ by } \psi(T_1, \dots, T_m) = R_1 T_1 + \dots + R_m T_m \end{array} \right\} \Rightarrow \psi = \varphi^{-1}.$ \square

6 For $m \in \mathbb{N}^+$, define V^m by $\underbrace{V \times \dots \times V}_{m \text{ times}}$. Prove V^m and $\mathcal{L}(\mathbb{F}^m, V)$ are iso.

SOLUS:

Define $T : (v_1, \dots, v_m) \mapsto \varphi$, where $\varphi : (a_1, \dots, a_m) \mapsto v$ is defined by $\varphi(a_1, \dots, a_m) = a_1 v_1 + \dots + a_m v_m$.

(a) Sups $T(v_1, \dots, v_m) = 0$. Then $\forall (a_1, \dots, a_m) \in \mathbb{F}^m$, $\varphi(a_1, \dots, a_m) = a_1 v_1 + \dots + a_m v_m = 0$

For each k , let $a_k = 1, a_j = 0$ for all $j \neq k$. Then each $v_k = 0 \Rightarrow (v_1, \dots, v_m) = 0$. Thus T is inje.

(b) Sups $\psi \in \mathcal{L}(\mathbb{F}^m, V)$. Let (e_1, \dots, e_m) be std bss of \mathbb{F}^m . Then $\forall (b_1, \dots, b_m) \in \mathbb{F}^m$,

$\left[T(\psi(e_1), \dots, \psi(e_m)) \right] (b_1, \dots, b_m) = b_1 \psi(e_1) + \dots + b_m \psi(e_m) = \psi(b_1 e_1 + \dots + b_m e_m) = \psi(b_1, \dots, b_m).$

Thus $T(\psi(e_1), \dots, \psi(e_m)) = \psi$. Hence T is surj. \square

3 Give an exa of a vecsp V and its two subsp U_1, U_2 suth

$U_1 \times U_2$ and $U_1 + U_2$ are iso but $U_1 + U_2$ is not a direct sum.

[V must be infinide.]

SOLUS: NOTE that at least one of U_1, U_2 must be infinide. And at least one must be finide??

Let $V = \mathbb{F}^\infty = U_1$, $U_2 = \{(x, 0, \dots) \in \mathbb{F}^\infty : x \in \mathbb{F}\}$. Then $V = U_1 + U_2$ is not a direct sum.

Define $T \in \mathcal{L}(U_1 \times U_2, U_1 + U_2)$ by $T((x_1, x_2, \dots), (x, 0, \dots)) = (x, x_1, x_2, \dots)$ $\left\{ \begin{array}{l} \text{Define } T \in \mathcal{L}(U_1 \times U_2, U_1 + U_2) \text{ by } T((x_1, x_2, \dots), (x, 0, \dots)) = (x, x_1, x_2, \dots) \\ \text{Define } S \in \mathcal{L}(U_1 + U_2, U_1 \times U_2) \text{ by } S(x, x_1, x_2, \dots) = ((x_1, x_2, \dots), (x, 0, \dots)) \end{array} \right\} \Rightarrow S = T^{-1}.$

Define $S \in \mathcal{L}(U_1 + U_2, U_1 \times U_2)$ by $S(x, x_1, x_2, \dots) = ((x_1, x_2, \dots), (x, 0, \dots))$ \square

- **NOTE FOR [3.79, 3.83]:** If $U = \{0\}$, then $v + U = v + \{0\} = \{v\}$, $V/U = V/\{0\} = \{\{v\} : v \in V\}$.
If $U = V$, then $v + V = 0 + V$, $V/V = \{v + V : v \in V\} = \{0\}$.
If $U = \emptyset$, then $v + U = v + \emptyset = \emptyset$, $V/U = V/\emptyset = \{\emptyset\}$.
-

- **COMMENT:** If U is merely a subset of V , then [3.85, 3.86] do not hold, and V/U is not a vecsp.
Becs $((v - w) + u) \in U$ or $u - u' \in U$ needs that U is clsd add.
And becs $(v - \hat{v}) + (w - \hat{w}) \in U$ and $\lambda(v - \hat{v}) \in U$ asum U is a subsp.
If U is a vecsp but not a subsp of V , then everything will be all right.
If U is a vecsp and $U \cap V = \{0\}$, then $v + U = w + U \Rightarrow v = w$.
-

- **NOTE FOR [3.85]:** $v + U = w + U \Leftrightarrow v \in w + U$, $w \in v + U$
 $\Leftrightarrow v - w \in U \Leftrightarrow (v + U) \cap (w + U) \neq \emptyset$.
-

- (4E 8) Sups $T \in \mathcal{L}(V, W)$, $w \in \text{range } T$. Prove $\{v \in V : Tv = w\} = u + \text{null } T$.

SOLUS: Let $\mathcal{K}_u = \{v \in V : Tv = w\}$. [Not a vecsp.] Sups $u \in \mathcal{K}_u$. Then $u + \text{null } T \subseteq \mathcal{K}_u$.

And $\forall u' \in \mathcal{K}_u$, $u' - u \in \text{null } T \Rightarrow u' \in u + \text{null } T$. Now $\mathcal{K}_u \subseteq u + \text{null } T$. □

- 7 Sups $v, x \in V$, and U, W are subsp of V . Prove $v + U = x + W \Rightarrow U = W$.

SOLUS: (a) $v \in v + U = x + W \Rightarrow \exists w_v \in W, v = x + w_v \Rightarrow v - x \in W$.

(b) $x \in x + W = v + U \Rightarrow \exists u_x \in U, x = v + u_x \Rightarrow x - v \in U$.

Now $x + U = v + U = x + W = v + W$. Thus $\{v + u : u \in U\} = \{v + w : w \in W\} \Rightarrow U = W$.

OR. $\pm(v - x) \in U \cap W \Rightarrow \left\{ \begin{array}{l} u_1 = (x - v) + w_1 \in W \Rightarrow U \subseteq W \\ w_2 = (v - x) + u_2 \in U \Rightarrow W \subseteq U \end{array} \right\} \Rightarrow U = W$. □

- 8 Sups A is a nonempty subset of V .

Prove A is a trslate of some subsp of $V \Leftrightarrow \lambda v + (1 - \lambda)w \in A, \forall v, w \in A, \lambda \in \mathbf{F}$.

SOLUS:

(a) Sups $A = a + U$. Then $\lambda(a + u_1) + (1 - \lambda)(a + u_2) = a + (\lambda(u_1 - u_2) + u_2) \in A$.

(b) Sups $\lambda v + (1 - \lambda)w \in A, \forall v, w \in A, \lambda \in \mathbf{F}$. Sups $\underline{a \in A}$ and let $A' = \{x - a : x \in A\}$.

Then $0 \in A'$ and $\forall (v - a), (w - a) \in A', \lambda \in \mathbf{F}$,

(I) $\lambda(v - a) = [\lambda v + (1 - \lambda)a] - a \in A'$.

(II) Becs $\lambda(v - a) + (1 - \lambda)(w - a) = [\lambda v + (1 - \lambda)w] - a \in A'$.

Let $\lambda = \frac{1}{2}$ here and use (I) above by $\lambda = 2$, we have $(v - a) + (w - a) \in A'$.

OR. Note that $v, a \in A \Rightarrow \lambda v + (1 - \lambda)a = 2v - a \in A$. Simlr $2w - a \in A$.

Now $(v - \frac{1}{2}a) + (w - \frac{1}{2}a) = v + w - a \in A \Rightarrow v + w - 2a = (v - a) + (w - a) \in A'$.

Thus $A' = -a + A$ is a subsp of V . Hence $a + A' = a + \{x - a : x \in A\} = A$ is a trslate. □

9 Sups $A = v + U$ and $B = x + W$ for some $v, x \in V$ and some subsp U, W of V .

Prove $A \cap B$ is either a trslate of some subsp of V or is \emptyset .

SOLUS: $\forall v + u, x + w \in A \cap B \neq \emptyset, \lambda \in \mathbf{F}, \lambda(v + u) + (1 - \lambda)(x + w) \in A \cap B$. By Exe (8). □

OR. Let $A = v + U, B = x + W$. Sups $\alpha \in (v + U) \cap (x + W) \neq \emptyset$.

Then $\alpha - v \in U \Rightarrow \alpha + U = v + U = A$, and $\alpha - x \in W \Rightarrow \alpha + W = x + W = B$.

We show $A \cap B = \alpha + (U \cap W)$. Note that $\alpha + (U \cap W) \subseteq A \cap B$.

And $\forall \beta = \alpha + u = \alpha + w \in A \cap B \Rightarrow u = w \in U \cap W \Rightarrow \beta \in \alpha + (U \cap W)$. □

10 Prove the intersec of any collec of trslates of subsp is either a trslate of some subsp or \emptyset .

SOLUS: Sups $\{A_\alpha\}_{\alpha \in \Gamma}$ is a collec of trslates of subsp of V , where Γ is an index set.

$\forall x, y \in \bigcap_{\alpha \in \Gamma} A_\alpha \neq \emptyset, \lambda \in \mathbf{F}, \lambda x + (1 - \lambda)y \in A_\alpha$ for each α . By Exe (8). □

OR. Let each $A_\alpha = w_\alpha + V_\alpha$. Sups $x \in \bigcap_{\alpha \in \Gamma} (w_\alpha + V_\alpha) \neq \emptyset$.

Then $x - w_\alpha \in V_\alpha \Rightarrow x + V_\alpha = w_\alpha + V_\alpha = A_\alpha$, for each α .

We show $\bigcap_{\alpha \in \Gamma} A_\alpha = \bigcap_{\alpha \in \Gamma} (x + V_\alpha) = x + \bigcap_{\alpha \in \Gamma} V_\alpha$.

$y \in \bigcap_{\alpha \in \Gamma} A_\alpha \Leftrightarrow$ for each $\alpha, y = x + v_\alpha \in A_\alpha$

\Leftrightarrow each $v_\alpha = y - x \in \bigcap_{\alpha \in \Gamma} V_\alpha \Leftrightarrow y \in x + \bigcap_{\alpha \in \Gamma} V_\alpha$. □

11 Sups $A = \{\lambda_1 v_1 + \dots + \lambda_m v_m : \sum_{i=1}^m \lambda_i = 1\}$, where each $v_i \in V, \lambda_i \in \mathbf{F}$.

(a) Prove A is a trslate of some subsp of V

(b) Prove if B is a trslate of some subsp of V and $\{v_1, \dots, v_m\} \subseteq B$, then $A \subseteq B$.

(c) Prove A is a trslate of some subsp of V of dim less than m .

SOLUS: (a) By Exe (8), $\forall u, w \in A, \lambda \in \mathbf{F}, \lambda u + (1 - \lambda)w = \left(\lambda \sum_{i=1}^m a_i + (1 - \lambda) \sum_{i=1}^m b_i\right) v_i \in A$.

(b) Sups $B = v + U$, where $v \in V$ and U is a subsp of V . Let each $v_k = v + u_k \in B, \exists ! u_k \in U$.

$\forall w \in A, w = \sum_{i=1}^m \lambda_i v_i = \sum_{i=1}^m \lambda_i (v + u_i) = \sum_{i=1}^m \lambda_i v + \sum_{i=1}^m \lambda_i u_i = v + \sum_{i=1}^m \lambda_i u_i \in v + U = B$. □

OR. Let $v = \lambda_1 v_1 + \dots + \lambda_m v_m \in A$. To show $v \in B$, use induc on m by k .

(i) $k = 1, v = \lambda_1 v_1 \Rightarrow \lambda_1 = 1$. $\forall v_1 \in B$. Hence $v \in B$.

$k = 2, v = \lambda_1 v_1 + \lambda_2 v_2 \Rightarrow \lambda_2 = 1 - \lambda_1$. $\forall v_1, v_2 \in B$. By Exe (8), $v \in B$.

(ii) $2 \leq k < m$. Asum $v = \lambda_1 v_1 + \dots + \lambda_k v_k \in A \subseteq B$. $[\forall \lambda_i$ suth $\sum_{i=1}^k \lambda_i = 1]$

For $u = \mu_1 v_1 + \dots + \mu_k v_k + \mu_{k+1} v_{k+1} \in A$. Fix one $\mu_i \neq 1$.

Then $\sum_{i=1}^{k+1} \mu_i - \mu_i = 1 - \mu_i \Rightarrow \left(\sum_{i=1}^{k+1} \frac{\mu_i}{1 - \mu_i}\right) - \frac{\mu_i}{1 - \mu_i} = 1$.

Let $w = \underbrace{\frac{\mu_1}{1 - \mu_i} v_1 + \dots + \frac{\mu_{i-1}}{1 - \mu_i} v_{i-1} + \frac{\mu_{i+1}}{1 - \mu_i} v_{i+1} + \dots + \frac{\mu_{k+1}}{1 - \mu_i} v_{k+1}}_{k \text{ terms}}$.

Let $\lambda_i = \frac{\mu_i}{1 - \mu_i}$ for $i \in \{1, \dots, i-1\}$; $\lambda_j = \frac{\mu_{j+1}}{1 - \mu_i}$ for $j \in \{i, \dots, k\}$. Then,

$\left. \begin{array}{l} \sum_{i=1}^k \lambda_i = 1 \Rightarrow w \in B \\ v_i \in B \Rightarrow u' = \lambda w + (1 - \lambda)v_i \in B \end{array} \right\} \Rightarrow$ Let $\lambda = 1 - \mu_i$. Thus $u' = u \in B \Rightarrow A \subseteq B$. □

(c) If $m = 1$, then let $A = v_1 + \{0\}$ and done. Now sups $m \geq 2$. Fix one $k \in \{1, \dots, m\}$.

$A \ni \lambda_1 v_1 + \dots + \lambda_{k-1} v_{k-1} + (1 - \lambda_1 - \dots - \lambda_{k-1} - \lambda_{k+1} - \dots - \lambda_m) v_k + \lambda_{k+1} v_{k+1} + \dots + \lambda_m v_m$

$= v_k + \lambda_1 (v_1 - v_k) + \dots + \lambda_{k-1} (v_{k-1} - v_k) + \lambda_{k+1} (v_{k+1} - v_k) + \dots + \lambda_m (v_m - v_k)$

$\in v_k + \text{span}(v_1 - v_k, \dots, v_m - v_k)$. □

• **NOTE FOR [3.88, 3.90, 3.91]:** Sups $W \in \mathcal{S}_V U$. Then V/U is iso to W . [Conversely not true.]

Becs $\forall v \in V, \exists! u_v \in U, w_v \in W, v = u_v + w_v$. Define $T \in \mathcal{L}(V)$ by $T(v) = w_v$.

Hence $\text{null } T = U$, $\text{range } T = W$, $\text{range } T \oplus \text{null } T = V$.

Then $\tilde{T} \in \mathcal{L}(V/\text{null } T, V)$ is defined by $\tilde{T}(v + U) = \tilde{T}(w'_v + U) = Tw'_v = w_v$. [See TIPS (1) below]

Now $\pi \circ \tilde{T} = I_{V/U}$, $\tilde{T} \circ \pi|_W = I_W = T|_W$. Hence \tilde{T} is iso of V/U onto W .

• **TIPS 1:** Sups U is a subsp of V . Define $S \in \mathcal{L}(V/U, V)$ by $S(v + U) = v$.

Then $\text{range } S$ is the *purest* in $\mathcal{S}_V U$. Now $\text{null } S = \{0\}$, $U \oplus \text{range } S = V$.

Let $E = S \circ \pi$. Becs S is inje and π is surj, $\text{null } E = \text{null } \pi = U$, $\text{range } E = \text{range } S$.

Then $\text{range } E \oplus \text{null } E = V$. NOTICE that $E : V \rightarrow W$ is the *purest eraser*. Now we explain why:

EXA: Let $V = \mathbb{F}^2, B_U = (e_1), B_W = (e_2 - e_1) \Rightarrow U \oplus W = V$.

Notice that $T(e_2 - e_1) = (e_2 - e_1)$, while $(e_2 - e_1) + U = e_2 + U$, but

becs $e_2 = e_1 + (e_2 - e_1)$, now still, $\tilde{T}((e_2 - e_1) + U) = e_2 - e_1 = Te_2$.

In contrast, $S((e_2 - e_1) + U) = S(e_2 + U) = e_2$, $E(e_2 - e_1) = e_2$.

And $\text{range } E = \text{range } S = \text{span}(e_2)$ is the *purest* in $\mathcal{S}_V U$.

12 Sups U is a subsp of V . Prove V is iso to $U \times (V/U)$.

SOLUS:

[Req V/U Finide] Let $B_{V/U} = (v_1 + U, \dots, v_n + U)$.

Note that $\forall v \in V, \exists! a_i \in \mathbb{F}, v + U = \sum_{i=1}^n a_i(v_i + U) = \left(\sum_{i=1}^n a_i v_i\right) + U$

$\Rightarrow (v - a_1 v_1 - \dots - a_n v_n) \in U \Rightarrow \exists! u \in U, v = \sum_{i=1}^n a_i v_i + u$.

Thus define $\varphi \in \mathcal{L}(V, U \times (V/U))$ and $\psi \in \mathcal{L}(U \times (V/U), V)$

by $\varphi(v) = (u, v + U)$ and $\psi(u, v + U) = v + u$. Then $\psi = \varphi^{-1}$. □

OR. Define $S \in \mathcal{L}(V/U, V)$ by $S(v + U) = v$.

By NOTE FOR [3.88, 90, 91], $\text{range } S \oplus U = V$. Thus $\forall v \in V, \exists! u \in U, w \in \text{range } S, v = u + w$.

Define $T \in \mathcal{L}(U \times (V/U), V)$ by $T(u, v + U) = u + S(v + U) = u + w = v$. Then T is surj.

And $T(u, v + U) = u + S(v + U) = 0 \Rightarrow \pi(T(u, v + U)) = v + U = 0$, and $u = -S(v + U) = 0$.

OR. Define $R \in \mathcal{L}(V, U \times (V/U))$ by $R(v) = (u, (w + U))$. Now $R \circ T = I_{U \times (V/U)}$, $T \circ R = I_V$. □

• (4E 14) Sups $V = U \oplus W$, $B_W = (w_1, \dots, w_m)$. Prove $B_{V/U} = (w_1 + U, \dots, w_m + U)$.

SOLUS: $\forall v \in V, \exists! u \in U, w \in W, v = u + w$. 又 $\exists! c_i \in \mathbb{F}, w = \sum_{i=1}^m c_i w_i \Rightarrow v = \sum_{i=1}^m c_i w_i + u$.

Hence $\forall v + U \in V/U, \exists! c_i \in \mathbb{F}, v + U = \sum_{i=1}^m c_i w_i + U$. □

13 Prove $B_{V/U} = (v_1 + U, \dots, v_m + U), B_U = (u_1, \dots, u_n) \Rightarrow B_V = (v_1, \dots, v_m, u_1, \dots, u_n)$.

SOLUS: $\forall v \in V, \exists! a_i \in \mathbb{F}, v + U = \sum_{i=1}^m a_i v_i + U \Rightarrow \exists! b_i \in \mathbb{F}, v - \sum_{i=1}^m a_i v_i = \sum_{i=1}^n b_i u_i \in U$

$\Rightarrow \forall v \in V, \exists! a_i, b_j \in \mathbb{F}, v = \sum_{i=1}^m a_i v_i + \sum_{j=1}^n b_j u_j$. □

OR. $\sum_{i=1}^m a_i v_i + \sum_{i=1}^n b_i u_i = 0 \Rightarrow \left(\sum_{i=1}^m a_i v_i + \sum_{i=1}^n b_i u_i\right) + U = 0 \Rightarrow \sum_{i=1}^m a_i(v_i + U) = 0$

$\Rightarrow a_1 = \dots = a_m = 0 \Rightarrow \sum_{i=1}^n b_i u_i \Rightarrow b_1 = \dots = b_n = 0$. 又 $\dim V = m + n$. □

OR. Note that $B = (v_1, \dots, v_m)$ is liney indep, and $[\text{span}(v_1, \dots, v_m) + U] \subseteq V$.

$v \in \text{span } B \cap U \Leftrightarrow v + U = \sum_{i=1}^m a_i(v_i + U) = 0 + U \Leftrightarrow v = 0$. Hence $\text{span } B \cap U = \{0\}$.

Becs $\dim[\text{span}(v_1, \dots, v_m) \oplus U] = m + n = \dim V$. Now by (2.B.8). □

- **NOTE FOR Exe (13) and (4E 14):** Let $U \oplus W = V$. Define $S(w + U) = w$. [See also TIPS (1).]
 (a) Let $B_W = (w_1, \dots, w_m) \Rightarrow B_{V/U} = (w_1 + U, \dots, w_m + U)$. Then $S(w_k + U)$ might not equal w_k .
 (b) Let $B_{V/U} = (w_1 + U, \dots, w_m + U)$, then let $B_W = (w_1, \dots, w_m)$. Now each $S(w_k + U) = w_k$.
- **NEW NOTA:** Pure $V/U = W \iff V = U \oplus W$, $W = \text{range } S$.
- **NEW THEO:** The uniqueness of Pure V/U follows from range S .

• **TIPS 2:** Sups U, W are subsp of V . Let $I = U \cap W$. Prove $V = U + W \iff V/I = U/I \oplus W/I$.

SOLUS: (a) Sups $U + W$. Then $\forall x \in V/I, \exists v \in V, (u_v, w_v) \in U \times W, x = v + I = (u_v + w_v) + I$.

Note that $U/I, W/I \subseteq V/I$. Thus $V/I = U/I + W/I$.

$$\forall x \in (U/I) \cap (W/I), x = u + I = w + I \Rightarrow \underline{u - w \in I = U \cap W}$$

$$\Rightarrow \exists w' \in I, u = w + w' \in U \cap W \Rightarrow x = u + I = 0 + I. \text{ Thus } (U/I) \cap (W/I) = \{0\}.$$

(b) Sups $V/I = U/I \oplus W/I$. Then $\forall v \in V, v + I = (u + I) + (w + I)$

$$\Rightarrow v - u - w \in I = U \cap W \Rightarrow \exists x \in U \cap W, v = u + w + x \in U + W. \quad \square$$

• **TIPS 3:** Sups I is a subsp of U . Sups U is a subsp of V .

Let $V = S_V I \oplus I = S_V U \oplus U$. Let $U = S_U I \oplus I$. Then $V = S_V U \oplus S_U I \oplus I$.

Sups $S_V I = \text{Pure } V/I$, simlr for $S_V U, S_U I$. Prove $S_V I = S_V U \oplus S_U I$.

SOLUS: $\forall v_i \in S_V I, v_i = v_u + u, \exists! v_u \in S_V U, u \in U \Rightarrow \exists! u_i \in S_U I, i \in I, v_i = v_u + u_i + i$.

又 $v_i \in \text{Pure } V/I$. Hence $i = 0$, and $v_i \in S_V U \oplus S_U I$. Now becs $S_V U, U \subseteq S_V I$. \square

15 Sups $\varphi \in \mathcal{L}(V, \mathbf{F}) \setminus \{0\}$. Prove $\dim V/(\text{null } \varphi) = 1$.

SOLUS: By [3.91] (d), $\dim \text{range } \varphi = 1 = \dim V/(\text{null } \varphi)$.

OR. By (3.B.29), $\exists u, \text{span}(u) \oplus \text{null } \varphi = V$. Then $B_{V/\text{null } \varphi} = (u + \text{null } \varphi)$. \square

16 Sups $\dim V/U = 1$. Prove $\exists \varphi \in \mathcal{L}(V, \mathbf{F}), \text{null } \varphi = U$.

SOLUS: Sups $V_0 \oplus U = V$. Then V_0 is iso to V/U . $\dim V_0 = 1$.

Define $\varphi \in \mathcal{L}(V, \mathbf{F})$ by $\varphi(v_0) = 1, \varphi(u) = 0$, where $v_0 \in V_0, u \in U$. \square

OR. Let $B_{V/U} = (w + U)$. Then $\forall v \in V, \exists! a \in \mathbf{F}, v + U = aw + U$.

Define $\varphi : V \rightarrow \mathbf{F}$ by $\varphi(v) = a$. Then $\varphi(v_1 + \lambda v_2) = a_1 + \lambda a_2 = \varphi(v_1) + \lambda \varphi(v_2)$.

Now $u \in U \iff u + U = 0w + U \iff \varphi(u) = 0$. \square

17 Sups V/U is finite, W is a subsp of V .

(a) Show if $V = U + W$, then $\dim W \geq \dim V/U$.

(b) Show $\exists W \in \mathcal{S}_V U, \dim W = \dim V/U$.

SOLUS: Let $B_W = (w_1, \dots, w_n)$.

(a) $\forall v \in V, \exists u \in U, w \in W, v = u + w \implies v + U = w + U = (a_1 w_1 + \dots + a_n w_n) + U, \exists! a_i \in \mathbf{F}$.

Then $V/U \subseteq \text{span}(w_1 + U, \dots, w_n + U)$. Hence $\dim V/U \leq \dim \text{span}(w_1 + U, \dots, w_n + U)$.

(b) Reduce $(w_1 + U, \dots, w_n + U)$ to $B_{V/U} = (w_1 + U, \dots, w_m + U)$, and let $W = \text{span}(w_1, \dots, w_m)$. \square

OR. Let $B_{V/U} = (v_1 + U, \dots, v_m + U)$ and define $\tilde{T} \in \mathcal{L}(V/U, V)$ by $\tilde{T}(v_k + U) = v_k$.

Note that $\pi \circ \tilde{T} = I$. By (3.B.20), \tilde{T} is inje. And (v_1, \dots, v_m) is liney indep.

Let $W = \text{range } \tilde{T} = \text{span}(v_1, \dots, v_m)$. Then $\tilde{T} \in \mathcal{L}(V/U, W)$ is iso. Thus $\dim W = \dim V/U$.

And $\forall v \in V, \exists! a_i \in \mathbf{F}, v + U = a_1 v_1 + \dots + a_m v_m + U \Rightarrow \exists! w \in W, u \in U, v = w + u$. \square

18 Sups $T \in \mathcal{L}(V, W)$ and U is a subsp of V . Let $\pi : V \rightarrow V/U$ be the quot map.

Prove $\exists S \in \mathcal{L}(V/U, W), T = S \circ \pi \iff U \subseteq \text{null } T$.

SOLUS:

(a) Sups $\exists S \in \mathcal{L}(V/U, W), T = S \circ \pi$. Then $U = \text{null } \pi \subseteq \text{null } (S \circ \pi) = \text{null } T$.

(b) Sups $U = \text{null } \pi \subseteq \text{null } T$. By (3.B.24), done. OR. Define $S : (v + U) \mapsto Tv$.

$v_1 + U = v_2 + U \iff v_1 - v_2 \in \text{null } T \iff Tv_1 = Tv_2$. Thus S is well-defined. Hence $S \circ \pi = T$. \square

CORO: Define $\Gamma : S \mapsto S \circ \pi$. Then Γ is inje, range $\Gamma = \{T \in \mathcal{L}(V, W) : U \subseteq \text{null } T\}$.

14 Sups $U = \{(x_1, x_2, \dots) \in \mathbf{F}^\infty : x_k \neq 0 \text{ for only finitely many } k\}$.

(a) Show U is a subsp of \mathbf{F}^∞ . [Do it in your mind] (b) Prove \mathbf{F}^∞/U is infinide.

SOLUS: For ease of nota, denote the p^{th} term of $u = (x_1, \dots, x_p, \dots) \in \mathbf{F}^\infty$ by $u[p]$.

For each $r \in \mathbf{N}^+$, let $e_r[k] = \begin{cases} 1, & (k-1) \equiv 0 \pmod{r} \\ 0, & \text{others} \end{cases}$ simply $e_r = (1, \underbrace{0, \dots, 0}_{(r-1)}, 1, \underbrace{0, \dots, 0}_{(r-1)}, 1, \dots)$.

For $m \in \mathbf{N}^+$. Let $a_1(e_1 + U) + \dots + a_m(e_m + U) = 0 + U \Rightarrow \exists u \in U, a_1e_1 + \dots + a_me_m = u$.

Sups $u = (x_1, \dots, x_L, 0, \dots)$, where L is the largest suth $u[L] \neq 0$.

Let $s \in \mathbf{N}^+$ be suth $h = s \cdot m! + 1 > L$, and $e_1[h] = \dots = e_m[h] = 1$.

NOTICE that for any $p, r \in \{1, \dots, m\}$, $e_r[s \cdot m! + 1 + p] = e_r[p + 1] = 1 \iff p \equiv 0 \pmod{r} \iff r | p$.

Let $1 = p_1 \leq \dots \leq p_{\tau(p)} = p$ be the disti factors of p . Moreover, $r | p \iff r = p_k$ for some k .

Now $u[h + p] = 0 = \left(\sum_{r=1}^m a_r e_r \right) [p + 1] = \sum_{k=1}^{\tau(p)} a_{p_k}$.

Let $q = p_{\tau(p)-1}$. Then $\tau(q) = \tau(p) - 1$, and each $q_k = p_k$. Again, $\left(\sum_{r=1}^m a_r e_r \right) [h + q] = 0 = \sum_{k=1}^{\tau(p)-1} a_{p_k}$.

Thus $a_{p_{\tau(p)}} = a_p = 0$ for all $p \in \{1, \dots, m\} \Rightarrow (e_1, \dots, e_m)$ is liney indep in \mathbf{F}^∞ .

So is $(e_1 + U, \dots, e_m + U)$ in \mathbf{F}^∞/U . Becs m is arb. By (2.A.14). \square

OR. For each $r \in \mathbf{N}^+$, let $e_r[p] = \begin{cases} 1, & \text{if } 2^r | p \\ 0, & \text{others} \end{cases}$.

Simlr, let $m \in \mathbf{N}^+$ and $a_1(e_1 + U) + \dots + a_m(e_m + U) = 0 \Rightarrow a_1e_1 + \dots + a_me_m = u \in U$.

Sups L is the largest suth $u[L] \neq 0$. And l is suth $2^{ml} > L$.

Then for each $k \in \{1, \dots, m\}$, $u[2^{ml} + 2^k] = 0 = \left(\sum_{r=1}^m a_r e_r \right) [2^k] = a_1 + \dots + a_k$.

Thus $a_1 = \dots = a_m = 0$ and (e_1, \dots, e_m) is liney indep. Simlr. \square

ENDED

4 Sups U is a subsp of V and $U \neq V$. Prove $\exists \varphi \in V' \setminus \{0\}, \varphi(u) = 0$ for all $u \in U$.

SOLUS: Let $X \oplus U = V \Rightarrow X \neq \{0\}$. Sups $s \in X \setminus \{0\}$. Let $Y \oplus \text{span}(s) = X$.

Define $\varphi \in V'$ by $\varphi(u + \lambda s + y) = \lambda$. Hence $\varphi \neq 0$ and $\varphi(u) = 0$ for all $u \in U$. □

OR. [Req V Finite] By [3.106], $\dim U^0 = \dim V - \dim U > 0$.

OR. Let $B_U = (u_1, \dots, u_m), B_V = (u_1, \dots, u_m, v_1, \dots, v_n)$ with $n \geq 1$.

Let $B_{V'} = (\psi_1, \dots, \psi_m, \varphi_1, \dots, \varphi_n)$. Then each $\varphi \in \text{span}(\varphi_1, \dots, \varphi_n)$ will do. □

CORO: (1) $U \neq V \Rightarrow U^0 \neq \{0\}$. (2) $U^0 = \{0\} \Rightarrow U = V$.

COMMENT: *Another proof of [3.108]:* T is surj $\Leftrightarrow T'$ is inje.

(a) Sups T' is inje. NOTICE that $\psi \neq 0 \Leftrightarrow T'(\psi) \neq 0 \Leftrightarrow \psi \notin (\text{range } T)^0$.

(b) T is surj $\Rightarrow (\text{range } T)^0 = \{0\} = \text{null } T'$. □

• Sups V is a vecsp and U is a subsp of V .

18 $U^0 = V' \Leftrightarrow \forall \varphi \in V', U \subseteq \text{null } \varphi \Leftrightarrow U = \{0\}$. [Which means $\{0\}_V^0 = V'$.]

19 $U_V^0 = \{0\} = V_V^0 \Leftrightarrow U = V$. By the inverse and ctrapos of Exe (4).

• NOTE FOR [3.102]: For $U = \emptyset$, U^0 is undefined. If U^0 is in the context, then certainly U is nonempty.

25 Sups U is a subsp of V . Explain why $U = \{v \in V : \varphi(v) = 0, \forall \varphi \in U^0\}$.

SOLUS: Note that $U = \{v \in V : v \in U\}$ is a subsp. Now we show $\forall \varphi \in U^0, \varphi(v) = 0 \Rightarrow v \in U$.

Asum $v \in V \setminus U$. Then let $\text{span}(v) \oplus U \oplus X = V$. $\exists \psi \in V', \text{null } \psi = U \oplus X$.

又 $\psi \in U^0 \Rightarrow \psi(v) = 0$. Ctradic. Hence $v \in U \Leftrightarrow \forall \varphi \in U^0, \varphi(v) = 0$. □

COMMENT: $W \subseteq X = \{v \in V : \varphi(v) = 0, \forall \varphi \in W^0\}$, the *promotion* of the subset W of V .

The promotion of every nonempty subset of V is a subsp of V .

20 Sups U, W are nonempty subsets of V . Prove $U \subseteq W \Rightarrow W^0 \subseteq U^0$.

SOLUS: $\forall \varphi \in W^0, u \in U \subseteq W, \varphi(u) = 0 \Rightarrow \varphi \in U^0$. Thus $W^0 \subseteq U^0$. □

21 Sups U, W are subsp of V . Prove $W^0 \subseteq U^0 \Rightarrow U \subseteq W$.

SOLUS: Using Exe (25). Now $v \in U \Rightarrow \forall \varphi \in W^0 \subseteq U^0, \varphi(v) = 0 \Rightarrow v \in W$. □

COMMENT: $\varphi \in W^0 \Leftrightarrow \text{null } \varphi \supseteq W \Rightarrow \text{null } \varphi \supseteq U \Leftrightarrow \varphi \in U^0$. But cannot conclude $W \supseteq U$.

COMMENT: (1) If U is merely a subset and W is a subsp. Promote U as X , let $W = Y$.

Then $Y^0 = W^0 \subseteq U^0 = X^0 \Rightarrow Y = W \supseteq X \supseteq U$. Still true.

(2) If W is merely a subset and U is a subsp. Promote W as Y , let $U = X$. For exa,

Let $W = \{(1, 0), (0, 1)\} \not\supseteq U = \{(x, 0) \in \mathbb{R}^2\}$. Then $Y = \mathbb{R}^2 \supseteq X = U$, $Y^0 = \{0\} \subseteq X^0$.

22 Sups U and W are subsp of V . Prove $(U + W)^0 = U^0 \cap W^0$.

SOLUS: (a) $\varphi \in (U + W)^0 \Rightarrow \forall u \in U, w \in W, \varphi(u + w) = 0$. $\left| \begin{array}{l} U \subseteq U + W \Rightarrow (U + W)^0 \subseteq U^0 \\ W \subseteq U + W \Rightarrow (U + W)^0 \subseteq W^0 \end{array} \right.$

$\varphi(u) = \varphi(w) = 0 \Rightarrow \varphi \in U^0 \cap W^0$.

(b) $\varphi \in U^0 \cap W^0 \subseteq V' \Rightarrow \forall u \in U, w \in W, \varphi(u + w) = 0 \Rightarrow \varphi \in (U + W)^0$. □

23 Sups U and W are subsp of V . Prove $(U \cap W)^0 = U^0 + W^0$.

SOLUS:

$$(a) \varphi = \psi + \beta \in U^0 + W^0 \Rightarrow \forall v \in U \cap W, \quad \left| \begin{array}{l} \text{OR. } U \cap W \subseteq U \Rightarrow (U \cap W)^0 \supseteq U^0 \\ U \cap W \subseteq W \Rightarrow (U \cap W)^0 \supseteq W^0 \end{array} \right. \\ \varphi(v) = (\psi + \beta)(v) = 0 \Rightarrow \varphi \in (U \cap W)^0.$$

(b) [Only in Finite; Req U, W Subsp] Using Exe (22).

$$\begin{aligned} \dim(U^0 + W^0) &= \dim U^0 + \dim W^0 - \dim(U^0 \cap W^0) \\ &= 2 \dim V - \dim U - \dim W - (\dim V - \dim(U + W)) = \dim V - \dim(U \cap W). \end{aligned}$$

OR. [Req U, W Subsp] Let $I = U \cap W$. Using [3E TIPS (3)].

Now $S_V I = S_V U \oplus S_U I = S_V W \oplus S_W I$. For $\varphi \in (U \cap W)^0 = I^0$.

Let $\text{span}(x) = \text{Pure } V / \text{null } \varphi$. If $x = 0$ then done.

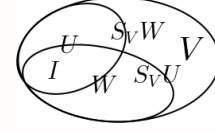
Now $0 \neq x \in S_V I \Rightarrow \exists! (u_v, i_u, w_v, i_w) \in S_V U \times S_U I \times S_V W \times S_W I$,

$x = u_v + i_u = w_v + i_w$. Define $\varphi \in U^0, \beta \in W^0$ by $\varphi : u_v \mapsto 1, u \mapsto 0$, and $\beta : i_u \mapsto 1, i \mapsto 0$, for all $u \in \text{Pure } V / \text{span}(u_v)$ and $i \in \text{Pure } V / \text{span}(i_u)$. OR Define $\psi \in W^0, \gamma \in U^0$, simlr.

Then $\varphi = \varphi + \beta = \psi + \gamma \in U^0 + W^0$. □

COMMENT: Not true if U or W is merely a subset. Promote $U \cap W$ as I , U as X , and W as Y .

EXA: Let $U = \{(x, x+1) \in \mathbb{R}^2\}, W = \mathbb{R}^2$. Then $U \cap W = I = U \neq \mathbb{R}^2 = X \cap Y$.



• **TIPS 1:** (a) Prove $V = U \oplus W \iff V' = U^0 \oplus W^0$.

(b) Sups $U \oplus W = V$. Prove $U^0 = \{\varphi \in V' : \varphi = \varphi \circ \iota\}$,

where $\iota \in \mathcal{L}(V, W) : u_v + w_v \rightarrow u_v$. **NEW NOTA:** Denote W^0 by U'_V , and U^0 by W'_V .

SOLUS: (a) $U \cap W = \{0\} \iff (U \cap W)^0 = \{0\}_V^0 = V' = U^0 + W^0$.

$$V = U + W \iff (U + W)^0 = V_V^0 = \{0\} = U^0 \cap W^0.$$

(b) NOTICE that by [3.B TIPS (3)], $\varphi \in W^0 \iff W \subseteq \text{null } \varphi \iff \varphi = \varphi \circ \iota$. □

31 Sups U is a subsp of V . Let $B_{U'_V} = (\varphi_1, \dots, \varphi_n)$. Show corres B_U exis.

SOLUS: Let each $\text{null } \varphi_i \oplus \text{span}(u_i) = V$ with $\varphi_i(u_i) = 1$.

Now $a_1 u_1 + \dots + a_n u_n = 0 \Rightarrow$ Each $a_i = \varphi_i(a_1 u_1 + \dots + a_n u_n) = 0$, by def of dual bss. □

EXA: Cannot extend B_U freely. Let $B_V = (e_1, e_2 - e_1)$. Let corres $B_{V'} = (\varphi_1, \varphi_2)$.

Let $U'_V = \text{span}(\varphi_1)$. Then extend to $B_U = (e_1)$ to $B'_V = (e_1, e_2)$. Corres $B'_{V'} \neq B_{V'}$.

• **TIPS 2:** Sups $\varphi_1, \dots, \varphi_m \in V'$. Let $\text{null}_I = (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m)$.

Sups Ω is a subsp of V' . Let $\text{null}_C = \{v \in V : \varphi(v) = 0, \forall \varphi \in \Omega\}$.

If $\Omega = \text{span}(\varphi_1, \dots, \varphi_m)$. Then $\text{null}_I = \text{null}_C$.

Becs $v \in \text{null}_I \iff \text{each } \varphi_i(v) = 0 \iff \forall \varphi \in \Omega, \varphi(v) = 0 \iff v \in \text{null}_C$.

COMMENT: If Ω is infinide. Then $\text{null}_I = \bigcap_{\varphi \in \Omega} \text{null } \varphi = \text{null}_C$.

• **TIPS 3:** Let $\Omega = \text{span}(\varphi_1, \dots, \varphi_m) \subseteq V'$. Prove (a) $\Omega = (\text{null}_I)^0$; (b) $\Omega = (\text{null}_C)^0$.

SOLUS:

Here (a) is [4E 23], (b) is Exe (26).

(a) For each $\varphi_k = 0$, $\text{span}(\varphi_k) = \{0\} = (\text{null } \varphi_k)^0$.

For each $\varphi_k \neq 0$. Using (3.B.29) and TIPS (1). Let $\varphi(v_k) \neq 0 \Rightarrow \text{null } \varphi_k \oplus \text{span}(v_k) = V$.

Then $(\text{null } \varphi_k)^0 = (\text{span}(v_k))'_V = \{\varphi \in V' : \varphi = \varphi \circ \iota\} = \text{span}(\varphi_k)$, where $\iota : cv_k + u_0 \rightarrow cv_k$.

Thus $\Omega = \text{span}(\varphi_1) + \dots + \text{span}(\varphi_m) = (\text{null } \varphi_1)^0 + \dots + (\text{null } \varphi_m)^0$

$$= ((\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m))^0 = (\text{null}_I)^0. \quad \square$$

OR. $\dim(\text{null } \varphi)^0 = \dim \text{range } \varphi = \dim \text{span}(\varphi)$. $\forall \text{span}(\varphi) \subseteq (\text{null } \varphi)^0$. OR. By Exe (26). \square

OR. $c \in F \setminus \{0\} \iff \text{null}(c\varphi_i) = \text{null } \varphi_i \iff c\varphi_i \in (\text{null}(c\varphi_i))^0 = (\text{null } \varphi_i)^0$.

And $0 \in \text{span}(\varphi_i), 0 \in (\text{null } \varphi_i)^0$. Hence $\text{span}(\varphi_i) = (\text{null } \varphi_i)^0$. \square

(b) $\forall \varphi \in \Omega, \text{null}_C \subseteq \text{null } \varphi \Rightarrow \varphi \in (\text{null}_C)^0$. Hence $\Omega = (\text{null}_I)^0 \subseteq (\text{null}_C)^0$. OR. By TIPS (2). \square

• **NOTE FOR Exe (26):** For every subsp Ω of V' , $\exists!$ subsp U of V such $\Omega = U^0$.

24 Sups V is finite and U is a subsp of V .

Prove, using the pattern of [3.104], that $\dim U + \dim U^0 = \dim V$.

SOLUS: Let $B_{U^0} = (\varphi_1, \dots, \varphi_m), B_{V'} = (\varphi_1, \dots, \varphi_m, \dots, \varphi_n)$. Let $B_{W^0} = (\varphi_{m+1}, \dots, \varphi_n)$.

And let corres (I) $B_U = (v_{m+1}, \dots, v_n)$, (II) $B_W = (v_1, \dots, v_m)$.

(I) NOTICE that each $\text{null } \varphi_k = \text{span}(v_1, \dots, v_{k-1}, v_{k+1}, \dots, v_n) = U_k$; $\dim U_k = \dim V - 1$.

By (4E 2.C.16), $U = (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m) = \bigcap_{k=1}^m U_k = \text{span}(v_{m+1}, \dots, v_n)$.

Hence $\text{span}(v_{m+1}, \dots, v_n)^0 = U^0 = \Omega = \text{span}(\varphi_1, \dots, \varphi_m)$.

(II) NOTICE that $V' = \Omega \oplus \text{span}(\varphi_{m+1}, \dots, \varphi_n) = U^0 \oplus \text{span}(v_1, \dots, v_m)^0$.

And that $\text{span}(\varphi_{m+1}, \dots, \varphi_n) \subseteq \text{span}(v_1, \dots, v_m)^0$.

By [1.C TIPS (2)] OR (2.C.1), $\text{span}(\varphi_{m+1}, \dots, \varphi_n) = \text{span}(v_1, \dots, v_m)^0$.

OR. Simlr to (II), let $\Omega = \text{span}(\varphi_{m+1}, \dots, \varphi_n)$, immediately. \square

• Sups $T \in \mathcal{L}(V, W), \varphi_k \in V', \psi_k \in W'$.

28 Prove $\text{null } T' = \text{span}(\psi_1, \dots, \psi_m) \iff \text{range } T = (\text{null } \psi_1) \cap \dots \cap (\text{null } \psi_m)$.

29 Prove $\text{range } T' = \text{span}(\varphi_1, \dots, \varphi_m) \iff \text{null } T = (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m)$.

SOLUS: Using [3.107], [3.109], Exe (23) and the CORO in Exe (20, 21).

(28) $(\text{range } T)^0 = \text{null } T' = \text{span}(\psi_1, \dots, \psi_m) = ((\text{null } \psi_1) \cap \dots \cap (\text{null } \psi_m))^0$.

(29) $(\text{null } T)^0 = \text{range } T' = \text{span}(\varphi_1, \dots, \varphi_m) = ((\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m))^0$. \square

CORO: Using the COMMENT in Exe (26).

$\text{null } T = \text{span}(v_1, \dots, v_m) \iff \text{null } T = (\text{null } \varphi_{m+1}) \cap \dots \cap (\text{null } \varphi_n) \iff \text{range } T' = \text{span}(\varphi_{m+1}, \dots, \varphi_n)$.

—Where $B_V = (v_1, \dots, v_m, \dots, v_n) \iff B_{V'} = (\varphi_1, \dots, \varphi_m, \dots, \varphi_n)$.

$\text{range } T = \text{span}(w_1, \dots, w_m) \iff \text{range } T = (\text{null } \psi_{m+1}) \cap \dots \cap (\text{null } \psi_n) \iff \text{null } T' = \text{span}(\psi_{m+1}, \dots, \psi_n)$.

—Where $B_W = (w_1, \dots, w_m, \dots, w_n) \iff B_{W'} = (\psi_1, \dots, \psi_m, \dots, \psi_n)$.

9 Let $B_V = (v_1, \dots, v_n), B_{V'} = (\varphi_1, \dots, \varphi_n)$. Then $\forall \psi \in V', \psi = \psi(v_1)\varphi_1 + \dots + \psi(v_n)\varphi_n$.

CORO: For other $B'_V = (u_1, \dots, u_n), B'_{V'} = (\rho_1, \dots, \rho_n), \forall \psi \in V', \psi = \psi(u_1)\rho_1 + \dots + \psi(u_n)\rho_n$.

SOLUS:

$\psi(v) = \psi\left(\sum_{i=1}^n a_i v_i\right) = \sum_{i=1}^n a_i \psi(v_i) = \sum_{i=1}^n \psi(v_i) \varphi_i(v) = [\psi(v_1)\varphi_1 + \dots + \psi(v_n)\varphi_n](v)$.

OR. $[\psi(v_1)\varphi_1 + \dots + \psi(v_n)\varphi_n]\left(\sum_{i=1}^n a_i v_i\right) = \psi(v_1)\varphi_1\left(\sum_{i=1}^n a_i v_i\right) + \dots + \psi(v_n)\varphi_n\left(\sum_{i=1}^n a_i v_i\right)$. \square

13 Define $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ by $T(x, y, z) = (4x + 5y + 6z, 7x + 8y + 9z)$.

Let $(\varphi_1, \varphi_2), (\psi_1, \psi_2, \psi_3)$ denote the dual bss of std bss of \mathbb{R}^2 and \mathbb{R}^3 .

(a) Describe the liney functionals $T'(\varphi_1), T'(\varphi_2) \in \mathcal{L}(\mathbb{R}^3, \mathbb{R})$

For any $(x, y, z) \in \mathbb{R}^3, (T'(\varphi_1))(x, y, z) = 4x + 5y + 6z, (T'(\varphi_2))(x, y, z) = 7x + 8y + 9z$.

(b) Write $T'(\varphi_1)$ and $T'(\varphi_2)$ as liney combinations of ψ_1, ψ_2, ψ_3 .

$$T'(\varphi_1) = 4\psi_1 + 5\psi_2 + 6\psi_3, \quad T'(\varphi_2) = 7\psi_1 + 8\psi_2 + 9\psi_3.$$

(c) What is $\text{null } T'$? What is $\text{range } T'$?

$$T(x, y, z) = 0 \iff \begin{cases} 4x + 5y + 6z = 0 \\ 7x + 8y + 9z = 0 \end{cases} \iff \begin{cases} x + y + z = 0 \\ y = 2z = 0 \end{cases} \iff (x, y, z) \in \text{span}(e_1 - 2e_2 + e_3).$$

Where (e_1, e_2, e_3) is std bss of \mathbb{R}^3 .

Let $(e_1 - 2e_2 + e_3, -2e_2, e_3)$ be a bss, with corres dual bss $(\varepsilon_1, \varepsilon_2, \varepsilon_3)$.

Thus $\text{span}(e_1 - 2e_2 + e_3) = \text{null } T \Rightarrow \text{span}(e_1 - 2e_2 + e_3)^0 = \text{span}(\varepsilon_2, \varepsilon_3) = \text{range } T'$.

Note that $\varepsilon_k = \varepsilon_k(e_1)\psi_1 + \varepsilon_k(e_2)\psi_2 + \varepsilon_k(e_3)\psi_3$.

$$\text{And } \begin{cases} \varepsilon_2(e_2) = -\frac{1}{2}, \varepsilon_2(e_1) = \varepsilon_2(e_1 - 2e_2 + e_3) + \varepsilon_2(2e_2) - \varepsilon_2(e_3) = 1, \\ \varepsilon_3(e_2) = 0, \varepsilon_3(e_3) = \varepsilon_3(e_1 - 2e_2 + e_3) + \varepsilon_3(2e_2) - \varepsilon_3(e_3) = -1. \end{cases}$$

Hence $\varepsilon_2 = \psi_1 - \frac{1}{2}\psi_2$, $\varepsilon_3 = -\psi_1 + \psi_3$. Now $\text{range } T' = \text{span}(\psi_1 - \frac{1}{2}\psi_2, -\psi_1 + \psi_3)$.

OR. $\text{range } T' = \text{span}(T'(\varphi_1), T'(\varphi_2)) = \text{span}(4\psi_1 + 5\psi_2 + 6\psi_3, 7\psi_1 + 8\psi_2 + 9\psi_3)$.

Sups $T'(x\varphi_1 + y\varphi_2) = (4x + 7y)\varphi_1 + (5x + 8y)\varphi_2 + (6x + 9y)\varphi_3 = 0$.

Then $x + y = 4x + 7y = x = y = 0$. Hence $\text{null } T' = \{0\}$.

OR. $\text{null } T = \text{span}(e_1 - 2e_2 + e_3) \Rightarrow V = \text{span}(-2e_2, e_3) \oplus \text{null } T$.

$\Rightarrow \text{range } T = \{Tx : x \in \text{span}(-2e_2, e_3)\} = \text{span}(T(-2e_2), T(e_3))$

$= \text{span}(-10f_1 - 16f_2, 6f_1 + 9f_2) = \text{span}(f_1, f_2) = \mathbb{R}^2$. Now $\text{null } T' = (\text{range } T)^0 = \{0\}$. \square

37 Sups U is a subsp of V and π is the quot map. Thus $\pi' \in \mathcal{L}((V/U)', V')$.

(a) Show π' is inje: Becs π is surj. Use [3.108].

(b) Show $\text{range } \pi' = U^0$: By [3.109](b), $\text{range } \pi' = (\text{null } \pi)^0 = U^0$.

(c) Conclude that π' is iso from $(V/U)'$ onto U^0 : Immediately.

SOLUS: OR. Using (3.E.18), also see (3.E.20).

(a) $\pi'(\varphi) = 0 \iff \forall v \in V (\forall v + U \in V), \varphi(\pi(v)) = \varphi(v + U) = 0 \iff \varphi = 0$.

(b) $\psi \in \text{range } \pi' \iff \exists \varphi \in (V/U)', \psi = \varphi \circ \pi \iff \text{null } \psi \supseteq U \iff \psi \in U^0$. Hence $\text{range } \pi' = U^0$. \square

• Sups U is a subsp of V . Prove $(V/U)'$ is iso to U^0 .

[Another proof of [3.106]]

SOLUS:

Define $\xi : U^0 \rightarrow (V/U)'$ by $\xi(\varphi) = \tilde{\varphi}$, where $\tilde{\varphi} \in (V/U)'$ is defined by $\tilde{\varphi}(v + U) = \varphi(v)$.

We show ξ is inje and surj.

Inje: $\xi(\varphi) = 0 = \tilde{\varphi} \Rightarrow \forall v \in V (\forall v + U \in V/U), \tilde{\varphi}(v + U) = \varphi(v) = 0 \Rightarrow \varphi = 0$.

Surj: $\Phi \in (V/U)' \Rightarrow \forall u \in U, \Phi(u + U) = \Phi(0 + U) = 0 \Rightarrow U \subseteq \text{null } (\Phi \circ \pi) \Rightarrow \xi(\Phi \circ \pi) = \Phi$. \square

OR. Define $\nu : (V/U)' \rightarrow U^0$ by $\nu(\Phi) = \Phi \circ \pi$. Now $\nu \circ \xi = I_{U^0}$, $\xi \circ \nu = I_{(V/U)'}$, $\Rightarrow \xi = \nu^{-1}$. \square

• Sups $V = U \oplus W$. Define $\iota : V \rightarrow U$ by $\iota(u + w) = u$. Thus $\iota' \in \mathcal{L}(U', V')$.

(a) Show $\text{null } \iota' = U_U^0 = \{0\}$: $\text{null } \iota' = (\text{range } \iota)_U^0 = U_U^0 = \{0\}$.

(b) Prove $\text{range } \iota' = W_V^0$: $\text{range } \iota' = (\text{null } \iota)_V^0 = W_V^0$.

(c) Prove $\tilde{\iota}'$ is iso from $U'/\{0\}$ onto W^0 : By (a), (b) and [3.91](d).

SOLUS:

(a) $\iota'(\psi) = \psi \circ \iota = 0 \iff U \subseteq \text{null } \psi$.

(b) Note that $W = \text{null } (\iota) \subseteq \text{null } (\psi \circ \iota)$. Then $\psi \circ \iota \in W^0 \Rightarrow \text{range } \iota' \in W^0$.

Sups $\varphi \in W^0$. Becs $\text{null } \iota = W \subseteq \text{null } \varphi$. By [3.B TIPS (3)], $\varphi = \varphi \circ \iota = \iota'(\varphi)$. □

36 Sups U is a subsp of V . Define $i : U \rightarrow V$ by $i(u) = u$. Thus $i' \in \mathcal{L}(V', U')$.

(a) Show $\text{null } i' = U^0$: $\text{null } i' = (\text{range } i)^0 = U^0 \Leftarrow \text{range } i = U$.

(b) Prove $\text{range } i' = U'$: $\text{range } i' = (\text{null } i)_U^0 = \{0\}_U^0 = U'$.

(c) Prove \tilde{i}' is iso from V'/U^0 onto U' : By (a), (b) and [3.91](d).

SOLUS:

(a) $\forall \varphi \in V', i'(\varphi) = \varphi \circ i = \varphi|_U$. Thus $i'(\varphi) = 0 \iff \forall u \in U, \varphi(u) = 0 \iff \varphi \in U^0$.

(b) Sups $\psi \in U'$. By (3.A.11), $\exists \varphi \in V', \varphi|_U = \psi$. Then $i'(\varphi) = \psi$. □

• Sups $T \in \mathcal{L}(V, W)$. Prove $\text{range } T' = (\text{null } T)^0$.

[*Another proof of [3.109](b)*]

SOLUS:

Sups $\Phi \in (\text{null } T)^0$. Becs by (3.B.12), $T|_U : U \rightarrow \text{range } T$ is iso; $V = U \oplus \text{null } T$.

And $\forall v \in V, \exists! u_v \in U, w_v \in \text{null } T, v = u_v + w_v$. Define $\iota \in \mathcal{L}(V, U)$ by $\iota(v) = u_v$.

Let $\psi = \Phi \circ (T^{-1}|_{\text{range } T})$. Then $T'(\psi) = \psi \circ T = \Phi \circ (T^{-1}|_{\text{range } T} \circ T|_V)$.

Where $T^{-1}|_{\text{range } T} : \text{range } T \rightarrow U$; $T : V \rightarrow \text{range } T$. Note that $T^{-1}|_{\text{range } T} \circ T|_V = \iota$.

By [3.B TIPS (3)], $\Phi = \Phi \circ \iota$. Thus $T'(\psi) = \psi \circ T = \Phi \circ \iota = \Phi$. □

• Sups $T \in \mathcal{L}(V, W)$. Using [3.108], [3.110].

$$\text{Now } T \text{ is inv} \iff \left| \begin{array}{l} \text{null } T = \{0\} \iff (\text{null } T)^0 = V' = \text{range } T' \\ \text{range } T = W \iff (\text{range } T)^0 = \{0\} = \text{null } T' \end{array} \right| \iff T' \text{ is inv.}$$

15 Sups $T \in \mathcal{L}(V, W)$. Prove $T' = 0 \iff T = 0$.

SOLUS:

Sups $T = 0$. Then $\forall \varphi \in W', T'(\varphi) = \varphi \circ T = 0$. Hence $T' = 0$.

Sups $T' = 0$. Then $\text{null } T' = W' = (\text{range } T)^0$, by [3.107](a).

[*W can be infinide*] By Exe (25),

$$\text{range } T = \{w \in W : \varphi(w) = 0, \forall \varphi \in (\text{range } T)^0\} = \{w \in W : \varphi(w) = 0, \forall \varphi \in W'\}.$$

Now we prove if $\forall \varphi \in W', \varphi(w) = 0$, then $w = 0$. So that $\text{range } T = \{0\}$ and done.

Asum $w \neq 0$. Then let U be suth $W = U \oplus \text{span}(w)$.

Define $\psi \in W'$ by $\psi(u + \lambda w) = \lambda$. So that $\psi(w) = 1 \neq 0$. □

OR. [*Only if W is finide*] By [3.106], $\dim \text{range } T = \dim W - \dim(\text{range } T)^0 = 0$. □

12 NOTICE that $I_{V'} : V' \rightarrow V'$. Now $\forall \varphi \in V', I_{V'}(\varphi) = \varphi = \varphi \circ I_V = I_V'(\varphi)$. Thus $I_{V'} = I_V'$.

16 Sups V, W are finide. Define Γ by $\Gamma(T) = T'$ for any $T \in \mathcal{L}(V, W)$.

Prove Γ is iso of $\mathcal{L}(V, W)$ onto $\mathcal{L}(W', V')$.

SOLUS: By [3.101], Γ is liney.

Sups $\Gamma(T) = T' = 0$. By Exe (15), $T = 0$. Thus Γ is inje.

Becs V, W are finide. $\dim \mathcal{L}(V, W) = \dim \mathcal{L}(W', V')$. Now Γ inje \Rightarrow inv. □

COMMENT: Let $X = \{T \in \mathcal{L}(V, W) : \text{range } T \text{ is finide}\}$.

Let $Y = \{\mathcal{T} \in \mathcal{L}(W', V') : \text{range } \mathcal{T} \text{ is finide}\}.$

Then $\Gamma|_X$ is iso of X onto Y , even if V and W are infinite.

The inje of $\Gamma|_X$ is equiv to the inje of Γ , as shown before.

Now we show $\Gamma|_X$ is surj without the cond that V or W is finite.

Sups $\mathcal{T} \in Y$. Let $B_{\text{range } \mathcal{T}} = (\varphi_1, \dots, \varphi_m)$, with corres (v_1, \dots, v_m) . Let $\varphi_k = \mathcal{T}(\psi_k)$.

Let \mathcal{K} be suth $W' = \mathcal{K} \oplus \text{null } \mathcal{T}$. Let $B_{\mathcal{K}} = (\psi_1, \dots, \psi_m)$, with corres (w_1, \dots, w_m) .

Define $T \in \mathcal{L}(V, W)$ by $Tv_k = w_k, Tu = 0; k \in \{1, \dots, m\}, u \in U$.

$\forall \psi \in \text{null } \mathcal{T}, [T'(\psi)](v) = \psi(Tv) = \psi(a_1 w_1 + \dots + a_p w_p) = 0 = [\mathcal{T}(\psi)](v)$.

$\forall k \in \{1, \dots, m\}, [T'(\psi_k)](v) = \psi_k(Tv) = \psi_k(a_1 w_1 + \dots + a_m w_m) = a_k = \varphi_k(v) = [\mathcal{T}(\psi)](v)$. \square

COMMENT: This is another proof of [3.109(a)]: $\dim \text{range } T = \dim \text{range } T'$.

5 Prove $(V_1 \times \dots \times V_m)'$ and $V'_1 \times \dots \times V'_m$ are iso. [Using notas in (3.E.2).]

Define $\varphi : (V_1 \times \dots \times V_m)' \rightarrow V'_1 \times \dots \times V'_m$
by $\varphi(T) = (T \circ R_1, \dots, T \circ R_m) = (R'_1(T), \dots, R'_m(T))$.
Define $\psi : V'_1 \times \dots \times V'_m \rightarrow (V_1 \times \dots \times V_m)'$
by $\psi(T_1, \dots, T_m) = T_1 S_1 + \dots + T_m S_m = S'_1(T_1) + \dots + S'_m(T_m)$. $\Rightarrow \psi = \varphi^{-1}$. \square

• (4E 8) Sups $B_V = (v_1, \dots, v_n), B_{V'} = (\varphi_1, \dots, \varphi_n)$.

Define $\Gamma : V \rightarrow \mathbf{F}^n$ by $\Gamma(v) = (\varphi_1(v), \dots, \varphi_n(v))$.
Define $\Lambda : \mathbf{F}^n \rightarrow V$ by $\Lambda(a_1, \dots, a_n) = a_1 v_1 + \dots + a_n v_n$. $\Rightarrow \Lambda = \Gamma^{-1}$.

6 Define $\Gamma : V' \rightarrow \mathbf{F}^m$ by $\Gamma(\varphi) = (\varphi(v_1), \dots, \varphi(v_m))$, where $v_1, \dots, v_m \in V$.

(a) Show $\text{span}(v_1, \dots, v_m) = V \iff \Gamma$ is inje.

(b) Show (v_1, \dots, v_m) is liney indep $\iff \Gamma$ is surj.

SOLUS:

(a) NOTICE that $\Gamma(\varphi) = 0 \iff \varphi(v_1) = \dots = \varphi(v_m) = 0 \iff \text{null } \varphi = \text{span}(v_1, \dots, v_m)$.

If Γ is inje, then $\Gamma(\varphi) = 0 \iff V = \text{null } \varphi = \text{span}(v_1, \dots, v_m)$.

If $V = \text{span}(v_1, \dots, v_m)$, then $\Gamma(\varphi) = 0 \iff \text{null } \varphi = \text{span}(v_1, \dots, v_m)$, thus Γ is inje.

(b) Sups Γ is surj. Then let $\Gamma(\varphi_i) = e_i$ for each i , where (e_1, \dots, e_m) is std bss of \mathbf{F}^m .

Then by (3.A.4), $(\varphi_1, \dots, \varphi_m)$ is liney indep.

Now $a_1 v_1 + \dots + a_m v_m = 0 \Rightarrow 0 = \varphi_i(a_1 v_1 + \dots + a_m v_m) = a_i$ for each i .

Sups (v_1, \dots, v_m) is liney indep. Let $U = \text{span}(\varphi_1, \dots, \varphi_m), B_{U'} = (\varphi_1, \dots, \varphi_m)$.

Thus $\forall (a_1, \dots, a_m) \in \mathbf{F}^m, \exists! \varphi = a_1 \varphi_1 + \dots + a_m \varphi_m$.

Let W be suth $V = U \oplus W$. Now $\forall v \in V, \exists! u_v \in U, w_v \in W, v = u_v + w_v$.

Define $\iota \in \mathcal{L}(V, U)$ by $\iota(v) = u_v$. So that $\Gamma(\varphi \circ \iota) = (a_1, \dots, a_m)$. \square

OR. Let (e_1, \dots, e_m) be std bss of \mathbf{F}^m and let (ψ_1, \dots, ψ_m) be corres dual bss.

Define $\Psi : \mathbf{F}^m \rightarrow (\mathbf{F}^m)'$ by $\Psi(e_k) = \psi_k$. Then Ψ is iso.

Define $T \in \mathcal{L}(\mathbf{F}^m, V)$ by $Te_k = v_k$. Now $T(x_1, \dots, x_m) = T(x_1 e_1 + \dots + x_m e_m) = x_1 v_1 + \dots + x_m v_m$.

$\forall \varphi \in V', k \in \{1, \dots, m\}, [T'(\varphi)](e_k) = \varphi(Te_k) = \varphi(v_k) = [\varphi(v_1) \circ \psi_1 + \dots + \varphi(v_m) \circ \psi_m](e_k)$

Now $T'(\varphi) = \varphi(v_1) \circ \psi_1 + \dots + \varphi(v_m) \circ \psi_m = \Psi(\varphi(v_1), \dots, \varphi(v_m)) = \Psi(\Gamma(\varphi))$. Hence $T' = \Psi \circ \Gamma$.

By (3.B.3), (a) $\text{range } T = \text{span}(v_1, \dots, v_m) = V \iff T' = \Psi \circ \Gamma \text{ inje} \iff \Gamma \text{ inje}$.

(b) (v_1, \dots, v_m) is liney indep $\iff T$ is inje $\iff T' = \Psi \circ \Gamma \text{ surj} \iff \Gamma \text{ surj}$. \square

• (4E 25) Define $\Gamma : V \rightarrow \mathbf{F}^m$ by $\Gamma(v) = (\varphi_1(v), \dots, \varphi_m(v))$, where $\varphi_1, \dots, \varphi_m \in V'$.

(c) Show $\text{span}(\varphi_1, \dots, \varphi_m) = V' \iff \Gamma$ is inje.

(d) Show $(\varphi_1, \dots, \varphi_m)$ is liney indep $\iff \Gamma$ is surj.

SOLUS:

(c) NOTICE that $\Gamma(v) = 0 \iff \varphi_1(v) = \dots = \varphi_m(v) = 0 \iff v \in (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m)$.

By Exe (4E 23) and (18), $\text{span}(\varphi_1, \dots, \varphi_m) = V' \iff (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m) = \{0\}$.

And $\text{null } \Gamma = (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m)$. Hence $\Gamma \text{ inje} \iff \text{null } \Gamma = \{0\} \iff \text{span}(\varphi_1, \dots, \varphi_m) = V'$.

(d) Sups $(\varphi_1, \dots, \varphi_m)$ is liney indep. Then by Exe (31), (v_1, \dots, v_m) is liney indep.

Thus $\forall (a_1, \dots, a_m) \in \mathbf{F}, \exists ! v = \sum_{i=1}^m a_i v_i \in V \Rightarrow \varphi_i(v) = a_i, \Gamma(v) = (a_1, \dots, a_m)$. Hence Γ is surj.

Sups Γ is surj. Let (e_1, \dots, e_m) be std bss of \mathbf{F}^m .

Sups $v_i \in V$ suth $\Gamma(v_i) = (\varphi_1(v_i), \dots, \varphi_m(v_i)) = e_i$, for each i .

Then (v_1, \dots, v_m) is liney indep. And $\varphi_j(v_k) = \delta_{j,k}$.

Now $a_1 \varphi_1 + \dots + a_m \varphi_m = 0 \Rightarrow 0(v_i) = a_i$ for each i . Hence $(\varphi_1, \dots, \varphi_m)$ is liney indep.

OR. Let $\text{span}(v_1, \dots, v_m) = U$. Then $B_{U'} = (\varphi_1|_U, \dots, \varphi_m|_U)$. Hence $(\varphi_1, \dots, \varphi_m)$ is liney indep. \square

OR. Simlr to Exe (6), we get $(e_1, \dots, e_m), (\psi_1, \dots, \psi_m)$ and the iso Ψ .

$\forall (x_1, \dots, x_m) \in \mathbf{F}^m, \Gamma'(\Psi(x_1, \dots, x_m)) = \Gamma'(\Psi(x_1 e_1 + \dots + x_m e_m)) = (x_1 \psi_1 + \dots + x_m \psi_m) \circ \Gamma$.

$\forall v \in V, [\Gamma'(\Psi(x_1, \dots, x_m))](v) = [x_1 \psi_1 + \dots + x_m \psi_m](\Gamma(v)) = [x_1 \varphi_1 + \dots + x_m \varphi_m](v)$.

Now $\Gamma'(\Psi(x_1, \dots, x_m)) = x_1 \varphi_1 + \dots + x_m \varphi_m$.

Define $\Phi : \mathbf{F}^m \rightarrow (\mathbf{F}^m)'$ by $\Phi = \Psi \circ \Gamma$. $\Phi(x_1, \dots, x_m) = x_1 \varphi_1 + \dots + x_m \varphi_m$. Thus by (4E 3.B.3),

(c) the inje of Φ corres to $(\varphi_1, \dots, \varphi_m)$ spanning V' ; 又 $\Phi = \Psi \circ \Gamma \text{ inje} \iff \Gamma \text{ inje}$.

(d) the surj of Φ corres to $(\varphi_1, \dots, \varphi_m)$ being liney indep; 又 $\Phi = \Psi \circ \Gamma \text{ surj} \iff \Gamma \text{ surj}$. \square

35 Prove $(\mathcal{P}(\mathbf{F}))'$ is iso to \mathbf{F}^∞ .

SOLUS:

Define $\theta \in \mathcal{L}((\mathcal{P}(\mathbf{F}))', \mathbf{F}^\infty)$ by $\theta(\varphi) = (\varphi(1), \varphi(z), \dots, \varphi(z^n), \dots)$.

Inje: $\theta(\varphi) = 0 \Rightarrow \forall z^k$ in the bss $(1, z, \dots, z^n)$ of $\mathcal{P}_n(\mathbf{F})$ ($\forall n$), $\varphi(z^k) = 0 \Rightarrow \varphi = 0$.

[NOTICE that $\forall p \in \mathcal{P}(\mathbf{R}), \exists ! a_i \in \mathbf{F}, m = \deg p, p = a_0 z + a_1 z + \dots + a_m z^m \in \mathcal{P}_m(\mathbf{F})$.]

Surj: $\forall (a_k)_{k=1}^\infty \in \mathbf{F}^\infty$, let ψ be suth $\forall k, \psi(z^k) = a_k$ [by [3.5]] and thus $\theta(\psi) = (a_k)_{k=1}^\infty$. \square

COMMENT: NOTICE that $\mathcal{P}(\mathbf{F})$ is not iso to \mathbf{F}^∞ , so is $\mathcal{P}(\mathbf{F})$ to $(\mathcal{P}(\mathbf{F}))'$

But if we let $\mathbf{F}^\infty = \{(a_1, \dots, a_n, \underbrace{0, \dots, 0}_{\text{all zero}}) \in \mathbf{F}^\infty \mid \exists ! n \in \mathbf{N}^+\}$. Then $\mathcal{P}(\mathbf{F})$ is iso to \mathbf{F}^∞ .

7 Show the dual bss of $(1, x, \dots, x^m)$ of $\mathcal{P}_m(\mathbf{R})$ is $(\varphi_0, \varphi_1, \dots, \varphi_m)$, where $\varphi_k(p) = \frac{p^{(k)}(0)}{k!}$.

Here $p^{(k)}$ denotes the k^{th} deri of p , with the understanding that the 0^{th} deri of p is p .

SOLUS:

$\forall j, k \in \mathbf{N}, (x^j)^{(k)} = \begin{cases} j(j-1) \dots (j-k+1) \cdot x^{(j-k)}, & j \geq k. \\ j(j-1) \dots (j-j+1) = j! & j = k. \\ 0, & j \leq k. \end{cases}$ Then $(x^j)^{(k)}(0) = \begin{cases} 0, & j \neq k. \\ k!, & j = k. \end{cases}$ \square

OR. Becs $\forall j, k \in \{1, \dots, m\}$ suth $j \neq k, \varphi_k(x^j) = \frac{(x^j)^{(k)}(0)}{k!} = \frac{0}{k!} = 0; \varphi_k(x^k) = \frac{(x^k)^{(k)}(0)}{k!} = 1$.

Thus $\frac{p^{(k)}(0)}{k!}$ act exactly the same as φ_k on the same bss $(1, \dots, x^m)$, hence is just another def of φ_k . \square

EXA: Sups $m \in \mathbf{N}^+$. By [2.C.10], $B = (1, x-5, \dots, (x-5)^m)$ is a bss of $\mathcal{P}_m(\mathbf{R})$.

Let $\varphi_k = \frac{p^{(k)}(5)}{k!}$ for each $k = 0, 1, \dots, m$. Then $(\varphi_0, \varphi_1, \dots, \varphi_m)$ is the dual bss of B .

34 The double dual space of V , denoted by V'' , is defined to be the dual space of V' .

In other words, $V'' = \mathcal{L}(V', \mathbf{F})$. Define $\Lambda : V \rightarrow V''$ by $(\Lambda v)(\varphi) = \varphi(v)$.

(a) Show Λ is a liney map from V to V'' .

(b) Show if $T \in \mathcal{L}(V)$, then $T'' \circ \Lambda = \Lambda \circ T$, where $T'' = (T')'$.

(c) Show if V is finide, then Λ **is iso from V onto V''** .

Sups V is finide. Then V and V' are iso, and finding iso from V onto V' generally requires choosing a bss of V . In contrast, the iso Λ from V onto V'' does not require a choice of bss and thus is considered more natural.

SOLUS:

(a) $\forall \varphi \in V', v, w \in V, a \in \mathbf{F}, (\Lambda(v + aw))(\varphi) = \varphi(v + aw) = \varphi(v) + a\varphi(w) = (\Lambda v)(\varphi) + a(\Lambda w)(\varphi)$.

Thus $\Lambda(v + aw) = \Lambda v + a\Lambda w$. Hence Λ is liney.

(b) $(T''(\Lambda v))(\varphi) = ((\Lambda v) \circ T')(\varphi) = (\Lambda v)(T'(\varphi))$
 $= (T'(\varphi))(v) = (\varphi \circ T)(v) = \varphi(Tv) = (\Lambda(Tv))(\varphi)$.

Hence $T''(\Lambda v) = (\Lambda(Tv)) \Rightarrow T'' \circ \Lambda = \Lambda \circ T$.

(c) Sups $\Lambda v = 0$. Then $\forall \varphi \in V', (\Lambda v)(\varphi) = \varphi(v) = 0 \Rightarrow v = 0$. Thus Λ is inje.

又 Becs V is finide. $\dim V = \dim V' = \dim V''$. Hence Λ is iso. □

ENDED

- **TIPS:** *Sups $p \in \mathcal{P}(\mathbf{F})$, $\deg p \leq m$ and p has at least $(m+1)$ disti zeros.*

Then by the ctrapos of [4.12], $\nexists \deg p = m$, we conclude that $m < 0$. Hence $p = 0$.

OR. We show if p has at least m disti zeros, then either $p = 0$ or $\deg p \geq m$.

If $p = 0$ then done. If not, then sups p has exactly n disti zeros $\lambda_1, \dots, \lambda_n$.

Becs $\exists! \alpha_i \geq 1, q \in \mathcal{P}(\mathbf{F})$, and $q \neq 0$, suth $p(z) = [(z - \lambda_1)^{\alpha_1} \dots (z - \lambda_n)^{\alpha_n}] q(z)$. □

- **COMMENT:** NOTICE that by [4.17], some term of the poly factoriz might not be in the form $(x - \lambda_k)^{\alpha_k}$.

- **NOTE FOR [4.7]:** *the uniqnes of coeffs of polys*

[Another proof]

If a poly had two different sets of coeffs, then subtracting the two exprs

would give a poly with some nonzero coeffs but infily many zeros. By TIPS. □

- **NOTE FOR [4.8]:** *div algo for polys*

[Another proof]

Sups $\deg p \geq \deg s$. Then $\left(\underbrace{1, z, \dots, z^{\deg s-1}}_{\text{of len } \deg s}, \underbrace{s, zs, \dots, z^{\deg p - \deg s} s}_{\text{of len } (\deg p - \deg s + 1)} \right)$ is a bss of $\mathcal{P}_{\deg p}(\mathbf{F})$.

Becs $q \in \mathcal{P}(\mathbf{F})$, $\exists! a_i, b_j \in \mathbf{F}$,

$$\begin{aligned} q &= a_0 + a_1 z + \dots + a_{\deg s-1} z^{\deg s-1} + b_0 s + b_1 zs + \dots + b_{\deg p - \deg s} z^{\deg p - \deg s} s \\ &= \underbrace{a_0 + a_1 z + \dots + a_{\deg s-1} z^{\deg s-1}}_r + s \underbrace{(b_0 + b_1 z + \dots + b_{\deg p - \deg s} z^{\deg p - \deg s})}_q. \end{aligned}$$

Note that r, q are uniq. □

- **NOTE FOR [4.11]:** *each zero of a poly corres to a deg-one factor;*

[Another proof]

First sups $p(\lambda) = 0$. Write $p(z) = a_0 + a_1 z + \dots + a_m z^m$, $\exists! a_0, a_1, \dots, a_m \in \mathbf{F}$ for all $z \in \mathbf{F}$.

Then $p(z) = p(z) - p(\lambda) = a_1(z - \lambda) + \dots + a_m(z^m - \lambda^m)$ for all $z \in \mathbf{F}$.

Hence $\forall k \in \{1, \dots, m\}$, $z^k - \lambda^k = (z - \lambda)(z^{k-1}\lambda^0 + z^{k-2}\lambda^1 + \dots + z^{k-(j+1)}\lambda^j + \dots + z\lambda^{k-2} + z^0\lambda^{k-1})$.

Thus $p(z) = \sum_{j=1}^m a_j(z - \lambda) \sum_{i=1}^k \lambda^{i-1} z^{k-i} = (z - \lambda) \sum_{j=1}^m a_j \sum_{i=1}^k \lambda^{i-1} z^{k-i} = (z - \lambda)q(z)$. □

- **NOTE FOR [4.13]:** *Every nonconst poly with complex coeffs has a zero in \mathbf{C} .*

[Another proof]

For any $w \in \mathbf{C}, k \in \mathbf{N}^+$, by polar coordinates, $\exists r \geq 0, \theta \in \mathbf{R}, r(\cos \theta + i \sin \theta) = w$.

By De Moivre' theorem, $w^k = [r(\cos \theta + i \sin \theta)]^k = r^k(\cos k\theta + i \sin k\theta)$.

Hence $(r^{1/k}(\cos \frac{\theta}{k} + i \sin \frac{\theta}{k}))^k = w$. Thus every complex number has a k^{th} root.

Sups a nonconst $p \in \mathcal{P}(\mathbf{C})$ with highest-order nonzero term $c_m z_m$.

Then $|p(z)| \rightarrow \infty$ as $|z| \rightarrow \infty$ (becs $\frac{|p(z)|}{|z_m|} \rightarrow |c_m|$ as $|z| \rightarrow \infty$).

Thus the continuous function $z \rightarrow |p(z)|$ has a global min at some point $\zeta \in \mathbf{C}$.

To show $p(\zeta) = 0$, asum $p(\zeta) \neq 0$. Define $q \in \mathcal{P}(\mathbf{C})$ by $q(z) = \frac{p(z + \zeta)}{p(\zeta)}$.

The function $z \rightarrow |q(z)|$ has a global min value of 1 at $z = 0$.

Write $q(z) = 1 + a_k z^k + \dots + a_m z^m$, where $k \in \mathbf{N}^+$ is the smallest suth $a_k \neq 0$.

Let $\beta \in \mathbf{C}$ be suth $\beta^k = -\frac{1}{a_k}$.

There is a const $c > 1$ so that if $t \in (0, 1)$, then $|q(t\beta)| \leq |1 + a_k t^k \beta^k| + t^{k+1}c = 1 - t^k(1 - tc)$.

Now letting $t = 1/(2c)$, we get $|q(t\beta)| < 1$. Ctradic. Hence $p(\zeta) = 0$, as desired. □

- (4E 4.2) Prove if $w, z \in \mathbf{C}$, then $||w| - |z|| \leq |w - z|$.

SOLUS:

$$\left. \begin{aligned} |w - z|^2 &= (w - z)(\bar{w} - \bar{z}) \\ &= |w|^2 + |z|^2 - (w\bar{z} + \bar{w}z) \\ &= |w|^2 + |z|^2 - (\overline{wz} + \overline{\bar{w}z}) \\ &= |w|^2 + |z|^2 - 2\operatorname{Re}(\overline{wz}) \\ &\geq |w|^2 + |z|^2 - 2|\overline{wz}| \\ &= |w|^2 + |z|^2 - 2|w||z| = ||w| - |z||^2. \end{aligned} \right\} \begin{array}{l} \text{OR. } \left. \begin{aligned} |w| &= |w - z + z| \leq |w - z| + |z| \Rightarrow |w| - |z| \leq |w - z| \\ |z| &= |z - w + w| \leq |z - w| + |w| \Rightarrow |z| - |w| \leq |w - z| \end{aligned} \right\} \\ \text{Geometric interpretation: The len of each side of a triangle} \\ \text{is greater than or equal to the diffce of the lens of the two other sides.} \end{array}$$

□

- (4E 4.3) Sups $\mathbf{F} = \mathbf{C}$, $\varphi \in V'$. Define $\sigma : V \rightarrow \mathbf{R}$ by $\sigma(v) = \operatorname{Re} \varphi(v)$ for each $v \in V$.

Show $\varphi(v) = \sigma(v) - i\sigma(iv)$ for all $v \in V$.

SOLUS: Notice that $\varphi(v) = \operatorname{Re} \varphi(v) + i \operatorname{Im} \varphi(v) = \sigma(v) + i \operatorname{Im} \varphi(v)$.

又 $\operatorname{Re} \varphi(iv) = \operatorname{Re}(i \varphi(v)) = -\operatorname{Im} \varphi(v) = \sigma(iv)$. Hence $\varphi(v) = \sigma(v) - i\sigma(iv)$.

□

- 4 Sups $m, n \in \mathbf{N}^+$ with $m \leq n$, $\lambda_1, \dots, \lambda_m \in \mathbf{F}$.

Prove $\exists p \in \mathcal{P}(\mathbf{F})$, $\deg p = n$, the zeros of p are $\lambda_1, \dots, \lambda_m$.

SOLUS: Let $p(z) = (z - \lambda_1)^{n-(m-1)}(z - \lambda_2) \cdots (z - \lambda_m)$.

□

- 5 Sups $m \in \mathbf{N}$, and z_1, \dots, z_{m+1} are disti in \mathbf{F} , and $w_1, \dots, w_{m+1} \in \mathbf{F}$.

Prove $\exists ! p \in \mathcal{P}_m(\mathbf{F})$, $p(z_k) = w_k$ for each $k \in \{1, \dots, m+1\}$.

SOLUS:

Define $T \in \mathcal{L}(\mathcal{P}_m(\mathbf{F}), \mathbf{F}^{m+1})$ by $Tq = (q(z_1), \dots, q(z_m), q(z_{m+1}))$.

We now show T is surj, so that such p exis; and that T is inje, so that such p is uniq.

Inje: $Tq = 0 \iff q(z_1) = \cdots = q(z_m) = q(z_{m+1}) = 0 \iff q = 0$, by TIPS.

Surj: $\dim \operatorname{range} T = \dim \mathcal{P}_m(\mathbf{F}) - \dim \operatorname{null} T = m+1 = \dim \mathbf{F}^{m+1}$ 又 $\operatorname{range} T \subseteq \mathbf{F}^{m+1} \Rightarrow T$ is surj. □

OR. Let $p_1 = 1$, $p_k(z) = \prod_{i=1}^{k-1} (z - z_i) = (z - z_1) \cdots (z - z_{k-1})$ for each $k \in \{2, \dots, m+1\}$.

By (2.C.10), $B_p = (p_1, \dots, p_{m+1})$ is a bss of $\mathcal{P}_m(\mathbf{F})$. Let $B_e = (e_1, \dots, e_{m+1})$ be the std bss of \mathbf{F}^{m+1} .

NOTICE that $Tp_1 = (1, \dots, 1)$, $Tp_k = \left(\prod_{i=1}^{k-1} (z_1 - z_i), \dots, \underbrace{\prod_{i=1}^{k-1} (z_j - z_i)}_{j^{\text{th}} \text{ ent}}, \dots, \prod_{i=1}^{k-1} (z_{m+1} - z_i) \right)$.

And that $\prod_{i=1}^{k-1} (z_j - z_i) = 0 \iff j \leq k-1$, becs z_1, \dots, z_{m+1} are disti.

$$\text{Thus } \mathcal{M}(T, B_p, B_e) = \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & A_{2,2} & 0 & \cdots & 0 \\ 1 & A_{3,2} & A_{3,3} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & A_{m+1,2} & A_{m+1,3} & \cdots & A_{m+1,m+1} \end{pmatrix}.$$

Where $A_{j,k} = \prod_{i=1}^{k-1} (z_j - z_i) \neq 0$ for all $j > k-1 \geq 1$. The rows of $\mathcal{M}(T)$ is liney indep.

By (4E 3.C.17) 又 $\dim \mathcal{P}_m(\mathbf{F}) = \dim \mathbf{F}^{m+1}$; OR By (3.F.32); T is inv.

□

- 2 Sups $m \in \mathbf{N}^+$. Is the set $U = \{0\} \cup \{p \in \mathcal{P}(\mathbf{F}) : \deg p = m\}$ a subsp of $\mathcal{P}(\mathbf{F})$?

SOLUS: $x^m, x^m + x^{m-1} \in U$ but $\deg[(x^m + x^{m-1}) - (x^m)] \neq m \Rightarrow (x^m + x^{m-1}) - (x^m) \notin U$.

□

3 Sups $m \in \mathbb{N}^+$. Is the set $U = \{0\} \cup \{p \in \mathcal{P}(\mathbb{F}) : 2 \mid \deg p\}$ a subsp of $\mathcal{P}(\mathbb{F})$?

SOLUS: $x^2, x^2 + x \in U$ but $\deg[(x^2 + x) - (x^2)]$ is odd and hence $(x^2 + x) - (x^2) \notin U$. □

6 Sups nonzero $p \in \mathcal{P}_m(\mathbb{F})$ has $\deg m$. Prove

$[P] p$ has m disti zeros $\iff p$ and its deri p' have no common zeros $[Q]$.

SOLUS:

(a) Sups p has m disti zeros. And $\deg p = m$. By [4.14], $\exists! c, \lambda_i \in \mathbb{R}, p(z) = c(z - \lambda_1) \cdots (z - \lambda_m)$.

If $m = 0$, then $p = c \neq 0 \Rightarrow p$ has no zeros, and $p' = 0$, done.

If $m = 1$, then $p(z) = c(z - \lambda_1)$, and $p' = c$ has no zeros, done.

For each $j \in \{1, \dots, m\}$, let $q_j \in \mathcal{P}_{m-1}(\mathbb{F})$ be suth $p(z) = (z - \lambda_j)q_j \Rightarrow q_j(\lambda_j) \neq 0$.

Now $p'(z) = (z - \lambda_j)q_j'(z) + q_j(z) \Rightarrow p'(\lambda_j) = q_j(\lambda_j) \neq 0$, as desired.

OR. We show $\neg Q \Rightarrow \neg P$:

Sups $p(z) = (z - \lambda)q(z)$, $p'(z) = (z - \lambda)r(z)$. $\nexists p'(z) = (z - \lambda)q'(z) + q(z)$.

Now $p'(\lambda) = q(\lambda) = 0 \Rightarrow q(z) = (z - \lambda)s(z)$, $p(z) = (z - \lambda)^2s(z)$.

Hence p has strictly less than m disti zeros.

(b) We prove $\neg P \Rightarrow \neg Q$:

Becs nonzero $p \in \mathcal{P}_m(\mathbb{F})$, we sups $\lambda_1, \dots, \lambda_M$ are all the disti zeros of p , where $M < m$.

By Pigeon Hole Principle, $\exists \lambda_k$ suth $p(z) = (z - \lambda_k)^2q(z)$ for some $q \in \mathcal{P}(\mathbb{F})$.

Hence $p'(z) = 2(z - \lambda_k)q(z) + (z - \lambda_k)^2q'(z) \Rightarrow p'(\lambda_k) = 0 = p(\lambda_k)$. □

7 Prove every $p \in \mathcal{P}(\mathbb{R})$ of odd \deg has a zero.

SOLUS:

Using the nota and proof of [4.17]. $\deg p = 2M + m$ is odd $\Rightarrow m$ is odd. Hence λ_1 exis. □

OR. Using calculus only. Sups $p \in \mathcal{P}_m(\mathbb{F})$, $\deg p = m$, m is odd.

Let $p(x) = a_0 + a_1x + \dots + a_mx^m$. Then $a_m \neq 0$. Denote $|a_m|^{-1}a_m$ by δ .

Write $p(x) = x^m \left(\frac{a_0}{x^m} + \frac{a_1}{x^{m-1}} + \dots + \frac{a_{m-1}}{x} + a_m \right)$.

Thus $p(x)$ is continuous, and $\lim_{x \rightarrow -\infty} p(x) = -\delta\infty$; $\lim_{x \rightarrow \infty} p(x) = \delta\infty$.

Hence we conclude that p has at least one real zero. □

9 Sups $p \in \mathcal{P}(\mathbb{C})$. Define $q : \mathbb{C} \rightarrow \mathbb{C}$ by $q(z) = p(z)\overline{p(\bar{z})}$. Prove $q \in \mathcal{P}(\mathbb{R})$.

SOLUS:

NOTICE that by [4.5], $\bar{\bar{z}}^n = z^n$.

Sups $q(z) = a_nz^n + \dots + a_1z + a_0 \Rightarrow q(\bar{z}) = a_n\bar{z}^n + \dots + a_1\bar{z} + a_0 \Rightarrow \overline{q(\bar{z})} = \overline{a_n}\bar{z}^n + \dots + \overline{a_1}\bar{z} + \overline{a_0}$.

Note that $q(z) = p(z)\overline{p(\bar{z})} = \overline{\overline{p(\bar{z})p(z)}} = \overline{p(\bar{z})\overline{p(z)}} = \overline{q(\bar{z})}$. Hence for each $a_k, \overline{a_k} = a_k \Rightarrow a_k \in \mathbb{R}$. □

OR. Sups $p(z) = a_mz^m + \dots + a_1z + a_0$. Now $\overline{p(\bar{z})} = \overline{a_m}\bar{z}^m + \dots + \overline{a_1}\bar{z} + \overline{a_0}$.

NOTICE that $q(z) = p(z)\overline{p(\bar{z})} = \sum_{k=0}^2 m \left(\sum_{i+j=k} a_i\overline{a_j} \right) z^k$.

NOTICE that by [4.5], $z - \bar{z} = 2(\text{Im } z) \Rightarrow z = \bar{z} + 2(\text{Im } z)$. So that $z = \bar{z} \iff \text{Im } z = 0 \iff z \in \mathbb{R}$.

Now for each $k \in \{0, \dots, 2m\}$, $\overline{\sum_{i+j=k} a_i\overline{a_j}} = \sum_{i+j=k} \overline{a_i}\overline{\overline{a_j}} = \sum_{i+j=k} \overline{a_j}\overline{a_i} = \sum_{i+j=k} a_i\overline{a_j} \in \mathbb{R}$. □

8 For $p \in \mathcal{P}(\mathbf{R})$, define $Tp : \mathbf{R} \rightarrow \mathbf{R}$ by $(Tp)(x) = \begin{cases} \frac{p(x) - p(3)}{x - 3} & \text{if } x \neq 3, \\ p'(3) & \text{if } x = 3. \end{cases}$

Show (a) $Tp \in \mathcal{P}(\mathbf{R})$ for all $p \in \mathcal{P}(\mathbf{R})$; (b) $T : \mathcal{P}(\mathbf{R}) \rightarrow \mathcal{P}(\mathbf{R})$ is liney.

SOLUS:

(a) For $x \neq 3$, $T(x^n) = \frac{x^n - 3^n}{x - 3} = \sum_{i=1}^n 3^{i-1} x^{n-i}$. For $x = 3$, $T(x^n) = n3^{n-1}$.

Note that if $x = 3$, then $\sum_{i=1}^n 3^{i-1} x^{n-i} = \sum_{i=1}^n 3^{n-1} = n3^{n-1}$.

Hence $T(x^n) = \sum_{i=1}^n 3^{i-1} x^{n-i} \Rightarrow T(x^n) \in \mathcal{P}(\mathbf{R})$.

(b) Now we show T is liney: $\forall p, q \in \mathcal{P}(\mathbf{R}), \lambda \in \mathbf{R}$,

$$T(p + \lambda q)(x) = \begin{cases} \frac{(p + \lambda q)(x) - (p + \lambda q)(3)}{x - 3}, & \text{if } x \neq 3, \\ (p + \lambda q)'(3), & \text{if } x = 3 \end{cases} = [T(p) + \lambda T(q)](x) \text{ for all } x \in \mathbf{R}. \quad \square$$

OR. (a) Note that $\exists! q \in \mathcal{P}(\mathbf{R}), p(x) - p(3) = (x - 3)q(x) \Rightarrow q(x) = \frac{p(x) - p(3)}{x - 3}$.

$$p'(x) = (p(x) - p(3))' = ((x - 3)q(x))' = q(x) + (x - 3)q'(x).$$

Hence $p'(3) = q(3)$. Now $Tp = q \in \mathcal{P}(\mathbf{R})$.

(b) $\forall p_1, p_2 \in \mathcal{P}(\mathbf{R}), \lambda \in \mathbf{R}, \exists! q_1, q_2 \in \mathcal{P}(\mathbf{R})$,

$$p_1(x) - p_1(3) = (x - 3)q_1(x) \text{ and } p_2(x) - p_2(3) = (x - 3)q_2(x).$$

By (a), $Tp_1 = q_1, Tp_2 = q_2$. Note that $(p_1 + \lambda p_2)(x) - (p_1 + \lambda p_2)(3) = (x - 3)(q_1 + \lambda q_2)(x)$.

Hence by the uniqueness of $q_1 + \lambda q_2$ for $p_1 + \lambda p_2$, we must have $T(p_1 + \lambda p_2) = q_1 + \lambda q_2$. \square

11 Sups $p \in \mathcal{P}(\mathbf{F})$ with $p \neq 0$. Let $U = \{pq : q \in \mathcal{P}(\mathbf{F})\}$.

(a) Show $\dim \mathcal{P}(\mathbf{F})/U = \deg p$.

(b) Find a bss of $\mathcal{P}(\mathbf{F})/U$.

SOLUS: NOTICE that $pq \neq p \circ q$, see (4E 3.A.10).

U is a subsp of $\mathcal{P}(\mathbf{F})$ becs $\forall s_1, s_2 \in \mathcal{P}(\mathbf{F}), \lambda \in \mathbf{F}, ps_1 + \lambda ps_2 = p(s_1 + \lambda s_2) \in U$.

If $\deg p = 0$, then $U = \mathcal{P}(\mathbf{F}), \mathcal{P}(\mathbf{F})/U = \{0\}$, with the uniq bss $()$. Sups $\deg p \geq 1$.

(a) By [4.8], $\forall s \in \mathcal{P}(\mathbf{F}), \exists! r \in \mathcal{P}_{\deg p-1}(\mathbf{F}), q \in \mathcal{P}(\mathbf{F}) [\exists! pq \in U], s = (p)q + (r)$.

Thus $\mathcal{P}(\mathbf{F}) = U \oplus \mathcal{P}_{\deg p-1}(\mathbf{F})$. By the NOTE FOR [3.91] in (3.E), $\mathcal{P}(\mathbf{F})/U$ and $\mathcal{P}_{\deg p-1}(\mathbf{F})$ are iso.

OR. Define $R : \mathcal{P}(\mathbf{F}) \rightarrow \mathcal{P}_{\deg p-1}(\mathbf{F})$ by $R(s) = r$ for all $s \in \mathcal{P}(\mathbf{F})$. We show R is liney.

$$\forall s_1, s_2 \in \mathcal{P}(\mathbf{F}), \lambda \in \mathbf{F}, \exists! r_1, r_2 \in \mathcal{P}_{\deg p-1}(\mathbf{F}), q_1, q_2 \in \mathcal{P}(\mathbf{F}), s_1 = (p)q_1 + (r_1); s_2 = (p)q_2 + (r_2).$$

$$\text{又 } \exists! r \in \mathcal{P}_{\deg p-1}(\mathbf{F}), q \in \mathcal{P}(\mathbf{F}), (s_1 + \lambda s_2) = (p)q + (r) = (p)(q_1 + \lambda q_2) + (r_1 + \lambda r_2).$$

$$\text{Note that } r_1, r_2 \in \mathcal{P}_{\deg p-1}(\mathbf{F}) \Rightarrow r_1 + \lambda r_2 \in \mathcal{P}_{\deg p-1}(\mathbf{F}).$$

$$\text{OR Note that } \deg(r_1 + \lambda r_2) \leq \max\{\deg r_1, \deg(\lambda r_2)\} \leq \max\{\deg r_1, \deg r_2\} < \deg p.$$

$$\text{By the uniqueness part of [4.8], } s = s_1 + \lambda s_2; r = r_1 + \lambda r_2. \text{ Thus } R(s_1 + \lambda s_2) = R(s_1) + \lambda R(s_2).$$

$$\text{Becs } Rs = 0 \iff s = pq, \exists! q \in \mathcal{P}(\mathbf{F}) \iff s \in U. \text{ And } \forall r \in \mathcal{P}_{\deg p-1}(\mathbf{F}), Rr = r.$$

$$\text{Now null } R = U, \text{ range } R = \mathcal{P}_{\deg p-1}(\mathbf{F}).$$

$$\text{Hence } \tilde{R} : \mathcal{P}(\mathbf{F})/U \rightarrow \mathcal{P}_{\deg p-1}(\mathbf{F}) \text{ is defined by } \tilde{R}(s + U) = Rs. \text{ By [3.91(d)], } \tilde{R} \text{ is iso.}$$

(b) For each $k \in \{0, 1, \dots, \deg p - 1\}$, $\tilde{R}(z^k + U) = R(z^k) = z^k \Rightarrow \tilde{R}^{-1}(z^k) = z^k + U$.

Thus $(1 + U, z + U, \dots, z^{\deg p-1} + U)$ can be a bss of $\mathcal{P}(\mathbf{F})/U$. \square

10 Sups $m \in \mathbf{N}, p \in \mathcal{P}_m(\mathbf{C})$ is suth $p(x_k) \in \mathbf{R}$ for each of disti $x_0, x_1, \dots, x_m \in \mathbf{R}$.
Prove $p \in \mathcal{P}(\mathbf{R})$.

SOLUS:

By TIPS and Exe (5), $\exists! q \in \mathcal{P}_m(\mathbf{R})$ suth $q(x_k) = p(x_k)$. Hence $p = q$. □

OR. Using the Lagrange Interpolating Polynomial.

Define $q(x) = \sum_{j=0}^m \frac{(x-x_0)(x-x_1)\cdots(x-x_{j-1})(x-x_{j+1})\cdots(x-x_m)}{(x_j-x_0)(x_j-x_1)\cdots(x_j-x_{j-1})(x_j-x_{j+1})\cdots(x_j-x_m)} p(x_j)$.

又 Each $x_j, p(x_j) \in \mathbf{R} \Rightarrow q \in \mathcal{P}_m(\mathbf{R})$. Notice that $q(x_k) = 1 \cdot p(x_k) \Rightarrow (q-p)(x_k) = 0$ for each x_k .
Then $(q-p)$ has $(m+1)$ zeros, while $(q-p) \in \mathcal{P}_m(\mathbf{C})$. By TIPS, $q-p=0 \Rightarrow p=q \in \mathcal{P}(\mathbf{R})$. □

• (4E 4 13) Sups nonconst $p, q \in \mathcal{P}(\mathbf{C})$ have no common zeros. Let $m = \deg p, n = \deg q$.
Define $T : \mathcal{P}_{n-1}(\mathbf{C}) \times \mathcal{P}_{m-1}(\mathbf{C}) \rightarrow \mathcal{P}_{m+n-1}(\mathbf{C})$ by $T(r, s) = rp + sq$. Prove T is iso.

CORO: $\exists! r \in \mathcal{P}_{n-1}(\mathbf{C}), s \in \mathcal{P}_{m-1}(\mathbf{C})$ suth $rp + sq = 1$.

SOLUS:

T is liney becs $\forall r_1, r_2 \in \mathcal{P}_{n-1}(\mathbf{C}), s_1, s_2 \in \mathcal{P}_{m-1}(\mathbf{C}), \lambda \in \mathbf{F}$,

$$T((r_1, s_1) + \lambda(r_2, s_2)) = T(r_1 + \lambda r_2, s_1 + \lambda s_2) = (r_1 + \lambda r_2)p + (s_1 + \lambda s_2)q = T(r_1, s_1) + \lambda T(r_2, s_2).$$

Let $\lambda_1, \dots, \lambda_M$ and μ_1, \dots, μ_N be the disti zeros of p and q respectively. NOTICE that $M \leq m, N \leq n$.

Note that the ctrapos of [4.13], $M = 0 \Leftrightarrow m = 0 \Rightarrow s = 0 \Leftrightarrow r = 0 \Leftarrow n = 0 \Leftrightarrow N = 0$.

Now sups $M, N \geq 1$. We show $s = 0$. Showing $r = 0$ is almost the same.

Write $p(z) = a(z - \lambda_1)^{\alpha_1} \cdots (z - \lambda_M)^{\alpha_M}$. ($\exists! \alpha_j \geq 1, a \in \mathbf{F}$.) Let $\max\{\alpha_1, \dots, \alpha_M\} = A$.

For each $D \in \{0, 1, \dots, A-1\}$, let $I_{D, \alpha} = \{\gamma_{D,1}, \dots, \gamma_{D,J}\}$ be suth each $\alpha_{\gamma_{D,j}} \geq D+1$.

Note that $I_{A-1, \alpha} \subseteq \cdots \subseteq I_{0, \alpha} = \{1, \dots, M\}$. Becs $rp + sq = 0 \Rightarrow (rp + sq)^{(k)} = 0$ for all $k \in \mathbf{N}^+$.

We use induc by D to show $s^{(D)}(\lambda_{\gamma_{D,j}}) = 0$ for each $D \in \{0, \dots, A-1\}$.

NOTICE that $p^{(D)}(\lambda_{\gamma}) = 0$ for each $D \in \{0, \dots, A-1\}$ and each $\lambda_{\gamma} \in I_{D, \alpha}$. (Δ)

(i) $D = 0$. $(rp + sq)(\lambda_{\gamma_{0,j}}) = (sq)(\lambda_{\gamma_{0,j}}) = s(\lambda_{\gamma_{0,j}}) = 0$.

$D = 1$. $(rp + sq)'(\lambda_{\gamma_{1,j}}) = (r'p + rp')(\lambda_{\gamma_{1,j}}) + (s'q + sq')(\lambda_{\gamma_{1,j}}) = (s'q)(\lambda_{\gamma_{1,j}}) = s'(\lambda_{\gamma_{1,j}}) = 0$.

(ii) $2 \leq D \leq A-1$. Asum $s^{(d)}(\lambda_{\gamma_{d,j}}) = 0$ for each $d \in \{1, \dots, D-1\}$ and each $\lambda_{\gamma_{d,j}} \in I_{d, \alpha}$.

(Becs $\forall p, q \in \mathcal{P}(\mathbf{F}), k \in \mathbf{N}^+, (pq)^{(k)} = C_k^k p^{(k)} q^{(0)} + \cdots + C_k^j p^{(j)} q^{(k-j)} + \cdots + C_k^0 p^{(0)} q^{(k)}$.) (Δ)

$$\begin{aligned} \text{Now } [rp + sq]^{(D)}(\lambda_{\gamma_{D,j}}) &= [C_D^D r^{(D)} p^{(0)} + \cdots + C_D^d r^{(d)} p^{(D-d)} + \cdots + C_D^0 r^{(0)} p^{(D)}](\lambda_{\gamma_{D,j}}) \\ &\quad + [C_D^D s^{(D)} q^{(0)} + \cdots + C_D^d s^{(d)} q^{(D-d)} + \cdots + C_D^0 s^{(0)} q^{(D)}](\lambda_{\gamma_{D,j}}) \\ &= [C_D^D s^{(D)} q^{(0)}](\lambda_{\gamma_{D,j}}). \text{ Where each } \lambda_{\gamma_{D,j}} \in I_{D, \alpha} \subseteq I_{D-1, \alpha}. \end{aligned}$$

Hence $s^{(D)}(\lambda_{\gamma_{D,j}}) = 0$. The asum holds for all $D \in \{0, \dots, A-1\}$.

NOTICE that $\forall k = \{0, \dots, A-2\}, s^{(k)}$ and $s^{(k+1)}$ have zeros $\{\lambda_{\gamma_{k+1,1}}, \dots, \lambda_{\gamma_{k+1,J}}\}$ in common.

Now $\forall D \in \{1, A-1\}, s = s^{(0)}, \dots, s^{(D)}$ have zeros $\{\lambda_{\gamma_{D,1}}, \dots, \lambda_{\gamma_{D,J}}\}$ in common.

Thus $\forall D \in \{0, A-1\}, s(z)$ is divisible by $(z - \lambda_{\gamma_{D,1}})^{\alpha_{\gamma_{D,1}}} \cdots (z - \lambda_{\gamma_{D,J}})^{\alpha_{\gamma_{D,J}}}$.

Hence we write $s(z) = ((z - \lambda_1)^{\alpha_1} \cdots (z - \lambda_M)^{\alpha_M}) s_0(z)$, while $\deg s \leq m-1 < m = \alpha_1 + \cdots + \alpha_M$.

Thus by TIPS, $s = 0$. Following the same pattern, we conclude that $r = 0$.

Hence T is inje. And $\dim(\mathcal{P}_{n-1}(\mathbf{C}) \times \mathcal{P}_{m-1}(\mathbf{C})) = \dim \mathcal{P}_{m+n-1}(\mathbf{C}) \Rightarrow T$ is surj. Thus T is iso. □

COMMENT: We now prove the statm that marked by (Δ) above.

L1: Prove $\forall p, q \in \mathcal{P}(\mathbf{F}), k \in \mathbf{N}^+, (pq)^{(k)} = C_k^k p^{(k)} q^{(0)} + \dots + C_k^j p^{(j)} q^{(k-j)} + \dots + C_k^0 p^{(0)} q^{(k)}$.

SOLUS:

We use induc by $k \in \mathbf{N}^+$.

(i) $k = 1$. $(pq)^{(1)} = pq = C_1^1 p^{(1)} q^{(0)} + C_1^0 p^{(0)} q^{(1)}$.

(ii) $k \geq 2$. Asum for $(pq)^{(k-1)} = C_{k-1}^{k-1} p^{(k-1)} q^{(0)} + \dots + C_{k-1}^j p^{(j)} q^{(k-1-j)} + \dots + C_{k-1}^0 p^{(0)} q^{(k-1)}$.

$$\begin{aligned} \text{Now } (pq)^{(k)} &= ((pq)^{(k-1)})' = \left(\sum_{j=0}^{k-1} C_{k-1}^j p^{(j)} q^{(k-1-j)} \right)' = \sum_{j=0}^{k-1} \left[C_{k-1}^j \left(p^{(j+1)} q^{(k-j-1)} + p^{(j)} q^{(k-j)} \right) \right] \\ &= \left[C_{k-1}^0 \left(\underbrace{p^{(1)} q^{(k-1)}} + \boxed{p^{(0)} q^{(k)}} \right) \right] + \left[C_{k-1}^1 \left(p^{(2)} q^{(k-2)} + \underbrace{p^{(1)} q^{(k-1)}} \right) \right] \\ &\quad + \dots + \left[C_{k-1}^{j-2} \left(\underbrace{p^{(j-1)} q^{(k-j+1)}} + p^{(j-2)} q^{(k-j+2)} \right) \right] + \left[C_{k-1}^{j-1} \left(\underbrace{p^{(j)} q^{(k-j)}} + \underbrace{p^{(j-1)} q^{(k-j+1)}} \right) \right] \\ &\quad + \left[C_{k-1}^j \left(\underbrace{p^{(j+1)} q^{(k-j-1)}} + \underbrace{p^{(j)} q^{(k-j)}} \right) \right] + \left[C_{k-1}^{j+1} \left(p^{(j+2)} q^{(k-j-2)} + \underbrace{p^{(j+1)} q^{(k-j-1)}} \right) \right] \\ &\quad + \dots + \left[C_{k-1}^{k-2} \left(\underbrace{p^{(k-1)} q^{(1)}} + p^{(k-2)} q^{(2)} \right) \right] + \left[C_{k-1}^{k-1} \left(\boxed{p^{(k)} q^{(0)}} + \underbrace{p^{(k-1)} q^{(1)}} \right) \right]. \end{aligned}$$

$$\text{Hence } (pq)^{(k)} = C_k^0 p^{(0)} q^{(k)} + \dots + \left[C_{k-1}^j + C_{k-1}^{j-1} \right] (p^{(j)} q^{(k-j)}) + \dots + C_k^k p^{(k)} q^{(0)}.$$

□

L2: Sups $p(z) = (z - \lambda)^\alpha q(z)$ and $\alpha \in \mathbf{N}^+$. Prove $p^{(\alpha-1)}(\lambda) = 0$.

SOLUS:

Sups $p \in \mathcal{P}(\mathbf{F})$. Write $p(z) = (z - \lambda)^A q(z)$, where $A \in \mathbf{N}^+, q(\lambda) \neq 0$.

We use induc to show for all $\alpha \in \{1, \dots, A\}, p^{(\alpha-1)}(\lambda) = 0$.

(i) $\alpha = 1$. $p^{(0)}(\lambda) = 0$.

(ii) $2 \leq \alpha \leq A$. Asum $p^{(a-2)}(\lambda) = 0$ for all $a \in \{1, \dots, \alpha\}$.

NOTICE that $p(z) = (z - \lambda)^{\alpha-1} q_{\alpha-1}(z) = (z - \lambda)^\alpha q_\alpha(z)$, where $q_\alpha(z) = (z - \lambda) q_{\alpha-1}(z)$.

$$\begin{aligned} \text{Becs } p^{(\alpha-1)}(z) &= \left[C_{\alpha-1}^{\alpha-1} (z - \lambda)^0 q_{\alpha-1}(z) + \dots + C_{\alpha-1}^k (z - \lambda)^{\alpha-1-k} q_{\alpha-1-k}(z) \right. \\ &\quad \left. + \dots + C_{\alpha-1}^0 (z - \lambda)^{\alpha-1} q_{\alpha-1}^{(\alpha-1)}(z) \right]. \text{ Now } p^{(\alpha-1)}(\lambda) = C_{\alpha-1}^{\alpha-1} q_{\alpha-1}(\lambda) = 0. \end{aligned}$$

□

ENDED

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• NOTE FOR [5.6]:

More generally, sups we do not know whether V is finide. We show $(a) \iff (b)$.

Sups (a) λ is an eigval of T with an eigvec v . Then $(T - \lambda I)v = 0$.

Hence we get (b), $(T - \lambda I)$ is not inje. And then (d), $(T - \lambda I)$ is not inv.

But (d) \Rightarrow (b) fails, becs S is not inv $\iff S$ is not inje OR S is not surj.

• TIPS: For $T_1, \dots, T_m \in \mathcal{L}(V)$:

(a) Sups T_1, \dots, T_m are all inje. Then $(T_1 \circ \dots \circ T_m)$ is inje.

(b) Sups $(T_1 \circ \dots \circ T_m)$ is not inje. Then at least one of T_1, \dots, T_m is not inje.

(c) At least one of T_1, \dots, T_m is not inje $\nRightarrow (T_1 \circ \dots \circ T_m)$ is not inje.

EXA: In infinide only. Let $V = \mathbf{F}^\infty$.

Let S be the backward shift (surj but not inje)
 Let T be the forward shift (inje but not surj) $\left. \vphantom{\begin{matrix} \text{Let } S \text{ be the backward shift (surj but not inje)} \\ \text{Let } T \text{ be the forward shift (inje but not surj)} \end{matrix}} \right\} \Rightarrow \text{Then } ST = I.$

□

• **NOTE FOR [5.2]:** Sups $T \in \mathcal{L}(V)$. Then U is invarsp of V under $T \iff \text{range } T|_U \subseteq U$.

• Sups V is finide, $T \in \mathcal{L}(V)$, and U is invarsp of V under T .

Prove there exis invarsp W of dimension $\dim V - \dim U$.

SOLUS:

Using the NOTE FOR [3.88,90,91]. Define the eraser S . Now $V = \text{range } S \oplus U$.

Define E_1 by $E_1(u + w) = u$. Define E_2 by $E_2(u + w) = w$. ($E_2 = S \circ \pi$.)

Note that $T - TE_1 = T(I - E_1) = TE_2$. And $\text{null } TE_2 = \text{null } T \oplus U$, $\text{range } T = \text{range } TE_2 \oplus U$.

Becs $\dim \text{null } TE_2 \geq \dim U \iff \dim \text{range } TE_2 \leq \dim V - \dim U$.

Let $B_U = (u_1, \dots, u_n)$, $B_{\text{range } TE_2} = (v_1, \dots, v_m) \Rightarrow B_V = (v_1, \dots, v_m, u_1, \dots, u_n, \dots, u_p)$.

Let $X = \text{span}(v_1, \dots, v_m, u_{\alpha_1}, \dots, u_{\alpha_{p-\dim U}})$. Where $\alpha_1, \dots, \alpha_{p-\dim U} \in \{1, \dots, p\}$ are disti.

Then $\dim X = \dim V - \dim U$. [$\text{range } TE_2 \subseteq$] X is invar TE_2 , by Exe (1)(b).

We have $x \in X \Rightarrow TE_2(x) \in X \Rightarrow Tx - TE_1(x) \in X \Rightarrow Tx \in X$. Hence X is invar T . □

(Note that $E_1(x) \in \text{span}(u_{\beta_1}, \dots, u_{\beta_t})$, where $\beta_1, \dots, \beta_t \in \{\alpha_1, \dots, \alpha_{p-\dim U}\}$ and each $u_{\beta_i} \in U$.)

COMMENT: Conversely, by rev the roles of U and W , we conclude that it is true as well.

• Sups $T \in \mathcal{L}(V)$ and U is invarsp of V under T .

Sups $\lambda_1, \dots, \lambda_m$ are the disti eigvals of T corres eigvecs v_1, \dots, v_m .

• **TIPS 1:** Prove $v_1 + \dots + v_m \in U \iff$ each $v_k \in U$.

SOLUS:

Sups each $v_k \in U$. Then becs U is a subsp, $v_1 + \dots + v_m \in U$.

Define the stam $P(k) : \text{if } v_1 + \dots + v_k \in U$, then each $v_j \in U$. We use induc on m .

(i) For $k = 1$, $v_1 \in U$.

(ii) For $2 \leq k \leq m$. Asum $P(k-1)$ holds. Sups $v = v_1 + \dots + v_k \in U$.

Then $Tv = \lambda_1 v_1 + \dots + \lambda_k v_k \in U \implies Tv - \lambda_k v = (\lambda_1 - \lambda_k)v_1 + \dots + (\lambda_{k-1} - \lambda_k)v_{k-1} \in U$.

For each $j \in \{1, \dots, k-1\}$, $\lambda_j - \lambda_k \neq 0 \implies (\lambda_j - \lambda_k)v_j = v'_j$ is an eigvec of T corres λ_j .

By asum, each $v'_j \in U$. Thus $v_1, \dots, v_{k-1} \in U$. So that $v_k = v - v_1 - \dots - v_{k-1} \in U$. □

• **TIPS 2:** If $\dim V = m$. Prove $U = (U \cap E_1) \oplus \dots \oplus (U \cap E_m)$, where $E_k = \text{span}(v_k)$.

SOLUS:

Becs $V = E_1 \oplus \dots \oplus E_m$. $\forall u \in U, \exists! e_j \in E_j, u = e_1 + \dots + e_m$.

If $e_j \neq 0$, then e_j is an eigvec corres λ_j . Othws $e_j = 0 \in U$. By TIPS (1), each nonzero $e_j \in U$.

Thus $u \in (U \cap E_1) + \dots + (U \cap E_m) = U$. Becs each $(U \cap E_j) \subseteq E_j$.

For each $k \in \{2, \dots, n\}$, $((U \cap E_1) + \dots + (U \cap E_{k-1})) \cap (U \cap E_k) \subseteq (E_1 + \dots + E_{k-1}) \cap E_k = \{0\}$. □

• **TIPS 3:** Sups W is a nonzero invarsp of V under T . If $\dim V = m \geq 1$.

Prove $W = \text{span}(v_{\alpha_1}, \dots, v_{\alpha_A})$ for some disti $\alpha_1, \dots, \alpha_A \in \{1, \dots, m\}$.

SOLUS:

Each $\text{span}(v_{\alpha_1}, \dots, v_{\alpha_A})$ is invar T .

By TIPS (2), $U = (U \cap E_1) \oplus \dots \oplus (U \cap E_m)$. Becs each $\dim E_k = 1$, $U \cap E_k = \{0\}$ or E_k .

There must be at least one k suth $E_k = U \cap E_k$, for if not, $U = \{0\}$ since $V = E_1 \oplus \dots \oplus E_m$.

Let $\alpha_1, \dots, \alpha_A \in \{1, \dots, m\}$ be all the disti indices for which $E_k = U \cap E_k$.

Thus $U = (U \cap E_1) \oplus \dots \oplus (U \cap E_m) = E_{\alpha_1} \oplus \dots \oplus E_{\alpha_A} = \text{span}(v_{\alpha_1}, \dots, v_{\alpha_A})$. □

1 Sups $T \in \mathcal{L}(V)$ and U is a subsp of V .

(a) If $U \subseteq \text{null } T$, then U is invard T . $\forall u \in U \subseteq \text{null } T, Tu = 0 \in U$. □

(b) If $\text{range } T \subseteq U$, then U is invard T . $\forall u \in U, Tu \in \text{range } T \subseteq U$. □

• Sups $S, T \in \mathcal{L}(V)$ are suth $ST = TS$.

(a) Prove $\text{null } (T - \lambda I)$ is invard S for any $\lambda \in \mathbf{F}$.

(b) Prove $\text{range } (T - \lambda I)$ is invard S for any $\lambda \in \mathbf{F}$.

SOLUS:

Note that $ST = TS \Rightarrow (T - \lambda I)S = S(T - \lambda I)$.

(a) $(T - \lambda I)(v) = 0 \Rightarrow (T - \lambda I)(Sv) = (S(T - \lambda I))(v) = 0$.

(b) $(T - \lambda I)(u) = v \in \text{range } (T - \lambda I) \Rightarrow Sv = (S(T - \lambda I))(u) = (T - \lambda I)(Su) \in \text{range } (T - \lambda I)$. □

• Sups $S, T \in \mathcal{L}(V)$ are suth $ST = TS$.

2 Show $W = \text{null } T$ is invard S . $\forall u \in W, Tu = 0 \Rightarrow STu = 0 = TSu \Rightarrow Su \in W$. □

3 Show $U = \text{range } T$ is invard S . $\forall w \in U, \exists v \in V, Tv = w, TSv = STv = Sw \in U$. □

• Sups $T \in \mathcal{L}(V)$ and V_1, \dots, V_m are invarsp of V under T .

4 $\forall v_i \in V_i, Tv_i \in V_i \Rightarrow \forall v = v_1 + \dots + v_m \in V_1 + \dots + V_m, Tv = Tv_1 + \dots + Tv_m \in V_1 + \dots + V_m$. □

5 $\forall v \in \bigcap_{i=1}^m V_i, Tv \in V_i, \forall i \in \{1, \dots, m\} \Rightarrow Tv \in \bigcap_{i=1}^m V_i$. Thus $\bigcap_{i=1}^m V_i$ is invard T . □

6 Sups U is invarsp of V under each $T \in \mathcal{L}(V)$. Show $U = \{0\}$ or $U = V$.

SOLUS: If $V = \{0\}$. Then done. Sups $V \neq \{0\}$. We show the ctrapos:

Sups $U \neq \{0\}$ and $U \neq V$. Prove $\exists T \in \mathcal{L}(V)$ suth U is not invard T .

Let W be suth $V = U \oplus W$. Define $T \in \mathcal{L}(V)$ by $T(u + w) = w$. □

• **TIPS:** Sups $T \in \mathcal{L}(\mathbf{R}^2)$ is the counterclockwise rotation by the angle $\theta \in \mathbf{R}$.

Define $\mathcal{C} \in \mathcal{L}(\mathbf{R}^2, \mathbf{C})$ by $\mathcal{C}(a, b) = a + ib = r(\cos \alpha + i \sin \alpha) \Rightarrow a = r \cos \alpha, b = r \sin \alpha$, where $r = a^2 + b^2$.

Then $(\cos \theta + i \sin \theta)(a + ib) = r(\cos(\alpha + \theta) + i \sin(\alpha + \theta)) = \mathcal{C}^{-1}T(a, b)$.

Hence $T(a, b) = (a \cos \theta - b \sin \theta, a \sin \theta + b \cos \theta)$. Now $\mathcal{M}(T) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$.

EXA: OR **7** Sups $T \in \mathcal{L}(\mathbf{R}^2)$ is defined by $T(x, y) = (-3y, x)$. Find all eigvals of T .

NOTICE that $\mathcal{M}(T) = \begin{pmatrix} \cos 90^\circ & -3 \sin 90^\circ \\ \sin 90^\circ & \cos 90^\circ \end{pmatrix}$. By [5.8](a), we conclude that T has no eigvals.

OR. Sups λ is an eigval with an eigvec (x, y) . Then $(\lambda x, \lambda y) = (-3y, x) \Rightarrow -3y = \lambda^2 y \Rightarrow \lambda^2 = -3$.

[Ignoring the possibility of $y = 0$, becs $x = 0 \Leftrightarrow y = 0$.] □

8 Define $T \in \mathcal{L}(\mathbf{F}^2)$ by $T(w, z) = (z, w)$. Find all eigvals and eigvecs.

SOLUS: Sups λ is an eigval with an eigvec (w, z) . Then $z = \lambda w$ and $w = \lambda z$.

Thus $z = \lambda^2 z \Rightarrow \lambda^2 = 1$, ignoring the possibility of $z = 0$ ($z = 0 \Leftrightarrow w = 0$).

Hence $\lambda_1 = -1$ and $\lambda_2 = 1$ are all the eigvals of T . And $T(z, z) = (z, z), T(z, -z) = (-z, z)$.

又 $\dim \mathbf{F}^2 = 2$. Thus the set of all eigvecs is $\{(z, z), (z, -z) : z \neq 0\}$. □

9 Define $T \in \mathcal{L}(\mathbf{F}^3)$ by $T(z_1, z_2, z_3) = (2z_2, 0, 5z_3)$. Find all eigvals and eigvecs.

SOLUS: Sups λ is an eigval with an eigvec (z_1, z_2, z_3) .

Then $(2z_2, 0, 5z_3) = \lambda(z_1, z_2, z_3)$. We discuss in two cases:

For $\lambda = 0$, $z_2 = z_3 = 0$ and z_1 can be arb ($z_1 \neq 0$).

For $\lambda \neq 0$, $z_2 = 0 = z_1$, and z_3 can be arb ($z_3 \neq 0$), then $\lambda = 5$.

The set of all eigvecs is $\{(0, 0, w), (w, 0, 0) : w \neq 0\}$. □

10 Define $T \in \mathcal{L}(\mathbf{F}^n)$ by $T(x_1, x_2, x_3, \dots, x_n) = (x_1, 2x_2, 3x_3, \dots, nx_n)$

(a) Find all eigvals and eigvecs; (b) Find all invarsp of V under T .

SOLUS:

(a) Sups $x = (x_1, x_2, x_3, \dots, x_n)$ is an eigvec with an eigval λ .

Then $Tx = \lambda v = (x_1, 2x_2, 3x_3, \dots, nx_n) = (\lambda x_1, \lambda x_2, \lambda x_3, \dots, \lambda x_n)$.

Hence $1, \dots, n$ of len $\dim \mathbf{F}^n$ are all the eigvals.

And $\{(0, \dots, 0, x_k, 0, \dots, 0) \in \mathbf{F}^n : x_k \neq 0, k = 1, \dots, n\}$ is the set of all eigvecs.

(b) Let (e_1, \dots, e_n) be the std bss of \mathbf{F}^n . Let $V_k = \text{span}(e_k)$. Then V_1, \dots, V_n are invard T .

Hence by TIPS (3), every sum of V_1, \dots, V_n is a invarsp of V under T . □

18 Define $T \in \mathcal{L}(\mathbf{F}^\infty)$ by $T(z_1, z_2, \dots) = (0, z_1, z_2, \dots)$. Show T has no eigvals.

SOLUS: Sups λ is an eigval of T with an eigvec (z_1, z_2, \dots) .

Then $T(z_1, z_2, \dots) = (\lambda z_1, \lambda z_2, \dots) = (0, z_1, z_2, \dots)$. Thus $\lambda z_1 = 0, \lambda z_k = z_{k-1}$.

If $\lambda = 0$, then $\lambda z_2 = z_1 = 0 = \dots = z_k \Rightarrow (z_1, z_2, \dots) = 0 \Rightarrow 0$ is not an eigval.

If $\lambda \neq 0$, then $\lambda z_1 = 0 \Rightarrow z_1 = \dots = z_k = 0 \Rightarrow \lambda$ is not an eigval. Now no $\lambda \in \mathbf{F}$ is an eigval. □

19 Sups $n \in \mathbf{N}^+$. Define $T \in \mathcal{L}(\mathbf{F}^n)$ by $T(x_1, \dots, x_n) = (x_1 + \dots + x_n, \dots, x_1 + \dots + x_n)$.

In other words, the ent of $\mathcal{M}(T)$ wrto the std bss are all 1's.

Find all eigvals and eigvecs of T .

SOLUS:

Sups λ is an eigval of T with an eigvec (x_1, \dots, x_n) .

Then $T(x_1, \dots, x_n) = (\lambda x_1, \dots, \lambda x_n) = (x_1 + \dots + x_n, \dots, x_1 + \dots + x_n)$.

Thus $\lambda x_1 = \dots = \lambda x_n = x_1 + \dots + x_n$.

For $\lambda = 0$, $x_1 + \dots + x_n = 0$ } $\Rightarrow 0, n$ are the eigvals of T .

For $\lambda \neq 0$, $x_1 = \dots = x_n \Rightarrow \lambda x_k = nx_k$ }

And the set of all eigvecs of T is $\{(x_1, \dots, x_n) \in \mathbf{F}^n \setminus \{0\} : x_1 + \dots + x_n = 0 \vee x_1 = \dots = x_n\}$. □

20 Define $S \in \mathcal{L}(\mathbf{F}^\infty)$ by $S(z_1, z_2, z_3, \dots) = (z_2, z_3, \dots)$.

(a) Show every ele of \mathbf{F} is an eigval of S ; (b) Find all eigvecs of S .

SOLUS:

Sups λ is an eigval of S with an eigvec (z_1, z_2, \dots) .

Then $S(z_1, z_2, \dots) = (\lambda z_1, \lambda z_2, \dots) = (z_2, z_3, \dots)$. Thus for each $k \in \mathbf{N}^+$, $\lambda z_k = z_{k+1}$.

If $\lambda = 0$, then $\lambda z_1 = z_2 = \dots = z_k = 0$ for all k , while z_1 can be nonzero. Thus 0 is an eigval.

If $\lambda \neq 0$, then $\lambda^k z_1 = \lambda^{k-1} z_2 = \dots = \lambda z_k = z_{k+1}$, let $z_1 \neq 0 \Rightarrow (1, \lambda, \lambda^2, \dots, \lambda^k, \dots)$ is an eigvec.

Now each $\lambda \in \mathbf{F}$ is an eigval of T , with corres eigvecs in $\text{span}((1, \lambda, \lambda^2, \dots, \lambda^k, \dots))$. □

11 Define $T : \mathcal{P}(\mathbf{R}) \rightarrow \mathcal{P}(\mathbf{R})$ by $Tp = p'$. Find all eigvals and eigvecs.

SOLUS:

Note that $\forall p \in \mathcal{P}(\mathbf{R}) \setminus \{0\}, \deg p' < \deg p$. And $\deg 0 = -\infty$. Sups λ is an eigval with an eigvec p .

Asum $\lambda \neq 0$. Then $\deg \lambda p > \deg p'$ while $\lambda p = p'$. Ctradic. Thus $\lambda = 0$.

Therefore $\deg \lambda p = -\infty = \deg p' \Rightarrow p \in \mathcal{P}_0(\mathbf{R})$. Hence the eigvecs are all the nonzero consts. \square

12 Define $T \in \mathcal{L}(\mathcal{P}_n(\mathbf{R}))$ by $(Tp)(x) = xp'(x)$ for all $x \in \mathbf{R}$. Find all eigvals and eigvecs.

SOLUS:

Sups λ is an eigval of T with an eigvec p , then $(Tp)(x) = xp'(x) = \lambda p(x)$.

Let $p = a_0 + a_1x + \dots + a_nx^n$. Then $xp'(x) = a_1x + 2a_2x^2 + \dots + na_nx^n = \lambda a_0 + \lambda a_1x + \lambda a_2x^2 + \dots + \lambda a_nx^n$.

Define $S \in \mathcal{L}(\mathbf{F}^{n+1}, \mathcal{P}_n(\mathbf{R}))$ by $S(a_0, a_1, \dots, a_n) = a_0 + a_1x + \dots + a_nx^n$.

Then $(S^{-1}TS)(a_0, a_1, \dots, a_n) = (0 \cdot a_0, 1 \cdot a_1, 2 \cdot a_2, \dots, n \cdot a_n)$. Thus $0, 1, \dots, n$ are the eigvals of $S^{-1}TS$.

By Exe (15), $0, 1, \dots, n$ are the eigvals of T . The set of all eigvecs is $\{cx^\lambda : c \neq 0, \lambda = 0, 1, \dots, n\}$. \square

• Sups V is finide, $T \in \mathcal{L}(V), \lambda \in \mathbf{F}$.

13 Prove $\forall \lambda \in \mathbf{F}, \exists \alpha \in \mathbf{F}, |\alpha - \lambda| < \frac{1}{1000}, (T - \alpha I)$ is inv.

SOLUS:

Let $\alpha_k \in \mathbf{F}$ be suth $|\alpha_k - \lambda| = \frac{1}{1000+k}$ for each $k = 1, \dots, \dim V + 1$.

Note that each $T \in \mathcal{L}(V)$ has at most $\dim V$ disti eigvals.

Hence $\exists k = 1, \dots, \dim V + 1$ suth α_k is not an eigval of T and therefore $(T - \alpha_k I)$ is inv. \square

• (4E 5.A.11) Prove $\exists \delta > 0$ suth $(T - \alpha I)$ is inv for all $\alpha \in \mathbf{F}$ suth $0 < |\alpha - \lambda| < \delta$.

SOLUS:

If T has no eigvals, then $(T - \alpha I)$ is inje for all $\alpha \in \mathbf{F}$ and done.

Sups $\lambda_1, \dots, \lambda_m$ are all the disti eigvals of T .

Let $\delta > 0$ be suth, for each eigval $\lambda_k, \lambda_k \notin (\lambda - \delta, \lambda) \cup (\lambda, \lambda + \delta)$.

So that for all $\alpha \in \mathbf{F}$ suth $0 < |\alpha - \lambda| < \delta, (T - \alpha I)$ is not inje. \square

OR. Let $\delta = \min\{|\lambda - \lambda_k| : k \in \{1, \dots, m\}, \lambda_k \neq \lambda\}$.

Then $\delta > 0$ and each $\lambda_k \neq \alpha \iff (T - \alpha I)$ is inv for all $\alpha \in \mathbf{F}$ suth $0 < |\alpha - \lambda| < \delta$. \square

• (5.B.4 OR 4E 3.B.27) Sups λ is an eigval of $P \in \mathcal{L}(V), P^2 = P$. Prove $\lambda = 0$ or $\lambda = 1$.

SOLUS: Sups λ is an eigval with an eigvec v . Then $P(Pv) = Pv \Rightarrow \lambda^2 v = \lambda v$. Thus $\lambda = 1$ or 0 . \square

14 Sups $V = U \oplus W$, where U and W are nonzero subsps of V .

Define $P \in \mathcal{L}(V)$ by $P(u + w) = u$ for each $u \in U$ and each $w \in W$.

Find all eigvals and eigvecs of P .

SOLUS:

Sups λ is an eigval of P with an eigvec $(u + w)$.

Then $P(u + w) = u = \lambda u + \lambda w \Rightarrow (\lambda - 1)u + \lambda w = 0$.

OR. Note that $P|_{\text{range } P} = I|_{\text{range } P} \iff P^2 = P$. By (4E 5.A.8), 1 and 0 are the eigvals.

By [1.44], $(\lambda - 1)u = \lambda w = 0$, hence $\lambda = 0 \iff u = 0$, and $\lambda = 1 \iff w = 0$.

Thus $Pu = u, Pw = 0$. Hence the eigvals are 0 and 1, the set of all eigvecs of P is $U \cup W$. \square

15 Sups $T \in \mathcal{L}(V)$. Sups $S \in \mathcal{L}(V)$ is inv.

(a) Prove T and $S^{-1}TS$ have the same eigvals.

(b) What is the relationship between the eigvecs of T and the eigvecs of $S^{-1}TS$?

SOLUS:

(a) λ is an eigval of T with an eigvec $v \Rightarrow S^{-1}TS(\underline{S^{-1}v}) = S^{-1}Tv = S^{-1}(\lambda v) = \underline{\lambda S^{-1}v}$.

λ is an eigval of $S^{-1}TS$ with an eigvec $v \Rightarrow S(S^{-1}TS)v = TSv = \underline{\lambda Sv}$.

OR. Note that $S(S^{-1}TS)S^{-1} = T$. Hence every eigval of $S^{-1}TS$ is an eigval of $S(S^{-1}TS)S^{-1} = T$.

OR. $Tv = \lambda v \Leftrightarrow (TS)(u) = \lambda Su \Leftrightarrow (S^{-1}TS)(u) = \lambda u$. Where $v = Su$.

$(S^{-1}TS)(u) = \lambda u \Leftrightarrow (S^{-1}T)(v) = \lambda S^{-1}v \Leftrightarrow Tv = \lambda v$. Where $u = S^{-1}v$.

(b) Becs λ is an eigval of $T \Leftrightarrow \lambda$ is an eigval of $S^{-1}TS$.

(See [5.36].) Now $E(\lambda, T) = \{Su : u \in E(\lambda, S^{-1}TS)\}; E(\lambda, S^{-1}TS) = \{S^{-1}v : v \in E(\lambda, T)\}$. \square

17 Give an exa of an optor on \mathbb{R}^4 that has no real eigvals.

SOLUS:

Let (e_1, e_2, e_3, e_4) be the std bss of \mathbb{R}^4 .

Define $T \in \mathcal{L}(\mathbb{R}^4)$ by $\mathcal{M}(T, (e_1, e_2, e_3, e_4)) = \begin{pmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & -1 \\ 3 & 8 & 11 & 5 \\ 3 & -8 & -11 & 5 \end{pmatrix}$.

Sups λ is an eigval of T with an eigvec (x, y, z, w) . Then we get
$$\begin{cases} (1-\lambda)x + y + z + w = 0, \\ -x + (1-\lambda)y - z - w = 0, \\ 3x + 8y + (11-\lambda)z + 5w = 0, \\ 3x - 8y - 11z + (5-\lambda)w = 0. \end{cases}$$

This set of liney equations has no solutions.

[You can type it on <https://zh.numberempire.com/equationsolver.php> to check.]

OR. Define $T \in \mathcal{L}(\mathbb{R}^4)$ by $T(x_1, x_2, x_3, x_4) = (-x_2, x_1, -x_4, x_3)$.

Sups λ is an eigval of T with an eigvec (x, y, z, w) .

Then $T(x, y, z, w) = (\lambda x, \lambda y, \lambda z, \lambda w) = (-y, x, -w, z) \Rightarrow \begin{cases} -y = \lambda x, x = \lambda y \Rightarrow -xy = \lambda^2 xy \\ -w = \lambda z, z = \lambda w \Rightarrow -zw = \lambda^2 zw \end{cases}$

If $xy \neq 0$ or $zw \neq 0$, then $\lambda^2 = -1$, we fail.

Othws, $xy = 0 \Rightarrow x = y = 0$, for if $x \neq 0$, then $\lambda = 0 \Rightarrow x = 0$, ctradic.

Simlr, $y = z = w = 0$. Then we fail. Thus T has no eigvals. \square

• (4E 5.A.16) Sups $B_V = (v_1, \dots, v_n)$, $T \in \mathcal{L}(V)$, $\mathcal{M}(T, (v_1, \dots, v_n)) = A$.

Prove if λ is an eigval of T , then $|\lambda| \leq n \max\{|A_{j,k}| : 1 \leq j, k \leq n\}$.

SOLUS:

Sups v is an eigval of T corres to λ . Let $v = c_1 v_1 + \dots + c_n v_n$.

Becs $\lambda c_1 v_1 + \dots + \lambda c_n v_n = c_1 T v_1 + \dots + c_n T v_n = \sum_k^n c_k (\sum_j^n A_{j,k} v_j)$.

We have $\lambda c_j = \sum_{k=1}^n c_k A_{j,k} \Rightarrow |\lambda| |c_j| = \sum_{k=1}^n |c_k| |A_{j,k}|$ for each $j \in \{1, \dots, n\}$

Let $|c_j| = \max\{|c_1|, \dots, |c_n|\}$. Note that $|c_j| \neq 0$, for if not, $c_1 = \dots = c_n = 0 \Rightarrow v = 0$, ctradic.

Let $M = \max\{|A_{j,k}| : 1 \leq j, k \leq n\}$. Note that for each j , $\sum_{k=1}^n |A_{j,k}| \leq \sum_{k=1}^n M = nM$.

Thus $|\lambda| |c_j| = \sum_{k=1}^n |c_k| |A_{j,k}| \Rightarrow |\lambda| \leq \sum_{k=1}^n |A_{j,k}| \frac{|c_k|}{|c_j|} \leq \sum_{k=1}^n |A_{j,k}| \leq nM$. \square

- (4E 5.A.15) Sups $T \in \mathcal{L}(V)$, and $\lambda \in \mathbf{F}$.

Show λ is an eigval of $T \iff \lambda$ is an eigval of the dual optor $T' \in \mathcal{L}(V')$.

SOLUS:

- (a) Sups λ is an eigval of T with an eigvec v .

Let U be invar suth $V = \text{span}(v) \oplus U$ [by (4E 5.A.39)].

Define $\psi \in V'$ by $\psi(cv + u) = c$.

Now $[T'(\psi)](cv + u) = \psi(cv + Tu) = \lambda cv = \lambda\psi(cv + u)$. Hence $T'(\psi) = \lambda\psi$.

- (b) Sups λ is an eigval T' with an eigvec ψ . Then $T'(\psi) = \psi \circ T = \lambda\psi$.

Note that $\psi \neq 0, \psi(Tv) = \lambda\psi(v)$ Thus $\exists v \in V \setminus \{0\}, Tv = \frac{\psi(Tv)}{\psi(v)}v = \lambda v$. □

OR. [Only in Finide] Using [5.6], (4E 3.F.17), [3.101] and (3.F.12).

λ is an eigval of $T \iff (T - \lambda I_V)$ is not inv

$\iff (T - \lambda I_V)' = T' - \lambda I_{V'}$, is not inv $\iff \lambda$ is an eigval of T' . □

24 Sups $A \in \mathbf{F}^{n,n}$. Define $T \in \mathcal{L}(\mathbf{F}^{n,1})$ by $Tx = Ax$.

- (a) Sups the sum of the ent in each row of A equals 1. Prove 1 is an eigval of T .

- (b) Sups the sum of the ent in each col of A equals 1. Prove 1 is an eigval of T .

SOLUS:

Sups λ is an eigval of T with an eigvec x . Then $Tx = Ax = \begin{pmatrix} \sum_{k=1}^n A_{1,k}x_k \\ \vdots \\ \sum_{k=1}^n A_{n,k}x_k \end{pmatrix} = \lambda \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}$.

- (a) Sups $\sum_{r=1}^n A_{r,c} = 1$ for each $c \in \{1, \dots, n\}$.

Then if we let $x_1 = \dots = x_n = 1$, then $\lambda = 1$, and hence is an eigval of T .

- (b) Sups $\sum_{r=1}^n A_{r,c} = 1$ for each $c \in \{1, \dots, n\}$.

Then $\sum_{r=1}^n (Ax)_{r,c} = \sum_{r=1}^n (Ax)_{r,1} = \sum_{c=1}^n (A_{1,c} + \dots + A_{n,c})x_c = \sum_{c=1}^n x_c = \lambda(x_1 + \dots + x_n)$.

Hence $\lambda = 1$ for all $x \in \mathbf{F}^{n,1}$ suth $\sum_{c=1}^n x_{c,1} \neq 0$. □

OR. We show $(T - I)$ is not inv, so that $\lambda = 1$ is an eigval.

$$\text{Becs } (T - I)x = (A - I)x = \begin{pmatrix} \sum_{r=1}^n A_{1,r}x_r - x_1 \\ \vdots \\ \sum_{r=1}^n A_{n,r}x_r - x_n \end{pmatrix} = \begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix}.$$

Then $y_1 + \dots + y_n = \sum_{r=1}^n \sum_{c=1}^n (A_{r,c}x_c - x_r) = \sum_{c=1}^n x_c \sum_{r=1}^n A_{r,c} - \sum_{r=1}^n x_r = 0$.

Thus $\text{range}(T - I) \subseteq \left\{ \begin{pmatrix} y_1 & \dots & y_n \end{pmatrix}^t \in \mathbf{F}^{n,1} : y_1 + \dots + y_n = 0 \right\}$. Hence $(T - I)$ is not surj. □

OR. Let (e_1, \dots, e_n) be the std bss of $\mathbf{F}^{n,1}$. Define $\psi \in (\mathbf{F}^{n,1})'$ by $\psi(e_k) = 1$.

Thus $(\psi \circ (T - I))(e_k) = \psi\left(\left(\sum_{j=1}^n A_{j,k}e_j\right) - e_k\right) = \left(\sum_{j=1}^n A_{j,k}\right) - 1 = 0$.

Which means that $\psi \circ (T - I) = 0$. 又 $\psi \neq 0$. Hence $(T - I)$ is not inje. □

OR. Define $S \in \mathcal{L}(\mathbf{F}^{n,1})$ by $Sx = A^t x$. Becs the rows of A^t are the cols of A .

Now by (a), 1 is an eigval of S . Let $(\varphi_1, \dots, \varphi_n)$ be the dual bss of (e_1, \dots, e_n) .

Define $\Phi \in \mathcal{L}(\mathbf{F}^{n,1}, (\mathbf{F}^{1,n})')$ by $\Phi(e_k) = \varphi_k$. Note that $\mathcal{M}(T') = A^t$.

Now $(\Phi^{-1}T'\Phi)(e_k) = (\Phi^{-1}T')(\varphi_k) = \Phi^{-1}\left(\sum_{j=1}^n A_{k,j}\varphi_j\right) = \sum_{j=1}^n A_{k,j}e_j = A^t e_k = S e_k$.

Thus 1 is an eigval of $S = \Phi^{-1}T'\Phi$, so of T' , [by Exe (15)], so of T , [by (4E 5.A.15)]. □

• Sups $A \in \mathbf{F}^{n,n}$. Define $T \in \mathcal{L}(\mathbf{F}^{1,n})$ by $Tx = xA$.

(a) Sups the sum of the ent in each col of A equals 1. Prove 1 is an eigval of T .

(b) Sups the sum of the ent in each row of A equals 1. Prove 1 is an eigval of T .

SOLUS:

Sups λ is an eigval with an eigvec x . Then $(\sum_{r=1}^n x_r A_{r,1} \quad \cdots \quad \sum_{r=1}^n x_r A_{r,n}) = \lambda(x_1 \quad \cdots \quad x_n)$.

(a) Sups $\sum_{r=1}^n A_{r,C} = 1$ for each $C \in \{1, \dots, n\}$.

Thus if $x_1 = \cdots = x_n$, then $\lambda = 1$, hence is an eigval of T .

(b) Sups $\sum_{c=1}^n A_{R,c} = 1$ for each $R \in \{1, \dots, n\}$.

Thus $\sum_{c=1}^n (xA)_{.,c} = \sum_{c=1}^n (A_{c,1} + \cdots + A_{c,n})x_c = \sum_{c=1}^n x_c = \lambda(x_1 + \cdots + x_n)$.

Hence $\lambda = 1$, for all x suth $\sum_{r=1}^n x_{1,r} \neq 0$. □

OR. We show $(T - I)$ is not inv, so that $\lambda = 1$ is an eigval.

Becs $(T - I)x = x(A - \mathcal{M}(I)) = (\sum_{c=1}^n x_c A_{c,1} - x_1 \quad \cdots \quad \sum_{c=1}^n x_c A_{c,n} - x_n) = (y_1 \quad \cdots \quad y_n)$.

Then $y_1 + \cdots + y_n = \sum_{c=1}^n \sum_{r=1}^n (x_r A_{r,c} - x_c) = \sum_{r=1}^n x_r \sum_{c=1}^n A_{r,c} - \sum_{c=1}^n x_c = 0$.

Thus $\text{range}(T - I) \subseteq \{(y_1 \quad \cdots \quad y_n) \in \mathbf{F}^{1,n} : y_1 + \cdots + y_n = 0\}$. Hence $(T - I)$ is not surj. □

OR. Let (e_1, \dots, e_n) be the std bss of $\mathbf{F}^{1,n}$. Define $\psi \in (\mathbf{F}^{n,1})'$ by $\psi(e_k) = 1$.

Becs $Te_k = e_k A = (A_{k,1} \quad \cdots \quad A_{k,n}) = \sum_{i=1}^n A_{k,i} e_i$. **CORO:** $\mathcal{M}(T) = A^t$.

$(\psi \circ (T - I))(e_k) = (\sum_{i=1}^n A_{k,i}) - 1 = 0$. Then $\psi \circ (T - I) = 0$. 又 $\psi \neq 0$. $(T - I)$ is not inje. □

OR. Define $S \in \mathcal{L}(\mathbf{F}^{1,n})$ by $Sx = xA^t$. Becs the rows of A are the cols of A^t .

Now by (a), 1 is an eigval of S . Let $(\varphi_1, \dots, \varphi_n)$ be the dual bss of (e_1, \dots, e_n) .

Define $\Phi \in \mathcal{L}(\mathbf{F}^{1,n}, (\mathbf{F}^{1,n})')$ by $\Phi(e_k) = \varphi_k$. Becs $[T'(\varphi_k)](e_j) = \varphi_k(\sum_{i=1}^n A_{j,i} e_i) = A_{j,k}$.

By (3.F.9), $T'(\varphi_k) = \sum_{j=1}^n A_{j,k} \varphi_j$. **CORO:** $\mathcal{M}(T') = A = \mathcal{M}(T)^t$. **FIXME:** $\mathcal{M}(T)e_k = A^t e_k = e_k A$

Now $(\Phi^{-1} T' \Phi)(e_k) = (\Phi^{-1} T')(\varphi_k) = \Phi^{-1}(\sum_{j=1}^n A_{j,k} \varphi_j) = \sum_{j=1}^n A_{j,k} e_j = e_k A^t = S e_k$.

Thus 1 is an eigval of $S = \Phi^{-1} T' \Phi$, so of T' , [by Exe (15)], so of T , [by (4E 5.A.15)]. □

• Sups $\mathbf{F} = \mathbf{R}$, $T \in \mathcal{L}(V)$.

(a) [OR (9.11)] $\lambda \in \mathbf{R}$. Prove λ is an eigval of $T \iff \lambda$ is an eigval of T_C .

(b) [OR **16** OR (9.16)] $\lambda \in \mathbf{C}$. Prove λ is an eigval of $T_C \iff \bar{\lambda}$ is an eigval of T_C .

SOLUS:

(a) Sups λ is an eigval of T with an eigvec v .

Then $Tv = \lambda v \implies T_C(v + i0) = Tv + iT0 = \lambda v$. Thus λ is an eigval of T_C .

Sups λ is an eigval of T_C with an eigvec $v + iu$.

Then $T_C(v + iu) = \lambda v + i\lambda u \implies Tv = \lambda v, Tu = \lambda u$. Thus λ is an eigval of T .

(Note that $v + iu$ is nonzero \iff at least one of v, u is nonzero).

(b) Sups λ is an eigval of T_C with an eigvec $v + iu$. Then $T_C(v + iu) = Tv + iTu = \lambda(v + iu)$.

Note that $\overline{T_C(v + iu)} = \overline{Tv + iTu} = \overline{Tv} - i\overline{Tu} = T_C(v - iu) = T_C(\overline{v + iu})$.

And that $\lambda(\overline{v + iu}) = \bar{\lambda}v - i\bar{\lambda}u = \bar{\lambda}(v - iu) = \bar{\lambda}(\overline{v + iu})$.

Hence $\bar{\lambda}$ is an eigval of T_C . To prove the other direction, notice that $\overline{\bar{\lambda}} = \lambda$. □

OR. Sups $\lambda = a + ib$ is an eigval of T_C with an eigvec $v + iu$.

Becs $T_C(v + iu) = \lambda(v + iu) = (av - bu) + i(au + bv) = Tv + iTu \implies Tv = av - bu, Tu = au + bv$.

Now $T_C(\overline{v + iu}) = Tv - iTu = (av - bu) - i(au + bv) = (a - ib)(v - iu) = \bar{\lambda}(\overline{v + iu})$. Simlr. □

21 Sups $T \in \mathcal{L}(V)$ is inv.

(a) Sups $\lambda \in \mathbf{F}$ with $\lambda \neq 0$. Prove λ is an eigval of $T \iff \lambda^{-1}$ is an eigval of T^{-1} .

(b) Prove T and T^{-1} have the same eigvecs.

SOLUS: (a) $Tv = \lambda v \iff v = \lambda T^{-1}v \iff \lambda^{-1}v = T^{-1}v$. Where $v \neq 0$.

(b) NOTICE that T is inv $\implies 0$ is not an eigval of T or T^{-1} . By (a), immediately. \square

22 Sups $T \in \mathcal{L}(V)$ and \exists nonzero vecs u, w in V suth $Tu = 3w, Tw = 3u$.

Prove 3 or -3 is an eigval of T .

SOLUS: $T(u + w) = 3(u + w), T(u - w) = 3(w - u) = -3(u - w)$. Note that $u - w \neq 0$ or $u + w \neq 0$.

OR. $T(Tu) = 9u \Rightarrow T^2 - 9 = (T - 3I)(T + 3I)$ is not injective $\Rightarrow 3$ or -3 is an eigval. \square

23 Sups $S, T \in \mathcal{L}(V)$. Prove ST and TS have the same eigvals.

SOLUS: Sups λ is an eigval of ST with an eigvec v . Then $T(STv) = \lambda Tv = TS(Tv)$.

If $Tv = 0$ (while $v \neq 0$), then T is not inje $\Rightarrow (TS - 0I)$ and $(ST - 0I)$ are not inje.

Thus $\lambda = 0$ is an eigval of ST and TS with the same eigvec v .

Othws, $Tv \neq 0$, then λ is an eigval of TS . Reversing the roles of T and S . \square

• (2E 20) Sups $T \in \mathcal{L}(V)$ has $\dim V$ disti eigvals and $S \in \mathcal{L}(V)$ has the same eigvecs (but might not with the same eigvals). Prove $ST = TS$.

SOLUS: Let $n = \dim V$. For each $j \in \{1, \dots, n\}$, let v_j be an eigvec with eigval λ_j of T and α_j of S .

Then $B_V = (v_1, \dots, v_n)$. Becs $(ST)v_j = \alpha_j \lambda_j v_j = (TS)v_j$ for each j . Hence $ST = TS$. \square

• (4E 5.A.37) Sups V is finide and $T \in \mathcal{L}(V)$.

Define $\mathcal{A} \in \mathcal{L}(\mathcal{L}(V))$ by $\mathcal{A}(S) = TS$ for each $S \in \mathcal{L}(V)$.

Prove the set of eigvals of T equals the set of eigvals of \mathcal{A} .

SOLUS:

(a) Sups λ is an eigval of T with an eigvec $v = v_1$. Let $B_V = (v_1, \dots, v_m, \dots, v_n)$.

Note that $\text{span}(v) \subseteq \text{null}(T - \lambda I)$. Define $S \in \mathcal{L}(V)$ by $S(v_j) = v$ for each $j \in \{1, \dots, n\}$.

OR. Define $S \in \mathcal{L}(V)$ by $Sv_1 = v_1, Sv_j = 0$ for $j \geq 2$. Then $(T - \lambda I)Sv_1 = 0 = (T - \lambda I)Sv_k = 0$.

Then $(T - \lambda I)S = 0$. Thus $\mathcal{A}(S) = TS = \lambda S$ while $S \neq 0$. Hence λ is an eigval of \mathcal{A} .

(b) Sups λ is an eigval of \mathcal{A} with an eigvec S .

Then $\exists v \in V, 0 \neq u = S(v) \in V \Rightarrow Tu = (TS)v = (\lambda S)v = \lambda u$. Thus λ is an eigval T .

OR. Becs $TS - \lambda S = (T - \lambda I)S = 0 \Rightarrow \{0\} \subsetneq \text{range } S \subseteq \text{null}(T - \lambda I)$. $(T - \lambda I)$ is not inje. \square

COMMENT: If $\mathcal{A}(S) = ST, \forall S \in \mathcal{L}(V)$. Then the eigvals of \mathcal{A} are not the eigvals of T .

25 Sups $T \in \mathcal{L}(V)$ and u, w are eigvecs of T suth $u + w$ is also an eigvec of T .

Prove u and w corres to the same eigval.

SOLUS: Sups $\lambda_1, \lambda_2, \lambda_0$ are eigvals of T with eigvecs to $u, w, u + w$ respectly.

Then $T(u + w) = \lambda_0(u + w) = Tu + Tw = \lambda_1 u + \lambda_2 w \Rightarrow (\lambda_0 - \lambda_1)u = (\lambda_2 - \lambda_0)w$.

If (u, w) is linely depe, then let $w = cu$, therefore $\lambda_2 cu = Tw = cTu = \lambda_1 cu \Rightarrow \lambda_2 = \lambda_1$.

Othws, (u, w) is liney indep. Then $\lambda_0 - \lambda_1 = \lambda_2 - \lambda_0 = 0 \Rightarrow \lambda_1 = \lambda_2 = \lambda_0$. \square

OR. Asum $\lambda_1 \neq \lambda_2$. Then (u, w) is liney indep. Thus $\lambda_0 - \lambda_1 = \lambda_0 - \lambda_2$. Ctradic. \square

26 Sups $T \in \mathcal{L}(V)$ is suth every nonzero vec in V is an eigvec of T .

Prove T is a scalar multi of the id optor.

SOLUS: If $\dim V = 0, 1$ then done. Sups $\dim V \geq 2$.

Becs $\forall v \in V, \exists! \lambda_v \in \mathbf{F}, Tv = \lambda_v v$. For any two disti nonzero vecs $v, w \in V$,

$$T(v + w) = \lambda_{v+w}(v + w) = Tv + Tw = \lambda_v v + \lambda_w w \Rightarrow (\lambda_{v+w} - \lambda_v)v = (\lambda_w - \lambda_{v+w})w. \quad \square$$

OR. For any two nonzero vecs $u, v \in V, u, v$ are eigvecs.

If $u + v \neq 0$, then $u + v$ is also an eigvec. Othws, $u + v = 0$, then $Tu = -Tv = \lambda u = -\lambda v$.

Thus by Exe (25), $\forall u, v \in V, Tu = \lambda u, Tv = \lambda v \Rightarrow \forall v \in V, Tv = \lambda v$. \square

27, 28 Sups V is finide and $k \in \{1, \dots, \dim V - 1\}$.

Sups $T \in \mathcal{L}(V)$ is suth every subsp of V of dim k is invard T .

Prove T is a scalar multi of the id optor.

SOLUS: If $\dim V \leq 1$ then done. Sups $\dim V \geq 2$.

We prove the ctrapos: If T is not a scalar multi of I . Then \exists subsp U of dim k not invard T .

By Exe (26), $\exists v \in V$ and $v \neq 0$ suth v is not an eigvec of T .

Thus (v, Tv) is liney indep. Extend to $B_V = (v, Tv, u_1, \dots, u_n)$.

Let $U = \text{span}(v, u_1, \dots, u_{k-1}) \Rightarrow U$ is not invarsp of V under T . \square

OR. Sups $0 \neq v = v_1 \in V$. Extend to $B_V = (v_1, \dots, v_n)$. Sups $Tv_1 = c_1 v_1 + \dots + c_n v_n, \exists! c_i \in \mathbf{F}$.

Consider a k -dim subsp $U = \text{span}(v_1, v_{\alpha_1}, \dots, v_{\alpha_{k-1}})$. Where $\alpha_1, \dots, \alpha_{k-1} \in \{2, \dots, n\}$ are disti.

Becs every subsp such U is invar. $Tv_1 = c_1 v_1 + \dots + c_n v_n \in U \Rightarrow c_2 = \dots = c_n = 0$.

For if not, $\exists c_i \neq 0$, let $W = \text{span}(v_1, v_{\beta_1}, \dots, v_{\beta_{k-1}})$, where each $\beta_j \in \{2, \dots, i-1, i+1, \dots, n\}$.

Hence $Tv_1 = c_1 v_1$. Becs $v_1 = v \in V$ is arb. We conclude that $T = \lambda I$ for some $\lambda \in \mathbf{F}$. \square

OR. For each $k \in \{1, \dots, \dim V - 1\}$, define $P(k)$: if every subsp of dim k is invar, then $T = \lambda I$.

(i) If every subsp of dim 1 is invar, then by Exe (26), $T = \lambda I$. Thus $P(1)$ holds.

(ii) Asum $P(k)$ holds for $k \in \{1, \dots, \dim V - 1\}$. And every subsp of dim $k + 1$ is invar.

Let U be a subsp of dim k . If $\dim U = \dim V - 1$ then extend B_U to B_V and done.

Sups $\dim U \in \{1, \dots, \dim V - 2\}$. Choose two liney indep vecs $v, w \notin U$.

Becs $U \oplus \text{span}(v)$ and $U \oplus \text{span}(w)$ of dim $k + 1$ are invar.

Sups $u \in U$. Let $Tu = a_1 u_1 + bv = a_2 u_2 + cw, \exists! u_1, u_2 \in U, a_1, a_2, b, c \in \mathbf{F}$.

Now $a_1 u_1 - a_2 u_2 = cw - bv \in U \cap \text{span}(v) = \{0\} \Rightarrow b = c = 0$. Thus $Tu \in U$.

Becs $P(k)$ holds, we conclude that $T = \lambda I$. Thus $P(k + 1)$ holds. \square

29 Sups $T \in \mathcal{L}(V)$ and range T is finide.

Prove T has at most $1 + \dim \text{range } T$ disti eigvals.

SOLUS:

Let $\lambda_1, \dots, \lambda_m$ be the disti eigvals of T with corres eigvecs v_1, \dots, v_m .

(Becs range T is finide. The corres eigvals are fini.)

Then (v_1, \dots, v_m) liney indep $\Rightarrow (\lambda_1 v_1, \dots, \lambda_m v_m)$ liney indep, if each $\lambda_k \neq 0$.

Othws, $\exists! \lambda_k = 0$. Now $(\lambda_1 v_1, \dots, \lambda_{k-1} v_{k-1}, \lambda_{k+1} v_{k+1}, \dots, \lambda_m v_m)$ is liney indep.

Hence, by [2.23], $m - 1 \leq \dim \text{range } T$. \square

30 Sups $T \in \mathcal{L}(\mathbf{R}^3)$ and $-4, 5, \sqrt{7}$ are eigvals. Prove $\exists x, Tx - 9x = (-4, 5, \sqrt{7})$.

SOLUS: T has $\dim \mathbf{R}^3$ eigvals not including 9 $\Rightarrow (T - 9I)$ is inv. $x = (T - 9I)^{-1}(-4, 5, \sqrt{7})$. \square

31 Sups V is finide, and $v_1, \dots, v_m \in V$. Prove

(v_1, \dots, v_m) is liney indep $\iff v_1, \dots, v_m$ are eigvecs of some T corres to disti eigvals.

SOLUS: Sups (v_1, \dots, v_m) is liney indep. Let $B_V = (v_1, \dots, v_m, \dots, v_n)$.

Define $T \in \mathcal{L}(V)$ by $Tv_k = k \cdot v_k$ for each $k \in \{1, \dots, m, \dots, n\}$. Conversely by [5.10]. \square

• Sups $\lambda_1, \dots, \lambda_n \in \mathbf{R}$ are disti.

(a) **32** Prove $(e^{\lambda_1 x}, \dots, e^{\lambda_n x})$ is liney indep in $\mathbf{R}^{\mathbf{R}}$.

HINT: Let $V = \text{span}(e^{\lambda_1 x}, \dots, e^{\lambda_n x})$. Define $D \in \mathcal{L}(V)$ by $Df = f'$. Find eigvals and eigvecs of D .

(b) [4E 36] Show $(\cos(\lambda_1 x), \dots, \cos(\lambda_n x))$ is liney indep in $\mathbf{R}^{\mathbf{R}}$.

SOLUS:

(a) Define V and $D \in \mathcal{L}(V)$ as in HINT. Then becs for each k , $D(e^{\lambda_k x}) = \lambda_k e^{\lambda_k x}$.

Thus $\lambda_1, \dots, \lambda_n$ are disti eigvals of D . By [5.10], $(e^{\lambda_1 x}, \dots, e^{\lambda_n x})$ is liney indep in $\mathbf{R}^{\mathbf{R}}$. \square

(b) Let $V = \text{span}(\cos(\lambda_1 x), \dots, \cos(\lambda_n x))$. Define $D \in \mathcal{L}(V)$ by $Df = f'$.

Then becs $D(\cos(\lambda_k x)) = -\lambda_k \sin(\lambda_k x)$. A $D(\sin(\lambda_k x)) = \lambda_k \cos(\lambda_k x)$.

Thus $D^2(\cos(\lambda_k x)) = -\lambda_k^2 \cos(\lambda_k x)$.

Notice that $\lambda_1, \dots, \lambda_n$ are disti $\implies -\lambda_1^2, \dots, -\lambda_n^2$ are disti. And $\dim V = n$.

Hence $-\lambda_1^2, \dots, -\lambda_n^2$ are all the eigvals of D^2 with corres eigvecs $\cos(\lambda_1 x), \dots, \cos(\lambda_n x)$.

And then $(\cos(\lambda_1 x), \dots, \cos(\lambda_n x))$ is liney indep in $\mathbf{R}^{\mathbf{R}}$. \square

33 Sups $T \in \mathcal{L}(V)$. Prove $T/(\text{range } T) = 0$.

SOLUS: $v + \text{range } T \in V/\text{range } T \implies v + \text{range } T \in \text{null}(T/(\text{range } T))$. Hence $T/(\text{range } T) = 0$. \square

34 Sups $T \in \mathcal{L}(V)$. Prove $T/(\text{null } T)$ is inje $\iff (\text{null } T) \cap (\text{range } T) = \{0\}$.

SOLUS: NOTICE that $(T/(\text{null } T))(u + \text{null } T) = Tu + \text{null } T = 0 \iff Tu \in (\text{null } T) \cap (\text{range } T)$.

Now $T/(\text{null } T)$ is inje $\iff u + \text{null } T = 0 \iff Tu = 0 \iff (\text{null } T) \cap (\text{range } T) = \{0\}$. \square

• Sups V is finide, $T \in \mathcal{L}(V)$, and U is invarsp of V under T .

Define $T/U : V/U \rightarrow V/U$ by $(T/U)(v + U) = Tv + U$ for each $v \in V$.

(a) Show T/U is well-defined and is liney. Req U invarsp of T .

(b) [OR 35] Show each eigval of T/U is an eigval of T .

SOLUS:

(a) $v + U = w + U \iff v - w \in U \implies T(v - w) \in U \iff Tv + U = Tw + U$.

Hence T/U is well-defined. Now we show T/U is liney.

$(T/U)((v + U) + \lambda(w + U)) = T(v + \lambda w) + U = (T/U)(v + U) + \lambda(T/U)(w)$. Checked.

(b) Sups λ is an eigval of T/U with an eigvec $v + U$. Then $Tv + U = \lambda v + U \implies (T - \lambda I)v = u \in U$.

If $u = 0 \implies Tv = \lambda v$, then done. Othws, we discuss in two cases.

If $(T - \lambda I)|_U$ is inv. Then $\exists! w \in U$, $(T - \lambda I)(w) = u = (T - \lambda I)v \implies T(v + w) = \lambda(v + w)$.

Note that $v + w \neq 0$, for if not, $v \in U \implies v + U = 0$, ctradic. Thus λ is an eigval of T .

If $(T - \lambda I)|_U$ is not inv. Then becs V is finide, $(T - \lambda I)|_U$ is not inje,

so that $\exists w \in \text{null}(T - \lambda I)|_U$, $w \neq 0$, $(T - \lambda I)w = 0 \implies Tw = \lambda w$. \square

OR. Let $B_U = (u_1, \dots, u_m)$. Then $((T - \lambda I)v, (T - \lambda I)u_1, \dots, (T - \lambda I)u_m)$ is liney indep in U .

So that $a_0(T - \lambda I)v + a_1(T - \lambda I)u_1 + \dots + a_m(T - \lambda I)u_m = 0$, $\exists a_0, a_1, \dots, a_m \in \mathbf{F}$ with some $a_i \neq 0$.

Let $w = a_0 v + a_1 u_1 + \dots + a_m u_m \implies Tw = \lambda w$. Note that $w \neq 0$, for if not, $a_0 v \in U$, each $a_i = 0$. \square

36 Prove or give a counterexa: The result in Exercise 35 is still true if V is infinide.

SOLUS: A counterexa:

Consider $V = \{f \in \mathbb{R}^{\mathbb{R}} : \exists ! m \in \mathbb{N}, f \in \text{span}(1, e^x, \dots, e^{mx})\}$. Note that V is infinide.

And a subsp $U = \{f \in \mathbb{R}^{\mathbb{R}} : \exists ! m \in \mathbb{N}^+, f \in \text{span}(e^x, \dots, e^{mx})\}$.

Define $T \in \mathcal{L}(V)$ by $Tf = e^x f$. Then $\text{range } T = U$ is invard T .

Consider $(T/U)(1 + U) = e^x + U = 0 \implies 0$ is an eigval of T/U but is not an eigval of T .

[$\text{null } T = \{0\}$, for if not, $\exists f \in V \setminus \{0\}, (Tf)(x) = e^x f(x) = 0, \forall x \in \mathbb{R} \implies f = 0$, ctrad.] □

• (4E 5.A.39) Sups V is finide and $T \in \mathcal{L}(V)$.

Prove T has an eigval $\iff \exists \text{ invarsp } U \text{ under } T \text{ of dimension } \dim V - 1$.

SOLUS:

(a) Sups λ is an eigval of T with an eigvec v . (If $\dim V = 1$, then $U = \{0\}$ and done.)

Extend $v_1 = v$ to $B_V = (v_1, v_2, \dots, v_n)$.

Step 1. If $\exists w_1 \in \text{span}(v_2, \dots, v_n)$ suth $0 \neq Tw_1 \in \text{span}(v_1)$.

Then extend $w_1 = \alpha_{1,2}$ to a bss of $\text{span}(v_2, \dots, v_n)$ as $(\alpha_{1,2}, \dots, \alpha_{1,n})$.

Othws, we stop at step 1.

Step 2. If $\exists w_2 \in \text{span}(\alpha_{1,3}, \dots, \alpha_{1,n})$ suth $0 \neq Tw_2 \in \text{span}(v_1, w_1)$.

Then extend $w_2 = \alpha_{2,3}$ to a bss of $\text{span}(\alpha_{1,3}, \dots, \alpha_{1,n})$ as $(\alpha_{2,3}, \dots, \alpha_{2,n})$.

Othws, we stop at step 2.

Step k. If $\exists w_k \in \text{span}(\alpha_{k-1,k+1}, \dots, \alpha_{k-1,n})$ suth $0 \neq Tw_k \in \text{span}(v_1, w_1, \dots, w_{k-1})$,

Then extend $w_k = \alpha_{k,k+1}$ to a bss of $\text{span}(\alpha_{k-1,k+1}, \dots, \alpha_{k-1,n})$ as $(\alpha_{k,k+1}, \dots, \alpha_{k,n})$.

Othws, we stop at step k .

Finally, we stop at step m , thus we get $(v_1, w_1, \dots, w_{m-1})$ and $(\alpha_{m-1,m}, \dots, \alpha_{m-1,n})$,

$\text{range } T|_{\text{span}(w_1, \dots, w_{m-1})} = \text{span}(v_1, w_1, \dots, w_{m-2}) \implies \dim \text{null } T|_{\text{span}(w_1, \dots, w_{m-1})} = 0$,

$\underbrace{\text{span}(v_1, w_1, \dots, w_{m-1})}_{\dim m}$ and $\underbrace{\text{span}(\alpha_{m-1,m}, \dots, \alpha_{m-1,n})}_{\dim (n-m)}$ are invard T .

Let $U = \text{span}(\alpha_{m-1,m}, \dots, \alpha_{m-1,n}) \oplus \text{span}(v_1, w_1, \dots, w_{m-2})$ and done. □

COMMENT: Both $\text{span}(v_2, \dots, v_n)$ and $U \oplus \text{span}(w_{m-1})$ are in $\mathcal{S}_V \text{span}(v_1)$.

If $T|_U$ is inv, then by the simlr algo, we can extend U to invarsp.

OR. Note that $\dim \text{null } (T - \lambda I) \geq 1$. And $\dim \text{range } (T - \lambda I) \leq \dim V - 1$.

Let $B_{\text{range } (T - \lambda I)} = (w_1, \dots, w_m)$, $B_V = (w_1, \dots, w_m, u_1, \dots, u_n)$.

If $m = \dim V - 1$. [$\iff n = 0$.] Then $\text{range } (T - \lambda I)$ is invarsp of $\dim \dim V - 1$.

Othws, choose $k \in \{1, \dots, n\}$ and then let $U = \text{span}(w_1, \dots, w_m, u_1, \dots, u_{k-1}, u_{k+1}, \dots, u_n)$.

By Exe (1)(b), U is invard $(T - \lambda I)$. Now $u \in U \implies (T - \lambda I)(u) \in U \implies Tu \in U$.

(b) Sups U is invarsp under T of $\dim m = \dim V - 1$. (If $m = 0$, then done.)

Let $B_U = (u_1, \dots, u_m)$, $B_V = (u_0, u_1, \dots, u_m)$. We discuss in cases:

(I) If $Tu_0 \in U$, then $\text{range } T = U$ so that T is not surj $\iff \text{null } T \neq \{0\} \iff 0$ is an eigval of T .

(II) If $Tu_0 \notin U$, then $Tu_0 = a_0 u_0 + a_1 u_1 + \dots + a_m u_m$.

If $\text{range } T|_U = U \iff a_1 = \dots = a_m = 0 \iff Tu_0 \in \text{span}(u_0)$ then done.

Othws, $T|_U : U \rightarrow U$ is not surj, so is not inje. Thus 0 is an eigval of $T|_U$, so of T . □

OR. Consider $T/U \in \mathcal{L}(V/U)$. Bcs $\dim V/U = 1$. $\exists \lambda \in \mathbb{F}, T/U = \lambda I$. By Exe (35). □

5.B: I [See 5.B: II below.]

COMMENT: 下面, 为了照顾原书 5.B 节两版过大的差距, 特别将此节补注分成 I 和 II 两部分。又考虑到第 4 版中 5.B 节的「本征值与极小多项式」与「奇维度实向量空间的本质征值」(相当一部分是从原第 3 版 8.C 节挪过来的) 是对原第 3 版「多项式作用于算子」与「本质征值的存在性」(也即第 3 版 5.B 前半部分) 的极大扩充, 这一扩充也大大改变了原第 3 版后半部分的「上三角矩阵」这一小节, 故而将第 4 版 5.B 节放在第 3 版前面。

I 部分除了覆盖第 4 版 5.B 节全部和第 3 版 5.B 节前半部分与之相关的所有习题, 还会覆盖第 4 版 5.A 节末。

II 部分除了覆盖第 3 版 5.B 节后半部分「上三角矩阵」这一小节, 还会覆盖第 4 版 5.C 节; 并且, 下面 5.C 还会覆盖第 4 版 5.D 节。

[注: [8.40] OR (4E 5.22) — min poly;
[8.44,8.45] OR (4E 5.25,5.26) — how to find the min poly;
[8.49] OR (4E 5.27) — eigvals are the zeros of the min poly;
[8.46] OR (4E 5.29) — $q(T) = 0 \Leftrightarrow q$ is a poly multi of the min poly.]

1 2 3 5 6 7 8 10 11 12 13 18 19 | 2E: Ch5.24
4E: 5.A.32 5.A.33 3 7 8 9 10 11 12 13 14 15
16 17 18 19 20 21 22 23 24 25 26 27 28 29

- (4E 5.A.33) *Sups $T \in \mathcal{L}(V)$ and m is a positive integer.*
 - (a) *Prove T is inje $\Leftrightarrow T^m$ is inje.*
 - (b) *Prove T is surj $\Leftrightarrow T^m$ is surj.*

SOLUS:

(a) Sups T^m is inje. Then $Tv = 0 \Rightarrow T^{m-1}Tv = T^mv = 0 \Rightarrow v = 0$.

Sups T is inje. Then $T^mv = T^{m-1}v = \dots = T^2v = Tv = v = 0$.

(b) Sups T^m is surj. $\forall u \in V, \exists v \in V, T^mv = u = Tw$, let $w = T^{m-1}v$.

Sups T is surj. Then $\forall u \in V, \exists v_1, \dots, v_m \in V, T(v_1) = T^2v_2 = \dots = T^mv_m = u$. □

• NOTE FOR [5.17]:

Sups $T \in \mathcal{L}(V), p \in \mathcal{P}(\mathbb{F})$. Prove null $p(T)$ and range $p(T)$ are invard T .

SOLUS: Using the commu in [5.10].

(a) Sups $u \in \text{null } p(T)$. Then $p(T)u = 0$.

Thus $p(T)(Tu) = (p(T)T)u(Tp(T))u = T(p(T)u) = 0$. Hence $Tu \in \text{null } p(T)$. □

(b) Sups $u \in \text{range } p(T)$. Then $\exists v \in V$ suth $u = p(T)v$.

Thus $Tu = T(p(T)v) = p(T)(Tv) \in \text{range } p(T)$. □

• NOTE FOR [5.21]: Every optor on a finide nonzero complex vecsp has an eigval.

Sups V is a finide complex vecsp of $\dim n > 0$ and $T \in \mathcal{L}(V)$.

Choose a nonzero $v \in V$. $(v, Tv, T^2v, \dots, T^nv)$ of len $n + 1$ is linely depe.

Sups $a_0I + a_1T + \dots + a_nT^n = 0$. Then $\exists a_j \neq 0$.

Thus \exists nonconst p of smallest deg ($\deg p > 0$) suth $p(T)v = 0$.

Becs $\exists \lambda \in \mathbb{C}$ suth $p(\lambda) = 0 \Rightarrow \exists q \in \mathcal{P}(\mathbb{C}), p(z) = (z - \lambda)q(z), \forall z \in \mathbb{C}$.

Thus $0 = p(T)v = (T - \lambda I)(q(T)v)$. By the min of $\deg p$ and $\deg q < \deg p, q(T)v \neq 0$.

Then $(T - \lambda I)$ is not inje. Thus λ is an eigval of T with eigvec $q(T)v$.

• EXA: an optor on a complex vecsp with no eigvals

Define $T \in \mathcal{L}(\mathcal{P}(\mathbb{C}))$ by $(Tp)(z) = zp(z)$.

Sups $p \in \mathcal{P}(\mathbb{C})$ is a nonzero poly. Then $\deg Tp = \deg p + 1$, and thus $Tp \neq \lambda p, \forall \lambda \in \mathbb{C}$.
Hence T has no eigvals.

13 Sups V is a complex vecsp and $T \in \mathcal{L}(V)$ has no eigvals.

Prove every subsp of V invard T is either $\{0\}$ or infinide.

SOLUS: Sups U is a finide nonzero invarsp on \mathbb{C} . Then by [5.21], $T|_U$ has an eigval. □

16 Sups $0 \neq v \in V$. Define $S \in \mathcal{L}(\mathcal{P}_{\dim V}(\mathbb{C}), V)$ by $S(p) = p(T)v$. Prove [5.21].

SOLUS:

Becs $\dim \mathcal{P}_{\dim V}(\mathbb{C}) = \dim V + 1$. Then S is not inje. Hence $\exists 0 \neq p \in \mathcal{P}_{\dim V}(\mathbb{C}), p(T)v = 0$.

Using [4.14], write $p(z) = c(z - \lambda_1) \cdots (z - \lambda_m)$. Apply T to both sides: $p(T) = c(T - \lambda_1 I) \cdots (T - \lambda_m I)$.

Thus at least one of $(T - \lambda_j I)$ is not inje (becs $p(T)$ is not inje). □

17 Sups $0 \neq v \in V$. Define $S \in \mathcal{L}(\mathcal{P}_{(\dim V)^2}(\mathbb{C}), \mathcal{L}(V))$ by $S(p) = p(T)$. Prove [5.21].

SOLUS:

Becs $\dim \mathcal{P}_{(\dim V)^2}(\mathbb{C}) = (\dim V)^2 + 1$. Then S is not inje.

Hence $\exists p \in \mathcal{P}_{(\dim V)^2}(\mathbb{C}) \setminus \{0\}, 0 = S(p) = p(T) = c(T - \lambda_1 I) \cdots (T - \lambda_m I)$, where $c \neq 0$.

Thus $(T - \lambda_1 I) \cdots (T - \lambda_m I) = 0 \implies \exists j, (T - \lambda_j I)$ is not inje. □

COMMENT: \exists monic $q \in \text{null } S \neq \{0\}$ of smallest deg, $S(q) = q(T) = 0$, then q is the *min poly*.

• **NOTE FOR [8.40]:** def for min poly

Sups V is finide and $T \in \mathcal{L}(V)$.

Sups $M_T^0 = \{p_j\}_{j \in \Gamma}$ is the set of all monic poly that give 0 whenever T is applied.

Prove $\exists ! p_k \in M_T^0, \deg p_k = \min\{\deg p_j\}_{j \in \Gamma} \leq \dim V$.

SOLUS: OR. Another Proof :

[Existns Part] We use induc on $\dim V$.

(i) If $\dim V = 0$, then $I = 0 \in \mathcal{L}(V)$ and let $p = 1$, done.

(ii) Sups $\dim V \geq 1$.

Asum $\dim V > 0$ and that the desired result is true for all optors on all vecsp of smaller dim.

Let $u \in V, u \neq 0$. The list $(u, Tu, \dots, T^{\dim V} u)$ of len $(1 + \dim V)$ is liney depe.

Then $\exists ! T^m$ of smallest deg suth $T^m u \in \text{span}(u, Tu, \dots, T^{m-1} u)$.

Thus $\exists c_j \in \mathbb{F}, c_0 u + c_1 Tu + \dots + c_{m-1} T^{m-1} u + T^m u = 0$.

Define q by $q(z) = c_0 + c_1 z + \dots + c_{m-1} z^{m-1} + z^m$.

Then $0 = T^k(q(T)u) = q(T)(T^k u), \forall k \in \{1, \dots, m-1\} \subseteq \mathbb{N}$.

Becs $(u, Tu, \dots, T^{m-1} u)$ is liney indep.

Thus $\dim \text{null } q(T) \geq m \implies \dim \text{range } q(T) = \dim V - \dim \text{null } q(T) \leq \dim V - m$.

Let $W = \text{range } q(T)$.

By asum, $\exists s \in M_T^0$ of smallest deg (and $\deg s \leq \dim W$,) so that $s(T|_W) = 0$.

Hence $\forall v \in V, ((sq)(T))(v) = s(T)(q(T)v) = 0$.

Thus $sq \in M_T^0$ and $\deg sq \leq \dim V$.

[Uniques Part]

Sups $p, q \in M_T^0$ are of the smallest deg. Then $(p - q)(T) = 0$. 又 $\deg(p - q) = m < \min\{\deg p_j\}_{j \in \Gamma}$.

Hence $p - q = 0$, for if not, $\exists ! c \in \mathbb{F}, c(p - q) \in M_T^0$. Ctradic. □

- (4E 5.31, 4E 5.B.25 and 26) *min poly of restr optor and min poly of quot optor*
Sups V is finide, $T \in \mathcal{L}(V)$, and U is invarsp of V under T .

Let p be the min poly of T .

- Prove p is a poly multi of the min poly of $T|_U$.
- Prove p is a poly multi of the min poly of T/U .
- Prove $(\text{min poly of } T|_U) \times (\text{min poly of } T/U)$ is a poly multi of p .
- Prove the set of eigvals of T equals
the union of the set of eigvals of $T|_U$ and the set of eigvals of T/U .

SOLUS:

- $p(T) = 0 \Rightarrow \forall u \in U, p(T)u = 0 \Rightarrow p(T|_U) = 0 \Rightarrow$ By [8.46]. □
- $p(T) = 0 \Rightarrow \forall v \in V, p(T)v = 0 \Rightarrow p(T/U)(v + U) = p(T)v + U = 0$. □
- Sups r is the min poly of $T|_U$, s is the min poly of T/U .
Becs $\forall v \in V, s(T/U)(v + U) = s(T)v + U = 0$. So that $\forall v \in V$ but $v \notin U, s(T)v \in U$.
 $\text{又 } \forall u \in U, r(T|_U)u = r(T)u = 0$.
Thus $\forall v \in V$ but $v \notin U, (rs)(T)v = r(s(T)v) = 0$.
And $\forall u \in U, (rs)(T)u = r(s(T)u) = 0$ (becs $s(T)u = s(T|_U)u \in U$).
Hence $\forall v \in V, (rs)(T)v = 0 \Rightarrow (rs)(T) = 0$. □
- By [8.49], immediately. □

- (4E 5.B.27) Sups $\mathbf{F} = \mathbf{R}$, V is finide, and $T \in \mathcal{L}(V)$.
Prove the min poly p of T_C equals the min poly q of T .

SOLUS:

- $\forall u + i0 \in V_C, p(T_C)(u) = p(T)u = 0 \Rightarrow \forall u \in V, p(T)u = 0 \Rightarrow p$ is a poly multi of q .
- $q(T) = 0 \Rightarrow \forall u + iv \in V_C, q(T_C)(u + iv) = q(T)u + iq(T)v = 0 \Rightarrow q$ is a poly multi of p . □

- (4E 5.B.28) Sups V is finide and $T \in \mathcal{L}(V)$.
Prove the min poly p of $T' \in \mathcal{L}(V')$ equals the min poly q of T .

SOLUS:

- $\forall \varphi \in V', p(T')\varphi = \varphi \circ (p(T)) = 0 \Rightarrow \forall \varphi \in V', p(T) \in \text{null } \varphi \Rightarrow p(T) = 0, p$ is a poly multi of q .
- $q(T) = 0 \Rightarrow \forall \varphi \in V', \varphi \circ (q(T)) = q(T')\varphi = 0 \Rightarrow q(T) = 0, q$ is a poly multi of p . □

- (4E 5.32) Sups $T \in \mathcal{L}(V)$ and p is the min poly.
Prove T is not inje \iff the const term of p is 0.

SOLUS:

- T is not inje $\iff 0$ is an eigval of $T \iff 0$ is a zero of $p \iff$ the const term of p is 0. □
- OR. Becs $p(0) = (z - 0)(z - \lambda_1) \cdots (z - \lambda_m) = 0 \Rightarrow T(T - \lambda_1 I) \cdots (T - \lambda_m I) = 0$
 $\text{又 } p$ is the min poly $\Rightarrow q$ define by $q(z) = (z - \lambda_1) \cdots (z - \lambda_m)$ is suth $q(T) \neq 0$.
Hence $0 = p(T) = Tq(T) \Rightarrow T$ is not inje.
Conversely, sups $(T - 0I)$ is not inje, then 0 is a zero of p , so that the const term is 0. □

- (4E 5.B.22)
Sups V is finide, $T \in \mathcal{L}(V)$. Prove T is inv $\iff I \in \text{span}(T, T^2, \dots, T^{\dim V})$.

SOLUS: Denote the min poly by p , where for all $z \in \mathbf{F}, p(z) = a_0 + a_1 z + \cdots + z^m$.

Notice that V is finide. T is inv $\iff T$ is inje $\iff p(0) \neq 0$.

Hence $p(T) = 0 = a_0I + a_1T + \dots + T^m$, where $a_0 \neq 0$ and $m \leq \dim V$. □

6 Sups $T \in \mathcal{L}(V)$ and U is a subsp of V invard T .

Prove U is invard $p(T)$ for every poly $p \in \mathcal{P}(\mathbf{F})$.

SOLUS:

$\forall u \in U, Tu \in U \Rightarrow Iu, Tu, T(Tu), \dots, T^m u \in U \Rightarrow \forall a_k \in \mathbf{F}, (a_0I + a_1T + \dots + a_m T^m)u \in U$. □

• (4E 5.B.10, 23) Sups V is finide, $T \in \mathcal{L}(V)$ and p is the min poly with deg m . Sups $v \in V$.

(a) Prove $\text{span}(v, Tv, \dots, T^{m-1}v) = \text{span}(v, Tv, \dots, T^{j-1}v)$ for some $j \leq m$.

(b) Prove $\text{span}(v, Tv, \dots, T^{m-1}v) = \text{span}(v, Tv, \dots, T^{m-1}v, \dots, T^n v)$.

SOLUS:

COMMENT: By NOTE FOR[8.40], j has an upper bound $m - 1$, m has an upper bound $\dim V$.

Write $p(z) = a_0 + a_1z + \dots + z^m$ ($m \leq \dim V$). If $v = 0$, then done. Sups $v \neq 0$.

(a) Sups $j \in \mathbf{N}^+$ is the smallest suth $T^j v \in \text{span}(v, Tv, \dots, T^{j-1}v) = U_0$. Then $j \leq m$.

Write $T^j v = c_0 v + c_1 Tv + \dots + c_{j-1} T^{j-1}v$. And becs $T(T^k v) = T^{k+1} v \in U_0$. U_0 is invard T .

By Exe (6), $\forall k \in \mathbf{N}$, $T^{j+k} v = T^k(T^j v) \in U_0$.

Thus $U_0 = \text{span}(v, Tv, \dots, T^{j-1}v, \dots, T^n v)$ for all $n \geq j - 1$. Let $n = m - 1$ and done.

(b) Let $U = \text{span}(v, Tv, \dots, T^{m-1}v)$.

By (a), $U = U_0 = \text{span}(v, Tv, \dots, T^{j-1}v, \dots, T^{m-1}v, \dots, T^n v)$ for all $n \geq m - 1$. □

• (4E 5.B.21) Sups V is finide and $T \in \mathcal{L}(V)$.

Prove the min poly p has deg at most $1 + \dim \text{range } T$.

If $\dim \text{range } T < \dim V - 1$, then this result gives a better upper bound for the deg of min poly.

SOLUS:

If T is inje, then $\text{range } T = V$ and done. Now choose $0 \neq v \in \text{null } T$, then $Tv + 0 \cdot v = 0$.

1 is the smallest positive integer suth $T^1 v \in \text{span}(v, \dots, T^0 v)$. Define q by $q(z) = z \Rightarrow q(T)v = 0$.

Let $W = \text{range } q(T) = \text{range } T$. \exists monic $s \in \mathcal{P}(\mathbf{F})$ of smallest deg ($\deg s \leq \dim W$), $s(T|_W) = 0$.

Hence sq is the min poly (see NOTE FOR[8.40]) and $\deg(sq) = \deg s + \deg q \leq \dim \text{range } T + 1$. □

19 Sups V is finide, $\dim V > 1$, $T \in \mathcal{L}(V)$. Prove $\{p(T) : p \in \mathcal{P}(\mathbf{F})\} \neq \mathcal{L}(V)$.

SOLUS: If $\forall S \in \mathcal{L}(V), \exists p \in \mathcal{P}(\mathbf{F}), S = p(T)$. Then by [5.20], $\forall S_1, S_2 \in \mathcal{L}(V), S_1 S_2 = S_2 S_1$.

Note that $\dim \geq 2$. By (3.A.14), $\exists S_1, S_2 \in \mathcal{L}(V), S_1 S_2 \neq S_2 S_1$. Ctradic. □

• Sups V is finide and $T \in \mathcal{L}(V)$. Let $\mathcal{E} = \{q(T) : q \in \mathcal{P}(\mathbf{F})\}$.

Prove $\dim \mathcal{E}$ equals the deg of the min poly of T .

SOLUS:

Becs the list $(I, T, \dots, T^{(\dim V)^2})$ of len $\dim \mathcal{L}(V) + 1$ is liney depe in $\dim \mathcal{L}(V)$.

Sups $m \in \mathbf{N}^+$ is the smallest suth $T^m = a_0 I + \dots + a_{m-1} T^{m-1}$.

Then q defined by $q(z) = z^m - a_{m-1} z^{m-1} - \dots - a_0$ is the min poly (see [8.40]).

For any $k \in \mathbf{N}^+$, $T^{m+k} = T^k(T^m) \in \text{span}(I, T, \dots, T^{m-1}) = U$.

Hence $\text{span}(I, T, \dots, T^{(\dim V)^2}) = \text{span}(I, T, \dots, T^{(\dim V)^2 - 1}) = U$.

Note that by the min of m , (I, T, \dots, T^{m-1}) is liney indep.

Thus $\dim U = m = \dim \text{span}(I, T, \dots, T^{(\dim V)^2 - 1}) = \dim \text{span}(I, T, \dots, T^n)$ for all $m < n \in \mathbf{N}^+$.

Define $\varphi \in \mathcal{L}(\mathcal{P}_{m-1}(\mathbf{F}), \mathcal{E})$ by $\varphi(p) = p(T)$.

(a) $\text{Sups } p(T) = 0$. $\text{又 } \deg p \leq m-1 \Rightarrow p = 0$. Then φ is inje.

(b) $\forall S = a_0I + a_1T + \dots + a_{m-1}T^{m-1} \in \mathcal{E}$, define $p \in \mathcal{P}_{m-1}(\mathbf{F})$ by
 $p(z) = a_0 + a_1z + \dots + a_{m-1}z^{m-1} \Rightarrow \varphi(p) = S$. Then φ is surj.

Hence \mathcal{E} and $\mathcal{P}_{m-1}(\mathbf{F})$ are iso. $\text{又 } \dim \mathcal{P}_{m-1}(\mathbf{F}) = m = \dim U$. □

• (4E 5.B.13) *Sups $T \in \mathcal{L}(V)$ and $q \in \mathcal{P}(\mathbf{F})$ is defined by*

$$q(z) = a_0 + a_1z + \dots + a_nz^n, \text{ where } a_n \neq 0, \text{ for all } z \in \mathbf{F}.$$

Denote the min poly of T by p defined by

$$p(z) = c_0 + c_1z + \dots + c_{m-1}z^{m-1} + z^m \text{ for all } z \in \mathbf{F}.$$

Prove $\exists ! r \in \mathcal{P}(\mathbf{F})$ suth $q(T) = r(T)$, $\deg r < \deg p$.

SOLUS:

If $\deg q < \deg p$, then done.

If $\deg q = \deg p$, notice that $p(T) = 0 = c_0I + c_1T + \dots + c_{m-1}T^{m-1} + T^m$

$$\Rightarrow T^m = -c_0I - c_1T - \dots - c_{m-1}T^{m-1},$$

$$\begin{aligned} \text{define } r \text{ by } r(z) &= q(z) + [-a_mz^m + a_m(-c_0 - c_1z - \dots - c_{m-1}z^{m-1})] \\ &= (a_0 - a_m c_0) + (a_1 - a_m c_1)z + \dots + (a_{m-1} - a_m c_{m-1})z^{m-1}, \end{aligned}$$

hence $r(T) = 0$, $\deg r < m$ and done.

Now $\text{sups } \deg q \geq \deg p$. We use induc on $\deg q$.

(i) $\deg q = \deg p$, then the desired result is true, as shown above.

(ii) $\deg q > \deg p$, asum the desired result is true for $\deg q = n$.

Sups $f \in \mathcal{P}(\mathbf{F})$ suth $f(z) = b_0 + b_1z + \dots + b_nz^n + b_{n+1}z^{n+1}$.

Apply the asum to g defined by $g(z) = b_0 + b_1z + \dots + b_nz^n$,

getting s defined by $s(z) = d_0 + d_1z + \dots + d_{m-1}z^{m-1}$.

Thus $g(T) = s(T) \Rightarrow f(T) = g(T) + b_{n+1}T^{n+1} = s(T) + b_{n+1}T^{n+1}$.

Apply the asum to t defined by $t(z) = z^n$,

getting δ defined by $\delta(z) = c_0' + c_1'z + \dots + c_{m-1}'z^{m-1}$.

Thus $t(T) = T^n = c_0' + c_1'T + \dots + c_{m-1}'T^{m-1} = \delta(T)$.

$\text{又 } \text{span}(v, Tv, \dots, T^{m-1}v)$ is invard T .

Hence $\exists ! k_j \in \mathbf{F}, T^{n+1} = T(T^n) = k_0 + k_1T + \dots + k_{m-1}T^{m-1}$.

And $f(T) = s(T) + b_{n+1}(k_0 + k_1T + \dots + k_{m-1}T^{m-1})$

$\Rightarrow f(T) = (d_0 + k_0) + (d_1 + k_1)z + \dots + (d_{m-1} + k_{m-1})z^{m-1} = h(T)$, thus defining h . □

• (4E 5.B.14) *Sups V is finide, $T \in \mathcal{L}(V)$ has min poly p*

defined by $p(z) = a_0 + a_1z + \dots + a_{m-1}z^{m-1} + z^m, a_0 \neq 0$.

Find the min poly of T^{-1} .

SOLUS:

Notice that V is finide. Then $p(0) = a_0 \neq 0 \Rightarrow 0$ is not a zero of $p \Rightarrow T - 0I = T$ is inv.

Then $p(T) = a_0I + a_1T + \dots + T^m = 0$. Apply T^{-m} to both sides,

$$a_0(T^{-1})^m + a_1(T^{-1})^{m-1} + \dots + a_{m-1}T^{-1} + I = 0.$$

Define q by $q(z) = z^m + \frac{a_1}{a_0}z^{m-1} + \dots + \frac{a_{m-1}}{a_0}z + \frac{1}{a_0}$ for all $z \in \mathbf{F}$.

We now show $(T^{-1})^k \notin \text{span}(I, T^{-1}, \dots, (T^{-1})^{k-1})$

for every $k \in \{1, \dots, m-1\}$ by ctradic, so that q is exactly the min poly of T^{-1} .

Sups $(T^{-1})^k \in \text{span}(I, T^{-1}, \dots, (T^{-1})^{k-1})$.

Then let $(T^{-1})^k = b_0I + b_1T^{-1} + \dots + b_{k-1}T^{k-1}$. Apply T^k to both sides,
getting $I = b_0T^k + b_1T^{k-1} + \dots + b_{k-1}T$, hence $T^k \in \text{span}(I, T, \dots, T^{k-1})$.

Thus f defined by $f(z) = z^k + \frac{b_1}{b_0}z^{k-1} + \dots + \frac{b_{k-1}}{b_0}z - \frac{1}{b_0}$ is a poly multi of p .

While $\deg f < \deg p$. Ctradic. □

• **NOTE FOR [8.49]:**

Sups V is a finide complex vecsp and $T \in \mathcal{L}(V)$.

By [4.14], the min poly has the form $(z - \lambda_1) \dots (z - \lambda_m)$,

where $\lambda_1, \dots, \lambda_m$ are all the eigvals of T , possibly with repetitions.

• **COMMENT:**

A nonzero poly has at most as many disti zeros as its deg (see [4.12]).

Thus by the upper bound for the deg of min poly given in NOTE FOR[8.40], and by [8.49,] we can give an alternative proof of [5.13].

• **NOTICE (See also 4E 5.B.20,24)**

Sups $\alpha_1, \dots, \alpha_n$ are all the disti eigvals of T ,

and therefore are all the disti zeros of the min poly.

Also, the min poly of T is a poly multi of, but not equal to, $(z - \alpha_1) \dots (z - \alpha_n)$.

If we define q by $q(z) = (z - \alpha_1)^{\dim V - (n-1)} \dots (z - \alpha_n)^{\dim V - (n-1)}$,

then q is a poly multi of the ch poly (see [8.34] and [8.26])

(Becs $\dim V > n$ and $n - 1 > 0$, $n[\dim V - (n - 1)] > \dim V$.)

The ch poly has the form $(z - \alpha_1)^{\gamma_1} \dots (z - \alpha_n)^{\gamma_n}$, where $\gamma_1 + \dots + \gamma_n = \dim V$.

The min poly has the form $(z - \alpha_1)^{\delta_1} \dots (z - \alpha_n)^{\delta_n}$, where $0 \leq \delta_1 + \dots + \delta_n \leq \dim V$.

10 Sups $T \in \mathcal{L}(V)$, λ is an eigval of T with an eigvec v .

Prove for any $p \in \mathcal{P}(\mathbf{F})$, $p(T)v = p(\lambda)v$.

SOLUS:

Sups p is defined by $p(z) = a_0 + a_1z + \dots + a_mz^m$ for all $z \in \mathbf{F}$. Becs for any $n \in \mathbf{N}^+$, $T^n v = \lambda^n v$.

Thus $p(T)v = a_0v + a_1Tv + \dots + a_mT^mv = a_0v + a_1\lambda v + \dots + a_m\lambda^mv = p(\lambda)v$. □

COMMENT: For any $p \in \mathcal{P}(\mathbf{F})$ suth $p(z) = (z - \lambda_1)^{\alpha_1} \dots (z - \lambda_m)^{\alpha_m}$, the result is true as well.

Now we prove that $(T - \lambda_1 I)^{\alpha_1} \dots (T - \lambda_m I)^{\alpha_m} v = (\lambda - \lambda_1)^{\alpha_1} \dots (\lambda - \lambda_m)^{\alpha_m} v$.

Define q_i by $q_i(z) = (z - \lambda_i)^{\alpha_i}$ for all $z \in \mathbf{F}$.

Becs $(a + b)^n = a^n + C_n^1 a^{n-1} b + \dots + C_n^k a^{n-k} b^k + \dots + C_n^n b^n$.

Let $a = z, b = \lambda_i, n = \alpha_i$, so we can write $q_i(z)$ in the form $a_0 + a_1z + \dots + a_mz^m$.

Hence $q_i(T)v = q_i(\lambda)v \Rightarrow (T - \lambda_i I)^{\alpha_i} v = (\lambda - \lambda_i)^{\alpha_i} v$.

Then for each $k \in \{2, \dots, m\}$, $(T - \lambda_{k-1} I)^{\alpha_{k-1}} (T - \lambda_k I)^{\alpha_k} v$

$$\begin{aligned} &= q_{k-1}(T)(q_k(T)v) \\ &= q_{k-1}(T)(q_k(\lambda)v) \\ &= q_{k-1}(\lambda)(q_k(\lambda)v) \\ &= (\lambda - \lambda_{k-1})^{\alpha_{k-1}} (\lambda - \lambda_k)^{\alpha_k} v. \end{aligned}$$

So that $(T - \lambda_1 I)^{\alpha_1} \dots (T - \lambda_m I)^{\alpha_m} v$

$$\begin{aligned} &= q_1(T) \left(q_2(T) \left(\dots (q_m(T)v) \dots \right) \right) \\ &= q_1(\lambda) (q_2(\lambda) (\dots (q_m(\lambda)v) \dots)) \end{aligned}$$

$$= (\lambda - \lambda_1)^{\alpha_1} \cdots (\lambda - \lambda_m)^{\alpha_m} v.$$
□

1 Sups $T \in \mathcal{L}(V)$ and $\exists n \in \mathbf{N}^+$ such $T^n = 0$.

Prove $(I - T)$ is inv and $(I - T)^{-1} = I + T + \dots + T^{n-1}$.

SOLUS: Note that $1 - x^n = (1 - x)(1 + x + \dots + x^{n-1})$.

$$\left. \begin{aligned} (I - T)(1 + T + \dots + T^{n-1}) &= I - T^n = I \\ (1 + T + \dots + T^{n-1})(I - T) &= I - T^n = I \end{aligned} \right\} \Rightarrow (I - T)^{-1} = 1 + T + \dots + T^{n-1}. \quad \square$$

2 Sups $T \in \mathcal{L}(V)$ and $(T - 2I)(T - 3I)(T - 4I) = 0$.

Sups λ is an eigval of T . Prove $\lambda = 2$ or $\lambda = 3$ or $\lambda = 4$.

SOLUS:

Sups v is an eigvec corres to λ . Then for any $p \in \mathcal{P}(\mathbf{F})$, $p(T)v = p(\lambda)v$.

Hence $0 = (T - 2I)(T - 3I)(T - 4I)v = (\lambda - 2)(\lambda - 3)(\lambda - 4)v$ while $v \neq 0 \Rightarrow \lambda = 2, 3$ or 4 . \square

COMMENT: Note that $(T - 2I)(T - 3I)(T - 4I) = 0$ is not inje, so that $2, 3, 4$ are eigvals of T .

But it doesn't mean that all the eigvals of T are exactly $2, 3, 4$.

7 [See 5.A.22] Sups $T \in \mathcal{L}(V)$. Prove 9 is an eigval of $T^2 \iff 3$ or -3 is an eigval of T .

SOLUS:

(a) Sups λ is an eigval of T with an eigvec v .

Then $(T - 3I)(T + 3I)v = (\lambda - 3)(\lambda + 3)v = 0 \Rightarrow \lambda = \pm 3$.

(b) Sups 3 or -3 is an eigval of T with an eigvec v . Then $Tv = \pm 3v \Rightarrow T^2v = T(Tv) = 9v$ \square

OR. 9 is an eigval of $T^2 \iff (T^2 - 9I) = (T - 3I)(T + 3I)$ is not inje $\iff \pm 3$ is an eigval. \square

3 Sups $T \in \mathcal{L}(V)$, $T^2 = I$ and -1 is not an eigval of T . Prove $T = I$.

SOLUS:

$T^2 - I = (T + I)(T - I)$ is not inje, $\nexists -1$ is not an eigval of $T \Rightarrow$ By TIPS. \square

OR. Note that $\forall v \in V, v = [\frac{1}{2}(I - T)v] + [\frac{1}{2}(I + T)v]$.

$$\left. \begin{aligned} (I + T)((I - T)v) &= 0 \Rightarrow (I - T)v \in \text{null}(I + T) \\ (I - T)((I + T)v) &= 0 \Rightarrow (I + T)v \in \text{null}(I - T) \end{aligned} \right\} \Rightarrow V = \text{null}(I + T) + \text{null}(I - T).$$

$\nexists -1$ is not an eigval of $T \iff (I + T)$ is inje $\iff \text{null}(I + T) = \{0\}$.

Hence $V = \text{null}(I - T) \Rightarrow \text{range}(I - T) = \{0\}$. Thus $I - T = 0 \in \mathcal{L}(V) \Rightarrow T = I$. \square

• (4E 5.A.32) Sups $T \in \mathcal{L}(V)$ has no eigvals and $T^4 = I$. Prove $T^2 = -I$.

SOLUS:

Becs $T^4 - I = (T^2 - I)(T^2 + I) = 0$ is not inje $\Rightarrow (T^2 - I)$ or $(T^2 + I)$ is not inje.

$\nexists T$ has no eigvals $\Rightarrow (T^2 - I) = (T - I)(T + I)$ is inje. Hence $T^2 + I = 0 \in \mathcal{L}(V)$, for if not, $\exists v \in V, (T^2 + I)v \neq 0$ while $(T^2 - I)((T^2 + I)v) = 0$ but $(T^2 - I)$ is inje. Ctradic.

OR. $\forall v \in V, 0 = (T^2 - I)(T^2 + I)v \iff 0 = (T^2 + I)v$. Hence $T^2 + I = 0$. \square

OR. Note that $\forall v \in V, v = [\frac{1}{2}(I - T^2)v] + [\frac{1}{2}(I + T^2)v]$.

$$\left. \begin{aligned} (I + T^2)((I - T^2)v) &= 0 \Rightarrow (I - T^2)v \in \text{null}(I + T^2) \\ (I - T^2)((I + T^2)v) &= 0 \Rightarrow (I + T^2)v \in \text{null}(I - T^2) \end{aligned} \right\} \Rightarrow V = \text{null}(I + T^2) + \text{null}(I - T^2).$$

$\nexists T$ has no eigvals $\iff (I - T^2)$ is inje $\iff \text{null}(I - T^2) = \{0\}$.

Hence $V = \text{null}(I + T^2) \Rightarrow \text{range}(I + T^2) = \{0\}$. Thus $I + T^2 = 0 \in \mathcal{L}(V) \Rightarrow T^2 = -I$. \square

8 [OR (4E 5.A.31)] Give an exa of $T \in \mathcal{L}(\mathbf{R}^2)$ suth $T^4 = -I$.

SOLUS:

Define $i \in \mathcal{L}(\mathbf{R}^2)$ by $i(x, y) = (-y, x)$. Just like $i : \mathbf{C} \rightarrow \mathbf{C}$ defined by $i(x + iy) = -y + ix$.

Define $i^n \in \mathcal{L}(\mathbf{R}^2)$ by $i^n(x, y) = (\operatorname{Re}(i^n x + i^{n+1} y), \operatorname{Im}(i^n x + i^{n+1} y))$.

$$T^4 + I = (T^2 + iI)(T^2 - iI) = (T + i^{1/2}I)(T - i^{1/2}I)(T - (-i)^{1/2}I)(T + (-i)^{1/2}I).$$

Note that $i^{1/2} = \frac{\sqrt{2}}{2} + i\frac{\sqrt{2}}{2}$, $(-i)^{1/2} = \frac{\sqrt{2}}{2} - i\frac{\sqrt{2}}{2}$. Hence $T = \pm(\pm i)^{1/2}I$.

Let $T = i^{1/2}I$ defined by $i^{1/2}(x, y) = (\frac{\sqrt{2}}{2}x - \frac{\sqrt{2}}{2}y, \frac{\sqrt{2}}{2}x + \frac{\sqrt{2}}{2}y)$. □

OR. Becs $\mathcal{M}(T^4) = \begin{pmatrix} \cos(-\pi) & \sin(-\pi) \\ -\sin(-\pi) & \cos(-\pi) \end{pmatrix}$. Using $\begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix}^n = \begin{pmatrix} \cos n\alpha & \sin n\alpha \\ -\sin n\alpha & \cos n\alpha \end{pmatrix}$.

We define $T \in \mathcal{L}(\mathbf{R}^2)$ suth $\mathcal{M}(T) = \begin{pmatrix} \cos(-\pi/4) & \sin(-\pi/4) \\ -\sin(-\pi/4) & \cos(-\pi/4) \end{pmatrix}$. □

• (4E 5.B.12) Find the min poly of T defined in (5.A.10).

SOLUS: By (5.A.9) and [8.40, 8.49], $1, 2, \dots, n$ are all the zeros of the min poly of T . □

• (4E 5.B.3) Find the min poly of T defined in (5.A.19).

SOLUS:

If $n = 1$ then 1 is the only eigval of T , and $(z - 1)$ is the min poly.

Becs n and 0 are all the eigvals of T , 又 $\forall k \in \{1, \dots, n\}, Te_k = e_1 + \dots + e_n; T^2e_k = n(e_1 + \dots + e_n)$.

Hence $T^2e_k = n(Te_k) \Rightarrow T^2 = nT \Rightarrow T^2 - nT = T(T - n) = 0$. Thus $(z(z - n))$ is the min poly. □

• (4E 5.B.8) Find the min poly of T . Where $T \in \mathcal{L}(\mathbf{R}^2)$ is the optor of counterclockwise rotation by θ , where $\theta \in \mathbf{R}^+$.

SOLUS:

If $\theta = \pi + 2k\pi$, then $T(w, z) = (-w, -z), T^2 = I$ and the min poly is $z + 1$.

If $\theta = 2k\pi$, then $T = I$ and the min poly is $z - 1$.

Othws (v, Tv) is liney indep. Then $\operatorname{span}(v, Tv) = \mathbf{R}^2$. Note that $\nexists b \in \mathbf{F}, T - bI = 0$.

Thus sups the min poly p is defined by $p(z) = z^2 + bz + c$ for all $z \in \mathbf{R}$.

Becs $\begin{array}{l} L = |OD| \\ T^2 \vec{v} = \vec{OA} \\ T \vec{v} = \vec{OC} \\ \vec{v} = \vec{OB} \end{array} \quad \begin{array}{c} \text{Diagram: A triangle OAB with point C on AB and D on OB. Vectors OA, OC, OB are shown. Angle theta is marked at O between OB and OC, and between OC and OD.} \end{array} \quad \left| \begin{array}{l} Tv = \frac{|\vec{v}|}{2L}(T^2v + v) \Rightarrow T = \frac{|\vec{v}|}{2L}(T^2 + I) \\ L = |\vec{v}| \cos \theta \Rightarrow \frac{|\vec{v}|}{2L} = \frac{1}{2 \cos \theta} \end{array} \right.$

Hence $p(T) = T^2 - 2 \cos \theta T + I = 0$ and $z^2 - 2 \cos \theta z + 1$ is the min poly of T . □

OR. Let (e_1, e_2) be the std bss of \mathbf{R}^2 . We use the pattern shown in [8.44].

Becs $Te_1 = \cos \theta e_1 + \sin \theta e_2, T^2e_1 = \cos 2\theta e_1 + \sin 2\theta e_2$.

Thus $ce_1 + bTe_1 = -T^2e_1 \Leftrightarrow \begin{pmatrix} 1 & \cos \theta \\ 0 & \sin \theta \end{pmatrix} \begin{pmatrix} c \\ b \end{pmatrix} = \begin{pmatrix} -\cos 2\theta \\ -\sin 2\theta \end{pmatrix}$. Now $\det = \sin \theta \neq 0, c = 1, b = 2 \cos \theta$. □

OR. $\mathcal{M}(T, (e_1, e_2)) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$. By (4E 5.B.11), the min poly is $(z \pm 1)$ or $(z^2 - 2 \cos \theta z + 1)$. □

- (4E 5.B.11) *Sups V is a two-dim vecsp, $T \in \mathcal{L}(V)$, and the matrix of T wrto some B_V is $\begin{pmatrix} a & c \\ b & d \end{pmatrix}$.*

(a) *Show $T^2 - (a + d)T + (ad - bc)I = 0$.*

(b) *Show the min poly of T equals*

$$\begin{cases} z - a & \text{if } b = c = 0 \text{ and } a = d, \\ z^2 - (a + d)z + (ad - bc) & \text{othws.} \end{cases}$$

SOLUS:

(a) Sups the bss is (v, w) . Becs $\begin{cases} Tv = av + bw \Rightarrow (T - aI)v = bw, \text{ then apply } (T - dI) \text{ to both sides.} \\ Tw = cv + dw \Rightarrow (T - dI)w = cv, \text{ then apply } (T - aI) \text{ to both sides.} \end{cases}$

Hence $(T - aI)(T - dI) = bcI \Rightarrow T^2 - (a + d)T + (ad - bc)I = 0$.

(b) If $b = c = 0$ and $a = d$. Then $\mathcal{M}(T) = \begin{pmatrix} a & 0 \\ 0 & a \end{pmatrix} = a\mathcal{M}(I)$. Thus $T = aI$. Hence the min poly is $z - a$.

Othws, by (a), $z^2 - (a + d)z + (ad - bc)$ is a poly multi of the min poly.

Now we prove that $T \notin \text{span}(I)$, so that then the min poly of T has exactly deg 2.

(At least one of the asum of (I),(II) below is true.)

(I) Sups $a = d$, then $Tv = av + bw \notin \text{span}(v)$, $Tw = cv + aw \notin \text{span}(w)$.

(II) Sups at most one of b, c is not 0. If $b = 0$, then $Tw \notin \text{span}(w)$; If $c = 0$, then $Tv \notin \text{span}(v)$. \square

- *Sups $S, T \in \mathcal{L}(V)$, S is inv, and $p \in \mathcal{P}(\mathbf{F})$. Prove $Sp(TS) = p(ST)S$.*

SOLUS:

We prove $S(TS)^m = (ST)^mS$ for each $m \in \mathbf{N}$ by induc.

(i) If $m = 0, 1$. Then $S(TS)^0 = I = (ST)^0S$; $S(TS)^1 = (ST)S$.

(ii) If $m > 1$. Asum $S(TS)^m = (ST)^mS$.

Then $S(TS)^{m+1} = S(TS)^m(TS) = (ST)^mSTS = (ST)^{m+1}S$.

Hence $\forall p \in \mathcal{P}(\mathbf{F}), Sp(TS) = \sum_{k=1}^m a_k S(TS)^k = \sum_{k=1}^m a_k p(ST)^k S = [\sum_{k=1}^m a_k (TS)^k] S$. \square

COMMENT: $p(TS) = S^{-1}p(ST)S$, $p(ST) = Sp(TS)S^{-1}$.

CORO: 5 Becs S is inv, $T \in \mathcal{L}(V)$ is arb $\iff R = ST$ is arb.

Hence $\forall R \in \mathcal{L}(V)$, inv $S \in \mathcal{L}(V)$, $p(S^{-1}RS) = S^{-1}p(R)S$.

- (4E 5.B.7) *Sups $S, T \in \mathcal{L}(V)$. Let p, q be the min polys of ST, TS respectively.*

(a) *If $V = \mathbf{F}^2$. Give an exa suth $p \neq q$; (b) If S or T is inv. Prove $p = q$.*

SOLUS:

(a) Define S by $S(x, y) = (x, x)$. Define T by $T(x, y) = (0, y)$.

Then $ST(x, y) = 0$, $TS(x, y) = (0, x)$ for all $(x, y) \in \mathbf{F}^2$. Thus $ST = 0 \neq TS$ and $(TS)^2 = 0$.

Hence the min poly of ST does not equal to the min poly of TS .

(b) Sups S is inv. Becs p, q are monic.

$$\left. \begin{aligned} p(ST) = 0 &= Sp(TS)S^{-1} \Rightarrow p(TS) = 0, p \text{ is a poly multi of } q \\ q(TS) = 0 &= S^{-1}q(ST)S \Rightarrow q(ST) = 0, q \text{ is a poly multi of } p \end{aligned} \right\} \Rightarrow p = q.$$

Reversing the roles of S and T , we conclude that if T is inv, then $p = q$ as well. \square

- 11** *Sups $\mathbf{F} = \mathbf{C}$, $T \in \mathcal{L}(V)$, $p \in \mathcal{P}(\mathbf{C})$, and $\alpha \in \mathbf{C}$.*

Prove α is an eigval of $p(T) \iff \alpha = p(\lambda)$ for some eigval λ of T .

SOLUS:

(a) Sups α is an eigval of $p(T) \iff (p(T) - \alpha I)$ is not inje.

Write $p(z) - \alpha = c(z - \lambda_1) \cdots (z - \lambda_m) \Rightarrow p(T) - \alpha I = c(T - \lambda_1 I) \cdots (T - \lambda_m I)$.

By TIPS, $\exists (T - \lambda_j I)$ not inje. Thus $p(\lambda_j) - \alpha = 0$.

(b) Sups $\alpha = p(\lambda)$ and λ is an eigval of T with an eigvec v . Then $p(T)v = p(\lambda)v = \alpha v$. □

OR. Define q by $q(z) = p(z) - \alpha$. λ is a zero of q .

Becs $q(T)v = (p(T) - \alpha I)v = q(\lambda)v = (p(\lambda) - \alpha)v = 0$.

Hence $q(T)$ is not inje $\Rightarrow (p(T) - \alpha I)$ is not inje. □

12 [OR (4E.5.B.6)] Give an exa of an optor on \mathbb{R}^2
that shows the result above does not hold if \mathbb{C} is replaced with \mathbb{R} .

SOLUS:

Define $T \in \mathcal{L}(\mathbb{R}^2)$ by $T(w, z) = (-z, w)$.

By Exe (4E 5.B.11), $\mathcal{M}(T, ((1, 0), (0, 1))) = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \Rightarrow$ the min poly of T is $z^2 + 1$.

Define p by $p(z) = z^2$. Then $p(T) = T^2 = -I$. Thus $p(T)$ has eigval -1 .

While $\nexists \lambda \in \mathbb{R}$ suth $-1 = p(\lambda) = \lambda^2$. □

• (4E 5.B.17) Sups V is finide, $T \in \mathcal{L}(V)$, $\lambda \in \mathbb{F}$, and p is the min poly of T .
Show the min poly of $(T - \lambda I)$ is the poly q defined by $q(z) = p(z + \lambda)$.

SOLUS:

$q(T - \lambda I) = 0 \Rightarrow q$ is poly multi of the min poly of $(T - \lambda I)$.

Sups the deg of the min poly of $(T - \lambda I)$ is n , and the deg of the min poly of T is m .

By definition of min poly,

n is the smallest suth $(T - \lambda I)^n \in \text{span}(I, (T - \lambda I), \dots, (T - \lambda I)^{n-1})$;

m is the smallest suth $T^m \in \text{span}(I, T, \dots, T^{m-1})$.

$\text{又 } T^k \in \text{span}(I, T, \dots, T^{k-1}) \iff (T - \lambda)^k \in \text{span}(I, (T - \lambda I), \dots, (T - \lambda I)^{k-1})$.

Thus $n = m$. 又 q is monic. By the uniqueness of min poly. □

• (4E 5.B.18) Sups V is finide, $T \in \mathcal{L}(V)$, $\lambda \in \mathbb{F} \setminus \{0\}$, and p is the min poly of T .
Show the min poly of λT is the poly q defined by $q(z) = \lambda^{\deg p} p(\frac{z}{\lambda})$.

SOLUS:

$q(\lambda T) = \lambda^{\deg p} p(T) = 0 \Rightarrow q$ is a poly multi of the min poly of λT .

Sups the deg of the min poly of λT is n , and the deg of the min poly of T is m .

By definition of min poly,

n is the smallest suth $(\lambda T)^n \in \text{span}(\lambda I, \lambda T, \dots, (\lambda T)^{n-1})$;

m is the smallest suth $T^m \in \text{span}(I, T, \dots, T^{m-1})$.

$\text{又 } (\lambda T)^k \in \text{span}(\lambda I, \lambda T, \dots, (\lambda T)^{k-1}) \iff T^k \in \text{span}(I, T, \dots, T^{k-1})$.

Thus $n = m$. 又 q is monic. By the uniqueness of min poly. □

18 [OR (4E 5.B.15)] Sups V is a finide complex vecsp with $\dim V > 0$ and $T \in \mathcal{L}(V)$.

Define $f : \mathbb{C} \rightarrow \mathbb{R}$ by $f(\lambda) = \dim \text{range}(T - \lambda I)$.

Prove f is not a continuous function.

SOLUS: Note that V is finide.

Let λ_0 be an eigval of T . Then $(T - \lambda_0 I)$ is not surj. Hence $\dim \text{range}(T - \lambda_0 I) < \dim V$.

Becs T has finitely many eigvals. There exists a sequence of numbers $\{\lambda_n\}$ suth $\lim_{n \rightarrow \infty} \lambda_n = \lambda_0$.

And λ_n is not an eigval of T for each $n \Rightarrow \dim \text{range}(T - \lambda_n I) = \dim V \neq \dim \text{range}(T - \lambda_0 I)$.

Thus $f(\lambda_0) \neq \lim_{n \rightarrow \infty} f(\lambda_n)$. □

- (4E 5.B.9) Sups $T \in \mathcal{L}(V)$ is suth wrto some bss of V ,
all ent of the matrix of T are rational numbers.

Explain why all coeffs of the min poly of T are rational numbers.

SOLUS:

Let (v_1, \dots, v_n) denote the bss suth $\mathcal{M}(T, (v_1, \dots, v_n))_{j,k} = A_{j,k} \in \mathbb{Q}$ for all $j, k = 1, \dots, n$.

Denote $\mathcal{M}(v_j, (v_1, \dots, v_n))$ by x_j for each v_j .

Sups p is the min poly of T and $p(z) = z^m + \dots + c_1 z + c_0$. Now we show each $c_j \in \mathbb{Q}$.

Note that $\forall s \in \mathbb{N}^+, \mathcal{M}(T^s) = \mathcal{M}(T)^s = A^s \in \mathbb{Q}^{n,n}$ and $T^s v_k = A_{1,k}^s v_1 + \dots + A_{n,k}^s v_n$ for all $k \in \{1, \dots, n\}$.

$$\text{Thus } \begin{cases} \mathcal{M}(p(T)v_1) = (A^m + \dots + c_1 A + c_0 I)x_1 = \sum_{j=1}^n (A^m + \dots + c_1 A + c_0 I)_{j,1} x_j = 0; \\ \vdots \\ \mathcal{M}(p(T)v_n) = (A^m + \dots + c_1 A + c_0 I)x_n = \sum_{j=1}^n (A^m + \dots + c_1 A + c_0 I)_{j,n} x_j = 0; \end{cases}$$

$$\text{More clearly, } \begin{cases} (A^m + \dots + c_1 A + c_0 I)_{1,1} = \dots = (A^m + \dots + c_1 A + c_0 I)_{n,1} = 0; \\ \vdots \quad \ddots \quad \vdots \\ (A^m + \dots + c_1 A + c_0 I)_{1,n} = \dots = (A^m + \dots + c_1 A + c_0 I)_{n,n} = 0; \end{cases}$$

Hence we get a system of n^2 liney equations in m unknowns c_0, c_1, \dots, c_{m-1} .

We conclude that $c_0, c_1, \dots, c_{m-1} \in \mathbb{Q}$. □

- [OR (4E 5.B.16), OR (8.C.18)] Sups $a_0, \dots, a_{n-1} \in \mathbb{F}$. Let T be the optor on \mathbb{F}^n suth

$$\mathcal{M}(T) = \begin{pmatrix} 0 & & & -a_0 \\ 1 & 0 & & -a_1 \\ & 1 & \ddots & \vdots \\ & & \ddots & 0 & -a_{n-2} \\ 0 & & & 1 & -a_{n-1} \end{pmatrix}, \text{ wrto the std bss } (e_1, \dots, e_n).$$

Show the min poly of T is p defined by $p(z) = a_0 + a_1 z + \dots + a_{n-1} z^{n-1} + z^n$.

$\mathcal{M}(T)$ is called the **companion matrix** of the poly above. This exercise shows that every monic poly is the min poly of some optor.

Hence a formula or an algo that could produce exact eigvals for each optor on each \mathbb{F}^n could then produce exact zeros for

each poly [by 8.36(b)]. Thus there is no such formula or algo. However, efficient numeric methods exis for obtaining very good approximations for the eigvals of an optor.

SOLUS: Note that $(e_1, Te_1, \dots, T^{n-1}e_1)$ is liney indep. \propto The deg of min poly is at most n .

$$\begin{aligned} T^n e_1 &= \dots = T^{n-k} e_{1+k} = \dots = T e_n = -a_0 e_1 - a_1 e_2 - a_2 e_3 - \dots - a_{n-1} e_n \\ &= (-a_0 I - a_1 T - a_2 T^2 - \dots - a_{n-1} T^{n-1}) e_1. \end{aligned}$$

Thus $p(T)e_1 = 0 = p(T)e_j$ for each $e_j = T^{j-1}e_1$. □

• EIGENVALUES ON ODD-DIMENSIONAL REAL VECTOR SPACES

• EVEN-DIMENSIONAL NULL SPACE

Sups $\mathbb{F} = \mathbb{R}$, V is finide, $T \in \mathcal{L}(V)$ and $b, c \in \mathbb{R}$ with $b^2 < 4c$.

Prove $\dim \text{null}(T^2 + bT + cI)$ is an even number.

SOLUS:

Denote $\text{null}(T^2 + bT + cI)$ by R . Then $T|_R + bT|_R + cI_R = (T + bT + cI)|_R = 0 \in \mathcal{L}(R)$.

Sups λ is an eigval of T_R with an eigvec $v \in R$.

$$\text{Then } 0 = (T|_R^2 + bT|_R + cI_R)(v) = (\lambda^2 + \lambda b + c)v = ((\lambda + \frac{b}{2})^2 + c - \frac{b^2}{4})v.$$

Becs $c - \frac{b^2}{4} > 0$ and we have $v = 0$. Thus T_R has no eigvals.

Let U be invarsp of R that has the largest, even dim among all invarsp.

Asum $U \neq R$. Then $\exists w \in R$ but $w \notin U$. Let W be suth $(w, T|_R w)$ is a bss of W .

Becs $T|_R^2 w = -bT|_R w - cw \in W$. Hence W is invarsp of dim 2.

Thus $\dim(U + W) = \dim U + 2 - \dim(U \cap W)$, where $U \cap W = \{0\}$,

for if not, becs $w \notin U, T|_R w \in U$,

$U \cap W$ is invar $T|_R$ of one dim (impossible becs $T|_R$ has no eigvecs).

Hence $U + W$ is even-dim invarsp under $T|_R$, ctradic the max of $\dim U$.

Thus the asum was incorrect. Hence $R = \text{null}(T^2 + bT + cI) = U$ has even dim. □

• OPERATORS ON ODD-DIMENSIONAL VECTOR SPACES HAVE EIGENVALUES

(a) Sups $\mathbf{F} = \mathbf{C}$. Then by [5.21], done.

(b) Sups $\mathbf{F} = \mathbf{R}$, V is finide, and $\dim V = n$ is an odd number.

Let $T \in \mathcal{L}(V)$ and the min poly is p . Prove T has an eigval.

SOLUS:

(i) If $n = 1$, then done.

(ii) Sups $n \geq 3$. Asum every optor, on odd-dim vecsp of dim less than n , has an eigval.

If p is a poly multi of $(x - \lambda)$ for some $\lambda \in \mathbf{R}$, then by [8.49] λ is an eigval of T and done.

Now sups $b, c \in \mathbf{R}$ suth $b^2 < 4c$ and p is a poly multi of $x^2 + bx + c$ (see [4.17]).

Then $\exists q \in \mathcal{P}(\mathbf{R})$ suth $p(x) = q(x)(x^2 + bx + c)$ for all $x \in \mathbf{R}$.

Now $0 = p(T) = (q(T))(T^2 + bT + cI)$, which means that $q(T)|_{\text{range}(T^2 + bT + cI)} = 0$.

Becs $\deg q < \deg p$ and p is the min poly of T , hence $\text{range}(T^2 + bT + cI) \neq V$.

又 $\dim V$ is odd and $\dim \text{null}(T^2 + bT + cI)$ is even (by our previous result).

Thus $\dim V - \dim \text{null}(T^2 + bT + cI) = \dim \text{range}(T^2 + bT + cI)$ is odd.

By [5.18], $\text{range}(T^2 + bT + cI)$ is invarsp of V under T that has odd dim less than n .

Our induc hypo now implies that $T|_{\text{range}(T^2 + bT + cI)}$ has an eigval.

By induc. □

• (2E Ch5.24) Sups $\mathbf{F} = \mathbf{R}, T \in \mathcal{L}(V)$ has no eigvals.

Prove every invarsp of V under T is even-dim.

SOLUS:

Sups U is such a subsp. Then $T|_U \in \mathcal{L}(U)$. We prove by ctradic.

If $\dim U$ is odd, then $T|_U$ has an eigval and so is T , so that \exists invarsp of 1 dim, ctradic. □

• (4E 5.B.29) Show every optor on a finide vecsp of $\dim \geq 2$ has a 2-dim invarsp.

SOLUS:

Using induc on $\dim V$.

(i) $\dim V = 2$, done.

(ii) $\dim V > 2$. Asum the desired result is true for vecsp of smaller dim.

Sups p is the min poly of $\deg m$ and $p(z) = (z - \lambda_1) \cdots (z - \lambda_m)$.

If $T = \lambda I$ ($\Leftrightarrow m = 1 \vee m = -\infty$), then done. ($m \neq 0$ becs $\dim V \neq 0$)

Now define a q by $q(z) = (z - \lambda_1)(z - \lambda_2)$.

By asum, $T|_{\text{null } q(T)}$ has invarsp of dim 2. □

5.B: II

9 14 15 20 | 4E: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 11, 12, 13, 14

- (4E 5.C.1) *Prove or give a counterexample:*

If $T \in \mathcal{L}(V)$ and T^2 has an upper-trig matrix, then T has an upper-trig matrix.

SOLUS:

- (4E 5.C.2) *Sups A and B are upper-trig matrices of the same size, with $\alpha_1, \dots, \alpha_n$ on the diag of A and β_1, \dots, β_n on the diag of B .*
 - Show $A + B$ is an upper-trig matrix with $\alpha_1 + \beta_1, \dots, \alpha_n + \beta_n$ on the diag.*
 - Show AB is an upper-trig matrix with $\alpha_1\beta_1, \dots, \alpha_n\beta_n$ on the diag.*

SOLUS:

- (4E 5.C.3) *Sups $T \in \mathcal{L}(V)$ is inv and $B = (v_1, \dots, v_n)$ is a bss of V suth $\mathcal{M}(T, B) = A$ is upper trig, with $\lambda_1, \dots, \lambda_n$ on the diag. Show the matrix of $\mathcal{M}(T^{-1}, B) = A^{-1}$ is also upper trig, with $\frac{1}{\lambda_1}, \dots, \frac{1}{\lambda_n}$ on the diag.*

SOLUS:

- 9** [4E 5.C.7] *Sups V is finite, $T \in \mathcal{L}(V)$, and $v \in V$.*
- Prove $\exists!$ monic poly p_v of smallest deg suth $p_v(T)v = 0$.*
 - Prove the min poly of T is a poly multi of p_v .*

SOLUS:

- 14** [OR (4E 5.C.4)] *Give an optor T suth wrto some bss, $\mathcal{M}(T)_{k,k} = 0$ for each k , while T is inv.*

SOLUS:

- 15** [OR (4E 5.C.5)] *Give an optor T suth wrto some bss, $\mathcal{M}(T)_{k,k} \neq 0$ for each k , while T is not inv.*

SOLUS:

- 20** [OR (OR 4E 5.C.6)] *Sups $\mathbf{F} = \mathbf{C}$, V is finite, and $T \in \mathcal{L}(V)$. Prove if $k \in \{1, \dots, \dim V\}$, then V has a k dim subsp invard T .*

SOLUS:

- (4E 5.C.8) *Sups V is finite, $T \in \mathcal{L}(V)$, and $\exists v \in V \setminus \{0\}$ suth $T^2v + 2Tv = -2v$.*
 - Prove if $\mathbf{F} = \mathbf{R}$, then \nexists a bss of V wrto which T has an upper-trig matrix.*
 - Prove if $\mathbf{F} = \mathbf{C}$ and A is an upper-trig matrix that equals the matrix of T wrto some bss of V , then $-1 + i$ or $-1 - i$ appears on the diag of A .*

SOLUS:

- (4E 5.C.9) *Sups $B \in \mathbf{F}^{n,n}$ with complex ent.*

Prove \exists inv $A \in \mathbf{F}^{n,n}$ with complex ent suth $A^{-1}BA$ is an upper-trig matrix.

SOLUS:

- (4E 5.C.10) Sups $T \in \mathcal{L}(V)$ and (v_1, \dots, v_n) is a bss of V .

Show the following are equi.

- (a) The matrix of T wrto (v_1, \dots, v_n) is lower trig.
- (b) $\text{span}(v_k, \dots, v_n)$ is invard T for each $k = 1, \dots, n$.
- (c) $Tv_k \in \text{span}(v_k, \dots, v_n)$ for each $k = 1, \dots, n$.

SOLUS:

- (4E 5.C.11) Sups $\mathbf{F} = \mathbf{C}$ and V is finide.

Prove if $T \in \mathcal{L}(V)$, then T has a lower-trig matrix wrto some bss.

SOLUS:

- (4E 5.C.12)

Sups V is finide, $T \in \mathcal{L}(V)$ has an upper-trig matrix wrto some bss, and U is a subsp of V that is invard T .

- (a) Prove $T|_U$ has an upper-trig matrix wrto some bss of U .
- (b) Prove T/U has an upper-trig matrix wrto some bss of V/U .

SOLUS:

- (4E 5.C.13) Sups V is finide, $T \in \mathcal{L}(V)$. Sups U is invarsp of V under T suth $T|_U, T/U$ have upper-trig matrix.

Prove T has upper-trig matrix.

SOLUS:

- (4E 5.C.14) Sups V is finide and $T \in \mathcal{L}(V)$.

Prove T has upper-trig matrix $\iff T'$ has upper-trig matrix.

SOLUS:

ENDED

5.C

XXXX

ENDED

5.E* [4E] 1 2 3 4 5 6 7 8 9 10

1 Give commu optors $S, T \in \mathbf{F}^4$ suth

\exists subsp of \mathbf{F}^4 invard S but not T and \exists subsp of \mathbf{F}^4 invard T but not S .

SOLUS:

2 Sups \mathcal{E} is a subset of $\mathcal{L}(V)$ and every ele of \mathcal{E} is diag.

Prove \exists a bss of V wrto which

every ele of \mathcal{E} has a diag matrix \iff every pair of ele of \mathcal{E} commu.

This exercise extends [5.76], which considers the case in which \mathcal{E} contains only two ele.

For this exercise, \mathcal{E} may contain any number of ele, and \mathcal{E} may even be an infini set.

SOLUS:

3 *Sups $S, T \in \mathcal{L}(V)$ are suth $ST = TS$. Sups $p \in \mathcal{P}(\mathbf{F})$.*

(a) Prove null $p(S)$ is invard T . (b) Prove range $p(S)$ is invard T .

See NOTE FOR[5.17] for the special case $S = T$.

SOLUS:

4 *Prove or give a counterexa: A diag matrix A and upper-trig matrix B of the same size commu.*

SOLUS:

5 *Prove a pair of optors on a finide vecsp commu \iff their dual optors commu.*

SOLUS:

6 *Sups V is a finide complex vecsp and $S, T \in \mathcal{L}(V)$ commu.*

Prove $\exists \alpha, \lambda \in \mathbf{C}$ suth $\text{range}(S - \alpha I) + \text{range}(T - \lambda I) \neq V$.

SOLUS:

7 *Sups V is a complex vecsp, $S \in \mathcal{L}(V)$ is diag, and T commu with S .*

Prove \exists bss B of V suth S has a diag matrix wrto B

and T has upper-trig matrix wrto B .

SOLUS:

8 *Sups $m = 3$ in [5.72] and D_x, D_y are the commu partial diff optors on $\mathcal{P}_3(\mathbf{R}^2)$ from [5.72].*

Find a bss of $\mathcal{P}_3(\mathbf{R}^2)$ wrto which D_x and D_y each have upper-trig matrix.

SOLUS:

9 *Sups V is a finide nonzero complex vecsp.*

Sups that $\mathcal{E} \subseteq \mathcal{L}(V)$ is suth S and T commu for all $S, T \in \mathcal{E}$.

(a) Prove \exists eigvec $v \in V$ for every ele of \mathcal{E} .

(b) Prove \exists a bss of V wrto which every ele of \mathcal{E} has upper-trig matrix.

SOLUS:

10 *Give commu optors S, T on a finide real vecsp suth*

$S + T$ has a eigval that does not equal an eigval of S plus an eigval of T

and ST has a eigval that does not equal an eigval of S times an eigval of T .

SOLUS:

ENDED