



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。

习题我有几不摘：(1) 太过小儿科的不摘，比如 1.A 节；(2) 虽然有难度，但习题都是一遍过，或者过不去明显是因为和教材无关的知识门槛；(3) 对书中定理显而易见的应用题；(4) 算术题；(5) 有前章基础者可轻易在书中原地解决的；(6) 暂时没想到一题多解的。

习题解答中，有我完全独立思考得出的，有抄 <https://linearalgebras.com/>（这个网站的稳定性非常差，我每每以为它被嘎了），有抄 [stackexchange](#)，有抄 [LADR2eSolutions \(By Axler\).pdf](#)，有抄最新的 [LADR4eSolutions 经典最全 \(By Axler?\) .pdf](#)（这些文档的许可证件，除最后这个找不到/没有指明外，都允许复制/引用），还有请教别人，乃至请教 AI 得出来的。不过别担心，我请教 AI 时，要么是要找出一个命题的反例（典型的就是有限维成立而无限维不成立的反例），要么是在已经得到正确解答后想看看有没有别的思路。

课文补注就是一些 **Tips** 和 **Notes**，有警示、简化方法、对正文的直接补充、还有从习题中总结出的二级结论。我将课文中简单而便利的定义（比如 3.E 节的积空间）前置（比如 1.C 节）使用。这相当于更改了原书的内容顺序。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，所以我对做了简写表。我很马虎的，所以会有很多小错误，如有发现就快告诉我！我自己也会不定期抓错玩。

题目目标为正常数字 **N** 的，为 3e 某章某节第 **N** 题（有个别题是 4e 又删去或增添设问的，仍用 3e 题号）。因为要面向以第三版为纸面教材的学习者，所以为了避免混淆，摘录 4e 题目时将题号略去或小字号括弧内标注；而一些新增过多内容的章节会全盘使用 4e 题号。题目顺序会有调换。除了原书 4e 新加入的章节外，均使用原书 3e 的索引。这也许对 4e 的使用者很不友好。然而 4e 并不算是全盘将 3e 覆盖后又增加新内容。比如 3e 第 9 章和第 10 章 B 节，复化的思想在 4e 中删减很多。

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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，（刨去笔记的工夫）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 $70 \times 8h$ 。出乎意料的是，后一半学习异常高效、顺利，也许前一半的学习困难多半是因为基础能力太差。最后实际用时约 $60 \times 8h$ ，刨去 TeX 笔记的代码工夫；若算上这个，则约 $95 \times 8h$ ，这里仍刨去了初学 TeX 和个人定制宏的时间，TeX 笔记用时很多还是因为不熟练和强迫症。

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，也已经了解过一众经典的数学分支，这些经历会化作一个叫“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，要么拿出足够的耐心和毅力。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 Open 到网上。实际的时间开销包括了很多不相干的额外项目：初学 TeX、调整代码架构、为我的视觉强迫症让步、了解许可证选用，诸如此类的各种波折。大把的时间花销还因为：早期的学习态度还不够主动，导致太多‘一遍过’的习题被摘录到这里；没有独立编撰大型文档的经验和模板，可能会强迫症似地纠结散乱的格式和对齐。

我在学习过程中碰到了很多重大误区：第一章中，我一开始误认为 $W = \mathbb{C}_V U \cup \{0\}$ 是唯一使得 $W \oplus U = V$ 的子空间，但这压根就不是子空间，而且 C 节习题中也提示这样的子空间 W 不唯一。第二章中，我随意地将“线性无关的序列”等同于有/无限维向量空间的基，没有任何理论依据，我也并不懂什么选择公理。第三章 B 到 D 节中，我总觉得子空间是超脱有限维的存在；因为放不下第二章无限维向量空间的基的情结，我刻意寻找那些避开涉及基的解法，一些臆测的结论和容易就找到反例。第三章 E 节中，我似乎对商空间有什么误解，觉得 $v + U = v' + U$ 如同变戏法一样，把 v 中一切带有 U 的部分抹除掉，让 v 变得纯粹独立于 U，为此我还单门发明了 Pure V/U 并试着证明一些命题，甚至用它发现了 F 节 23 题无限维情况下不依赖基和同构的解法。后来我猛然发现我最开始的想法多么荒诞，却仍然放不下 Pure V/U 的情结。这些挫折让我思维变得更加缜密，于是在内化抽象的第三章 F 节时比想象中的要顺利，及时避开了一些误区。作为回报，我仅用了两小时就完结了第六章 C 节（包括 4E）除计算题以外的所有内容。

最后，我愿说，与“mathematical maturity”相反的“mathematical naivety”，反而是一种财富。前期因为这种 naivety，许多荒诞不经的奇思妙想就能在脑海中飞驰；后期因为上升来的 maturity，我就再也没有像前期那样灵感乍现过了。

ABBREVIATION TABLE

A B

abs	absolute
add	addi(tion)(tive)
adj	adjoint
algo	algorithm
arb	arbitrary
assoc	associa(tive)(tivity)
asum	assum(e)(ption)
becs	because
bss	basis
bses	bases
B_V	basis of V

E

-ec	-ec(t)(tor)(tion)(tive)
eig-	eigen-
elem	element(s)
ent	entr(y)(ies)
equa	equality
equiv	equivalen(t)(ce)
exa	example
exe	exercise
exist	exist(s)(ing)
existns	existence
expo	exponent
expr	expression

L

liney	linear(ly)
linity	linearity
len	length
low-	lower-

R

recurly	recursively
repeti	repetition(s)
representa	representation(s)
req	require(s)(d)/requiring
respectly	respectively
restr	restrict(ion)(ive)(ing)
rev	revers(e(s))(ed)(ing)
rotat	rotation

C

ch	characteristic
closd	closed under
coeff	coefficient
col	column
combina	combination
commu	commut(es)(ing)(ativity)
cond	condition
conjug	conjugat(e)(ing)(ion)
corres	correspond(s)(ing)
const	constant
conveni	convenience
convly	conversely
countexa	counterexample
countclockws	counterclockwise
ctradic	contradict(s)(ion)
ctrapos	contrapositive

D

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

I

id	identity
immed	immediately
induc	induct(ion)(ive)
infly	infinitely
inje	injectiv(e)(ity)
inv	inver(se)(tib-le/ility)
invar	invariant
inward	invariant under
invarsp	invariant subspace
invarsdpd	invariant subspace under
iso	isomorph(ism)(ic)
isomet	isometry

F G H

factoriz	factorizaion
fini	finite(ly)
finide	finite-dimensional
g-eig-	generalized eig-
G disk	Gershgorin disk
homo	homogeneity
hypo	hypothesis

M N

max	maxi(mal(ity))(mum)
min	mini(mal(ity))(mum)
multi	multipl(e)(icati-on/ve)
multy	multiplicity
nilp	nilpotent
non0	nonzero
nonC	nonconst
notat	notation(al)

O P Q

optr	operator
othws	otherwise
orthog	orthogonal
orthon	orthonormal
poly	polynomial
posi	positive
prod	product
quad	quadratic
quot	quot

S

seq	sequence
simlr	similar(ly)
singval	singular value
solus	solution
sp	space
stmt	statement
std	standard
supp	suppose
surj	surjectiv(e)(ity)
suth	such that
symm	symmetry

T U V W X Y Z

trig	triangular
trslate	translate
trspose	transpose
uniq	unique
uniqnes	uniqueness
unit	unitary
up-	upper-
val	value
-wd	-ward
-ws	-wise
wrto	with respect to

1·B

- **NOTE FOR Fields:** Many choices. [Req Multi Inv Uniq]

Exa: $\mathbf{Z}_m = \{K_0, K_1, \dots, K_{m-1}\}$ is a field $\Leftrightarrow m \in \mathbf{N}^+$ is a prime.

- (4E 1.B.7) $\text{Supp } V \neq \emptyset$ 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, Assoc, Distr are omitted.

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

Multi Id: $(1f)(x) = 1f(x) = f(x)$.

We must have used the same properties in W . [If W^V is a vecsp, then W must be a vecsp.] \square

1·C

注意: 这里我将 3.E 积空间的定义前置; 仅涉及概念。

- **NOTE FOR Exe (5):** $\mathbf{C} = \mathbf{R} \oplus \{ci : c \in \mathbf{R}\} = \{a + bi : a, b \in \mathbf{R}\}$ if we let $\mathbf{F} = \mathbf{R}$ and $i^2 = -1$.

- **NOTE FOR Exe (6):** $\text{Supp } V$ is a vecsp over \mathbf{R} . Then V is not a vecsp over \mathbf{C} .

- $\text{Supp } U, W, V_1, V_2, V_3$ are subsps of V .

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

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

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

• $(U \cap W)_C \ni u_1 + iu_2 = w_1 + iw_2 \in U_C \cap W_C$. \square

• $U_C = W_C \Leftrightarrow U = W$. $\text{Supp } U_C \ni u + iv \in W_C$. Then $U \ni u, v \in W$. \square

• $V_{1C} \times \dots \times V_{mC} = (V_1 \times \dots \times V_m)_C$. \square

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

SOLUS: $\text{Supp } \Omega$ 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) $\text{Supp } U + W = \Omega$. Becs $U + W \supseteq U, W \Rightarrow \Omega \supseteq U, W \Rightarrow U = W = \{0\}$. \square

- **NOTE FOR [1.45]:** Another proof: $\text{Supp } \forall v \in V, \exists! (u, w) \in U \times W, v = u + w$.

Asum non0 $v \in U \cap W$. Then the (u, w) can be $(v, 0)$ or $(0, v)$, ctradic the uniques.

- **NOTE FOR “ $C_V U \cup \{0\}$ ”:** “ $C_V U \cup \{0\}$ ” 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 $\begin{cases} w \in C_V U \cup \{0\} \\ u \pm w \in C_V U \cup \{0\} \end{cases} \Rightarrow u \in C_V U \cup \{0\}$. Ctradic.

To fix this, denote the set $\{W_1, W_2, \dots\}$ by $\mathcal{S}_V U$, where each $W_i \oplus U = V$.

- $\text{Supp } V_1, V_2, U_1, U_2$ are vecsps, $V_1 \oplus U_1 = V_2 \oplus U_2$, $V_1 \subseteq V_2$, $U_2 \subseteq U_1$.

Give a countexa: $V_1 = V_2$, $U_1 = U_2$. Let $U_2 = \{0\} \Rightarrow V_2 = V_1 \oplus U_1$.

V_1	U_1
V_2	U_2

• **TIPS 1:** *Supp* $V_1 \subseteq V_2$ and $V_1 \oplus U = V_2 \oplus U$. Prove $V_1 = V_2$.

SOLUS: Becs the subset V_1 of vecsp V_2 is closd add and scalar multi, V_1 is a subsp of V_2 .

Supp W is suth $V_2 = V_1 \oplus W$. 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 $V_1 \oplus U \subsetneq (V_1 \oplus U) \oplus W$, ctradic. Hence $W = \{0\}$, $V_1 = V_2$. \square

• **TIPS 2:** *Supp* $V = X \oplus Y$, and Z is a subsp of V . Show $X \subseteq Z \Rightarrow Z = X \oplus (Y \cap Z)$.

SOLUS: $\forall z \in Z, \exists! (x, y) \in X \times Y, z = x + y$.

Becs $x \in Z \Rightarrow z - x = y \in Z \Rightarrow z \in X + (Y \cap Z)$. As $X \cap (Y \cap Z) \subseteq X \cap Y$. \square

• **TIPS 3:** 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 ctradic.

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

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

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

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

(b) Supp $U \cup W$ 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 $a + b \in U \cup W$.

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

$a + b \in W \Rightarrow a = (a + b) + (-b) \in W$, ctradic $\Rightarrow U \subseteq W$. \square

13 Supp U_1, U_2, U_3 are subsps of V , and the union $U_1 \cup U_2 \cup U_3 = \mathcal{U}$ is a subsp of V .

Prove one of the subsps contains the other two.

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

SOLUS: 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.

NOTICE that, $U \cup W = V$ is vecsp $\not\Rightarrow U, W$ are subsps of V .

This trick is invalid: $(A \cup B) \cup (B \cup C) = (A \cup C) \cup (B \cup C) = (A \cup B) \cup (A \cup C)$.

(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 one is contained in the union of other two, and no one contains 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 $U_2, U_3 \neq \{0\}$. Becs $W \subseteq U_2 \cup U_3$ has at least three disti elems.

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

$\exists \lambda_1 \neq \lambda_2, v + \lambda_1 u$ and $v + \lambda_2 u$ both in U_2 or $U_3 \Rightarrow u \in U_2 \cap U_3$, ctradic. \square

2·A

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

SOLUS: Note that $V = \text{span}(v_1, \dots, v_n) \iff \forall v \in V, \exists a_1, \dots, a_n \in \mathbf{F}, v = a_1v_1 + \dots + a_nv_n$.

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

$$v = a_1v_1 + a_2v_2 + a_3v_3 + a_4v_4 = b_1(v_1 - v_2) + b_2(v_2 - v_3) + b_3(v_3 - v_4) + b_4v_4$$

$$= b_1v_1 + (b_2 - b_1)v_2 + (b_3 - b_2)v_3 + (b_4 - b_3)v_4$$

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

□

• (4E 3, 14) $\text{Supp } (v_1, \dots, v_m)$ 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) is liney indep $\iff (w_1, \dots, w_m)$ is liney indep [Q].

SOLUS:

(a) Asum $a_1v_1 + \dots + a_mv_m = b_1w_1 + \dots + b_mw_m = b_1v_1 + \dots + b_k(v_1 + \dots + v_k) + \dots + b_m(v_1 + \dots + v_m)$.

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) $P \Rightarrow Q$: $b_1w_1 + \dots + b_mw_m = 0 = a_1v_1 + \dots + a_mv_m$, where $0 = a_k = b_k + \dots + b_m$.

$Q \Rightarrow P$: $a_1v_1 + \dots + a_mv_m = 0 = b_1w_1 + \dots + b_mw_m = 0$, where $0 = b_m = a_m, 0 = b_k = a_k - a_{k+1}$.

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

□

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

(b) [P] A list (v, w) of len 2 in V is liney indep $\iff \forall \lambda, \mu \in \mathbf{F}, v \neq \lambda w, w \neq \mu v$. [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 $av = 0 \not\Rightarrow a = 0$.

$\neg Q \Rightarrow \neg P : v = 0 \Rightarrow av = 0$ 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.

$Q \Rightarrow P : \text{no scalar multi} \Rightarrow$ 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.

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

□

10 $\text{Supp } (v_1, \dots, v_m)$ is liney indep in V and $w \in V$.

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

SOLUS:

Note that $a_1(v_1 + w) + \dots + a_m(v_m + w) = 0 \Rightarrow a_1v_1 + \dots + a_mv_m = -(a_1 + \dots + a_m)w$.

Then $a_1 + \dots + a_m \neq 0$, for if not, $a_1v_1 + \dots + a_mv_m = 0$ while $a_i \neq 0$ for some i , ctradic.

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

Thus $a_1v_1 + \dots + a_mv_m = 0 \Rightarrow a_1 = \dots = a_m = 0$. Hence $(v_1 + w, \dots, v_m + w)$ is liney indep.

□

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 $\exists a_i \in \mathbf{F}, v_j + w = a_1(v_1 + w) + \dots + a_{j-1}(v_{j-1} + w) \iff v_j + \lambda w = a_1v_1 + \dots + a_{j-1}v_{j-1}$.

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 $w = \lambda^{-1}(a_1v_1 + \dots + a_{j-1}v_{j-1} - v_j) \Rightarrow w \in \text{span}(v_1, \dots, v_m)$.

□

11 $\text{Supp } (v_1, \dots, v_m)$ is liney indep in V and $w \in V$.

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

SOLUS: Equiv to (v_1, \dots, v_m, w) liney dep $\Leftrightarrow w \in \text{span}(v_1, \dots, v_m)$. By [2.21], immed. \square

NOTE: (a) $\text{Supp } (v_1, \dots, v_m, w)$ is liney indep. Then (v_1, \dots, v_m) liney indep $\Leftrightarrow w \notin \text{span}(v_1, \dots, v_m)$.

(b) $\text{Supp } (v_1, \dots, v_m, w)$ is liney dep. Then (v_1, \dots, v_m) liney indep $\Leftrightarrow w \in \text{span}(v_1, \dots, v_m)$.

14 Prove $[P]$ V is infinide $\Leftrightarrow \exists$ seq (v_1, v_2, \dots) in V suth each (v_1, \dots, v_m) liney indep. $[Q]$

SOLUS: $P \Rightarrow Q$: $\text{Supp } V$ is infinide, so that no list spans V . Define the desired seq recurly via:

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.

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

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

Or. $Q \Rightarrow P$: $\text{Supp } V$ there is such a seq.

Choose an m . $\text{Supp } V$ 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 . \square

17 Prove (p_0, p_1, \dots, p_m) cannot be liney indep in $\mathcal{P}_m(\mathbf{F})$ with each $p_k(2) = 0$.

SOLUS:

Define $p(z) = z$. Becs if $z = 2$, then $\forall a_i \in \mathbf{F}$, $p(z) \neq \sum_{i=0}^m a_i p_i(z)$. Now $p \notin \text{span}(p_0, p_1, \dots, p_m)$.

Asum (p_0, p_1, \dots, p_m) liney indep. Then $(p_0, p_1, \dots, p_m, p)$ of len $(m+2)$ is liney indep,

while $(1, z, \dots, z^m)$ of len $(m+1)$ spans $\mathcal{P}_m(\mathbf{F})$. Ctradic by [2.23]. \square

Or. Becs $(1, z, \dots, z^m)$ of len $(m+1)$ spans $\mathcal{P}_m(\mathbf{F})$. Then $(p_0, p_1, \dots, p_m, z)$ of len $(m+2)$ is liney dep.

As shown above, $z \notin \text{span}(p_0, p_1, \dots, p_m)$. By the NOTE (a) in Exe(11). \square

ENDED

2.B

• **NOTE FOR liney indep seq 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? [See higher courses]

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.

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

- (4E9) $\text{Supp } (v_1, \dots, v_m)$ is a list in V . For $k \in \{1, \dots, m\}$, let $w_k = v_1 + \dots + v_k$.

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

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: OR. Using [3.C NOTE FOR [3.30, 32](a)].

- 8** $\text{Supp } B_U = (u_1, \dots, u_m), B_W = (w_1, \dots, w_n)$.

Prove $V = U \oplus W \iff B_V = (u_1, \dots, u_m, w_1, \dots, w_n)$.

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

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) $\text{Supp } V$ is on \mathbf{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_C . $[Q]$

(b) Show $[P] B$ spans $V \iff B$ spans V_C . $[Q]$

SOLUS:

(a) $P \Rightarrow Q$: Note that each $v_k \in V_C$. $\text{Supp } \lambda_1 v_1 + \dots + \lambda_n v_n = 0$ with $\mathbf{F} = \mathbf{C}$.

Then $(\text{Re}\lambda_1)v_1 + \dots + (\text{Re}\lambda_n)v_n = 0 \Rightarrow \text{each Re}\lambda_i = 0$, simlr for $\text{Im}\lambda_i$.

$Q \Rightarrow P$: If $\lambda_k \in \mathbf{R}$ with $\lambda_1 v_1 + \dots + \lambda_n v_n = 0$, then each $\text{Re}\lambda_k = \lambda_k = 0$.

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

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

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

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

$\neg P \Rightarrow \neg Q$: $\exists v \in V, v \notin \text{span}B$ with $\mathbf{F} = \mathbf{R} \Rightarrow v + i0 \notin \text{span}B$ with $\mathbf{F} = \mathbf{C}$.

$\neg Q \Rightarrow \neg P$: $\exists u + iv \in V_C, u + iv \notin \text{span}B \Rightarrow (\text{Re}1)u + (\text{Re}i)v = u$ or $(\text{Im}1)u + (\text{Im}i)v = v \notin \text{span}B$. \square

- **TIPS:** $\text{Supp dim } V = n$, 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. $\text{Supp } (v_1, \dots, v_{k-1})$ 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. $\text{Supp } U \neq \{0\}$. 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

2.C

- **NOTE FOR EXE (15):** $\text{Supp } v \in V \setminus \{0\}$. 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. $\text{Supp } n > 1$.

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

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

COMMENT: Let $B_V = (v_1, \dots, v_n)$ and $\text{supp } v = u_1 + \dots + u_n$, 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 $u_i = 0$.

- 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 $n = \dim \text{span}(v_1, \dots, v_n)$.

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

SOLUS: Using (2.A.10, 11).

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

(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.

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

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

- (4E 16) $\text{Supp } V$ 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 each $U_i = \text{span}(v_1, \dots, v_m, u_1, \dots, u_{i-1}, u_{i+1}, \dots, u_{n-m}) \Rightarrow U \subseteq U_i$.

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

14 $\text{Supp } V_1, \dots, V_m$ 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 $k \in \{1, \dots, m-1\}$, $(V_1 \oplus \dots \oplus V_k) \cap V_{k+1} = \{0\}$, $(\mathcal{E}_1 \cup \dots \cup \mathcal{E}_{k-1}) \cap \mathcal{E}_k = \emptyset$

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

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

- **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) simlr.

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

- $\text{Supp } V_1, V_2, V_3$ are subsps 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, $\dim(V_1 \cap V_2 \cap V_3) \geq 2 \dim V - \dim(V_2 + V_3) - \dim(V_1 + (V_2 \cap V_3)) \geq 0$. \square

17 Supp V_1, V_2, V_3 are subsp of a finide vecsp. Explain and give a countexa:

$$\dim(V_1 + V_2 + V_3) = \dim V_1 + \dim V_2 + \dim V_3$$

$$\text{SOLUS: } -\dim(V_1 \cap V_2) - \dim(V_1 \cap V_3) - \dim(V_2 \cap V_3) + \dim(V_1 \cap V_2 \cap V_3).$$

$$(1) |(A \cup B) \cup C| = |A \cup B| + |C| - |(A \cup B) \cap C|.$$

$$(2) |(A \cup B) \cap C| = |(A \cap C) \cup (B \cap C)| = |A \cap C| + |B \cap C| - |A \cap B \cap C|.$$

$$\text{Thus } |(A \cup B) \cup C| = |A| + |B| + |C| + |A \cap B \cap C| - |A \cap B| - |A \cap C| - |B \cap C|.$$

$$\text{Becs } (V_1 + V_2) + V_3 = V_1 + (V_2 + V_3) = (V_1 + V_3) + V_2.$$

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

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

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

Generally, $(X + Y) \cap Z \neq (X \cap Z) + (Y \cap Z)$. **Exa:** $X = \{(x, 0)\}, Y = \{(0, y)\}, Z = \{(z, z)\} \subseteq \mathbf{F}^2$.

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 formula holds. Simlr for $Y \subseteq Z$, $X \subseteq Z$, and $X, Y \subseteq Z$.

NOTE: However, it's true that $(X + Y) \cap Z \supseteq (X \cap Z) + (Y \cap Z) = (X + (Y \cap Z)) \cap Z$.

Becs $(X \cap Z) + (Y \cap Z) \ni v = x + y = z_1 + z_2 \in (X + (Y \cap Z)) \cap Z \Rightarrow v \in (X + Y) \cap Z$.

ENDED

3·A 注意: 这里我将 3.B 的值空间、零空间、单满射、和 3.D 的可逆性定义前置; 仅涉及概念。

- **TIPS 1:** $T : V \rightarrow W$ is liney $\iff \begin{cases} (\text{一}) \forall v, u \in V, T(v + u) = Tv + Tu; \\ (\text{二}) \forall v, u \in V, \lambda \in \mathbf{F}, T(\lambda v) = \lambda(Tv). \end{cases} \iff T(v + \lambda u) = Tv + \lambda Tu.$

NOTE: Supp V is a vecsp. For $U \subseteq V$, U is a subsp of $V \iff \forall u_1, u_2 \in U, \lambda \in \mathbf{F}, u_1 + \lambda u_2 \in U$.

- (3.E.1) **A function $T : V \rightarrow W$ is liney \iff The graph of T is a subsp of $V \times W$.**

- (4E 10) **NOTE:** Composition and product are not the same in $\mathcal{P}(\mathbf{F})$.

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

• **NOTE FOR Restr:** U is a subsp of V . (a) $(T + \lambda S)|_U = T|_U + \lambda S|_U$. (b) $(ST)|_U = ST|_U$.

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

(b) If U is a subsp of V . Then $U \subseteq \text{null } T \iff T|_U = 0$.

• (4E 4.3) *Supp F = R, $T \in \mathcal{L}(V, W)$, $S = \text{Re} \circ T_C$. Show $T_C = S - iS \circ iI$.*

SOLUS: $T_C = S + i \text{Im } T_C$. 又 $\text{Re} \circ (T_C iI) = \text{Re} \circ (i T_C) = -\text{Im} \circ T_C = S \circ iI$. □

COMMENT: $\text{Re}, \text{Im} : \mathbf{C} \mapsto \mathbf{R}$ is not liney, while they have the add.

• **NOTE FOR Complex of Liney Maps:** Supp V, W are vecsps over \mathbf{R} . Then $\mathcal{L}(V, W)_C = \mathcal{L}(V_C, W_C)$.

For $S, T \in \mathcal{L}(V, W)$, $(S + \lambda T)_C = S_C + \lambda T_C$. For $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$, $(ST)_C = S_C T_C$.

For $T \in \mathcal{L}(V, W)$, $\text{null}(T_C) = (\text{null } T)_C$, $\text{range}(T_C) = (\text{range } T)_C$.

• (9.A.17) *Supp F = R, $T \in \mathcal{L}(V)$ suth $T^2 = -I$. Define complex scalar multi on V as*

$(a + bi)v = av + bTv$. Then V itself is already a complex vecsp with these defs.

Show the dim of V as a complex vecsp is half of the dim of V as the usual real vecsp.

SOLUS: Supp $V \neq \{0\}$. Let $N = \dim V$ as real vecsp. We construct a real B_V via a $(N - 1)$ -step process.

Let (v_1, Tv_1) be liney indep in V as real vecsp. Let $v_2 \notin \text{span}(v_1, Tv_1) \Rightarrow (v_1, Tv_1, v_2)$ liney indep.

Step 1. We show (v_1, Tv_1, v_2, Tv_2) liney indep in V as real vecsp. Asum $Tv_2 = a_1 v_1 + b_1 Tv_1 + a_2 v_2$.

Then $-v_2 = a_1 Tv_1 - b_1 v_1 + a_2 Tv_2$. Note that $a_2 \neq 0$ and $a_2^2 = -1$ while $a_2 \in \mathbf{R}$, contradic.

Step k. $[k \leq N - 1]$ We show $(v_1, Tv_1, \dots, v_k, Tv_k, v_{k+1}, Tv_{k+1})$ liney indep in V as real vecsp. Simlr.

Asum $Tv_{k+1} = a_1 v_1 + b_1 Tv_1 + \dots + a_{k+1} v_{k+1}$. Then $-v_{k+1} = a_1 Tv_1 - b_1 v_1 + \dots + a_{k+1} Tv_{k+1}$. □

• **NOTE FOR \mathbf{F}^S :**

Supp $S \neq \emptyset$, $C_S = \{f \in \mathbf{F}^S : \exists \text{ finitely many } x, \text{suth } f(x) \neq 0\}$. Then C_S is a subsp of \mathbf{F}^S .

(a) If $S = \{x_1, \dots, x_n\}$. Find a bss of \mathbf{F}^S and conclude $\mathbf{F}^S = C_S$. \mathbf{F}^S infinide $\Rightarrow S$ infini.

(b) If S has inflitely many elem. Prove \mathbf{F}^S is infinide. \mathbf{F}^S finide $\Rightarrow S$ fini.

(c) Supp V is on \mathbf{F} . Prove \exists surj $T \in \mathcal{L}(C_V, V)$.

SOLUS: (a) Define each $f_i(x_j) = \delta_{i,j}$. Supp $f \in C_S$, let each $y_k = f(x_k) = (y_1 f_1 + \dots + y_n f_n)(x_k)$.

Then $f = y_1 f_1 + \dots + y_n f_n \in \text{span}(f_1, \dots, f_n)$. 又 If $f = 0$, then each $y_k = 0$.

(b) Let $S = \{x_1, \dots, x_n, \dots\}$. Define each $f_i(x_j) = \delta_{i,j} \Rightarrow f_i \in C_S$. 又 (f_1, \dots, f_n, \dots) liney indep.

CORO: S fini $\iff \mathbf{F}^S$ finide.

(c) Define $T : C_V \rightarrow V$ by $T(f) = \sum f(x)x$. Note that $f(x) \neq 0$ for finitely many $x \in V$.

Becs for any $v \in V, \exists$ liney indep (v_1, \dots, v_n) suth $v = a_1 v_1 + \dots + a_n v_n$. [See higher courses]

Define each $f(v_k) = a_k$ and $f(x) = 0$ for $x \notin \{v_1, \dots, v_n\}$. Then $T(f) = v$. □

13 $\text{Supp } (v_1, \dots, v_m)$ is liney dep 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 dep lemma, $\exists j \in \{1, \dots, m\}, v_j \in \text{span}(v_1, \dots, v_{j-1})$.

$\text{Supp } a_1v_1 + \dots + a_mv_m = 0$, where $a_j \neq 0$. Now let $w_j \neq 0$, while $w_1 = \dots = w_{j-1} = w_{j+1} = w_m = 0$.

Define $T \in \mathcal{L}(V, W)$ with each $Tv_k = w_k$. Then $T(a_1v_1 + \dots + a_mv_m) = 0 = a_1w_1 + \dots + a_mw_m$.

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

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

Now we show (v_1, \dots, v_n) is liney indep. $\text{Supp } \exists a_i \in \mathbf{F}, a_1v_1 + \dots + a_nv_n = 0$.

Choose a non0 $w \in W$. By asum, for $(\bar{a}_1w, \dots, \bar{a}_mw)$, $\exists T \in \mathcal{L}(V, W)$, each $Tv_k = \bar{a}_kw$.

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

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. \square

• (4E 11) $\text{Supp } V$ 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: 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 $S(av + bTv + c_1u_1 + \dots + c_nu_n) = bv \Rightarrow S(Tv) = v = T(Sv) = 0$.

Asum $V \neq \{0\}$ and $\forall v \in V, (v, Tv)$ is liney dep, then $\exists \lambda_v \in \mathbf{F}, Tv = \lambda_v v$.

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

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

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

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

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

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

Hence $S_k(Tv_k) = T(S_k v_k) = Tv_k \Rightarrow Tv_k = a_k v_k$. Becs v_k is arb. Simlr to above. Done.

Or. 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 $\left| \begin{array}{l} A^{(j,k)}Tv_j = TA^{(j,k)}v_j = Tv_k = a_k v_k \\ A^{(j,k)}Tv_j = A^{(j,k)}a_j v_j = a_j A^{(j,k)}v_j = a_j v_k \end{array} \right. \Rightarrow a_k = a_j$. Hence a_k is indep of v_k . \square

• (4E 17) $\text{Supp } V$ 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 $TE \in \mathcal{E}, ET \in \mathcal{E}$ for all $E \in \mathcal{E}$ and all $T \in \mathcal{L}(V)$.

SOLUS: If $\mathcal{E} = \{0\}$, then done. $\text{Supp } 0 \neq S \in \mathcal{E}$, a two-sided ideal of $\mathcal{L}(V)$. Let $B_V = (v_1, \dots, v_n)$.

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

Then $(R_{1,1} + \dots + R_{n,n})v_j = v_j \Rightarrow \sum_{r=1}^n R_{r,r} = I \Rightarrow \mathcal{L}(V) \ni T = I \circ T = T \circ I \in \mathcal{E}$.

Or. Let each $Tv_j = w_j = A_{1,j}v_1 + \dots + A_{n,j}v_n \Rightarrow T = \sum_{x=1}^n \sum_{y=1}^n A_{y,x}R_{x,y} \in \mathcal{E}$. Now we prove the asum.

$\text{Supp } Sv_i \neq 0$ and $Sv_i = a_1v_1 + \dots + a_nv_n$, where $a_k \neq 0$. We show $R_{k,y}SR_{x,i} = a_k R_{x,y} \in \mathcal{E}$.

Becs $SR_{x,i} = a_1R_{x,1} + \dots + a_kR_{x,k} + \dots + a_nR_{x,n} \in \mathcal{E}$, for all $x \in \{1, \dots, n\}$.

Or. $(R_{k,y}S)v_i = a_k v_y \Rightarrow ((R_{k,y}S) \circ R_{x,i})v_z = \delta_{z,x}(a_k v_y)$, for all $y \in \{1, \dots, n\}$. Immed. \square

COMMENT: Not true if infinide. Consider the subsp $X = \{T \in \mathcal{L}(V) : \text{range } T \text{ is finide}\}$.

For any $T \in X, \forall E \in \mathcal{L}(V), \text{range } TE \subseteq \text{range } T; \text{range } ET = \text{span}(Ew_1, \dots, Ew_n) \Rightarrow TE, ET \in X$.

- (4E 3.B.32) $\text{Supp dim } V = n$. and $\varphi : \mathcal{L}(V) \rightarrow \mathbf{F}$ is liney.

Show if $\forall S, T \in \mathcal{L}(V)$, $\varphi(ST) = \varphi(S) \cdot \varphi(T)$, then $\varphi = 0$.

SOLUS: Using notats in (4E 17) and NOTE FOR [3.60].

$\text{Supp } \varphi \neq 0 \Rightarrow \exists i, j \in \{1, \dots, n\}, \varphi(R_{i,j}) \neq 0$. 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 $k \neq i, j \neq l \Rightarrow \varphi(R_{i,j} \circ R_{l,k}) = \varphi(R_{l,k} \circ R_{i,j}) = \varphi(0) = 0 = \varphi(R_{l,k}) \cdot \varphi(R_{i,j})$

$\Rightarrow \varphi(R_{l,k}) = 0$ or $\varphi(R_{i,j}) = 0$. Ctradic. \square

Or. Becs $\exists S, T \in \mathcal{L}(V)$, $ST - TS \neq 0$. While $\varphi(ST - TS) = \varphi(S)\varphi(T) - \varphi(T)\varphi(S) = 0$.

Note that $\forall E \in \text{null } \varphi, T \in \mathcal{L}(V)$, $\varphi(ET) = \varphi(TE) = 0 \Rightarrow ET, TE \in \text{null } \varphi$. By (4E 17). \square

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

By [3.2], the add and homo imply that V is closd add and scalar multi. While W^V might not be a vecsp.

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

(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. Exa: Let $V = \mathbf{R}$, but with the scalar multi defined by $a \odot v = 0$.

(II) If W^V is a non0 vecsp $\Leftrightarrow W$ is a non0 vecsp.

(a) If $\mathcal{L}(V, W) = \{0\}$, then by Exa (I), V might not be vecsp.

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

Then both W and V have a non0 elem.

(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 $\Leftrightarrow W$ is not a vecsp.

(a) If $\mathcal{L}(V, W) = \{0\}$, then by Exa (I), V might not be vecsp.

(b) If not. \square

ENDED

3.B 注意: 这里我将 3.D 可逆性、同构部分前置。

- TIPS 1: Supp U is a subsp of V . Then for $T \in \mathcal{L}(V, W)$, $U \cap \text{null } T = \text{null } T|_U$.
- TIPS 2: Supp $T \in \mathcal{L}(V, W)$. Let $V = M + N$, $U = X + Y$.
Then $\text{range } T = \text{range } T|_M + \text{range } T|_N$, $\text{range } T|_U = \text{range } T|_X + \text{range } T|_Y$.
(a) If $T|_U$ is inj. Show $U = X \oplus Y \iff \text{range } T|_U = \text{range } T|_X \oplus \text{range } T|_Y$.
(b) Give an exa suth $V = M \oplus N$, $\text{range } T \neq \text{range } T|_M \oplus \text{range } T|_N$.

SOLUS: Supp $U = X \oplus Y$. Asum for some $u \in U$, there exis two disti pairs $(x_1, y_1), (x_2, y_2)$ in $X \times Y$ suth $Tu = Tx_1 + Ty_1 = Tx_2 + Ty_2$. Becs $\forall u \in U, \exists! (x, y) \in X \times Y, v = x + y$.
Now $T(x_1 + y_1) = T(x_2 + y_2) \Rightarrow x_1 + y_1 = x_2 + y_2 \Rightarrow (x_1, y_1) = (x_2, y_2)$, ctradic.
Thus $\forall u \in U, \exists! (Tx, Ty) \in \text{range } T|_X \times \text{range } T|_Y, Tu = Tx + Ty$. Convly, becs T inj. \square

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 $\forall T \in \mathcal{L}(V, W), \exists$ subsp U of V 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 subsp U of V suth $V = U \oplus \text{null } T$.
 $\forall v \in V, \exists! w \in \text{null } T, u \in U, v = w + u$. Then $Tv = T(w + u) = Tu \in \{Tu : u \in U\}$. \square

CORO: $[P] \quad T|_U : U \rightarrow \text{range } T$ 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 $v = (v - u) + u \in U + \text{null } T$. 又 $U \cap \text{null } T = \text{null } T|_U$. \square

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 $\text{range } T = \text{range } T|_X \oplus \text{range } T|_{U \oplus \text{null } T}$. And X is non0.

Asum $\text{range } T = \text{range } T|_U$. Then $\text{range } T|_X = \{0\}$. While $T|_X$ is inj. 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), immed. \square

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: Supp $T \in \mathcal{L}(V, W)$ 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: Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n) \Rightarrow R = (v_1, \dots, v_n)$ is liney indep in V . Let $\text{span } R = U$.
 - (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) $Tv = \sum_{i=1}^n a_i Tv_i \iff v - \sum_{i=1}^n a_i v_i \in \text{null } T \iff v = (v - \sum_{i=1}^n a_i v_i) + (\sum_{i=1}^n a_i v_i)$.
Thus $U + \text{null } T = V$. Or. $\text{range } T = \{Tu : u \in U\} = \text{range } T|_U$. Using Exe (12). \square

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

- **TIPS 5:** $\text{Supp } S \in \mathcal{L}(U, V)$ 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 inj. Becs $\mathcal{B}(T) = TS = 0 \iff T|_{\text{range } S} = 0$.

- (4E 27) $\text{Supp } P \in \mathcal{L}(V)$ 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 $\dim V = \dim \text{null } P + \dim \text{range } P = \dim(\text{null } P \oplus \text{range } P)$. \square

Or. Becs $P|_{\text{range } P} : Pv \mapsto Pv^2 = Pv \Rightarrow P|_{\text{range } P} = I$ is iso. By CORO in Exe (12). \square

- (4E 21) $\text{Supp } V$ is finide, $T \in \mathcal{L}(V, W)$, Y is a subsp of W . Let $\mathcal{K}_Y = \{v \in V : Tv \in Y\}$.

Then \mathcal{K}_Y is a subsp. Prove $\mathcal{K}_Y = \dim \text{null } T + \dim(Y \cap \text{range } T)$.

SOLUS: 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 $v \in \text{null } T \iff Tv = 0 \in Y \iff Rv = 0 \in \text{range } T \iff v \in \text{null } R$. By [3.22]. \square

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) $\text{Supp } V$ is finide, X is a subsp of V , and Y is a finide 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 $\forall v \in V, \exists! a_i \in \mathbb{F}, x \in X, v = \sum_{i=1}^m a_i v_i + x$.

Let $B_Y = (w_1, \dots, w_m)$. Define $T \in \mathcal{L}(V, W)$ with each $Tv_i = w_i, Tx = 0$.

Now $v \in \text{null } T \iff Tv = a_1 w_1 + \dots + a_m w_m = 0 \iff v = x \in X$. Hence $\text{null } T = X$.

And $Y \ni w = a_1 w_1 + \dots + a_m w_m = a_1 T v_1 + \dots + a_m T v_m \in \text{range } T$. 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 $\text{range } T = \text{span}(Tv_1, \dots, Tv_m, Tx_1, \dots, Tx_n) = \text{span}(w_1, \dots, w_m) = Y$. \square

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

(b) $\text{Supp } T \in \mathcal{L}(V, W)$. Prove if T is inj, then \exists surj $S \in \mathcal{L}(W, V)$, $ST = I$.

(c) $\text{Supp } S \in \mathcal{L}(W, V)$. Prove if S is surj, then \exists inj $T \in \mathcal{L}(V, W)$, $ST = I$.

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 $S \in \mathcal{L}(W, V)$ with each $S(Tv_i) = v_i, Su = 0$ for $u \in U$. 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 $ST(a_1 Sw_1 + \dots + a_n Sw_n) = (a_1 Sw_1 + \dots + a_n Sw_n)$. \square

22 Supp U, V are finide, $S \in \mathcal{L}(V, W), T \in \mathcal{L}(U, V)$.

Prove $\dim \text{null } ST = \dim \text{null } S|_{\text{range } T} + \dim \text{null } T$.

SOLUS: 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 $u \in \text{null } ST \iff S(Tu) = 0 \iff Tu \in \text{null } S$.

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). □

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 inj $\Rightarrow \dim \text{null } ST = \dim \text{null } T$.

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

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

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) $S|_{\text{range } T}$ inj $\Rightarrow \dim \text{range } ST = \dim \text{range } T$.

(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 $\Rightarrow \text{range } ST = \text{range } S$.

(3) $\dim U = \dim V \Rightarrow \dim \text{null } ST \geq \dim V - \min\{\dim \text{range } S, \dim \text{range } T\}$
 $= \max\{\dim V - \dim \text{range } S, \dim V - \dim \text{range } T\}$.

Exa: Let $U = W = \mathbf{R}, V = \mathbf{R}^2$. Define $T \in \mathcal{L}(\mathbf{R}, \mathbf{R}^2) : x \mapsto (x, 0)$, and $S \in \mathcal{L}(\mathbf{R}^2, \mathbf{R}) : (x, y) \mapsto ax, a \neq 0$.

Now $\dim \text{null } S = 1, \dim \text{null } T = 0$, and $\dim \text{null } S|_{\text{range } T} = 0$.

• (a) Supp $\dim V = n, ST = 0$ 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 ctradic.

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

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 $\lfloor \frac{n}{2} \rfloor + \lceil \frac{n}{2} \rceil = n$.

We show $\dim \text{null } TS \geq \lceil \frac{n}{2} \rceil$. 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 $\dim \text{null } S \geq \lceil \frac{n}{2} \rceil$. Then done.

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

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

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

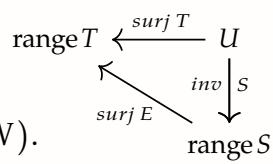
24 Supp $S \in \mathcal{L}(V, M)$, $T \in \mathcal{L}(V, W)$, and $\text{null } S \subseteq \text{null } T$. Prove $\exists E \in \mathcal{L}(M, W)$, $T = ES$.

SOLUS:

Let $V = U \oplus \text{null } S$

$\Rightarrow S|_U : U \rightarrow \text{range } S$ is iso.

Extend $T(S|_U)^{-1}$ to $E \in \mathcal{L}(M, W)$.



Or. Define $E : \text{range } S \rightarrow W$ by $E : Sv \mapsto Tv$.

Extend $E \in \mathcal{L}(\text{range } S, W)$ to $E \in \mathcal{L}(M, W)$. \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	$\text{null } S$

$$\text{range } S \xleftarrow{s} \begin{matrix} U_\Delta \\ \oplus \\ \Delta \end{matrix} \xrightarrow{T} \text{range } T$$

Becs $\Delta = \text{null } T|_U = \text{null } T \cap \text{range}(S|_U)^{-1}$.

Thus $E = T(S|_U)^{-1}$ is not inje $\Leftrightarrow \Delta \neq \{0\}$.

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 $T = E_2 S E_1$.

CORO: If $\text{null } S = \text{null } T$. Then $\Delta = \{0\}$, $U_\Delta = U$. [Req W Finide] By (3.D.3),

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

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

Define $E \in \mathcal{L}(\text{range } S, W)$ by $E(Sv_i) = Tv_i$. Extend to $E \in \mathcal{L}(M, W)$.

Hence $\forall v = \sum_{i=1}^n a_i v_i + u \in V$, $(\exists! u \in \text{null } S \subseteq \text{null } T)$, $Tv = \sum_{i=1}^n a_i Tv_i + 0 = E\left(\sum_{i=1}^n a_i Sv_i + 0\right)$. \square

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

Redefine $E \in \mathcal{L}(M, W)$ 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 $B_M = (Sv_1, \dots, Sv_m, x_1, \dots, x_n)$. \square

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

SOLUS: Let $Y = U \oplus \text{null } S$

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

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

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

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

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

$$\begin{array}{c} U_1 \xrightarrow[S]{\text{inv}} \text{range } S \\ || \\ \Delta \xrightarrow[S]{\text{inv}} \text{range } S|_\Delta \\ \oplus \\ U_{1\Delta} \xrightarrow[S]{\text{inv}} \text{range } T \xleftarrow[T]{\text{inv}} U_2 \\ \uparrow \text{inv } E|_{U_2} \end{array}$$

[Req range T Finide] Let $B_{\text{range } T} = (Tv_1, \dots, Tv_n)$. Now $B_{U_2} = (v_1, \dots, v_n)$.

Let $S(u_i) = Tv_i$ for each Tv_i . Define E with each $Ev_i = u_i$, $Ex = 0$ for $x \in \text{null } T$. \square

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 $i \in \{1, \dots, \dim U_2\}$, $k \in \{1, \dots, \dim \text{null } S\} = K$, $j \in \{1, \dots, \dim \text{null } T\} \setminus K$.

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 $\text{inv } E \in \mathcal{L}(V, Y)$ suth $T = SE$.

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 $E \in \mathcal{L}(V, Y)$ is inv. \square

• **NOTE:** $\text{null } T = \text{null } S \Rightarrow E : Sv \mapsto Tv$ and $E^{-1} : Tv \mapsto Sv$ well-defined $\Rightarrow \text{range } T, \text{range } S$ iso.

While $\text{range } T = \text{range } S \not\Rightarrow \text{null } T, \text{null } S$ iso. Exa: Backwd shift opto and id opto on \mathbb{F}^∞ .

- (3.D.6) *Supp V, W are finite, and S, T ∈ L(V, W), and dim null S = dim null T = n.*
Prove S = E₂TE₁, ∃ inv E₁ ∈ L(V), E₂ ∈ L(W).

SOLUS: Define E₁ : v_i ↠ r_i; u_j ↠ s_j; for each i ∈ {1, …, m}, j ∈ {1, …, n}.

Define E₂ : Tv_i ↠ Sr_i; x_j ↠ y_j; for each i ∈ {1, …, m}, j ∈ {1, …, n}. Where:

Let B _{range T} = (Tv ₁ , …, Tv _m); B _{range S} = (Sr ₁ , …, Sr _m). Let B _W = (Tv ₁ , …, Tv _m , x ₁ , …, x _p); B' _W = (Sr ₁ , …, Sr _m , y ₁ , …, y _p). Let B _{null T} = (u ₁ , …, u _n); B _{null S} = (s ₁ , …, s _n). Thus B _V = (v ₁ , …, v _m , u ₁ , …, u _n); B' _V = (r ₁ , …, r _m , s ₁ , …, s _n).	∴ E ₁ , E ₂ are inv and S = E ₂ TE ₁ . □
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- 28** *Supp T ∈ L(V, W). Let (Tv₁, …, Tv_m) be a bss of range T and each w_i = Tv_i.*

(a) *Prove ∃ φ₁, …, φ_m ∈ L(V, F) such that ∀v ∈ V, Tv = φ₁(v)w₁ + … + φ_m(v)w_m.*

(b) [4E 3.F.5] *∀v ∈ V, ∃! φ_i(v) ∈ F, Tv = φ₁(v)w₁ + … + φ_m(v)w_m.*

Thus defining each φ_i : V → F. Show each φ_i ∈ L(V, F).

SOLUS: The solus to (b) with (b) itself is another solus to (a).

(a) span(v₁, …, v_m) ⊕ null T = V ⇒ ∀v ∈ V, ∃! a_i ∈ F, u ∈ null T, v = ∑_{i=1}^m a_iv_i + u.

Define φ_i ∈ L(V, F) by φ_i(v_j) = δ_{i,j}, φ_i(u) = 0 for all u ∈ null T.

Linearity: ∀v, w ∈ V [∃! a_i, b_i ∈ F], λ ∈ F, φ_i(v + λw) = a_i + λb_i = φ_i(v) + λφ_i(w). □

(b) ∑_{i=1}^m φ_i(u + λv)w_i = T(u + λv) = Tu + λTv = (∑_{i=1}^m φ_i(u)w_i) + λ(∑_{i=1}^m φ_i(v)w_i). □

- 30** *Supp non0 φ, β ∈ L(V, F) and null φ = null β = η. Prove ∃ c ∈ F, φ = cβ.*

SOLUS: Let u be such that φ(u) ≠ 0, equivalent to β(u) ≠ 0. Then V = null φ ⊕ span(u) = null β ⊕ span(u).

Note that ∀v ∈ V, ∃! u₀ ∈ η, a_v ∈ F, v = u₀ + a_vu | Let c = φ(u) / β(u) ∈ F \ {0}.
 ⇒ φ(u₀ + a_vu) = a_vφ(u), β(u₀ + a_vu) = a_vβ(u). □

- (4E 3.F.6) *Supp non0 φ, β ∈ L(V, F). Prove null β ⊆ null φ ⇔ φ = cβ, ∃ c ∈ F.*

CORO: null φ = null β ⇔ φ = cβ, ∃ c ∈ F \ {0}.

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

(a) u ∉ null φ ⊇ null β ⇒ V = null φ ⊕ span(u) = null β ⊕ span(u) ⇒ null φ = null β. Let c = φ(u) / β(u).

Or. We discuss in two cases. If null β = null φ, then done. Otherwise,

∃ u' ∈ null φ \ null β, ∃ u ∉ null φ ⊇ null β ⇒ V = null β ⊕ span(u') = null β ⊕ span(u).

∀v ∈ V, v = w + au = w' + bu', ∃! w, w' ∈ null β | Let c = aφ(u) / bβ(u') ∈ F \ {0}. Done.

Thus φ(w + au) = aφ(u), β(w' + bu) = bβ(u').

NOTICE that by (b) below, we have null φ ⊆ null β, contradicting the assumption.

(b) If c = 0, then null φ = V ⊇ null β, done. Otherwise, because v ∈ null β ⇔ v ∈ null φ.

Or. By Exe (24), null β ⊆ null φ ⇔ ∃ E ∈ L(F), φ = E ◦ β. [If E is inv. Then null β = null φ.]

Now ∃ E ∈ L(F), φ = E ◦ β ⇔ ∃ c = E(1) ∈ F, φ = cβ. [E is inv ⇔ E(1) ≠ 0 ⇔ c ≠ 0.] □

ENDED

3.C 注意: 这里我将原书中 3.D 后半节正文前置。

- **NOTE FOR [3.30, 32]: matrix of span**

$\text{Supp } L_\alpha = (\alpha_1, \dots, \alpha_n)$ and $L_\beta = (\beta_1, \dots, \beta_m)$ are in a vecsp V .

Let each $\alpha_k = A_{1,k}\beta_1 + \dots + A_{m,k}\beta_m$, forming $A = \mathcal{M}(\text{span } L_\beta \supseteq L_\alpha) \in \mathbf{F}^{m,n}$.

Which is the *matrix of span*. Then $(\beta_1 \dots \beta_m) \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & \ddots & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} = (\alpha_1 \dots \alpha_n)$.

(a) $\text{Supp } m = n$. If $(A_{\cdot,1}, \dots, A_{\cdot,n})$ is a bss of $\mathbf{F}^{n,1}$. We show L_α liney indep $\Leftrightarrow L_\beta$ liney indep.

(\Leftarrow) Immed. (\Rightarrow) Asum L_β is liney dep and $\beta_j = c_1\beta_1 + \dots + c_{j-1}\beta_{j-1}$. By ctradic. \square

(b) $\text{Supp } m \geq n$. If L_β liney indep. We show $(A_{\cdot,1}, \dots, A_{\cdot,n})$ liney indep $\Leftrightarrow L_\alpha$ liney indep.

(\Rightarrow) Immed. (\Leftarrow) By ctradic. \square

NOTE: $\mathcal{M}(\text{span } L_\beta \supseteq L_\alpha) = \mathcal{M}(I, L_\alpha, L_\beta) \Leftrightarrow L_\alpha, L_\beta$ liney indep $\Rightarrow (A_{\cdot,1}, \dots, A_{\cdot,n})$ liney indep.

Where I is the id opto restr to $\text{span } L_\alpha \subseteq \text{span } L_\beta$.

(c) $\text{Supp } m < n$. Then $(A_{\cdot,1}, \dots, A_{\cdot,n})$ is liney dep, so is L_α .

$\text{Supp } T \in \mathcal{L}(V, W)$ and $B_V = (v_1, \dots, v_m), B_W = (w_1, \dots, w_n)$.

Then $\mathcal{M}(T, B_V, B_W) = \mathcal{M}(\text{span } B_W \supseteq (Tv_1, \dots, Tv_m))$. See also (4E 3.D.23).

- **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 $\mathcal{T}\mathcal{C}_k\mathcal{T} = \mathcal{R}_k$, $\mathcal{T}\mathcal{R}_j\mathcal{T} = \mathcal{C}_j$, 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 [3.47]:** $(AC)_{j,k} = \sum_{r=1}^n A_{j,r}C_{r,k} = \sum_{r=1}^n (A_{\cdot,r})_{1,r}(C_{\cdot,k})_{r,1} = (A_{\cdot,r}C_{\cdot,k})_{1,1} = A_{j,\cdot}C_{\cdot,k}$ \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:** $[(AC)_{j,\cdot}]_{1,k} = (AC)_{j,k} = \sum_{r=1}^n A_{j,r}C_{r,k} = \sum_{r=1}^n (A_{j,r})_{1,r}C_{r,k} = (A_{j,r}C_{\cdot,k})_{1,k}$ \square

- **NOTE:** Let $C = \mathcal{M}(T) \in \mathbf{F}^{n,p}, A = \mathcal{M}(S) \in \mathbf{F}^{m,n}$ wrto std bses, where $U = \mathbf{F}^p, V = \mathbf{F}^n, W = \mathbf{F}^m$.

For [3.49], $\mathcal{M}(Te_k, B_V) = C_{\cdot,k} \Rightarrow \mathcal{M}(S(Te_k), B_W) = AC_{\cdot,k}$, 又 $\mathcal{M}((ST)(e_k), B_W) = (AC)_{\cdot,k}$ \square

For Exe (10), $(AC)_{j,\cdot} = [((AC)^t)_{\cdot,j}]^t = (C^t(A^t)_{\cdot,j})^t = ((A^t)_{\cdot,j})^t C = A_{j,\cdot}C$ \square

- [4E 3.51] $\text{Supp } C \in \mathbf{F}^{m,c}$. (a) For $k = 1, \dots, p$, $(CR)_{\cdot,k} = C_{\cdot,r}R_{r,k} = \sum_{r=1}^c C_{\cdot,r}R_{r,k} = R_{1,k}C_{\cdot,1} + \dots + R_{c,k}C_{\cdot,c}$
 $R \in \mathbf{F}^{c,p}$. (b) For $j = 1, \dots, m$, $(CR)_{j,\cdot} = C_{j,r}R_{r,\cdot} = \sum_{r=1}^c C_{j,r}R_{r,\cdot} = C_{j,1}R_{1,\cdot} + \dots + C_{j,c}R_{c,\cdot}$

- **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)], $(Ac)_{\cdot,1} = c_1A_{\cdot,1} + \dots + c_nA_{\cdot,n}$. \square

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

$\therefore Ac = A_{\cdot,r}c_{r,1} = \sum_{r=1}^n A_{\cdot,r}c_{r,1} = c_1A_{\cdot,1} + \dots + c_nA_{\cdot,n}$ 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 $Ac = \mathcal{M}(Tv, B_W) = \mathcal{M}(T(c_1v_1 + \dots + c_nv_n)) = c_1A_{\cdot,1} + \dots + c_nA_{\cdot,n}$. \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)], $(aC)_{1,\cdot} = a_1 C_{1,\cdot} + \dots + a_n C_{n,\cdot}$. \square
 OR. $\because (aC)_{1,k} = \sum_{r=1}^n a_{1,r} C_{r,k} = \left[\sum_{r=1}^n a_{1,r} (C_{r,\cdot}) \right]_{1,k} = (a_1 C_{1,\cdot} + \dots + a_n C_{n,\cdot})_{1,k}$
 $\therefore aC = a_{1,\cdot} C_{\cdot,\cdot} = \sum_{r=1}^n a_{1,r} C_{r,\cdot} = a_1 C_{1,\cdot} + \dots + a_n C_{n,\cdot}$. OR. $(aC)_{1,k} = (aC)_{\cdot,k} = aC_{\cdot,k} \in \mathbf{F}$. \square
 OR. $aC = ((aC)^t)^t = (C^t a^t)^t = [a_1^t (C^t)_{\cdot,1} + \dots + a_n^t (C^t)_{\cdot,n}]^t = a_1 C_{1,\cdot} + \dots + a_n C_{n,\cdot}$. \square

- **CR FACTORIZ** $\text{Supp non0 } A \in \mathbf{F}^{m,n}$. Prove, with p below, that $\exists C \in \mathbf{F}^{m,p}, R \in \mathbf{F}^{p,n}, A = CR$.
 - $\text{Supp col } A = \text{span}(A_{\cdot,1}, \dots, A_{\cdot,n}) \subseteq \mathbf{F}^{m,1}$, $\dim \text{col } A = c$, the col rank. Let $p = c$.
 - $\text{Supp row } A = \text{span}(A_{1,\cdot}, \dots, A_{m,\cdot}) \subseteq \mathbf{F}^{1,n}$, $\dim \text{row } A = r$, the row rank. Let $p = r$.

SOLUS: Using [4E 3.51]. Notice that $A \neq 0 \Rightarrow c, r \geq 1$.

- Reduce to bss $B_C = (C_{\cdot,1}, \dots, C_{\cdot,c})$, forming $C \in \mathbf{F}^{m,c}$. Then $\forall k \in \{1, \dots, n\}$,
 $A_{\cdot,k} = R_{1,k} C_{\cdot,1} + \dots + R_{c,k} C_{\cdot,c} = (CR)_{\cdot,k}, \exists! R_{1,k}, \dots, R_{c,k} \in \mathbf{F}$, forming $R \in \mathbf{F}^{c,n}$. Thus $A = CR$.
- Reduce to bss $B_R = (R_{1,\cdot}, \dots, R_{r,\cdot})$, forming $R \in \mathbf{F}^{r,n}$. Then $\forall j \in \{1, \dots, m\}$,
 $A_{j,\cdot} = C_{j,1} R_{1,\cdot} + \dots + C_{j,r} R_{r,\cdot} = (CR)_{j,\cdot}, \exists! C_{j,1}, \dots, C_{j,r} \in \mathbf{F}$, forming $C \in \mathbf{F}^{m,r}$. Thus $A = CR$. \square

- **Exa:** $\begin{pmatrix} 10 & 7 & 4 & 1 \\ 26 & 19 & 12 & 5 \\ 46 & 33 & 20 & 7 \end{pmatrix} \xrightarrow{\text{(I)}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 10 & 7 & 4 & 1 \\ 26 & 19 & 12 & 5 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 4 & 1 \\ 12 & 5 \end{pmatrix} \begin{pmatrix} 3 & 2 & 1 & 0 \\ -2 & -1 & 0 & 1 \end{pmatrix}$
 $\xrightarrow{\text{(II)}} \begin{pmatrix} 7 & 4 \\ 19 & 12 \\ 33 & 20 \end{pmatrix} \begin{pmatrix} 2 & 1 & 0 & -1 \\ -1 & 0 & 1 & 2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 7 & 4 \\ 19 & 12 \end{pmatrix} \begin{pmatrix} 2 & 1 & 0 & -1 \\ -1 & 0 & 1 & 2 \end{pmatrix}$.

- **COL RANK = ROW RANK** Using CR Factoriz. Let $A = CY$ by (a) and $A = XR$ by (b).
 - $A_{j,\cdot} = (CY)_{j,\cdot} = C_{j,\cdot} Y = C_{j,1} Y_{1,\cdot} + \dots + C_{j,c} Y_{c,\cdot} \in \text{row } A = \text{span}(A_{1,\cdot}, \dots, A_{n,\cdot}) = \text{span}(Y_{1,\cdot}, \dots, Y_{c,\cdot})$.
 - $A_{\cdot,k} = (XR)_{\cdot,k} = XR_{\cdot,k} = R_{1,k} X_{\cdot,1} + \dots + R_{r,k} X_{\cdot,r} \in \text{col } A = \text{span}(A_{\cdot,1}, \dots, A_{\cdot,m}) = \text{span}(X_{\cdot,1}, \dots, X_{\cdot,r})$.

Thus (a) $\dim \text{row } A = r \leq c = \dim \text{col } A$, and (b) $\dim \text{col } A = c \leq r = \dim \text{row } A$. \square

OR. Apply (a) to $A^t \in \mathbf{F}^{n,m} \Rightarrow \dim \text{row } A^t = \dim \text{col } A = c \leq r = \dim \text{row } A = \dim \text{col } A^t$. \square

- (4E 16) $\text{Supp } A \in \mathbf{F}^{m,n} \setminus \{0\}$. Prove $\text{rank } A = 1 \Rightarrow \exists c_j, d_k \in \mathbf{F}$, each $A_{j,k} = c_j d_k$.

SOLUS: Let $c_j = \frac{A_{j,1}}{A_{1,1}} = \frac{A_{j,2}}{A_{1,2}} = \dots = \frac{A_{j,n}}{A_{1,n}}$, $d'_k = \frac{A_{1,k}}{A_{1,1}} = \frac{A_{2,k}}{A_{2,1}} = \dots = \frac{A_{m,k}}{A_{m,1}}$
 $\Rightarrow A_{j,k} = d'_k A_{j,1} = c_j A_{1,k} = c_j d'_k A_{1,1} = c_j d_k$, where $d_k = d'_k A_{1,1}$. OR. By CR Factoriz, immed. \square

- 5 $\text{Supp } B_W = (w_1, \dots, w_n)$ and V is finide. $\text{Supp } T \in \mathcal{L}(V, W)$.

Prove $\exists B_V = (v_1, \dots, v_m)$, $\mathcal{M}(T, B_V, B_W)_{1,\cdot} = (0 \ \dots \ 0)$ or $(1 \ 0 \ \dots \ 0)$.

SOLUS:

Let (u_1, \dots, u_n) be a bss of V . Let $A = \mathcal{M}(T, (u_1, \dots, u_n), B_W)$.

If $A_{1,\cdot} = 0$, then $B_V = (u_1, \dots, u_n)$ and done. Othws, $\text{supp } A_{1,k} \neq 0$.

Let $v_1 = \frac{u_k}{A_{1,k}} \Rightarrow Tv_1 = 1w_1 + \frac{A_{2,k}}{A_{1,k}} w_2 + \dots + \frac{A_{n,k}}{A_{1,k}} w_n$. $\left| \begin{array}{l} \text{Let } v_{j+1} = u_j - A_{1,j} v_1 \text{ for } j \in \{1, \dots, k-1\}. \\ \text{Let } v_i = u_i - A_{1,i} v_1 \text{ for } i \in \{k+1, \dots, n\}. \end{array} \right.$

NOTICE that $Tu_i = A_{1,i} w_1 + \dots + A_{n,i} w_n$. \forall Each $u_i \in \text{span}(v_1, \dots, v_n) = V$. Let $B_V = (v_1, \dots, v_n)$. \square

OR. Using Exe (4). Let B_W be the B_V . Now $\exists B_{V,1}, \mathcal{M}(T', B_W, B_V)_{\cdot,1} = (1 \ 0 \ \dots \ 0)^t$ or $(0 \ \dots \ 0)^t$.

Equiv to $\exists B_V$ [by (3.F.31)] suth $\mathcal{M}(T, B_V, B_W)_{1,\cdot} = (1 \ 0 \ \dots \ 0)$ or $(0 \ \dots \ 0)$. \square

6 *Supp V, W are finide and $T \in \mathcal{L}(V, W)$. $\text{Supp dim range } T = 1$.*

Prove $\exists B_V, B_W$, all ent of $A = \mathcal{M}(T, B_V, B_W)$ equal 1.

SOLUS: Let $B_{\text{null } T} = (u_2, \dots, u_n)$. Extend to a bss (u_1, u_2, \dots, u_n) of V.

Extend to (Tu_1, w_2, \dots, w_m) a bss of W. Let $w_1 = Tu_1 - w_2 - \dots - w_m \Rightarrow B_W = (w_1, \dots, w_m)$.

Let $v_1 = u_1$, $v_i = u_1 + u_i \Rightarrow B_V = (v_1, \dots, v_n)$. \square

Or. $\text{Supp } B_{\text{range } T} = (w)$. By NOTE FOR (2.C.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 $Tu_k \in \text{range } T = \text{span}(w) \Rightarrow Tu_k = \lambda_k w, \exists \lambda_k \in \mathbb{F} \setminus \{0\}$. Let each $v_k = \lambda_k^{-1} u_k$. \square

- (10.A.3, OR 4E 3.D.19) *Supp V is finide and $T \in \mathcal{L}(V)$.*

$\text{Supp } A = \mathcal{M}(T)$ wrto any B_V . Prove $T = \lambda I, \exists \lambda \in \mathbb{F}$.

SOLUS: We show (v, Tv) liney dep by ctradic. Let $B_V = (v, Tv, u_1, \dots, u_m)$, $B'_V = (2v, Tv, u_1, \dots, u_m)$.

Then $Tv = 1 \cdot Tv = 2 \cdot Tv = T(2v) \Rightarrow Tv = 0$. Ctradic. Thus $Tv = \lambda_v v$. Simlr to (4E 3.A.11). \square

Or. 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 $T(\frac{1}{2}v_k) = A_{1,k}v_1 + \dots + A_{k,k}(\frac{1}{2}v_k) + \dots + A_{m,k}v_m$

$$\Rightarrow Tv_k = 2A_{1,k}v_1 + \dots + A_{k,k}v_k + \dots + 2A_{m,k}v_m = A_{1,k}v_1 + \dots + A_{k,k}v_k + \dots + A_{m,k}v_m.$$

Then $A_{j,k} = 0$ for all $j \neq k$. Thus each $Tv_k = A_{k,k}v_k$. We show $A_{k,k} = A_{j,j}$ for all $j \neq k$. Fix one such pair.

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 $T(v'_j) = T(v_k) = A_{j,j}v_j$. \square

- **TIPS 1:** *Supp $p \in \mathcal{P}(\mathbb{F}^n)$. 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: Supp 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:** Supp τ is an algebraic property. Then τ holds for liney maps $\Leftrightarrow \tau$ holds for matrices.

Supp $\alpha_1, \dots, \alpha_n$ are disti with each $\alpha_k \in \{1, \dots, n\}$.

Now $p(T_1, \dots, T_n) = p(T_{\alpha_1}, \dots, T_{\alpha_n}) \Leftrightarrow p(\mathcal{M}(T_1), \dots, \mathcal{M}(T_n)) = p(\mathcal{M}(T_{\alpha_1}), \dots, \mathcal{M}(T_{\alpha_n}))$.

- **TIPS 2:** *Supp $T \in \mathcal{L}(V, W)$, $B_V = (v_1, \dots, v_n)$, $B_W = (w_1, \dots, w_m)$.*

Let $L = (Tv_{\alpha_1}, \dots, Tv_{\alpha_k})$, $L_{\mathcal{M}} = (A_{\cdot, \alpha_1}, \dots, A_{\cdot, \alpha_k})$, where each $\alpha_i \in \{1, \dots, n\}$.

(a) *Show [P] L is liney indep $\Leftrightarrow L_{\mathcal{M}}$ is liney indep. [Q]*

(b) *Show [P] $\text{span } L = W \Leftrightarrow \text{span } L_{\mathcal{M}} = \mathbb{F}^{m,1}$. [Q] [Let $A = \mathcal{M}(T, B_V, B_W)$.]*

SOLUS: (a) Becs $\mathcal{M}: Tv_k \mapsto A_{\cdot, k}$ is an iso of $\text{span } L$ onto $\text{span } L_{\mathcal{M}}$. By (3.B.9).

(b) Reduce to liney indep lists. By (a) and [2.39]. \square

$$\begin{aligned} \text{Or. } c_1 T v_{\alpha_1} + \dots + c_k T v_{\alpha_k} &= c_1 (A_{1,\alpha_1} w_1 + \dots + A_{m,\alpha_1} w_m) + \dots + c_k (A_{1,\alpha_k} w_1 + \dots + A_{m,\alpha_k} w_m) \\ &= (c_1 A_{1,\alpha_1} + \dots + c_k A_{1,\alpha_k}) w_1 + \dots + (c_1 A_{m,\alpha_1} + \dots + c_k A_{m,\alpha_k}) w_m. \end{aligned}$$

$$\text{And } c_1 A_{\cdot, \alpha_1} + \dots + c_k A_{\cdot, \alpha_k} = c_1 \begin{pmatrix} A_{1,\alpha_1} \\ \vdots \\ A_{m,\alpha_1} \end{pmatrix} + \dots + c_k \begin{pmatrix} A_{1,\alpha_k} \\ \vdots \\ A_{m,\alpha_k} \end{pmatrix} = \begin{pmatrix} c_1 A_{1,\alpha_1} + \dots + c_k A_{1,\alpha_k} \\ \vdots \\ c_1 A_{m,\alpha_1} + \dots + c_k A_{m,\alpha_k} \end{pmatrix}.$$

(a) $P \Rightarrow Q$: $\text{Supp } c_1 A_{\cdot, \alpha_1} + \cdots + c_k A_{\cdot, \alpha_k} = 0$. Let $v = c_1 v_{\alpha_1} + \cdots + c_k v_{\alpha_k}$.
 Then $Tv = (c_1 A_{1, \alpha_1} + \cdots + c_k A_{1, \alpha_k})w_1 + \cdots + (c_1 A_{m, \alpha_1} + \cdots + c_k A_{m, \alpha_k})w_m = 0w_1 + \cdots + 0w_m$.
 Now $c_1 T v_{\alpha_1} + \cdots + c_k T v_{\alpha_k} = 0$. Then each $c_i = 0 \Rightarrow L_{\mathcal{M}}$ liney indep.

$Q \Rightarrow P$: Becs $c_1 T v_{\alpha_1} + \cdots + c_k T v_{\alpha_k} = 0$. For each $i \in \{1, \dots, m\}$, $c_1 A_{i, \alpha_1} + \cdots + c_k A_{i, \alpha_k} = 0$.
 Which is equiv to $c_1 A_{\cdot, \alpha_1} + \cdots + c_k A_{\cdot, \alpha_k} = 0$. Thus each $c_i = 0 \Rightarrow L$ liney indep.

OR. $\exists A_{\cdot, \alpha_j} = c_1 A_{\cdot, \alpha_1} + \cdots + c_{j-1} A_{\cdot, \alpha_{j-1}}$
 \Leftrightarrow For each $i \in \{1, \dots, m\}$, $A_{i, \alpha_j} = c_1 A_{i, \alpha_1} + \cdots + c_{j-1} A_{i, \alpha_{j-1}}$
 $\Leftrightarrow T v_{\alpha_j} = A_{1, \alpha_j} w_1 + \cdots + A_{m, \alpha_j} w_m$
 $= (c_1 A_{1, \alpha_1} + \cdots + c_{j-1} A_{1, \alpha_{j-1}})w_1 + \cdots + (c_1 A_{m, \alpha_1} + \cdots + c_{j-1} A_{m, \alpha_{j-1}})w_m$
 $\Leftrightarrow \exists T v_{\alpha_j} = c_1 T v_{\alpha_1} + \cdots + c_{j-1} T v_{\alpha_{j-1}}$.

(b) Each $\mathcal{M}(T v_{\alpha_i}) = A_{\cdot, \alpha_i}$

$P \Rightarrow Q$: Supp each $w_i = I w_i = J_{1,i} T v_{\alpha_1} + \cdots + J_{k,i} T v_{\alpha_k}$.
 $\forall a \in \mathbf{F}^{m,1}, \exists ! w = a_1 w_1 + \cdots + a_m w_m \in W, a = \mathcal{M}(w, B_W)$.
 Becs $w = a_1 (J_{1,1} T v_{\alpha_1} + \cdots + J_{k,1} T v_{\alpha_k}) + \cdots + a_m (J_{1,m} T v_{\alpha_1} + \cdots + J_{k,m} T v_{\alpha_k})$
 $= (a_1 J_{1,1} + \cdots + a_m J_{1,m}) T v_{\alpha_1} + \cdots + (a_1 J_{k,1} + \cdots + a_m J_{k,m}) T v_{\alpha_k}$.

Apply \mathcal{M} to both sides, $a = c_1 A_{\cdot, \alpha_1} + \cdots + c_k A_{\cdot, \alpha_k}$, where each $c_i = a_1 J_{i,1} + \cdots + a_m J_{i,m}$.

$Q \Rightarrow P$: $\forall w \in W, \exists a = \mathcal{M}(w, B_W) \Rightarrow \exists c_k \in \mathbf{F}, a = c_1 A_{\cdot, \alpha_1} + \cdots + c_k A_{\cdot, \alpha_k} \in \mathbf{F}^{m,1}$
 $\Rightarrow w = (c_1 A_{1, \alpha_1} + \cdots + c_k A_{1, \alpha_k})w_1 + \cdots + (c_1 A_{m, \alpha_1} + \cdots + c_k A_{m, \alpha_k})w_m = c_1 T v_{\alpha_1} + \cdots + c_k T v_{\alpha_k}$.

$\neg Q \Rightarrow \neg P$: $\exists w \in W, \exists a \in \mathbf{F}^{m,1}, \mathcal{M}(w, B_W) = a$, but $\nexists (c_1, \dots, c_k) \in \mathbf{F}^k, a = c_1 A_{\cdot, \alpha_1} + \cdots + c_k A_{\cdot, \alpha_k}$
 $\Rightarrow \nexists (c_1, \dots, c_k) \in \mathbf{F}^k, w = c_1 T v_{\alpha_1} + \cdots + c_k T v_{\alpha_k}$. For if not, contradic. \square

NOTE: Let $L = (T v_1, \dots, T v_n)$, $L_{\mathcal{M}} = (A_{\cdot,1}, \dots, A_{\cdot,n})$.

Then (a*) By [3.B.9, TIPS (4)], T is inj $\Leftrightarrow L$ is liney indep, so is $L_{\mathcal{M}}$.

And (b*) T is surj $\Leftrightarrow \text{span } L = W \Leftrightarrow \text{span } L_{\mathcal{M}} = \mathbf{F}^{m,1}$.

CORO: $B_{\mathbf{F}^{n,1}} = (A_{\cdot,1}, \dots, A_{\cdot,n}) \Leftrightarrow T$ is inj and surj $\Leftrightarrow B_{\mathbf{F}^{1,n}} = (A_{1,\cdot}, \dots, A_{m,\cdot})$.

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 $\Leftrightarrow T'$ inj $\Leftrightarrow (T'(\psi_1), \dots, T'(\psi_m))$ liney indep
 $\stackrel{(a)}{\Leftrightarrow} ((A^t)_{\cdot,1}, \dots, (A^t)_{\cdot,m})$ liney indep in $\mathbf{F}^{n,1}$, so is $(A_{1,\cdot}, \dots, A_{m,\cdot})$ in $\mathbf{F}^{1,n}$.
- (d) T inj $\Leftrightarrow T'$ surj $\Leftrightarrow V' = \text{span}(T'(\psi_1), \dots, T'(\psi_m))$
 $\stackrel{(b)}{\Leftrightarrow} \mathbf{F}^{n,1} = \text{span}((A^t)_{\cdot,1}, \dots, (A^t)_{\cdot,m}) \Leftrightarrow \mathbf{F}^{1,n} = \text{span}(A_{1,\cdot}, \dots, A_{m,\cdot})$.

ENDED

3.D

- (3.E.2) *Supp $V_1 \times \dots \times V_m$ is finide. Prove each V_j is finide.*

SOLUS: Define each $S_k \in \mathcal{L}(V_1 \times \dots \times V_m, V_k)$ by $S_k(v_1, \dots, v_m) = v_k$. By [3.22], range $S_k = V_k$ is finide. \square

OR. Denote $V_1 \times \dots \times V_m$ by U . Denote $\{0\} \times \dots \times \{0\} \times V_i \times \{0\} \dots \times \{0\}$ by U_i .

We show each U_i is iso to V_i . Then U is finide \Rightarrow its subsp U_i is finide, so is V_i .

$$\left. \begin{array}{l} \text{Define } R_i \in \mathcal{L}(V_i, U_i) \text{ by } R_i(u_i) = (0, \dots, 0, u_i, 0, \dots, 0) \\ \text{Define } S_i \in \mathcal{L}(U, V_i) \text{ by } S_i(u_1, \dots, u_i, \dots, u_m) = u_i \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} R_i S_j|_{U_i} = \delta_{i,j} I_{U_i}, \\ S_i R_j = \delta_{i,j} I_{V_i}. \end{array} \right.$$

COMMENT: The key tool in solus of (3.E.4,5). \square

18 Show V and $\mathcal{L}(F, V)$ are iso vecsps.

SOLUS: Define $\Psi \in \mathcal{L}(V, \mathcal{L}(F, V))$ by $\Psi(v) = \Psi_v$; where $\Psi_v \in \mathcal{L}(F, V)$ and $\Psi_v(\lambda) = \lambda v$.

(a) $\Psi(v) = \Psi_v = 0 \Rightarrow \forall \lambda \in F, \Psi_v(\lambda) = \lambda v = 0 \Rightarrow v = 0$. Now Ψ inj.

(b) $\forall T \in \mathcal{L}(F, V)$, let $v = T(1) \Rightarrow T(\lambda) = \lambda v = \Psi_v(\lambda), \forall \lambda \in F \Rightarrow T = \Psi(T(1)) \in \text{range } \Psi$. \square

OR. Define $\Phi \in \mathcal{L}(\mathcal{L}(F, V), V)$ by $\Phi(T) = T(1)$.

(a) $\text{Supp } \Phi(T) = 0 = T(1) = \lambda T(1) = T(\lambda), \forall \lambda \in F \Rightarrow T = 0$. Now Φ inj.

(b) For any $v \in V$, define $T \in \mathcal{L}(F, V)$ by $T(\lambda) = \lambda v$. Then $\Phi(T) = T(1) = v \in \text{range } \Phi$. \square

COMMENT: $\Phi = \Psi^{-1}$. This is a countexa of the stmt that $\mathcal{L}(V, W)$ and $\mathcal{L}(W, V)$ are iso if infinde. See (3.F).

- (3.E.6) *Supp $m \in \mathbf{N}^+$. Prove V^m and $\mathcal{L}(F^m, V)$ are iso.* By (3.D.18, 3.E.4), immed.

SOLUS: OR. Define $T : (v_1, \dots, v_m) \rightarrow \varphi$, where $\varphi : (a_1, \dots, a_m) \mapsto a_1 v_1 + \dots + a_m v_m$.

(a) $\text{Supp } T(v_1, \dots, v_m) = 0$. Then $\forall (a_1, \dots, a_n) \in F^m, \varphi(a_1, \dots, a_m) = a_1 v_1 + \dots + a_m v_m = 0$

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 inj.

(b) $\text{Supp } \psi \in \mathcal{L}(F^m, V)$. Let (e_1, \dots, e_m) be std bss of F^m . Then $\forall (b_1, \dots, b_n) \in F^m,$

$$[T(\psi(e_1), \dots, \psi(e_m))] (b_1, \dots, b_m) = b_1 \psi(e_1) + \dots + b_m \psi(e_m) = \psi(b_1 e_1 + \dots + b_m e_m) = \psi(b_1, \dots, b_m).$$

Thus $T(\psi(e_1), \dots, \psi(e_m)) = \psi$. Hence T is surj. \square

- (3.E.3) *Give an exa of a vecsp V and its two subsps 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. Both can be infinide. [Req Other Courses.]

Let $V = F^\infty = U_1, U_2 = \{(x, 0, \dots) \in F^\infty : x \in F\}$. 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 $T((x_1, x_2, \dots), (x, 0, \dots)) = (x, x_1, x_2, \dots)$

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

- $\text{Supp } T \in \mathcal{L}(V)$. Prove $\exists \text{ inv } T_1, T_2 \in \mathcal{L}(V)$ suth $T = T_1 + T_2$.

SOLUS: Let $U \oplus \text{null } T = V, W \oplus \text{range } T = V$. Let $S : \text{null } T \rightarrow W$ be an iso.

Define $T_1 \in \mathcal{L}(V)$ by $T_1(u) = \frac{1}{2} Tu, T_1(w) = Sw$

Define $T_2 \in \mathcal{L}(V)$ by $T_2(u) = \frac{1}{2} Tu, T_2(w) = -Sw$

\square

- $\text{Supp } A, B \in \mathcal{L}(V)$ and $A + B, A - B$ are inv. $\text{Supp } C, D \in \mathcal{L}(V)$.

Prove $\exists X, Y \in \mathcal{L}(V)$ suth $AX + BY = C$ and $BX + AY = D$.

SOLUS: Asum $AX + BY = C, BX + AY = D$. Then $(A \pm B)(X \pm Y) = C \pm D$.

Let $S = (A + B)^{-1}(C + D), T = (A - B)^{-1}(C - D)$. Now $X = \frac{1}{2}(S + T), Y = \frac{1}{2}(S - T)$. \square

3 *Supp V and W are finide, U is a subsp of V, and S ∈ L(U, W).*

Prove ∃ inv T ∈ L(V, W), Tu = Su, ∀u ∈ U ⇔ S is inj.

[See also (3.A.11).]

SOLUS: (a) $\forall u \in U, u = T^{-1}Su \Rightarrow T^{-1}S = I \in L(U)$. OR. $\text{null } S = \text{null } T|_U = \text{null } T \cap U = \{0\}$.

(b) Get a B_U , apply S, then extend to B_V, B_W . \square

ExA: Let $V = W = \mathbf{F}^\infty$. Define $S(x_1, x_2, \dots) = (0, x_1, x_2, \dots) \Rightarrow S$ inj.

Asum $\exists \text{ inv } T \in L(V, W)$ suth $T|_V = S$. Then $T = S$ while S is not surj.

8 *Supp T ∈ L(V, W) is surj. Prove ∃ subsp U of V, $T|_U : U \rightarrow W$ is iso.*

SOLUS: By (3.B.12). Note that $\text{range } T = W$. OR. [Req range T Finide] By [3.B TIPS (4)]. \square

• **TIPS 1:** *Supp V = U ⊕ X = W ⊕ X. Prove U, W are iso.*

SOLUS: $\forall u \in U, \exists !(w, x_1) \in W \times X, u = w + x_1$. Thus $\pi : U \rightarrow W$ well defined by $\pi(u) = w$.

While $\exists !(u', x_2) \in U \times X, w = u' + x_2$. Now $x_1 = -x_2, u = u' \Rightarrow \pi$ inj and surj.

OR. $\forall w \in W, \exists !(u, x_1) \in U \times X, w = u + x_1$. Thus $\xi : W \rightarrow U$ well defined by $\xi(w) = u$.

While $\exists !(w', x_2) \in W \times X, u = w' + x_2$. Now $x_1 = -x_2, w = w' \Rightarrow \xi \circ \pi = I$, and $\pi \circ \xi = I$. \square

ExA: Let $V = X = \mathbf{F}^\infty, Y = \{(0, x_1, x_2, \dots) \in \mathbf{F}^\infty\} \Rightarrow X, Y$ iso.

But \nexists iso subsp M, N of V, suth $V = M \oplus X = N \oplus Y$.

• **Supp U, V, W are finide.** **NOTE:** Not true if U, V, W infinide. **ExA:** Forwd and backwd shift.

9 *Supp S ∈ L(V, W), T ∈ L(U, V), and ST inv. Prove S, T are inv.*

SOLUS: Let $R = (ST)^{-1}$. Becs $R(ST) = (RS)T = I_U$ OR $(ST)R = S(TR) = I_W$, T inj and S surj. \square

Or. $\dim W = \dim \text{range } ST \leq \min\{\text{range } S, \text{range } T\} \Rightarrow S, T$ surj. \square

10 *Supp dim V = dim W, and T ∈ L(V, W), S ∈ L(W, V). Prove ST = I ⇔ TS = I.*

SOLUS: $ST = I \Rightarrow S, T$ inv. Let $B_V = (v_1, \dots, v_n) \Rightarrow$ each $S(Tv_i) = v_i$. Thus $TS = I$. Rev the roles. \square

Or. $S((TS)w) = ST(Sw) = Sw \Rightarrow (TS)w = w$. Or. $S^{-1} = T$ & $S = S \Rightarrow TS = S^{-1}S = I$. \square

• **TIPS 2:** Supp each $S_k \in L(V_k, W_k), W_k \subseteq V_{k+1} \Rightarrow S_m \circ S_{m-1} \circ \dots \circ S_2 \circ S_1$ makes sense.

(a) By the ctrapos of (3.B.11), $S_m \circ \dots \circ S_1$ not inj $\Rightarrow \exists S_k$ not inj. Convly not true unless $k = 1$.

(b) By Exe (9), if all V_k finide and iso to each other, then $S_m \circ \dots \circ S_1$ inj \Rightarrow inv, so are all S_k .

(c) $\text{null } S_1 \subseteq \text{null}(S_2S_1) \subseteq \dots \subseteq \text{null}(S_m \dots S_2S_1); S_m \circ \dots \circ S_1$ inj \Rightarrow each $S_k \circ \dots \circ S_1$ inj.

Supp each $W_k = V_{k+1}$, for if $W_k \subsetneq V_{k+1}$, then S_1, S_2 surj $\not\Rightarrow S_2 \circ S_1 \in L(V_1, W_2)$ surj.

(d) Each S_k surj $\Rightarrow S_m \circ \dots \circ S_1$ surj. Convly not true unless all V_k finide and iso to each other.

(e) $\text{range } S_m \supseteq \text{range}(S_mS_{m-1}) \supseteq \dots \supseteq \text{range}(S_mS_{m-1} \dots S_1); S_m \circ \dots \circ S_1$ surj \Rightarrow each $S_m \circ \dots \circ S_k$ surj.

• (4E 23, OR 10.A.4) *Supp $(\beta_1, \dots, \beta_n)$ and $(\alpha_1, \dots, \alpha_n)$ are bses of V.*

Let T ∈ L(V) be suth each $T\alpha_k = \beta_k$. Prove A = M(T, α → α) = M(I, β → α) = B.

SOLUS: Each $I\beta_k = \beta_k = B_{1,k}\alpha_1 + \dots + B_{n,k}\alpha_n = T\alpha_k = A_{1,k}\alpha_1 + \dots + A_{n,k}\alpha_n \Rightarrow A = B$. \square

Or. $M(T, \alpha \rightarrow \alpha) = M(I, \beta \rightarrow \alpha) \underline{M(T, \alpha \rightarrow \beta)} = M(I, \beta \rightarrow \alpha)$. \square

Or. $M(T, \alpha \rightarrow \alpha) = M(I, \alpha \rightarrow \beta)^{-1} [\underline{M(T, \beta \rightarrow \beta) M(I, \alpha \rightarrow \beta)}] = M(I, \beta \rightarrow \alpha)$. \square

COMMENT: $M(T, \beta \rightarrow \beta) = M(T, \alpha \rightarrow \beta) M(I, \beta \rightarrow \alpha) = B$. Or. Let $A' = M(T, \beta \rightarrow \beta)$.

Simlr. Now each $T\beta_k = T(B_{1,k}\alpha_1 + \dots + B_{n,k}\alpha_n) = A'_{1,k}\beta_1 + \dots + A'_{n,k}\beta_n \Rightarrow A' = B$.

- **NOTE FOR [3.62]:** $\mathcal{M}(v) = \mathcal{M}(I, (v), B_V)$. Here I is restr to $\text{span}(v)$, and $(v) = (\)$ if $v = 0$.
 - **NOTE FOR [3.65]:** $\mathcal{M}(Tv) = \mathcal{M}(I, (Tv), B_W) = \mathcal{M}(T, B_V, B_W) \mathcal{M}(I, (v), B_V) = \mathcal{M}(T, (v), B_W)$.
-

- **NOTE FOR Exe (15):** $\underline{Tx = \mathcal{M}(Tx, B_2)} = \mathcal{M}(I, B'_2, B_2) \mathcal{M}(Tx, B'_2) = \mathcal{M}(I, B'_2, B_2) \mathcal{M}(T, B'_1, B'_2) \mathcal{M}(x, B'_1)$
 $= \mathcal{M}(I, B'_2, B_2) \mathcal{M}(T, B'_1, B'_2) \mathcal{M}(I, B_1, B'_1) \underline{\mathcal{M}(x, B_1)} = \mathcal{M}(T, B_1, B_2) \underline{x} = Ax$.

Where B_1, B_2 are std bses, and B'_1, B'_2 are arb bses. Now A is uniq.

Convly, $\forall A \in \mathbf{F}^{m,n}, \exists ! T \in \mathcal{L}(\mathbf{F}^{n,1}, \mathbf{F}^{m,1}), Tx = Ax = \mathcal{M}(T)x \Rightarrow \mathcal{M}(T) = A$.

Hence $\text{range } A = \text{range } T$ and $\text{null } A = \text{range } T$ are well-defined becs the def of T is indep of bses.

Let $P_1 \in \mathcal{L}(\mathbf{F}^{n,1}), P_2 \in \mathcal{L}(\mathbf{F}^{m,1})$ be suth $\mathcal{M}(P_1, B_1) = \mathcal{M}(I, B'_1, B_1), \mathcal{M}(P_2, B_2) = \mathcal{M}(I, B_2, B'_2)$.

Now $\mathcal{M}(T, B_1, B_2)$ inje $\Leftrightarrow T$ inje $\Leftrightarrow P_2 T P_1$ inje $\Leftrightarrow \mathcal{M}(T, B'_1, B'_2) = \mathcal{M}(P_2 T P_1, B_1, B_2)$ inje.

Supp $S \in \mathcal{L}(V, W), A_1 = \mathcal{M}(S, B_V, B_W) = \mathcal{M}(T, B_1, B_2)$,

$C_V = \mathcal{M}(I, B'_V, B_V), C_W = \mathcal{M}(I, B_W, B'_W), A_2 = \mathcal{M}(S, B'_V, B'_W) = C_W A_1 C_V$.

Let $P_1 \in \mathcal{L}(\mathbf{F}^{n,1}), P_V \in \mathcal{L}(V), P_2 \in \mathcal{L}(\mathbf{F}^{m,1}), P_W \in \mathcal{L}(W)$ and bses B'_1, B'_2 be suth

$\mathcal{M}(P_1, B_1) = \mathcal{M}(I, B'_1, B_1) = C_V = \mathcal{M}(P_V, B_V), \mathcal{M}(P_2, B_2) = \mathcal{M}(I, B_2, B'_2) = C_W = \mathcal{M}(P_W, B_W)$.

Now A_1 inje $\Leftrightarrow T$ inje \Leftrightarrow the cols of A_1 liney indep $\Leftrightarrow S$ inje. Simlr for surj.

And $\mathcal{M}(S, B_V, B_W)$ inje $\Leftrightarrow T$ inje $\Leftrightarrow P_2 T P_1$ inje $\Leftrightarrow C_W A_1 C_V = \mathcal{M}(S, B'_V, B'_W)$ inje.

Thus S inje $\Leftrightarrow \mathcal{M}(S)$ inje, wrto any bses. Simlr for surj and inv.

- **TIPS 3:** Identify $\mathbf{F}^{m,n}$ with $\mathcal{L}(\mathbf{F}^{n,1}, \mathbf{F}^{m,1})$, due to $Tx = Ax$; or with $\mathcal{L}(\mathbf{F}^{1,n}, \mathbf{F}^{1,m})$, due to $Tx = xA^t$.

Details about the latter: $x = \mathcal{M}(x)^t \Rightarrow x\mathcal{M}(T)^t = \mathcal{M}(Tx)^t = \mathcal{M}(xA^t)^t = xA^t \Rightarrow \mathcal{M}(T) = A$.

NOTE: If we define $\mathcal{M}(v) = (c_1 \ \dots \ c_n)$. Then [3.64]: $\mathcal{M}(T)_{k,\cdot} = \mathcal{M}(v_k) \mathcal{M}(T) = \mathcal{M}(Tv_k)$.

Note that $A = \mathcal{M}(T, (v_1, \dots, v_n), (w_1, \dots, w_m)) \in \mathbf{F}^{n,m}$, and each $Tv_k = A_{k,1}w_1 + \dots + A_{k,m}w_m$.

[3.65]: $\mathcal{M}(Tv) = c_1\mathcal{M}(Tv_1) + \dots + c_n\mathcal{M}(Tv_n) = c_1\mathcal{M}(T)_{1,\cdot} + \dots + c_n\mathcal{M}(T)_{n,\cdot} = \mathcal{M}(v)\mathcal{M}(T)$.

[3.41]: $C = \mathcal{M}(T, (u_1, \dots, u_p), (v_1, \dots, v_n)) \in \mathbf{F}^{p,n}, A = \mathcal{M}(S, (v_1, \dots, v_n), (w_1, \dots, w_m)) \in \mathbf{F}^{n,m}$.

$$\sum_{j=1}^m (AC)_{k,j} w_j = STu_k = \sum_{j=1}^m \left(\sum_{r=1}^n C_{k,r} A_{r,j} \right) w_j \Rightarrow (AC)_{k,j} = \sum_{r=1}^n C_{k,r} A_{r,j}.$$

Exactly in trspose with the original. Now Exe (15): $T \in \mathcal{L}(\mathbf{F}^{1,n}, \mathbf{F}^{1,m}) : Tx = xA$.

Becs $Tx = \mathcal{M}(Tx) = \mathcal{M}(x)\mathcal{M}(T) = x\mathcal{M}(T)$ wrto std bses.

- **TIPS 4:** You must first declare bses and the purpose when using $\mathcal{M}^{-1} : \mathbf{F}^{n,1} \mapsto v$, or $\mathbf{F}^{m,n} \mapsto \mathcal{L}(V, W)$.

- **NOTE FOR Exe (4E 3, 4E 22):** $T \in \mathcal{L}(V, W)$ inv $\Leftrightarrow \mathcal{M}(T)$ inv, wrto any (\Leftrightarrow some) B_V, B_W .

Supp $\mathcal{M}(T)$ wrto some B_V, B_W is inv. Let $S \in \mathcal{L}(W, V)$ be suth $\mathcal{M}(S, B_W, B_V) = \mathcal{M}(T, B_V, B_W)^{-1}$.

Then $\mathcal{M}(TS, B_W) = \mathcal{M}(T, B_V, B_W) \mathcal{M}(S, B_W, B_V) = I_W$. Apply \mathcal{M}^{-1} , we get $S = T^{-1}$.

CORO: $\mathcal{M}(T, B_V, B_W)^{-1} = \mathcal{M}(T^{-1}, B_W, B_V)$, if T or $\mathcal{M}(T)$ inv.

- **NOTE FOR [3.60]:** Supp $B_V = (v_1, \dots, v_n), B_W = (w_1, \dots, w_m)$.

Define $E_{i,j} \in \mathcal{L}(V, W)$ by $E_{i,j}(v_x) = \delta_{i,x} w_j$. Define $R_{i,j} \in \mathcal{L}(W, V) : w_x \mapsto \delta_{i,x} v_j$.

Define $G_{i,j} = R_{x,j} E_{i,x}$, and $Q_{i,j} = E_{x,j} R_{i,x}$. Let $\mathcal{E}^{(j,i)} = \mathcal{M}(E_{i,j})$, simlr for $\mathcal{R}^{(j,i)}, \mathcal{G}^{(j,i)}$.

Now $R_{l,k} E_{i,j} = \delta_{j,l} G_{i,k}, \mathcal{R}^{(k,l)} \mathcal{E}^{(j,i)} = \delta_{l,j} \mathcal{G}^{(k,i)}$. Simlr for $Q_{i,k}$ and $\mathcal{Q}^{(k,i)}$.

Becs $\mathcal{M} : \mathcal{L}(V, W) \rightarrow \mathbf{F}^{m,n}$ is iso.

$E_{i,j} = \mathcal{M}^{-1} \mathcal{E}^{(j,i)}$. By [2.42] and [3.61]: $B_{\mathcal{L}(V, W)} = \begin{pmatrix} E_{1,1}, & \dots, & E_{n,1}, \\ \vdots & \ddots & \vdots \\ E_{1,m}, & \dots, & E_{n,m} \end{pmatrix}; B_{\mathbf{F}^{m,n}} = \begin{pmatrix} \mathcal{E}^{(1,1)}, & \dots, & \mathcal{E}^{(1,n)}, \\ \vdots & \ddots & \vdots \\ \mathcal{E}^{(m,1)}, & \dots, & \mathcal{E}^{(m,n)} \end{pmatrix}$.

We can rewrite the matrix multi in (3.C).

- **TIPS:** Let $B_{\text{range } T} = (Tv_1, \dots, Tv_p)$, $B_V = (v_1, \dots, v_p, \dots, v_n)$. Let each $w_k = Tv_k$. Extend to $B_W = (w_1, \dots, w_p, \dots, w_m)$. Then $T = E_{1,1} + \dots + E_{p,p}$, $\mathcal{M}(T) = \mathcal{E}^{(1,1)} + \dots + \mathcal{E}^{(p,p)}$.

- (4E 17) *Supp U, V, W finide, S ∈ L(V, W), A ∈ L(L(U, V), L(U, W)) : T ↦ ST.*
Show dim null A = (dim U)(dim null S), dim range A = (dim U)(dim range S).

SOLUS: (a) $\forall T \in L(U, V), ST = 0 \iff \text{range } T \subseteq \text{null } S$. Thus $\text{null } A = L(U, \text{null } S)$.
(b) $\forall R \in L(U, W), \text{range } R \subseteq \text{range } S \iff \exists T \in L(U, V), R = ST$, by (3.B 25).
Thus $\text{range } A = L(U, \text{range } S)$. □

Or. Let $B_{\text{range } S} = (w_1, \dots, w_s)$ with each $w_i = Sv_i$. Let $B_W = (w_1, \dots, w_n)$, $B_{\text{null } S} = (v_{s+1}, \dots, v_p)$.
Let $B_U = (u_1, \dots, u_m)$. Define $E_{i,j} \in L(V, W) : v_x \mapsto \delta_{i,x} w_j$. Now $S = E_{1,1} + \dots + E_{s,s}$.
Define $R_{i,j} \in L(U, V) : u_x \mapsto \delta_{i,x} v_j$. Let $E_{k,j} R_{i,k} = Q_{i,j} : u_x \mapsto \delta_{i,x} w_j$.
For any $T \in L(V), \exists ! A_{i,j} \in F, T = \sum_{j=1}^p \sum_{i=1}^m A_{j,i} R_{i,j} \Rightarrow \mathcal{M}(T, u \rightarrow v) = \begin{pmatrix} A_{1,1} & \cdots & A_{1,s} & \cdots & A_{1,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{s,1} & \cdots & A_{s,s} & \cdots & A_{s,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{p,1} & \cdots & A_{p,s} & \cdots & A_{p,m} \end{pmatrix}$
 $\Rightarrow A(T) = ST = \left(\sum_{k=1}^s E_{k,k} \right) \left(\sum_{j=1}^p \sum_{i=1}^m A_{j,i} R_{i,j} \right) = \sum_{j=1}^p \sum_{i=1}^m A_{j,i} Q_{j,i}$.
 $\mathcal{M}(S, v \rightarrow w) \mathcal{M}(T, u \rightarrow v) = \mathcal{M}(ST, u \rightarrow w) = \begin{pmatrix} A_{1,1} & \cdots & A_{1,s} & \cdots & A_{1,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{s,1} & \cdots & A_{s,s} & \cdots & A_{s,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \end{pmatrix}$ 又 $\mathcal{M}(T, R) = \mathcal{M}(T, u \rightarrow v)$.
 $\mathcal{M}(A, R \rightarrow Q) \mathcal{M}(T, R) = \mathcal{M}(A(T), Q) = \begin{pmatrix} A_{1,1} & \cdots & A_{1,s} & \cdots & A_{1,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{s,1} & \cdots & A_{s,s} & \cdots & A_{s,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \end{pmatrix}$ If $m = p$, let $\mathcal{M}(T, R) = I$,
 $\mathcal{M}(A, R \rightarrow Q) = \mathcal{M}(S, v \rightarrow w)$.

$$B_{\text{range } A} = \{Q_{x,y} : 1 \leq x \leq m, \text{ and } 1 \leq y \leq s\}, B_{\text{null } A} = \{R_{x,y} : 1 \leq x \leq m, \text{ and } s+1 \leq y \leq p\}. \quad \square$$

- (4E 10) *Supp V, W finide, U is a subsp of V, E = {T ∈ L(V, W) : T|_U = 0}. Find dim E.*

SOLUS: Define $\Phi : L(V, W) \rightarrow L(U, W)$ by $\Phi(T) = T|_U$. By [3.A NOTE FOR Restr], Φ is liney.

$$\Phi(T) = 0 \iff \forall u \in U, Tu = 0 \iff T \in E. \text{ Thus } \text{null } \Phi = E.$$

Extend $S \in L(U, W)$ to $T \in L(V, W) \Rightarrow \Phi(T) = S \in \text{range } \Phi$. Thus $\text{range } \Phi = L(U, W)$. □

Or. Let $B_U = (u_1, \dots, u_m)$, $B_V = (u_1, \dots, u_m, \dots, u_n)$, $B_W = (w_1, \dots, w_p)$.

Define $E_{i,j} \in L(V, W) : u_x \mapsto \delta_{i,x} w_j$.
 $\forall T \in E, k \in \{1, \dots, m\}, TE_{k,k} = 0 \Rightarrow \text{span} \left\{ \underbrace{\begin{matrix} E_{1,1}, \dots, E_{m,1}, \\ \vdots & \ddots & \vdots \end{matrix}}_{=R} \right\} \cap E = \{0\}$.
 $\text{Now } L(V, W) = \text{span } R \oplus C$
 $\text{As } C = \text{span} \left\{ \underbrace{\begin{matrix} E_{m+1,1}, \dots, E_{n,1}, \\ \vdots & \ddots & \vdots \end{matrix}}_{=R} \right\} \subseteq E. \quad \Rightarrow L(V, W) = \text{span } R + E. \quad \square$

- *Supp U, V, W finide, S ∈ L(U, V), B ∈ L(L(V, W), L(U, W)) : T ↦ TS.*
Show dim null B = (dim W)(dim null S), dim range B = (dim W)(dim range S).

SOLUS: (a) $\forall T \in L(V, W), TS = 0 \iff \text{range } S \subseteq \text{null } T$. Thus $\text{null } B = \{T \in L(V, W) : T|_{\text{range } S} = 0\}$.

$$(b) \forall R \in L(U, W), \text{null } S \subseteq \text{null } R \iff \exists T \in L(V, W), R = TS, \text{ by (3.B.24).}$$

Thus $\text{range } B = \{R \in L(U, W) : R|_{\text{null } S} = 0\}$. Now by Exe (4E 10). □

Or. Let $B_{\text{range } S} = (v_1, \dots, v_r)$ with each $v_i = Su_i$. Let $B_V = (v_1, \dots, v_m)$, $B_{\text{null } S} = (u_{r+1}, \dots, u_n)$.

Let $B_W = (w_1, \dots, w_p)$. Define $E_{i,j} \in L(U, V) : u_x \mapsto \delta_{i,x} v_j \Rightarrow S = E_{1,1} + \dots + E_{r,r}$.

Define $R_{i,j} \in L(V, W) : v_x \mapsto \delta_{i,x} w_j$. Let $R_{k,j} E_{i,k} = Q_{i,j} : u_x \mapsto \delta_{i,x} w_j$.
 $TS = \left(\sum_{j=1}^p \sum_{i=1}^m A_{j,i} R_{i,j} \right) \left(\sum_{k=1}^r E_{k,k} \right) = \sum_{j=1}^p \sum_{i=1}^m A_{j,i} Q_{i,j} \Rightarrow \mathcal{M}(TS, v) = \begin{pmatrix} A_{1,1} & \cdots & A_{1,r} & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{r,1} & \cdots & A_{r,r} & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{p,1} & \cdots & A_{p,r} & \cdots & 0 \end{pmatrix}$
 $\text{range } B = \text{span} \left\{ \underbrace{\begin{matrix} Q_{1,1}, \dots, Q_{r,1}, \\ \vdots & \ddots & \vdots \end{matrix}}_{=R} \right\}, \text{null } B = \text{span} \left\{ \underbrace{\begin{matrix} R_{r+1,1}, \dots, R_{n,1}, \\ \vdots & \ddots & \vdots \end{matrix}}_{=R} \right\}$. □

• *Supp A ∈ F^{n,n}. Define T, S ∈ L(F^{n,n}) by T(X) = AX, S(Y) = YA^t. Find dim range ST.*

SOLUS: Becs $A\mathcal{E}^{(j,k)} = [\sum_{x=1}^n A_{x,j} \mathcal{E}^{(x,j)}] \mathcal{E}^{(j,k)} = \sum_{x=1}^n A_{x,j} \mathcal{E}^{(x,k)}$. Let $B_{\text{col}A} = (C_{\cdot,1}, \dots, C_{\cdot,r})$.

Each $A_{\cdot,j} = R_{1,j}C_{\cdot,1} + \dots + R_{r,j}C_{\cdot,r} \Rightarrow B_{\text{range}T} = \{\mathcal{C}_{j,k} = \sum_{x=1}^n C_{x,j} \mathcal{E}^{(x,k)} : 1 \leq j \leq r, 1 \leq k \leq n\}$.

Becs $\mathcal{C}_{j,k} A^t = \mathcal{C}_{j,k} [\sum_{y=1}^n A_{k,y}^t \mathcal{E}^{(k,y)}] = \sum_{x=1}^n \sum_{y=1}^n C_{x,j} A_{y,k} \mathcal{E}^{(x,y)}$. $\left| \begin{array}{l} \mathcal{X}_{j,k} = \begin{pmatrix} C_{1,j} C_{1,k} \cdots C_{1,j} C_{n,k} \\ \vdots \\ C_{n,j} C_{1,k} \cdots C_{n,j} C_{n,k} \end{pmatrix} \\ \text{Simlr, } B_{\text{range}ST} = \{\mathcal{X}_{j,k} = \sum_{x=1}^n \sum_{y=1}^n C_{x,j} C_{y,k} \mathcal{E}^{(x,y)} : 1 \leq j, k \leq r\}. \\ \text{Each } \mathcal{X}_{j,k} = C_{1,k} \mathcal{C}_{j,1} + \dots + C_{n,k} \mathcal{C}_{j,n} = C_{1,j} (\mathcal{C}_{k,1})^t + \dots + C_{n,j} (\mathcal{C}_{k,n})^t. \end{array} \right. \quad \square$

Or. By TIPS (3). Define $\varphi \in L(L(F^{n,1})) : X \mapsto AX$; $\psi \in L(L(F^{n,1}, \text{range}A)) : Y \mapsto YA^t$.

$\text{range } \psi\varphi = \{X \in L(F^{n,1}, \text{range}A) : X|_{\text{null}A^T} = 0\}$ of $\dim(\dim \text{range}A)(\dim \text{range}A^t) = (\text{rank}A)^2 \square$

16 *Supp V is finide and non0 S ∈ L(V) suth ∀T ∈ L(V), ST = TS. Prove ∃λ ∈ F, S = λI.*

SOLUS: Let $B_{\text{range}S} = (w_1, \dots, w_m)$ with each $w_i = Sv_i$.

Let $B_{\text{null}T} = (v_{m+1}, \dots, v_n)$. Let $B_1 = (v_1, \dots, v_n)$, $B_2 = (w_1, \dots, w_n)$.

Let $S = E_{1,1} + \dots + E_{m,m} \Rightarrow \mathcal{M}(S, B_1, B_2) = \mathcal{M}(P_{\text{range}S}, B_2, B_2)$. 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 $G_{i,j} = R_{i,j}S = SR_{i,j} = Q_{i,j}$. \forall For each w_i , $\exists! a_{k,i} \in F, w_i = a_{1,i}v_1 + \dots + a_{n,i}v_n$.

Then fix one i . Now for each $j \in \{1, \dots, n\}$, $Q_{i,j}(w_i) = w_j = a_{i,i}v_j = G_{i,j} \left(\sum_{k=1}^n a_{k,i}v_k \right)$.

Let $\lambda = a_{i,i}$. Hence each $w_j = \lambda v_j$. Now fix one j , we have $a_{1,1}v_1 = \dots = a_{n,n}v_j$. \square

ENDED

3.E

- **NOTE FOR [3.79], def of $v + U$:** Given $v + U$, v is already uniquely determined, as a sort of precond.
Even though $v + U = v' + U$, where v' is purer than v .
- **NOTE FOR [3.85]:** $v + U = w + U \iff v \in w + U, w \in v + U$
 $\iff v - w \in U \iff (v + U) \cap (w + U) \neq \emptyset$.

• NOTE FOR [3.79, 3.83]:

If U is merely a subset of V , then [3.85, 86] do not hold $\Rightarrow V/U$ not a vecsp.

If V is merely a subset of a vecsp of which U is a subsp, then [3.79, 86] do not hold $\Rightarrow V/U$ not a vecsp.

If U is a vecsp but not a subsp of V , while U, V are subsps of some vecsp, then everything's alright.

Hence if V/U is a vecsp, then V, U are subsps of some vecsp.

COMMENT: $\text{Supp } U, V$ are subsps and U is not a subsp of V . Note that $V/U = (V + U)/U$.

$\text{Supp } v + U \in V/U$. Then $v \in V$, or possibly $v \in V + U$ as well. To avoid this ambiguity, you have to specify the precond, what subsp that v belongs to.

Exa: $\text{Supp } U + W = V$. Then $V/U = (U + W)/U = W/U$. Let $W \cap U = I, U_I \oplus I = U, W_I \oplus I = W$.

Now $U_I \oplus W_I \oplus I = V$. Thus $W/U = (W_I \oplus I)/U = W_I/U$.

$\forall w'_1, w'_2 \in W_I$ such $w'_1 + U = w'_2 + U \in W_I/U$, we have $w'_1 - w'_2 \in U \cap W_I = \{0\} \Rightarrow w'_1 = w'_2$.

• Trivial Cases:

If $v \in U$, then $v + U = 0 + U = \{u : u \in U\} = U$. Now $U = 0 \in V/U$.

If $U = \{0\}$, then $v + U = v + \{0\} = \{v\}, V/U = V/\{0\} = \{\{v\} : v \in V\}$.

If $U = \emptyset$, then $v + U = v + \emptyset = \emptyset, V/U = V/\emptyset = \{\emptyset\}$.

• TIPS 1:

V is a subsp of $U \iff \forall v \in V, v + U = 0 + U = U \iff V/U = \{0\} = \{U\}$.

• NOTE FOR [3.88]:

If U, V are subsp of some vecsp \mathcal{V} . Define the quot map $\pi \in \mathcal{L}(V, V/U)$.
Then π is surj by def, and $\text{null } \pi = V \cap U$. Thus if \mathcal{V} is finide, then $\dim V = \dim V/U + \dim(V \cap U)$.

Or. Let $I = V \cap U, V_I \oplus I = V$. Becs $V/U = V_I/U$, iso to V_I . Now $\dim V = \dim V_I + \dim I$.

7 Supp $\alpha, \beta \in V$, and U, W are subsps of V . Prove $\alpha + U = \beta + W \Rightarrow U = W$.

SOLUS: (a) $\alpha \in \alpha + U = \beta + W \Rightarrow \exists w \in W, \alpha = \beta + w \Rightarrow \alpha - \beta \in W \Rightarrow \alpha + W = \beta + W$.

(b) $\beta \in \beta + W = \alpha + U \Rightarrow \exists u \in U, \beta = \alpha + u \Rightarrow \beta - \alpha \in U \Rightarrow \alpha + U = \beta + U$. □

Or. $\pm(\alpha - \beta) \in U \cap W \Rightarrow \left\{ \begin{array}{l} U \ni u = (\beta - \alpha) + w \in W \Rightarrow U \subseteq W \\ W \ni w = (\alpha - \beta) + u \in U \Rightarrow W \subseteq U \end{array} \right\} \Rightarrow U = W$. □

8 Supp $\emptyset \neq A \subseteq V$. Prove A is a trslate $\iff \lambda v + (1 - \lambda)w \in A, \forall v, w \in A, \lambda \in \mathbf{F}$.

SOLUS: (a) $\text{Supp } A = a + U$. Then $\lambda(a + u_1) + (1 - \lambda)(a + u_2) = a + (\lambda(u_1 - u_2) + u_2) \in A$.

(b) $\text{Supp } \lambda v + (1 - \lambda)w \in A, \forall v, w \in A, \lambda \in \mathbf{F}$. $\text{Supp } a \in A$ and let $A' = \{x - a : x \in A\} \Rightarrow 0 \in A'$, and $\forall(v - a), (w - a) \in A', \forall \lambda \in \mathbf{F}$, (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 $\text{Supp } A = \alpha + U$ and $B = \beta + W$ for some $\alpha, \beta \in V$ and some subspes U, W of V .

Prove $A \cap B$ is either a trslate of some subsp of V or is \emptyset .

SOLUS: $\forall \alpha + u, \beta + w \in A \cap B \neq \emptyset, \forall \lambda \in \mathbf{F}, \lambda(\alpha + u) + (1 - \lambda)(\beta + w) \in A \cap B$. By Exe (8). \square

Or. Let $A = \alpha + U, B = \beta + W$. $\text{Supp } v \in (\alpha + U) \cap (\beta + W) \neq \emptyset$.

Then $v - \alpha \in U \Rightarrow v + U = \alpha + U = A$, and simlr $v + W = \beta + W = B$.

We show $A \cap B = v + (U \cap W)$. Note that $v + (U \cap W) \subseteq A \cap B$.

And $\forall \gamma = v + u = v + w \in A \cap B \Rightarrow u = w \in U \cap W \Rightarrow \gamma \in v + (U \cap W)$. \square

10 Prove the intersec of any collec of trslates of subspes is either a trslate of some subspes or \emptyset .

SOLUS: $\text{Supp } \{A_\alpha\}_{\alpha \in \Gamma}$ is a collec of trslates of subspes of V , where Γ is an index set.

$\forall x, y \in \bigcap_{\alpha \in \Gamma} A_\alpha \neq \emptyset, \forall \lambda \in \mathbf{F}, \lambda x + (1 - \lambda)y \in A_\alpha$ for each α . By Exe (8). \square

Or. Let each $A_\alpha = w_\alpha + V_\alpha$. $\text{Supp } x \in \bigcap_{\alpha \in \Gamma} (w_\alpha + V_\alpha) \neq \emptyset$.

Then $x - w_\alpha \in V_\alpha \Rightarrow x + V_\alpha = w_\alpha + V_\alpha = A_\alpha$, for each α .

We show $\bigcap_{\alpha \in \Gamma} A_\alpha = \bigcap_{\alpha \in \Gamma} (x + V_\alpha) = x + \bigcap_{\alpha \in \Gamma} V_\alpha$.

$y \in \bigcap_{\alpha \in \Gamma} A_\alpha \iff$ for each $\alpha, y = x + v_\alpha \in A_\alpha$

\iff each $v_\alpha = y - x \in \bigcap_{\alpha \in \Gamma} V_\alpha \iff y \in x + \bigcap_{\alpha \in \Gamma} V_\alpha$. \square

11 $\text{Supp } A = \{\lambda_1 v_1 + \dots + \lambda_m v_m : \sum_{i=1}^m \lambda_i = 1\}$, 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 $< m$.

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) $\text{Supp } B = v + U$, where $v \in V$ and U is a subsp of V . Let each $v_k = v + u_k \in B, \exists! u_k \in U$.

$$\forall w \in A, w = \sum_{i=1}^m \lambda_i v_i = \sum_{i=1}^m \lambda_i (v + u_i) = \sum_{i=1}^m \lambda_i v + \sum_{i=1}^m \lambda_i u_i = v + \sum_{i=1}^m \lambda_i u_i \in v + U = B. \square$$

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 $v = \lambda_1 v_1 + \dots + \lambda_k v_k \in A \subseteq B$. $[\forall \lambda_i \text{ suth } \sum_{i=1}^k \lambda_i = 1]$

For $u = \mu_1 v_1 + \dots + \mu_k v_k + \mu_{k+1} v_{k+1} \in A$. Fix one $\mu_i \neq 1$.

$$\text{Then } \sum_{i=1}^{k+1} \mu_i - \mu_i = 1 - \mu_i \Rightarrow \left[\sum_{i=1}^{k+1} \frac{\mu_i}{1 - \mu_i} \right] - \frac{\mu_i}{1 - \mu_i} = 1.$$

$$\text{Let } w = \underbrace{\frac{\mu_1}{1 - \mu_1} v_1 + \dots + \frac{\mu_{i-1}}{1 - \mu_i} v_{i-1} + \frac{\mu_{i+1}}{1 - \mu_i} v_{i+1} + \dots + \frac{\mu_{k+1}}{1 - \mu_i} v_{k+1}}_{k \text{ terms}}.$$

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,

$$v_i \in B \Rightarrow u' = \lambda w + (1 - \lambda)v_i \in B \quad \left. \begin{aligned} \sum_{i=1}^k \lambda_i = 1 \Rightarrow w \in B \end{aligned} \right\} \Rightarrow \text{Let } \lambda = 1 - \mu_i. \text{ Thus } u' = u \in B \Rightarrow A \subseteq B. \quad \square$$

(c) If $m = 1$, then let $A = v_1 + \{0\}$ and done. Now supp $m \geq 2$. Fix one $k \in \{1, \dots, m\}$.

$$\begin{aligned} A &\ni \lambda_1 v_1 + \dots + \lambda_{k-1} v_{k-1} + (1 - \lambda_1 - \dots - \lambda_{k-1} - \lambda_{k+1} - \dots - \lambda_m) v_k + \lambda_{k+1} v_{k+1} + \dots + \lambda_m v_m \\ &= v_k + \lambda_1(v_1 - v_k) + \dots + \lambda_{k-1}(v_{k-1} - v_k) + \lambda_{k+1}(v_{k+1} - v_k) + \dots + \lambda_m(v_m - v_k) \\ &\in v_k + \text{span}(v_1 - v_k, \dots, v_m - v_k). \end{aligned} \quad \square$$

18 *Supp $T \in \mathcal{L}(V, W)$ and U, V are subsp of \mathcal{V} . Let $\pi : V \rightarrow V/U$ be the quot map.*

Prove $\exists S \in \mathcal{L}(V/U, W), T = S \circ \pi \iff U \cap V = \text{null } \pi \subseteq \text{null } T$.

SOLUS: $\text{Supp null } \pi \subseteq \text{null } T$. By (3.B.24), done. OR. Define $S : (v + U) \mapsto Tv$.

$\forall v_1, v_2 \in V$ suth $v_1 + U = v_2 + U \iff v_1 - v_2 \in U \cap V \subseteq \text{null } T \iff Tv_1 = Tv_2$.

Thus S is well-defined. Convly true as well. \square

CORO: $\Gamma : \mathcal{L}(V/U, W) \rightarrow \mathcal{L}(V, W)$ with $S \mapsto S \circ \pi$ is inj, $\text{range } \Gamma = \{T \in \mathcal{L}(V, W) : U \subseteq \text{null } T\}$.

COMMENT: If $T = I_V$. Then $S : v + U \mapsto v$ is not well-defined, unless $U \cap V = \{0\} \subseteq \text{null } I_V$.

• **NOTE FOR [3.88, 3.90, 3.91]:** $\text{Supp } W \oplus U = V$. Then $V/U = W/U$ is iso to W . [Convly 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 Exa below]

Now $\pi \circ \tilde{T} = I_{V/U}$, $\tilde{T} \circ \pi|_W = I_W = T|_W$. Hence $\tilde{T} = (\pi|_W)^{-1}$ is iso of V/U onto W .

• **Exa:** Let $V = \mathbb{F}^2, B_U = (e_1), B_W = (e_2 - e_1) \Rightarrow U \oplus W = V$.

Although $(e_2 - e_1) + U = e_2 + U, \tilde{T}(e_2 + U) = T(e_2) = e_2 - e_1$. Becs $e_2 = e_1 + (e_2 - e_1) \in U \oplus W$.

17 *Supp V/U is finide. Supp W is finide and $V = U + W$. Show $\dim W \geq \dim V/U$.*

SOLUS: Let $Y \oplus (U \cap W) = W$. Then by [1.C TIPS (3)], $V = U \oplus Y$. Note that V/U and Y are iso. \square

Or. Let $B_W = (w_1, \dots, w_n) \Rightarrow V/U = \text{span}(w_1, \dots, w_n)/U = \text{span}(w_1 + U, \dots, w_n + U)$. \square

NOTE: If $\dim W = \dim V/U$. Then $B_{V/U} = (w_1 + U, \dots, w_n + U)$. $\text{Supp } v = \sum_{i=1}^n a_i w_i \in U \cap W$

$\Rightarrow v + U = 0 = \sum_{i=1}^n a_i(w_i + U) \Rightarrow \text{each } a_i = 0$. Thus $V = U \oplus W$.

12 *Supp U is a subsp of V . Prove is V is iso to $U \times (V/U)$.*

SOLUS:

[Req V/U Finide] Let $B_{V/U} = (v_1 + U, \dots, v_n + U)$.

Now $\forall v \in V, \exists! a_i \in \mathbb{F}, v + U = \sum_{i=1}^n a_i v_i + U \Rightarrow v - \sum_{i=1}^n a_i v_i \in U \Rightarrow \exists! u \in U, v = \sum_{i=1}^n a_i v_i + u$.

Thus define $\varphi \in \mathcal{L}(V, U \times (V/U))$ and $\psi \in \mathcal{L}(U \times (V/U), V)$

by $\varphi(v) = (u, \sum_{i=1}^n a_i v_i + U)$, and $\psi(u, v + U) = \sum_{i=1}^n a_i v_i + u$. Then $\psi = \varphi^{-1}$. \square

Or. Let $W \oplus U = V$. Define $Tv = u_v, Sv = w_v \Rightarrow \tilde{T} \in \mathcal{L}(V/W, U), \tilde{S} \in \mathcal{L}(V/U, W)$ are iso.

Define $\psi(u, v + U) = u + \tilde{S}(v + U) = u + w_v$. Define $\varphi(v) = (\tilde{T}(v), v + U)$.

$$\begin{cases} (\psi \circ \varphi)(u_v + w_v) = \psi(u_v, w_v + U) = u_v + w_v \\ (\psi \circ \varphi)(u, v + U) = \varphi(u + w_v) = (u, w_v + U) \end{cases} \Rightarrow \psi = \varphi^{-1}$$
. Or Becs ψ or φ is inj and surj. \square

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: $\forall v \in V, \exists! a_i \in \mathbb{F}, v + U = \sum_{i=1}^m a_i v_i + U \Rightarrow \exists! b_i \in \mathbb{F}, v - \sum_{i=1}^m a_i v_i = \sum_{i=1}^n b_i u_i \in U$

$\Rightarrow \forall v \in V, \exists! a_i, b_j \in \mathbb{F}, v = \sum_{i=1}^m a_i v_i + \sum_{j=1}^n b_j u_j$. \square

Or. $\sum_{i=1}^m a_i v_i + \sum_{j=1}^n b_j u_j = 0 \Rightarrow \sum_{i=1}^m a_i(v_i + U) = 0 \Rightarrow \text{each } a_i = 0 \Rightarrow \text{each } b_j = 0$. \square

Or. Note that $B = (v_1, \dots, v_m)$ is liney indep, and $\text{span}(v_1, \dots, v_m) + U \subseteq V$.

$v \in \text{span } B \cap U \iff v + U = \sum_{i=1}^m a_i(v_i + U) = 0 + U \iff v = 0$. 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). \square

- (4E 14) $\text{Supp } V = U \oplus W$, $B_W = (w_1, \dots, w_m)$. 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 $\exists! c_i \in \mathbf{F}, w = \sum_{i=1}^m c_i w_i \Rightarrow v = \sum_{i=1}^m c_i w_i + u$.

Hence $\forall v + U \in V/U, \exists! c_i \in \mathbf{F}, v + U = \sum_{i=1}^m c_i w_i + U$. □

Or. Becs $\pi|_W : W \rightarrow W/U$ is inv, and $V/U = W/U$. □

- 16 $\text{Supp dim } V/U = 1$. Prove $\exists \varphi \in \mathcal{L}(V, \mathbf{F})$, $\text{null } \varphi = U$.

SOLUS: $\text{Supp } V_0 \oplus U = V$. Then V_0 is iso to V/U . Define $\varphi \in \mathcal{L}(V, \mathbf{F})$ by $\varphi(av_0 + u) = a$.

Or. Let $B_{V/U} = (w + U)$. Then $\forall v \in V, \exists! a \in \mathbf{F}, v + U = aw + U$.

Define $\varphi \in \mathcal{L}(V/U, \mathbf{F})$ by $\varphi(aw + U) = a$. Then $\text{null}(\varphi \circ \pi) = U$. □

- $\text{Supp } U, W$ are subsps of \mathcal{V} , and X, Y are subsps of \mathcal{W} .

$\text{Supp } U, X$ are iso, W, Y are iso. Prove or give a countexa: U/W and X/Y are iso.

SOLUS: A countexa: Let $\mathcal{V} = \mathcal{W} = \mathbf{F}^2$. Let $U = X = Y = \text{span}(e_1), W = \text{span}(e_2)$.

Then $\dim U/W = \dim U - \dim(U \cap W) = 1 \neq 0 = \dim X - \dim(X \cap Y) = \dim X/Y$. □

Or. Let $\mathcal{V} = U = W = \mathbf{F}^\infty = X, Y = \{(0, x_1, x_2, \dots)\}$. Then $U/W = \{0\}$, while $\dim X/Y = 1$. □

- TIPS 2: $\text{Supp } U, W$ are vecsp, $I = U \cap W$. Prove $V = U + W \iff V/I = U/I \oplus W/I$.

SOLUS: (a) $\text{Supp } V = U + W$. Then $\forall v + I \in V/I, \exists (u_v, w_v) \in U \times W, v + I = (u_v + w_v) + I$.

Note that $U/I, W/I \subseteq V/I$. Thus $V/I = U/I + W/I$.

$\forall u + I = w + I \in (U/I) \cap (W/I), \underline{u - w \in I} = U \cap W$

$\Rightarrow \exists w' \in I, u = w + w' \in U \cap W \Rightarrow u + I = 0 + I = w + I$. Thus $(U/I) \cap (W/I) = \{0\}$.

(b) $\text{Supp } V/I = U/I \oplus W/I$. Then $\forall v \in V, v + I = (u + I) + (w + I)$

$\Rightarrow v - u - w \in I = U \cap W \Rightarrow \exists x \in U \cap W, v = u + w + x \in U + W$. □

- $\text{Supp } T \in \mathcal{L}(V, W)$, and U, V are subsps of some vecsp, and X, W are subsps of some vecsp.

Define $T/X : V/U \rightarrow W/X$ by $T/X(v + U) = Tv + X$.

(a) Prove T/X is well-defined $\iff (\text{range } T|_{U \cap V})/(X \cap W) = \{0\} \iff \text{range } T|_{U \cap V}$ is a subsp of $X \cap W$.

$\text{Supp } T/X$ is well-defined, and thus is liney. Define $\pi_U \in \mathcal{L}(V, V/U), \pi_X \in \mathcal{L}(W, W/X)$.

Then $T/X \circ \pi_U = \pi_X \circ T$. Define $T/X \in \mathcal{L}(V, W/X)$ by $T/X(v) = Tv + X$.

(b) $\text{range } T/X = \text{range}(T/X \circ \pi_U) = \text{range}(\pi_X \circ T) = (\text{range } T)/X$.

(c) Prove T/X is surj $\iff W = \text{range } T + X \cap W$.

(d) Show $\text{null } T/X = (\text{null } T)/U$. (e) T/X is inje $\iff \text{null } T/X \subseteq U$.

SOLUS: (a) For $v, w \in V$. If $v + U = w + U \iff v - w \in U \Rightarrow Tv - Tw \in X \cap W \iff Tv + X = Tw + X$.

Then $\forall u \in V \cap U, Tu \in X \Rightarrow \text{range } T|_{U \cap V} \subseteq X \cap W$. Convly true as well.

(c) $\text{Supp } T/X$ is surj. $\forall w \in W, w + X \in W/X \Rightarrow \exists v + U \in V/U, Tv + X = w + X$

$\Rightarrow w - Tv \in X \cap W \Rightarrow w \in \text{range } T + X \cap W$. Hence $W \subseteq \text{range } T + X \cap W$.

Convly, $W = \text{range } T + X \cap W \Rightarrow (\text{range } T)/X = (\text{range } T + X \cap W)/X = W/X$.

(d) $v + U \in \text{null } T/X \iff Tv \in X \iff v \in \text{null } T/X \iff v + U \in (\text{null } T)/U$. □

- COMMENT: $\text{Supp } T \in \mathcal{L}(V)$. Define $T/U \in \mathcal{L}(V/U)$ by $T/U = T|_U^U$. Then

(a) T/U well-defined $\iff U \cap V$ invard T . (b) $\text{range } T/U = \text{range}(\pi \circ T) = (\text{range } T)/U$.

(c) T/U surj $\iff V = \text{range } T + U \cap V$. (d) $\text{null } T/U = (\text{null } T)/U$. (e) T/U inje $\iff \text{null } T/U \subseteq U$.

- (5.A.33) $\text{Supp } T \in \mathcal{L}(V)$. Prove $T/\text{range } T = 0$. By (b) or (d) above, immed.

SOLUS: $v + \text{range } T \in V/\text{range } T \Rightarrow v + \text{range } T \in \text{null}(T/\text{range } T)$. Thus $T/\text{range } T = 0$. \square

- (5.A.34) $\text{Supp } T \in \mathcal{L}(V)$. Prove $T/\text{null } T$ is inje $\Leftrightarrow \text{null } T \cap \text{range } T = \{0\}$.

SOLUS: NOTICE that $(T/\text{null } T)(u + \text{null } T) = Tu + \text{null } T = 0 \Leftrightarrow Tu \in \text{null } T \cap \text{range } T$.

Now $T/\text{null } T$ is inje $\Leftrightarrow u + \text{null } T = 0 \Leftrightarrow Tu = 0 \Leftrightarrow \text{null } T \cap \text{range } T = \{0\}$. \square

- **TIPS 3:** $\text{Supp } U, W$ are subsp of V and X is a subsp of $U \cap W$.

Prove U/W and $(U/X)/(W/X)$ are iso.

SOLUS: Let $U_X \oplus X = U, W_X \oplus X = W$. Becs $U/W = U_X/W$, and $U/X = U_X/X$.

Define $T \in \mathcal{L}((U_X/X)/(W/X), U_X/W)$ by $T((u_x + X) + W/X) = u_x + W$.

$\forall u_1, u_2 \in U_X$ suth $(u_1 + X) + W/X = (u_2 + X) + W/X \Rightarrow u_1 - u_2 + X \in W/X$

$\Rightarrow u_1 - u_2 \in X + W$ & $u_1, u_2 \in U_X \Rightarrow u_1 - u_2 \in W \Rightarrow u_1 + W = u_2 + W$. Now T is well-defined.

Inje: $\forall u_x \in U_X$ suth $u_x + W = 0 \Rightarrow u_x \in W_X \Rightarrow (u_x + X) \in W_X/X$.

Surj: $\forall u_x \in U_X, u_x + W = T((u_x + X) + W/X)$. Hence T is iso. \square

OR. Define $S \in \mathcal{L}(U_X/X, U_X)$ by $S(u_x + X) = u_x$. Becs $\forall u_1 + X = u_2 + X \in U_X/X$,

$u_1 - u_2 \in X$ & $u_1, u_2 \in U_X \Rightarrow u_1 = u_2$. Now S well-defined, and $S|_{W/X \cap U_X/X}^{(W/X)} = T$ defined above.

Becs $\text{range } S|_{W/X \cap U_X/X} \subseteq W$, and $U_X = \text{range } S \Rightarrow U_X \subseteq \text{range } S + W$. Well-defined. Surj.

For $u_x \in U_X, u_x + W = 0 \Leftrightarrow u_x \in U_X \cap W \Leftrightarrow u_x + X \in (U_X \cap W)/X = \text{null } S|_W$. Inje. \square

ENDED

3.F

- $\text{Supp } V = U_1 \oplus \dots \oplus U_m$, and each $V_k = \bigoplus_{i \in \Gamma_k} U_i$, where $\Gamma_k = \{1, \dots, n\} \setminus \{k\}$.

Prove $V' = V_1^0 \oplus \dots \oplus V_m^0 = [\bigcap_{k=1}^n [\bigoplus_{i \in \Gamma_k} U_i]]^0 = \bigoplus_{k=1}^n [\bigcap_{i \in \Gamma_k} U_i^0]$. \square

SOLUS: $\text{Supp } \varphi \in V'$. Define each $\varphi_k \in V_k^0$ by $\varphi_k(u_k) = \varphi(u_k)$ for all $u_k \in U_k$. Then $\varphi = \varphi_1 + \dots + \varphi_m$.

We use induc by k on m to show the directness of sum. (i) $k = 2$. $\psi \in V_1^0 \cap V_2^0 \Rightarrow \psi = 0$.

(ii) $k > 2$. Asum it holds for smaller k . Then $\psi \in (V_1^0 \oplus \dots \oplus V_{k-1}^0) \cap V_k^0 \Rightarrow \psi = 0$. \square

- 4 $\text{Supp } U$ is a subsp of $V \neq U$. Prove $U^0 \neq \{0\}$.

SOLUS: Let $X \oplus U = V \Rightarrow X \neq \{0\}$. $\text{Supp } s \in X \setminus \{0\}$. 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 $u \in U$. \square

OR. [Req V Finide] 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. \square

CORO: 19 $U^0 = \{0\} = V^0 \Leftrightarrow U = V$.

COMMENT: Another proof of [3.108]: T is surj $\Leftrightarrow T'$ is inje.

$\text{Supp } T'$ inje. Becs $\psi \neq 0 \Leftrightarrow T'(\psi) \neq 0 \Leftrightarrow \psi \notin (\text{range } T)^0$. & T surj $\Rightarrow (\text{range } T)^0 = \{0\} = \text{null } T'$. \square

- **NOTE FOR [3.102] and Exe (18):** For $U = \emptyset$, $U^0 = \{\varphi \in V' : U \subseteq \text{null } \varphi\} = V'$. While $\{0\}_V^0 = V'$.

Not a ctradic to Exe (21) becs \emptyset is not a subsp. Now $U^0 = V'$ can be true with $U = \emptyset \neq \{0\}$.

• **TIPS 1:** $\text{Supp } \varphi_1, \dots, \varphi_m \in V'$. Denote $[\text{null } \varphi_a \cap \dots \cap \text{null } \varphi_b]$ by $\bigcap_a^b \text{null } \varphi_I$.

$\text{Supp } \Omega$ is a subsp of V' . Denote $\{v \in V : \varphi(v) = 0, \forall \varphi \in \Omega\}$ by $C^0 \Omega$.

(a) Ω is infinide. By def, $\bigcap_{\varphi \in \Omega} \text{null } \varphi = C^0 \Omega$.

(b) $\Omega = \text{span}(\varphi_1, \dots, \varphi_m)$. Becs $v \in \bigcap_1^m \text{null } \varphi_I \iff \forall \varphi = \sum_{i=1}^n a_i \varphi_i \in \Omega, \varphi(v) = 0 \iff v \in C^0 \Omega$.

25 $\text{Supp } U$ is a subsp of V . Explain why $U = C^0 U^0$.

SOLUS: Asum $v \in C^0 U^0$ while $v \in V \setminus U$. Then let $\text{span}(v) \oplus U \oplus X = V$.

$\exists \varphi \in V', \text{null } \varphi = U \oplus X \Rightarrow \varphi \in U^0$. As $\varphi(v) = 0 \Rightarrow 0 \neq v \in \text{null } \varphi \cap \text{span}(v)$. Ctradic. \square

COMMENT: $X \subseteq W = \{v \in V : \varphi(v) = 0, \forall \varphi \in X^0\}$, the *promotion* of the subset X of V .

• $\text{Supp } U, W$ are subsps of V . Prove the promotion of $U \cup W$ is $U + W$.

SOLUS: $(U \cup W)^0 = \{\varphi \in V' : \varphi(u) = \varphi(w) = \varphi(u+w) = 0, \forall u \in U, w \in W\} = (U + W)^0$. \square

21 $\text{Supp } U, W$ are subsps of V . Prove $W^0 \subseteq U^0 \Rightarrow U \subseteq W$.

SOLUS: $\varphi \in W^0 \iff \text{null } \varphi \supseteq W \Rightarrow \text{null } \varphi \supseteq U \iff \varphi \in U^0$. Wrong becs generally $\exists \varphi \in V'$ with $\text{null } \varphi = W$.

$v \in U \Rightarrow \forall \varphi \in W^0 \subseteq U^0, \varphi(v) = 0 \Rightarrow v \in W$, by Exe (25). \square

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 $\text{Supp } U, W$ subsps of V . Prove $(U + W)^0 = U^0 \cap W^0$. Then $(U_1 + \dots + U_m)^0 = U_1^0 \cap \dots \cap U_m^0$.

SOLUS: (a) $\varphi \in (U + W)^0 \Rightarrow \forall u \in U, w \in W, \quad \left| \begin{array}{l} U \subseteq U + W \Rightarrow (U + W)^0 \subseteq U^0 \\ \varphi(u) = \varphi(w) = 0 \Rightarrow \varphi \in U^0 \cap W^0 \end{array} \right. \quad \left| \begin{array}{l} W \subseteq U + W \Rightarrow (U + W)^0 \subseteq W^0 \end{array} \right.$

(b) $\varphi \in U^0 \cap W^0 \subseteq V' \Rightarrow \forall u \in U, w \in W, \varphi(u+w) = 0 \Rightarrow \varphi \in (U + W)^0$. \square

37 $\text{Supp } U$ subsp of V , and π is the quot map. Thus $\pi' \in \mathcal{L}((V/U)', V')$.

(a) *Show π' is injc:* Becs π is surj. Use [3.108].

(b) *Show range $\pi' = U^0$:* By [3.109](b), $\text{range } \pi' = (\text{null } \pi)^0 = U^0$.

CORO: π' is iso.

SOLUS: (a) Or. $\pi'(\varphi) = 0 \iff \forall v \in V (\forall v+U \in V), \varphi(\pi(v)) = \varphi(v+U) = 0 \iff \varphi = 0$.

(b) Or. $\psi \in \text{range } \pi' \iff \exists \varphi \in (V/U)', \psi = \varphi \circ \pi \iff \text{null } \psi \supseteq U \iff \psi \in U^0$. \square

• $\text{Supp } U$ 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 $\tilde{\varphi}(v+U) = \varphi(v)$.

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: $\Phi \in (V/U)' \Rightarrow \forall u \in U, \Phi(u+U) = \Phi(0+U) = 0 \Rightarrow U \subseteq \text{null}(\Phi \circ \pi) \Rightarrow \xi(\Phi \circ \pi) = \Phi$.

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

23 $\text{Supp } U, W$ subsps of V . Prove $(U \cap W)^0 = U^0 + W^0$. Then $(U_1 \cap \dots \cap U_m)^0 = U_1^0 + \dots + U_m^0$.

SOLUS:

(a) $\varphi = \psi + \beta \in U^0 + W^0 \Rightarrow \forall v \in U \cap W, \quad \left| \begin{array}{l} \text{Or. } U \cap W \subseteq U \Rightarrow (U \cap W)^0 \supseteq U^0 \\ \varphi(v) = (\psi + \beta)(v) = 0 \Rightarrow \psi \in (U \cap W)^0 \end{array} \right. \quad \left| \begin{array}{l} U \cap W \subseteq W \Rightarrow (U \cap W)^0 \supseteq W^0 \end{array} \right.$

(b) [Req Finide] By Exe (22), $\dim(U^0 + W^0) = \dim V - \dim(U \cap W)$. \square

Or. Let $I = U \cap W$. We show $(U \cap W)^0 \subseteq U^0 + W^0$.

Define $\chi \in \mathcal{L}(V/I, V/U \times V/W)$ by $\chi : v + I \mapsto (v + U, v + W)$.

Well-defined: $v_1 + I = v_2 + I \in V/I \iff v_1 - v_2 \in I$

$$\iff v_1 - v_2 \in U \text{ and } v_1 - v_2 \in W \Rightarrow (v_1 + U, v_1 + W) = (v_2 + U, v_2 + W).$$

Inje: $(v + U, v + W) = 0 \iff v \in U \cap W = I \iff v + I = 0$.

Surj: $\forall v \in V$ suth $(v + U, v + W) \in V/U \times V/W$, becs $\emptyset \neq (v + U) \cap (v + W) = v + I \in V/I$.

Thus $\chi' \in \mathcal{L}((V/U \times V/W)', (V/I)')$ is iso. Now we find an iso of $U^0 \times W^0$ onto $(U \cap W)^0$.

By (3.E.4), $\text{supp } \xi : (V/U)' \times (V/W)' \rightarrow (V/U \times V/W)'$ is iso.

By (c) in Exe (37), $\text{supp } \Lambda_1 : U^0 \times W^0 \rightarrow (V/U)' \times (V/W)'$ and $\Lambda_2 : (V/I)' \rightarrow (U \cap W)^0$ are isos.

Hence $(\Lambda_2 \circ \chi' \circ \xi \circ \Lambda_1) : U^0 \times W^0 \rightarrow (U \cap W)^0$ is iso. Now we see how it works:

$\forall (\varphi_U, \varphi_W) \in U^0 \times W^0$, $\text{null } \pi_U \subseteq \text{null } \varphi_U \Rightarrow \exists \psi_U \in (V/U)', \psi_U \circ \pi_U = \varphi_U$, simlr for φ_W , thus $\Lambda_1 : (\varphi_U, \varphi_W) \mapsto (\psi_U, \psi_W)$. Then $\xi : (\psi_U, \psi_W) \mapsto (\psi_U S_U + \psi_W S_W)$, [See notats in (3.E.2).]

Now $(\psi_U S_U + \psi_W S_W) \xrightarrow{\chi'} (\psi_U S_U + \psi_W S_W) \circ \chi \xrightarrow{\Lambda_2} (\psi_U S_U + \psi_W S_W) \circ \chi \circ \pi_I$,

which sends v to $\psi_U(v + U) + \psi_W(v + W) = (\varphi_U + \varphi_W)(v)$, which is $\varphi_U + \varphi_W$.

Thus $(\Lambda_2 \circ \chi' \circ \xi \circ \Lambda_1)$ is the surj $\Lambda : U^0 \times W^0 \rightarrow U^0 + W^0$ defined in [3.77]. \square

Exa: Not true if U or W is merely a subset. Let $V = \mathbf{F}^2$, $U = \text{span}(e_1)$, $W = \{(1, 1), (0, 1)\}$.

• **CORO:** $V = U \oplus W \iff V' = U^0 \oplus W^0$.

• *Supp* $V = U \oplus W$. Define $\iota : V \rightarrow U$ by $\iota(u + w) = u$. Thus $\iota' \in \mathcal{L}(U', V')$.

(a) Show $\text{null } \iota' = \{0\}$: $\text{null } \iota' = (\text{range } \iota)_U^0 = U_U^0 = \{0\}$. Or. $\iota'(\psi) = \psi \circ \iota = 0 \iff U \subseteq \text{null } \psi$.

(b) Prove $\text{range } \iota' = W_V^0$: $\text{range } \iota' = (\text{null } \iota)_V^0 = W_V^0$. Now $\tilde{\iota}'$ is iso from U' onto W^0 .

SOLUS: (b) Or. Note that $W = \text{null } \iota \subseteq \text{null } (\psi \circ \iota)$. Then $\psi \circ \iota \in W^0 \Rightarrow \text{range } \iota' \in W^0$.

$\text{Supp } \varphi \in W^0$. Becs $\text{null } \iota = W \subseteq \text{null } \varphi$. By [3.B TIPS (3)], $\varphi = \varphi \circ \iota = \iota'(\varphi)$. \square

• *Supp* $V = U \oplus W$. Then $U^0 = \{\varphi \in V' : \varphi = \varphi \circ \iota\}$, where $\iota \in \mathcal{L}(V, W) : u_v + w_v \rightarrow w_v$.

NOTE: The notat $W'_V = \{\varphi \in V' : \varphi = \varphi \circ \iota\} = U^0$ is not well-defined [without a bss].

Simply becs W is not uniq. A bss of V' as precond would fix this. See NOTE FOR Exe (31).

Exa: Let $B_V = (e_1, e_2)$. Let $B_U = (e_1)$, $B_X = (e_2 - e_1)$, $B_Y = (e_2)$. Now by notat asum, $X'_V = Y'_V = U^0$.

(1) For $V = U \oplus X$, let $B_{U'_V} = (\varphi)$ with $\varphi : e_1 \mapsto 1, e_2 - e_1 \mapsto 0 \Rightarrow e_2 \mapsto 1$. Now $X^0 = U'_V$.

(2) For $V = U \oplus Y$, let $B_{U'_V} = (\psi)$ with $\psi : e_1 \mapsto 1, e_2 \mapsto 0$. Now $Y^0 = U'_V$.

COMMENT: *Supp* U is a subsp of V . Then finding the corres subsp in V' req another 'half' $W \in \mathcal{S}_V U$ to be uniq, while finding the corres subsp of V for a subsp of V' must have the another 'half' asumed as precond.

31 *Supp* V is finide and $B_{V'} = (\varphi_1, \dots, \varphi_n)$. Show $\exists ! B_V$ whose dual bss is the $B_{V'}$.

SOLUS: For each $k \in \{1, \dots, n\}$, let $\Gamma_k = \{1, \dots, n\} \setminus \{k\}$. Let each $U_k = \bigcap_{j \in \Gamma_k} \text{null } \varphi_j$.

By Exe (4E 23), $V' = \text{span}(\varphi_1, \dots, \varphi_n) = (\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_n)^0 \Rightarrow U_k \cap \text{null } \varphi_k = \{0\}$.

Thus $\forall x_k \in U_k \setminus \{0\}$, $x_k \notin \text{null } \varphi_k$ while $x_k \in \text{null } \varphi_j$ for all $j \in \Gamma_k$.

Fix one x_k and let $v_k = [\varphi_k(x_k)]^{-1} x_k \Rightarrow \varphi_k(v_k) = 1, \varphi_j(v_k) = 0$ for all $j \neq k$.

Simply for each v_k , $\varphi_j(v_k) = \delta_{j,k}$ for all $j \iff$ for each φ_j , $\varphi_j(v_k) = \delta_{j,k}$ for all k .

又 $a_1 v_1 + \dots + a_n v_n = 0 \Rightarrow$ each $\varphi_k(0) = a_k$.

Now we prove the uniques part. Supp the dual bss of $B'_V = (u_1, \dots, u_n)$ is the $B_{V'}$.

For each k , we have $\varphi_j(v_k) = \varphi_j(u_k)$ for all $k \Rightarrow v_k - u_k \in \bigcap_{j=1}^n \text{null } \varphi_j = \{0\}$. \square

- **NOTE FOR EXE (31):** Supp V is finide, and Ω is a subsp of V' with $B_\Omega = (\varphi_1, \dots, \varphi_m)$. The ' W ' is not clear when we are to find one suth $W'_V = \Omega$, becs the another 'half' is undefined. Extend to $B_V = (\varphi_1, \dots, \varphi_n)$. By EXE (31), $\exists!$ corres $B_V = (v_1, \dots, v_n)$. Let $B_U = (v_{m+1}, \dots, v_n)$. Let $B_W = (v_1, \dots, v_m)$. Thus $W'_V = \Omega$. Now W is well-defined with B_V as precond.

- **NOTE FOR EXE (1):** Every liney functional is either surj or is a zero map. Which means, for $\varphi \in V'$, $\varphi = 0 \iff \dim \text{span}(\varphi) = 0 \iff \dim \text{range } \varphi = 0$. And $\varphi \neq 0 \iff \dim \text{span}(\varphi) = 1 \iff \dim \text{range } \varphi = 1$. Thus $\dim \text{span}(\varphi) = \dim \text{range } \varphi$.

- (4E 23) *Supp V is finide, $\Omega = \text{span}(\varphi_1, \dots, \varphi_m) \subseteq V'$. Prove $\Omega = (\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m)^0$.*

SOLUS: Becs each $\text{span}(\varphi_k) \subseteq (\text{null } \varphi_k)^0$. By NOTE FOR EXE (1) and EXE (23), immed. \square

OR. Reduce to $B_\Omega = (\beta_1, \dots, \beta_p)$. We show $\Omega = (\text{null } \beta_1 \cap \dots \cap \text{null } \beta_p)^0$, then done by TIPS (2).

Let $B_V = (\beta_1, \dots, \beta_p, \gamma_1, \dots, \gamma_q) \Rightarrow B_V = (v_1, \dots, v_p, u_1, \dots, u_q)$, by EXE (31).

Define each $\Gamma_k = \{1, \dots, p\} \setminus \{k\}$. Then $\text{null } \beta_k = \text{span}\{v_j\}_{j \in \Gamma_k} \oplus \text{span}(u_1, \dots, u_q)$.

Now $(\text{null } \beta_1 \cap \dots \cap \text{null } \beta_p) = \text{span}(u_1, \dots, u_q)$, simlr to (4E 2.C.16).

$\text{Supp } \varphi = \sum_{i=1}^p a_i \beta_i + \sum_{j=1}^q b_j \gamma_j \in \text{span}(u_1, \dots, u_q)^0$. Then each $\varphi(u_k) = 0 = b_k$

Thus $(\text{null } \beta_1 \cap \dots \cap \text{null } \beta_p)^0 \subseteq \text{span}(\beta_1, \dots, \beta_p) = \Omega$. 又 Each $\text{span}(\beta_k) \subseteq (\text{null } \beta_k)^0$. \square

- **TIPS 2:** *Supp each $\varphi_i, \beta_j \in \mathcal{L}(V, W)$. $\text{Supp } \text{span}(\varphi_1, \dots, \varphi_m) = \text{span}(\beta_1, \dots, \beta_n)$.*

Prove $\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m = \text{null } \beta_1 \cap \dots \cap \text{null } \beta_n$.

SOLUS: Becs each $\beta_k \in \text{span}(\varphi_1, \dots, \varphi_m)$.

$\forall v \in \bigcap_1^m \text{null } \varphi_I, \beta_k(v) = 0$. Thus $\bigcap_1^m \text{null } \varphi_I \subseteq \bigcap_1^n \text{null } \beta_I$. Rev the roles and done. \square

COMMENT: $\text{Supp } (\varphi_1, \dots, \varphi_j)$ is a bss of $\text{span}(\varphi_1, \dots, \varphi_m)$. Let $N_k \oplus \bigcap_1^j \text{null } \varphi_I = \text{null } \varphi_k$.

Now $\bigcap_1^j \text{null } \varphi_I \cap (\text{null } \varphi_k) = \bigcap_1^j \text{null } \varphi_I$. Thus $\bigcap_1^m \text{null } \varphi_I = \bigcap_1^j \text{null } \varphi_I$.

又 $\beta_k \in \text{span}(\varphi_1, \dots, \varphi_j)$. Let $M_k \oplus \bigcap_1^j \text{null } \varphi_I = \text{null } \beta_k$. \square

26 Supp V is finide, Ω is a subsp of V' . Then get a B_Ω and by TIPS (1) and EXE (4E 23), $\Omega = (C^0 \Omega)^0$.

Exa: Immed, $\Omega \subseteq (C^0 \Omega)^0$. Now we give a countexa for $\Omega \supseteq (C^0 \Omega)^0$.

Let $V = \{(x_1, x_2, \dots) \in F^\infty : x_k \neq 0 \text{ for only finily many } k\}$. Then $V' = (F^\infty)'$.

Let $\Omega = \{\varphi \in \text{span}(\varphi_{\alpha_1}, \dots, \varphi_{\alpha_m}) : \exists m, \alpha_k \in N^+\} \subsetneq V'$. Then $C^0 \Omega = \{0\} \Rightarrow (C^0 \Omega)^0 = V'$.

CORO: Supp V is finide. For every subsp Ω of V' , $\exists!$ subsp U of V suth $\Omega = U^0$.

- **TIPS 3:** Let $B_{U^0} = (\varphi_1, \dots, \varphi_m), B_V = (\varphi_1, \dots, \varphi_n) \Rightarrow B_V = (v_1, \dots, v_n)$.

We show (a) $B_U = (v_{m+1}, \dots, v_n)$; (b) $U = \text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m$.

(a) Becs $\text{span}(v_{m+1}, \dots, v_n)^0 = \text{span}(\varphi_1, \dots, \varphi_m) = U^0$. Now by EXE (20, 21).

Or. Becs by (b), $U = \bigcap_1^m \text{null } \varphi_I = \text{span}(v_{m+1}, \dots, v_n)$.

(b) Each $\text{null } \varphi_k = \text{span}\{B_V \setminus \{v_k\}\} \Rightarrow \bigcap_1^m \text{null } \varphi_I = \text{span}(v_{m+1}, \dots, v_n)$. Now by (a).

Or. Becs $\text{span}(\varphi_1, \dots, \varphi_m) = U^0 = (\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m)^0$. Now by EXE (20, 21). \square

24 Prove, using the pattern of [3.104], that $\dim U + \dim U^0 = \dim V$.

SOLUS: By TIPS (3). Or. Let $B_U = (u_1, \dots, u_m), B_V = (u_1, \dots, u_m, v_1, \dots, v_n), B_{V'} = (\psi_1, \dots, \psi_m, \varphi_1, \dots, \varphi_n)$. $\text{Supp } \psi = \sum_{i=1}^m a_i \psi_i + \sum_{j=1}^n b_j \varphi_j \in U^0 \Rightarrow \text{each } \psi(u_k) = a_k = 0$. Thus $U^0 \subseteq \text{span}(\varphi_1, \dots, \varphi_n)$. \square

- $\text{Supp } T \in \mathcal{L}(V, W)$. Prove $\text{range } T' \supseteq (\text{null } T)^0$. [Another proof of [3.109](b)]

SOLUS: Let $V = U \oplus \text{null } T$. Let $R = (T|_U)^{-1}|_{\text{range } T}$. Define $\iota \in \mathcal{L}(V, U)$ by $\iota(u + w) = u$.

$$\forall \Phi \in (\text{null } T)^0, \text{ let } \psi = \Phi \circ R, \text{ then } T'(\psi) = \psi \circ T = \Phi \circ (R \circ T|_V) = \Phi \circ \iota = \Phi \in \text{range } T'. \quad \square$$

CORO: [3.108] and [3.110] hold without the hypo of finide. Now $T \text{ inv} \iff T' \text{ inv}$.

- Let $B_V = (v_1, \dots, v_n), B_{V'} = (\varphi_1, \dots, \varphi_n), B_W = (w_1, \dots, w_m), B_{W'} = (\psi_1, \dots, \psi_m)$.

- **TIPS 4:** Define $\Phi \in \mathcal{L}(V', V) : \varphi_k \mapsto v_k; \Psi \in \mathcal{L}(W, W') : w_j \mapsto \psi_j$.

Define $T \in \mathcal{L}(V, W)$ suth $\mathcal{M}(T, B_V, B_W) = A$. Let $S = \Phi T' \Psi \Rightarrow \mathcal{M}(S, B_W, B_V) = A^t$.

- **TIPS 5:** Define each $E_{j,k} \in \mathcal{L}(V, W) : v_x \mapsto \delta_{j,x} w_k$, and each $\exists_{k,j} \in \mathcal{L}(W', V') : \psi_x \mapsto \delta_{k,x} \varphi_j$.

Note that each $E'_{j,k}(\psi_x) = \psi_x \circ E_{j,k} = \delta_{k,x} \varphi_j = \exists_{k,j}(\psi_x) \Rightarrow E'_{j,k} = \exists_{k,j}$.

$\mathcal{L}(V, W) \ni \sum_{j=1}^n \sum_{k=1}^m A_{k,j} E_{j,k} \iff \sum_{j=1}^n \sum_{k=1}^m A_{k,j} \exists_{k,j} \in \mathcal{L}(W', V')$. Uniqlly by Exe (16).

- 6 Define $\Gamma : V' \rightarrow \mathbf{F}^m$ by $\Gamma(\varphi) = (\varphi(v_1), \dots, \varphi(v_m))$, where $v_1, \dots, v_m \in V$.

Show (a) $\text{span}(v_1, \dots, v_m) = V \iff \Gamma \text{ inj}$. (b) (v_1, \dots, v_m) liney indep $\iff \Gamma \text{ surj}$.

SOLUS: Let (e_1, \dots, e_m) be the std bss of \mathbf{F}^m .

(a) Becs $\Gamma(\varphi) = 0 \iff \varphi(v_1) = \dots = \varphi(v_m) = 0 \iff \text{null } \varphi = \text{span}(v_1, \dots, v_m)$. Immed.

(b) Supp Γ is surj. Let each $e_k = \Gamma(\varphi_k) \Rightarrow \varphi_k(v_j) = \delta_{j,k}$. Now $a_1 v_1 + \dots + a_m v_m = 0 \Rightarrow \text{each } a_k = \varphi_k(0)$.

Supp (v_1, \dots, v_m) is liney indep. Let $U = \text{span}(v_1, \dots, v_m), B_{U'} = (\psi_1, \dots, \psi_m)$. Let $W \oplus U = V$.

Define $\iota : u_v + w_v \mapsto u_v$. Each $\psi_k \circ \iota = \varphi_k \in V' \Rightarrow \varphi_k(v_j) = \psi_k(v_j) = \delta_{j,k} \Rightarrow \text{each } e_k = \Gamma(\varphi_k)$. \square

Or. Let (ψ_1, \dots, ψ_m) be dual bss of the std bss of \mathbf{F}^m . Define an iso $\Psi : \mathbf{F}^m \rightarrow (\mathbf{F}^m)'$ by $\Psi(e_k) = \psi_k$.

Define $T \in \mathcal{L}(\mathbf{F}^m, V)$ by $T e_k = v_k$. Now $T(x_1, \dots, x_m) = x_1 v_1 + \dots + x_m v_m$.

$\forall \varphi \in V', k \in \{1, \dots, m\}, [T'(\varphi)](e_k) = \varphi(T e_k) = \varphi(v_k) = [\varphi(v_1)\psi_1 + \dots + \varphi(v_m)\psi_m](e_k)$

Now $T'(\varphi) = \varphi(v_1)\psi_1 + \dots + \varphi(v_m)\psi_m = \Psi(\Gamma(\varphi))$. Hence $T' = \Psi \circ \Gamma$.

By (3.B.3), (a) $\text{range } T = \text{span}(v_1, \dots, v_m) = V \iff T \text{ inj} \iff \Gamma \text{ inj}$.

(b) (v_1, \dots, v_m) is liney indep $\iff T$ is inj $\iff T'$ surj $\iff \Gamma$ surj. \square

- (4E 25) Define $\Gamma : V \rightarrow \mathbf{F}^m$ by $\Gamma(v) = (\varphi_1(v), \dots, \varphi_m(v))$, where $\varphi_1, \dots, \varphi_m \in V'$.

Show (c) $\text{span}(\varphi_1, \dots, \varphi_m) = V' \iff \Gamma \text{ inj}$. (d) $(\varphi_1, \dots, \varphi_m)$ liney indep $\iff \Gamma \text{ surj}$.

SOLUS: Let (e_1, \dots, e_m) be the std bss of \mathbf{F}^m .

(c) Becs $\Gamma(v) = 0 \iff \varphi_1(v) = \dots = \varphi_m(v) = 0 \iff v \in (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m)$.

By Exe (4E 23), $\text{span}(\varphi_1, \dots, \varphi_m) = V' \iff \text{null } \Gamma = (\text{null } \varphi_1) \cap \dots \cap (\text{null } \varphi_m) = \{0\}$.

(d) Supp $(\varphi_1, \dots, \varphi_m)$ is liney indep. [Req Finide] Extend to $B_{V'} = (\varphi_1, \dots, \varphi_n)$.

By Exe (31), $B_V = (v_1, \dots, v_n)$ and each $\varphi_k(v_j) = \delta_{j,k} \Rightarrow \text{each } e_k = \Gamma(v_k)$.

Convly, let each v_k be suth $e_k = \Gamma(v_k) = (\varphi_1(v_k), \dots, \varphi_m(v_k))$. If $a_1 \varphi_1 + \dots + a_m \varphi_m = 0$. Immed.

Or. Let $U = \text{span}(v_1, \dots, v_m)$. Then $B_{U'} = (\varphi_1|_U, \dots, \varphi_m|_U) \Rightarrow (\varphi_1, \dots, \varphi_m)$ liney indep. \square

Or. Let (ψ_1, \dots, ψ_m) be dual bss of the std bss of \mathbf{F}^m . Define an iso $\Psi : \mathbf{F}^m \rightarrow (\mathbf{F}^m)'$ by $\Psi(e_k) = \psi_k$.

$\forall (x_1, \dots, x_m) \in \mathbf{F}^m, \Gamma'(\Psi(x_1, \dots, x_m)) = x_1 \varphi_1 + \dots + x_m \varphi_m$. Define $\Phi = \Gamma' \circ \Psi$. Thus by (3.B.3),

(c) $\Gamma \text{ inj} \iff \Gamma' \text{ surj} \iff \Phi \text{ surj} \iff (\varphi_1, \dots, \varphi_m)$ spanning V' . Simlr for (d). \square

- 34 Define $\Lambda : V \rightarrow \mathbf{F}^{V'}$ by $\Lambda v = \bar{v}$, and $\bar{v} \in V''$ by $\bar{v}(\varphi) = \varphi(v) \Rightarrow \Lambda \in \mathcal{L}(V, V'')$.

Show if $T \in \mathcal{L}(V)$, then $T'' \circ \Lambda = \Lambda \circ T$, where $T'' = (T')'$.

SOLUS: $(T'' \bar{v})(\varphi) = (\bar{v} \circ T')(\varphi) = \bar{v}(T'(\varphi)) = (\varphi \circ T)(v) = \bar{Tv}(\varphi) \Rightarrow T'' \bar{v} = \bar{Tv}$. \square

36 *Supp U is a subsp of V. Define $i : U \rightarrow V$ by $i(u) = u$. Thus $i' \in \mathcal{L}(V', U')$.*

(a) *Show $\text{null } i' = U^0$: $\text{null } i' = (\text{range } i)^0 = U^0 \Leftrightarrow \text{range } i = U$.*

(b) *Prove $\text{range } i' = U'$: $\text{range } i' = (\text{null } i)_U^0 = \{0\}_U^0 = U'$. CORO: \tilde{i}' is iso from V'/U^0 onto U'*

SOLUS: (a) OR. $\forall \varphi \in V', i'(\varphi) = \varphi \circ i = \varphi|_U$. Thus $i'(\varphi) = 0 \Leftrightarrow \forall u \in U, \varphi(u) = 0 \Leftrightarrow \varphi \in U^0$.

(b) OR. $\text{Supp } \psi \in U'$. By (3.A.11), $\exists \varphi \in V', \varphi|_U = \psi$. \square

ENDED

I Will Never Forget — In 3.E, naive but fantastical:

• **TIPS 1:** *Supp U is a subsp of V. Define $S \in \mathcal{L}(V/U, V)$ by $S(v + U) = v$. Badly defined.*

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 inj 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 $\mathcal{S}_V U$.

• **NOTE FOR Exe (13) and (4E 14):** Let $U \oplus W = V$. Define $S(w + U) = w$ as in 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 $V/U = W \Leftrightarrow V = U \oplus W, W = \text{range } S$. The uniqueness of Pure V/U follows from $\text{range } S$.

• **TIPS 2:** *Supp I is a subsp of U. Supp 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 $V = S_V U \oplus S_U I \oplus I$.

$\text{Supp } S_V I = \text{Pure } V/I$, simlr for $S_V U, S_U I$. Prove $S_V I = S_V U \oplus S_U I$.

SOLUS: $\forall v_i \in S_V I, v_i = v_u + u, \exists ! v_u \in S_V U, u \in U \Rightarrow \exists ! u_i \in S_U I, i \in I, v_i = v_u + u_i + i$.

As $v_i \in \text{Pure } V/I$. Hence $i = 0$, and $v_i \in S_V U \oplus S_U I$. Now becs $S_V U, S_U I \subseteq S_V I$. \square

• **TIPS 3:** *Supp T $\in \mathcal{L}(V, W)$ is inv, $V = M \oplus N$, $\text{range } T|_M = X, \text{range } T|_N = Y$.*

Then $W = \text{range } T = X \oplus Y$. Show Pure $V/M = N \Leftrightarrow \text{Pure } W/X = Y$.

SOLUS: Define $S_1 : V/M \rightarrow V$ and $S_2 : W/X \rightarrow W$ by $S_1 : v + M \mapsto v$ and $S_2 : w + X \mapsto w$.

Now $v = v_m + v_n \Leftrightarrow Tv = Tv_m + Tv_n$. We show $S_1(v + M) = v_n \Leftrightarrow S_2(Tv + X) = Tv_n$.

(a) $\text{Supp } S_2(Tv_n + X) = Tv'_n$. Then $Tv_n - Tv'_n \in X \Leftrightarrow v_n - v'_n = v'_m \in M, v = v'_n + (v'_m + v_m)$.

(b) $\text{Supp } S_1(v_n + M) = v'_n$. Then $v_n - v'_n \in M \Leftrightarrow Tv_n - Tv'_n = Tv'_m \in X, Tv = Tv'_n + (Tv'_m + Tv_m)$.

Hence by def, $\text{Pure } V/M = N \Leftrightarrow \text{Pure } W/X = Y$. \square

3.F.23 $\text{Supp } U \text{ and } W \text{ are subsps of } V$. Prove $(U \cap W)^0 \subseteq U^0 + W^0$.

SOLUS: Let $I = U \cap W$. Using TIPS (2). $\text{Supp } \varphi \in I^0$.

Now $S_V I = S_V U \oplus S_W I = S_V W \oplus S_W I$.

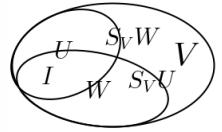
Let $\text{span}(x) = \text{Pure } V/\text{null } \varphi$. If $x = 0$ then done. $\text{Supp } 0 \neq x \in S_V I$.

Now $\exists! (u_v, i_u, w_v, i_w) \in S_V U \times S_U I \times S_V W \times S_W I$, $x = u_v + i_u = w_v + i_w$.

Define $\alpha \in U^0, \beta \in W^0$ by $\alpha : u_v \mapsto \varphi(u_v), u \mapsto 0$, and $\beta : i_u \mapsto \varphi(i_u), i \mapsto 0$,

for all $u \in \text{Pure } V/\text{span}(u_v)$ and $i \in \text{Pure } V/\text{span}(i_u)$. Or Define $\rho \in W^0, \gamma \in U^0$, simlr.

Then $\varphi = \alpha + \beta = \rho + \gamma \in U^0 + W^0$. □



- The def of Pure V/U is indeed ridic. To fix it, simply re-define Pure $V/U = U^\perp$, but may fail TIPS (3) and the weird solus of (3.F.23) above.

- NOTE:** $\text{Supp } U, W$ are subsps of finite V . Define $X'_V = (X^\perp)^0$ for all $X \subseteq V$. Then by [6.C TIPS (3,4)], $(U + W)'_V = ((U + W)^\perp)^0 = (U^\perp \cap W^\perp)^0 = U'_V + W'_V$, and simlr, $(U \cap W)'_V = U'_V \cap W'_V$.

- $\text{Supp } \text{span}(\varphi_1, \dots, \varphi_m) \subseteq V'$. Let each $\text{span}(u_k) \oplus \text{null } \varphi_k = V$.

Prove or give a counterexa: $\text{span}(u_1, \dots, u_m) \oplus (\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m) = V$.

SOLUS: Let $V = \mathbf{R}^2$. Define $\varphi_1 = \varphi_2 : (x, y) \mapsto x$. Let $u_1 = e_1, u_2 = e_1 + e_2 \Rightarrow \text{span}(u_1, u_2) = V$.

Or. Let $B_V = (\varphi_1, \varphi_2)$ be corres to the std bss. Let $u_1 = u_2 = e_1 + e_2 \Rightarrow \text{span}(u_1, u_2) \subsetneq V$. □

NOTE: $\text{Supp each } \text{span}(u_k) = (\text{null } \varphi_k)^\perp$. Then $\text{span}(u_1, \dots, u_m) = (\text{null } \varphi_1 \cap \dots \cap \text{null } \varphi_m)^\perp$.

ENDED

Exes about Sequences and Number Theory before Chapter 4

- (2.A.16) Prove the vecsp U of all continuous functions in $\mathbf{R}^{[0,1]}$ is infinite.

SOLUS: By [3.A NOTE FOR \mathbf{F}^S], immed. □

Or. Fix one $m \in \mathbf{N}^+$ and $p(x) = a_0 + a_1x + \dots + a_mx^m$ for $x \in [0, 1]$.

Then p has infly many roots and hence each coeff is zero, othws $\deg p \geq 0$, contradic [4.12].

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

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

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 (2.A.14). □

- (3.F.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 $\theta(\varphi) = (\varphi(1), \varphi(z), \dots, \varphi(z^m), \dots)$.

NOTICE that $\forall p \in \mathcal{P}(\mathbf{R})$, $\exists! c_i \in \mathbf{F}$, $m = \deg p$, $p(z) = c_0 + c_1z + \dots + c_m z^m \in \mathcal{P}_m(\mathbf{F})$.

Inje: $\theta(\varphi) = 0 \Rightarrow \forall p \in \mathcal{P}(\mathbf{F})$, $\varphi(p) = c_0\varphi(1) + c_1\varphi(z) + \dots + c_m\varphi(z^m) = 0$.

Surj: $\text{Supp } x = (x_0, x_1, \dots) \in \mathbf{F}^\infty$. Define $\psi_x(p) = x_0c_0 + \dots + x_m c_m \Rightarrow$ each $\psi_x(z^k) = x_k$.

$\forall p, q \in \mathcal{P}(\mathbf{F})$, $\text{supp } \deg p = m \geq n = \deg q$, [which is why we do not write $(p + \lambda q)$.]

$$\psi_x(\lambda p + \mu q) = \sum_{j=0}^n x_j(\lambda a_j + \mu b_j) + \sum_{k=1}^{m-n} x_{n+k} \lambda a_{n+k} = \lambda \psi_x(p) + \mu \psi_x(q).$$
□

COMMENT: $\mathcal{P}(\mathbf{F}), \mathbf{F}^\infty$ not iso $\Rightarrow \mathcal{P}(\mathbf{F}), (\mathcal{P}(\mathbf{F}))'$ not iso. But $\mathcal{P}(\mathbf{F})$ is iso to \mathbf{F}^N , see the 'U' in (3.E.14).

- (3.E.14) $\text{Supp } U = \{(x_1, x_2, \dots) \in \mathbf{F}^\infty : x_k \neq 0 \text{ for only finitely many } k\}$. Denote it by \mathbf{F}^N .

(a) Show U is a subsp of \mathbf{F}^∞ . [Do it in your mind] (b) Prove \mathbf{F}^∞/U is infinite.

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 $e_r[k] = \begin{cases} 1, & (k-1) \equiv 0 \pmod{r} \\ 0, & \text{othws} \end{cases}$ | 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 $a_1(e_1 + U) + \dots + a_m(e_m + U) = 0 + U \Rightarrow \exists u \in U, a_1e_1 + \dots + a_m e_m = u$.

$\text{Supp } u = (x_1, \dots, x_L, 0, \dots)$, 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 $p, r \in \{1, \dots, m\}$, $e_r[s \cdot m! + 1 + p] = e_r[p + 1] = 1 \Leftrightarrow p \equiv 0 \pmod{r} \Leftrightarrow r \mid p$.

Let $1 = p_1 \leq \dots \leq p_{\tau(p)} = p$ be the disti factors of p . Moreover, $r \mid p \Leftrightarrow r = p_k$ for some k .

Now $u[h+p] = 0 = \sum_{r=1}^m a_r e_r[p+1] = \sum_{k=1}^{\tau(p)} a_{p_k}$.

Let $q = p_{\tau(p)-1}$. Then $\tau(q) = \tau(p) - 1$, and each $q_k = p_k$. Again, $\sum_{r=1}^m a_r e_r[h+q] = 0 = \sum_{k=1}^{\tau(p)-1} a_{p_k}$.

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}^∞ . □

Or. For each $r \in \mathbf{N}^+$, let $e_r[p] = \begin{cases} 1, & \text{if } 2^r \mid p \\ 0, & \text{othws} \end{cases}$ | Simlr, let $m \in \mathbf{N}^+$ and $a_1(e_1 + U) + \dots + a_m(e_m + U) = 0 \Rightarrow a_1e_1 + \dots + a_m e_m = u \in U$.

$\text{Supp } L$ is the largest suth $u[L] \neq 0$. And l is suth $2^{ml} > L$. Then for each $k \in \{1, \dots, m\}$,

$u[2^{ml} + 2^k] = 0 = \sum_{r=1}^m a_r e_r[2^k] = a_1 + \dots + a_k$. Thus each $a_k = 0$. Simlr. □

Exes about Polys before Chapter 4

- (1.C.9) A function $f : \mathbf{R} \rightarrow \mathbf{R}$ is called periodic if $\exists p \in \mathbf{N}^+$, $f(x) = f(x + p)$ for all $x \in \mathbf{R}$. Is the set of periodic functions $\mathbf{R} \rightarrow \mathbf{R}$ a subspace of $\mathbf{R}^\mathbf{R}$? Explain.

SOLUS: Denote the set by S .

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

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

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

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

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

Or. Becs $\cos x + \sin \sqrt{2}x = \cos(x + p) + \sin(\sqrt{2}x + \sqrt{2}p)$. By diff twice,

$$\cos x + 2 \sin \sqrt{2}x = \cos(x + p) + 2 \sin(\sqrt{2}x + \sqrt{2}p).$$

$$\left. \begin{array}{l} \sin \sqrt{2}x = \sin(\sqrt{2}x + \sqrt{2}p) \\ \cos x = \cos(x + p) \end{array} \right\} \Rightarrow \text{Let } x = 0, p = \frac{m\pi}{\sqrt{2}} = 2k\pi. \text{ Ctradic.}$$
□

- (1.C.24) Let $V_E = \{f \in \mathbf{F}^\mathbf{R} : f \text{ is even}\}$, $V_O = \{f \in \mathbf{F}^\mathbf{R} : f \text{ is odd}\}$. Show $V_E \oplus V_O = \mathbf{F}^\mathbf{R}$.

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

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

- (2.C.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 (a) to a bss of $\mathcal{P}_4(\mathbf{F})$, and find a W suth $\mathcal{P}_4(\mathbf{F}) = U \oplus W$.

SOLUS: Using (2.C.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 $B = (1, (z-2)(z-5)(z-6), z(z-2)(z-5)(z-6))$.

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

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 $(1, z, z^2, (z-2)(z-5)(z-6), z(z-2)(z-5)(z-6))$.

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

- **NOTE FOR (2.C.10):** For each nonC $p \in \text{span}(1, z, \dots, z^m)$, \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

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

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

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

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

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

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

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

- (2.C.10) $\text{Supp } m \in \mathbf{N}^+$, $p_0, p_1, \dots, p_m \in \mathcal{P}(\mathbf{F})$ are such each $\deg p_k = k$.

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

OR. By comparing coeffs. Denote the coeff of x^k in $p \in \mathcal{P}(\mathbf{F})$ by $\xi_k(p)$.

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

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

- **TIPS:** $\text{Supp } m \in \mathbf{N}^+$, $p_0, p_1, \dots, p_m \in \mathcal{P}_m(\mathbf{F})$ 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 $\mathcal{P}_m(\mathbf{F}) = \text{span}(x^m, \dots, x, 1) = \text{span}(p_m, \dots, p_1, p_0)$. \square

OR. By comparing coeffs. Denote the coeff of x^k in $p \in \mathcal{P}(\mathbf{F})$ by $\xi_k(p)$.

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

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 $L = a_{k+1} p_{k+1}(x) + \dots + a_m p_m(x)$. \square

- **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 notation convenience. 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 2.C.10) Supp m is a positi 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.

$$\text{Note that each } p_k(x) = \sum_{j=0}^{m-k} C_{m-k}^j (-1)^j \cdot x^{j+k} \cdot 1^j = \underbrace{(-1)^0 \cdot x^k \cdot 1^0}_{\text{of deg } k} + \underbrace{\sum_{j=1}^{m-k} C_{m-k}^j (-1)^j \cdot x^{j+k} \cdot 1^j}_{\text{of deg } m; \text{ denote it by } q_k(x)}$$

And, each $q_k \in \text{span}(x^{k+1}, \dots, x^m)$. Using TIPS above. \square

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- (3.D.19) Supp $T \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ is inj. And $\deg Tp \leq \deg p$ for every non0 $p \in \mathcal{P}(\mathbf{R})$.

$$(a) \text{Prove } T \text{ is surj.} \quad (b) \text{Prove for every non0 } p, \deg Tp = \deg p.$$

SOLUS: (a) T is inj $\iff \forall n \in \mathbf{N}^+, T|_{\mathcal{P}_n(\mathbf{R})} \in \mathcal{L}(\mathcal{P}_n(\mathbf{R}))$ is inj, so is inv $\iff T$ is surj.

$$(b) (i) \deg p = -\infty \geq \deg Tp \iff p = 0 = Tp. \text{ And } \deg p = 0 \geq \deg Tp \iff p = C \neq 0.$$

$$(ii) \text{Asum } \forall s \in \mathcal{P}_n(\mathbf{R}), \deg s = \deg Ts. \text{ We show } \forall p \in \mathcal{P}_{n+1}(\mathbf{R}), \deg Tp = \deg p \text{ by ctradic.}$$

$$\text{Supp } \exists r \in \mathcal{P}_{n+1}(\mathbf{R}), \deg Tr \leq n < n+1 = \deg r. \text{ By (a), } \exists s \in \mathcal{P}_n(\mathbf{R}), T(s) = (Tr).$$

$$\text{又 } T \text{ is inj } \Rightarrow s = r. \text{ While } \deg s = \deg Ts = \deg Tr < \deg r. \text{ Ctradic.} \quad \square$$

- (3.B.26) $\text{Supp } D \in \mathcal{L}(\mathcal{P}(\mathbf{R}))$ and $\forall p, \deg(Dp) = (\deg p) - 1$. Prove $D \in \mathcal{P}(\mathbf{R})$ is surj.

SOLUS: [D might not be $D : p \mapsto p'$.] The proof here is too informal to be valid:

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

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

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

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

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

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

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

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

(ii) Supp 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 $D(x^{n+2}) = a_{n+1}x^{n+1} + a_nx^n + \dots + a_1x + a_0$, 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 $Dp_{n+1} = x^{n+1}$. \square

- $\text{Supp } V = \mathbf{R}^{\mathbf{R}}$ with a subsp $U = \{f \in \mathbf{R}^{\mathbf{R}} : f(x_1) = \dots = f(x_m) = 0\}$, where each $x_k \in \mathbf{R}$.

Prove if $W \in \mathcal{S}_V U$, then $\dim W = m$.

Hint: Find an iso from V/U onto \mathbf{R}^m .

SOLUS: Define $T \in \mathcal{L}(V/U, \mathbf{R}^m)$ by $T(f + U) = (f(x_1), \dots, f(x_m))$.

$\forall f + U = g + U \in V/U, f - g \in U \Rightarrow f(x_k) = g(x_k)$. Well-defined.

Inje: Each $f(x_k) = 0 \Rightarrow f + U = 0$. Surj: Immed. \square

- (3.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 $\varphi_k(p) = \frac{p^{(k)}(0)}{k!}$.

SOLUS: The uniqueness of dual bss is guaranteed by [3.5].

$$\text{For } j, k \in \mathbf{N}, (x^j)^{(k)} = \begin{cases} j(j-1)\dots(j-k+1) \cdot x^{(j-k)}, & j \geq k. \\ j(j-1)\dots(j-j+1) = j!, & j = k. \\ 0, & j \leq k. \end{cases} \Rightarrow (x^j)^{(k)}(0) = \begin{cases} 0, & j \neq k. \\ k!, & j = k. \end{cases} \square$$

Exa: By [2.C.10], $B_m = (1, 7x - 5, \dots, (7x - 5)^m)$ is a bss of $\mathcal{P}_m(\mathbf{R})$. Let each $\varphi_k = \frac{p^{(k)}(5/7)}{7^k \cdot k!}$.

ENDED

4

- **TIPS 1:** *Supp $p \in \mathcal{P}_n(\mathbf{F})$ has at least $n + 1$ disti zeros. Then by the ctrapos of [4.12], $\deg p < 0 \Rightarrow p = 0$.*

Or. We show if $p \in \mathcal{P}(\mathbf{F})$ has at least m disti zeros, then either $p = 0$ or $\deg p \geq m$.

Becs $\exists! \alpha_i \geq 1, q \in \mathcal{P}(\mathbf{F}), p(z) = [(z - \lambda_1)^{\alpha_1} \cdots (z - \lambda_m)^{\alpha_m}]q(z)$. \square

[*Another proof of [4.7]*] If a poly had two different sets of coeffs, then subtracting the two exprs would give a poly with some non0 coeffs but infly many zeros.

- **NOTE FOR [4.8]:** *div algo for polys* [*Another proof*]

Supp $\deg p \geq \deg s$. Then $(1, z, \dots, z^{\deg s-1}, \overbrace{s, zs, \dots, z^{\deg p-\deg s}s}^{\text{of len } (\deg p - \deg s + 1)})$ is a bss of $\mathcal{P}_{\deg p}(\mathbf{F})$.

$$p(z) = a_0 + a_1 z + \cdots + a_{\deg s-1} z^{\deg s-1} + s(z) [b_0 + b_1 z + \cdots + b_{\deg p-\deg s} z^{\deg p-\deg s}]. \quad \square$$

- **NOTE FOR [4.11]:** *each zero of a poly corres to a deg-one factor;* [*Another proof*]

First supp $p(\lambda) = 0$. Write $p(z) = a_0 + a_1 z + \cdots + a_m z^m, \exists! a_0, a_1, \dots, a_m \in \mathbf{F}$ for all $z \in \mathbf{F}$.

Then $p(z) = p(z) - p(\lambda) = a_1(z - \lambda) + \cdots + a_m(z^m - \lambda^m)$ for all $z \in \mathbf{F}$.

Hence $\forall k \in \{1, \dots, m\}, z^k - \lambda^k = (z - \lambda)(z^{k-1}\lambda^0 + z^{k-2}\lambda^1 + \cdots + z^{k-(j+1)}\lambda^j + \cdots + z\lambda^{k-2} + z^0\lambda^{k-1})$.

Thus $p(z) = \sum_{j=1}^m a_j(z - \lambda) \sum_{i=1}^k \lambda^{i-1} z^{k-i} = (z - \lambda) \sum_{j=1}^m a_j \sum_{i=1}^k \lambda^{i-1} z^{k-i} = (z - \lambda)q(z)$. \square

- 5 *Supp $m \in \mathbf{N}$, 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 $Tq = (q(z_1), \dots, q(z_m), q(z_{m+1}))$.

Becs $Tq = 0 \Rightarrow (m+1)$ disti zeros for q of deg no more than $m \Rightarrow q = 0$. Now T iso. \square

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} .

Now $Tp_1 = (1, \dots, 1), Tp_k = \left(\prod_{i=1}^{k-1} (z_1 - z_i), \dots, \prod_{i=1}^{k-1} (z_j - z_i), \dots, \prod_{i=1}^{k-1} (z_{m+1} - z_i) \right)$;

$$\begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & A_{2,2} & 0 & \cdots & 0 \\ 1 & A_{3,2} & A_{3,3} & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 1 & A_{m+1,2} & A_{m+1,3} & \cdots & A_{m+1,m+1} \end{pmatrix} \quad \begin{array}{l} \text{And } \prod_{i=1}^{k-1} (z_j - z_i) = 0 \iff j \leq k-1, \text{ becs } z_1, \dots, z_{m+1} \text{ are disti.} \\ = \mathcal{M}(T, B_p, B_e). \text{ Where } A_{j,k} = \prod_{i=1}^{k-1} (z_j - z_i) \neq 0 \text{ for all } j > k-1 \geq 1. \end{array}$$

Now the rows of $\mathcal{M}(T)$ liney indep. By (4E 3.C.17) OR (3.F.32). \square

- 6 *Supp non0 $p \in \mathcal{P}_m(\mathbf{C})$ with $\deg p = m > 1$.*

Prove [P] p has m disti zeros $\iff p$ and p' have no common zeros. [Q]

SOLUS: (a) Supp [P] holds. Write $p(z) = c(z - \lambda_1) \cdots (z - \lambda_m)$.

For each $j \in \{1, \dots, m\}$, let $q_j(z)(z - \lambda_j) = p(z) \Rightarrow q_j(\lambda_j) \neq 0$.

Now $p'(z) = (z - \lambda_j)q_j(z) + q_j(z) \Rightarrow p'(\lambda_j) = q_j(\lambda_j) \neq 0$.

Or. $\neg Q \Rightarrow \neg P : \text{Supp } p(z) = (z - \lambda)q(z), p'(z) = (z - \lambda)r(z)$.

Becs $p'(z) = (z - \lambda)q'(z) + q(z) \Rightarrow p'(\lambda) = q(\lambda) = 0 \Rightarrow q(z) = (z - \lambda)s(z)$.

(b) $\neg P \Rightarrow \neg Q : \text{Becs } 0 \neq p \in \mathcal{P}_m(\mathbf{C}). \text{ Supp all disti zeros are } \lambda_1, \dots, \lambda_M, \text{ with } M < m$.

By Pigeon Hole Principle, $(z - \lambda_k)^2 q(z) = p(z)$ for some $\lambda_k \Rightarrow p'(\lambda_k) = 0 = p(\lambda_k)$. \square

NOTE: If $\mathbf{F} = \mathbf{R}$. Then replace “ m disti zeros” with “ m disti zeros in \mathbf{C} ” and the result still holds.

8 $\text{Supp } p \in \mathcal{P}(\mathbf{R})$. Let $(Tp)(x) = \begin{cases} \frac{p(x)-p(3)}{x-3} & \text{if } x \neq 3, \\ p'(3) & \text{if } x = 3. \end{cases}$ Show $Tp \in \mathcal{P}(\mathbf{R})$.

SOLUS:

NOTICE that $\exists! q \in \mathcal{P}(\mathbf{R})$, $p(x) - p(3) = (x-3)q(x)$. For $x \neq 3$, $q(x) = \frac{p(x)-p(3)}{x-3}$.
 $p'(x) = (p(x) - p(3))' = q(x) + (x-3)q'(x)$. For $x = 3$, $q(3) = p'(3)$. Now $Tp = q$. \square

- $\text{Supp non0 } p, q \in \mathcal{P}(\mathbf{F})$ are multi of each other. Prove $p = cq$ for a $c \neq 0$.

SOLUS: Let $p = rq$, $q = sp \Rightarrow p = rsp \Rightarrow r(z)s(z) = 1$ for all z with $p(z) \neq 0$.

Thus $(rs)(z) = 1$ for infily many z , so for all z . Now $\deg rs = 1 = \deg r + \deg s$. \square

- **TIPS 2:** $\text{Supp } \alpha, \beta \in \mathbf{N}^+, \alpha \geq \beta$. Show $p(z) = (z-\lambda)^\alpha q(z) \Rightarrow p^{(\beta)}(z) = (z-\lambda)^{\alpha-\beta} s(z)$.

SOLUS: By induc on β . Immed. Or. By (L1), $[(z-\lambda)^\alpha q(z)]^{(\beta)} = \sum_{j=0}^{\beta} C_\beta^j [(z-\lambda)^\alpha]^{(j)} [q(z)]^{(\beta-j)}$.

Note that $[(z-\lambda)^\alpha]^{(j)} = [\alpha(\alpha-1)\cdots(\alpha-j+1)](z-\lambda)^{(\alpha-j)}$ for all $j \in \{0, \dots, \alpha\}$. \square

- (4E 13) $\text{Supp nonC } p, q \in \mathcal{P}(\mathbf{C})$ 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 inj.

CORO: $\exists! r \in \mathcal{P}_{n-1}(\mathbf{C}), s \in \mathcal{P}_{m-1}(\mathbf{C})$ suth $rp + sq = 1$.

SOLUS: Immed, T is liney. $\text{Supp } T(r, s) = rp + sq = 0$.

Then $rp = -sq$. Becs p, q are coprime $\Rightarrow p \mid s$, while $\deg s \leq m-1 \Rightarrow s = 0 \Rightarrow r = 0$. \square

Or. Let $\lambda_1, \dots, \lambda_M$ and μ_1, \dots, μ_N be the disti zeros of p and q respectively. NOTICE that $M \leq m, N \leq n$.

By the ctrapos of [4.13], $M = 0 \iff m = 0 \Rightarrow s = 0 \iff r = 0 \iff n = 0 \iff N = 0$.

Now supp $M, N \geq 1$. We show $s = 0$. Simlr for $r = 0$. Or. $s = 0 \Rightarrow r = 0$.

Write $p(z) = a(z-\lambda_1)^{\alpha_1} \cdots (z-\lambda_M)^{\alpha_M}$. Let $\max\{\alpha_1, \dots, \alpha_M\} = A = \alpha_L$.

For each $D \in \{0, 1, \dots, A-1\}$, let $I_{>D} = \{I_{D,1}, \dots, I_{D,J_D}\}$ be suth each $\alpha[I_{D,j}] = \alpha_{I_{D,j}} \geq D+1$.

Now $\{L\} = I_{>A-1} \subseteq \dots \subseteq I_{>0} = \{1, \dots, M\}$. Becs $rp + sq = 0 \Rightarrow (rp + sq)^{(k)} = 0$ for all $k \in \mathbf{N}^+$.

We use induc on D to show $s^{(D)}(\lambda[I_{D,j}]) = 0$ for each $D \in \{0, \dots, A-1\}$.

NOTICE that by TIPS (2), $p^{(D)}(\lambda[I_{D,j}]) = 0$ for each $D \in \{0, \dots, A-1\}$ and each $I_{D,j} \in I_{>D}$.

(i) $D = 0$. Each $(rp + sq)(\lambda[I_{0,j}]) = (sq)(\lambda[I_{0,j}]) = s(\lambda[I_{0,j}]) = 0$. Where $q(\lambda[I_{0,j}]) \neq 0$.

$D = 1$. Each $(r'p + rp')(\lambda[I_{1,j}]) + (s'q + sq')(\lambda[I_{1,j}]) = (s'q)(\lambda[I_{1,j}]) = s'(\lambda[I_{1,j}]) = 0$.

Where $p'(\lambda[I_{1,j}]) = 0$, and each $I_{1,j} \subseteq I_{0,j} \Rightarrow s(\lambda[I_{1,j}]) = 0$.

(ii) $2 \leq D \leq A-1$. Asum $s^{(d)}(\lambda[I_{d,j}]) = 0$ for each $d \in \{0, 1, \dots, D-1\}$ and each $\lambda[I_{d,j}] \in I_{>d}$.

$$\begin{aligned} \text{Each } [rp + sq]^{(D)}(\lambda[I_{D,j}]) &= [C_D^D r^{(D)} p^{(0)} + \dots + C_D^d r^{(d)} p^{(D-d)} + \dots + C_D^0 r^{(0)} p^{(D)}](\lambda[I_{D,j}]) \quad (\text{L1}) \\ &\quad + [C_D^D s^{(D)} q^{(0)} + \dots + C_D^d s^{(d)} q^{(D-d)} + \dots + C_D^0 s^{(0)} q^{(D)}](\lambda[I_{D,j}]) \\ &= [C_D^D s^{(D)} q^{(0)}](\lambda[I_{D,j}]). \text{ Where each } \lambda[I_{D,j}] \in I_{>D} \subseteq I_{D-1,\alpha}. \end{aligned}$$

Hence $s^{(D)}(\lambda[I_{D,j}]) = 0$. 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 common zeros $\{\lambda[I_{k+1,1}], \dots, \lambda[I_{k+1,J_{k+1}}]\}$.

Now $\forall D \in \{1, \dots, A-1\}$, $s = s^{(0)}, \dots, s^{(D)}$ have common zeros $\{\lambda[I_{D,1}], \dots, \lambda[I_{D,J_D}]\}$.

Thus $s(z)$ is div by $(z-\lambda[I_{D,1}])^{\alpha[I_{D,1}]} \cdots (z-\lambda[I_{D,J_D}])^{\alpha[I_{D,J_D}]}$, for each $D \in \{0, \dots, A-1\}$.

Hence $s(z) = [(z-\lambda_1)^{\alpha_1} \cdots (z-\lambda_M)^{\alpha_M}] s_0(z)$, while $\deg s < m = \alpha_1 + \dots + \alpha_M$. Now by TIPS (1). \square

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 on $k \in \mathbf{N}^+$. (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 $(pq)^{(k-1)} = C_{k-1}^{k-1} p^{(k-1)} q^{(0)} + \dots + C_{k-1}^j p^{(j)} q^{(k-1-j)} + \dots + C_{k-1}^0 p^{(0)} q^{(k-1)}$.

$$\begin{aligned} \text{Now } (pq)^{(k)} &= ((pq)^{(k-1)})' = \left(\sum_{j=0}^{k-1} C_{k-1}^j p^{(j)} q^{(k-j-1)} \right)' = \sum_{j=0}^{k-1} \left[C_{k-1}^j \left(p^{(j+1)} q^{(k-j-1)} + p^{(j)} q^{(k-j)} \right) \right] \\ &= \left[C_{k-1}^0 \left(\underbrace{p^{(1)} q^{(k-1)}} + \boxed{p^{(0)} q^{(k)}} \right) \right] + \left[C_{k-1}^1 \left(p^{(2)} q^{(k-2)} + \underbrace{p^{(1)} q^{(k-1)}} \right) \right] \\ &\quad + \dots + \left[C_{k-1}^{j-2} \left(\underbrace{p^{(j-1)} q^{(k-j+1)}} + p^{(j-2)} q^{(k-j+2)} \right) \right] + \left[C_{k-1}^{j-1} \left(\underbrace{p^{(j)} q^{(k-j)}} + \underbrace{p^{(j-1)} q^{(k-j+1)}} \right) \right] \\ &\quad + \left[C_{k-1}^j \left(\underbrace{p^{(j+1)} q^{(k-j-1)}} + \underbrace{p^{(j)} q^{(k-j)}} \right) \right] + \left[C_{k-1}^{j+1} \left(p^{(j+2)} q^{(k-j-2)} + \underbrace{p^{(j+1)} q^{(k-j-1)}} \right) \right] \\ &\quad + \dots + \left[C_{k-1}^{k-2} \left(\underbrace{p^{(k-1)} q^{(1)}} + p^{(k-2)} q^{(2)} \right) \right] + \left[C_{k-1}^{k-1} \left(\boxed{p^{(k)} q^{(0)}} + \underbrace{p^{(k-1)} q^{(1)}} \right) \right]. \end{aligned}$$

Hence $(pq)^{(k)} = C_k^0 p^{(0)} q^{(k)} + \dots + [C_{k-1}^j + C_{k-1}^{j-1}] (p^{(j)} q^{(k-j)}) + \dots + C_k^k p^{(k)} q^{(0)}$. □

ENDED

凭借我的经验，我认为，好的自学教材，除了提供足够的一级知识外，还能通过各种方式，将二级、三级知识顺理成章地经过学科思维的浓缩喻于习题或课文中。在 LADR 的熏陶下，我渐渐认为，自学教材带来的长期收益更重要——所谓素养一类的隐形东西，无论堆砌多少知识记忆都难以学到；外在的选拔，表面上看都是知识竞赛，但真正有含金量的选拔，往往十二分地注重隐性能力；实际的工作表现也是如此；客观上看这确实是在当今公共信息过剩的时代下人与人拉开差距的核心原因之一，也是我相信最能仅通过自身努力耕耘获得长期稳定回报的地方。现在看看速学速成应付选拔竞争的选择有多愚蠢吧：考不上放弃吧，因为几乎没有习得那些隐性能力，就确实是除了知识和解题技巧之外啥也没得到，这些知识中实用的那些内容怎么着都能学到，不具有不可替代性，实际工作更需要隐形的素养；再考再战吧，就得辛苦刷题，总归不如在学的过程中把“和习题的挣扎”当作练习对学科思维的启发最好。考上了吧又要和更“拔尖创新人才”竞争隐形的能力，一样难以优胜，只不过这个情况下可以做一个更“优越”的平庸之人罢了，除了短期速成而来的外在“纪念品”之外再也没有什么学习成果可长期变现——和质量至上、不怕耽误时间进度的学习者相比又能有什么优越之处呢？

此章核心内容 3/4e 差距过大。4e 将第 2 章线性相关性引理和多项式结合，更自然地引出原来 3e 的 8.C 节的极小多项式，并前置了相关习题，让定理和习题更加富有动机和系统性。这份笔记主要面向 3e 纸质书的读者，所以题号和定理索引都采用 3e (除 4e 新增章节)。为了严密性，我决定将 3e 第 8 章提前到第 5 章后，对应到 4e 只有第 8 章前三节。

5.A

注意: 这里将 5.B 节多项式作用于算子部分与 5.C 节的本征空间的定义前置.

- TIPS 1: $\text{Supp } V = U \oplus W$ and U, W inward $T \in \mathcal{L}(V)$. Prove $\text{null } T|_U \oplus \text{null } T|_W = \text{null } T$.

SOLUS: $\forall v = u + w \in \text{null } T, Tv = Tu + Tw = 0 \Rightarrow Tu, Tw = 0 \Rightarrow v \in \text{null } T|_U \oplus \text{null } T|_W$. \square

CORO: $E(\lambda, T) = E(\lambda, T|_U) \oplus E(\lambda, T|_W)$. Replace T with $T - \lambda I$, immed.

- NOTE FOR EXE (2, 3): $ST = TS \Rightarrow p(S)q(T) = q(T)p(S)$. And $\text{null } q(T), \text{range } q(T)$ inward $p(S)$.

- (5.E.1) Give $S, T \in \mathbf{F}^4$ such $ST = TS$ while \exists invars pd S but not T , invars pd T but not S .

SOLUS: Define $S: (x, y, z, w) \mapsto (y, x, 0, 0)$ and $T: (x, y, z, w) \mapsto (0, 0, w, z) \Rightarrow TS = ST = 0$.

Thus e_1, e_2 are eigvecs of T but not of S , and e_3, e_4 are eigvecs of S but not of T .

- 10 Define $T \in \mathcal{L}(\mathbf{F}^n)$ by $T(x_1, x_2, x_3, \dots, x_n) = (x_1, 2x_2, 3x_3, \dots, nx_n)$.

Find all invarsps of V under T . Let (e_1, \dots, e_n) be the std bss of \mathbf{F}^n . Let each $E_k = \text{span}(e_k)$.

SOLUS: The eigvals are $\{1, \dots, n\}$ of len $\dim \mathbf{F}^n$. The set of all eigvecs is $(E_1 \cup \dots \cup E_n) \setminus \{0\}$.

$\text{Supp } U$ is invarsp. Then $u = (x_1, x_2, \dots, x_n) \in U \Rightarrow Tu = (x_1, 2x_2, \dots, x_n) \in U$.

And $Tu - u = (0, x_2, 2x_3, \dots, (n-1)x_n) \in U \Rightarrow \dots \Rightarrow (0, \dots, 0, x_n) \Rightarrow$ each $x_k e_k \in U$.

Get a B_U and pick/count all possible non0 x_k . Forming $\text{span}(e_{k_1}, \dots, e_{k_m}) = U$. \square

COMMENT: The result (b) holds generally where $\exists B_V$ consists of eigvecs of T .

- $\text{Supp } T \in \mathcal{L}(V), \lambda_1, \dots, \lambda_m$ are the disti eigvals corres v_1, \dots, v_m , and U invars pd T .

- TIPS 2: $\text{Supp } v_1 + \dots + v_m \in U$. Prove each $v_k \in U$.

SOLUS: Consider the stmt $P(k)$: if $v_1 + \dots + v_k \in U$, then each $v_j \in U$.

(i) $v_1 \in U$. $P(1)$ holds. (ii) For $2 \leq k \leq m$. Asum $P(k-1)$ holds. $\text{Supp } v = v_1 + \dots + v_k \in U$.

Then $Tv = \lambda_1 v_1 + \dots + \lambda_k v_k \in U \Rightarrow Tv - \lambda_k v = (\lambda_1 - \lambda_k)v_1 + \dots + (\lambda_{k-1} - \lambda_k)v_{k-1} \in U$.

For each $j \in \{1, \dots, k-1\}, \lambda_j - \lambda_k \neq 0 \Rightarrow (\lambda_j - \lambda_k)v_j = v'_j$ 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 $v_k = v - v_1 - \dots - v_{k-1} \in U$. \square

- TIPS 3: $\text{Supp } V = E(\lambda_1, T) \oplus \dots \oplus E(\lambda_m, T)$. Prove $U = E(\lambda_1, T|_U) \oplus \dots \oplus E(\lambda_m, T|_U)$.

SOLUS: Becs $\forall u \in U, \exists! v_j \in E(\lambda_j, T), v = v_1 + \dots + v_m$. By TIPS (2), each $v_j \in U$. \square

- TIPS 4: $\text{Supp } T \in \mathcal{L}(\mathbf{R}^2)$ is the countclockws rotat by $\theta \in \mathbf{R}$. Define $\mathcal{C}(a, b) = a + ib$.

Becs $(\cos \theta + i \sin \theta)(a + ib) = r(\cos(\alpha + \theta) + i \sin(\alpha + \theta))$.

Hence $T(a, b) = (a \cos \theta - b \sin \theta, a \sin \theta + b \cos \theta)$. Now $\mathcal{M}(T) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$.

- 19 $\text{Supp } n \in \mathbf{N}^+$. Define $T \in \mathcal{L}(\mathbf{F}^n)$ by $T(x_1, \dots, x_n) = (x_1 + \dots + x_n, \dots, x_1 + \dots + x_n)$.

Find all eigvals and eigvecs of T .

SOLUS: $\text{Supp } x_k \neq 0$ and $T(x_1, \dots, x_n) = (\lambda x_1, \dots, \lambda x_n) = (x_1 + \dots + x_n, \dots, x_1 + \dots + x_n)$.

Then (I) $\lambda = 0 \Rightarrow x_1 + \dots + x_n = 0$. If $n > 1$, then $\lambda = 0$ is eigval; othws not, becs $T = I$.

(II) $\lambda \neq 0 \Rightarrow x_1 = \dots = x_n \Rightarrow \lambda x_k = nx_k$. Now n is eigval. \square

To show no other eigvals. Note that $\text{range } T = \{(x, \dots, x) \in \mathbf{F}^n\}$ of dim 1. By Exe (29). \square

Or. $\text{Supp } n > 1$, and non0 $x \neq 0$ with $Tx = \lambda x$. Becs $\exists! \alpha \in \text{range } T, \lambda x = \alpha$.

Now x corres λ and α corres n are liney dep. By the ctrapos of [5.10], $\lambda = n$. \square

20 Define $S \in \mathcal{L}(\mathbf{F}^\infty)$ by $S(z_1, z_2, z_3, \dots) = (z_2, z_3, \dots)$.

Show every elem of \mathbf{F} is an eigval of S , and find all eigvecs of S .

SOLUS: Supp $z_k \neq 0$ and $S(z_1, z_2, \dots) = (\lambda z_1, \lambda z_2, \dots) = (z_2, z_3, \dots)$. Then each $\lambda z_k = z_{k+1}$.

(I) $\lambda = 0 \Rightarrow$ each $z_k = \dots = z_2 = \lambda z_1 = 0$. Thus $E(0, S) = \text{span}(e_1)$.

(II) $\lambda \neq 0 \Rightarrow \lambda^k z_1 = \lambda^{k-1} z_2 = \dots = \lambda z_k = z_{k+1}$. Thus $E(\lambda, S) = \text{span}[(1, \lambda^1, \dots, \lambda^k, \dots)]$. \square

• Supp V is finide, $T \in \mathcal{L}(V), \lambda \in \mathbf{F}$.

13 Prove $\exists \alpha \in \mathbf{F}, |\alpha - \lambda| < \frac{1}{1000}$ suth $(T - \alpha I)$ is inv.

SOLUS: Let each $|\alpha_k - \lambda| = \frac{1}{1000+k}$, where $k \in \{1, \dots, \dim V + 1\}$. Then $\exists \alpha_k$ not an eigval. \square

• (4E 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 inj for all $\alpha \in \mathbf{F}$, done.

Supp $\lambda_1, \dots, \lambda_m$ are all the disti eigvals of T unequal to λ .

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 inv. \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

• Supp $T \in \mathcal{L}(V)$. Give a countexa: λ is eigval of $T \iff$ of T' .

SOLUS: Let T be the forwd shift optor on $V = \mathbf{F}^\infty$. No eigvals for T , by Exe (18).

Define $\psi \in V'$ by $\psi(x_1, x_2, \dots) = x_1$. Then $[T'(\psi)](x_1, x_2, \dots) = \psi(0, x_1, x_2, \dots) = 0$. \square

15 Supp $R, S, T \in \mathcal{L}(V)$, and S is inv.

(a) Prove T and $S^{-1}TS$ have the same eigvals.

(b) Describe the relationship between eigvecs of T and eigvecs of $S^{-1}TS$.

(c) Supp R, T have the same eigvecs $B_V = (v_1, \dots, v_n)$. Then $RT = TR$.

(d) Prove RT and TR have the same eigvals.

SOLUS: (a) λ is an eigval of T with an eigvec $v \Rightarrow S^{-1}TS(S^{-1}v) = S^{-1}Tv = S^{-1}(\lambda v) = \underline{\lambda S^{-1}v}$.

λ is an eigval of $S^{-1}TS$ with an eigvec $v \Rightarrow S(S^{-1}TS)v = TS\underline{v} = \underline{\lambda Sv}$.

OR. Note that $S(S^{-1}TS)S^{-1} = T$. Every eigval of $S^{-1}TS$ is an eigval of $S(S^{-1}TS)S^{-1} = T$.

OR. $Tv = \lambda v \iff TSu = \lambda Su \iff (S^{-1}TS)u = \lambda u$. Where $v = Su$.

$(S^{-1}TS)u = \lambda u \iff S^{-1}Tv = \lambda S^{-1}v \iff Tv = \lambda v$. Where $u = S^{-1}v$.

(b) $E(\lambda, T) = \{Su : u \in E(\lambda, S^{-1}TS)\}; E(\lambda, S^{-1}TS) = \{S^{-1}v : v \in E(\lambda, T)\}$.

(d) [False if infinide. See Exe (18, 20).] Supp $v \neq 0$ and $RTv = \lambda v \Rightarrow T(RTv) = \lambda Tv = TR(Tv)$.

If $Tv = 0$, then T not inj, so are TR, RT . Othws, λ is eigval of TR . Rev the roles. \square

• **TIPS 5:** Supp $S, T \in \mathcal{L}(V), p \in \mathcal{P}(\mathbf{F})$. Prove $Sp(TS) = p(ST)S$.

SOLUS: We prove each $S(TS)^m = (ST)^m S$ by induc. (i) $m = 0, 1$. Immed.

(ii) $m > 1$. $S(TS)^{m-1} = (ST)^{m-1}S \Rightarrow S(TS)^m = S(TS)^{m-1}(TS) = (ST)^{m-1}(ST)S = (ST)^m S$. \square

COMMENT: If S is inv. Then $p(TS) = S^{-1}p(ST)S, p(ST) = Sp(TS)S^{-1}$.

CORO: Becs S is inv, $T \in \mathcal{L}(V)$ is arb $\iff ST = R \in \mathcal{L}(V)$ is arb. Hence $p(S^{-1}RS) = S^{-1}p(R)S$.

- (4E 37) *Supp V is finide, $T \in \mathcal{L}(V)$. Define $\mathcal{A} \in \mathcal{L}(\mathcal{L}(V))$ by $\mathcal{A}(S) = TS$. Prove the set of eigvals of T equals the set of eigvals of \mathcal{A} .* Not true if $\mathcal{A} : S \mapsto ST$.
- SOLUS:** (a) For $v \neq 0$ and $Tv = \lambda v$, let $v_1 = v \Rightarrow B_V = (v_1, \dots, v_n)$.
Define $S \in \mathcal{L}(V) : v_j \mapsto v$, OR $v_j \mapsto \delta_{1,j}v_1$. Then each $(T - \lambda I)Sv_j = 0$.
(b) $\text{Supp } S \neq 0$ and $TS = \lambda S$. Then $\exists v \in V \setminus \text{null } S$. Let $u = Sv \Rightarrow Tu = TSv = \lambda Sv = \lambda u$.
OR. $TS - \lambda S = (T - \lambda I)S = 0 \Rightarrow \{0\} \neq \text{range } S \subseteq \text{null}(T - \lambda I) \Rightarrow (T - \lambda I) \text{ not inj.}$ \square

27, 28 *Supp $\dim V > 1$, $k \in \{1, \dots, \dim V - 1\}$.*

Supp every subsp of dim k is inward a $T \in \mathcal{L}(V)$. Prove $T = \lambda I$.

SOLUS: We prove the contrapos. $\text{Supp } \exists v \in V \setminus \{0\}$ not eigvec.

Then (v, Tv) liney indep $\Rightarrow B_V = (v, Tv, u_1, \dots, u_n)$. Let $U = \text{span}(v, u_1, \dots, u_{k-1})$. \square

OR. $\text{Supp } v = v_1 \in V \setminus \{0\} \Rightarrow B_V = (v_1, \dots, v_n)$. Let $Tv_1 = c_1v_1 + \dots + c_nv_n$.

Let $B_U = (v_1, v_{\alpha_1}, \dots, v_{\alpha_{k-1}})$. Becs every such U invar. Now $Tv_1 \in U \Rightarrow Tv_1 = c_1v_1$.

By Exe (26), done. [For $0 \neq c_j \in \{c_2, \dots, c_n\}$, let $B_W = (v_1, v_{\beta_1}, \dots, v_{\beta_{k-1}})$ with each $\beta_i \neq j$.] \square

29 *Supp $T \in \mathcal{L}(V)$, range T is finide. Prove T has at most $1 + \dim \text{range } T$ disti eigvals.*

SOLUS: Becs range T finide \Rightarrow not too many. Let $\lambda_1, \dots, \lambda_m$ be the disti eigvals of T with corres v_1, \dots, v_m .

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 $\{\lambda_j v_j : j \neq k\}$ liney indep. Thus $m - 1 \leq \dim \text{range } T$. \square

35 *Supp V is finide, $T \in \mathcal{L}(V)$, and U is inward T. Show λ is eigval of $T/U \Rightarrow$ of T.*

SOLUS:

$\text{Supp } v + U \neq 0$ and $Tv + U = \lambda v + U \Rightarrow (T - \lambda I)v = u \in U$. If $u = 0$, done. Othws, two cases.

If $(T - \lambda I)|_U$ inj \Rightarrow surj. Then $(T - \lambda I)v = u = (T - \lambda I)|_U(w)$, $\exists w \in U \Rightarrow T(v + w) = \lambda(v + w)$.

If $(T - \lambda I)|_U = T|_U - \lambda I|_U$ not inj. Then λ is eigval of $T|_U \Rightarrow$ of T. \square

Or. Let $B_U = (u_1, \dots, u_m) \Rightarrow (Tv - \lambda v, Tu_1 - \lambda u_1, \dots, Tu_m - \lambda u_m)$ of len $(m + 1)$ liney dep in U.

So that $a_0(T - \lambda I)v + a_1(T - \lambda I)u_1 + \dots + a_m(T - \lambda I)u_m = 0, \exists a_k \neq 0$.

Then $Tv = \lambda v$, where $w = a_0v + a_1u_1 + \dots + a_mu_m \neq 0 \Leftarrow w \notin U \Leftarrow v \notin U$. \square

Exa: Let $V = \mathbb{F}^N$, $U = \{x \in \mathbb{F}^N : x_1 = 0\}$, $T \in \mathcal{L}(V) : e_k \mapsto e_{k+1}$. Then $(T/U)(e_1 + U) = e_2 + U = 0$.

• (4E 39) *Supp $T \in \mathcal{L}(V)$, V is finide. Prove \exists eigval of T $\iff \exists$ invarsps U of dim $\dim V - 1$.*

SOLUS: Supp λ is eigval with v . Becs $\dim E(\lambda, T) \geq 1 \iff \dim \text{range}(T - \lambda I) \leq \dim V - 1 = N$.

Let $B_{\text{range}(T - \lambda I)} = (w_1, \dots, w_m)$. Extend to a liney indep $(w_1, \dots, w_m, \dots, w_N) = B_U$.

Now U inward $(T - \lambda I) \Rightarrow$ inward T. Convly, becs $\dim V/U = 1$. By (3.A.7), Exe (35). \square

• (4E 16) *Supp $B_V = (v_1, \dots, v_n)$, $T \in \mathcal{L}(V)$, and λ is eigval.*

Let A_M be the max of all ent of $A = \mathcal{M}(T, B_V)$. Prove $|\lambda| \leq A_M \cdot \dim V$.

SOLUS: Supp λ is eigval with v . Let $v = c_1v_1 + \dots + c_nv_n$.

Becs $\lambda c_1v_1 + \dots + \lambda c_nv_n = c_1Tv_1 + \dots + c_nTv_n = \sum_{k=1}^n c_k \left[\sum_{j=1}^n A_{j,k}v_j \right] = \sum_{j=1}^n \left[\sum_{k=1}^n c_k A_{j,k} \right] v_j$.

Thus $\lambda c_j = \sum_{k=1}^n c_k A_{j,k} \Rightarrow$ each $|\lambda| |c_j| = \sum_{k=1}^n |c_k| |A_{j,k}|$. Let $|c_M| = \max\{|c_1|, \dots, |c_n|\}$.

Becs $v \neq 0 \Rightarrow |c_M| \neq 0$. Now $|\lambda| |c_M| = \sum_{k=1}^n |c_k| |A_{M,k}| \Rightarrow |\lambda| \leq \sum_{k=1}^n |A_{M,k}| \leq nM$. \square

24 Suppose $A \in \mathbf{F}^{n,n}$. Define $T \in \mathcal{L}(\mathbf{F}^{n,1})$ by $Tx = Ax$. Prove λ is eigenvalue of T if:

- (a) the sum of the entries in each row of A equals λ . (b) each col of A .

SOLUS: Suppose $x \neq 0$ and $Ax = (A_{j,1}x_1 + \dots + A_{j,n}x_n)_{j=1}^n = \alpha(x_j)_{j=1}^n = \alpha x$.

- (a) $\text{Supp } A_{R,1} + \dots + A_{R,n} = \lambda$. Let $x_1 = \dots = x_n$. Immed.

(b) $\text{Supp } A_{1,C} + \dots + A_{n,C} = \lambda$. Note that $\left[\sum_{R=1}^n A_{R,C} \right] x = \sum_{k=1}^n (A_{1,k} + \dots + A_{n,k})x_k$.

Each $(Ax)_{R,1} = \lambda(x)_{R,1}$. Thus for x with $\sum_{k=1}^n x_k \neq 0$, λ is the corresponding eigenvalue. \square

Or. Since $(T - \lambda I)x = ((A_{j,1}x_1 + \dots + A_{j,n}x_n) - \lambda x_j)_{j=1}^n = (y_j)_{j=1}^n$.

Now $y_1 + \dots + y_n = \sum_{k=1}^n x_k \left[\sum_{j=1}^n A_{j,k} \right] - \lambda \sum_{j=1}^n x_j = 0$. Thus $(T - \lambda I)$ is not surjective. \square

Or. Let (e_1, \dots, e_n) be the standard basis of $\mathbf{F}^{n,1}$. Define $\psi \in (\mathbf{F}^{n,1})'$ with each $\psi(e_k) = 1$.

Since $Ae_k = A_{.,k} = \sum_{j=1}^n A_{j,k}e_j \Rightarrow \psi[(T - \lambda I)e_k] = \psi\left(\sum_{j=1}^n A_{j,k}e_j - \lambda e_k\right) = \sum_{j=1}^n A_{j,k} - \lambda = 0$. \square

Or. Define $S \in \mathcal{L}(\mathbf{F}^{n,1})$ by $Sx = A^t x$. By (a), [3.F TIPS (4)], and Example (15, 4E 15),

the sum of the entries in each row of A^t equals $\lambda \Rightarrow \lambda$ is eigenvalue of $S = \Phi^{-1}T'\Phi$, so of T' , of T . \square

• Suppose $A \in \mathbf{F}^{n,n}$. Define $T \in \mathcal{L}(\mathbf{F}^{1,n})$ by $Tx = xA$. Prove λ is eigenvalue of T if:

- (a) the sum of the entries in each column of A equals λ . (b) each row of A .

SOLUS: Suppose $x \neq 0$ and $xA = (x_1 A_{1,k} + \dots + x_n A_{n,k})_{k=1}^n = \alpha(x_k)_{k=1}^n = \alpha x$.

- (a) $\text{Supp } A_{1,C} + \dots + A_{n,C} = \lambda$. Let $x_1 = \dots = x_n$. Immed.

(b) $\text{Supp } A_{R,1} + \dots + A_{R,n} = \lambda$. Note that $\sum_{C=1}^n xA_{.,C} = \sum_{j=1}^n (A_{j,1} + \dots + A_{j,n})x_j$.

Each $(xA)_{1,C} = \lambda(x)_{1,C}$. Thus for x such that $\sum_{k=1}^n x_k \neq 0$, λ is the corresponding eigenvalue. \square

Or. Since $(T - \lambda I)x = ((x_1 A_{1,k} + \dots + x_n A_{n,k}) - \lambda x_k)_{k=1}^n = (y_k)_{k=1}^n$.

Now $y_1 + \dots + y_n = \sum_{j=1}^n x_j \left[\sum_{k=1}^n A_{j,k} \right] - \lambda \sum_{k=1}^n x_k = 0$. \square

Or. Similar. Since $e_j A = A_{j,.} = \sum_{k=1}^n A_{j,k}e_k \Rightarrow \psi[(T - \lambda I)e_j] = \sum_{k=1}^n A_{j,k} - \lambda = 0$. \square

Or. Define $S \in \mathcal{L}(\mathbf{F}^{1,n})$ by $Sx = xA^t \Rightarrow S = \Phi^{-1}T'\Phi$. Similar and by [3.D TIPS (3)]. \square

ENDED

5.B (I) 覆盖 4e 的本节全部、3e 前半部分。 (II) 覆盖 3e 本节后半部分「上三角矩阵」、4e 5.C 节。

注意: 4e 的 5.B 节和 3e 的 8.C 节、9.A 节许多结论和习题有交集。5.B(II) 的题号使用 4e 5.C 节。

I.9 Suppose V is finite-dimensional, $T \in \mathcal{L}(V)$, and non-zero $v \in V$. Let $p \in \mathcal{P}(\mathbf{F})$ be non-zero of smallest degree with $p(T)v = 0$. Show every zero of p is eigenvalue of T . By division algorithm, p divides the minimum polynomial of T .

SOLUS: Or. Let $p(z) = (z - \lambda)q(z) \Rightarrow p(T)v = 0 = (T - \lambda I)q(T)v \Rightarrow T(q(T)v) = \lambda q(T)v$. \square

• **I.TIPS 1:** Suppose V is finite-dimensional, $T \in \mathcal{L}(V)$, and $v \in V$.

(a) Prove \exists ! monic p_v of smallest degree such that $p_v(T)v = 0$.

(b) Prove p_v is the minimum of $T|_{\text{null } p_v(T)}$. So that the minimum of T is a multiple of p_v .

SOLUS: (a) [Existence] If $v = 0$, then let $p_v(z) = 1$. Suppose $v \neq 0$. Then $(v, Tv, \dots, T^{\dim V}v)$ is linearly dependent.

\exists smallest m such that $-T^m v = c_0 v + c_1 Tv + \dots + c_{m-1} T^{m-1}v$. Thus define p_v .

Or. Let $U = \text{span}(v, Tv, \dots, T^{m-1}v)$ of dimension m invariant under T . Let p_v be the minimum of $T|_U$.

[Uniqueness] p_v is monic of smallest degree [$= \deg p_v$] and $p_v(T)v = 0$.

Then $(p_v - q_v)(T)v = 0$, while $\deg p_v = m = \deg q_v \Rightarrow \deg(p_v - q_v) < m$.

(b) Since $p_v(T|_{\text{null } p_v(T)}) = 0 \Rightarrow p_v$ is a multiple of q . And $q(T)v = 0 \Rightarrow q = p_v$, by the minimum of $\deg p_v$. \square

11 $\text{Supp } \mathbf{F} = \mathbf{C}$, $T \in \mathcal{L}(V)$, nonC $p \in \mathcal{P}(\mathbf{F})$.

Prove α is eigval of $p(T) \iff \alpha = p(\lambda)$ for some eigval λ of T .

SOLUS: $\text{Supp } p(T) - \alpha I$ not inj. Let $p(z) - \alpha = c(z - \lambda_1) \cdots (z - \lambda_m)$, with $c \neq 0$, becs p nonC.

Then $\exists (T - \lambda_j I)$ not inj. Now $p(\lambda_j) - \alpha = 0$. Convly true immed. \square

• $\text{Supp non0 } v \in V$. Prove [5.21] using the given map below, and also [4E 5.22], in Exe (I.17).

I.16 Define $S : \mathcal{P}_{\dim V}(\mathbf{C}) \rightarrow V$ by $S(p) = p(T)v$. Then S not inj $\Rightarrow \exists \text{ non0 } p \in \text{null } S$.

I.17 Define $S : \mathcal{P}_{\dim V^2}(\mathbf{C}) \rightarrow \mathcal{L}(V)$ by $S(p) = p(T)$. Then S not inj $\Rightarrow \exists \text{ non0 } p \in \text{null } S$.

• (4E I.7) $\text{Supp } S, T \in \mathcal{L}(V)$ and p, q are mins of ST, TS respectively. Prove S or T is inv $\Rightarrow p = q$.

SOLUS: S inv $\Rightarrow p(TS) = S^{-1}p(ST)S = 0$ and $q(ST) = Sq(TS)S^{-1} = 0 \Rightarrow p = q$. Rev the roles. \square

• (4E I.21) $\text{Supp } V$ finide, $T \in \mathcal{L}(V)$. Prove the min p has deg at most $1 + \dim \text{range } T$.

SOLUS: Let q be the min of $T|_{\text{range } T}$. Then $q(T)Tv = 0 \Rightarrow zq(z)$ of deg $\leq 1 + \dim \text{range } T$ is multi of p . \square

• (4E I.28) $\text{Supp } V$ is finide and $T \in \mathcal{L}(V)$. Prove the min p of T' equals the min q of T .

SOLUS: $\forall \varphi \in V', p(T')(\varphi) = \varphi \circ p(T) = 0 \Rightarrow \text{range } p(T) \subseteq C^0 V'$. Thus $p(T) = 0$. $\forall \varphi \circ q(T) = 0$. \square

Or. By (3.F.15), for any $s \in \mathcal{P}(\mathbf{F})$, $s(T') = s(T)' = 0 \iff s(T) = 0$. Simlr. \square

• Define $T \in \mathcal{L}(\mathbf{F}^n) : (x_1, \dots, x_n) \mapsto (-a_0 x_n, x_1 - a_1 x_n, \dots, x_{n-1} - a_{n-1} x_n)$.

Show the min p of T is $q(z) = a_0 + a_1 z + \dots + a_{n-1} z^{n-1} + z^n$.

SOLUS: Becs $Te_1 = e_2, T^2 e_1 = e_3, \dots, T^{n-1} e_1 = e_n, T^n e_1 = T^{n-k} e_{k+1} = Te_n = -(a_0 e_1 + \dots + a_{n-1} e_n)$.

Let $-T^n = c_0 I + c_1 T + \dots + c_{n-1} T^{n-1} \Rightarrow$ each $c_k = a_k$. Becs $n = \dim V$. No smaller deg. \square

• (4E I.8) Find the min p of $T \in \mathcal{L}(\mathbf{R}^2)$, the countclockws rotat optor by $\theta \in \mathbf{R}^+$.

SOLUS: If $\theta = 2k\pi$, then $p(z) = z - 1$. If $\theta = \pi + 2k\pi$, then $p(z) = z + 1$.

Othws, let $\text{span}(v, Tv) = \mathbf{R}^2$. Let $L = x^2 + y^2$, where $v = (x, y)$.

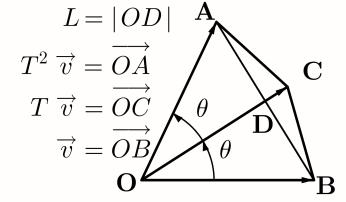
$\text{Supp } p(z) = z^2 + bz + c$. Let $P = L \cos \theta \Rightarrow L/2P = 1/(2 \cos \theta)$.

Then $Tv = (L/2P)(T^2 v + v) \Rightarrow T = (L/2P)(T^2 + I)$.

Hence $p(T) = T^2 - 2 \cos \theta T + I = 0$.

Or. Let (e_1, e_2) be the std bss. Becs $Te_1 = \cos \theta e_1 + \sin \theta e_2, T^2 e_1 = \cos 2\theta e_1 + \sin 2\theta e_2$.

$ce_1 + bTe_1 = -T^2 e_1 \iff \begin{pmatrix} 1 & \cos \theta \\ 0 & \sin \theta \end{pmatrix} \begin{pmatrix} c \\ b \end{pmatrix} = \begin{pmatrix} -\cos 2\theta \\ -\sin 2\theta \end{pmatrix}$. Now $\det = \sin \theta \neq 0, c = 1, b = -2 \cos \theta$. \square



• (4E I.11) $\text{Supp } V$ is 2-dim, $T \in \mathcal{L}(V)$ with the min p , and $\mathcal{M}(T, (v, w)) = \begin{pmatrix} a & c \\ b & d \end{pmatrix}$.

(a) Show $q(z) = (z - a)(z - d) - bc$ is a multi of p .

(b) Show if $b = c = 0$ and $a = d$, then $p(z) = z - a$; othws $p = q$.

SOLUS: (a) $Tv = av + bw \Rightarrow (T - aI)v = bw \Rightarrow (T - dI)(T - aI)v = bTw - bdw = bcv$.

$Tw = cv + dw \Rightarrow (T - dI)w = cv \Rightarrow (T - aI)(T - dI)w = cTv - acv = bcw$.

(b) If $b = c = 0$ and $a = d$. Then $\mathcal{M}(T) = a\mathcal{M}(I) \Rightarrow T = aI$. Othws, we show $T \notin \text{span}(I)$,

so that $\deg p = \dim V$. Let (1) $a = d$, (2) $b = 0$, (3) $c = 0$. Then (1), (2) and (3) cannot be all true.

(I) Asum (1) is true, with (2) or (3) not true. Then $Tv = av + bw$, or $Tw = cv + aw \notin \text{span}(w)$.

(II) Asum (2) or (3) are true, with (1) not true. Then $Tv = av + bw$, or $Tw = cv + dw$. \square

- (4E I.29) *Supp V is finide, $\dim V = n \geq 2$, and $T \in \mathcal{L}(V)$. Show T has a 2-dim invarsps.*

SOLUS: See [9.8] for a graceful proof. OR. Let each V_k be an arb vecsp of dim k with an arb $T_k \in \mathcal{L}(V_k)$.

Define the stmt $P(k)$: every optor on a V_k has invarsps of dim 2. (i) $k = 2$. Immed.

(ii) $k \geq 2$. Asum $P(k)$ holds. Let p be the min of $T_{k+1} = T$. Note that V_{k+1} non0 $\Rightarrow p$ nonC, $\deg p \geq 1$.

(a) If $p(z) = (z - \lambda)q(z)$, then by (4E 5.A.39), $\exists U$ invarspsd T of dim k .

By asum, the optor $T|_U$ on a k -dim vecsp has invarsps of dim 2, so has T .

(b) Othws, T_{k+1} has no eigvals $\Rightarrow p$ of $\deg \geq 1$ has no zeros, thus $F = R$, and $\deg p$ is even.

Let $p(z) = (z^2 + b_1z + c_1) \cdots (z^2 + b_mz + c_m) \Rightarrow \exists (T^2 + b_jT + c_j)$ not inj

$\Rightarrow \exists v \neq 0, (T^2 + b_jT + c_j)v = 0 \Rightarrow T^2v \in \text{span}(v, Tv)$, invard T , while $\dim \text{span}(v, Tv) = 2$. \square

- **NOTE FOR [4E 5.33]:** *Supp F = R, V is finide, $T \in \mathcal{L}(V)$, and $b^2 < 4c$ for $b, c \in F$.*

Prove $\dim \text{null}(T^2 + bT + cI)^j$ is even for each $j \in N^+$.

SOLUS: Using induc on j . (i) Immed. (ii) $j > 1$. Asum it holds for $j - 1$.

Replace V with $\text{null}(T^2 + bT + cI)^j$ and T with T restr to $\text{null}(T^2 + bT + cI)^j$.

Then $(T^2 + bT + cI)^j = 0 \Rightarrow (z^2 + bz + c)^j$ is a multi of the min of $T \Rightarrow$ no eigvecs for T .

Let U be invarspsd T and has the largest even dim of all such invarsps. If $V = U$, done. Othws, for $w \in V \setminus U \Rightarrow W = (w, Tw)$ invard T of dim 2 $\Rightarrow U + W$ of dim ($\dim U + 2$) invard T . \square

Or. Let $q(z) = z^2 + bz + c$. Note that the min of T restr to each $\text{null } q(T)^j$ has no real zeros.

If some $\dim \text{null } q(T)^j$ is odd. Then T restr to $\text{null } q(T)^j$ must have a real eigval, ctradic. \square

- *Supp V finide, $T \in \mathcal{L}(V)$ with the min p.*

- (4E I.13) *Prove $\forall q \in \mathcal{P}(F), \exists ! r \in \mathcal{P}_{\deg p-1}(F), q(T) = r(T)$.*

SOLUS: Becs $p \neq 0$. By the div algo, immed. [$r = 0$ if $q = p$.] OR. By Exe (4E I.19). \square

Or. Let $\deg p = m$. Becs $T^m \in \text{span}(I, T, \dots, T^{m-1})$. For $\deg q < m$, the expr of $q(T)$ is uniq.

If $\deg q \geq m$. Note that for each $k \in N$, $\exists ! b_{j,k} \in F, T^{m+k} = b_{0,k}I + b_{1,k}T + \dots + b_{m-1,k}T^{m-1}$. \square

- (4E I.19) *Let $\mathcal{E} = \{q(T) : q \in \mathcal{P}(F)\}$, a subsp of $\mathcal{L}(V)$. Prove $\dim \mathcal{E} = \deg p$.*

SOLUS: Becs $\mathcal{E} = \text{span}(I, T, \dots, T^{\dim \mathcal{L}(V)-1}) = \text{span}(I, T, \dots, T^{\deg p-1})$, by Exe (4E I.13). Immed. \square

Or. Define $\Phi \in \mathcal{L}(\mathcal{P}(F), \mathcal{L}(V))$ by $\Phi(q) = q(T) \Rightarrow \text{range } \Phi = \mathcal{E}$.

Becs $\Phi(q) = q(T) = 0 \iff q$ is a multi of the min $p \iff q \in \{ps : s \in \mathcal{P}(F)\} = \text{null } \Phi$.

Now by (4.11), $\dim \mathcal{P}(F)/\text{null } \Phi = \deg p$. By [3.91](d). \square

- (8.C.11) *Supp $T \in \mathcal{L}(V)$ is inv. Prove $\exists q \in \mathcal{P}(F), T^{-1} = q(T)$.*

SOLUS: Becs the const term of p is non0. Let $I = a_1T + \dots + a_mT^m \Rightarrow T^{-1} = a_1I + a_2T + \dots + a_mT^{m-1}$. \square

- (4E I.14) *Supp $p(z) = a_0 + a_1z + \dots + a_{m-1}z^{m-1} + z^m$, and $a_0 \neq 0$.*

Give a representa of s, the min of T^{-1} . $s(z) = z^m p(0)^{-1} p(z^{-1})$, $z \neq 0$.

SOLUS: Define $q(z) = z^m + \frac{a_1}{a_0}z^{m-1} + \dots + \frac{a_{m-1}}{a_0}z + \frac{1}{a_0} \Rightarrow q(T^{-1}) = T^{-m}p(T) = 0$.

Now $\deg s \leq \deg q = \deg p$. Revly, $\deg q = \deg p \leq \deg s$. \square

Or. Becs each $T^{-k} \notin \text{span}(I, T^{-1}, \dots, T^{-(k-1)})$ for $k \in \{1, \dots, m-1\}$. Done.

For if not, $\exists T^{-k} = b_0I + b_1T^{-1} + \dots + b_{k-1}T^{-(k-1)}$. Apply T^k . Now $a_kT^k + \dots + a_1T + a_0I = 0$. \square

- (4E I.17) Show the min s of $(T - \lambda I)$ is $q(z) = p(z + \lambda)$.

SOLUS: Becs $\deg q = \deg p$, and $q(T - \lambda I) = p(T) = 0 \Rightarrow q$ a multi of s .

Now the deg of min p of T is no less than the deg of min s of $(T - \lambda I)$.

Revlly, the deg of min s of $S = T - \lambda I$ is no less than the deg of min p of $(S + \lambda I)$. \square

Or. Define $r(z) = s(z - \lambda) \Rightarrow r(T) = 0 \Rightarrow \deg r = \deg s \geq \deg p$. \square

Or. Becs $T^k \in \text{span}(I, T, \dots, T^{k-1}) = \text{span}(I, (T - \lambda I), \dots, (T - \lambda I)^{k-1}) \ni (T - \lambda I)^k$. \square

- (4E I.18) Supp $\deg p = m$, and $\lambda \neq 0$. Show the min s of λT is $q(z) = \lambda^m p(z/\lambda)$.

SOLUS: Becs $\deg q = \deg p$, and $q(\lambda T) = \lambda^m p(T) = 0 \Rightarrow q$ is multi s .

Now the deg of min p of T is no less than the deg of min s of λT .

Revlly, the deg of min s of $S = \lambda T$ is no less than the deg of min p of $\lambda^{-1}S$. \square

Or. Define $r(z) = s(\lambda z) \Rightarrow r(T) = 0 \Rightarrow \deg r = \deg s \geq \deg p$. \square

Or. Becs $(\lambda T)^k \in \text{span}(\lambda I, \lambda T, \dots, (\lambda T)^{k-1}) = \text{span}(I, T, \dots, T^{k-1}) \ni T^k$. \square

- (4E I.10,23) Supp $\deg p = m$, and non0 $v \in V$. Let each $U_k = \text{span}(v, Tv, \dots, T^k v)$.

Prove $\exists j \in \{1, \dots, m\}$, $U_{j-1} = U_n$ for all $n \geq j - 1$.

SOLUS: Supp j is the smallest suth $T^j v = a_0 v + a_1 T v + \dots + a_{j-1} T^{j-1} v \in U_{j-1} \Rightarrow j \leq m$.

Then U_{j-1} is invard T , so is each $U_n = \text{span}(v, Tv, \dots, T^{j-1} v, \dots, T^n v)$. \square

II.8 Supp V is finide, and $v \in V$ is non0 suth $q(T)v = 0$, where $q(z) = z^2 + 2z + 2$.

(a) Supp $\mathbf{F} = \mathbf{R}$. Prove $\nexists B_V$ suth $\mathcal{M}(T)$ up-trig.

(b) Supp $\mathbf{F} = \mathbf{C}$, and $\exists B_V$ suth $A = \mathcal{M}(T)$ up-trig. Prove $-1 + i$ or $-1 - i$ on diag.

SOLUS: Define p_v as in [I TIPS (1)]. Note that $v \neq 0 \Rightarrow \deg p_v \neq 0$. 又 $q(T|_{\text{null } p_v(v)}) = 0$.

Now q of deg 2 is a multi of the min of $T|_{\text{null } p_v(v)}$, which is p_v , of which the min of T is a multi.

(a) Note that q has no 1-deg factors $\Rightarrow \deg p_v \geq 2$. By [4E 5.44].

(b) $q(z) = (z + 1 + i)(z + 1 - i) \Rightarrow -1 - i$ or $-1 + i$ zero of $p_v \Rightarrow$ is eigval \Rightarrow on diag. \square

- **II.TIPS 1:** Supp $B_V = (v_1, \dots, v_n), B_{V'} = (\varphi_1, \dots, \varphi_n), T \in \mathcal{L}(V), A = \mathcal{M}(T, B_V)$.

(a) A up-trig $\iff T = \sum_{k=1}^n \sum_{j=1}^k A_{j,k} E_{k,j} \iff T' = \sum_{k=1}^n \sum_{j=1}^k A_{j,k}^t \mathfrak{E}_{j,k} \iff A^t$ low-trig.

(b) A low-trig $\iff T = \sum_{k=1}^n \sum_{j=1}^k A_{k,j} E_{j,k} \iff T' = \sum_{k=1}^n \sum_{j=1}^k A_{j,k}^t \mathfrak{E}_{k,j} \iff A^t$ up-trig.

- **II.TIPS 2:** Supp $(\alpha_1, \dots, \alpha_n), (\beta_1, \dots, \beta_n)$ are bses of V , with each $\alpha_k = \beta_{n-k+1}$.

Prove $\mathcal{M}(T, \alpha \rightarrow \alpha)$ up-trig $\iff \mathcal{M}(T, \beta \rightarrow \beta)$ low-trig.

SOLUS: For each $k \in \{1, \dots, n\}$, $T\beta_{n-k+1} = T\alpha_k \in \text{span}(\alpha_1, \dots, \alpha_k) = \text{span}(\beta_n, \dots, \beta_{n-k+1})$. \square

CORO: (a) Supp $\mathbf{F} = \mathbf{C}$. Then $\exists B_V$ suth $\mathcal{M}(T, B_V)$ low-trig. (b) T up-trig $\iff T'$ up-trig.

II.12,13 Supp V finide, $T \in \mathcal{L}(V)$. Prove $T|_U, T/U$ up-trig for some invarsps $U \iff T$ up-trig.

SOLUS: Supp $B_U = (u_1, \dots, u_p), B_{V/U} = (w_1 + U, \dots, w_q + U)$ suth $\mathcal{M}(T|_U), \mathcal{M}(T/U)$ up-trig.

Then each $Tu_k \in \text{span}(u_1, \dots, u_p)$ and each $Tw_j + U \in \text{span}(w_1 + U, \dots, w_q + U)$.

By (3.E.13), $B_V = (u_1, \dots, u_p, w_1, \dots, w_q)$. Now each $Tw_j \in \text{span}(u_1, \dots, u_p, w_1, \dots, w_q)$. \square

Or. By (4E 5.B.25)(b) and [4E 5.44], immed. Convly, by [4E 5.44], immed.

5.C & [4E] 5.D

注意: 这一节的题号主要使用第四版 5.D 节.

L1 $\text{Supp } T \in \mathcal{L}(V), \alpha, \beta \in \mathbf{F}$ and $\alpha \neq \beta$. Prove $\text{null}(T - \alpha I) \subseteq \text{range}(T - \beta I)$.

SOLUS: $\forall v \in \text{null}(T - \alpha I), Tv = \alpha v \Rightarrow (T - \beta I)[v / (\alpha - \beta)] = v \in \text{range}(T - \beta I)$. \square

5 $\text{Supp } \mathbf{F} = \mathbf{C}, V$ is finide, and $T \in \mathcal{L}(V)$.

$\text{Supp } V = \text{null}(T - \lambda I) \oplus \text{range}(T - \lambda I)$ for all $\lambda \in \mathbf{C}$. Prove T is diag.

SOLUS: (i) $\dim V = 1$. Immed. (ii) $\dim V > 1$. Asum it holds for vecsps of smaller dim.

$\exists \text{eigval } \lambda_0 \Rightarrow U = \text{range}(T - \lambda_0 I)$ invard $T \Rightarrow U = \text{null}(T|_U - \lambda I) \oplus \text{range}(T|_U - \lambda I)$.

While $V = E(\lambda_0, T) \oplus U \Rightarrow \dim U < \dim V$. By asum, $T|_U$ is diag wrto B_U of eigvecs. \square

Or. $\text{Supp } T$ not diag. We show $\exists \lambda \in \mathbf{C}, \text{null}(T - \lambda I) \cap \text{range}(T - \lambda I) \neq \{0\}$.

Let the min of T be $p(z) = (z - \lambda_1)^{\alpha_1} \cdots (z - \lambda_m)^{\alpha_m}$, where each $\alpha_k \geq 1$ and $\exists \alpha_j > 1$.

Let $q(z)(z - \lambda_j) = p(z) \Rightarrow 0 = p(T) = (T - \lambda_j I)q(T) \Rightarrow \text{range } q(T) \subseteq \text{null}(T - \lambda_j I)$.

Let $q(z) = (z - \lambda_j)s(z) \Rightarrow \text{range } q(T) \subseteq \text{range}(T - \lambda_j I)$. Note that $q(T) \neq 0$. \square

Or. Let $\lambda_1, \dots, \lambda_m$ be disti eigvals. Now $V = \text{null}(T - \lambda_k I) \oplus \text{range}(T - \lambda_k I)$ for each λ_k .

Asum $V = [\bigoplus_{i=1}^j \text{null}(T - \lambda_i I)] \oplus [\bigcap_{i=1}^j \text{range}(T - \lambda_i I)]$ for $j \in \{1, \dots, m-1\}$.

Becs by (L1), $\bigcap_{i=1}^j \text{range}(T - \lambda_i I) \supseteq \text{null}(T - \lambda_{j+1} I)$, and by [1.C TIPS (2)],

$\bigcap_{i=1}^j \text{range}(T - \lambda_i I) = \text{null}(T - \lambda_{j+1} I) \oplus [\bigcap_{i=1}^j \text{range}(T - \lambda_i I) \cap \text{range}(T - \lambda_{j+1} I)]$.

By induc, $V = [\text{null}(T - \lambda_1 I) \oplus \cdots \oplus \text{null}(T - \lambda_m I)] \oplus [\text{range}(T - \lambda_1 I) \cap \cdots \cap \text{range}(T - \lambda_m I)]$.

Asum $U = \bigcap_{k=1}^m \text{range}(T - \lambda_k I) \neq \{0\}$. Becs U invard T . Thus $\exists \mu = \lambda_j$ eigval of $T|_U$. Ctradic. \square

13 $\text{Supp } A, B \in \mathbf{F}^{n,n}$ and A is diag with dist ents on diag. Prove $AB = BA \Rightarrow B$ is diag.

SOLUS: NOTICE that for any diag C , each $C_{j,k} = 0$ for $j \neq k$.

Becs (I) $A_{j,j}B_{j,k} = A_{j,1}B_{1,k} + \cdots + [A_{j,j}B_{j,k}] + \cdots + A_{j,n}B_{n,k} = (AB)_{j,k}$.

And (II) $B_{j,k}A_{k,k} = B_{j,1}A_{1,k} + \cdots + [B_{j,k}A_{k,k}] + \cdots + B_{j,n}A_{n,k} = (BA)_{j,k}$.

$\text{Supp } AB = BA \Rightarrow A_{j,j}B_{j,k} = A_{k,k}B_{j,k}$. Asum $B_{j,k} \neq 0$ with $j \neq k$. Then $A_{j,j} = A_{k,k}$, ctradic. \square

14 $\text{Supp } \mathbf{F} = \mathbf{C}, k \in \mathbf{N}^+$, and $T \in \mathcal{L}(V)$ is inv. Prove T^k diag $\Rightarrow T$ diag.

SOLUS: Let the min of T^k be $p(z) = (z - \lambda_1) \cdots (z - \lambda_m) \Rightarrow$ each λ_k non0 and disti.

Becs any non0 $\lambda \in \mathbf{C}$ has k disti k^{th} roots. Let $\{\mu_{1,j}, \dots, \mu_{k,j}\}$ be the roots of $z^k = \lambda_j$.

For $x, y \in \{1, \dots, n\}, x \neq y \Leftrightarrow \mu_{p,x}^k = \lambda_x \neq \lambda_y = \mu_{q,y}^k$ for each $p, q \in \{1, \dots, k\} \Rightarrow \mu_{p,x} \neq \mu_{q,y}$.

Thus all μ 's are dist. Let $s(z) = (z^k - \lambda_1) \cdots (z^k - \lambda_m) = \prod_{j=1}^m \prod_{i=1}^k (z - \mu_{i,j}) \Rightarrow s(T) = 0$. \square

Exa: Not true if $\mathbf{F} = \mathbf{R}$. Define $T \in \mathcal{L}(\mathbf{R}^2) : (x, y) \mapsto (-y, x)$. No eigvals.

• $\text{Supp } \mathbf{F} = \mathbf{C}, n \in \mathbf{N}, n \geq 2$. Prove T is diag $\Leftrightarrow \forall p \in \mathcal{P}(\mathbf{F}), \text{null } p(T) = \text{null}[p(T)]^n$.

SOLUS: (a) $\text{Supp } T$ diag. Let $p(z) = (z - \alpha_1) \cdots (z - \alpha_m)$. We show each $\text{null}(T - \alpha_k I)^n = \text{null}(T - \alpha_k I)$.

Done if $T - \alpha_k I = S$ inj. $\text{Supp } S$ not inj. NOTICE that $\text{null } S|_{\text{range } S} = \text{null } S \cap \text{range } S = \{0\}$.

By (3.B.22), $\dim \text{null } S^2 = \dim \text{null } S \Rightarrow \text{null } S^2 = \text{null } S$. Asum $\text{null } S^j = \text{null } S$ for $j \geq 2$.

Becs $\dim \text{null}(S^j S) = \dim(\text{null } S^j \cap \text{range } S) + \dim \text{null } S$. By induc.

(b) $\text{Supp } \text{null}(T - \lambda I) = \text{null}(T - \lambda I)^n$ for all $\lambda \in \mathbf{C}$. Let $\lambda_1, \dots, \lambda_m$ be disti eigvals of T .

Define $p(z) = (z - \lambda_1) \cdots (z - \lambda_m)$. Then $[p(T)]^{\dim V} = 0 \Rightarrow p(T) = 0 \Rightarrow p$ is the min. \square

Or. By (4E 8.A.3) and Exe (5), T diag $\Leftrightarrow \forall \lambda \in \mathbf{F}, \text{null}(T - \lambda I) = \text{null}(T - \lambda I)^2$. \square

18 *Supp $T \in \mathcal{L}(V)$ is diag. Prove $T/U \in \mathcal{L}(V/U)$ is diag for any U invars pd T .*

SOLUS: By [5.A TIPS (2)], $\exists B_U = (v_1, \dots, v_m)$ consists of eigvecs of T .

Extend to eigvecs $B_V = (v_1, \dots, v_m, w_1, \dots, w_p) \Rightarrow B_{V/U} = (w_1 + U, \dots, w_p + U)$.

Becs for each w_k , \exists eigval λ of T , $Tw_k = \lambda w_k \Rightarrow (T/U)(w_k + U) = \lambda w_k + U$. \square

Or. Becs the min of T is multi of that of T/U . By [4E 5.62]. \square

COMMENT: In Exa [5.15]: $T \in \mathcal{L}(V)$ not diag while $T|_U, T/U$ diag. \square

ENDED

5.E [4E]

7 *Supp $F = \mathbf{C}$, and $S, T \in \mathcal{L}(V)$ commu, S diag. Prove $\exists B_V$ suth S diag and T up-trig.*

SOLUS: Let $\lambda_1, \dots, \lambda_m$ be disti eigvals of $S \Rightarrow V = E(\lambda_1, S) \oplus \dots \oplus E(\lambda_m, S)$.

Becs each $E_k = E(\lambda_k, S)$ invard T . Let each $T|_{E_k}$ be up-trig with $B_{E_k} = (v_{1,k}, \dots, v_{M_k,k})$.

Then S diag while T up-trig with the same $B_V = (v_{1,1}, \dots, v_{M_n,n})$. \square

Or. Using induc on $n = \dim V$. (i) $n = 1$. Immed. (ii) $n > 1$. Asum it holds for smaller V .

\exists eigval λ of S , $U = \text{null}(S - \lambda I)$, $W = \text{range}(S - \lambda I) \Rightarrow V = \text{null}(S - \lambda I) \oplus \text{range}(S - \lambda I)$.

Apply the asum to $T|_U, S|_U$ and $T|_W, S|_W$, then put B_U, B_W together. \square

2 *Supp $\mathcal{E} \subseteq \mathcal{L}(V)$ and every elem of \mathcal{E} diag.*

Prove each pair of elems of \mathcal{E} commu $\Rightarrow \exists B_V$ suth all elem of \mathcal{E} diag.

SOLUS: Let $\dim V = n \Rightarrow \dim \mathcal{L}(V) = n^2$. Write $V = \bigoplus_{\lambda_k \in F} E(\lambda_k, T)$ for each $T \in \mathcal{E}$.

$\exists \{T_1, \dots, T_m\} \subseteq \mathcal{E}$ with each elem of \mathcal{E} in $\text{span}(T_1, \dots, T_m)$ and $m \leq n^2$.

NOTICE that $U_k = E(\lambda_1, T_1) \cap \dots \cap E(\lambda_k, T_k) = E(\lambda_k, T_k|_{U_{k-1}}) = \bigoplus_{\lambda_{k+1}} E(\lambda_{k+1}, T_{k+1}|_{U_k})$.

Hence $V = \bigoplus_{\lambda_1} E(\lambda_1, T_1) = \bigoplus_{\lambda_1, \dots, \lambda_m} [E(\lambda_1, T_1) \cap \dots \cap E(\lambda_m, T_m)]$. Take bss of each summand.

Then we form B_V . For any $T \in \mathcal{E}$, $\mathcal{M}(T, B_V) = c_1 \mathcal{M}(T_1, B_V) + \dots + c_m \mathcal{M}(T_m, B_V)$. \square

9 *Supp $F = \mathbf{C}$, V finide and non0. Supp $\mathcal{E} \subseteq \mathcal{L}(V)$ is suth all $S, T \in \mathcal{E}$ commu.*

(a) *Prove \exists eigvec $v \in V$ of all elem of \mathcal{E} . (b) $\exists B_V$ suth all elem of \mathcal{E} has up-trig matrix.*

SOLUS: Simlr to Exe (2). $\exists \{T_1, \dots, T_m\} \subseteq \mathcal{E}$. Let $U_0 = V, U_k = E(\lambda_1, T_1) \cap \dots \cap E(\lambda_k, T_k)$.

(a) Let $\lambda_1, \dots, \lambda_m$ be eigvals of T_1, \dots, T_m respectively with each λ_k eigval of $T_k|_{U_k} \Rightarrow U_k \neq 0$

Now for non0 $v \in U_m$, $\forall T = c_1 T_1 + \dots + c_m T_m \in \mathcal{E}, Tv = (c_1 \lambda_1 + \dots + c_m \lambda_m)v$.

(b) Using induc on $\dim V$. (i) Immed. (ii) $\dim V > 1$. Asum it holds for smaller V .

Let v_1 be a common eigvec of all T_k . Let $W \oplus \text{span}(v_1) = V, P : av_1 + w \mapsto w$.

Simlr in [4E 5.80], each pair of $\{\hat{T}_1, \dots, \hat{T}_m\}$ commu. By asum, $\exists B_W \Rightarrow \exists B_V$.

Now each $\mathcal{M}(T_k, B_V)$ up-trig $\Rightarrow \forall T \in \mathcal{E}, \mathcal{M}(T) = c_1 \mathcal{M}(T_1) + \dots + c_m \mathcal{M}(T_m)$, wrto B_V . \square

ENDED

8 **NOTE:** $\text{Supp } V$ is a non0 finide vecsp over \mathbf{F} . Let m_T be the min of $T \in \mathcal{L}(V)$.

An Exe marked by ■ is still true if infinide or partially finide.

- $\text{Supp } T \text{ nilp, } U \text{ non0 and } U \oplus \text{null } T = \text{null } T^2$. Prove U is not inward T .

SOLUS: Let $u \in U$ and $T^2u = 0 \neq Tu \in \text{null } T$. If U invar, then $Tu \in U \cap \text{null } T = \{0\}$, ctradic. \square

A.3 $\text{Supp } T \text{ inv. Prove } G(\lambda, T) = G(\lambda^{-1}, T^{-1})$ for any non0 $\lambda \in \mathbf{F}$. ■

SOLUS: $(T - \lambda I)^j v = 0 = \sum_{i=0}^j C_j^i (-\lambda)^{j-i} T^i v$. Apply $(-\lambda)^{-j} T^{-j}$ to both sides. $(T^{-1} - \lambda^{-1} I)^j v = 0$. \square

Or. We use induc on j to show each $\text{null}(T - \lambda I)^j = \text{null}(T^{-1} - \lambda^{-1} I)^j$. (i) Immed. (ii) $j > 1$.

Asum true for $(j-1) \Rightarrow \forall v \in \text{null}(T - \lambda I)^j, (T - \lambda I)v \in \text{null}(T - \lambda I)^{j-1} = \text{null}(T^{-1} - \lambda^{-1} I)^{j-1}$.

Which equiv $\text{null}(T^{-1} - \lambda^{-1} I)^{j-1} v \in \text{null}(T - \lambda I) = \text{null}(T^{-1} - \lambda^{-1} I)$, by (i). \square

A.5 $\text{Supp } T^{n-1}v \neq 0, T^n v = 0$. Prove $(v, Tv, \dots, T^{n-1}v)$ is liney indep.

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

- **NOTE FOR [8.19] OR [4E 8.18]:** If $m_T(z) = z^m$. Then $\exists v$ suth $T^{m-1}v \neq 0$.

If $m = \dim V$. Then $B_V = (T^{m-1}v, \dots, T v, v)$. Let each $w_k = T^{m-k}v$. Then $T w_1 = 0, T(w_k) = w_{k-1}$.

A.6 $\text{Supp } T \text{ nilp, } n = \dim V, T^{n-1} \neq 0$. Prove $\nexists S \in \mathcal{L}(V), S^k = T$ for all $k > 1$.

SOLUS: Asum $\exists S$ suth $S \Rightarrow S$ is nilp. Then $\text{null } S^n = \dots = \text{null } S^{kn} = \text{null } T^n = V$.

Now $\exists t \in \mathbf{N}$ with $(n-t)k \in \{n, \dots, kn\} \Rightarrow \text{null } T^{n-t} = \text{null } S^{nk-tk} = V$. \square

- (4E A.4) $\text{Supp } m_T$ is a multi of $(z - \lambda)^m$ with $m \in \mathbf{N}^+$. Prove $\dim \text{null}(T - \lambda I)^m \geq m$.

SOLUS: Becs λ is eigval of T . We show z^m is the min of $N = (T - \lambda I)|_{\text{null}(T - \lambda I)^m} \Rightarrow N^m = 0 \neq N^{m-1}$.

Let each $U_k \oplus \text{null } N^{k-1} = \text{null } N^k$ for $k \in \{2, \dots, m\} \Rightarrow U_k$ not inward $N \Rightarrow U_k$ non0.

Thus $\text{null } N^0 \subsetneq \text{null } N \subsetneq \dots \subsetneq \text{null } N^m \Rightarrow \dim \text{null}(T - \lambda I)^m = \dim \text{null } N^m \geq m$. \square

Or. Let $m_T(z) = (z - \lambda)^m q(z)$. We show $\{0\} \subsetneq \text{null}(T - \lambda I) \subsetneq \dots \subsetneq \text{null}(T - \lambda I)^m$ by ctradic.

Asum $\text{null}(T - \lambda I)^k = \text{null}(T - \lambda I)^{k+1}$ for $k \in \{1, \dots, m-1\}$.

Then $\text{null}(T - \lambda I)^k = \text{null}(T - \lambda I)^m \Rightarrow (T - \lambda I)^m q(T)v = 0 = (T - \lambda I)^k q(T)v$. \square

- (4E A.3) Prove $V = \text{null } T \oplus \text{range } T \iff \text{null } T^2 = \text{null } T$.

SOLUS: (a) $\text{null } T^2 = \text{null } T = \text{null } T^{\dim V} \Rightarrow \dim \text{range } T^{\dim V} = \dim \text{range } T$.

(b) $V = \text{null } T \oplus U, U = \text{range } T$, 又 $\dim \text{null } T^2 = \dim \text{null } T + \dim \text{null } T|_{\text{range } T}$. \square

Or. (a) $\text{Supp null } T^2 = \text{null } T$. Then $Tu \in \text{null } T \cap \text{range } T \iff T^2u = 0 \iff Tu = 0$.

(b) $\text{Supp null } T \cap \text{range } T = \{0\}$. Then $T^2u = 0 \iff Tu \in \text{null } T \iff Tu = 0$. ■

A.17 $\text{Supp range } T^m = \text{range } T^{m+1}$. Show $\text{range } T^m = \text{range } T^{m+1} = \dots$.

SOLUS: By Exe (A.19), $\text{null } T^m = \text{null } T^{m+1} = \dots \Rightarrow \dim \text{range } T^m = \dim \text{range } T^{m+1} = \dots$. \square

Or. Supp $w = T^{m+k}v$. Then becs $T^m v \in \text{range } T^{m+1}, \exists T^{m+1}u = T^m v$. Thus $w = T^{m+k+1}u$. ■

A.18 $\text{Supp dim } V = n$. Show $\text{range } T^n = \text{range } T^{n+1} = \dots$

By Exe (A.19), simlr. \square

SOLUS: Asum $\text{range } T^n \supsetneq \text{range } T^{n+1}$. By Exe (A.17), $V = \text{range } T^0 \supsetneq \text{range } T \supsetneq \dots \supsetneq \text{range } T^{n+1}$.

Now each $\dim \text{range } T^{k+1} \leq \dim \text{range } T^k - 1 \Rightarrow \dim \text{range } T^{n+1} \leq \dim \text{range } T^0 - (n+1)$. \square

A.10 $\text{Supp } T \text{ not nilp}, n = \dim V$. Show $V = \text{null } T^{n-1} \oplus \text{range } T^{n-1}$.

SOLUS: NOTICE that $\text{null } T^{n-1} \neq \text{null } T^n \Rightarrow \dim \text{null } T^n = \dim V$. Thus $\text{null } T^{n-1} = \text{null } T^n$.

又 $V = \text{null } T^n \oplus \text{range } T^n$, $\text{range } T^n \subseteq \text{range } T^{n-1} \Rightarrow V = \text{null } T^{n-1} + \text{range } T^{n-1}$. \square

Or. Then $\dim \text{range } T^{n-1} = \dim \text{range } T^n \Rightarrow \text{range } T^{n-1} = \text{range } T^n$. \square

Or. By Exe (4E A.3), $\text{null } T^{2(n-1)} = \text{null } T^{n-1} \Leftrightarrow V = \text{null } T^{n-1} \oplus \text{range } T^{n-1}$. \square

- (4E A.18) $\text{Supp } T \text{ nilp}$. Prove $T^{1+\dim \text{range } T} = 0$.

SOLUS: Let $\dim V = n$. Then $\dim \text{null } T^{n-1}|_{\text{range } T} + \dim \text{null } T = \dim V$.

Now $\text{null } T^{n-1}|_{\text{range } T} = \text{range } T \Rightarrow T|_{\text{range } T} \in \mathcal{L}(\text{range } T)$ is nilp. \square

Or. Let $\dim \text{range } T = k$. Asum $T^{k+1} \neq 0$. Let m be suth $T^m = 0 \neq T^{m-1}$. Then $k+2 \leq m$.

Let v be suth $T^{m-1}v \neq 0 = T^m v \Rightarrow (v, \underline{Tv, \dots, T^{m-1}v})$ liney indep $\Rightarrow k \geq m-1 \geq k+1$. \blacksquare

- (4E A.12) $\text{Supp every } v \in V \text{ is a g-eigvec of } T$. Prove $V = G(\lambda, T)$.

SOLUS: Becs for any liney indep $(v, w), (v, w, v+w)$ of g-eigvecs is liney dep; say corres α, β, γ repectly.

If $\alpha = \beta$ then done. If $\alpha = \gamma$, then $v, v+w \in G(\alpha, T) \Rightarrow w \in G(\alpha, T)$. If $\beta = \gamma$, then simlr.

Thus $\alpha = \beta = \gamma$. Any two liney indep v, w corres one eigval. \blacksquare

B.5 [4E A.15] Prove non0 T diag \Rightarrow each $G(\lambda, T) = E(\lambda, T)$.

Convly true if req $\mathbf{F} = \mathbf{C}$.

SOLUS: $\forall w \in G(\lambda_j, T), \exists! v_i \in E(\lambda_i, T), w = v_1 + \dots + v_m$.

Note that $(T - \lambda_j I)^k w = 0 = \sum_{i=1}^m (\lambda_i - \lambda_j)^k v_i \Rightarrow w = v_j \in E(\lambda_j, T)$. \square

Or. By (4E B.6), immed. Or. $\text{Supp } G(\lambda_j, T) \supseteq E(\lambda_j, T)$. Let $w \in G(\lambda_j, T) \setminus E(\lambda_j, T)$

Let $(T - \lambda_j I)^k w = 0 \neq (T - \lambda_j I)^{k-1} w$. By [5.B(I) TIPS (1)], m_T is a multi of $(z - \lambda_j)^k$. 又 $k \geq 2$ \square

- (4E A.16) $\text{Supp } S, T \in \mathcal{L}(V)$ nilp and commu. Prove $S + T, ST$ are nilp

SOLUS: By [4E 5.80], $\exists B_V$ suth S, T up-trig (with only 0's on diags). By (4E 5.C.2). \square

Or. Let $S^p = T^q = 0$. Becs S, T commu, $(ST)^{\max\{p, q\}} = 0 = (S + T)^{p+q} = \sum_{i=0}^{p+q} C_{p+q}^i S^i T^{p+q-i}$. \blacksquare

B.10 $\text{Supp } \mathbf{F} = \mathbf{C}$. Prove \exists commu $D, N \in \mathcal{L}(V)$, $T = D + N$, D diag, N nilp.

SOLUS: NOTE: D diag, N nilp $\not\Rightarrow D, N$ commu. EXA: $De_1 = e_1, De_2 = 0, Ne_1 = 0, Ne_2 = e_1$.

We use induc on $\dim V = n$. (i) Immed. (ii) $n > 1$. Asum it holds for smaller V .

Becs $V = G_1 \oplus U$, where $U = G_2 \oplus \dots \oplus G_m$, and each $G_k = G(\lambda_k, T)$.

$\exists B_{G_1}$ suth $T|_{G_1} = (T - \lambda_1 I)|_{G_1} + \lambda_1 I|_{G_1} = N_1 + D_1$ up-trig and N_1, D_1 commu.

\exists commu $D_2, N_2 \in \mathcal{L}(U)$, $T|_U = D_2 + N_2$, D_2 diag, N_2 nilp; wrto some B_U , by (4E 5.E.7).

Define $P_1, P_2 \in \mathcal{L}(V)$ by $P_1(v_1 + u) = v_1$, $P_2 = I - P_1$. Let $D = D_1 P_1 + D_2 P_2$, $N = N_1 P_1 + N_2 P_2$.

$D + N = (D_1 + N_1)P_1 + (D_2 + N_2)P_2 = T$, $DN = D_1 N_1 P_1 + D_2 N_2 P_2 = NP$. \square

Or. $\forall v \in V, \exists! v_k \in G_k, v = v_1 + \dots + v_m$. Define $D \in \mathcal{L}(V) : v \mapsto (\lambda_1 v_1 + \dots + \lambda_m v_m)$

Then $D|_{G_k} = \lambda_k I$. Let $N = T - D \Rightarrow N|_{G_k} = (T - D)|_{G_k} = (T - \lambda_k I)|_{G_k}$ is nilp $\Rightarrow N$ nilp.

Becs $DN = DT - D^2, ND = TD - D^2$, 又 each $TDv_k = \lambda_k T v_k = DT v_k \Rightarrow TD = DT$. \square

Or. Define $P_j \in \mathcal{L}(V) : w_j + u \mapsto w_j$, where $w_j \in G_j, u \in \bigoplus_{i \neq j} G_i$.

Now $T = T|_{G_1} P_1 + \dots + T|_{G_m} P_m$. Let $N_j = T|_{G_j} - \lambda_j I \Rightarrow N_1 P_1 + \dots + N_m P_m : v_{j,k} \mapsto N_k v_{j,k}$.

Where each $B_{G_k} = (v_{1,k}, \dots, v_{n_k, k})$. Let $D = \lambda_1 P_1 + \dots + \lambda_m P_m : v_{j,k} \mapsto \lambda_k v_{j,k}$.

Hence $T = D + N$, and $DN = ND : v_{j,k} \mapsto \lambda_k N_k v_{j,k}$. \square

- (4E B.7) *Supp λ is an eigval of T with multy d . Prove $G(\lambda, T) = \text{null}(T - \lambda I)^d$.*

SOLUS: Let $N = T - \lambda I$, and $\text{null } N \subsetneq \dots \subsetneq \text{null } N^m = \text{null } N^{m+1}$. Choose $B_{\text{null } N}$.

Extend to $B_{\text{null } N^2} \Rightarrow \dots \Rightarrow B_{\text{null } N^m}$, with each step adding at least one bss vec. Thus $m \leq d$. \square

Or. Let $m_T(z) = (z - \lambda)^m q(z)$ with $q(\lambda) \neq 0$.

Becs by (4E B.6), $G(\lambda, T) = \text{null}(T - \lambda I)^m$. Now by (4E A.4). \square

Or. Let the min of $N = (T - \lambda I)|_{G(\lambda, T)}$ be $z^m \Rightarrow$ the min of $N + \lambda I = T|_{G(\lambda, T)}$ is $s(z) = (z - \lambda)^m$.

Becs the char of T [See [9.21] for the case $\mathbf{F} = \mathbf{R}$] is a multi of m_T , which is a multi of s . \square

- (4E B.6) *Supp λ is an eigval of T . Explain why the expo of $(z - \lambda)$*

in the factoriz of m_T is the smallest $m \in \mathbf{N}^+$ suth $(T - \lambda I)^m|_{G(\lambda, T)} = 0$.

SOLUS: Each $(T - \alpha I)^k|_{G(\lambda, T)}$ are inv for $\alpha \neq \lambda$. Becs $m_T(T|_{G(\lambda, T)}) = 0 \Leftrightarrow (T - \lambda I)^k|_{G(\lambda, T)} = 0$. \square

Or. Let $m_T(z) = (z - \lambda)^m q(z)$, with $q(\lambda) \neq 0$. We show $\text{null}(T - \lambda I)^m \supseteq \text{null}(T - \lambda I)^{m+1}$.

$\text{Supp } v \in \text{null}(T - \lambda I)^{m+1} \Leftrightarrow (T - \lambda I)^m v \in \text{null}(T - \lambda I) = E(\lambda, T)$.

Then $0 = m_T(T)v = q(T)[(T - \lambda I)^m v] = q(\lambda)[(T - \lambda I)^m v] \Rightarrow v \in \text{null}(T - \lambda I)^m$.

Let k be suth $\text{null}(T - \lambda I)^k = G(\lambda, T) = \text{null}(T - \lambda I)^m$. Becs $(T - \lambda I)^k q(T) = 0 \Rightarrow k \geq m$. \square

NOTE: The expo of an irreducible ω in the factoriz of m_T is the smallest m suth $\omega^m(T)|_{\text{null } \omega(T)} = 0$.

- *Supp $\lambda_1, \dots, \lambda_m$ are the disti eigvals of T .*

- **B.TIPS 1:** *Supp $\mathbf{F} = \mathbf{C}$, U invars pd T . Prove $U = G(\lambda_1, T|_U) \oplus \dots \oplus G(\lambda_m, T|_U)$.*

SOLUS: We use induc on $\dim U = N$. (i) Immed. (ii) $N > 1$. Asum it holds for smaller U .

$\text{Supp } \lambda_1$ is an eigval of $T|_U$. Let $W \oplus G(\lambda_1, T|_U) = U$, where $W = \text{range}(T|_U - \lambda_1 I)^N$ invard $T|_U$.

Note that $T|_U|_W = T|_W$. By asum, $W = G(\lambda_2, T|_W) \oplus \dots \oplus G(\lambda_m, T|_W)$.

Now we show $G(\lambda_k, T|_U) \subseteq G(\lambda_k, T|_W)$ for each $k \in \{2, \dots, m\}$.

$\forall v \in G(\lambda_k, T|_U), \exists ! u_1 \in G(\lambda_1, T|_U), w_k \in G(\lambda_k, T|_W), v = u_1 + w_k$. By [8.13]. \square

COMMENT: Note that generally, $X \oplus Y \supseteq U \neq (X \cap U) \oplus (Y \cap U)$, and $(X + U) \cap (Y + U) \neq U$.

- **B.TIPS 2:** *Supp $V = U \oplus W$, and U, W inward T . Then $G(\lambda, T) = G(\lambda, T|_U) \oplus G(\lambda, T|_W)$.*

- **B.TIPS 3:** *Supp $\mathbf{F} = \mathbf{C}$, and $q(z) = (z - \lambda_1)^{\alpha_1} \dots (z - \lambda_k)^{\alpha_k}$.*

Let $F_j = \text{null}(T - \lambda_j I)^{\alpha_j}$. Prove $\text{null } q(T) = F_1 \oplus \dots \oplus F_m$.

SOLUS: Each $(T - \lambda_k I)^{\alpha_k}|_{G(\lambda_j, T)}$ is inje for $k \neq j \Rightarrow \text{null } q(T)|_{G(\lambda_j, T)} = F_j$. Or. By [B TIPS (1,4)]. \blacksquare

- *Supp $p, q \in \mathcal{P}(\mathbf{F})$ have no common zeros on \mathbf{C} .*

- **B.TIPS 4:** (a) *Prove $\text{null } p(T) \oplus \text{null } q(T) = \text{null}(pq)(T)$, $\text{range } p(T) + \text{range } q(T) = V$.*
 (b) *Prove $\text{range } p(T) \cap \text{range } q(T) = \text{range}(pq)(T)$.*

SOLUS: (a) By Exe (4E 4.13), $\forall v \in V, v = r(T)p(T)v + s(T)q(T)v$.

(b) $v \in \text{range } p(T) \cap \text{range } q(T) \Rightarrow \exists u, w \in V, v = p(T)u = q(T)w = (pq)(T)(r(T)w + s(T)u)$. \blacksquare

CORO: $\text{Supp } (pq)(T) = 0$. We show $\text{null } p(T) = \text{range } q(T)$.

Becs '⊇' holds $\Rightarrow \text{null } q(T) \cap \text{range } p(T) = \{0\}$. By (5.C.3) and [1.C TIPS (1)]. \square

$\text{Supp } (p_1 \dots p_k)(T) = 0$, and $p_1, \dots, p_k \in \mathcal{P}(\mathbf{F})$ have no common zeros on \mathbf{C} .

(c) Each $\text{null } p_j(T) = \text{range}(\prod_{i \neq j}^k p_i)(T) = \bigcap_{i \neq j}^k \text{range } p_i(T)$. Or. By (d).

(d) Each $\text{range } p_j(T) = \bigoplus_{i \neq j}^k \text{null } p_i(T)$. Note that $V = \text{null } p_j(T) \oplus [\bigoplus_{i \neq j}^k \text{null } p_i(T)]$. \square

- **NOTE:** If $(pq)(T) = 0$. Let $V_C = G(\lambda_1, T_C) \oplus \dots \oplus G(\lambda_m, T_C)$, and $m_T(z) = (z - \lambda_1)^{k_1} \dots (z - \lambda_m)^{k_m}$. Let $\mathcal{A} = \{\alpha_1, \dots, \alpha_A\}$ be the intersec of the zeros of p and the eigvals of T . Simlr for \mathcal{B} . Then $\mathcal{A} \cap \mathcal{B} = \emptyset$. Let $p = \omega_{\alpha_1} \dots \omega_{\alpha_A} p_0$, $q = \omega_{\beta_1} \dots \omega_{\beta_B} q_0$, where $\omega_{\lambda_i}(z) = (z - \lambda_i)^{k_i}$. By [B TIPS (3)], $\text{null } p(T_C) = G(\alpha_1, T_C) \oplus \dots \oplus G(\alpha_A, T_C)$. Simlr for $q(T_C)$. For $F = R$, if $\exists \alpha_j \notin R$, then $\exists \alpha_i = \bar{\alpha}_j$. Simlr for \mathcal{B} . Now $V_C = \text{null } p(T_C) \oplus \text{null } q(T_C)$.

- **NOTE FOR [8.55]:** $\text{Supp } N^m = 0 \neq N^{m-1}$. Let each $\text{null } N^k = \text{null } N^{k-1} \oplus U_k$ for $k \in \{2, \dots, m\}$.
 - (1) Start by $B_{U_m} = (v_{1,1}, \dots, v_{n_1,1})$. But $(Nv_{1,1}, \dots, Nv_{n_1,1})$ might be liney dep. Invalid method.
 - (2) $\mathcal{M}(N, B_{\text{null } N} \cup B_{U_2} \cup \dots \cup B_{U_m})$ is a block up-trig matrix with the diag blocks all zero.
- **NOTE FOR Exe (D.6):** Let $B = (N^{m_1}v_1, \dots, N^{m_1-k}v_1, \dots, N^{m_n}v_n, \dots, N^{m_n-k}v_n)$, $0 \leq k \leq \min\{m_1, \dots, m_n\}$. All liney indep in $\text{null } N^{k+1}$. $\text{Supp } N^{k+1}$ sends a liney combina of the Jordan B_V to zero. Then all coeffs of $N^{m_1-k-i}v_k$ are zero. Thus $\text{null } N^{k+1} \subseteq \text{span } B$. Now B is a bss of $\text{null } N^{k+1}$.

C.20 [4E B.20] *Supp F = C, and each V_k non0 invarsps of $V = V_1 \oplus \dots \oplus V_m$.*

Let p_k be the char of $T|_{V_k}$. Prove the char of T is $p_1 \dots p_m$.

- SOLUS:** By [B TIPS (1)], $V = G(\lambda_1, T) \oplus \dots \oplus G(\lambda_n, T) \Rightarrow V_k = G(\lambda_1, T|_{V_k}) \oplus \dots \oplus G(\lambda_n, T|_{V_k})$. By [B TIPS (2)], each $G(\lambda_j, T) = G(\lambda_j, T|_{V_1}) \oplus \dots \oplus G(\lambda_j, T|_{V_m})$. Let $d_{j,k}$ be the multy of λ_j of $T|_{V_k}$. Then $d_{j,1} + \dots + d_{j,n} = d_j$, the multy of λ_j of T . Thus each $p_k(z) = (z - \lambda_1)^{d_{1,k}} \dots (z - \lambda_n)^{d_{n,k}}$. While the char of T is $(z - \lambda_1)^{d_1} \dots (z - \lambda_n)^{d_n}$. □
OR. Let A be a block diag matrix of T , with each $A_k = \mathcal{M}(T|_{V_k})$ up-trig. By Exe (B.11). □

D.8 *Supp F = C. Prove \nexists non0 invarsps U, W suth $U \oplus W = V \iff m_T(z) = (z - \lambda)^{\dim V}$.*

SOLUS: Let $N = T - \lambda I \Rightarrow$ the min of N is $z^{\dim V}$.

Then by Exe (D.3), the line directly above the diag of *any* Jordan $\mathcal{M}(N)$ is all 1.

Thus the only Jordan block of $\mathcal{M}(N)$ is $\mathcal{M}(N)$ itself. Convly true as well. □

OR. (a) If \exists two or more eigvals of $T|_U$ or $T|_W$, then m_T has two or more disti factors, done.

Now supp \exists only one eigval λ for $T|_U$, $T|_W$, and T . $\text{Supp } m_T(z) = (z - \lambda)^m$.

Let $M = \max\{\dim U, \dim W\}$. Let $S = (T - \lambda I)^M \Rightarrow \text{null } S|_U \oplus \text{null } S|_W = \text{null } S$.

Becs $G(\lambda, T|_U) = U$, $G(\lambda, T|_W) = W$, $G(\lambda, T) = V \Rightarrow S = 0$. Now by Exe (4E B.6).

OR. Becs \exists Jordan $\mathcal{M}(T|_U)$, $\mathcal{M}(T|_W) \Rightarrow$ Jordan $\mathcal{M}(T)$. Consider z^M by Exe (D.3).

(b) Supp T has only one eigval. Let $m_T(z) = (z - \lambda)^m$ with $m < \dim V$.

Becs \exists Jordan $B_V = (\underbrace{v_{1,1}, \dots, v_{m_1,1}}_{\text{bss for } U}, \underbrace{v_{1,2}, \dots, v_{m_2,2}, \dots, v_{1,k}, \dots, v_{m_k,k}}_{\text{bss for } W})$ for T . □

ENDED

9.A NOTE: V denotes a finite non0 vecsp over \mathbf{F} .

- **NOTE FOR [9.10]:** Let $q \in \mathcal{P}(\mathbf{C})$ be the min of T_C . Note that $A = \mathcal{M}(T_C) = \mathcal{M}(T)$.

Then $q(A) = 0 = \overline{q(A)} = \bar{q}(A) \Rightarrow \bar{q}(T_C) = q(T_C) = 0 \Rightarrow q = \bar{q} \Rightarrow q \in \mathcal{P}(\mathbf{R})$. 又 $q(T) = 0$.

- **NOTE FOR [9.12]:** Another proof: $\overline{T_C(u + iv)} = \overline{Tu + iTv} = Tu - iTv = T_C(\overline{u + iv})$.

$$(T_C - \lambda I)(u + iv) = \overline{T_C(u + iv) - \lambda(u + iv)} = T_C(u - iv) - \bar{\lambda}(u - iv) = (T_C - \bar{\lambda}I)(\overline{u + iv}).$$

We use induc on m to show $(T_C - \lambda I)^m(u + iv) = (T_C - \bar{\lambda}I)^m(\overline{u + iv})$. (i) Immed. (ii) $m > 1$.

Asum it holds for $(m - 1)$. Let $(T_C - \lambda I)^{m-1}(u + iv) = x + iy \Rightarrow (T_C - \bar{\lambda}I)^{m-1}(\overline{u + iv}) = x - iy$.

Then $\overline{(T_C - \lambda I)^m(u + iv)} = \overline{(T_C - \lambda I)(x + iy)} = (T_C - \bar{\lambda}I)(x - iy) = (T_C - \bar{\lambda}I)^m(\overline{u + iv})$. \square

- **NOTE FOR [9.17]:** Detailed proof:

Let $B = (u_1 + iv_1, \dots, u_m + iv_m)$ be a bss of $G(\lambda, T_C)$. By [9.12], $\overline{B} = (u_1 - iv_1, \dots, u_m - iv_m)$ in $G(\bar{\lambda}, T_C)$.

(a) If $a_1(u_1 - iv_1) + \dots + a_m(u_m - iv_m) = 0$. Conjuging, now each $\overline{a_k} = 0$. Liney indep.

(b) $\forall u - iv \in G(\bar{\lambda}, T_C), u + iv \in G(\lambda, T_C) \Rightarrow u + iv \in \text{span}B \Rightarrow u - iv \in \text{span}\overline{B}$. \square

13 $\text{Supp } \mathbf{F} = \mathbf{R}, T \in \mathcal{L}(V)$, and $b^2 < 4c$. Let $q(z) = z^2 + bz + c = (z - \lambda)(z - \bar{\lambda})$.

Prove $\dim \text{null } q(T)^j$ is even for each $j \in \mathbf{N}^+$.

[See also NOTE FOR [4E 5.33] in (5.BI).]

SOLUS: By [8.B TIPS (3)], $\text{null } q(T_C)^j = \text{null}(T_C - \lambda I)^j \oplus \text{null}(T_C - \bar{\lambda}I)^j$. By [9.17] and [9.4]. \square

NOTE: Let $Q(\lambda, T) = \text{null } q(T)^{\dim V}$. Then by (4E 8.B.6,7) for T_C , by [9.10,20], and by [8.B TIPS (4)],

(a) $Q(\lambda, T) = \text{null } q(T)^d$, where $d = \dim G(\lambda, T_C)$.

(b) The expo of q in the factoriz of m_T is the smallest $m \in \mathbf{N}^+$ suth $q(T)^m|_{Q(\lambda, T)} = 0$.

(c) $m_T = p_1^{\alpha_1} \cdots p_m^{\alpha_m} q_1^{\beta_1} \cdots q_M^{\beta_M} \iff V = [\bigoplus_{j=1}^m G(\mu_j, T)] \oplus [\bigoplus_{k=1}^M Q(\lambda_k, T)]$.

Where each $p_j(z) = z - \mu_j$, $q_k(z) = z^2 - 2(\text{Re } \lambda_k)z + |\lambda_k|^2 = z^2 + b_k z + c_k$.

Fix one k . Let $q(z) = q_k(z) = (z - \lambda)(z - \bar{\lambda}), \lambda = a + bi, G = G(\lambda, T_C), \overline{G} = G(\bar{\lambda}, T_C)$.

Replace T with $T|_Q$. Let $Q = Q(\lambda, T)$ of dim β , and $Q_C = G \oplus \overline{G}$, and Jordan bss B_J of Q_C .

Now $\mathcal{M}(T_C) = \begin{pmatrix} A_1 & 0 \\ 0 & A_2 \end{pmatrix}, \mathcal{M}(T_C - \lambda I) = \begin{pmatrix} \overline{R_1} & 0 \\ 0 & R_2 \end{pmatrix}, \mathcal{M}(T_C - \bar{\lambda}I) = \begin{pmatrix} R_2 & 0 \\ 0 & R_1 \end{pmatrix}$ wrto Jordan bss.

So then $\mathcal{M}(T_C^2 + bT_C + cI) = \mathcal{M}(T_C - \lambda I)\mathcal{M}(\overline{T_C - \lambda I}) = \begin{pmatrix} R & 0 \\ 0 & \overline{R} \end{pmatrix}$, where $R = R_1R_2$.

Where A_1, R_1, R_2, R are block diag matrices, and $A_1 = \mathcal{M}(T_C|_G), A_2 = \mathcal{M}(T_C|\overline{G}) = \overline{\mathcal{M}(T_C|_G)}$.

Each $A_{1,k} = \begin{pmatrix} \lambda & 1 & 0 \\ \ddots & \ddots & 1 \\ 0 & \ddots & \lambda \end{pmatrix}, R_{1,k} = \begin{pmatrix} 0 & 1 & 0 \\ \ddots & \ddots & 1 \\ 0 & \ddots & 0 \end{pmatrix}, R_{2,k} = \begin{pmatrix} 2bi & 1 & 0 \\ \ddots & \ddots & 1 \\ 0 & \ddots & 2bi \end{pmatrix}, R_k = \begin{pmatrix} 0 & 2bi & 1 & 0 \\ 0 & \ddots & \ddots & 1 \\ \vdots & 0 & \ddots & 2bi \\ 0 & 0 & \cdots & 0 \end{pmatrix}$.

Let the Jordan bss Q_C for T_C be $(u_1 + iv_1, \dots, u_\beta + iv_\beta, u_1 - iv_1, \dots, u_\beta - iv_\beta)$.

Now due to $\mathcal{M}(T_C), T(u_1 \pm iv_1) = (a \pm bi)(u_1 \pm iv_1) = (au_1 - bv_1) \pm i(bu_1 + av_1)$,

$T(u_j \pm iv_j) = (a \pm bi)(u_j \pm iv_j) + (u_{j-1} \pm iv_{j-1}) = (au_j - bv_j + u_{j-1}) \pm i(bu_j + av_j + v_{j-1})$.

Hence $Tu_1 = au_1 - bv_1, Tv_1 = bu_1 + av_1$, and $Tu_j = u_{j-1} + au_j - bv_j, Tv_j = v_{j-1} + bu_j + av_j$.

Let $B_Q = (u_1, v_1, \dots, u_\beta, v_\beta) \Rightarrow \mathcal{M}(T, B_Q) = \begin{pmatrix} \mathcal{R} & I_2 & 0 \\ \ddots & \ddots & I_2 \\ 0 & \ddots & \mathcal{R} \end{pmatrix}$, where $\mathcal{R} = \begin{pmatrix} a & b \\ -b & a \end{pmatrix}$ and $I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$.

Or $B_Q = (v_1, u_1, \dots, v_\beta, u_\beta) \Rightarrow \mathcal{R} = \begin{pmatrix} a & -b \\ b & a \end{pmatrix}$.

6.A

- (a) $\|u + v\|^2 = \|u\|^2 + \|v\|^2 + 2\operatorname{Re}\langle u, v \rangle$. $\|u + iv\|^2 = \|u\|^2 + \|v\|^2 + 2\operatorname{Im}\langle u, v \rangle$.
- (b) $\|u\| - \|v\| \leq \|u - v\|$. Equa $\iff u = cv$, $c > 0$. Where $u, v \neq 0$.
- (c) $\|v\| - 1 = \|v - v/\|v\|\| \leq \|v - u\|$ if $\|u\| = 1$. Equa $\iff u = v/\|v\|$.
- (d) $\|u\|^2 - \|v\|^2 = |\langle u + v, u - v \rangle| \leq \|u + v\| \|u - v\| \leq \|u\|^2 + \|v\|^2 = \frac{1}{2} [\|u + v\|^2 + \|u - v\|^2]$.

21 Implement the corres inner prod from a norm $\|\cdot\| : U \rightarrow [0, \infty)$ satisfying [6.22].

SOLUS: If $F = R$. Define $\langle u, v \rangle = \frac{1}{4} (\|u + v\|^2 - \|u - v\|^2) = \langle v, u \rangle$. Before we start:

$$1. \langle u, v \rangle = -\langle -u, v \rangle = -\langle u, -v \rangle.$$

$$\begin{aligned} 2. \langle u + v, v \rangle &= \frac{1}{4} [\|u + v + v\|^2 + \| -u + v + v\|^2 - \| -u + v + v\|^2 - \|u + v - v\|^2] \\ &= \frac{1}{2} [(\|u\|^2 + \|2v\|^2) - (\|-u + v\|^2 + \|v\|^2)] \\ &= \frac{1}{4} [2\|u\|^2 + 2\|v\|^2 + 4\|v\|^2 - 2\|u - v\|^2] = \frac{1}{4} (\|u + v\|^2 - \|u - v\|^2) + \|v\|^2. \end{aligned}$$

$$\begin{aligned} 3. \langle u, 2v \rangle &= \frac{1}{4} [\|u + v + v\|^2 - \|u - v - v\|^2] \\ &= \frac{1}{4} [\|u + v + v\|^2 + \|u + v - v\|^2 - \|u + v - v\|^2 - \|u - v - v\|^2] \\ &= \frac{1}{2} [(\|u + v\|^2 + \|v\|^2) - (\|u - v\|^2 + \|v\|^2)] = 2\langle u, v \rangle. \end{aligned}$$

$$\text{Add: } \langle u + w, v \rangle = \langle u, v \rangle + \langle w, v \rangle.$$

$$\text{We show } \|u + w + v\|^2 - \|u + w - v\|^2 = \|u + v\|^2 + \|w + v\|^2 - \|u - v\|^2 - \|w - v\|^2.$$

$$RHS = \frac{1}{2} (\|u + w + 2v\|^2 + \|u - w\|^2) - \frac{1}{2} (\|u + w - 2v\|^2 + \|u - w\|^2) = 2\langle u + w, 2v \rangle = LHS.$$

$$\text{Homo: } \langle \lambda u, v \rangle = \lambda \langle u, v \rangle. \text{ True by add if } \lambda \in N, \text{ and then by (1) if } \lambda \in Z.$$

$$\text{Note that by add, } n \cdot \langle n^{-1}u, v \rangle = \langle u, v \rangle \text{ for } n \in N^+. \text{ Thus the case for } \lambda \in Q^+ \text{ holds, so for } Q.$$

$$\text{We show the case for } \lambda \in R. \text{ By def, } \exists! (a_n)_{n=0}^\infty \in Q^\infty \text{ suth } \lim_{n \rightarrow \infty} a_n = \lambda.$$

$$4\lambda \langle u, v \rangle = 4 \lim_{n \rightarrow \infty} a_n \langle u, v \rangle = 4 \lim_{n \rightarrow \infty} \langle a_n u, v \rangle = \lim_{n \rightarrow \infty} [\|a_n u + v\|^2 - \|a_n u - v\|^2].$$

$$\text{To show } \lim_{n \rightarrow \infty} \|a_n u + v\| = \|\lambda u + v\|, \text{ so then } \lambda \langle u, v \rangle = \langle \lambda u, v \rangle.$$

$$\text{NOTICE that } \|u \pm v\| \leq \|u\| + \|v\| \Rightarrow \|u\| - \|v\| \leq \|u \pm v\|.$$

$$\text{Thus } |\lim_{n \rightarrow \infty} \|a_n u + v\| - \|\lambda u + v\| | \leq \|\lim_{n \rightarrow \infty} a_n v - \lambda v\| = 0.$$

$$\text{If } F = C. \text{ Define } \langle u, v \rangle = R(u, v) + iI(u, v).$$

$$\text{Where } R(u, v) = \frac{1}{4} (\|u + v\|^2 - \|u - v\|^2) \text{ and } I(u, v) = R(u, iv) = \frac{1}{4} (\|u + iv\|^2 - \|u - iv\|^2).$$

$$\text{Conjug Symm: } \langle u, v \rangle = R(u, v) + iI(u, v) = R(v, u) - iI(v, u) = \overline{\langle v, u \rangle}$$

$$\text{Note that } R(u, v) = R(v, u) \text{ and } R(v, iu) = R(iu, v). \text{ Thus we show } -I(u, v) = I(v, u).$$

$$\text{Which equiv } \|u - iv\|^2 - \|u + iv\|^2 = \|i(-iu - v)\|^2 - \|i(-iu + v)\|^2 = \|iu + v\|^2 - \|iu - v\|^2.$$

$$\text{Homo: } \langle \lambda u, v \rangle = \lambda \langle u, v \rangle. \text{ True if } \lambda \in R. \text{ We show the case for } \lambda = i.$$

$$\begin{aligned} \langle iu, v \rangle &= \frac{1}{4} [\|iu + v\|^2 - \|iu - v\|^2 + i(\|iu + iv\|^2 - \|iu - iv\|^2)] \\ &= \frac{1}{4} [\|u - iv\|^2 - \|u + iv\|^2 + i(\|u + v\|^2 - \|u - v\|^2)] \\ &= i \frac{1}{4} [-i\|u - iv\|^2 + i\|u + iv\|^2 + (\|u + v\|^2 - \|u - v\|^2)] = i \langle u, v \rangle \end{aligned}$$

□

3 Supp $F = R, V \neq \{0\}$. Replace the positivity cond in [6.3] with $\exists v \in V, \langle v, v \rangle > 0$.

Show this does not change the inner prods from $V \times V$ to R .

SOLUS: Supp $w \in V$ with $\langle w, w \rangle > 0$. Asum $\exists u \in V$ with $\langle u, u \rangle < 0$.

Define $p(x) = \langle u + xw, u + xw \rangle = \langle w, w \rangle x^2 + 2\langle u, w \rangle x + \langle u, u \rangle \Rightarrow$ two disti zeros.

Supp $\langle u + \lambda w, u + \lambda w \rangle = 0 \Rightarrow u + \lambda w = 0 \Rightarrow \langle u, u \rangle = \lambda^2 \langle -w, -w \rangle \geq 0$, ctradic.

□

6 Supp $u, v \in V$. Prove $\|u\| \leq \|u + av\|$ for all $a \in \mathbf{F} \Rightarrow \langle u, v \rangle = 0$.

SOLUS: Becs $\|u\|^2 \leq \|u + av\|^2$. Let $\langle u - cv, cv \rangle = 0 \Rightarrow \|u - cv\|^2 = \langle u, u - cv \rangle = \|u\|^2 - \bar{c}\langle u, v \rangle$.

$$\text{Thus } \|u\|^2 \leq \|u - cv\|^2 = \|u\|^2 - |\langle u, v \rangle|^2 / \|v\|^2.$$

$$\text{OR. } \|u\|^2 \leq \|u\|^2 + |a|^2 \|v\|^2 + 2\operatorname{Re} \bar{a}\langle u, v \rangle \Rightarrow -2\operatorname{Re} \bar{a}\langle u, v \rangle \leq |a|^2 \|v\|^2 \text{ for all } a \in \mathbf{F}.$$

$$\text{Let } a = -\langle u, v \rangle \Rightarrow 2|\langle u, v \rangle|^2 \leq |\langle u, v \rangle|^2 \|v\|^2. \text{ If } \langle u, v \rangle \neq 0, \text{ then } 2 \leq \|v\|^2; \text{ might not be true.}$$

• TIPS 1: Supp $u, v \in V$, $\|xu + yv\|^2 = |x|^2\|u\|^2 + |y|^2\|v\|^2$ for $x, y \in \mathbf{F}$. Prove $\langle u, v \rangle = 0$.

SOLUS: Becs $\operatorname{Re}(xy\langle u, v \rangle) = 0$. Take $(x, y) = (1, 1)$ and $(i, 1)$. OR. By Exe (6), immed. \square

• TIPS 2: Supp $A \in \mathbf{F}^{m,n}$. Prove $\|Ax\|^2 \leq \sum_{j=1}^m \sum_{k=1}^n |A_{j,k}|^2 \cdot \|x\|^2$ for all $x \in \mathbf{F}^{m,1}$.

SOLUS: $\|Ax\|^2 = \|A_{\cdot,1}x_1 + \dots + A_{\cdot,n}x_n\|^2 = \sum_{j=1}^m |x_1 A_{j,1} + \dots + x_n A_{j,n}|^2 \leq \sum_{j=1}^m \|A_{j,\cdot}\|^2 \cdot \|x\|^2$. \square

• (4E 23) Supp $v_1, \dots, v_m \in V$, each $\|v_k\| \leq 1$. Show $\exists a_k = \pm 1$, $\|a_1 v_1 + \dots + a_m v_m\| \leq \sqrt{m}$.

SOLUS: We use induc on m . (i) $m = 1$. Immed. (ii) $m > 1$. Asum it holds for smaller m .

$$\text{Let } u = a_1 v_1, w = a_2 v_2 + \dots + a_m v_m \Rightarrow \|u\|^2 \leq 1, \|w\|^2 \leq m - 1.$$

$$\text{Then } \|u + w\|^2 + \|u - w\|^2 \leq 2m. \text{ OR. } \|u + w\| \cdot \|u - w\| \leq m.$$

• Supp u, v_1, \dots, v_n are non0 in V suth each $\langle v_i, u \rangle > 0$ and $\langle v_i, v_j \rangle \leq 0$ for $i \neq j$. Show (v_1, \dots, v_n) liney indep.

SOLUS: (i) Asum $v_1 = cv_2$. Then $\langle cv_2, u \rangle > 0 \Rightarrow c > 0$, while $\langle v_1, v_1 \rangle = c\langle v_2, v_1 \rangle \geq 0 \Rightarrow c \leq 0$. ctradic.

(ii) Asum (v_1, \dots, v_{n-1}) liney indep. Asum $v_n = c_1 v_1 + \dots + c_{n-1} v_{n-1}$.

Then $\langle v_n, u \rangle = c_1 \langle v_1, u \rangle + \dots + c_{n-1} \langle v_{n-1}, u \rangle > 0$. Thus we can choose all $c_k \in \mathbf{R}$.

Write $c_1 v_1 + \dots + c_n v_n = 0$, $c_n = -1$. Let $P = \{i : c_i \geq 0\}$, $N = \{i : c_i < 0\}$.

Then $\sum_{j \in P} c_j v_j = \sum_{k \in N} -c_k v_k \Rightarrow 0 \leq \langle \sum_{j \in P} c_j v_j, \sum_{k \in N} -c_k v_k \rangle = \sum -c_j c_k \langle v_j, v_k \rangle \leq 0$.

While $\langle \sum_{j \in P} c_j v_j, u \rangle, \langle \sum_{k \in N} -c_k v_k, u \rangle \geq 0$, where the equas hold \Leftrightarrow all $c_i = 0$. \square

6.B

14 Supp (e_1, \dots, e_m) orthon, each $v_j \in V$ suth $\|e_j - v_j\| < \frac{1}{\sqrt{m}}$. Show (v_1, \dots, v_m) liney indep.

SOLUS: Let $a_1 v_1 + \dots + a_m v_m = 0$.

$$\sum_{j=1}^m |a_j|^2 = \left\| \sum_{j=1}^m a_j (e_j - v_j) \right\|^2 \leq \left[\sum_{j=1}^m |a_j| \cdot \|e_j - v_j\| \right]^2 \leq \left\| (|a_j|)_{j=1}^m \right\|^2 \cdot \left\| (\|e_j - v_j\|)_{j=1}^m \right\|^2. \quad \square$$

ExA: Let $v_j = e_j - (e_1 + \dots + e_m)/m \Rightarrow \|e_j - v_j\|^2 = 1/m$. Note that $v_1 + \dots + v_m = 0$. \square

• For orthog non0 (e_1, \dots, e_m) , if $v = a_1 e_1 + \dots + a_m e_m \Rightarrow \langle v, e_k \rangle = a_k \|e_k\|^2$, $v = \frac{\langle v, e_1 \rangle}{\|e_1\|^2} e_1 + \dots + \frac{\langle v, e_m \rangle}{\|e_m\|^2} e_m$.

Now $\|v\|^2 = \frac{|\langle v, e_1 \rangle|^2}{\|e_1\|^2} + \dots + \frac{|\langle v, e_m \rangle|^2}{\|e_m\|^2}$. Replace each e_k with $\|e_k\|^{-1} e_k$, now (e_1, \dots, e_m) is a orthon list.

• Supp (e_1, \dots, e_m) orthog, $v \in V$. Show $\sum_{k=1}^m (1 - \|e_k\|^2) |\langle v, e_k \rangle|^2 \leq \|v\|^2 - \sum_{k=1}^m |\langle v, e_k \rangle|^2$.

SOLUS: Let $u = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_m \rangle e_m \Rightarrow \|u\|^2 = \sum_{k=1}^m \|e_k\| |\langle v, e_k \rangle|^2$, $\langle u, v \rangle = \sum_{k=1}^m |\langle v, e_k \rangle|^2$.

$$\text{Let } \|v - u\|^2 = \|v\|^2 + \|u\|^2 - \langle v, u \rangle - \langle u, v \rangle = \|v\|^2 + \sum_{k=1}^m (\|e_k\|^2 - 2) |\langle v, e_k \rangle|^2 \geq 0. \quad \square$$

CORO: If orthon, $\langle u, v - u \rangle = 0 \Rightarrow \|v\|^2 = \|u\|^2 + \|v - u\|^2$.

Bessel's Inequa: $\sum_{k=1}^m |\langle v, e_k \rangle|^2 \leq \|v\|^2$. [Exe (2)] Equa $\Leftrightarrow v \in \operatorname{span}(e_1, \dots, e_m)$.

- (4E9) $\text{Supp } (e_1, \dots, e_m)$ is the result of applying [6.31] to a liney indep (v_1, \dots, v_m) in V . Show each $\langle v_j, e_j \rangle > 0$.

SOLUS: Let $f_j = v_j - \langle v_j, e_1 \rangle e_1 - \dots - \langle v_j, e_{j-1} \rangle e_{j-1}$.

Becs $\|f_j\| \langle v_j, e_j \rangle = \langle v_j, f_j \rangle = \|v_j\|^2 - |\langle v_j, e_1 \rangle|^2 - \dots - |\langle v_j, e_{j-1} \rangle|^2 \geq 0$, by Bessel's Inequa.

If $\langle v_j, f_j \rangle = 0$, then by Exe (2), $v_j \in \text{span}(e_1, \dots, e_{j-1}) = \text{span}(v_1, \dots, v_{j-1})$. 又 $\|f_j\| \neq 0$. \square

NOTE: $\text{Supp } (v_1, \dots, v_m)$ liney dep. Let j be the largest suth (v_1, \dots, v_{j-1}) liney indep.

Apply [6.31]. Now $v_j \in \text{span}(v_1, \dots, v_{j-1}) = \text{span}(e_1, \dots, e_{j-1}) \Rightarrow f_j = 0$.

- **TIPS:** $\text{Supp } (v_1, \dots, v_m)$ liney indep in V . Get the corres orthon (e_1, \dots, e_m) via [6.31].

Let $S = \{\lambda \in \mathbb{F} : |\lambda| = 1\}$. Supp orthon (u_1, \dots, u_m) suth each $\text{span}(u_1, \dots, u_k) = \text{span}(v_1, \dots, v_k)$.

We show it equals $(c_1 e_1, \dots, c_m e_m)$ for some $(c_1, \dots, c_m) \in S^m$ by induc on k .

(i) $k = 1$. $\text{span}(e_1) = \text{span}(u_1) \Rightarrow u_1 = \langle u_1, e_1 \rangle e_1$, 又 $|\langle u_1, e_1 \rangle| = 1$. Let $c_1 = \langle u_1, e_1 \rangle$.

(ii) $k > 1$. Asum each $|c_i| = 1$ and $c_i e_i = u_i$ for $i \in \{1, \dots, k-1\}$.

Becs $u_k = \langle u_k, e_1 \rangle e_1 + \dots + \langle u_k, e_k \rangle e_k$. 又 $\langle u_i, u_k \rangle = 0 = c_i \langle e_i, u_k \rangle$. Simlr, $c_k = \langle u_k, e_k \rangle$. \square

- (4E10) $\text{Supp } (v_1, \dots, v_m)$ liney indep. Explain why the orthon list produced by [6.31] is the only orthon (e_1, \dots, e_m) suth each $\langle v_k, e_k \rangle > 0$ and $\text{span}(v_1, \dots, v_k) = \text{span}(e_1, \dots, e_k)$.

SOLUS: Supp such orthon $B_1 = (e_1, \dots, e_m)$. Apply [6.31] to get $B_2 = (u_1, \dots, u_m)$. We show $B_1 = B_2$.

Step 1 Becs $e_1 = cv_1 \Rightarrow c = \langle v_1, e_1 \rangle > 0$, 又 $|c| = 1/\|v_1\|$. Immed.

Step k Let $v_k = a_1 e_1 + \dots + a_k e_k \Rightarrow$ each $a_j = \langle v_k, e_j \rangle$. Let $f_k = v_k - a_1 e_1 - \dots - a_{k-1} e_{k-1}$.

Becs $e_k = f_k/a_k \Rightarrow \|f_k\|^2/|a_k|^2 = 1 \Rightarrow |a_k| = \|f_k\|$. 又 $a_k = \langle v_k, e_k \rangle > 0 \Rightarrow a_k = \|f_k\|$. \square

10 $\text{Supp } \mathbf{F} = \mathbf{R}, (v_1, \dots, v_m)$ is liney indep in V .

Prove \exists exactly 2^m orthon lists spans $\text{span}(v_1, \dots, v_m)$.

SOLUS: Using induc on m . (i) $m = 1$. Let $e_1 = \pm v_1/\|v_1\|$. (ii) $m > 1$. Asum it holds for $(m-1)$.

Get 2^{m-1} orthon lists corres (v_1, \dots, v_{m-1}) . Fix one as (e_1, \dots, e_{m-1}) and apply [6.31] at step m .

$\text{Supp } (e_1, \dots, e_{m-1}, e'_m)$ is also orthon. NOTICE that $e'_m = \langle e'_m, e_m \rangle e_m$. So $|\langle e'_m, e_m \rangle| = 1$.

Let $e'_m = -e_m$. Sum it up, we have $2^{m-1} \times 2 = 2^m$ orthon lists. OR. By TIPS, immed. \square

11 $\text{Supp } V \neq 0$, and $\langle \cdot, \cdot \rangle_1, \langle \cdot, \cdot \rangle_2$ are inner prods suth $\langle v, w \rangle_1 = 0 \iff \langle v, w \rangle_2 = 0$.

Prove $\exists c > 0$, $\langle v, w \rangle_1 = c \langle v, w \rangle_2$ for all $v, w \in V$.

SOLUS: Fix non0 $v_1, v_2 \in V$. Define $\varphi_1, \psi_1 \in V'$ by $\varphi_1 : v \mapsto \langle v, v_1 \rangle_1$, $\psi_1 : v \mapsto \langle v, v_2 \rangle_1$. Simlr for φ_2, ψ_2 .

Becs $\langle v, v_1 \rangle_1 = 0 \iff \langle v_1, v \rangle_2 = 0$. By (3.B.30), let $c_1 = \langle v_1, v_1 \rangle_1 / \langle v_1, v_1 \rangle_2 > 0 \Rightarrow \varphi_1 = c_1 \varphi_2$.

Simlr, let $c_2 = \langle v_2, v_2 \rangle_1 / \langle v_2, v_2 \rangle_2 \Rightarrow \psi_1 = c_2 \psi_2$. Choose $v_1 = v_2$ so that $c = c_1 = c_2$.

For any $v'_1 \in V$, get c'_1 simlr. Becs $\langle v, v_1 \rangle_1 = c_1 \langle v, v_1 \rangle_2$ while $\langle v, v'_1 \rangle_1 = c'_1 \langle v, v'_1 \rangle_2$.

Now $c_1 \langle v'_1, v_1 \rangle_2 = \langle v'_1, v_1 \rangle_1 = \overline{\langle v_1, v'_1 \rangle_1} = \overline{c'_1 \langle v_1, v'_1 \rangle_2} \Rightarrow c_1 = c'_1$. Simlr for $c_2 = c'_2$. \square

OR. For any $v'_1, v'_2 \in V$, get $c'_1 = c'_2$ simlr. Becs $c_2 \langle v'_1, v_2 \rangle_2 = \langle v'_1, v_2 \rangle_1 = c'_1 \langle v'_1, v_2 \rangle_2$. \square

Or. Define $c_v = \langle v, v \rangle_1 / \langle v, v \rangle_2$ for all non0 $v \in V$. Fix non0 $u, v \in V$.

Let $c = \langle u, v \rangle_2 / \langle v, v \rangle_2 \Rightarrow \langle u - cv, v \rangle_1 = \langle u - cv, v \rangle_2 = 0 \Rightarrow \langle u, v \rangle_1 = c \langle v, v \rangle_1 = c_v \langle u, v \rangle_2$.

Rev the roles of $u, v \Rightarrow c_v \langle u, v \rangle_2 = \langle u, v \rangle_1 = \overline{\langle v, u \rangle_1} = \overline{c_u \langle v, u \rangle_2} = c_u \langle u, v \rangle_2 \Rightarrow c_v = c_u$. \square

12 *Supp V is finide. Let $\langle \cdot, \cdot \rangle_1$ and $\langle \cdot, \cdot \rangle_2$ be inner prods with corres norms $\|\cdot\|_1$ and $\|\cdot\|_2$.*

Prove $\exists c > 0$, $\|v\|_1 \leq c\|v\|_2$ for all $v \in V$.

SOLUS: Let $B_V = (e_1, \dots, e_n)$ be orthon wrto $\langle \cdot, \cdot \rangle_2$. $\text{Supp } v = a_1e_1 + \dots + a_ne_n$.

NOTICE that $\|v\|_1 \leq \|a_1e_1\|_1 + \dots + \|a_ne_n\|_1 \leq \max\{\|e_1\|_1, \dots, \|e_n\|_1\} \cdot (|a_1| + \dots + |a_n|)$.

又 $|a_1| + \dots + |a_n| \leq n \cdot \max\{|a_1|, \dots, |a_n|\} \leq n \cdot \sqrt{|a_1|^2 + \dots + |a_n|^2} \leq n \cdot \|v\|_2$. \square

• (4E 19) *Supp $B_V = (v_1, \dots, v_n)$. Prove $\exists B'_V = (u_1, \dots, u_n)$ suth $\langle v_j, u_k \rangle = \delta_{j,k}$.*

SOLUS: Let $(\varphi_1, \dots, \varphi_n)$ be the corres dual bss of B_V . Becs $\exists! u_k \in V$, $\varphi_k(v) = \langle v, u_k \rangle$ for all $v \in V$.

Then $\varphi_k(v_j) = \delta_{j,k} = \langle v_j, u_k \rangle$. Now let $a_1u_1 + \dots + a_nu_n = 0 \Rightarrow$ each $\langle v_j, 0 \rangle = a_j$. \square

16 *Supp F = C, V finide, non0 T $\in \mathcal{L}(V)$, all eigvals have abs vals less than 1.*

Let $\epsilon > 0$. Prove $\exists m \in \mathbf{N}^+$, $\|T^m v\| \leq \epsilon \|v\|$ for all $v \in V$.

SOLUS: Let $\langle \cdot, \cdot \rangle_V$ be the inner prod on V , and $\|\cdot\|_V$ be the corres norm on V .

Using Euclid inner prod $\langle \cdot, \cdot \rangle$ and the corres norm $\|\cdot\|$ on $\mathbf{C}^{n,1}$ id with \mathbf{C}^n .

$\text{Supp } A = \mathcal{M}(T)$ up-trig wrto orthon $B_V = (e_1, \dots, e_n)$.

Then $\forall v = x_1e_1 + \dots + x_ne_n \in V$, $\|v\|_V = \|x\|$. Now we show $\|A^m x\| \leq \epsilon \|x\|$ for all $x \in \mathbf{C}^{n,1}$.

Define $D, N \in \mathbf{C}^{n,n}$ by $D_{j,k} = \delta_{j,k}A_{j,k}$, $N = A - D$. Then N is nilp with $N^p = 0 \neq N^{p-1}$.

Let $\rho = \max\{|D_{1,1}|, \dots, |D_{n,n}|\} \Rightarrow 0 \leq \rho < 1$, and each $\|D^k x\| \leq \rho^k \|x\| \leq \|x\|$.

Let $M = \sum_{j=1}^n \sum_{k=1}^n |N_{j,k}|^2$. By [6.A TIPS (2)], $\|Nx\| \leq M\|x\| \Rightarrow \|N^k x\| \leq M^k \|x\|$.

Hence $\|A^{p+q}x\| = \|b_0D^{p+q}x + \dots + b_kD^{p+q-k}N^kx + \dots + b_{p-1}D^{q+1}N^{p-1}x\| \\ \leq [b_0\rho^{p+q} + \dots + b_k\rho^{p+q-k}M^k + b_{p-1}\rho^{q+1}M^{p-1}] \|x\|$.

Where each $b_j = C_{p+q}^j \leq (p+q)^j \leq (p+q)^{p-1}$ for $j \in \{0, \dots, p-1\}$.

Let $\sigma = \max\{1, M, \dots, M^{p-1}\}$. 又 $\max\{\rho^{p+q}, \dots, \rho^{q+1}\} = \rho^{q+1}$.

Now $\|A^{p+q}x\| \leq (p+q)^{p-1}\rho^{q+1}\sigma\|x\|$. Note that as $q \rightarrow \infty$, $(p+q)^{p-1}\rho^{q+1} \rightarrow 0$. \square

ENDED

6.C

• **TIPS 1:** *Supp V finide, $T \in \mathcal{L}(V)$, and all vecs in null T orthog to all vecs in range T.*

Prove $(\text{null } T)^\perp = \text{range } T$.

SOLUS: Becs $\text{range } T \subseteq (\text{null } T)^\perp$. 又 $\text{null } T \cap \text{range } T = \{0\}$. By [1.C TIPS (1)]. \square

Or. $\forall v \in (\text{null } T)^\perp, \exists! (u, w) \in \text{null } T \times \text{range } T, \langle u + w, v \rangle = \langle u, v \rangle = 0 \Rightarrow v \in \text{range } T$. \square

8 *Supp V is finide, $P^2 = P \in \mathcal{L}(V)$, $\|Pv\| \leq \|v\|$ for all $v \in V$. Prove $\text{range } P = (\text{null } P)^\perp$.*

SOLUS: $\|w\| = \|Pv\| \leq \|Pv + (v - Pv)\| = \|w + u\|$, where $w = Pv, u \in \text{null } P$. Supp non0 $u \in \text{null } P$.

Or. $\forall a \in \mathbf{F}$, $\|w\| \leq \|w + au\|$, Or. $\|Pv\| = \|P(Pv + au)\| \leq \|Pv + au\|$. Thus $\langle Pv, v - Pv \rangle = 0$. \square

10 *Supp V finide, U a subsp, $T \in \mathcal{L}(V)$, and $P_U T = TP_U$. Prove U and U^\perp inward T.*

SOLUS: (a) $P_U TP_U = TP_U P_U = TP_U$. (b) $P_{U^\perp} TP_{U^\perp} = (I - P_U)T(I - P_U) = T(I - P_U)^2 = TP_{U^\perp}$. \square

Or. (a) $\text{range } T|_U = \text{range } TP_U = \text{range } P_U T \subseteq U$.

(b) $\text{range } T|_{U^\perp} = \text{range } T(I - P_U) = \text{range } (I - P_U)T \subseteq U^\perp$. \square

COMMENT: The trick $T = (P_U|_{\text{range } T})^{-1}TP_U$ is invalid.

• **TIPS 2:** Supp U finide subsp of V , $v \in V$, $\varphi \in U' : u \mapsto \langle u, v \rangle$.

Then $\exists ! w \in U, \varphi(u) = \langle u, w \rangle = \langle u, v \rangle$ for all $u \in U \Rightarrow v - w \in U^\perp$. Now $w = P_U v$.

• **TIPS 3:** Supp U, W finide subsps of V . Prove $W^\perp \subseteq U^\perp \Rightarrow U \subseteq W$.

SOLUS: $v \in U \Rightarrow \forall x \in W^\perp \subseteq U^\perp, \langle v, x \rangle = 0 \Rightarrow v \in (W^\perp)^\perp = W$, by [6.51]. \square

• **TIPS 4:** Supp U, W subsps of V . Prove $(U + W)^\perp = U^\perp \cap W^\perp$, $(U \cap W)^\perp = U^\perp + W^\perp$.

SOLUS: (a) Supp $v \in V$. Then $\forall u + w \in U + W, \langle u + w, v \rangle = 0 \Leftrightarrow \forall u \in U, w \in W, \langle u, v \rangle = \langle u, w \rangle = 0$.

(b) $v_1 \in U^\perp, v_2 \in W^\perp \Rightarrow \forall x \in U \cap W, \langle v_1 + v_2, x \rangle = 0$. Thus $U^\perp + W^\perp \subseteq (U \cap W)^\perp$.

Or. $U \cap W \subseteq U, W \Rightarrow (U \cap W)^\perp \supseteq U^\perp + W^\perp$.

[Req Finide] By (a), $\dim(U^\perp + W^\perp) = \dim V - \dim(U \cap W)$. \square

Exa: Not true if infinide. Let $U = \{(x_1, 0, \dots, 0, x_{2k-1}, 0, \dots) \in \mathbb{F}^\infty\}$, $W = \{\sum_{k=1}^{\infty} a_k (e_{2n} + \frac{1}{n} e_{2n-1})\}$.

Then $U \cap W = \{0\} \Rightarrow (U \cap W)^\perp = \mathbb{F}^\infty$. While $U^\perp + W^\perp \not\ni (0, 1, 0, \frac{1}{2}, 0, \dots, 0, \frac{2}{k}, 0, \dots)$.

ENDED

7.A,B,C & 7.D[4E]

NOTE: V denotes a finide vecsp over \mathbb{F} . 7.D[4E] 处结合了 3e 的 9.B 节。

A.TIPS: Supp $T \in \mathcal{L}(V)$ is normal. Prove $p(T)$ is normal for any $p \in \mathcal{P}(\mathbb{F})$.

SOLUS: Becs T normal $\Rightarrow T^j$ normal. We use induc on $\deg p = k$.

(i) $k = 0, 1$. $p(z) = c_0 + c_1 z \Rightarrow p(T)^* p(T) = (\overline{c_0} I + \overline{c_1} T^*) (c_0 I + c_1 T) = p(T)p(T)^*$.

(ii) $k > 1$. Asum true for smaller deg. Let $q(z) = c_0 + c_1 z + \dots + c_{k-1} z^{k-1} \Rightarrow p(z) = q(z) + c_k z^k$.

Then $p(T)^* p(T) = [q(T)^* + \overline{c_k} (T^k)^*] [q(T) + c_k T^k] = p(T)p(T)^*$. \square

A.17 Supp $T \in \mathcal{L}(V)$ is normal. Prove each $\text{null } T^k = \text{null } T$ and $\text{range } T^k = \text{range } T$.

SOLUS: Becs $\text{range } T = (\text{null } T^*)^\perp = (\text{null } T)^\perp \Rightarrow T|_{\text{range } T}$ is inj. Thus $\text{null } T^k = \text{null } T$.

And $\text{range } T^2 = \text{range } T|_{\text{range } T} = \text{range } T = \text{range } T \Rightarrow \text{range } T^{k-1}|_{\text{range } T} = \text{range } T^{k-1}|_{\text{range } T^2}$. \square

Or. $v \in \text{null } T^{k+1} \Rightarrow T^k v \in \text{null } T = \text{null } T^* \Rightarrow 0 = \langle T^* T^k v, T^{k-1} v \rangle = \langle T^k v, T^k v \rangle \Rightarrow v \in \text{null } T^k$.

Note that T normal $\Rightarrow T^k$ normal. Then $\text{range } T^k = (\text{null } T^k)^\perp = (\text{null } T)^\perp = \text{range } T$. \square

• (4E A.28) Supp $T \in \mathcal{L}(V)$ is normal. Prove the min of T is not a multi of any $(z - \lambda)^2$.

SOLUS: Supp the min of T is $p(z) = (z - \lambda)^k q(z)$ with $k \geq 1$ and $q(\lambda) \neq 0$.

Then $p(T)v = 0 \Rightarrow q(T)v \in \text{null}(T - \lambda I)^k = \text{null}(T - \lambda I) \Rightarrow k = 1$. \square

Or. By TIPS and [8.B TIPS (4)]. Factoriz the min of $T \Rightarrow$ each liney factor has expo 1. \square

Or. Becs $\text{range}(T - \lambda I) = \text{null}(T - \lambda I)^\perp \Rightarrow V = \text{null}(T - \lambda I) \oplus \text{range}(T - \lambda I)$ for all $\lambda \in \mathbb{F}$.

By (5.C.5). If $\mathbb{F} = \mathbb{R}$, then apply to T_C . Now every liney factor has expo 1. \square

B.14 Supp $\mathbb{F} = \mathbb{R}$, $T \in \mathcal{L}(V)$. Prove T diag \Rightarrow self-adj wrto some $\langle \cdot, \cdot \rangle_V$.

SOLUS: Let eigvecs $B_V = (e_1, \dots, e_n)$ be orthon wrto $\langle e_j, e_k \rangle_V = \delta_{j,k}$. Becs $\mathcal{M}(T) = \mathcal{M}(T)^t = \mathcal{M}(T^*)$. \square

NOTE: (a) $\mathcal{M}(T) = \overline{\mathcal{M}(T)^t}$ wrto some $B_V \Leftrightarrow T$ self-adj wrto some $\langle \cdot, \cdot \rangle_V \Leftrightarrow$ diag.

(b) $\mathcal{M}(T) \overline{\mathcal{M}(T)^t} = \overline{\mathcal{M}(T)^t} \mathcal{M}(T)$ wrto some $B_V \Leftrightarrow T$ normal wrto some $\langle \cdot, \cdot \rangle_V \Leftrightarrow$ diag on \mathbb{C} .

- (4E B.8) $\text{Supp } \mathbf{F} = \mathbf{C}, T \in \mathcal{L}(V)$. Prove each eigvec of T is an eigvec of T^* $\Rightarrow T$ is normal.

SOLUS: Supp v is eigvec of T corres λ and of T^* corres μ .

$$\text{Then } \lambda\|v\|^2 = \langle Tv, v \rangle = \langle v, T^*v \rangle = \bar{\mu}\|v\|^2 \Rightarrow \lambda = \bar{\mu}.$$

Thus each $E(\lambda, T) = E(\bar{\lambda}, T^*)$ invard $T, T^* \Rightarrow E(\lambda, T)^\perp = E(\bar{\lambda}, T^*)^\perp$ invard T^*, T .

Let $W = \bigcap_{\lambda \in \mathbf{F}} E(\lambda, T)^\perp$ invard T, T^* . By [6.C TIPS (4)], no eigvals of $T|_W, T^*|_W \Rightarrow W = \{0\}$. \square

Or. \exists orthon $B_V = (e_1, \dots, e_n)$ suth $\mathcal{M}(T)$ up-trig $\Rightarrow \overline{A}^t = \mathcal{M}(T^*)$ low-trig.

(i) Now $Te_1 = A_{1,1}e_1 \Rightarrow \overline{A_{1,1}}e_1 + \dots + \overline{A_{1,n}}e_n = T^*e_1 \Rightarrow A_{1,2} = \dots = A_{1,n} = 0$.

(ii) Asum $(A_{1,2} \dots A_{1,n}) = \dots = (A_{k-1,k} \dots A_{k-1,n}) = 0$. $\forall A$ is up-trig.

$$\text{Then } Te_k = A_{k,k}e_k \Rightarrow \overline{A_{k,k}}e_1 + \dots + \overline{A_{k,n}}e_n = T^*e_k \Rightarrow A_{k,k+1} = \dots = A_{k,n} = 0.$$

\square

- (4E B.12) $\text{Supp } \mathbf{F} = \mathbf{C}, T \in \mathcal{L}(V)$ is normal, $S \in \mathcal{L}(V)$ and $ST = TS$. Prove $ST^* = T^*S$.

SOLUS: Let $B_V = (e_1, \dots, e_n)$ be orthon eigvecs of T corres $\lambda_1, \dots, \lambda_n$.

$$\text{Becs each } E(\lambda_k, T) = E(\bar{\lambda}_k, T^*) \text{ invard } S \Rightarrow ST^*e_k = \overline{\lambda_k}Se_k = T^*Se_k. \text{ Or. Becs } T^* = p(T).$$

- (4E B.20) $\text{Supp } \mathbf{F} = \mathbf{C}, T \in \mathcal{L}(V)$ is normal and U invarsdpd T .

Prove (a) U^\perp invard T , (b) $(T|_U)^* = T^*|_U \in \mathcal{L}(U)$, (c) $T|_U, T|_{U^\perp}$ normal.

SOLUS: By [5.A TIPS (3)], and apply [6.31] to each $E(\lambda_k, T|_U)$, let $B_U = (e_1, \dots, e_m)$ be orthon eigvecs.

Let $B_V = (e_1, \dots, e_n)$ be orthon eigvecs. Then $B_{U^\perp} = (e_{m+1}, \dots, e_n)$, invard T . And U invard T^* .

(b) $\forall u, v \in U, \langle v, (T|_U)^*u \rangle = \langle T|_U v, u \rangle = \langle v, T^*|_U u \rangle \Rightarrow [(T|_U)^* - (T^*|_U)](u) \in U \cap U^\perp$.

(c) $\forall u \in U, \|T|_U u\| = \|T^*|_U u\| = \|(T|_U)^*u\|$. Or. $(T|_U)(T|_U)^* = T^*T|_U = T^*|_U T|_U$. \square

COMMENT: See [9.30] without using [7.24] and the hypo $\mathbf{F} = \mathbf{C}$.

NOTE: Another proof of [7.24]: Induc step: For $\dim V > 1$. Asum it holds for smaller dim.

Let u be an eigvec with $\|u\| = 1$. Let $B_U = (u) \Rightarrow U$ invard T , so is $U^\perp \Rightarrow T|_{U^\perp}$ normal.

By asum, \exists orthon B_{U^\perp} of eigvecs of $T|_{U^\perp}$. Now $B_V = B_U \cup B_{U^\perp}$ of orthon eigvecs. \square

- **NOTE FOR [7.28], a quot version:** Supp V finide and self-adj $T \in \mathcal{L}(V)$ with U invard T , so is U^\perp .

Define inner prod on V/U by $\langle v + U, w + U \rangle_{V/U} = \langle P_{U^\perp}v, P_{U^\perp}w \rangle$.

We show $LHS = \langle Tv + U, w + U \rangle_{V/U} = \langle v + U, T^*w + U \rangle_{V/U} = RHS$,

so that $\langle v + U, (T/U)^*(w + U) \rangle_{V/U} = LHS = RHS = \langle v + U, (T^*/U)(w + U) \rangle_{V/U}$.

By (6.C.10), $LHS = \langle P_{U^\perp}Tv, P_{U^\perp}w \rangle = \langle TP_{U^\perp}v, P_{U^\perp}w \rangle = \langle P_{U^\perp}v, T^*P_{U^\perp}w \rangle = \langle P_{U^\perp}v, P_{U^\perp}T^*w \rangle = RHS$. \square

- **COMMENT:** This avails another approach to [7.29].

- **NOTE FOR Square Root of Id:** Supp $T \in \mathcal{L}(\mathbf{F}^2)$ and $T^2 = I$. Let $\mathcal{M}(T) = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ wrto std bss.

(a) If T is self-adj $\iff b = c$. Then $ab + bd = 0, a^2 + b^2 = b^2 + d^2 = 1$.

$|a| = |d| = 1, b = 0$, Or $a = \pm\sqrt{1 - b^2} = -d, b \neq 0$, Or $b = \pm\sqrt{1 - a^2} = \pm\sqrt{1 - d^2} \neq 0, a = -d$.

If $\mathbf{F} = \mathbf{R}, |b| < 1$, then $\mathcal{M}(T) = \begin{pmatrix} \cos \alpha & \sin \alpha \\ \sin \alpha & -\cos \alpha \end{pmatrix}$, and $T(r \cos \beta, r \sin \beta) = (r \cos(\alpha - \beta), r \sin(\alpha - \beta))$.

(b) If T is not self-adj and $T \neq \pm I$. Then by (4E 5.B.11), $a = -d, a^2 + bc = 1$.

If $a = -d = \pm 1$, then $bc = 0$, and if $\|Te_1\| \neq \|Te_2\|$ or $\langle Te_1, Te_2 \rangle \neq 0$, then T is not an isomet.

- **C.20** Supp $T \in \mathcal{L}(V)$ and orthon $B_V = (e_1, \dots, e_n)$.

Supp $v_1, \dots, v_n \in V$ and each $\langle Te_k, e_j \rangle = \langle v_k, v_j \rangle$. Prove T posi.

SOLUS: Define $R \in \mathcal{L}(V) : e_k \mapsto v_k \Rightarrow \langle Te_k, e_j \rangle = \langle Re_k, Re_j \rangle = \langle R^*Re_k, e_j \rangle \Rightarrow \mathcal{M}(T, B_V) = \mathcal{M}(R^*R, B_V) \square$

C.22 Supp T posi, $u \in V$ with $\|u\| = 1$ suth $\|Tu\| \geq \|Tv\|$ for all $v \in V$ with $\|v\| = 1$.
Show u is eigvec corres the largest eigval of T .

SOLUS: Supp orthon eigvecs $B_V = (e_1, \dots, e_n)$ corres $\lambda_1 \geq \dots \geq \lambda_n$. Let $u = \sum_{k=1}^n c_k e_k \Rightarrow \sum_{k=1}^n |c_k|^2 = 1$.
Supp $v = \sum_{j=1}^n a_j e_j$ and $\|v\| = 1$. Then $\|Tv\|^2 = \sum_{j=1}^n |\lambda_j|^2 |a_j|^2 \leq |\lambda_1|^2$. Simlr, $\|Tu\|^2 \leq |\lambda_1|^2$.
又 $\|Tv\|^2 = |\lambda_1|^2 \iff v = a_1 e_1 + \dots + a_J e_J$, where $\lambda_1 = \dots = \lambda_J > \lambda_{J+1}$, if $\lambda_n \neq \lambda_1$; othws $J = n$.
Hence $\sum_{k=1}^n |\lambda_k|^2 |c_k|^2 = \|Tu\|^2 = \sum_{k=1}^n |\lambda_1|^2 |c_k|^2 \Rightarrow \sum_{k=J}^n [|\lambda_1|^2 - |\lambda_k|^2] \cdot |c_k|^2 = 0$. \square

C.23 Supp $\langle \cdot, \cdot \rangle_1, \langle \cdot, \cdot \rangle_2$ are inner prods on V . Prove \exists inv posi $T \in \mathcal{L}(V)$, $\langle u, v \rangle_2 = \langle Tu, v \rangle_1$.

SOLUS: Let $(e_1, \dots, e_n), (f_1, \dots, f_n)$ be orthon bses wrto $\langle \cdot, \cdot \rangle_2, \langle \cdot, \cdot \rangle_1$. Define $R \in \mathcal{L}(V)$ by $Re_k = f_k$.
 $\forall u = \sum_{i=1}^n x_i e_i, v = \sum_{i=1}^n y_i e_i, \langle u, v \rangle_2 = x_1 \bar{y}_1 + \dots + x_n \bar{y}_n = \langle Ru, Rv \rangle_1 = \langle R^* Ru, v \rangle_1$. \square

D.2 Supp $T \in \mathcal{L}(V, W)$, $\langle Tu, Tv \rangle = 0$ for all orthog $u, v \in V$. Prove \exists isomet $S, T = \lambda S$.

SOLUS: Supp orthog $B_V = (v_1, \dots, v_n) \Rightarrow (Tv_1, \dots, Tv_n)$ is orthog.

Let $g_k = Tv_k / \|Tv_k\|, e_k = v_k / \|v_k\|$. Define isomet $S \in \mathcal{L}(V, W) : e_k \mapsto g_k$.

Let $\lambda_k = \|Tv_k\| / \|v_k\|$. Then $S^* : g_k \mapsto e_k \Rightarrow S^*(Tv_k) = \|Tv_k\| e_k = \lambda_k v_k$.

NOTICE that v_1 is arb. Simlr to (4E 3.A.11). Hence $S^* T = \lambda I \Rightarrow T = \lambda S$. \square

Or. Let orthon $B_V = (e_1, \dots, e_n)$. Becs $\langle u + v, u - v \rangle = \|u\|^2 - \|v\|^2$.

Now $0 = \langle e_1 + e_k, e_1 - e_k \rangle = \langle Te_1 + Te_k, Te_1 - Te_k \rangle \Rightarrow$ each $\|Te_k\| = \lambda$. Supp $\lambda \neq 0$.

Let $S = \lambda^{-1} T$. Becs $\langle e_j, e_k \rangle = 0 \Rightarrow \langle Te_j, Te_k \rangle = \langle \lambda Se_j, \lambda Se_k \rangle = 0 \iff \langle Se_j, Se_k \rangle = 0$. \square

D.5 Supp $S \in \mathcal{L}(V)$. Prove S self-adj and unit $\iff \exists P_U, S = 2P_U - I$.

SOLUS: Supp S self-adj and unit. Then $V = E(1, S) \oplus E(-1, S)$, $E(1, S) = E(-1, S)^\perp \Rightarrow S = 2P_U - I$.

Or. $S^2 = I$. Let $P = \frac{1}{2}(S + I) \Rightarrow P^2 = P$ self-adj $\Rightarrow \text{range } P = (\text{null } P)^\perp = U$.

Supp $S = 2P_U - I \Rightarrow S$ self-adj. Then $\forall u \in U, Su = u$, and $\forall w \in U^\perp, Sw = -w$.

$\|S(u + w)\|^2 = \|u + w\|^2$. Or. $S^2(u + w) = u + w \Rightarrow S^{-1} = S = S^*$. Or. Apply to a orthon B_V . \square

D.TIPS: Supp $T \in \mathcal{L}(V)$, each eigval of T_C has abs val 1.

Supp $\|Tv\| \leq \|v\|$ for all $v \in V$. Prove T unit.

SOLUS: Supp Jordan $\mathcal{M}(T_C)$ wrto $B_1 = (u_1 + i v_1, \dots, u_n + i v_n) \Rightarrow \mathcal{M}(T, B_1) = \mathcal{M}(T, B_2)$,

where $B_2 = (x_1 + i y_1, \dots, x_n + i y_n)$ with each $x_k + i y_k = (\sqrt{\|u_k\|^2 + \|v_k\|^2})^{-1} (u_k + i v_k)$.

Becs $\|T_C(u + i v)\|^2 = \|Tu\|^2 + \|Tv\|^2 \leq \|u + i v\|^2$. By Exe (D.9), T_C is unit.

Consider $\mathcal{M}(T)$ wrto $B_V = (v_1, u_1, \dots, v_n, u_n)$ and by [9.36]. \square

D.11 Supp $S \in \mathcal{L}(V)$, and $\{Sv : v \in \odot\} = \{v \in V : \|v\| \leq 1\} = \odot$. Prove S is unit.

SOLUS: NOTICE that $\|S(\|v\|^{-1}v)\| \leq 1 \Rightarrow \|Sv\| \leq \|v\|$ for all $v \in \odot$.

Asum S not inv. Then $\exists w \in V \setminus \text{range } S, \|w\|^{-1}w \notin \{Sv : v \in \odot\} = \odot$. Ctradic.

NOTE: If $v \neq 0, Sv = 0 \in \odot$, then $v \in \odot$. Wrong becs only $a\|v\|^{-1}v \in \odot$, where $0 \leq a \leq 1$.

Now $\forall v \in V \setminus \{0\}, S[\|Sv\|^{-1}v] \in \odot \iff \|Sv\|^{-1}v \in \odot \Rightarrow \|Sv\|^{-1}\|v\| \leq 1$. \square

Or. NOTICE that $\odot_C = \{u + i v \in V_C : \|u\|^2 + \|v\|^2 \leq 1\} = \{Su + i Sv : u, v \in V, \|u\|^2 + \|v\|^2 \leq 1\}$.

We show each eigval of S_C has abs val 1. Then done by TIPS.

Asum $|\lambda| < 1$ and λ is eigval of S_C with $u + i v$ and $\|u\|^2 + \|v\|^2 = 1$.

Then $S_C[\lambda^{-1}(u + i v)] = u + i v \in \odot_C$ while $\lambda^{-1}(u + i v) \notin \odot_C$. Ctradic. \square

7.E [4E] & 7.F [4E]

NOTE: V, W are finide **non0** vecspes over \mathbf{F} .

E.1 $\text{Supp } T \in \mathcal{L}(V, W)$. Show $T = 0 \iff \text{all singvals are } 0$.

SOLUS: (a) $T = 0 \iff T^* = 0 \iff T^*T = 0 \Rightarrow \text{all singvals are } 0$.

(b) all singvals are $0 \iff T^*T$ nilp. Becs T^*T diag $\Rightarrow T^*T = 0 = T$. \square

Or. $\text{Supp } T$ has N posi singvals. Now $N = 0 \iff \dim \text{range } T = 0 \iff T = 0$. \square

E.4 $\text{Supp } T \in \mathcal{L}(V, W)$, and s_1, s_n are the max and min of singvals.

Prove $\{\|Tv\| : v \in V, \|v\| = 1\} = [s_n, s_1]$.

SOLUS: Get the SVD $(e_1, \dots, e_m), (f_1, \dots, f_m)$ in V, W . We show $\forall s \in [s_n, s_1], \exists v \in V, \|Tv\| = s$.

Say $v = xe_1 + ye_n$ with (I) $\|v\|^2 = x^2 + y^2 = 1$, (II) $\|Tv\|^2 = s_1^2 x^2 + s_n^2 y^2 = s^2$.

If $s_1 = s_n$. Done. $\text{Supp } s_1 > s_n$. Then $s_1^2 - s^2 = (s_1^2 - s_n^2) y^2$, and $s^2 - s_n^2 = (s_1^2 - s_n^2) x^2$. \square

COMMENT: T is a scalar multi of an isomet $\iff \{\|Tv\| : v \in V, \|v\| = 1\} = \{s_1\}$.

E.11 $\text{Supp } T \in \mathcal{L}(V)$ is posi, $B_V = (v_1, \dots, v_n)$ is orthon, and s_1, \dots, s_n are the singvals.

Prove $\langle Tv_1, v_1 \rangle + \dots + \langle Tv_n, v_n \rangle = s_1 + \dots + s_n$.

SOLUS: $\langle Tv_k, v_k \rangle = \langle \sqrt{T}v_k, \sqrt{T}v_k \rangle = \|\sqrt{T}v_k\|^2$. Note that $\sqrt{T} = \sqrt{T^*} = (\sqrt{T})^*$ is posi.

NOTICE that s_1, \dots, s_n are the eigvals of $\sqrt{T^*}\sqrt{T} = T \Rightarrow \sqrt{s_1}, \dots, \sqrt{s_n}$ are the singvals of \sqrt{T} .

Get the SVD $(e_1, \dots, e_n), (f_1, \dots, f_n)$. By (4E 7.A.5), $\sum \|\sqrt{T}v_k\|^2 = \sum \|\sqrt{T}e_k\|^2 = \sum s_k$. \square

E.17 $\text{Supp } T \in \mathcal{L}(V)$. Prove T self-adj $\iff T^\dagger$ self-adj.

By Exe (E.16), immed.

SOLUS: Let $\lambda_1, \dots, \lambda_m$ be disti eigvals of T with $\lambda_1 = 0$ if any. Let $U = (\text{null } T)^\perp$.

$m_T(z) = (z - \lambda_1) \cdots (z - \lambda_m) \iff m_{T|_U} = m_T$ if T inje, othws $m_{T|_U}(z) = (z - \lambda_2) \cdots (z - \lambda_m)$

\iff the min of $(T|_U)^{-1}$ is $(z - \lambda_1^{-1}) \cdots (z - \lambda_m^{-1})$ if T inje, and is $(z - \lambda_2^{-1}) \cdots (z - \lambda_m^{-1})$ othws

$\iff m_{T^\dagger}$ is the min of $(T|_U)^{-1}$ if T inje, othws $m_{T^\dagger}(z) = z(z - \lambda_2^{-1}) \cdots (z - \lambda_m^{-1})$. \square

F.3 $\text{Supp } T \in \mathcal{L}(V, W)$ and $v \in V$. Prove $\|Tv\| = \|T\| \|v\| \iff T^*Tv = \|T\|^2 v$.

SOLUS: Let $s_1 = \dots = s_j \geq \dots \geq s_n$ be the singvals with the SVD bses $(e_1, \dots, e_n), (f_1, \dots, f_n)$.

NOTICE that $\|Tv\|^2 = s_1^2 |\langle v, e_1 \rangle|^2 + \dots + s_n^2 |\langle v, e_n \rangle|^2 = s_1^2 \|v\|^2$

$\iff v \in \text{span}(e_1, \dots, e_j) \iff T^*Tv = \sum s_i^2 \langle v, e_i \rangle e_i = \sum s_1^2 \langle v, e_i \rangle e_i$. \square

Or. $\text{Supp } T^*Tv = \|T\|^2 v$. Then $\|T\|^2 \|v\| = \|T^*Tv\| \leq \|T\| \|Tv\| \Rightarrow \|T\| \|v\| \leq \|Tv\|$.

$\text{Supp } \|Tv\| = \|T\| \|v\|$. Then $\|T^*Tv - \|T\|^2 v\|^2 = \|T^*Tv\|^2 + \|T\|^4 \|v\|^2 - 2\text{Re} \langle T^*Tv, \|T\|^2 v \rangle \leq 0$.

Becs $\|T^*Tv\|^2 \leq \|T\|^2 \|Tv\|^2 = \|T\|^2 \|T\|^2 \|v\|^2$, and $\langle T^*Tv, \|T\|^2 v \rangle = \langle Tv, \|T\|^2 Tv \rangle = \|T\|^2 \|Tv\|^2$. \square

F.5 $\text{Supp } U$ is finide inner prodsp, $T \in \mathcal{L}(U, V), S \in \mathcal{L}(U, W)$. Prove $\|ST\| \leq \|S\| \|T\|$.

SOLUS: Take v suth $\|ST\| = \|STv\| \leq \|S\| \|Tv\| \leq \|S\| \|T\| \|v\| \leq \|S\| \|T\|$. \square

Or. $\|STv\| \leq \|S \frac{Tv}{\|Tv\|}\| \|Tv\| \leq \|S \frac{Tv}{\|Tv\|}\| \|T\| \leq \|S\| \|T\|$. \square

F.19 Prove $\|T^*T\| = \|T\|^2$.

$\|T\| = \|\sqrt{T^*T}\| = \sqrt{\|T^*T\|}$. Or. By Exe (F.2), $\|T^*T\| = s_1^2$. \square

SOLUS: $\forall v \in V, \|Tv\| = \|\sqrt{T^*T}v\| \leq \|\sqrt{T^*T}\| \|v\| \Rightarrow \|T\| \leq \|\sqrt{T^*T}\|$. 又 $\|T^*T\| \leq \|T^*\| \|T\|$. \square

Or. $T = S\sqrt{T^*T}, \sqrt{T^*T} = S^*T$. Simlr. \square

F.20 Supp $T \in \mathcal{L}(V)$ normal. Prove $\|T^k\| = \|T\|^k$.

SOLUS: Let $B_V = (e_1, \dots, e_n)$ be orthon eigvecs of T^*T with corres eigvals s_1^2, \dots, s_n^2 .

Becs $(T^k)^*T^k e_j = (T^*T)^k e_j = s_j^{2k} e_j$. Now $\max\{s_1, \dots, s_n\}^k = \max\{s_1^k, \dots, s_n^k\}$. \square

OR. Note that $(T^*T)_C$ and T^*T have the same eigvals $\Rightarrow \|T_C\|_C = \|T\|$.

Let $B_{V_C} = (e_1, \dots, e_n)$ be orthon eigvecs of T_C corres eigvals $\lambda_1, \dots, \lambda_n$ of T^k corres $\lambda_1^k, \dots, \lambda_n^k$.

By Exe (F.2), $\|T_C^k\| = \max\{|\lambda_j^k|\} = \max\{|\lambda_j|\}^k = \|T_C\|^k$. \square

OR. Becs singvals of T are the abs of eigvals in \mathbf{C} . Let $T_C v = \|T\|v$ with $v \in V_C$ and $\|v\| = 1$.

Then $T_C^k v = \|T\|^k v \Rightarrow \|T\|^k = \|T_C^k v\| \leq \|T_C^k\|$. 又 By Exe (F.5), $\|T_C^k\| \leq \|T_C\|^k$. \square

F.28 Supp $T \in \mathcal{L}(V)$. Prove \exists unit $S \in \mathcal{L}(V)$, $T = \sqrt{TT^*} S$.

Let $T^* = S\sqrt{TT^*}$. \square

SOLUS: Supp s_1, \dots, s_m are the posi singvals of T with SVD $(e_1, \dots, e_m), (f_1, \dots, f_m)$.

Becs $T^*Te_k = s_k^2 e_k$, $f_k = Te_k/s_k \Rightarrow TT^*f_k = TT^*Te_k/s_k = s_k Te_k = s_k^2 f_k \Rightarrow \sqrt{TT^*} f_k = s_k f_k$.

$\dim E(s_k, \sqrt{TT^*}) \leq \dim E(s_k, \sqrt{TT^*})$. Apply revly. Thus $\dim E(0, \sqrt{T^*T}) = \dim E(0, \sqrt{TT^*})$.

Get orthon bses of $E(0, \sqrt{T^*T})$ and $E(0, \sqrt{TT^*})$. Forming two orthon bses of V .

Define $S \in \mathcal{L}(V)$ by $Se_j = f_j$. **NOTE:** The same S in $T = S\sqrt{T^*T}$. \square

CORO: $T = S\sqrt{T^*T} \Rightarrow T^* = \sqrt{T^*T} S^* \Rightarrow TT^* = ST^*TS^*$.

Or. $T = S\sqrt{T^*T} = \sqrt{TT^*} S \Rightarrow \sqrt{T^*T} = S^*\sqrt{TT^*} S \Rightarrow T^*T = S^*TT^*S$.

F.31 Supp $T \in \mathcal{L}(V)$ self-adj. Or supp $\mathbf{F} = \mathbf{C}$ and $T \in \mathcal{L}(V)$ normal.

Prove \exists unit S with $T = S\sqrt{T^*T}$ suth $S, \sqrt{T^*T}$ diag wrto same orthon bss.

SOLUS: Becs $T = S\sqrt{T^*T} = \sqrt{TT^*} S = \sqrt{T^*T} S$. If $\mathbf{F} = \mathbf{C}$, then done. But othws ?

Let $B_V = (e_1, \dots, e_n)$ be orthon eigvecs of T with corres $\lambda_1, \dots, \lambda_n$, which are real if self-adj.

Note that $T^*e_k = \overline{\lambda_k} e_k \Rightarrow T^*Te_k = |\lambda_k|^2 e_k$. Define $S \in \mathcal{L}(V)$ by $Se_k = |\lambda_k|^{-1} \lambda_k e_k$. \square

F.8 Supp $S \in \mathcal{L}(V)$ inv. Prove if $T \in \mathcal{L}(V)$ and $\|S - T\| < 1/\|S^{-1}\|$, then T inv.

SOLUS: Note that $1/\|S^{-1}\| = s_n$, where $s_1 \geq \dots \geq s_n$ are the singvals of T .

Becs $s_n = \min\{\|S - T\| : \dim \text{range } T = 0, 1, \dots, n-1\} > \|S - T\| \Rightarrow \dim \text{range } T = n$. \square

Or. $v \neq 0, Tv = 0 \Rightarrow \|v\| = \|S^{-1}Sv\| \leq \|S^{-1}\| \|Sv\| = \|S^{-1}\| \|(S - T)v\|$. \square

F.14 Supp U, W subsps of V suth $\|P_U - P_W\| < 1$. Prove $\dim U = \dim W$.

SOLUS: Note that $1 = s_m = \min\{\|P_U - T\| : T \in \mathcal{L}(V) \text{ and } \dim \text{range } T = 0, 1, \dots, m-1\}$.

Thus $\dim \text{range } P_W \geq \dim \text{range } P_U$. Apply revly, done. \square

Or. Becs $P_U = I - P_{U^\perp}$ OR $P_W = I - P_{W^\perp} \Rightarrow P_W - P_U = P_W + P_{U^\perp} - I$ OR $P_U - P_W = P_U + P_{W^\perp} - I$.

By Exe (F.8), $P_W + P_{U^\perp}$ and $P_U + P_{W^\perp}$ are inv $\Rightarrow \{0\} = \text{null}(P_W + P_{U^\perp}) \supseteq \text{null } P_W \cap \text{null } P_{U^\perp}$.

And $V = \text{range}(P_U + P_{W^\perp}) \subseteq \text{range } P_U + \text{range } P_{W^\perp} = U + W^\perp$. \square

F.22 Supp $T \in \mathcal{L}(V, W)$. Let $n = \dim V$ and $s_1 \geq \dots \geq s_n$ are the singvals.

Prove $s_{n-k+1} = \min\{\|T|_U\| : U \text{ is subsp of } V, \dim U = k\}$ for $1 \leq k \leq n$.

SOLUS: Get the SVD bses $(e_1, \dots, e_n), (f_1, \dots, f_n)$. Let $U = \text{span}(e_{n-k+1}, \dots, e_n) \Rightarrow \|T|_U\| = s_{n-k+1}$.

Supp U is a k -dim subsp of V . NOTICE that $\|T|_U\| = \|T|_U P_U\| = \|T - T|_{U^\perp} P_{U^\perp}\| \geq s_{n-k+1}$. \square

F.13 Supp $S, T \in \mathcal{L}(V)$ are posi. Show $\|S - T\| \leq \max\{\|S\|, \|T\|\} \leq \|S + T\|$.

SOLUS: $\|S + T\| = \|\sqrt{S + T}\|^2 \geq \|\sqrt{S + T}v\|^2 = \langle Sv + Tv, v \rangle = \langle Sv, v \rangle + \langle Tv, v \rangle = \|\sqrt{S}v\|^2 + \|\sqrt{T}v\|^2$.

Let $v \in V$ suth $\|\sqrt{S}v\|^2 = \|\sqrt{S}\|^2 = \|S\| \Rightarrow \|S + T\| \geq \|S\|$. Simlr, $\|S + T\| \geq \|T\|$.

Denote $\max\{|\lambda| : \lambda \text{ is eigval of } T\}$ by $|\lambda_M|_T$. We show $|\lambda_M|_{S-T} \leq \max\{|\lambda_M|_S, |\lambda_M|_T\}$.

Note that $\|T\|I - T$ is posi, so is $R = \|T\|I - T + S = \|T\|I - (T - S)$.

Thus $\|T\| - |\lambda_M|_R = |\lambda_M|_{S-T} \leq \|T\|$. Simlr, $\|T\| - |\lambda_M|_{\|S\|I - (S-T)} = |\lambda_M|_{T-S} \leq \|S\|$. \square

F.11 Supp $\mathbf{F} = \mathbf{C}, T \in \mathcal{L}(V)$. Prove $\forall \epsilon > 0, \exists \text{ diag } S$ suth $0 < \|T - S\| < \epsilon$.

SOLUS: Supp $A = \mathcal{M}(T)$ up-trig wrto orthon $B_V = (e_1, \dots, e_n)$. Let $\lambda_k = A_{k,k}$.

Becs T has finely many eigvals, $\exists \delta \in (0, \epsilon/n)$, \nexists disti j, k suth $\lambda_j + j\delta = \lambda_k + k\delta$.

Thus define $Re_k = k\delta e_k \Rightarrow T + R$ has n disti eigvals, while R posi and $0 < \|R\| < \delta$. \square

F.16 Supp $S \in \mathcal{L}(V)$ posi inv. Prove $\exists \delta > 0, \forall \text{self-adj } T$ suth $\|S - T\| < \delta, T$ posi.

SOLUS: Let δ be the smallest singval of posi inv S . Then $\forall v \in V, \langle Sv, v \rangle = \|\sqrt{S}v\|^2 \geq \delta\|v\|^2$.

Supp T self-adj and $0 < \|S - T\| < \delta = \min\{\|S - R\| : \dim \text{range } R \leq \dim V - 1\} \Rightarrow T$ inv.

Then $|\langle (S - T)v, v \rangle| \leq \|S - T\| \|v\|^2 < \delta\|v\|^2$ for all non0 $v \in V$.

Asum $\exists v \in V, \langle Tv, v \rangle < 0 \Rightarrow \delta\|v\|^2 \leq |\langle Sv, v \rangle| \leq |\langle Sv - Tv, v \rangle| < \delta\|v\|^2$.

Or. $\langle Tv, v \rangle = \langle Sv, v \rangle + \langle (T - S)v, v \rangle \geq \delta\|v\|^2 - \langle (S - T)v, v \rangle > 0$ for $v \neq 0$. \square

ENDED

少了关于无限维内积空间及其算子的基本内容，LADR 第七章学起来明显更快更平常，没有前半部分许多题目去掉有限维假设后的悬疑和激动时刻。也许研究无限维内积空间有硬性的分析学知识门槛，所以这本书的性质不允许过多涉及这方面。

10.A NOTE: V denotes a finide non0 vecsp over \mathbf{F} . For (10.B), see [4E] Chapter 9.

17 $\text{Supp } T \in \mathcal{L}(V)$ suth $\text{tr}(ST) = 0$ for all $S \in \mathcal{L}(V)$. Prove $T = 0$.

SOLUS: Let $S = T^*$ $\Rightarrow \text{tr}(T^*T) = s_1^2 + \dots + s_n^2 = 0$. By (4E 7.E.1) OR Exe (11). \square

Or. Asum $T \neq 0 \Rightarrow \exists \text{non0 } v \in V$ suth $Tv \neq 0$. Extend $v = v_1$ to $B_V = (v_1, \dots, v_n)$.

$\text{Supp } Tv_1 = A_{1,1}v_1 + \dots + A_{n,1}v_n \Rightarrow \exists A_{j,1} \neq 0$. Define $S \in \mathcal{L}(V)$ by each $Sv_k = \delta_{j,k}v_1$.

Now $S = E_{j,1} \Rightarrow \mathcal{M}(ST) = \mathcal{E}^{(1,j)}\mathcal{M}(T) \Rightarrow 0 = \text{tr}(ST) = A_{j,1}$. Ctradic. \square

Or. Asum $\exists Tv \neq 0$. Extend to $B_V = (Tv, u_1, \dots, u_n)$. Define $S \in \mathcal{L}(V) : Tv \mapsto v, u_i \mapsto 0$.

Now $(TS)(Tv) = Tv, (TS)(u_i) = 0 \Rightarrow \text{tr}(TS) = 1$. Ctradic. \square

• (4E 8.D.10) $\text{Supp } \tau \in (\mathcal{L}(V))'$, $\tau(I) = \dim V$, and $\tau(ST) = \tau(TS)$. Prove $\tau = \text{tr}$.

SOLUS: $\tau(E_{i,j}) = \tau(E_{x,j}E_{i,x}) = \tau(E_{i,x}E_{x,j}) = \delta_{i,j}\tau(E_{x,x})$. 又 $I = E_{1,1} + \dots + E_{n,n} \Rightarrow n = n\tau(E_{x,x})$. \square

• (4E 8.D.12) $\text{Supp } V, W$ are finide inner prodsps. Define $\langle \cdot, \cdot \rangle$ on $\mathcal{L}(V, W)$ by $\langle S, T \rangle = \text{tr}(ST^*)$.

Let orthon $B_V = (e_1, \dots, e_n), B_W = (f_1, \dots, f_m)$. Show $\langle S, T \rangle = \sum_{j=1}^m \sum_{k=1}^n \mathcal{M}(S)_{j,k} \overline{\mathcal{M}(T)_{j,k}}$.

SOLUS: Becs $\mathcal{M}(ST^*)_{j,k} = \mathcal{M}(S)_{j,r}\mathcal{M}(T^*)_{r,k} = \mathcal{M}(S)_{j,r} \overline{\mathcal{M}(T)_{k,r}}$. Take $k = j$. \square

Or. Define $E_{k,j}(e_x) = \delta_{k,x}f_j$, $R_{j,k}(f_y) = \delta_{j,y}e_k$, and $Q_{j,k}(f_y) = \delta_{j,y}f_k$. See NOTE FOR [3.60].

Becs $E_{k,j}^* = R_{j,k}$, and $\langle E_{k,l}, E_{i,j} \rangle = \text{tr}(E_{k,l}R_{j,i}) = \text{tr}(\delta_{i,k}Q_{j,l}) = \delta_{i,k}\delta_{j,l}$.

Now $\langle \sum A_{j,k}E_{k,j}, \sum C_{x,y}E_{y,x} \rangle = \sum A_{j,k} \overline{C_{j,k}}$ \square

ENDED

[4E] 9 NOTE: V, W denote finite non0 vecsps over \mathbf{F} .

A.2 $\text{Supp } \beta$ is biliney on V of dim n . Prove $\exists \varphi_k, \tau_k \in V'$, $\beta(u, v) = \sum_{k=1}^n \varphi_k(u) \tau_k(v)$.

SOLUS: $\forall v \in V, \exists \varphi_v \in V'$ suth $\varphi_v : u \mapsto \beta(u, v)$. Define such $\varphi_1, \dots, \varphi_n$ for a $B_V = (v_1, \dots, v_n)$.

$\forall u, v \in V, \beta(u, v) = \beta(u, \sum a_i v_i) = \sum a_i \beta(u, v_i) = \sum a_i \varphi_i(u)$. Get the dual bss of B_V . \square

A.4 $\text{Supp } V$ is real inner prodsp, β is biliney on V . Show $\exists ! T \in \mathcal{L}(V), \beta(u, v) = \langle Tu, v \rangle$.

SOLUS: Let orthon $B_V = (e_1, \dots, e_n) \Rightarrow \beta(u, v) = \sum \beta(u, e_i) \langle e_i, v \rangle = \langle \sum \beta(u, e_i) e_i, v \rangle$.

$\text{Supp } \beta(u, v) = \langle Tu, v \rangle = \sum \langle Tu, e_i \rangle \langle e_i, v \rangle$. Then each $\langle Tu, e_i \rangle = \beta(u, e_i) \Rightarrow Tu = \sum \beta(u, e_i) e_i$. \square

B.1 $\text{Supp } m \in \mathbf{N}^+$. Show $\dim V^{(m)} = \dim V^m$.

SOLUS: Let $B_V = (e_1, \dots, e_n)$ with corres $B_{V'} = (\varphi_1, \dots, \varphi_n)$. $\text{Supp } \alpha$ is m -liney.

$\forall v_j = \sum_{i=1}^n \varphi_i(v_j) e_i, \alpha(v_1, \dots, v_m) = \sum_{i_1=1}^n \dots \sum_{i_m=1}^n \varphi_{i_1}(v_1) \dots \varphi_{i_m}(v_m) \alpha(e_{i_1}, \dots, e_{i_m})$.

Define m -liney $\alpha_I(v_1, \dots, v_m) = \varphi_{i_1}(v_1) \dots \varphi_{i_m}(v_m)$, for each $I = (i_1, \dots, i_m) \in \Gamma = \{1, \dots, n\}^m$.

Hence $\alpha = \sum_{I \in \Gamma} \alpha(e_{i_1}, \dots, e_{i_m}) [\alpha_I] \in \text{span}(\alpha_I)_{I \in \Gamma}$. $\text{Supp } \exists c_I \in \mathbf{F}, I \in \Gamma$ suth $\sum_{I \in \Gamma} c_I \alpha_I = 0$.

Note that for each $J = (j_1, \dots, j_m) \in \Gamma, \alpha_I(e_{j_1}, \dots, e_{j_m}) = \delta_{I,J} \Rightarrow 0(e_{j_1}, \dots, e_{j_m}) = c_J$. \square

Or. We show $V^{(m)} = \mathcal{B}(V, \dots, V)$ iso to $\mathbf{F}^{n, \dots, n}$ via liney $\alpha \mapsto \mathcal{M}(\alpha)$. $\text{Supp } A \in \mathbf{F}^{n, \dots, n}$.

Define $\alpha_A \in \mathcal{B}(V, \dots, V)$ by $\alpha_A(\sum_{i=1}^n c_{i,1} e_{i,1}, \dots, \sum_{i=1}^n c_{i,m} e_{i,m}) = \sum_{I \in \Gamma} c_{j_1,1} \dots c_{j_m,m} A_I$.

Let $\mathcal{M}(\alpha) \in \mathbf{F}^{n, \dots, n}$ with each $\mathcal{M}(\alpha)_{j_1, \dots, j_m} = \alpha(e_{j_1}, \dots, e_{j_m})$. Becs $\alpha_{\mathcal{M}(\alpha)} = \alpha$. \square

C.2,5 $\text{Supp square } B, C$ on diag of block up-trig A . Prove $\det A = (\det B)(\det C)$.

SOLUS: If the cols of B are liney dep, then the cols of A are liney dep, done. Now supp B is inv.

Let $A = \begin{pmatrix} B & D \\ 0 & C \end{pmatrix}, P = \begin{pmatrix} B & 0 \\ 0 & C \end{pmatrix}, Q = \begin{pmatrix} 0 & D \\ 0 & 0 \end{pmatrix}$. $\text{Supp } A \in \mathbf{F}^{n,n}, B \in \mathbf{F}^{m,m}, C \in \mathbf{F}^{p,p}$.

Now $\det(A_{\cdot,1} \dots A_{\cdot,n}) = \det(P_{\cdot,1} \dots P_{\cdot,m} (P+Q)_{\cdot,m+1} \dots (P+Q)_{\cdot,n})$.

Becs each col of D is in $\text{col}B = \mathbf{F}^m \Rightarrow$ each $Q_{\cdot,m+k} \in \text{span}(P_{\cdot,1}, \dots, P_{\cdot,m}) \Rightarrow \det A = \det P$. \square

C.22 $\text{Supp } n \in \mathbf{N}^+$, and $\delta : \mathbf{C}^{n,n} \rightarrow \mathbf{C}$ suth $\delta(AB) = \delta(A) \cdot \delta(B)$, and $\delta(D) = D_{1,1} \dots D_{n,n}$, for all $A, B \in \mathbf{C}^{n,n}$ and all diag $D \in \mathbf{C}^{n,n}$. Prove $\delta = \det$.

SOLUS: Define $\mathcal{K}_{i,j}^{(\alpha)} = I + \alpha \mathcal{E}^{(i,j)}$. We show $\delta(\mathcal{K}_{i,j}^{(\alpha)}) = 1 + \delta_{i,j} \alpha$. Supp $i \neq j$.

$$\begin{aligned} \text{NOTICE that } \mathcal{K}_{i,j}^{(\alpha)} \mathcal{K}_{i,j}^{(\alpha)} &= (I + \alpha \mathcal{E}^{(i,j)})^2 = I + 2\alpha \mathcal{E}^{(i,j)} \\ &= [I + \mathcal{E}^{(j,j)} + 2\alpha \mathcal{E}^{(i,j)}] - \frac{1}{2} \mathcal{E}^{(j,j)} [I + \mathcal{E}^{(j,j)} + 2\alpha \mathcal{E}^{(i,j)}] \\ &= (I - \frac{1}{2} \mathcal{E}^{(j,j)}) [(I + \alpha \mathcal{E}^{(i,j)})(I + \mathcal{E}^{(j,j)})] = \mathcal{K}_{j,j}^{(1/2)} \mathcal{K}_{i,j}^{(\alpha)} \mathcal{K}_{j,j}^{(1)}. \end{aligned}$$

又 $\mathcal{K}_{i,j}^{(\alpha)} \mathcal{K}_{i,j}^{(-\alpha)} = I \Rightarrow \delta(\mathcal{K}_{i,j}^{(\alpha)}) \neq 0$. Thus $\delta(\mathcal{K}_{i,j}^{(\alpha)}) = \delta(\mathcal{K}_{j,j}^{(1/2)} \mathcal{K}_{j,j}^{(1)}) = 1$.

$\text{Supp } A \in \mathbf{C}^{n,n}$. Define $T \in \mathcal{L}(\mathbf{C}^n) : e_k \mapsto A_{\cdot,k} \Rightarrow \mathcal{M}(T) = A$ wrto std bses.

Write $A = \mathcal{M}(I, Tv \rightarrow e) \mathcal{M}(T, v \rightarrow Tv) \mathcal{M}(I, e \rightarrow v)$. Thus A not inv $\Rightarrow \delta(A) = 0$. $\text{Supp } A$ inv.

$\text{Supp } T$ up-trig wrto $(u_1, \dots, u_n) \Rightarrow C = \mathcal{M}(T, u \rightarrow u) = \mathcal{M}(I, e \rightarrow u) \mathcal{M}(T, e \rightarrow e) \mathcal{M}(I, u \rightarrow e)$.

Then $A \mathcal{K}_{i,j}^{(\alpha)} = A + \alpha A \mathcal{E}^{(i,j)}$, which is the result of adding i^{th} col times α to the j^{th} col.

Step 1. Let $c_1 = C_{1,2}/C_{1,1}$. Then let $R_1 = C \mathcal{K}_{1,2}^{(-c_1)}$. Now $(R_1)_{1,2} = 0$.

Step k. Let $c_k = (C_{1,k+1}/C_{1,1}, \dots, C_{k,k+1}/C_{k,k})$. Then let $R_{k+1} = R_k \mathcal{K}_{1,k+1}^{(-c_{1,k})} \dots \mathcal{K}_{k,k+1}^{(-c_{k,k})}$.

We stop at step $(n-1)$. Becs each $\delta(R_{k+1}) = \delta(R_k)$. \square

- **NOTE FOR EXE (D.6):** Let $R_r = \{v_1 \otimes w_1 + \dots + v_r \otimes w_r : ((v_1, \dots, v_r), (w_1, \dots, w_r)) \in V^r \times W^r\}$.
 Let $V = \mathbf{F}^m, W = \mathbf{F}^n$. Let $M_r = \{A \in \mathbf{F}^{m,n} : \text{rank } A \leq r\}$. Id $v \otimes w$ with vw^t .
 Then $(v_1 w_1^t + \dots + v_r w_r^t)_{\cdot, k} = w_1[k] \cdot v_1 + \dots + w_r[k] \cdot v_r \in \text{span}(v_1, \dots, v_r)$.
 Simlr $(v_1 w_1^t + \dots + v_r w_r^t)_{j, \cdot} = v_1[j] \cdot w_1^t + \dots + v_r[j] \cdot w_r^t \in \text{span}(w_1, \dots, w_r)$.
 Let $N = \min\{m, n\}$. Then $R_1, \dots, R_{N-1} \neq V \otimes W$ id with $\mathbf{F}^{m,n} = M_N$.
 Immed by using a bss of the smaller vecsp, $R_N = M_N$ via $v \otimes w = vw^t$.
 - **COMMENT:** For $r \in \{1, \dots, N-1\}$, R_r is not a subsp of $V \otimes W$, as M_r is not a subsp of $\mathbf{F}^{m,n}$,
 as the set of non-inv $T \in \mathcal{L}(V, W)$ is not a subsp of $\mathcal{L}(V, W)$.
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