这是我个人挑战自学「***Measure, Integration & Real Analysis, by Sheldon Axler***」的学习笔记，包括课文补注和部分习题。
我先从 ***Supplement*** 即第 0 章开始。我当时并没有学过数学分析，以为学完 Axler 的这个 Supplement 就能具备所有必要的知识基础。
0.B 节是我碰到的第一个挫折。本来课文非常温顺，但习题做起来却让我感到知识的桀骜不训。
的确，它们不需要硬性知识门槛，可以用初中学过的不等式和高中学过的集合与量词来推导 $\mathcal{D}$ 的一切。如你所见，字越少，事越大。

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

C

closd	closed under
coeff	coefficient
combina	combination
commu	commut(es)(ing)(ativity)
cond	condition
continu	countinu(ous)(ity)
corres	correspond(s)(ing)
conveni	convenience
convly	conversely
countexa	counterexample
ctradic	contradict(s)(ion)
ctrapos	constrapositive

D

Ddkd	Dedekind
decr	decreasing
def	definition
deg	degree
deri	derivative(s)
diff	differentia(ble)(l)(ting)(tion)
dim	dimension(al)
disj	disjoint
disti	distinct
distr	distributive propert(ies)(ty)
div	div(ide)(ision)

E

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

F G H

factoriz	factorizaion
fini	finite(ly)
finide	finite-dimensional
homo	homogeneity
hypo	hypothesis

I

id	identity
immed	immediately
induc	induct(ion)(ive)
infily	infinitely
inje	injectiv(e)(ity)
inv	inver(se)(tib-le/ility)
iso	isomorph(ism)(ic)

L

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

M N

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

O P Q

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

R

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

S

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

T U V W X Y Z

uniq	unique
uniqnes	uniqueness
up-	upper-
val	value
-wd	-ward
-ws	-wise
wrto	with respect to

0·B **Note:** C, D are Dedekind cuts. Numbers used here are always rational.

- Define $\tilde{q} = \{a : a < q\}$, and $-\tilde{q} = \widetilde{-q} = \{a : a < -q\}$.
  Then $\tilde{0} = \{a : a < 0\} = \mathbf{Q}\backslash\mathbf{Q}^* \Rightarrow -\tilde{0} = \{a : a < -b \leqslant 0\} = \tilde{0}$.
- Define $-D = \{a : a < -b,\ b \notin D\} = \{-a : -a < -b \Longleftrightarrow a > b,\ b \notin D\}$.
  $-(-D) = -\{a : a < -b,\ b \notin D\} = \{c : c < -a,\ a \geqslant -b,\ \forall b \notin D\} = \{c : c < b,\ \forall b \notin D\} = D$.
  The last equa is becs (a) $d \notin D \Rightarrow \exists\, b \notin D,\ d \geqslant b$, and (b) $d \in D \Rightarrow$ if $\exists\, b \notin D$ suth $d \geqslant b$, then $b \in D$, ctradic.

- **Tips:** *Prove $\forall \varepsilon > 0,\ \exists\, b \notin D$ suth $b - \varepsilon \in D$.*

Solus: Asum $\exists\, \varepsilon > 0$ suth $\nexists\, b \notin D,\ b - \varepsilon \in D \Longleftrightarrow \forall b \notin D,\ b - \varepsilon \notin D$.
Then $(b - \varepsilon) - \cdots - \varepsilon = b - n \cdot \varepsilon \notin D$ for any $n \in \mathbf{N}^+$.
Now $\forall d \in D,\ \exists\, n \in \mathbf{N}^+$ suth $b - n \cdot \varepsilon < d \Rightarrow b - n \cdot \varepsilon \in D$, ctradic. □

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1 *Prove* (a) $D + \tilde{0} = D$, (b) *$-D$ is Dedekind cut, and $D + (-D) = \tilde{0}$.*

Solus: (a) $\forall d \in D,\ \exists\, \varepsilon > 0,\ d + \varepsilon \in D \Rightarrow (d + \varepsilon) + (-\varepsilon) \in D + \tilde{0}$.

(b) Asum $x \in -D$ is the largest elem of $-D \Rightarrow \exists\, b \notin D,\ x < -b \Rightarrow 0 < -b - x$.
Let $\delta = (-b - x)/2 \Rightarrow 0 < \delta < -b - x \Rightarrow x < x + \delta < -b$.
Thus by def, $x + \delta \in -D$, ctradic the max of $x \in -D$. Hence $-D$ is Ddkd cut.
$D + (-D) = \{x + y : x + y < x - b,\ x \in D,\ b \notin D\}$.
Supp $a \in \tilde{0} \Rightarrow -a > 0$. By Tips, $\exists\, b \notin D$ suth $b + a \in D$.
Note that $b < b - a \notin D \Rightarrow -b > -b + a \in -D$. Then $(-b + a) + (b + a) = 2a < 0$.
Thus $\forall a \in \tilde{0},\ \exists\, b \notin D,\ d = b + \frac{1}{2}a \in D,\ c = -b + \frac{1}{2}a \in -D \Rightarrow c + d = a \in D + (-D)$. □

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3 *Show $C \subsetneq D \Longleftrightarrow D - C = \{d - y : d \in D,\ y > x,\ x \notin C\}$ posi.*

Solus: (a) $C \subsetneq D \Rightarrow \exists\, x \in D\backslash C \Rightarrow \exists\, y \in D,\ y > x \Rightarrow \exists\, d \in D,\ d > y \Longleftrightarrow 0 < d - y \in D - C$.

(b) $0 \in D - C \Rightarrow \exists\, y > x \notin C,\ y \in D \Rightarrow \forall c \in C,\ c < x < y \in D \Rightarrow C \subseteq D$. 又 $D - C \neq \tilde{0}$. □

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5 *Prove* (a) *D posi $\Rightarrow -D$ not posi,* (b) *non0 $-D$ not posi $\Rightarrow D$ posi.*

Solus: (a) $0 \notin \{a : a < -b,\ b \notin D\} \Longleftrightarrow \nexists\, b \notin D,\ 0 < -b \Longleftrightarrow \forall b \notin D,\ b \geqslant 0 \Longleftarrow 0 \in D$.

(b) Becs $\tilde{0}$ is the largest non posi cuts. Thus $-D \neq \tilde{0} \Rightarrow -D \subsetneq \tilde{0} \Rightarrow \tilde{0} - (-D) = D$ posi.
Or. $\exists\, a < 0,\ a \notin -D = \{a : -a > b,\ b \notin D\} \Longleftrightarrow \nexists\, b \notin D,\ -a > b \Longleftrightarrow \forall b \notin D,\ 0 < -a \leqslant b$. □

- Define $D^+ = \{d \in D : d > 0\} = D \cap \mathbf{Q}^+$. Then $D^+ \neq \emptyset \Longleftrightarrow \mathbf{Q}\backslash\mathbf{Q}^+ \subsetneq D \Longleftrightarrow 0 \in D \Longleftrightarrow D$ posi.
  Define $D^- = \{r \notin D : r \leqslant 0\} = (\mathbf{Q}\backslash D) \cap (\mathbf{Q}\backslash\mathbf{Q}^+) = \mathbf{Q}\backslash(D \cup \mathbf{Q}^+)$.
  (a) $D^- = \{0\} \Longleftarrow D = \tilde{0}$. Convly, $\{r \notin D : r \leqslant 0\} = \{0\} \Longrightarrow \mathbf{Q}\backslash D = \mathbf{Q}^*$.
  (b) $D^- = \emptyset \Longleftrightarrow D \cup \mathbf{Q}^+ = \mathbf{Q} \Longleftrightarrow \mathbf{Q}\backslash\mathbf{Q}^+ \subseteq D \Longleftrightarrow 0 \in D \Longleftrightarrow D$ posi. **Coro:** D not posi $\Longleftrightarrow 0 \in D^-$.
  (c) $(D^-)^- = \{r \in D : r \leqslant 0\} = \mathbf{Q}\backslash D^+$. **Coro:** D not posi $\Longleftrightarrow (D^-)^- = D$.

- $(-D)^+ = (-D) \cap \mathbf{Q}^+ = \{a : 0 < a < -b,\ b \notin D \Longleftrightarrow b \in D^-\backslash\{0\}\}$.
  $(-D)^- = (\mathbf{Q}\backslash -D) \cap (\mathbf{Q}\backslash\mathbf{Q}^+) = \{a : 0 \geqslant a \geqslant -b,\ \forall b \notin D\}$.

- For C, D posi, define $CD = \{a : a \leqslant cd,\ c \in C^+,\ d \in D^+\} = \{cd : c \in C^+, d \in D^+\} \cup (\mathbf{Q}\backslash\mathbf{Q}^+)$.
  $\{cd : c \in C^+, d \in D^+\} = CD \cap \mathbf{Q}^+ = (CD)^+$. Note that '$a \leqslant cd$' here is equiv to '$a < cd$'.

- For $-C, -D$ posi, define $CD = (-C)(-D) = \{cd : c \in (-C)^+, d \in (-D)^+\} \cup (\mathbf{Q}\backslash\mathbf{Q}^+)$.
  $CD = \{0 < cd < (-r)(-s) : r \in C^-\backslash\{0\}, s \in D^-\backslash\{0\}\} \cup (\mathbf{Q}\backslash\mathbf{Q}^+) = \{a : a < rs, r \in C^-, s \in D^-\}$.
  If $C, -C$ not posi $\Rightarrow C = \tilde{0}$, then with the asum $\tilde{0}D = \tilde{0}$, it still holds. Simlr for D.

- For D posi, define $D^{-1} = \{a : a < 1/b,\ b \notin D\} \Rightarrow DD^{-1} = \{a : a \leqslant d/b < 1,\ b \notin D, d \in D^+\} = \tilde{1}$.
  The last equa holds becs $\forall a \in \tilde{1} \cap \mathbf{Q}^+$, $\exists\, d \in D^+$ suth $b = d/a \notin D \Rightarrow d/b = a \in DD^{-1}$.
- For non0 D not posi, define $D^{-1} = -(-D)^{-1} = -\{a : a < 1/b,\ \exists\, b \notin -D \iff \exists\, b \geqslant -s,\ \forall s \notin D\}$
  $= \{a : a < -x,\ \exists\, x \geqslant 1/b,\ \forall b$ suth $b \geqslant -s,\ \forall s \notin D\} = \{a : a < -1/b,\ \forall b$ suth $b \geqslant -s,\ \forall s \notin D\}$
  $= \{a : a < 1/b,\ \forall b$ suth $b \leqslant s,\ \forall s \notin D\} \neq \{a : a < 1/s,\ \forall s \notin D\}$.
  Let $b_1 < \cdots < b_m < \cdots \leqslant s,\ \forall s \notin D \iff \forall s \in D^- \Rightarrow$ each $s_j, b_k < 0 \Rightarrow 1/s_j \leqslant \cdots < 1/b_m < \cdots < 1/b_1$.
  Thus '$a < 1/b$' is equiv to '$a < 1/s,\ \exists\, s \in D^-$'. Hence $D^{-1} = \{a : a < 1/b,\ b \in D^-\}$.
  $DD^{-1} = \{a : a < rs,\ \exists\, r \in D^-, \exists\, s$ suth $0 \geqslant s \geqslant 1/b,\ \forall b \in D^-\} \subseteq \tilde{1}$.
  Asum $\exists\, x$ suth $rs \leqslant x < 1,\ \forall r, s$. Let $D \not\ni \cdots \leqslant b_m < \cdots < b_1 \leqslant 0$, and $D \not\ni \cdots \leqslant r_m < \cdots < r_1 \leqslant 0$.
  $1/b_1 < \cdots < 1/b_m \leqslant \cdots \leqslant \cdots \leqslant s_n < \cdots < s_1 \leqslant 0$, and $r_m/b_m \geqslant \cdots \geqslant \cdots \geqslant r_m s_n > \cdots > r_j s_k > \cdots > r_1 s_1$.
  Let $r_m = b_m$. Ctradic. OR. $DD^{-1} = D[(-\tilde{1})(-D)^{-1}] = [D(-\tilde{1})](-D)^{-1} = (-D)(-D)^{-1} = \tilde{1}$.

- For C not posi and D posi, we expect that CD not posi. Consider C and $-D$ both not posi.
  $CD = -[C(-D)] = -\{a : a < rt,\ r \in C^-,\ t \in (-D)^-\} = \{-a : a > b,\ b \geqslant rt,\ \forall r \in C^-,\ t \in (-D)^-\}$
  $= \{-a : a > rt,\ \forall r \in C^-,\ \forall t$ suth $0 \geqslant t \geqslant -s,\ \forall s \notin D\}$
  $= \{a : a < ru,\ \forall r \in C^-,\ \forall u$ suth $0 \leqslant u \leqslant s,\ \forall s \notin D\}$. $\quad (r \leqslant 0 < s,\ rs \leqslant ru = -rt \leqslant 0 \leqslant rt \leqslant -rs.)$
- Note the '$0 \leqslant u$'. Becs $C^- \neq \emptyset \Rightarrow 0 \in C^-$. If it is to be exactly $CD = \{a : a < 0\}$, then $C^- = \{0\}$,
  for if not, $\exists\, u > 0$, and $\exists\, r \in C^-\backslash\{0\}$, suth $\exists\, a < ru < 0$. Hence '$0 \leqslant u$' is actually '$0 < u$'.
- '$u \leqslant s$' cannot be abbreviated as in $\{-a : a > -rs,\ \forall s \notin D,\ r \in C^-\} = \{a : a < rs,\ \forall s \notin D,\ r \in C^-\}$.
  '$u \leqslant s$' cannot be '$u < s$', becs here $rs < ru \Rightarrow \exists\, a = rs$.
- Note that $\{u : 0 < u \leqslant s,\ \forall s \notin D\} = \begin{cases} D^+ \cup \{\min \mathbf{Q}\backslash D\}, & \text{if it exis,} \\ D^+, & \text{othws.} \end{cases}$ Denote it by $D^{\oplus} = D^{\otimes}\backslash\{0\}$.

- For C not posi and D posi. If $C = \tilde{0}$, then $CD = -[C(-D)] = -\tilde{0}$. Now consider $-C$ and D both posi.
  But $CD = -(-C)D = -\{a : a \leqslant cd,\ c \in (-C)^+, d \in D^+\} \neq \{a : a < -cd,\ \forall c \in (-C)^+, d \in D^+\}$.
  Altho "$a \leqslant cd$" is equiv to "$a < cd$" so that $b \notin (-C)D \Rightarrow b \geqslant cd$, which is actually $b > cd,\ \forall c, d$.
  And $a < -b < -cd,\ \forall c, d \Rightarrow \forall a, \exists\, x$ suth $a < x < -cd,\ \forall c, d$. While a can be the 'boundary' in RHS.

- $LHS = \{a : a < ru,\ \forall r \in C^-,\ \forall u \in D^{\oplus}\}$, $\{cs : c \in C, s \notin D\} = RHS$.
  Becs $cs \leqslant cu < ru$. We show $LHS \subseteq RHS$. Let $c_1 < \cdots < c_n < \cdots \in C$, and $s_1 > \cdots > s_m \geqslant \cdots \notin D$.
  Then $\underline{c_1 s_1 < \cdots < c_n s_m < \cdots < ru,\ \forall r, u \text{ as in } LHS. \text{ Thus } a \in LHS \Rightarrow \exists\, a < c_j s_k.}$ □
  OR. Note that in LHS, '$a < ru$' is equiv to '$a < rs,\ \exists\, s \notin D$.' Now $LHS = \{a : a/s \in C,\ \exists\, s \notin D\}$. □

- For C posi and D not posi. If $D = \tilde{0}$, then $CD = -[(-C)D] = -\tilde{0}$.
  $CD = (-C)(-D) = \{a : a < ru,\ \forall r \in (-C)^-,\ \forall u \in (-D)^{\oplus}\}$ $\qquad \mathbf{Q}\backslash -D = \{s : s \geqslant -y,\ \forall y \notin D\}$
  $= \{a : a < ru,\ \forall r$ suth $\forall x \notin C,\ 0 \geqslant r \geqslant -x,\ \forall u$ suth $0 < u \leqslant s,\ \forall s \geqslant -y,\ \forall y \notin D\}$
  $= \{a : a < (-r)(-u),\ \forall r$ suth $\forall x \notin C,\ 0 \leqslant -r \leqslant x,\ \forall u$ suth $y \leqslant -u < 0,\ \forall y \notin D\}$
  $= \{a : a < ru,\ \forall r$ suth $\forall x \notin C,\ 0 \leqslant r \leqslant x,\ \forall u \in D^-\} = \{a : a < ru,\ \forall r \in C^{\oplus},\ \forall u \in D^-\}$, simlr.

- We show $-D = \{a : a < -b,\ b \notin D\} = (-\tilde{1})D$.
  For D posi, $RHS = \{a : a < ru,\ \forall r \text{ suth } -1 \leqslant r \leqslant 0,\ \forall u \in D^{\oplus}\} = \{a : a < -u,\ \forall u \in D^{\oplus}\} \supseteq -D$.
  Supp x suth $-b \leqslant x < -u,\ \forall b \notin D,\ \forall u \text{ suth } -s \leqslant -u < 0,\ \forall s \notin D \Longrightarrow -s \leqslant x < -u$. Let $-u = x$.
  For D not posi, $RHS = \{a : a < rb,\ \exists r \text{ suth } -1 \leqslant r \leqslant 0,\ b \in D^-\} = \{a : a < -b,\ 0 \geqslant b \notin D\} = -D$.

- We show $\tilde{1}D = D$. For D not posi, immed. Othws, $\tilde{1}D = \{a : a \leqslant ij < j,\ 0 < i < 1,\ j \in D^+\} \subseteq D$.
  Now $(\tilde{1}D)^+ \subseteq D^+$. 又 $\forall d \in D^+, \exists \varepsilon > 0,\ d + \varepsilon \in D^+ \Rightarrow d = (d+\varepsilon)\frac{d}{d+\varepsilon} \in (\tilde{1}D)^+$.

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4 *Supp B, C, D non0 Dedekind cuts. Show $(BC)D = B(CD)$, $B(C+D) = BC + BD$.*

Solus: We discuss in cases.

\	1	2	3	4	5	6
B	+	+	+	-	-	-
C	+	+	-	-	+	+
D	+	-	-	-	-	+

(1) $[(BC)D]^+ = \{(bc)d : bc \in (BC)^+,\ d \in D^+\} = \{b(cd) : b \in B^+,\ cd \in (CD)^+\} = [B(CD)]^+$.

$B(C+D) = \{a : a \leqslant bc + bd,\ \exists b \in B^+,\ 0 < c + d \in C + D\}$.

$$BC + BD = \{x : x \leqslant uc,\ u \in B^+,\ c \in C^+\} + \{y : y \leqslant vd,\ v \in B^+,\ d \in D^+\}$$
$$= \{a : a \leqslant uc + vd,\ \exists u, v \in B^+,\ c \in C^+,\ d \in D^+\}.$$ Done.

(3) $(BC)^- = \{r : 0 \geqslant r \geqslant bc,\ \exists c \in C^-,\ \exists b \in B^{\oplus}\}$.

$$(BC)D = \{a : a < rs,\ r \in (BC)^-,\ s \in D^-\}$$
$$= \{a : a < bcs,\ \exists s \in D^-,\ c \in C^-,\ \exists b \in B^{\oplus}\}.$$
$$B(CD) = \{a : a \leqslant bx < bcs,\ \exists s \in D^-,\ c \in C^-,\ \exists b \in B^+, \text{ and } cs > x \in (CD)^+\}$$
$$= \{a : a < bcs,\ \exists s \in D^-,\ c \in C^-,\ \exists b \in B^+\}.$$

Note that $\{q : q < b,\ b \in B^+\} = \{q : q < b,\ \exists b \in B^{\oplus}\}$. Done.

$$B(C+D) = \{a : a < ru,\ \forall r \text{ suth } \forall x \notin B,\ 0 < r \leqslant x,\ \forall u \text{ suth } 0 \geqslant u > c + d,\ \forall c \in C,\ d \in D\}$$
$$= \{a : a < ru,\ \forall r \in B^{\oplus},\ \forall u \text{ suth } 0 \geqslant u \geqslant c + d,\ \exists c \in C^-,\ d \in D^-\}$$
$$= \{a : a < r(c+d),\ \forall r \in B^{\oplus},\ \forall c \in C^-,\ d \in D^-\}.$$
$$BC + BD = \{x : x < pc,\ \forall p \in B^{\oplus},\ \forall c \in C^-\} + \{y : y < qd,\ \forall q \in B^{\oplus},\ \forall d \in D^-\}$$
$$= \{a : a < pc + qd,\ \forall p, q \in B^{\oplus},\ \forall c \in C^-,\ d \in D^-\}.$$ Done immed.

(5) $(BC)^- = \{r : 0 \geqslant r \geqslant bc,\ \exists b \in B^-,\ \exists c \in C^{\oplus}\}$. $(CD)^- = \{r : 0 \geqslant r \geqslant cd,\ \exists d \in D^-,\ \exists c \in C^{\oplus}\}$.

$(BC)D = \{a : a < rd \leqslant bcd,\ \exists d \in D^-,\ b \in B^-,\ \exists c \in C^{\oplus}\}$.

$B(CD) = \{a : a < br \leqslant bcd,\ \exists b \in B^-,\ d \in D^-,\ \exists c \in C^{\oplus}\}$. Done.

Or. By commu and (3), $(BC)D = (CB)D = C(BD) = C(DB) = (CD)B = B(CD)$.

$$BC + BD = \{x : x < bc,\ \forall b \in B^-,\ \forall c \in C^{\oplus}\} + \{y : y < bd,\ \exists b \in B^-,\ d \in D^-\}$$
$$= \{a : a < pc + qd,\ \forall p \in B^-,\ \forall c \in C^{\oplus}, \text{ and } \exists q \in B^-,\ d \in D^- \Rightarrow q \geqslant p\}$$
$$= \{a : a < pc + y,\ \forall p \in B^-,\ \forall c \in C^{\oplus}, \text{ and } \forall y \text{ suth } y \geqslant qd,\ \forall q \in B^-,\ d \in D^-\}$$
$$= \{a : a < p(c + d'),\ \forall p \in B^-,\ \forall c \in C^{\oplus}, \text{ and } \forall d' \text{ suth } d' \leqslant d,\ \forall d \in D^-\}.$$

(I) If $C + D$ not posi. Then $B(C+D) = \{a : a < bx,\ \exists b \in B^-,\ 0 \geqslant x > c + d,\ \forall (c,d) \in C \times D\}$.
Rewrite as $\{a : a < t,\ \forall t \text{ suth } t \geqslant bx,\ \forall b \in B^-,\ x \in (C+D)^-\}$. Done.

(II) If $C + D$ posi. Then $B(C+D) = \{a : a < bx,\ \forall b \in B^-,\ x \in (C+D)^{\oplus}\}$.
If $(C+D)^{\oplus} = (C+D)^+$. Then $B(C+D) = \{a : a < bc + bd,\ \forall b \in B^-,\ \forall (c,d) \in C^{\oplus} \times D^{\oplus}\}$.
Othws, $\exists s = \min \mathbf{Q} \backslash (C+D) \Rightarrow B(C+D) = \{a : a < bs,\ \forall b \in B^-\}$. Done.

$$\begin{aligned}(4)\ (BC)D &= \{xd : d \in D,\ x \geqslant bc,\ \forall b \in B^-,\ c \in C^-\} \\ &= \{a : a < bcd,\ \forall d \in D^-,\ \forall b \in B^-,\ c \in C^-\} \\ &= \{by : b \in B,\ y \geqslant cd,\ \forall c \in C^-,\ d \in D^-\} = B(CD).\end{aligned}$$

$$\begin{aligned}B(C+D) &= \{a : a < t,\ \forall t \text{ suth } t \geqslant b(c+d),\ \forall b \in B^-,\ (c,d) \in C^- \times D^-\} \\ &= \{a : a < t_1,\ \forall t_1 \text{ suth } t_1 \geqslant bc,\ \forall (b,c) \in B^- \times C^-\} \\ &\quad + \{a : a < t_2,\ \forall t_2 \text{ suth } t_2 \geqslant bd,\ \forall (b,d) \in B^- \times D^-\} = BC + BD. \text{ Done.}\end{aligned}$$

Note: Supp for any B posi, C posi, D not posi, assoc holds.

Supp B posi, C not posi, D posi. Then $(\overset{+}{B}\overset{-}{C})\overset{+}{D} = \overset{+}{D}(\overset{+}{B}\overset{-}{C}) = (\overset{+}{D}\overset{+}{B})\overset{-}{C} = \overset{+}{B}(\overset{+}{D}\overset{-}{C})$. Convly true.

Simlr for the case B not posi, C posi, D not posi, equiv to the case B not posi, C not posi, D posi.

(2) holds $\Rightarrow$ $(\overset{-}{B}\overset{+}{C})\overset{+}{D} = \overset{+}{D}(\overset{+}{C}\overset{-}{B}) = (\overset{+}{C}\overset{+}{D})\overset{-}{B}$, (6) holds. Convly true. Simlr to (3) with (5) in assoc.

(5) holds $\Rightarrow$ $\overset{+}{B}(\overset{+}{C} + \overset{-}{D}) = (-\overset{-}{B})[-(\overset{+}{C} + \overset{-}{D})] \overset{(5)}{=\!=} (-\overset{-}{B})[(-\overset{-}{C}) + (-\overset{+}{D})] \overset{(5)}{=\!=} \overset{+}{B}\overset{+}{C} + \overset{+}{B}\overset{-}{D}$, by def of multi.

Thus (5) $\Rightarrow$ (2) in distr. Convly as well.

(6) $(BC)^- = \{r : 0 \geqslant r \geqslant bc,\ \exists\, b \in B^-,\ c \in C^\oplus\}$.

$(BC)D = \{a : a < ru,\ \forall r \in (BC)^-,\ u \in D^\oplus\} = \{a : a < bcd,\ \forall b \in B^-,\ c \in C^\oplus,\ d \in D^\oplus\}$.

$(CD)^\oplus = \{u : 0 < u \leqslant s,\ \forall s > cd,\ \forall c \in C^+,\ d \in D^+\}$.

$B(CD) = \{a : a < ru,\ \forall r \in B^-,\ u \in (CD)^\oplus\}$. Done.

$B(C+D) = \{a : a < b(c+d),\ \forall b \in B^-,\ \forall (c,d) \in C^\oplus \times D^\oplus\}$.

$BC + BD = \{a : a < bc,\ \forall b \in B^-,\ c \in C^\oplus\} + \{a : a < bd,\ \forall b \in B^-,\ d \in D^\oplus\}$. Done.

Or. (2) instead of (6) ? Notice that the distr in (6) cannot be shown without (6). ☐

Ended

0·C

2 *Supp nonempty $U \subseteq V \subseteq \mathbf{R}$. Show $\sup U \leqslant \sup V$.*

Solus: Asum $\sup U > \sup V \Rightarrow \exists\, t \in U \cap (\sup V, \sup U] \Rightarrow \sup V < t \in V$, ctradic. ☐

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5 *Supp $a_1, a_2, \cdots \in \mathbf{Q}$, and $\sup\{a_1, a_2, \dots\} = \sqrt{2}$.*
Prove $\sup\{a_n, a_{n+1}, \dots\} = \sqrt{2}$ for all $n \in \mathbf{N}^+$.

Solus: Becs the sup not in seq $\Rightarrow$ infily many disti elem.

$\forall a_i,\ \exists\, a_j,\ a_i < a_j < \sqrt{2}$. For a_{n+k}, choose $a_i > a_{n+k}$. If $i \in \{1, \dots, n\}$, then choose $a_j > a_i$.

After at most n steps, we must have a_m with $m > n$. Thus $\forall a_{n+i},\ \exists\, a_{n+j},\ a_{n+i} < a_{n+j} < \sqrt{2}$. ☐

• *Supp nonempty $A \subseteq \mathbf{R}$.*

• **Tips 1:** *Define $-A = \{-a : a \in A\} \Rightarrow -(-A) = A$. Prove $\sup(-A) = -\inf A$.*

Solus: $-b$ is an up-bound of $-A \iff \forall a \in A,\ -a \leqslant -b \iff a \geqslant b \iff b$ is a low-bound of A.

Thus $-b_M = \sup(-A) \iff -b_M \leqslant -b \iff b_M \geqslant b \iff b_M = \inf A$. ☐

• **Tips 2:** *Show if $x \in \mathbf{R}$,* (a) *$\sup A > x \Rightarrow \exists\, a \in A,\ a > x$,* (b) *$\inf A < x \Rightarrow \exists\, a \in A,\ a < x$.*

Solus: (a) $\nexists\, a > x \iff \forall a \in A,\ a \leqslant x \Longrightarrow \sup A \leqslant x$.

Or. By (b), $\inf(-A) = -\sup A < -x \Rightarrow \exists -a \in A,\ -a < -x$. Simlr for (b). ☐

---

6 *Supp nonempty* $A, B \subseteq \mathbf{R}$. *Prove* $\sup(A+B) = \sup A + \sup B$, *and* $\inf(A+B) = \inf A + \inf B$.

Solus: $\inf A + \inf B \leqslant a + b \leqslant \sup A + \sup B \Rightarrow \sup(A+B) \leqslant \sup A + \sup B$, $\inf A + \inf B \leqslant \inf(A+B)$.
$\sup A + \sup B > \sup(A+B) \iff \sup A > \sup(A+B) - \sup B$
$\iff \exists\, a + \sup B > \sup(A+B) \iff \sup B > \sup(A+B) - a \iff \exists\, a + b > \sup(A+B)$. Ctradic.
Simlr for $\inf(A+B) \in A+B$. Or. Apply to $-A-B$, becs $\sup(-A) = -\inf A$. □

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16 *Supp* $\mathbf{R}_1, \mathbf{R}_2$ *are complete ordered fields. Define* φ_1, φ_2 *as in* $[0.11]$.
Define $\psi : \mathbf{R}_1 \to \mathbf{R}_2$ *by* $\psi(a) = \sup\{\varphi_2(q) : q \in \mathbf{Q},\ \varphi_1(q) \leqslant a\}$. *Show*
(a) $\psi : \mathbf{R}_1 \to \mathbf{R}_2$ *is one-to-one.* (b) $\psi(0) = 0$, $\psi(1) = 1$.
(c) $\psi(a+b) = \psi(a) + \psi(b)$. (d) $\psi(ab) = \psi(a)\psi(b)$.

Solus: (a) Define $\mathcal{R}_1(a) = \{q \in \mathbf{Q} : \varphi_1(q) \leqslant a\} \Rightarrow \sup_{\mathcal{R}_1(a)} \varphi_1 = a$. Let $\psi_1(a) = \sup_{\mathcal{R}_1(a)} \varphi_2 = \psi(a)$.
Define $\mathcal{R}_2(c) = \{q \in \mathbf{Q} : \varphi_2(q) \leqslant c\} \Rightarrow \sup_{\mathcal{R}_2(c)} \varphi_2 = c$.
Define $\psi_2(c) = \sup_{\mathcal{R}_2(c)} \varphi_1$. Then $\psi_2 : \mathbf{R}_2 \to \mathbf{R}_1$ well-defined.
Note that $\mathcal{R}_2\big(\psi_1(a)\big) = \{q \in \mathbf{Q} : \varphi_2(q) \leqslant \sup_{\mathcal{R}_1(a)} \varphi_2\} = \mathcal{R}_1(a)$.
Now $\psi_2\big(\psi_1(a)\big) = \sup_{\mathcal{R}_1(a)} \varphi_1 = a$. Rev the roles of $\mathbf{R}_1, \mathbf{R}_2$.

(b) Becs $\varphi_1(q) \leqslant \varphi_1(0) \iff q \leqslant 0 \iff \varphi_2(q) \leqslant \varphi_2(0)$. Simlr for $\psi(1) = 1$.

(c) $S = \{\varphi_2(t) : t \in \mathbf{Q},\ \varphi_1(t) \leqslant a+b\} \supseteq \{\varphi_2(p+q) : p, q \in \mathbf{Q},\ \varphi_1(p) \leqslant a,\ \varphi_1(q) \leqslant b\} = T$
$\Rightarrow \sup S \geqslant \sup T$. Asum it is '$>$'. Now $\exists\, t \in \mathbf{Q}$ suth $\sup S \geqslant \varphi_2(t) > \sup T = \psi(a) + \psi(b)$.
Which means $\varphi_2(t) > \varphi_2(p+q)$, $\forall p, q \in \mathbf{Q}$ suth $\varphi_1(p) \leqslant a$ and $\varphi_1(q) \leqslant b$.
Now $a + b \geqslant \varphi_1(t) > \varphi_1\big[(t+p+q)/2\big] > \varphi_1(p+q)$, $\forall p, q$. Ctradic.

(d) We show it for (I) $a, b > 0$, (II) $a > 0 > b$.
$LHS = \sup\{\varphi_2(t) : t \in \mathbf{Q},\ \varphi_1(t) \leqslant ab\}$, $\sup\{\psi(a)\varphi_2(q) : q \in \mathbf{Q},\ \varphi_1(q) \leqslant b\} = RHS$.
(I) $RHS = \sup\{\varphi_2(p)\varphi_2(q) : p, q \in \mathbf{Q},\ 0 < \varphi_1(p) \leqslant a,\ \varphi_1(q) \leqslant b \Longrightarrow \varphi_1(pq) \leqslant ab\}$.
(II) $RHS = \sup\{\varphi_2(s)\varphi_2(q) : s, q \in \mathbf{Q},\ \varphi_1(q) \leqslant b$, and $s \geqslant p, \forall p$ suth $0 < \varphi_1(p) \leqslant a\}$.
Note that $\varphi_1(s) \geqslant \varphi_1(p), \forall p \Rightarrow \varphi_1(s) \geqslant a$, for if not, $\exists\, p' \in \mathbf{Q}$ suth $\varphi_1(s) < \varphi_1(p') \leqslant a$.
So that $\varphi_1(sq) \leqslant a\varphi_1(q) \leqslant ab$.
Now $LHS \geqslant RHS$. Asum it is '$>$'. Then $\exists\, t \in \mathbf{Q}$ suth $LHS \geqslant \varphi_2(t) > RHS$.
Which means $\varphi_2(t) > \psi(a)\varphi_2(q)$, $\forall q \in \mathbf{Q}$ suth $\varphi_1(q) \leqslant b$.
(I) $\Longrightarrow \varphi_2(t) > \varphi_2(s)\varphi_2(q)$, $\forall q$ and $\forall s \in \mathbf{Q}$ suth $0 < \varphi_1(s) \leqslant a$.
(II) $\Longrightarrow \varphi_2(t) > \varphi_2(s)\varphi_2(q)$, $\forall q$ and $\forall s \in \mathbf{Q}$ suth $\varphi_2(s) \geqslant \varphi_2(p), \forall p$ suth $0 < \varphi_1(p) \leqslant a$.
Thus $ab \geqslant \varphi_1(t) > \varphi_1\big[(t+sq)/2\big] > \varphi_1(sq)$, $\forall s, q$. Ctradic. □

Ended

0·D

• *Supp nonempty* A *is closed and open subsets of* $\mathbf{R}^n$. *Prove* $A = \mathbf{R}^n$.

Solus: Asum $A \neq \mathbf{R}^n$. Let $a \in A$, $b \in \mathbf{R}^n \backslash A$. Define $f(t) = (1-t)a + tb$.
If $f(t_1) = f(t_2) \Rightarrow (t_1 - t_2)(b-a) = 0 \Rightarrow t_1 = t_2$. Inje.
Let $\mathcal{A} = \{t \in [0,1) : f(t) \in A\}$, and $\sup \mathcal{A} = t_M \in [0,1]$. Let $c = f(t_M)$.
(I) If $c \in A \Rightarrow \exists\, \delta > 0$, $B(c,\delta) \subseteq A$. Let $t \neq t_M$ be suth $f(t) \in B(c,\delta) \Rightarrow \big\|(t - t_M)(b-a)\big\|_\infty < \delta$.
Let $\varepsilon = |t - t_M| > 0 \Rightarrow f(t_M + \varepsilon) \in B(c,\delta) \subseteq A \Rightarrow t_M \geqslant t_M + \varepsilon$, ctradic.
(II) If $c \in \mathbf{R}^n \backslash A$. Simlr. $\forall t' \in [t_M - \varepsilon,\ t_M)$, $t' \notin \mathcal{A}$. Now $\forall t \in \mathcal{A}$, $t < t_M \Rightarrow t < t_M - \varepsilon$. □

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15 *Supp F is a closed subset of $\mathbf{R}$. Prove $S = \{a^2 : a \in F\}$ is closed.*

Solus: Supp S not closed $\Rightarrow \exists\, a_1^2, a_2^2, \cdots \in S$ convg to L^2 suth $\pm L \notin F$. Let $\varepsilon_1 > \varepsilon_2 > \cdots \in \mathbf{R}^+$.
Becs $\forall \varepsilon_p, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m$, $\|a_k^2 - L^2\|_\infty = |a_k - L| \cdot |a_k + L| < \varepsilon_p$,
if $|a_k - L| < \varepsilon_p$, then let $b_p = a_k$, if $|a_k + L| < \varepsilon_p$, then let $c_p = a_k$.
Then we have at least one seq in F with lim $\pm L \notin F \Rightarrow F$ not closed. $\square$

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17 *Supp $F \subseteq \mathbf{R}$, and $\forall n \in \mathbf{N}^+$, $F \cap [-n, n]$ is closed. Prove F is closed.*

Solus: Becs $G = (\mathbf{R} \backslash F) \cup (-\infty, -n) \cup (n, \infty)$ is open for all $n \in \mathbf{N}^+$. Let $n > \sup\{|a| : a \in \mathbf{R} \backslash F\}$.
By [0.59], $G = (-\infty, -n) \cup (n, \infty) \cup I_1 \cup I_2 \cup \cdots$ (disj) $\Longrightarrow I_1 \cup I_2 \cup \cdots = \mathbf{R} \backslash F$. $\square$

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20 *Prove $\forall b \in \mathbf{R}^n$, $\delta > 0$, $B = \{a \in \mathbf{R}^n : \|a - b\| \leqslant \delta\}$ is closed.* *See below [0.46].*

Solus: Asum $\exists\, a_1, a_2, \cdots \in B$ convg to L suth $\|L - b\| > \delta$. Then $\forall \varepsilon > 0, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m$,
$\underline{\|a_k - L\| < \varepsilon} \Rightarrow \delta < \|L - b\| \leqslant \|a_k - L\| + \|a_k - b\| < \delta + \varepsilon$. Now $0 < \|L - b\| - \delta < \varepsilon$. Ctradic. $\square$

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21 *Supp X is an open subset of $\mathbf{R}$. Prove $\exists\, a_k, b_k \in \mathbf{R}$ suth $X = \bigcup_{k=1}^{\infty} [a_k, b_k]$.*

Solus: Let $X = \bigcup_{k=1}^{\infty} (c_k, d_k)$, where each $d_k < c_{k+1}$. Let $I_k = (c_k, d_k)$.
Let $a_{1,k}, a_{2,k}, \ldots$ be convg of lim c_k. Simlr, let $b_{1,k}, b_{2,k}, \ldots$ of lim d_k. Let $E_{j,k} = [a_{j,k}, b_{j,k}]$.
Now $\bigcup_{k=1}^{\infty} \bigcup_{j=1}^{\infty} E_{j,k} = \bigcup_{k=1}^{\infty} I_k = X$. Rearrange the order of $E_{j,k}$'s. $\square$

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23 *Supp F_1, F_2 are disj closed subsets of $\mathbf{R}$ suth $U = F_1 \cup F_2$ is interval. Prove F_1 or F_2 open.*

Solus: If U open, then $F_1 = \emptyset$, $F_2 = \emptyset$ or $\mathbf{R}$. Now supp U not open $\Rightarrow F_1$ or F_2 not open.
We show F_1 open $\Longleftrightarrow F_2$ not open. Note that F_1 open $\Longleftrightarrow F_1 = \emptyset$. Simlr for F_2.
WLOG, asum F_1, F_2 both not open, and $x \in F_1, y \in F_2$ with $x < y \Rightarrow x, y \in U \supseteq [x, y]$.
Notice that $T = [x, y] \cap F_1$ is a closed subset that has infily many elem. 又 $\sup T < y$.
(I) If $\sup T \notin F_1$. Then $\exists$ a convg seq in T with lim $\sup T$.
(II) Othws, $\forall t \in (\sup T, y]$, $t \notin F_1 \Longleftrightarrow t \in F_2$. Now $\exists$ a convg seq in F_2 with lim $\sup T \notin F_2$.
Ctradic the asum $\Rightarrow$ at least one of F_1, F_2 is empty. $\square$

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25 *Give an exa of inv $f : \mathbf{R} \to \mathbf{R} \backslash \mathbf{Q}$.*

Solus: Consider a seq disti $a_1, b_1, a_2, b_2, \cdots \in \mathbf{R}$ where $\{a_1, a_2, \ldots\} \in \mathbf{Q}$ and each $b_i \in \mathbf{R} \backslash \mathbf{Q}$.
Define $\varphi(a_j) = b_{2j-1}$, $\varphi(b_k) = b_{2k} \Rightarrow \varphi^{-1}(b_i) = \begin{cases} a_{(i+1)/2}, & \text{if } i \text{ is odd,} \\ b_{i/2}, & \text{if } i \text{ is even.} \end{cases}$
Let $B = \{b_1, b_2, \ldots\}$, $U = \mathbf{Q} \cup B$, $K = \mathbf{R} \backslash U$. Extend $\varphi \in B^U$ to $\psi \in (K \cup B)^{K \cup U}$ by $\psi|_K = I$. $\square$

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26 *Supp $E, G \subseteq \mathbf{R}^n$, and G is open. Prove $E + G = \{x + y : x \in E, y \in G\}$ is open.*

Solus: Asum $E + G$ not open $\Longleftrightarrow \mathbf{R}^n \backslash (E + G)$ not closed.
Then $\exists\, a = x + y \in E + G$ suth $\forall \delta > 0, \exists\, b \notin E + G$ suth $\|a - b\|_\infty < \delta$.
Let $z = b - x \notin G \Rightarrow \|y - z\|_\infty < \delta \Rightarrow z \in B(y, \delta) \subseteq G$, $\exists\, \delta > 0$. $\square$
Or. $\exists\, a_1, a_2, \cdots \notin E + G$ while its lim $L = e + g \in E + G$. 又 $\forall x \in E$, $a_k - x \notin G$
$\Rightarrow \lim_{k \to \infty}(a_k - e) = L - e = g \in G$. Thus $\mathbf{R}^n \backslash G$ not closed $\Longleftrightarrow G$ not open. $\square$

Ended

0·E

1 *Prove every convg seq in* $\mathbf{R}^n$ *is bounded.*

Solus: Supp $a_1, a_2, \cdots \in \mathbf{R}^n$ suth $\forall \varepsilon > 0, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m,\ \left| \|a_k\|_\infty - \|L\|_\infty \right| \leqslant \|a_k - L\|_\infty < \varepsilon$.
Thus $\|a_k\|_\infty \in \left(\left| \varepsilon - \|L\|_\infty \right|,\ \varepsilon + \|L\|_\infty \right)$. Now asum $\sup\{\|a_k\|_\infty : k \in \mathbf{N}^+\} = \infty$.
Which means $\forall t \in \mathbf{R}^+, \forall m \in \mathbf{N}^+, \exists\, k \geqslant m,\ \max\{\|a_1\|_\infty, \ldots, \|a_m\|_\infty\} \leqslant \|a_k\|_\infty > t$. Ctradic. □

• **Tips 1:** By def, a seq $a_1, a_2, \cdots \in \mathbf{R}^n$ convg to $L \Longrightarrow$ every subseq convg to L.

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3 *Supp* $F \subseteq \mathbf{R}^n$*, every seq in* F *has a convg subseq with lim in* F*. Prove* F *is closed bounded.*

Solus: Supp $a_1, a_2, \cdots \in F$ convg with lim L. Becs $\exists$ subseq with lim in F. By Tips (1), $L \in F$.
Asum $\sup\left\{\|a\|_\infty : a \in F\right\} = \infty \Rightarrow \forall \Delta > 0, \exists\, a_1, a_2, \cdots \in F$ with each $\|a_{k+1}\|_\infty \geqslant \|a_k\|_\infty + \Delta$.
Thus every subseq is unbounded $\Rightarrow$ not convg. Ctradic. □

• *Supp* $b \in A \subseteq \mathbf{R}^m, f : A \to \mathbf{R}^n$*. Prove*
$[P]$ f *is continu at* $b \iff \forall b_1, b_2, \cdots \in A$ *suth* $\lim_{k\to\infty} b_k = b, \lim_{k\to\infty} f(b_k) = f(b)$. $[Q]$

Solus: $Q \Rightarrow P:$ Supp $\varepsilon > 0$ suth $\forall \delta > 0, \exists\, a \in A$ with $\|a - b\|_\infty < \delta$ and $\left\| f(a) - f(b) \right\|_\infty \geqslant \varepsilon$.
Fix a δ. Define $\delta_k = \delta / k \Rightarrow \exists\, a_k$ for each. Now $\lim_{k\to\infty} a_k = b$.
Thus $\forall m, \forall k \geqslant m,\ \left\| f(a_k) - f(b) \right\|_\infty \geqslant \varepsilon$. Ctradic Q.

$P \Rightarrow Q:$ Supp $b_1, b_2, \cdots \in A$ suth $\forall \delta > 0,\ \exists\, m, \forall k \geqslant m,\ \|b_k - b\|_\infty < \delta$.
Asum $\varepsilon > 0$ suth $\forall m, \forall k \geqslant m,\ \left\| f(b_k) - f(b) \right\|_\infty \geqslant \varepsilon$. Ctradic P. □

Solus:

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10 *Supp bounded* $A \subseteq \mathbf{R}^m$ *and uniformly continu* $f \in \mathbf{R}^A$*. Prove* f *is bounded.*

Solus: Asum $\forall \Delta > 0, \exists\, a_1, a_2, \cdots \in A$ suth each $\left| f(a_{k+1}) - f(a_k) \right| \geqslant \left| f(a_{k+1}) \right| - \left| f(a_k) \right| \geqslant \Delta$.
$\exists$ subseq $a_{j_1}, a_{j_2}, \cdots$ convg to $L \Rightarrow \forall \delta > 0, \exists\, j_m, \forall j_x, j_y \in \left\{ j_m, j_{m+1}, \cdots \right\},\ \|a_{j_x} - a_{j_y}\| < \delta$.
$\forall \varepsilon > 0, \exists\, \delta > 0, \forall a, b \in A$ suth $\|a - b\| < \delta$, we have $f(a) \in \left(f(b) - \varepsilon,\ f(b) + \varepsilon \right)$.
Let $b_{k_i} = a_{j_{k_i}}$. Becs $\exists\, k_1 < k_2 < \cdots$ suth $f(b_{k_1}), f(b_{k_2}), \cdots$ is monotone.
If incre, then let k_1 suth $f(b_{k_1}) > 0 \Rightarrow f(b_{k_{i+1}}) > f(b_{k_i}) + \Delta$. Ctradic. Simlr for decre. □

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18 *Supp* $h : \mathbf{R}^m \to \mathbf{R}^n$*. Prove* h *continu* $\iff h^{-1}(G)$ *is open for all open* $G \subseteq \mathbf{R}^n$*.*

Solus: Supp h continu and open $G \subseteq \mathbf{R}^n$. We show $\mathbf{R}^m \backslash h^{-1}(G) = \left\{ t \in \mathbf{R}^m : h(t) \notin G \right\}$ is closed.
Let $t_1, t_2, \cdots \in \mathbf{R}^m \backslash h^{-1}(G)$ convg to $L \Rightarrow h(t_1), h(t_2), \cdots \in \mathbf{R}^n \backslash G$ convg to $h(L)$.
Supp open $G \subseteq \mathbf{R}^n$ suth $\mathbf{R}^m \backslash h^{-1}(G)$ not closed. Asum show h continu.
$\exists\, t_1, t_2, \cdots \in \mathbf{R}^m \backslash h^{-1}(G)$ convg to $L \in h^{-1}(G) \Longrightarrow h(t_1), h(t_2), \cdots \in \mathbf{R}^n \backslash G$ convg to $h(L) \notin G$. □

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22 *Supp decre seq* $F_1 \supsetneq F_2 \supsetneq \cdots$ *non-*$\emptyset$ *closed bounded subsets of* $\mathbf{R}^n$*. Prove* $\bigcap_{k=1}^{\infty} F_k \neq \emptyset$*.*

Solus: Fix one k. Supp $a_1, a_2, \cdots \in F_1$ convg to $L \in F_k \Rightarrow \exists$ subseq $a_{j_1}, a_{j_2}, \cdots \in F_k$ convg to L.
Asum $\bigcup_{k=1}^{\infty} \mathbf{R}^n \backslash F_k = \mathbf{R}^n$. Note that $\mathbf{R}^n \backslash F_1 \subsetneq \mathbf{R}^n \backslash F_2 \subsetneq \cdots$ is an incre seq of non-$\emptyset$ open subsets.
Fix $k > 1$. Then $\forall a \in \left(\mathbf{R}^n \backslash F_k \right) \big\backslash \left(\mathbf{R}^n \backslash F_{k-1} \right),\ a \in F_{k-1} \backslash F_k$, and $\exists\, \delta > 0,\ B(a, \delta) \subseteq \mathbf{R}^n \backslash F_k$.

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26 *Supp $F \subseteq \mathbf{R}^n$ suth every continu $f \in \mathbf{R}^F$ attains a max. Prove F is closed bounded.*

SOLUS: Supp $f(a_1), f(a_2), \cdots$ convg to $\sup\{f(a) : a \in F\}$. Becs F is bounded $\Rightarrow \exists$ subseq $a_{j_1}, a_{j_2}, \cdots \in F$ convg.

---

27 *Supp $f \in \mathbf{R}^{\mathbf{R}}$ is incre. Prove $\exists$ countable $A \subseteq \mathbf{R}$ suth $f|_{\mathbf{R}\backslash A}$ is continu.*

SOLUS: Asum $\forall$countable $A \subseteq \mathbf{R}$, $f|_{\mathbf{R}\backslash A}$ is not continu at some $b \in \mathbf{R}\backslash A$.

Then $\exists\, \varepsilon > 0, \forall \delta > 0, \exists\, a \in \mathbf{R}\backslash A$ suth $|a-b| < \delta$, $\big|f(a) - f(b)\big| \geqslant \varepsilon$.

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29 *Supp continu $f : [a,b] \to \mathbf{R}$, and t is between $f(a), f(b)$. Prove $\exists\, c \in [a,b]$, $f(c) = t$.*

SOLUS: Let $a_0 = a$, $b_0 = b$.

Step 1 Pick $c_1 \in (a_0, b_0)$. If $f(c_1) = t$, then stop.

If $f(a_0) < t < f(b_0)$. Let $(a_1, b_1) = \begin{cases} (a_0, c_1), & \text{if } t < f(c_1), \\ (c_1, b_0), & \text{if } f(c_1) < t. \end{cases}$

If $f(b_0) < t < f(a_0)$. Let $(a_1, b_1) = \begin{cases} (c_1, b_0), & \text{if } t < f(c_1), \\ (a_0, c_1), & \text{if } f(c_1) < t. \end{cases}$

Step m Pick $c_m \in (a_{m-1}, b_{m-1})$. If $f(c_m) = t$, then stop.

If $f(a_{m-1}) < t < f(b_{m-1})$. Let $(a_m, b_m) = \begin{cases} (a_{m-1}, c_m), & \text{if } t < f(c_m), \\ (c_m, b_{m-1}), & \text{if } f(c_m) < t. \end{cases}$

If $f(b_{m-1}) < t < f(a_{m-1})$. Let $(a_m, b_m) = \begin{cases} (c_m, b_{m-1}), & \text{if } t < f(c_m), \\ (a_{m-1}, c_m), & \text{if } f(c_m) < t. \end{cases}$

Either we stop at some m and done or we get a seq $(a_1, b_1) \supsetneq (a_2, b_2) \supsetneq \cdots$
suth $\forall \varepsilon > 0, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m, b_k - a_k < \varepsilon \Longrightarrow \lim_{k\to\infty} a_k = \lim_{k\to\infty} b_k$, let it be $c \in (a_0, b_0)$.
Now $\forall \varepsilon > 0, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m$, $\big|t - f(a_k)\big| < \varepsilon \Longrightarrow \lim_{k\to\infty} f(a_k) = t = f(c)$. □

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30 *Prove for every continu $f : \mathbf{R} \to \mathbf{R}\backslash\mathbf{Q}$, $f(\mathbf{R}) = \{c\}$ for some $c \in \mathbf{R}\backslash\mathbf{Q}$.*

SOLUS: If $f(a) \neq f(b)$. By Exe(29), $\forall t \in \mathbf{Q}$ suth t between $f(a), f(b)$, $\exists\, c \in (a,b)$, $f(c) = t$, ctradic.

OR. Asum $f(\mathbf{R})$ has more than one elem $\Rightarrow \exists$ convg $a_1, a_2, \cdots \in \mathbf{R}$ and convg $b_1, b_2, \cdots \in \mathbf{R}$ suth $\lim_{k\to\infty} |a_k - b_k| = 0$ while $\lim_{k\to\infty} a_k < \lim_{k\to\infty} b_k$. TODO □

L1 *Supp $p \in \mathbf{R}^{\mathbf{R}}$ is a poly. Prove p continu.*

SOLUS: Write $p(x) = a_0 + a_1 x + \cdots + a_m x^m$ with $a_m \neq 0$. Supp $x_0 \in \mathbf{R}$. Then write:

$\forall \varepsilon > 0, \exists\, \delta_M > 0, \forall \delta$ suth $|\delta| < \delta_M$, $\big|p(x_0 + \delta) - p(x_0)\big| = \big|\delta \cdot q(x_0, \delta)\big| < \varepsilon \Longleftrightarrow \big|q(x_0, \delta)\big| < |\varepsilon/\delta|$

where $q(x_0, \delta) = \sum_{k=1}^{m} \left(\sum_{i=1}^{k} a_k C_k^i \delta^{k-i-1} x_0^i \right) \Rightarrow \big|q(x_0, \delta)\big| \leqslant \sum_{k=1}^{m} \sum_{i=1}^{k} |\delta|^{k-i-1} \big|a_k C_k^i x_0^i\big|$.

Let $|\delta| < 1$ suth $\max\{|a_k C_k^i x_0^i| : i, k \in \mathbf{N}^+, 1 \leqslant k \leqslant m, 1 \leqslant i \leqslant k\} \cdot |\delta| \leqslant |\varepsilon| < |\varepsilon/\delta|$. □

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31 *Supp* $p \in \mathbf{R}^{\mathbf{R}}$ *is a poly with odd deg. Prove* $\exists\, b \in \mathbf{R}$ *suth* $p(b) = 0$.

Solus: Write $p(x) = a_0 + a_1 x + \cdots + a_m x^m$ with $a_m \neq 0$. Supp $a_m > 0$. $[$If $a_m < 0$, then apply to $-p$.$]$
Now $p(x) = x^m\left[\frac{a_0}{x^m} + \frac{a_1}{x^{m-1}} + \cdots + \frac{a_{m-1}}{x} + a_m\right]$ for all $x \in \mathbf{R}\backslash\{0\}$.
While $\left|\frac{a_0}{x^m} + \frac{a_1}{x^{m-1}} + \cdots + \frac{a_{m-1}}{x}\right| \leqslant \delta^m|a_0| + \delta^{m-1}|a_1| + \cdots + \delta|a_{m-1}|$; let $\delta = |x|$.
Let x be suth $\delta < 1$ and $\max\{|a_0|, |a_1|, \dots, |a_{m-1}|\} \cdot \delta \leqslant |a_m|/m$. Thus $p(-|x|) < 0 < p(|x|)$. $\square$

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33 *Supp* $a_1, a_2, \cdots \in \mathbf{R}^n$ *is Cauchy seq and* $\exists$ *subseq convg to* L*. Prove the seq convg to* L*.*

Solus: Supp subseq $a_{j_1}, a_{j_2}, \cdots$ convg to L. Then $\forall \varepsilon > 0, \exists\, j_m, \forall j_k \in \{j_m, j_{m+1}, \cdots\}$, $\|a_{j_k} - L\| < \varepsilon$,
and $\exists\, n \in \mathbf{N}^+, \forall i \geqslant n$, $\|a_i - L\| = \left\|(a_i - a_{j_k}) + (a_{j_k} - L)\right\| \leqslant \|a_i - a_{j_k}\| + \|a_{j_k} - L\| < 2\varepsilon$. $\square$

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34 *Supp closed* $F_1 \subseteq \mathbf{R}^n$ *and closed bounded* $F_2 \subseteq \mathbf{R}^n$*. Prove* $F_1 + F_2$ *is closed.*

Solus: Asum $\exists$ convg $a_1, a_2, \cdots \in F_1 + F_2$ with lim $L \notin F_1 + F_2$. Let each $a_k = x_k + y_k$, and $z_k = L - x_k$.
$\forall \varepsilon > 0, \exists\, m \in \mathbf{N}^+, \forall k \geqslant m$, $\|a_k - L\| = \|x_k + y_k - L\| = \|y_k - z_k\| < \varepsilon$.
Supp subseq $y_{j_1}, y_{j_2}, \cdots$ convg to $L_y \in F_2$. Then $\forall \varepsilon > 0, \exists\, j_m, \forall j_k \in \{j_m, j_{m+1}, \cdots\}$,
$\|z_{j_k} - L_y\| = \|(z_{j_k} - y_{j_k}) + (y_{j_k} - L_y)\| < \varepsilon$. Now $x_{j_1}, x_{j_2}, \cdots \in F_1$ convg to $L - L_y \notin F_1$. $\square$

Ended