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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驯。

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

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)
existsns	existence
expo	exponent
expr	expression

L

liney	linear.ly
linity	linearity
len	length
low-	lower-

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)

C

closd	closed under
coeff	coefficient
combina	combination
commu	commut(es)(ing)(ativity)
cond	condition
corres	correspond(s)(ing)
conveni	convenience
convly	conversely
count-	counter-
ctradic	contradict(s)(ion)
ctrapos	contrapositive

D

Ddkd	Dedekind
def	definition
deg	degree
deri	derivative(s)
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)
infil	infinitely
inje	injectiv(e)(ity)
inv	inver(se)(tib-le/ility)
iso	isomorph(ism)(ic)

F G H

factoriz	factorizaion
fini	finite
finide	finite-dimensional
homo	homogeneity
hypo	hypothesis

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)

S

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

O P Q

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

T U V W X Y Z

uniq	unique
uniqnes	uniqueness
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 $-\tilde{q} = \tilde{-q} = \{a : a < -q\}$.
Then $\tilde{0} = \{a : a < 0\} = \mathbf{Q} \setminus \mathbf{Q}^*$ $\Rightarrow -\tilde{0} = \{a : a < -b \leq 0\} = \tilde{0}$.
- Define $-D = \{a : a < -b, b \notin D\} = \{-a : -a < -b \Leftrightarrow a > b, b \notin D\}$.
 $-(-D) = -\{a : a < -b, b \notin D\} = \{c : c < -a, a \geq -b, \forall b \notin D\} = \{c : c < b, \forall b \notin D\} = D$.
The last equa is becs (a) $d \notin D \Rightarrow \exists b \notin D, d \geq b$, and (b) $d \in D \Rightarrow$ if $\exists b \notin D$ suth $d \geq b$, 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 $\nexists b \notin D, b - \varepsilon \in D \Leftrightarrow \forall b \notin D, b - \varepsilon \notin D$.

Then $(b - \varepsilon) - \dots - \varepsilon = b - n \cdot \varepsilon \notin D$ 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. \square

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 $\forall a \in \tilde{0}, \exists b \notin D, d = b + \frac{1}{2}a \in D, c = -b + \frac{1}{2}a \in -D \Rightarrow c + d = a \in D + (-D)$. \square

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

SOLUS: (a) $C \subsetneq D \Rightarrow \exists x \in D \setminus C \Rightarrow \exists y \in D, y > x \Rightarrow \exists d \in D, d > y \Leftrightarrow 0 < d - y \in D - C$.

(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 $D - C \neq \tilde{0}$. \square

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

SOLUS: (a) $0 \notin \{a : a < -b, b \notin D\} \Leftrightarrow \nexists b \notin D, 0 < -b \Leftrightarrow \forall b \notin D, b \geq 0 \Leftrightarrow 0 \in D$.

(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. $\exists a < 0, a \notin -D = \{a : -a > b, b \notin D\} \Leftrightarrow \nexists b \notin D, -a > b \Leftrightarrow \forall b \notin D, 0 < -a \leq b$. \square

- Define $D^+ = \{d \in D : d > 0\} = D \cap \mathbf{Q}^+$. Then $D^+ \neq \emptyset \Leftrightarrow \mathbf{Q} \setminus \mathbf{Q}^+ \subsetneq D \Leftrightarrow 0 \in D \Leftrightarrow D$ posi.

Define $D^- = \{r \notin D : r \leq 0\} = (\mathbf{Q} \setminus D) \cap (\mathbf{Q} \setminus \mathbf{Q}^+) = \mathbf{Q} \setminus (D \cup \mathbf{Q}^+)$.

(a) $D^- = \{0\} \Leftrightarrow D = \tilde{0}$. Convly, $\{r \notin D : r \leq 0\} = \{0\} \Rightarrow \mathbf{Q} \setminus D = \mathbf{Q}^*$.

(b) $D^- = \emptyset \Leftrightarrow D \cup \mathbf{Q}^+ = \mathbf{Q} \Leftrightarrow \mathbf{Q} \setminus \mathbf{Q}^+ \subseteq D \Leftrightarrow 0 \in D \Leftrightarrow D$ posi. CORO: D not posi $\Leftrightarrow 0 \in D^-$.

(c) $(D^-)^- = \{r \in D : r \leq 0\} = \mathbf{Q} \setminus D^+$. CORO: D not posi $\Leftrightarrow (D^-)^- = D$.

- $(-D)^+ = (-D) \cap \mathbf{Q}^+ = \{a : 0 < a < -b, b \notin D \Leftrightarrow b \in D^- \setminus \{0\}\}$.

$(-D)^- = (\mathbf{Q} \setminus -D) \cap (\mathbf{Q} \setminus \mathbf{Q}^+) = \{a : 0 \geq a \geq -b, \forall b \notin D\}$.

- For C, D posi, define $CD = \{a : a \leq cd, c \in C^+, d \in D^+\} = \{cd : c \in C^+, d \in D^+\} \cup (\mathbf{Q} \setminus \mathbf{Q}^+)$.

$\{cd : c \in C^+, d \in D^+\} = CD \cap \mathbf{Q}^+ = (CD)^+$. Note that ' $a \leq cd$ ' here is equiv to ' $a < cd'$.

- For $-C, -D$ posi, define $CD = (-C)(-D) = \{cd : c \in (-C)^+, d \in (-D)^+\} \cup (\mathbf{Q} \setminus \mathbf{Q}^+)$.
 $CD = \{0 < cd < (-r)(-s) : r \in C^- \setminus \{0\}, s \in D^- \setminus \{0\}\} \cup (\mathbf{Q} \setminus \mathbf{Q}^+) = \{a : a < rs, r \in C^-, s \in D^-\}$.
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 $D^{-1} = \{a : a < 1/b, b \notin D\} \Rightarrow DD^{-1} = \{a : a \leq d/b < 1, b \notin D, d \in D^+\} = \tilde{1}$.
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 $D^{-1} = -(-D)^{-1} = -\{a : a < 1/b, \exists b \notin -D \Leftrightarrow \exists b \geq -s, \forall s \notin D\}$
 $= \{a : a < -x, \exists x \geq 1/b, \forall b$ suth $b \geq -s, \forall s \notin D\} = $\{a : a < -1/b, \forall b$ suth $b \geq -s, \forall s \notin D\}$
 $= \{a : a < 1/b, \forall b$ suth $b \leq s, \forall s \notin D\} \neq $\{a : a < 1/s, \forall s \notin D\}$.
Let $b_1 < \dots < b_m < \dots \leq s, \forall s \notin D \Leftrightarrow \forall s \in D^- \Rightarrow$ each $s_j, b_k < 0 \Rightarrow 1/s_j \leq \dots < 1/b_m < \dots < 1/b_1$.
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 $0 \geq s \geq 1/b, \forall b \in D^-\} \subseteq \tilde{1}$.
Asum $\exists x$ suth $rs \leq x < 1, \forall r, s$. Let $D \not\ni \dots \leq b_m < \dots < b_1 \leq 0$, and $D \not\ni \dots \leq r_m < \dots < r_1 \leq 0$.
 $1/b_1 < \dots < 1/b_m \leq \dots \leq s_n < \dots < s_1 \leq 0$, and $r_m/b_m \geq \dots \geq r_m s_n > \dots > r_j s_k > \dots > r_1 s_1$.
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.
 $CD = -[C(-D)] = -\{a : a < rt, r \in C^-, t \in (-D)^-\} = \{-a : a > b, b \geq rt, \forall r \in C^-, t \in (-D)^-\}$
 $= \{-a : a > rt, \forall r \in C^-, \forall t$ suth $0 \geq t \geq -s, \forall s \notin D\}$
 $= \{a : a < ru, \forall r \in C^-, \forall u$ suth $0 \leq u \leq s, \forall s \notin D\}$. ($r \leq 0 < s, rs \leq ru = -rt \leq 0 \leq rt \leq -rs$.)
- Note the ' $0 \leq u$ '. 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 $\exists r \in C^- \setminus \{0\}$, suth $\exists a < ru < 0$. Hence ' $0 \leq u$ ' is actually ' $0 < u$ '.
- ' $u \leq s'$ cannot be abbreviated as in $\{-a : a > -rs, \forall s \notin D, r \in C^-\} = \{a : a < rs, \forall s \notin D, r \in C^-\}$.
' $u \leq s'$ cannot be ' $u < s'$ ', becs here $rs < ru \Rightarrow \exists a = rs$. Simlr for ' $a < ru$ ' to be ' $a \leq ru$ ' with ' $u < s'$ '.
- Note that $\{u : 0 < u \leq s, \forall s \notin D\} = \begin{cases} D^+ \cup \{\min \mathbf{Q} \setminus D\}, & \text{if it exists,} \\ D^+, & \text{othws.} \end{cases}$ Denote it by $D^\oplus = D^\otimes \setminus \{0\}$.
- 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 $CD = -(-C)D = -\{a : a \leq cd, c \in (-C)^+, d \in D^+\} \neq \{a : a < -cd, \forall c \in (-C)^+, d \in D^+\}$.
Altho " $a \leq cd$ " is equiv to " $a < cd$ " so that $b \notin (-C)D \Rightarrow b \geq cd$, 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 $cs \leq cu < ru$. We show $LHS \subseteq RHS$. Let $c_1 < \dots < c_n < \dots \in C$, and $s_1 > \dots > s_m \geq \dots \notin D$.
Then $c_1 s_1 < \dots < c_n s_m < \dots < ru, \forall r, u$ as in LHS. Thus $a \in LHS \Rightarrow \exists a < c_j s_k$. \square
Or. Note that in LHS, ' $a < ru$ ' is equiv to ' $a < rs, \exists s \notin D$ '. Now $LHS = \{a : a/s \in C, \exists s \notin D\}$. \square

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

- We show $-D = \{a : a < -b, b \notin D\} = (-\tilde{1})D$.

For D posi, $RHS = \{a : a < ru, \forall r \text{ suth } -1 \leq r \leq 0, \forall u \in D^\oplus\} = \{a : a < -u, \forall u \in D^\oplus\} \supseteq -D$.

Supp x suth $-b \leq x < -u, \forall b \notin D, \forall u \text{ suth } -s \leq -u < 0, \forall s \notin D \Rightarrow -b \leq x < -s, \forall b, s \notin D$.

For D not posi, $RHS = \{a : a < rb, \exists r \text{ suth } -1 \leq r \leq 0, b \in D^-\} = \{a : a < -b, 0 \geq b \notin D\} = -D$.

- We show $\tilde{1}D = D$. For D not posi, immed. Othws, $\tilde{1}D = \{a : a \leq ij < j, 0 < i < 1, j \in D^+\} \subseteq D$.

Now $(\tilde{1}D)^+ \subseteq D^+$. 又 $\forall d \in D^+, \exists \varepsilon > 0, d + \varepsilon \in D^+ \Rightarrow d = (d + \varepsilon) \frac{d}{d + \varepsilon} \in (\tilde{1}D)^+$.

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	+	-	-	-	-	+

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

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

$$\begin{aligned} BC + BD &= \{x : x \leq uc, u \in B^+, c \in C^+\} + \{y : y \leq vd, v \in B^+, d \in D^+\} \\ &= \{a : a \leq uc + vd, \exists u, v \in B^+, c \in C^+, d \in D^+\}. \text{ Done.} \end{aligned}$$

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

$$\begin{aligned} (BC)D &= \{a : a < rs, r \in (BC)^-, s \in D^-\} \\ &= \{a : a < bcs, \exists s \in D^-, c \in C^-, \exists b \in B^\oplus\}. \end{aligned}$$

$$\begin{aligned} B(CD) &= \{a : a \leq bx < bcs, \exists s \in D^-, c \in C^-, \exists b \in B^+, \text{ and } cs > x \in (CD)^+\} \\ &= \{a : a < bcs, \exists s \in D^-, c \in C^-, \exists b \in B^+\}. \end{aligned}$$

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

$$\begin{aligned} B(C + D) &= \{a : a < ru, \forall r \text{ suth } \forall x \notin B, 0 < r \leq x, \forall u \text{ suth } 0 \geq u > c + d, \forall c \in C, d \in D\} \\ &= \{a : a < ru, \forall r \in B^\oplus, \forall u \text{ suth } 0 \geq u \geq c + d, \exists c \in C^-, d \in D^-\} \\ &= \{a : a < r(c + d), \forall r \in B^\oplus, \forall c \in C^-, d \in D^-\}. \end{aligned}$$

$$\begin{aligned} BC + BD &= \{x : x < pc, \forall p \in B^\oplus, \forall c \in C^-\} + \{y : y < qd, \forall q \in B^\oplus, \forall d \in D^-\} \\ &= \{a : a < pc + qd, \forall p, q \in B^\oplus, \forall c \in C^-, d \in D^-\}. \end{aligned} \quad \text{Done immed.}$$

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

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

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

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

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

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

Rewrite as $\{a : a < t, \forall t \text{ suth } t \geq bx, \forall b \in B^-, x \in (C + D)^-\}$. 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, $\exists s = \min \mathbf{Q} \setminus (C + D) \Rightarrow B(C + D) = \{a : a < bs, \forall b \in B^-\}$. Done.

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

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

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

Supp B posi, C not posi, D posi. Then $(\bar{B}\bar{C})\bar{D} = \bar{D}(\bar{B}\bar{C}) = (\bar{D}\bar{B})\bar{C} = \bar{B}(\bar{D}\bar{C})$. 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 $\Rightarrow (\bar{B}\bar{C})\bar{D} = \bar{D}(\bar{C}\bar{B}) = (\bar{C}\bar{D})\bar{B}$, (6) holds. Convly true. Simlr to (3) with (5) in assoc.

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

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

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

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

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

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

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

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

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 $\sup U \leq \sup V$.*

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

5 *Supp (a_1, a_2, \dots) is a seq 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 inflly 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 $\forall a_{n+i}, \exists a_{n+j}, a_{n+i} < a_{n+j} < \sqrt{2}$. \square

• *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 upper bound of $-A \Leftrightarrow \forall a \in A, -a \leq -b \Leftrightarrow a \geq b \Leftrightarrow b$ is a lower bound of A .

Thus $-b_M = \sup(-A) \Leftrightarrow -b_M \leq -b \Leftrightarrow b_M \geq b \Leftrightarrow b_M = \inf A$. \square

• **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) $\nexists a > x \Leftrightarrow \forall a \in A, a \leq x$. Then by def of sup.

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

Simlr for (b). \square

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: $\inf A + \inf B \leq a + b \leq \sup A + \sup B \Rightarrow \sup(A + B) \leq \sup A + \sup B$, $\inf A + \inf B \leq \inf(A + B)$.

$\sup A + \sup B > \sup(A + B) \Leftrightarrow \sup A > \sup(A + B) - \sup B$

$\Leftrightarrow \exists a + \sup B > \sup(A + B) \Leftrightarrow \sup B > \sup(A + B) - a \Leftrightarrow \exists a + b > \sup(A + B)$. Ctradic.

Simlr for $\inf(A + B) \in A + B$. Or. Apply to $-A - B$, becs $\sup(-A) = -\inf A$. \square

16 *Supp $\mathbf{R}_1, \mathbf{R}_2$ are complete ordered fields. Define φ_1, φ_2 as in [0.11].*

Define $\mathcal{R}_1(a) = \{q \in \mathbf{Q} : \varphi_1(q) \leq a\} \Rightarrow \sup_{\mathcal{R}_1(a)} \varphi_1 = a$. Define $\psi_1(a) = \sup_{\mathcal{R}_1(a)} \varphi_2$.

(a) Show $\psi = \psi_1 : \mathbf{R}_1 \rightarrow \mathbf{R}_2$ is one-to-one. (b) Show $\psi(0) = 0, \psi(1) = 1$.

(c) Show $\psi(a \pm b) = \psi(a) \pm \psi(b)$, and $\psi(ab^{-1}) = \psi(a)\psi(b)^{-1}$.

(d) Supp $a \in \mathbf{R}_1$. Show $a > 0 \Leftrightarrow \psi(a) > 0$.

SOLUS: (a) Define $\mathcal{R}_2(c) = \{q \in \mathbf{Q} : \varphi_2(q) \leq c\} \Rightarrow \sup_{\mathcal{R}_2(c)} \varphi_2 = c$.

Define $\psi_2(c) = \sup_{\mathcal{R}_2(c)} \varphi_1$. Then $\psi_2 : \mathbf{R}_2 \rightarrow \mathbf{R}_1$ well-defined.

Note that $\mathcal{R}_2(\psi_1(a)) = \{q \in \mathbf{Q} : \varphi_2(q) \leq \sup_{\mathcal{R}_1(a)} \varphi_2\} = \mathcal{R}_1(a)$.

Now $\psi_2(\psi_1(a)) = \sup_{\mathcal{R}_1(a)} \varphi_1 = a$. Rev the roles of $\mathbf{R}_1, \mathbf{R}_2$.

(b) Note that $\varphi(q) < 0 \Leftrightarrow q < 0$, and $\varphi(0) = 0$.

$\forall q \in \mathcal{R}_1(1) = \{1/m \in \mathbf{Q} : m \in \mathbf{N}^+, \varphi_1(1/m) = (1 + \dots + 1)^{-1} \leq 1\} \cup (\mathbf{Q} \setminus \mathbf{Q}^+), \varphi_2(q) \leq 1$.

(c) $\mathcal{R}_1(a \pm b) = \{p \pm q \in \mathbf{Q} : \varphi_1(p) \pm \varphi_1(q) \leq a \pm b\}$.

$\mathcal{R}_1(ab^{-1}) = \{pq^{-1} \in \mathbf{Q} : \varphi_1(p) \cdot \varphi_1(q)^{-1} \leq ab^{-1}\}$.

(d) $a > 0 \Leftrightarrow \exists n \in \mathbf{N}^+, 1/n < a \Leftrightarrow \psi_1(a) > 0$. \square