
这是我个人挑战「***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 节本来不太要命，但超出课文的补助却让我折戟沉沙——的确，它们不需要硬性知识门槛，可以用集合和数理逻辑来推导 $\mathcal{D}$ 的一切。或许是缺乏 Dedekind cut 的系统学习，我推导这一切时感到我在亲手缔造一个数学分支；我不是自傲的意思，只是说，**这非常艰难**。但我还是坚持下来了；在此过程中我肉眼可见我在数理逻辑上的提升。

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
corres	correspond(s)(ing)
conveni	convenience
convly	conversely
count-	counter-
ctradic	contradict(s)(ion)
ctrapos	constrapositive

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)

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
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
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 $-D = \{a : a < -b,\ b \notin D\} = \{-a : -a < -b \iff a > b,\ b \notin D\}$.
  $-(-D) = -\{a : a < -b,\ b \notin D\} = \{c : c < -a,\ a \geqslant -b,\ \forall b \notin D\} = \{c : c < b,\ \forall b \notin D\} = D$.
  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 $\nexists\, b \notin D,\ b - \varepsilon \in D \iff \forall b \notin D,\ b - \varepsilon \notin D$.
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* $C \subsetneq D \iff D - C = \{d - y : d \in D,\ y > x,\ x \notin C\}$ *posi.*

SOLUS: (a) $C \subsetneq D \Rightarrow \exists\, x \in D\backslash C \Rightarrow \exists\, y \in D,\ y > x \Rightarrow \exists\, d \in D,\ d > y \iff 0 < d - y \in D - C$.
(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) $0 \notin \{a : a < -b,\ b \notin D\} \iff \nexists\, b \notin D,\ 0 < -b \iff \forall b \notin D,\ b \geqslant 0 \Longleftarrow 0 \in D$.
(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. $\exists\, a < 0,\ a \notin -D = \{a : -a > b,\ b \notin D\} \iff \nexists\, b \notin D,\ -a > b \iff \forall b \notin D,\ 0 < -a \leqslant b$. □

- Define $D^+ = \{d \in D : d > 0\} = D \cap \mathbf{Q}^+$. Then $D^+ \neq \emptyset \iff \mathbf{Q}\backslash\mathbf{Q}^+ \subsetneq D \iff 0 \in D \iff D$ 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) $D^- = \emptyset \iff D \cup \mathbf{Q}^+ = \mathbf{Q} \iff \mathbf{Q}\backslash\mathbf{Q}^+ \subseteq D \iff 0 \in D \iff D$ posi. **CORO:** D not posi $\iff 0 \in D^-$.
  (c) $(D^-)^- = \{r \in D : r \leqslant 0\} = \mathbf{Q}\backslash D^+$. **CORO:** D not posi $\iff (D^-)^- = D$.

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

- 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 $D,-D$ not posi.
- The intuitive key point is that the prod of cuts is the cut with the endpoint being the prod of endpoints of cuts.

- 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 $D^{-1}=\{a: a<1/b,\ b\in D^-\}\Rightarrow(D^{-1})^-=\{s: 0\geqslant s\geqslant 1/b,\ \forall b\in D^-\}$.
  Then $DD^{-1}=\{a: a<rs,\ r\in D^-,\ s\in(D^{-1})^-\}=\{a: a<rs,\ \exists\, r\in D^-,\ 0\leqslant rs\leqslant r/b,\ \forall b\in D^-\}$.
  Asum $\exists\, a\in\tilde{1}\cap\mathbf{Q}^+,\ \forall r\in D^-,\ s\in(D^{-1})^-,\ a\geqslant rs\Longrightarrow a\geqslant r/b\Longleftrightarrow r/a\leqslant b,\ \forall b\in D^-$. Let $r=0$.

- For C not posi and D posi, we expect that CD not posi. Consider C and $-D$ both not posi.
  $CD=-C(-D)=-\{a: a<rt,\ r\in C^-,\ t\in(-D)^-\}=\{-a: a>b,\ b\geqslant rt,\ \forall r\in C^-,\ t\in(-D)^-\}$
  $=\{-a: a>rt,\ \forall r\in C^-,\ 0\geqslant t\geqslant -s,\ \forall s\notin D\}=\{a: a<ru,\ \forall r\in C^-,\ 0\leqslant u\leqslant s,\ \forall s\notin D\}$.
  $(r\leqslant 0<s,\ rs\leqslant ru=-rt\leqslant 0\leqslant rt\leqslant -rs.)$
- 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 $\exists\, r\in C^-\backslash\{0\}$, such that $\exists\, a<ru<0$. 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 $rs<ru\Rightarrow\exists\, a=rs$. Simlr for '$a<ru$' to be '$a\leqslant ru$' with '$u<s$'.
- Note that $\{u: 0<u\leqslant s,\ \forall s\notin D\}\supsetneq D^+$. We show "$0<u\leqslant s,\ \forall s\notin D$" is equiv to "$\forall u\in D^+$".
  $LHS=\{a: a<ru,\ \forall r\in C^-,\ 0<u\leqslant s,\ \forall s\notin D\}$, $\{a: a<rd,\ \forall r\in C^-,\ \forall d\in D^+\}=RHS$.
  Immed, $LHS\subseteq RHS$. For $RHS\subseteq LHS$:
  (I) If we cannot fix "$\min\mathbf{Q}\backslash D$" by a certain scalar s_M, then becs '$u\leqslant s$' is actually '$u<s$',
  $u\in\mathbf{Q}^+,\ u\notin D^+\Longleftrightarrow u\geqslant s,\ \exists\, s\notin D\Longleftrightarrow u\notin\{u: 0<u<s,\ \forall s\notin D\}$.
  (II) Othws, $s_M=\max D$. Now in LHS, "$a<rs_M,\ \forall r\in C^-$".
  Supp $0<d_1<\cdots<d_n<\cdots\in D^+\ [d_n<s_M]$ and $0>r_1>\cdots>r_m>\cdots\in C^-$.
  Becs $r_{m+1}s_M<r_m s_M<r_m d_{n+1}<r_m d_n>r_{m+1}d_{n+1}$. Now $r_{m+1}s_M<r_m s_M\notin CD=RHS$.
  Asum $\exists\, t\in RHS\backslash LHS\Rightarrow \underline{r_m s_M<t}<r_m d_n,\ \forall m,n\in\mathbf{N}^+$. Let $u=t/r_m\Rightarrow s_M>u>d_n$. Ctradic. $\square$

- Consider $-C$ and D both posi. Omitting $C=\tilde{0}$.
  $CD=-[(-C)D]=-\{a: a\leqslant cd,\ c\in(-C)^+,\ d\in D^+\}=\{-a: a>b,\ b>cd,\ \forall c\in(-C)^+,\ d\in D^+\}$
  $=\{a: a<-cd,\ \forall d\in D^+,\ \forall c$ suth $\underline{0<c<-r,\ \exists\, r}\in C^-\}$ $\qquad(rd<\underline{-cd<0})$
  $=\{a: a<td,\ \forall d\in D^+,\ \forall t$ suth $r<t<0,\ \exists\, r\in C^-\}$
  $=\{a: a<rd,\ \forall d\in D^+,\ \forall r\in C^-\backslash\{0\}\}$.

- For C posi and D not posi, to make $CD=DC$, we define $CD=\{a: a<cs,\ \forall c\in C^+,\ s\in D^-\}$.

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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	7	8
B	+	+	+	+	-	-	-	-
C	+	+	-	-	-	+	-	+
D	+	-	+	-	-	-	+	+

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

(4) $(BC)D = \big\{a : a < rs,\, r \in (BC)^-,\, s \in D^-\big\}$.

$\big(B(C+D)\big)^+ = \big\{bs : b \in B^+,\, s \in (C+D)^+\big\} = \big\{bc + bd : b \in B^+,\, -bc < bd,\, c \in C,\, d \in D\big\} = P$.

$\big\{bc : b \in B^+,\, c \in C^+\big\} + \big\{b'd : b' \in B^+,\, d \in D^+\big\} = \big\{bc + b'd : b, b' \in B^+,\, c \in C^+,\, d \in D^+\big\} = Q$.

Ended

0·C

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 $\Rightarrow$ 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 $(n+1)$ steps, we 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 $-A \iff \forall a \in A,\ -a \leqslant -b \iff a \geqslant b \iff b$ is a lower bound of A.
Thus $-b_M = \sup(-A) \iff -b_M \leqslant -b \iff b_M \geqslant b \iff b_M = \inf A$. $\square$

- **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) $\nexists a > x \iff \forall a \in A,\ a \leqslant x$. Then by def of sup.
Or. By (b), $\inf(-A) = -\sup A < -x \Rightarrow \exists -a \in A,\ -a < -x$. Simlr for (b). $\square$

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6 *Supp* $A, B \subseteq \mathbf{R}$ *has infily many disti elem, so has* $A + B = \{a + b : a \in A, b \in B\}$.
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 $\sup(-A) = -\inf A$. $\square$

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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 $\mathcal{R}_1(a) = \{q \in \mathbf{Q} : \varphi_1(q) \leqslant a\} \Rightarrow \sup_{\mathcal{R}_1(a)} \varphi_1 = a$. *Define* $\psi_1(a) = \sup_{\mathcal{R}_1(a)} \varphi_2$.
(a) *Show* $\psi = \psi_1 : \mathbf{R}_1 \to \mathbf{R}_2$ *is one-to-one.* (b) *Show* $\psi(0) = 0,\ \psi(1) = 1$.
(c) *Show* $\psi(a \pm b) = \psi(a) \pm (b)$, *and* $\psi(ab^{-1}) = \psi(a)\psi(b)^{-1}$.
(d) *Supp* $a \in \mathbf{R}_1$. *Show* $a > 0 \iff \psi(a) > 0$.

Solus: (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 $\mathcal{R}_2(\psi_1(a)) = \{q \in \mathbf{Q} : \varphi_2(q) \leqslant \sup_{\mathcal{R}_1(a)} \varphi_2\} = \mathcal{R}_1(a)$.
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 $\varphi(q) < 0 \iff q < 0$, and $\varphi(0) = 0$.
$\forall q \in \mathcal{R}_1(1) = \{1/m \in \mathbf{Q} : m \in \mathbf{N}^+, \varphi_1(1/m) = (1 + \cdots + 1)^{-1} \leqslant 1\} \cup (\mathbf{Q} \backslash \mathbf{Q}^+),\ \varphi_2(q) \leqslant 1$.
(c) $\mathcal{R}_1(a \pm b) = \{p \pm q \in \mathbf{Q} : \varphi_1(p) \pm \varphi_1(q) \leqslant a \pm b\}$.
$\mathcal{R}_1(ab^{-1}) = \{pq^{-1} \in \mathbf{Q} : \varphi_1(q) \cdot \varphi_1(q)^{-1} \leqslant ab^{-1}\}$.
(d) $a > 0 \iff \exists n \in \mathbf{N}^+,\ 1/n < a \iff \psi_1(a) > 0$. $\square$

Ended