谢惠民数学分析习题课讲义上册笔记整理

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Chapter 1 引论

1.1 关于习题课教案的组织

1.1.1 书中常用记号

1. $\mathbf{N}_+$：所有正整数组成的集合.
2. $\mathbf{R}$：所有实数组成的集合 (同时也用于表示无限区间 $(-\infty, \infty)$).
3. $\mathbf{Q}$：所有有理数组成的集合.
4. $\mathbf{C}$：所有复数组成的集合.
5. $\iff$ 是等价关系的记号.$A \iff B$ 表示 A 和 B 等价. 例如，A 代表 $x > 3$，B 代表 $x - 3 > 0$，则 $x > 3 \iff x - 3 > 0$.
6. $[x]$ 是实数 x 的整数部分，即不超过 x 的最大整数. 例如，$[\sqrt{2}] = 1, [-\sqrt{2}] = -2$. 关于 $[x]$ 的基本不等式是：$[x] \leq x < [x] + 1$，或 $x - 1 < [x] \leq x$
7. 空心方块表示一个证明或解的结束.
8. $\binom{n}{k} = C_n^k = \frac{n(n-1)\cdots(n-k+1)}{k!}$.
9. 记号 $\approx$ 表示近似值. 例如 $\sqrt{2} \approx 1.4$.
10. 复合函数 $f(g(x))$ 也写成 $(f \circ g)(x)$ 或 $f \circ g$.
11. 若 A 和 B 为两个集合，则用记号 $A - B$ 或 $A \backslash B$ 表示 A 与 B 的差集，也就是集合 $\{x | x \in A \text{且} x \notin B\}$.
12. 用 $O_\delta(a)$ 表示以 a 为中心，以 $\delta > 0$ 为半径的邻域. 它就是开区间 $(a - \delta, a + \delta)$(也可以用 $U_\delta(a)$ 等记号). 如不必指出半径，则可简记为 $O(a)$ (或 $U(a)$).

1.1.2 几个常用的初等不等式

1.1.2.1 几个初等不等式的证明

A.G 不等式 $a_1, a_2, \cdots, a_n$, n 个非负实数

$$\frac{a_1 + a_2 + \cdots + a_n}{n} \geq \sqrt[n]{a_1 \cdots a_n} \tag{1.1}$$

$\geq$ in inequation became $= \iff a_1 = a_2 = \cdots = a_n$

Proof

method 1. induction method

$$
\begin{aligned}
&k=1 \qquad a_1=a_1\\
&k=2 \qquad \frac{a_1+a_2}{2}\geq\sqrt{a_1a_2}\\
&k=n \qquad \text{suppose} \quad \frac{a_1+a_2+\cdots+a_n}{n}\geq\sqrt[n]{a_1\cdots a_n}\\
&k=n+1\\
&\quad \frac{a_1+a_2+\cdots+a_{n+1}}{n+1}-\frac{a_1+a_2+\cdots+a_n}{n}\\
&\quad =\frac{n(a_1+a_2+\cdots+a_{n+1})-(n+1)(a_1+a_2+\cdots+a_n)}{n(n+1)}\\
&\quad =\frac{na_{n+1}-(a_1+a_2+\cdots+a_n)}{n(n+1)}
\end{aligned}
$$

Set $A=\frac{a_1+a_2+\cdots+a_n}{n}$, $B=\frac{na_{n+1}-(a_1+a_2\cdots+a_n)}{n(n+1)}$

$$(\frac{a_1+a_2+\cdots+a_{n+1}}{n+1})^{n+1}=(A+B)^{n+1}$$

$A>0, B\geq 0$

$$
\begin{aligned}
&(A+B)^{n+1}\geq A^{n+1}+(n+1)A^nB\\
&A^{n+1}+(n+1)A^nB=A^n(A+(n+1)B)\\
&A^n=(\frac{a_1+a_2+\cdots+a_n}{n})^n\geq a_1a_2\cdots a_n\\
&A+(n+1)B=\frac{a_1+a_2+\cdots+a_n}{n}+\frac{na_{n+1}-(a_1+a_2+\cdots+a_n)}{n}=a_{n+1}\\
&\therefore (A+B)^{n+1}\geq A^n(A+(n+1)B)\geq a_1a_2\cdots a_n\cdot a_{n+1}\\
&\therefore \frac{a_1+a_2+\cdots+a_{n+1}}{n+1}\geq \sqrt[n+1]{a_1a_2\cdots a_na_{n+1}}
\end{aligned}
$$

使用二项式展开定理的条件

在归纳法第二步，将 $a_1,a_2,\cdots,a_{n+1}$ 重编号，使得 $n+1$ 为其中最大的数 (之一)，这使得分解式右边第二项 $(na_{n+1}-(a_1+a_2+\cdots+a_n))/n(n+1)$ 一定是非负数。

method 2. Forward and Backward (Cauchy, 1897)

Forward part

$$
\begin{aligned}
&k=2. \frac{a_1+a_2}{2}\geq\sqrt{a_1a_2}.\\
&k=4. \frac{a_1+a_2+a_3+a_4}{4}\geq\sqrt{(\frac{a_1+a_2}{2})\cdot(\frac{a_3+a_4}{2})}.\\
&\qquad \geq\sqrt{\sqrt{a_1a_2}\sqrt{a_3a_4}}=\sqrt[4]{a_1a_2a_3a_4}.\\
&k=2^n. \text{Suppose} \quad \frac{a_1+a_2+\cdots a_{2^n}}{2^n}\geq\sqrt[2^n]{a_1a_2\cdots a_{2^n}}\\
&k=2^{n+1}.
\end{aligned}
$$

$$\frac{a_1+a_2+\cdots+a_{2^n}+\cdots+a_{2^{n+1}}}{2^{n+1}}\geq\sqrt{(\frac{a_1+a_2+\cdots+a_2^n}{2^n})\cdot(\frac{a_{2^n+1}+a_{2^n+2}+\cdots+a_2^{n+1}}{2^n})}$$

$$I\geq\sqrt{\sqrt[2^n]{a_1a_2\cdots a_{2^n}}\ \sqrt[2^n]{a_{2^n+1}a_{2^n+2}\cdots a_{2^{n+1}}}}=\sqrt[2^{n+1}]{a_1a_2\cdots a_{2^{n+1}}}$$

Backward part suppose A.G inequality is valid when $k = n$, Consider $k = n - 1$.

$$\frac{1}{n-1}\sum_{i=1}^{n-1} a_i = \frac{1}{n}(\frac{n}{n-1})\sum_{i=1}^{n-1} a_i$$
$$\frac{1}{n-1}\sum_{i=1}^{n-1} a_i = \frac{1}{n}(\sum_{i=1}^{n-1} a_i + \frac{1}{n-1}\sum_{i=1}^{n-1} a_i)$$
$$\frac{1}{n-1}\sum_{i=1}^{n-1} a_i \geq \sqrt[n]{(\prod_{i=1}^{n-1} a_i)(\frac{1}{n-1}\sum_{i=1}^{n-1} a_i)}$$
$$(\frac{1}{n-1}\sum_{i=1}^{n-1} a_i)^n \geq (\prod_{i=1}^{n-1} a_i)(\frac{1}{n-1}\sum_{i=1}^{n-1} a_i)$$
$$(\frac{1}{n-1}\sum_{i=1}^{n-1} a_i)^{n-1} \geq (\prod_{i=1}^{n-1} a_i)$$
$$\frac{1}{n-1}\sum_{i=1}^{n-1} a_i \geq \sqrt[n-1]{\prod_{i=1}^{n-1} a_i}$$

Proposition 1.1. 柯

-施瓦茨不等式对 $a_1, a_2, \cdots, a_n$ 和 $b_1, b_2, \cdots, b_n$，成立

$$|\sum_{i=1}^{n} a_i b_i \leq \sqrt{\sum_{i=1}^{n} a_i^2}\sqrt{\sum_{i=1}^{n} b_i^2}|$$

Proof

$$0 \leq \sum_{i=1}^{n}(a_i - \lambda b_i)^2 = \sum_{i=1}^{n} a_i^2 - 2\lambda\sum_{i=1}^{n} a_i b_i + \lambda^2\sum_{i=1}^{n} b_i^2$$

由韦达定理 (视 λ 为未知数). 原方程无解或只有唯一解。

$$\Delta = b^2 - 4ac \leq 0$$
$$(-2\sum_{i=1}^{n} a_i b_i)^2 - 4\sum_{i=1}^{n} a_i^2\sum_{i=1}^{n} b_i^2 \leq 0$$
$$(\sum_{i=1}^{n} a_i b_i)^2 \leq \sum_{i=1}^{n} a_i^2\sum_{i=1}^{n} b_i^2$$
$$\sum_{i=1}^{n} a_i b_i \leq \sqrt{\sum_{i=1}^{n} a_i^2}\sqrt{\sum_{i=1}^{n} b_i^2}$$

1.1.2.2 练习题

Example 1.1 关于 Bernoulli 不等式的推广:

(1) 证明: 当 $-2 \leq h \leq -1$ 时 Bernoulli 不等式 $(1+h)^n \geq 1 + nh$ 仍成立;

(2) 证明: 当 $h \geq 0$ 时成立不等式 $(1+h)^n \geq \frac{n(n-1)h^2}{2}$, 并推广之;

(3) 证明: 若 $a_i > -1 (i = 1, 2, \ldots, n)$ 且同号, 则成立不等式

$$\prod_{i=1}^{n}(1 + a_i) \geq 1 + \sum_{i=1}^{n} a_i$$

Proof (1)

$$
\begin{aligned}
&-2 \le h \le -1 \\
&-1 \le 1+h \le 0 && -1 \le (1+h)^n \le 0 \\
&-2n \le nh \le -n && 1-2n \le 1+nh \le 1-n
\end{aligned}
$$

$$
\begin{aligned}
&n = 0. && (1+h)^0 = 1 = 1 + 0 \times h \\
&n = 1. && 1+h = 1+h \\
&n \ge 2. && 1-n \le -2
\end{aligned}
$$

$$0 \ge (1+h)^n \ge -1 \ge -2 \ge 1-n \ge 1+nh \ge 1-2n$$

$$(1+h)^n \ge 1+nh$$

(2)

$$
\begin{aligned}
&h \ge 0 \\
(1+h)^n =& 1 + nh + \frac{n(n-1)}{2}h^2 + \cdots \ge \frac{n(n-1)}{2}h^2
\end{aligned}
$$

推广:

$$(1+h)^n \ge \binom{n}{3}h^3, \binom{n}{4}h^4, \dots, \binom{n}{k}h^k, 0 \le k \le n$$

(3) $k=1$ 时显然成立. 使用归纳法证明. 假设 $k=n$ 时不等式 $\prod_{i=1}^{n}(1+a_i) \ge 1 + \sum_{i=1}^{n} a_i$ 成立, 证明 $k=n+1$ 时 $\prod_{i=1}^{n+1}(1+a_i) \ge 1 + \sum_{i=1}^{n+1} a_i$ 成立.

$$
\begin{aligned}
k = n+1 \qquad & \prod_{i=1}^{n+1}(1+a_i) = \prod_{i=1}^{n}(1+a_i)(1+a_{n+1}) \\
& \because \prod_{i=1}^{n}(1+a_i) \ge 1 + \sum_{i=1}^{n} a_i \\
& \prod_{i=1}^{n}(1+a_i)(1+a_{n+1}) \ge (1 + \sum_{i=1}^{n} a_i)(1+a_{n+1})
\end{aligned}
$$

$$
\begin{aligned}
(1 + \sum_{i=1}^{n} a_i)(1+a_{n+1}) &= 1 + \sum_{i=1}^{n} a_i + a_{n+1} + a_{n+1}\sum_{i=1}^{n} a_i \\
&= 1 + \sum_{i=1}^{n+1} a_i + a_{n+1}\sum_{i=1}^{n} a_i \\
&\ge 1 + \sum_{i=1}^{n+1} a_i
\end{aligned}
$$

Example 1.2 利用 A.G. 不等式求解:

(1). $n! \le (\frac{n+1}{2})^n$, while $n > 1$

(2). $(n!)^2 = (n \cdot 1)[(n-1) \cdot 2] \dots (1 \cdots n)$. 证明: 当 $n > 1$ 时成立

$$n! < (\frac{n+2}{6})^n$$

(3). 比较上述两个不等式的优劣

(4). 证明: 对任意实数 r 成立:

$$(n!)^r \le \frac{1}{n^n}(\sum_{k=1}^{n} k^r)^n \tag{1.2}$$

Proof (1).

$$n > 1 \qquad n! = 1 \times 2 \times \cdots \times n < (\frac{1+2+\cdots+n}{n})^n = (\frac{(1+n)n}{2n})^n = (\frac{n+1}{2})^n$$

$\because 1 \neq 2 \neq \cdots n$, 所以不会有等号出现的情况

(2). $n > 1$

$$\begin{aligned}(n!)^2 &= (n \cdot 1)[(n-1) \cdot 2] \dots (1 \cdots n) \\ &< (\frac{n \times 1 + (n-1) \times 2 + \cdots + 1 \times n}{n})^n\end{aligned}$$

Consider this equation

$$(\frac{n \times 1 + (n-1) \times 2 + \cdots + 1 \times n}{n})^n \tag{1.3}$$

$$\begin{aligned}\sum_{k=1}^{n}(n-k+1)k &= (n+1)\sum_{k=1}^{n} k - \sum_{k=1}^{n} k^2 \\ &= (n+1)\frac{(n+1)n}{2} - \frac{n(n+1)(2n+1)}{6} \\ &= \frac{n(n+1)}{6}(3(n+1) - (2n+1)) \\ &= \frac{n(n+1)(n+2)}{6}\end{aligned}$$

$$\begin{aligned}(n!)^2 &< (\frac{n \times 1 + (n-1) \times 2 + \cdots + 1 \times n}{n})^n \\ &= (\frac{(n+1)(n+2)}{6})^n\end{aligned}$$

$\because n+1 < n+2, \therefore n! < (\frac{n+2}{\sqrt{6}})^n$

(3). $n > 3$ 时,$\frac{n+2}{\sqrt{6}} < \frac{n+1}{2}$ (2) 的结果较好.

(4).$\forall r \in \mathbb{R}$, prove formula 1.2

$$\frac{1}{n}\sum_{k=1}^{n} k^r \geq \sqrt[n]{\prod_{k=1}^{n} k^r}$$

$$(n!)^r = \prod_{k=1}^{n} k^r \leq (\frac{1}{n}\sum_{k=1}^{n} k^r)^n = \frac{1}{n^n}(\sum_{k=1}^{n} k^r)^n$$

my answer

$$\forall r \in \mathbb{R}, \qquad (\sum_{k=1}^{n} k^r)^n \geq n^n (n!)^r$$

$$(n!)^r = \sum_{k=1}^{n} k^r \leq (\frac{1^r + 2^r + \cdots + n^r}{n})^n = \frac{1}{n^n}(\sum_{k=1}^{n} k^r)^n$$

$$\therefore \quad (\sum_{k=1}^{n} k^r)^n \geq n^n (n!)^r$$

Example 1.3 $a_k > 0, k = 1, 2, \dots, n$ 证明几何–调和平均值不等式

$$(\prod_{k=1}^{n} a_k)^{\frac{1}{n}} \geq \frac{n}{\sum_{k=1}^{n} \frac{1}{a_k}}$$

Proof from A.G inequality

$$\frac{\sum_{k=1}^{n} \frac{1}{a_k}}{n} \geq \sqrt[n]{\prod_{k=1}^{n} \frac{1}{a_k}} = \frac{1}{\sqrt[n]{\prod_{k=1}^{n} a_k}}$$

$$a_k > 0, \quad \sqrt[n]{\prod_{k=1}^{n} a_k} \geq \frac{n}{\sum_{k=1}^{n} \frac{1}{a_k}}$$

Example 1.4 $a, b, c \geq 0$. prove $\sqrt[3]{abc} \leq \sqrt{\frac{ab+bc+ca}{3}} \leq \frac{a+b+c}{3}$. 并推广到 n 个非负数的情况

Proof 1. $\sqrt[3]{abc} = \sqrt{\sqrt[3]{ab \cdot bc \cdot ca}} \leq \sqrt{\frac{ab+bc+ca}{3}}$.

2.

$$\begin{aligned} \sqrt{\frac{ab+bc+ca}{3}} &\leq \sqrt{\frac{(\frac{a+b}{2})^2 + (\frac{b+c}{2})^2 + (\frac{c+a}{2})^2}{3}} \\ &= \sqrt{\frac{2(a^2+b^2+c^2) + 2(ab+bc+ca)}{12}} \\ &= \sqrt{\frac{a^2+b^2+c^2+ab+bc+ca}{6}} \end{aligned}$$

$a, b, c \geq 0$, 希望证明

$$\sqrt{\frac{ab+bc+ca}{3}} \leq \frac{a+b+c}{3}$$

$$\begin{aligned} \frac{ab+bc+ca}{3} &\leq \frac{a^2+b^2+c^2}{6} + \frac{ab+bc+ca}{6} \\ \frac{ab+bc+ca}{2} &\leq \frac{a^2+b^2+c^2}{6} + 2\frac{ab+bc+ca}{6} \qquad (\text{add} \frac{ab+bc+ca}{6}) \\ \frac{ab+bc+ca}{3} &\leq \frac{ab+bc+ca}{2} \leq (\frac{a+b+c}{3})^2 \\ \sqrt{\frac{ab+bc+ca}{3}} &\leq \frac{a+b+c}{3} \end{aligned}$$

推广至 n 个

$$\begin{aligned} [l] n = 2 \qquad & \sqrt{ab} \leq \frac{a+b}{2} \\ n = 3 \qquad & \sqrt[3]{abc} \leq \sqrt{\frac{ab+bc+ca}{3}} \leq \frac{a+b+c}{3} \\ n = 4 \qquad & \sqrt[4]{abcd} \leq \sqrt[3]{\frac{abc+bcd+cda+dab}{4}} \leq \sqrt{\frac{a+b+c}{3}} \leq \frac{a+b+c+d}{4} \\ k = n \qquad & \sqrt[n]{a_1 a_2 \dots a_n} \leq \sqrt{\frac{a_1+a_2+\dots+a_n}{n}} \leq \frac{a_1+a_2+\dots+a_n}{n} \end{aligned}$$

This is

$$\sqrt[n]{\sum_{k=1}^{n} a_k} \leq \sqrt{\frac{\sum_{k=1}^{n} a_k}{k}} \leq \frac{\sum_{k=1}^{n} a_k}{k}$$

1. $\sqrt[n]{a_1 a_2 \dots a_n} = \sqrt{\sqrt[n]{a_1^2 a_2^2 \dots a_n^2}} \leq \sqrt{\frac{a_1a_2+a_2a_3+\dots+a_na_1}{n}}$

2. $\sqrt{\frac{a_1a_2+a_2a_3+\dots+a_na_1}{n}} \leq \sqrt{\frac{a_1+a_2+\dots+a_n}{n}}$?

Example 1.5 (1) $|\alpha + \beta| \leq |\alpha| + |\beta|$

Proof let $\alpha = a - b, \beta = b$, the identity became $|(a-b)+b| \leq |a-b| + |b|$. This is $|a-b| \geq |a| - |b|$.

$$||a| - |b|| = \begin{cases} |a| - |b|. & a \geq b \\ |b| - |a|. & a < b \end{cases}$$

When $a \geq b$, $||a| - |b|| = |a| - |b|$. There is $|a-b| \geq |a| - |b| = ||a| - |b||$

When $a < b$, $|a-b| = |b-a| \geq |b| - |a| = ||a| - |b||$.

$\therefore$, We have$|a-b| \geq ||a| - |b||$

(2) $\sum |a_k| \geq |\sum a_k|$

Proof We can prove this statement by induction.

$$\begin{aligned} k = 2, &\qquad |a_1| + |a_2| \geq |a_1 + a_2| \\ k = 3, &\qquad |a_1| + |a_2| + |a_3| \geq |a_1 + a_2 + a_3| \\ \text{Suppose } k = n, &\qquad \sum_{k=1}^{n} |a_k| \geq |\sum_{k=1}^{n} a_k| \\ k = n+1, &\qquad \text{prove} \sum_{k=1}^{n+1} |a_k| \geq |\sum_{k=1}^{n+1} a_k| \end{aligned}$$

$$\begin{aligned} \sum_{k=1}^{n+1} |a_k| &= \sum_{k=1}^{n} |a_k| + |a_{n+1}| \\ &\geq |\sum_{k=1}^{n} a_k| + |a_{n+1}| \\ &\geq |\sum_{k=1}^{n+1} a_k| \end{aligned}$$

$$\begin{aligned} k = 2, &\qquad |a_1| - |a_2| \leq |a_1 - a_2| \\ \text{Suppose } k = n, &\qquad |a_1| - \sum_{k=2}^{n} |a_k| \leq |\sum_{k=1}^{n} a_k| \\ k = n+1, &\qquad \text{prove} |a_1| - \sum_{k=2}^{n+1} |a_k| \leq |\sum_{k=1}^{n+1} a_k| \end{aligned}$$

$$\begin{aligned} |a_1| - \sum_{k=2}^{n+1} |a_k| &= |a_1| - \sum_{k=2}^{n} |a_k| - |a_{n+1}| \\ &\leq |\sum_{k=1}^{n} a_k| - |a_{n+1}| \\ &\leq |\sum_{k=1}^{n+1} a_k| \end{aligned}$$

Can left side became$||a_1| - \sum_{k=2}^{n} |a_k||$?

$$\left| |a_1| - \sum_{k=2}^{n} |a_k| \right| = |a_1| - \sum_{k=2}^{n} |a_k| \qquad |a_1| \geq \sum_{k=2}^{n} a_k \tag{1.4}$$

$$\left| |a_1| - \sum_{k=2}^{n} |a_k| \right| = \sum_{k=2}^{n} |a_k| - |a_1| \qquad |a_1| \geq \sum_{k=2}^{n} a_k \tag{1.5}$$

in eq1.4, the inequality is still vaild. However in eq1.5, $\sum_{k=2}^{n} |a_k| - |a_1|$ and $|a_1|$

(3). $\frac{|a+b|}{1+|a+b|} \leq \frac{|a|}{1+|a|} + \frac{|b|}{1+|b|}$

Proof

$$\frac{|a+b|}{1+|a+b|} \leq \frac{|a|}{1+|a|} + \frac{|b|}{1+|b|}$$

$$\frac{|a+b|}{1+|a+b|} \leq \frac{|a|+|b|+2|a||b|}{(1+|a|)(1+|b|)}$$

$$1-\frac{|a+b|}{1+|a+b|} \geq 1-\frac{|a|+|b|+2|a||b|}{(1+|a|)(1+|b|)}$$

$$\frac{1}{1+|a+b|} \geq \frac{1-|a||b|}{(1+|a|)(1+|b|)}$$

$$1+|a|+|b|+|a||b| \geq 1+|a+b|-|a||b|-|a||b||a+b|$$

$$|a|+|b|+2|a||b|+|a||b||a+b| > 0, \text{Since } +2|a||b|+|a||b||a+b| \geq |a+b|$$

Therefore $\frac{|a+b|}{1+|a+b|} \leq \frac{|a|}{1+|a|} + \frac{|b|}{1+|b|}$

Example 1.6 (4).$|(a+b)^n - a^n| \leq (|a|+|b|)^n - |a|^n$

$$(a+b)^n - a^n = \binom{n}{1}a^{n-1}b^1 + \binom{n}{2}a^{n-2}b^2 + \cdots + \binom{n}{n}a^0b^n$$

$$(|a|+|b|)^n - |a|^n = \binom{n}{1}|a|^{n-1}|b|^1 + \binom{n}{2}|a|^{n-2}|b|^2 + \cdots + \binom{n}{n}|a|^0|b|^n$$

$$\because |a|^j|b|^k \geq a^jb^k$$

$$\therefore \sum |a|^j|b|^k \geq |\sum a^jb^k|$$

$$|(a+b)^n - a^n| = \begin{cases}(a+b)^n - a^n, & a+b \geq a; b \geq 0\\ a^n - (a+b)^n, & a+b < a; b < 0\end{cases}$$

$$|(a+b)^n - a^n| \leq (|a|+|b|)^n - |a|^n. \tag{1.6}$$

Proposition 1.2. 1

3.5(Cauchy inequality)

For $a_1, a_2, \ldots, a_n$. and $b_1, b_2, \ldots, b_n$. $a_i, b_i \in \mathbb{R}$, There is

$$\left|\sum_{i=1}^{n} a_ib_i\right| \leq \sqrt{\sum_{i=1}^{n} a_i^2}\sqrt{\sum_{i=1}^{n} b_i^2} \tag{1.7}$$

Proof Let's prove eq1.7

First way on book:

Use variable λ, change the inequality into nonnegative binomial.

$$0 \leq \sum_{i=1}^{n}(a_i - \lambda b_i)^2 \qquad = \sum_{i=1}^{n} a_i^2 - 2\lambda\sum_{i=1}^{n} a_ib_i + \lambda^2\sum_{i=1}^{n}$$

$$\Delta = B^2 - 4AC \qquad = (-2\sum_{i=1}^{n} a_ib_i)^2 - 4(\sum_{i=1}^{n} a_i^2)(\sum_{i=1}^{n} b_i^2) \leq 0$$

$$(\sum_{i=1}^{n} a_ib_i)^2 \leq (\sum_{i=1}^{n} a_i^2)(\sum_{i=1}^{n} b_i^2)$$

sqrt on both side of the inequality above, we can get

$$\left|\sum_{i=1}^{n} a_ib_i\right| \leq \sqrt{\sum_{i=1}^{n} a_i^2}\sqrt{\sum_{i=1}^{n} b_i^2}$$

6. Cauchy 不等式的不同证明

(1). 数学归纳法.

$$
\begin{aligned}
k=1,\quad & |ab|=\sqrt{a^2}\sqrt{b^2}\\
k=1,\quad & |a_1b_1+a_2b_2|=\sqrt{a_1^2+a_2^2}\sqrt{b_1^2+b_1^2}\\
\text{Suppose } k=n,\quad & |\sum_{i=1}^{n}a_ib_i|=\sqrt{\sum_{i=1}^{n}a_i}\sqrt{\sum_{i=1}^{n}b_i}\\
k=n+1,\quad & |\sum_{i=1}^{n+1}a_ib_i|=|\sum_{i=1}^{n}a_ib_i+a_{n+1}b_{n+1}|
\end{aligned}
$$

$$
\begin{aligned}
|\sum_{i=1}^{n+1}a_ib_i| &= |\sum_{i=1}^{n}a_ib_i+a_{n+1}b_{n+1}|\\
&\le |\sqrt{\sum_{i=1}^{n}a_i}\sqrt{\sum_{i=1}^{n}b_i}+a_{n+1}b_{n+1}|
\end{aligned}
$$

Note that $A=\sqrt{\sum_{i=1}^{n}a_i}$, $B=\sqrt{\sum_{i=1}^{n}b_i}$

$$
\begin{aligned}
|\sum_{i=1}^{n+1}a_ib_i| &\le |AB+a_{n+1}b_{n+1}|\\
&\le \sqrt{A^2+a_{n+1}^2}\sqrt{B^2+b_{n+1}^2}\\
&= \sqrt{\sum_{i=1}^{n}a_i^2}\sqrt{\sum_{i=1}^{n}b_i^2}
\end{aligned}
$$

(2) Lagrange 恒等式

$$
\sum_{i=1}^{n}a_k^2\sum_{i=1}^{n}b_k^2-(\sum_{i=1}^{n}|a_kb_k|)=\frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n}(|a_k||b_i|-|a_i||b_k|)^2 \tag{1.8}
$$

$$
\begin{aligned}
(|a_k||b_i|-|a_i||b_k|)^2 &= |a_k|^2|b_i|^2-2|a_i||a_k||b_i||b_k|+|b_k|^2|a_i|^2\\
&= a_k^2b_i^2+b_k^2a_i^2-2|a_ia_kb_ib_k|
\end{aligned}
$$

$$
\sum_{i=1}^{n}\sum_{k=1}^{n}(|a_k||b_i|-|a_i||b_k|)^2=2\sum_{i=1}^{n}a_i^2\sum_{k=1}^{n}b_k^2-2\sum_{i=1}^{n}\sum_{k=1}^{n}|a_ia_kb_ib_k|
$$

$$
\sum_{i=1}^{n}a_k^2\sum_{i=1}^{n}b_k^2-(\sum_{i=1}^{n}|a_kb_k|)=\frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n}(|a_k||b_i|-|a_i||b_k|)^2\ge 0
$$

$$
\begin{aligned}
&\therefore (\sum_{i=1}^{n}|a_ib_i|)^2\le\sum_{i=1}^{n}a_i^2\sum_{i=1}^{n}b_i^2\\
&\because |\sum_{i=1}^{n}a_ib_i|\le\sum_{i=1}^{n}|a_ib_i|\\
&\therefore (|\sum_{i=1}^{n}a_ib_i|)^2\le(\sum_{i=1}^{n}|a_ib_i|)^2\\
&\therefore (|\sum_{i=1}^{n}a_ib_i|)^2\le\sum_{i=1}^{n}a_i^2\sum_{i=1}^{n}b_i^2
\end{aligned}
$$

不等式两边开平方，得到：

$$|\sum_{i=1}^{n} a_i b_i| \leq \sqrt{\sum_{i=1}^{n} a_i^2} \sqrt{\sum_{i=1}^{n} b_i^2}$$

(3). 用不等式 $|AB| \leq \frac{A^2+B^2}{2}$

$$|a_i b_i| \leq \frac{a_i^2 + b_i^2}{2}$$

$$|\sum_{i=1}^{n} a_i b_i| \leq \sum_{i=1}^{n} |a_i b_i| \qquad \leq \frac{\sum_{i=1}^{n} a_i^2 + \sum_{i=1}^{n} b_i^2}{2}$$

$$\frac{\sum_{i=1}^{n} a_i^2 + \sum_{i=1}^{n} b_i^2}{2} \geq \sqrt{\sum_{i=1}^{n} a_i^2} \sqrt{\sum_{i=1}^{n} b_i^2} \qquad ??$$

如何用均值不等式证明 Cauchy 不等式?

由切比雪夫不等式，有

$$\frac{a_1 b_1 + a_2 b_2 + \cdots + a_n b_n}{n} \leq (\frac{a_1 + a_2 + \cdots + a_n}{n})(\frac{b_1 + b_2 + \cdots + b_n}{n}) \tag{1.9}$$

由均值不等式，有

$$\frac{a_1 + a_2 + \cdots + a_n}{n} \leq \sqrt{\frac{a_1^2 + a_2^2 + \cdots + a_n^2}{n}}$$
$$\frac{b_1 + b_2 + \cdots + b_n}{n} \leq \sqrt{\frac{b_1^2 + b_2^2 + \cdots + b_n^2}{n}}$$

$$\begin{aligned}
\therefore \frac{a_1 b_1 + a_2 b_2 + \cdots + a_n b_n}{n} &\leq (\frac{a_1 + a_2 + \cdots + a_n}{n})(\frac{b_1 + b_2 + \cdots + b_n}{n}) \\
&\leq \sqrt{\frac{a_1^2 + a_2^2 + \cdots + a_n^2}{n}} \sqrt{\frac{b_1^2 + b_2^2 + \cdots + b_n^2}{n}} \\
&= \frac{1}{n} \sqrt{a_1^2 + a_2^2 + \cdots + a_n^2} \sqrt{b_1^2 + b_2^2 + \cdots + b_n^2}
\end{aligned}$$

This is

$$\sum_{i=1}^{n} a_i b_i \leq \sqrt{\sum_{i=1}^{n} a_i^2} \sqrt{\sum_{i=1}^{n} b_i^2}$$

Square on both side of the inequality, The calculate square root. We can get eq1.9:

(4). 构造复的辅助数列

$$c_k = a_k^2 - b_k^2 + 2|a_k b_k|, \qquad k = 1, 2, \ldots, n$$

Then we use

$$\left|\sum_{k=1}^{n} c_k\right| \leq \sum_{k=1}^{n} |c_k|$$

Solve 1

$$c_k = (|a_k| + |b_k|)^2 = a_k^2 + b_k^2 + 2|a_k b_k|$$
$$\sum_{k=1}^{n} c_k = \sum_{k=1}^{n} a_k^2 + \sum_{k=1}^{n} b_k^2 + 2\sum_{k=1}^{n} |a_k b_k|$$
$$|c_k| = \sqrt{\Re^2 c_k + \Im^2 c_k} = \sqrt{(a_k^2 - b_k^2)^2 + (2a_k b_k)^2} = a_k^2 + b_k^2$$

$$\therefore \left|\sum_{k=1}^{n} a_k^2 + \sum_{k=1}^{n} b_k^2 + 2\sum_{k=1}^{n} |a_k b_k|\right| = \sqrt{\Re^2 \sum_{k=1}^{n} c_k + \Im^2 \sum_{k=1}^{n} c_k}$$

$$= \sqrt{(\sum_{k=1}^{n}(a_k^2 - b_k^2))^2 + \sum_{k=1}^{n}(2a_k b_k)^2}$$

$$= \sqrt{(\sum_{k=1}^{n} a_k^2)^2 + (\sum_{k=1}^{n} a_k^2)^2 - 2(\sum_{k=1}^{n} a_k^2)(\sum_{k=1}^{n} a_k^2) + 4\sum_{k=1}^{n}(a_k b_k)^2}$$

$$\because |\sum c_k| \le \sum |c_k|$$

$$\therefore (\sum_{k=1}^{n} a_k^2)^2 + (\sum_{k=1}^{n} a_k^2)^2 - 2(\sum_{k=1}^{n} a_k^2)(\sum_{k=1}^{n} a_k^2) + 4\sum_{k=1}^{n}(a_k b_k)^2 \le (\sum_{k=1}^{n} a_k^2 + \sum_{k=1}^{n} b_k^2)^2$$

$$\therefore 4(\sum_{k=1}^{n} a_k b_k)^2 \le 4(\sum_{k=1}^{n} a_k^2)(\sum_{k=1}^{n} b_k^2)$$

extracting both side: $\left|\sum_{k=1}^{n} a_k b_k\right| \le \sqrt{\sum_{k=1}^{n} a_k^2}\sqrt{\sum_{k=1}^{n} b_k^2}$

Example 1.7 7. Suppose $0 < x_i \le \frac{1}{2}, i = 1, 2, \ldots, n$, then

$$\frac{\prod_{i=1}^{n} x_i}{(\sum_{i=1}^{n} x_i)^n} \le \frac{\prod_{i=1}^{n}(1-x_i)}{(\sum_{i=1}^{n}(1-x_i))^n} \tag{1.10}$$

Proof Let's prove eq1.10 by induction method.

$$n = 2, \qquad \frac{x_1 x_2}{(x_1+x_2)^2} \le \frac{(1-x_1)(1-x_2)}{((1-x_1)+(1-x_2))^2}$$

$$\frac{(x_1 x_2)}{(x_1^2 + 2x_1 x_2 + x_2^2)} \le \frac{1 - x_1 - x_2 + x_1 x_2}{(1-x_1)^2 + 2(1-x_1)(1-x_2) + (1-x_2)^2}$$

$$\frac{(x_1+x_2)^2}{(x_1 x_2)} \ge \frac{((1-x_1)(1-x_2))^2}{1 - x_1 - x_2 + x_1 x_2}$$

$$\frac{x_1}{x_2} + 2 + \frac{x_2}{x_1} \ge \frac{1-x_1}{1-x_2} + 2\frac{1-x_2}{1-x_1}$$

$$\frac{x_1}{x_2} - \frac{1-x_1}{1-x_2} \ge \frac{1-x_2}{1-x_1} - \frac{x_2}{x_1}$$

$$\frac{x_1(1-x_2) - x_2(1-x_1)}{x_2(1-x_2)} \ge \frac{x_1(1-x_2) - x_2(1-x_1)}{x_1(1-x_1)}$$

$$\frac{x_1 - x_2}{x_2(1-x_2)} \ge \frac{x_1 - x_2}{x_1(1-x_1)}$$

$f(x) = x - x^2, f'(x) = 1 - 2x > 0,$ while $x \in (0, \frac{1}{2})$

When $x_1 > x_2, 0 < x_2 < x_1 \le \frac{1}{2}, x_1 - x_1^2 \ge x_2 - x_2^2, x_1 - x_2 > 0$

When $x_1 < x_2, 0 < x_1 < x_2 \le \frac{1}{2}, x_1 - x_1^2 \le x_2 - x_2^2, x_1 - x_2 < 0$

$$\frac{x_1 - x_2}{x_2(1-x_2)} \ge \frac{x_1 - x_2}{x_1(1-x_1)}$$

$$k=2, \qquad \frac{x_1x_2}{(x_1+x_2)^2} \le \frac{(1-x_1)(1-x_2)}{((1-x_1)+(1-x_2))^2}$$

$$k=4, \qquad \frac{x_1x_2x_3x_4}{(x_1+x_2+x_3+x_4)^2} \le \frac{(1-x_1)(1-x_2)(1-x_3)(1-x_4)}{((1-x_1)+(1-x_2)+(1-x_3)+(1-x_4))^2}$$

Use Cauchy's forward and backward method, We can prove this equation

Suppose $k=n, \frac{\prod_{i=1}^{n} x_i}{(\sum_{i=1}^{n} x_i)^2} \le \frac{\prod_{i=1}^{n}(1-x_i)}{(\sum_{i=1}^{n}(1-x_i))^2}$

$$k=n-1, \qquad \text{prove } \frac{\prod_{i=1}^{n-1} x_i}{(\sum_{i=1}^{n-1} x_i)^2} \le \frac{\prod_{i=1}^{n-1}(1-x_i)}{(\sum_{i=1}^{n-1}(1-x_i))^2}$$

todo! need to complete!

Proposition 1.3. 1.3.1 Bernoulli inequality

uppose that $h > -1, n \in \mathbb{N}$, Then:

$$(1+h)^n \geq 1+nh \tag{1.11}$$

When $n > 1$, the inequality became equation iff $h = 0$.

Proof When $n = 1$, $1+h = 1+h$

$h = 0$, $1^n = 1$

Let's consider the condition $n > 1, h \neq 0$.

i). $h > 0$, $(1+h)^n = \binom{n}{0}h^0 + \binom{n}{1}h^1 + \binom{n}{2}h^2 + \cdots + \binom{n}{n}h^n$.

$\because \binom{n}{2}h^2 + \cdots + \binom{n}{n}h^n > 0$, $\therefore (1+h)^n > 1+nh$

ii). $-1 < h < 0, 0 < 1+h < 1$.

$$\begin{aligned}(1+h)^n - 1 &= (1+h-1)\Big(1+(1+h)+(1+h)^2+\cdots+(1+h)^{n-1}\Big)\\ &= h\Big(1+(1+h)+(1+h)^2+\cdots+(1+h)^{n-1}\Big)\end{aligned}$$

$\because 1+(1+h)+(1+h)^2+\cdots+(1+h)^{n-1} < n$ when$h < 0$

$\therefore (1+h)^n > 1+nh$

Two variable extension of the Bernoulli inequality, Suppose $h = \frac{B}{A}, A > 0, A+B > 0$, Then$1+h > 0$ is established.

Proposition 1.4. 1.3.2

uppose $A > 0, A+B > 0, n \in \mathbb{N}$, Then the inequality is true:

$$(A+B)^n \geq A^n + nA^{n-1}B \tag{1.12}$$

The inequalty became equation iff $B = 0$.

Proof divide A^n on both side of the inequality 1.12. Set$h = \frac{B}{A}(A > 0)$, Then the inequality became Eq 1.11. So we can prove Eq 1.12 by prove Eq 1.11. Eq 1.11 is true when $h > -1$. $\therefore 1+h > 0, 1+\frac{B}{A} > 0$, $\because A > 0$, $\therefore A+B > 0$. And when $n > 1$ the equation is true iff $h = 0.\frac{B}{A} = 0, \therefore B = 0$.

Example 1.8 Ex 1.3.2 exercise 8

$a, c, t, g \geq 0, a+c+t+g = 1$. Prove that $a^2+c^2+t^2+g^2 \geq \frac{1}{4}$.

The inequality became equatio iff $a = c = t = g = \frac{1}{4}$.

Proof from A.G inequality,

$$\frac{a+c+t+g}{4} \geq \sqrt[4]{actg}, \quad a+c+t+g = 1 \tag{1.13}$$

$\therefore \sqrt[4]{actg} \leqslant \frac{1}{4}$

$$a+c+t+g = 1, (a+c+t+g)^2 = 1$$

$$(a+c+t+g)^2 = a^2+c^2+t^2+g^2+2ac+2at+2ag+2ct+2cg+2tg = 1 \tag{1.14}$$

$$a^2+c^2 \geq 2acc^2+t^2 \geq 2ct \tag{1.15}$$

$$a^2+t^2 \geq 2atc^2+g^2 \geq 2cg \tag{1.16}$$

$$a^2+g^2 \geq 2agt^2+g^2 \geq 2tg \tag{1.17}$$

substitude $2ac, 2ag, \ldots$ in equation 1.14, we can get

$$4(a^2+c^2+t^2+g^2) \geq a^2+c^2+t^2+g^2+2ac+2at+2ag+2ct+2cg+2tg$$

Then we get the inequality 1.13.

1.2 1.4 逻辑符号与对偶法则

The law of duality: $\forall(\exists) \to \exists(\forall)$ with negative statement

Inverse proposition?

1. A have upper limit, $\exists M > 0 . \forall x \in A, x \leqslant M$.

It's negative statement is 'A don't have upper limit'. $\forall M > 0, \exists x \in A, x > M$.

2. the minum item in A is b, $b \in A, \forall x \in A, x \geq b$.

It's negative statement is 'b is not the minum item in A'. $b \in A, \exists x \in A, x < b$.

3. $f \in (a, b)$ is a monotonic augmentation function, $\forall x, y \in (a, b), x < y, f(x) \leqslant f(y)$.(or $f(x) < f(y)$, depends on monotonic function's definition)

It's negative statement is '$f \in (a, b)$ isn't a monotonic augmentation function'. $\exists x, y \in (a, b), x < y, f(x) > f(y)$ (or $f(x) \geq f(y)$).

4. $f \in (a, b)$ is a monotonic function, $\forall x, y, z \in (a, b), x < y < z, (f(x)-f(y))(f(y)-f(z)) \geq 0$.

It's negative statement is '$f \in (a, b)$ isn't a monotonic function'. $\exists x, y, z \in (a, b), x < y < z, (f(x)-f(y))(f(y)-f(z)) < 0$.

(Another way $\forall x, y \in (a, b), x < y, f(x)-f(y) \geq 0$ or $f(x)-f(y) \leqslant 0$.)

5. $A \subset B$, $\forall x \in A, x \in B$.

It's negative statement is $A \subsetneq B$, $\exists x \in A, x \notin B$.

6. $A - B \neq \emptyset$, $\exists x \in A, x \in B$.

It's negative statement is $A - B = \emptyset$, $\forall x \in A, x \notin B$.

7. x_n is an infinitesimal amounts, $\forall \epsilon > 0, \exists N \in \mathbb{N}^{+}, \forall n > N, |x_n| < \epsilon$.

It's negative statement is 'x_n is not an infinitesimal amounts', $\exists \epsilon > 0, \forall N \in \mathbb{N}^{+}, \exists n > N, |x_n| \geq \epsilon$.

8. x_n is infinitely large, $\forall M > 0, \exists N \in \mathbb{N}^{+}, \forall n > N, x_n > M$.

It's negative statement is 'x_n is not infinitely large', $\exists M > 0, \forall N \in \mathbb{N}^{+}, \exists n > N, x_n \leqslant M$.

Chapter 2 数列极限

2.1 数列极限的基本概念

2.1.1 2.1.5 练习题

1. prove by Limit definition:
(1). $\lim_{n\to\infty} \frac{3n^2}{n^2-4} = 3$.
(2). $\lim_{n\to\infty} \frac{\sin n}{n} = 0$.
(3). $\lim_{n\to\infty} (1+n)^{\frac{1}{n}} = 0$.
(4). $\lim_{n\to\infty} \frac{a^n}{n!} = 0, (a>0)$.

2. Suppose $a_n, n \in \mathbb{N}_+$. sequence a_n converge to a.
Prove $\lim_{n\to\infty} \sqrt{a_n} = \sqrt{a}$.

Proof $n \to \infty a_n \to a$.
$\forall \epsilon > 0, \exists N(\epsilon) \in \mathbb{N}^+, \forall n > N(\epsilon), |a_n - a| < \epsilon$.

$$|\sqrt{a_n} - \sqrt{a}| = \left|\frac{a_n - a}{\sqrt{a_n} + \sqrt{a}}\right| < \frac{\epsilon}{\sqrt{a_n} + \sqrt{a}}$$

$\therefore \lim_{n\to\infty} \sqrt{a_n} = \sqrt{a}$. $\square$ (check, not consider the condition$a = 0$) add $a = 0, \forall \epsilon \in (0,1), \exists N(\epsilon) \in \mathbb{N}^+, \forall n > N(\epsilon), |a_n - a| < \epsilon$. s.t $a_n < \epsilon^2 < \epsilon$, $\sqrt{a_n} < \epsilon$.

3. If $\lim_{n\to\infty} a_n = a$.
Prove $\lim_{n\to\infty} |a_n| = |a|$. Vice versa?

Proof $\forall \epsilon > 0, \exists N(\epsilon) \in \mathbb{N}^+, \forall n > N(\epsilon), |a_n - a| < \epsilon$.

$$\Big||a_n| - |a|\Big| \leqslant |a_n - a| < \epsilon$$

$\therefore \lim_{n\to\infty} |a_n| = |a|$
If We know $\lim_{n\to\infty} |a_n| = |a|$.
$\forall \epsilon > 0, \exists N(\epsilon) \in \mathbb{N}^+, \forall n > N(\epsilon), \Big||a_n| - |a|\Big| < \epsilon$. We can't get $\lim_{n\to\infty} a_n = a$. For example: $a_n = \frac{1}{n} + 1, a = -1, \lim_{n\to\infty} |a_n| = |a|$ is $\lim_{n\to\infty} |\frac{1}{n} + 1| = |-1|$, but $\lim_{n\to\infty} \frac{1}{n} + 1 \neq -1$ $\square$

(1). Suppose $p(x)$ is a polynomial of x, if $\lim_{n\to\infty} a_n = a$, Prove $\lim_{n\to\infty} p(a_n) = p(a)$.
(2). Suppose $b > 0$, $\lim\limits_{n\to\infty} a_n = a$. Prove $b^{a_n} = b^a$.
(3). Suppose $b > 0$, $\{a_n\}, a_n > 0, \forall n \in \mathbb{N}$. $\lim\limits_{n\to\infty} a_n = a.a > 0$. Prove $\lim\limits_{n\to\infty} \log_b a_n = \log_b a$.
(4) Suppose $b \in \mathbb{R}$, $\{a_n\}, a_n > 0$ when $n \in \mathbb{N}$. $\lim\limits_{n\to\infty} a_n = a$. Prove $\lim\limits_{n\to\infty} {a_n}^b = a^b$.
(5) Suppose $\lim\limits_{n\to\infty} a_n = a$. Prove $\lim\limits_{n\to\infty} \sin a_n = \sin a$.

Proof 4.(1)
$\forall \epsilon > 0, \exists N(\epsilon) \in \mathbb{N}^+, \forall n \geqslant N(\epsilon)$, $|a_n - a| < \epsilon$.
$p(a) = k_m a^m + k_{m-1} a^{m-1} + \cdots + k_0 a^0$.
$\therefore p(a_n) - p(a) = k_m(a_n^m - a^m) + k_{m-1}(a_n^{m-1} - a^{m-1}) + \cdots + k_0(a_n^0 - a^0)$.

$$\begin{aligned} |a_n^m - a^m| &= |a_n - a| \cdot |a_n^{m-1} + a_n^{m-2}a + \cdots + a^{m-1}| \\ &< \epsilon \cdot |a_n^{m-1} + a_n^{m-2}a + \cdots + a^{m-1}| \\ &< \epsilon(m-1)\cdots(a+\delta)^{m-1} \end{aligned}$$

$\therefore \lim_{n\to\infty} p(a_n) = p(a)$. $\square$

Proof 4.(2)

$\forall \epsilon > 0, \exists N \in \mathbb{N}^+ . \forall n \geqslant N, |a_n - a| < \epsilon$.

If $b = 1$, $1^{a_n} = 1^a = 1$.

If $b > 1$, $b^{a_n} - b^a = b^a(b^{a_n - a} - 1) < b^a(b^\epsilon - 1)$ $0 < |b^{a_n} - b^a| < b^a \cdot (b^\epsilon - 1)$ $\because b > 0, \epsilon \to 0$, $\therefore b^\epsilon - 1 \to 0$. $\therefore \lim\limits_{n\to\infty} b_n^a = b^a$.

If $b < 1$, $b^{a_n} = \frac{1}{(\frac{1}{b})^{a_n}}$, we can prove this condition by considering $\frac{1}{b} > 1$.

Proof 4.(3)

$\forall \epsilon > 0, \exists N \in \mathbb{N}^+ . \forall n \geqslant N, |a_n - a| < \epsilon$.

$$\begin{aligned}\log_b a_n - \log_b a &= \log_b \frac{a_n}{a} \\ &= \log_b(\frac{a_n - a}{a} + 1) < \log_b(\frac{\epsilon}{a} + 1)\end{aligned}$$

$0 < |\log_b a_n - \log_b a| < \log_b(1 + \frac{\epsilon}{a})$. $\because b > 0, a \neq 0$, $a_n > 0$ when $\epsilon \to 0$. $\therefore \log_b(1 + \frac{\epsilon}{a}) \to 0$.

$\therefore \lim\limits_{n\to\infty} \log_b a_n = \log_b a$

Proof 4.(4)

$\forall \epsilon > 0, \exists N \in \mathbb{N}^+ . \forall n \geqslant N, |a_n - a| < \epsilon$.

$a_n^b = e^{b \ln a_n}$, $a_n^b - a^b = e^{b \ln a_n} - e^{b \ln a}$.

$$\begin{aligned}e^{b \ln a_n} - e^{b \ln a} &= e^{b \ln a}(e^{b \ln a_n - b \ln a} - 1) \\ &= e^{b \ln a}(e^{b \ln \frac{a_n}{a}} - 1)\end{aligned}$$

$0 < |a_n^b - a^b| < e^{b \ln a}(e^{b \ln(1 + \frac{\epsilon}{a})} - 1)$

$\therefore \lim\limits_{n\to\infty} a_n^b = a^b$

Proof 4.(5)

$\forall \epsilon > 0, \exists N \in \mathbb{N}^+ . \forall n \geqslant N, |a_n - a| < \epsilon$.

$$\begin{aligned}\sin(A + B) - \sin(A - B) &= \sin A \cos B + \cos A \sin B \\ &\quad - (\sin A \cos B - \cos A \sin B) \\ &= 2 \cos A \sin B \\ \sin a_n - \sin a &= 2 \cos \frac{a_n + a}{2} \sin \frac{a_n - a}{2}\end{aligned}$$

$|\sin a_n - \sin a| = |2 \cos \frac{a_n + a}{2} \sin \frac{a_n - a}{2}| < |2 \sin \frac{a_n - a}{2}|$

$|2 \sin \frac{a_n - a}{2}| < |2 \frac{a_n - a}{2}| = \epsilon$

$|\sin a_n - \sin a| < \epsilon$, $\therefore \lim\limits_{n\to\infty} \sin a_n = \sin a$

assume $a > 1$. Prove $\lim\limits_{n\to\infty} \frac{\log_a n}{n} = 0$

Proof $\frac{1}{n} \log_a n = \log_a \sqrt[n]{n}$. We already know that $\lim\limits_{n\to\infty} \sqrt[n]{n} = 1$, $\log_a 1 = 0$.

$\forall \epsilon > 0, \exists N \in \mathbb{N}^+, N = \max\{2, [\frac{4}{\epsilon^2}]\} . \forall n \geqslant N, |\sqrt[n]{n} - 1| < \epsilon$.

$a > 1$, and $\lim\limits_{n\to\infty} \sqrt[n]{n} = 1$. $\therefore$ when $n \to \infty$, $\sqrt[n]{n} < a^\epsilon$, take logarithm on base of a, we can get $\frac{1}{n} \log_a n < \epsilon$

$\therefore \lim\limits_{n\to\infty} \frac{\log_a n}{n} = 0$

2.2 收敛数列的基本性质

收敛数列的性质

1. 收敛数列的极限是唯一的
2. 收敛数列一定有界
3. 收敛数列的比较定理，包括保号性定理
4. 收敛数列满足一定的四则运算规则
5. 收敛数列的每一个子列一定收敛于同一极限

2.2.1 思考题

1. $\{a_n\}$ 收敛, $\{b_n\}$ 发散, $\{a_n+b_n\}$ 发散, $\{a_n\cdot b_n\}$ 可能收敛，可能发散.
2. $\{a_n\},\{b_n\}$ 都发散, $\{a_n+b_n\}$ 可能收敛，可能发散 (ex: $n+-n$, $n+-2n$), $\{a_n\cdot b_n\}$ 发散 (?).
3. $a_n\leqslant b_n\leqslant c_n$, $n\in\mathbb{N}_+$. 已知 $\lim\limits_{n\to\infty}(c_n-a_n)=0$. 问数列 $\{b_n\}$ 是否收敛?
4. $\lim\limits_{n\to\infty}(\frac{1}{n+1}+\cdots+\frac{1}{2n})$
5. $a_n\to a(n\to 0)$. $\forall n, b<a_n<c$. 是否成立 $b<a<c$?
6. $a_n\to a(n\to 0)$. and $b\leqslant a\leqslant c$, 是否存在 $N\in\mathbb{N}_+$, s.t. 当 $n>N$ 时，成立 $b\leqslant a_n\leqslant c$
7. 已知 $\lim\limits_{n\to\infty}a_n=0$, 问: 是否有 $\lim\limits_{n\to\infty}(a_1a_2\dots a_n)=0$. 反之如何?

Proof 5.4

$$\frac{n}{2n}\leqslant\frac{1}{n+1}+\cdots+\frac{1}{2n}\leqslant\frac{n}{n+1}$$

$\because \lim\limits_{n\to\infty}\frac{n}{2n}=\frac{1}{2}\lim\limits_{n\to\infty}\frac{n}{n+1}=1$, $\therefore \lim\limits_{n\to\infty}(\frac{1}{n+1}+\cdots+\frac{1}{2n})$ 收敛.

$$\begin{aligned}\frac{1}{n+1}+\cdots+\frac{1}{2n}&=\frac{1}{n}(\frac{1}{1+\frac{1}{n}}+\frac{1}{1+\frac{2}{n}}+\cdots+\frac{1}{1+\frac{n}{n}})\\&=\int_0^1\frac{1}{1+x}\mathrm{d}x\\&=\ln(1+x)|_0^1=\ln 2\end{aligned}$$

$\lim\limits_{n\to\infty}(\frac{1}{n+1}+\cdots+\frac{1}{2n})=\ln 2$

Proof 5.5

不成立，应当为小于等于号。b=0, c=2, $a_n=\frac{1}{n}$, $\lim_{n\to\infty}a_n=0=c$.

Proof 5.6

不成立。$a=0,b=0,c=2$, $a_n=(-1)^n\frac{1}{n}$.

$b\leqslant a\leqslant c$, but $(-1)^{2n+1}\frac{1}{2n+1}<0=b$.

Proof $\lim\limits_{n\to\infty}a_n=0, a_n=\frac{1}{n}.a_1a_2\dots a_n=\frac{1}{n!}$, $\lim\limits_{n\to\infty}\frac{1}{n!}=0$.

$\lim\limits_{n\to\infty}a_n=0\to\lim\limits_{n\to\infty}(a_1a_2\dots a_n)=0\quad\checkmark$

$\lim\limits_{n\to\infty}(a_1a_2\dots a_n)=0\to\lim\limits_{n\to\infty}a_n=0\quad\times$

$|a_n|<\epsilon$, $|a_{N+1}\dots a_n|<\epsilon^{n-N}<\epsilon$, $a_n<\sqrt[n]{\epsilon}$.

for example, $a_n=\frac{n}{n+1}, a_1=\frac{1}{2}, a_2=\frac{2}{3},\dots,a_n=\frac{n}{n+1}$.

$$\begin{aligned}a_1a_2\dots a_n=\frac{1}{2}\cdot\frac{2}{3}\cdots\frac{n}{n+1}&=\frac{1}{n+1}.\\\lim_{n\to\infty}(a_1a_2\dots a_n)&\\=\lim_{n\to\infty}\frac{1}{n}&=0\end{aligned}$$

but $\lim\limits_{n\to\infty}a_n=\lim\limits_{n\to\infty}\frac{n}{n+1}=1\neq 0$

研究数列收敛方面的两个基本工具:

1. 夹逼定理.
2. 单调有界数列的收敛定理.

Example 2.1 2.2.2 $\lim_{n\to\infty}\frac{x_n-1}{x_n+a}=0$,
prove $\lim_{n\to\infty}x_n=a$

Proof $\forall\epsilon>0,\exists N\in\mathbb{N}^+.\forall n\geqslant N,|\frac{x_n-1}{x_n+a}-0|<\epsilon.$
$|x_n-1|<\epsilon|x_n+a|<4a\cdot\epsilon$.(这个 4 是怎么取得的?)
$|x_n-a|<\epsilon|x_n+a|=\epsilon|(x_n-a)+2a|\leqslant\epsilon(|x_n-a|+2a)$.
限制 $\epsilon<1$, $|x_n-a|<2\epsilon|a|/(1-\epsilon)$.
限制 $\epsilon<\frac{1}{2}$, $|x_n-a|<2\epsilon|a|/(1-\epsilon)<4|a|\epsilon$.
Let $\epsilon'=4a\epsilon$, $|x_n-1|<\epsilon'$. $\therefore\lim\lim_{n\to\infty}x_n=a$.

Example 2.2 2.2.3 $a>0,b>0$, 计算 $\lim\limits_{n\to\infty}(a_n+b_n)^{\frac{1}{n}}$.

Proof Suppose $a\leqslant b$.
$b=(b^b)^{\frac{1}{n}}<(a^n+b^n)^{\frac{1}{n}}\leqslant(2b^n)^{\frac{1}{n}}$.
$b<(a^n+b^n)^{\frac{1}{n}}\leqslant\sqrt[n]{2}b$, $\lim\limits_{n\to\infty}=1$. 夹逼定理.
$\lim\limits_{n\to\infty}(a^n+b^n)^{\frac{1}{n}}=\max\{a,b\}$.
两数 n 次方之和再开 n 次根号的结果由较大的值决定, a,b 中较大的值为这个数的主要部分.

Example 2.3 2.2.4 $a_n=\frac{1!+2!+\cdots+n!}{n!},n\in\mathbb{N}^+$

$\lim\limits_{n\to\infty}a_n=1$

Example 2.4 $\lim\limits_{n\to\infty}\frac{n^3+n-7}{n+3}=+\infty$

Example 2.5 $H_n=1+\frac{1}{2}+\cdots+\frac{1}{n}$

调和级数 H_n 发散.

2.2.2 练习 2.2.4

Proof 1.
$\{a_n\}$ 收敛于 a, $\to$ 两个子列 $\{a_{2n}\},\{a_{2n+1}\}$ 均收敛于 a.
两个子列 $\{a_{2n}\},\{a_{2n+1}\}$ 均收敛于 a, $\to\{a_n\}$ 收敛于 a.

2. 应用夹逼定理
(1). 给定 p 个正数 $a_1,a_2,\ldots,a_p$. 求 $\lim\limits_{n\to\infty}\sqrt[n]{a_1^n+a_2^n+\ldots a_p^n}$.
Let$a_s=\max_{1\leqslant i\leqslant p}\{a_1,a_2,\ldots,a_p\}$.

$$a_s=(a_s^n)^{\frac{1}{n}}<(a_1^n+a_2^n+\ldots a_p^n)^{\frac{1}{n}}\leqslant(pa_s^n)^{\frac{1}{n}}=p^{\frac{1}{n}}a_s$$

$n\to\infty,p^{\frac{1}{n}}\to1$. $\lim\limits_{n\to\infty}(a_1^n+a_2^n+\ldots a_p^n)^{\frac{1}{n}}=a_s$

(2). $x_n=\frac{1}{\sqrt{n^2+1}}+\frac{1}{\sqrt{n^2+2}}+\cdots+\frac{1}{\sqrt{n^2+n}}$, $n\in\mathbb{N}_+$. 求 $\lim\limits_{n\to\infty}x_n$

$$\frac{2n+1}{(n+1)}\leqslant x_n\leqslant\frac{2n+1}{\sqrt{n^2+1}}$$

$\lim\limits_{n\to\infty}\frac{2n+1}{n+1}=2$, $\lim\limits_{n\to\infty}\frac{2n+1}{\sqrt{n^2+1}}=2$. $\therefore\lim\limits_{n\to\infty}x_n=2$

(3). $a_n=(1+\frac{1}{2}+\cdots+\frac{1}{n})^{\frac{1}{n}}$, $n\in\mathbb{N}_+$. 求 $\lim\limits_{n\to\infty}a_n$

$$1=(\frac{n}{n})^{\frac{1}{n}}<a_n\leqslant(1\cdot n)^{\frac{1}{n}}=\sqrt[n]{n}$$

$\lim\limits_{n\to\infty}\sqrt[n]{n}=1$, $\therefore\lim\limits_{n\to\infty}a_n=1$

(4). $a_n > 0$. $\lim\limits_{n\to\infty} a_n = a$, $a > 0$. 证明 $\lim\limits_{n\to\infty} \sqrt[n]{a_n} = 1$

Proof

$\lim\limits_{n\to\infty} a_n = a$

$\forall\epsilon > 0, \exists N \in \mathbb{N}^+ . \forall n \geqslant N, |a_n - a| < \epsilon$.

$$0 < a - \epsilon < a_n < a + \epsilon$$

$\therefore \sqrt[n]{a-\epsilon} < \sqrt[n]{a_n} < \sqrt[n]{a+\epsilon}$.

$\lim\limits_{n\to\infty} \sqrt[n]{a-\epsilon} = 1$, $\lim\limits_{n\to\infty} \sqrt[n]{a+\epsilon} = 1$. $\therefore \lim\limits_{n\to\infty} \sqrt[n]{a_n} = 1$.

$\lim\limits_{n\to\infty} (1+x)(1+x^2)\dots(1+x^{2^n}) = \lim\limits_{n\to\infty} \prod_{i=1}^{2^n}(1+x^i)$, $|x| < 1$.

$|x| < 1, \quad 1 > x^2 > x^4 > \dots > x^{2^n} > 0$

$x \in (0,1) \quad 1 < (1+x)(1+x^2)\dots(1+x^{2^n}) < (1+x)^{n+1} \qquad \lim\limits_{n\to\infty} (1+x)^{n+1} = 1$

$x \in (-1,0) \quad 0 < (1+x)(1+x^2)\dots(1+x^{2^n}) < (1+x)(1+x^2)^n \qquad \lim\limits_{n\to\infty} (1+x)(1+x^2)^n = 1$

$$\begin{aligned}
&\lim_{n\to\infty} (1+x)(1+x^2)\dots(1+x^n) \\
=&\lim_{n\to\infty} \frac{(1-x)(1+x)(1+x^2)\dots(1+x^n)}{1-x} \\
=&\lim_{n\to\infty} \frac{(1-x^{2^{n+1}})}{1-x} \\
=&\frac{1}{1-x}
\end{aligned}$$

$$\begin{aligned}
&\lim_{n\to\infty} (1-\frac{1}{2^2})(1-\frac{1}{3^2})\dots(1-\frac{1}{n^2}) \\
=&\lim_{n\to\infty} \frac{1}{2}\cdot\frac{3}{2}\cdot\frac{2}{3}\cdot\frac{4}{3}\cdot\frac{3}{4}\cdot\frac{5}{4}\cdot\frac{4}{5}\cdot\frac{6}{5}\cdot\dots\frac{n-1}{n}\cdot\frac{n+1}{n} \\
=&\lim_{n\to\infty} \frac{1}{2}\frac{n+1}{n} \\
=&\lim_{n\to\infty} \frac{1}{2}
\end{aligned}$$

$$\begin{aligned}
&\lim_{n\to\infty} \left(1-\frac{1}{1+2}\right)\left(1-\frac{1}{1+2+3}\right)\dots\left(1-\frac{1}{1+2+\dots+n}\right) \\
=&\lim_{n\to\infty} \left(1-\frac{2}{3\times 2}\right)\left(1-\frac{2}{4\times 3}\right)\dots\left(1-\frac{2}{(n+1)\times n}\right) \\
=&\lim_{n\to\infty} \left(\frac{3\times 2-2}{3\times 2}\right)\left(\frac{4\times 3-2}{4\times 3}\right)\dots\left(\frac{(n+1)\times n-2}{(n+1)\times n}\right) \\
=&\lim_{n\to\infty} \left(\frac{4}{3\times 2}\right)\left(\frac{10}{4\times 3}\right)\dots\left(\frac{n^2+n-2}{(n+1)\times n}\right) \\
=&\lim_{n\to\infty} \left(\frac{1\times 4}{3\times 2}\right)\left(\frac{2\times 5}{4\times 3}\right)\dots\left(\frac{(n-2)\times(n+1)}{n\times(n-1)}\right)\left(\frac{(n-1)\times(n+2)}{(n+1)\times n}\right) \\
=&\lim_{n\to\infty} \frac{1}{3}\times\frac{n+2}{n} \\
=&\frac{1}{3}
\end{aligned}$$

$$
\begin{aligned}
&\lim_{n\to\infty}[\frac{1}{1\cdot 2}+\frac{1}{2\cdot 3}+\cdots+\frac{1}{n\cdot(n+1)}] \\
=&\lim_{n\to\infty}\frac{1}{1}-\frac{1}{2}+\frac{1}{2}-\frac{1}{3}+\cdots+\frac{1}{n}-\frac{1}{n+1} \\
=&\lim_{n\to\infty}\frac{1}{1}-\frac{1}{n+1} \\
=&\lim_{n\to\infty}\frac{n}{n+1} \\
=&1
\end{aligned}
$$

3.(4).

$$
\begin{aligned}
&\lim_{n\to\infty}\left[\frac{1}{1\cdot 2\cdot 3}+\frac{1}{2\cdot 3\cdot 4}+\cdots+\frac{1}{n\cdot(n+1)\cdot(n+2)}\right] \\
=&\lim_{n\to\infty}\frac{1}{2}\Big(\frac{1}{1\cdot 2}-\frac{1}{2\cdot 3}\Big)+\frac{1}{2}\Big(\frac{1}{2\cdot 3}-\frac{1}{3\cdot 4}\Big)+\cdots+\frac{1}{2}\Big(\frac{1}{n(n+1)}-\frac{1}{(n+1)(n+2)}\Big) \\
=&\lim_{n\to\infty}\frac{1}{2}\Big(\frac{1}{1\cdot 2}-\frac{1}{(n+1)(n+2)}\Big) \\
=&\frac{1}{2}\times\frac{1}{2} \\
=&\frac{1}{4}
\end{aligned}
$$

3.(5).

$$
\begin{aligned}
&\lim_{n\to\infty}\sum_{k=1}^{n}\frac{1}{k(k+1)\ldots(k+\gamma)},\qquad \text{其中}\gamma\text{为正整数} \\
=&\lim_{n\to\infty}\sum_{k=1}^{n}\frac{1}{\gamma}\Big[\frac{1}{k(k+1)\ldots(k+\gamma-1)}-\frac{1}{(k+1)(k+2)\ldots(k+\gamma)}\Big] \\
=&\lim_{n\to\infty}\frac{1}{\gamma}\Big[\sum_{k=1}^{n}\frac{1}{k(k+1)\ldots(k+\gamma-1)}-\sum_{k=1}^{n}\frac{1}{(k+1)(k+2)\ldots(k+\gamma)}\Big] \\
=&\lim_{n\to\infty}\frac{1}{\gamma}\Big[\frac{1}{\gamma^{\underline{\gamma}}}-\frac{1}{(n+\gamma)^{\underline{\gamma}}}\Big] \\
=&\lim_{n\to\infty}\frac{1}{\gamma}\Big[\frac{1}{\gamma!}-\frac{1}{(n+\gamma)^{\underline{\gamma}}}\Big] \\
=&\frac{1}{\gamma}\cdot\frac{1}{\gamma!}
\end{aligned}
$$

其中 $x^{\underline{n}}=x(x-1)(x-2)\ldots(x-n+1)$, 称为下阶乘. 而 $x^{\overline{n}}=x(x+1)(x+2)\ldots(x+n-1)$, 称为上阶乘.

2.2.4-4 $S_n=a+3a^2+\cdots+(2n-1)a^n$, $|a|<1$. 求 $\{S_n\}$ 的极限.

$$
\begin{aligned}
S_n-aS_n&=a+3a^2+\cdots+(2n-1)a^n \\
&\quad-\quad a^2-\cdots+(2n-3)a^n-(2n-1)a^n+1 \\
&=a+2a^2+\cdots+2aa^n-(2n-1)a^{n+1} \\
&=2(a+a^2+\cdots+a^n)-a-(2n-1)a^{n+1} \\
&=2\cdot a\frac{1-a^{n+1}}{1-a}-a-(2n-1)a^{n+1}
\end{aligned}
$$

$|a|<1$, $\lim\limits_{n\to\infty}a_n=0$

$\lim\limits_{n\to\infty}(S_n - aS_n) = (1-a)\lim\lim_{n\to\infty} S_n$

$$\begin{aligned}\lim_{n\to\infty}(S_n - aS_n) &= \lim_{n\to\infty} 2a\cdot\frac{1-a^{n+1}}{1-a} - a - (2n-1)a^{n+1} \\ &= 2a\cdot\frac{1}{1-a} - a \\ &= a\Big(\frac{2}{1-a} - a\Big) \\ &= a\frac{1+a}{1-a}\end{aligned}$$

$\therefore \lim\limits_{n\to\infty} S_n = \frac{a(a+1)}{(1-a)^2}$

2.2.4-5 设 $\lim\limits_{n\to\infty} x_n = A > 0$. 取 $\epsilon = \frac{A}{2}$, 则 $\exists N \in \mathbb{N}_+$. $\forall n > N$. 成立 $|x_n - A| < \frac{A}{2}$

$$A - \frac{A}{2} < x_n < A + \frac{A}{2}, \frac{A}{2} < x_n < \frac{3A}{2}$$

即 $x_n > \frac{A}{2}$.

令 $m = \min\{x_1, x_2, \ldots, x_N, \frac{A}{2}\} > 0$. 则 m 为 $\{x_n\}$ 的正下界.

不一定有最小数的例子 $x_n = 1 + \frac{1}{n}$. $\lim\limits_{n\to\infty} x_n = 1$, 下界 $m = \frac{1}{2}$. 但 $\{x_n\}$ 取不到下界.

Proof 2.2.4-6 $\because \lim\limits_{n\to\infty} a_n = +\infty$. $\forall M > 0, \exists N \in \mathbb{N}_+, \forall n > N, a_n > M$.

$m = \min\{a_1, a_2, \ldots, a_N, M\}$, 但 M 在数列 $\{a_n\}$ 中不一定取的到!

$M = a_1 + 1$, $\exists N_1 \in \mathbb{N}_+, \forall n > N_1, a_n > M > a_1$

则 $m = \min\{a_1, a_2, \ldots, a_{N_1}\}$ 为数列的最小数.

Proof 2.2.4-7 构造数列

不妨设无界数列 $\{a_n\}$ 无上界.

$\forall M \in \mathbb{R}, \exists N \in \mathbb{N}_+, \forall n_k > N, a_{n_k} > M$.

取 $M_1 = 1$, 则 $\exists n_1 \in \mathbb{N}_+$ s.t. $a_{n_1} > M_1$.

取 $M_2 = \max\{a_n, 2\}$, $\exists n_2 \in \mathbb{N}_+$ s.t. $a_{n_2} > M_2$.

以此类推，构造数列 $\{a_{n_k}\}$. s.t.$a_{n_k} > k$. 即 a_{n_k} 为无穷大量.

Proof 2.2.4-8 证明 $\{a_n\}, a_n = \tan n$ 发散.

构造 a_n 的发散子列即可. 已知 $\tan\frac{\pi}{2} = \infty$, π 是一个无理数, 因此存在数列 $\{b_n\}$, $\lim\limits_{n\to\infty} b_n = \frac{\pi}{2}$.

Proof 2.2.4-8 证明 $\{a_n\}, a_n = \tan n$ 发散. 参考别人的答案

由于 $\{\sin 2n\}$ 极限不存在, 又

$$\begin{aligned}\sin 2n = 2\sin n\cos n &= \frac{2\sin n\cos n}{\sin^2 n + \cos^2 n} \\ &= \frac{2\tan n}{\tan^n + 1}\end{aligned}$$

若 $\{\tan n\}$ 极限存在 $\to \{\sin 2n\}$ 极限存在, 矛盾.

故 $\{\tan n\}$ 极限不存在.

2.2.4-9 $S_n = \frac{1}{1^p} + \frac{1}{2^p} + \cdots + \frac{1}{n^p}$, $\quad n \in \mathbb{N}_+$. S_n 在 1. $p \leqslant 0$, 2. $0 < p < 1$ 情况下均发散

Proof 1. $p \leqslant 0$. $\lim\limits_{n\to\infty} n^{-p} = \infty$, S_n 发散.

2. $0 < p < 1$. $\frac{1}{n^p} > \frac{1}{n}$. $\because H_n = \sum_{k=1}^n \frac{1}{k}$(调和级数) 发散, $S_n > H_n$,$\therefore \{S_n\}$ 也发散.

ex2.3.5 $0 < b < a$ 令 $a_0 = a, b_0 = b$ 递推公式

$$a_n = \frac{a_{n-1} + b_{n-1}}{2}, b_n = \sqrt{a_{n-1}b_{n-1}}, \quad n \in \mathbb{N}_+ \tag{2.1}$$

定义数列a_n,b_n. 证明这两个数列收敛于同一个极限 $AG(a,b)$.

由 AG 不等式 $a > \frac{a+b}{2} > \sqrt{ab} > b > 0$, 利用单调有界数列收敛原则可以证明上述结论.

$$AG(a,b) = \frac{\pi}{2G} \tag{2.2}$$

如果令 $a_1 = \frac{a+b}{2}, b_1 = \sqrt{ab}$. 则

$$G = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\phi}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}} = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\theta}{\sqrt{a_1^2\cos^2\theta + b_1^2\sin^2\theta}} \tag{2.3}$$

上面这个公式是怎么得到的:

参考菲赫金哥尔茨 - 微积分学教程. 第二卷 315 小节的高斯公式, 蓝登变换.

$$G = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\phi}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}} \qquad (a > b > 0) \tag{2.4}$$

这里令

$$\sin\phi = \frac{2a\sin\theta}{(a+b) + (a-b)\sin^2\theta} \tag{2.5}$$

$\theta \in [0, \frac{\pi}{2}] \to \phi \in [0, \frac{\pi}{2}]$, 取微分

$$\cos\phi\mathrm{d}\phi = 2a\frac{(a+b) - (a-b)\sin^2\theta}{[(a+b) + (a-b)\sin^2\theta]^2}\cos\theta\mathrm{d}\theta \tag{2.6}$$

但是

$$\cos\phi = \frac{\sqrt{(a+b)^2 - (a-b)^2\sin^2\theta}}{(a+b) + (a-b)\sin^2\theta}\cos\theta. \tag{2.7}$$

(2.6) / (2.7), 两式相除, 得到

$$\mathrm{d}\phi = 2a\frac{(a+b) - (a-b)\sin^2\theta}{(a+b) + (a-b)\sin^2\theta}\frac{\mathrm{d}\theta}{\sqrt{(a+b)^2 - (a-b)^2\sin^2\theta}} \tag{2.8}$$

另一方面

$$\sqrt{a^2\cos^2\phi + b^2\sin^2\phi} = a\frac{(a+b) - (a-b)\sin^2\theta}{(a+b) + (a-b)\sin^2\theta} \tag{2.9}$$

因而

$$\frac{\mathrm{d}\phi}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}} = \frac{\mathrm{d}\theta}{\sqrt{(\frac{a+b}{2})^2\cos^2\theta + ab\sin^2\theta}}. \tag{2.10}$$

如果令 $a_1 = \frac{a+b}{2}, b_1 = \sqrt{ab}$, 则

$$G = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\phi}{\sqrt{a^2\cos^2\phi + b^2\sin^2\phi}} = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\theta}{\sqrt{a_1^2\cos^2\theta + b_1^2\sin^2\theta}} \tag{2.11}$$

反复应用该公式, 得到

$$G = \int_0^{\frac{\pi}{2}} \frac{\mathrm{d}\phi}{\sqrt{a_n^2\cos^2\phi + b_n^2\sin^2\phi}}, \qquad (n = 1, 2, 3, \dots) \tag{2.12}$$

$$\frac{\pi}{2a_n} < G < \frac{\pi}{2b_n} \tag{2.13}$$

积分 G 可以归结到第一类全椭圆积分 $K(k) = (1+k_1)K(k_1) = \frac{\pi}{2}(1+k_1)(1+k_2)\dots(1+k_n)$

$$\int_0^{\frac{pi}{2}} \frac{\mathrm{d}\phi}{\sqrt{1-k^2\sin^2\phi}} = (1+k_1)\int_0^{\frac{pi}{2}} \frac{\mathrm{d}\theta}{\sqrt{1-k_1^2\sin^2\theta}} \tag{2.14}$$

其中

$a_1 = \frac{1+\sqrt{1-k^2}}{2} = \frac{1+k'}{2}, b_1 = \sqrt{k'}$

$k_1 = \frac{\sqrt{a_1^2-b_1^2}}{a_1} = \frac{1-k'}{1+k'}, \frac{1}{a_1} = 1 + k_1$

2.3 2.3 单调数列

Example 2.6 2.3.6

$$\begin{aligned}\frac{a_{n+1}}{a_n}&=\frac{\frac{1!+2!+\cdots+(n+1)!}{(n+1)!}}{\frac{1!+2!+\cdots+n!}{n!}}\\&=\frac{1}{n+1}\frac{1!+2!+\cdots+(n+1)!}{1!+2!+\cdots+n!}\\&=\frac{3+3!+\cdots+(n+1)!}{(n+1)1!+(n+1)2!+\cdots+(n+1)!}\end{aligned}$$

$n>2$ 时, 分母每一项大于等于分子对应项.. $n>2$ 后a_n 单调减少. 由于 0 是下界, 因此 a_n 单调有界, 数列收敛.

$$\begin{aligned}a_{n+1}&=\frac{1!+2!+\cdots+(n+1)!}{(n+1)!}\\&=\frac{1!+2!+\cdots+n!}{n!}\frac{1}{n+1}+1\\&=1+\frac{a_n}{n+1}\end{aligned}$$

设 $n\to\infty$ 时, $a_n\to a$

$$a=1+\left(\frac{1}{n+1}\to 0\right)=1+0,\qquad \therefore a=1$$

$\therefore \lim\limits_{n\to\infty}a_n=\lim\limits_{n\to\infty}\frac{1!+2!+\cdots+n!}{n!}=1$

2.3.1 2.3.2 练习题

证明, 若x_n 单调, 则$|x_n|$ 至少从某项开始后单调, 又问: 反之如何?

Proof 分类讨论, 不妨设 $x_1\geqslant 0$

1. x_n 单调递增, $|x_n|$ 从第一项开始单调.
2. x_n 单调递减, 且 $|x_n|\geqslant 0$. $|x_n|$ 从第一项开始单调.
3. x_n 单调递减, 且 $\exists N$ s.t. $x_n<0$(第一个负数项). 则$|x_n|$ 从第 N 项 (x_N) 开始单调.

反之该结论不成立.

反例: $x_n=\frac{(-1)^n}{n}$, $|x_n|$ 单调递减. 但 $x_{2k}=\frac{1}{2k}>0>x_{2k-1}=\frac{-1}{2k-1}$

设a_n 单调增加, b_n 单调减少, 且有 $\lim\limits_{n\to\infty}(a_n-b_n)=0$.

证明: 数列a_n 和b_n 都收敛, 且极限相等.

Proof $\lim\limits_{n\to\infty}(a_n-b_n)=0, \forall\epsilon>0, \exists N\in\mathbb{N}_+, \text{s.t.}\forall n>N, |a_n-b_n-0|<\epsilon$.

$b_n-\epsilon<a_n<b_n+\epsilon$, 同时有 $a_n-\epsilon<b_n<a_n+\epsilon$.

b_n 单调减少, $\therefore\exists N_2, \forall m<N_2, b_m>b_n+\epsilon$.

使用反证法证明 b_m 是a_n 的上界.

假设 b_m 不是a_n 的上界，则存在 $a_n>b_m>b_n+\epsilon$, 这与 $|a_n-b_n|<\epsilon$ 矛盾.

$\therefore$ b_m 是a_n 的上界, 根据单调有界收敛准则, a_n 收敛. 同理可证b_n 收敛. $\lim\limits_{n\to\infty}(a_n-b_n)=0$.

$\therefore\lim\limits_{n\to\infty}a_n=\lim\limits_{n\to\infty}b_n$.

按照极限定义证明:

1. 单调增加有上界的数列的极限不小于数列中的任何一项.
2. 单调减少有下界的数列的极限不大于数列中的任何一项.

设 $x_n=\frac{2}{3}\cdot\frac{3}{5}\cdots\frac{n+1}{2n+1}$, $n\in\mathbb{N}_+$, 求数列x_n 的极限.

$$\frac{x_{n+1}}{x_n}=\frac{(n+1)+1}{2(n+1)+1}=\frac{n+2}{2n+3}<1.\qquad(n>0)\tag{2.15}$$

x_n 单调递减. $\because x_n > 0, \therefore x_n$ 有下界, x_n 收敛.

$$\lim_{n\to\infty}\frac{x_{n+1}}{x_n}=\lim_{n\to\infty}\frac{n+2}{2n+3}=\frac{1}{2}$$

$\left(\frac{1}{2}\right)^n < x_n < \left(\frac{2}{3}\right)^n$, 由夹逼定理, $\lim\limits_{n\to\infty} x_n = 0$

6. 在例题 2.2.6 的基础上证明: 当 $p>1$ 时，数列S_n 收敛. 其中

$$S_n = 1+\frac{1}{2^p}+\frac{1}{3^p}+\frac{1}{4^p}+\cdots++\frac{1}{n^p},\quad n\in\mathbb{N}_+$$

(S_n 就是 p 级数, 当 $p=1$ 时为调和级数.)

Proof　S_n 单调递增, 记 $\frac{1}{2^{p-1}}=r$, 则 $0<r<1$.

$$\begin{aligned}
\frac{1}{2^p}+\frac{1}{3^p} &< \frac{1}{2^p}+\frac{1}{2^p} &&= \frac{1}{2^{p-1}} = r\\
\frac{1}{4^p}+\frac{1}{5^p}+\frac{1}{6^p}+\frac{1}{7^p} &< \frac{1}{4^p}+\frac{1}{4^p}+\frac{1}{4^p}+\frac{1}{4^p} &&= \frac{1}{4^{p-1}} = r^2\\
\frac{1}{(2^k)^p}+\cdots+\frac{1}{(2^{k+1}-1)^p} &< \frac{1}{(2^k)^p}+\frac{1}{(2^k)^p}+\cdots+\frac{1}{(2^k)^p} &&= \frac{1}{(2^k)^{p-1}} = r^k
\end{aligned}$$

由此可知

$$S_n \leqslant S_{2^n-1} < 1+r+r^2+\cdots+r^{n-1} = \frac{1-r^n}{1-r} < \frac{1}{1-r}$$

S_n 单调递增有上界，由单调有界收敛准则知S_n 收敛。

7. 设 $0<x_0<\frac{\pi}{2}$, $x_n=\sin x_{n-1}$. $n\in\mathbb{N}_+$.

证明x_n 收敛，并求其极限。

Proof

$x_0\in(0,\frac{\pi}{2})$, $\sin x$,

$0<x_1=\sin x_0<x_0<\frac{\pi}{2}$.

$0<x_2=\sin x_1<x_1<\frac{\pi}{2}$.

$0<\cdots<x_n<x_{n-1}<\cdots<x_2<x_1<\frac{\pi}{2}$.

x_n 单调递减有下界，x_n 收敛。

$a=\sin a,\quad a\in[0,\frac{\pi}{2}]$

解得 $a=0$，$\therefore \lim\limits_{n\to\infty} x_n = 0$.