Chapter 4 Infinite Series

An infinite series is of the form

$$a_1 + a_2 + a_3 + \cdots \quad \text{or} \quad \sum_{k=1}^{\infty} a_k$$

where $a_1, a_2, a_3, \ldots$ are numbers.

For $n \in \mathbb{N}$, $S_n = \sum_{k=1}^{n} a_k$ is the n^{th} partial sum of the series.

Examples ① $\sum_{k=1}^{\infty} \frac{1}{2^{k-1}} = 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \cdots$,

$$S_n = \sum_{k=1}^{n} \frac{1}{2^{k-1}} = 2 - \frac{1}{2^n} \Rightarrow \sum_{k=1}^{\infty} \frac{1}{2^{k-1}} = \lim_{n\to\infty} S_n = 2$$

We say the series converges to 2 in this case.

② $\sum_{k=1}^{\infty} 1 = 1+1+1+1+\cdots$, $\quad S_n = \sum_{k=1}^{n} 1 = n$

We have $\lim_{n\to\infty} S_n = \infty$. We say the series diverges to ∞

③ $\sum_{k=1}^{\infty} (-1)^{k-1} = 1 + (-1) + 1 + (-1) + \cdots$; $S_n = \begin{cases} 0 & n \text{ even} \\ 1 & n \text{ odd} \end{cases}$

$\lim_{n\to\infty} S_n$ doesn't exist. We say the series diverges.

Definitions For an infinite series $\sum_{k=1}^{\infty} a_k$,

① it converges to a number S iff $\lim_{n\to\infty} S_n = S$.
(S is the sum of the series.)

② it diverges to ∞ iff $\lim_{n\to\infty} S_n = \infty$.

③ it diverges iff $\lim_{n\to\infty} S_n$ doesn't exist.

Facts

① For $\sum_{k=1}^{\infty} a_k$ with partial sums S_n, we have

$\boxed{a_1 = S_1}$, $a_2 = (a_1+a_2) - a_1 = S_2 - S_1$, ...

$\underline{k>1} \Rightarrow a_k = (a_1+\cdots+a_k) - (a_1+\cdots+a_{k-1})$

$\Rightarrow \boxed{a_k = S_k - S_{k-1}}$

② For $m \in \mathbb{N}$, $\sum_{k=1}^{\infty} a_k$ converges to A <u>iff</u> $\sum_{k=m}^{\infty} a_k$ converges to

$$B = \lim_{n\to\infty}(a_m + \cdots + a_n) = \lim_{n\to\infty}(S_n - (a_1+\cdots+a_{m-1}))$$

$$= \lim_{n\to\infty} S_n - (a_1+\cdots+a_{m-1}) = A - (a_1+\cdots+a_{m-1}).$$

To check $\sum_{k=1}^{\infty} a_k$ converge, it is enough to check $\sum_{k=m}^{\infty} a_k$ converge for some $m \in \mathbb{N}$.

③ If $\sum_{k=1}^{\infty} a_k = A$ and $\sum_{k=1}^{\infty} b_k = B$, where A, B <u>numbers</u>

then $$\sum_{k=1}^{\infty}(a_k+b_k) = A+B = \sum_{k=1}^{\infty} a_k + \sum_{k=1}^{\infty} b_k$$

$$\sum_{k=1}^{\infty}(a_k-b_k) = A-B = \sum_{k=1}^{\infty} a_k - \sum_{k=1}^{\infty} b_k$$

$\forall c \in \mathbb{R}$, $\sum_{k=1}^{\infty}(c a_k) = c\sum_{k=1}^{\infty} a_k$.

Geometric Series Test

$$\sum_{k=0}^{\infty} r^k = \lim_{n\to\infty}(1+r+r^2+\cdots+r^n) = \lim_{n\to\infty}\frac{1-r^{n+1}}{1-r}$$

$$= \begin{cases} \frac{1}{1-r} & \text{if } |r|<1 \\ \text{doesn't exist} & \text{if } |r|\geq 1. \end{cases}$$

<u>Example</u> $$0.999\ldots = \frac{9}{10}+\frac{9}{100}+\frac{9}{1000}+\cdots$$

$$= \frac{9}{10}\left(1+\frac{1}{10}+\frac{1}{100}+\cdots\right)$$

$$= \frac{9}{10}\cdot\frac{1}{1-\frac{1}{10}} = 1 = 1.000\cdots$$

Telescoping Series Test

$(b_1-b_2)+(b_2-b_3)+(b_3-b_4)+\cdots$

$$= \sum_{k=1}^{\infty}(b_k - b_{k+1}) = \lim_{n\to\infty}((b_1-b_2)+(b_2-b_3)+\cdots+(b_n-b_{n+1}))$$

$$= \lim_{n\to\infty}(b_1 - b_{n+1}) = b_1 - \lim_{n\to\infty} b_{n+1}$$

<u>Examples</u> ① $\sum_{k=1}^{\infty}\frac{1}{k(k+1)} = \sum_{k=1}^{\infty}\left(\frac{1}{k}-\frac{1}{k+1}\right)$ $\quad b_k = \frac{1}{k}$

$$= \left(1-\tfrac{1}{2}\right)+\left(\tfrac{1}{2}-\tfrac{1}{3}\right)+\left(\tfrac{1}{3}-\tfrac{1}{4}\right)+\cdots = 1 - \lim_{n\to\infty}\frac{1}{n+1} = 1$$

② $$\sum_{k=1}^{\infty}\left(5^{1/k} - 5^{1/(k+1)}\right) = (5-\sqrt{5})+(\sqrt{5}-\sqrt[3]{5})+\cdots$$

$$= 5 - \lim_{n\to\infty} 5^{1/(n+1)} = 5 - 5^0 = 5-1 = 4.$$

Term Test If $\sum_{k=1}^{\infty} a_k$ converges, then $\lim_{n\to\infty} a_n = 0$.

(**Contrapositive**: If $\lim_{n\to\infty} a_n \neq 0$, then $\sum_{k=1}^{\infty} a_k$ diverges.)

Reason $\sum_{k=1}^{\infty} a_k = \lim_{n\to\infty} S_n = S \Rightarrow \lim_{n\to\infty} a_n = \lim_{n\to\infty}(S_n - S_{n-1})$
$= S - S = 0.$

Examples ① $1+1+1+\cdots = \sum_{k=1}^{\infty} 1$ $\quad a_n = 1$, $\lim_{n\to\infty} a_n = 1 \neq 0$

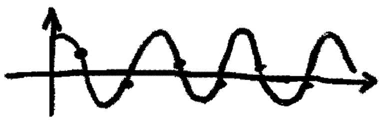
series diverges.

② $\sum_{k=1}^{\infty} \cos\left(\frac{1}{k}\right)$ $\quad a_n = \cos\frac{1}{n}$, $\lim_{n\to\infty} a_n = \cos 0 = 1 \neq 0$

series diverges

③ $\sum_{k=1}^{\infty} \cos k$ $\quad a_n = \cos n$, $\lim_{n\to\infty} a_n \neq 0$

series diverges $\qquad$ why?



Assume $\lim_{n\to\infty} \cos n = 0$.

Then $\cos 1, \cos 2, \cos 3, \ldots \to 0$

So $\cos 2, \cos 3, \cos 4, \ldots \to 0 \Leftrightarrow \lim_{n\to\infty} \cos(n+1) = 0$

$\lim_{n\to\infty} |\sin n| = \lim_{n\to\infty} \sqrt{1-\cos^2 n} = \sqrt{1-0^2} = 1$

$0 = \lim_{n\to\infty} |\cos(n+1)| = \lim_{n\to\infty} |\underbrace{\cos n}_{0} \cos 1 - \sin n \sin 1|$
$= |\sin 1| \neq 0$

Contradiction.

Question What if $\lim_{n\to\infty} a_n = 0$?

Answer $\sum_{k=1}^{\infty} a_k$ may or may not converge.

Examples ④ $1 - \frac{1}{2} + \frac{1}{4} - \frac{1}{8} + \frac{1}{16} - \cdots = \sum_{k=0}^{\infty} \left(-\frac{1}{2}\right)^k$

$a_n = \left(-\frac{1}{2}\right)^n$, $\underline{\lim_{n\to\infty} a_n = 0}$, $\quad$ series converges by geometric series test
$r = -\frac{1}{2}$, $|r| = \frac{1}{2} < 1$.

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⑤ $1 + \underbrace{\frac{1}{2} + \frac{1}{2}}_{2 \text{ times}} + \underbrace{\frac{1}{4} + \frac{1}{4} + \frac{1}{4} + \frac{1}{4}}_{4 \text{ times}} + \underbrace{\frac{1}{8} + \cdots + \frac{1}{8}}_{8 \text{ times}} + \cdots$

$a_1 \geq a_2 \geq a_3 \geq \cdots$ $\quad a_n$ is "decreasing to 0"
$\underline{\lim_{n\to\infty} a_n = 0}$

$S_1 \leq S_2 \leq S_3 \leq \cdots$ $\quad S_{2^n-1} = n$ $\quad \lim_{n\to\infty} S_n = \infty$

Series diverges to ∞. S_n is "increasing" to ∞.

Nonnegative Series $\sum_{k=1}^{\infty} a_k$ with $a_k \geq 0 \ \forall k$

$\Rightarrow \forall n,\ S_{n+1} = S_n + a_{n+1} \geq S_n$

$\Rightarrow S_1 \leq S_2 \leq S_3 \leq \cdots \Rightarrow \lim_{n\to\infty} S_n =$ number or $+\infty$

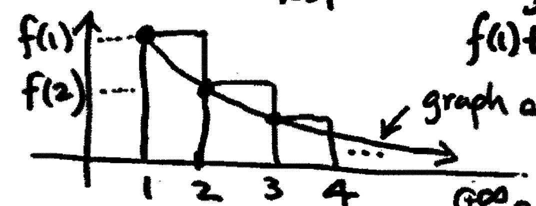
$\Rightarrow \sum_{k=1}^{\infty} a_k$ converges or $\sum_{k=1}^{\infty} a_k$ diverges to $+\infty$.

Integral Test Let $f : [1,\infty) \to \mathbb{R}$ decrease to 0 as $x \to \infty$. Then

$$\sum_{k=1}^{\infty} f(k) \text{ converges} \iff \underbrace{\int_1^{+\infty} f(x)\,dx}_{=\lim_{t\to\infty}\int_1^t f(x)\,dx} < \infty$$

Reason $(\Rightarrow)$ "$\sum_{k=1}^{\infty} f(k)$ converges" means

$f(1)+f(2)+f(3)+f(4)+\cdots < \infty$

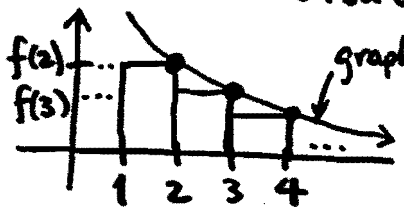


$\int_1^{+\infty} f(x)\,dx \leq f(1)+f(2)+\cdots < \infty$

area under graph of f on $[1,\infty)$ / area of rectangles on $[1,\infty)$

$(\Leftarrow)$ "$\int_1^{\infty} f(x)\,dx < \infty$" means

area under graph of f on $[1,\infty) < \infty$



$f(2)+f(3)+\cdots \leq \int_1^{+\infty} f(x)\,dx < \infty$

$\Rightarrow \underbrace{f(1) + (f(2)+f(3)+\cdots)}_{=\sum_{k=1}^{\infty} f(k) \text{ converges.}} < \infty$

$f(1) \in \mathbb{R}$

Examples (1) Consider $\sum_{k=1}^{\infty} \frac{1}{1+k^2}$. $f(x) = \frac{1}{1+x^2}$

As $x \nearrow \infty$, $1+x^2 \nearrow \infty$, so $\frac{1}{1+x^2} \searrow 0$.

$$\int_1^{\infty} \frac{1}{1+x^2}\,dx = \text{Arctan}\,x \Big|_1^{\infty} = \text{Arctan}\,\infty - \text{Arctan}\,1 = \frac{\pi}{2} - \frac{\pi}{4} < \infty.$$

$\therefore \sum_{k=1}^{\infty} \frac{1}{1+k^2}$ converges by integral test.

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(2) Consider $\sum_{k=2}^{\infty} \frac{1}{k \ln k}$ and $\sum_{k=2}^{\infty} \frac{1}{k(\ln k)^2}$.

As $x \nearrow \infty$, $\ln x \nearrow \infty$, $x \ln x \nearrow \infty$, $x(\ln x)^2 \nearrow \infty$

so $\frac{1}{x \ln x} \searrow 0$, $\frac{1}{x(\ln x)^2} \searrow 0$.

$$\int_2^{\infty} \frac{1}{x\ln x}\,dx \underset{u=\ln x}{=} \int_{\ln 2}^{+\infty} \frac{1}{u}\,du = \ln u \Big|_{\ln 2}^{+\infty} = \infty - \ln(\ln 2) = \infty$$

$\therefore \sum_{k=2}^{\infty} \frac{1}{k \ln k}$ diverges to ∞

$$\int_2^{\infty} \frac{1}{x(\ln x)^2}\,dx \underset{u=\ln x}{=} \int_{\ln 2}^{+\infty} \frac{1}{u^2}\,du = -\frac{1}{u}\Big|_{\ln 2}^{+\infty} = 0 - \left(-\frac{1}{\ln 2}\right) = \frac{1}{\ln 2}$$

$\therefore \sum_{k=2}^{\infty} \frac{1}{k(\ln k)^2}$ converges.

<u>p-test</u> For $p \in \mathbb{R}$, p constant

$$\zeta(p) = \sum_{k=1}^{\infty} \frac{1}{k^p} = 1 + \frac{1}{2^p} + \frac{1}{3^p} + \frac{1}{4^p} + \cdots \text{ converges} \iff p > 1.$$

"p-series"

<u>Reason</u> For $p \le 0$, $\frac{1}{k^p} = k^{-p} = k^{|p|} \ge k^0 = 1$

$$\Rightarrow \lim_{k\to\infty} \frac{1}{k^p} \ne 0 \Rightarrow \sum_{k=1}^{\infty} \frac{1}{k^p} \text{ diverges by term test.}$$

For $p > 0$, as $x \nearrow \infty$, $x^p \nearrow \infty$, so $\frac{1}{x^p} \searrow 0$.

$$\int_1^{+\infty} \frac{1}{x^p}\,dx = \int_1^{+\infty} x^{-p}\,dx = \begin{cases} \ln x \big|_1^{\infty} & p = 1 \\ \frac{x^{-p+1}}{-p+1}\Big|_1^{\infty} & 0 < p < 1 \text{ or } p > 1 \end{cases}$$

$$= \begin{cases} +\infty & p = 1 \\ +\infty & 0 < p < 1 \\ \frac{1}{p-1} & p > 1 \end{cases} \qquad \therefore \sum_{k=1}^{\infty} \frac{1}{k^p} \text{ converges} \iff p > 1.$$

<u>Known Cases</u> In 1736, Euler showed

$$\zeta(2) = 1 + \frac{1}{4} + \frac{1}{9} + \frac{1}{16} + \cdots = \frac{\pi^2}{6}$$

$$\zeta(4) = 1 + \frac{1}{16} + \frac{1}{81} + \frac{1}{256} + \cdots = \frac{\pi^4}{90}$$

$$\vdots$$

$$\zeta(2n) = r_n \pi^{2n}, \quad r_n \in \mathbb{Q}$$

In 1980, Apery showed

$\zeta(3) = 1 + \frac{1}{8} + \frac{1}{27} + \frac{1}{64} + \cdots$ is <u>irrational</u>.

<u>Comparison Test</u> Given $v_k \ge u_k \ge 0$ $\forall k \in \mathbb{N}$.

$$\sum_{k=1}^{\infty} v_k \text{ converges} \Rightarrow \sum_{k=1}^{\infty} u_k \text{ converges.}$$

(<u>Contrapositive</u>: $\sum_{k=1}^{\infty} u_k$ diverges $\Rightarrow \sum_{k=1}^{\infty} v_k$ ~~converges~~ diverges)

<u>Reason</u> $v_k \ge u_k \ge 0$ $\forall k \Rightarrow \sum_{k=1}^{\infty} v_k \ge \sum_{k=1}^{\infty} u_k \ge 0$

If $\sum_{k=1}^{\infty} v_k$ is a number, then $\sum_{k=1}^{\infty} u_k$ is a number.

If $\sum_{k=1}^{\infty} u_k = +\infty$, then $\sum_{k=1}^{\infty} v_k = +\infty$.

<u>Limit Comparison Test</u> Given $u_k, v_k \ge 0$ $\forall k \in \mathbb{N}$.

$\lim_{k\to\infty} \frac{v_k}{u_k}$ = positive number $\Rightarrow$ Both $\sum u_k$, $\sum v_k$ converges or both $\sum u_k$, $\sum v_k$ diverges

$\forall$ large k, $v_k \approx c\,u_k$, $c > 0$

$$\lim_{k\to\infty} \frac{v_k}{u_k} = 0 \Rightarrow \begin{cases} \sum u_k \text{ converges} \Rightarrow \sum v_k \text{ converges} \\ \sum v_k \text{ diverges} \Rightarrow \sum u_k \text{ diverges} \end{cases}$$

$\forall$ large k, $\frac{v_k}{u_k} < 1 \Rightarrow v_k < u_k$

$$\lim_{k\to\infty} \frac{v_k}{u_k} = +\infty \Rightarrow \begin{cases} \sum u_k \text{ diverges} \Rightarrow \sum v_k \text{ diverges} \\ \sum v_k \text{ converges} \Rightarrow \sum u_k \text{ converges.} \end{cases}$$

$\forall$ large k, $\frac{v_k}{u_k} > 1 \Rightarrow v_k > u_k$

<u>Examples</u> (1) Consider $\sum_{k=1}^{\infty} \frac{1}{k^2} \underbrace{\cos\left(\frac{1}{k}\right)}_{>0 \text{ as } \cos 1, \cos\frac{1}{2}, \dots > 0}$

$$\left.\begin{array}{l} 0 \le \frac{1}{k^2}\cos\left(\frac{1}{k}\right) \le \frac{1}{k^2} \\ \sum_{k=1}^{\infty} \frac{1}{k^2} \text{ converges} \\ \text{p series, } p = 2 > 1 \end{array}\right\} \Rightarrow \sum_{k=1}^{\infty} \frac{1}{k^2}\cos\left(\frac{1}{k}\right) \text{ converges by comparison test}$$

(2) Consider $\sum_{k=2}^{\infty} \underbrace{\frac{3^k}{k^2-1}}_{>0}$ When k large, $\frac{3^k}{k^2-1}$ is dominated by 3^k

$0 \le \left(\frac{3}{2}\right)^k < \frac{3^k}{k^2-1}$ because $k^2-1 < 2^k$ for $k \ge 2$.

$\sum_{k=1}^{\infty} \left(\frac{3}{2}\right)^k$ diverges, geometric series $r = \frac{3}{2} > 1$ $\Rightarrow \sum_{k=1}^{\infty} \frac{3^k}{k^2-1}$ diverges by comparison test

(3) Consider $\sum_{k=1}^{\infty} \underbrace{\frac{\sqrt{k+1}}{k^2+5k}}_{>0}$ When k large, $\frac{\sqrt{k+1}}{k^2+5k} \approx \frac{\sqrt{k}}{k^2} = \frac{1}{k^{3/2}}$

Set $u_k = \frac{\sqrt{k}}{k^2} = \frac{1}{k^{3/2}}$ and $v_k = \frac{\sqrt{k+1}}{k^2+5k}$. $u_k, v_k > 0$.

$$\lim_{k\to\infty} \frac{v_k}{u_k} = \lim_{k\to\infty} \frac{\sqrt{k+1}}{k^2+5k} \cdot \frac{k^2}{\sqrt{k}} = \lim_{k\to\infty} \sqrt{\frac{k+1}{k}}\ \frac{k^2}{k^2+5k} = 1 \cdot 1 = 1$$

$\sum u_k = \sum \frac{1}{k^{3/2}}$ converges, p-series $p = 3/2 > 1$ $\Rightarrow \sum v_k = \sum_{k=1}^{\infty} \frac{\sqrt{k+1}}{k^2+5k}$ converges by limit comp. test.

(4) Consider $\sum_{k=1}^{\infty} \underbrace{\sin\left(\frac{1}{k}\right)}_{>0}$ When k large $\sin\left(\frac{1}{k}\right) \approx \frac{1}{k}$ as $\lim_{\theta\to 0} \frac{\sin\theta}{\theta} = 1$

$\theta = \frac{1}{k} \to 0$, $\sin\theta \approx \theta$

Set $u_k = \frac{1}{k}$, $v_k = \sin\frac{1}{k}$, $u_k, v_k > 0$

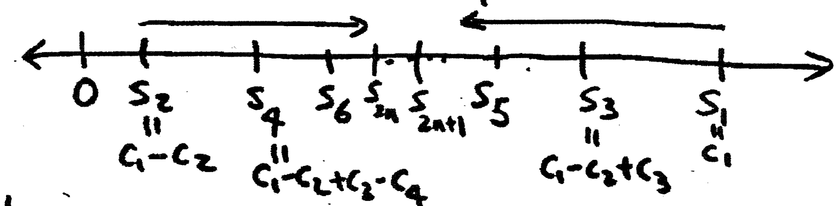
$$\lim_{k\to\infty} \frac{v_k}{u_k} = \lim_{k\to\infty} \frac{\sin(1/k)}{1/k} \underset{\theta = \frac{1}{k} \to 0}{=} \lim_{\theta\to 0} \frac{\sin\theta}{\theta} = 1$$

$\sum u_k = \sum \frac{1}{k}$ diverges, p-series $p=1$ $\Rightarrow \sum v_k = \sum_{k=1}^{\infty} \sin\left(\frac{1}{k}\right)$ diverges by limit comp. test

<u>Alternating Series Test</u> If c_k decreases to 0 as $k \to \infty$ (i.e. $c_1 \ge c_2 \ge c_3 \ge \cdots$ and $\lim_{k\to\infty} c_k = 0$), then

$$\sum_{k=1}^{\infty} (-1)^{k+1} c_k = \underbrace{c_1 - c_2 + c_3 - c_4 + c_5 - c_6 + \cdots}_{\text{"alternating series"}} \text{ converges.}$$

<u>Reason</u> For these series, partial sums are as follow



$$\lim_{n\to\infty} |S_{2n} - S_{2n+1}| = \lim_{n\to\infty} (S_{2n+1} - S_{2n}) = \lim_{n\to\infty} c_{2n+1} = 0$$

$\Rightarrow \lim_{n\to\infty} S_n$ is a number $\Rightarrow \sum_{k=1}^{\infty} (-1)^{k+1} c_k$ converges

Examples Consider $\sum_{k=2}^{\infty} \frac{(-1)^k}{k\ln k}$ and $\sum_{k=1}^{\infty} e^{-k}\underbrace{\cos(k\pi)}_{=(-1)^k}$

For $c_k = \frac{1}{k\ln k}$, as $k \nearrow \infty$, $\ln k \nearrow \infty$, $k\ln k \nearrow \infty$

so $\frac{1}{k\ln k} \searrow 0$. $\therefore \sum_{k=2}^{\infty} \frac{(-1)^k}{k\ln k}$ converges by alt. series test.

For $c_k = e^{-k}$, as $k \nearrow \infty$, $-k \searrow -\infty$, $e^{-k} \searrow 0$

$\therefore \sum_{k=1}^{\infty} e^{-k}\cos(k\pi) = \sum_{k=1}^{\infty} (-1)^k e^{-k}$ converges by alt. series test.

Tests for general series $a_k \in \mathbb{R}\ \forall k \in \mathbb{N}$

Absolute Convergence Test $\underbrace{\sum_{k=1}^{\infty} |a_k|}_{\text{converges}} \Rightarrow \underbrace{\sum_{k=1}^{\infty} a_k}_{\text{converges}}$

(**Converse is false:** $\sum_{k=2}^{\infty} \frac{(-1)^k}{k\ln k}$ converges from above example

$\sum_{k=2}^{\infty} \left|\frac{(-1)^k}{k\ln k}\right| = \sum_{k=2}^{\infty} \frac{1}{k\ln k}$ diverges from integral test)

page 31, example 2

Reason for Absolute Convergence Test

$\forall k \in \mathbb{N}$, $-|a_k| \le a_k \le |a_k| \Rightarrow 0 \le |a_k| + a_k \le 2|a_k|$

Add $|a_k|$ to all parts

$\underbrace{\sum |a_k| \text{ converges}}_{\text{Given}} \Rightarrow \sum 2|a_k|$ converges

$\Rightarrow \sum(|a_k| + a_k)$ converges by comparison test

$\Rightarrow \underbrace{\sum a_k}_{\text{Converges}} = \sum((|a_k| + a_k) - |a_k|) = \underbrace{\sum(|a_k| + a_k)}_{\text{Converges}} - \underbrace{\sum |a_k|}_{\text{Converges}}$

Definitions $\sum_{k=1}^{\infty} a_k$ converges absolutely iff $\sum_{k=1}^{\infty} |a_k|$ converges

$\sum_{k=1}^{\infty} a_k$ converges conditionally iff $\sum_{k=1}^{\infty} |a_k|$ diverges and $\sum_{k=1}^{\infty} a_k$ converges

Facts to be presented later

Dirichlet proved that for absolute convergent $\sum_{k=1}^{\infty} a_k$,

$\forall$ bijection $f: \mathbb{N} \to \mathbb{N}$, $\underbrace{\sum_{k=1}^{\infty} a_{f(k)}}_{\text{permutation of terms}} = \sum_{k=1}^{\infty} a_k$. , same sum

Riemann proved that for condition convergent $\sum_{k=1}^{\infty} a_k$,

$\forall -\infty \le c \le \infty$, $\exists$ bijection $f: \mathbb{N} \to \mathbb{N}$,

$\underbrace{\sum_{k=1}^{\infty} a_{f(k)}}_{\text{permutation of terms}} = c \leftarrow$ sum may be arbitrary

Examples Consider $\sum_{k=1}^{\infty} \frac{\cos k}{k^3}$ and $\sum_{k=1}^{\infty} \underbrace{\frac{\cos k\pi}{1+k}}_{=\frac{(-1)^k}{1+k}}$

$$\left.\begin{array}{l} 0 \le \left|\frac{\cos k}{k^3}\right| \le \frac{1}{k^3} \\ \sum \frac{1}{k^3} \text{ converges} \\ \text{p-series, } p = 3 > 1 \end{array}\right\} \Rightarrow \sum_{k=1}^{\infty} \left|\frac{\cos k}{k^3}\right| \text{ converges}$$

$\therefore \sum_{k=1}^{\infty} \frac{\cos k}{k^3}$ converges absolutely.

$\sum \left|\frac{\cos k\pi}{1+k}\right| = \sum \frac{1}{1+k}$ As $x \nearrow \infty$, $1+x \nearrow \infty$, so $\frac{1}{1+x} \searrow 0$

$\int_1^{\infty} \frac{1}{1+x}\,dx = \ln(1+x)\Big|_1^{\infty} = \infty \Rightarrow \sum \frac{1}{1+k}$ diverges

Alt. series test

$\frac{1}{1+k} \searrow 0 \Rightarrow \sum (-1)^k \frac{1}{1+k} = \sum_{k=1}^{\infty} \frac{\cos k\pi}{1+k}$ converges (hence conditionally)

Ratio Test If $\forall k$, $a_k \neq 0$ and $\lim_{k\to\infty}\left|\frac{a_{k+1}}{a_k}\right|$ exists, then

$$\lim_{k\to\infty}\left|\frac{a_{k+1}}{a_k}\right| \begin{cases} <1 \Rightarrow \sum a_k \text{ converges absolutely} \\ =1 \Rightarrow \sum a_k \text{ may or may not converge} \\ >1 \Rightarrow \sum a_k \text{ diverges} \end{cases}$$

Reason Let $r = \lim_{k\to\infty}\left|\frac{a_{k+1}}{a_k}\right|$. Then $\forall k$ large,

$$\left|\frac{a_{k+1}}{a_k}\right|, \left|\frac{a_{k+2}}{a_{k+1}}\right|, \cdots, \left|\frac{a_{k+n}}{a_{k+n-1}}\right| \approx r \Rightarrow \left|\frac{a_{k+n}}{a_k}\right| = r^n$$

$$\Rightarrow |a_{k+n}| \approx |a_k| r^n$$

$$\Rightarrow |a_k| + |a_{k+1}| + |a_{k+2}| + \cdots \approx |a_k|(1+r+r^2+\cdots)$$

So for $r<1$, $|a_k|+|a_{k+1}|+|a_{k+2}|+\cdots \approx \frac{|a_k|}{1-r}$

"hence" $\sum |a_k|$ converges

For $r>1$, $1+r+r^2+\cdots$ diverges, "so" $\lim_{k\to\infty} a_k \neq 0$

"hence" $\sum a_k$ diverges.

Root Test If $\lim_{k\to\infty}\sqrt[k]{|a_k|}$ exists, then

$$\lim_{k\to\infty}\sqrt[k]{|a_k|} \begin{cases} <1 \Rightarrow \sum a_k \text{ converges absolutely} \\ =1 \Rightarrow \sum a_k \text{ may or may not converge} \\ >1 \Rightarrow \sum a_k \text{ diverges.} \end{cases}$$

Reason Let $r = \lim_{k\to\infty}\sqrt[k]{|a_k|}$. Then $\forall k$ large,

$$\sqrt[k]{|a_k|} \approx r \Rightarrow |a_k| \approx r^k \Rightarrow \sum |a_k| \approx \sum r^k.$$

Examples Consider (1) $\sum_{k=1}^{\infty}\frac{1}{3^k-2^k}$ (2) $\sum_{k=1}^{\infty}\frac{k!}{k^k}$

(1) **Ratio Test**

$$\lim_{k\to\infty}\frac{\frac{1}{3^{k+1}-2^{k+1}}}{\frac{1}{3^k-2^k}} = \lim_{k\to\infty}\frac{3^k-2^k}{3^{k+1}-2^{k+1}} \times \frac{\frac{1}{3^{k+1}}}{\frac{1}{3^{k+1}}} = \lim_{k\to\infty}\frac{\frac{1}{3}-\left(\frac{2}{3}\right)^k\frac{1}{3}}{1-\left(\frac{2}{3}\right)^{k+1}}$$

$$= 1/3 < 1$$

$\therefore$ series converges.

Root Test

$$\lim_{k\to\infty}\sqrt[k]{\frac{1}{3^k-2^k}} = \lim_{k\to\infty}\frac{1}{\sqrt[k]{3^k-2^k}} = \lim_{k\to\infty}\frac{1}{3\sqrt[k]{1-\left(\frac{2}{3}\right)^k}} = \frac{1}{3}$$

$\therefore$ series converges.

(2) **Ratio Test**

$$\lim_{k\to\infty}\frac{(k+1)!}{(k+1)^{k+1}}\,\frac{k^k}{k!} = \lim_{k\to\infty}\frac{k^k}{(k+1)^k} = \lim_{k\to\infty}\underbrace{\frac{1}{\left(1+\frac{1}{k}\right)^k}}_{1^\infty \neq 1} = \frac{1}{e} < 1.$$

$$\frac{k^k}{(k+1)^k} = \frac{1}{\frac{(k+1)^k}{k^k}}$$

$\therefore$ Series $\sum_{k=1}^{\infty}\frac{k!}{k^k}$ converges.

Theorem Let $a_k > 0$. If $\lim_{k\to\infty} \frac{a_{k+1}}{a_k} = r \in \mathbb{R}$, then $\lim_{k\to\infty} \sqrt[k]{a_k} = r$. Converse is false.

Examples (1) $a_k = k \Rightarrow \lim_{k\to\infty} \frac{k+1}{k} = 1 \Rightarrow \lim_{k\to\infty} \sqrt[k]{k} = 1$

(2) $a_k = \frac{k!}{k^k}$, $\lim_{k\to\infty} \frac{a_{k+1}}{a_k} = \frac{1}{e} \Rightarrow \lim_{k\to\infty} \sqrt[k]{\frac{k!}{k^k}} = \frac{1}{e}$

Stirling's Formula

$\forall$ k large, $\sqrt[k]{\frac{k!}{k^k}} \approx \frac{1}{e} \Rightarrow \frac{k!}{k^k} \approx \left(\frac{1}{e}\right)^k \Rightarrow k! \approx \left(\frac{k}{e}\right)^k$.

Application Find the number of digits of 100! approximately.

$100! \approx \left(\frac{100}{e}\right)^{100}$ $\quad \log_{10} \frac{100}{e} \approx 1.566 \Rightarrow \frac{100}{e} \approx 10^{1.566}$

$\Rightarrow 100! \approx \left(\frac{100}{e}\right)^{100} \approx 10^{156.6}$

100! has about 157 digits.

Summation by Parts Let $S_j = a_1 + a_2 + \cdots + a_j$ and $\Delta b_k = b_{k+1} - b_k$. Then

$$\sum_{k=1}^{n} a_k b_k = a_1 b_1 + a_2 b_2 + \cdots + a_n b_n$$
$$= S_1 b_1 + (S_2 - S_1) b_2 + \cdots + (S_n - S_{n-1}) b_n$$
$$= S_n b_n - S_1(b_2 - b_1) - \cdots - S_{n-1}(b_n - b_{n-1})$$
$$= S_n b_n - \sum_{k=1}^{n-1} S_k \Delta b_k .$$

Example Consider $\sum_{k=1}^{\infty} \frac{\sin k}{k}$. $\quad \frac{\sin k}{k} = \underbrace{(\sin k)}_{a_k} \underbrace{\frac{1}{k}}_{b_k}$

$$\sin m \sin\tfrac{1}{2} = \tfrac{1}{2}\left(\cos(m-\tfrac{1}{2}) - \cos(m+\tfrac{1}{2})\right)$$

$$S_k = \sum_{m=1}^{k} \sin m = \sum_{m=1}^{k} \frac{\cos(m-\frac{1}{2}) - \cos(m+\frac{1}{2})}{2\sin\frac{1}{2}}$$
$$= \frac{\cos\frac{1}{2} - \cos(k+\frac{1}{2})}{2\sin\frac{1}{2}}$$

$$|S_k| \le \frac{1+1}{2\sin\frac{1}{2}} = \frac{1}{\sin\frac{1}{2}} \Rightarrow \lim_{n\to\infty} S_n b_n = \lim_{n\to\infty} \frac{S_n}{n} = 0$$

$$\sum_{k=1}^{\infty} \frac{\sin k}{k} = \lim_{n\to\infty} \sum_{k=1}^{n} \frac{\sin k}{k} = \lim_{n\to\infty} \left(\frac{S_n}{n} - \sum_{k=1}^{n-1} S_k\left(\frac{1}{k+1} - \frac{1}{k}\right)\right)$$
$$= \sum_{k=1}^{\infty} S_k\left(\frac{1}{k} - \frac{1}{k+1}\right)$$

$$\sum_{k=1}^{\infty} \left|S_k\left(\frac{1}{k} - \frac{1}{k+1}\right)\right| \le \frac{1}{\sin\frac{1}{2}} \underbrace{\sum_{k=1}^{\infty}\left(\frac{1}{k} - \frac{1}{k+1}\right)}_{\text{example of telescoping series}} = \frac{1}{\sin\frac{1}{2}}$$

$\therefore \sum_{k=1}^{\infty} \frac{\sin k}{k} = \sum_{k=1}^{\infty} S_k\left(\frac{1}{k} - \frac{1}{k+1}\right)$ converges.

Summary

Geometric Series Test $1+a+a^2+\cdots=\sum_{k=1}^{\infty}a^k$ for geometric series only

Telescoping Series Test for telescoping series only
$$b_1-\lim_{n\to\infty}b_{n+1}=\sum_{k=1}^{\infty}(b_k-b_{k+1})$$

Term Test ① Use to show series diverges only
② May use in the beginning to scan for divergent series

Integral Test for $a_k=f(k)$, $f(x)$ integrable and decreases to 0

p-test ① Use this for p-series only
② Use to do Comparison with other series

Comparison Test
Use when you can do inequalities to compare a_k with known examples.

Limit Comparison Test
Use when there are dominated terms in a_k (when k is large) that can be singled out for comparison

Alternating Series Test
for alternating series only with $|a_k|\searrow 0$.

Absolute Convergence Test
for series with positive and negative terms.

Ratio Test for a_k involving $k!$, polynomials in k, k-th power expressions $a_k=(\cdots)^k$

Root Test for k-th power expressions $a_k=(\cdots)^k$

Summation by Parts
for series of the form $\sum a_k b_k$ with $S_n b_n=(a_1+\cdots+a_n)b_n$ having a limit.

$a_1+a_2+a_3+a_4+a_5+a_6+a_7+a_8+a_9+a_{10}+\cdots$

$$\underbrace{(a_1+a_2)}_{=b_1}+\underbrace{(a_3+a_4+a_5+a_6)}_{=b_2}+\underbrace{(a_7)}_{=b_3}+\underbrace{(a_8+a_9+a_{10})}_{=b_4}+\cdots$$

k_1 terms $\quad$ k_2 terms $\quad$ k_3 terms $\quad$ k_4 terms

$\sum_{k=1}^{\infty} b_k$ is obtained from $\sum_{k=1}^{\infty} a_k$ by inserting parentheses.

Grouping Theorem Let $\sum_{k=1}^{\infty} b_k$ be obtained from $\sum_{k=1}^{\infty} a_k$ by inserting parentheses.

- If $\sum_{k=1}^{\infty} a_k$ converges to S, then $\sum_{k=1}^{\infty} b_k$ converges to S.

The converse is false.

Examples ① $\sum_{k=1}^{\infty} \frac{1}{2^k} = \frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+\cdots = 1$

$\Rightarrow \frac{1}{2}+\left(\frac{1}{4}+\frac{1}{8}\right)+\left(\frac{1}{16}+\frac{1}{32}+\frac{1}{64}\right)+\cdots = 1$

② $(1-1)+(1-1)+(1-1)+\cdots = 0+0+0+\cdots = 0$,

but $1-1+1-1+1-1+\cdots$ diverges by term test.

$(1-1)+\left(\frac{1}{2}+\frac{1}{2}-\frac{1}{2}-\frac{1}{2}\right)+\left(\frac{1}{3}+\frac{1}{3}+\frac{1}{3}-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}\right)+\cdots = 0$,

but $1-1+\frac{1}{2}+\frac{1}{2}-\frac{1}{2}-\frac{1}{2}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}+\cdots$

diverges since $S_{n^2}=1$ and $S_{n^2+n}=0$ so that $\lim_{n\to\infty} S_n$ doesn't exist.

- If $\lim_{n\to\infty} a_n = 0$, k_n is bounded, $\sum_{k=1}^{\infty} b_k$ converges to S, then $\sum_{k=1}^{\infty} a_k$ converges to S. $\boxed{\forall n,\ k_n \le \text{Constant}}$

Example ③ $\left(1-\frac{1}{2}\right)+\left(\frac{1}{3}-\frac{1}{4}\right)+\cdots = \sum_{j=1}^{\infty}\left(\frac{1}{2j-1}-\frac{1}{2j}\right)$

$= \sum_{j=1}^{\infty} \frac{1}{2j(2j-1)}$ converges by limit comparison test with $\sum_{j=1}^{\infty}\frac{1}{j^2}$.

Since $\frac{1}{2j-1}, \frac{1}{2j} \to 0$, $\underbrace{\left(\frac{1}{2j-1}-\frac{1}{2j}\right)}_{2 \text{ terms}}$ $\quad \forall n,\ k_n = 2$

we get $\left(1-\frac{1}{2}\right)+\left(\frac{1}{3}-\frac{1}{4}\right)+\cdots = 1-\frac{1}{2}+\frac{1}{3}-\frac{1}{4}+\cdots$

Note $1-\frac{1}{2}+\frac{1}{3}-\frac{1}{4}+\cdots$ converges by alternating series test.
It converges conditionally because $1+\frac{1}{2}+\frac{1}{3}+\frac{1}{4}+\cdots = \sum_{k=1}^{\infty}\frac{1}{k}$ diverges by p-test.

To find the sum of $1-\frac{1}{2}+\frac{1}{3}-\frac{1}{4}+\cdots$,
define $f(x) = x-\frac{1}{2}x^2+\frac{1}{3}x^3-\frac{1}{4}x^4+\cdots$ converge for $x\in[0,1]$ by ratio test

Then $f'(x) = 1-x+x^2-x^3+\cdots = \frac{1}{1+x}$ for $x\in[0,1)$

$1-\frac{1}{2}+\frac{1}{3}-\frac{1}{4}+\cdots = f(1)$

$= f(1)-f(0) = \int_0^1 f'(t)\,dt = \int_0^1 \frac{1}{1+t}\,dt$

$= \ln(1+t)\Big|_0^1 = \ln 2 - \ln 1 = \ln 2$

Definition Let $f: \mathbb{N} \to \mathbb{N}$ be a bijection.

$\sum_{k=1}^{\infty} b_k = \sum_{k=1}^{\infty} a_{f(k)}$ is a rearrangement of $\sum_{k=1}^{\infty} a_k$.

Example $\ln 2 = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \cdots$

Terms are $1, -\frac{1}{2}, \frac{1}{3}, -\frac{1}{4}, \frac{1}{5}, -\frac{1}{6}, \cdots$

Rearrange terms to $1, \frac{1}{3}, -\frac{1}{2}, \frac{1}{5}, \frac{1}{7}, -\frac{1}{4}, \cdots$

By Grouping Theorem

every term appears exactly once.

$$\left(1-\frac{1}{2}\right)+\left(\frac{1}{3}-\frac{1}{4}\right)+\left(\frac{1}{5}-\frac{1}{6}\right)+\left(\frac{1}{7}-\frac{1}{8}\right)+\cdots=\ln 2$$

$$+ \quad \frac{1}{2} \quad -\frac{1}{4} \quad +\frac{1}{6} \quad -\frac{1}{8}+\cdots=\frac{1}{2}\ln 2$$

$$1+\left(\frac{1}{3}-\frac{1}{2}\right)+\frac{1}{5}+\left(\frac{1}{7}-\frac{1}{4}\right)+\cdots=\frac{3}{2}\ln 2$$

$$= 1+\frac{1}{3}-\frac{1}{2}+\frac{1}{5}+\frac{1}{7}-\frac{1}{4}+\cdots$$

By Grouping theorem (terms $\to 0$, $k_n \leq 2$)

Riemann's Rearrangement Theorem

Let $a_k \in \mathbb{R}\ \forall k$ and $\sum_{k=1}^{\infty} a_k$ converges conditionally.

$\forall x \in \mathbb{R} \cup \{+\infty, -\infty\}$, $\exists$ a rearrangement $\sum_{k=1}^{\infty} b_k$ of $\sum_{k=1}^{\infty} a_k$ such that $\sum_{k=1}^{\infty} b_k = x$.

Dirichlet's Rearrangement Theorem

Let $a_k \in \mathbb{R}\ \forall k$ and $\sum_{k=1}^{\infty} a_k$ converges absolutely.

$\forall$ rearrangement $\sum_{k=1}^{\infty} b_k$ of $\sum_{k=1}^{\infty} a_k$, $\sum_{k=1}^{\infty} b_k = \sum_{k=1}^{\infty} a_k$.

Example $\sum_{k=1}^{\infty}\left(-\frac{1}{2}\right)^k = -\frac{1}{2}+\frac{1}{2^2}-\frac{1}{2^3}+\frac{1}{2^4}-\cdots = \frac{-\frac{1}{2}}{1-\left(-\frac{1}{2}\right)} = -\frac{1}{3}$

So by Dirichlet's rearrangement theorem,

$$-\frac{1}{2}+\frac{1}{2^2}+\underbrace{\frac{1}{2^4}-\frac{1}{2^3}}_{\text{switched 2 terms}}+\underbrace{\frac{1}{2^8}-\frac{1}{2^7}+\frac{1}{2^6}-\frac{1}{2^5}}_{\text{switched 4 terms}}+\underbrace{\cdots}_{\text{switched } 2^n \text{ terms}}=-\frac{1}{3}$$

Complex Series $z_1+z_2+z_3+\cdots=\sum_{k=1}^{\infty} z_k$, $z_k\in\mathbb{C}$

- $z=a+ib \Rightarrow |z|=\sqrt{a^2+b^2}$
- $S_n=u_n+iv_n$ Definition of Limit
  $\lim_{n\to\infty} S_n=u+iv \Leftrightarrow \lim_{n\to\infty} u_n=u$ and $\lim_{n\to\infty} v_n=v$
- $z_k=x_k+iy_k$ $\quad S_n=z_1+z_2+\cdots+z_n$
  $\sum_{k=1}^{\infty} z_k=\lim_{n\to\infty} S_n=x+iy \Leftrightarrow \sum_{k=1}^{\infty} x_k=x$ and $\sum_{k=1}^{\infty} y_k=y$
- Definitions of absolute convergence and conditional convergence for series are the same.
- Geometric series test, telescoping series test, term test, absolute convergence test, ratio test and root test are true for complex series for the same reasons.

Examples (1) Since $|i|=1$, $\lim_{n\to\infty}|i^n|=\lim_{n\to\infty} 1=1\neq 0$
so $\sum_{k=1}^{\infty} i^k$ diverges by term test.

(2) If $|z|\leq 1$, then $\left|\frac{z^k}{k^2}\right|\leq\frac{1}{k^2}$ and $\sum_{k=1}^{\infty}\frac{1}{k^2}$ converges by p-test
so $\sum_{k=1}^{\infty}\frac{z^k}{k^2}$ converges absolutely.

If $|z|>1$, then $\lim_{k\to\infty}\left|\frac{z^{k+1}}{(k+1)^2}\frac{k^2}{z^k}\right|=\lim_{k\to\infty}\frac{k^2}{(k+1)^2}|z|=\underbrace{|z|}_{>1}$.

By ratio test, $\sum_{k=1}^{\infty}\frac{z^k}{k^2}$ diverges.

Chapter 5 Real Numbers

The set of all real numbers (denoted by $\mathbb{R}$) satisfies the following axioms:

① Field Axiom
② Order Axiom
③ Well-ordering Axiom
④ Completeness Axiom

An *axiom* is a self-evident statement that is assumed to be foundational in order to obtain more important consequences by deduction.

Field Axiom $\mathbb{R}$ has 2 operations $+$ and $\cdot$ such that $\forall a,b,c \in \mathbb{R}$,

(i) $a+b,\ a\cdot b \in \mathbb{R}$
(ii) $a+b=b+a$, $a\cdot b = b\cdot a$
(iii) $(a+b)+c = a+(b+c)$, $(a\cdot b)\cdot c = a\cdot(b\cdot c)$
(iv) $\exists$ unique elements $0, 1 \in \mathbb{R}$ with $1\neq 0$ such that $a+0=a$, $a\cdot 1 = a$
(v) $\exists\ -a \in \mathbb{R}$ such that $a+(-a)=0$; if $a\neq 0$, then $\exists\ a^{-1}\in\mathbb{R}$ such that $a\cdot(a^{-1})=1$
(vi) $a\cdot(b+c) = a\cdot b + a\cdot c$.

$\boxed{-a \text{ and } a^{-1} \text{ are unique}}$

Remarks ① From this axiom, we can define

$a-b = a+(-b)$ ← definition of subtraction
$ab = a\cdot b$ ← shorthand notation of multiplication
$\frac{a}{b} = a\cdot(b^{-1})$ for $b\neq 0$ ← definition of division

Define $2=1+1$, $3=2+1$, ...

② $\forall x\in\mathbb{R}$, $x+x\cdot 0 = x(1+0) = x\cdot 1 = x$. Add $-x$, we get $x\cdot 0 = 0$.

③ $(-1)(-1)=1$ because $(-1)(-1) = (-1)(-1) + \underbrace{(-1)+1}_{=0} = (-1)((-1)+1)+1 = (-1)0+1 = 1$

Order Axiom $\mathbb{R}$ has an (ordering) relation $<$ such that $\forall a,b,c\in\mathbb{R}$,

(i) exactly one of the following $a<b$, $a=b$, $b<a$ is true
(ii) if $a<b$ and $b<c$, then $a<c$
(iii) if $a<b$, then $a+c<b+c$
(iv) if $a<b$ and $0<c$, then $ac<bc$.

Remarks We also write $a>b \iff b<a$,
$a\le b \iff a<b$ or $a=b$, $a\ge b \iff b\le a$.
$[a,b] = \{x : x\in\mathbb{R} \text{ and } a\le x\le b\}$
$(a,b) = \{x : x\in\mathbb{R} \text{ and } a<x<b\}$
$\max(a_1,\dots,a_n)$ or $\max\{a_1,\dots,a_n\}$ denote the maximum of $a_1,\dots,a_n$ (similarly for $\min(a_1,\dots,a_n)$)
$|x| = \max(x,-x)$ (then $\underbrace{x\le |x| \text{ and } -x\le|x|}_{\iff -|x|\le x\le |x|}$)
$|x|\le a \iff x\le a \text{ and } -x\le a \iff -a\le x\le a$.

Triangle Inequality $\forall x,y\in\mathbb{R}$, $|x+y|\le|x|+|y|$
(Adding $-|x|\le x\le|x|$ and $-|y|\le y\le|y|$, we get $-|x|-|y|\le x+y\le|x|+|y|$. So $|x+y|\le|x|+|y|$)

$0<1$ Since $1\neq 0$, by (i), $0<1$ or $1<0$.
Assume $1<0$. Then $0=1+(-1)<0+(-1)=-1$.
By (iv), $0=0\cdot(-1)<(-1)\cdot(-1)=1$, contradiction to (i)

CAUTIONS ① $a<b$ and $c<d$ does not imply $a-c<b-d$
② $a<b$ does not imply $|a|<|b|$. nor $\frac{a}{c}<\frac{b}{d}$

Well-ordering Axiom $\mathbb{N}=\{1,2,3,\cdots\}$ is well-ordered which means "$\forall$ nonempty $S\subseteq\mathbb{N}$, $\exists\, m\in S$ such that $m\le x$ for all $x\in S$." This m is the least element (or the minimum) of S.

Examples ① S = set of all prime numbers, $m=2$

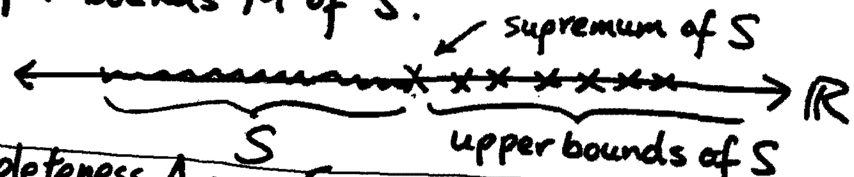
② S = set of all 4-digit positive integers, $m=1000$

③ $S=(\pi,\sqrt{99})\cap\mathbb{N}$, $m=4$

Definitions For a nonempty subset S of $\mathbb{R}$, we say S is bounded above iff $\exists\, M\in\mathbb{R}$ such that $M\ge x$ for all $x\in S$. ← M may not be in S

Such an M is called an upper bound of S.

A supremum or least upper bound of S (denoted by $\sup S$ or $\operatorname{lub} S$) is ① an upper bound $\widetilde{M}$ of S such that ② $\widetilde{M}\le M$ for all upper bounds M of S.



$$\boxed{\text{Completeness Axiom: Every nonempty subset of } \mathbb{R} \text{ which is bounded above has a supremum in } \mathbb{R}.}$$

↑ The supremum may or may not be in the set!!!

Examples ① $S=\{\frac{1}{n}: n\in\mathbb{N}\}=\{1,\frac{1}{2},\frac{1}{3},\cdots\}$

Upper bounds of S: every real number $M\ge 1$

Supremum of S is 1. ← the least number among upper bounds of S

In this case $\sup S=1\in S$.

② $S=\{x: x\in\mathbb{R} \text{ and } x<0\}=(-\infty,0)$

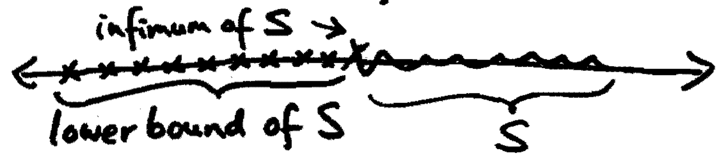
Upper bounds of S: every real number $M\ge 0$

Supremum of S is 0. However, $\sup S=0\notin S$.

Definitions For a nonempty subset S of $\mathbb{R}$, we say S is bounded below iff $\exists\, m\in\mathbb{R}$ such that $m\le x$ for all $x\in S$

Such an m is called a lower bound of S.

An infimum or greatest lower bound of S (denoted by $\inf S$ or $\operatorname{glb} S$) is ① a lower bound $\widetilde{m}$ of S such that ② $m\le\widetilde{m}$ for all lower bounds m of S.



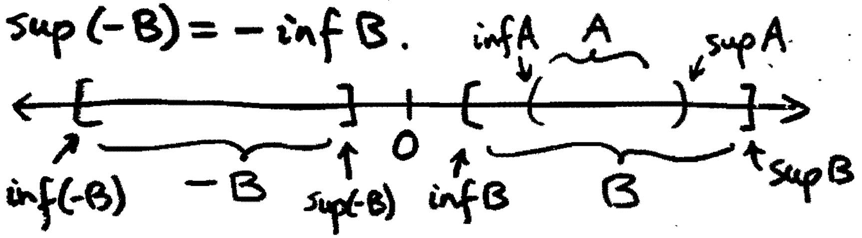
Exercises Let $c\in\mathbb{R}$. Let A,B be nonempty subsets of $\mathbb{R}$. Define

$-B=\{-x: x\in B\}$, $c+B=\{c+x: x\in B\}$,

$cB=\{cx: x\in B\}$,

$A+B=\{x+y: x\in A \text{ and } y\in B\}$.

① B is bounded above $\Leftrightarrow$ $-B$ is bounded below
$\inf(-B) = -\sup B$.
B is bounded below $\Leftrightarrow$ $-B$ is bounded above
$\sup(-B) = -\inf B$.



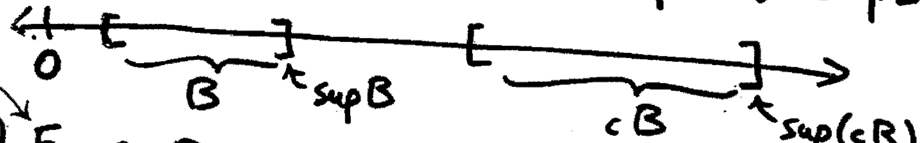
If $\emptyset \neq A \subseteq B$, then $\inf B \leq \inf A$ (when B is bounded below) and $\sup A \leq \sup B$ (when B is bounded above).

Remarks From ① and completeness axiom, we get

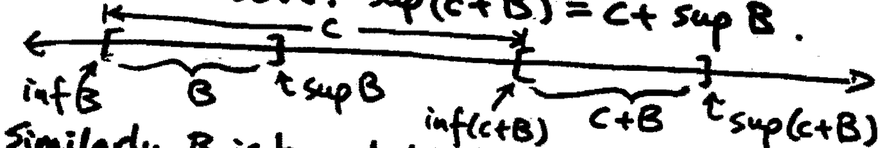
Completeness Axiom for Infimum Every nonempty subset of $\mathbb{R}$ which is bounded below has an infimum in $\mathbb{R}$.

Exercises

② If B is bounded above and $c \geq 0$, then cB is bounded above and $\sup(cB) = c\sup B$.



③ For $c \in \mathbb{R}$, B is bounded above $\Leftrightarrow$ $c+B$ is bounded above. $\sup(c+B) = c + \sup B$.



Similarly, B is bounded below $\Leftrightarrow$ $c+B$ is bounded below. $\inf(c+B) = c + \inf B$.

More generally, if A and B are bounded above and below, then $A+B = \{x+y : x \in A, y \in B\}$ is bounded above and below, $\sup(A+B) = \sup A + \sup B$ and $\inf(A+B) = \inf A + \inf B$. ← Exercises

Definition Let S be a nonempty subset of $\mathbb{R}$. S is bounded iff S is bounded above and below.

Remarks

① S is bounded $\overset{②}{\Longrightarrow}$ $\forall x \in S$, $x \leq \sup S$, $\inf S \leq x$ ($-x \leq -\inf S$)

$\overset{③}{\Longrightarrow}$ $\forall x \in S$, $|x| \leq \max(\sup S, -\inf S)$

$\overset{④}{\Longrightarrow}$ $\exists c \in \mathbb{R}, \forall x \in S$, $|x| \leq c$. ($-c \leq x \leq c$)

$\therefore$ all 4 statements are equivalent.

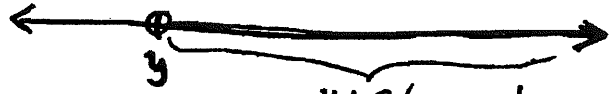
Consequences of Axioms

$\alpha, \beta, \gamma, \delta, \varepsilon$ ← epsilon

↑ delta

theorem (Infinitesimal Principle) Let $x, y \in \mathbb{R}$.

(*) $x < y + \varepsilon$ for all $\varepsilon > 0 \iff x \le y$



Similarly $y - \varepsilon < x$ for all $\varepsilon > 0 \iff y \le x$.)

Proof. ($\Leftarrow$) If $x \le y$, then $\forall \varepsilon > 0$, $x \le y \underset{\text{Field Axiom}}{=} y + 0 \overset{\text{Order Axiom}}{<} y + \varepsilon$.

($\Rightarrow$) If $\forall \varepsilon > 0$, $x < y + \varepsilon$, then assume $x > y$. By order axiom, $\varepsilon_0 = x - y > y - y = 0$. Then $x \overset{\text{by (*)}}{<} y + \varepsilon_0$. But also $x = y + \varepsilon_0$, contradicting (i) of order axiom. $\therefore x \le y$.

Remarks Letting $x = |a-b|$ and $y = 0$, we have

$|a-b| < \varepsilon$ for all $\varepsilon > 0 \iff |a-b| \le 0 \iff a = b$.

The principle is often used this way to show expressions are equal.

theorem (Mathematical Induction Principle)

(1) $\forall n \in \mathbb{N}$, $A(n)$ is a statement that is either true or false
(2) $A(1)$ is true
(3) $\forall k \in \mathbb{N}$ $A(k)$ true $\Rightarrow$ $A(k+1)$ true

Then $\forall n \in \mathbb{N}$, $A(n)$ is true.

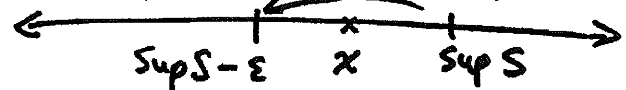
Proof. Assume $\sim(\forall n \in \mathbb{N}, A(n) \text{ is true}) = \exists n \in \mathbb{N}$ such that $A(n)$ is false. Then $S = \{n : A(n) \text{ is false}\}$ is a nonempty subset of $\mathbb{N}$.

By the well-ordering axiom, S has a least element m in S. So $A(m)$ is false and if $A(n)$ is false, then $m \le n$. Taking contrapositive, if $n < m$, then $A(n)$ is true.

Since $A(1)$ is true, $m \ne 1$. Now $m \in \mathbb{N}$ and $m \ne 1$ $\Rightarrow m \ge 2 \Rightarrow m - 1 \ge 1 \Rightarrow \therefore m - 1 \in \mathbb{N}$. Now $m - 1 < m$. So $A(m-1)$ is true. By (3), we get $A(m)$ is true, contradiction

theorem (Supremum Property) If a set S has a supremum in $\mathbb{R}$ and $\varepsilon > 0$, then $\exists x \in S$ such that

$$\sup S - \varepsilon < x \le \sup S.$$



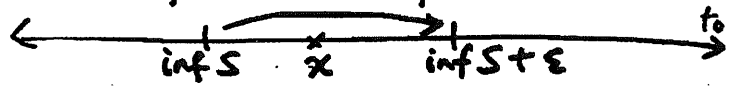
Recall M is an upper bound of S
$\iff \forall x \in S$, $x \le M$.

Proof of Supremum Property Since $\sup S - \varepsilon < \sup S$, $\sup S - \varepsilon$ is not an upper bound of S. So $\exists x \in S$ such that $\sup S - \varepsilon < x$. Since $x \in S$, $x \le \sup S$. $\therefore \sup S - \varepsilon < x \le \sup S$.

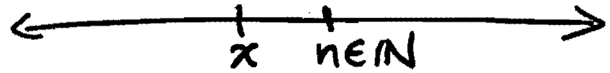
Theorem (Infimum Property) If a set S has an infimum in $\mathbb{R}$ and $\varepsilon > 0$, then $\exists x \in S$ such that

$$\inf S \le x < \inf S + \varepsilon.$$

(Proof is similar to supremum property.)



Theorem (**Archimedean Principle**) $\forall x \in \mathbb{R}, \exists n \in \mathbb{N}$ such that $n > x$.



Proof. Assume $\sim(\forall x \in \mathbb{R}, \exists n \in \mathbb{N}$ such that $n > x)$
$= \exists x \in \mathbb{R}, \forall n \in \mathbb{N}, n \le x$. Then $\mathbb{N}$ is bounded above by x. By the completeness axiom, $\mathbb{N}$ has a supremum in $\mathbb{R}$. By supremum property, $\exists n \in \mathbb{N}$ such that $\sup \mathbb{N} - 1 < n \le \sup \mathbb{N}$. Then $\sup \mathbb{N} < n+1 \in \mathbb{N}$, a contradiction to $\sup \mathbb{N}$ is an upper bound of $\mathbb{N}$.

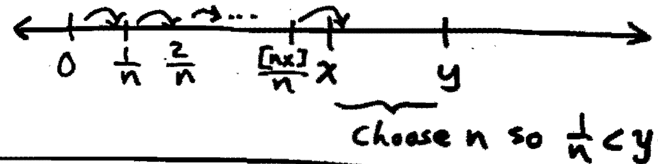
Questions How is $\mathbb{Q}$ contained in $\mathbb{R}$? How is $\mathbb{R} \setminus \mathbb{Q}$ contained in $\mathbb{R}$?

Lemma $\forall x \in \mathbb{R}$, $\exists$ a least integer (denoted by $\lceil x \rceil$ ← ceiling of x) greater than or equal to x. Similarly, $\exists$ a greatest integer (denoted by $\lfloor x \rfloor$ or $[x]$ ← floor of x) less than or equal to x.

Proof. By Archimedean principle, $\exists n \in \mathbb{N}$ such that $n > |x|$. Then $-n < x < n$. By order axiom, $0 < x+n < 2n$. So $S = \{k : k \in \mathbb{N}, k \ge x+n\}$ is a nonempty subset of $\mathbb{N}$ because $2n \in S$. By the well-ordering axiom, $\exists$ a least positive integer $m \ge x+n$. Then $m-n$ is the least ~~positive~~ integer $\ge x$. So $\lceil x \rceil$ exists. Next, let k be the least ~~positive~~ integer $\ge -x$. Then $-k$ is the greatest ~~positive~~ integer $\le x$. So $\lfloor x \rfloor$ exists.

Theorem (**Density of $\mathbb{Q}$**) If $x<y$, then $\exists \frac{m}{n} \in \mathbb{Q}$ such that $x < \frac{m}{n} < y$.

Proof. By Archimedean principle, $\exists n \in \mathbb{N}$ such that $n > \frac{1}{y-x}$. So $ny - nx > 1$. Hence $nx + 1 < ny$. Let $m = [nx]+1$, then $m - 1 = [nx] \le nx < [nx]+1 = m$. So $nx < m \le nx+1 < ny$. $\therefore x < \frac{m}{n} < y$.

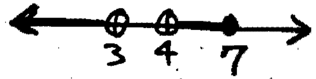


Theorem (**Density of $\mathbb{R} \setminus \mathbb{Q}$**) If $x<y$, then $\exists w \in \mathbb{R}\setminus\mathbb{Q}$ such that $x < w < y$.

Proof. Let $w_0 \in \mathbb{R}\setminus\mathbb{Q}$ (e.g. $w_0 = \sqrt{2}$). By density of $\mathbb{Q}$, $\exists \frac{m}{n} \in \mathbb{Q}$ such that $\frac{x}{|w_0|} < \frac{m}{n} < \frac{y}{|w_0|}$. (If $\frac{m}{n} = 0$, then pick another rational number between 0 and $\frac{y}{|w_0|}$. So we may take $\frac{m}{n} \ne 0$.) Let $w = \frac{m}{n}|w_0|$, then $w \in \mathbb{R}\setminus\mathbb{Q}$ and $x < w < y$.

Examples of Supremum and Infimum

① Consider $S = (-\infty, 3) \cup (4, 7]$



S is not bounded below. So S has no infimum. S is bounded above by 7 and every upper bound of S is greater than or equal to 7 because $7 \in S$. So 7 is an upper bound and is the least among upper bounds. $\therefore \sup S = 7$.

② Consider $S=\{\frac{1}{n}: n\in\mathbb{N}\}=\{1,\frac{1}{2},\frac{1}{3},\cdots\}$

$\forall n\in\mathbb{N}$,

$\left.\begin{array}{l}\frac{1}{n}\le 1 \Rightarrow 1 \text{ is an upper bound} \\ 1\in S \Rightarrow \text{every upper bound} \ge 1\end{array}\right\} \Rightarrow \sup S=1.$

Next we claim $\inf S=0$.

$\forall n\in\mathbb{N}$, $0<\frac{1}{n} \Rightarrow 0$ is a lower bound of S.

(However, $0\notin S$, so we cannot say "every lower bound ≤ 0.") Assume S has a lower bound $t>0$. (To get a contradiction, we will try to get a $\frac{1}{n}\in S$ such that $\frac{1}{n}<t$.) By the Archimedean principle, $\exists n\in\mathbb{N}$ such that $n>\frac{1}{t}$. Then $\frac{1}{n}\in S$ and $\frac{1}{n}<t$, contradicting t is a lower bound of S. So every lower bound $t\le 0$ $\therefore \inf S=0$.

③ Consider $S=[2,6)\cap\mathbb{Q}$

$\left.\begin{array}{l}\forall x\in S,\ 2\le x \Rightarrow 2 \text{ is a lower bound} \\ 2\in S \Rightarrow \text{every lower bound} \le 2\end{array}\right\} \Rightarrow \inf S=2.$

Next we claim $\sup S=6$.

$\forall x\in S$, $x<6 \Rightarrow 6$ is an upper bound of S. Note $6\notin S$.

Assume S has an upper bound $u<6$. Since $2\in S$, $2\le u$. By the density of $\mathbb{Q}$, $\exists r\in\mathbb{Q}$ such that $u<r<6$. Then $r\in[2,6)\cap\mathbb{Q}=S$.

Now $u<r$ contradicts u is an upper bound of S. So every upper bound $u\ge 6$. $\therefore \sup S=6$.

Supremum Limit Theorem

Let c be an upper bound of a nonempty set S. Then $(\exists w_n\in S \text{ such that } \lim_{n\to\infty} w_n=c) \Leftrightarrow c=\sup S$.

Infimum Limit Theorem

Let c be a lower bound of a nonempty set S. Then $(\exists w_n\in S \text{ such that } \lim_{n\to\infty} w_n=c) \Leftrightarrow c=\inf S$.

Proofs will be given in the next chapter.

Examples ① Let $S=\{\frac{1}{n}: n\in\mathbb{N}\}=\{1,\frac{1}{2},\frac{1}{3},\frac{1}{4},\cdots\}$.

$\left.\begin{array}{l}0\le\frac{1}{n}\ \forall n\in\mathbb{N} \Rightarrow 0 \text{ is a lower bound of } S \\ w_n=\frac{1}{n}\in S,\ \lim_{n\to\infty} w_n=0\end{array}\right\} \Rightarrow \inf S = 0.$

② Let $S=\{x\pi+\frac{1}{y}: x\in\mathbb{Q}\cap(0,1],\ y\in[1,2]\}$.

$\forall x\in\mathbb{Q}\cap(0,1], y\in[1,2]$, $x\pi+\frac{1}{y}>0\pi+\frac{1}{2}=\frac{1}{2}$

$\left.\begin{array}{l}\Rightarrow \frac{1}{2} \text{ is a lower bound of } S \\ w_n=\frac{1}{n}\pi+\frac{1}{2}\in S,\ \lim_{n\to\infty} w_n=\frac{1}{2}\end{array}\right\} \Rightarrow \inf S=\frac{1}{2}.$

③ Let A and B be bounded sets in $\mathbb{R}$.

Let $A-2B=\{a-2b: a\in A, b\in B\}$.

Prove $\sup(A-2B)=\sup A-2\inf B$.

Solution. Since A bounded, $\sup A$ exists in $\mathbb{R}$. Since B bounded, $\inf B$ exists in $\mathbb{R}$. $\forall a\in A, b\in B$, we have $a\le\sup A$, $\inf B\le b \Rightarrow a-2b\le\sup A-2\inf B$.

$\therefore$ $c=\sup A-2\inf B$ is an upper bound of $A-2B$.

By supremum limit theorem, $\exists a_n\in A$, $\lim_{n\to\infty} a_n=\sup A$.

By infimum limit theorem, $\exists b_n\in B$, $\lim_{n\to\infty} b_n=\inf B$.

Then $a_n-2b_n\in A-2B$ and $\lim_{n\to\infty}(a_n-2b_n)=\sup A-2\inf B$.

$\therefore$ by supremum limit theorem, $\sup(A-2B)=\sup A-2\inf B$.