Analysis I (Math 3205)
Fall 2020

Book 3

Let $(a_n)_n$ be a sequence of real numbers. It is possible for such a sequence to have no limit point e.g. $a_n = n$. The sequence of positive integers has only isolated points. However, if (a_n) is bounded then it must have at least one limit point by the Bolzano-Weierstrass Theorem.

Eg. consider the sequence $(\sin n)_{n\in\mathbb{N}} = (\sin 1, \sin 2, \sin 3, \sin 4, \dots)$.

This sequence diverges. But the sequence is bounded (all terms lie in $[-1,1]$)

So the sequence has a convergent subsequence. Thus there is at least one limit point. All limit points must lie in $[-1, 1]$.

$\sin 0 = 0.000\dots$
$\sin 1 = 0.841\dots$
$\sin 2 = 0.909\dots$
$\vdots$

$\sin 22 = -0.009$

$\sin 44 = 0.018$
$\sin 45 = 0.850$
$\sin 46 = 0.902$

$\pi \approx \frac{22}{7}$

$7\pi \approx 22$

$\sin 22 \approx \sin 7\pi = 0$

$\sin n \neq 0$ for any positive integer n because $\pi \notin \mathbb{Q}$.

$\sin x = 0 \iff x = k\pi$ for some $k\in\mathbb{Z}$

Also since $\pi \notin \mathbb{Q}$, the sequence $(\sin n)_n$ has no repeated terms and the limit points of $(\sin n)_n$ are all points of $[-1,1]$.

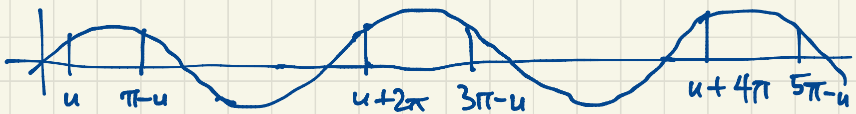
$\sin n = 0 \iff n = k\pi$ for some $k\in\mathbb{Z}$

$\Leftarrow \left(\pi = \frac{n}{k} \in \mathbb{Q}\right.$

If π is irrational then the sequence $(\sin n)_n$ has distinct terms (it never repeats).

Why? If $\sin u = \sin v$ then either $v-u = 2k\pi$ for some $k\in\mathbb{Z}$

or $v+u = (2k+1)\pi$ for some $k \in \mathbb{Z}$.



So if $\sin m = \sin n$ where $m\neq n$ are integers then either $m-n = 2k\pi$ with $0\neq k\in\mathbb{Z}$ so $\pi = \frac{m-n}{2k} \in \mathbb{Q}$; or $m+n = (2k+1)\pi$ for some $k\in\mathbb{Z}$ so $\pi = \frac{m+n}{2k+1} \in \mathbb{Q}$

again contradicting $\pi\notin\mathbb{Q}$.

Let's prove $\pi \notin \mathbb{Q}$. Warm-up: prove $e\notin\mathbb{Q}$.

$0! = 1$

$1! = 1$

$2! = 1\times 2 = 2$

$3! = 1\times 2\times 3 = 6$

$4! = 1\times2\times3\times4 = 24$

$$e = \sum_{n=0}^{\infty} \frac{1}{n!} = \lim_{n\to\infty}\left(1+\frac{1}{n}\right)^n.$$

Recall: $e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!} = \lim_{n\to\infty}\left(1+\frac{x}{n}\right)^n$

$$e = 1+1+\frac{1}{2!}+\frac{1}{3!}+\frac{1}{4!}+\frac{1}{5!}+\cdots$$

Suppose $e\in\mathbb{Q}$, say $e = \frac{a}{b}$ in lowest terms $(a,b\in\mathbb{N},\ \gcd(a,b)=1)$.

$$\frac{a}{b} = e = 1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \frac{1}{5!} + \cdots$$

Suppose $e \in \mathbb{Q}$; say $e = \frac{a}{b}$ in lowest terms ($a, b \in \mathbb{N}$, $\gcd(a,b) = 1$).

Multiply both sides by $b! = 1 \times 2 \times 3 \times \cdots \times (b-1)b$.

$$b!\,\frac{a}{b} = \overbrace{(b-1)!\,a}^{\text{integer}} = b!\left(1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \cdots + \frac{1}{(b-1)!} + \frac{1}{b!} + \frac{1}{(b+1)!} + \cdots\right)$$

$$= \underbrace{b! + b! + \frac{b!}{2!} + \frac{b!}{3!} + \cdots + \underbrace{\frac{b!}{(b-1)!}}_{=\,b} + \underbrace{\frac{b!}{b!}}_{=\,1}}_{\text{integers}} + \underbrace{\underbrace{\frac{b!}{(b+1)!}}_{=\,\frac{1}{b+1}} + \underbrace{\frac{b!}{(b+2)!}}_{=\,\frac{1}{(b+1)(b+2)}} + \cdots}_{\text{Not an integer by comparison test}}$$

The series $\frac{1}{b+1} + \frac{1}{(b+1)(b+2)} + \frac{1}{(b+1)(b+2)(b+3)} + \cdots$ converges by comparison with

$$\frac{1}{b+1} + \frac{1}{(b+1)^2} + \frac{1}{(b+1)^3} + \frac{1}{(b+1)^4} + \cdots = \frac{1/(b+1)}{1 - \frac{1}{b+1}} = \frac{1}{(b+1)-1} = \frac{1}{b} < 1.$$

$$a + ar + ar^2 + ar^3 + \cdots = \frac{a}{1-r} \quad (\text{for } |r| < 1).$$

This is a contradiction. So $e \notin \mathbb{Q}$.

$$(uv)' = u'v + uv'$$

$$(uv)'' = (u'v + uv')' = u''v + u'v' + u'v' + uv'' = u''v + 2u'v' + uv''$$

$$(uv)''' = (u''v + 2u'v' + uv'')' = (u'''v + u''v') + 2(u''v' + u'v'') + (u'v'' + uv''')$$

$$= u'''v + 3u''v' + 3u'v'' + uv'''$$

$$(u+v)^1 = u+v$$

$$(u+v)^2 = u^2 + 2uv + v^2$$

$$(u+v)^3 = u^3 + 3u^2v + 3uv^2 + v^3$$

Pascal's Triangle

1

1 1

1 2 1

1 3 3 1

1 4 6 4 1

1 5 10 10 5 1

$$(u+v)^n = \sum_{k=0}^{n} \binom{n}{k} u^k v^{n-k}$$

(Binomial Theorem)

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!} \in \mathbb{Z}$$

"binomial coefficients" are the entries in Pascal's Triangle

Leibniz' Formula

$$(uv)^{(n)} = \sum_{k=0}^{n} \binom{n}{k} u^{(k)} v^{(n-k)}$$

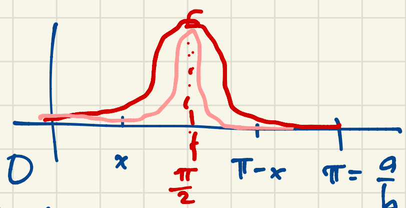
Theorem $\pi \notin \mathbb{Q}$.

Proof Suppose $\pi = \frac{a}{b}$ in lowest terms (i.e. $a, b \in \mathbb{N}$, $\gcd(a,b)=1$). We look for a contradiction. Consider the function $f(x) = \frac{1}{n!}x^n(a-bx)^n$ where $n \in \mathbb{N}$ will be chosen later. Note: $f(x) = u(x)v(x)$ where $u(x) = \frac{1}{n!}x^n$, $v(x) = (a-bx)^n$.

Lemma For every $k \geq 0$, $f^{(k)}(0) = (-1)^k f^{(k)}(\pi) \in \mathbb{Z}$.

Proof $f(\pi - x) = f(\frac{a}{b} - x) = \frac{1}{n!}(\frac{a}{b}-x)^n(a - b(\frac{a}{b}-x))^n = \frac{1}{n!}(\frac{a}{b}-x)^n(a-(a-bx))^n$

$= \frac{1}{n!}(\frac{a}{b}-x)^n(bx)^n = \frac{1}{n!}(\frac{a}{b}-x)^n b^n x^n = \frac{1}{n!}((\frac{a}{b}-x)b)^n x^n = \frac{1}{n!}(a-bx)^n x^n = f(x)$.



$f(x) = \frac{1}{n!}(ax - bx^2)^n$

$$f(\pi - x) = f(x)$$
$$-f'(\pi - x) = f'(x)$$
$$f''(\pi - x) = f''(x)$$
$$-f'''(\pi - x) = f'''(x)$$

$$f^{(k)}(x) = (-1)^k f^{(k)}(\pi - x)$$
$$f^{(k)}(0) = (-1)^k f^{(k)}(\pi)$$

We must show this $\in \mathbb{Z}$.

$f(x) = u(x)v(x)$, $u(x) = \frac{1}{n!}x^n$

$u'(x) = \frac{1}{n!} \cdot n x^{n-1} = \frac{1}{(n-1)!}x^{n-1}$

$u''(x) = \frac{1}{(n-2)!}x^{n-2}$

$\dots$ $u^{(n-2)}(x) = \frac{1}{2!}x^2 = \frac{1}{2}x^2$

$u^{(n-1)}(x) = x$ $\quad u^{(n+1)}(x) = 0$

$u^{(n)}(x) = 1$ $\quad u^{(n+2)}(x) = 0$ etc.

$$u^{(k)}(0) = \begin{cases} 0 & \text{if } k \neq n; \\ 1 & \text{if } k = n. \end{cases} \in \mathbb{Z}$$

Recall: $f(x) = u(x)v(x)$, $\quad u(x) = \frac{1}{n!}x^n$, $\quad \underbrace{v(x) = (a-bx)^n}$ $\in \mathbb{Z}[x]$

$$f^{(k)}(x) = \sum_{r=0}^{k} \binom{k}{r} u^{(r)}(x)\, v^{(k-r)}(x)$$

i.e. a polynomial in x with integer coefficients

$$f^{(k)}(0) = \sum_{r=0}^{k} \underbrace{\binom{k}{r}}_{\text{integers}} \underbrace{u^{(r)}(0)}_{\text{integers}} \underbrace{v^{(k-r)}(0)}_{\text{integers}} \in \mathbb{Z}.$$

This proves the Lemma.

Note: $f(x)$ is a poly. in x of degree $2n$.

Return to the Theorem.

$$F''(x) = \cancel{f''(x) - f^{(4)}(x)} + \cancel{f^{(6)}(x)} - \cdots + \cancel{(-1)^{n-1} f^{(2n)}(x)}$$

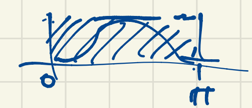
Consider $F(x) = f(x) - \cancel{f''(x)} + \cancel{f^{(4)}(x)} - \cancel{f^{(6)}(x)} + \cdots + \cancel{(-1)^n f^{(2n)}(x)}$

$$\frac{d}{dx}\left[F'(x)\sin x - F(x)\cos x\right] = F''(x)\sin x + \cancel{F'(x)\cos x} - \left(\cancel{F'(x)\cos x} - F(x)\sin x\right)$$

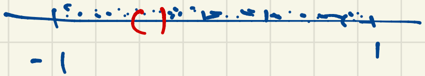
$$= \left[F''(x) + F(x)\right]\sin x = f(x)\sin x$$

$$\int_0^\pi f(x)\sin x\,dx = \left[\cancel{F'(x)\sin x} - F(x)\cos x\right]_0^\pi = F(\pi) - F(0) = F(0) - F\left(\tfrac{a}{b}\right) \in \mathbb{Z} \text{ by the Lemma}$$

$$0 < \int_0^\pi f(x)\sin x\,dx < \pi \cdot f\left(\tfrac{\pi}{2}\right) = \frac{\pi}{n!}\left(\frac{\pi}{2}\right)^{2n} \to 0 \text{ as } n \to \infty.$$



$f(x) = \frac{1}{n!}(ax - bx^2)^n$ is maximized at $x = \frac{\pi}{2} = \frac{a}{2b}$ on $[0,\pi]$. For n sufficiently large the integral is in $(0,1)$, it can't be an integer. $\square$



Topology

Recall: If $A \subseteq \mathbb{R}^n$, a limit point of A $b \in \mathbb{R}^n$ is a point such that for all $\varepsilon > 0$, there exists $a \in A$ satisfying $0 < |a - b| < \varepsilon$.

The <u>derived</u> set of A is A' = the set of all limit points of A. Note: Limit points of A can belong to A but they don't have to.

eg. $[0,1)' = [0,1]$ $\qquad \overline{[0,1)} = [0,1]$

$\mathbb{Z}' = \emptyset$ $\qquad \overline{\mathbb{Z}} = \mathbb{Z}$

$\mathbb{Q}' = \mathbb{R}$ $\qquad \overline{\mathbb{Q}} = \mathbb{R}$

The <u>closure</u> of A is $\overline{A} = A \cup A'$.

Note: $\overline{\overline{A}} = \overline{A}$.

An open set in $\mathbb{R}^n$ is a union of open balls.

In $\mathbb{R}$, an open ball $B_r(a) = \{x \in \mathbb{R} : |x-a| < r\}$ of radius r centered at $a \in \mathbb{R}$ is the same thing as an open interval $(a-r, a+r)$.

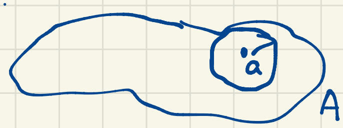
Every open interval (a,b) is an open set. $(a,b) = B_{\frac{b-a}{2}}\left(\frac{a+b}{2}\right)$

Also $(a,\infty) = \bigcup_{c \geq a} (c, c+1)$ is open.

$[0,1]$ is not open.

$[0,1)$ is not open. Proof: If $[0,1) = \bigcup_{i \in I} (a_i, b_i)$ for some collection of open intervals $\{(a_i, b_i) : i \in I\}$ then $0 \in (a_i, b_i)$ for some $i \in I$. Every such interval also contains some negative numbers, a contradiction.

Alternatively, a subset $A \subseteq \mathbb{R}^n$ is open if every $a \in A$ lies inside a ball $B_\delta(a) \subseteq A$ for some $\delta > 0$.



A set $A \subseteq \mathbb{R}$ is <u>closed</u> if it contains all its limit points (i.e. $A' \subseteq A$ i.e. $\bar{A} = A$) eg. $[a,b]$ is closed. $[a,b]' = [a,b]$.

$\overline{[a,b]} = [a,b] \cup [a,b]' = [a,b]$.

$[a,\infty)$ is closed. $[a,\infty)' = [a,\infty)$, $\overline{[a,\infty)} = [a,\infty) \cup [a,\infty)' = [a,\infty)$

$\bar{A}$ is the smallest closed set containing A.

$\mathbb{Z}$ is closed.

$\mathbb{Q}$ is not closed. $\bar{\mathbb{Q}} = \mathbb{Q} \cup \mathbb{Q}' = \mathbb{Q} \cup \mathbb{R} = \mathbb{R}$.

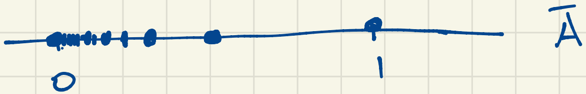
$\mathbb{Q}$ is not open. ($0 \in \mathbb{Q}$ is not covered by any $B_\delta(0) = (-\delta,\delta)$ for $\delta > 0$ inside $\mathbb{Q}$.)

Let $A \subseteq \mathbb{R}^n$. Then A is open iff its complement $\mathbb{R}^n - A$ is closed.

eg. $\mathbb{Z}$ is closed. $\mathbb{R} - \mathbb{Z} = \bigcup_{n\in\mathbb{Z}} (n, n+1) = \cdots \cup (-2,-1) \cup (-1,0) \cup (0,1) \cup (1,2) \cup (2,3) \cup \cdots$ is open.

eg. $A = \{\frac{1}{n} : n \in \mathbb{N}\} = \{1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \dots\}$ is neither open nor closed.

$A' = \{0\}$. $\quad \bar{A} = A \cup A' = \{0, 1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \frac{1}{5}, \dots\}$ is closed.



Its complement is open: $\mathbb{R} - \bar{A} = (-\infty, 0) \cup (1, \infty) \cup \left(\bigcup_{n=1}^{\infty} \left(\frac{1}{n+1}, \frac{1}{n}\right) \right)$

$= (-\infty, 0) \cup (1, \infty) \cup (\frac{1}{2}, 1) \cup (\frac{1}{3}, \frac{1}{2}) \cup (\frac{1}{4}, \frac{1}{3}) \cup (\frac{1}{5}, \frac{1}{4}) \cup \dots$

Can a set be both open and closed?

$\emptyset$ is both open and closed (i.e. clopen)

$\mathbb{R}$ is clopen.

$\emptyset$ and $\mathbb{R}$ are the only clopen sets in $\mathbb{R}$. This is an important theorem which forms the basis for the Intermediate Value Theorem. The proof uses the completeness of $\mathbb{R}$.