MA101 Mathematics I

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Sequences

Plan

- Convergence of sequences
- Sandwich theorem
- Monotone convergence theorem
- Bolzano Weierstrass theorem
- Cauchy's criterion

- A sequence of real numbers or a sequence in $\mathbb{R}$ is a mapping $f : \mathbb{N} \to \mathbb{R}$.
- Notation: We write x_n for $f(n)$, $n \in \mathbb{N}$ and so the notation for a sequence is (x_n).
- Examples:
  1. Constant sequence: $(a, a, a, ...)$, where $a \in \mathbb{R}$
  2. Sequence defined by listing: $(1, 4, 8, 11, 52, ...)$
  3. Sequence defined by rule: (x_n), where $x_n = 3n^2$ for all $n \in \mathbb{N}$
  4. Sequence defined recursively: (x_n), where $x_1 = 5$ and $x_{n+1} = 2x_n - 5$ for all $n \in \mathbb{N}$

- Convergence: What does it mean?
- Think of the examples:
  $(2, 2, 2, ...)$
  $(\frac{1}{n})$
  $((-1)^n \frac{1}{n})$
  $(1, 2, 1, 2, ...)$
  $(-1)^n(1 - \frac{1}{n})$
  $(n^2 - 1)$
- Definition: The sequence (x_n) is convergent if there exists $\ell \in \mathbb{R}$ such that for every $\varepsilon > 0$, there exists $n_0 \in \mathbb{N}$ such that $|x_n - \ell| < \varepsilon$ for all $n \geq n_0$.
- We say: ℓ is a limit of (x_n): $\lim_{n\to\infty} x_n = \ell$

A sequence which is not convergent is called divergent.

Result: The limit of a convergent sequence is unique.

Ex. Examine whether the sequences listed earlier are convergent. Also, find their limits if they are convergent.

Ex. Same question for the following sequences.
(i) $(\frac{n+1}{2n+3})$ (ii) $(n + \frac{3}{2})$ (iii) $(n^3 + 1)$
(iv) (α^n), where $|\alpha| < 1$

Definition: The sequence (x_n) is bounded if there exists $M > 0$ such that $|x_n| \leq M$ for all $n \in \mathbb{N}$.
Otherwise (x_n) is called unbounded (not bounded).

Examples: (i) $(\frac{3n+2}{2n+5})$ (ii) $(1, 2, 1, 3, 1, 4, ...)$

Result: Every convergent sequence is bounded.
So, Not bounded implies Not convergent.

Limit rules for convergent sequences

Let $x_n \to x$ and $y_n \to y$.
Then

(i) $x_n + y_n \to x + y$

(ii) $kx_n \to kx$ for all $k \in \mathbb{R}$

(iii) $|x_n| \to |x|$

(iv) $x_n y_n \to xy$

(v) $\frac{x_n}{y_n} \to \frac{x}{y}$ if $y \neq 0$

Ex. Similar results for divergent sequences?

Ex. If $x_n \to x$ and $x \neq 0$, then show that there exists $n_0 \in \mathbb{N}$ such that $x_n \neq 0$ for all $n \geq n_0$.

Ex. Examine the convergence and find the limits (if possible) of the following sequences.

(i) $\left(\frac{2n^2-3n}{3n^2+5n+3}\right)$ (ii) $(\sqrt{n+1} - \sqrt{n})$ (iii) $(\sqrt{4n^2+n} - 2n)$

Sandwich theorem: Let (x_n), (y_n), (z_n) be sequences such that $x_n \leq y_n \leq z_n$ for all $n \in \mathbb{N}$.
If both (x_n) and (z_n) converge to the same limit ℓ, then (y_n) also converges to ℓ.

Examples: (i) $(\frac{1}{n}\sin^2 n)$ (ii) $((2^n + 3^n)^{\frac{1}{n}})$

(iii) $\left(\frac{1}{\sqrt{n^2+1}} + \cdots + \frac{1}{\sqrt{n^2+n}}\right)$

Result: Let $x_n \neq 0$ for all $n \in \mathbb{N}$ and let $L = \lim\limits_{n\to\infty} \left|\frac{x_{n+1}}{x_n}\right|$ exist.

(i) If $L < 1$, then $x_n \to 0$.

(ii) If $L > 1$, then (x_n) is divergent.

Examples: (i) $(\frac{\alpha^n}{n!})$, $\alpha \in \mathbb{R}$ (ii) $(\frac{n^k}{\alpha^n})$, $|\alpha| > 1, k > 0$.

Example: If $x \in \mathbb{R}$, then there exists a sequence (r_n) of rationals converging to x.

Similarly, if $x \in \mathbb{R}$, then there exists a sequence (t_n) of irrationals converging to x.

Definition: (x_n) is increasing if $x_{n+1} \geq x_n$ for all $n \in \mathbb{N}$

(x_n) is decreasing if $x_{n+1} \leq x_n$ for all $n \in \mathbb{N}$.

(x_n) is monotonic if it is either increasing or decreasing

Ex. Examine whether the following sequences are monotonic.

(i) $(1 - \frac{1}{n})$ (ii) $(n + \frac{1}{n})$ (iii) $(\cos \frac{n\pi}{3})$ (iv) $((1 + \frac{1}{n})^n)$

Monotone convergence theorem: An increasing sequence (x_n) which is bounded above converges to $\sup\{x_n : n \in \mathbb{N}\}$.

A decreasing sequence (x_n) which is bounded below converges to $\inf\{x_n : n \in \mathbb{N}\}$.

So a monotonic sequence converges iff it is bounded.

Example: $x_1 = 1$, $x_{n+1} = \frac{1}{3}(x_n + 1)$ for all $n \in \mathbb{N}$. Then (x_n) is convergent and $\lim\limits_{n\to\infty} x_n = \dfrac{1}{2}$.

Ex. Let $x_n = \frac{1}{n+1} + \frac{1}{n+2} + \cdots + \frac{1}{n+n}$ for all $n \in \mathbb{N}$.

Is (x_n) convergent?

Subsequence: Let (x_n) be a sequence in $\mathbb{R}$. If (n_k) is a sequence of positive integers such that $n_1 < n_2 < n_3 < \cdots$, then (x_{n_k}) is called a subsequence of (x_n).

Examples: Think of some divergent sequences and their convergent subsequences.

Ex. (a) (x_n) with $x_n = (-1)^n$, (b) (x_n) with $x_n = \sin(n\pi/2)$.

Result: If a sequence (x_n) converges to ℓ, then every subsequence of (x_n) must converge to ℓ.

So, if (x_n) has a subsequence (x_{n_k}) such that $x_{n_k} \not\to \ell$, then $x_n \not\to \ell$.

Also, if (x_n) has two subsequences converging to two different limits, then (x_n) cannot be convergent.

Example: Let $x_n = (-1)^n(1 - \frac{1}{n})$ for all $n \in \mathbb{N}$. Then $x_n \not\to 1$.
In fact, (x_n) is not convergent.

Ex. Let (x_n) be a sequence such that $x_{2n} \to \ell$ and $x_{2n+1} \to \ell$. Show that $x_n \to \ell$.

Example: The sequence $(1, \frac{1}{2}, 1, \frac{2}{3}, 1, \frac{3}{4}, ...)$ converges to 1.

Ex. Can you find a convergent subsequence of $((-1)^n n^2)$?

Result: Every sequence in $\mathbb{R}$ has a monotone subsequence.

Bolzano-Weierstrass Theorem: Every bounded sequence in $\mathbb{R}$ has a convergent subsequence.

Cauchy sequence: A sequence (x_n) is called a Cauchy sequence if for each $\varepsilon > 0$, there exists $n_0 \in \mathbb{N}$ such that $|x_m - x_n| < \varepsilon$ for all $m, n \geq n_0$.

Result: A Cauchy sequence in $\mathbb{R}$ is bounded.

Cauchy's criterion: A sequence in $\mathbb{R}$ is convergent iff it is a Cauchy sequence.

Ex. Let $x_n = 1 + \frac{1}{1!} + \frac{1}{2!} + \cdots + \frac{1}{n!}$ for all $n \in \mathbb{N}$. Show that (x_n) is convergent.

Ex. Let (x_n) satisfy either of the following conditions:

(i) $|x_{n+1} - x_n| \leq \alpha^n$ for all $n \in \mathbb{N}$

(ii) $|x_{n+2} - x_{n+1}| \leq \alpha |x_{n+1} - x_n|$ for all $n \in \mathbb{N}$,

where $0 < \alpha < 1$.

Show that (x_n) is a Cauchy sequence.

Ex. Let $x_1 = 1$ and let $x_{n+1} = \frac{1}{x_n + 2}$ for all $n \in \mathbb{N}$. Show that (x_n) is convergent and find $\lim_{n \to \infty} x_n$.

Ex. Let $x_n = 1 + \frac{1}{2} + \cdots + \frac{1}{n}$ for all $n \in \mathbb{N}$. Test whether or not (x_n) is a Cauchy sequence.

Ex. Show that both the following sequences are convergent with limit 1.

(i) $(\alpha^{\frac{1}{n}})$, where $\alpha > 0$ (ii) $(n^{\frac{1}{n}})$

*** End ***