

2025

MATHEMATICS

(Major)

Paper : MAT0500204

(Theory of Real Functions)

Full Marks : 60

Time : 2½ hours

The figures in the margin indicate full marks for the questions.

1. Answer the following questions : 1×8=8

(a) Is every limit point of a set $A \subseteq \mathbb{R}$ necessarily an element of A ?

(b) Write the ϵ - δ definition for

$$\lim_{x \rightarrow 3} (2x) = 6$$

(c) A function f is continuous at a if whenever a sequence $\{x_n\}$ gets closer to a , what must happen to the sequence $\{f(x_n)\}$?

(d) If f is continuous on $[a, b]$ and $f(a) < 0 < f(b)$, what must happen according to the intermediate value theorem?

(e) Is every continuous function on a closed and bounded interval $[a, b]$ uniformly continuous?

(f) If f' exists on $[a, b]$, what must be true about f' on the interval $[a, b]$?

(g) Taylor's theorem can be used to approximate functions. If $R_n(x)$ is the remainder term of order n , what inequality does it satisfy for some ξ between 0 and x ?

(h) A function f is differentiable at $x = a$ if and only if there exists a function $\phi(x)$ continuous at a such that $f(x) = f(a) + \phi(x)(x - a)$. What is $\phi(a)$?

2. Answer any six of the following questions :

2×6=12

(a) Let $A = \{\frac{1}{n} : n \in \mathbb{N}\}$.

(i) Find all limit points of A ;

(ii) Is 0 an element of A ?

(b) Using ϵ - δ definition prove that

$$\lim_{x \rightarrow 2} (3x + 1) = 7$$

(Continued)

(3)

(c) Evaluate :

(i) $\lim_{x \rightarrow 0^+} \frac{1}{x^2}$

(ii) $\lim_{x \rightarrow -\infty} \frac{2x^2 + 3}{x^2 - 1}$

(d) Let $f(x) = x^2$. Using sequence, show that f is continuous at $x = 3$.

(e) Let $f(x) = x^3 - 3x$ on $[-2, 2]$. Find the maximum and minimum values of f on this interval.

(f) Let $f(x) = x^3 - x - 2$, show that f has a root in the interval $[1, 2]$.

(g) Let $f(x) = x^2$. Using Caratheodory's approach, write $f(x)$ in the form $f(x) = f(a) + \phi(x)(x - a)$ and find $\phi(a)$ at $a = 1$.

(h) If $y = \sin(x^2)$, find $\frac{dy}{dx}$ using the chain rule.

(i) Find the first four terms of the Taylor series of $f(x) = \frac{1}{1+x}$ about $x = 0$.

(j) Suppose f is differentiable on $[0, 2]$ with $f'(0) = 1$ and $f'(2) = 5$. What can you say about the values of f' on $(0, 2)$?

(4)

3. Answer any four of the following questions :

5×4=20

(a) Let

$$A = \left\{ \frac{n}{n+1} : n \in N \right\}$$

(i) Find all limit points of the set A .

(ii) Using the sequential criterion,

prove that $\lim_{x \rightarrow 1} f(x) = 2$, for $f(x) = 2x$.

(iii) Is 1 an element of A ? Justify.

1+2+2=5

(b) (i) Using the ϵ - δ definition, prove that

$$\lim_{x \rightarrow 3} (5x - 4) = 11$$

(ii) Evaluate the one-sided limit

$$\lim_{x \rightarrow 0^+} \frac{1}{x}$$

(iii) Find $\lim_{x \rightarrow \infty} \frac{3x^2 + 2}{x^2 - 1}$.

(c) Let $f(x) = x^2$ and $g(x) = \sin x$.

(i) Using the sequential criterion, prove that f is continuous at $x = 2$

(ii) Using continuity of f and g , prove that $f(x) + g(x)$ is continuous at $x = 2$.

- (d) Let $f(x) = x^3 - 6x^2 + 9x + 2$ on the interval $[0, 4]$.
- (i) Find the points where $f(x)$ attains its maximum and minimum on $[0, 4]$ and determine the corresponding values.
- (ii) Show that $f(x)$ has at least one root in the interval $[0, 1]$.
- (e) (i) Prove that $f(x) = \sqrt{x}$ is uniformly continuous on $[0, 4]$.
- (ii) If f is strictly increasing and continuous on $[a, b]$, show that f^{-1} exists and is continuous on $[f(a), f(b)]$.
- (f) Let $f(x) = \ln(1+x)$.
- (i) Show that f is differentiable at $x = 1$.
- (ii) Using Caratheodory's theorem, express $f(x) = f(1) + \phi(x)(x-1)$ and find $\phi(1)$.
- (iii) Verify that $\phi(1) = f'(1)$.
- (g) Let $f(x) = x^3 - 3x$ on $[-\sqrt{3}, \sqrt{3}]$.
- (i) Verify that f satisfies the conditions of Rolle's theorem.
- (ii) Find all points c in $(-\sqrt{3}, \sqrt{3})$ where $f'(c) = 0$.

- (iii) Apply the mean value theorem for the interval $[-1, 2]$ to find c , such that $f'(c) = \frac{f(2) - f(-1)}{2 - (-1)}$.
- (h) (i) Find the first four non-zero terms of the Taylor series of $\sin x$ about $x = 0$.
- (ii) Find the first three non-zero terms of the Taylor's series of $\frac{1}{1+x}$ about $x = 0$.
- (iii) Use the first two terms of the expansion of $(1+x)^5$, to approximate $(1.02)^5$.

4. Answer any two of the following questions : 10×2=20

(a) Let $f : R - \{2\} \rightarrow R$ be defined by

$$f(x) = \begin{cases} \frac{x^2 - 4}{x - 2} & , x \neq 2 \\ \text{undefined} & , x = 2 \end{cases}$$

- (i) Show that 2 is a limit point of the domain.
- (ii) Using the ϵ - δ definition of limit, prove that

$$\lim_{x \rightarrow 2} f(x) = 4$$

(7)

(iii) Determine whether

$$\lim_{x \rightarrow 2^-} f(x) \text{ and } \lim_{x \rightarrow 2^+} f(x)$$

exist. Justify your answer.

(iv) Evaluate

$$\lim_{x \rightarrow \infty} f(x) \text{ and } \lim_{x \rightarrow \infty} (2x - f(x))$$

using appropriate limit theorems and state whether either limit diverges to infinity, diverges without limit or converges.

(b) Let $f : [0, 3] \rightarrow \mathbb{R}$ be defined by

$$f(x) = \begin{cases} x^2 - 2x, & 0 \leq x \leq 2 \\ 4 - x, & 2 < x \leq 3 \end{cases}$$

(i) Using the sequential criterion determine whether f is continuous at $x = 2$.

(ii) On the interval $[0, 3]$ verify that the maximum-minimum theorem holds and hence determine $\max f$ and $\min f$.

(iii) Show that the equation $f(x) = 1$ has at least one solution in $[0, 3]$.

(iv) State with justification whether f is uniformly continuous on $[0, 3]$.

(8)

(c) Let $g : (1, 4] \rightarrow \mathbb{R}$ be defined by $g(x) = \sqrt{x-1}$.

(i) Prove that g is continuous on its domain.

(ii) Determine whether g is uniformly continuous on $(1, 4]$. Give a justification using the uniform continuity.

(iii) Let $h(x) = x^3$. Show that since h is continuous and monotone on \mathbb{R} , its inverse h^{-1} is also continuous.

(iv) If $k(x) = g(x) + h(x)$, discuss whether k is continuous on $(1, 4]$.

(d) Let $f(x) = xe^x$, $x \in \mathbb{R}$.

(i) Show that f is differentiable at all $x \in \mathbb{R}$ and find $f'(x)$.

(ii) Let $g(x) = \ln(1+x)$, $x > -1$. Compute $\frac{d}{dx} g(f(x))$.

(iii) Using Rolle's theorem, show that there exists at least one $c \in (0, 1)$ such that

$$f'(c) = \frac{f(1) - f(0)}{1 - 0}$$

(iv) Using Taylor's theorem, derive an inequality for e^x on $[0, 1]$ of the form

$$1 + x + \frac{x^2}{2} \leq e^x \leq 1 + x + \frac{x^2}{2} + \frac{e}{6}x^3$$

(v) Using derivative of the inverse function, find $\frac{d}{dx}(f^{-1}(x))$ at $x = f(0)$.

(e) Let $h(x) = \ln(1+x)$, $x > -1$.

(i) Show that h is differentiable and find $h'(x)$.

(ii) Let $k(x) = e^x - 1$, $x \in \mathbb{R}$. Using derivative of the inverse function, find $\frac{d}{dx}k^{-1}(x)$.

(iii) Using the Cauchy mean value theorem to show that $f(x) = \ln(1+x)$ and $g(x) = x$, there exists $c \in (0, a)$, such that

$$\frac{f(a) - f(0)}{g(a) - g(0)} = f'(c)$$

(iv) State Caratheodory's theorem in \mathbb{R}^n . Then using the theorem, explain why any point in the convex hull of a set $S \subset \mathbb{R}^3$ can be written as a convex combination of at most four points.

(v) If $f'(x_0) < 0$ and $f'(x_1) > 0$ for some differentiable function f , use Darboux's theorem to explain why there must exist a point c between x_0 and x_1 such that $f'(c) = 0$.
