

# Calculus Notes

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## Contents

<b>1</b>	<b>Limits</b>	<b>3</b>
1.1	Precise Definition of a Limit . . . . .	3
1.2	Precise Definition of One-Sided Limit . . . . .	3
1.3	Precise Definition of Infinite Limit . . . . .	4
1.4	Precise Definition of a Limit at Infinity . . . . .	4
1.5	Precise Definition of Infinite Limit at Infinity . . . . .	4
1.6	Limit Laws . . . . .	4
1.7	Relationship between the Limit and One-Sided Limits . . . . .	5
1.8	Comparison Theorem . . . . .	5
1.9	Squeeze Theorem . . . . .	5
1.10	Continuity . . . . .	5
1.11	Properties of Continuous Functions . . . . .	5
1.12	Types of Discontinuity . . . . .	6
1.13	Limits of Continuous Functions . . . . .	6
1.14	Intermediate Value Theorem . . . . .	6
1.15	Asymptotes . . . . .	6
1.16	Common Limits . . . . .	7
<b>2</b>	<b>Derivatives</b>	<b>7</b>
2.1	Derivative at a Point . . . . .	7
2.2	Derivative as a Function . . . . .	7
2.3	Differentiability . . . . .	8
2.4	Differentiability Implies Continuity . . . . .	8
2.5	Properties of Derivatives . . . . .	8
2.6	Table of Derivatives . . . . .	9
2.7	Absolute and Local Extrema . . . . .	9
2.8	Extreme Value Theorem . . . . .	9
2.9	Critical and Stationary Points . . . . .	9
2.10	Rolle's Theorem . . . . .	10
2.11	Mean Value Theorem . . . . .	10
2.12	Increasing/Decreasing Test . . . . .	10
2.13	First Derivative Test . . . . .	10
2.14	Concavity and Inflection Points . . . . .	11
2.15	Concavity Test . . . . .	11
2.16	Second Derivative Test . . . . .	11
2.17	L'Hôpital's Rule . . . . .	11
2.18	Indeterminate Forms . . . . .	11

<b>3</b>	<b>Integrals</b>	<b>12</b>
3.1	Antiderivatives . . . . .	12
3.2	Indefinite Integrals . . . . .	12
3.3	Riemann Sum . . . . .	12
3.4	Partitions of an Interval . . . . .	12
3.5	Types of Riemann Sums . . . . .	13
3.6	Definite Integral . . . . .	14
3.7	Properties of Definite Integrals . . . . .	15
3.8	Net and Total Area . . . . .	15
3.9	Mean Value Theorem for Integrals . . . . .	16
3.10	Fundamental Theorem of Calculus. Part 1 . . . . .	16
3.11	Fundamental Theorem of Calculus. Part 2 . . . . .	16
3.12	Table of Indefinite Integrals . . . . .	16
<b>4</b>	<b>Sequences and Series</b>	<b>17</b>
4.1	Definition of a Sequence . . . . .	17
4.2	Monotonic Sequence . . . . .	17
4.3	Bounded Sequence . . . . .	17
4.4	Limit of a Sequence . . . . .	18
4.5	Limit of a Sequence Defined by a Function . . . . .	18
4.6	Squeeze Theorem for Sequences . . . . .	18
4.7	Limit of Absolute Value of a Sequence . . . . .	18
4.8	Monotone Convergence Theorem . . . . .	18
4.9	Series . . . . .	18
4.10	Convergence and Divergence of Series . . . . .	19
4.11	Types of Series . . . . .	19
4.12	Properties of Series . . . . .	19
4.13	Geometric Series . . . . .	20
4.14	Telescoping Series . . . . .	20
4.15	Harmonic Series . . . . .	21
4.16	Limit of Terms in a Convergent Series . . . . .	21
4.17	List of Convergence Tests . . . . .	21
4.18	Divergence Test ( $n$ th-Term Test) . . . . .	22
4.19	Direct Comparison Test . . . . .	22
4.20	Limit Comparison Test . . . . .	22
4.21	Integral Test (Maclaurin-Cauchy Test) . . . . .	22
4.22	$p$ -Series Test . . . . .	22
4.23	Integral Remainder Estimate . . . . .	23
4.24	Alternating Series Test (Leibniz Criterion) . . . . .	23
4.25	Alternating Series Estimation Theorem . . . . .	23
4.26	Ratio Test (d'Alembert's Criterion) . . . . .	23
4.27	Root Test (Cauchy's Criterion) . . . . .	24
4.28	Absolute Convergence Test . . . . .	24
4.29	Riemann Series Theorem . . . . .	24
4.30	Power Series . . . . .	24
4.31	Radius of Convergence . . . . .	25
4.32	Interval of Convergence . . . . .	25
4.33	Differentiation and Integration of Power Series . . . . .	26
4.34	Taylor Series . . . . .	26
4.35	Taylor Polynomial . . . . .	27
4.36	Taylor's Theorem . . . . .	27

4.37	Taylor's Inequality . . . . .	27
4.38	Binomial Series . . . . .	27
<b>5</b>	<b>Multivariable Calculus</b>	<b>28</b>
5.1	Limit of a Function of Two Variables . . . . .	28
5.2	Test for Nonexistence of a Limit . . . . .	28
5.3	Partial Derivatives . . . . .	28
5.4	Clairaut's Theorem . . . . .	28
5.5	Equation of a Tangent Plane . . . . .	28
5.6	Total Differential . . . . .	28
5.7	Chain Rule For a Function of Two Variables . . . . .	29
5.8	Implicit Differentiation of a Function of Two Variables . . . . .	29
5.9	Gradient Vector . . . . .	29
5.10	Directional Derivative . . . . .	29
5.11	Tangent Plane to a Level Surface . . . . .	30
5.12	Maximum and Minimum Values of a Function of Two Variables . . . . .	30
5.13	Parametric Derivative . . . . .	30
5.14	Area Under a Parametric Curve . . . . .	30
5.15	Arc Length of a Parametric Curve . . . . .	31
5.16	Surface Area of a Solid Revolution for a Parametric Curve . . . . .	31
5.17	Polar Coordinates . . . . .	31
5.18	Area in Polar Coordinates . . . . .	31
5.19	Arc Length in Polar Coordinates . . . . .	31
5.20	Tangents to Polar Curves . . . . .	32
5.21	Double Integral . . . . .	32
5.22	Iterated Integral . . . . .	32
5.23	Average Value of a Function over a Region . . . . .	32
5.24	Double Integral Over a General Region . . . . .	32
5.25	Double Integral in Polar Coordinates . . . . .	33
5.26	Double Integral in Polar Coordinates Over a General Region . . . . .	33

# 1 Limits

## 1.1 Precise Definition of a Limit

### Standard Limit:

$$\lim_{x \rightarrow a} f(x) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists \delta > 0 \text{ such that } 0 < |x - a| < \delta \Rightarrow |f(x) - L| < \varepsilon.$$

## 1.2 Precise Definition of One-Sided Limit

### Right-Hand Limit:

$$\lim_{x \rightarrow a^+} f(x) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists \delta > 0 \text{ such that } 0 < x - a < \delta \Rightarrow |f(x) - L| < \varepsilon.$$

### Left-Hand Limit:

$$\lim_{x \rightarrow a^-} f(x) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists \delta > 0 \text{ such that } 0 < a - x < \delta \Rightarrow |f(x) - L| < \varepsilon.$$

### 1.3 Precise Definition of Infinite Limit

**Infinite Limit:**

$$\lim_{x \rightarrow a} f(x) = \infty \quad \text{if} \quad \forall M > 0, \exists \delta > 0 \text{ such that } 0 < |x - a| < \delta \Rightarrow f(x) > M.$$

$$\lim_{x \rightarrow a} f(x) = -\infty \quad \text{if} \quad \forall M > 0, \exists \delta > 0 \text{ such that } 0 < |x - a| < \delta \Rightarrow f(x) < -M.$$

### 1.4 Precise Definition of a Limit at Infinity

**Limit at Infinity:**

$$\lim_{x \rightarrow \infty} f(x) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists M > 0 \text{ such that } x > M \Rightarrow |f(x) - L| < \varepsilon.$$

$$\lim_{x \rightarrow -\infty} f(x) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists M > 0 \text{ such that } x < -M \Rightarrow |f(x) - L| < \varepsilon.$$

### 1.5 Precise Definition of Infinite Limit at Infinity

**Infinite Limit at Infinity:**

$$\lim_{x \rightarrow \infty} f(x) = \infty \quad \text{if} \quad \forall M > 0, \exists N > 0 \text{ such that } x > N \Rightarrow f(x) > M.$$

$$\lim_{x \rightarrow \infty} f(x) = -\infty \quad \text{if} \quad \forall M > 0, \exists N > 0 \text{ such that } x > N \Rightarrow f(x) < -M.$$

$$\lim_{x \rightarrow -\infty} f(x) = \infty \quad \text{if} \quad \forall M > 0, \exists N > 0 \text{ such that } x < -N \Rightarrow f(x) > M.$$

$$\lim_{x \rightarrow -\infty} f(x) = -\infty \quad \text{if} \quad \forall M > 0, \exists N > 0 \text{ such that } x < -N \Rightarrow f(x) < -M.$$

### 1.6 Limit Laws

Suppose that  $c$  is a constant and the limits  $\lim_{x \rightarrow a} f(x)$  and  $\lim_{x \rightarrow a} g(x)$  exist. Then

1.  $\lim_{x \rightarrow a} c = c$
2.  $\lim_{x \rightarrow a} x = a$
3.  $\lim_{x \rightarrow a} [f(x) \pm g(x)] = \lim_{x \rightarrow a} f(x) \pm \lim_{x \rightarrow a} g(x)$
4.  $\lim_{x \rightarrow a} [cf(x)] = c \lim_{x \rightarrow a} f(x)$
5.  $\lim_{x \rightarrow a} [f(x)g(x)] = \lim_{x \rightarrow a} f(x) \cdot \lim_{x \rightarrow a} g(x)$
6.  $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \frac{\lim_{x \rightarrow a} f(x)}{\lim_{x \rightarrow a} g(x)}, \text{ if } \lim_{x \rightarrow a} g(x) \neq 0$
7.  $\lim_{x \rightarrow a} [f(x)]^n = [\lim_{x \rightarrow a} f(x)]^n$
8.  $\lim_{x \rightarrow a} \sqrt[n]{f(x)} = \sqrt[n]{\lim_{x \rightarrow a} f(x)}$

## 1.7 Relationship between the Limit and One-Sided Limits

$$\begin{aligned}\lim_{x \rightarrow a} f(x) = L &\iff \lim_{x \rightarrow a^+} f(x) = \lim_{x \rightarrow a^-} f(x) = L. \\ \lim_{x \rightarrow a^+} f(x) \neq \lim_{x \rightarrow a^-} f(x) &\implies \lim_{x \rightarrow a} f(x) \text{ does not exist.}\end{aligned}$$

## 1.8 Comparison Theorem

If  $f(x) \leq g(x)$  when  $x$  is near  $a$ , and  $\lim_{x \rightarrow a} f(x)$  and  $\lim_{x \rightarrow a} g(x)$  exist, then

$$\lim_{x \rightarrow a} f(x) \leq \lim_{x \rightarrow a} g(x).$$

## 1.9 Squeeze Theorem

If  $f(x) \leq g(x) \leq h(x)$  when  $x$  is near  $a$ , then

$$\lim_{x \rightarrow a} f(x) = \lim_{x \rightarrow a} h(x) = L \implies \lim_{x \rightarrow a} g(x) = L.$$

## 1.10 Continuity

A function  $f(x)$  is **continuous at**  $x = a$  if and only if it satisfies **all** the following:

- (1)  $f(a)$  exists
- (2)  $\lim_{x \rightarrow a} f(x)$  exists
- (3)  $\lim_{x \rightarrow a} f(x) = f(a)$

Otherwise,  $f(x)$  is discontinuous at  $x = a$ .

## 1.11 Properties of Continuous Functions

If  $f(x)$  and  $g(x)$  are continuous at  $x = a$  and  $c$  is a constant, then the following functions are also continuous at  $x = a$ :

- |            |                                   |         |
|------------|-----------------------------------|---------|
| 1. $f + g$ | 2. $f - g$                        | 3. $cf$ |
| 4. $fg$    | 5. $\frac{f}{g}$ if $g(a) \neq 0$ |         |



Source: calcworkshop.com

## 1.12 Types of Discontinuity

## 1.13 Limits of Continuous Functions

If  $f(x)$  is continuous at  $b$  and  $\lim_{x \rightarrow a} g(x) = b$ , then

$$\lim_{x \rightarrow a} f(g(x)) = f(\lim_{x \rightarrow a} g(x)) = f(b).$$

If  $g$  is continuous at  $a$  and  $f$  is continuous at  $g(a)$ , then the composite  $f \circ g$  is continuous at  $a$ .

## 1.14 Intermediate Value Theorem

If  $f$  is continuous on a closed interval  $[a, b]$ , then for any  $N$  between  $f(a)$  and  $f(b)$ ,

$$\exists c \in [a, b] \text{ such that } f(c) = N$$

## 1.15 Asymptotes

**Vertical Asymptote:**  $x = a$  is a vertical asymptote if

$$\lim_{x \rightarrow a^\pm} f(x) = \pm\infty.$$

**Horizontal Asymptote:**  $y = L$  is a horizontal asymptote if

$$\lim_{x \rightarrow \pm\infty} f(x) = L.$$

For  $f(x) = \frac{P(x)}{Q(x)}$ , compare degrees of  $P$  and  $Q$ :

$$\deg P < \deg Q \implies y = 0.$$

$$\deg P = \deg Q \implies y = \frac{\text{leading coef. of } P}{\text{leading coef. of } Q}.$$

$$\deg P > \deg Q \implies \text{no horizontal asymptote.}$$

**Oblique Asymptote:**  $y = mx + b$  is an oblique asymptote if

$$\lim_{x \rightarrow \pm\infty} [f(x) - (mx + b)] = 0.$$

For a rational function  $f(x) = \frac{P(x)}{Q(x)}$ , if  $\deg P = \deg Q + 1$ , then  $f(x)$  has an oblique asymptote. Find it by polynomial long division:

$$f(x) = D(x) + \frac{R(x)}{Q(x)}, \quad \text{as } x \rightarrow \pm\infty, \quad f(x) \approx D(x).$$

**Curvilinear Asymptote:**  $y = g(x)$  is a curvilinear asymptote if

$$\lim_{x \rightarrow \pm\infty} [f(x) - g(x)] = 0,$$

where  $g(x)$  is any non-linear function.

## 1.16 Common Limits

Assume  $a > 0$  in the following.

$$1. \lim_{x \rightarrow 0} \frac{\sin ax}{bx} = \frac{a}{b}$$

$$8. \lim_{x \rightarrow 0} \frac{\log_a(1+x)}{x} = \log_a e$$

$$2. \lim_{x \rightarrow 0} \frac{1 - \cos x}{x} = 0$$

$$9. \lim_{x \rightarrow 0^+} x^x = 1$$

$$3. \lim_{x \rightarrow 0} \frac{1 - \cos x}{x^2} = \frac{1}{2}$$

$$10. \lim_{x \rightarrow \infty} \sqrt[x]{x} = \lim_{x \rightarrow \infty} x^{\frac{1}{x}} = 1$$

$$4. \lim_{x \rightarrow 0} \frac{e^{ax} - 1}{x} = a$$

$$11. \lim_{x \rightarrow 0^+} x^a \ln x = 0$$

$$5. \lim_{x \rightarrow 0} \frac{a^x - 1}{x} = \ln a$$

$$12. \lim_{x \rightarrow \infty} x^{-a} \ln x = 0$$

$$6. \lim_{x \rightarrow \infty} \left(1 + \frac{k}{x}\right)^{mx} = e^{mk}$$

$$13. \lim_{n \rightarrow \infty} \frac{x^n}{n!} = 0$$

$$7. \lim_{x \rightarrow 0} \frac{\ln(1+x)}{x} = 1$$

$$14. \lim_{n \rightarrow \infty} \frac{n^n}{n!} = \infty$$

## 2 Derivatives

### 2.1 Derivative at a Point

The **derivative** of  $f(x)$  at  $x = a$  is the **instantaneous rate of change** at that point:

$$f'(a) = \left. \frac{df}{dx} \right|_{x=a} = \lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h} = \lim_{x \rightarrow a} \frac{f(x) - f(a)}{x - a}.$$

### 2.2 Derivative as a Function

The derivative of a function  $f(x)$  at a point  $x$  is defined as the limit

$$f'(x) = \lim_{\Delta x \rightarrow 0} \frac{f(x + \Delta x) - f(x)}{\Delta x}.$$

## 2.3 Differentiability

A function  $f(x)$  is **differentiable** at  $x = a$  if its derivative  $f'(x)$  exists. That is:

$$f(x) \text{ is differentiable at } x = a \iff \text{The limit } \lim_{h \rightarrow 0} \frac{f(a+h) - f(a)}{h} \text{ exists.}$$

## 2.4 Differentiability Implies Continuity

If  $f(x)$  is differentiable at  $x = a$ , then it is continuous at  $x = a$  :

$$f \text{ differentiable at } a \implies f \text{ continuous at } a.$$

However, the converse is false:

$$f \text{ continuous at } a \not\implies f \text{ differentiable at } a.$$

## 2.5 Properties of Derivatives

Let  $f(x)$  and  $g(x)$  be differentiable functions. Then the following rules hold:

$$(1) \quad \frac{d}{dx}(c) = 0.$$

$$(2) \quad \frac{d}{dx}(x^n) = nx^{n-1}.$$

$$(3) \quad \frac{d}{dx}[cf(x)] = c[\frac{d}{dx}f(x)].$$

$$(4) \quad \frac{d}{dx}[f(x) \pm g(x)] = \frac{d}{dx}f(x) \pm \frac{d}{dx}g(x).$$

$$(5) \quad \frac{d}{dx}[f(x)g(x)] = f'(x)g(x) + f(x)g'(x).$$

$$(6) \quad \frac{d}{dx}\left[\frac{f(x)}{g(x)}\right] = \frac{f'(x)g(x) - f(x)g'(x)}{g(x)^2}.$$

$$(7) \quad \frac{d}{dx}[f(g(x))] = f'(g(x))g'(x).$$



## 2.6 Table of Derivatives

$(\sin x)' = \cos x$	$(\arcsin x)' = \frac{1}{\sqrt{1-x^2}}$	$(e^x)' = e^x$
$(\cos x)' = -\sin x$	$(\arccos x)' = -\frac{1}{\sqrt{1-x^2}}$	$(a^x)' = a^x \ln a$
$(\tan x)' = \sec^2 x$	$(\arctan x)' = \frac{1}{1+x^2}$	$(\log_a x)' = \frac{1}{x \ln a}$
$(\cot x)' = -\csc^2 x$	$(x)' = -\frac{1}{1+x^2}$	$(\ln x)' = \frac{1}{x}$
$(\sec x)' = \sec x \tan x$	$(x)' = \frac{1}{x\sqrt{x^2-1}}$	$( x )' = \frac{x}{ x }$
$(\csc x)' = -\csc x \cot x$	$(x)' = -\frac{1}{x\sqrt{x^2-1}}$	$(x^x)' = x^x(1 + \ln x)$

## 2.7 Absolute and Local Extrema

Let  $f$  be defined on a domain  $D$ , and let  $c \in D$ .

- **Absolute Maximum:**  $f(c)$  is an absolute maximum if  $f(c) \geq f(x)$ ,  $\forall x \in D$ .
- **Absolute Minimum:**  $f(c)$  is an absolute minimum if  $f(c) \leq f(x)$ ,  $\forall x \in D$ .
- **Local Maximum:**  $f(c)$  is a local maximum if  $\exists \delta > 0$  such that  $f(c) \geq f(x)$ ,  $\forall x \in (c - \delta, c + \delta)$ .
- **Local Minimum:**  $f(c)$  is a local minimum if  $\exists \delta > 0$  such that  $f(c) \leq f(x)$ ,  $\forall x \in (c - \delta, c + \delta)$ .

## 2.8 Extreme Value Theorem

If  $f$  is continuous on a closed interval  $[a, b]$ , then  $f$  attains an absolute maximum and an absolute minimum on  $[a, b]$ :

$$\exists c, d \in [a, b] \text{ such that } f(c) \leq f(x) \leq f(d), \quad \forall x \in [a, b].$$

## 2.9 Critical and Stationary Points

Let  $f$  be defined on an interval  $I$  and  $c \in I$ .

- **Critical Point:**  $c$  is a critical point of  $f$  if either
  1.  $f'(c) = 0$ , or
  2.  $f'(c)$  does not exist
- **Stationary Point:**  $c$  is a stationary point of  $f$  if  $f'(c) = 0$ .

Note: Every stationary point is a critical point, but not conversely.

## 2.10 Rolle's Theorem

Let  $f$  satisfy all conditions:

1.  $f$  is continuous on  $[a, b]$ .
2.  $f$  is differentiable on  $(a, b)$ .
3.  $f(a) = f(b)$ .

Then, there exists at least one  $c \in (a, b)$  such that  $f'(c) = 0$ .

## 2.11 Mean Value Theorem

Let  $f$  satisfy all conditions:

1.  $f$  is continuous on  $[a, b]$ .
2.  $f$  is differentiable on  $(a, b)$ .

Then, there exists at least one  $c \in (a, b)$  such that:

$$f'(c) = \frac{f(b) - f(a)}{b - a}.$$

Note: Rolle's Theorem is a special case of the Mean Value Theorem where  $f(a) = f(b)$ .

## 2.12 Increasing/Decreasing Test

Let  $f$  be differentiable on an interval  $I$ . Then, for all  $x \in I$ :

1. If  $f'(x) > 0$ , then  $f$  is strictly increasing on  $I$ .
2. If  $f'(x) < 0$ , then  $f$  is strictly decreasing on  $I$ .
3. If  $f'(x) = 0$ , then  $f$  is constant on  $I$ .

## 2.13 First Derivative Test

Let  $c$  be a critical point of a differentiable function  $f(x)$ , meaning  $f'(c) = 0$  or  $f'(c)$  does not exist. Then:

1. If  $f'(x)$  changes from positive to negative at  $x = c$ , then  $f(c)$  is a **local maximum**.
2. If  $f'(x)$  changes from negative to positive at  $x = c$ , then  $f(c)$  is a **local minimum**.
3. If  $f'(x)$  does not change sign at  $x = c$ , then  $f(c)$  is **neither** a local maximum nor a local minimum.

## 2.14 Concavity and Inflection Points

Concave up  $\iff$  Curve **lies above** all of its **tangent lines**.

Concave down  $\iff$  Curve **lies below** all of its **tangent lines**.

Inflection point  $\iff$  Point where **concavity changes**.

## 2.15 Concavity Test

Let  $f(x)$  be twice differentiable on interval  $I$ . Then:

- If  $f''(x) > 0$ ,  $\forall x \in I \implies f(x)$  is **concave up** on  $I$ .
- If  $f''(x) < 0$ ,  $\forall x \in I \implies f(x)$  is **concave down** on  $I$ .

## 2.16 Second Derivative Test

Let  $c$  be a critical point of  $f$  where  $f'(c) = 0$ . If  $f''(c)$  exists, then:

1. If  $f''(c) > 0$ ,  $f(x)$  is **concave up** at  $c$ , so  $f(c)$  is a **local minimum**.

Local Maximum at  $c \iff f'(c) = 0$  and  $f''(c) < 0$

2. If  $f''(c) < 0$ ,  $f(x)$  is **concave down** at  $c$ , so  $f(c)$  is a **local maximum**.

Local Minimum at  $c \iff f'(c) = 0$  and  $f''(c) > 0$

3. If  $f''(c) = 0$  or **does not exist**, the test is **inconclusive**—use the First Derivative Test instead.

## 2.17 L'Hôpital's Rule

Let  $f(x)$  and  $g(x)$  be differentiable on an open interval containing  $a$  (except possibly at  $a$ ). If

$$\lim_{x \rightarrow a} f(x) = \lim_{x \rightarrow a} g(x) = 0 \text{ or } \lim_{x \rightarrow a} f(x) = \lim_{x \rightarrow a} g(x) = \pm\infty$$

then

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}.$$

## 2.18 Indeterminate Forms

The following symbols are “indeterminate”:

$$\frac{0}{0} \quad \frac{\infty}{\infty} \quad 0 \cdot \infty \quad \infty - \infty \quad 1^\infty \quad 0^\infty \quad \infty^0$$

*Warning:* The following symbols are *not* indeterminate:

$$\frac{1}{0} \quad \frac{\infty}{0} \quad \frac{1}{\infty} \quad 1 \cdot \infty \quad \infty + \infty \quad 1 + \infty \quad 0^\infty$$

## 3 Integrals

### 3.1 Antiderivatives

A function  $F(x)$  is an **antiderivative** (or primitive function) of  $f(x)$  on an interval  $I$  if:

$$F'(x) = f(x), \quad \forall x \in I.$$

### 3.2 Indefinite Integrals

The **indefinite integral** (or general antiderivative) of a function  $f(x)$  is the family of all its antiderivatives:

$$\int f(x)dx = F(x) + C$$

where  $F(x)$  is any antiderivative of  $f(x)$  and  $C$  is an arbitrary constant.

### 3.3 Riemann Sum

Let  $f(x)$  be a function defined on a closed interval  $[a, b]$ , and let the interval be partitioned into  $n$  subintervals by inserting  $n - 1$  points  $x_1, x_2, \dots, x_{n-1}$  such that:

$$a = x_0 < x_1 < x_2 < \dots < x_n = b$$

where the subintervals  $[x_{i-1}, x_i]$  have length  $\Delta x_i = x_i - x_{i-1}$ . For each subinterval  $[x_{i-1}, x_i]$ , let  $x_i^*$  be an **arbitrary sample point** within the interval. Then, a **Riemann sum**, which **approximates** the area under the curve  $f(x)$  over  $[a, b]$ , is defined as:

$$S_n = \sum_{i=1}^n f(x_i^*)\Delta x_i, \quad x_i^* \in [x_{i-1}, x_i].$$

### 3.4 Partitions of an Interval



Comparison of uniform and non-uniform partitions of an interval (generated using R).

A partition of  $[a, b]$  divides it into  $n$  subintervals:

$$P = \{a = x_0 < x_1 < x_2 < \cdots < x_n = b\}$$

Each subinterval has width:

$$\Delta x_i = x_i - x_{i-1}.$$

- **Uniform Partition:** All subintervals have the same width:

$$\Delta x_i = \Delta x = \frac{b-a}{n}, \quad \forall i.$$

- **Non-Uniform Partition:** Subintervals have different widths, and  $\Delta x_i$  varies for each  $i$ .

### 3.5 Types of Riemann Sums

The type of Riemann sum depends on how the sample points  $x_i^*$  are chosen within each subinterval  $[x_{i-1}, x_i]$ .

1. **Arbitrary-Point Rule:**  $x_i^* \in [x_{i-1}, x_i] \rightarrow$  **General Riemann Sum**

$$S_n = \sum_{i=1}^n f(x_i^*) \Delta x_i, \quad \Delta x_i = x_i - x_{i-1}.$$

**Uniform Partition:** If all subintervals have equal width  $\Delta x = \frac{b-a}{n}$ , then  $x_i^* \in [x_{i-1}, x_i] = [a + (i-1)\Delta x, a + i\Delta x]$  or  $x_i^* = a + (i-1+c)\Delta x$ , where  $c \in [0, 1]$  determines its position within the subinterval:

$$S_n = \sum_{i=1}^n f(a + (i-1+c)\Delta x) \Delta x = \sum_{i=1}^n f(a + (i-1+c)\frac{(b-a)}{n}) \frac{b-a}{n}.$$

- Uses arbitrary sample points  $x_i^*$ .

2. **Left Rule:**  $x_i^* = x_{i-1} \rightarrow$  **Left Riemann Sum**

$$S_{\text{left}} = \sum_{i=1}^n f(x_{i-1}) \Delta x_i.$$

**Uniform Partition:**  $c = 0$

$$S_{\text{left}} = \sum_{i=1}^n f(a + (i-1)\Delta x) \Delta x.$$

- Underestimates for increasing functions, overestimates for decreasing functions.

3. **Right Rule:**  $x_i^* = x_i \rightarrow$  **Right Riemann Sum**

$$S_{\text{right}} = \sum_{i=1}^n f(x_i) \Delta x_i$$

**Uniform Partition:**  $c = 1$

$$S_{\text{right}} = \sum_{i=1}^n f(a + i\Delta x) \Delta x.$$

- Overestimates for increasing functions, underestimates for decreasing functions.

4. **Midpoint Rule:**  $x_i^* = \frac{x_{i-1} + x_i}{2} \rightarrow$  **Midpoint Riemann Sum**

$$S_{\text{mid}} = \sum_{i=1}^n f\left(\frac{x_{i-1} + x_i}{2}\right) \Delta x_i.$$

**Uniform Partition:**  $c = \frac{1}{2}$

$$S_{\text{mid}} = \sum_{i=1}^n f\left(a + \left(i - \frac{1}{2}\right)\Delta x\right) \Delta x.$$

- Tends to give better approximations than left or right sums.

5. **Upper Rule:**  $x_i^* = \arg \sup_{x \in [x_{i-1}, x_i]} f(x) \rightarrow$  **Upper Riemann Sum** (or **Upper Darboux Sum**)

$$S_{\text{upper}} = \sum_{i=1}^n \sup_{x \in [x_{i-1}, x_i]} f(x) \Delta x_i.$$

- Always **overestimates** the integral.

6. **Lower Rule:**  $x_i^* = \arg \inf_{x \in [x_{i-1}, x_i]} f(x) \rightarrow$  **Lower Riemann Sum** (or **Lower Darboux Sum**)

$$S_{\text{lower}} = \sum_{i=1}^n \inf_{x \in [x_{i-1}, x_i]} f(x) \Delta x_i.$$

- Always **underestimates** the integral.

### 3.6 Definite Integral

The **definite integral** of a function  $f(x)$  over the interval  $[a, b]$  is defined as the limit of a Riemann sum:

$$\int_a^b f(x) dx = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(x_i^*) \Delta x_i$$

where:

- $[a, b]$  is divided into  $n$  subintervals.
- $\Delta x_i = x_i - x_{i-1}$  is the width of the  $i$ -th subinterval.
- $x_i^*$  is any sample point in the  $i$ -th subinterval.

### 3.7 Properties of Definite Integrals

Let  $f(x)$  and  $g(x)$  be integrable functions on  $[a, b]$  and  $c$  be a constant. Then:

- (1)  $\int_a^b c \, dx = c(b - a).$
- (2)  $\int_a^a f(x) \, dx = 0.$
- (3)  $\int_b^a f(x) \, dx = - \int_a^b f(x) \, dx.$
- (4)  $\int_a^b c f(x) \, dx = c \int_a^b f(x) \, dx.$
- (5)  $\int_a^b [f(x) \pm g(x)] \, dx = \int_a^b f(x) \, dx \pm \int_a^b g(x) \, dx.$
- (6)  $\int_a^b f(x) \, dx = \int_a^c f(x) \, dx + \int_c^b f(x) \, dx.$
- (7)  $\int_a^b f(x) \, dx \leq \int_a^b g(x) \, dx$  if  $f(x) \leq g(x)$  on  $[a, b].$
- (8)  $\left| \int_a^b f(x) \, dx \right| \leq \int_a^b |f(x)| \, dx.$
- (9)  $m(b - a) \leq \int_a^b f(x) \, dx \leq M(b - a)$  if  $m \leq f(x) \leq M$  on  $[a, b].$

### 3.8 Net and Total Area

Let  $f(x)$  be integrable on  $[a, b]$ . Define:

- $A_1$  = area of region where  $f(x) > 0$  (area above  $x$ -axis).
- $A_2$  = area of region where  $f(x) < 0$  (area below  $x$ -axis).

Then:

- **Net Area:**

$$\int_a^b f(x) \, dx = A_1 - A_2.$$

- **Total Area:**

$$\int_a^b |f(x)| \, dx = A_1 + A_2.$$

### 3.9 Mean Value Theorem for Integrals

Let  $f$  be continuous on  $[a, b]$ . Then:

$$\exists c \in (a, b) \text{ such that } \frac{1}{b-a} \int_a^b f(x) dx = f(c)$$

The expression on the left is the **average value** of the function  $f(x)$  on the interval  $[a, b]$ .

### 3.10 Fundamental Theorem of Calculus. Part 1

Let  $f$  be a continuous on  $[a, b]$ . Define the function

$$F(x) = \int_a^x f(t) dt.$$

Then:

$$F'(x) = \frac{d}{dx} \left[ \int_a^x f(t) dt \right] = f(x), \quad \forall x \in (a, b).$$

### 3.11 Fundamental Theorem of Calculus. Part 2

If  $f$  is continuous on  $[a, b]$  and  $F'(x) = f(x)$ , then

$$\int_a^b f(x) dx = F(b) - F(a) = F(x) \Big|_a^b = F(x) \Big|_a^b.$$

### 3.12 Table of Indefinite Integrals

$$\int a dx = ax + C$$

$$\int x^n dx = \frac{x^{n+1}}{n+1} + C, \quad n \neq -1$$

$$\int x^{-1} dx = \int \frac{1}{x} dx = \ln |x| + C$$

$$\int e^{ax} dx = \frac{1}{a} e^{ax} + C$$

$$\int \sin x dx = -\cos x + C$$

$$\int \cos x dx = \sin x + C$$

$$\int \sec x dx = \ln |\sec x + \tan x| + C$$

$$\int \csc x dx = \ln |\csc x - \cot x| + C$$

$$\int \log_a x dx = \frac{x}{\ln a} (\ln x - 1) + C$$

$$\int (ax + b)^n dx = \frac{(ax + b)^{n+1}}{a(n+1)} + C$$

$$\int \frac{c}{ax + b} dx = \frac{c}{a} \ln |ax + b| + C$$

$$\int a^x dx = \frac{a^x}{\ln a} + C, \quad a > 0, a \neq 1$$

$$\int \tan x dx = \ln |\sec x| = -\ln |\cos x| + C$$

$$\int \cot x dx = -\ln |\csc x| = \ln |\sin x| + C$$

$$\int \sec^2 x dx = \tan x + C$$

$$\int \csc^2 x dx = -\cot x + C$$



$$\left| \begin{array}{l} \int \sec x \tan x \, dx = \sec x + C \\ \int \csc x \cot x \, dx = -\csc x + C \end{array} \right| \begin{array}{l} \int \frac{1}{\sqrt{1-x^2}} \, dx = \arcsin x + C \\ \int \frac{1}{1+x^2} \, dx = \arctan x + C \end{array}$$

## 4 Sequences and Series

### 4.1 Definition of a Sequence

A sequence is a function  $a : \mathbb{N} \rightarrow \mathbb{R}$  that assigns to each  $n \in \mathbb{N}$  a real number  $a_n$ .

$$\{a_n\} = \{a_n\}_{n=1}^{\infty} = (a_n) = \{a_1, a_2, a_3, \dots, a_n, \dots\}$$

### 4.2 Monotonic Sequence

A sequence  $\{a_n\}$  is **monotonic** if it is either monotonically increasing or monotonically decreasing.

- **Increasing:**

$$a_n \leq a_{n+1}, \quad \forall n \in \mathbb{N} \text{ (weakly increasing).}$$

$$a_n < a_{n+1}, \quad \forall n \in \mathbb{N} \text{ (strictly increasing).}$$

- **Decreasing:**

$$a_n \geq a_{n+1}, \quad \forall n \in \mathbb{N} \text{ (weakly decreasing).}$$

$$a_n > a_{n+1}, \quad \forall n \in \mathbb{N} \text{ (strictly decreasing).}$$

### 4.3 Bounded Sequence

A sequence  $\{a_n\}$  is **bounded** if and only if:

$$\exists M > 0 \text{ such that } |a_n| \leq M, \quad \forall n \in \mathbb{N}.$$

or

$$\exists M_1, M_2 \in \mathbb{R} \text{ such that } M_1 \leq a_n \leq M_2, \quad \forall n \in \mathbb{N}.$$

Equivalently,  $\{a_n\}$  is **bounded** if it is both **bounded above** and **bounded below**:

- **Bounded above:**  $\exists M_2 \in \mathbb{R}$  such that  $a_n \leq M_2, \quad \forall n \in \mathbb{N}.$

- **Bounded below:**  $\exists M_1 \in \mathbb{R}$  such that  $a_n \geq M_1, \quad \forall n \in \mathbb{N}.$

A sequence is bounded  $\iff$  It is both bounded above and bounded below

## 4.4 Limit of a Sequence

A sequence  $\{a_n\}$  has a limit  $L \in \mathbb{R}$  if:

$$\lim_{n \rightarrow \infty} a_n = L \quad \text{if} \quad \forall \varepsilon > 0, \exists N \in \mathbb{N} \text{ such that } |a_n - L| < \varepsilon, \forall n \geq N.$$

If such an  $L$  exists, the sequence is **convergent**; otherwise, it is **divergent**.

## 4.5 Limit of a Sequence Defined by a Function

Let  $f : \mathbb{R} \rightarrow \mathbb{R}$  be a function and  $\{a_n\}$  be defined by  $a_n = f(n)$ . Then:

$$\lim_{x \rightarrow \infty} f(x) = L \implies \lim_{n \rightarrow \infty} a_n = L.$$

## 4.6 Squeeze Theorem for Sequences

If  $a_n \leq b_n \leq c_n$  for all  $n \geq N$ , then:

$$\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} c_n = L \implies \lim_{n \rightarrow \infty} b_n = L.$$

## 4.7 Limit of Absolute Value of a Sequence

$$\lim_{n \rightarrow \infty} |a_n| = 0 \implies \lim_{n \rightarrow \infty} a_n = 0.$$

## 4.8 Monotone Convergence Theorem

Every bounded and monotonic sequence is convergent.

- (1) Monotonic  $\wedge$  Bounded  $\implies$  Convergent.
- (2) Monotonically Increasing  $\wedge$  Bounded Above  $\implies$  Convergent.
- (3) Monotonically Decreasing  $\wedge$  Bounded Below  $\implies$  Convergent.

## 4.9 Series

An **infinite series** is the sum of the terms of a sequence  $\{a_n\}$ :

$$\sum_{n=1}^{\infty} a_n = a_1 + a_2 + a_3 + \dots$$

The  $n^{\text{th}}$  partial sum of series:

$$S_n = \sum_{k=1}^n a_k.$$

## 4.10 Convergence and Divergence of Series

A infinite series  $\sum a_n$  **converges** if the sequence of partial sums  $\{S_n\}$  has a finite limit:

$$\sum_{k=1}^{\infty} a_k = \lim_{n \rightarrow \infty} \sum_{k=1}^n a_k \quad \text{or} \quad \lim_{n \rightarrow \infty} S_n = S.$$

Otherwise, the series **diverges**.

## 4.11 Types of Series

- |                                |                      |                   |
|--------------------------------|----------------------|-------------------|
| • Arithmetic Series            | • Telescoping Series | • Taylor Series   |
| • Geometric Series             | • Alternating Series | • Laurent Series  |
| • Arithmetico-Geometric Series | • Power Series       | • Fourier Series  |
| • Harmonic Series              | • Taylor Series      | • Binomial Series |
| • p-Series                     | • Maclaurin Series   | • Mercator Series |

## 4.12 Properties of Series

Let  $\sum a_n$  and  $\sum b_n$  be series, and let  $c, d$  be a constant. Then:

$$(1) \quad \sum_{k=a}^b c = c(b - a + 1).$$

$$(2) \quad \sum_{n=k}^{\infty} \pm c = \pm \infty, \quad c > 0.$$

$$(3) \quad \sum_{n=k}^m (ca_n \pm db_n) = c \sum_{n=k}^m a_n \pm d \sum_{n=k}^m b_n.$$

$$(4) \quad \sum_{n=k}^m a_n = \sum_{n=k}^p a_n + \sum_{n=p+1}^m a_n.$$

$$(5) \quad \sum_{n=k}^m a_n = \sum_{n=0}^{m-k} a_{m-n}.$$

$$(6) \quad \sum_{n=k}^m a_n = \sum_{j=k-h}^{m-h} a_{j+h}.$$

$$(7) \quad \sum_{k=1}^n k = \sum_{k=0}^{n-1} (k+1).$$

### 4.13 Geometric Series

$$\text{Geometric} \implies \sum_{n=0}^{\infty} ar^n = a + ar + ar^2 + ar^3 + \dots$$

- **Partial Sum:**

$$S_n = \sum_{k=0}^{n-1} ar^k = a \frac{1-r^n}{1-r}, \quad r \neq 1.$$

- **Convergence:**

$$|r| < 1 \implies \sum_{n=0}^{\infty} ar^n = \frac{a}{1-r}.$$

- **Divergence:**

$$|r| \geq 1 \implies \text{Series diverges.}$$

### 4.14 Telescoping Series

$$\text{Telescoping} \implies \sum_{n=1}^{\infty} (a_n - a_{n+1}) = (a_1 - a_2) + (a_2 - a_3) + (a_3 - a_4) + \dots$$

- **Partial Sum:**

$$S_n = \sum_{k=1}^n (a_k - a_{k+1}) = (a_1 - a_2) + (a_2 - a_3) + \dots + (a_n - a_{n+1}) = a_1 - a_{n+1}.$$

- **Convergence:**

$$\lim_{n \rightarrow \infty} a_{n+1} = L \implies \sum_{n=1}^{\infty} (a_n - a_{n+1}) = a_1 - L.$$

- **Divergence:**

$$\lim_{n \rightarrow \infty} a_{n+1} \text{ does not exist} \implies \text{Series diverges.}$$

#### 4.15 Harmonic Series

$$\text{Harmonic} \implies \sum_{n=1}^{\infty} \frac{1}{n} = 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \dots$$

- **Partial Sum and Approximation:**

$$H_n = \sum_{k=1}^n \frac{1}{k} = 1 + \frac{1}{2} + \dots + \frac{1}{n} \approx \ln(n) + \gamma$$

where  $\gamma \approx 0.57721$  is the Euler-Mascheroni constant.

- **Divergence:**

$$\sum_{n=1}^{\infty} \frac{1}{n} = \infty \text{ even though } \lim_{n \rightarrow \infty} \frac{1}{n} = 0.$$

#### 4.16 Limit of Terms in a Convergent Series

Let  $\{a_n\}$  be a sequence and  $\sum a_n$  be its series. Then:

$$\sum a_n \text{ convergent} \implies \lim_{n \rightarrow \infty} a_n = 0.$$

Note: The converse is false. ( $\lim_{n \rightarrow \infty} a_n = 0 \not\Rightarrow \sum a_n \text{ convergent}$ )

#### 4.17 List of Convergence Tests

- **Tests for Positive Series:**

- Direct Comparison Test
- Integral Test
- Limit Comparison Test
- p-Series Test

- **Tests for Alternating Series:**

- Alternating Series Test
- Dirichlet's Test

- **General Tests:**

- Divergence Test
- Root Test
- Ratio Test
- Absolute Convergence Test

- **Advanced or Specialized Tests:**

- Cauchy Condensation Test
- Kummer's Test
- Abel's Test
- Gauss's Test
- Raabe's Test
- Bertrand's Test

#### 4.18 Divergence Test (*n*th-Term Test)

$$\lim_{n \rightarrow \infty} a_n \neq 0 \vee \lim_{n \rightarrow \infty} a_n \text{ does not exist} \implies \sum a_n \text{ diverges.}$$

#### 4.19 Direct Comparison Test

If  $0 \leq a_n \leq b_n$  for all  $n \geq N$ :

- $\sum b_n \text{ converges} \implies \sum a_n \text{ converges.}$
- $\sum a_n \text{ diverges} \implies \sum b_n \text{ diverges.}$

#### 4.20 Limit Comparison Test

Let  $\sum a_n$  and  $\sum b_n$  be series with  $a_n > 0$ ,  $b_n > 0$  for all  $n \geq N$ . Define the limit:

$$L = \lim_{n \rightarrow \infty} \frac{a_n}{b_n}.$$

- $0 < L < \infty \implies \sum a_n \text{ and } \sum b_n \text{ both converge or both diverge.}$
- $L = 0 \wedge \sum b_n \text{ converges} \implies \sum a_n \text{ converges.}$
- $L = \infty \wedge \sum b_n \text{ diverges} \implies \sum a_n \text{ diverges.}$

Note: The order of division does not matter.

#### 4.21 Integral Test (Maclaurin-Cauchy Test)

For a series  $\sum a_n$  where  $a_n = f(n)$ , if  $f(x)$  is a positive, continuous, and decreasing function for all  $x \geq N$ , then:

- $\sum_{n=N}^{\infty} a_n \text{ converges} \iff \int_N^{\infty} f(x) dx \text{ converges.}$
- $\sum_{n=N}^{\infty} a_n \text{ diverges} \iff \int_N^{\infty} f(x) dx \text{ diverges.}$

#### 4.22 *p*-Series Test

For the *p*-series  $\sum_{n=1}^{\infty} \frac{1}{n^p}$ , where  $p \in \mathbb{R}$ :

- $p > 1 \iff \text{Series converges.}$
- $p \leq 1 \iff \text{Series diverges.}$

### 4.23 Integral Remainder Estimate

For a convergent series  $\sum_{n=1}^{\infty} a_n$  with  $a_n = f(n)$ , where  $f(x)$  is positive, continuous, and decreasing for all  $x \geq N$ , if the remainder  $R_n = S - S_n$  then

$$\int_{n+1}^{\infty} f(x) dx \leq R_n \leq \int_n^{\infty} f(x) dx$$
$$S_n + \int_{n+1}^{\infty} f(x) dx \leq S \leq S_n + \int_n^{\infty} f(x) dx$$

### 4.24 Alternating Series Test (Leibniz Criterion)

For an alternating series  $\sum_{n=1}^{\infty} (-1)^{n-1} a_n$ , where  $a_n > 0$ , the series converges if:

- $\lim_{n \rightarrow \infty} a_n = 0$ . (terms approach zero)
- $a_{n+1} \leq a_n$  for all  $n \geq N$ . (monotonically decreasing)

### 4.25 Alternating Series Estimation Theorem

For an alternating series approximated by its  $n$ th partial sum, the absolute error (or remainder) is less than or equal to the absolute value of the next term in the series.

$$|R_n| = |S - S_n| \leq a_{n+1} = |S_{n+1} - S_n|.$$

### 4.26 Ratio Test (d'Alembert's Criterion)

Let  $\sum a_n$  be an infinite series with  $a_n \neq 0$ . Define the limit:

$$L = \lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right|.$$

- $L < 1 \implies \sum a_n$  converges absolutely.
- $L > 1 \vee L = \infty \implies \sum a_n$  diverges.
- $L = 1 \implies$  Test is inconclusive.

## 4.27 Root Test (Cauchy's Criterion)

Let  $\sum a_n$  be an infinite series. Define the limit:

$$L = \lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \lim_{n \rightarrow \infty} |a_n|^{1/n}.$$

- $L < 1 \implies \sum a_n$  converges absolutely.
- $L > 1 \vee L = \infty \implies \sum a_n$  diverges.
- $L = 1 \implies$  Test is inconclusive.

## 4.28 Absolute Convergence Test

- **Absolute Convergence:**

$$\sum |a_n| \text{ converges} \implies \sum a_n \text{ converges absolutely.}$$

- **Conditional Convergence:**

$$\left( \sum a_n \text{ converges} \right) \wedge \left( \sum |a_n| \text{ diverges} \right) \implies \sum a_n \text{ converges conditionally.}$$

Note: All rearrangements of absolutely convergent series converge to the same sum.

## 4.29 Riemann Series Theorem

Conditionally convergent series  $\sum_{n=1}^{\infty} a_n$  can be rearranged to:

- Converge to any real number:  $\forall M \in \mathbb{R}, \exists \sigma$  such that  $\sum_{n=1}^{\infty} a_{\sigma(n)} = M$ .
- Diverge to  $\pm\infty$ :  $\exists \sigma$  such that  $\sum_{n=1}^{\infty} a_{\sigma(n)} = \pm\infty$ .
- Fail to approach any limit:  $\exists \sigma$  such that  $\lim_{N \rightarrow \infty} \sum_{n=1}^N a_{\sigma(n)}$  does not exist.

## 4.30 Power Series

A power series centered at  $c$  is an infinite series of the form

$$\sum_{n=0}^{\infty} a_n(x-c)^n = a_0 + a_1(x-c) + a_2(x-c)^2 + \dots$$

where  $\{a_n\}$  is a sequence of coefficients,  $x$  is a variable, and  $c$  is the center of the series.



### 4.31 Radius of Convergence

For a power series  $\sum_{n=0}^{\infty} a_n(x - c)^n$ , the radius of convergence  $R$  is a non-negative real number (possibly 0 or  $\infty$ ) such that:

- If  $R = 0$ : The series converges only at  $x = c$ .
- If  $R = \infty$ : The series converges for all values of  $x$ .
- If  $0 < R < \infty$ :
  - The series converges absolutely for  $|x - c| < R$ .
  - The series diverges for  $|x - c| > R$ .
  - The series may or may not converge at  $|x - c| = R$ .

**Ratio Test:**

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}(x - c)^{n+1}}{a_n(x - c)^n} \right| < 1 \implies \lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| \cdot |x - c| < 1$$

$$L \cdot |x - c| < 1 \implies |x - c| < \frac{1}{L} = \frac{1}{\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right|}$$

$$R = \frac{1}{L} = \lim_{n \rightarrow \infty} \left| \frac{a_n}{a_{n+1}} \right|$$

**Root Test:**

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n(x - c)^n|} < 1 \implies \lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} \cdot |x - c| < 1$$

$$L \cdot |x - c| < 1 \implies |x - c| < \frac{1}{L} = \frac{1}{\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|}}$$

$$R = \frac{1}{L} = \frac{1}{\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|}}$$

### 4.32 Interval of Convergence

The interval of convergence of a power series  $\sum_{n=0}^{\infty} a_n(x - c)^n$  is the set of values of  $x$  for which the series converges absolutely.

- If  $R = 0$ , the interval is  $\{c\}$ .
- If  $R = \infty$ , the interval is  $(-\infty, +\infty)$ .
- If  $0 < R < \infty$ , the interval is one of the following depending on the convergence at the endpoints:
  - $(c - R, c + R)$       ◦  $[c - R, c + R)$       ◦  $(c - R, c + R]$       ◦  $[c - R, c + R]$

### 4.33 Differentiation and Integration of Power Series

For a power series centered at  $c$

$$f(x) = \sum_{n=0}^{\infty} a_n(x-c)^n = a_0 + a_1(x-c) + a_2(x-c)^2 + a_3(x-c)^3 + \dots$$

with radius of convergence  $R$ :

• **Differentiation:**

$$f'(x) = \frac{d}{dx} \left[ \sum_{n=0}^{\infty} a_n(x-c)^n \right] = 0 + a_1 + 2a_2(x-c) + 3a_3(x-c)^2 + \dots$$

$$f'(x) = \sum_{n=1}^{\infty} n a_n(x-c)^{n-1}$$

• **Integration:**

$$\int f(x) dx = \int \sum_{n=0}^{\infty} a_n(x-c)^n dx = C + a_0(x-c) + \frac{a_1}{2}(x-c)^2 + \frac{a_2}{3}(x-c)^3 + \dots$$

$$\int f(x) dx = C + \sum_{n=0}^{\infty} \frac{a_n}{n+1} (x-c)^{n+1}$$

Note: Both operations preserve the radius of convergence  $R$ , however, convergence at the endpoints  $x = c \pm R$  may change and must be checked separately.

### 4.34 Taylor Series

Let  $f$  be infinitely differentiable at a point  $a$ . The Taylor Series of  $f$  centered at  $a$  is the infinite series

$$\begin{aligned} f(x) &= \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x-a)^n \\ &= f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \dots \end{aligned}$$

If there exists an interval where  $f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x-a)^n$ , then  $f$  is analytic at  $a$ . Note that analyticity implies infinite differentiability, but the converse is false.

### 4.35 Taylor Polynomial

The  $n$ th degree Taylor polynomial of a function  $f(x)$  at point  $a$  is the finite sum:

$$\begin{aligned} P_n(x) &= \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k \\ &= f(a) + f'(a)(x-a) + \frac{f''(a)}{2!} (x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!} (x-a)^n. \end{aligned}$$

### 4.36 Taylor's Theorem

Let  $f$  be a function that is  $n+1$  times differentiable on an open interval  $I$  containing a point  $a$ . Then for any  $x \in I$ , there exists a point  $\xi$  between  $a$  and  $x$  such that:

$$\begin{aligned} f(x) &= P_n(x) + R_n(x) \\ &= \sum_{k=0}^n \frac{f^{(k)}(a)}{k!} (x-a)^k + \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1}. \end{aligned}$$

Note:  $R_n(x) = \frac{f^{(n+1)}(\xi)}{(n+1)!} (x-a)^{n+1}$  is the Lagrange form of the remainder.

### 4.37 Taylor's Inequality

Taylor's Inequality provides an upper bound on the error when approximating a function with its Taylor polynomial. Let  $f$  be a function that is  $n+1$  times differentiable on an open interval containing  $a$  and  $x$ . If there exists a constant  $M$  such that  $f^{(n+1)}(t) \leq M$  for all  $t$  between  $a$  and  $x$ , then:

$$|R_n(x)| \leq \frac{M}{(n+1)!} |x-a|^{n+1}.$$

### 4.38 Binomial Series

For any real number  $|x| < 1$ , the binomial series is given by

$$\begin{aligned} (1+x)^\alpha &= \sum_{n=0}^{\infty} \binom{\alpha}{n} x^n \\ &= 1 + \alpha x + \frac{\alpha(\alpha-1)}{2!} x^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{3!} x^3 + \cdots \end{aligned}$$

where

$$\binom{\alpha}{n} = \frac{\alpha(\alpha-1)\cdots(\alpha-n+1)}{n!}.$$

## 5 Multivariable Calculus

### 5.1 Limit of a Function of Two Variables

$$\lim_{(x,y) \rightarrow (a,b)} f(x,y) = L \quad \text{if} \quad \forall \varepsilon > 0, \exists \delta > 0 \text{ such that } \forall (x,y) \in D,$$
$$0 < \sqrt{(x-a)^2 + (y-b)^2} < \delta \Rightarrow |f(x,y) - L| < \varepsilon.$$

### 5.2 Test for Nonexistence of a Limit

$$\bullet \lim_{(x,y) \rightarrow (a,b) \text{ along } C_1} f(x,y) = L_1 \qquad \bullet \lim_{(x,y) \rightarrow (a,b) \text{ along } C_2} f(x,y) = L_2$$

$$L_1 \neq L_2 \implies \lim_{(x,y) \rightarrow (a,b)} f(x,y) \text{ does not exist.}$$

### 5.3 Partial Derivatives

The **partial derivative** of a function  $f(x,y)$  with respect to  $x$  is defined by:

$$f_x(x,y) = \frac{\partial f}{\partial x} = \lim_{h \rightarrow 0} \frac{f(x+h,y) - f(x,y)}{h}.$$

### 5.4 Clairaut's Theorem

If the mixed partial derivatives exist and are continuous then:

$$\frac{\partial^2 f}{\partial x \partial y} = \frac{\partial^2 f}{\partial y \partial x},$$

or equivalently,

$$f_{xy} = f_{yx}.$$

### 5.5 Equation of a Tangent Plane

The **tangent plane** to the surface  $z = f(x,y)$  at the point  $(a,b,f(a,b))$  is given by:

$$z = f(a,b) + f_x(a,b)(x-a) + f_y(a,b)(y-b).$$

### 5.6 Total Differential

$$dz = f_x(x,y)dx + f_y(x,y)dy = \frac{\partial z}{\partial x}dx + \frac{\partial z}{\partial y}dy.$$

## 5.7 Chain Rule For a Function of Two Variables

If  $z = f(x, y)$  and  $x = g(t), y = h(t)$ , then:

$$\frac{dz}{dt} = \frac{\partial z}{\partial x} \frac{dx}{dt} + \frac{\partial z}{\partial y} \frac{dy}{dt}.$$

## 5.8 Implicit Differentiation of a Function of Two Variables

If  $F(x, y) = 0$  where  $y$  is implicitly defined as a function of  $x$ :

$$\frac{dy}{dx} = -\frac{F_x}{F_y} = -\frac{\frac{\partial F}{\partial x}}{\frac{\partial F}{\partial y}}.$$

## 5.9 Gradient Vector

The **gradient vector** of a function points in the direction of steepest increase of the function at a given point, with its magnitude representing the rate of that increase. It collects all the partial derivatives of the function into a single vector.

The gradient vector of  $f(x, y)$  at a point  $(x_0, y_0)$  is the vector whose components are the partial derivatives of  $f$  at that point.

$$\nabla f(x_0, y_0) = (f_x(x_0, y_0), f_y(x_0, y_0))$$

or,

$$\nabla f(x_0, y_0) = \left( \frac{\partial f}{\partial x}(x_0, y_0), \frac{\partial f}{\partial y}(x_0, y_0) \right).$$

## 5.10 Directional Derivative

The **directional derivative** of a function  $f(x, y)$  at a point  $(x_0, y_0)$  in the direction of a unit vector  $\vec{u} = (u_1, u_2)$ , where  $\|\vec{u}\| = 1$ , is the rate of change of  $f$  at  $(x_0, y_0)$  along the direction  $\vec{u}$  and is defined as:

$$D_{\vec{u}}f(x, y) = \lim_{h \rightarrow 0} \frac{f(x_0 + hu_1, y_0 + hu_2) - f(x_0, y_0)}{h}$$

If  $f(x, y)$  is differentiable at a point  $(x_0, y_0)$ , the directional derivative of  $f$  in the direction of a unit vector  $\vec{u} = (u_1, u_2)$  is defined as:

$$D_{\vec{u}}f(x_0, y_0) = \frac{\partial f}{\partial x}(x_0, y_0)u_1 + \frac{\partial f}{\partial y}(x_0, y_0)u_2,$$

or equivalently,

$$D_{\vec{u}}f(x_0, y_0) = \nabla f(x_0, y_0) \cdot \vec{u}.$$

## 5.11 Tangent Plane to a Level Surface

The **tangent plane** to the level surface at point  $(x_0, y_0, z_0)$  of  $F(x, y, z) = c$  is:

$$\nabla F(x_0, y_0, z_0) \cdot (x - x_0, y - y_0, z - z_0) = 0,$$

or written out fully,

$$F_x(x_0, y_0, z_0)(x - x_0) + F_y(x_0, y_0, z_0)(y - y_0) + F_z(x_0, y_0, z_0)(z - z_0) = 0.$$

## 5.12 Maximum and Minimum Values of a Function of Two Variables

1. **Critical Points:** Solve the system of equations

$$\frac{\partial f}{\partial x}(x, y) = 0, \quad \frac{\partial f}{\partial y}(x, y) = 0.$$

2. **Second Derivative Test:** Compute the second-order partial derivatives  $f_{xx}$ ,  $f_{yy}$ ,  $f_{xy}$  and evaluate the discriminant

$$D(x, y) = f_{xx}(x, y)f_{yy}(x, y) - [f_{xy}(x, y)]^2.$$

- If  $D > 0$  and  $f_{xx}(x_0, y_0) > 0$ : Local minimum.
- If  $D > 0$  and  $f_{xx}(x_0, y_0) < 0$ : Local maximum.
- If  $D < 0$ : Saddle point (neither max nor min).
- If  $D = 0$ : Inconclusive.

3. **Boundary Analysis.**

## 5.13 Parametric Derivative

If  $x = f(t)$  and  $y = g(t)$ , the derivative of  $y$  with respect to  $x$  is:

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}}.$$

## 5.14 Area Under a Parametric Curve

Let a parametric curve be defined by  $x = f(t)$  and  $y = g(t)$  from  $t = a$  to  $t = b$ . Then, the area is given by:

$$A = \int_{x=f(a)}^{x=f(b)} y \, dx = \int_{t=a}^{t=b} g(t) \cdot f'(t) \, dt.$$

### 5.15 Arc Length of a Parametric Curve

The **arc length** of a parametric curve defined by  $x = f(t)$  and  $y = g(t)$  from  $t = a$  to  $t = b$  is given by:

$$L = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt.$$

### 5.16 Surface Area of a Solid Revolution for a Parametric Curve

If the curve, defined by  $x = f(t)$  and  $y = g(t)$  from  $t = a$  to  $t = b$ , is rotated about the  $x$ -axis, the surface area  $S$  is given by:

$$S = 2\pi \int_a^b g(t) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt.$$

### 5.17 Polar Coordinates

- **From Polar to Cartesian:**

$$x = r \cos(\theta), \quad y = r \sin(\theta).$$

- **From Cartesian to Polar:**

$$r = \sqrt{x^2 + y^2}, \quad \theta = \arctan\left(\frac{y}{x}\right).$$

### 5.18 Area in Polar Coordinates

The area  $A$  of a region enclosed by a polar curve  $r = f(\theta)$  from  $\theta = a$  to  $\theta = b$  is given by:

$$A = \frac{1}{2} \int_a^b r^2 d\theta.$$

### 5.19 Arc Length in Polar Coordinates

The arc length  $L$  of a polar curve defined by  $r = f(\theta)$  from  $\theta = a$  to  $\theta = b$  is given by:

$$L = \int_a^b \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} d\theta.$$

## 5.20 Tangents to Polar Curves

The slope of the tangent line to a polar curve  $r = f(\theta)$  at a given point  $(r, \theta)$  is given by:

$$\frac{dy}{dx} = \frac{\frac{dr}{d\theta} \sin(\theta) + r \cos(\theta)}{\frac{dr}{d\theta} \cos(\theta) - r \sin(\theta)}.$$

## 5.21 Double Integral

If  $R$  is a bounded region and  $f$  is integrable over  $R$ , then:

$$\iint_R f(x, y) dA = \lim_{m, n \rightarrow \infty} \sum_{i=1}^m \sum_{j=1}^n f(x_{ij}^*, y_{ij}^*) \Delta A_{ij}.$$

## 5.22 Iterated Integral

For a function  $f(x, y)$  defined over a rectangular region  $R = [a, b] \times [c, d]$ , the double integral

$$\int_c^d \int_a^b f(x, y) dx dy.$$

## 5.23 Average Value of a Function over a Region

The average value of  $f$  the region  $R$  is defined by:

$$f_{avg} = \frac{1}{A(R)} \iint_R f(x, y) dA.$$

## 5.24 Double Integral Over a General Region

- **Type I Region** (vertical slices):

If  $R = \{(x, y) : a \leq x \leq b, g_1(x) \leq y \leq g_2(x)\}$ , then:

$$\iint_R f(x, y) dA = \int_a^b \int_{g_1(x)}^{g_2(x)} f(x, y) dy dx.$$

- **Type II Region** (horizontal slices):

If  $R = \{(x, y) : c \leq y \leq d, h_1(y) \leq x \leq h_2(y)\}$ , then:

$$\iint_R f(x, y) dA = \int_c^d \int_{h_1(y)}^{h_2(y)} f(x, y) dx dy.$$



## 5.25 Double Integral in Polar Coordinates

The double integral in polar coordinates is given by:

$$\iint_R f(x, y) \, dA = \iint_{R'} f(r \cos \theta, r \sin \theta) r \, dr \, d\theta.$$

## 5.26 Double Integral in Polar Coordinates Over a General Region

If  $R = \{(r, \theta) : \alpha \leq \theta \leq \beta, r_1(\theta) \leq r \leq r_2(\theta)\}$ , then:

$$\iint_R f(x, y) \, dA = \int_{\alpha}^{\beta} \int_{r_1(\theta)}^{r_2(\theta)} f(r \cos \theta, r \sin \theta) r \, dr \, d\theta.$$