

# Calculus Notes

Abror Maksudov

February 23, 2025

## Contents

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

|          |   |           |
|----------|---|-----------|
| <b>3</b> | <b>Integrals</b>                                    | <b>11</b> |
| 3.1      | Antiderivatives . . . . .                           | 11        |
| 3.2      | Indefinite Integrals . . . . .                      | 11        |
| 3.3      | Riemann Sum . . . . .                               | 11        |
| 3.4      | Partitions of an Interval . . . . .                 | 11        |
| 3.5      | Types of Riemann Sums . . . . .                     | 12        |
| 3.6      | Definite Integral . . . . .                         | 13        |
| 3.7      | Properties of Definite Integrals . . . . .          | 14        |
| 3.8      | Net and Total Area . . . . .                        | 14        |
| 3.9      | Mean Value Theorem for Integrals . . . . .          | 15        |
| 3.10     | Fundamental Theorem of Calculus. Part 1 . . . . .   | 15        |
| 3.11     | Fundamental Theorem of Calculus. Part 2 . . . . .   | 15        |
| 3.12     | Table of Indefinite Integrals . . . . .             | 15        |
| <b>4</b> | <b>Sequences and Series</b>                         | <b>16</b> |
| 4.1      | Definition of a Sequence . . . . .                  | 16        |
| 4.2      | Monotonic Sequence . . . . .                        | 16        |
| 4.3      | Bounded Sequence . . . . .                          | 16        |
| 4.4      | Limit of a Sequence . . . . .                       | 17        |
| 4.5      | Limit of a Sequence Defined by a Function . . . . . | 17        |
| 4.6      | Squeeze Theorem for Sequences . . . . .             | 17        |
| 4.7      | Limit of Absolute Value of a Sequence . . . . .     | 17        |
| 4.8      | Monotone Convergence Theorem . . . . .              | 17        |
| 4.9      | Series . . . . .                                    | 17        |
| 4.10     | Convergence and Divergence of Series . . . . .      | 18        |
| 4.11     | Types of Series . . . . .                           | 18        |
| 4.12     | Properties of Series . . . . .                      | 18        |
| 4.13     | Geometric Series . . . . .                          | 19        |

# 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

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

## 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  $a$ , and

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

then

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

## 1.10 Continuity

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

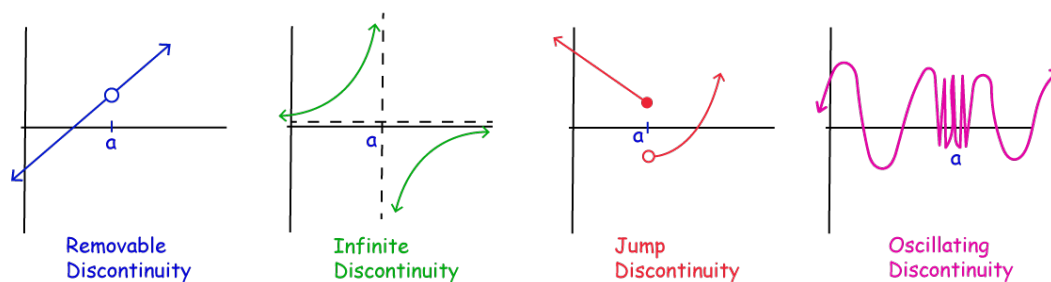
- (1)  $f(a)$  exists
- (2)  $\lim_{x \rightarrow a} f(x)$  exists
- (3)  $\lim_{x \rightarrow a} f(x) = f(a)$

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  $Q$ :

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

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

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

**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.

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

$$7. \lim_{x \rightarrow 0} \left(1 + \frac{k}{x}\right)^{mx} = e^{mk}$$

$$2. \lim_{x \rightarrow 0} \frac{\tan ax}{bx} = \frac{a}{b}$$

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

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

$$9. \lim_{x \rightarrow 0} \frac{\log_a(1+x)}{x} = \log_a e$$

$$4. \lim_{x \rightarrow 0} \frac{1 - \cos x}{x^2} = \frac{1}{2}$$

$$10. \lim_{x \rightarrow 0^+} x^x = 1$$

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

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

$$6. \lim_{x \rightarrow 0} \frac{a^x - 1}{x} = \ln a$$

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

## 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:

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

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

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

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

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

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

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

## 2.6 Table of Derivatives

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

## 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

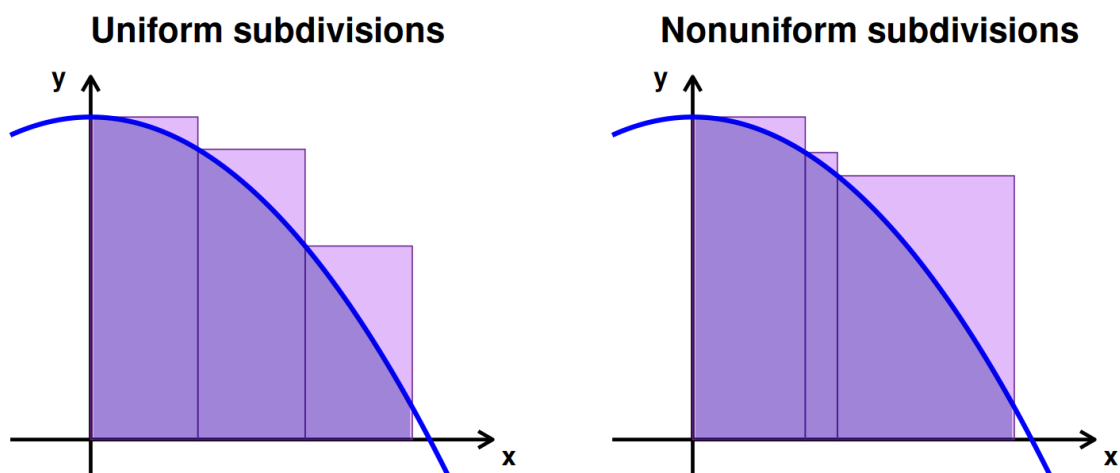
Let  $f(x)$  be a function defined on a closed interval  $[a, b]$ , and let the interval be partitioned into  $n$  subintervals by inserting  $n - 1$  points  $x_1, x_2, \dots, x_{n-1}$  such that:

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

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:

$$(1) \quad \int_a^b c \, dx = c(b - a).$$

$$(2) \quad \int_a^a f(x) \, dx = 0.$$

$$(3) \quad \int_b^a f(x) \, dx = - \int_a^b f(x) \, dx.$$

$$(4) \quad \int_a^b cf(x) \, dx = c \int_a^b f(x) \, dx.$$

$$(5) \quad \int_a^b [f(x) \pm g(x)] \, dx = \int_a^b f(x) \, dx \pm \int_a^b g(x) \, dx.$$

$$(6) \quad \int_a^b f(x) \, dx = \int_a^c f(x) \, dx + \int_c^b f(x) \, dx.$$

$$(7) \quad \int_a^b f(x) \, dx \leq \int_a^b g(x) \, dx \quad \text{if } f(x) \leq g(x) \text{ on } [a, b].$$

$$(8) \quad \left| \int_a^b f(x) \, dx \right| \leq \int_a^b |f(x)| \, dx.$$

$$(9) \quad m(b - a) \leq \int_a^b f(x) \, dx \leq M(b - a) \quad \text{if } m \leq f(x) \leq M \text{ on } [a, b].$$

### 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## 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:**

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