

# Advanced Engineering Mathematics

## Series

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### Module 1: Infinite Series

This lecture introduces the fundamental theory of infinite series as used in Advanced Engineering Mathematics. Emphasis is placed on convergence concepts and power series representations, which are essential in engineering analysis, modeling, and later topics such as differential equations and signal processing.

#### Series

A **series** is the sum of the terms of a sequence. If  $\{a_n\}$  is a sequence, then the corresponding series is written as

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

The value of a series is determined by the behavior of its **partial sums**

$$S_N = \sum_{n=1}^N a_n.$$

- The series **converges** if  $\lim_{N \rightarrow \infty} S_N$  exists and is finite.
- The series **diverges** if this limit does not exist or is infinite.

**Necessary Condition for Convergence:**

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

If this condition is not satisfied, the series must diverge.

**Example 1** Determine if the series

$$\sum_{n=1}^{\infty} n$$

converges or diverges.

**Solution:** The  $n$ th partial sum is

$$s_n = \sum_{i=1}^n i = \frac{n(n+1)}{2}.$$

As  $n \rightarrow \infty$ ,

$$\lim_{n \rightarrow \infty} \frac{n(n+1)}{2} = \infty,$$

so the sequence of partial sums diverges and thus the series diverges.

**Example 2** Determine if the series

$$\sum_{n=2}^{\infty} \frac{1}{n^2 - 1}$$

converges or diverges, and if it converges, find its value.

**Solution:** A known formula for the partial sums of this series is

$$s_n = \sum_{i=2}^n \frac{1}{i^2 - 1} = \frac{3}{4} - \frac{1}{2n} - \frac{1}{2(n+1)}.$$

Taking the limit as  $n \rightarrow \infty$ ,

$$\lim_{n \rightarrow \infty} s_n = \frac{3}{4}.$$

Thus the series converges and

$$\sum_{n=2}^{\infty} \frac{1}{n^2 - 1} = \frac{3}{4}.$$

**Example 3** Determine if the series

$$\sum_{n=0}^{\infty} (-1)^n$$

converges or diverges.

**Solution:** The partial sums oscillate:

$$s_0 = 1, \quad s_1 = 0, \quad s_2 = 1, \quad s_3 = 0, \quad \dots$$

Since the sequence of partial sums does not approach a single value, this series diverges.

**Example 4** Determine if the series

$$\sum_{n=1}^{\infty} \frac{1}{3^{n-1}}$$

converges or diverges. If it converges, find the value.

**Solution:** A formula for the partial sums is

$$s_n = \sum_{i=1}^n \frac{1}{3^{i-1}} = \frac{3}{2} \left( 1 - \frac{1}{3^n} \right).$$

Taking the limit,

$$\lim_{n \rightarrow \infty} s_n = \frac{3}{2}.$$

Therefore, the series converges with

$$\sum_{n=1}^{\infty} \frac{1}{3^{n-1}} = \frac{3}{2}.$$

**Observation:** In Examples 2 and 4, the terms of the series approach zero and the series converges; in Examples 1 and 3, they do not approach a limit that yields a convergent series. Thus, the limit of the series terms is an important preliminary check for convergence before applying tests.

## 1.1 Power Series and Their Convergence

### Definition of a Power Series

A **power series** is an infinite series of the form

$$\sum_{n=0}^{\infty} c_n (x - x_0)^n$$

where:

- $c_n$  are constant coefficients,
- $x_0$  is a fixed real number called the **center** of the series,
- $(x - x_0)^n$  represents powers of the variable  $x$ .

Unlike ordinary numerical series, a power series depends on the value of  $x$ . As a result, a power series may converge for some values of  $x$  and diverge for others.

## General Behavior of Power Series

For a given power series

$$\sum_{n=0}^{\infty} c_n(x - x_0)^n,$$

there exists a real number  $R \geq 0$ , called the **radius of convergence**, such that:

$$\begin{cases} \text{The series converges absolutely if } |x - x_0| < R, \\ \text{The series diverges if } |x - x_0| > R, \\ \text{The series may converge or diverge if } |x - x_0| = R. \end{cases}$$

The radius of convergence can be determined from the coefficients of the series through:

$$\boxed{(a) \quad R = \frac{1}{\lim_{n \rightarrow \infty} \sqrt[n]{|c_n|}}} \quad \boxed{(b) \quad R = \frac{1}{\lim_{n \rightarrow \infty} \left| \frac{c_{n+1}}{c_n} \right|}}$$

provided the limit exists.

The interval

$$(x_0 - R, x_0 + R)$$

together with any endpoints where the series converges is called the **interval of convergence**.

## Convergence, Divergence, and Absolute Convergence

Let

$$\sum_{n=0}^{\infty} c_n(x - x_0)^n$$

be a power series.

- The series is said to **converge** at a value  $x = b$  if the numerical series

$$\sum_{n=0}^{\infty} c_n(b - x_0)^n$$

converges.

- The series **diverges** at  $x = b$  if the corresponding numerical series diverges.
- The series is **absolutely convergent** at  $x = b$  if

$$\sum_{n=0}^{\infty} |c_n(b - x_0)^n|$$

converges.

**Important Result:** If a power series converges at a point  $x = b$ , then it converges absolutely for all values of  $x$  such that  $|x - x_0| < |b - x_0|$ .

### Focus on Convergence of Power Series

The convergence of a power series depends primarily on the distance of  $x$  from the center  $x_0$ . The farther  $x$  is from  $x_0$ , the more likely the series is to diverge.

To determine where a power series converges, the following steps are followed:

1. Apply a convergence test to find the radius of convergence  $R$ .
2. Determine the interval  $|x - x_0| < R$ .
3. Test the endpoints  $x = x_0 \pm R$  separately.

### Convergence Tests for Power Series

**1. Ratio Test** Let the power series be

$$\sum_{n=0}^{\infty} c_n(x - x_0)^n,$$

and define

$$a_n = c_n(x - x_0)^n.$$

Compute

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

- If the limit is less than 1, the series converges absolutely.
- If the limit is greater than 1, the series diverges.
- If the limit equals 1, the test is inconclusive.

## Examples: Radius and Interval of Convergence Using the Ratio Test

**Example 1: Power Series of  $e^x$**  Consider the power series

$$\sum_{n=0}^{\infty} \frac{x^n}{n!}.$$

Let

$$a_n = \frac{x^n}{n!}.$$

Applying the Ratio Test,

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n \rightarrow \infty} \left| \frac{x^{n+1}}{(n+1)!} \cdot \frac{n!}{x^n} \right| = \lim_{n \rightarrow \infty} \frac{|x|}{n+1} = 0.$$

Since the limit is zero for all real values of  $x$ , the series converges for every  $x$ .

$$\boxed{R = \infty}$$

Thus, the interval of convergence is

$$\boxed{(-\infty, \infty)}.$$

**Example 2: Geometric Series  $\frac{1}{1-x}$**  Consider the power series

$$\sum_{n=0}^{\infty} x^n.$$

Let

$$a_n = x^n.$$

Applying the Ratio Test,

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

For convergence,

$$|x| < 1.$$

Thus, the radius of convergence is

$$\boxed{R = 1}.$$

**Endpoint Testing:**

- At  $x = -1$ :

$$\sum_{n=0}^{\infty} (-1)^n \quad \text{diverges.}$$

- At  $x = 1$ :

$$\sum_{n=0}^{\infty} 1 \quad \text{diverges.}$$

Hence, the interval of convergence is

$$\boxed{(-1, 1)}.$$

**Example 3: Series Involving Factorials** Consider the power series

$$\sum_{n=0}^{\infty} n! x^n.$$

Let

$$a_n = n! x^n.$$

Applying the Ratio Test,

$$\lim_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n \rightarrow \infty} \left| \frac{(n+1)! x^{n+1}}{n! x^n} \right| = \lim_{n \rightarrow \infty} (n+1) |x|.$$

For convergence,

$$(n+1)|x| < 1.$$

As  $n \rightarrow \infty$ , this inequality holds only when  $x = 0$ .

$$\boxed{R = 0}.$$

Thus, the series converges only at  $x = 0$ , and the interval of convergence is

$$\boxed{\{0\}}.$$

**Summary of Results:**

Series	Radius of Convergence	Interval of Convergence
$\sum \frac{x^n}{n!}$	$R = \infty$	$(-\infty, \infty)$
$\sum x^n$	$R = 1$	$(-1, 1)$
$\sum n!x^n$	$R = 0$	$\{0\}$

**2. Root Test** The **Root Test** may also be applied:

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|}.$$

The conclusions are the same as those of the Ratio Test.

**Example 4: Power Series with Exponential Coefficients** Consider the power series

$$\sum_{n=0}^{\infty} \frac{(2x)^n}{n}.$$

Let

$$a_n = \frac{(2x)^n}{n}.$$

Apply the Root Test:

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \lim_{n \rightarrow \infty} \sqrt[n]{\frac{|2x|^n}{n}} = |2x| \cdot \lim_{n \rightarrow \infty} \sqrt[n]{\frac{1}{n}}.$$

Since

$$\lim_{n \rightarrow \infty} \sqrt[n]{\frac{1}{n}} = 1,$$

we obtain

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = |2x|.$$

For convergence,

$$|2x| < 1 \quad \Rightarrow \quad |x| < \frac{1}{2}.$$

Thus, the radius of convergence is

$$\boxed{R = \frac{1}{2}}.$$

**Endpoint Testing:**



- At  $x = \frac{1}{2}$ :

$$\sum_{n=0}^{\infty} \frac{1}{n} \quad \text{diverges.}$$

- At  $x = -\frac{1}{2}$ :

$$\sum_{n=0}^{\infty} \frac{(-1)^n}{n} \quad \text{converges (alternating series).}$$

Hence, the interval of convergence is

$$\left[ -\frac{1}{2}, \frac{1}{2} \right).$$

**Example 5: Power Series with Polynomial Growth** Consider the power series

$$\sum_{n=0}^{\infty} n^2 x^n.$$

Let

$$a_n = n^2 x^n.$$

Apply the Root Test:

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \lim_{n \rightarrow \infty} \sqrt[n]{n^2 |x|^n} = |x| \cdot \lim_{n \rightarrow \infty} \sqrt[n]{n^2}.$$

Since

$$\lim_{n \rightarrow \infty} \sqrt[n]{n^2} = 1,$$

we have

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = |x|.$$

For convergence,

$$|x| < 1.$$

Thus, the radius of convergence is

$$\boxed{R = 1}.$$

**Endpoint Testing:**

- At  $x = 1$ :

$$\sum_{n=0}^{\infty} n^2 \quad \text{diverges.}$$

- At  $x = -1$ :

$$\sum_{n=0}^{\infty} (-1)^n n^2 \quad \text{diverges.}$$

Hence, the interval of convergence is

$$\boxed{(-1, 1)}.$$

**Example 6: Power Series with Factorials in the Denominator** Consider the power series

$$\sum_{n=0}^{\infty} \frac{x^n}{(n!)^2}.$$

Let

$$a_n = \frac{x^n}{(n!)^2}.$$

Apply the Root Test:

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = \lim_{n \rightarrow \infty} \frac{|x|}{(n!)^{2/n}}.$$

Since  $(n!)^{1/n} \rightarrow \infty$  as  $n \rightarrow \infty$ , it follows that

$$\lim_{n \rightarrow \infty} \sqrt[n]{|a_n|} = 0$$

for all real  $x$ .

Therefore, the series converges for all  $x$ , and

$$\boxed{R = \infty}.$$

The interval of convergence is

$$\boxed{(-\infty, \infty)}.$$

### Endpoint Testing: Common Tests and When to Use Them

After finding the radius of convergence  $R$ , the power series must be tested at the endpoints

$$x = x_0 - R \quad \text{and} \quad x = x_0 + R.$$

At each endpoint, the power series becomes a numerical series. Since the Ratio and Root Tests are inconclusive at endpoints, other convergence tests must be used.

**1.  $p$ -Series Test** A series of the form

$$\sum_{n=1}^{\infty} \frac{1}{n^p}$$

is called a  **$p$ -series**.

- The series converges if  $p > 1$ .
- The series diverges if  $p \leq 1$ .

**When to use:** This test is used when the endpoint series simplifies to a rational expression involving powers of  $n$ , such as

$$\sum \frac{1}{n^2}, \quad \sum \frac{1}{\sqrt{n}}, \quad \sum \frac{1}{n}.$$

**Example:**

$$\sum_{n=1}^{\infty} \frac{1}{n^2} \quad \text{converges} \quad (p = 2 > 1),$$

$$\sum_{n=1}^{\infty} \frac{1}{n} \quad \text{diverges} \quad (p = 1).$$

**2. Alternating Series Test** An alternating series has the form

$$\sum_{n=1}^{\infty} (-1)^n b_n \quad \text{or} \quad \sum_{n=1}^{\infty} (-1)^{n+1} b_n,$$

where  $b_n > 0$  for all  $n$ .

The series converges if:

1.  $b_n$  is decreasing, and
2.  $\lim_{n \rightarrow \infty} b_n = 0$ .

**When to use:** This test is used when substituting an endpoint produces alternating signs, typically from terms such as  $(-1)^n$ .

**Important Note:** An alternating series may converge even if it does not converge absolutely.

**Example:**

$$\sum_{n=1}^{\infty} \frac{(-1)^n}{n} \quad \text{converges (conditionally)}.$$

**3. Comparison Test** Let  $\sum a_n$  and  $\sum b_n$  be series with  $0 \leq a_n \leq b_n$  for all sufficiently large  $n$ .

- If  $\sum b_n$  converges, then  $\sum a_n$  converges.
- If  $\sum a_n$  diverges, then  $\sum b_n$  diverges.

**When to use:** This test is used when the endpoint series resembles a known series (such as a  $p$ -series) but does not match it exactly.

**Example:**

$$\sum_{n=1}^{\infty} \frac{1}{n^2 + 1} \text{ converges by comparison with } \sum \frac{1}{n^2}.$$

**Choosing the Appropriate Test** At an endpoint:

- If the series resembles  $\frac{1}{n^p}$ , use the  **$p$ -series test**.
- If the series alternates in sign, try the **Alternating Series Test** first.
- If the series resembles a known convergent or divergent series but is not exact, use the **Comparison Test**.

Each endpoint must be tested **independently**. A power series may converge at one endpoint and diverge at the other.

## 1.2 Divergence of Series

A series  $\sum a_n$  is said to **diverge** if the sequence of partial sums

$$S_n = a_1 + a_2 + \cdots + a_n$$

does not approach a finite limit as  $n \rightarrow \infty$ .

**Important Observation** A necessary condition for convergence is

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

If this limit does not exist or is not zero, the series **must diverge**. However, this condition alone does not guarantee convergence.

## Key Divergence Tests

- $n$ th-Term Test for Divergence
- Harmonic Series
- Comparison with Known Divergent Series

### 1. $n$ th-Term Test for Divergence

If

$$\lim_{n \rightarrow \infty} a_n \neq 0 \quad \text{or does not exist,}$$

then the series

$$\sum_{n=1}^{\infty} a_n$$

diverges.

**Important Note:** If  $\lim_{n \rightarrow \infty} a_n = 0$ , the test is inconclusive.

#### Example 1: $n$ th-Term Test

$$\sum_{n=1}^{\infty} \frac{n}{n+1}$$

Since

$$\lim_{n \rightarrow \infty} \frac{n}{n+1} = 1 \neq 0,$$

the series diverges by the  $n$ th-term test.

#### Example 2: Oscillating Terms

$$\sum_{n=1}^{\infty} (-1)^n$$

Here, the sequence  $a_n = (-1)^n$  does not approach a limit. Therefore, the series diverges by the  $n$ th-term test.

### 2. Harmonic Series

The **harmonic series** is defined as

$$\sum_{n=1}^{\infty} \frac{1}{n}.$$

Although

$$\lim_{n \rightarrow \infty} \frac{1}{n} = 0,$$

the harmonic series **diverges**.

This example shows that the condition  $\lim_{n \rightarrow \infty} a_n = 0$  is necessary but not sufficient for convergence.

### Example 3: Constant Multiple of the Harmonic Series

$$\sum_{n=1}^{\infty} \frac{5}{n}$$

Since this is a constant multiple of the harmonic series, it also diverges.

### 3. Comparison with Divergent Series

If  $0 \leq a_n \leq b_n$  for all sufficiently large  $n$  and

$$\sum b_n \text{ diverges,}$$

then

$$\sum a_n \text{ also diverges.}$$

### Example 4: Comparison Test

$$\sum_{n=1}^{\infty} \frac{1}{\sqrt{n}}$$

This is a  $p$ -series with  $p = \frac{1}{2} < 1$ , which diverges. Therefore, any series comparable to it will also diverge.

### Example 5: Rational Function

$$\sum_{n=1}^{\infty} \frac{n+1}{n}$$

Since

$$\frac{n+1}{n} = 1 + \frac{1}{n},$$

and the terms do not approach zero, the series diverges by the  $n$ th-term test.

## Summary of Divergence Results

- If  $\lim_{n \rightarrow \infty} a_n \neq 0$ , the series diverges.
- The harmonic series diverges even though its terms approach zero.
- Series comparable to divergent  $p$ -series with  $p \leq 1$  diverge.

## 1.3 Absolute Convergence

A series  $\sum a_n$  is **absolutely convergent** if

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

Absolute convergence guarantees convergence of the original series.

### Example 1

$$\sum_{n=1}^{\infty} \frac{(-1)^n}{n^2}$$

The absolute series

$$\sum_{n=1}^{\infty} \frac{1}{n^2}$$

converges; hence the given series is absolutely convergent.

### Example 2

$$\sum_{n=1}^{\infty} (-1)^n \frac{1}{n}$$

The absolute series diverges, but the original series converges conditionally.

### Example 3

$$\sum_{n=1}^{\infty} (-1)^n \frac{n}{n^2 + 1}$$

The absolute series behaves like  $\sum \frac{1}{n}$  and diverges. The original series converges conditionally.

## 1.4 Taylor Series

If a function  $f(x)$  has derivatives of all orders at  $x = a$ , then its Taylor series is

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} (x - a)^n$$

**Example 1: Taylor Series of  $e^x$  about  $a = 1$**

$$e^x = e \left[ 1 + (x - 1) + \frac{(x - 1)^2}{2!} + \dots \right]$$

**Example 2: Taylor Series of  $\ln x$  about  $a = 1$**

$$\ln x = (x - 1) - \frac{(x - 1)^2}{2} + \frac{(x - 1)^3}{3} - \dots$$

**Example 3: Polynomial Approximation** Approximate  $\sqrt{x}$  near  $x = 4$ :

$$\sqrt{x} = 2 + \frac{1}{4}(x - 4) - \frac{1}{64}(x - 4)^2 + \dots$$

## 1.5 Maclaurin Series

A Maclaurin series is a Taylor series centered at  $a = 0$ :

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(0)}{n!} x^n$$

**Example 1:  $e^x$**

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

**Example 2:  $\sin x$**

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots$$

**Example 3:  $\cos x$**

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \dots$$

**Engineering Insight:** Power series allow engineers to approximate complex functions, solve differential equations, and analyze system behavior near operating points.