Math 141

Lecture 13

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Outline

1. Alternating Series
   - Estimating Sums
   - Absolute Convergence

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   - Estimating Sums
   - Absolute Convergence
2. Absolute Convergence and the Ratio and Root Tests
   - The Ratio Test
   - The Root Test

Alternating Series

Definition (Alternating Series)

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Here are two examples:

$$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \cdots = \sum_{n=1}^{\infty} \qquad -$$

$$-\frac{1}{2} + \frac{2}{3} - \frac{3}{4} + \frac{4}{5} - \frac{5}{6} + \frac{6}{7} - \cdots = \sum_{n=1}^{\infty} \qquad \overline{\qquad\qquad}$$

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The nth term of an alternating series has the form

$$a_n = (-1)^{n-1} b_n \qquad \text{or} \qquad a_n = (-1)^n b_n$$

where b_n is positive.

Theorem (The Alternating Series Test)

If the alternating series

$$\sum_{n=1}^{\infty}(-1)^{n-1}b_n = b_1 - b_2 + b_3 - b_4 + b_5 - \cdots, \qquad b_n > 0$$

satisfies

1. $b_{n+1} \leq b_n$ *for all* n *and*
2. $\lim_{n\to\infty} b_n = 0$

then the series is convergent.

Example

The alternating harmonic series

$$1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n}$$

satisfies

1. $b_{n+1} < b_n$ because $\frac{1}{n+1} < \frac{1}{n}$.
2. $\lim_{n\to\infty} b_n = \lim_{n\to\infty} \frac{1}{n}$

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2. $\lim_{n\to\infty} b_n = \lim_{n\to\infty} \frac{1}{n} = 0$.

Therefore the series is convergent by the Alternating Series Test.

Example

The series $\sum_{n=1}^{\infty}(-1)^n \frac{3n}{4n-1}$ is alternating, but

$$\lim_{n\to\infty} b_n = \lim_{n\to\infty} \frac{3n}{4n-1}$$

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Therefore the series is divergent by the Alternating Series Test.

Estimating Sums

This theorem allows us to estimate the size of the remainder $R_n = s - s_n$ in an alternating series.

Theorem (Alternating Series Estimation Theorem)

Let $\sum(-1)^{n-1} b_n$ *be the sum of an alternating series that satisfies*

1. $0 \leq b_{n+1} \leq b_n$ *and*
2. $\lim_{n\to\infty} b_n = 0$.

Then the size of the error is less than the first omitted term; that is,

$$|R_n| = |s - s_n| \leq b_{n+1}.$$

Example

Find the sum of $\sum_{n=0}^{\infty} \frac{(-1)^n}{n!}$ correct to three decimal places. $(0! = 1.)$

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- $|s - s_6| \le b_7 = \frac{1}{5040} < 0.0002.$

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- $|s - s_6| \leq b_7 = \frac{1}{5040} < 0.0002.$
- $s_6 = 1 - 1 + \frac{1}{2} - \frac{1}{6} + \frac{1}{24} - \frac{1}{120} + \frac{1}{720} \approx 0.368056.$

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- $|s - s_6| \leq b_7 = \frac{1}{5040} < 0.0002$.
- $s_6 = 1 - 1 + \frac{1}{2} - \frac{1}{6} + \frac{1}{24} - \frac{1}{120} + \frac{1}{720} \approx 0.368056$.
- The error of less than 0.0002 doesn't affect the third decimal place, so $s \approx s_6 \approx 0.368$.

Absolute Convergence and the Ratio and Root Tests

In this section, we start with any series $\sum a_n$ and consider the corresponding series

$$\sum |a_n| = |a_1| + |a_2| + |a_3| + \cdots$$

consisting of the absolute values of the terms of the original series.

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If $\sum a_n$ is a series with all positive terms, then $|a_n| = a_n$ and absolute convergence is the same thing as convergence in this case.

Example

The series

$$\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} = 1 - \frac{1}{2^2} + \frac{1}{3^2} - \frac{1}{4^2} + \cdots$$

is absolutely convergent because

$$\sum_{n=1}^{\infty} \left| \frac{(-1)^{n-1}}{n^2} \right| = 1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \cdots$$

is a convergent p-series with $p = 2$.

Example

The alternating harmonic series

$$\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots$$

is convergent (by the alternating series test, as already demonstrated).

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- This is a p-series with $p = 1$.
- Therefore $\sum_{n=1}^{\infty} \left| \frac{(-1)^{n-1}}{n} \right|$ is divergent.
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Example

The alternating harmonic series

$$\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \cdots$$

is convergent (by the alternating series test, as already demonstrated).

- Is it absolutely convergent?

$$\sum_{n=1}^{\infty} \left| \frac{(-1)^{n-1}}{n} \right| = 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots$$

- This is a *p*-series with $p = 1$.
- Therefore $\sum_{n=1}^{\infty} \left| \frac{(-1)^{n-1}}{n} \right|$ is divergent.
- Therefore $\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n}$ is not absolutely convergent.

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A series $\sum a_n$ is called conditionally convergent if it is convergent but not absolutely convergent.

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- Question: Is it possible for a series to be absolutely convergent but not convergent?

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A series $\sum a_n$ is called conditionally convergent if it is convergent but not absolutely convergent.

- The alternating harmonic series is conditionally convergent.
- Therefore it is possible for a series to be convergent but not absolutely convergent.
- Question: Is it possible for a series to be absolutely convergent but not convergent?
- Answer: No. This is the content of the next theorem.

Theorem (Absolute Convergence Implies Convergence)

If a series is absolutely convergent, then it is convergent.

Example

Determine whether

$$\sum_{n=1}^{\infty} \frac{\cos n}{n^2} = \frac{\cos 1}{1^2} + \frac{\cos 2}{2^2} + \frac{\cos 3}{3^2} + \frac{\cos 4}{4^2} + \cdots$$

is convergent or divergent.

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$$0 \quad \leq \quad |\cos n| \quad \leq \quad 1$$

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- Therefore $\sum \frac{\cos n}{n^2}$ is absolutely convergent.

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- Therefore $\sum \frac{\cos n}{n^2}$ is absolutely convergent.
- Therefore by the previous theorem, $\sum \frac{\cos n}{n^2}$ is convergent.

The Ratio Test

Theorem (The Ratio Test)

1. *If* $\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = L < 1$, *then the series* $\sum a_n$ *is absolutely convergent (and therefore convergent).*
2. *If* $\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = L > 1$ *or* $\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \infty$, *then the series* $\sum a_n$ *is divergent.*
3. *If* $\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = L = 1$, *then the Ratio Test is inconclusive.*

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Test the series $\sum_{n=1}^{\infty}(-1)^n \frac{n^3}{3^n}$ for absolute convergence.

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$$\left|\frac{a_{n+1}}{a_n}\right| = \left|\frac{(-1)^{n+1}\frac{(n+1)^3}{3^{n+1}}}{(-1)^n \frac{n^3}{3^n}}\right|$$

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&\to \frac{1}{3}
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Test the series $\sum_{n=1}^{\infty}(-1)^n \frac{n^3}{3^n}$ for absolute convergence.

$$\begin{aligned}
\left|\frac{a_{n+1}}{a_n}\right| &= \left|\frac{(-1)^{n+1}\frac{(n+1)^3}{3^{n+1}}}{(-1)^n\frac{n^3}{3^n}}\right| \\
&= \frac{(n+1)^3}{3^{n+1}} \cdot \frac{3^n}{n^3} \\
&= \frac{1}{3}\left(\frac{n+1}{n}\right)^3 \\
&= \frac{1}{3}\left(1+\frac{1}{n}\right)^3 \\
&\to \frac{1}{3}
\end{aligned}$$

Therefore the series is by the Ratio Test.

Example

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Therefore the series is absolutely convergent by the Ratio Test.

Example

Test the convergence of the series $\sum_{n=1}^{\infty} \frac{n^n}{n!}$.

Example

Test the convergence of the series $\displaystyle\sum_{n=1}^{\infty} \frac{n^n}{n!}$.

$$\left|\frac{a_{n+1}}{a_n}\right| = \left|\frac{\frac{(n+1)^{n+1}}{(n+1)!}}{\frac{n^n}{n!}}\right|$$

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$$\begin{aligned} \left|\frac{a_{n+1}}{a_n}\right| &= \left|\frac{\frac{(n+1)^{n+1}}{(n+1)!}}{\frac{n^n}{n!}}\right| \\ &= \frac{(n+1)^{n+1}}{(n+1)!} \cdot \frac{n!}{n^n} \end{aligned}$$

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&= \frac{(n+1)(n+1)^n}{(n+1)n!} \cdot \frac{n!}{n^n} \\
&= \left(\frac{n+1}{n}\right)^n = \left(1 + \frac{1}{n}\right)^n
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&\to e
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Therefore the series is by the Ratio Test.

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&= \left(\frac{n+1}{n}\right)^n = \left(1+\frac{1}{n}\right)^n \\
&\to e > 1
\end{aligned}$$

Therefore the series is divergent by the Ratio Test.

The Root Test

Theorem (The Root Test)

1. *If* $\lim_{n\to\infty} \sqrt[n]{|a_n|} = L < 1$*, then the series* $\sum a_n$ *is absolutely convergent (and therefore convergent).*
2. *If* $\lim_{n\to\infty} \sqrt[n]{|a_n|} = L > 1$ *or* $\lim_{n\to\infty} \sqrt[n]{|a_n|} = \infty$*, then the series* $\sum a_n$ *is divergent.*
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3. *If* $\lim\limits_{n\to\infty} \sqrt[n]{|a_n|} = L = 1$, *then the Root Test is inconclusive.*

If $L = 1$ in the Ratio Test, don't try the Root Test, because it will be inconclusive too.
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Test convergence of the series $\displaystyle\sum_{n=1}^{\infty}\left(\frac{2n+3}{3n+2}\right)^{n}$.

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&= \frac{2+\frac{3}{n}}{3+\frac{2}{n}} \\
&\to \frac{2}{3} < 1
\end{aligned}
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Therefore the series is absolutely convergent by the Root Test.