

Calculus 2

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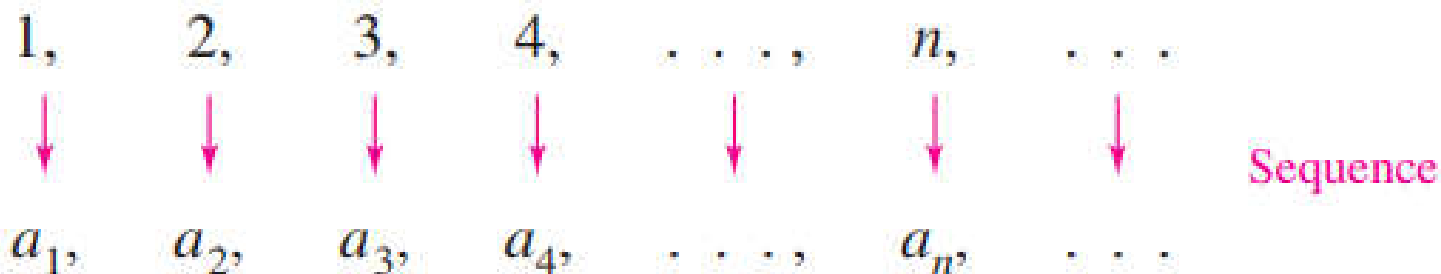
Lecture 3

Infinite Sequences and Series

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Infinite Sequences and Series

- **List the terms of a sequence.**
- **Determine whether a sequence converges or diverges.**
- **Write a formula for the n th term of a sequence.**
- **Use properties of monotonic sequences and bounded sequences**



1 is mapped onto a_1 , 2 is mapped onto a_2 , and so on. The numbers

$$a_1, a_2, a_3, \dots, a_n, \dots$$

are the **terms** of the sequence. The number a_n is the **n th term** of the sequence, and the entire sequence is denoted by $\{a_n\}$. Occasionally, it is convenient to begin a sequence with a_0 , so that the terms of the sequence become $a_0, a_1, a_2, a_3, \dots, a_n, \dots$ and the domain is the set of nonnegative integers.

Example:

$$\{a_n\} = \{ \sqrt{1}, \sqrt{2}, \sqrt{3}, \dots, \sqrt{n}, \dots \}$$

$$\{b_n\} = \left\{ 1, -\frac{1}{2}, \frac{1}{3}, -\frac{1}{4}, \dots, (-1)^{n+1} \frac{1}{n}, \dots \right\}$$

$$\{c_n\} = \left\{ 0, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \dots, \frac{n-1}{n}, \dots \right\}$$

$$\{d_n\} = \{ 1, -1, 1, -1, 1, -1, \dots, (-1)^{n+1}, \dots \}.$$

Example: Listing the Terms of a Sequence

The terms of the sequence $\{b_n\} = \left\{ \frac{n}{1 - 2n} \right\}$ are

$$\frac{1}{1 - 2 \cdot 1}, \frac{2}{1 - 2 \cdot 2}, \frac{3}{1 - 2 \cdot 3}, \frac{4}{1 - 2 \cdot 4}, \dots$$
$$-1, \quad -\frac{2}{3}, \quad -\frac{3}{5}, \quad -\frac{4}{7}, \quad \dots$$

The terms of the sequence $\{c_n\} = \left\{ \frac{n^2}{2^n - 1} \right\}$ are

$$\frac{1^2}{2^1 - 1}, \frac{2^2}{2^2 - 1}, \frac{3^2}{2^3 - 1}, \frac{4^2}{2^4 - 1}, \dots$$
$$\frac{1}{1}, \quad \frac{4}{3}, \quad \frac{9}{7}, \quad \frac{16}{15}, \quad \dots$$

The terms of the **recursively defined** sequence $\{d_n\}$, where $d_1 = 25$ and $d_{n+1} = d_n - 5$, are

$$25, \quad 25 - 5 = 20, \quad 20 - 5 = 15, \quad 15 - 5 = 10, \dots$$

Convergence and Divergence

Sometimes the numbers in a sequence approach a single value as the index n increases. This happens in the sequence

$$\left\{ 1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots, \frac{1}{n}, \dots \right\}$$

whose terms approach 0 as n gets large, and in the sequence

$$\left\{ 0, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \dots, 1 - \frac{1}{n}, \dots \right\}$$

whose terms approach 1. On the other hand, sequences like

$$\left\{ \sqrt{1}, \sqrt{2}, \sqrt{3}, \dots, \sqrt{n}, \dots \right\}$$

have terms that get larger than any number as n increases, and sequences like

$$\left\{ 1, -1, 1, -1, 1, -1, \dots, (-1)^{n+1}, \dots \right\}$$

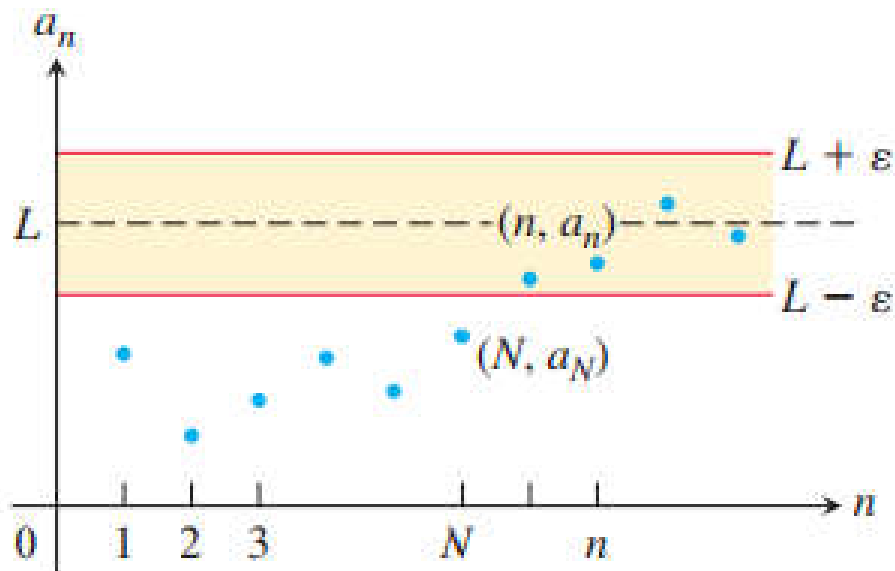
bounce back and forth between 1 and -1 , never converging to a single value.

DEFINITIONS The sequence $\{a_n\}$ **converges** to the number L if for every positive number ε there corresponds an integer N such that

$$|a_n - L| < \varepsilon \quad \text{whenever} \quad n > N.$$

If no such number L exists, we say that $\{a_n\}$ **diverges**.

If $\{a_n\}$ converges to L , we write $\lim_{n \rightarrow \infty} a_n = L$, or simply $a_n \rightarrow L$, and call L the **limit** of the sequence (Figure 10.2).



THEOREM 1 Let $\{a_n\}$ and $\{b_n\}$ be sequences of real numbers, and let A and B be real numbers. The following rules hold if $\lim_{n \rightarrow \infty} a_n = A$ and $\lim_{n \rightarrow \infty} b_n = B$.

1. *Sum Rule:* $\lim_{n \rightarrow \infty} (a_n + b_n) = A + B$
2. *Difference Rule:* $\lim_{n \rightarrow \infty} (a_n - b_n) = A - B$
3. *Constant Multiple Rule:* $\lim_{n \rightarrow \infty} (k \cdot b_n) = k \cdot B$ (any number k)
4. *Product Rule:* $\lim_{n \rightarrow \infty} (a_n \cdot b_n) = A \cdot B$
5. *Quotient Rule:* $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \frac{A}{B}$ if $B \neq 0$

Example:

$$(a) \lim_{n \rightarrow \infty} \left(-\frac{1}{n} \right) = -1 \cdot \lim_{n \rightarrow \infty} \frac{1}{n} = -1 \cdot 0 = 0$$

Constant Multiple Rule and Example 1a

$$(b) \lim_{n \rightarrow \infty} \left(\frac{n-1}{n} \right) = \lim_{n \rightarrow \infty} \left(1 - \frac{1}{n} \right) = \lim_{n \rightarrow \infty} 1 - \lim_{n \rightarrow \infty} \frac{1}{n} = 1 - 0 = 1$$

Difference Rule
and Example 1a

$$(c) \lim_{n \rightarrow \infty} \frac{5}{n^2} = 5 \cdot \lim_{n \rightarrow \infty} \frac{1}{n} \cdot \lim_{n \rightarrow \infty} \frac{1}{n} = 5 \cdot 0 \cdot 0 = 0$$

Product Rule

$$(d) \lim_{n \rightarrow \infty} \frac{4 - 7n^6}{n^6 + 3} = \lim_{n \rightarrow \infty} \frac{(4/n^6) - 7}{1 + (3/n^6)} = \frac{0 - 7}{1 + 0} = -7.$$

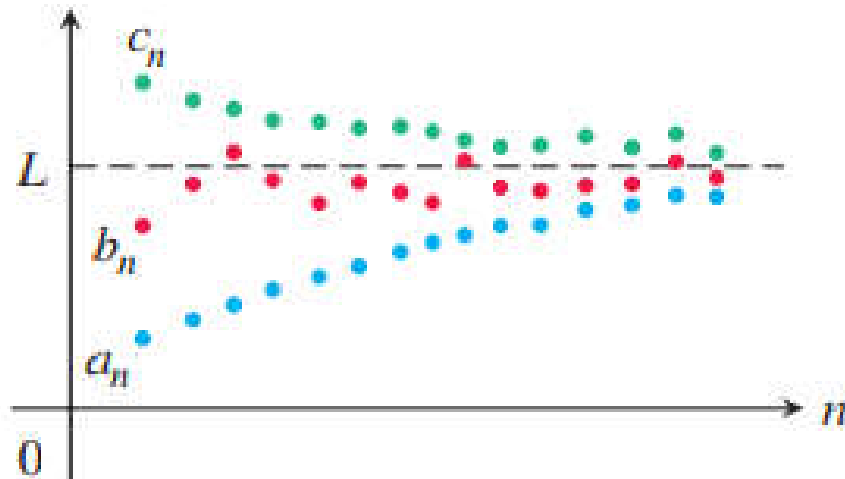
Divide numerator and denominator
by n^6 and use the Sum and Quotient
Rules.



The Sandwich Theorem for Sequences

THEOREM – The Sandwich Theorem for Sequences

Let $\{a_n\}$, $\{b_n\}$, and $\{c_n\}$ be sequences of real numbers. If $a_n \leq b_n \leq c_n$ holds for all n beyond some index N , and if $\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} c_n = L$, then $\lim_{n \rightarrow \infty} b_n = L$ also.



Example:

(a) $\frac{\cos n}{n} \rightarrow 0$

because $-\frac{1}{n} \leq \frac{\cos n}{n} \leq \frac{1}{n};$

(b) $\frac{1}{2^n} \rightarrow 0$

because $0 \leq \frac{1}{2^n} \leq \frac{1}{n};$

(c) $(-1)^n \frac{1}{n} \rightarrow 0$

because $-\frac{1}{n} \leq (-1)^n \frac{1}{n} \leq \frac{1}{n}.$

THEOREM Suppose that $f(x)$ is a function defined for all $x \geq n_0$ and that $\{a_n\}$ is a sequence of real numbers such that $a_n = f(n)$ for $n \geq n_0$. Then

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

Example: Show that $\lim_{n \rightarrow \infty} \frac{\ln n}{n} = 0$.

Solution:

$$\lim_{x \rightarrow \infty} \frac{\ln x}{x} = \lim_{x \rightarrow \infty} \frac{1/x}{1} = \frac{0}{1} = 0.$$

We conclude that $\lim_{n \rightarrow \infty} (\ln n)/n = 0$.

Example: Does the sequence whose n th term is

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

converge? If so, find $\lim_{n \rightarrow \infty} a_n$.

Solution:

$$\ln a_n = \ln \left(\frac{n+1}{n-1} \right)^n = n \ln \left(\frac{n+1}{n-1} \right).$$

Using L'Hôpital's Rule

$$\lim_{n \rightarrow \infty} \ln a_n = \lim_{n \rightarrow \infty} n \ln \left(\frac{n+1}{n-1} \right) \quad \infty \cdot 0 \text{ form}$$

$$= \lim_{n \rightarrow \infty} \frac{\ln \left(\frac{n+1}{n-1} \right)}{1/n} \quad \frac{0}{0} \text{ form}$$

$$= \lim_{n \rightarrow \infty} \frac{-2/(n^2 - 1)}{-1/n^2} \quad \text{L'Hôpital's Rule: differentiate numerator and denominator.}$$

$$= \lim_{n \rightarrow \infty} \frac{2n^2}{n^2 - 1} = 2. \quad \text{Simplify and evaluate.}$$

The sequence $\{a_n\}$ converges to e^2 .

Monotonic Sequences and Bounded Sequences

Definition of Monotonic Sequence

A sequence $\{a_n\}$ is **monotonic** when its terms are nondecreasing

$$a_1 \leq a_2 \leq a_3 \leq \cdots \leq a_n \leq \cdots$$

or when its terms are nonincreasing

$$a_1 \geq a_2 \geq a_3 \geq \cdots \geq a_n \geq \cdots$$

Example:

Determine whether each sequence having the given n th term is monotonic.

a. $a_n = 3 + (-1)^n$

b. $b_n = \frac{2n}{1+n}$

Solution

- a. This sequence alternates between 2 and 4. So, it is not monotonic.
- b. This sequence is monotonic because each successive term is greater than its predecessor. To see this, compare the terms b_n and b_{n+1} . [Note that, because n is positive, you can multiply each side of the inequality by $(1 + n)$ and $(2 + n)$ without reversing the inequality sign.]

$$\begin{aligned} b_n &= \frac{2n}{1+n} \stackrel{?}{<} \frac{2(n+1)}{1+(n+1)} = b_{n+1} \\ 2n(2+n) &\stackrel{?}{<} (1+n)(2n+2) \\ 4n+2n^2 &\stackrel{?}{<} 2+4n+2n^2 \\ 0 &< 2 \end{aligned}$$

Definition of Bounded Sequence

1. A sequence $\{a_n\}$ is **bounded above** when there is a real number M such that $a_n \leq M$ for all n . The number M is called an **upper bound** of the sequence.
2. A sequence $\{a_n\}$ is **bounded below** when there is a real number N such that $N \leq a_n$ for all n . The number N is called a **lower bound** of the sequence.
3. A sequence $\{a_n\}$ is **bounded** when it is bounded above and bounded below.

THEOREM : Bounded Monotonic Sequences

If a sequence $\{a_n\}$ is bounded and monotonic, then it converges.

Example: a. $a_n = 3 + (-1)^n$

b. $b_n = \frac{2n}{1+n}$

sequences are bounded. To see this, note that

$$2 \leq a_n \leq 4, \quad 1 \leq b_n \leq 2,$$

Write the first five terms of the sequence

1. $a_n = 3^n$

2. $a_n = \left(-\frac{2}{5}\right)^n$

3. $a_n = \sin \frac{n\pi}{2}$

4. $a_n = \frac{3n}{n+4}$

5. $a_n = (-1)^{n+1} \left(\frac{2}{n}\right)$

6. $a_n = 2 + \frac{2}{n} - \frac{1}{n^2}$



EXERCISES

write the next two apparent terms of the sequence. Describe the pattern you used to find these terms

$$2, 5, 8, 11, \dots$$

$$8, 13, 18, 23, 28, \dots$$

$$5, 10, 20, 40, \dots$$

$$6, -2, \frac{2}{3}, -\frac{2}{9}, \dots$$

.



Proof For any number x , $\lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^n = e^x$

Solution:

$$a_n = \left(1 + \frac{x}{n}\right)^n.$$

Then

$$\ln a_n = \ln \left(1 + \frac{x}{n}\right)^n = n \ln \left(1 + \frac{x}{n}\right) \rightarrow x,$$

as we can see by the following application of L'Hôpital's Rule, in which we differentiate with respect to n :

$$\begin{aligned} \lim_{n \rightarrow \infty} n \ln \left(1 + \frac{x}{n}\right) &= \lim_{n \rightarrow \infty} \frac{\ln(1 + x/n)}{1/n} \\ &= \lim_{n \rightarrow \infty} \frac{\left(\frac{1}{1 + x/n}\right) \cdot \left(-\frac{x}{n^2}\right)}{-1/n^2} = \lim_{n \rightarrow \infty} \frac{x}{1 + x/n} = x. \end{aligned}$$

$$\left(1 + \frac{x}{n}\right)^n = a_n = e^{\ln a_n} \rightarrow e^x.$$

Proof

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

Proof

$$(a) \quad \frac{\ln(n^2)}{n} = \frac{2 \ln n}{n} \rightarrow 2 \cdot 0 = 0$$

$$(b) \quad \sqrt[n]{n^2} = n^{2/n} = (n^{1/n})^2 \rightarrow (1)^2 = 1$$

$$(c) \quad \sqrt[n]{3n} = 3^{1/n} (n^{1/n}) \rightarrow 1 \cdot 1 = 1$$

$$(d) \quad \left(-\frac{1}{2}\right)^n \rightarrow 0$$

$$(e) \quad \left(\frac{n-2}{n}\right)^n = \left(1 + \frac{-2}{n}\right)^n \rightarrow e^{-2}$$

Show that the sequence whose n th term is $a_n = \frac{n^2}{2^n - 1}$ converges.

Solution Consider the function of a real variable

$$f(x) = \frac{x^2}{2^x - 1}.$$

Applying L'Hôpital's Rule twice produces

$$\lim_{x \rightarrow \infty} \frac{x^2}{2^x - 1} = \lim_{x \rightarrow \infty} \frac{2x}{(\ln 2)2^x} = \lim_{x \rightarrow \infty} \frac{2}{(\ln 2)^2 2^x} = 0.$$

Because $f(n) = a_n$ for every positive integer, you can apply Theorem 9.1 to conclude that

$$\lim_{n \rightarrow \infty} \frac{n^2}{2^n - 1} = 0.$$

See Example 1(c), page 584.

So, the sequence converges to 0.





EXERCISES

Find a sequence $\{a_n\}$ whose first five terms are

$$\frac{2}{1}, \frac{4}{3}, \frac{8}{5}, \frac{16}{7}, \frac{32}{9}, \dots$$

and then determine whether the sequence you have chosen converges or diverges.

Solution First, note that the numerators are successive powers of 2, and the denominators form the sequence of positive odd integers. By comparing a_n with n , you have the following pattern.

$$\frac{2^1}{1}, \frac{2^2}{3}, \frac{2^3}{5}, \frac{2^4}{7}, \frac{2^5}{9}, \dots, \frac{2^n}{2n-1}, \dots$$

Consider the function of a real variable $f(x) = 2^x/(2x - 1)$. Applying L'Hôpital's Rule produces

$$\lim_{x \rightarrow \infty} \frac{2^x}{2x - 1} = \lim_{x \rightarrow \infty} \frac{2^x(\ln 2)}{2} = \infty.$$

Next, apply Theorem 9.1 to conclude that

$$\lim_{n \rightarrow \infty} \frac{2^n}{2n - 1} = \infty.$$

So, the sequence diverges.





Determine whether the sequence with the given the term is bounded

$$a_n = 4 - \frac{1}{n}$$

$$a_n = \sin \frac{n\pi}{6}$$

$$a_n = \left(\frac{2}{3}\right)^n$$

$$a_n = \frac{\cos n}{n}$$

.

determine the convergence or divergence of the sequence with the given n th term. If the sequence converges, find its limit

$$a_n = \frac{5}{n+2}$$

$$a_n = \frac{\sqrt[3]{n}}{\sqrt[3]{n} + 1}$$

$$a_n = \frac{\ln(n^3)}{2n}$$

$$a_n = 8 + \frac{5}{n}$$

$$a_n = \frac{5^n}{3^n}$$

$$a_n = 2^{1/n}$$

$$a_n = \frac{10n^2 + 3n + 7}{2n^2 - 6}$$

$$a_n = n \sin \frac{1}{n}$$

$$a_n = \frac{\sin n}{n}$$

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

$$a_n = \frac{\cos \pi n}{n^2}$$

$$a_n = -3^{-n}$$



Thank you for your attention

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