Calculus 2

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Calculus 2

Lecture 2

Improper Integrals

Improper Integrals

■ **Evaluate an improper integral that has an infinite limit of integration.**

■ **Evaluate an improper integral that has an infinite discontinuity.**

■ **Tests for Convergence and Divergence**

The Fundamental Theorem of Calculus

Quick Review

If f is continuous on the interval $[a,b]$ and F is any function that satisfies $F'(x) = f(x)$ throughout this interval then

$$\int_a^b f(x)\,dx = F(b) - F(a)$$

REMEMBER: [a,b] is a closed interval

introduction

Up to now we have focused on **definite integrals** with **continuous integrands** and **finite intervals of integration**.

we extend the concept of a definite integral to the cases where:

- The interval is infinite
- f has an infinite discontinuity in $[a, b]$

These are called **improper integrals**

INTEGRALS OF TYPE 1: INFINITE INTERVALS

Recall in the definition of $\int_a^b f(x)dx,$

the interval [*a*, *b*] was finite. If *a* or *b* (or both) are ∞ or −∞, we call the integral an **improper integral of type 1 with an infinite interval**. For example:

- $\int_0^{\infty} \frac{dx}{1+x^2}$
- $\int_{-\infty}^{-1} xe^{-x^2} dx$
- $\int_{-\infty}^{\infty} x^2 e^{-x^2} dx$

Improper integral: type I:

1) If $f(x)$ is continuous on $[a,\infty)$, then

$$\int_a^{\infty} f(x)\,dx = \lim_{b\to\infty}\int_a^b f(x)\,dx$$

2) If $f(x)$ is continuous on $[-\infty, b)$, then

$$\int_{-\infty}^{b} f(x)\,dx = \lim_{a\to-\infty}\int_a^b f(x)\,dx$$

If the Limit is finite, then the Improper Integral converges.

If the Limit fails, then it diverges

3) If $f(x)$ is continuous on $(-\infty,\infty)$, then

$$\int_{-\infty}^{\infty} f(x)\,dx = \int_{-\infty}^{c} f(x)\,dx + \int_c^{\infty} f(x)\,dx$$

If both Improper Integrals converge, then so does $\int_{-\infty}^{\infty} f(x)\,dx$.

→

Evaluating an Improper Integral on [1,∞)

Does the improper integral $\int_0^\infty e^{-x}\,dx$ converge or diverge?

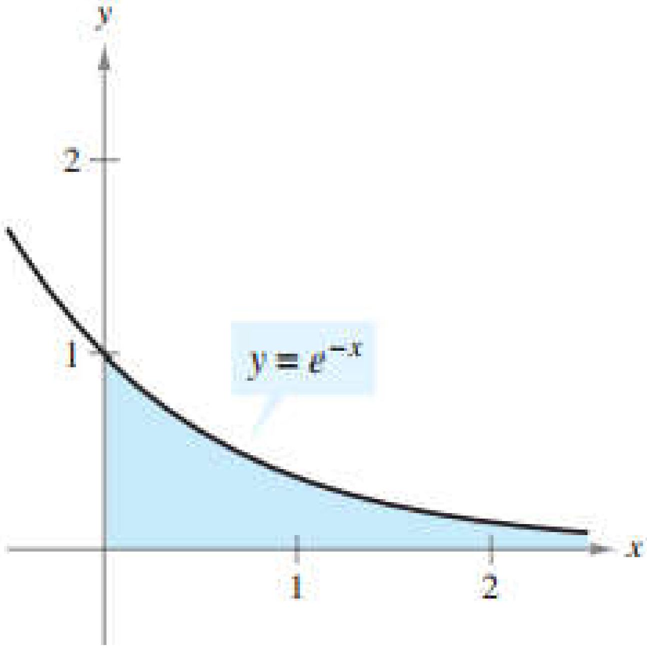
$$\int_0^\infty e^{-x}\,dx = \lim_{b\to\infty}\int_0^b e^{-x}\,dx$$

$$= \lim_{b\to\infty}\left(-e^{-x}\Big|_0^b\right)$$

$$= \lim_{b\to\infty}\left(-e^{-b}+e^{-0}\right)$$

$$= \lim_{b\to\infty}\left(1-e^{-b}\right)$$

$$=1$$



Example Using L'Hôpital's Rule with Improper Integrals

Evaluate $\int_1^{\infty} xe^{-x}\,dx$.

$$\int_1^{\infty} xe^{-x}\,dx = \lim_{b\to\infty}\int_1^{b} xe^{-x}\,dx$$

$$u = x \qquad dv = e^{-x}\,dx$$

$$du = 1\,dx \qquad v = -e^{-x}$$

$$= \lim_{b\to\infty}\left(-xe^{-x}\Big|_1^b - \int_1^b -e^{-x}\,dx\right)$$

$$= \lim_{b\to\infty}\left(\left(-xe^{-x} - e^{-x}\right)\Big|_1^b\right)$$

$$= \lim_{b\to\infty}\left(\left(-be^{-b} - e^{-b}\right) - \left(-1\cdot e^{-1} - e^{-1}\right)\right)$$

$$= \lim_{b\to\infty}\left(-e^{-b}(b+1) + 2e^{-1}\right)$$

$$= \lim_{b\to\infty}\left(-\frac{(b+1)}{e^b}\right) + \frac{2}{e}$$

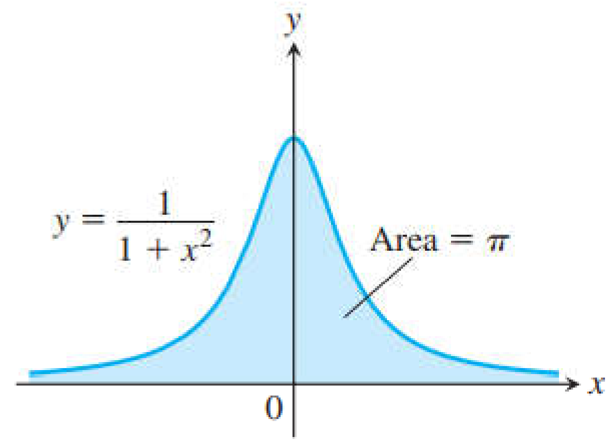
Use L'Hôpital's Rule

$$= \lim_{b\to\infty}\left(-\frac{1}{e^b}\right) + \frac{2}{e}$$

$$= \frac{2}{e}$$

Express the Example Evaluating an Integral on (- ∞,∞)

Evaluate $\int_{-\infty}^{\infty} \frac{1}{1+x^2} dx$.



$$\int_{-\infty}^{\infty} \frac{1}{1+x^2} dx = \int_{-\infty}^{0} \frac{1}{1+x^2} dx + \int_{0}^{\infty} \frac{1}{1+x^2} dx$$

$$= \lim_{a \to -\infty} \int_{a}^{0} \frac{1}{1+x^2} dx + \lim_{b \to \infty} \int_{0}^{b} \frac{1}{1+x^2} dx$$

$$= \lim_{a \to -\infty} \left(\arctan x \Big|_{a}^{0} \right) + \lim_{b \to \infty} \left(\arctan x \Big|_{0}^{b} \right)$$

$$= \lim_{a \to -\infty} \left(\arctan 0 - \arctan a \right) + \lim_{b \to \infty} \left(\arctan b - \arctan 0 \right)$$

$$= \left(0 - -\frac{\pi}{2} \right) + \left(\frac{\pi}{2} - 0 \right) = \pi$$

IMPROPER INTEGRALS OF TYPE 2: INFINITE INTEGRANDS

Recall in the definition of $\int_a^b f(x)dx,$

the functions f was bounded on [a, b]. If f is <u>not bounded</u> on [a, b] (that is, has an x-value, a ≤ x ≤ b, where the limit is ∞ or −∞, we call the integral an **improper integral of type 2 with infinite integrand.** For example

$$\int_0^1 \frac{dx}{x^2}, \quad \int_{-2}^0 \frac{dx}{x^2}, \quad \int_{-2}^1 \frac{dx}{x^2}$$

Improper integral: type 2:

1) If $f(x)$ is continuous on $(a, b]$, then

$$\int_a^b f(x)\,dx = \lim_{c \to a^+} \int_c^b f(x)\,dx$$

2) If $f(x)$ is continuous on $[a, b)$, then

$$\int_a^b f(x)\,dx = \lim_{c \to b^-} \int_a^c f(x)\,dx$$

If the Limit is finite, then the Improper Integral converges.

If the Limit fails, then it diverges

3) If $f(x)$ is continuous on $[a, c) \cup (c, b]$, then

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

If both Improper Integrals converge, then so does $\int_a^b f(x)\,dx$.

→

Example Infinite Discontinuity at an Interior Point

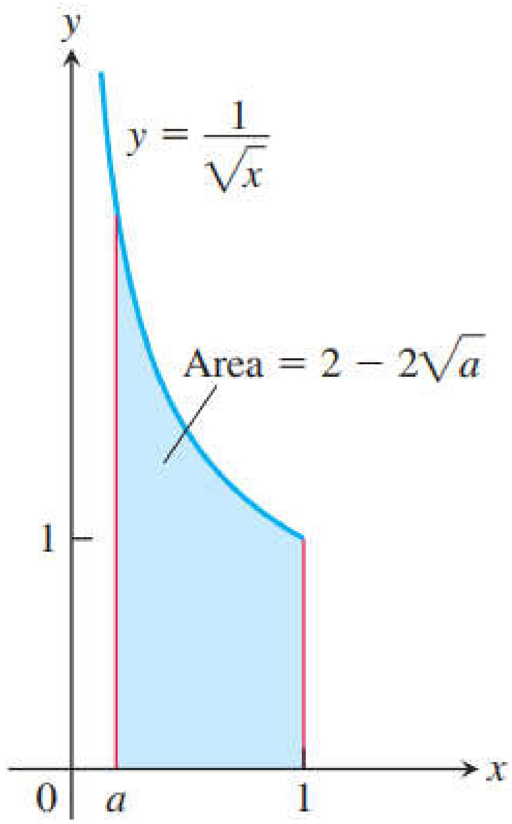
Evaluate $\int_0^1 \frac{1}{\sqrt{x}}\,dx$.

$$\int_0^1 \frac{1}{\sqrt{x}}\,dx = \lim_{c\to 0^+}\int_c^1 \frac{1}{\sqrt{x}}\,dx$$

$$= \lim_{c\to 0^+}\left(2\sqrt{x}\Big|_c^1\right)$$

$$= \lim_{c\to 0^+}\left(2\sqrt{1}-2\sqrt{c}\right)$$

$$= 2$$



Example Infinite Discontinuity at an Interior Point

Evaluate $\int_0^3 \frac{1}{(x-1)^{2/3}}\,dx$.

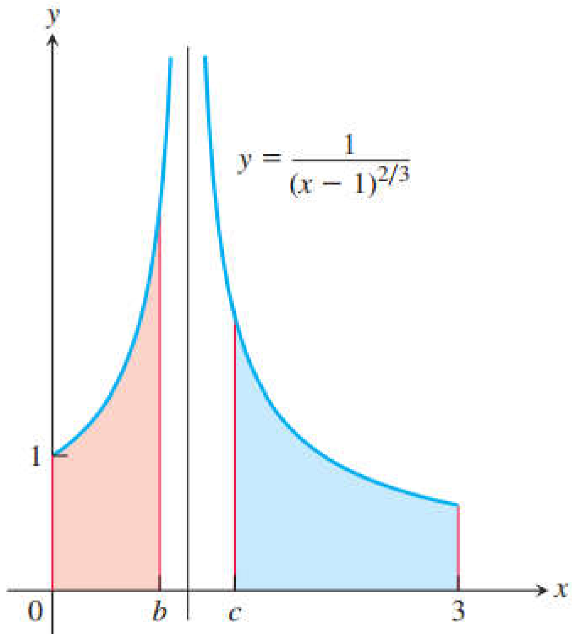
$$\int_0^3 \frac{1}{(x-1)^{2/3}}\,dx = \int_0^1 \frac{1}{(x-1)^{2/3}}\,dx + \int_1^3 \frac{1}{(x-1)^{2/3}}\,dx$$

$$= \lim_{c\to 1^-}\int_0^c \frac{1}{(x-1)^{2/3}}\,dx + \lim_{c\to 1^+}\int_c^3 \frac{1}{(x-1)^{2/3}}\,dx$$

$$= \lim_{c\to 1^-}\left(3(x-1)^{1/3}\Big|_0^c\right) + \lim_{c\to 1^+}\left(3(x-1)^{1/3}\Big|_c^3\right)$$

$$= \lim_{c\to 1^-}\left(3(c-1)^{1/3} - 3(0-1)^{1/3}\right) + \lim_{c\to 1^+}\left(3(3-1)^{1/3} - 3(c-1)^{1/3}\right)$$

$$= (0+3) + \left(3\sqrt[3]{2} - 0\right) \quad = 3 + 3\sqrt[3]{2}$$



Example : Improper integral

$$\int_1^\infty e^{-x}dx$$ ← **Converges**

$$\lim_{b\to\infty}\int_1^b e^{-x}dx$$

$$\lim_{b\to\infty} -e^{-x}\Big|_1^b$$

$$\lim_{b\to\infty} -e^{-b}-\left(-e^{-1}\right)$$

$$\lim_{b\to\infty} -\frac{1}{e^b}+\frac{1}{e} = \frac{1}{e}$$

($\frac{1}{e^b} \to 0$)

→

Example : Improper integral

Does $\int_1^\infty e^{-x^2}\,dx$ converge?

Compare:

$\frac{1}{e^{x^2}}$ to $\frac{1}{e^x}$ for positive values of x.

For $x > 1,\ e^{x^2} > e^x \quad \therefore \quad \frac{1}{e^{x^2}} < \frac{1}{e^x}$

Since $\frac{1}{e^x}$ converges to a finite number, $\frac{1}{e^{x^2}}$ must also converge!

→

Comparison Test (Using estimation to show convergence or divergence)

Let f and g be continuous on $\left[a,\infty\right)$ with $0 \le f\left(x\right) \le g\left(x\right)$

for all $x \ge a$, then:

① $\int_a^\infty f\left(x\right)\,dx$ converges if $\int_a^\infty g\left(x\right)\,dx$ converges.

② $\int_a^\infty g\left(x\right)\,dx$ diverges if $\int_a^\infty f\left(x\right)\,dx$ diverges.

→

Using estimation to show convergence or divergence

Example $\int_1^\infty \frac{\sin^2 x}{x^2}\, dx$

Solution:

$$0 \le \frac{\sin^2 x}{x^2} \le \frac{1}{x^2} \quad \text{on} \quad [1, \infty)$$

Since $\frac{1}{x^2}$ converges, $\frac{\sin^2 x}{x^2}$ converges.

→

Using estimation to show convergence or divergence

Example $\displaystyle\int_1^{\infty} \frac{1}{\sqrt{x^2 - 0.1}}\, dx$

Solution:

$\sqrt{x^2 - 0.1} < x$ for positive values of x, so:

$$\frac{1}{\sqrt{x^2 - 0.1}} \geq \frac{1}{x} \quad \text{on} \quad [1, \infty)$$

Since $\dfrac{1}{x}$ diverges, $\dfrac{1}{\sqrt{x^2 - 0.1}}$ diverges.

→

Thank you for your attention