Lecture 11

Section 8.7 Numerical Integration

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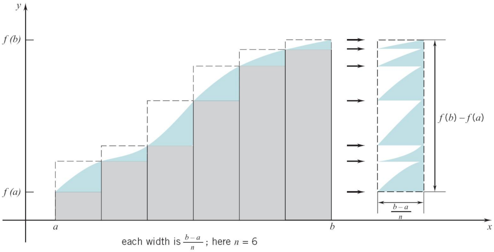
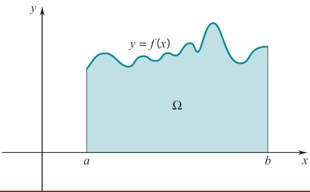
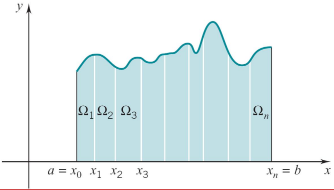


Area Problem





Partition of $[a, b]$

Take a partition $P = \{x_0, x_1, \cdots, x_n\}$ of $[a, b]$. Then P splits up the interval $[a, b]$ into a finite number of subintervals $[x_0, x_1]$, $\cdots$, $[x_{n-1}, x_n]$ with $a = x_0 < x_1 < \cdots < x_n = b$. We have

$$[a, b] = [x_0, x_1] \cup \cdots \cup [x_{i-1}, x_i] \cup \cdots \cup [x_{n-1}, x_n]$$

Remark

This breaks up the region Ω into n subregions $\Omega_1, \cdots, \Omega_n$:

$$\Omega = \Omega_1 \cup \cdots \cup \Omega_i \cup \cdots \cup \Omega_n$$

We can estimate the total area of Ω by estimating the area of each subregion Ω_i and adding up the results.

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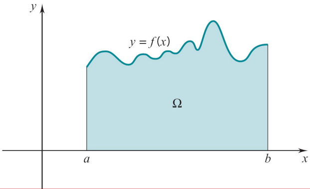

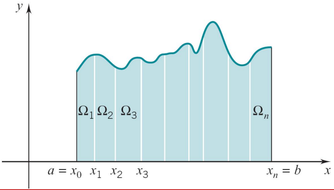

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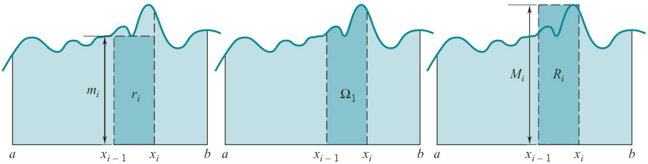
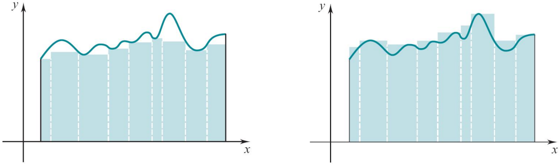
Lower and Upper Sums



Let $\Delta x_i = x_i - x_{i-1}$, $m_i = \min_{x \in [x_{i-1}, x_i]} f(x)$, $M_i = \max_{x \in [x_{i-1}, x_i]} f(x)$

$$m_i \Delta x_i = \text{area of } r_i \leq \text{area of } \Omega_i \leq \text{area of } R_i = M_i \Delta x_i$$

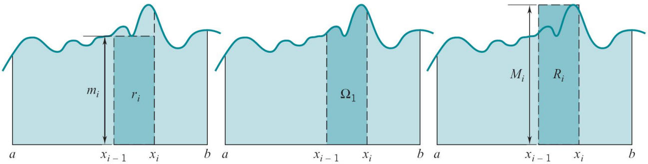


area of shaded region is a lower sum for f

area of shaded region is an upper sum for f

$$L_f(P) := \sum_{i=1}^{n} m_i \Delta x_i \leq I = \int_a^b f(x)\,dx \leq \sum_{i=1}^{n} M_i \Delta x_i =: U_f(P)$$

Lower and Upper Sums



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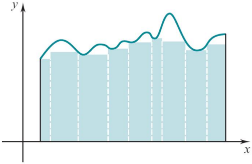

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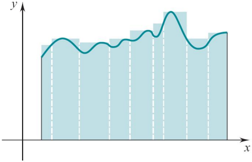

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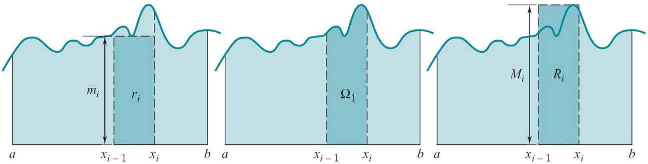

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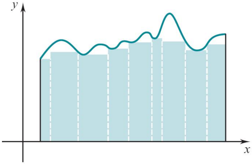

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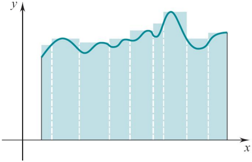

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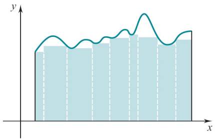

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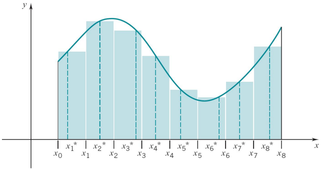

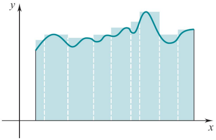

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Riemann Sum

$$S^*(P) = f(x_1^*)\Delta x_1 + f(x_2^*)\Delta x_2 + \cdots + f(x_n^*)\Delta x_n$$

where x_i^* is any point picked in $[x_{i-1}, x_i]$ for $i = 1, \cdots, n$. We have

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Limit of Riemann Sums

$$\int_a^b f(x)\,dx = \lim_{\|P\|\to 0} [f(x_1^*)\Delta x_1 + f(x_2^*)\Delta x_2 + \cdots + f(x_n^*)\Delta x_n]$$

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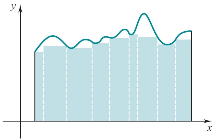

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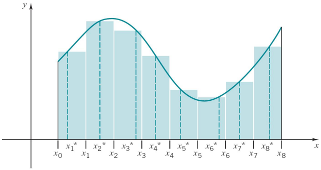

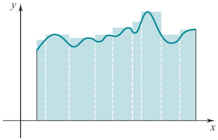

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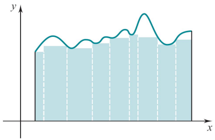

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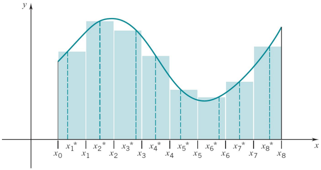

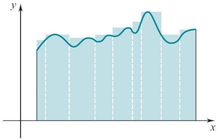

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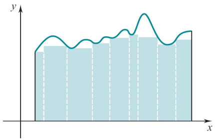

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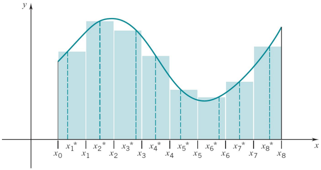

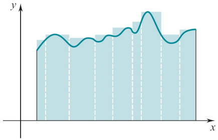

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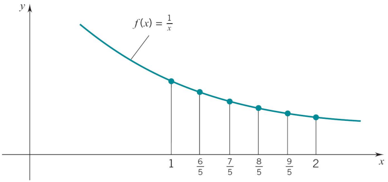

Problem

Find the approximate value of

$$\ln 2 = \int_1^2 \frac{dx}{x}$$

using only the values of $f(x) = \frac{1}{x}$ at

$$1, \quad \frac{6}{5}, \quad \frac{7}{5}, \quad \frac{8}{5}, \quad \frac{9}{5}, 2.$$

Numerical Integration

Approximate $\int_a^b f(x)\,dx$ using only values of f at $n+1$ equally-spaced points between a and b.

Regular Partition of $[a, b]$

Let $x_i = a + i\Delta x$, $i = 0, 1, \cdots, n$, where $\Delta x = \frac{b-a}{n}$. Then

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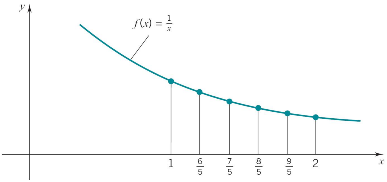

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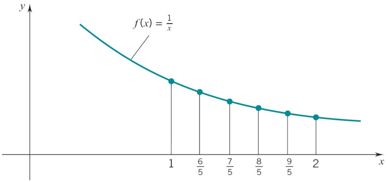

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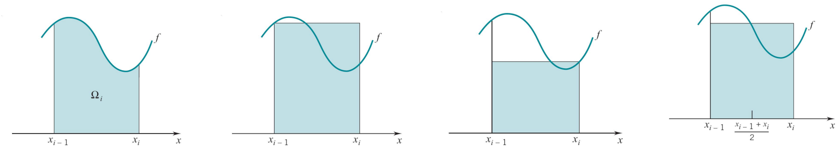
Rectangle Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$ $\quad f(x_{i-1})\Delta x$ $\quad f(x_i)\Delta x$ $\quad f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$

Rectangle Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$f(x_{i-1})\Delta x$,	$f(x_i)\Delta x$,	$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
left-endpoints	right-endpoints	midpoints

Rectangle Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

$\sum_{i=1}^n f(x_{i-1})\Delta x$,	$\sum_{i=1}^n f(x_i)\Delta x$,	$\sum_{i=1}^n f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
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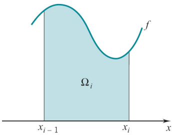
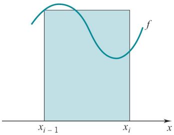
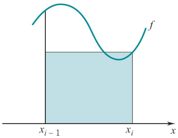


$\int_{x_{i-1}}^{x_i} f(x)\,dx$



$f(x_{i-1})\Delta x$



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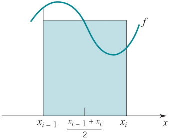

$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$

Rectangle Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$f(x_{i-1})\Delta x,$	$f(x_i)\Delta x,$	$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
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Rectangle Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

$\sum_{i=1}^n f(x_{i-1})\Delta x,$	$\sum_{i=1}^n f(x_i)\Delta x,$	$\sum_{i=1}^n f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
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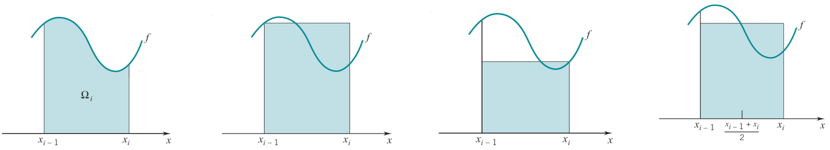

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$f(x_{i-1})\Delta x$, left-endpoints

$f(x_i)\Delta x$, right-endpoints

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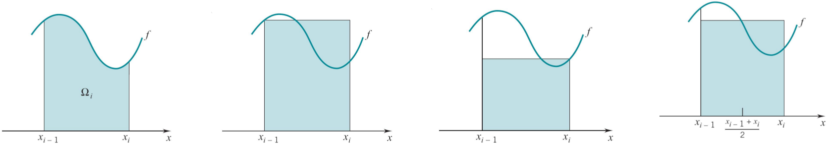

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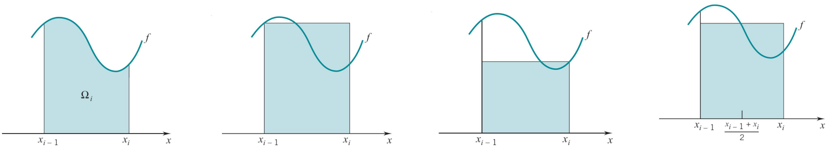

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$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$ midpoints

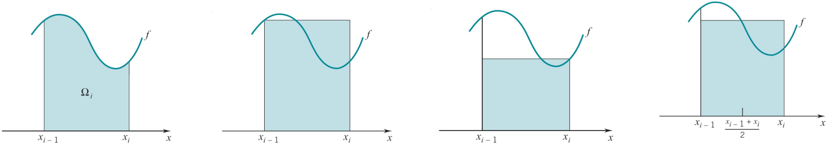
Rectangle Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

$\sum_{i=1}^n f(x_{i-1})\Delta x$, left-endpoints

$\sum_{i=1}^n f(x_i)\Delta x$, right-endpoints

$\sum_{i=1}^n f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$ midpoints

Rectangle Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$ $\quad f(x_{i-1})\Delta x$ $\quad f(x_i)\Delta x$ $\quad f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$

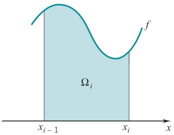
Rectangle Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$f(x_{i-1})\Delta x$,	$f(x_i)\Delta x$,	$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
left-endpoints	right-endpoints	midpoints

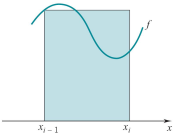
Rectangle Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

$\sum_{i=1}^{n} f(x_{i-1})\Delta x$,	$\sum_{i=1}^{n} f(x_i)\Delta x$,	$\sum_{i=1}^{n} f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$
left-endpoints	right-endpoints	midpoints

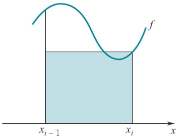
Rectangle Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



$f(x_{i-1})\Delta x$



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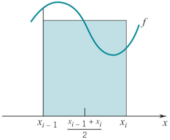

$f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$

Rectangle Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$f(x_{i-1})\Delta x$, $f(x_i)\Delta x$, $f\left(\frac{x_{i-1}+x_i}{2}\right)\Delta x$

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Rectangle Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

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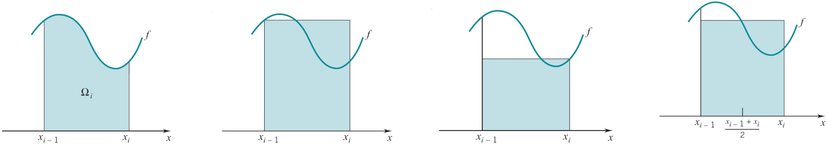
Rectangle Approximations



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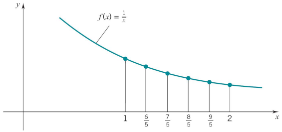

Problem

Find the approximate value of $\ln 2 = \int_1^2 \frac{dx}{x}$ using only the values of $f(x) = \frac{1}{x}$ at $1, \frac{6}{5}, \frac{7}{5}, \frac{8}{5}, \frac{9}{5}, 2.$

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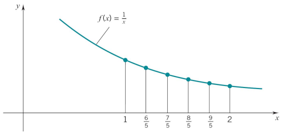

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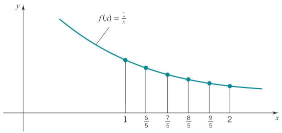

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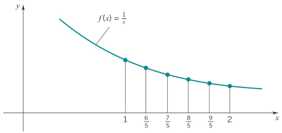

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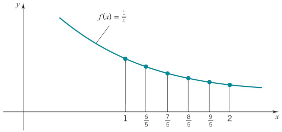

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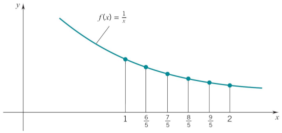

Approximating $\ln 2 = 0.69314718\cdots$

$$L_5 = \frac{1}{5}\left(1 + \frac{5}{6} + \frac{5}{7} + \frac{5}{8} + \frac{5}{9}\right) \approx 0.7456$$

$$R_5 = \frac{1}{5}\left(\frac{5}{6} + \frac{5}{7} + \frac{5}{8} + \frac{5}{9} + \frac{1}{2}\right) \approx 0.6456$$

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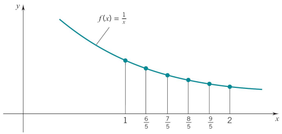

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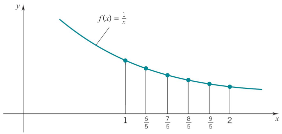

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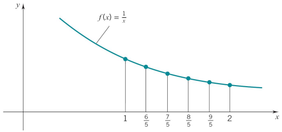

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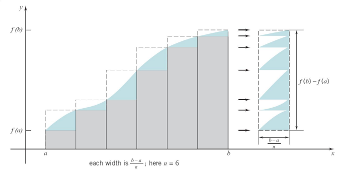
Error Estimates



$$\left| \int_a^b f(x)\,dx - L_n \right| \le \left(\frac{b-a}{n} \right) [f(b) - f(a)]$$

Error Estimates

- Left-endpoint rule:

$$E_n^L = \int_a^b f(x)\,dx - L_n = \frac{1}{2} \frac{(b-a)^2}{n} f'(c) = O(\Delta x)$$

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$$E_n^R = \int_a^b f(x)\,dx - R_n = \frac{1}{2} \frac{(b-a)^2}{n} f'(c) = O(\Delta x)$$

- Midpoint rule:

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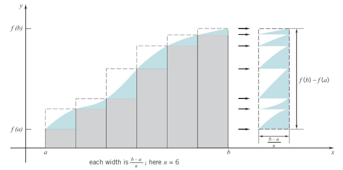
Error Estimates



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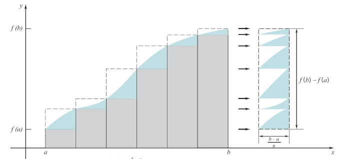

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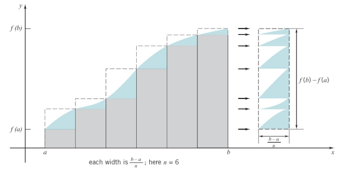

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Error Estimates: Example

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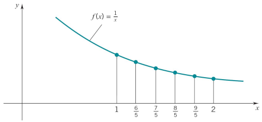

Approximating $\ln 2 = 0.69314718\cdots$

Note that $f(x) = \frac{1}{x}$, $f'(x) = -\frac{1}{x^2}$, $f''(x) = \frac{2}{x^3}$.

$$|E_n^L| = |E_n^R| \le \frac{1}{2}\frac{(2-1)^2}{5}\max_{c\in[1,2]}|f'(c)| = \frac{1}{10}$$

$$|E_n^M| \le \frac{1}{24}\frac{(2-1)^3}{5^2}\max_{c\in[1,2]}|f''(c)| = \frac{1}{300}$$

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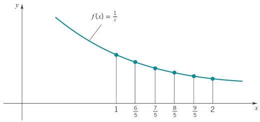

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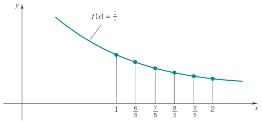


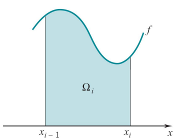
Approximating $\ln 2 = 0.69314718\cdots$

Note that $f(x) = \frac{1}{x}$, $f'(x) = -\frac{1}{x^2}$, $f''(x) = \frac{2}{x^3}$.

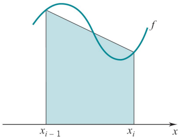
$$|E_n^L| = |E_n^R| \le \frac{1}{2}\frac{(2-1)^2}{5} \max_{c\in[1,2]} |f'(c)| = \frac{1}{10}$$

$$|E_n^M| \le \frac{1}{24}\frac{(2-1)^3}{5^2} \max_{c\in[1,2]} |f''(c)| = \frac{1}{300}$$

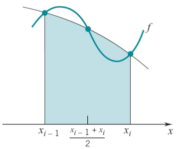
Trapeziodal and Parabolic Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



Trapeziodal



Parabolic

Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$\frac{1}{2}\left[f(x_{i-1}) + f(x_i)\right]\Delta x$, $\frac{1}{6}\left[f(x_{i-1}) + 4f\left(\frac{x_{i-1}+x_i}{2}\right) + f(x_i)\right]\Delta x$

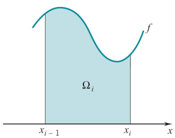
trapeziodal Parabolic

Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

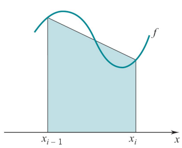
$\sum_{i=1}^n \frac{\Delta x}{2}\left[f(x_{i-1}) + f(x_i)\right]$, $\sum_{i=1}^n \frac{\Delta x}{6}\left[f(x_{i-1}) + 4f\left(\frac{x_{i-1}+x_i}{2}\right) + f(x_i)\right]$

Trapeziodal Parabolic

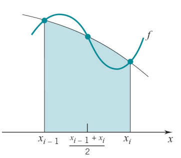
Trapeziodal and Parabolic Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



Trapeziodal



Parabolic

Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$\frac{1}{2}\left[f(x_{i-1}) + f(x_i)\right]\Delta x$, $\frac{1}{6}\left[f(x_{i-1}) + 4f\left(\frac{x_{i-1}+x_i}{2}\right) + f(x_i)\right]\Delta x$

trapeziodal Parabolic

Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

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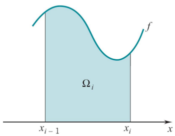
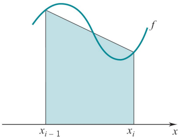
Trapeziodal Parabolic

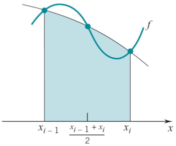
Trapeziodal and Parabolic Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



Trapeziodal



Parabolic

Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$$\frac{1}{2}\left[f(x_{i-1})+f(x_i)\right]\Delta x, \quad \frac{1}{6}\left[f(x_{i-1})+4f\left(\frac{x_{i-1}+x_i}{2}\right)+f(x_i)\right]\Delta x$$

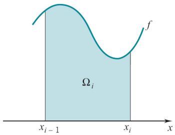
trapeziodal — Parabolic

Approximations of $\int_a^b f(x)\,dx = \sum_{i=1}^n \int_{x_{i-1}}^{x_i} f(x)\,dx$

$$\sum_{i=1}^n \frac{\Delta x}{2}\left[f(x_{i-1})+f(x_i)\right], \quad \sum_{i=1}^n \frac{\Delta x}{6}\left[f(x_{i-1})+4f\left(\frac{x_{i-1}+x_i}{2}\right)+f(x_i)\right]$$

Trapeziodal — Parabolic

Trapeziodal and Parabolic Approximations



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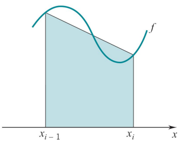
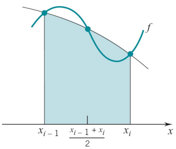


Trapeziodal



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Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$$\frac{1}{2}\left[f(x_{i-1}) + f(x_i)\right]\Delta x, \quad \frac{1}{6}\left[f(x_{i-1}) + 4f\left(\frac{x_{i-1}+x_i}{2}\right) + f(x_i)\right]\Delta x$$

trapeziodal — Parabolic

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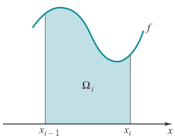
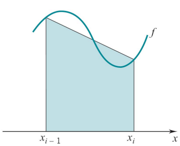
Trapeziodal — Parabolic

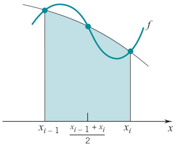
Trapeziodal and Parabolic Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



Trapeziodal



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trapeziodal Parabolic

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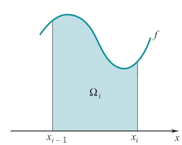
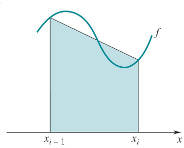
Trapeziodal Parabolic

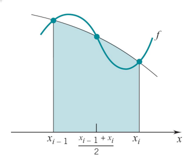
Trapeziodal and Parabolic Approximations



$\int_{x_{i-1}}^{x_i} f(x)\,dx$



Trapeziodal



Parabolic

Approximations of $\int_{x_{i-1}}^{x_i} f(x)\,dx$

$$\frac{1}{2}\left[f(x_{i-1}) + f(x_i)\right]\Delta x, \quad \frac{1}{6}\left[f(x_{i-1}) + 4f\left(\frac{x_{i-1}+x_i}{2}\right) + f(x_i)\right]\Delta x$$

trapeziodal Parabolic

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Trapeziodal Parabolic

Trapeziodal and Simpson's Rules

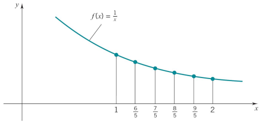
Trapeziodal and Simpson's Rules for Approximating $\int_a^b f(x)\,dx$

- Trapeziodal Rule:

$$T_n = \frac{b-a}{2n}\left[f(x_0) + 2f(x_1) + \cdots + 2f(x_{n-1}) + f(x_n)\right]$$

- Simpson's Rule (Parabolic):

$$S_n = \frac{b-a}{6n}\left\{f(x_0) + f(x_n) + 2\Big[f(x_1) + \cdots + 2f(x_{n-1})\Big] + 4\left[f\left(\frac{x_0+x_1}{2}\right) + \cdots + f\left(\frac{x_{n-1}+x_n}{2}\right)\right]\right\}$$



Problem

Find the approximate value of $\ln 2 = \int_1^2 \frac{dx}{x}$ using only the values of $f(x) = \frac{1}{x}$ at $1, \frac{6}{5}, \frac{7}{5}, \frac{8}{5}, \frac{9}{5}, 2$.

Trapeziodal and Simpson's Rules

Trapeziodal and Simpson's Rules for Approximating $\int_a^b f(x)\,dx$

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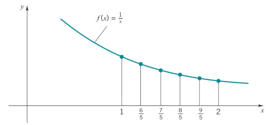

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Trapeziodal and Simpson's Rules

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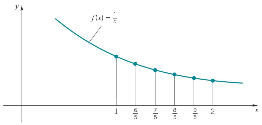

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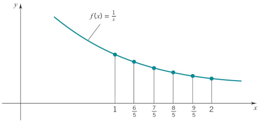

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Find the approximate value of $\ln 2 = \int_1^2 \frac{dx}{x}$ using only the values of $f(x) = \frac{1}{x}$ at $1, \frac{6}{5}, \frac{7}{5}, \frac{8}{5}, \frac{9}{5}, 2$.

Trapeziodal and Simpson's Rules

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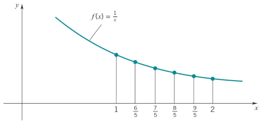
$$S_n = \frac{b-a}{6n}\left\{f(x_0) + f(x_n) + 2\left[f(x_1) + \cdots + 2f(x_{n-1})\right]\right.$$
$$\left. +4\left[f\left(\frac{x_0+x_1}{2}\right) + \cdots + f\left(\frac{x_{n-1}+x_n}{2}\right)\right]\right\}$$



Approximating $\ln 2 = 0.69314718\cdots$

$$T_5 = \frac{1}{10}\left(1 + \frac{10}{6} + \frac{10}{7} + \frac{10}{8} + \frac{10}{9} + \frac{1}{2}\right) \approx 0.6956$$

$$S_5 = \frac{1}{30}\left\{1 + \frac{1}{2} + 2\left(\frac{5}{6} + \frac{5}{7} + \frac{5}{8} + \frac{5}{9}\right)\right.$$
$$\left. +4\left[\frac{10}{11} + \frac{10}{13} + \frac{10}{15} + \frac{10}{17} + \frac{10}{19}\right]\right\} \approx 0.6932$$

Trapeziodal and Simpson's Rules

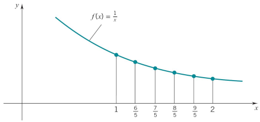
Trapeziodal and Simpson's Rules for Approximating $\int_a^b f(x)\,dx$

- Trapeziodal Rule:

$$T_n = \frac{b-a}{2n}\left[f(x_0) + 2f(x_1) + \cdots + 2f(x_{n-1}) + f(x_n)\right]$$

- Simpson's Rule (Parabolic):

$$S_n = \frac{b-a}{6n}\left\{f(x_0) + f(x_n) + 2\left[f(x_1) + \cdots + 2f(x_{n-1})\right] + 4\left[f\left(\frac{x_0+x_1}{2}\right) + \cdots + f\left(\frac{x_{n-1}+x_n}{2}\right)\right]\right\}$$



Approximating $\ln 2 = 0.69314718\cdots$

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Trapeziodal and Simpson's Rules

Trapeziodal and Simpson's Rules for Approximating $\int_a^b f(x)\,dx$

- Trapeziodal Rule:

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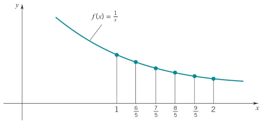

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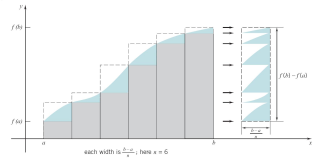
Error Estimates



$$\left| \int_a^b f(x)\,dx - T_n \right| \le \frac{1}{2}\left(\frac{b-a}{n}\right)[f(b)-f(a)]$$

Error Estimates

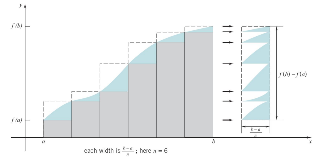
- Trapeziodal Rule:

$$E_n^T = \int_a^b f(x)\,dx - T_n = -\frac{1}{12}\frac{(b-a)^3}{n^2}f''(c) = O((\Delta x)^2)$$

- Simpson's Rule:

$$E_n^S = \int_a^b f(x)\,dx - S_n = -\frac{1}{2880}\frac{(b-a)^5}{n^4}f^{(4)}(c) = O((\Delta x)^4)$$

Error Estimates



$$\left|\int_a^b f(x)\,dx - T_n\right| \le \frac{1}{2}\left(\frac{b-a}{n}\right)[f(b)-f(a)]$$

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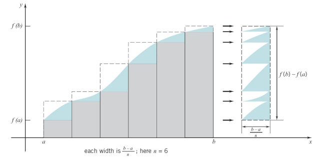
Error Estimates



$$\left|\int_a^b f(x)\,dx - T_n\right| \le \frac{1}{2}\left(\frac{b-a}{n}\right)[f(b)-f(a)]$$

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$$E_n^S = \int_a^b f(x)\,dx - S_n = -\frac{1}{2880}\frac{(b-a)^5}{n^4}f^{(4)}(c) = O((\Delta x)^4)$$

Error Estimates: Example

Error Estimates

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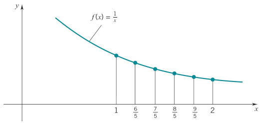

Approximating $\ln 2 = 0.69314718\cdots$

Note that $f(x) = \frac{1}{x}$, $f'(x) = -\frac{1}{x^2}$, $f''(x) = \frac{2}{x^3}$, $f^{(3)}(x) = -\frac{6}{x^4}$, $f^{(4)}(x) = \frac{24}{x^5}$.

$$|E_n^T| \le \frac{1}{12}\frac{(2-1)^3}{5^2}\max_{c\in[1,2]}|f''(c)| = \frac{1}{150}$$

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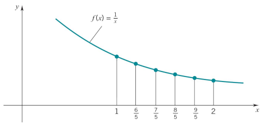

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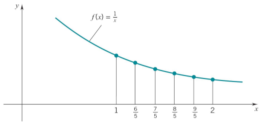

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Outline

- Riemann Sums
  - Area Problem
  - Lower and Upper Sums
  - Riemann Sum
- Rectangle Approximations
  - Regular Partition
  - Approximations
  - Error Estimates
- Trapeziodal and Parabolic Approximations
  - Approximations
  - Error Estimates