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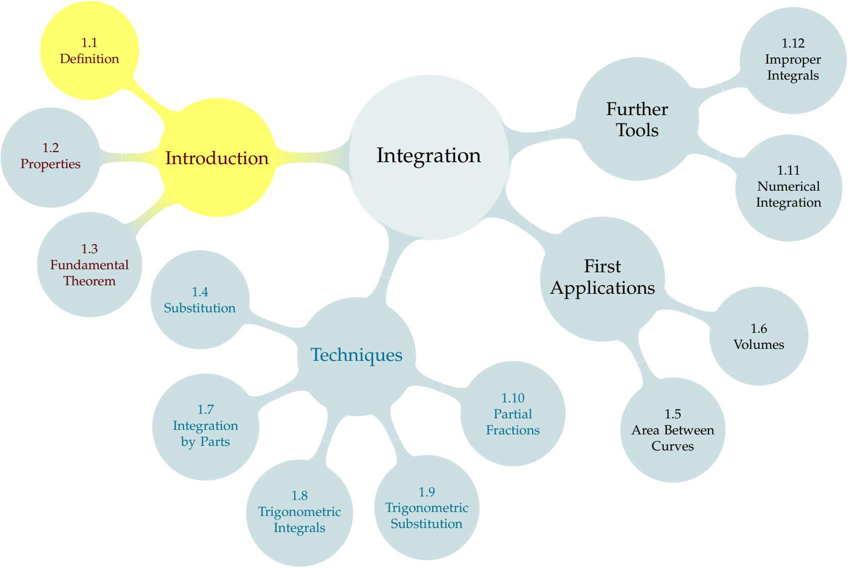

Calculus is build on two operations: differentiation and integration.

Differentiation

- Slope of a line
- Rate of change

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Differentiation

- Slope of a line
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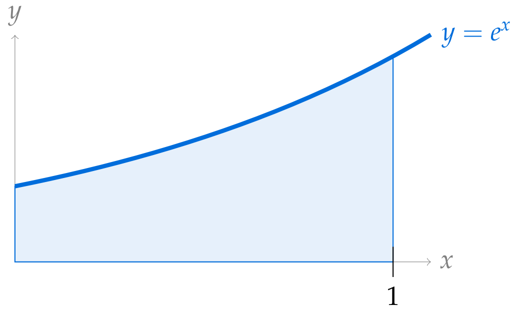
Integration

- Area under a curve
- “Reverse” of differentiation
- Solving differential equations
- Calculate net change from rate of change
- Volume of solids
- Work (in the physics sense)

Approximate the area of the shaded region using rectangles.



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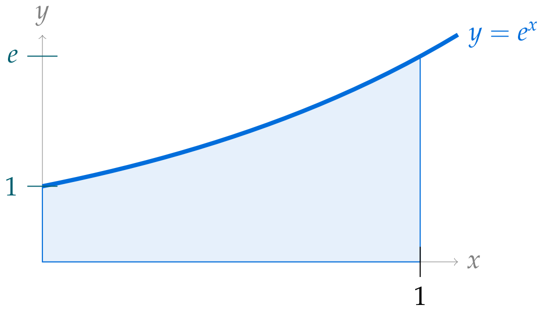

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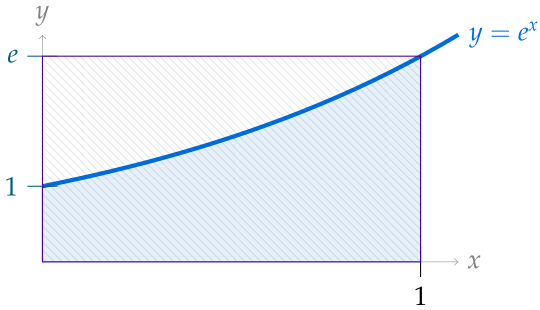

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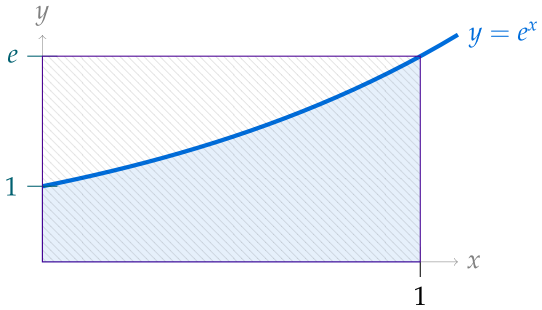

Area $\leq e$

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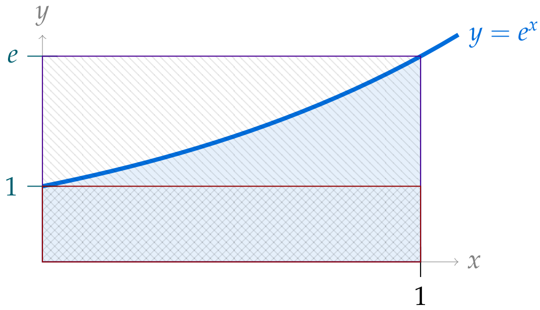

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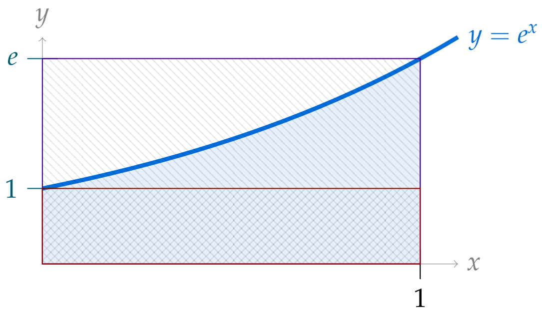

$$1 \leq \text{ Area } \leq e$$

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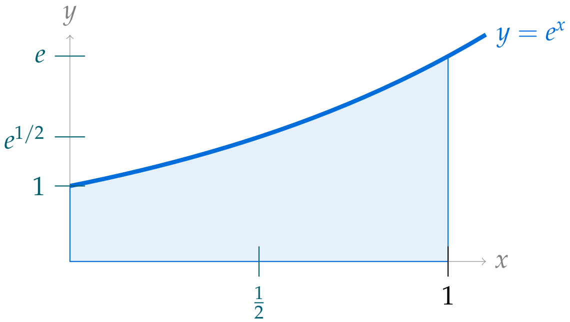

Area

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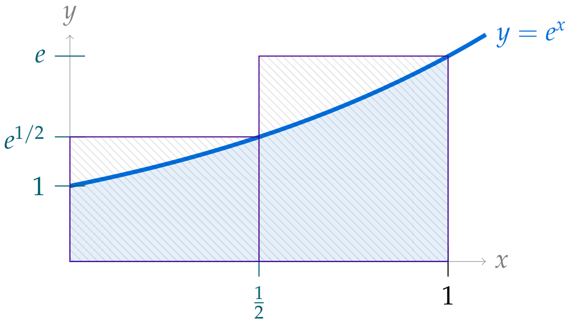

$$\text{Area} \leq \left(\tfrac{1}{2}e^{1/2} + \tfrac{1}{2}e\right)$$

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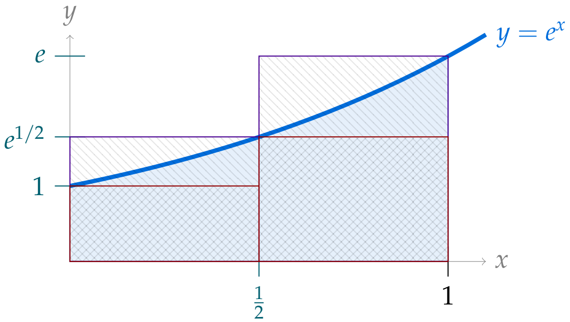

$$\left(\frac{1}{2} + \frac{1}{2}e^{1/2}\right) \leq \text{ Area } \leq \left(\frac{1}{2}e^{1/2} + \frac{1}{2}e\right)$$

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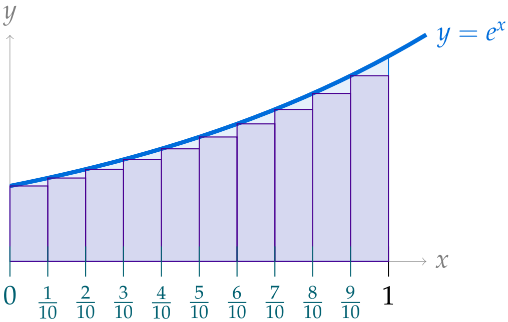

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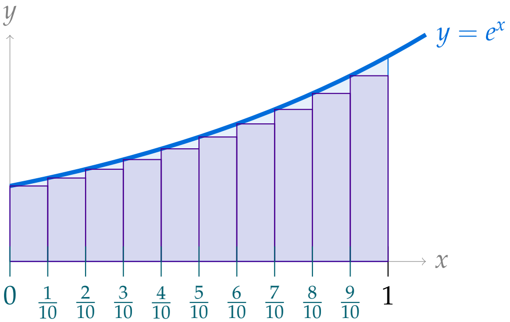

$$\text{Area} \approx \frac{1}{10}(1) + \frac{1}{10}\left(e^{1/10}\right) + \frac{1}{10}\left(e^{2/10}\right) + \frac{1}{10}\left(e^{3/10}\right) + \cdots + \frac{1}{10}\left(e^{9/10}\right)$$

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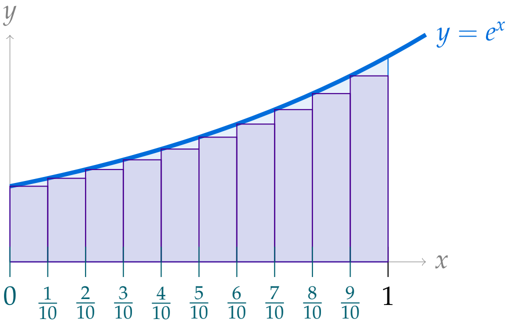

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We're going to be doing a lot of adding.

Summation (Sigma) Notation

$$\sum_{i=a}^{b} f(i)$$

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$$\sum_{i=a}^{b} f(i) = f(a) + f(a+1) + f(a+2) + \cdots + f(b)$$

Sigma Notation

$$\text{Expand } \sum_{i=2}^{4}(2i+5).$$

Sigma Notation

Expand $\displaystyle\sum_{i=1}^{4}(i+(i-1)^2)$.

Q

Write the following expressions in sigma notation:

- $3+4+5+6+7$
- $8+8+8+8+8$
- $1+(-2)+4+(-8)+16$

Arithmetic of Summation Notation

Let c be a constant.

- Adding constants: $\sum_{i=1}^{10} c =$

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- Addition is Commutative: $\sum_{i=1}^{10}(i+i^2) = \left(\sum_{i=1}^{10} i\right) + \left(\sum_{i=1}^{10} i^2\right)$

COMMON SUMS

Let $n \geq 1$ be an integer, a be a real number, and $r \neq 1$.

$$\sum_{i=0}^{n} ar^i = a + ar + ar^2 + \cdots + ar^n = a\frac{1-r^{n+1}}{1-r}$$

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

$$\sum_{i=1}^{n} i^2 = 1^2 + 2^2 + \cdots + n^2 = \frac{n(n+1)(2n+1)}{6}$$

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Simplify: $\sum_{i=1}^{13}(i^2 + i^3)$

Q

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Simplify: $\sum_{i=1}^{50}(1-i^2)$

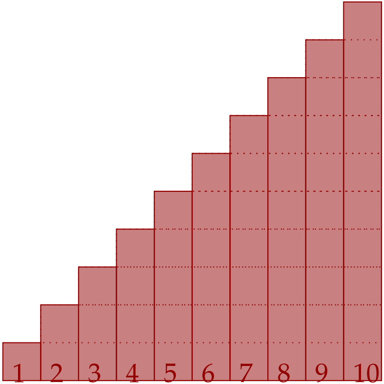
Q

(Optional) Proof of a Common Sum

Here is a derivation of $\displaystyle\sum_{i=0}^{n} r^i = \frac{1-r^{n+1}}{1-r}$:

(Optional) Proof of Another Common Sum

$$\sum_{i=1}^{10} i = 1+2+3+4+5+6+7+8+9+10 =$$



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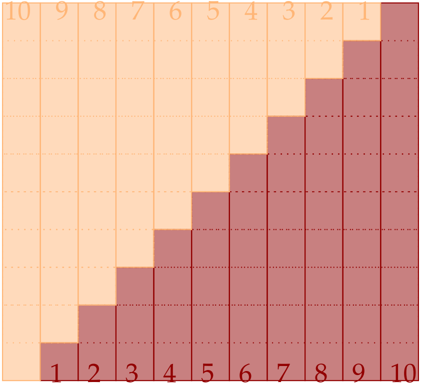

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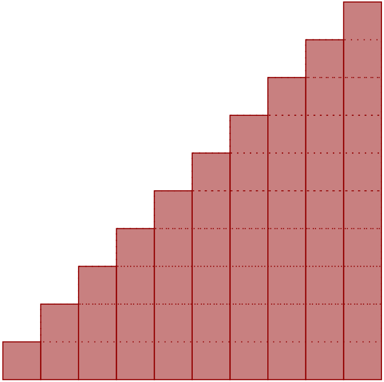
$$\sum_{i=1}^{n} i = 1 + 2 + 3 + \cdots + n =$$



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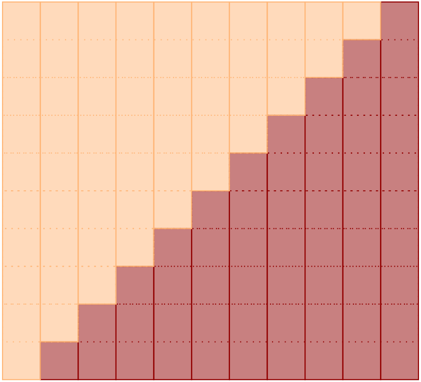

The purpose of these sums is to describe areas.

Notation

The symbol

$$\int_a^b f(x)\, \mathrm{d}x$$

is read "the definite integral of the function $f(x)$ from a to b."

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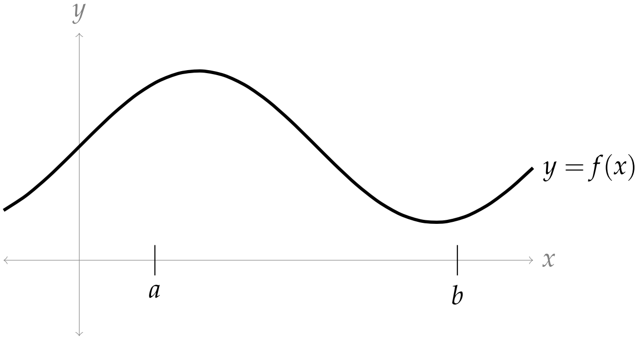
- $f(x)$: integrand
- a and b: limits of integration
- $\mathrm{d}x$: differential

If $f(x) \geq 0$ and $a \leq b$, one interpretation of

$$\int_a^b f(x)\,\mathrm{d}x$$

is "the area of the region bounded above by $y = f(x)$, below by $y = 0$, to the left by $x = a$, and to the right by $x = b$."



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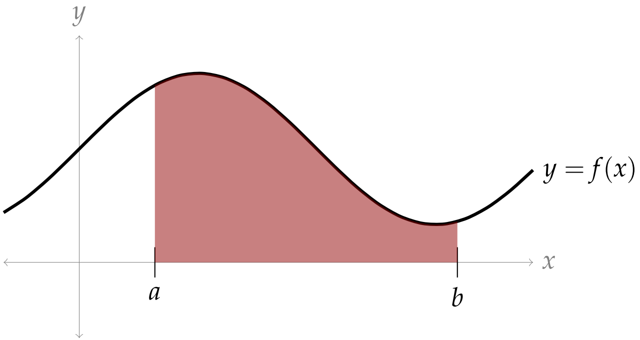

If ~~$f(x) \geq 0$ and~~ $a \leq b$, one interpretation of

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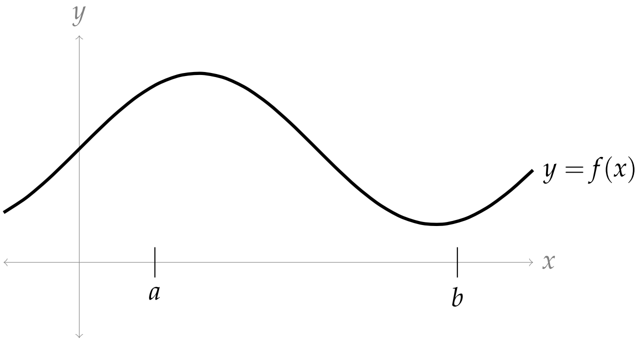
is the signed area of the region between $y = f(x)$ and $y = 0$, from $x = a$ to $x = b$. Area above the axis is positive, and area below it is negative.



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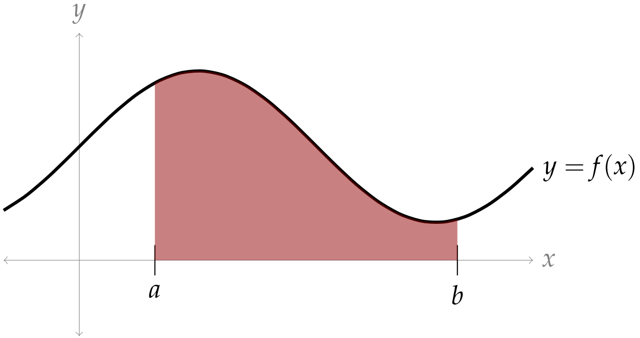

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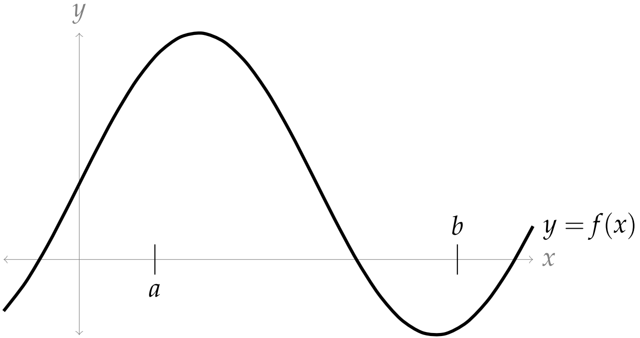

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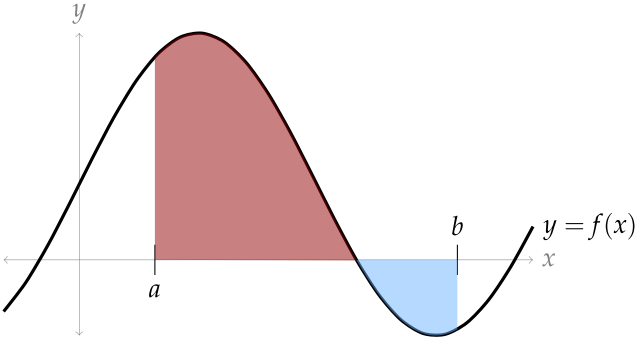
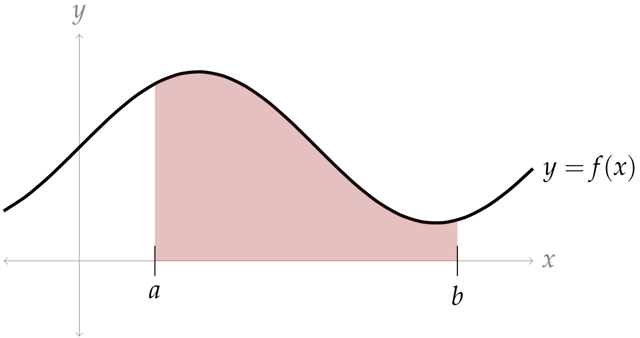


Riemann Sums

A Riemann sum approximates the area under a curve by cutting it into equal-width segments, and approximating each segment as a rectangle.



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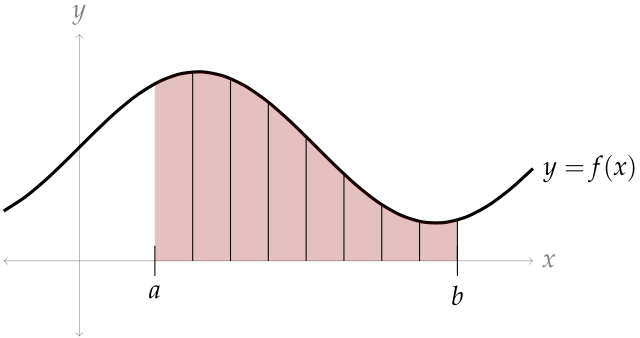

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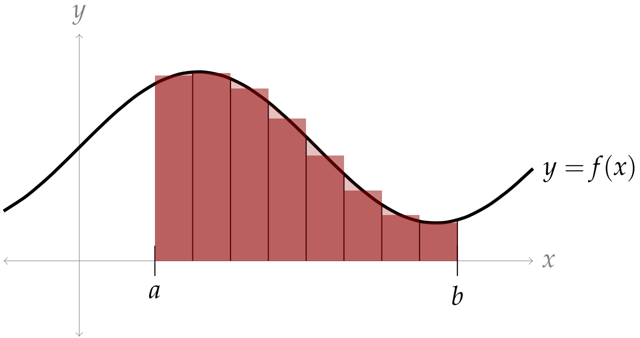

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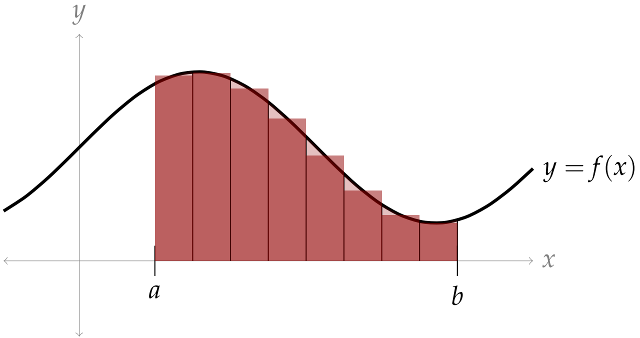
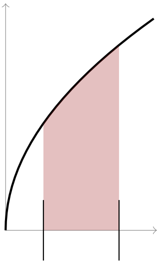
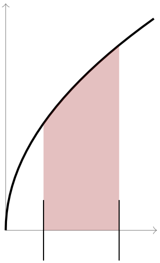


There are different ways to choose the height of each rectangle.

Types of Riemann Sums (RS)



Left RS



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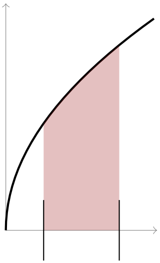

Midpoint RS

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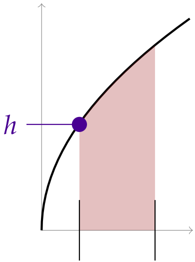

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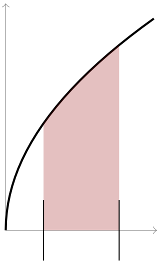

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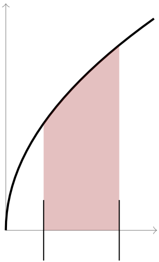

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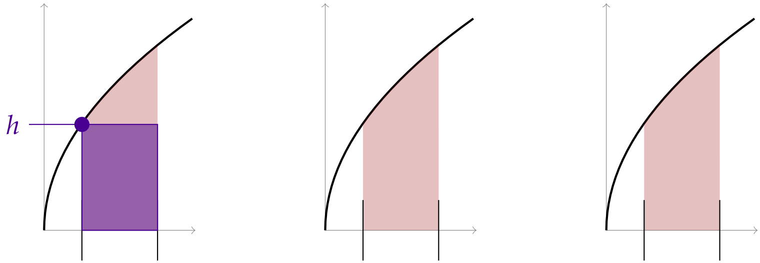

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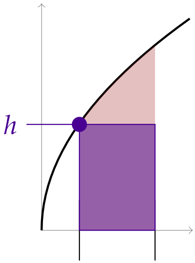

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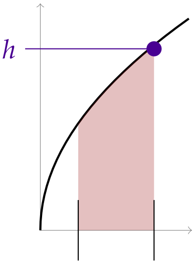

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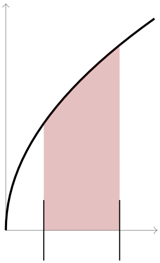

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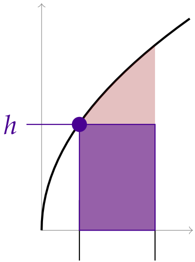

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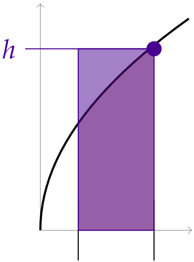

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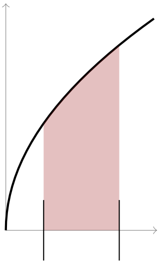

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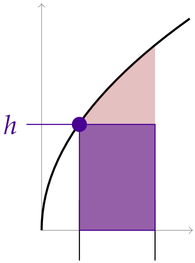

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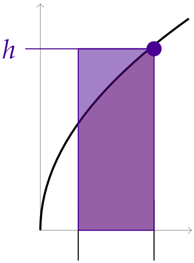

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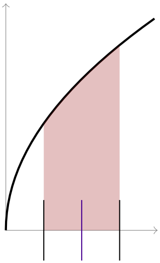

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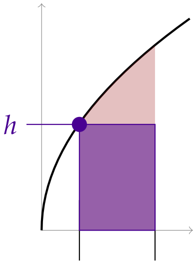
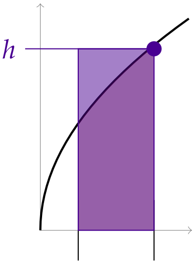
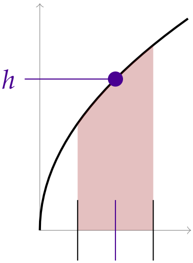


Left RS

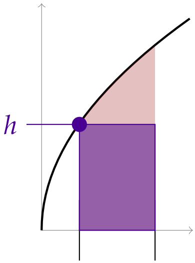


Right RS

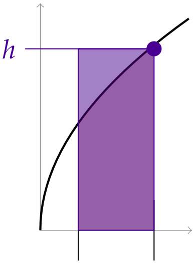


Midpoint RS

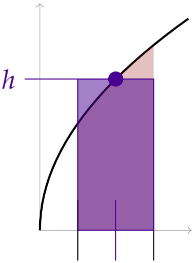
Types of Riemann Sums (RS)



Left RS

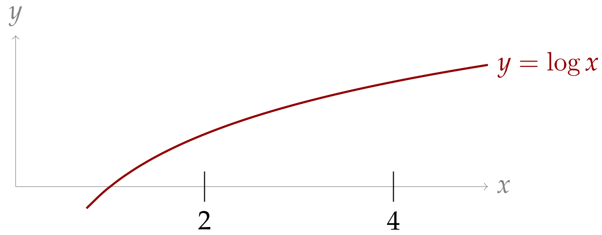


Right RS

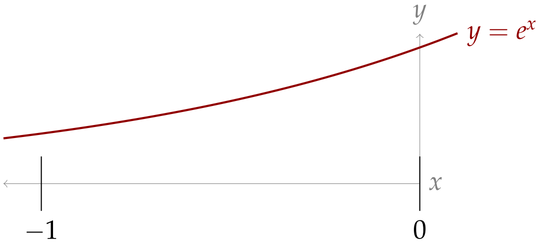


Midpoint RS

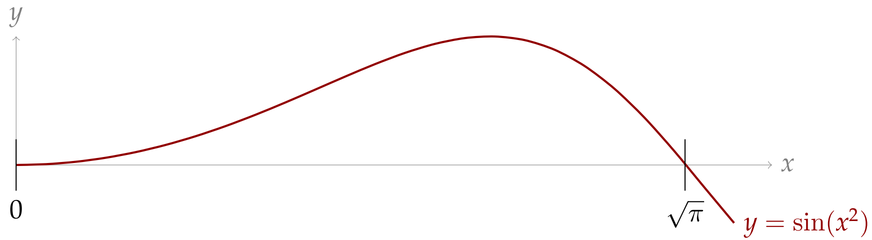
Approximate $\int_2^4 \log(x)\,\mathrm{d}x$ using a right Riemann sum with $n = 4$ rectangles. For now, do not use sigma notation.



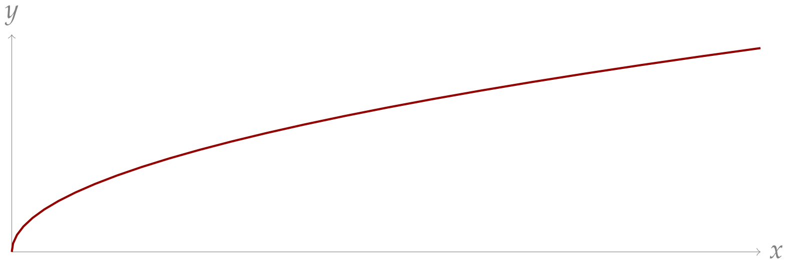
Approximate $\int_{-1}^{0} e^x \, dx$ using a left Riemann sum with $n = 3$ rectangles. For now, do not use sigma notation.



Approximate $\int_0^{\sqrt{\pi}} \sin\left(x^2\right) \mathrm{d}x$ using a midpoint Riemann sum with $n = 5$ rectangles. For now, do not use sigma notation.

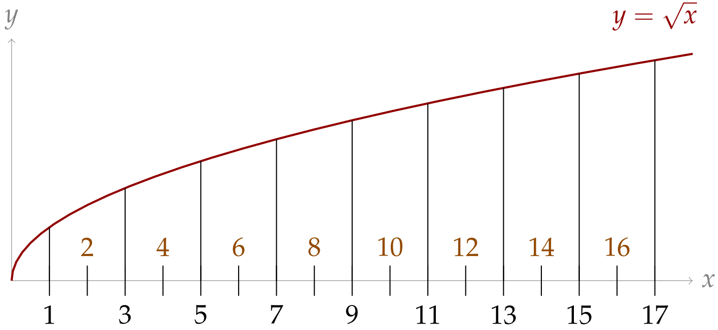


Approximate $\int_1^{17} \sqrt{x}\,\mathrm{d}x$ using a midpoint Riemann sum with 8 rectangles. Write the result in sigma notation.



Q

$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



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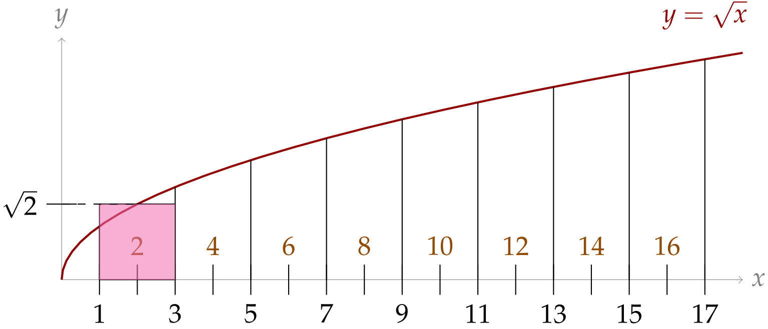
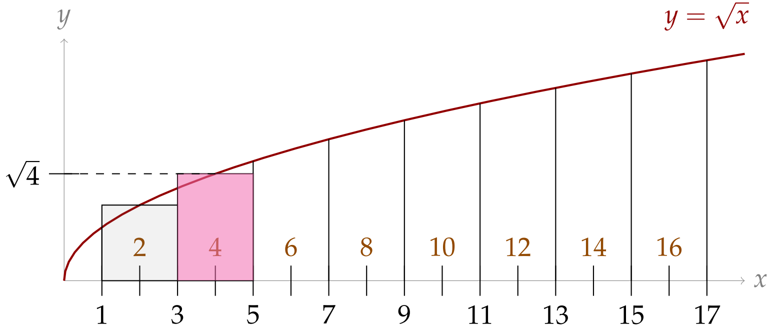


Base: 2

Height: $\sqrt{2}$

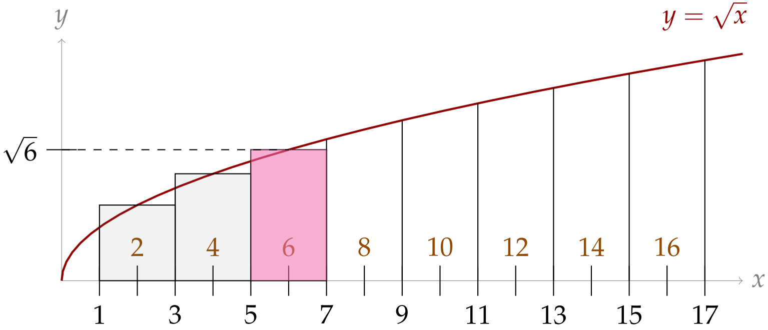
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{4}$

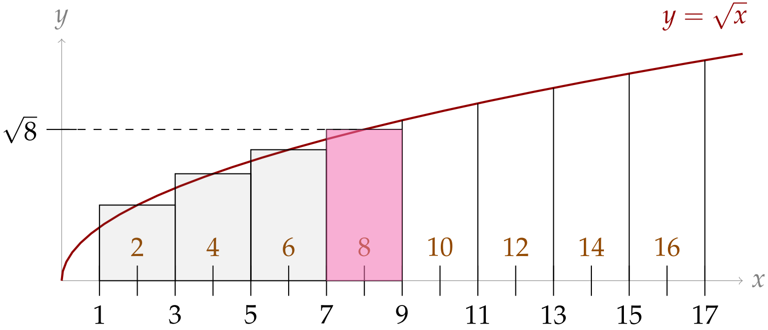
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{6}$

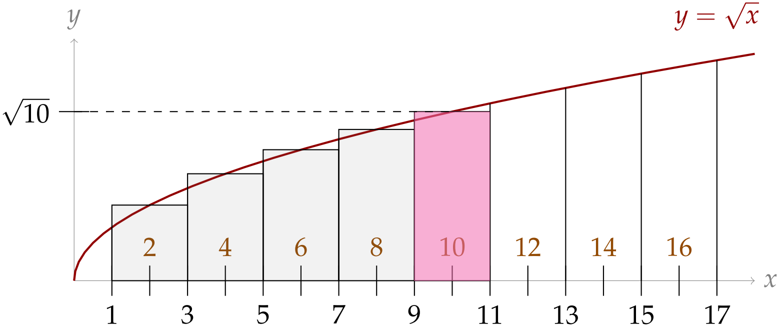
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{8}$

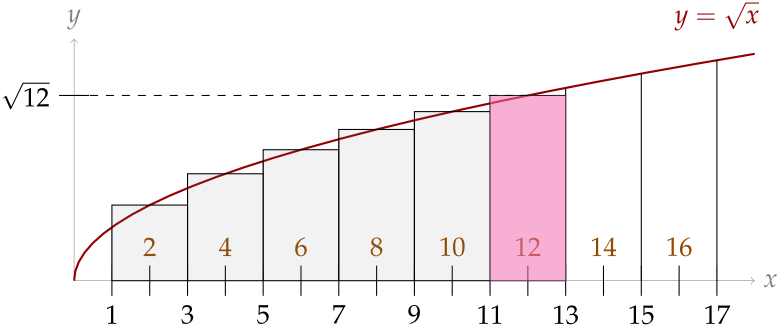
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{10}$

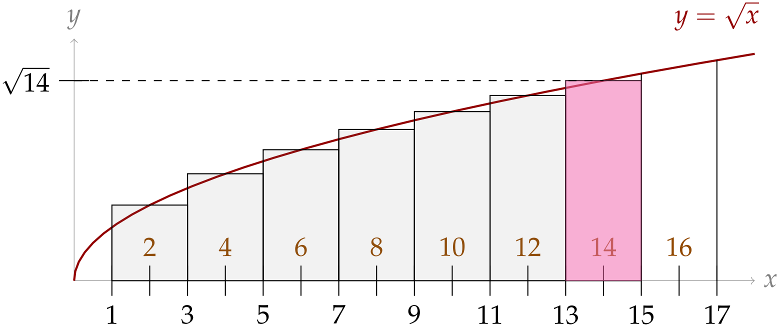
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{12}$

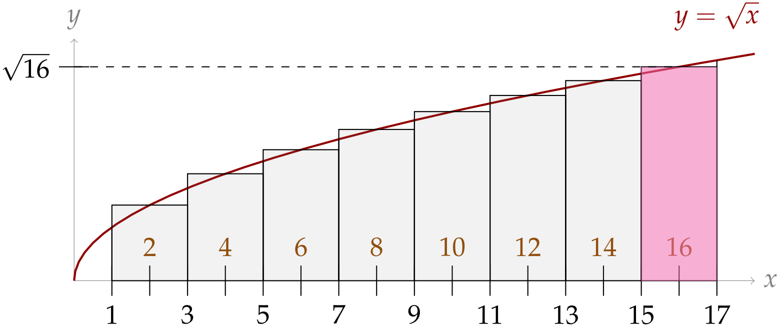
$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

Height: $\sqrt{14}$

$$\sum_{i=1}^{8} 2\sqrt{2i} = \underbrace{2\sqrt{2}}_{i=1} + \underbrace{2\sqrt{4}}_{i=2} + \underbrace{2\sqrt{6}}_{i=3} + \underbrace{2\sqrt{8}}_{i=4} + \underbrace{2\sqrt{10}}_{i=5} + \underbrace{2\sqrt{12}}_{i=6} + \underbrace{2\sqrt{14}}_{i=7} + \underbrace{2\sqrt{16}}_{i=8}$$



Base: 2

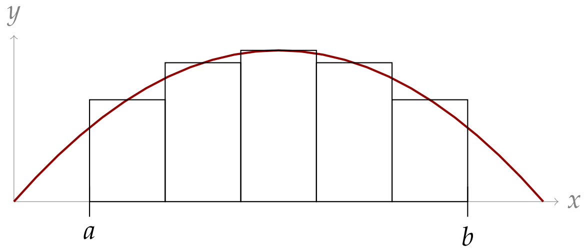
Height: $\sqrt{16}$

Riemann sum with n rectangles

$$\int_a^b f(x)\,\mathrm{d}x \approx \sum_{i=1}^{n} \Delta x \cdot f(x_{i,n}^*)$$

where $\Delta x = \frac{b-a}{n}$ and $x_{i,n}^*$ is an x-value in the ith rectangle.

$$\sum_{i=1}^{n} \Delta x \cdot f(x_{i,n}^*) = \Delta x \cdot f\left(x_{1,n}^*\right) + \Delta x \cdot f\left(x_{2,n}^*\right) + \Delta x \cdot f\left(x_{3,n}^*\right) + \cdots + \Delta x \cdot f\left(x_{n,n}^*\right)$$



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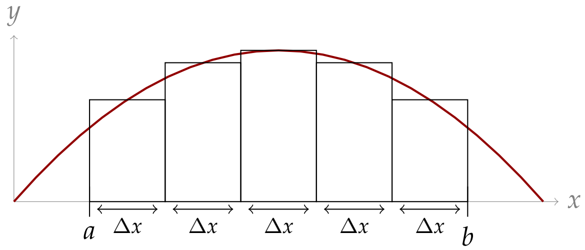

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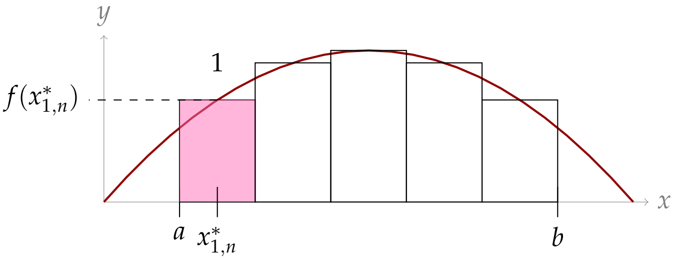
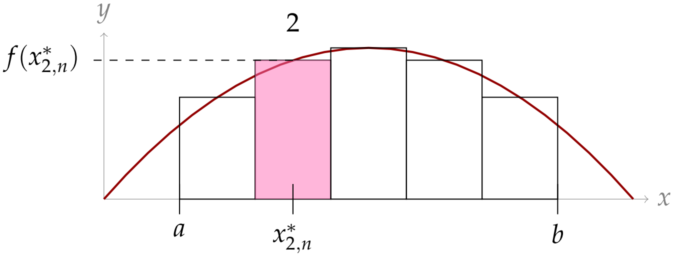


Riemann sum with n rectangles

$$\int_a^b f(x)\,\mathrm{d}x \approx \sum_{i=1}^{n} \Delta x \cdot f(x^*_{i,n})$$

where $\Delta x = \frac{b-a}{n}$ and $x^*_{i,n}$ is an x-value in the ith rectangle.

$$\sum_{i=1}^{n} \Delta x{\cdot}f(x^*_{i,n}) = \Delta x{\cdot}f\left(x^*_{1,n}\right) + \Delta x{\cdot}f\left(x^*_{2,n}\right) + \Delta x{\cdot}f\left(x^*_{3,n}\right) + \cdots + \Delta x{\cdot}f\left(x^*_{n,n}\right)$$



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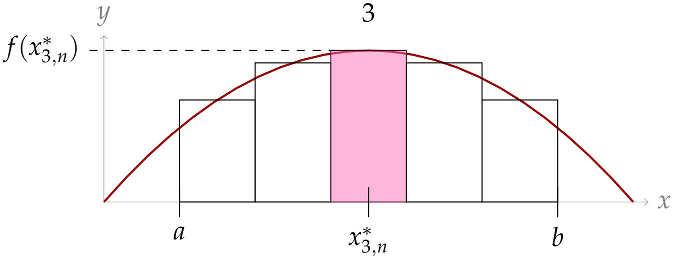
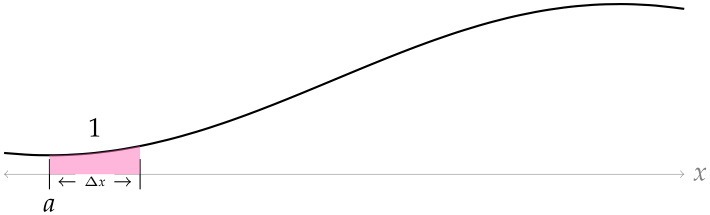


Right Riemann sum with n rectangles

$$\int_a^b f(x)\mathrm{d}x \approx \sum_{i=1}^{n} \Delta x \cdot f\left(\qquad\qquad \right)$$

where $\Delta x = \frac{b-a}{n}$ and $x_{i,n}^* =$



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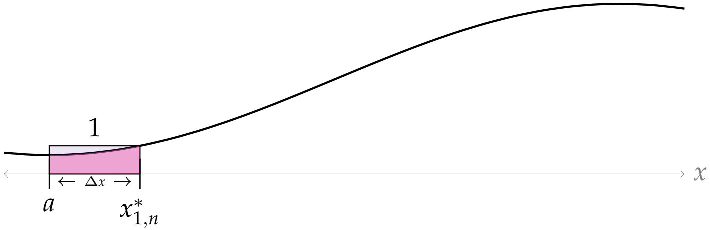

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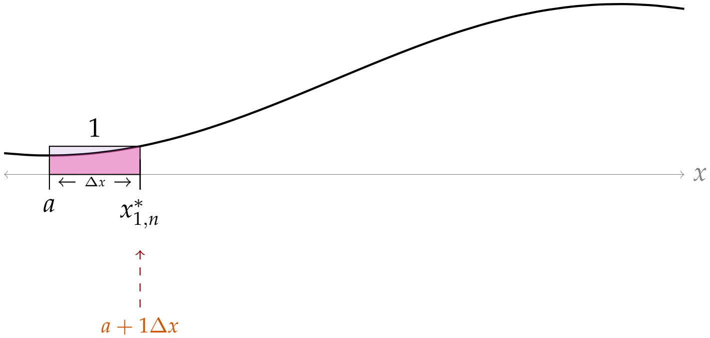

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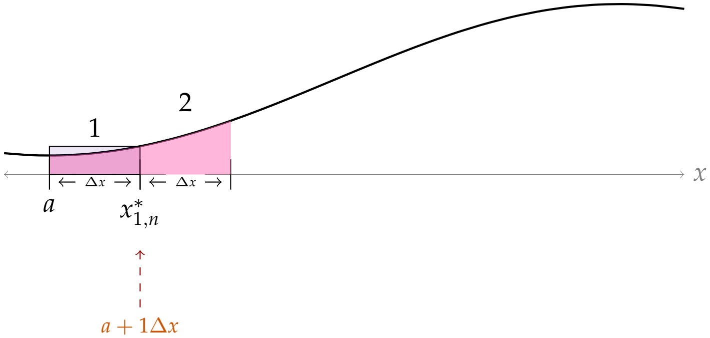

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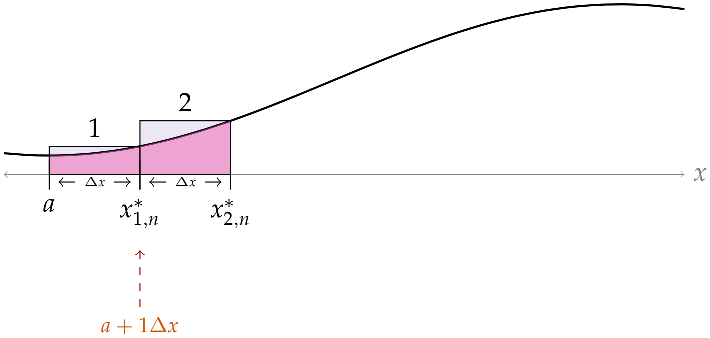

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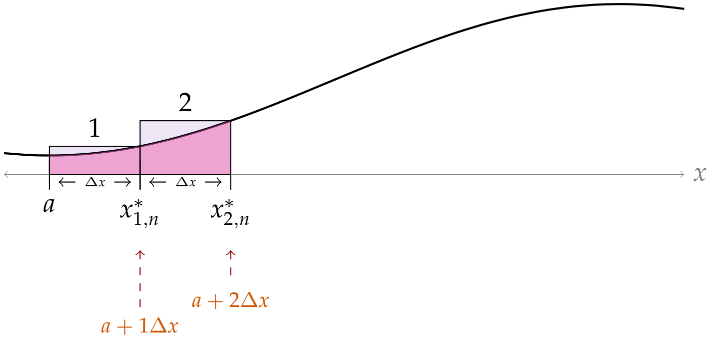
where $\Delta x = \frac{b-a}{n}$ and $x^*_{i,n} =$



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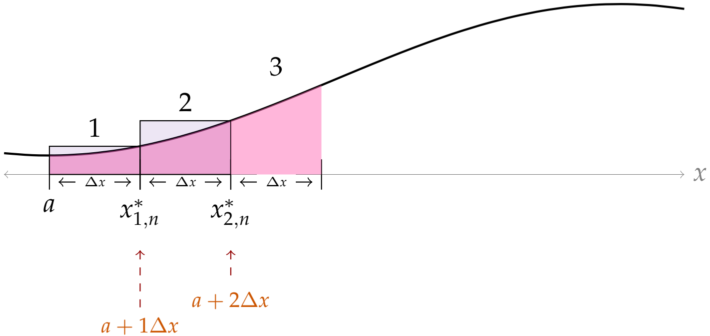

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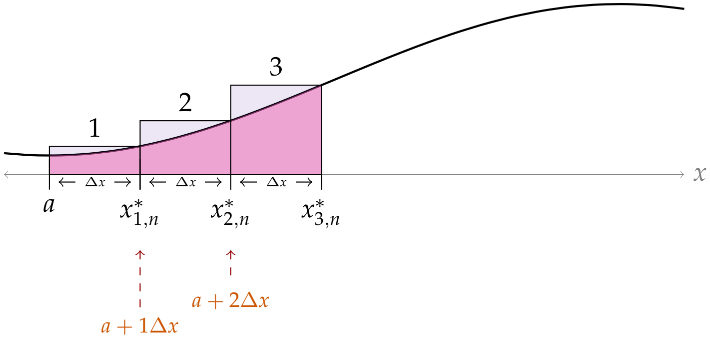

Right Riemann sum with n rectangles

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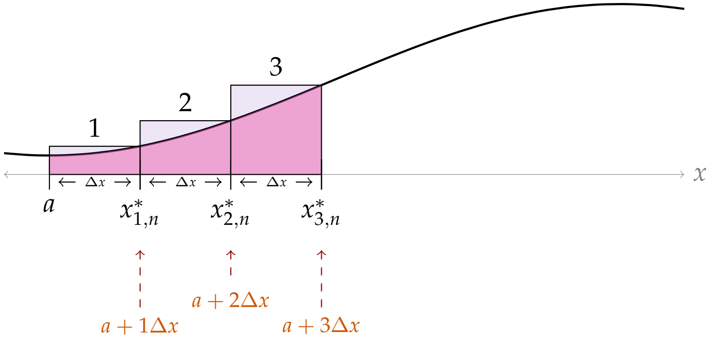

Right Riemann sum with n rectangles

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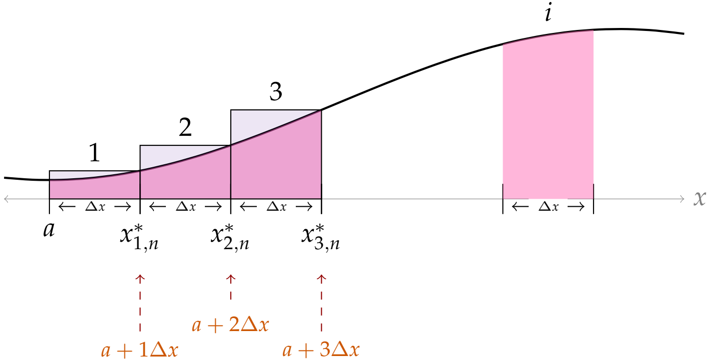

Right Riemann sum with n rectangles

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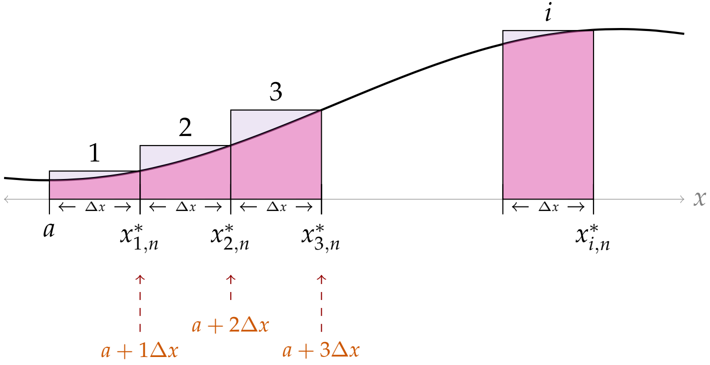
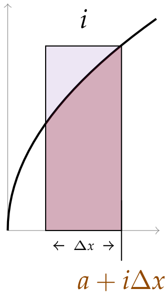
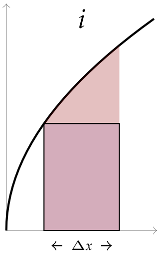


Types of Riemann Sums (RS)

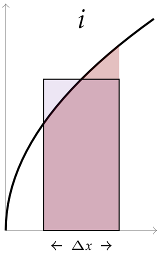
What height would you choose for the *i*th rectangle?



Right RS



Left RS



Midpoint RS

Riemann sums with n rectangles. Let $\Delta x = \frac{b-a}{n}$

The right Riemann sum approximation of $\int_a^b f(x)\,\mathrm{d}x$ is:

$$\sum_{i=1}^{n} \Delta x \cdot f\left(a + i\Delta x\right)$$

The left Riemann sum approximation of $\int_a^b f(x)\,\mathrm{d}x$ is:

$$\sum_{i=1}^{n} \Delta x \cdot f\left(a + (i-1)\Delta x\right)$$

The midpoint Riemann sum approximation of $\int_a^b f(x)\,\mathrm{d}x$ is:

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

Riemann sums with n rectangles: Let $\Delta x = \frac{b-a}{n}$

The right Riemann sum approximation of $\int_a^b f(x)\,\mathrm{d}x$ is:

$$\sum_{i=1}^{n} \Delta x \cdot f\left(a + i\Delta x\right)$$

Give a right Riemann Sum for the area under the curve $y = x^2 - x$ from $a = 1$ to $b = 6$ using $n = 1000$ intervals.

Riemann sums with n rectangles: Let $\Delta x = \frac{b-a}{n}$

The midpoint Riemann sum approximation of $\int_a^b f(x)\,\mathrm{d}x$ is:

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

Give a midpoint Riemann Sum for the area under the curve $y = 5x - x^2$ from $a = 6$ to $b = 9$ using $n = 1000$ intervals.

Q

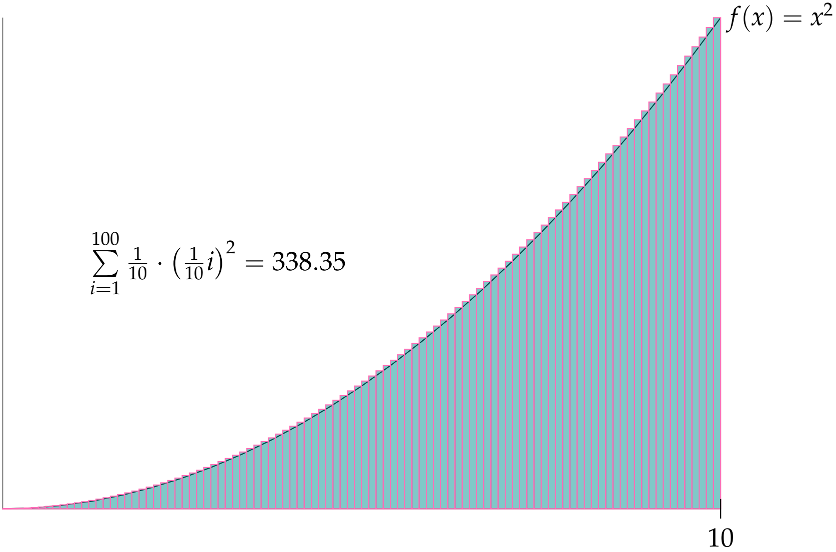
Evaluating Riemann Sums

SKIP RIEMANN EVALUATIONS

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}$$

Give the right Riemann sum of $f(x) = x^2$ from $a = 0$ to $b = 10$, $n = 100$:

$$\sum_{i=1}^{n} \Delta x \cdot f\,(a + i\Delta x) =$$



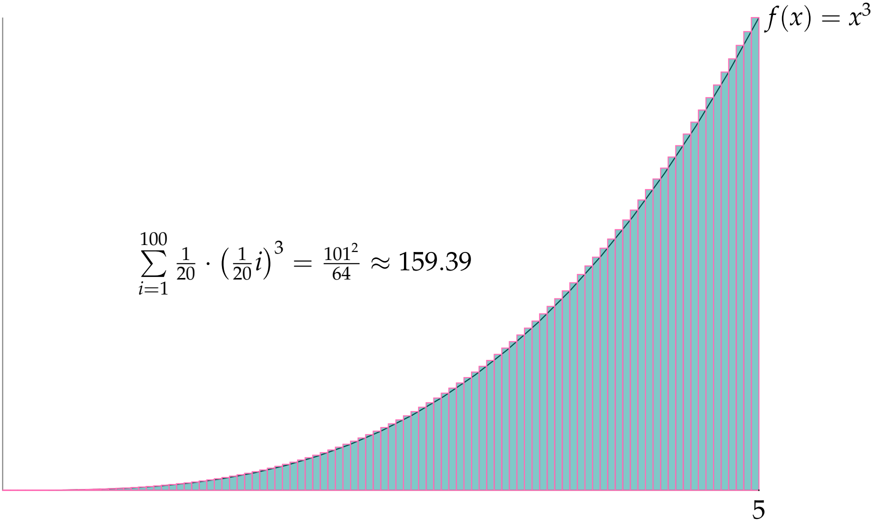
$$\sum_{i=1}^{100} \frac{1}{10} \cdot \left(\frac{1}{10} i\right)^2 = 338.35$$

Evaluating Riemann Sums in Sigma Notation

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}$$

Give the right Riemann sum of $f(x) = x^3$ from $a = 0$ to $b = 5$, $n = 100$:

Q



$$\sum_{i=1}^{100} \frac{1}{20} \cdot \left(\frac{1}{20} i\right)^3 = \frac{101^2}{64} \approx 159.39$$

Definition

Let a and b be two real numbers and let $f(x)$ be a function that is defined for all x between a and b. Then we define $\Delta x = \frac{b-a}{N}$ and

$$\int_a^b f(x)\,\mathrm{d}x = \lim_{N\to\infty} \sum_{i=1}^{N} f(x_{i,N}^*) \cdot \Delta x$$

when the limit exists and when the choice of $x_{i,N}^*$ in the i^{th} interval doesn't matter.

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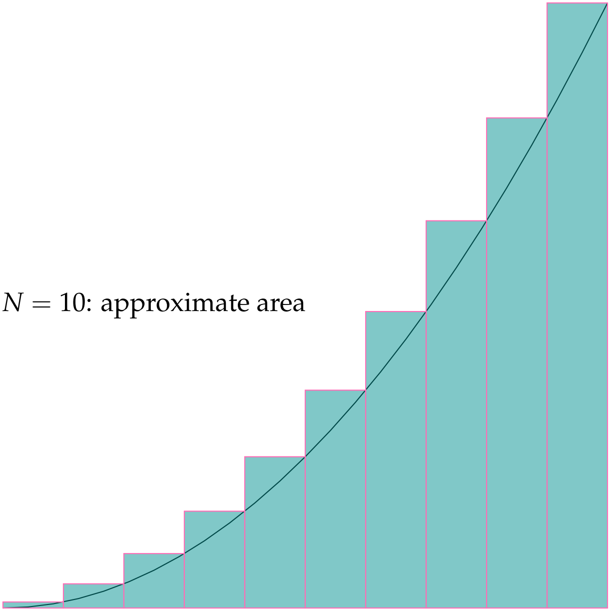
It's understood we're taking a limit as N goes to infinity, so we don't bother specifying N (or each location where we find our height) in the second notation.


$N = 10$: approximate area

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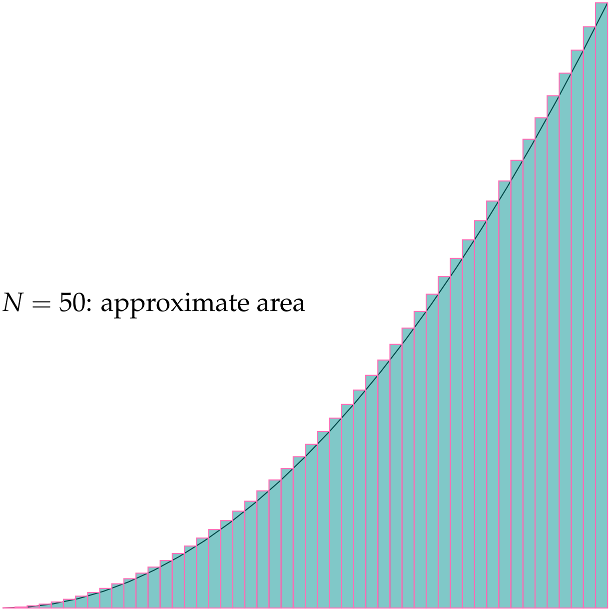
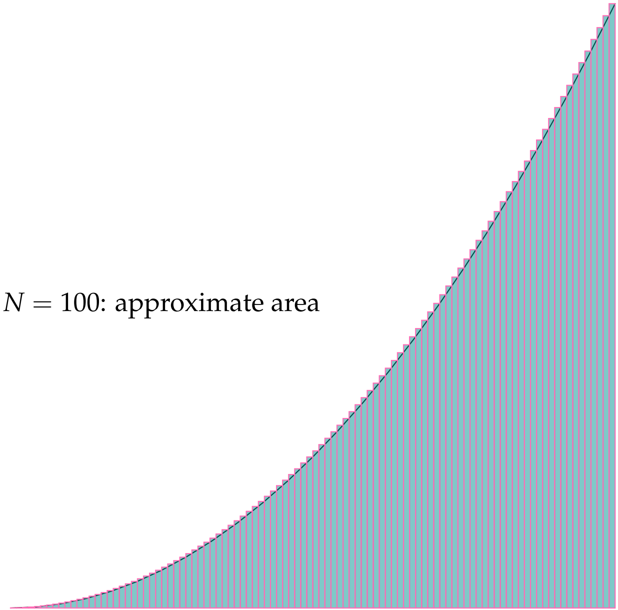
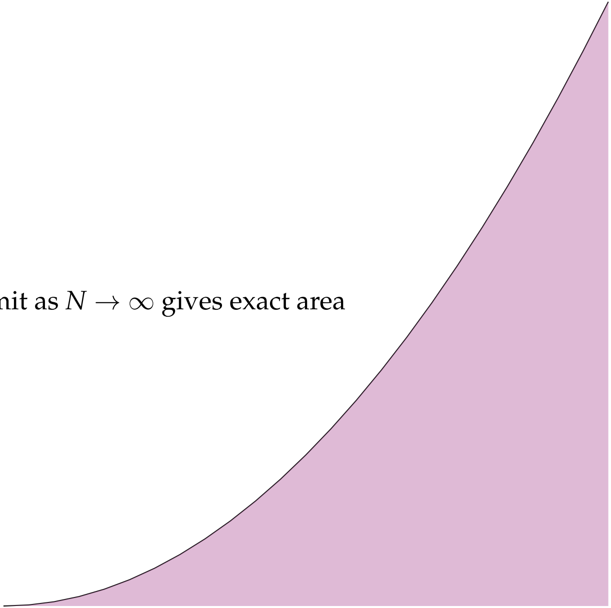



$N = 100$: approximate area



Limit as $N \to \infty$ gives exact area

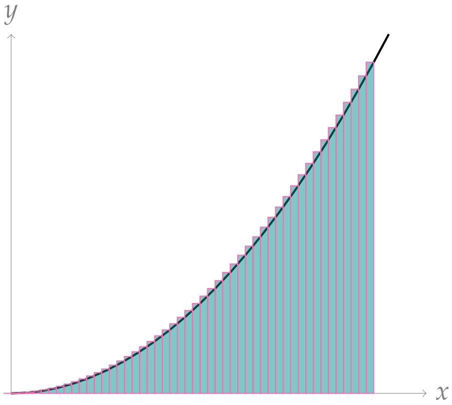
$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}$$

Give the right Riemann sum of $y = x^2$ from $a = 0$ to $b = 5$ with n slices, and simplify:

We found the right Riemann sum of $y = x^2$ from $a = 0$ to $b = 5$ using n slices:

$$\frac{125}{6} \cdot \frac{2n^2 + 3n + 1}{n^2}$$

Use it to find the exact area under the curve.



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Refresher: Limits of Rational Functions

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$$\lim_{n\to\infty} \frac{n^3+2n+15}{3n^2-9n+5} =$$

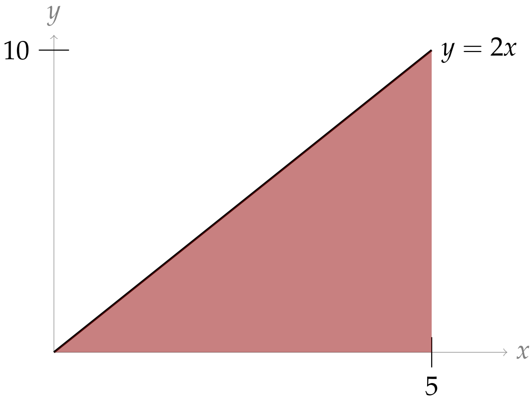
When the degree of the top is larger than the degree of the bottom, the limit as n goes to infinity is positive or negative infinity.

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}$$

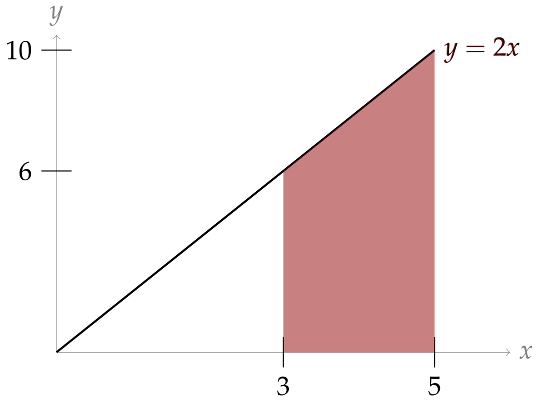
Evaluate $\displaystyle\int_0^1 x^2\, \mathrm{d}x$ exactly using midpoint Riemann sums.

Let's see some special cases where we can use geometry to evaluate integrals without Riemann sums.

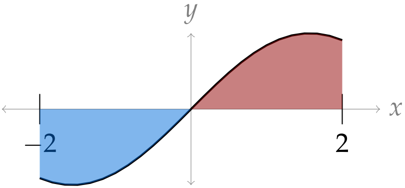
$$\int_0^5 2x \, dx$$



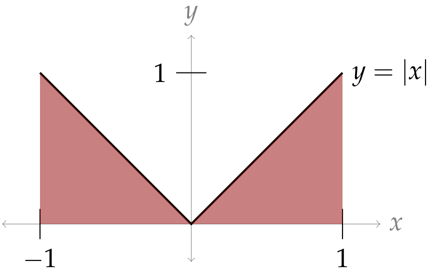
$$\int_3^5 2x\,dx$$



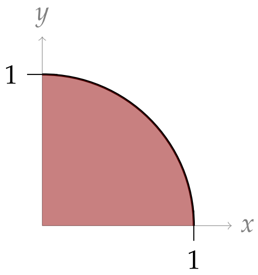
$$\int_{-2}^{2} \sin x \, dx$$



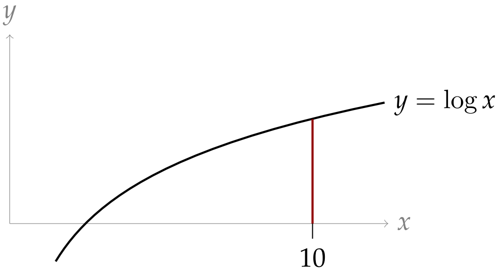
$$\int_{-1}^{1} |x| \, \mathrm{d}x$$



$$\int_0^1 \sqrt{1-x^2}\,\mathrm{d}x$$



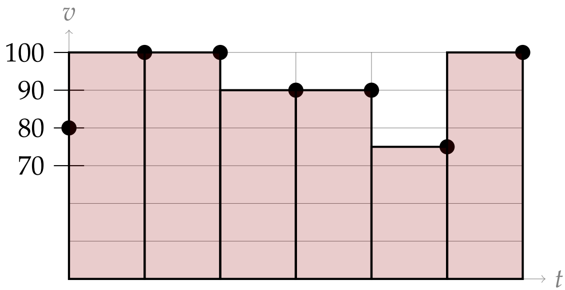
$$\int_{10}^{10} \log x \, dx$$



A car travelling down a straight highway records the following measurements:

Time	12:00	12:10	12:20	12:30	12:40	12:50	1:00
Speed (kph)	80	100	100	90	90	75	100

Approximately how far did the car travel from 12:00 to 1:00?



The computation

$$\text{distance} = \text{rate} \times \text{time}$$

looks a lot like the computation

$$\text{area} = \text{base} \times \text{height}$$

for a rectangle. This gives us another interpretation for an integral.

Another interpretation of the integral

Let $x(t)$ be the position of an object moving along the x-axis at time t, and let $v(t) = x'(t)$ be its velocity. Then for all $b > a$,

$$x(b) - x(a) = \int_a^b v(t)\, \mathrm{d}t$$

That is, $\int_a^b v(t)\, \mathrm{d}t$ gives the *net distance* moved by the object from time a to time b.

Included Work

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