

Lecture 11

- 30. Antiderivatives
- 31. Integration
- 32. The Definite Integral



Antiderivatives

30. Antiderivatives



Definition

F is an *antiderivative* of f on an interval I if $F'(x) = f(x)$ for all $x \in I$.

Example

$2x$ is the derivative of x^2 .

x^2 is an antiderivative of $2x$.

30. Antiderivatives



Example

If $g(x) = \cos x$, then an antiderivative of g is

$$G(x) = \sin x$$

because

$$G'(x) = \frac{d}{dx} (\sin x) = \cos x = g(x).$$

30. Antiderivatives



Example

If $h(x) = 2x + \cos x$, then $H(x) = x^2 + \sin x$ is an antiderivative of $h(x)$.

30. Antiderivatives



Remark

$F(x) = x^2$ is not the only antiderivative of $f(x) = 2x$.

$x^2 + 1$ is an antiderivative of $2x$ because $\frac{d}{dx} (x^2 + 1) = 2x$.

$x^2 + 5$ is an antiderivative of $2x$ because $\frac{d}{dx} (x^2 + 5) = 2x$.

$x^2 - 1234$ is an antiderivative of $2x$ because $\frac{d}{dx} (x^2 - 1234) = 2x$.

30. Antiderivatives



Theorem

If F is an antiderivative of f on I , then the general antiderivative of f is

$$F(x) + C$$

where C is a constant.

30. Antiderivatives

Example

Find an antiderivative of $f(x) = 3x^2$ that satisfies $F(1) = -1$.

solution: x^3 is an antiderivative of f because $\frac{d}{dx}(x^3) = 3x^2$. So the general antiderivative of f is

$$F(x) = x^3 + C.$$

Then we calculate that

$$-1 = F(1) = 1^3 + C = 1 + C \implies C = -2.$$

Therefore $F(x) = x^3 - 2$.

30. Antiderivatives



function	derivative
$f(x)$	$f'(x)$
x^n	nx^{n-1}
$\sin kx$	$k \cos kx$
$\cos kx$	$-k \sin kx$
e^{kx}	ke^{kx}

30. Antiderivatives

function	derivative	function	general antiderivative
$f(x)$	$f'(x)$	$f(x)$	$F(x)$
x^n	nx^{n-1}	$x^n \ (n \neq -1)$	
$\sin kx$	$k \cos kx$	$\sin kx$	
$\cos kx$	$-k \sin kx$	$\cos kx$	
e^{kx}	ke^{kx}	e^{kx}	

30. Antiderivatives



function	derivative	function	general antiderivative
$f(x)$	$f'(x)$	$f(x)$	$F(x)$
x^n	nx^{n-1}	$x^n \ (n \neq -1)$	$\frac{x^{n+1}}{n+1} + C$
$\sin kx$	$k \cos kx$	$\sin kx$	
$\cos kx$	$-k \sin kx$	$\cos kx$	
e^{kx}	ke^{kx}	e^{kx}	

30. Antiderivatives



function	derivative	function	general antiderivative
$f(x)$	$f'(x)$	$f(x)$	$F(x)$
x^n	nx^{n-1}	$x^n \ (n \neq -1)$	$\frac{x^{n+1}}{n+1} + C$
$\sin kx$	$k \cos kx$	$\sin kx$	$-\frac{1}{k} \cos kx + C$
$\cos kx$	$-k \sin kx$	$\cos kx$	
e^{kx}	ke^{kx}	e^{kx}	

30. Antiderivatives



function	derivative	function	general antiderivative
$f(x)$	$f'(x)$	$f(x)$	$F(x)$
x^n	nx^{n-1}	$x^n \ (n \neq -1)$	$\frac{x^{n+1}}{n+1} + C$
$\sin kx$	$k \cos kx$	$\sin kx$	$-\frac{1}{k} \cos kx + C$
$\cos kx$	$-k \sin kx$	$\cos kx$	$\frac{1}{k} \sin kx + C$
e^{kx}	ke^{kx}	e^{kx}	

30. Antiderivatives



function	derivative	function	general antiderivative
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x^n	nx^{n-1}	$x^n \ (n \neq -1)$	$\frac{x^{n+1}}{n+1} + C$
$\sin kx$	$k \cos kx$	$\sin kx$	$-\frac{1}{k} \cos kx + C$
$\cos kx$	$-k \sin kx$	$\cos kx$	$\frac{1}{k} \sin kx + C$
e^{kx}	ke^{kx}	e^{kx}	$\frac{1}{k} e^{kx} + C$

The Sum Rule and the Constant Multiple Rule

Suppose that

- F is an antiderivative of f ;
- G is an antiderivative of g ;
- $k \in \mathbb{R}$.

The Sum Rule: The general antiderivative of $f + g$ is

$$F(x) + G(x) + C.$$

The Constant Multiple Rule: The general antiderivative of kf is

$$kF(x) + C.$$

30. Antiderivatives

Example

Find the general antiderivative of $f(x) = \frac{3}{\sqrt{x}} + \sin 2x$.

solution: We have $f = 3g + h$ where $g(x) = x^{-\frac{1}{2}}$ and $h(x) = \sin 2x$. An antiderivative of g is

$$G(x) = \frac{x^{-\frac{1}{2}+1}}{-\frac{1}{2}+1} = \frac{x^{\frac{1}{2}}}{\frac{1}{2}} = 2\sqrt{x}.$$

An antiderivative of h is

$$H(x) = -\frac{1}{2} \cos 2x.$$

Therefore the general antiderivative of f is

$$F(x) = 6\sqrt{x} - \frac{1}{2} \cos 2x + C.$$

30. Antiderivatives



Definition

The general antiderivative of f is also called the *indefinite integral* of f with respect to x , and is denoted by

$$\int f(x) \, dx.$$

30. Antiderivatives



the integral sign
integral işaretti

x is the variable of integration
 x ise integral değişkeni olarak tanımlanır

$$\int f(x) \, dx$$

the integrand
integralin integrandi

30. Antiderivatives



Example

$$\int 2x \, dx = x^2 + C$$

$$\int \cos x \, dx = \sin x + C$$

$$\int (2x + \cos x) \, dx = x^2 + \sin x + C$$

30. Antiderivatives



Example

Calculate $\int (x^2 - 2x + 5) dx$.

solution 1. Since $\frac{d}{dx} \left(\frac{x^3}{3} - x^2 + 5x \right) = x^2 - 2x + 5$ we have that

$$\int (x^2 - 2x + 5) dx = \frac{x^3}{3} - x^2 + 5x + C.$$

30. Antiderivatives



solution 2.

$$\begin{aligned}\int (x^2 - 2x + 5) \, dx &= \int x^2 \, dx - \int 2x \, dx + \int 5 \, dx \\&= \left(\frac{x^3}{3} + C_1 \right) - (x^2 + C_2) + (5x + C_3) \\&= \left(\frac{x^3}{3} - x^2 + 5x \right) + (C_1 - C_2 + C_3).\end{aligned}$$

Because we only need one constant, we can define
 $C := C_1 - C_2 + C_3$. Therefore

$$\int (x^2 - 2x + 5) \, dx = \frac{x^3}{3} - x^2 + 5x + C.$$

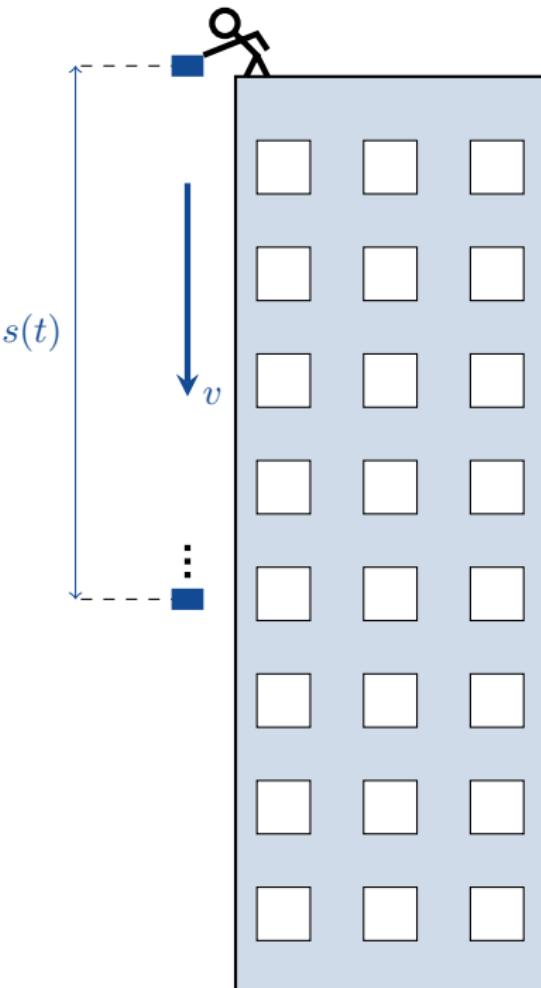
30. Antiderivatives



Example

You drop a box off the top of a tall building. The acceleration due to gravity is 9.8 ms^{-2} . You can ignore air resistance. How far does the box fall in 5 seconds?

30. Antiderivat



30. Antiderivatives

solution: The acceleration is

$$a(t) = 9.8\text{ms}^{-2}$$

downwards. Since

$$\text{acceleration} = \frac{d}{dt}(\text{velocity}),$$

the velocity is an antiderivative of the acceleration. Therefore the velocity is

$$v(t) = 9.8t + C \text{ ms}^{-1}.$$

30. Antiderivatives



You let go of the box at time $t = 0$. So $v(0) = 0$. Thus $C = 0$.
Hence

$$v(t) = 9.8t \text{ ms}^{-1}.$$

30. Antiderivatives



Now velocity = $\frac{d}{dt}$ (position). So the distance fallen is an antiderivative of velocity. Hence

$$s(t) = 4.9t^2 + \tilde{C} \text{ m.}$$

Because you let go of the box at time $t = 0$, we have $s(0) = 0$. Thus $\tilde{C} = 0$. Therefore

$$s(t) = 4.9t^2 \text{ m.}$$

30. Antiderivatives



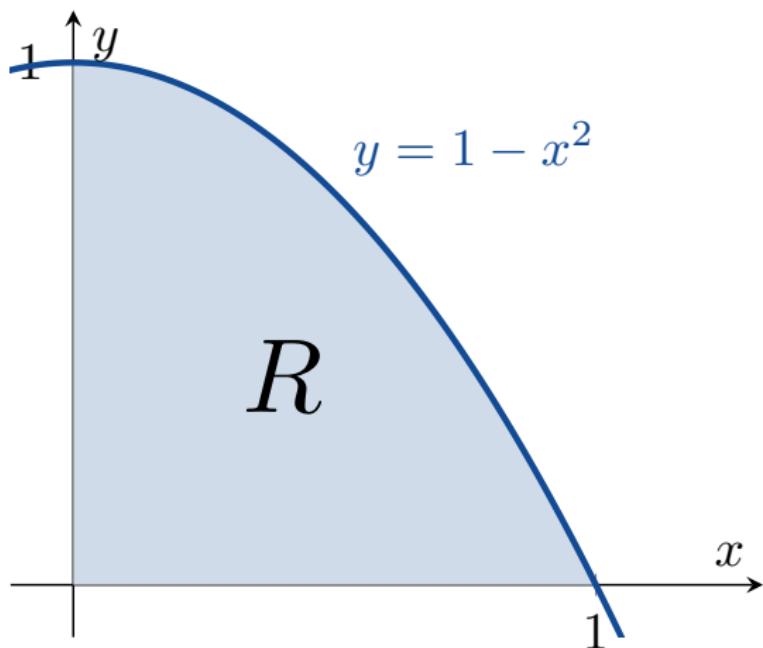
After 5 seconds, the box has fallen

$$s(5) = 4.9 \times 25 = 122.5 \text{ metres.}$$



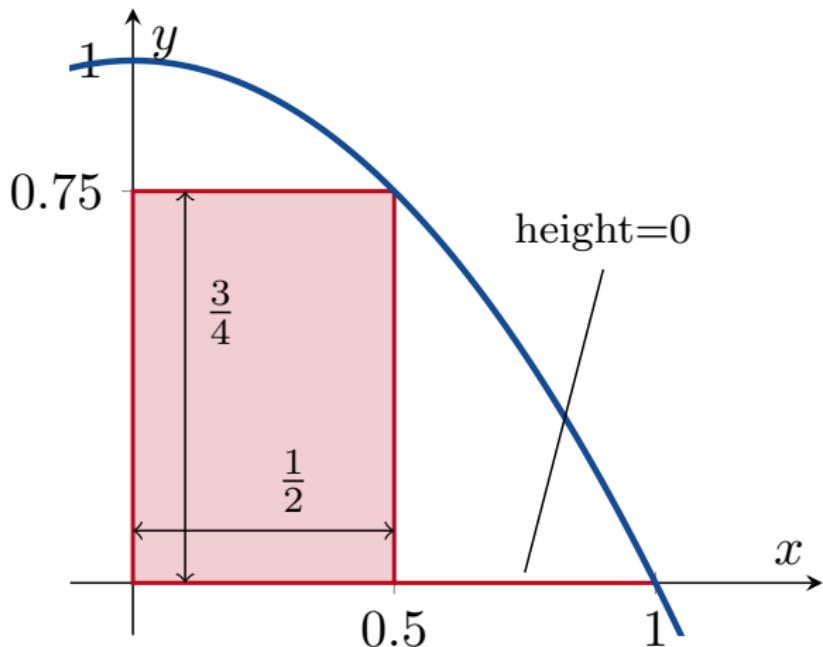
Integration

31. Integration



Question: What is the area of R ?

31. Integration



We can use two rectangles to approximate the area of R .

31. Integration



Then we have

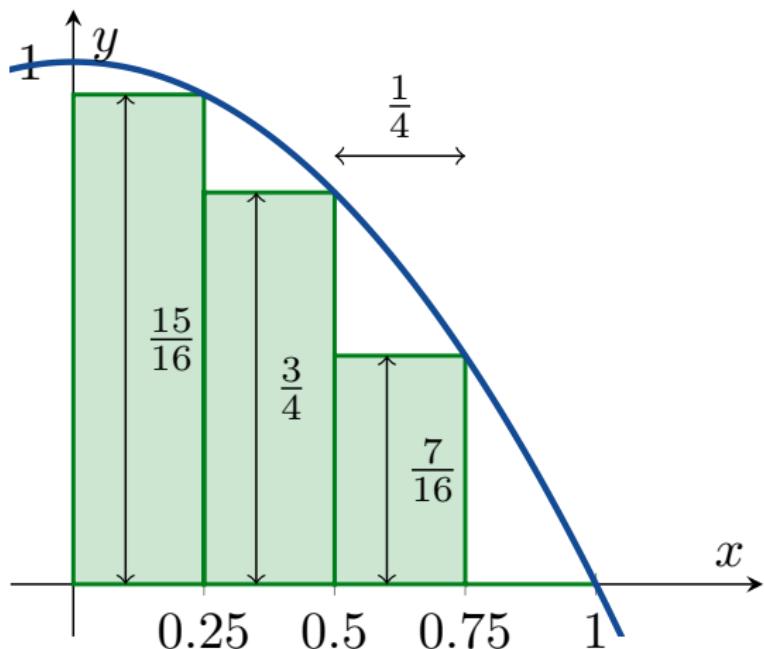
$$\begin{aligned}\text{area of } R &\approx \text{area of 2 rectangles} \\ &= \left(\frac{3}{4} \times \frac{1}{2} \right) + \left(0 \times \frac{1}{2} \right) \\ &= \frac{3}{8} = 0.375.\end{aligned}$$

31. Integration



Can we do better than this? Yes! We could use more rectangles.

31. Integration



31. Integration



We can say that

area of $R \approx$ area of 4 rectangles

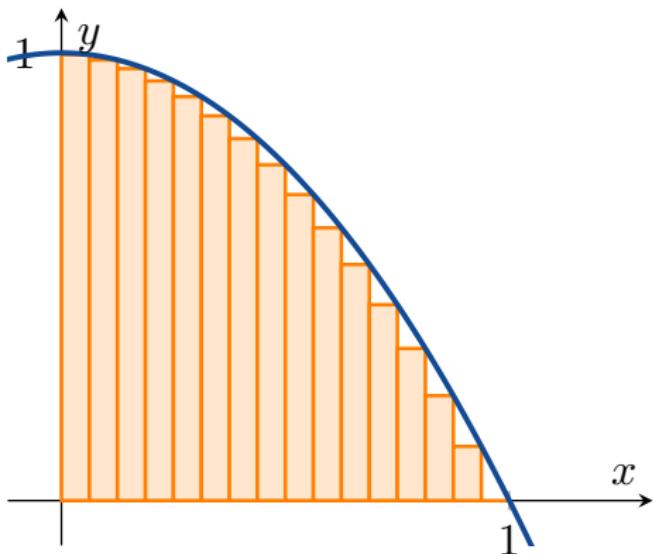
$$\begin{aligned} &= \left(\frac{15}{16} \times \frac{1}{4} \right) + \left(\frac{3}{4} \times \frac{1}{4} \right) \\ &\quad + \left(\frac{7}{16} \times \frac{1}{4} \right) + \left(0 \times \frac{1}{4} \right) \\ &= \frac{17}{32} = 0.53125. \end{aligned}$$

31. Integration



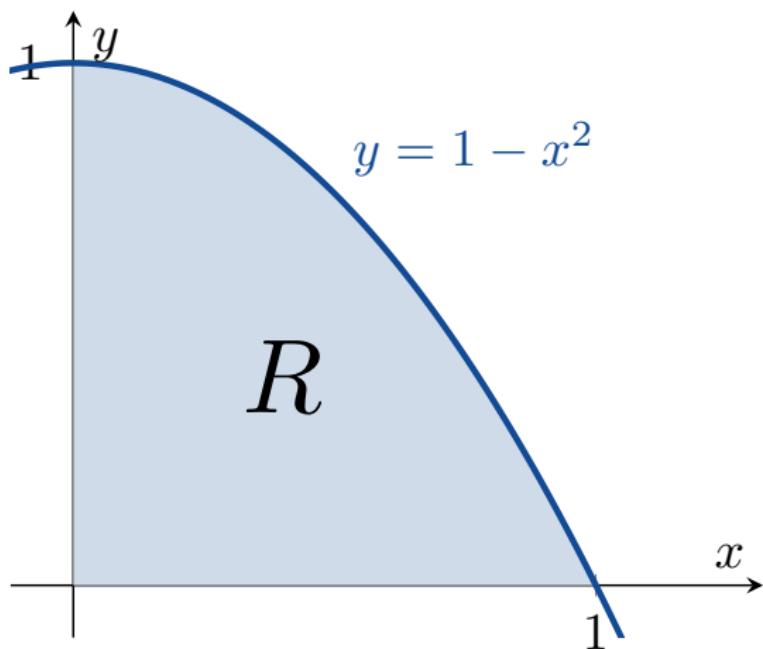
Every time we increase the number of rectangles, the total area of the rectangles gets closer and closer to the area of R .

31. Integration



area of $R \approx$ area of 16 rectangles
 $= 0.63476.$

Limits of Finite Sums

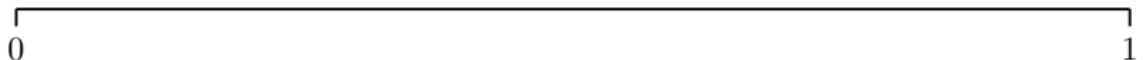


31. Integration



STEP 1: We will cut $[0, 1]$ into n pieces of width

$$\Delta x = \frac{1 - 0}{n} = \frac{1}{n}.$$

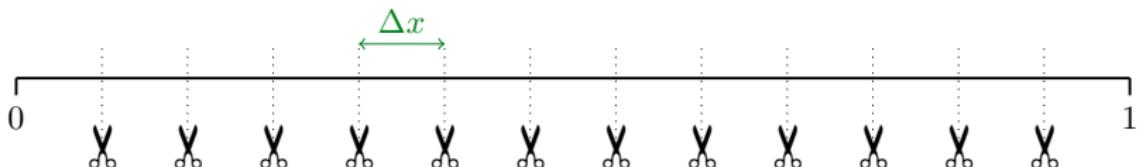


31. Integration

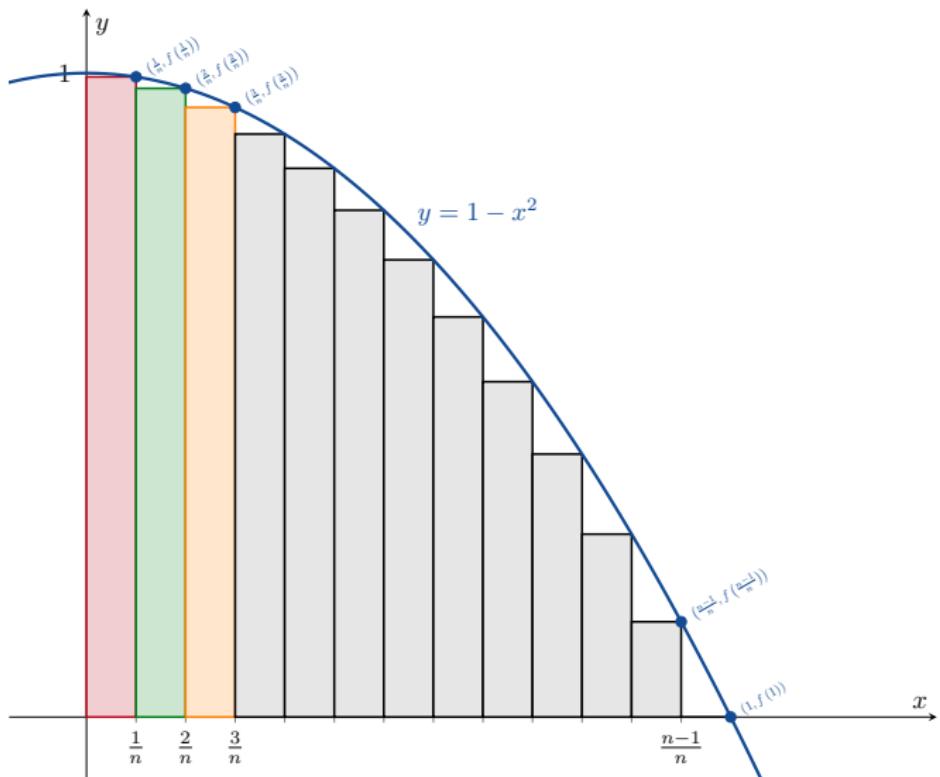


STEP 1: We will cut $[0, 1]$ into n pieces of width

$$\Delta x = \frac{1 - 0}{n} = \frac{1}{n}.$$



31. Integration



STEP 2: We will use n rectangles to approximate the area of R .

31. Integration



STEP 3: Then we will take the limit as $n \rightarrow \infty$.

31. Integration

Let $f(x) = 1 - x^2$. Then

- the **first rectangle** has area $\frac{1}{n}f\left(\frac{1}{n}\right)$;
- the **second rectangle** has area $\frac{1}{n}f\left(\frac{2}{n}\right)$;
- the **third rectangle** has area $\frac{1}{n}f\left(\frac{3}{n}\right)$;

and so on.

31. Integration

The area of all n rectangles is

$$\begin{aligned}
 \text{area} &= \sum_{k=1}^n (\text{area of the } k\text{th rectangle}) = \sum_{k=1}^n \frac{1}{n} f\left(\frac{k}{n}\right) \\
 &= \sum_{k=1}^n \frac{1}{n} \left(1 - \left(\frac{k}{n}\right)^2\right) = \sum_{k=1}^n \left(\frac{1}{n} - \frac{k^2}{n^3}\right) \\
 &= \sum_{k=1}^n \frac{1}{n} - \sum_{k=1}^n \frac{k^2}{n^3} \\
 &= n \left(\frac{1}{n}\right) - \frac{1}{n^3} \sum_{k=1}^n k^2 \\
 &= 1 - \frac{1}{n^3} \left(\frac{n(n+1)(2n+1)}{6}\right) \\
 &= 1 - \frac{2n^2 + 3n + 1}{6n^2}.
 \end{aligned}$$

31. Integration

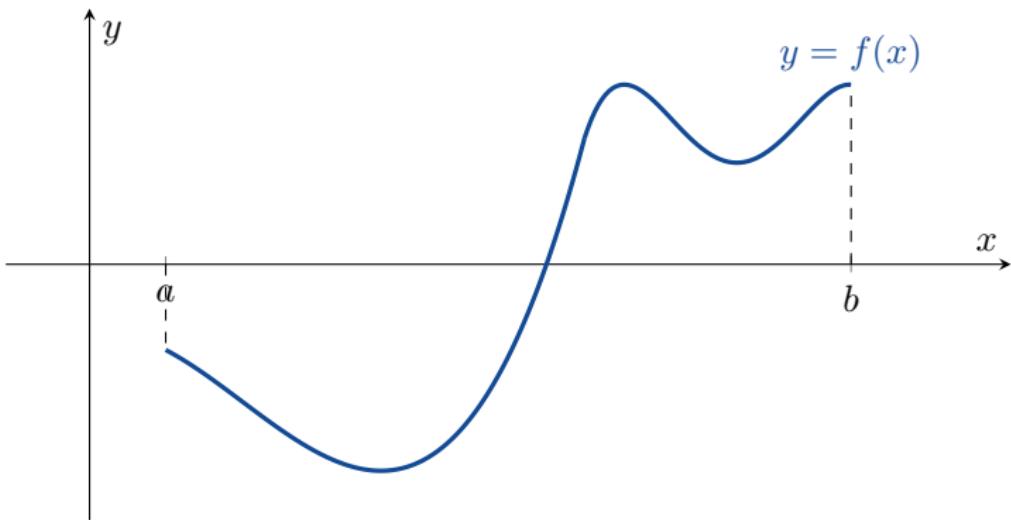


Taking the limit gives

$$\begin{aligned}\lim_{n \rightarrow \infty} \left(\sum_{k=1}^n \frac{1}{n} f\left(\frac{k}{n}\right) \right) &= \lim_{n \rightarrow \infty} \left(1 - \frac{2n^2 + 3n + 1}{6n^2} \right) \\ &= 1 - \frac{2}{6} = \frac{2}{3}.\end{aligned}$$

Therefore the area of R is $\frac{2}{3}$.

Riemann Sums

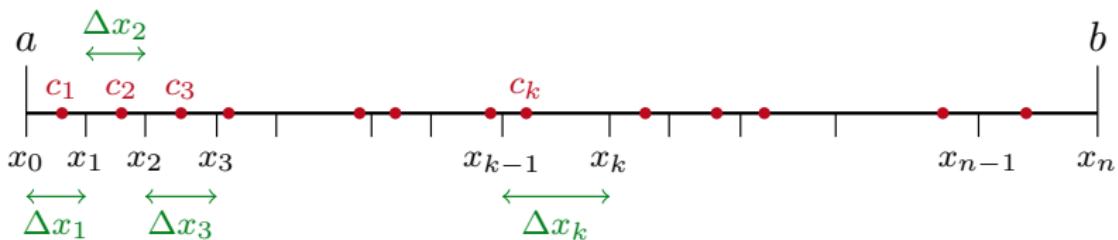


31. Integration

Now let $f[a, b] \rightarrow \mathbb{R}$ be a function. We will cut $[a, b]$ into n subintervals (the pieces don't have to all be the same size).

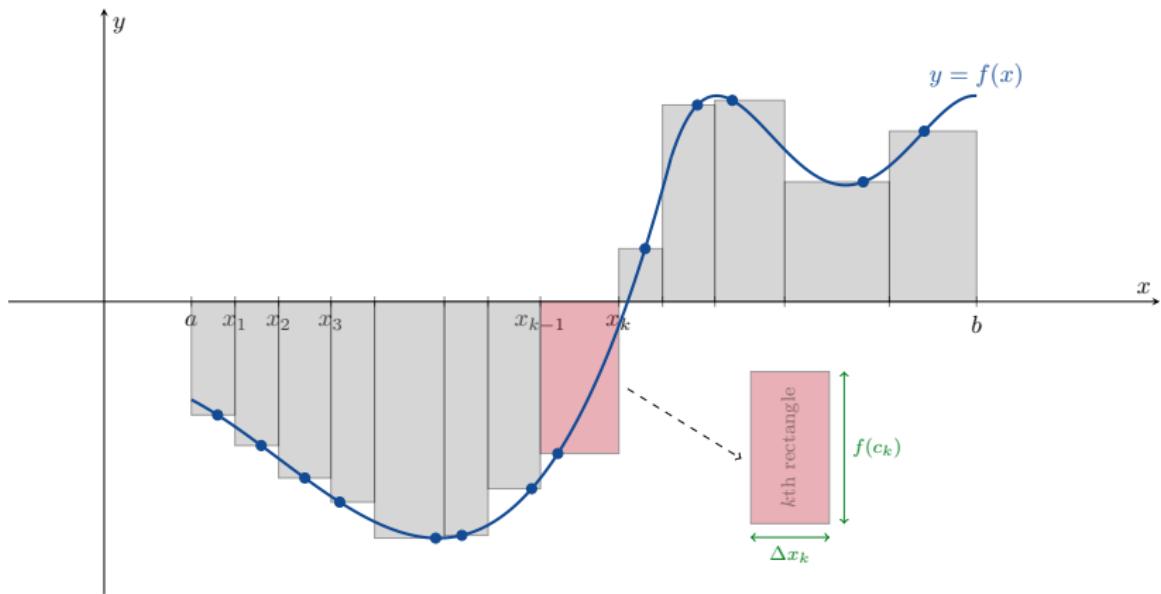
In each subinterval we will choose one point $c_k \in [x_{k-1}, x_k]$.

The width of each subinterval is $\Delta x_k = x_k - x_{k-1}$.



31. Integration

On each subinterval $[x_{k-1}, x_k]$, we draw a rectangle of width Δx_k and height $f(c_k)$.



31. Integration



Note that if $f(c_k) < 0$, then the rectangle on $[x_{k-1}, x_k]$ will have ‘negative area’ – this is ok.

The total of the n rectangles is

$$\sum_{k=1}^n f(c_k) \Delta x_k.$$

This is called a *Riemann Sum for f on $[a, b]$* .

Then we want to take the limit as $n \rightarrow \infty$ (or more precisely, we want to take the limit as $\max\{\Delta x_1, \Delta x_2, \dots, \Delta x_n\} \rightarrow 0$).

Sometimes this limit exists, sometimes this limit does not exist.



The Definite Integral

32. The Definite Integral



Definition

If the limit

$$\lim_{n \rightarrow \infty} \sum_{k=1}^n f(c_k) \Delta x_k$$

exists, then it is called the *definite integral of f over [a, b]*. We write

$$\int_a^b f(x) dx = \lim_{n \rightarrow \infty} \sum_{k=1}^n f(c_k) \Delta x_k$$

if the limit exists.

32. The Definite Integral

$$\int_a^b f(x) \, dx$$

the integrand
integralin integrandı

upper limit of integration
integralin üst sınırı

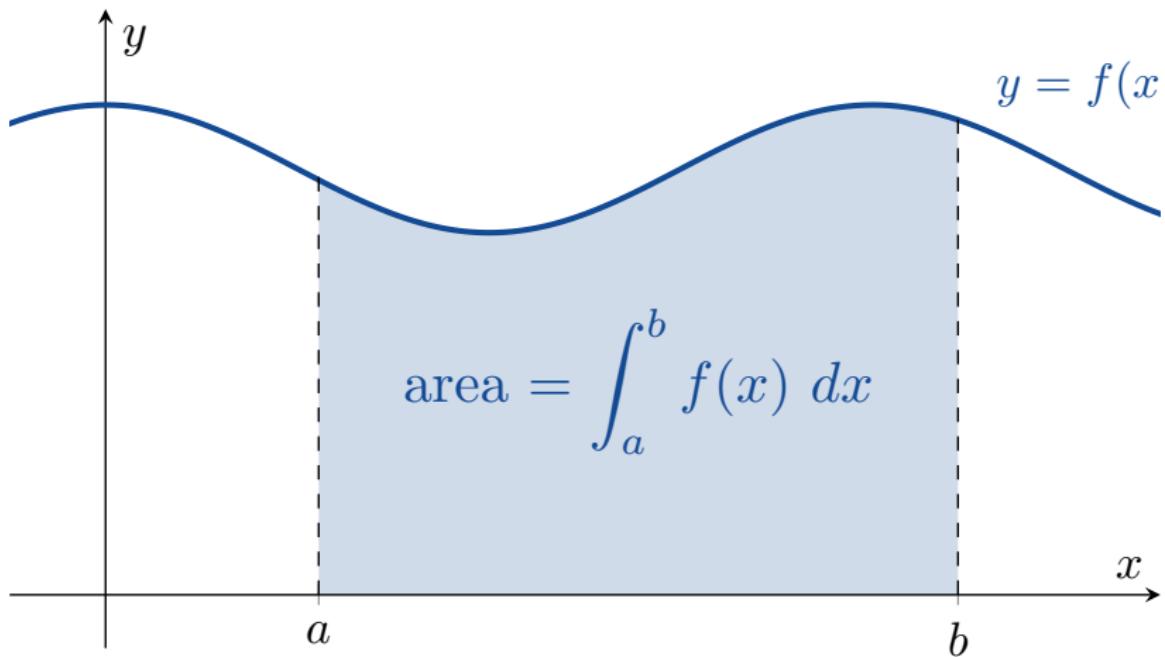
integral sign
integral işaretti

lower limit of integration
integralin alt sınırı

x is the variable of integration
x, integral değişkenidir

“the integral of f from a to b ”

32. The Definite Integral



32. The Definite Integral



Definition

If $\int_a^b f(x) dx$ exists, then we say that f is *integrable on $[a, b]$* .

32. The Definite Integral



Example

$f(x) = 1 - x^2$ is integrable on $[0, 1]$ and $\int_0^1 (1 - x^2) dx = \frac{2}{3}$.

32. The Definite Integral

Remark

$$\int_a^b f(\textcolor{blue}{x}) \, dx = \int_a^b f(\textcolor{blue}{u}) \, du = \int_a^b f(\textcolor{blue}{t}) \, dt$$

It doesn't matter which letter we use for the *dummy variable*.

32. The Definite Integral

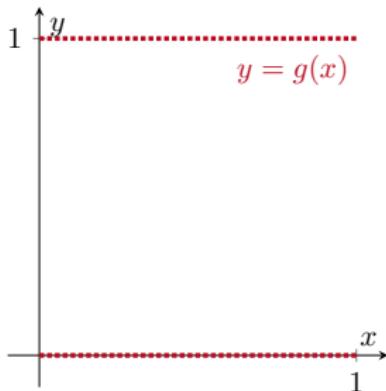


Theorem

If f is continuous on $[a, b]$, then f is integrable on $[a, b]$.

If f has finitely many jump discontinuities but is otherwise continuous on $[a, b]$, then f is integrable on $[a, b]$.

32. The Definite Integral



Example

Define a function $g : [0, 1] \rightarrow \mathbb{R}$ by

$$g(x) = \begin{cases} 1 & x \in \mathbb{Q} \\ 0 & x \notin \mathbb{Q}. \end{cases}$$

This function is not integrable on $[0, 1]$.

32. The Definite Integral



Theorem

Suppose that f and g are integrable. Let k be a number.

32. The Definite Integral



Theorem

Suppose that f and g are integrable. Let k be a number. Then

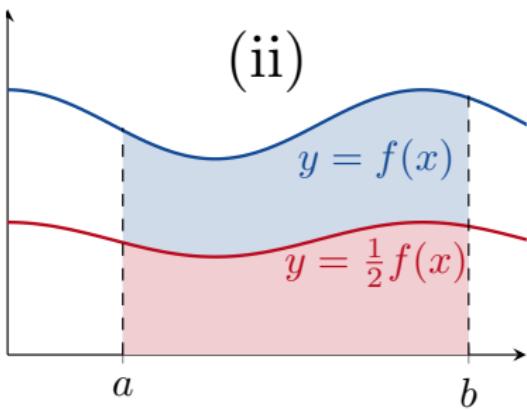
$$1 \quad \int_b^a f(x) \, dx = - \int_a^b f(x) \, dx;$$

32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

2 $\int_a^b kf(x) \, dx = k \int_a^b f(x) \, dx;$

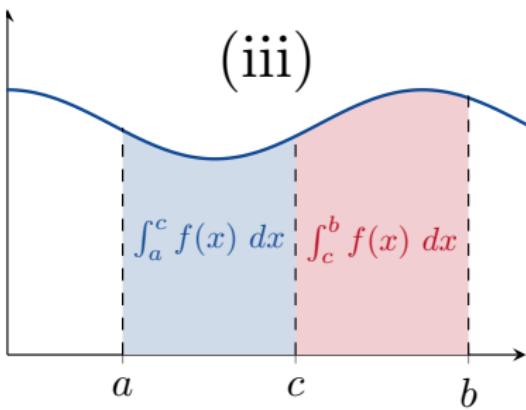


32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

3 $\int_a^c f(x) \, dx + \int_c^b f(x) \, dx = \int_a^b f(x) \, dx$

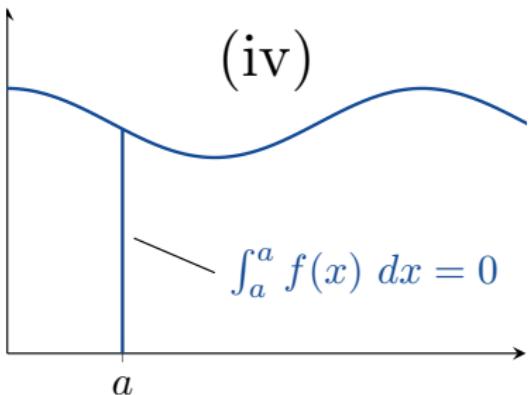


32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

4 $\int_a^a f(x) \, dx = 0;$



32. The Definite Integral



Theorem

Suppose that f and g are integrable. Let k be a number. Then

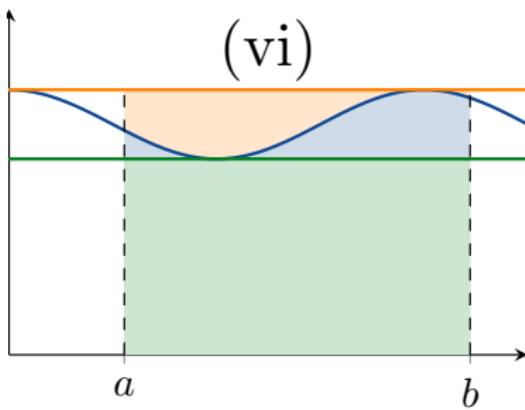
$$5 \quad \int_a^b (f(x) + g(x)) \, dx = \int_a^b f(x) \, dx + \int_a^b g(x) \, dx;$$

32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

6 $(b - a) \min f \leq \int_a^b f(x) dx \leq (b - a) \max f;$



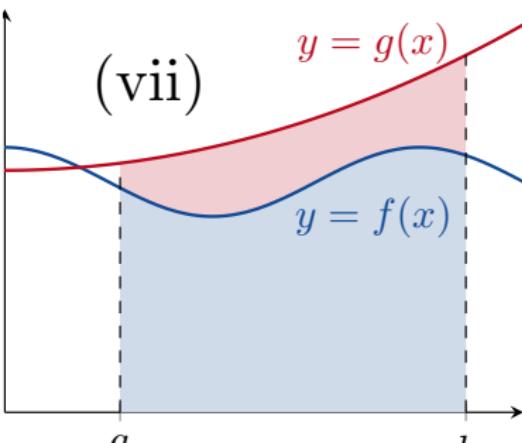
32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

- 7 if $f(x) \leq g(x)$ on $[a, b]$, then

$$\int_a^b f(x) \, dx \leq \int_a^b g(x) \, dx;$$



32. The Definite Integral



Theorem

Suppose that f and g are integrable. Let k be a number. Then

- 8 if $g(x) \geq 0$ on $[a, b]$, then

$$\int_a^b g(x) \, dx \geq 0;$$

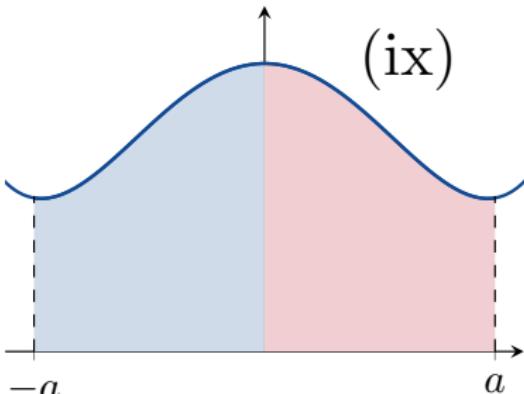
32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

- 9 if f is an even function, then

$$\int_{-a}^a f(x) \, dx = 2 \int_0^a f(x) \, dx;$$



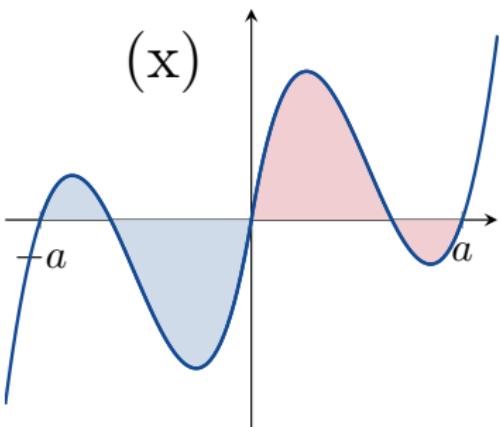
32. The Definite Integral

Theorem

Suppose that f and g are integrable. Let k be a number. Then

- 10 if f is an odd function, then

$$\int_{-a}^a f(x) \, dx = 0.$$



32. The Definite Integral

Example

Suppose that $\int_{-1}^1 f(x) dx = 5$, $\int_1^4 f(x) dx = -2$ and $\int_{-1}^1 h(x) dx = 7$. Then

$$\int_4^1 f(x) dx = - \int_1^4 f(x) dx = 2,$$

$$\begin{aligned}\int_{-1}^1 (2f(x) + 3h(x)) dx &= 2 \int_{-1}^1 f(x) dx + 3 \int_{-1}^1 h(x) dx \\ &= 2(5) + 3(7) = 31\end{aligned}$$

and

$$\begin{aligned}\int_{-1}^4 f(x) dx &= \int_{-1}^1 f(x) dx + \int_1^4 f(x) dx \\ &= 5 + (-2) = 3.\end{aligned}$$

32. The Definite Integral



Example

Show that $\int_0^1 \sqrt{1 + \cos x} dx \leq \sqrt{2}$.

solution: The maximum value of $\sqrt{1 + \cos x}$ on $[0, 1]$ is $\sqrt{1 + 1} = \sqrt{2}$. Therefore

$$\int_0^1 \sqrt{1 + \cos x} dx \leq (1 - 0) \max \sqrt{1 + \cos x} = 1 \times \sqrt{2}.$$

32. The Definite Integral



Example

Calculate $\int_{-2}^2 (x^3 + x) dx$.

solution: Because $(x^3 + x)$ is an odd function, we have that

$$\int_{-2}^2 (x^3 + x) dx = 0.$$

32. The Definite Integral



Example

Calculate $\int_{-1}^1 (1 - x^2) dx$.

solution: Because $(1 - x^2)$ is an even function, we have that

$$\int_{-1}^1 (1 - x^2) dx = 2 \int_0^1 (1 - x^2) dx = 2 \times \frac{2}{3} = \frac{4}{3}.$$

32. The Definite Integral



Example

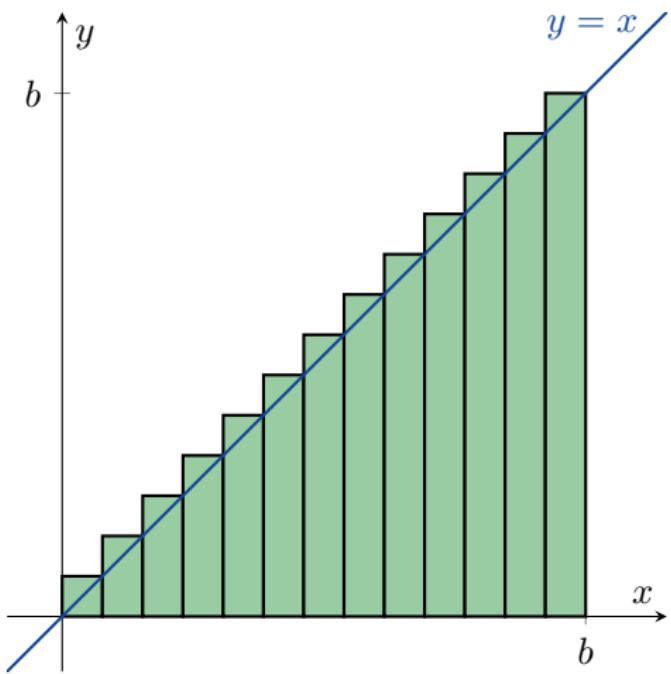
Calculate $\int_0^b x \, dx$ for $b > 0$.

solution 1: We will use a Riemann Sum. First we cut $[0, b]$ in to n pieces using

$$0 < \frac{b}{n} < \frac{2b}{n} < \frac{3b}{n} < \dots < \frac{(n-1)b}{n} < b$$

and $c_k = \frac{kb}{n}$. Note that $\Delta x_k = \frac{b}{n}$ for all k .

32. The Definite Integral



32. The Definite Integral

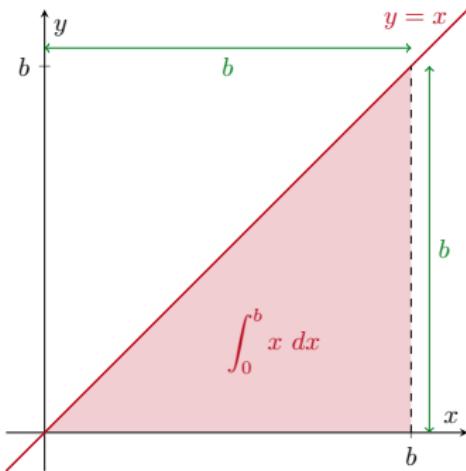
Then

$$\begin{aligned}\sum_{k=1}^n f(c_k) \Delta x_k &= \sum_{k=1}^n \frac{kb}{n} \frac{b}{n} = \frac{b^2}{n^2} \sum_{k=1}^n k \\ &= \frac{b^2}{n^2} \left(\frac{n(n+1)}{2} \right) = \frac{b^2}{2} \left(1 + \frac{1}{n} \right).\end{aligned}$$

Then

$$\begin{aligned}\int_0^b x \, dx &= \lim_{n \rightarrow \infty} \sum_{k=1}^n f(c_k) \Delta x_k \\ &= \lim_{n \rightarrow \infty} \frac{b^2}{2} \left(1 + \frac{1}{n} \right) = \frac{b^2}{2}.\end{aligned}$$

32. The Definite Integral



solution 2: Alternately, we can look at the triangle above and say that

$$\int_0^b x \, dx = \text{area of a triangle} = \frac{1}{2} \times b \times b = \frac{b^2}{2}.$$

32. The Definite Integral



Example

$$\begin{aligned}\int_a^b x \, dx &= \int_a^0 x \, dx + \int_0^b x \, dx \\&= -\int_0^a x \, dx + \int_0^b x \, dx \\&= -\frac{a^2}{2} + \frac{b^2}{2} \\&= \frac{b^2}{2} - \frac{a^2}{2}.\end{aligned}$$



Next Time

- 33. The Fundamental Theorem of Calculus
- 34. The Substitution Method
- 35. Area Between Curves