

## Integration

### Riemann Sum

The primary application of integration is to determine the area between a function and the  $x$ -axis. A **Riemann sum** is an approximation of this area that is found using rectangles.

A Riemann sum of a function  $f$  defined on the interval  $[a, b]$  is determined by a partition, which is a finite division of  $[a, b]$  into subintervals. This interval is typically expressed by  $a = x_0 < x_1 < x_2 < \dots < x_n = b$  and a sampling of points with one point from each subinterval, for example,  $x_i$  from  $[x_{i-1}, x_i]$ . The associated

$$\text{Riemann sum is } \sum_{i=1}^n f(x_i)(x_i - x_{i-1}).$$

A regular partition has subintervals of the same length. If  $x_i = \frac{b-a}{n}i$  and  $x_0 = a = x_{-1}$ , a partition's points is its maximum subinterval length. A **left sum** takes the left endpoint  $x_{i-1}$ , a **right sum** takes the right endpoint

$x_i$ . The sum of the areas of the rectangles that graph represents a left Riemann sum of  $f(x)$  on the interval  $[a, b]$  using partitions that are  $n$  units wide.



The sum of the areas of the rectangles that graph represents a right Riemann sum of  $f(x)$  on the interval  $[a, b]$  using partitions that are  $n$  units wide.

An upper sum of a continuous function,  $f$ , takes a point  $c_i$  in each subinterval where the maximum value of  $f$  is achieved. A lower sum takes the minimum value of  $f$  for each subinterval.

### Definite Integral

As the partition of a Riemann sum gets smaller and smaller, the area approximation gets closer and closer to the actual area under the curve. The **definite integral** of  $f$  on the interval  $[a, b]$  is defined as

$$\int_a^b f(x) dx = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(x_i)(x_i - x_{i-1}).$$

The expression to be integrated,  $f(x)$ , is called the **integrand**. The definite integral exists when  $f$  is continuous on  $[a, b]$ . Then the function is said to be **integrable**.

### Antiderivative

The **antiderivative** of a function  $f$  is a function  $F$  whose derivative is  $f$ ,  $F'(x) = f(x)$  for all  $x$  in some domain, normally an interval. Any two antiderivatives of a function on an interval differ by a constant.

EX: The functions  $\sin x = x^2 - 3x + 2$  and  $\sin x = x^2 + 3x - 7$  are both antiderivatives of  $f(x) = 2x + 3$  because  $\frac{d}{dx}(x^2 - 3x + 2) = 2x + 3$  and  $\frac{d}{dx}(x^2 + 3x - 7) = 2x + 3$ .

EX: The **indefinite integral** of a function,  $f$ , is denoted  $\int f(x) dx$  and represents the family of antiderivatives of a typical value, typically  $x$ .

EX:  $\int \frac{1}{x^2} dx = \int x^{-2} dx = -x^{-1} + C = -\frac{1}{x} + C$ , where  $C$  is a constant called the **constant of integration**.

### Mean Value Theorem

Let  $f$  be a continuous function on the interval  $[a, b]$ . Then there exists a number  $c$  in  $(a, b)$  such that  $\int_a^b f(x) dx = (b-a)f(c)$ .

In other words,  $f(c)$  is the average value of  $f(x)$  on  $[a, b]$ .

### Mean Value Theorem for Integrals



### Fundamental Theorem of Calculus

There are two parts to the **Fundamental Theorem of Calculus**.

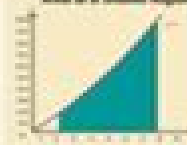
1. **First Part (Evaluating Integrals)** If  $f$  is a continuous function on  $[a, b]$ , and  $F$  is an antiderivative of  $f$  on that interval, then  $\int_a^b f(x) dx = F(b) - F(a)$ .

EX: Evaluate  $\int_1^4 x^2 dx$  using the fact that  $\int x^2 dx = \frac{1}{3}x^3 + C = F(x)$ .

$$\begin{aligned} \int_1^4 x^2 dx &= F(4) - F(1) \\ &= \left(\frac{1}{3}4^3\right) - \left(\frac{1}{3}1^3\right) \\ &= \frac{64}{3} - \frac{1}{3} \\ &= \frac{63}{3} \\ &= 21 \end{aligned}$$

The area of the shaded region between  $f(x)$  and the  $x$ -axis on  $[1, 4]$  is 21 square units.

### Area of a Shaded Region



2. **Second Part (Evaluating Antiderivatives)**

If  $f$  is a continuous function on  $[a, b]$ , then the function  $F(x) = \int_a^x f(t) dt$  is an antiderivative of  $f$  on  $[a, b]$  and  $F'(x) = f(x)$ .

EX:  $\int_0^x (x^2 + 2x + 1) dx = \frac{1}{3}x^3 + x^2 + x$ .

## Interpretation of Integrals

### Area Under a Curve

If  $f$  is a continuous and continuous on  $[a, b]$ , then  $F(x) = \int_a^x f(t) dt$  gives the area between the graph of the function and the  $x$ -axis.

The **area function**,  $A(x) = \int_a^x f(t) dt$  gives the accumulated area on the interval from  $a$  up to  $x$ . If  $f$  is negative, the integral is the opposite of the area.

### Average Value

The average value of  $f$  over an interval  $[a, b]$  is defined by the expression

$$\text{average value} = \frac{1}{b-a} \int_a^b f(x) dx$$

EX: Find the average value of  $f(x) = \cos(x)$  on the interval  $[0, \pi]$ .

$$\begin{aligned} \text{average value} &= \frac{1}{\pi - 0} \int_0^\pi \cos(x) dx \\ &= \frac{1}{\pi} [\sin(x)]_0^\pi \\ &= \frac{1}{\pi} (\sin(\pi) - \sin(0)) = 0 \end{aligned}$$

The average value of  $f(x)$  on the interval  $[a, b]$  is  $\frac{1}{b-a} \int_a^b f(x) dx$ .

A rough estimate of an integral may be made by approximating the average value of the function (by computing and multiplying it by the length of the interval).

### Accumulated Change

The integral of rates of change of a quantity over a time interval gives the total change in the quantity over the time interval.

EX: Let  $s(t)$  represent the position of an object as a function of time. Then  $s'(t) = v(t)$  represents the velocity (the rate of change of position) of the object. Furthermore,  $\int_a^b v(t) dt$  approximates the approximate displacement according to the time measured from  $t = a$  to  $t = b$ .

Adding the displacements for all time increments gives the approximate change in position over the entire time interval. In the limit of small time increments, the exact total displacement (or increment) is found:  $\int_a^b v(t) dt = s(b) - s(a)$ .

### Area Under a Curve



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