Gauss Quadrature Rule of Integration

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What is Integration?

Integration

The process of measuring the area under a curve.

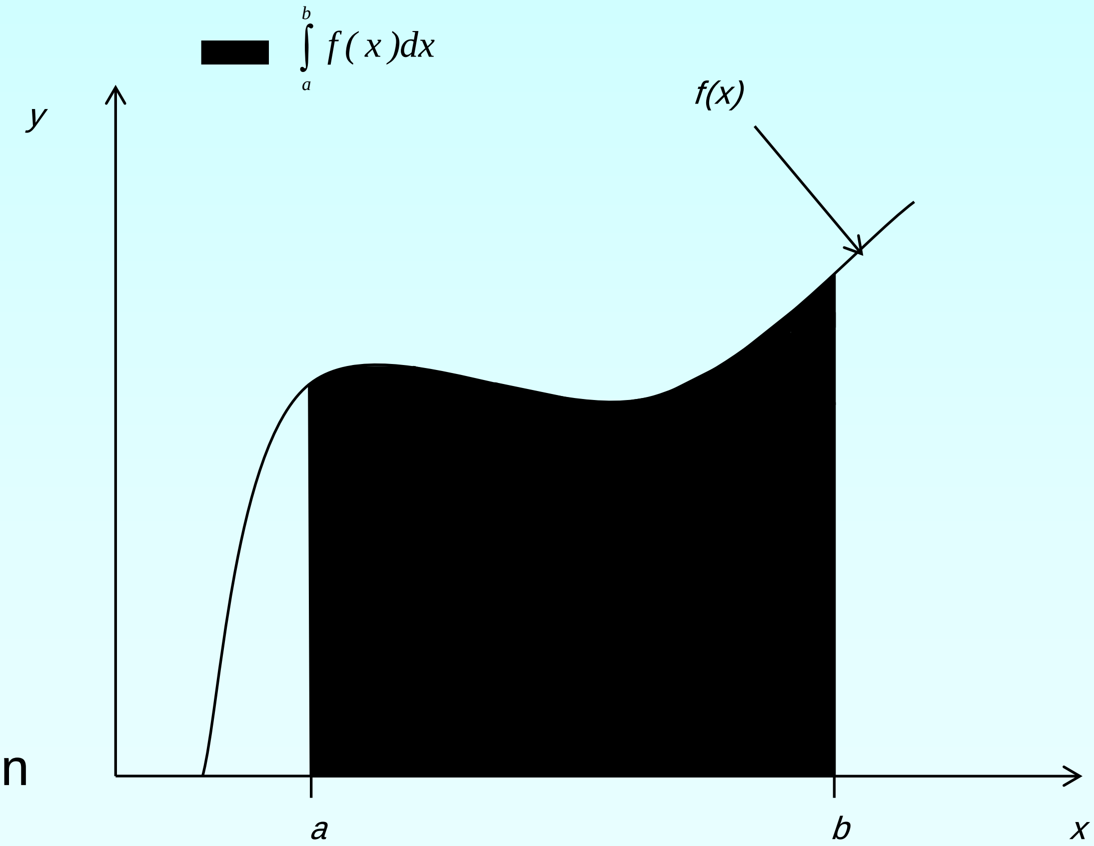
$$I = \int_a^b f(x)dx$$

Where:

f(x) is the integrand

a= lower limit of integration

b= upper limit of integration



Two-Point Gaussian Quadrature Rule

Basis of the Gaussian Quadrature Rule

Previously, the Trapezoidal Rule was developed by the method of undetermined coefficients. The result of that development is summarized below.

$$\int_a^b f(x)dx \approx c_1 f(a) + c_2 f(b)$$

$$= \frac{b-a}{2} f(a) + \frac{b-a}{2} f(b)$$

Basis of the Gaussian Quadrature Rule

The two-point Gauss Quadrature Rule is an extension of the Trapezoidal Rule approximation where the arguments of the function are not predetermined as a and b but as unknowns x_1 and x_2. In the two-point Gauss Quadrature Rule, the integral is approximated as

$$I = \int_a^b f(x)dx \approx c_1 f(x_1) + c_2 f(x_2)$$

Basis of the Gaussian Quadrature Rule

The four unknowns x_1, x_2, c_1 and c_2 are found by assuming that the formula gives exact results for integrating a general third order polynomial, $f(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$.

Hence

$$\int_a^b f(x)dx = \int_a^b \left(a_0 + a_1 x + a_2 x^2 + a_3 x^3\right)dx$$

$$= \left[a_0 x + a_1 \frac{x^2}{2} + a_2 \frac{x^3}{3} + a_3 \frac{x^4}{4}\right]_a^b$$

$$= a_0(b-a) + a_1\left(\frac{b^2 - a^2}{2}\right) + a_2\left(\frac{b^3 - a^3}{3}\right) + a_3\left(\frac{b^4 - a^4}{4}\right)$$

Basis of the Gaussian Quadrature Rule

It follows that

$$\int_a^b f(x)dx = c_1\left(a_0 + a_1x_1 + a_2x_1{}^2 + a_3x_1{}^3\right) + c_2\left(a_0 + a_1x_2 + a_2x_2{}^2 + a_3x_2{}^3\right)$$

Equating Equations the two previous two expressions yield

$$a_0(b-a) + a_1\left(\frac{b^2-a^2}{2}\right) + a_2\left(\frac{b^3-a^3}{3}\right) + a_3\left(\frac{b^4-a^4}{4}\right)$$

$$= c_1\left(a_0 + a_1x_1 + a_2x_1{}^2 + a_3x_1{}^3\right) + c_2\left(a_0 + a_1x_2 + a_2x_2{}^2 + a_3x_2{}^3\right)$$

$$= a_0(c_1 + c_2) + a_1(c_1x_1 + c_2x_2) + a_2\left(c_1x_1{}^2 + c_2x_2{}^2\right) + a_3\left(c_1x_1{}^3 + c_2x_2{}^3\right)$$

Basis of the Gaussian Quadrature Rule

Since the constants a_0, a_1, a_2, a_3 are arbitrary

$$b - a = c_1 + c_2$$

$$\frac{b^2 - a^2}{2} = c_1 x_1 + c_2 x_2$$

$$\frac{b^3 - a^3}{3} = c_1 x_1^{\,2} + c_2 x_2^{\,2}$$

$$\frac{b^4 - a^4}{4} = c_1 x_1^{\,3} + c_2 x_2^{\,3}$$

Basis of Gauss Quadrature

The previous four simultaneous nonlinear Equations have only one acceptable solution,

$$x_1 = \left(\frac{b-a}{2}\right)\left(-\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2}$$

$$x_2 = \left(\frac{b-a}{2}\right)\left(\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2}$$

$$c_1 = \frac{b-a}{2}$$

$$c_2 = \frac{b-a}{2}$$

Basis of Gauss Quadrature

Hence Two-Point Gaussian Quadrature Rule

$$\int_a^b f(x)dx \approx c_1 f(x_1) + c_2 f(x_2)$$

$$= \frac{b-a}{2} f\left(\frac{b-a}{2}\left(-\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2}\right) + \frac{b-a}{2} f\left(\frac{b-a}{2}\left(\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2}\right)$$

Higher Point Gaussian Quadrature Formulas

Higher Point Gaussian Quadrature Formulas

$$\int_a^b f(x)dx \approx c_1 f(x_1) + c_2 f(x_2) + c_3 f(x_3)$$

is called the three-point Gauss Quadrature Rule.

The coefficients c_1, c_2, and c_3, and the functional arguments x_1, x_2, and x_3 are calculated by assuming the formula gives exact expressions for integrating a fifth order polynomial

$$\int_a^b \left(a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5\right)dx$$

General n-point rules would approximate the integral

$$\int_a^b f(x)dx \approx c_1 f(x_1) + c_2 f(x_2) + \ldots\ldots\ldots + c_n f(x_n)$$

Arguments and Weighing Factors for n-point Gauss Quadrature Formulas

In handbooks, coefficients and arguments given for n-point Gauss Quadrature Rule are given for integrals

$$\int_{-1}^{1} g(x)dx \cong \sum_{i=1}^{n} c_i g(x_i)$$

as shown in Table 1.

Table 1: Weighting factors c and function arguments x used in Gauss Quadrature Formulas.

Points	Weighting Factors	Function Arguments
2	c_1 = 1.000000000 c_2 = 1.000000000	x_1 = -0.577350269 x_2 = 0.577350269
3	c_1 = 0.555555556 c_2 = 0.888888889 c_3 = 0.555555556	x_1 = -0.774596669 x_2 = 0.000000000 x_3 = 0.774596669
4	c_1 = 0.347854845 c_2 = 0.652145155 c_3 = 0.652145155 c_4 = 0.347854845	x_1 = -0.861136312 x_2 = -0.339981044 x_3 = 0.339981044 x_4 = 0.861136312

Arguments and Weighing Factors for n-point Gauss Quadrature Formulas

Table 1 (cont.) : Weighting factors c and function arguments x used in Gauss Quadrature Formulas.

Points	Weighting Factors	Function Arguments
5	c_1 = 0.236926885 c_2 = 0.478628670 c_3 = 0.568888889 c_4 = 0.478628670 c_5 = 0.236926885	x_1 = -0.906179846 x_2 = -0.538469310 x_3 = 0.000000000 x_4 = 0.538469310 x_5 = 0.906179846
6	c_1 = 0.171324492 c_2 = 0.360761573 c_3 = 0.467913935 c_4 = 0.467913935 c_5 = 0.360761573 c_6 = 0.171324492	x_1 = -0.932469514 x_2 = -0.661209386 x_3 = -0.2386191860 x_4 = 0.2386191860 x_5 = 0.661209386 x_6 = 0.932469514

Arguments and Weighing Factors for n-point Gauss Quadrature Formulas

So if the table is given for $\int_{-1}^{1} g(x)dx$ integrals, how does one solve $\int_{a}^{b} f(x)dx$? The answer lies in that any integral with limits of $[a,b]$ can be converted into an integral with limits $[-1,1]$ Let

$$x = mt + c$$

If $x = a,$ then $t = -1$

If $x = b,$ then $t = 1$

Such that:

$$m = \frac{b-a}{2}$$

Arguments and Weighing Factors for n-point Gauss Quadrature Formulas

Then $c = \dfrac{b+a}{2}$ Hence

$$x = \frac{b-a}{2}t + \frac{b+a}{2} \qquad dx = \frac{b-a}{2}dt$$

Substituting our values of x, and dx into the integral gives us

$$\int_a^b f(x)dx = \int_{-1}^{1} f\left(\frac{b-a}{2}t + \frac{b+a}{2}\right)\frac{b-a}{2}dt$$

Example 1

For an integral $\int_a^b f(x)dx,$ derive the one-point Gaussian Quadrature Rule.

Solution

The one-point Gaussian Quadrature Rule is

$$\int_a^b f(x)dx \approx c_1 f\left(x_1\right)$$

Solution

The two unknowns x_1, and c_1 are found by assuming that the formula gives exact results for integrating a general first order polynomial,

$$f(x) = a_0 + a_1 x.$$

$$\int_a^b f(x)dx = \int_a^b (a_0 + a_1 x)dx$$

$$= \left[a_0 x + a_1 \frac{x^2}{2} \right]_a^b$$

$$= a_0(b-a) + a_1\left(\frac{b^2 - a^2}{2}\right)$$

Solution

It follows that

$$\int_a^b f(x)dx = c_1\left(a_0 + a_1 x_1\right)$$

Equating Equations, the two previous two expressions yield

$$a_0(b-a) + a_1\left(\frac{b^2 - a^2}{2}\right) = c_1\left(a_0 + a_1 x_1\right) = a_0(c_1) + a_1(c_1 x_1)$$

Basis of the Gaussian Quadrature Rule

Since the constants a_0, and a_1 are arbitrary

$$b - a = c_1$$

$$\frac{b^2 - a^2}{2} = c_1 x_1$$

giving

$$c_1 = b - a$$

$$x_1 = \frac{b + a}{2}$$

Solution

Hence One-Point Gaussian Quadrature Rule

$$\int_a^b f(x)dx \approx c_1 f\left(x_1\right) = (b-a)\ f\left(\frac{b+a}{2}\right)$$

Example 2

Human vision has the remarkable ability to infer 3D shapes from 2D images. The intriguing question is: can we replicate some of these abilities on a computer? Yes, it can be done and to do this, integration of vector fields is required. The following integral needs to integrated.

$$I = \int_{0}^{100} f(x)dx$$

where

$$\begin{aligned} f(x) &= 0,\ 0 < x < 30 \\ &= -9.1688\times10^{-6}x^3 + 2.7961\times10^{-3}x^2 - 2.8487\times10^{-1}x + 9.6778, \\ &\quad 30 \le x \le 172 \\ &= 0,\ \ 172 < x < 200 \end{aligned}$$

Use two-point Gauss Quadrature Rule to find the value of the integral. Also, find the absolute relative true error.

Solution

First, change the limits of integration from [0,100] to [-1,1] by previous relations as follows

$$\int_{0}^{100} f(x)dx = \frac{100-0}{2}\int_{-1}^{1} f\left(\frac{100-0}{2}x + \frac{100+0}{2}\right)dx$$

$$= 50\int_{-1}^{1} f(50x + 50)dx$$

Solution (cont)

Next, get weighting factors and function argument values from Table 1 for the two point rule,

$$c_1 = \ 1.0000$$

$$x_1 = -0.57735$$

$$c_2 = \ 1.0000$$

$$x_2 = \ 0.57735$$

Solution (cont.)

Now we can use the Gauss Quadrature formula

$$50\int_{-1}^{1} f(50x+50)dx$$

$$\approx 50\left[c_1 f(50x_1+50)+c_2 f(50x_2+50)\right]$$

$$=50\left[f(50(-0.57735)+50)+ f(50(0.57735)+50)\right]$$

$$=50\left[f(21.132)+ f(78.868)\right]$$

$$=50\left[(0)+(0.10492)\right]$$

$$=5.2460$$

Solution (cont)

since

$$f\left(21.132\right)=0$$

$$f\left(78.868\right)=-9.1688\times10^{-6}\times\left(78.868\right)^{3}+2.7961\times10^{-3}\times\left(78.868\right)^{2}-2.8487\times10^{-1}\times\left(78.868\right)+9.6778$$

$$=0.10492$$

Solution (cont)

b) True error is

$$E_t = True\ Value - Approximate\ Value$$

$$= 60.793 - 5.2460$$

$$= 55.546$$

c) The absolute relative true error, $|\in_t|$, is (Exact value = 60.793)

$$|\in_t| = \left|\frac{60.793 - 5.2460}{60.793}\right| \times 100\%$$

$$= 91.371\%$$

Additional Resources

For all resources on this topic such as digital audiovisual lectures, primers, textbook chapters, multiple-choice tests, worksheets in MATLAB, MATHEMATICA, MathCad and MAPLE, blogs, related physical problems, please visit

http://numericalmethods.eng.usf.edu/topics/gauss_quadrature.html

THE END

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