Gauss Quadrature Rule of Integration

Mechanical Engineering Majors

Authors: Autar Kaw, Charlie Barker

http://numericalmethods.eng.usf.edu

Transforming Numerical Methods Education for STEM Undergraduates

Gauss Quadrature Rule of Integration

http://numericalmethods.eng.usf.edu

What is Integration?

Integration

The process of measuring the area under a curve.

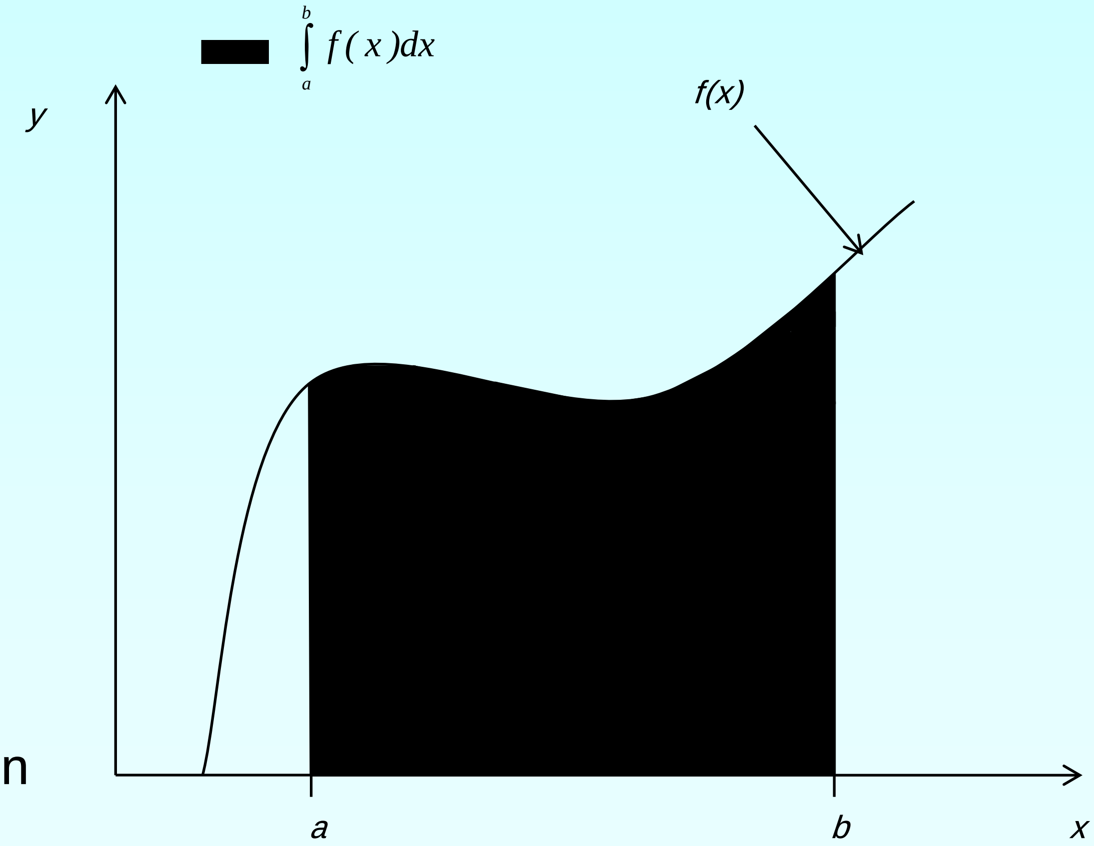
$$I = \int_a^b f(x)dx$$

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,

$$x_1 = \left(\frac{b-a}{2}\right)\left(-\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2} \qquad x_2 = \left(\frac{b-a}{2}\right)\left(\frac{1}{\sqrt{3}}\right) + \frac{b+a}{2}$$

$$c_1 = \frac{b-a}{2} \qquad c_2 = \frac{b-a}{2}$$

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

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

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

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

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

A trunnion of diameter 12.363" has to be cooled from a room temperature of 80°F before it is shrink fit into a steel hub (Figure 2).

The equation that gives the diametric contraction of the trunnion in dry-ice/alcohol (boiling temperature is -108°F) is given by:

$$\Delta D = 12.363 \int_{80}^{-108} \left(-1.2278 \times 10^{-11} T^2 + 6.1946 \times 10^{-9} T + 6.015 \times 10^{-6} \right) dT$$

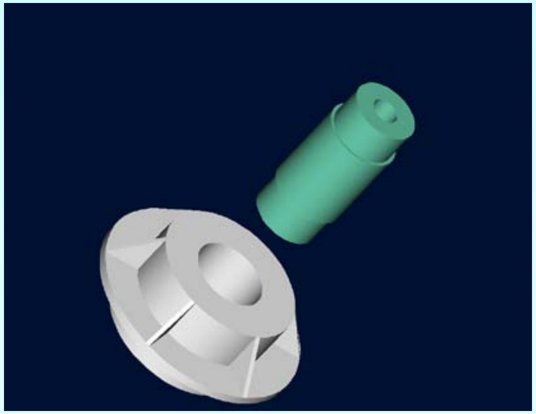


Figure 2 Trunnion to be slided through the hub after contracting.

a) Use two-point Gauss Quadrature Rule to find the contraction.
b) Find the true error, E_t for part (a).
c) Also, find the absolute relative true error, $\left| \in_t \right|$ for part (a).

Solution

a) First, change the limits of integration from [80,-108] to [-1,1] by previous relations as follows

$$\int_{80}^{-108} f(T)\,dT = \frac{-108-80}{2}\int_{-1}^{1} f\left(\frac{-108-80}{2}T + \frac{-108+80}{2}\right)dT$$

$$= -94\int_{-1}^{1} f(-94T - 14)\,dT$$

Solution (cont)

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

$$c_1 = \ \ 1.0000$$

$$T_1 = -0.57735$$

$$c_2 = \ \ 1.0000$$

$$T_2 = \ \ 0.57735$$

Solution (cont.)

Now we can use the Gauss Quadrature formula

$$
\begin{aligned}
-94\int_{-1}^{1} f\left(-94T-14\right)dx &\approx -94\left[c_1 f\left(-94T_1-14\right)+c_2 f\left(-94T_2-14\right)\right] \\
&\approx -94\left[f\left(-94\left(-0.57735\right)-14\right)+f\left(-94\left(0.57735\right)-14\right)\right] \\
&\approx -94\left[f\left(40.271\right)+f\left(-68.271\right)\right] \\
&\approx -94\left[\left(7.7201\times10^{-5}\right)+\left(6.8428\times10^{-5}\right)\right] \\
&\approx -0.013689 in
\end{aligned}
$$

Solution (cont)

since

$$f(40.271)=12.363\left(-1.2278\times10^{-11}(40.271)^2+6.1946\times10^{-9}(40.271)+6.015\times10^{-6}\right)$$
$$=7.7201\times10^{-5}$$

$$f(-68.271)=12.363\left(-1.2278\times10^{-11}(-68.271)^2+6.1946\times10^{-9}(-68.271)+6.015\times10^{-6}\right)$$
$$=6.8428\times10^{-5}$$

Solution (cont)

b) The true error, E_t , is

$$E_t = True\ Value - Approximate\ Value$$
$$= -0.013689 - \left(-0.013689\right)$$
$$= -5.5179 \times 10^{-14}$$

c) The absolute relative true error, $\left|\in_t\right|$, is (Exact value = −0.013689)

$$\left|\in_t\right| = \left|\frac{\text{True Error}}{\text{True Value}}\right| \times 100\%$$
$$= \left|\frac{-0.013689 - \left(-0.013689\right)}{-0.013689}\right| \times 100\%$$
$$= 4.0309 \times 10^{-10}$$

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

http://numericalmethods.eng.usf.edu