

Numerical Integration

David Eberly
Geometric Tools, LLC
<http://www.geometrictools.com/>
Copyright © 1998-2008. All Rights Reserved.

Created: March 2, 1999
Last Modified: March 2, 2008

Contents

1 Richardson Extrapolation	2
1.1 Trapezoid Rule	3
2 Romberg Integration	3
3 Implementation	4

1 Richardson Extrapolation

This method is very powerful. The key idea is to get high-order accuracy by using low-order formulas. It is used in Romberg integration (which my integration code is based on), but it is also the key idea in the adaptive Runge-Kutta differential equation solver.

Let Q be an unknown quantity which is approximated by $A(h)$ with approximation error of order $O(h^2)$. That is,

$$Q = A(h) + C_1 h^2 + O(h^4) = A(h) + O(h^2) \tag{1}$$

for some constant C_1 . We can use this formula to produce a (possibly) more accurate approximation. Replacing h by $h/2$ in the formula yields

$$Q = A\left(\frac{h}{2}\right) + \frac{C_1}{2} h^2 + O(h^4). \tag{2}$$

Of course I used $O(h^2/4) = O(h^2)$. Taking four times equation (2) and subtracting equation (2), then dividing by three yields

$$Q = \frac{4A\left(\frac{h}{2}\right) - A(h)}{3} + O(h^4). \tag{3}$$

The goal is for the $O(h^4)$ terms in equations (1) and (3) to be about the same size. If so, equation (3) is more accurate since it does not have the h^2 term in it.

Define $A_1(h) = A(h)$ and $A_2(h) = (4A_1(h/2) - A_1(h))/3$. Other approximations can be written in an extrapolation table

$$\begin{array}{cc} A_1(h) & \\ A_1\left(\frac{h}{2}\right) & A_2(h) \\ A_1\left(\frac{h}{4}\right) & A_2\left(\frac{h}{2}\right) \\ A_1\left(\frac{h}{8}\right) & A_2\left(\frac{h}{4}\right) \\ \vdots & \vdots \\ A_1\left(\frac{h}{2^n}\right) & A_2\left(\frac{h}{2^{n-1}}\right) \end{array}$$

The approximation $A_1(h/2^k)$ is order $O(h^2)$ and the approximation $A_2(h/2^k)$ is order $O(h^4)$.

If the original approximation is written as

$$Q = A(h) + C_1 h^2 + C_2 h^4 + O(h^6),$$

then the extrapolation table has an additional column

$$\begin{array}{ccc} A_1(h) & & \\ A_1\left(\frac{h}{2}\right) & A_2(h) & \\ A_1\left(\frac{h}{4}\right) & A_2\left(\frac{h}{2}\right) & A_3(h) \\ A_1\left(\frac{h}{8}\right) & A_2\left(\frac{h}{4}\right) & A_3\left(\frac{h}{2}\right) \\ \vdots & \vdots & \\ A_1\left(\frac{h}{2^n}\right) & A_2\left(\frac{h}{2^{n-1}}\right) & A_3\left(\frac{h}{2^{n-2}}\right) \end{array}$$

where

$$A_3(h) = \frac{16A_2\left(\frac{h}{2}\right) - A_2(h)}{15}.$$

The approximation $A_3(h/2^k)$ is order $O(h^6)$.

In general the extrapolation table is an $n \times m$ lower triangular matrix $T = [T_{rc}]$ where

$$T_{rc} = A_c\left(\frac{h}{2^{r-1}}\right)$$

and

$$A_c(h) = \frac{4^{c-1}A_{c-1}\left(\frac{h}{2}\right) - A_{c-1}(h)}{4^{c-1} - 1}.$$

1.1 Trapezoid Rule

An approximation for $\int_a^b f(x) dx$ can be computed by first approximating $f(x)$ by the linear function

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

and using $h[f(b) + f(a)]/2 = \int_a^b L(x) dx \doteq \int_a^b f(x) dx$. Some calculus shows that

$$\int_a^b f(x) dx = \frac{f(b) + f(a)}{2}h + O(h^3).$$

When $f(x) > 0$, the approximation is the area of a trapezoid with vertices at $(a, 0)$, $(a, f(a))$, $(b, 0)$, and $(b, f(b))$.

The integration interval $[a, b]$ can be divided into N subintervals over which the integration can be composited. Define $h = (b - a)/N$ and $x_j = a + jh$ for $0 \leq j \leq N$. It can be shown that

$$\int_a^b f(x) dx = \frac{h}{2} \left[f(a) + 2 \sum_{j=1}^{N-1} f(x_j) + f(b) \right] + O(h^2).$$

Note that the order of the approximation decrease by a power of one.

2 Romberg Integration

This method of integration uses the trapezoid rule to obtain preliminary approximations to the integral followed by Richardson extrapolation to obtain improvements.

Define $h_k = (b - a)/2^{k-1}$ for $k \geq 1$. The trapezoidal approximations corresponding to the interval partitions are

$$T_{k,1} = \frac{h_k}{2} \left[f(a) + 2 \left(\sum_{j=1}^{2^{k-1}-1} f(a + jh_k) \right) + f(b) \right]$$

and so

$$\int_a^b f(x) dx = T_{k,1} + O(h_k^2)$$

for all $k \geq 1$. The following recursion formula can be shown to hold:

$$2T_{k,1} = T_{k-1,1} + h_{k-1} \sum_{j=1}^{2^{k-2}} f(a + (j - 0.5)h_{k-1}) \quad (4)$$

for $k \geq 2$.

Richardson extrapolation can be applied; that is, generate the table

$$T_{i,j} = \frac{4^{j-1}T_{i,j-1} - T_{i-1,j-1}}{4^{j-1} - 1}$$

for $2 \leq j \leq i$. It can be shown that

$$\lim_{k \rightarrow \infty} T_{k,1} = \int_a^b f(x) dx \text{ if and only if } \lim_{k \rightarrow \infty} T_{k,k} = \int_a^b f(x) dx.$$

The second limit typically converges much faster than the first. The idea now is to choose a value n and use $T_{n,n}$ as an approximation to the integral.

3 Implementation

The code is shown below.

```
class mgcIntegrate
{
public:
    typedef float (*Function)(float);

    mgcIntegrate () {}

    float RombergIntegral (float a, float b, Function F);
};

float mgcIntegrate::
RombergIntegral (float a, float b, Function F)
{
    const int order = 5;

    float rom[2][order];
    float h = b-a;

    // initialize T_{1,1} entry
```

```

rom[0][0] = h*(F(a)+F(b))/2;

for (int i = 2, ipower = 1; i <= order; i++, ipower *= 2, h /= 2) {
    // calculate summation in recursion formula for  $T_{k,1}$ 
    float sum = 0;
    for (int j = 1; j <= ipower; j++)
        sum += F(a+h*(j-0.5));

    // trapezoidal approximations
    rom[1][0] = (rom[0][0]+h*sum)/2;

    // Richardson extrapolation
    for (int k = 1, kpower = 4; k < i; k++, kpower *= 4)
        rom[1][k] = (kpower*rom[1][k-1] - rom[0][k-1])/(kpower-1);

    // save extrapolated values for next pass
    for (j = 0; j < i; j++)
        rom[0][j] = rom[1][j];
}

return rom[0][order-1];
}

```

I have arbitrarily chosen $n = 5$ (as the variable `integral_order`). The values of $T_{i,j}$ are stored in `rom[2][order]`. Note that not all the values must be saved to build the next ones (so the first dimension of `rom` does not have to be `order`). This follows from the recursion given in equation (4).