

Numerical Integration

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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 the [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 that 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

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

Of course I used $O(h^2/4) = O(h^2)$. Taking four times equation (2) and subtracting equation (1) and 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 because 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*,

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

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

$$Q = A(h) + C_1 h^2 + C_2 h^4 + O(h^6) \tag{5}$$

then the extrapolation table has an additional column

$$\begin{array}{ccc} A_1(h) & & \\ A_1\left(\frac{h}{2}\right) & A_2(h) & \\ A_1\left(\frac{h}{4}\right) & A_2\left(\frac{h}{2}\right) & A_3(h) \\ A_1\left(\frac{h}{8}\right) & A_2\left(\frac{h}{4}\right) & A_3\left(\frac{h}{2}\right) \\ \vdots & \vdots & \\ A_1\left(\frac{h}{2^n}\right) & A_2\left(\frac{h}{2^{n-1}}\right) & A_3\left(\frac{h}{2^{n-2}}\right) \end{array} \tag{6}$$

where

$$A_3(h) = \frac{16A_2\left(\frac{h}{2}\right) - A_2(h)}{15} \quad (7)$$

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

$$T_{rc} = A_c\left(\frac{h}{2^{r-1}}\right) \quad (8)$$

and

$$A_c(h) = \frac{4^{c-1}A_{c-1}\left(\frac{h}{2}\right) - A_{c-1}(h)}{4^{c-1} - 1} \quad (9)$$

2 Trapezoid Rule

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

$$L(x) = \frac{x-b}{a-b}f(a) + \frac{x-a}{b-a}f(b) \quad (10)$$

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

$$\int_a^b f(x) dx = \frac{f(b) + f(a)}{2}h + O(h^3) \quad (11)$$

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

$$\int_a^b f(x) dx = \frac{h}{2} \left[f(a) + 2 \sum_{j=1}^{N-1} f(x_j) + f(b) \right] + O(h^2) \quad (12)$$

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

3 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

$$T_{k,1} = \frac{h_k}{2} \left[f(a) + 2 \left(\sum_{j=1}^{2^{k-1}-1} f(a + jh_k) \right) + f(b) \right] \quad (13)$$

and so

$$\int_a^b f(x) dx = T_{k,1} + O(h_k^2) \quad (14)$$

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

$$2T_{k,1} = T_{k-1,1} + h_{k-1} \sum_{j=1}^{2^{k-2}} f\left(a + \left(j - \frac{1}{2}\right) h_{k-1}\right) \quad (15)$$

for $k \geq 2$. Richardson extrapolation can be applied; that is, generate the table

$$T_{i,j} = \frac{4^{j-1}T_{i,j-1} - T_{i-1,j-1}}{4^{j-1} - 1} \quad (16)$$

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

$$\lim_{k \rightarrow \infty} T_{k,1} = \int_a^b f(x) dx \text{ if and only if } \lim_{k \rightarrow \infty} T_{k,k} = \int_a^b f(x) dx. \quad (17)$$

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.