

ASYMPTOTIC METHODS

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Introduction

In this course, we will be interested in finding so-called *asymptotic series*, leading to approximations to the values of integrals depending on some parameter, or to the solutions of differential equations. For instance, consider *Stirling's Approximation*

$$n! \sim (2\pi n)^{1/2} \left(\frac{n}{e}\right)^n \quad \text{as } n \rightarrow \infty \quad \text{or} \quad \Gamma(n) = (n-1)! \sim \left(\frac{2\pi}{n}\right)^{1/2} \left(\frac{n}{e}\right)^n$$

We will also be interested in the *Stieltjes Integral*: let $\rho(t)$ be a well-behaved non-negative function that decays sufficiently fast as $t \rightarrow \infty$. Then

$$\int_a^\infty \frac{\rho(t)}{1+xt} dt \sim \int_a^\infty \rho(t) dt \quad \text{for small } x > 0$$

The *modified Bessel function of order zero*, I_0 , solves the differential equation

$$\frac{d^2 y}{dx^2} + \frac{1}{x} \frac{dy}{dx} - y = 0$$

and has the following expansion with infinite radius of convergence:

$$I_0(x) = \sum_{n=0}^{\infty} \frac{x^{2n}}{2^{2n}(n!)^2} \sim (2\pi x)^{-1/2} e^x \quad \text{as } x \rightarrow \infty$$

Asymptotic expansions are widely used in applied mathematics and theoretical physics, e.g. when deriving the leading-order contribution to the electrostatic potential corresponding to a charge distribution of limited spatial extent when viewed from far away. In number theory, the prime number theorem states that the number $\pi(n)$ of primes at most n satisfies $\pi(n) \sim \frac{n}{\ln n}$ as $n \rightarrow \infty$.

In the above examples, the symbol \sim means that the ratio of the two sides tends to unity in the appropriate limit. If we seek better approximations, we can derive *asymptotic series*, such as the Stirling series

$$\Gamma(n) \sim \left(\frac{2\pi}{n}\right)^{1/2} \left(\frac{n}{e}\right)^n \left[1 + \frac{1}{12n} + \frac{1}{2880n^2} + \dots\right]$$

where the coefficients are known, but not elementary. The coefficients get smaller for a while, but eventually grow rapidly. The series does not converge for any n . Upon truncating, this series gives a sequence of approximations:

$$\frac{\Gamma(n)}{\left(\frac{2\pi}{n}\right)^{1/2} \left(\frac{n}{e}\right)^n} - 1 = o(1), \quad \frac{\Gamma(n)}{\left(\frac{2\pi}{n}\right)^{1/2} \left(\frac{n}{e}\right)^n} - 1 - \frac{1}{12n} = o\left(\frac{1}{n}\right), \quad \dots \quad \text{for large } n$$

For $n = 4$, these approximations give $3! = 5.877$ and $3! = 5.999$. For $n = 4$, the approximation using six terms gives the best answer; with more terms, the error increases, since the series does not converge.

For the Stieltjes integral, we will show that, using the Taylor expansion $(1+xt)^{-1} = 1 - xt + x^2 t^2 + \dots$ valid for $t < 1/x$,

$$\int_a^\infty \frac{\rho(t)}{1+xt} dt \sim \sum_{n=0}^{\infty} (-1)^n c_n x^n \quad \text{where } c_n = \int_a^\infty t^n \rho(t) dt$$

Asymptotic Methods In Analysis

SJ Ball



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