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*

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

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

$$\int_0^\infty \frac{\rho(t)}{1+xt}\,\mathrm{d}t \sim \int_0^\infty \rho(t)\,\mathrm{d}t \quad \text{for small } x > 0$$

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

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

and has the following expansion with infinite radius of convergence:

$$\mathrm{I}_0(x) = \sum_{n=0}^\infty \frac{x^{2n}}{2^{2n}(n!)^2} \sim (2\pi x)^{-1/2}e^x \quad \text{as } x \to \infty$$

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 $\pi(n) \sim \frac{n}{\log n}$ as $n \to \infty$.

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

$$\Gamma(n) \sim \left(\frac{2\pi}{n}\right)^{1/2}\left(\frac{n}{e}\right)^n\left[1 + \frac{1}{12n} + \frac{1}{288n^2} + \cdots\right]$$

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:

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

For $n = 4$, these approximations give $3! \approx 5.877$ and $3! \approx 5.999$. 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 $(1+xt)^{-1} = 1 - xt + x^2t^2 + \cdots$ valid for $t < 1/x$,

$$\int_0^\infty \frac{\rho(t)}{1+xt}\,\mathrm{d}t \sim \sum_{n=0}^\infty (-1)^n c_n x^n \quad \text{where } c_n = \int_0^\infty t^n\rho(t)\,\mathrm{d}t$$

Asymptotic Methods In Analysis

Puja Mehta

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