Computing the Beta Function for Large Arguments

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Abstract

I was excited about having derived nice asymptotic formulas enabling to accurately compute $\log B(a, b)$ for very large b etc, but then realized there were other existing solutions, partly applied already e.g., in TOMS 708 `algdiv()` (which I now also provide as R function in package `DPQ`).

1 Introduction

The beta distribution function and its inverse are widely used in statistical software, since, e.g., the critical values of the F and t distributions can be expressed using the inverse beta distribution, see, e.g., **?**, sec. 5.5.

Whereas sophisticated algorithms are available for computing the beta distribution function and its inverse (Majumder and Bhattacharjee (1973a) and 1973b, Cran et al. (1977); Berry et al. (1990), (Johnson et al., 1995, ch. 25)), these algorithms rely on the computation of the beta function itself which is not a problem in most cases. However, for large arguments p, the usual formula of the beta which uses the gamma function can suffer severely from cancellation when two almost identical numbers are subtracted or divided.

The beta function B is defined as

$$B(p, q) = \frac{\Gamma(p)\Gamma(q)}{\Gamma(p+q)}, \tag{1}$$

where p and q must be positive, and Γ is the widely used gamma function which for positive arguments x is defined by Euler's integral,

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t}\, dt. \tag{2}$$

For $x > 0$, $\Gamma(x)$ is positive and analytical, i.e. infinitely many times continuously differentiable. From (2), integrating by parts gives $\Gamma(x + 1) = x\Gamma(x)$, and hence the recursion formula

$$\Gamma(x + n) = \Gamma(x) \cdot x \cdot (x + 1) \cdots (x + n - 1). \tag{3}$$

This entails the best-known property of the gamma function, i.e., the fact that it generalizes the factorial $n!$. Namely, for *integer* arguments $n \in \mathbb{N}$, one has $\Gamma(n + 1) = n!$. For this and many more properties, see, e.g., **?**, ch. 6.

For the beta function $B(p, q)$, it is well known that for larger values of p, q the corresponding Γ values may become larger than the maximal (floating point) number on the computer, even though $B(p, q)$ itself may remain relatively small. For this and other numerical reasons, one usually works with the (natural) logarithms of beta and gamma functions, i.e.,

$$\log B(p,q) = \log\Gamma(p) + \log\Gamma(q) - \log\Gamma(p+q). \tag{4}$$

For the beta function $B(p,q)$ which is symmetric in p,q we assume without loss of generality that $p < q$, and now consider the situation where q is very large, or more generally q is large compared to p,

$$p \ll q. \tag{5}$$

For convenience, we write

$$B(p,q) = \Gamma(p) \ / \ Q_{pq} \qquad \text{where} \qquad Q_{pq} := \frac{\Gamma(p+q)}{\Gamma(q)}. \tag{6}$$

The beta function is closely related to the binomial binomial coefficient $\binom{N}{n}$,

$$\binom{N}{n} = \frac{N!}{n!\ (N-n)!} = \frac{\Gamma(N+1)}{n!\ \Gamma(N-n+1)} = \frac{Q_{n,N-n+1}}{n!}. \tag{7}$$

where we need Q_{pq} for integers $p = n$ and $q = N - n + 1$.

Note that for $p \ll q$, or $q/p \to \infty$, the ratio in (6) will become more and more imprecise, since $\log Q_{pq} = \log\Gamma(p+q) - \log\Gamma(q)$ tends to the difference of two almost identical numbers which extinguishes most significant digits. The goal of this paper can be restated as finding numerically useful asymptotic formula for Q_{pq} when $q \to \infty$.

For the problem of the binomial coefficient when $N \to \infty$ and because Q_{pq} is a smooth (infinitely continuous) function in both arguments, we will consider the special case of $p = n \in \mathbb{N}$. Using the recursion (3) for the numerator of Q_{nq} , we get

$$\begin{aligned} Q_{n,q} &= q\cdot(q+1)\cdots(q+n-1) = q^n \cdot \left(1+\frac{1}{q}\right)\left(1+\frac{2}{q}\right)\cdots\left(1+\frac{n-1}{q}\right) \\ &= q^n \prod_{k=1}^{n-1}(1+k/q) \quad = q^n \cdot f_n(1/q), \end{aligned} \tag{8}$$

where

$$f_n(x) = \prod_{k=1}^{n-1}(1+kx) \ = \sum_{k=0}^{n-1} a_{kn}x^k, \qquad \text{where } a_{0n} \equiv 1, \tag{9}$$

and from (8),

$$Q_{n,q} = q^n \cdot \left(1 + \frac{a_{1n}}{q} + \frac{a_{2n}}{q^2} + \ldots + \frac{a_{n-1,n}}{q^{n-1}}\right). \tag{10}$$

In the following section, I will derive closed formulas (in n) for a_{kn}.

2 Series Expansions

If we apply (9) for $n+1$, we get

$$\begin{aligned} f_{n+1}(x) &= \sum_{k=0}^{n} a_{k,n+1}x^k = \prod_{k=1}^{n}(1+kx) \ = (1+nx)\prod_{k=1}^{n-1}(1+kx) = (1+nx)\cdot f_n(x) \\ &= (1+nx)\sum_{k=0}^{n-1} a_{kn}x^k = 1 + \sum_{k=1}^{n-1}\left(a_{kn} + na_{k-1,n}\right)x^k + na_{n-1,n}x^n. \end{aligned}$$

Comparison of coefficients gives

$$\begin{aligned} a_{k,n+1} &= a_{kn} + n a_{k-1,n} \qquad (k = 1, \ldots, n), \qquad (11) \\ \text{where} \qquad a_{n,n} &:= 0. \end{aligned}$$

If we set $n = k$, and let $\tilde{a}_n := a_{n,n+1}$, we get $\tilde{a}_n = a_{n,n} + n\tilde{a}_{n-1}$ from which we conclude that $\tilde{a}_n = n!$, since $a_{n,n} = 0$ and $\tilde{a}_0 = a_{0,1} = 1$ by definition (9). Hence,

$$a_{k,k+1} = k!\ , \qquad (12)$$

and applying (11) successively for n, $n-1, \ldots$ yields

$$a_{k,n} = \sum_{m=1}^{n-1} m \cdot a_{k-1,m} \qquad (k = 1, \ldots, n-1). \qquad (13)$$

Hence, we can compute $a_{k,n}$ if $a_{k-1,n}$ are known and therefore may compute all $a_{k,n}$ starting with $k = 0$ where $a_{0,n} \equiv 1$. To derive useful *direct* formulae, we consider a_{kn} for given k as a polynomial in n. It is now useful, to apply (13) for *all* $n = 1, 2, \ldots$, instead of only for $n > k$, i.e., $k \leq n-1$.

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