Note on fast polylogarithm computation

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Abstract: The polylogarithm function $\mathrm{Li}_n(z) = \sum_{k=1}^{\infty} z^k/k^n$, manifestly convergent for $|z| \le 1$, integer $n > 1$, is sometimes numerically/symbolically relevant for $|z| > 1$, i.e. the analytic continuation may be required. By exploiting analytic symmetry relations, we give, for integer n, simple and efficient algorithms for complete continuation in complex z.

1. Nomenclature and relations.

The definition

$$\mathrm{Li}_n(z) := \sum_1^\infty \frac{z^k}{k^n} \tag{1.1}$$

allows rapid computation for small $|z|$—one may sum directly. For z barely inside, or on the unit circle, transformations allow rapid convergence. Outside the unit circle, there are two difficulties: First, there is no absolute convergence, and second, cuts in the complex plane must be carefully considered. So for example, it is known that

$$\mathrm{Li}_2\left(\frac{1}{2}\right) = \frac{\pi^2}{12} - \frac{1}{2}\log^2,$$

as may be verified numerically by direct summation of (1.1), with a precision gain of about 1 bit per summand. However, it is also known that the analytic continuation has

$$\mathrm{Li}_2(2) = \frac{\pi^2}{4} - i\pi\log 2,$$

even though the sum (1.1) cannot be performed directly. Incidentally, all along the cut $z \in [1, \infty]$ there is a discontinuity in the correct analytic continuation, exemplified (for $\epsilon > 0$) by

$$\mathrm{Li}_2(2 + i\epsilon) = \frac{\pi^2}{4} + i\pi\log 2,$$

and in general

$$\mathrm{Disc}\ \mathrm{Li}_s(z) = 2\pi i \frac{\log^{s-1} z}{\Gamma(s)},$$

with $\Im(\mathrm{Li})$ always being split equally across the cut—thus we know exactly the imaginary part of any $\mathrm{Li}_n(z)$ on the real ray $z \in [1, \infty]$; said part is $(i/2)$Disc. This discontinuity relation is quite useful in checking of any software.

There are relations that allow analytic continuation, namely these (references [1], [2], but see analytic corrections of the classical work in [3]):

$$\mathrm{Li}_s(z) + \mathrm{Li}_s(-z) = 2^{1-s}\mathrm{Li}_s(z^2), \tag{1.2}$$

true for all complex s, z, and for n integer, and complex z,

$$\mathrm{Li}_n(z) + (-1)^n \mathrm{Li}_n(1/z) = -\frac{(2\pi i)^n}{n!} B_n\left(\frac{\log z}{2\pi i}\right) - 2\pi i \Theta(z) \frac{\log^{n-1} z}{(n-1)!}, \tag{1.3}$$

where B_n is the standard Bernoulli polynomial and Θ is a domain dependent step function: $\Theta(z) := 1$, if $\Im(z) < 0$ or $z \in [1, \infty]$, else $\Theta = 0$. That is, the final term in (1.3) is included when and only when z is in the lower open half-plane union the real cut $[1, \infty)$.

Another relation we shall use is an expansion for constrained values of $\log z$, this time for integers $n > 1$,

$$\mathrm{Li}_n(z) = \sum_{m=0}^{\infty}{}' \frac{\zeta(n-m)}{m!} \log^m z + \frac{\log^{n-1} z}{(n-1)!} \left(H_{n-1} - \log(-\log z)\right), \tag{1.4}$$

valid for $|\log z| < 2\pi$. Here, the $\sum{}'$ notation means we avoid the singular $\zeta(1)$ summand, and $H_q := \sum_{k=1}^{q} 1/k$ with $H_0 := 0$ being the harmonic numbers.

The final relation we shall need for a comprehensive algorithm, any integer n and any complex z, is, for $n = 0, -1, -2, -3, \ldots$,

$$\mathrm{Li}_n(z) = (-n)!(-\log z)^{n-1} - \sum_{k=0}^{\infty} \frac{B_{k-n+1}}{k!(k-n+1)} \log^k z. \tag{1.5}$$

The central idea of the algorithms to follow is to employ analytic relations to render $|\log z| < 2\pi$, so that either (1.4) or (1.5) applies efficiently.

2. Explicit algorithm for complete analytic continuation.

Some instances of Li_n with integer n are elementary, as

$$\begin{aligned} \mathrm{Li}_n(1) &= \zeta(n), \\ \mathrm{Li}_n(-1) &= -\left(1 - 2^{1-n}\right)\zeta(n), \\ \mathrm{Li}_0(z) &= \frac{z}{1-z}, \quad z \neq 1, \\ \mathrm{Li}_1(z) &= -\log(1-z), \quad z \neq 1, \\ \mathrm{Li}_{-1}(z) &= \frac{z}{(1-z)^2}, \end{aligned} \tag{2.1}$$

and generally Li_n is a rational-polynomial function of z for $n \leq 0$ (however, the algorithm following simply provides a sufficient approximation to such representations without expanding out the requisite rational form).

Algorithm 2.1 ($poly(n, z)$)**:** Computation of $\mathrm{Li}_n(z)$ for any $n \in \mathcal{Z}, z \in \mathcal{C}$. It is always assumed that $-\pi < \arg z \leq \pi$, whence the analytic continuation with proper branch cut behavior is assured in the algorithm's return value. This algorithm resolves Li at the worst-case rate of about 1 precision bit per loop iteration.

0) For D-decimal-digit precision, choose summation limit $L := \lceil D \log_2 10 \rceil$, where we define functions

   $F_n^{(0)}(L, z) :=$ R.H.S. of (1.1) through summation limit L;
   $F_n^{(1)}(L, z) :=$ R.H.S. of (1.4) through summation limit L;
   $F_n^{(-1)}(L, z) :=$ R.H.S. of (1.5) through summation limit L;
   $G_n(L, z) :=$ R.H.S. of (1.3);

1) if($z == \pm 1$ or $n = -1, 0, 1$) return result of (2.1);

2) if($|z| \leq 1/2$) return $F_n^{(0)}(L, z)$;

3) if($|z| \geq 2$) return $G_n(L, z) - (-1)^n F_n^{(0)}\left(L, \frac{1}{z}\right)$;

4) (Here, we have $|z| \in (1/2, 2)$, and $n < -1$ or $n > 1$.)
   return $F_n^{(\mathrm{sign}(n))}(L, z)$;

3. Enhancements and extensions

Though Algorithm 2.1 achieves about 1 precision bit per summand in any of the F_n evaluations, somewhat more acceleration can be obtained by adjusting the interval endpoints of $(1/2, 2)$ to say (r_1, r_2). Convergence of any part of Algorithm 2.1 is assured if both $|\log r_k| < \pi\sqrt{3}$.

One enhancement is to use some recursion on the quadratic relation (1.2), for said relation can improve the convergence rate in some cases. In fact, full recursion is certainly a possibilityin the sense of

Algorithm 3.1 ($polyrec(n, z)$)**:** Recursive algorithm for $\mathrm{Li}_n(z)$. We refer to the overall function of Algorithm 2.1 as *poly*, and define a new function based on analytic relation (1.2).

0) Choose a threshold $r2 > 1$, for example $r2 := 2$;
1) function $polyrec(n, z)$ {
      if($|z| < r2$) return $poly(n, z)$; // This can be refined just to invoke parts of *poly*.
      return $2^{n-1}(polyrec(\sqrt{z}) + polyrec(-\sqrt{z}))$;
   }

The attractive simplicity of this recursion must be weighed against the number of calls required to reduce the effective z parameter down to the size of $r2$ via the nested square roots. Still, some partial recursion of this kind should accelerate step (4) of Algorithm 2.1 by reducing the $\log z$ magnitude for the requisite summations.

Finally, it is possible to *parallelize* these algorithms to obtain $\mathrm{Li}_n(z)$ on a set $\{z_1, z_2, \dots\}$. Such parallelization is called for in experimental mathematics work, where say a numerical integral having polylogarithms in its integrand is to be resolved.

References

[1] Erdlyi, A., Magnus, W., Oberhettinger, F., and Tricomi, F. G. *Higher Transcendental Functions*, Vol. 1, New York: Krieger.

[2] L. Lewin *Polylogarithms and Associated functions*, North Holland, 1981.

[3] Wikipedia, the free encyclopedia, *Polylogs*, 2005: `http://en.wikipedia.org/w/index.php?title=Polylog&redirect=no`