

Lectures on Resurgence and Trans-Series

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Week 7, Version: May 14, 2020

6. (WARMUP: **Euler's Equation**)

The differential equation

$$\phi'(z) - \phi(z) = -\frac{1}{z}, \quad (1)$$

is not really called Euler's equation, but he studied it. Here we are working in the $z \rightarrow \infty$ limit.

(a) (**Perturbative Solution**)

Show that the alternating (asymptotic) series

$$\tilde{\phi}(z) = \sum_{n=0}^{\infty} (-1)^n n! z^{-n-1}, \quad (2)$$

solves eq. (1).

(b) (**Borel Transformation and Analytic Continuation**)

Perform the Borel transform

$$\tilde{\phi}(z) = \sum_{n=0}^{\infty} a_n z^{-n-1} \in z^{-1} \mathbb{C}[[z^{-1}]], \quad (3)$$

$$\hat{\phi}(z) = \mathcal{B}[\tilde{\phi}][\zeta] = \sum_{n=0}^{\infty} \frac{a_n}{n!} \zeta^n. \quad (4)$$

on the perturbative solution (2). Perform an analytic continuation of the Borel transform by sharply looking at it and realizing that it's a geometric series. Where are the poles of the analytic continuation of the Borel transform?

(c) (**OPTIONAL: Laplace transform**)

Do the Laplace transform and find

$$\mathcal{L}^0[\hat{\phi}](z) = e^z \Gamma(0; z). \quad (5)$$

The most general solution is $e^z \Gamma(0; z) + ce^z$, which you can find by plugging the differential equation into Mathematica's `DSolve`. Why can't we find the ce^z term? Keep in mind that we are approximating around $z = \infty$.

7. (**Modification of Euler's Equation**)

Let's change a sign,

$$\phi'(z) + \phi(z) = +\frac{1}{z}. \quad (6)$$

Then the asymptotic series changes to

$$\tilde{\phi}(z) = \sum_{n=0}^{\infty} n! z^{-n-1}, \quad (7)$$

which is no longer alternating.

(a) **(Borel Transform and Analytic Continuation)**

Perform the Borel transform as in eq. (4) and use your magic powers to find the analytic continuation $\hat{\phi}(\zeta) = \frac{1}{1-\zeta}$. Where is the pole and will it matter for the Laplace transform?

(b) **(Lateral Laplace Transform)**

Perform a lateral Laplace transform

$$\mathcal{L}^\theta[\hat{\phi}](z) = \int_0^{\infty e^{i\theta}} d\zeta e^{-z\zeta} \hat{\phi}(\zeta), \quad (8)$$

by first making a change of variables, $\zeta = e^{i\theta}\xi$, and then asking Mathematica.

(c) **(Ambiguity is Purely Imaginary)**

By *e.g.* using `ReImPlot` in Mathematica, show that for $z \in \mathbb{R}$ the lateral Laplace transforms for $\frac{\pi}{2} > \theta > 0$ and $0 > \theta > -\frac{\pi}{2}$ have the same real part, but differ in the imaginary part. This is by the way a general feature of this Borel-Laplace stuff.

The imaginary part goes like $\text{sgn}(\theta)\pi e^{-z}$, thus it is non-analytic and can't be “touched” by the perturbative expansion.

(d) **(Median Summation)**

Simply perform a *median resummation* (for $\theta = 0$) defined as

$$S_\theta^{\text{med}} \sim \frac{1}{2}(S_{\theta+} + S_{\theta-}),$$

$$S_\theta \tilde{\phi} = \mathcal{L}^\theta[\mathcal{B}[\tilde{\phi}]],$$

in order to get rid of the imaginary part. Plot the Borel-Laplace (median resummed) solution, a truncation of the asymptotic series (7) and the analytic solution from `DSolve`.