Generalization of classical summation methods

O. Costin, X. Xia

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This page is deliberately left as it is.
Convergent power series are very convenient local representations of functions in solving many types of equations, ODEs, PDEs, difference equations which are regular enough.

E.g. $y'' = xy$ (Airy). Inserting $y = \sum_{k=0}^{\infty} c_k x^k$ we get

$$c_{k+1} = \frac{c_{k-1}}{(k+1)(k+2)} \Rightarrow c_k = 9^{-k/3} \Gamma(k/3 + 2/3)^{-1} \Gamma(k/3 - 1)^{-1} C$$

Even when everywhere convergent, Taylor representations are useful for $x$ near the center of expansion but less so farther away. If, say, $y = \sum_{k=0}^{\infty} \frac{(-x)^k}{(k/e)^k}$ how does $y$ behave as $x \to \infty$? Does it decay? Oscillate? Grow? Scope: One goal is to obtain global info, often in closed form, for three types of expansions:

$$\sum_{k \geq 0} c_k z^k \quad (1), \quad \sum_{k \geq 0} c_k \frac{z^k}{k!} \quad \text{(or combinations of Gamma functions)}$$

$$\sum_{k \geq 0} c_k k! z^k; \quad \log(c_k)/\log k \to a \neq 0 \quad \text{as } k \to \infty \quad (2)$$

Generalization of classical summation methods

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Transseries and Écalle’s theory

1. \[ \sum_{k \geq 0} c_k z^k \text{ e.g. } \sum_{n \geq 1} \frac{z^k}{k^b + \ln k} \]
2. \[ \sum_{k \geq 0} c_k \frac{z^k}{k!} \text{ e.g. } \sum_{k \geq 1} \frac{z^k}{(k/e)^k} \]
3. \[ \sum_{k \geq 0} c_k k! z^k \text{ e.g. } \sum_{k \geq 1} \frac{k^k}{(\ln k) z^k} \]

Questions
1. Does the analytic function extend past disk of convergence? All the way to infinity? If so, what is the behavior at \( \infty \)?
2. Question (1).
3. Make sense of (3), and then answer similar questions.

Solve in closed form new type of eqns. s.a.

\[ A\eta^2 f^{(4)} + 2A\eta f''' + \frac{1}{2} \eta f' - (1 + a)f = 0 \]

arising as the scaling pinching profile \( h \sim (t_c - t)f(x(t_c - t)^{-1/2}) \) of the thin film PDE, \( h_t + (h_{xxx} h)_x = 0 \) where \( t_c \) is the singularity time. We solved it from explicitly summing Taylor series at zero, and we know of no other way.

Find all sings. in \( \mathbb{C} \) of classes of PDEs, e.g. (w. H. Park and Y. Takei)

\[ w_{qq} = z h_{zz}; \ h(z, 0) = (z^2 + 1)^{-1}; \ w_q(z, 0) = 0 \]
In essence the method generalizes the Poisson, Euler-Maclaurin, Abel-Plana, Borel methods.

Will need a short discussion of transseries and generalized Borel summability before. There are surprising dualities. One is that essentially, the answer is that the answers *can* be found quite explicitly, essentially *iff* the $c_k$ have generalized Borel summable transseries in $k$. Proving this in full generality would be a huge task, and we'll limit the analysis to transseries of level one, almost always enough in applications.

Transseries were invented/discovered by Écalle to deal with local information at points where classical local expansions don't exist or are divergent. In the Airy case, and generically, the $c_k$ have divergent transseries.

Transseries are obtained from convergent power series by closing them under a wide class of operations. Convergent series are not closed:

$$z \mapsto 1/z \mapsto \log z \mapsto 1/\log z \mapsto z \sum_{k=0}^{\infty} \frac{k!}{(\ln z)^{k+1}}$$

(integration by parts)
**Closure of expansions.** Here is a natural but seemingly hopeless way. Take for $T_0$ the space of convergent Taylor series at 0 and apply to it the differential field operations, $\int$, restricted $\circ$, function inversions, (and others, depending), and for each combination of operations find a unique asymptotic-like expansion (allowing for direction dependence) say $z \to 0^+$. This defines $T_1$. Let $T_2$ be obtained from $T_1$ in the same way, etc. Then $T_\infty := \bigcup_{0}^{\infty} T_k$ will be closed under all these operations.

**Is this enterprise doable? Is this a reasonable one? What is $T_\infty$?!**

**Surprisingly perhaps, $T_\infty$ is quite simple.** This is a first major discovery of Écalle in the 80s. $T_\infty$ is a subspace of transseries: ordered combinations of exponentials, powers and logs. Formal multiseries in monomials built recursively from the exponential alone.
Closure under “all operations of natural origin” is perhaps the best to chat about this property. Invariably, to make it mathematical one specifies explicitly the “natural operations”, at the expense of losing, invariably too, some important ones.

By a theorem transseries are a differential field, also closed under \( \{ \circ, \circ^{-1}, \int \} \). This was sketched by Écalle, and the proof was made rigorous and general about 15 years ago (M. Aschenbrenner, J. van der Hoefen, OC (I added to all these closure under solutions of formally contractive mappings, to try to beat the game of “other operations”).

Transseries are formal multiseries in a finite \# of small variables called transmonomials, each of them obtained from only from the exp, allowing for zero radius of convergence which occurs quickly in the closure. Transseries are not functions, as convergent expansions are not closed under operations above:
\[
\begin{align*}
    z &\mapsto 1/z \\
    \log z &\mapsto 1/\log z \\
    z &\mapsto z \sum_{k=0}^{\infty} \frac{k!}{(\ln z)^{k+1}} \tag{*}
\end{align*}
\]
(integration by parts).

Generalization of classical summation methods
Example of transseries as $z \to 0^+$

$$
\sum_{k=0}^{\infty} \frac{k!z}{(\ln z)^{k+1}} + \text{Ae}^{1/z^2} \sum_{k=1}^{\infty} k^k z^k + \frac{1}{\ln z} + \sum_{k=0}^{\infty} k!z^{k+1}
$$

It is more convenient computationally to place the singularity $z = 0$ at infinity, $z = 1/x$,

$$
\text{Ae}^{x^2} \sum_{k=1}^{\infty} k^k x^{-k} - \frac{1}{\ln x} + \sum_{k=0}^{\infty} \frac{k!}{x^{k+1}}
$$

More generally (though nothing this complicated arises naturally in problems)

$$
\sum \frac{k!^2}{(\ln x)^{k+1}} + e^{-e^x} \sum_{k=0}^{\infty} k! x^{-k-1} + e^{-e^{x^2}} + \cdots
$$

In a transseries, the requirement is that the terms decrease from left to right.

For most 1-variable problems s.a. ODEs, transseries are obtained algorithmically.
Obtaining transseries solutions of \( y' = -y + 1/T \) formally:

\[
y^{[k+1]}_0 = 1/T - Dy^k_0 \Rightarrow y_0 = \sum_{k=0}^{\infty} \frac{k!}{T^{k+1}};
\]

\[
y = y_0 + \delta \Rightarrow \delta' = -\delta \Rightarrow \delta = Ce^{-T} \Rightarrow y = \sum_{k=0}^{\infty} \frac{k!}{T^{k+1}} + Ce^{-T} \quad (7)
\]

**Closure, on the function side.** As presented, these are not actual solutions. Of course, divergence is a serious issue. (And it comes with complications too.) Of all operations listed (\( \{+,-,\times,/,\circ,\circ^{-1},D,\int,\ldots\} \)) iterated differentiation is responsible of divergence.
How to find an extension $\Sigma$ of summation on $T_\infty$?

$\Sigma$ should coincide with summation in convergent cases, and preserve the properties of usual summation: commutation with all listed transseries operations; i.e., we are looking for an isomorphism between functions and transseries.

Accept for now $\Sigma$ exists, and assume, say, an ODE ($P_1$) has a transseries solution $S$. Let $\Sigma$ be the summation operator, assumed to be an isomorphism. Then,

$$S'' - 6S^2 = z \iff \Sigma(S'' - 6S^2) = \Sigma(z) = z$$

$$= [\Sigma(S)]'' - 6[\Sigma(S)]^2 = z \iff f'' - 6f^2 = z \quad (8)$$

That is, a formal solution is transformed into an actual one.
To deal with divergence, since it originates in iterated $D$, it is natural to apply the spectral thm. to map $D$ to $F(p) \rightarrow pF(p)$. After the transform, instead of iterating on $D$ we iterate on multiplication by symbol, generating geometric behavior. E.g. the previous iteration becomes $Y^{[k+1]} = 1 + pY^{[k]} (p = ik) \Rightarrow \sum_{0}^{\infty} p^k = \frac{1}{1-p}$. The transform would be the Fourier transform $\mathcal{F}$, except it requires global info, from all $\mathbb{R}$. We prefer a “far away” half plane $\mathcal{L}^{-1} = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} (\cdot)e^{pt} dt$ (Gelfand transf). does this. Note also that $\sum_{k=0}^{\infty} \mathcal{L}^{-1} \frac{k!}{x^{k+1}} = \sum_{0}^{\infty} p^k$. 

Generalization of classical summation methods
A candidate for $\Sigma$

- $\mathcal{L}\Sigma\mathcal{L}^{-1}$ is a candidate for $\Sigma$. Return to the prototypical example before and write, with the spectral measure theorem in mind, $I = \mathcal{L}\mathcal{L}^{-1}$. Formal $\mathcal{L}^{-1} := \mathcal{B}$.

\[
I \sum_{k=0}^{\infty} \frac{k!}{x^{k+1}} = \mathcal{L}\mathcal{L}^{-1} \sum_{k=0}^{\infty} \frac{k!}{x^{k+1}} = \mathcal{L} \sum_{k=0}^{\infty} \mathcal{B} \frac{k!}{x^{k+1}} = \mathcal{L} \sum_{k=0}^{\infty} p^k = \mathcal{L} \frac{1}{1 - p}, \tag{9}
\]

except that Fubini does not apply and the last integral does not exist...

- If it were not for the integral, “Fubini” could be part of the definition of summation (which would be Borel summation, actually). In the problem above, we can resort to the Cauchy’s PV: $f(x) := \text{PV} \int_0^\infty e^{-px}(1 - p)^{-1} dp$, also $= \text{half sum of} \int_{\mathbb{R}^+} e^{\pm i \epsilon}$.  

- Nonlinear ODEs have infinitely many singularities, and of a worse kind. the average of two solutions is not a solution. Can we extend PV in any generality?
The second major discovery of Écalle is that there is a universal sequence of weights s.t. analytically continuing the integrand around singularities and the averaged $\mathcal{L}^{-1} := B$ (Borel transform) commutes with the transseries operations, should always work on $T_\infty$.

A deep form of regularity called analyzability, implying in particular unique continuation, withstands all classical operations we can think of.

In this utmost generality, the statement is still however conjectural. That’s not because we don’t have a good plan on how to prove this, but the proof would be huge, and the game of “find another natural operation” may continue forever, or end without a hope to prove it ended.
Why $B \neq L^{-1}$ and other quirks

- Note that \( \sum_{k=0}^{\infty} (2k!)/x^k \) is not (directly) summable in \( x \) but it is in \( x' \), \( x' = \sqrt{x} \). Neither is \( \sum_{k=0}^{\infty} (k/2)!/x^k \) (!!), but it is in \( x = \sqrt{x'} \). There is however no change of variables to deal with \( S = \sum_{k=0}^{\infty} (2k! + (k/2)!)/x^k \). And entangled factorial growth can come in many shapes.

- Here comes a third major invention of Écalle, acceleration. After a sequence of acceleration operators \( S \) becomes GB-summable.

- With these tools, summable transseries seem closed under all operations. Proved in restricted, nonetheless useful particular cases: nonlinear (or linear) meromorphic systems of ODEs (OC, Duke 98), quite general classes of nonlinear PDEs (OC, S. Tanveer 2007) and difference equations (Braaksma 2000) very important for us here.
Borel summation as a regularizing procedure.

I will still denote by $\mathcal{B}(=\mathcal{B}_x)$ (x is large) the combination of $\mathcal{B}$ with acceleration operators and averaging, if needed, and $\mathcal{L}$ will be the Laplace transform.

The first step, $\mathcal{B}$ transforms divergent series solutions into convergent ones, and is thus smoothening.

It must then smoothen equations too. $\mathcal{B}[y' - y = 1/x] = (p + 1)Y = 1$.

Another simple example: Modified Bessel f. equation:

$$t^2y'' + ty' - (\nu^2 + t^2)y = 0 \quad (10)$$

We take $y(t) = t^{-\nu}e^{-t}h(t)$ (to eliminate expo behavior and be able to take $\mathcal{L}^{-1}$) we get

$$h'' - \left(2 - \frac{2\nu + 1}{t}\right)h' - \frac{2\nu + 1}{t}h = 0 \quad (11)$$

Applying $\mathcal{B}$ we get a first order ODE

$$p(p + 2)H' + (1 - 2\nu + p(1 - 2\nu))H = 0 \Rightarrow H = Cp^{\nu-\frac{1}{2}}(2 + p)^{-\frac{1}{2}} \quad (12)$$

Generalization of classical summation methods
\[ p(p + 2)H' + (1 - 2\nu + p(1 - 2\nu))H = 0 \Rightarrow H = Cp^{\nu - \frac{1}{2}}(2 + p)^{\nu - \frac{1}{2}} \quad (13) \]

only regular singularities, and only 2 since Bessel is second order. Thus elementary solution.

Thus \( K_\nu(t) = Ce^{-t^\nu} \int_{0}^{\infty} p^{\nu - \frac{1}{2}}(2 + p)^{\nu - \frac{1}{2}}e^{-tp}dp \) (\( C = \frac{\sqrt{\pi}}{2^\nu \Gamma(\nu + \frac{1}{2})} \)) by comparing with the definition of \( K \).

Same can be done on all classical special functions, to obtain the integral representations, and more generally to n-systems of ODEs or PDEs to regularize them.

Same can be done from the Taylor series by the summation I’ll talk about, but in these simple cases it’s not worth it.
Poisson summation serves as an inspiration. Will do roughly the same, but more generally, and discover interesting identities. Wikipedia:

\[
\sum_{k=\infty}^{\infty} \hat{f}(k) = \sum_{k=\infty}^{\infty} \left( \int_{-\infty}^{\infty} f(x) \ e^{-i2\pi kx} \, dx \right) = \int_{-\infty}^{\infty} f(x) \left( \sum_{k=\infty}^{\infty} e^{-i2\pi kx} \right) \, dx
\]

"Poisson transform" of \( \hat{f} \)

\[
= \sum_{n=\infty}^{\infty} \left( \int_{-\infty}^{\infty} f(x) \ \delta(x-n) \, dx \right) = \sum_{n=\infty}^{\infty} f(n).
\]

(rigorous in distributions). Here, key to re-presentation of the sum is the Fourier transform \( \hat{f}(n) \mapsto T_f(e^{n(2\pi i x)}) \). A similar transform is possible in much wider generality using Borel summation.

Poisson summation is a special case of a trace formula, for \( Tu = \int_{\mathbb{R}} g(s-t)u(t) \, dt \) leading to deep results s.a. the Riemann-von Mangoldt formula and the Selberg trace formula. We are not going in that direction.
Braaksma’s class of normalized difference equations:
\[ x(n + 1) = \hat{\Lambda} \left( I + \frac{1}{n} \hat{A} \right) x(n) + g(n, x(n)) \quad (14) \]

where \( \hat{\Lambda} \) and \( \hat{A} \) are constant coefficient matrices, \( g \) is convergently given for small \( x \) by \( g(n, x) = \sum_{k \in \mathbb{N}^m} g_k(n) x^k \) with \( g_k(n) \) analytic in \( n \) at infinity and \( g_k(n) = O(n^{-2}) \) as \( n \to \infty \), if \( \sum_{j=1}^{m} k_j \leq 1 \), \( \Lambda \) non-resonant.

Theory of DEs is remarkably similar to that of ODEs. Braaksma: recurrences (14) possess generalized Borel summable transseries solutions:
\[ \tilde{x}(n) := \sum_{k \in \mathbb{N}^m} C_k e^{-k \cdot \mu n} \tilde{x}_k(n) \quad (15) \]

where \( \tilde{x}_k(n) \) are formal power series in \( n^{-1} \) and the small solutions (or all in linear DEs) are Borel sums of transseries of this type.
\[ x(n) := \sum_{k \in \mathbb{N}^m} C_k e^{-k \cdot \mu n} \int_0^\infty e^{-np} X_k(p) dp \quad (16) \]

\( k \) takes only finitely many values in linear case. We see the “Poisson transform” appearing, in this generality.
The $\Gamma$ function: $\Gamma(x + 1) = x\Gamma(x)$ ($\Gamma$ grows faster than exponentially). Look then at $f = \ln \Gamma$: $f(x+1) - f(x) = \log x$. $f$ still grows too fast. Approximating sums by integrals (Euler-Maclaurin summation) we get $f(x) = (x \log x - x - \frac{1}{2} \log x) + g(x)$, $g$ small. $g$ satisfies $g(x + 1) - g(x) = 1 - \left(\frac{1}{2} + x\right) \ln \left(1 + \frac{1}{x}\right)$.

By taking $G := \mathcal{L}^{-1} g$, we get $g(x) = \int_0^\infty e^{-xp} G(p) dp$, where

$$\frac{e^{-p} - 1}{p} G = \frac{1 - p/2 - (1 + p/2)e^{-p}}{p^2} \quad \text{and thus, since } \sum_{k=n}^\infty e^{-kp} = \frac{e^{-np}}{1 - e^{-p}}$$

$$f(x) = \frac{1}{2} \ln(2\pi) + x(\log x - 1) - \frac{1}{2} \log x + \int_0^\infty \frac{1 - p}{2} - \left(\frac{p}{2} + 1\right) e^{-p} \frac{e^{-xp}}{p^2(e^{-p} - 1)} dp$$

The constant $C = \frac{1}{2} \ln(2\pi)$ is gotten e.g. by calculating the integral for $x = 1$. Global info: analytic continuation to $x = -z$ (rotating the contour and collecting residues) we get

$$\Gamma(1 - x)\Gamma(x) = \frac{\pi}{\sin(\pi x)} \quad (17)$$
Some of the answers

Let $\int_0^\infty$ be an integral around $\mathbb{R}^+$ in the positive direction,

$$G(p) = \frac{1}{2\pi i} \int_0^\infty \frac{e^{-up}}{(-u)^b + \ln(-u)} du$$

Note that $G$ is singular (ramified) only at zero. Define

$$\tilde{G}(s) = G(\ln(1 + s))/(1 + s)$$

Then, $(k^b + \ln k)^{-1} = \int_0^\infty e^{-kp} G(p) dp$, and

$$\sum_{k=1}^\infty \frac{z^k}{k^b + \ln k} = z \int_0^\infty \frac{\tilde{G}(s)}{s - (z - 1)} ds$$

essentially a Hilbert transform of $1_{\mathbb{R}^+} \tilde{G}$. This is analytic except at $z = 1$, goes to zero at $\infty$ and has a Frobenius expansion at $z = 1$. More about the duality of singularities later.

Generalization of classical summation methods

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\[
\sum_{k=1}^{\infty} \frac{x^k}{k^{k+1}} = \int_0^\infty (1 + u)^{-1} G(\ln(1 + u)) \left[ \exp \left( \frac{x}{1 + u} \right) - 1 \right] \, du =: f_2(x)
\]

where now \( G(p) = s_2'(1 + p) - s_1'(1 + p) \) and \( s_{1,2} \) are two branches of the functional inverse of \( s - \ln s \). It is easy to see that the behavior of the integral is \( e^x + o(x) \) as \( x \to \infty \) (the complete asymptotics is also easy to obtain). This was clear from the sum too.

But, as \( x \to -\infty \), \( f_2 \sim C + x^{-1/2} e^{-x} \tilde{y}(1/x) \) where \( \tilde{y} \) is a factorially divergent series (whose terms, and \( C \), can be calculated).
\[ A\eta^2 f^{(4)} + 2A\eta f''' + \frac{1}{2} \eta f' - (1 + a)f = 0 \]  \hspace{1cm} (18)

has the general solution

\[ \eta^{2a+2} \int_0^\infty p^{7/4-a} B(\omega_j p^{1/4}) e^{-p/\eta^2} dp \]

where \( \omega_j \) are the quartic roots of \(-1\), \( B \) is the Bessel function \( J \) or the modified Bessel function \( K \) –depending on the parameter \( a \).
\[ w_{qq} = zw_{zz} \text{ has singular manifolds} \]

\[ Si = \{(q, z) : q = 2c_1 \sqrt{z} + c_2 \sqrt{2}(1 + c_3 i); c_1, c_2, c_3 \in \{-1, 1\}\} \tag{19} \]

where

\[ w(z, q) \sim \frac{f_{c_1, c_2, c_3}(\sqrt{z}, q)}{(q - 2c_1 \sqrt{z} - c_2 \sqrt{2}(1 + c_3 i))} \]

for \( c_1, c_2, c_3 \in \{-1, 1\} \), where \( f_{c_1, c_2, c_3} \) are analytic at each point on the singular manifold.

The point \( z = 0 \) is special: near \( z = 0 \) the singularity is to leading order of the form

\[
\frac{(q - c_2 \sqrt{2}(1 + c_3 i))E\left(\frac{q+2c_1 \sqrt{z}-c_2 \sqrt{2}(1+c_3 i)}{q-2c_1 \sqrt{z}-c_2 \sqrt{2}(1+c_3 i)}\right) + 2c_1 \sqrt{z}K\left(\frac{q+2c_1 \sqrt{z}-c_2 \sqrt{2}(1+c_3 i)}{q-2c_1 \sqrt{z}-c_2 \sqrt{2}(1+c_3 i)}\right)}{3(q + 2c_1 \sqrt{z} - c_2 \sqrt{2}(1 + c_3 i))^{\sqrt{q - 2c_1 \sqrt{z} - c_2 \sqrt{2}(1 + c_3 i)}}} \]

\[ (20) \]

Here \( E \) is a complete elliptic integral of second kind, \( K \) is a complete elliptic integral of first kind. Note that the leading term in (20) is \( O([q - 2c_1 \sqrt{z} - c_2 \sqrt{2}(1 + c_3 i)]^{-1}) \).
Thank you.