

# BOREL RESUMMATION AND THE SOLUTION OF INTEGRAL EQUATIONS

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*ABSTRACT: In this paper we study the methods of Borel resummation applied to the solution of integral equation with symmetric Kernels  $K(xs)$  and to the study of the Riesz criterion , which is important to the Riemann Hypothesis*

- *Keywords: Integral equation, Borel resummation, divergent series*

## 1. INTRODUCTION

Divergent series are widely known and appear in many context involving Physics or Mathematics , for example if we integrate by parts the error function :

$$erfc(x) = \int_x^\infty dt e^{-t^2} \rightarrow \frac{e^{-x^2}}{\sqrt{\pi}} \left( 1 + \sum_{n=1}^{\infty} (-1)^n \frac{(2n)!}{n!(2x)^{2n}} \right) \quad (1.1)$$

Or if we apply a ‘Saddle point mehtod’ to evaluate  $n!$  For big ‘ $n$ ’

$$\Gamma(x+1) \rightarrow \sqrt{2\pi} n^{(n+1)/2} \left( 1 + \frac{1}{12n} + \frac{1}{288n^2} + \dots \right) \quad \int_0^\infty dt e^{-t} t^{x-1} = \Gamma(x) \quad (1.2)$$

But (1.1) and (1.2) are only convergent in the limit  $x \rightarrow \infty$  for small values of  $x$  both series diverge.

Another example with ODE’s is the following

$$x^2 \frac{dy}{dx} + y = x \quad , y(x) = x \int_0^\infty dt \frac{e^{-t}}{1+xt} \quad (\text{exact solution}) \quad (1.3)$$

For (1.3) Euler gave the series solution:  $y(x) = x - (1!)x^2 + (2!)x^3 - (3!)x^4 - \dots$  (1.4)

Which converges only for  $x=0$  !!! , A similar thing happens with the series:

$$a_0 + a_1 g + a_2 g^2 + a_3 g^3 + \dots \quad g \ll 1 \quad (1.5)$$

That appear in QFT and Quantum Mechanics , here g is the ‘coupling constant’ in general series of the form (1.5) although divergent are used to calculate the ‘mass’ or ‘charge’ , for a given physical theory.

Also as a last example let be the next Taylor series around x=0 :

$$x + x^2 + x^3 + x^4 + \dots = \frac{x}{1-x} \quad , \quad x + 2x^2 + 3x^3 + 4x^4 + \dots = \frac{x}{(1-x)^2} \quad (1.6)$$

Convergent for  $|x| < 1$  However taking the limit  $x \rightarrow -1^-$  (-1 by the left) we find the amazing results  $-1/2$  and  $-1/4$  .

Of course this sections pretends to be only a kind of introduction to the subject for further references I strongly recommend ‘Divergent series’ by G.H Hardy or ‘Zeta regularization methods’ by E.Elizalde and others for historical examples involving divergent series and integrals.

## 2. BOREL RESUMMATION FOR SERIES AND INTEGRALS

Let be the divergent (Numerical) series:

$$S = a_0 + a_1 + a_2 + a_3 + \dots \quad (2.1)$$

Borel gave a very ingenious method to calculate it, first we multiply and divide each term by n!

$$\sum_{n=0}^{\infty} \frac{a_n}{n!} \int_0^{\infty} dt t^n e^{-t} \quad \sum_{n=0}^{\infty} \frac{a_n}{n!} t^n = f(t) \quad (2.2)$$

Then we use (2.1) and (2.2) and supposing that  $f(t) = O(e^{bt})$  for a real positive number b then we can write the ‘sum’ of the series in (2.1)

$$\int_0^{\infty} dt f(t) e^{-st} = B(S) \rightarrow \sum_{n=0}^{\infty} a_n \quad \text{or} \quad s \int_0^{\infty} dt f(t) e^{-st} \rightarrow \sum_{n=0}^{\infty} a_n s^{-n} \quad s > 0 \quad (2.3)$$

As a ‘toy model’ of our Borel resummation method we have:

$$1 - 1 + 1 - 1 + 1 - 1 + 1 - 1 + \dots \rightarrow 1/2 \quad f(t) = \exp(-t) \quad (2.4)$$

Unfortunately we can’t always know an exact expression for f(t), To give an approximate evaluation of our Borel transform, we can use the ‘Euler-Abel’ transform applied ot our divergent series

$$\sum_{n=0}^{\infty} a(n) (-1)^n x^n \approx \sum_{k=0}^p \frac{(-1)^k x^k \Delta^k [a_n]_{n=0}}{(1+x)^{k+1}} \left( \frac{x}{1+x} \right)^{p+1} \sum_{n=0}^{\infty} \mathcal{H}^{+k} \mathcal{H}^{-p} \Delta [a_n]_0 x$$

$$\Delta^n a(0) = \sum_{n=0}^n (-1)^m \frac{n!}{n!(n-m)!} a_{n-m} \quad (2.5)$$

Also we need another well-known property of the ‘Laplace transform’

$$\int_0^\infty dt \frac{t^p}{(t+c)^{p+1}} e^{-st} = \frac{1}{p!} \frac{\partial^p}{\partial s^p} \frac{\partial^p}{\partial c^p} E_1(cs) e^{cs} \quad E_1(x) = \int_x^\infty dt \frac{e^{-t}}{t} = -E_i(-x) \quad (2.6)$$

The first expression in (2.5) is an approximate evaluation for  $f(x)$ , let  $x=t$  the B(S) ‘Borel sum’ for our divergent series (3.1) is:

$$B(S) \approx \frac{1}{s} \sum_{k=0}^p (-1)^k \frac{1}{k!} \frac{\partial^k}{\partial s^k} \frac{\partial^k}{\partial c^k} \Big|_{c=1, s=1} \Delta^k [b_n]_{n=0} E_1(s) e^{cs} \quad (2.7)$$

With  $a_n = b_n n!$ , only in case that the coefficients of our initial series (2.1) were of the form  $a_n = (-1)^n P(n)$  with  $P(n)$  a Polynomial (2.7) is exact.

The error term is given by the expression:

$$E = O \left( \frac{1}{s} \frac{1}{p!} \frac{\partial^{p+1}}{\partial s^{p+1}} \frac{\partial^p}{\partial c^p} E_1(cs) e^{cs} \Big|_{c=1, s=1} \right) \quad (2.8)$$

In case (2.1) were convergent, then its ‘Borel sum’ is equivalent to the term-by-term Laplace transform at  $s=1$ .

The formalism of Borel resummation for integrals is immediately accomplished if we define the Riemann sum multiplying and dividing each term by a Gamma function we have:

$$\sum_{n=0}^\infty \frac{f(a+n\Delta x) s^{\Delta x + a}}{\Gamma(a+n\Delta x+1+\alpha)} \int_0^\infty dt t^{a+n\Delta x} e^{-t} t^\alpha \Delta x \quad (2.9)$$

Now we take the limit,  $\Delta x \rightarrow 0$ , the sums becomes the double-integral :

$$s \int_0^\infty dt \left( \int_0^\infty dx \frac{f(x) t^x}{\Gamma(x+1+\alpha)} \right)^\alpha e^{-st} \quad (2.10)$$

Of course in general, unless  $\int_0^\infty dx f(x)$  is convergent ‘Fubini’s theorem’ does not hold for (2.9) and (2.10) so:

$$\int_0^\infty dt \int_0^\infty dx \sigma(x, t) \neq \int_0^\infty dx \int_0^\infty dt \sigma(x, t) \quad \sigma(x, t) = \frac{f(x)}{\Gamma(x+1+\alpha)} t^{x+\alpha} e^{-t} \quad (2.11)$$

Now if we define the integral transform

$$H_\alpha(t) = \int_0^\infty dx \frac{f(x)}{\Gamma(x+1+\alpha)} t^x \quad \text{With } H_\alpha(t) = O(e^{bt}) \quad (2.12)$$

If the 2 conditions inside (2.14) holds then the ‘Borel integral’ is just the Laplace transform of  $H_\alpha(t)t^\alpha$ ,  $\alpha > 0$

But. Can a ‘Borel sum’ be the real sum of the series?, let’s take :

$$E_i(x) = -\int_{-x}^\infty dt \frac{e^{-t}}{t} \approx \frac{e^{-x}}{x} \sum_{n=0}^\infty \frac{(-1)^n}{x^n} n! \quad (2.13)$$

The alternating series has the Borel transform:

$$x \int_0^\infty dt e^{-xt} \frac{1}{t+1} \rightarrow \sum_{n=0}^\infty \frac{(-1)^n}{x^n} n! \quad (2.14)$$

Using the result for the Laplace transform of  $1/(t+1)$ , we find:

$$L\left\{\frac{1}{t+1}\right\} = e^s E_i(s) \quad (2.15)$$

Setting  $s=1$  we find that the ‘asymptotic’ expansion (2.14) can be ‘summed’ even for high values of  $x$ .

Also, if the integral is convergent then using the property of Laplace transform with  $s=1$   $L\{t^x\}_{s=1} = \Gamma(x+1)$  then the definition of ‘integral’ (2.12) is the same as the usual definition for the integral in terms of convergent Riemann sums.

The relationship of this ‘Borel resummation’ for integrals can be written as this, using the next property for Laplace transforms:

$$L\left\{\int_0^\infty dx t^x \frac{f(x)}{\Gamma(x+1)}\right\} = \frac{F(\ln s)}{s \ln s} \quad \text{and} \quad L\{t^n f(t)\} = (-1)^n D^n F(s) \quad (2.16)$$

Then we can write (2.14) in terms of Laplace transforms:

$$\int_0^\infty dx f(x) s^{-x} \rightarrow s(-1)^\alpha \frac{d^\alpha}{ds^\alpha} \left( \frac{F_\alpha(\ln s)}{s \ln s} \right) \quad (2.17)$$

Where  $F_\alpha(s)$  is the Laplace transform of  $g(x) = \frac{f(x)}{(x+1)(x+2)\dots(x+\alpha)}$

Valid for  $\alpha > 0$  and integer

For  $\alpha \notin \mathbb{Z}$ , we must apply the analytic prolongation of the Gamma function  $\Gamma(z)$  and use the definition of the differintegral  $D_x^\alpha f$ .

For the case of Fourier sums  $g(x) = \sum_{n=0}^{\infty} a_n \cos(nx)$  the Borel resummation method can be applied, if we use the Real part of the identity

$$\sum_{n=0}^{\infty} t^n e^{inx} =_{reg} \frac{1}{1 - te^{ix}} \text{ and use the Borel resummation formula}$$

$$\sum_{n=0}^{\infty} a_n \cos(nx) = p.v \int_0^{\infty} dt \frac{g(t) - g(t) \cos(x)}{1 - 2t \cos(x) + t^2} \quad a_n = \int_0^{\infty} dt g(t) t^n \quad (2.18)$$

This last integral in (2.18) will only exist in Cauchy's principal value sense due to the singularities of the integrand when  $1 - 2t \cos(x) + t^2 = 0$

### 3. BOREL RESUMMATION AND INTEGRAL EQUATIONS

We could write a generalization to (2.3) as the integral expressions

$$B(a_n) = \int_0^{\infty} dt f(t) h(t) \quad f(t) = \sum_{n=0}^{\infty} \frac{a_n}{M(n+1)} t^n \quad (3.1)$$

With  $M(n+1) = \int_0^{\infty} dt h(t) t^n$ , in case  $h(t) = e^{-t}$  and  $M(n+1) = n!$ ,

Expression (4.1) is just the Borel transform of the sequence  $\{a_n\}$ , with the advantage that now  $f(t)$  can grow faster than  $e^{bt}$  so  $f(t) \neq O(e^{bt})$ ,

We will study the applications of this Borel resummation to solve integral equations and to study the Riesz criterion for Riemann Hypothesis

In order to apply the Borel generalized resummation to integral equations, let be the Fredholm equation of first kind :

$$g(s) = s \int_0^{\infty} dt K(st) y(t) \quad \hat{K}(n+1) = \int_0^{\infty} dt K(t) t^n \quad (3.2)$$

Here  $K(st)$  is the Kernel of the integral equation, and  $g(s)$  has the form of a Z-transform involving inverse powers of 's' :

$$g(s) = c_0 + \frac{c_1}{s} + \frac{c_2}{s^2} + \frac{c_3}{s^3} + \dots \quad c_n = \frac{1}{2\pi i} \int_{\gamma} dz g(z) z^{n-1} \quad (3.3)$$

Since the Mellin transform for Kernel  $K(u)$  exists, we will apply Borel resummation to solve the integral equation given in (3.2)

$$g(s) = \sum_{n=0}^{\infty} c_n s^{-n} = \int_0^{\infty} dt \left( \sum_{n=0}^{\infty} \frac{c_n}{\hat{K}(n+1)} \cdot \frac{t^n}{s^n} \right) K(t) = s \int_0^{\infty} dt K(st) y(t) \quad (3.4)$$

Here ‘ $\mathcal{Y}$ ’ is a certain closed path on the complex plane

From expression (3.4) We have proven that a infinite power series in the

form  $\sum_{n=0}^{\infty} \frac{c_n}{\hat{K}(n+1)} t^n = y(t)$  can be used to solve an integral equation

of the form (4.2) with the Kernel  $K(xs)$  .

As an example of our method let be the integral equation for the Prime counting function [1]

$$\log \zeta(s) = s \int_0^{\infty} dt \frac{\pi(e^t)}{e^{st} - 1} \quad \pi(x) = \sum_{p \leq x} 1 \quad (3.5)$$

The Kernel of (3.5) is  $K(t) = \frac{1}{e^t - 1}$  and its Mellin transform

$\Gamma(s+1)\zeta(s+1)$  , then the solution to (3.5) is given by the Gram series

$$\pi(x) \approx \sum_{n=1}^{\infty} \frac{1}{n} \frac{(\log x)^n}{n! \zeta(n+1)}$$

, from the Prime number theorem

$\lim_{x \rightarrow \infty} \frac{\pi(x) \log x}{x} = 1$  , the coefficients inside the Gramm series must be

equal to  $c_n \approx \frac{1}{n}$  , so in the limit  $x \rightarrow \infty$  , the Gram series is just the

Taylor expansion for the logarithmic integral

$$Li(x) = \int_2^{\infty} \frac{dt}{\log t} \approx \sum_{n=1}^{\infty} \frac{1}{n} \frac{(\log x)^n}{n!}$$

Another important example is the Laplace transform with the Kernel  $K(st) = e^{-st}$  in this case we have the power series solution

$$g(s) = \int_0^{\infty} dt e^{-st} y(t) \quad y(t) = \sum_{n=0}^{\infty} \frac{a_n}{n!} t^n \quad (3.6)$$

Since  $\Gamma(s) = \int_0^{\infty} dt e^{-t} t^{s-1}$  , the entire paper may be seen as a generalizatio

of the expression (3.6) but not only for the Laplace transform

This method of the Borel transform can be extended to include integral equation with non-constant limit of integration or Volterra equations

$$sg\left(\frac{1}{s}\right) = \int_s^\infty dt K\left(\frac{t}{s}\right) f(t) \quad f(t) = \sum_{n=0}^\infty \frac{c_n}{\hat{K}(n+1)_1} t^n \quad (3.7)$$

With  $\hat{K}(n+1)_1 = \int_1^\infty dt K(t) t^{n-1}$ , the Mellin transform with lower limit '1' using the same reasoning as we did inside (3.2 -3.4) and with the change of variable  $s \rightarrow \frac{1}{s}$ , we can immediatly check that  $f(t) = \sum_{n=0}^\infty \frac{c_n}{\hat{K}(n+1)_1} t^n$  solves the integral equation in (3.7)

In these cases, to solve integral equations of the form

$$g(s) = s \int_0^\infty dt K(st) f(t),$$

we have assumed that the Mellin transform of the

Kernel  $K(t)$  will exists for every positive integer 'n' and for  $n=0$ , but

what happens for example if  $\int_0^\infty dt \frac{t^{s-1}}{1+t} = \frac{\pi}{\sin(\pi s)}$ ?, in this case the

Mellin transform is singular and has poles at the integers,so the series solution will have all its terms equal to 0.

We call this the 'Kernel problem'this appear for example when the

integral  $\int_0^\infty dt K(t) t^n$  takes the value 0 or  $\infty$  for every positive integer

$n \in Z$  and it may produce nonsensical results such as

$$\sum_{n=0}^\infty \frac{a_n x^n}{M(n+1)} = \sum_{n=0}^\infty \frac{a_n x^n}{\infty} = 0+0+..=0 \quad \sum_{n=0}^\infty \frac{a_n x^n}{0} = \infty + \infty + \dots = \infty \quad (3.8)$$

If the Mellin transform of the Kernel  $M[K(t)](s) = \int_0^\infty dt K(t) t^{s-1}$  has

poles at the integers, we introduce a real or complex number  $\alpha$ , so the Mellin transform defined by analytic continuation

$$M[K(t)](s + \alpha) = \int_0^\infty dt K(t) t^{s+\alpha-1}$$

has no poles  $\forall n \in Z$ . In this case we re-

write the integral equation in the form

$$g(s) = s \int_0^\infty dt K(st) y(t) \rightarrow s^\alpha g(s) = s \int_0^\infty dt (st)^\alpha K(st) \phi(t) \quad (3.9)$$

Here  $\phi(t) = \frac{f(t)}{t^\alpha}$ , in this case and due to the extra term inside the

Kernel (3.8), the solution may have fractional powers of 't', if the

function  $g(s)$  admits the expansion  $g(s) = \sum_{n=-\infty}^\infty c_n s^{-n}$ , then the solution to

(3.8) is given by the power series  $f(t) = \sum_{n=-\infty}^{\infty} \frac{c_n}{\hat{K}(n+1+\alpha)} t^n$  and  $\hat{K}(s)$  is the Mellin transform of the Kernel  $K(t)$ .

To solve equation (3.8) we have made the ‘ansatz’  $\phi(t) = \sum_{m=-\infty}^{\infty} \frac{a_m}{\hat{M}(m+\alpha+1)} t^{m-\alpha}$ , that is because the Laurent series expansion of the term on the left is  $s^\alpha g(s) = \sum_{n=-\infty}^{\infty} c_n s^{-n+\alpha}$ , so both functions  $g(s)$  and  $\phi(t)$  inside (3.8) must have an expansion including also fractional powers so the borel transform gives the exact result.

We can extend our method to include also negative powers of ‘t’ if the function  $g(s)$  admits a Z-transform

$$\sum_{m=-\infty}^{\infty} \frac{c_m}{s^m} = g(s) \quad f(t) = \sum_{m=-\infty}^{\infty} \frac{c_m}{\hat{K}(m+1+\alpha)} t^m \quad (3.10)$$

The number  $\alpha$  is chosen so the Mellin transform  $\hat{K}(n+1+\alpha)$  has no zeros nor poles for integer ‘n’.

Depending on which expansion (laurent series, Taylor series Z-transform) we use for the functions  $g(s)$  and  $s^\alpha g(s)$  our solution will have only positive powers of ‘x’ or even fractional powers of ‘x’ the scheme is as follows

$$g(s) = \sum_{m=k}^{\infty} c_m \frac{1}{s^{m+\alpha}} \rightarrow \text{implies} \rightarrow \phi(t) = \sum_{m=k}^{\infty} \frac{c_m t^{m+\alpha}}{\hat{M}(m+\alpha+1)} \quad (3.11)$$

Where  $\hat{M}(s)$  is the Mellin transform of  $K(t)$  and the 2 functions inside (3.11) are related by an integral equation

$g(s) = s \int_0^{\infty} dt K(st) \phi(t) = \int_0^{\infty} dt K(t) \phi\left(\frac{t}{s}\right)$ , anyway if we are interested only in the behavior of the solution as  $t \rightarrow \infty$ , then only the power series solution with positive powers of ‘t’ is interesting

$$f(t) = \sum_{m=0}^{\infty} \frac{c_m}{\hat{K}(m+1+\alpha)} t^m.$$

if we apply the Borel transform and use expression (3.10) we can give a meaning to the solution of the integral equation in a form of a power series.

In the special case of the integral equation  $g\left(\frac{1}{s}\right) = s \int_0^{\infty} dt K(st) f(t)$  with a function  $g(x)$  which can be expanded into a Taylor-Riemann series



involving integer or fractional derivatives with coefficients  $\frac{D^{n+\alpha}g(0)}{\Gamma(n+1+\alpha)}$  the solution is a bit easier and it can be written in the form

$$f(t) = \sum_{m=-\infty}^{\infty} \frac{D^{n+\alpha}g(0)t^{m+\alpha}}{\hat{K}(m+1+\alpha)\Gamma(n+\alpha+1)} = \sum_{n=-\infty}^{\infty} \frac{D^{n+\alpha}g(0)}{\Gamma(n+1+\alpha)} \frac{1}{s^{n+\alpha}} = g\left(\frac{1}{s}\right) \quad (3.12)$$

For the special case  $\alpha = 0$ , there would be only normal derivatives and positive powers of 'x' in this case the solution takes the form of a Taylor series about the origin  $f(t) = \sum_{m=0}^{\infty} \frac{D^m g(0)}{\hat{K}(m+1)m!} t^m$

Although we have only applied our method to integral equation of first kind, we can also apply this method of power series to the integral equation of second kind

$$g(s) + f\left(\frac{1}{s}\right) = s \int_0^{\infty} dt K(st) f(t) \quad (3.13)$$

In this case we can use the trick  $s \int_0^{\infty} dt \delta(st-1) f(t) = f\left(\frac{1}{s}\right)$ , so we have the new kernel  $R(st) = K(st) - \delta(st-1)$ , and the solution to equation (3.13) is the following

$$f(t) = \sum_{m=-\infty}^{\infty} \frac{a_n}{\hat{K}(m+1+\alpha)-1} t^m \quad g(s) = \sum_{n=-\infty}^{\infty} \frac{a_n}{s^n} \quad (3.14)$$

Depending on the value of  $\alpha$  it may happen that  $\hat{K}(n+\alpha+1) = 1$ , for some value of 'n' and the equation may have no solution

This method of power series may seem useless since for example for an integral equation with Kernel  $K(st)$  the solution may be obtained with the aid of the Mellin transform

$$f(t) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{ds}{x^s} \frac{G(1-s)}{K(1-s)} \quad g(s) = \int_0^{\infty} dt K(st) f(t) \quad (3.15)$$

Where  $G(s) = \int_0^{\infty} dt g(t) t^{s-1}$  and  $K(s) = \int_0^{\infty} dt k(t) t^{s-1}$  are the Mellin transforms for the Kernel and for the function  $g(t)$ , however it may happen that the function  $g(t)$  has no well-defined Mellin transform, for example in the case of the Gram series, also the function  $K(1-s)$  may have an infinite number of zeros, so by residue theorem the evaluation

of the complex integral inside (3.14) is also an infinite series and no gain is obtained.

In general in this paper we have used the expressions  $g(s) = \sum_{n=-\infty}^{\infty} \frac{a_n}{s^n}$  and  $g(s) = \sum_{n=0}^{\infty} \frac{a_n}{s^n}$ , these are equivalent provided that  $a(n) = 0$  for every  $n < 0$ .

o *Asymptotic evaluation of some integrals:*

Conversely Borel transform analysis could be used to the evaluation of several integrals, for example let be the function  $f(x) = \sum_{n=0}^{\infty} a_n x^n$  having a power series expansion near  $x=0$ , then for every  $K(t)$  so its Mellin transform  $M(n+1) = \int_0^{\infty} dt t^n K(t)$  exists for every positive integer 'n' then we have the following

$$\int_0^{\infty} dt K(st) f(t) \approx \sum_{n=0}^{\infty} a_n \frac{M(n+1)}{s^{n+1}} \quad s \rightarrow \infty \quad (3.16)$$

If the function  $f(x)$  has a taylor series near the origin then  $a_n = \frac{D^{(n)} f(0)}{n!}$ . Also it may happen that the function  $g(s)$  has a power

series expansion in the form  $g(s) = \sum_{n=0}^{\infty} a_n (s+1)^{-n}$ , in this case to obtain the series expansion in terms of the powers of  $\frac{1}{s}$  we will need the

identity  $\frac{1}{(x+1)^n} = \sum_{k=0}^{\infty} \binom{-n}{k} x^{-k-n}$

#### 4. RIESZ CRITERION AND THE BOREL TRANSFORM:

The Riesz function, introduced by Marcel Riesz, ref [6] has the 2 equivalent formulations

$$Riesz(x) = -\sum_{n=1}^{\infty} \frac{(-x)^n}{(k-1)! \zeta(2n)} \quad \frac{Riesz(x)}{x} = \sum_{n=1}^{\infty} \frac{\mu(n)}{n^2} \exp\left(-\frac{x}{n^2}\right) \quad (4.1)$$

Here  $\mu(n) = \begin{cases} 0 & \text{if } n \text{ is not square-free.} \\ (-1)^k & \text{if } n \text{ is square-free with } k\text{-distinct prime factor} \end{cases}$  and

$\mu(1) = 1$  is the Möbius function

We will use the Borel transform method to give an integral equation for the Riesz(x) function using the Borel resummation method

$$1 - e^{-x} = -\sum_{n=1}^{\infty} (-1)^n \frac{x^n}{n!} = \int_0^{\infty} \frac{dt}{t} \left\{ \frac{1}{\sqrt{t}} \right\} \left( \sum_{n=1}^{\infty} \frac{(-1)^n (xt)^n}{\zeta(2n) (n-1)!} \right) \quad (4.2)$$

The last expression inside the integral in (4.2) is precisely the Riesz function, so for the Riesz function using the Borel resummation method we have obtained the integral equation for the Riesz function

$$e^{-x} - 1 = \int_0^{\infty} \frac{dt}{t} \left\{ \sqrt{\frac{x}{t}} \right\} Riesz(t) \quad \{t\} = t - [t] = \frac{1}{2} - \frac{1}{\pi} \sum_{k=1}^{\infty} \frac{\sin(2\pi kt)}{k} \quad (4.3)$$

Inside (4.2) and (4.3) we have used the definition of the Riemann Zeta function as the Mellin transform of the fractional part

$$-\frac{\zeta(2s)}{s} = \int_0^{\infty} \frac{dt}{t} \left\{ \sqrt{\frac{1}{t}} \right\} t^s, \text{ before applying Borel resummation}$$

Truncation of the Fourier series inside (4.3) may be needed if we want to use numerical method to solve this integral equation).

We can check that (4.3) is correct, if we apply the Mellin transform to both sides and use the Mellin convolution theorem

$$\int_0^{\infty} (f * g)(x) x^{s-1} dx = \int_0^{\infty} dt \int_0^{\infty} dx f(xt) g(t) \frac{dt}{t} x^{s-1} = \hat{F}(s) \int_0^{\infty} dt g(t) t^{-s-1} \quad (4.4)$$

Together with the change of variable  $z = xt$ , if we apply this to (4.3)

$$-\Gamma(s) = -\frac{\zeta(-2s)}{s} \int_0^{\infty} dt Riesz(t) t^{s-1} = \int_0^{\infty} dt Riesz(t) t^{s-1} = \frac{\Gamma(s+1)}{\zeta(-2s)} \quad (4.5)$$

Inside (4.5) is the Mellin transform of the Riesz function, so our integral equation (4.3) is correct.

Also if we take the derivative with respect to 'x' on both sides of (4.3) and use the fact that

$$\frac{d}{dx} \{x\} = 1 - \frac{d[x]}{dx} = 1 - \sum_{m=-\infty}^{\infty} \delta(x-m) \quad (4.6)$$

And the identity relating a sum and an integral

$$\sum_{n=1}^{\infty} f(n) = -\int_0^{\infty} dx [x] f'(x) \quad \lim_{x \rightarrow \infty} [x] f(x) = 0 \quad (4.7)$$

Where  $f(x)$  is a suitable function with continuous first derivative, then, we recover the well known functional equation for the Riesz function

$x e^{-x} = \sum_{n=1}^{\infty} Riesz\left(\frac{x}{n^2}\right)$ . To prove this equation we have used a change of

variable of the form  $\frac{x}{t} = u^2$  inside (4.3), also we have used formulae

(4.6) and (4.7) and the differential identity (assuming both derivatives with respect to 'u' and 'x' exist)

$$-u \frac{\partial f}{\partial u} = 2x \frac{\partial f}{\partial x} \quad f = f\left(\frac{x}{u^2}\right) \quad (4.8)$$

An alternative to equation (4.3) is to use the representation of the

Riemann zeta function  $\frac{\zeta(s)}{s} = \int_0^{\infty} \frac{dt}{t} \left[ \sqrt{\frac{1}{t}} \right] t^s$ , in this case we have on the

left side of (4.3) the expression  $1 - e^{-x}$ , here  $[x]$  is the floor function, the

kernel of the integral equation would be now  $\left[ \sqrt{\frac{x}{t}} \right]$ .

In any case both Kernel can give two equivalent kernel and two

equivalent integral equations, if we replace the function  $\sqrt{\frac{x}{t}}$  by  $\left(\frac{x}{t}\right)^{\frac{1}{2}+\epsilon}$

for any positive epsilon, then we find the regularized integral

$$\lim_{\epsilon \rightarrow 0} \int_0^{\infty} \frac{dx}{x^{\frac{3}{2}+\epsilon}} R(x) = 0 \quad \text{since} \quad \zeta(1+2\epsilon) = \frac{1}{2\epsilon} + \gamma + O(\epsilon) \quad \epsilon \rightarrow 0 \quad (4.9)$$

This regularization is admissible since the Mellin transform of the Riesz

function is equal to  $\frac{\Gamma(s+1)}{\zeta(-2s)}$  for every 's' so  $\text{Re}(s) < -\frac{1}{2}$ .

The integral equation (4.3) can be written also in the form

$$e^{-\frac{1}{x}} - 1 = x \int_0^{\infty} \frac{dt}{xt} \left\{ \sqrt{\frac{1}{xt}} \right\} Riesz(t) \quad e^{-\frac{1}{x}} - 1 = \sum_{n=1}^{\infty} \frac{(-1)^n}{n! x^n} \quad (4.10)$$

If we insert this series inside (3.9) for the function  $e^{-\frac{1}{x}} - 1$ , and use the fact that  $-\frac{\zeta(2s)}{s} = \int_0^\infty \frac{dt}{t} \left\{ \sqrt{\frac{1}{t}} \right\} t^s$ , with  $\alpha = 0$  then we get the solution to

$$(4.10) \text{ in terms of the series } -\sum_{n=1}^{\infty} \frac{(-x)^n}{(k-1)! \zeta(2n)} .$$

The integral (4.10) is of the form  $g(s) = \int_0^\infty dt K\left(\frac{x}{t}\right) f(t)$ , so we can generalize this result and the function  $f(t)$  of the previous integral equation will have the power series solution

$$f(t) = \sum_{n=0}^{\infty} \frac{a_n}{M(-n)} x^n \quad g\left(\frac{1}{s}\right) = \sum_{n=0}^{\infty} a_n s^n \quad M(n) = \int_0^\infty dt K(t) t^{n-1} \quad (4.11)$$

The asymptotic behavior of the power series inside (4.11) is dictated by the zeros of  $M(s)$  since

$$f(t) = \sum_{n=0}^{\infty} \frac{a_n}{M(-n)} x^n = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{ds}{x^s} \frac{G(s)}{M(s)} \quad G(s) = \int_0^\infty dt g(t) t^{s-1} \quad (4.12)$$

## 5. APPLICATION OF THE FRACTIONAL CALCULUS TO THE SOLUTION OF THE INTEGRAL EQUATIONS

In the section 3 of this paper, we explained the ‘Kernel problem’, now we devote this section to solve this problem by using the tools of the fractional Calculus.

A good web-based introduction to fractional calculus is given in [11], however we will only need some basic properties of the fractional derivatives, here they are

$$D_s^\alpha t^m = \frac{\Gamma(m+1)}{\Gamma(m-\alpha+1)} t^{m-\alpha} \quad \int_0^\infty dt t^{s-1} D_t^\alpha f(t) = \frac{\Gamma(s)}{\Gamma(s-\alpha)} M(s-\alpha) \quad (5.1)$$

$$\int_0^\infty dt t^{s-1} f(t^u) = \frac{1}{u} M\left(\frac{s}{u}\right) \quad \int_0^\infty dt t^{s-1} f(t) = M(s) \quad (5.2)$$

Now if we take the fractional derivative with respect to ‘s’ inside of our integral equation, we get the result

$$s D_s^\alpha g(s) = s \int_0^\infty dt D_s^\alpha K(st) \varphi(t) = \int_0^\infty dt D_s^\alpha K(t) \varphi\left(\frac{t}{s}\right) \quad \varphi(t) = f(t) t^\alpha \quad (5.3)$$

The formal power series solution to equation (5.3) is given by the formula

$$\varphi(t) = \sum_{n=0}^{\infty} \frac{c_n}{n!} \frac{\hat{M}(n+1-\alpha)}{\Gamma(n+1-\alpha)} x^{n+\alpha-1} \quad c_n = \frac{1}{2\pi i} \frac{\Gamma(1-n)}{\Gamma(1-n-\alpha)} \int_C \frac{g(z)}{z^{n+1}} \quad (5.4)$$

Here 'C' is a curve which encloses all the poles of the function  $g(z)$ , and the Z-transform of the function  $sD_s^\alpha g(s)$  is  $\sum_{n=0}^{\infty} \frac{c_n}{s^{n+\alpha-1}}$

An easier method would just to make the change of variable  $t \rightarrow t^u$  and  $s \rightarrow s^u$  with  $u > 0$ , in this case we have the new integral equation

$$g(s^u) = s \int_0^{\infty} dt K(s^u t^u) \varphi_u(t) = \int_0^{\infty} dt K(t^u) \varphi_u\left(\frac{t}{s}\right) \quad \varphi_u(t) = ut^{u-1} f(t^u) \quad (5.5)$$

The power series solution to (5.5) in terms of the coefficients of the Zeta transform of  $g(s^u)$  is

$$\varphi_u(t) = ut^{u-1} f(t^u) = u \sum_{n=0}^{\infty} \frac{d_n}{\hat{M}\left(\frac{n+1}{u}\right)} t^n \quad g(s^u) = \sum_{n=-\infty}^{\infty} d_n s^{-n} \quad (5.6)$$

## APPENDIX A: RAMANUJAN'S MASTER THEOREM AND BOREL RESUMMATION

Let be the function  $f(x) = \sum_{n=0}^{\infty} (-1)^n a(n) x^n$ , which can be expanded into a Taylor series in a neighborhood of  $x=0$ , Ramanujan's master theorem states

$$\int_0^{\infty} dx f(x) x^{s-1} = \frac{\pi}{\sin(\pi s)} a(-s) \quad (A.1)$$

We can prove (A.1) with the Borel generalized transform

$$a(n) = \int_0^{\infty} dt t^n g(t) \quad (A.2)$$

The sum  $\sum_{n=0}^{\infty} (-xt)^n = \frac{1}{1+xt}$  can be evaluated without any problem, then we apply the Mellin transform to both sides of (A.2), and use the Mellin convolution theorem

for the expression  $\int_0^{\infty} dt \frac{g(t)}{1+xt}$

$$\int_0^{\infty} f(x)x^{s-1}dx = \int_0^{\infty} x^{s-1}dx \int_0^{\infty} dt \frac{g(t)}{1+xt} = \frac{\pi}{\sin(\pi s)} \int_0^{\infty} dt g(t)t^{-s} = \frac{\pi}{\sin(\pi s)} a(-s) \quad (\text{A.3})$$

The last expression (A.3) is precisely Ramanujan's master theorem, here we have used the identity  $\int_0^{\infty} dt \frac{t^{s-1}}{1+t} = \frac{\pi}{\sin(\pi s)}$ , and the definition of  $a(n)$  in terms of the function  $g(t)$ .

This Ramanujan master theorem can be generalized to include the general power series with only positive terms  $f_+(x) = \sum_{n=0}^{\infty} a(n)x^n$ , the generalization using Cauchy's principal value is

$$f_+(x) = \sum_{n=0}^{\infty} a(n)x^n = P.V \int_0^{\infty} dt \left( \sum_{n=0}^{\infty} (xt)^n \right) g(t) \quad a(n) = \int_0^{\infty} dt t^n g(t) \quad (\text{A.4})$$

In this principal value sense the integral  $P.V \int_0^{\infty} \frac{x^{s-1}}{t-1} dt = -\pi \cot(\pi s)$  with

$\sum_{n=0}^{\infty} (xt)^n = \frac{1}{1-xt}$  is convergent for  $0 < \text{Re}(s) < 1$  so in this case the Mellin transform of the power series in a regularized sense is equal to  $P.V \int_0^{\infty} dx f_+(x)x^{s-1} = -a(-s)\pi \cot(\pi s)$

## APPENDIX B: RIESZ FUNCTION AND A SUM OVER RIEMANN ZEROS

From the formula (4.1)  $\frac{Riesz(x)}{x} = \sum_{n=1}^{\infty} \frac{\mu(n)}{n^2} \exp\left(-\frac{x}{n^2}\right)$  a question is could we express a sum involving the Möbius function using the Riemann Zeros ??.

Titchmarsh [8] used the Residue theorem and assumed that all the Riemann zeros were simple to obtain the following formula for the Mertens function

$$M(x) = \sum_{n \leq x} \mu(n) = \sum_{\rho} \frac{x^{\rho}}{\rho \zeta'(\rho)} - 2 + \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{(2n)! n \zeta(2n+1)} \left(\frac{2\pi}{x}\right)^{2n} \quad (\text{B.1})$$

Valid for  $x > 1$ , if we set  $x = e^u$  and differentiate respect to 'x', since the Mertens function is just an step function its derivative must be a delta comb

$$\int_0^{\infty} du e^{-u/2} \frac{dM_0(e^u)}{du} g(u) = \sum_{n=1}^{\infty} \frac{\mu(n)}{\sqrt{n}} g(\log n) \quad (\text{B.2})$$

Now if we write the Riemann zeros as  $\rho = 1/2 + i\gamma$ , then after some trivial manipulations we get from (B.2) the formula

$$\sum_{n=1}^{\infty} \frac{\mu(n)}{\sqrt{n}} g(\log n) = \sum_{\gamma} \frac{h(\gamma)}{\zeta' \left( \frac{1}{2} + i\gamma \right)} + \sum_{n=1}^{\infty} \frac{2(2\pi)^{2n} (-1)^n}{(2n)! \zeta(2n+1)} \int_{-\infty}^{\infty} dug(u) e^{-(2n+1/2)u} \quad (\text{B.3})$$

The firstright part of (B.3) runs over all the Riemann zeros on the critical strip  $0 < \text{Re}(s) < 1$  and  $g(x) = \frac{1}{\pi} \int_0^{\infty} h(u) \cos(ux) du = g(-x)$  is a Fourier transform pair

A straight application to the Riesz function of (B.3) with  $g(t, x) = e^{-(3/2)t} e^{-xe^{-2t}}$  gives for big  $x \gg 1$ , after grouping the terms of the sum over the imaginary part of the Riemann zeros.

$$\frac{R(x)}{x} \approx 2 \Re e \lim_{n \rightarrow \infty} \left( \sum_{0 < \gamma < T_n} \frac{1}{\zeta' \left( \frac{1}{2} + i\gamma \right)} \cdot \frac{\Gamma \left( \frac{3 - 2i\gamma}{4} \right)}{2x^{\left( \frac{3 - 2i\gamma}{4} \right)}} \right) \quad x \rightarrow \infty \quad (\text{B.4})$$

We have used the integral representation of the Gamma function  $\Gamma(s) = \int_0^{\infty} dt e^{-t} t^{s-1}$  inside the equation (B.4)

So if all the imaginary part of the Riemann zeros were REAL , Riemann Hypothesis true then the Riesz function would obey the bound  $R(x) = O \left( x^{\frac{1}{4} + \epsilon} \right)$  for any positive epsilon, at least for big values of 'x' .

Equation (B.3) must be understood more rigorously as the limit of a sum over the imaginary part of the Riemann zeros  $\rho = \frac{1}{2} + i\gamma$  (assuming they are simple).

$$\sum_{n=1}^{\infty} \frac{\mu(n)}{\sqrt{n}} g(\log n) = 2 \lim_{n \rightarrow \infty} \Re e \left( \sum_{0 < \gamma < T_n} \frac{h(\gamma)}{\zeta'(\rho)} + \sum_{n=1}^{\infty} \frac{2(2\pi)^{2n} (-1)^n}{(2n)! \zeta(2n+1)} \int_{-\infty}^{\infty} dug(u) e^{-(2n+1/2)u} \right) \quad (\text{B.5})$$

## APPENDIX C: A FUNCTIONAL DIFFERENTIAL EQUATION FOR INFINITE PRODUCTS

Let be the infinite product

$$S(x) = \prod_{n=0}^{\infty} \left( 1 + \frac{x}{a_n} \right) \quad S(0) = 1 \quad (\text{C.1})$$

This product also can be defined (regularization) As



$$-\partial_s Z(0, x) + \partial_s Z(0, 0) = \log S(x) \quad Z(s, x) = \sum_{n=0}^{\infty} \frac{1}{(x + a_n)^s} \quad (\text{C.2})$$

We may take the logarithmic derivative inside (D.1), this is equal to

$$\frac{S'(x)}{S(x)} = \frac{d \log S(x)}{dx} = \sum_{n=0}^{\infty} \frac{1}{(x + a_n)} \quad (\text{C.3})$$

If we take now the (s-1) derivative inside (C.3) we get

$$\frac{d^{s-1}}{dx^{s-1}} \left( \frac{S'(x)}{S(x)} \right) = - \sum_{n=0}^{\infty} \frac{(-1)^s \Gamma(s)}{(x + a_n)^s} \quad (\text{C.4})$$

Then, if we combine and , and set  $y(x) = \log S(x)$ , we have a functional differential equation valid for every infinite product of the form (C.1)

$$\frac{d}{ds} \left( \frac{D_x^{s-1}}{(-1)^s \Gamma(s)} \left( \frac{dy}{dx}(x) \right) \right)_{s=0} - \frac{d}{ds} \left( \frac{D_x^{s-1}}{(-1)^s \Gamma(s)} \left( \frac{dy}{dx}(0) \right) \right)_{s=0} = y(x) \quad (\text{C.5})$$

Where  $(-1)^s = e^{i\pi s}$  and  $D_x^{s-1} = \frac{d^{s-1}}{dx^{s-1}}$  is the (s-1) fractional derivative operator, this operator can be defined by the Grunwald-Letnikov differintegral.

$$D_x^{s-1} y(x) = \lim_{h \rightarrow 0} \frac{1}{h^{s-1}} \left( \sum_{m=0}^{\infty} (-1)^m \binom{s-1}{m} f(x - mh) \right) \quad (\text{C.6})$$

$$\binom{s-1}{m} = \frac{\Gamma(s)}{\Gamma(s-m)m!} \text{ are the generalized binomial coefficients.}$$

## APPENDIX D: LAPLACE TRANSFORM AND Z-TRANSFORM

Given the Zeta transform of a function

$$g(s) = a_0 + \frac{a_1}{s} + \frac{a_2}{s^2} + \dots \quad (\text{D.1})$$

If the function  $g(e^s)$  admits an inverse Laplace transform, we can set the change of variable  $s = e^t$  and use the summation by parts to write

$$g(e^t) = \sum_{n=0}^{\infty} a_n e^{-nt} = t \int_0^{\infty} dx A(x) e^{-tx} \quad A(x) = \sum_{n \leq x} a_n \quad (\text{D.2})$$

Then the coefficients  $\{a_n\}$  for the Z-transform may be recovered

$$A(x) = \sum_{n \leq x} a_n = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{ds}{s} g(e^s) e^{sx} \quad a_n = A(n) - A(n-1) \quad (D.3)$$

A similar method can be obtained for the Laurent expansion  $g(s) = \sum_{n=-\infty}^{\infty} \frac{c_n}{s^n}$ , with the

change of variable  $s = e^{iu}$ , this series becomes the Fourier series  $g(e^{iu}) = \sum_{n=-\infty}^{\infty} c_n e^{-iun}$

and the coefficients are given by the integral  $c_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} dx g(e^{ix}) e^{-iun}$

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