

On a new method towards proof of Riemann's Hypothesis

Akhila Raman

University of California at Berkeley. Email: akhila.raman@berkeley.edu.

Abstract

We consider the analytic continuation of Riemann's Zeta Function derived from **Riemann's Xi function** $\xi(s)$ which is evaluated at $s = \frac{1}{2} + \sigma + i\omega$, given by $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$, where σ, ω are real and $-\infty \leq \omega \leq \infty$ and compute its inverse Fourier transform given by $E_p(t)$.

We use a new method and show that the Fourier Transform of $E_p(t)$ given by $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega)$ **does not have zeros** for finite and real ω when $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip **excluding** the critical line and prove Riemann's hypothesis.

More importantly, the new method **does not** contradict the existence of non-trivial zeros on the critical line with real part of $s = \frac{1}{2}$ and **does not** contradict Riemann Hypothesis. It is shown that the new method is **not** applicable to Hurwitz zeta function and related functions and **does not** contradict the existence of their non-trivial zeros away from the critical line.

If the specific solution presented in this paper is incorrect, it is **hoped** that the new method discussed in this paper will lead to a correct solution by other researchers.

Keywords: Riemann, Hypothesis, Zeta, Xi, exponential functions

1. Introduction

It is well known that Riemann's Zeta function given by $\zeta(s) = \sum_{m=1}^{\infty} \frac{1}{m^s}$ converges in the half-plane where the real part of s is greater than 1. Riemann proved that $\zeta(s)$ has an analytic continuation to the whole s-plane apart from a simple pole at $s = 1$ and that $\zeta(s)$ satisfies a symmetric functional equation given by $\xi(s) = \xi(1-s) = \frac{1}{2}s(s-1)\pi^{-\frac{s}{2}}\Gamma(\frac{s}{2})\zeta(s)$ where $\Gamma(s) = \int_0^{\infty} e^{-u}u^{s-1}du$ is the Gamma function.^{[4] [5]} We can see that if Riemann's Xi function has a zero in the critical strip, then Riemann's Zeta function also has a zero at the same location. Riemann made his conjecture in his 1859 paper, that all of the non-trivial zeros of $\zeta(s)$ lie on the critical line with real part of $s = \frac{1}{2}$, which is called the Riemann Hypothesis.^[1]

Hardy and Littlewood later proved that infinitely many of the zeros of $\zeta(s)$ are on the critical line with real part of $s = \frac{1}{2}$.^[2] It is well known that $\zeta(s)$ does not have non-trivial zeros when real part of $s = \frac{1}{2} + \sigma + i\omega$, given by $\frac{1}{2} + \sigma \geq 1$ and $\frac{1}{2} + \sigma \leq 0$. In this paper, **critical strip** $0 < \text{Re}[s] < 1$ corresponds to $0 \leq |\sigma| < \frac{1}{2}$.

In this paper, a **new method** is discussed and a specific solution is presented to prove Riemann's Hypothesis. If the specific solution presented in this paper is incorrect, it is **hoped** that the new method discussed in this paper will lead to a correct solution by other researchers.

In Section 2, we prove Riemann's hypothesis by taking the analytic continuation of Riemann's Zeta Function derived from Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ and compute inverse Fourier transform of $E_{p\omega}(\omega)$ given by $E_p(t)$ and show that its Fourier transform $E_{p\omega}(\omega)$ does not have zeros for finite and real ω when $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip **excluding** the critical line.

In Appendix A to Appendix E, well known results which are used in this paper are re-derived.

We present an **outline** of the new method below.

1.1. Step 1: Inverse Fourier Transform of $\xi(\frac{1}{2} + i\omega)$

Let us start with Riemann's Xi Function $\xi(s)$ evaluated at $s = \frac{1}{2} + i\omega$ given by $\xi(\frac{1}{2} + i\omega) = \Xi(\omega) = E_{0\omega}(\omega)$, where $-\infty \leq \omega \leq \infty$. Its inverse Fourier Transform is given by $E_0(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega) e^{i\omega t} d\omega$, where ω, t are real, as follows (link).^[3]

$$E_0(t) = \Phi(t) = 2 \sum_{n=1}^{\infty} [2n^4 \pi^2 e^{\frac{9t}{2}} - 3n^2 \pi e^{\frac{5t}{2}}] e^{-\pi n^2 e^{2t}} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} \quad (1)$$

We see that $E_0(t) = E_0(-t)$ is a real and **even** function of t , given that $E_{0\omega}(\omega) = E_{0\omega}(-\omega)$ because $\xi(s) = \xi(1-s)$ and hence $\xi(\frac{1}{2} + i\omega) = \xi(\frac{1}{2} - i\omega)$ when evaluated at $s = \frac{1}{2} + i\omega$.

The inverse Fourier Transform of $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ is given by the real function $E_p(t)$. We can write $E_p(t)$ as follows for $0 < |\sigma| < \frac{1}{2}$ and this is shown in detail in Appendix A using contour integration.

$$E_p(t) = E_0(t) e^{-\sigma t} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} \quad (2)$$

We can see that $E_p(t)$ is an analytic function in the interval $|t| \leq \infty$, given that the sum and product of exponential functions are analytic in the same interval and hence infinitely differentiable in that interval.

1.2. Step 2: On the zeros of a related function $G(\omega)$

Statement 1: Let us assume that Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$ where ω_0 is real and finite and $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line. We will prove that this assumption leads to a **contradiction**.

Let us consider $0 < \sigma < \frac{1}{2}$ at first. Let us consider a new function $g(t) = e^{\sigma t_0} E_p(t + t_0) e^{-\sigma t} u(-t) + e^{\sigma t_0} E_p(t + t_0) e^{\sigma t} u(t)$ where $g(t)$ is a real function of variable t and $u(t)$ is Heaviside unit step function. We can see that $g(t)h(t) = e^{\sigma t_0} E_p(t + t_0)$ where $h(t) = [e^{\sigma t} u(-t) + e^{-\sigma t} u(t)]$.

In Section 2.1, we will show that the Fourier transform of the **odd function** $g_{odd}(t) = \frac{1}{2}[g(t) - g(-t)]$ given by $G_{odd}(\omega) = G_I(\omega)$ must have **at least one zero** at $\omega = \omega_2(t_0) \neq 0$, for every value of t_0 , to satisfy Statement 1, where $\omega_2(t_0)$ is real and finite.

1.3. Step 3: On the zeros of the function $G_R(\omega)$

In Section 2.2, we compute the Fourier transform of the function $g_{odd}(t)$ given by $G_I(\omega)$. We require $G_I(\omega) = 0$ for $\omega = \omega_2(t_0)$ for every value of t_0 , to satisfy **Statement 1**. In general, $\omega_2(t_0) \neq \omega_0$.

It is shown that $R(t_0) = -G_I(\omega_2(t_0), t_0) = 0$ for all t_0 as follows.

$$\begin{aligned} R(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad - [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] = 0 \\ R(t_0) &= \int_{-\infty}^0 [E_0(\tau + t_0) e^{-2\sigma\tau} - E_0(\tau - t_0)] \sin(\omega_2(t_0)\tau) d\tau = 0 \end{aligned} \quad (3)$$

1.4. Step 4: $\omega_2(t_0)$ is an even function of variable t_0

In Section 2.3, we show the result in Eq. 4 and that $\omega_0(t_0) = \omega_2(t_0) = \omega_2(-t_0)$.

$$P(t_0) = \int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} + E_{0m}(\tau - t_0)] \cos(\omega_0(t_0)\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} + E_{0m}(\tau + t_0)] \cos(\omega_0(t_0)\tau) d\tau = 0 \quad (4)$$

1.5. Step 5: Final Step

In Section 3.2, it is shown that there **exists** a value of $t_0 > 0$ for which $\omega_2(t_0)t_0 = \frac{\pi}{2}$. In Section 3.3, we **set** $\omega_2(t_0)t_0 = \frac{\pi}{2}$ in the equation for $R(t_0)$ in Eq. 3 and $P(t_0)$ Eq. 4 and show that this leads to the result in Eq. 5.

$$\int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau = 0 \quad (5)$$

We see that the **each** of the terms in the integrand in Eq. 5 are **greater than or equal to zero**, in the interval $\tau = [0, t_0]$ where $t_0 > 0$. For $\omega_2(t_0)t_0 = \frac{\pi}{2}$, we see that $\omega_2(t_0)\tau = \frac{\pi}{2t_0}\tau$ lies in the range $[0, \frac{\pi}{2}]$ and hence $\cos(\omega_2(t_0)\tau) \geq 0$ in that interval $\tau = [0, t_0]$.

Hence the result $\int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau = 0$ in Eq. 5 leads to a **contradiction**.

We have shown this result for $0 < \sigma < \frac{1}{2}$ and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$. Hence we have produced a **contradiction** of **Statement 1** that the Fourier Transform of the function $E_p(t) = E_0(t)e^{-\sigma t}$ has a zero at $\omega = \omega_0$ for $0 < |\sigma| < \frac{1}{2}$.

2. An Approach towards Riemann's Hypothesis

Theorem 1: Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ does not have zeros for any real value of $-\infty < \omega < \infty$, for $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line, given that $E_0(t) = E_0(-t)$ is an even function of variable t , where $E_p(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega) e^{i\omega t} d\omega$, $E_p(t) = E_0(t)e^{-\sigma t}$ and $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$.

Proof: We assume that Riemann Hypothesis is false and prove its truth using proof by contradiction.

Statement 1: Let us assume that Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$ where ω_0 is real and finite and $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line. We will prove that this assumption leads to a **contradiction**.

We will prove it for $0 < \sigma < \frac{1}{2}$ first and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$ and hence show the result for $0 < |\sigma| < \frac{1}{2}$.

We know that $\omega_0 \neq 0$, because $\zeta(s)$ has no zeros on the real axis between 0 and 1, when $s = \frac{1}{2} + \sigma + i\omega$ is real, $\omega = 0$ and $0 < |\sigma| < \frac{1}{2}$. [3] This is shown in detail in first two paragraphs in Appendix C.1.

2.1. New function $g(t)$

Let us consider the function $f(t) = e^{\sigma t_0} E_p(t + t_0)$ where $|t_0| \leq \infty$ and we can see that the Fourier Transform of this function $F(\omega) = e^{\sigma t_0} E_{p\omega}(\omega) e^{i\omega t_0}$ also has a zero at $\omega = \omega_0$.

Let us consider a new function $g(t) = g_-(t)u(-t) + g_+(t)u(t)$ where $g(t)$ is a real function of variable t and $u(t)$ is Heaviside unit step function and $g_-(t) = f(t)e^{-\sigma t}$ and $g_+(t) = f(t)e^{\sigma t}$. We can see that $g(t)h(t) = f(t)$ where $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$.

We can show that $E_p(t), h(t), g(t)$ are real absolutely integrable functions and go to zero as $t \rightarrow \pm\infty$. Hence their respective Fourier transforms given by $E_{p\omega}(\omega), H(\omega), G(\omega)$ are finite for $|\omega| \leq \infty$ and go to zero as $|\omega| \rightarrow \infty$, as per Riemann Lebesgue Lemma (link). This is shown in detail in Appendix C.1.

We can see that $g(t)$ is a real L^1 integrable function, its Fourier transform $G(\omega)$ is finite for $|\omega| < \infty$ and goes to zero as $\omega \rightarrow \pm\infty$, as per **Riemann-Lebesgue Lemma** [Riemann Lebesgue Lemma]. This is explained in detail in Appendix C.1.

If we take the Fourier transform of the equation $g(t)h(t) = f(t)$ where $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$, we get $\frac{1}{2\pi}[G(\omega) * H(\omega)] = F(\omega) = E_{p\omega}(\omega) e^{\sigma t_0} e^{i\omega t_0} = F_R(\omega) + iF_I(\omega)$ as per convolution theorem (link), where $*$ denotes convolution operation given by $F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega')H(\omega - \omega')d\omega'$ and $H(\omega) = H_R(\omega) = [\frac{1}{\sigma - i\omega} + \frac{1}{\sigma + i\omega}] = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ is real and is the Fourier transform of the function $h(t)$ and $G(\omega) = G_R(\omega) + iG_I(\omega)$ is the Fourier transform of the function $g(t)$. This is shown in detail in Appendix B.1.

For **every value** of t_0 , we require the Fourier transform of the function $f(t)$ given by $F(\omega)$ to have a zero at $\omega = \omega_0$. This implies that the Fourier transform of the **odd** function $g_{odd}(t)$ given by $G_I(\omega)$ must have **at least one real zero** at $\omega = \omega_2(t_0)$ for **every value** of t_0 . Because $H(\omega) = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ does not have real zeros, if $G_I(\omega)$ does not have real zeros, then $F_I(\omega) = G_I(\omega) * H_R(\omega)$ obtained by the convolution of $H_R(\omega)$ and $G_I(\omega)$, cannot possibly have real zeros, which goes against **Statement 1**.

We can write $g(t) = g_{even}(t) + g_{odd}(t)$ where $g_{even}(t)$ is an even function and $g_{odd}(t)$ is an odd function of variable t . If Statement 1 is true, then the **imaginary** part of the Fourier transform of the **odd function** $g_{odd}(t) = \frac{1}{2}[g(t) - g(-t)]$ given by $G_I(\omega)$ must have **at least one zero** at $\omega = \omega_2(t_0) \neq 0$ where $\omega_2(t_0)$ is real and finite and can be different from ω_0 in general. We call this **Statement 2**.

Because $H(\omega) = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ is real and does not have zeros for any finite value of ω , **if** $G_I(\omega)$ does not have at least one zero for some $\omega = \omega_2(t_0) \neq 0$, **then** the **imaginary part** of $F(\omega)$ given by $F_I(\omega) = \frac{1}{2\pi}[G_I(\omega) * H(\omega)]$, obtained by the convolution of $H(\omega)$ and $G_I(\omega)$, **cannot** possibly have zeros for any non-zero finite value of ω , which goes against **Statement 1**. This is shown in detail in Lemma 1.

Lemma 1: If Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0 \neq 0$ where ω_0 is real and finite, then the **imaginary** part of the Fourier transform of the **odd function** $g_{odd}(t) = \frac{1}{2}[g(t) - g(-t)]$ given by $G_I(\omega)$ must have **at least one zero** at $\omega = \omega_2(t_0) \neq 0$ for **every value** of t_0 , where $\omega_2(t_0)$ is real and finite, where $g(t)h(t) = f(t) = e^{\sigma t_0} E_p(t + t_0)$ and $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ and $0 < \sigma < \frac{1}{2}$.

Proof: If $E_{p\omega}(\omega)$ has a zero at finite $\omega = \omega_0 \neq 0$ to satisfy Statement 1, then $F(\omega) = E_{p\omega}(\omega) e^{\sigma t_0} e^{i\omega t_0}$ also has a zero at $\omega = \omega_0$ and its imaginary part given by $F_I(\omega)$ also has a zero at the same location $\omega = \omega_0 \neq 0$.

Let us consider the case where $G_I(\omega)$ **does not** have at least one zero for finite $\omega = \omega_2(t_0) \neq 0$ and show that $F_I(\omega)$ does not have at least one zero at finite $\omega \neq 0$ for this case, which **contradicts** Statement 1. Given that $H(\omega)$ is real, we can write the convolution theorem only for the imaginary parts as follows.

$$F_I(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G_I(\omega')H(\omega - \omega')d\omega' \quad (6)$$

We can show that the above integral converges for all $|\omega| \leq \infty$, given that $G(\omega)$ and $H(\omega)$ have fall-off rate of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ because the first derivatives of $g(t)$ and $h(t)$ are discontinuous at $t = 0$. (Appendix C.2)

We substitute $H(\omega) = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ in Eq. 6 and we get

$$F_I(\omega) = \frac{\sigma}{\pi} \int_{-\infty}^{\infty} G_I(\omega') \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' \quad (7)$$

We can split the integral in Eq. 7 as follows.

$$F_I(\omega) = \frac{\sigma}{\pi} \left[\int_{-\infty}^0 G_I(\omega') \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' + \int_0^{\infty} G_I(\omega') \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' \right] \quad (8)$$

We see that $G_I(-\omega) = -G_I(\omega)$ because $g(t)$ is a real function (Appendix B.2). We can substitute $\omega' = -\omega''$ in the first integral in Eq. 8 and substituting $\omega'' = \omega'$ in the result, we can write as follows.

$$F_I(\omega) = \frac{\sigma}{\pi} \int_0^{\infty} G_I(\omega') \left[\frac{1}{(\sigma^2 + (\omega - \omega')^2)} - \frac{1}{(\sigma^2 + (\omega + \omega')^2)} \right] d\omega' \quad (9)$$

In Appendix C.1 last paragraph, it is shown that $G(\omega)$ is finite for $|\omega| \leq \infty$ and goes to zero as $|\omega| \rightarrow \infty$. We can see that for $\omega' = 0$ and $\omega' = \infty$, the integrand in Eq. 9 is zero. For finite $\omega > 0$, and $0 < \omega' < \infty$, we can see that the term $\frac{1}{(\sigma^2 + (\omega - \omega')^2)} - \frac{1}{(\sigma^2 + (\omega + \omega')^2)} > 0$.

• **Case 1:** $G_I(\omega') > 0$ for all finite $\omega' > 0$

We see that $F_I(\omega) > 0$ for all finite $\omega > 0$. We see that $F_I(-\omega) = -F_I(\omega)$ because $E_p(t)$ is a real function (Appendix B.2). Hence $F_I(\omega) < 0$ for all finite $\omega < 0$.

This **contradicts** Statement 1 which requires $F_I(\omega)$ to have at least one zero at finite $\omega \neq 0$ because we showed that $\omega_0 \neq 0$ in **Section 2** paragraph 5. Therefore $G_I(\omega')$ must have **at least one zero** at $\omega' = \omega_2(t_0) \neq 0$, where $\omega_2(t_0)$ is real and finite.

• **Case 2:** $G_I(\omega') < 0$ for all finite $\omega' > 0$

We see that $F_I(\omega) < 0$ for all finite $\omega > 0$. We see that $F_I(-\omega) = -F_I(\omega)$ because $E_p(t)$ is a real function (Appendix B.2). Hence $F_I(\omega) > 0$ for all finite $\omega < 0$.

This **contradicts** Statement 1 which requires $F_I(\omega)$ to have at least one zero at finite $\omega \neq 0$. Therefore $G_I(\omega')$ must have **at least one zero** at $\omega' = \omega_2(t_0) \neq 0$, where $\omega_2(t_0)$ is real and finite.

We have shown that, $G_I(\omega)$ must have **at least one zero** at finite $\omega = \omega_2(t_0) \neq 0$ to satisfy **Statement 1**. We call this **Statement 2**. We will investigate if Statement 2 leads to a contradiction for $0 < \sigma < \frac{1}{2}$.

2.2. On the zeros of a related function $G(\omega)$

We can compute the fourier transform of the function $g_{odd}(t) = \frac{1}{2}[g(t) - g(-t)]$ given by $G_I(\omega)$. We require $G_I(\omega) = 0$ for $\omega = \omega_2(t_0)$ for **every value** of t_0 , to satisfy **Statement 1**. In general, $\omega_2(t_0) \neq \omega_0$.

First we compute the fourier transform of the function $g(t)$ given by $G(\omega) = G_R(\omega) + iG_I(\omega)$. We use $g(t) = e^{\sigma t_0} E_p(t + t_0) e^{-\sigma t} u(-t) + e^{\sigma t_0} E_p(t + t_0) e^{\sigma t} u(t)$.

$$\begin{aligned}
G(\omega) &= \int_{-\infty}^{\infty} g(t)e^{-i\omega t} dt = \int_{-\infty}^0 g_-(t)e^{-i\omega t} dt + \int_0^{\infty} g_+(t)e^{-i\omega t} dt \\
G(\omega) &= \int_{-\infty}^0 e^{\sigma t_0} E_p(t+t_0)e^{-\sigma t} e^{-i\omega t} dt + \int_0^{\infty} e^{\sigma t_0} E_p(t+t_0)e^{\sigma t} e^{-i\omega t} dt
\end{aligned} \tag{10}$$

We use $E_p(t) = E_0(t)e^{-\sigma t}$ and $E_p(t+t_0) = E_0(t+t_0)e^{-\sigma t}e^{-\sigma t_0}$. Substituting $t = -t$ in the second integral in Eq. 10, we have

$$\begin{aligned}
G(\omega) &= \int_{-\infty}^0 E_0(t+t_0)e^{-2\sigma t} e^{-i\omega t} dt + \int_0^{\infty} E_0(t+t_0)e^{-i\omega t} dt \\
G(\omega) &= \int_{-\infty}^0 E_0(t+t_0)e^{-2\sigma t} e^{-i\omega t} dt + \int_{-\infty}^0 E_0(-t+t_0)e^{i\omega t} dt
\end{aligned} \tag{11}$$

We define $E_{0m}(t) = E_0(-t)$ and get $E_0(-t+t_0) = E_{0m}(t-t_0)$ and write Eq. 11 as follows.

$$G(\omega) = \int_{-\infty}^0 E_0(t+t_0)e^{-2\sigma t} e^{-i\omega t} dt + \int_{-\infty}^0 E_{0m}(t-t_0)e^{i\omega t} dt = G_R(\omega) + iG_I(\omega) \tag{12}$$

The above equations can be expanded as follows using the identity $e^{i\omega t} = \cos(\omega t) + i\sin(\omega t)$. Comparing the **imaginary parts** of $G(\omega)$, we have

$$G_I(\omega) = - \int_{-\infty}^0 E_0(t+t_0)e^{-2\sigma t} \sin(\omega t) dt + \int_{-\infty}^0 E_{0m}(t-t_0) \sin(\omega t) dt \tag{13}$$

We require $G_I(\omega) = 0$ for $\omega = \omega_2(t_0)$ for every value of t_0 , to satisfy **Statement 1**. Hence we can see that $R(t_0) = -G_I(\omega_2(t_0)) = 0$ and we can write as follows using $t = \tau$.

$$R(t_0) = \int_{-\infty}^0 [E_0(\tau+t_0)e^{-2\sigma\tau} - E_{0m}(\tau-t_0)] \sin(\omega_2(t_0)\tau) d\tau = 0 \tag{14}$$

We can rewrite Eq. 14 as follows, using the substitution $\tau+t_0 = \tau'$ in the first integral and $\tau-t_0 = \tau''$ in the second integral and substituting back $\tau' = \tau$ and $\tau'' = \tau$.

$$\begin{aligned}
R(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\
&\quad - [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_{0m}(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_{0m}(\tau) \cos(\omega_2(t_0)\tau) d\tau] = 0
\end{aligned} \tag{15}$$

Now we replace t_0 by $-t_0$ in $f(t)$ and consider the function $f_2(t) = e^{-\sigma t_0} E_p(t-t_0)$ where $|t_0| \leq \infty$ and use the procedure in above section and we can write as follows.

$$\begin{aligned}
R(-t_0) &= \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_2(-t_0)\tau) d\tau = 0 \\
R(t_0) + R(-t_0) &= \int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega_2(t_0)\tau) d\tau \\
&\quad + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_2(-t_0)\tau) d\tau = 0
\end{aligned} \tag{16}$$

2.3. $\omega_2(t_0)$ is an even function of variable t_0

Now we consider the function $f_T(t) = f(t) + f_2(t) = e^{\sigma t_0} E_p(t + t_0) + e^{-\sigma t_0} E_p(t - t_0)$ where $|t_0| \leq \infty$ and $g_T(t)h(t) = f_T(t)$ where $g_T(t) = f_T(t)e^{-\sigma t}u(-t) + f_T(t)e^{\sigma t}u(t)$ and $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$ and compute the Fourier transform of the function $g_T(t)$ and compute its imaginary part using the procedure in above section, similar to Eq. 13 and we can write as follows. We use $E_0(-\tau) = E_0(\tau)$.

$$\begin{aligned}
G_{T_I}(\omega, t_0) &= G_1(\omega, t_0) + G_1(\omega, -t_0) \\
G_1(\omega, t_0) &= - \int_{-\infty}^0 E_0(t + t_0)e^{-2\sigma t} \sin(\omega t) dt + \int_{-\infty}^0 E_{0m}(t - t_0) \sin(\omega t) dt \\
G_{T_I}(\omega, t_0) &= - \left[\int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega\tau) d\tau \right]
\end{aligned} \tag{17}$$

We require $G_{T_I}(\omega, t_0) = 0$ for $\omega = \omega_0(t_0)$ for every value of t_0 , to satisfy **Statement 1**. In general $\omega_0(t_0) \neq \omega_2(t_0)$. Hence we can see that $P(t_0) = -G_{T_I}(\omega_0(t_0)) = 0$ and we can rewrite as follows using the substitution $t = \tau$.

$$P(t_0) = \int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega_0(t_0)\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_0(t_0)\tau) d\tau = 0 \tag{18}$$

We see that $f_T(t) = e^{\sigma t_0} E_p(t + t_0) + e^{-\sigma t_0} E_p(t - t_0)$ is **unchanged** by the substitution $t_0 = -t_0$ and hence $\omega_0(t_0)$ is an **even** function of variable t_0 . Hence we can rewrite the second integral in Eq. 18 as follows using $\omega_0(t_0) = \omega_0(-t_0)$.

$$\int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega_0(t_0)\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_0(-t_0)\tau) d\tau = 0 \tag{19}$$

We compare Eq. 19 and Eq. 16 as follows.

$$\begin{aligned}
&\int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega_0(t_0)\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_0(-t_0)\tau) d\tau = 0 \\
&\int_{-\infty}^0 [E_0(\tau + t_0)e^{-2\sigma\tau} - E_{0m}(\tau - t_0)] \sin(\omega_2(t_0)\tau) d\tau + \int_{-\infty}^0 [E_0(\tau - t_0)e^{-2\sigma\tau} - E_{0m}(\tau + t_0)] \sin(\omega_2(-t_0)\tau) d\tau = 0
\end{aligned} \tag{20}$$

We can see that there must be **at least one** common solution where $\omega_2(t_0) = \omega_0(t_0)$ to satisfy Eq. 20. Because $\omega_0(t_0)$ is an **even** function of variable t_0 , we see that $\omega_2(t_0) = \omega_0(t_0)$ is also an **even** function of variable t_0 .

The results in this section apply **only** for the case $0 < \sigma < \frac{1}{2}$. For $\sigma = 0$, $g_T(t) = E_0(t + t_0) + E_0(t - t_0)$ is an even function of variable t_0 and $2g_{T_{odd}}(t) = g_T(t) - g_T(-t) = 0$ and hence $G_{T_I}(\omega) = 0$ for all $|\omega| \leq \infty$.

3. Alternate Method 6

We define $A(t_0) = e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau]$ and $B(t_0) = \cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ and we write $R(t_0) = A(t_0) - B(-t_0) = 0$ in Eq. 15 as follows. We use $E_{0m}(\tau) = E_0(-\tau) = E_0(\tau)$.

$$\begin{aligned} R(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &- [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] = A(t_0) - B(-t_0) = 0 \end{aligned} \quad (21)$$

We use $\int_{-\infty}^{t_0} = \int_{-\infty}^{-t_0} + \int_{-t_0}^{t_0}$ in the first term and $\int_{-\infty}^{-t_0} = \int_{-\infty}^{t_0} - \int_{-t_0}^{t_0}$ in the second term in Eq. 21 and write as follows.

$$\begin{aligned} R(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &+ e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &- [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \\ &+ [\cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] = 0 \end{aligned} \quad (22)$$

Next, we define $X(t_0) = X_1(t_0) - X_2(t_0)$ as follows. We replace the integral $\int_{-\infty}^{t_0}$ in Eq. 21 with the integral $\int_{-\infty}^{\infty}$ and we replace the integral $\int_{-\infty}^{-t_0}$ in Eq. 21 with the integral $\int_{t_0}^{\infty}$ as follows.

$$\begin{aligned} X(t_0) &= X_1(t_0) - X_2(t_0) \\ X_1(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-t_0}^{\infty} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-t_0}^{\infty} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ X_2(t_0) &= [\cos(\omega_2(t_0)t_0) \int_{t_0}^{\infty} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{t_0}^{\infty} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \end{aligned} \quad (23)$$

The integrals in Eq. 23 converge because $\int_{-\infty}^{\infty} |E_0(\tau) e^{-2\sigma\tau}| d\tau$ converges for $|\sigma| < \frac{1}{2}$ (Appendix C.1).

We add $R(t_0) = 0$ in Eq. 22 with $X(t_0)$ in Eq. 23 as follows. We use $\int_{-\infty}^{-t_0} + \int_{-t_0}^{\infty} = \int_{-\infty}^{\infty}$ and $\int_{-\infty}^{t_0} + \int_{t_0}^{\infty} = \int_{-\infty}^{\infty}$.

$$\begin{aligned} X(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &+ e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &- [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \\ &+ [\cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \end{aligned}$$

We use $e^{-2\sigma\tau} = \cosh(2\sigma\tau) - \sinh(2\sigma\tau)$ in the integrals $\int_{-t_0}^{t_0}$ in Eq. 24 and note that $\int_{-t_0}^{t_0} E_0(\tau) \sinh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau = 0$ and $\int_{-t_0}^{t_0} E_0(\tau) \cosh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$ because the integrands are **odd** functions of variable τ .

Given that $E_0(\tau) = E_0(-\tau)$, we see that $E_0(\tau) \sin(\omega_2(t_0)\tau)$ is an **odd** function of variable τ and $\int_{-\infty}^{\infty} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$ and $\int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$.

Given that $E_0(\tau) \cos(\omega_2(t_0)\tau)$ is an **even** function of variable τ , we can write $\int_{-\infty}^{\infty} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 2 \int_{-\infty}^0 E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ and $\int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 2 \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ as follows.

$$\begin{aligned} X(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &+ e^{2\sigma t_0} [-2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad - 2 \sin(\omega_2(t_0)t_0) \int_{-\infty}^0 E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + 2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \end{aligned} \quad (25)$$

We compute $X_3(t_0) = X(t_0)e^{-2\sigma t_0}$ as follows.

$$\begin{aligned} X_3(t_0) &= X(t_0)e^{-2\sigma t_0} = \cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau \\ &+ [-2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad - 2 \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-\infty}^0 E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + 2 \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \end{aligned} \quad (26)$$

3.1. Another expression for $X(t_0)$

We use $\int_{-t_0}^{\infty} = \int_{-\infty}^{\infty} - \int_{-\infty}^{-t_0}$ in the integrals in $X_1(t_0)$ and $\int_{t_0}^{\infty} = \int_{-\infty}^{\infty} - \int_{-\infty}^{-t_0}$ in the integrals in $X_2(t_0)$ in Eq. 23 as follows.

$$\begin{aligned} X(t_0) &= X_1(t_0) - X_2(t_0) \\ X(t_0) &= e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad - e^{2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad - [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \\ &\quad + [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau] \end{aligned} \quad (27)$$

We compute $X_4(t_0) = X(t_0)e^{-2\sigma t_0}$ and use $\int_{-\infty}^{\infty} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$ because the integrand is an **odd** function of variable t_0 , and we use $\int_{-\infty}^{\infty} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 2 \int_{-\infty}^0 E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ because the integrand is an **even** function of variable t_0 , as follows.

$$\begin{aligned}
X_4(t_0) &= X(t_0)e^{-2\sigma t_0} = [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau)d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{\infty} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau)d\tau] \\
&\quad - [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau)d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau)d\tau] \\
&\quad - e^{-2\sigma t_0} [2 \sin(\omega_2(t_0)t_0) \int_{-\infty}^0 E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau] \\
&\quad + e^{-2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau)d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau]
\end{aligned} \tag{28}$$

We compare Eq. 26 and Eq. 28 and cancel out common terms as follows.

$$\begin{aligned}
X_5(t_0) &= -2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau)d\tau - 2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau)d\tau \\
&\quad + 2 \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau \\
&= -[\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau)d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau)d\tau] \\
&\quad + e^{-2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau)d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau]
\end{aligned} \tag{29}$$

We compute the **even part** of $X_5(t_0)$ given by $X_6(t_0) = \frac{1}{2}[X_5(t_0) + X_5(-t_0)]$ as follows. The term $-2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau)d\tau$ is an **odd** function of variable t_0 and is omitted. We note that $2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau)d\tau$ is an **even** function of variable t_0 and the term $-2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau$ is an **even** function of variable t_0 . Hence the even part of $2 \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau$ is given by $2 \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau$. We use $\omega_2(-t_0) = \omega_2(t_0)$.

$$\begin{aligned}
X_6(t_0) &= -2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau)d\tau + 2 \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau \\
&= -\frac{1}{2} \cos(\omega_2(t_0)t_0) [\int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau)d\tau + \int_{-\infty}^{t_0} E_0(\tau)e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau)d\tau] \\
&\quad + \frac{1}{2} \sin(\omega_2(t_0)t_0) [\int_{-\infty}^{-t_0} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau)d\tau - \int_{-\infty}^{t_0} E_0(\tau)e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau)d\tau] \\
&\quad + \frac{1}{2} \cos(\omega_2(t_0)t_0) [e^{-2\sigma t_0} \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau)d\tau + e^{2\sigma t_0} \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau)d\tau] \\
&\quad + \frac{1}{2} \sin(\omega_2(t_0)t_0) [e^{-2\sigma t_0} \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau - e^{2\sigma t_0} \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau)d\tau]
\end{aligned} \tag{30}$$

We use $\int_{-\infty}^{t_0} = \int_{-\infty}^{-t_0} + \int_{-t_0}^{t_0}$ in the right hand side of Eq. 42 and cancel common terms as follows.

$$\begin{aligned}
X_6(t_0) &= -2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau + 2 \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \frac{1}{2} \cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau \\
&\quad - \frac{1}{2} \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau \\
&\quad + \cos(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \cos(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \\
&\quad - \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau
\end{aligned} \tag{31}$$

We use $\int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$ and $\int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 2 \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ and see that the term $\frac{1}{2} \cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau = -\cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau$ is an **odd** function of variable t_0 which is **omitted** because we are considering only the even terms in $X_6(t_0)$.

We note that the term $\frac{1}{2} \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau = \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau$.

$$\begin{aligned}
X_6(t_0) &= -2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau + 2 \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&\quad + \cos(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \\
&\quad - \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau
\end{aligned} \tag{32}$$

We can simplify as follows, consolidating the terms $\int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau$ on both sides of Eq. 32.

$$\begin{aligned}
X_6(t_0) &= -\sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau + 2 \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau + \cos(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \\
&\quad - \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau
\end{aligned} \tag{33}$$

In Section 3.2, it is shown that there **exists** a value of $t_0 = t_1 > 0$ for which $\omega_2(t_1)t_1 = \frac{\pi}{2}$. We **set** $\omega_2(t_1)t_1 = \pi$ in Eq. 33 and we get $\cos(\omega_2(t_1)t_1) = -1$ and $\sin(\omega_2(t_1)t_1) = 0$.

$$\int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = \cosh(2\sigma t_1) \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau \tag{34}$$

Now we set $t_0 = -t_1$ in Eq. 21 such that $\omega_2(-t_1)(-t_1) = -\pi$, using $\omega_2(-t_1) = \omega_2(t_1)$, as follows.

$$e^{-2\sigma t_1} \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = \int_{-\infty}^{t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau$$

(35)

We see that $\int_{-\infty}^{t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau + \int_{-t_1}^{t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau$ because $E_0(\tau) \sin(\omega_2(t_1)\tau)$ is an **odd** function of variable t_1 . Hence we can write Eq. 35 as follows.

$$e^{-2\sigma t_1} \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau \quad (36)$$

Now we multiply Eq. 34 by $e^{-2\sigma t_1}$ and then compare it with Eq. 36 and equate the right hand sides of both equations as follows.

$$\begin{aligned} e^{-2\sigma t_1} \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= e^{-2\sigma t_1} \cosh(2\sigma t_1) \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau \\ e^{-2\sigma t_1} \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau \\ e^{-2\sigma t_1} \cosh(2\sigma t_1) \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau &= \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau \end{aligned} \quad (37)$$

In Section 3.3, it is shown that the integral $\int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau > 0$. Hence we can cancel the term $\int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau$ on both sides of Eq. 37 and write as follows.

$$\begin{aligned} e^{-2\sigma t_1} \cosh(2\sigma t_1) &= 1 \\ \frac{1}{2} e^{-2\sigma t_1} [e^{2\sigma t_1} + e^{-2\sigma t_1}] &= 1 \\ \frac{1}{2} + \frac{1}{2} e^{-2\sigma t_1} &= 1 \\ e^{-2\sigma t_1} &= 1 \end{aligned} \quad (38)$$

We see that Eq. 38 is possible only for $\sigma = 0$, for $t_1 > 0$ such that $\omega_2(t_1)t_1 = \frac{\pi}{2}$. The result derived in Eq. 38 leads to a **contradiction** for $0 < \sigma < \frac{1}{2}$.

We have shown this result for $0 < \sigma < \frac{1}{2}$ and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$. Hence we have produced a **contradiction** of **Statement 1** that the Fourier Transform of the function $E_p(t) = E_0(t)e^{-\sigma t}$ has a zero at $\omega = \omega_0$ for $0 < |\sigma| < \frac{1}{2}$.

Therefore, the assumption in **Statement 1** that Riemann's Xi Function given by $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$, where ω_0 is real and finite, leads to a **contradiction** for the region $0 < |\sigma| < \frac{1}{2}$ which corresponds to the critical strip excluding the critical line. This means $\zeta(s)$ does not have non-trivial zeros in the critical strip excluding the critical line and we have proved Riemann's Hypothesis.

3.1.1. Alternate proof for Even $X_4(t_0)$

If $\int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = 0$ for the case $\omega_2(t_1)t_1 = \frac{\pi}{2}$, then we can write Eq. 36 as follows.

$$\begin{aligned} e^{-2\sigma t_1} \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = 0 \\ \int_{\mathbb{R}^\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= 0 \end{aligned}$$

(39)

Now we set $t_0 = t_1$ in Eq. ?? such that $\omega_2(t_1)(t_1) = \pi$ and use the result $\int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = 0$ as follows.

$$\begin{aligned} e^{2\sigma t_1} \int_{-\infty}^{t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= \int_{-\infty}^{-t_1} E_0(\tau) \sin(\omega_2(t_1)\tau) d\tau = 0 \\ \int_{-\infty}^{t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= 0 \end{aligned}$$

(40)

Now we split the integral and use the results in Eq. ?? and Eq. ?? and simplify as follows.

$$\begin{aligned} \int_{-\infty}^{t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= \int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau + \int_{-t_1}^{t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = 0 \\ \int_{-t_1}^{t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau &= 0 \end{aligned}$$

(41)

We use $e^{-2\sigma\tau} = \cosh(2\sigma\tau) - \sinh(2\sigma\tau)$ and use $\int_{-t_1}^{t_1} E_0(\tau) \cosh(2\sigma\tau) \sin(\omega_2(t_1)\tau) d\tau = 0$ because the integrand is an **odd** function of variable t_0 .

$$\begin{aligned} - \int_{-t_1}^{t_1} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_1)\tau) d\tau &= 0 \\ -2 \int_0^{t_1} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_1)\tau) d\tau &= 0 \\ \int_0^{t_1} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_1)\tau) d\tau &= 0 \end{aligned}$$

(42)

For $0 < \sigma < \frac{1}{2}$, we see that the **each** of the terms in the integrand in Eq. ?? are **greater than or equal to zero**, in the interval $\tau = [0, t_1]$ where $t_1 > 0$. For $\omega_2(t_1)t_1 = \pi$, $\omega_2(t_1)\tau = \frac{\pi}{t_1}\tau$ lies in the range $[0, \pi]$ and hence $\sin(\omega_2(t_1)\tau) \geq 0$ in that interval $\tau = [0, t_1]$. Hence the integral in Eq. ?? is **greater than zero** for $0 < \sigma < \frac{1}{2}$.

For $\sigma = 0$, Eq. ?? **does not** lead to a contradiction.

We have shown this result for $0 < \sigma < \frac{1}{2}$ and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$. Hence we have produced a **contradiction** of **Statement 1** that the Fourier Transform of the function $E_p(t) = E_0(t)e^{-\sigma t}$ has a zero at $\omega = \omega_0$ for $0 < |\sigma| < \frac{1}{2}$.

Therefore, the assumption in **Statement 1** that Riemann's Xi Function given by $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$, where ω_0 is real and finite, leads to a **contradiction** for the region $0 < |\sigma| < \frac{1}{2}$ which corresponds to the critical strip excluding the critical line. This means $\zeta(s)$ does not have non-trivial zeros in the critical strip excluding the critical line and we have proved Riemann's Hypothesis.

3.2. **Existence of** $\omega_2(t_0)t_0 = \pi$

We consider the case $\omega_2(t_0)t_0 \neq \pi$. In this case, we consider the **"t" scaled** function $E_{pr}(t) = E_p(Rt)$ whose Fourier transform $E_{pr\omega}(\omega) = \frac{1}{R}E_{p\omega}(\frac{\omega}{R})$ has a real zero at $\omega = R\omega_0$ and $\sigma_r = R\sigma$. We consider $f_r(t) = E_{pr}(t + t_0)$ and see that $G_{rR}(\omega)$ has a real zero at $\omega = \omega_{2r}(t_0) = R\omega_2(t_0)$ and we can derive similar results in earlier sections as follows. We use $E_{0m}(\tau) = E_0(-\tau) = E_0(\tau)$. ((link))

$$\begin{aligned}
R_r(t_0) &= e^{2\sigma_r t_0} [\sin(\omega_{2r}(t_0)t_0) \int_{-\infty}^{t_0} E_{0r}(\tau) e^{-2\sigma_r \tau} \cos(\omega_{2r}(t_0)\tau) d\tau - \cos(\omega_{2r}(t_0)t_0) \int_{-\infty}^{t_0} E_{0r}(\tau) e^{-2\sigma_r \tau} \sin(\omega_{2r}(t_0)\tau) d\tau] \\
&\quad - [-\sin(\omega_{2r}(t_0)t_0) \int_{-\infty}^{-t_0} E_{0r}(\tau) \cos(\omega_{2r}(t_0)\tau) d\tau - \cos(\omega_{2r}(t_0)t_0) \int_{-\infty}^{-t_0} E_{0r}(\tau) \sin(\omega_{2r}(t_0)\tau) d\tau] = 0 \\
R_r(t_0) &= e^{2R\sigma t_0} [\sin(R\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(R\tau) e^{-2R\sigma \tau} \cos(R\omega_2(t_0)\tau) d\tau - \cos(R\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(R\tau) e^{-2R\sigma \tau} \sin(R\omega_2(t_0)\tau) d\tau] \\
&\quad - [-\sin(R\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(R\tau) \cos(R\omega_2(t_0)\tau) d\tau - \cos(R\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(R\tau) \sin(R\omega_2(t_0)\tau) d\tau] = 0
\end{aligned} \tag{43}$$

In this case, we can choose R such that $\omega_{2r}(t_0) = R\omega_2(t_0)t_0 = \pi$ in Eq. 43 and get $\cos(R\omega_2(t_0)t_0) = -1$ and $\sin(R\omega_2(t_0)t_0) = 0$ and derive the results in previous section.

$$R_r(t_0) = e^{2\sigma_r t_0} \int_{-\infty}^{t_0} E_{0r}(\tau) e^{-2\sigma_r \tau} \cos(\omega_{2r}(t_0)\tau) d\tau + \int_{-\infty}^{-t_0} E_{0r}(\tau) \cos(\omega_{2r}(t_0)\tau) d\tau = 0 \tag{44}$$

3.3. **Show that** $\int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau < 0$

It is well known that $E_0(t) = \Phi(t)$ is positive for $t > 0$ and its first derivative is negative for $t > 0$ and hence $E_0(t)$ is a **strictly decreasing** function for $t > 0$. (link and link) We rederive this result below.

We start with the equation for $E_0(t)$ and substitute $x = e^{2t}$ and take the first derivative with respect to x , as follows.

$$\begin{aligned}
 E_0(t) = \Phi(t) &= 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} = \sum_{n=1}^{\infty} [4\pi^2 n^4 e^{2t} - 6\pi n^2] e^{-\pi n^2 e^{2t}} e^{\frac{5t}{2}} = D(e^{2t}) e^{\frac{5t}{2}} \\
 D(x) &= \sum_{n=1}^{\infty} [4\pi^2 n^4 x - 6\pi n^2] e^{-\pi n^2 x} = \sum_{n=1}^{\infty} 2\pi n^2 [2\pi n^2 x - 3] e^{-\pi n^2 x} \\
 \frac{dD(x)}{dx} &= \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 x} [2\pi n^2 - \pi n^2 (2\pi n^2 x - 3)] = \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 x} [5\pi n^2 - 2\pi^2 n^4 x] = \sum_{n=1}^{\infty} 2\pi^2 n^4 e^{-\pi n^2 x} [5 - 2\pi n^2 x]
 \end{aligned} \tag{45}$$

We see that the term $(2\pi n^2 x - 3) > 0$ and hence $D(x) > 0$, for $x \geq 1$ and for all $n = 1, 2, \dots$

We see that the term $(5 - 2\pi n^2 x) < 0$ and hence $\frac{dD(x)}{dx} < 0$, for $x \geq 1$ and for all $n = 1, 2, \dots$

If $x = e^{2t}$, then $\frac{dx}{dt} = 2e^{2t} > 0$ for $x \geq 1$. Using chain rule with derivatives, we see that $\frac{dD(e^{2t})}{dt} = \frac{dD(x)}{dx} \frac{dx}{dt} < 0$ for all $t \geq 0$.

For $t < 0$, we see that $\frac{dD(e^{2t})}{dt} > 0$ and $D(e^{2t})$ is a **strictly increasing** function for $t < 0$. Now we consider $E_a(t) = E_0(t) e^{-2\sigma t} = D(e^{2t}) e^{(\frac{5}{2} - 2\sigma)t}$ and we see that, for $0 < \sigma < \frac{1}{2}$, $E_a(t)$ is a **strictly increasing** function for $t < 0$.

Now we consider $\int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau$ for $\omega_2(t_1)t_1 = \pi$, we can show that this integral is less than zero. Let $F(t) = D(e^{2t})$.

$$\int_{-\infty}^{-t_1} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = \int_{-\infty}^{-t_1} F(\tau) e^{\frac{5}{2}\tau} e^{-2\sigma\tau} \sin(\omega_2(t_1)\tau) d\tau = - \int_{t_1}^{\infty} F(-\tau) e^{-(\frac{5}{2} - 2\sigma)\tau} \sin(\omega_2(t_1)\tau) d\tau \tag{46}$$

$$E_0(t) = \Phi(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} = \sum_{n=1}^{\infty} [4\pi^2 n^4 e^{2t} - 6\pi n^2] e^{-\pi n^2 e^{2t}} e^{\frac{5t}{2}} = D(e^{2t})$$

$$D(x) = \sum_{n=1}^{\infty} [4\pi^2 n^4 x - 6\pi n^2] e^{-\pi n^2 x} x^{\frac{5}{4}} = \sum_{n=1}^{\infty} 2\pi n^2 [2\pi n^2 x - 3] e^{-\pi n^2 x} x^{\frac{5}{4}}$$

$$\begin{aligned} \frac{dD(x)}{dx} &= \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 x} x^{\frac{5}{4}} [2\pi n^2 + (2\pi n^2 x - 3)(-\pi n^2 + \frac{5}{4} x^{\frac{1}{4}})] \\ &= \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 x} x^{\frac{5}{4}} [5\pi n^2 - 2\pi^2 n^4 x + 2\pi n^2 \frac{5}{4} x^{\frac{5}{4}} - 3\frac{5}{4} x^{\frac{1}{4}}] \\ &\quad \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 x} x^{\frac{5}{4}} [5\pi n^2 + 2\pi n^2 \frac{5}{4} x^{\frac{5}{4}} - 2\pi^2 n^4 x - 3\frac{5}{4} x^{\frac{1}{4}}] \end{aligned}$$

(47)

For $x = 1$ and for all $n = 1$, we see that the term $5\pi n^2 + 2\pi n^2 \frac{5}{4} x^{\frac{5}{4}} - 2\pi^2 n^4 x - 3\frac{5}{4} x^{\frac{1}{4}} = 5\pi + \pi \frac{5}{2} - 2\pi^2 - \frac{15}{4} < 0$. Now we consider the first derivative of $E_0(t)e^{-2\sigma t}$ as follows.

$$\begin{aligned} E_a(t) &= E_0(t)e^{-2\sigma t} = D(e^{2t})e^{(\frac{5}{2}-2\sigma)t} \\ \frac{dE_a(t)}{dt} &= e^{(\frac{5}{2}-2\sigma)t} \left[\frac{dD(e^{2t})}{dt} + D(e^{2t})\left(\frac{5}{2} - 2\sigma\right) \right] \end{aligned}$$

(48)

We have shown that $D(e^{2t}) > 0$ and $\frac{dD(e^{2t})}{dt} < 0$ for $t > 0$ and we see that, for $0 < \sigma < \frac{1}{2}$, $D(e^{2t})(\frac{5}{2} - 2\sigma) > 0$. Hence $\frac{dE_a(t)}{dt} > 0$ for $t > 0$.

4. Odd Part

We compare Eq. 26 and Eq. 28 and cancel out common terms as follows.

$$\begin{aligned}
X_5(t_0) &= -2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&\quad + 2 \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -[\cos(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau] \\
&\quad + e^{-2\sigma t_0} [\cos(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau]
\end{aligned} \tag{49}$$

We compute the **odd part** of $X_5(t_0)$ given by $X_6(t_0) = \frac{1}{2}[X_5(t_0) - X_5(-t_0)]$ as follows. The term $2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau$ is an **even** function of variable t_0 and is omitted. We note that $-2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau$ is an **odd** function of variable t_0 and the term $2 \sin(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau$ is an **even** function of variable t_0 . We use $\omega_2(-t_0) = \omega_2(t_0)$.

$$\begin{aligned}
X_6(t_0) &= -2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -\frac{1}{2} \cos(\omega_2(t_0)t_0) \left[\int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau - \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau \right] \\
&\quad + \frac{1}{2} \sin(\omega_2(t_0)t_0) \left[\int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau + \int_{-\infty}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau \right] \\
&\quad + \frac{1}{2} \cos(\omega_2(t_0)t_0) \left[e^{-2\sigma t_0} \int_{-\infty}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau - e^{2\sigma t_0} \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \right] \\
&\quad + \frac{1}{2} \sin(\omega_2(t_0)t_0) \left[e^{-2\sigma t_0} \int_{-\infty}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + e^{2\sigma t_0} \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \right]
\end{aligned} \tag{50}$$

We use $\int_{-\infty}^{t_0} = \int_{-\infty}^{-t_0} + \int_{-t_0}^{t_0}$ and cancel common terms as follows.

$$\begin{aligned}
X_6(t_0) &= -2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= \frac{1}{2} \cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau \\
&\quad + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau \\
&\quad - \cos(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \cos(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \\
&\quad + \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau
\end{aligned} \tag{51}$$

We use $\int_{-t_0}^{t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau = 0$ and see that the term $\frac{1}{2} \cos(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \sin(\omega_2(t_0)\tau) d\tau = -\cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau$ as follows.

We note that the term $\frac{1}{2} \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau = 2 \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \cosh(2\sigma\tau) \cos(\omega_2(t_0)\tau) d\tau$ is an **even** function of variable t_0 which is **omitted** because we are considering only the odd terms.

$$\begin{aligned}
X_6(t_0) &= -2 \cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau - 2 \sin(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&= -\cos(\omega_2(t_0)t_0) \int_0^{t_0} E_0(\tau) \sinh(2\sigma\tau) \sin(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) e^{-2\sigma\tau} \cos(\omega_2(t_0)\tau) d\tau \\
&\quad - \cos(\omega_2(t_0)t_0) \sinh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \sin(\omega_2(t_0)\tau) d\tau \\
&\quad + \sin(\omega_2(t_0)t_0) \cosh(2\sigma t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \frac{1}{2} \sin(\omega_2(t_0)t_0) e^{-2\sigma t_0} \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau
\end{aligned} \tag{52}$$

We consider the case $\sigma = 0$ in Eq. 53.

$$\begin{aligned}
X_6(t_0) &= \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \sin(\omega_2(t_0)t_0) \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&\quad + \frac{1}{2} \sin(\omega_2(t_0)t_0) \int_{-t_0}^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 0
\end{aligned} \tag{53}$$

For $\sin(\omega_2(t_0)t_0) \neq 0$, we can write as follows.

$$\begin{aligned}
X_6(t_0) &= \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau + \int_{-\infty}^{-t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau \\
&\quad + \int_0^{t_0} E_0(\tau) \cos(\omega_2(t_0)\tau) d\tau = 0
\end{aligned} \tag{54}$$

5. Hurwitz Zeta Function and related functions

We can show that the new method is **not** applicable to Hurwitz zeta function and related zeta functions and **does not** contradict the existence of their non-trivial zeros away from the critical line with real part of $s = \frac{1}{2}$. The new method requires the **symmetry** relation $\xi(s) = \xi(1-s)$ and hence $\xi(\frac{1}{2} + i\omega) = \xi(\frac{1}{2} - i\omega)$ when evaluated at the critical line $s = \frac{1}{2} + i\omega$. This means $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega) = E_{0\omega}(-\omega)$ and $E_0(t) = E_0(-t)$ where $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ and this condition is satisfied for Riemann's Zeta function.

It is **not** known that Hurwitz Zeta Function given by $\zeta(s, a) = \sum_{m=0}^{\infty} \frac{1}{(m+a)^s}$ satisfies a symmetry relation similar to $\xi(s) = \xi(1-s)$ where $\xi(s)$ is an entire function, for $a \neq 1$ and hence the condition $E_0(t) = E_0(-t)$ is **not** known to be satisfied^[6]. Hence the new method is **not** applicable to Hurwitz zeta function and **does not** contradict the existence of their non-trivial zeros away from the critical line.

Dirichlet L-functions satisfy a symmetry relation $\xi(s, \chi) = \epsilon(\chi) \xi(1-s, \bar{\chi})$ ^[7] which does **not** translate to $E_0(t) = E_0(-t)$ required by the new method and hence this proof is **not** applicable to them.

We know that $\zeta(s) = \sum_{m=1}^{\infty} \frac{1}{m^s}$ diverges for real part of $s \leq 1$. Hence we derive a convergent and entire function $\xi(s)$ using the well known theorem $F(x) = 1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2 x} = \frac{1}{\sqrt{x}} (1 + 2 \sum_{n=1}^{\infty} e^{-\pi \frac{n^2}{x}})$, where $x > 0$ is real and then derive $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ (Appendix E). In the case of **Hurwitz zeta** function and **other zeta functions** with non-trivial zeros away from the critical line, it is **not** known if a corresponding relation similar to $F(x)$ exists, which enables derivation of a convergent and entire function $\xi(s)$ and results in $E_0(t)$ as a Fourier transformable, real, even and analytic function. Hence the new method presented in this paper is **not** applicable to Hurwitz zeta function and related zeta functions.

The proof of Riemann Hypothesis presented in this paper is **only** for the specific case of Riemann's Zeta function and **only** for the **critical strip** $0 \leq |\sigma| < \frac{1}{2}$. This proof requires both $E_p(t)$ and $E_{p\omega}(\omega)$ to be Fourier transformable where $E_p(t) = E_0(t)e^{-\sigma t}$ is a real analytic function. These conditions may **not** be satisfied for many other functions including those which have non-trivial zeros away from the critical line and hence the new method may **not** be applicable to such functions.

If the proof presented in this paper is internally consistent and does not have mistakes and gaps, then it should be considered correct, **regardless** of whether it contradicts any previously known external theorems, because it is possible that those previously known external theorems may be incorrect.

References

- [1] Bernhard Riemann, On the Number of Prime Numbers less than a Given Quantity.(Ueber die Anzahl der Primzahlen untereiner gegebenen Grosse.) Monatsberichte der Berliner Akademie, November 1859. (Link to Riemann's 1859 paper)
- [2] Hardy, G.H., Littlewood, J.E. The zeros of Riemann's zeta-function on the critical line. Mathematische Zeitschrift volume 10, pp.283 to 317 (1921).
- [3] E. C. Titchmarsh, The Theory of the Riemann Zeta Function. (1986) pp.254 to 255
- [4] Fern Ellison and William J. Ellison, Prime Numbers (1985).pp147 to 152
- [5] J. Brian Conrey, The Riemann Hypothesis (2003). (Link to Brian Conrey's 2003 article)
- [6] Mathworld article on Hurwitz Zeta functions. (Link)
- [7] Wikipedia article on Dirichlet L-functions. (Link)

Appendix A. Derivation of $E_p(t)$

Let us start with Riemann's Xi Function $\xi(s)$ evaluated at $s = \frac{1}{2} + i\omega$ given by $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega)$. Its inverse Fourier Transform is given by $E_0(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega) e^{i\omega t} d\omega = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ (link). This is re-derived in Appendix E.

We will show in this section that the inverse Fourier Transform of the function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$, is given by $E_p(t) = E_0(t) e^{-\sigma t}$ where $0 \leq |\sigma| < \frac{1}{2}$ is real.

$$\begin{aligned} \xi(\frac{1}{2} + \sigma + i\omega) &= \xi(\frac{1}{2} + i(\omega - i\sigma)) = E_{p\omega}(\omega) = E_{0\omega}(\omega - i\sigma) \\ E_p(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega) e^{i\omega t} d\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega - i\sigma) e^{i\omega t} d\omega \end{aligned} \tag{A.1}$$

We substitute $\omega' = \omega - i\sigma$ in Eq. A.1 as follows.

$$E_p(t) = e^{-\sigma t} \frac{1}{2\pi} \int_{-\infty - i\sigma}^{\infty - i\sigma} E_{0\omega}(\omega') e^{i\omega' t} d\omega' \tag{A.2}$$

We can evaluate the above integral in the complex plane using contour integration, substituting $\omega' = z = x + iy$ and we use a rectangular contour comprised of C_1 along the line $x = [-\infty, \infty]$, C_2 along the line $y = [\infty, \infty - i\sigma]$, C_3 along the line $x = [\infty - i\sigma, -\infty - i\sigma]$ and then C_4 along the line $y = [-\infty - i\sigma, -\infty]$. We can see that $E_{0\omega}(z) = \xi(\frac{1}{2} + iz)$ has no singularities in the region bounded by the contour because $\xi(\frac{1}{2} + iz)$ is an entire function in the Z-plane.

In **Appendix C.1**, we show that $\int_{-\infty}^{\infty} |E_p(t)| dt$ is finite and $E_p(t) = E_0(t) e^{-\sigma t}$ is an absolutely integrable function, for $0 \leq |\sigma| < \frac{1}{2}$.

We use the fact that $E_{0\omega}(z) = \xi(\frac{1}{2} + iz) = \xi(\frac{1}{2} - y + ix) = \int_{-\infty}^{\infty} E_0(t) e^{-izt} dt = \int_{-\infty}^{\infty} E_0(t) e^{yt} e^{-ixt} dt$, **goes to zero** as $x \rightarrow \pm\infty$ when $-\sigma \leq y \leq 0$, as per Riemann-Lebesgue Lemma (link), because $E_0(t) e^{yt}$ is a absolutely integrable function in the interval $-\infty \leq t \leq \infty$. Hence the integral in Eq. A.2 **vanishes** along the contours C_2 and C_4 . Using Cauchy's Integral theroem, we can write Eq. A.2 as follows.

$$\begin{aligned} E_p(t) &= e^{-\sigma t} \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega') e^{i\omega' t} d\omega' \\ E_p(t) &= E_0(t) e^{-\sigma t} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} \end{aligned} \tag{A.3}$$

Thus we have arrived at the desired result $E_p(t) = E_0(t) e^{-\sigma t}$.

Appendix B. Properties of Fourier Transforms Part 1

In this section, some well-known properties of Fourier transforms are re-derived.

Appendix B.1. Convolution Theorem: Multiplication of $g(t)$ and $h(t)$ corresponds to convolution in Fourier transform domain

We start with the Fourier transform equation $F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt$ where $f(t) = g(t)h(t)$ and show that $F(\omega) = \frac{1}{2\pi}[G(\omega) * H(\omega)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega')H(\omega - \omega')d\omega'$ obtained by the **convolution** of the functions $G(\omega)$ and $H(\omega)$ which correspond to the Fourier transforms of $g(t)$ and $h(t)$ respectively.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt = \int_{-\infty}^{\infty} g(t)h(t)e^{-i\omega t}dt \quad (\text{B.1})$$

We use the inverse Fourier transform equation $g(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega')e^{i\omega' t}d\omega'$ and we interchange the order of integration in equations below using Fubini's theorem (link).

$$\begin{aligned} F(\omega) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} G(\omega')e^{i\omega' t}d\omega' \right] h(t)e^{-i\omega t}dt \\ F(\omega) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega') \left[\int_{-\infty}^{\infty} e^{i\omega' t} h(t)e^{-i\omega t}dt \right] d\omega' \\ F(\omega) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega') \left[\int_{-\infty}^{\infty} h(t)e^{-i(\omega - \omega')t}dt \right] d\omega' \end{aligned} \quad (\text{B.2})$$

We substitute $\int_{-\infty}^{\infty} h(t)e^{-i(\omega - \omega')t}dt = H(\omega - \omega')$ in Eq. B.2 and arrive at the convolution theorem.

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega')H(\omega - \omega')d\omega' = \int_{-\infty}^{\infty} g(t)h(t)e^{-i\omega t}dt \quad (\text{B.3})$$

Appendix B.2. Fourier transform of Real $g(t)$

In this section, we show that the Fourier transform of a real function $g(t)$, given by $G(\omega) = G_R(\omega) + iG_I(\omega)$ has the properties given by $G_R(-\omega) = G_R(\omega)$ and $G_I(-\omega) = -G_I(\omega)$.

$$\begin{aligned} G(\omega) &= \int_{-\infty}^{\infty} g(t)e^{-i\omega t}dt = G_R(\omega) + iG_I(\omega) \\ G_R(\omega) &= \int_{-\infty}^{\infty} g(t) \cos(\omega t)dt = G_R(-\omega) \\ G_I(\omega) &= - \int_{-\infty}^{\infty} g(t) \sin(\omega t)dt = -G_I(-\omega) \end{aligned} \quad (\text{B.4})$$

Appendix B.3. Even part of $g(t)$ corresponds to real part of Fourier transform $G(\omega)$

In this section, we show that the **even part** of real function $g(t)$, given by $g_{\text{even}}(t) = \frac{1}{2}[g(t) + g(-t)]$, corresponds to **real part** of its Fourier transform $G(\omega)$. We use the fact that $G_R(-\omega) = G_R(\omega)$ and $G_I(-\omega) = -G_I(\omega)$ for a real function $g(t)$.

$$\begin{aligned} G(\omega) &= \int_{-\infty}^{\infty} g(t)e^{-i\omega t}dt = G_R(\omega) + iG_I(\omega) \\ \int_{-\infty}^{\infty} g_{\text{even}}(t)e^{-i\omega t}dt &= \int_{-\infty}^{\infty} \frac{1}{2}[g(t) + g(-t)]e^{-i\omega t}dt = \frac{1}{2}[G(\omega) + G(-\omega)] = G_R(\omega) \end{aligned} \quad (\text{B.5})$$

Appendix B.4. Odd part of $g(t)$ corresponds to imaginary part of Fourier transform $G(\omega)$

In this section, we show that the **odd part** of real function $g(t)$, given by $g_{\text{odd}}(t) = \frac{1}{2}[g(t) - g(-t)]$, corresponds to **imaginary part** of its Fourier transform $G(\omega)$. We use the fact that $G_R(-\omega) = G_R(\omega)$ and $G_I(-\omega) = -G_I(\omega)$ for a real function $g(t)$.

$$\begin{aligned} G(\omega) &= \int_{-\infty}^{\infty} g(t)e^{-i\omega t} dt = G_R(\omega) + iG_I(\omega) \\ \int_{-\infty}^{\infty} g_{\text{odd}}(t)e^{-i\omega t} dt &= \int_{-\infty}^{\infty} \frac{1}{2}[g(t) - g(-t)]e^{-i\omega t} dt = \frac{1}{2}[G(\omega) - G(-\omega)] = iG_I(\omega) \end{aligned} \tag{B.6}$$

Appendix C. Properties of Fourier Transforms Part 2

Appendix C.1. $E_p(t), h(t), g(t)$ are absolutely integrable functions and their Fourier Transforms are finite.

The inverse Fourier Transform of the function $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega)$ is given by $E_p(t) = E_0(t)e^{-\sigma t} = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega)e^{i\omega t} d\omega$. We see that $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} > 0$ for all $0 \leq t < \infty$. Given that $E_0(t) = E_0(-t)$, we see that $E_0(t) > 0$ and $E_p(t) = E_0(t)e^{-\sigma t} > 0$ for all $-\infty < t < \infty$.

As $t \rightarrow \infty$, $E_p(t)$ goes to zero, due to the term $e^{-\pi n^2 e^{2t}}$. As $t \rightarrow -\infty$, $E_p(t)$ goes to zero, because for every value of n , the term $e^{-\pi n^2 e^{2t}} e^{\frac{5t}{2}} e^{-\sigma t}$ goes to zero, for $0 \leq |\sigma| < \frac{1}{2}$. Hence $E_p(t) = E_0(t)e^{-\sigma t} = 0$ at $t = \pm\infty$ and we showed that $E_p(t) > 0$ for all $-\infty < t < \infty$. Hence $E_{p\omega}(\omega) = \int_{-\infty}^{\infty} E_p(t)e^{-i\omega t} dt$, evaluated at $\omega = 0$ **cannot** be zero. Hence $E_{p\omega}(\omega)$ **does not have a zero** at $\omega = 0$ and hence $\omega_0 \neq 0$.

Given that $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ is an entire function in the whole of s-plane, it is finite for $|\omega| \leq \infty$ and also for $\omega = 0$. Hence $\int_{-\infty}^{\infty} E_p(t) dt$ is finite. We see that $E_p(t) \geq 0$ for all $|t| \leq \infty$. Hence we can write $\int_{-\infty}^{\infty} |E_p(t)| dt$ is finite and $E_p(t)$ is an absolutely **integrable function** and its Fourier transform $E_{p\omega}(\omega)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

Let us consider a new function $g(t) = E_p(t)e^{-\sigma t}u(-t) + E_p(t)e^{\sigma t}u(t)$ where $g(t)$ is a real function of variable t and $u(t)$ is Heaviside unit step function and $0 < \sigma < \frac{1}{2}$. We can see that $g(t)h(t) = E_p(t)$ where $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$.

We can see that $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ is an absolutely **integrable function** because $\int_{-\infty}^{\infty} |h(t)| dt = \int_{-\infty}^{\infty} h(t) dt = [\int_{-\infty}^{\infty} h(t)e^{-i\omega t} dt]_{\omega=0} = [\frac{1}{\sigma - i\omega} + \frac{1}{\sigma + i\omega}]_{\omega=0} = \frac{2}{\sigma}$, is finite for $0 < \sigma < \frac{1}{2}$ and its Fourier transform $H(\omega)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

It is shown in Appendix C.4 that $E_0(t)$ and $E_0(t)e^{-2\sigma t}$ have fall-off rates **at least** $\frac{1}{t^2}$ as $|t| \rightarrow \infty$ and hence are absolutely **integrable** functions and the integrals $\int_{-\infty}^{\infty} |E_0(t)| dt < \infty$ and $\int_{-\infty}^{\infty} |E_0(t)e^{-2\sigma t}| dt < \infty$. Hence $g(t) = E_0(t)e^{-2\sigma t}u(-t) + E_0(t)u(t)$ is an absolutely **integrable function** and $\int_{-\infty}^{\infty} |g(t)| dt = \int_{-\infty}^{\infty} g(t) dt$ is finite and its Fourier transform $G(\omega)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

Appendix C.2. Convolution integral convergence

Let us consider $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ whose **first derivative is discontinuous** at $t = 0$. The second derivative of $h(t)$ given by $h_2(t)$ has a Dirac delta function $A_0\delta(t)$ where $A_0 = -2\sigma$ and its Fourier transform $H_2(\omega)$ has a constant term A_0 , corresponding to the Dirac delta function.

This means $h(t)$ is obtained by integrating $h_2(t)$ twice and its Fourier transform $H(\omega)$ has a term $-\frac{A_0}{\omega^2}$ (link) and has a **fall off rate** of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ and $\int_{-\infty}^{\infty} H(\omega) d\omega$ converges.

We see that $E_p(t) = E_0(t)e^{-\sigma t}$ where $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$.

Let us consider a new function $g(t) = E_p(t)e^{-\sigma t}u(-t) + E_p(t)e^{\sigma t}u(t)$ where $g(t)$ is a real function of variable t and $u(t)$ is Heaviside unit step function and $0 < \sigma < \frac{1}{2}$. We can see that $g(t)h(t) = E_p(t)$ where $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$.

We can see that $G(\omega), H(\omega)$ have **fall-off rate** of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ because the **first derivatives** of $g(t), h(t)$ are **discontinuous** at $t = 0$. Also, $h(t), g(t)$ are absolutely integrable functions and their Fourier Transforms are finite as shown in Appendix C.1. Hence the convolution integral below converges to a finite value for $|\omega| \leq \infty$.

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega') H(\omega - \omega') d\omega' = \frac{1}{2\pi} [G(\omega) * H(\omega)] \quad (\text{C.1})$$

Appendix C.3. **Fall off rate of Fourier Transform of functions**

Let us consider a real Fourier transformable function $P(t) = P_+(t)u(t) + P_-(t)u(-t)$ whose $(N-1)^{th}$ **derivative** is **discontinuous** at $t = 0$. The $(N)^{th}$ derivative of $P(t)$ given by $P_N(t)$ has a Dirac delta function $A_0\delta(t)$ where $A_0 = [\frac{d^{N-1}P_+(t)}{dt^{N-1}} - \frac{d^{N-1}P_-(t)}{dt^{N-1}}]_{t=0}$ and its Fourier transform $P_N(\omega)$ has a constant term A_0 , corresponding to the Dirac delta function.

This means $P(t)$ is obtained by integrating $P_N(t)$, N times and its Fourier transform $P(\omega)$ has a term $\frac{A_0}{(i\omega)^N}$ (link) and has a **fall off rate** of $\frac{1}{\omega^N}$ as $|\omega| \rightarrow \infty$.

We have shown that if the $(N-1)^{th}$ **derivative** of the function $P(t)$ is **discontinuous** at $t = 0$ then its Fourier transform $P(\omega)$ has a **fall-off rate** of $\frac{1}{\omega^N}$ as $|\omega| \rightarrow \infty$.

In Section 1.1, we showed that $E_0(t)$ is an analytic function which is infinitely differentiable which produces no discontinuities in $|t| \leq \infty$. Hence its Fourier transform $E_{0\omega}(\omega)$ has a fall-off rate faster than $\frac{1}{\omega^M}$ as $M \rightarrow \infty$, as $|\omega| \rightarrow \infty$ and it should have a fall-off rate **at least** of the order of $\omega^A e^{-B|\omega|}$ as $|\omega| \rightarrow \infty$, where $A, B > 0$ are real.

Appendix C.4. **Payley-Weiner theorem and Exponential Fall off rate of analytic functions.**

We know that Payley-Weiner theorem relates analytic functions and exponential decay rate of their Fourier transforms (link). Using similar arguments, we will show that the functions $E_0(t), E_p(t)$ and $x(t) = E_0(t)e^{-2\sigma t}$ and $\frac{d^{2r}x(t)}{dt^{2r}}$ have fall-off rates **at least** $\frac{1}{t^2}$ as $|t| \rightarrow \infty$ for $0 < \sigma < \frac{1}{2}$.

We know that the order of Riemann's Xi function $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega) = \Xi(\omega)$ is given by $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ where A is a constant^[3] (link). Hence both $E_{0\omega}(\omega)$ and $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega) = E_{0\omega}(\omega - i\sigma)$ have **exponential fall-off** rate $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ as $|\omega| \rightarrow \infty$ and they are absolutely integrable and Fourier transformable, given that they are derived from an entire function $\xi(s)$.

Given that $\xi(s)$ is an entire function in the s -plane, we see that $E_{0\omega}(\omega)$ and $E_{p\omega}(\omega)$ are **analytic** functions which are infinitely differentiable which produce no discontinuities for all $|\omega| \leq \infty$ and $0 < \sigma < \frac{1}{2}$. Hence their respective **inverse Fourier transforms** $E_0(t), E_p(t)$ have fall-off rates faster than $\frac{1}{t^M}$ as $M \rightarrow \infty$, as $|t| \rightarrow \infty$ (Appendix C.3) and hence it should have **exponential fall-off** rates as $|t| \rightarrow \infty$.

We can use similar arguments to show that $x(t) = E_0(t)e^{-2\sigma t}$ and $\frac{d^{2r}x(t)}{dt^{2r}}$ have fall-off rates **at least** $\frac{1}{t^2}$ as $|t| \rightarrow \infty$, because their Fourier transforms are **analytic** functions for all $|\omega| \leq \infty$ with **exponential fall-off** rate $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ as $|\omega| \rightarrow \infty$.

Appendix D. $\omega_2(t_0)$ is a continuous function around $t_0 = 0$

This result is shown as follows.

- $G_R(\omega) = G_R(\omega, t_0)$ in Eq. 13 is copied below, which is a **continuous** function of ω which is differentiable **at least** once with respect to ω . (Eq. D.2 and Appendix D.3)

$$G_R(\omega) = G_R(\omega, t_0) = \int_{-\infty}^0 [E_0(t + t_0)e^{-2\sigma t} + E_{0m}(t - t_0)] \cos(\omega t) dt \quad (\text{D.1})$$

Given that $E_0(t) \geq 0$ for $|t_0| \leq \infty$ (Appendix C.1), we see that $G_R(\omega) > 0$ at $\omega = 0$. **Set** $t_0 = 0$ and $G_R(\omega, t_0)$ passes through its **first zero** at $\omega = \omega_2(t_0) = \omega_2(0)$. In the rest of this section, we consider the **interval** $[-\delta t_0, \delta t_0]$ around $t_0 = 0$, in $\omega_2(t_0)$. There are 3 possibilities.

Case 1: $G_R(\omega) < 0$ for $\omega = \omega_2(0) + dw$, $G_R(\omega) > 0$ for $\omega = \omega_2(0) - dw$ for infinitesimal dw (example plot)

In this case, we will show in Appendix D.1 that $\omega_2(t_0)$ is a continuous function of t_0 in the interval $[-\delta t_0, \delta t_0]$, in the neighborhood around the first zero crossing at $\omega = \omega_2(t_0) = \omega_2(0)$.

Case 2: $G_R(\omega) > 0$ for $\omega = \omega_2(0) + dw$, $G_R(\omega) > 0$ for $\omega = \omega_2(0) - dw$ (example plot)

In this case, $\frac{dG_R(\omega)}{d\omega} = 0$ at the **same** $\omega = \omega_2(0)$ because $\frac{dG_R(\omega)}{d\omega} < 0$ at $\omega = \omega_2(0) - dw$ and $\frac{dG_R(\omega)}{d\omega} > 0$ at $\omega = \omega_2(0) + dw$.

$$\frac{dG_R(\omega)}{d\omega} = - \int_{-\infty}^0 t [E_0(t + t_0)e^{-2\sigma t} + E_{0m}(t - t_0)] \sin(\omega t) dt \quad (\text{D.2})$$

In this case, we will show Appendix D.2 that $\omega_2(t_0)$ is a continuous function of t_0 in the interval $[-\delta t_0, \delta t_0]$, in the neighborhood around the first zero crossing at $\omega = \omega_2(t_0) = \omega_2(0)$.

Case 3: $G_R(\omega) = 0$ for $\omega = \omega_2(0)$ and $\omega = \omega_2(0) + dw$.

This is **not** possible because $G_R(\omega, t_0)$ in Eq. D.1 is an **analytic** function and infinitely differentiable with respect to ω (Appendix D.3). We know that analytic functions have **isolated** zeros. (link). Hence we cannot have $G_R(\omega) = 0$ for $\omega = \omega_2(0)$ and $\omega = \omega_2(0) + dw$ as $dw \rightarrow 0$.

Appendix D.1. Case 1: $G_R(\omega) < 0$ **for** $\omega = \omega_2(0) + dw$, $G_R(\omega) > 0$ **for** $\omega = \omega_2(0) - dw$

- Consider the **segment** S in $G_R(\omega, t_0)$ in the neighborhood around the first zero crossing where $\frac{dG_R(\omega, t_0)}{d\omega} < 0$. (Segment S is the portion between the green lines in example plot)

- In the **segment** S, $G_R(\omega, t_0)$ in Eq. D.1 is a **continuous** function of ω , for **each** value of t_0 . Hence $G_R(\omega, t_0 - \delta t_0)$ and $G_R(\omega, t_0 + \delta t_0)$ are **continuous** functions of ω , which are differentiable **at least** once, and $G_R(\omega, t_0 \pm \delta t_0)$ tends to $G_R(\omega, t_0)$, as infinitesimal $\delta t_0 \rightarrow 0$.

$$G_R(\omega, t_0) = \int_{-\infty}^0 [E_0(t + t_0)e^{-2\sigma t} + E_{0m}(t - t_0)] \cos(\omega t) dt$$

$$G_R(\omega, t_0 + \delta t_0) = \int_{-\infty}^0 [E_0(t + t_0 + \delta t_0)e^{-2\sigma t} + E_{0m}(t - t_0 - \delta t_0)] \cos(\omega t) dt$$

• In the **segment S**, $G_R(\omega, t_0)$ in Eq. D.3 is a **continuous** function of ω , for **each** value of t_0 and $\frac{dG_R(\omega, t_0)}{d\omega} < 0$ in the neighborhood around the **first zero crossing**. If we fix the X-coordinate ω , $G_R(\omega, t_0)$ is a **continuous** function of t_0 , for **each** value of ω . Hence, for **each** value of ω , as we change t_0 by an infinitesimal δt_0 , $G_R(\omega, t_0)$ moves towards $G_R(\omega, t_0 + \delta t_0)$ in a **continuous** manner, as $\delta t_0 \rightarrow 0$. Every point in the segment S, moves continuously, as we change t_0 by an infinitesimal δt_0 .

This also applies to the first **zero crossing** in $G_R(\omega, t_0)$ in the segment S, which corresponds to $\omega_2(t_0) = \omega_2(0)$ at $t_0 = 0$ where $G_R(\omega, t_0) = 0$ in Eq. D.3. The zero crossing moves continuously, as we change t_0 by an infinitesimal δt_0 . This is explained below.

• **Explanation:** This is shown by an **example** plot. **Red** plot corresponds to $G_R(\omega, t_0)$ with zero crossing at point P_0 , **Green** plot corresponds to $G_R(\omega, t_0 + \delta t_0)$ with zero crossing at point P_{11} and **Blue** plot corresponds to $G_R(\omega, t_0 - \delta t_0)$ with zero crossing at point P_{21} .

We **define** the **point** P_{12} in $G_R(\omega, t_0 + \delta t_0)$ as the point which has the **fixed X-coordinate** $\omega = \omega_2(0)$. We **define** the **point** P_{22} in $G_R(\omega, t_0 - \delta t_0)$ as the point which has the **fixed X-coordinate** $\omega = \omega_2(0)$.

We **define** the **point** P_{11} in $G_R(\omega, t_0 + \delta t_0)$ as the **zero crossing point** which has the **fixed Y-coordinate** which equals zero. We **define** the **point** P_{21} in $G_R(\omega, t_0 - \delta t_0)$ as the **zero crossing point** which has the **fixed Y-coordinate** which equals zero.

As we change t_0 by an infinitesimal δt_0 , $G_R(\omega, t_0 + \delta t_0)$ in Eq. D.4 moves towards $G_R(\omega, t_0)$ in a **continuous** manner as follows. The **point** P_{12} in $G_R(\omega, t_0 + \delta t_0)$ which corresponds to the **fixed X-coordinate** $\omega = \omega_2(0)$, moves towards corresponding point P_0 in $G_R(\omega, t_0)$, for the **same** $\omega = \omega_2(0)$ in a **continuous** manner, as $\delta t_0 \rightarrow 0$. Given that P_0 is a **zero crossing point** in $G_R(\omega, t_0)$, this is equivalent to the **Zero crossing point** P_{11} in $G_R(\omega, t_0 + \delta t_0)$ moving towards corresponding **zero crossing point** P_0 in $G_R(\omega, t_0)$ in a **continuous** manner, as $\delta t_0 \rightarrow 0$.

Similarly, as we change t_0 by an infinitesimal δt_0 , $G_R(\omega, t_0 - \delta t_0)$ in Eq. D.4 moves towards $G_R(\omega, t_0)$ in a **continuous** manner as follows. The **point** P_{22} in $G_R(\omega, t_0 - \delta t_0)$ which corresponds to the **fixed X-coordinate** $\omega = \omega_2(0)$, moves towards corresponding point P_0 in $G_R(\omega, t_0)$, for the **same** $\omega = \omega_2(0)$ in a **continuous** manner, as $\delta t_0 \rightarrow 0$. Given that P_0 is a **zero crossing point** in $G_R(\omega, t_0)$, this is equivalent to the **Zero crossing point** P_{21} in $G_R(\omega, t_0 - \delta t_0)$ moving towards corresponding **zero crossing point** P_0 in $G_R(\omega, t_0)$ in a **continuous** manner, as $\delta t_0 \rightarrow 0$.

$$\begin{aligned}
G_R(\omega, t_0) &= \int_{-\infty}^0 [E_0(t + t_0)e^{-2\sigma t} + E_{0m}(t - t_0)] \cos(\omega t) dt \\
G_R(\omega, t_0 + \delta t_0) &= \int_{-\infty}^0 [E_0(t + t_0 + \delta t_0)e^{-2\sigma t} + E_{0m}(t - t_0 - \delta t_0)] \cos(\omega t) dt \\
G_R(\omega, t_0 - \delta t_0) &= \int_{-\infty}^0 [E_0(t + t_0 - \delta t_0)e^{-2\sigma t} + E_{0m}(t - t_0 + \delta t_0)] \cos(\omega t) dt \\
\lim_{\delta t_0 \rightarrow 0} G_R(\omega, t_0 + \delta t_0) &= G_R(\omega, t_0) \\
\lim_{\delta t_0 \rightarrow 0} G_R(\omega, t_0 - \delta t_0) &= G_R(\omega, t_0)
\end{aligned}$$

• Hence in the **segment S**, $\omega_2(t_0)$ is a **continuous** function of t_0 in the neighborhood $[-\delta t_0, \delta t_0]$ around the first zero crossing at $\omega = \omega_2(t_0) = \omega_2(0)$ at $t_0 = 0$.

$$G_R(\omega_2(t_0), t_0) = \int_{-\infty}^0 [E_0(t+t_0)e^{-2\sigma t} + E_{0m}(t-t_0)] \cos(\omega_2(t_0)t) dt = 0$$

$$G_R(\omega_2(t_0 + \delta t_0), t_0 + \delta t_0) = \int_{-\infty}^0 [E_0(t+t_0 + \delta t_0)e^{-2\sigma t} + E_{0m}(t-t_0 - \delta t_0)] \cos((\omega_2(t_0 + \delta t_0)t) dt = 0$$

(D.5)

Appendix D.2. Case 2: $G_R(\omega) > 0$ **for** $\omega = \omega_2(0) + dw$, $G_R(\omega) > 0$ **for** $\omega = \omega_2(0) - dw$

- In this case, $\frac{dG_R(\omega)}{d\omega} = 0$ at the **same** $\omega = \omega_2(t_0)$ because $\frac{dG_R(\omega)}{d\omega} < 0$ at $\omega = \omega_2(t_0) - dw$ and $\frac{dG_R(\omega)}{d\omega} > 0$ at $\omega = \omega_2(t_0) + dw$.

- Consider the **segment S'** in $\frac{dG_R(\omega, t_0)}{d\omega}$ in the neighborhood around the first zero crossing where $\frac{d^2G_R(\omega, t_0)}{d\omega^2} > 0$. (Segment S' is the portion between the green lines in example plot) In this segment S', $\frac{dG_R(\omega, t_0)}{d\omega}$ is a **continuous** function of ω which is differentiable **at least** once. (Appendix D.3)

- In the **segment S'**, $\frac{dG_R(\omega, t_0)}{d\omega} = 0$ at the **same** $\omega = \omega_2(t_0)$. The arguments in Appendix D.1 can be applied here, with $G_R(\omega, t_0)$ replaced by $\frac{dG_R(\omega, t_0)}{d\omega}$.

Hence $\omega_2(t_0)$ is a **continuous** function of t_0 in the neighborhood $[-\delta t_0, \delta t_0]$ around the first zero crossing at $\omega = \omega_2(t_0) = \omega_2(0)$ at $t_0 = 0$ in the **segment S'**.

Appendix D.3. Integral convergence in $\frac{dG_R(\omega)}{d\omega}$

It is shown in Appendix C.4 that $E_0(t)$ and $E_0(t)e^{-2\sigma t}$ have exponential fall-off rates as $|t| \rightarrow \infty$ and hence are absolutely **integrable** functions and the integrals $\int_{-\infty}^{\infty} |E_0(t)| dt < \infty$ and $\int_{-\infty}^{\infty} |E_0(t)e^{-2\sigma t}| dt < \infty$. Hence the integrand $A_r(t) = \frac{t^r}{r!} [E_0(t+t_0)e^{-2\sigma t} + E_{0m}(t-t_0)] \sin(\omega t)$ in Eq. D.2 copied below, is an absolutely **integrable function** and $\int_{-\infty}^0 |A_r(t)| dt = \int_{-\infty}^0 \frac{|t^r|}{r!} [E_0(t+t_0)e^{-2\sigma t} + E_{0m}(t-t_0)] dt$ is **finite**, for $r = 0, 1, \dots$, given the **exponential** fall-off rate of $E_0(t)e^{-2\sigma t}$ and $E_0(t)$.

$$\begin{aligned} \frac{1}{r!} \frac{d^r G_R(\omega)}{d\omega^r} &= (-1)^{\frac{r+1}{2}} \int_{-\infty}^0 \frac{t^r}{r!} [E_0(t+t_0)e^{-2\sigma t} + E_{0m}(t-t_0)] \sin(\omega t) dt, \quad r = \text{odd} \\ \frac{1}{r!} \frac{d^r G_R(\omega)}{d\omega^r} &= (-1)^{\frac{r}{2}} \int_{-\infty}^0 \frac{t^r}{r!} [E_0(t+t_0)e^{-2\sigma t} + E_{0m}(t-t_0)] \cos(\omega t) dt, \quad r = \text{even} \end{aligned}$$

(D.6)

Appendix E. Derivation of entire function $\xi(s)$

In this section, we will re-derive Riemann's Xi function $\xi(s)$ and the inverse Fourier Transform of $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega)$ and show the result $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$.

We will use the steps in Ellison's book "Prime Numbers" pages 151-152 and re-derive the steps below^[4] (link). We start with the gamma function $\Gamma(s) = \int_0^{\infty} y^{s-1} e^{-y} dy$ and substitute $y = \pi n^2 x$ and derive as follows.

$$\begin{aligned} \Gamma\left(\frac{s}{2}\right) &= \int_0^{\infty} y^{\frac{s}{2}-1} e^{-y} dy \\ \Gamma\left(\frac{s}{2}\right) (\pi n^2)^{-\frac{s}{2}} &= \int_0^{\infty} x^{\frac{s}{2}-1} e^{-\pi n^2 x} dx \end{aligned}$$

(E.1)

For real part of s greater than 1, we can do a summation of both sides of above equation for all positive integers n and obtain as follows. We note that $\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$.

$$\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) = \sum_{n=1}^{\infty} \int_0^{\infty} x^{\frac{s}{2}-1} e^{-\pi n^2 x} dx \quad (\text{E.2})$$

For real part of s (σ') greater than 1, we can use theorem of dominated convergence and interchange the order of summation and integration as follows. We use the fact that $w(x) = \sum_{n=1}^{\infty} e^{-\pi n^2 x}$ and

$$\sum_{n=1}^{\infty} \int_0^{\infty} |x^{\frac{s}{2}-1} e^{-\pi n^2 x}| dx = \Gamma\left(\frac{\sigma'}{2}\right)\pi^{-\frac{\sigma'}{2}} \zeta(\sigma').$$

$$\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) = \int_0^{\infty} x^{\frac{s}{2}-1} w(x) dx \quad (\text{E.3})$$

For real part of s less than or equal to 1, $\zeta(s)$ **diverges**. Hence we do the following. In Eq. E.3, first we consider real part of s greater than 1 and we divide the range of integration into two parts: $(0, 1]$ and $[1, \infty)$ and make the substitution $x \rightarrow \frac{1}{x}$ in the first interval $(0, 1]$. We use **the well known theorem** $1 + 2w(x) = \frac{1}{\sqrt{x}}(1 + 2w(\frac{1}{x}))$, where $x > 0$ is real.^[4]

$$\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) = \int_1^{\infty} x^{\frac{s}{2}-1} w(x) dx + \int_1^{\infty} \frac{x^{-(\frac{s}{2}-1)}}{x^2} \frac{(1 + 2w(x))\sqrt{x} - 1}{2} dx \quad (\text{E.4})$$

Hence we can simplify Eq. E.4 as follows.

$$\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) = \frac{1}{s(s-1)} + \int_1^{\infty} x^{\frac{s}{2}-1} w(x) dx + \int_1^{\infty} x^{\frac{-(s+1)}{2}} w(x) dx \quad (\text{E.5})$$

We multiply above equation by $\frac{1}{2}s(s-1)$ and get

$$\xi(s) = \frac{1}{2}s(s-1)\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}\zeta(s) = \frac{1}{2}[1 + s(s-1) \int_1^{\infty} (x^{\frac{s}{2}} + x^{\frac{1-s}{2}}) w(x) \frac{dx}{x}] \quad (\text{E.6})$$

We see that $\xi(s)$ is an entire function, for all values of $Re[s]$ in the complex plane and hence we get an analytic continuation of $\xi(s)$ over the entire complex plane. We see that $\xi(s) = \xi(1-s)$ ^[4].

Appendix E.1. **Derivation of $E_p(t)$ and $E_0(t)$**

Given that $w(x) = \sum_{n=1}^{\infty} e^{-\pi n^2 x}$, we substitute $x = e^{2t}$, $\frac{dx}{x} = 2dt$ in Eq. E.6 and evaluate at $s = \frac{1}{2} + \sigma + i\omega$ as follows.

$$\xi(\frac{1}{2} + \sigma + i\omega) = \frac{1}{2} [1 + 2(\frac{1}{2} + \sigma + i\omega)(-\frac{1}{2} + \sigma + i\omega) \int_0^{\infty} \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} (e^{\frac{t}{2}} e^{\sigma t} e^{i\omega t} + e^{\frac{t}{2}} e^{-\sigma t} e^{-i\omega t}) dt] \quad (\text{E.7})$$

We can substitute $t = -t$ in the first term in above integral and simplify above equation as follows.

$$\begin{aligned} \xi(\frac{1}{2} + \sigma + i\omega) = \frac{1}{2} + (-\frac{1}{4} + \sigma^2 - \omega^2 + i\omega(2\sigma)) & [\int_{-\infty}^0 \sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} e^{-\sigma t} e^{-i\omega t} dt \\ & + \int_0^{\infty} \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} e^{-i\omega t} dt] \end{aligned} \quad (\text{E.8})$$

We can write this as follows.

$$\xi(\frac{1}{2} + \sigma + i\omega) = \frac{1}{2} + (-\frac{1}{4} + \sigma^2 - \omega^2 + i\omega(2\sigma)) \int_{-\infty}^{\infty} [\sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} u(-t) + \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} u(t)] e^{-\sigma t} e^{-i\omega t} dt \quad (\text{E.9})$$

We define $A(t) = [\sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} u(-t) + \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} u(t)] e^{-\sigma t}$ and get the **inverse Fourier transform** of $\xi(\frac{1}{2} + \sigma + i\omega)$ in above equation given by $E_p(t)$ as follows. We use dirac delta function $\delta(t)$.

$$\begin{aligned} E_p(t) &= \frac{1}{2} \delta(t) + (-\frac{1}{4} + \sigma^2) A(t) + 2\sigma \frac{dA(t)}{dt} + \frac{d^2 A(t)}{dt^2} \\ A(t) &= [\sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} u(-t) + \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} u(t)] e^{-\sigma t} \\ \frac{dA(t)}{dt} &= \sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} e^{-\sigma t} [-\frac{1}{2} - \sigma + 2\pi n^2 e^{-2t}] u(-t) + \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} [\frac{1}{2} - \sigma - 2\pi n^2 e^{2t}] u(t) \\ \frac{d^2 A(t)}{dt^2} &= \sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} e^{-\sigma t} [-4\pi n^2 e^{-2t} + (-\frac{1}{2} - \sigma + 2\pi n^2 e^{-2t})^2] u(-t) \\ &+ \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} [-4\pi n^2 e^{2t} + (\frac{1}{2} - \sigma - 2\pi n^2 e^{2t})^2] u(t) + \delta(t) [\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2)] \end{aligned} \quad (\text{E.10})$$

We can simplify above equation as follows.

$$\begin{aligned} \frac{d^2 A(t)}{dt^2} &= \sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} e^{-\sigma t} [\frac{1}{4} + \sigma^2 + \sigma + 4\pi^2 n^4 e^{-4t} - 6\pi n^2 e^{-2t} - 4\sigma \pi n^2 e^{-2t}] u(-t) \\ &+ \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} [\frac{1}{4} + \sigma^2 - \sigma + 4\pi^2 n^4 e^{4t} - 6\pi n^2 e^{2t} + 4\sigma \pi n^2 e^{2t}] u(t) + \delta(t) [\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2)] \end{aligned} \quad (\text{E.11})$$

We use the fact that $F(x) = 1 + 2w(x) = \frac{1}{\sqrt{x}}(1 + 2w(\frac{1}{x}))$, where $w(x) = \sum_{n=1}^{\infty} e^{-\pi n^2 x}$ and $x > 0$ is real^[4], and we take the first derivative of $F(x)$ and evaluate it at $x = 1$. We see that $\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2) = -\frac{1}{2}$ (Appendix E.2) and hence **dirac delta terms cancel each other** in equation below.

$$\begin{aligned}
E_p(t) &= \frac{1}{2}\delta(t) + \left(-\frac{1}{4} + \sigma^2\right)A(t) + 2\sigma\frac{dA(t)}{dt} + \frac{d^2A(t)}{dt^2} \\
E_p(t) &= \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} \left[-\frac{1}{4} + \sigma^2 + 2\sigma\left(\frac{1}{2} - \sigma - 2\pi n^2 e^{2t}\right) + \frac{1}{4} + \sigma^2 - \sigma + 4\pi^2 n^4 e^{4t} - 6\pi n^2 e^{2t} + 4\sigma\pi n^2 e^{2t}\right] u(t) \\
&\quad + \sum_{n=1}^{\infty} e^{-\pi n^2 e^{-2t}} e^{\frac{-t}{2}} e^{-\sigma t} \left[-\frac{1}{4} + \sigma^2 + 2\sigma\left(-\frac{1}{2} - \sigma + 2\pi n^2 e^{-2t}\right) + \frac{1}{4} + \sigma^2 + \sigma + 4\pi^2 n^4 e^{-4t} - 6\pi n^2 e^{-2t} - 4\sigma\pi n^2 e^{-2t}\right] u(-t)
\end{aligned} \tag{E.12}$$

We can simplify above equation as follows.

$$\begin{aligned}
E_p(t) &= [E_0(-t)u(-t) + E_0(t)u(t)]e^{-\sigma t} \\
E_0(t) &= 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}
\end{aligned} \tag{E.13}$$

We use the fact that $E_0(t) = E_0(-t)$ because $\xi(s) = \xi(1-s)$ and hence $\xi(\frac{1}{2} + i\omega) = \xi(\frac{1}{2} - i\omega)$ when evaluated at the critical line $s = \frac{1}{2} + i\omega$. This means $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega) = E_{0\omega}(-\omega)$ and $E_0(t) = E_0(-t)$ and we arrive at the desired result for $E_p(t)$ as follows.

$$\begin{aligned}
E_0(t) &= 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} \\
E_p(t) &= E_0(t)e^{-\sigma t} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t}
\end{aligned} \tag{E.14}$$

Appendix E.2. Derivation of $\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2) = -\frac{1}{2}$

In this section, we derive $\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2) = -\frac{1}{2}$. We use the fact that $F(x) = 1 + 2w(x) = \frac{1}{\sqrt{x}}(1 + 2w(\frac{1}{x}))$, where $w(x) = \sum_{n=1}^{\infty} e^{-\pi n^2 x}$ and $x > 0$ is real^[4], and we take the first derivative of $F(x)$ and evaluate it at $x = 1$.

$$\begin{aligned}
F(x) &= 1 + 2w(x) = \frac{1}{\sqrt{x}}(1 + 2w(\frac{1}{x})) \\
F(x) &= 1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2 x} = \frac{1}{\sqrt{x}}(1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2 \frac{1}{x}}) \\
\frac{dF(x)}{dx} &= 2 \sum_{n=1}^{\infty} (-\pi n^2) e^{-\pi n^2 x} = \frac{1}{\sqrt{x}} \sum_{n=1}^{\infty} (2\pi n^2) e^{-\pi n^2 \frac{1}{x}} \left(\frac{1}{x^2}\right) + (1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2 \frac{1}{x}}) \left(\frac{-1}{2}\right) \frac{1}{x^{\frac{3}{2}}}
\end{aligned} \tag{E.15}$$

We evaluate the above equation at $x = 1$ and we simplify as follows.

$$\begin{aligned}
\left[\frac{dF(x)}{dx}\right]_{x=1} &= 2 \sum_{n=1}^{\infty} (-\pi n^2) e^{-\pi n^2} = \sum_{n=1}^{\infty} (2\pi n^2) e^{-\pi n^2} + (1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2}) \left(\frac{-1}{2}\right) \\
&\sum_{n=1}^{\infty} e^{-\pi n^2} (1 - 4\pi n^2) = -\frac{1}{2}
\end{aligned}$$

(E.16)