

Riemann Hypothesis

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1 Zeta function

1.1 Definition

The zeta function is defined as

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \quad \operatorname{Re}(s) > 0$$

1.2 Euler product

The zeta function can be represented as an Euler product.

We will start by using the first prime number: 2, and multiply both sides by 2^{-s} .

$$\zeta(s) \frac{1}{2^s} = \sum_{n=1}^{\infty} \frac{1}{(2n)^s}$$

We then subtract the second definition from the first one, such that

$$\begin{aligned} \zeta(s) - \zeta(s) \frac{1}{2^s} &= \sum_{n=1}^{\infty} \left[\frac{1}{n^s} \right] - \sum_{n=1}^{\infty} \left[\frac{1}{(2n)^s} \right] \\ \zeta(s) \left(1 - \frac{1}{2^s} \right) &= \sum_{n=1}^{\infty} \frac{1}{n^s}, \quad n \neq 2k, k \in \mathbb{Z} \end{aligned}$$

Here we are excluding the multiples of 2 from the series.

If we do the same with the next prime number, which is 3, we get

$$\zeta(s) \left(1 - \frac{1}{2^s} \right) \left(1 - \frac{1}{3^s} \right) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \quad n \neq 2k, n \neq 3k, k \in \mathbb{Z}$$

We can repeat this process with every prime number.

Eventually, we will exclude every nth-term to sum as we use every prime number, except for n=1.

$$\zeta(s) \prod_{p \in P} \left(1 - \frac{1}{p^s} \right) = \frac{1}{1^s} = 1$$

Finally, we get the identity

$$\zeta(s) = \prod_{p \in P} \frac{1}{1 - p^{-s}}$$

2 Analytic continuation

2.1 Zeta function for positive $\text{Re}(s)$

We have seen that the classical zeta function definition only converges for $\text{Re}(s) > 1$

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \quad \text{Re}(s) > 1$$

We can use the eta function $\eta(s)$, which is defined for $\text{Re}(s) > 0 \setminus \{1\}$, to analytically extend the zeta function domain to $\text{Re}(s) > 0 \setminus \{1\}$.

The eta function is a Dirichlet series defined as

$$\eta(s) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^s}, \quad \text{Re}(s) > 0 \setminus \{1\}$$

We start by splitting the zeta function into two distinct series, one for n even and the other one for n odd. The index for the even series will be $2n$, while the odd one will use $2n - 1$ as the index.

$$\zeta(s) = \sum_{n=1}^{\infty} \left[\frac{1}{(2n)^s} \right] + \sum_{n=1}^{\infty} \left[\frac{1}{(2n-1)^s} \right]$$

We do the same thing with the eta function.

Notice that $(-1)^n$ is 1 when n is even and -1 when n is odd.

$$\eta(s) = \sum_{n=1}^{\infty} \left[\frac{1}{(2n)^s} \right] - \sum_{n=1}^{\infty} \left[\frac{1}{(2n-1)^s} \right]$$

We subtract these two definition from eachother

$$\begin{aligned} \zeta(s) - \eta(s) &= 2 \sum_{n=1}^{\infty} \frac{1}{(2n)^s} \\ &= 2^{1-s} \sum_{n=1}^{\infty} \frac{1}{k^s} \\ \zeta(s) - \eta(s) &= 2^{1-s} \zeta(s) \\ \frac{1}{1-2^{1-s}} \eta(s) &= \zeta(s) \end{aligned}$$

We finally get

$$\zeta(s) = \frac{1}{1-2^{1-s}} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^s}, \quad \text{Re}(s) > 0 \setminus \{1\}$$

This series can be used to compute value of the zeta function along the critical strip $0 < \text{Re}(s) < 1$.

3 Prime-counting function

3.1 Properties of the prime-counting function

The prime-counting function $\pi(x)$ is defined as the number of primes less or equals than x .

We can consider the difference between $\pi(x)$ of two consecutive integers

$$\pi(x) - \pi(x-1) = \begin{cases} 1, & \text{if } x \in P \\ 0, & \text{otherwise} \end{cases}$$

Given a series over all prime numbers, we can extend it to all integers and multiply each term by this difference.

The terms whose index is not a prime number will be multiplied by 0.

$$\sum_{p \in P}^{\infty} a_k = \sum_{n=2}^{\infty} [\pi(n) - \pi(n-1)] a_n$$

Here we start at 2 since there are no prime numbers less than 2.

3.2 Relationship with the zeta function

We have seen that the zeta function can be written as an Euler Product

$$\zeta(s) = \prod_{p \in P}^{\infty} \frac{1}{1 - p^{-s}}$$

However, we need convert this product into a series in order to apply the identity of the last paragraph. We can take the natural logarithm of both sides and use the multiplication property

$$\begin{aligned} \ln(\zeta(s)) &= \ln \prod_{p \in P}^{\infty} \frac{1}{1 - p^{-s}} \\ &= \sum_{p \in P}^{\infty} \ln \left(\frac{1}{1 - p^{-s}} \right) \\ &= \sum_{p \in P}^{\infty} -\ln(1 - p^{-s}) \end{aligned}$$

Now we can apply the identity

$$\ln(\zeta(s)) = \sum_{n=2}^{\infty} -\ln(1 - n^{-s}) [\pi(n) - \pi(n-1)]$$

The next goal is to factor out $\pi(n)$

$$\begin{aligned} \ln(\zeta(s)) &= \sum_{n=2}^{\infty} [\pi(n-1) \ln(1 - n^{-s})] - \sum_{n=2}^{\infty} [\pi(n) \ln(1 - n^{-s})] \\ &= \sum_{n=2}^{\infty} [\pi(n) \ln(1 - (n+1)^{-s})] - \sum_{n=2}^{\infty} [\pi(n) \ln(1 - n^{-s})] \\ &= \sum_{n=2}^{\infty} \pi(n) [\ln(1 - (n+1)^{-s}) - \ln(1 - n^{-s})] \end{aligned}$$

To simplify further more, we consider the derivative of the function $\ln(1 - x^{-s})$.
Using the chain rule we get

$$\frac{d}{dx} \ln(1 - x^{-s}) = \frac{s}{x(x^s - 1)}$$

Therefore,

$$\ln(1 - x^{-s}) = \int \frac{s}{x(x^s - 1)} dx + C$$

Considering $f(x) = \ln(1 - x^{-s})$, our series can be expressed as

$$\ln(\zeta(s)) = \sum_{n=2}^{\infty} \pi(n) [f(n+1) - f(n)]$$

which can be written as an integral from n to $n+1$

$$\begin{aligned} \ln(\zeta(s)) &= \sum_{n=2}^{\infty} \pi(n) \int_n^{n+1} f'(x) dx \\ &= \sum_{n=2}^{\infty} \pi(n) \int_n^{n+1} \frac{s}{x(x^s - 1)} dx \\ &= \sum_{n=2}^{\infty} \int_n^{n+1} \frac{s\pi(x)}{x(x^s - 1)} dx \end{aligned}$$

Instead of taking the sum of each of these integrals (2 to 3, 3 to 4, ...), we can make a single integral

$$\ln(\zeta(s)) = s \int_2^{\infty} \frac{\pi(x)}{x(x^s - 1)} dx$$