

Prime Numbers

Definition 1. The **prime numbers** are defined as the set of all natural numbers greater than one which are not divisible by any natural number other than one and itself.

Fundamental Theorem of Arithmetic

Theorem 1. Every integer greater than one is either a prime or the product of prime numbers. This product is unique up to the ordering of the factors.

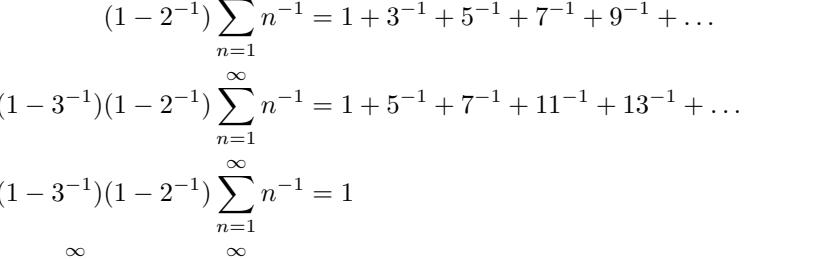
Proof. Consider an ordered (e.g. ascending) and grouped (into powers) complete factorisation of an integer H greater than one. Such a factorisation takes the form $H = f_1^{r_1} f_2^{r_2} \dots f_M^{r_M}$ where each f_m is a unique prime. Assume that there exists a different factorisation of $H = g_1^{s_1} g_2^{s_2} \dots g_N^{s_N}$. Then either for some m or n there is no corresponding $f_m = g_n$, or for some $f_m = g_n$, $r_m \neq s_n$. In the first case, at least one of f_m or g_m both divides H and does not divide H , a contradiction. In the second case, the larger of $f_m^{r_m}$ or $g_m^{s_m}$ both divides H and does not divide H , also a contradiction. Thus, any such factorisation is unique. \square

The Number of Primes

Theorem 2. The number of primes is infinite.

Proof. Assume that the number of primes is finite. Consider the number constructed by adding one to the product of those primes. None of those primes divide the number (because the remainder is one), so either it is an additional prime or it is divisible by at least one additional prime, both of which contradict the initial assumption. Therefore, the number of primes is infinite. \square

Prime Gaps



The differences between the first one thousand pairs of successive primes.

The Harmonic Series and Prime Numbers

Theorem 3.

$$\sum_{n=1}^{\infty} \frac{1}{n} = \prod_{n=1}^{\infty} \frac{1}{1 - p_n^{-1}}$$

Proof.

$$\begin{aligned} \sum_{n=1}^{\infty} n^{-1} &= 1 + 2^{-1} + 3^{-1} + 4^{-1} + \dots \\ &\quad - \left[2^{-1} \sum_{n=1}^{\infty} n^{-1} = 2^{-1} + 4^{-1} + 6^{-1} + 8^{-1} + \dots \right] \quad \text{multiply and subtract} \\ (1 - 2^{-1}) \sum_{n=1}^{\infty} n^{-1} &= 1 + 3^{-1} + 5^{-1} + 7^{-1} + 9^{-1} + \dots \quad \text{prime sieve} \\ (1 - 3^{-1})(1 - 2^{-1}) \sum_{n=1}^{\infty} n^{-1} &= 1 + 5^{-1} + 7^{-1} + 11^{-1} + 13^{-1} + \dots \\ (\dots)(1 - 5^{-1})(1 - 3^{-1})(1 - 2^{-1}) \sum_{n=1}^{\infty} n^{-1} &= 1 \\ \prod_{n=1}^{\infty} (1 - p_n^{-1}) \sum_{n=1}^{\infty} n^{-1} &= 1 \\ \sum_{n=1}^{\infty} n^{-1} &= \prod_{n=1}^{\infty} (1 - p_n^{-1})^{-1} \end{aligned}$$

\square

The Sum of the Reciprocals of the Primes

$$\sum_{n=1}^{\infty} \frac{1}{p_n} \text{ diverges.}$$

Proof. Given $\sum_{n=1}^{\infty} \frac{1}{n}$ divergent and $\sum_{n=1}^{\infty} \frac{1}{n} = \prod_{n=1}^{\infty} \frac{1}{1 - p_n^{-1}}$,

$$\ln \left(\sum_{n=1}^{\infty} \frac{1}{n} \right) = \ln \left(\prod_{n=1}^{\infty} \frac{1}{1 - p_n^{-1}} \right) = \sum_{n=1}^{\infty} \ln \left(\frac{p_n}{p_n - 1} \right) = \sum_{n=1}^{\infty} \ln \left(1 + \frac{1}{p_n - 1} \right) \text{ all diverge.}$$

Since $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$, we have $e^x > 1 + x$ and $x > \ln(1 + x)$.

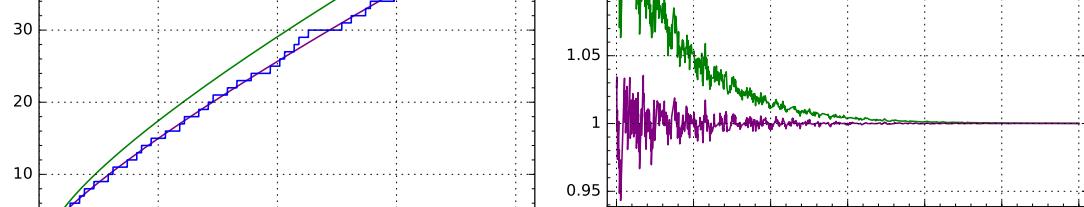
Therefore $\sum_{n=1}^{\infty} \ln \left(1 + \frac{1}{p_n - 1} \right) < \sum_{n=1}^{\infty} \frac{1}{p_n - 1}$ and $\sum_{n=1}^{\infty} \frac{1}{p_n - 1}$ diverges.

Since $\frac{1}{p_n - 1} < \frac{1}{p_n}$, $\sum_{n=1}^{\infty} \frac{1}{p_n}$ is also divergent. \square

The Prime Counting Function and the Logarithmic Integral

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

The logarithmic integral, $\text{Li}(x) \equiv \int_2^x \frac{dt}{\ln(t)}$



The logarithmic integral is asymptotic to $x / \ln(x)$.

$$\text{Li}(x) \sim \frac{x}{\ln(x)}$$

Prime Number Theorem (PNT)

$$\pi(x) \sim \frac{x}{\ln(x)}$$

Riemann Function $R(x)$

$$R(x) = \sum_{n=1}^{\infty} \frac{\mu(n)}{n} \text{Li}(x^{1/n})$$

$$\mu(n) = \begin{cases} 1 & n \text{ is square-free and has an even number of prime factors} \\ -1 & n \text{ is square-free and has an odd number of prime factors} \\ 0 & n \text{ has a squared prime factor,} \end{cases}$$

