

PMATH 440 COURSE NOTES

ANALYTIC NUMBER THEORY

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1 Introduction to Prime Numbers and Their Counting Function

1.1 Primes

DEFINITION 1.1. A **prime number** is a positive integer greater than 1 such that its only factors are 1 and itself. We denote by \mathcal{P} the set of all prime numbers. For a positive real number x , we define the **prime counting function** by

$$\pi(x) = \#\{p \leq x : p \in \mathcal{P}\},$$

where $\#S$ denotes the cardinality of the set S .

We would like to know how the primes are distributed among the integers. Let p_n denote the n -th prime. Is there a formula to obtain p_n ? Is there a polynomial $f(x) \in \mathbb{Z}[x]$ such that $f(n) = p_n$ for all $n \in \mathbb{N}$? The answer to the latter question is no, due to the following result.

PROPOSITION 1.2. There is no non-constant polynomial $f(x) \in \mathbb{Z}[x]$ such that $f(n)$ is prime for all $n \in \mathbb{N}$.

PROOF. Suppose such a polynomial $f(x) \in \mathbb{Z}[x]$ existed, and write

$$f(x) = a_n x^n + \cdots + a_1 x + a_0.$$

Let q be a prime with $f(n) = q$ for some $n \in \mathbb{N}$. Then $q \mid f(n + kq)$ for each $k \in \mathbb{N}$. In particular, notice that if $f(m)$ is prime for every positive integer m , then $f(x)$ must be constant with $f(x) = q$ for some prime q . \square

REMARK 1.3.

- (1) There are examples of polynomials whose initial values are surprisingly often prime. For example, the polynomial $n^2 + n + 41$ is prime for all $0 \leq n \leq 39$, and the polynomial $(n - 40)^2 + (n - 40) + 41$ is prime for all $0 \leq n \leq 79$.
- (2) In the 1970s, Matijasevic proved Hilbert's tenth problem, and in the process, he was able to show that there is a polynomial $f \in \mathbb{Z}[a, b, \dots, z]$ such that the set of positive values in $f(\mathbb{N}^{26})$ is exactly the set of primes. In 1977, he showed that only 10 variables are needed.

Let us instead ask a weaker question. Can we find a non-constant polynomial $f(x) \in \mathbb{Z}[x]$ such that $f(n)$ yields a prime for infinitely many $n \in \mathbb{N}$? Trivially, we see that $f(x) = x + k$ works for any $k \in \mathbb{Z}$. When the coefficient of x is not equal to 1, we have the following result, which we will prove at the end of this course.

THEOREM 1.4 (Dirichlet). Let k and ℓ be coprime positive integers. Then $kn + \ell$ is prime for infinitely many positive integers n .

REMARK 1.5.

- (1) At the moment, there is no known polynomial of degree greater than 1 in one variable known to take prime values infinitely often. The best result known to date is that $n^2 + 1$ is a product of two primes for infinitely many n .
- (2) If we instead consider polynomials of two variables, we can go further. It is known that an odd prime p is the sum of two squares if and only if $p \equiv 1 \pmod{4}$. In 1998, Friedlander and Iwaniec proved that there are infinitely many primes of the form $n^2 + m^4$. In 2001, Heath-Brown showed that there are infinitely many primes of the form $n^3 + 2m^3$.

THEOREM 1.6 (Euclid). There are infinitely many prime numbers.

PROOF. Assume that there are only finitely many primes, say p_1, \dots, p_n , and consider

$$m = p_1 \cdots p_n + 1.$$

Then m can be written as a product of primes by unique factorization, and $p_k \mid m$ for some $1 \leq k \leq n$. Hence, we see that $p_k \mid m - p_1 \cdots p_n$ and $p_k \mid 1$, which is a contradiction. \square

We would like to estimate the prime counting function $\pi(x)$.

PROPOSITION 1.7. For all $n \in \mathbb{N}$, we have $p_n \leq 2^{2^n}$.

PROOF. We proceed by induction. For $n = 1$, we have $2 = p_1 \leq 2^{2^1} = 4$. Suppose the result holds for all $1 \leq k \leq n$. By Euclid's argument, we obtain $p_{n+1} \leq p_1 \cdots p_n + 1$. It follows from induction that

$$p_{n+1} \leq 2^{2^1} 2^{2^2} \cdots 2^{2^n} + 1 \leq 2^{2^{n+1}-2} + 1 \leq 2^{2^{n+1}},$$

which completes the proof. \square

COROLLARY 1.8. For all $x \geq 2$, we have $\pi(x) > \log \log x$. (In this course, \log denotes the natural logarithm.)

PROOF. Let $x \geq 2$, and let s be the integer satisfying

$$2^{2^s} \leq x < 2^{2^{s+1}}.$$

By Proposition 1.7, we have $\pi(x) \geq s$. On the other hand, since $x < 2^{2^{s+1}}$, taking logarithms yields $\log_2(\log_2 x) < s + 1$, and hence

$$\frac{\log(\frac{\log x}{\log 2})}{\log 2} < s + 1.$$

It follows that

$$\pi(x) \geq s > \frac{\log(\frac{\log x}{\log 2})}{\log 2} - 1 \geq \log \log x. \quad \square$$

There is an alternative way to prove Euclid's theorem, due to Euler, which is left as part of the homework. Using the same idea, we can derive a slightly better lower bound for $\pi(x)$.

PROPOSITION 1.9. For all $x \geq 2$, we have

$$\pi(x) \geq \frac{\log \log x}{\log 2}.$$

PROOF. Suppose that $x \geq 2$. Then we have

$$2^{\pi(x)} \geq \prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1} = \prod_{p \leq x} \left(1 + \frac{1}{p} + \frac{1}{p^2} + \cdots\right) \geq \sum_{n \leq x} \frac{1}{n} \geq \int_1^{\lfloor x \rfloor + 1} \frac{1}{u} du \geq \log x,$$

where the product $\prod_{p \leq x}$ means that p runs through all primes at most x , and $\lfloor y \rfloor$ is the greatest integer less than or equal to y . We will use this notation for the rest of the course. Taking logarithms yields the desired inequality. \square

Fermat had conjectured that the numbers of the form $2^{2^n} + 1$ are prime for $n \in \mathbb{N}$. He had checked it for the values $0 \leq n \leq 4$. These are known as the **Fermat numbers** and are denoted by

$$F_n = 2^{2^n} + 1.$$

In 1732, Euler showed that $641 \mid F_5$. It is also known that F_6, \dots, F_{21} are composite. It is quite likely that only finitely many Fermat numbers are prime.

THEOREM 1.10 (Polyá). If n and m are positive integers with $1 \leq n < m$, then $(F_n, F_m) = 1$.

PROOF. Write $m = n + k$ with $k \geq 1$. First, we will show that $F_n \mid F_m - 2$. Observe that

$$F_m - 2 = (2^{2^{n+k}} + 1) - 2 = 2^{2^{n+k}} - 1.$$

The polynomial $x^{2^k} - 1$ is divisible by $x + 1$ in $\mathbb{Z}[x]$. Now, letting $x = 2^{2^n}$, we get

$$\frac{F_m - 2}{F_n} = \frac{x^{2^k} - 1}{x + 1} = x^{2^k-1} - x^{2^k-2} + \cdots - 1 \in \mathbb{Z}.$$

Hence, we have $F_n \mid F_m - 2$. Suppose now that $d \mid F_n$ and $d \mid F_m$. Then $d \mid 2$ and $2 \nmid F_n$, which implies that $d = \pm 1$. The result follows. \square

This gives yet another proof of Euclid's theorem, as well as the bound $p_n \leq 2^{2^n} + 1$.

1.2 Elementary Approximations of $\pi(x)$

In 1896, Hadamard and de la Vallée Poussin each proved the Prime Number Theorem independently.

THEOREM 1.11 (Prime Number Theorem). We have

$$\lim_{x \rightarrow \infty} \frac{\pi(x)}{x / \log x} = 1.$$

This was initially conjectured by Gauss. We will prove this theorem later in the course; for now, we will see how to approach this problem using elementary methods.

THEOREM 1.12. For all $x \geq 2$, we have

$$\pi(x) \geq \frac{\log x}{2 \log 2}.$$

Moreover, for all $n \geq 1$, we have $p_n \leq 4^n$.

PROOF. Let $x \geq 2$ be an integer. Let p_1, \dots, p_j be the primes less than or equal to x . Note that we have $j = \pi(x)$ here. For every integer n with $n \leq x$, we can write $n = n_1^2 m$ where n_1 is a positive integer and m is squarefree. Then m is of the form

$$m = p_1^{\varepsilon_1} \cdots p_j^{\varepsilon_j},$$

where $\varepsilon_i \in \{0, 1\}$ for each $1 \leq i \leq j$. We see that there are at most 2^j possible values for m . Moreover, there are at most \sqrt{x} possible values for n_1 . Hence, we have $2^j \sqrt{x} \geq x$, which implies that $2^j \geq \sqrt{x}$. Denote this inequality by (\star) . Since $j = \pi(x)$, we see that

$$\pi(x) \log 2 \geq \frac{\log x}{2},$$

so the first equality follows. For the second equality, take $x = p_n$ so that $\pi(p_n) = n$. By (\star) , we obtain $2^n \geq \sqrt{p_n}$ and hence $4^n \geq p_n$. \square

Let n be a positive integer and let p be a prime. Recall that the exact power of p dividing $n!$ is

$$\sum_{k=1}^{\infty} \left\lfloor \frac{n}{p^k} \right\rfloor = \sum_{k=1}^{\left\lfloor \frac{\log n}{\log p} \right\rfloor} \left\lfloor \frac{n}{p^k} \right\rfloor.$$

THEOREM 1.13. For all $x \geq 2$, we have

$$\left(\frac{3 \log 2}{8} \right) \frac{x}{\log x} < \pi(x) < (6 \log 2) \frac{x}{\log x}.$$

PROOF. This argument was given by Erdős. First, we will prove the lower bound. Note that $\binom{2n}{n}$ is an integer, and

$$\binom{2n}{n} = \frac{(2n)!}{(n!)^2} \left| \prod_{p \leq 2n} p^{r_p} \right|,$$

where r_p is an integer satisfying $p^{r_p} \leq 2n < p^{r_p+1}$. Indeed, note that the exact power of p dividing $(2n)!$ is

$$\sum_{k=1}^{r_p} \left\lfloor \frac{2n}{p^k} \right\rfloor,$$

and the exact power of p dividing $n!$ is

$$\sum_{k=1}^{r_p} \left\lfloor \frac{n}{p^k} \right\rfloor.$$

Thus, the exact power of p dividing $\binom{2n}{n}$ is

$$\sum_{k=1}^{r_p} \left(\left\lfloor \frac{2n}{p^k} \right\rfloor - \left\lfloor \frac{n}{p^k} \right\rfloor \right) \leq r_p,$$

since $\lfloor 2a \rfloor - 2\lfloor a \rfloor \leq 1$ for all $a \in \mathbb{R}$. In particular, we have

$$\binom{2n}{n} \leq \prod_{p \leq 2n} p^{r_p} \leq (2n)^{\pi(2n)}.$$

Notice that

$$\binom{2n}{n} = \frac{2n \cdot (2n-1) \cdots (n+1)}{n \cdot (n-1) \cdots 1} = \frac{2n}{n} \cdots \frac{n+1}{1} \geq 2^n.$$

Hence, we get $2^n \leq (2n)^{\pi(2n)}$. Now, we have

$$\pi(2n) \geq \left(\frac{\log 2}{2} \right) \frac{2n}{\log(2n)}.$$

Recall that $\frac{x}{\log x}$ is increasing for $x > e$. If $x \geq 6$, choose $n \in \mathbb{N}$ such that $3x/4 \leq 2n \leq x$. We see that

$$\pi(x) \geq \pi(2n) \geq \left(\frac{\log 2}{2} \right) \frac{2n}{\log(2n)} \geq \left(\frac{\log 2}{2} \right) \frac{\frac{3}{4}x}{\log(\frac{3}{4}x)} > \frac{3 \log 2}{8} \frac{x}{\log x}.$$

One can manually check that the result holds for $2 \leq x \leq 6$, which finishes the proof of the lower bound.

We now turn to the upper bound. Observe that

$$\prod_{n < p \leq 2n} p \mid \binom{2n}{n},$$

so by the binomial theorem, we have

$$\prod_{n < p \leq 2n} p \leq \binom{2n}{n} \leq (1+1)^{2n} = 2^{2n}.$$

On the other hand, notice that

$$\prod_{n < p \leq 2n} p \geq n^{\pi(2n) - \pi(n)},$$

so it follows that

$$\pi(2n) \log n - \pi(n) \log(n/2) < (\log 2)2n + (\log 2)\pi(n) < (3 \log 2)n.$$

By taking $n = 2^k, 2^{k-1}, \dots, 4$, we obtain a telescoping collection of inequalities, given by

$$\begin{aligned} \pi(2^{k+1}) \log 2^k - \pi(2^k) \log 2^{k-1} &< (3 \log 2)2^k, \\ \pi(2^k) \log 2^{k-1} - \pi(2^{k-1}) \log 2^{k-2} &< (3 \log 2)2^{k-1}, \\ &\vdots \\ \pi(8) \log 4 - \pi(4) \log 2 &< (3 \log 2)4. \end{aligned}$$

Putting these inequalities together, we have

$$\pi(2^{k+1}) \log 2^k < (3 \log 2)(2^k + 2^{k-1} + \cdots + 4) + \pi(4) \log 2 < (3 \log 2)2^{k+1},$$

and hence

$$\pi(2^{k+1}) < (3 \log 2) \left(\frac{2^{k+1}}{\log(2^k)} \right).$$

If $x > e$, choose k such that $2^k \leq x \leq 2^{k+1}$. Then $\pi(x) \leq \pi(2^{k+1})$, and so

$$\pi(x) \leq (3 \log 2) \left(\frac{2^{k+1}}{\log(2^k)} \right) \leq (6 \log 2) \left(\frac{2^k}{\log(2^k)} \right) \leq (6 \log 2) \left(\frac{x}{\log x} \right),$$

where in the last equality, we use the fact that $\frac{x}{\log x}$ is increasing for $x > e$. The values $2 \leq x \leq e$ can be checked manually, proving the lower bound. \square

We should note that $\frac{3 \log 2}{8}$ is in some sense arbitrary. In the proof, we could have picked $n \in \mathbb{N}$ such that $1 - \varepsilon \leq 2n \leq x$ instead of $3x/4 \leq 2n \leq x$ for ε arbitrarily small. However, this comes at the cost that the bound may potentially fail for small x , and there is little purpose in a better lower bound for large x as it is overshadowed by the Prime Number Theorem.

1.3 Bertrand's Postulate

In 1845, Bertrand showed that there is always a prime p in the interval $[n, 2n]$ for $n \in \mathbb{Z}^+$ provided that $n < 6 \cdot 10^6$, and he had conjectured that this holds for all $n \in \mathbb{Z}^+$. Chebyshev proved that this was indeed the case in 1950. Note that this is not a trivial result; it doesn't occur for free just because $\pi(x) \sim x/\log x$.

PROPOSITION 1.14. For all $n \in \mathbb{Z}^+$, we have

$$\prod_{p \leq n} p < 4^n.$$

PROOF. The result is clearly true for $n = 1$ and $n = 2$. Suppose that it holds for all $1 \leq n \leq k - 1$. Note that we can restrict our attention to the case where n is odd, because if n is even and $n > 2$, then

$$\prod_{p \leq n} p = \prod_{p \leq n-1} p,$$

and the result will follow by induction. Write $n = 2m + 1$ for some $m \in \mathbb{Z}^+$, and consider $\binom{2m+1}{m}$. In particular, we have

$$\prod_{m+1 < p \leq 2m+1} p \mid \binom{2m+1}{m}.$$

Since $\binom{2m+1}{m}$ and $\binom{2m+1}{m+1}$ both appear in the binomial expansion of $(1+1)^{2m+1}$ with $\binom{2m+1}{m} = \binom{2m+1}{m+1}$, we obtain

$$\binom{2m+1}{m} \leq \frac{1}{2} (2^{2m+1}) = 4^m.$$

By our inductive hypothesis and the previous inequality, it follows that

$$\prod_{p \leq 2m+1} p = \left(\prod_{p \leq m+1} p \right) \left(\prod_{m+1 < p \leq 2m+1} p \right) \leq 4^{m+1} 4^m = 4^{2m+1}. \quad \square$$

LEMMA 1.15. If $n \geq 3$ and p is a prime with $\frac{2}{3}n < p \leq n$, then $p \nmid \binom{2n}{n}$.

PROOF. Since $n \geq 3$, we see that if p is in the range $\frac{2}{3}n < p \leq n$, then $p > 2$. Then p and $2p$ are the only multiples of p at most $2n$, and so

$$p^2 \parallel (2n)!,$$

where we write $p^k \parallel b$ to mean that $p^{k+1} \nmid b$ and $p^k \mid b$. Furthermore, since $\frac{2}{3}n < p \leq n$, we have $p \parallel n!$ and hence $p^2 \parallel (n!)^2$. Using the identity

$$\binom{2n}{n} = \frac{(2n)!}{(n!)^2},$$

we see that $p \nmid \binom{2n}{n}$. \square

THEOREM 1.16 (Chebyshev). For every $n \in \mathbb{Z}^+$, there exists a prime satisfying $n < p \leq 2n$.

PROOF. This argument was given by Erdős. Note that the result holds for $1 \leq n \leq 3$. Assume that the result is false for some integer $n \geq 4$. By Lemma 1.15, every prime dividing $\binom{2n}{n}$ is at most $\frac{2}{3}n$.

Let p be a prime divisor of $\binom{2n}{n}$ where we have $p \leq \frac{2}{3}n$. Suppose that $p^{\alpha_p} \parallel \binom{2n}{n}$ for some integer α_p . Recall that in the proof of Theorem 1.13, we defined r_p to be the integer satisfying $p^{r_p} \leq 2n < p^{r_p+1}$. Then we have $\alpha_p \leq r_p$, and hence $p^{\alpha_p} \leq p^{r_p} \leq 2n$.

If $\alpha_p \geq 2$, then $p^2 \leq p^{\alpha_p} \leq 2n$ so that $p \leq \sqrt{2n}$. By Proposition 1.14, we have

$$\binom{2n}{n} \leq \left(\prod_{\substack{p \leq \frac{2}{3}n \\ \alpha_p \leq 1}} p \right) \left(\prod_{\substack{p \leq \frac{2}{3}n \\ \alpha_p \geq 2}} p \right) \leq 4^{2n/3} (2n)^{\pi(\sqrt{2n})} \leq 4^{2n/3} (2n)^{\sqrt{2n}}.$$

Note that $\binom{2n}{n}$ is the largest of the $2n+1$ terms in the binomial expansion of

$$(1+1)^{2n} = \binom{2n}{0} + \binom{2n}{1} + \cdots + \binom{2n}{2n},$$

so we get

$$\binom{2n}{n} \geq \frac{2^{2n}}{2n+1}.$$

Combining the above inequalities gives

$$\frac{4^n}{2n+1} \leq \binom{2n}{n} \leq 4^{2n/3} (2n)^{\sqrt{2n}},$$

which implies that

$$4^{n/3} \leq (2n)^{\sqrt{2n}} (2n+1) < (2n)^{\sqrt{2n}+2}.$$

One can check manually that the result holds for $4 \leq n \leq 16$, so assume that $n > 16$. Taking logarithms, we find that

$$\frac{n}{3} \log 4 < (\sqrt{2n} + 2) \log(2n) < 2\sqrt{n} \log(2n) < 2\sqrt{n} \log(n^{5/4}) < \frac{5}{2} \sqrt{n} \log n.$$

Notice that $\frac{\sqrt{n}}{\log n}$ is increasing for $n > e^2$. Putting this together with the fact that

$$\frac{\sqrt{1600}}{\log 1600} \approx 5.421 > 5.410 \approx \frac{15}{2 \log 4},$$

we have $n \leq 1600$. Finally, we know that $\{2, 3, 5, 7, 13, 23, 43, 83, 163, 317, 557, 1109, 2207\}$ are all primes, where each number in the set is the largest prime less than twice the previous one. Thus, no counterexample exists, and the result holds for all $n \geq 4$. \square

1.4 Gaps Between Twin Primes

By Theorem 1.16, we have

$$p_{n+1} - p_n \leq p_n$$

as there is a prime between p_n and $2p_n$. What more can we say about differences of consecutive primes?

By the Prime Number Theorem, there are about $x/\log x$ primes p at most x . Therefore, the “average gap” between primes p at most x is $\log x$. However, the value of $p_{n+1} - p_n$ can vary widely.

Notice that for any $n \geq 2$, the numbers $n! + k$ for $2 \leq k \leq n$ are all composite. This implies that

$$\limsup_{n \rightarrow \infty} (p_{n+1} - p_n) = \infty.$$

In 1931, Weszynthius showed that

$$\limsup_{n \rightarrow \infty} \left(\frac{p_{n+1} - p_n}{\log p_n} \right) = \infty.$$

By probabilistic reasoning, Cramer had conjectured in 1936 that

$$\limsup_{n \rightarrow \infty} \left(\frac{p_{n+1} - p_n}{(\log p_n)^2} \right) \leq 1.$$

In the 1930s, Erdős proved that for infinitely many integers n , we have

$$p_{n+1} - p_n > c \log p_n \frac{\log \log p_n}{(\log \log \log p_n)^2}$$

for some positive constant c . In 1938, Rankin added a factor of $\log \log \log \log p_n$.

What about small gaps between consecutive primes? The famous Twin Prime Conjecture states that there are infinitely many $n \in \mathbb{Z}^+$ such that $p_{n+1} - p_n = 2$. Equivalently, it can be stated that

$$\liminf_{n \rightarrow \infty} (p_{n+1} - p_n) = 2.$$

If we assume that the primes are randomly distributed and an integer is prime with probability $1/\log x$, then we might expect x and $x + 2$ to both be prime with probability $1/(\log x)^2$.

Therefore, we expect about $x/(\log x)^2$ primes p such that $p + 2$ is also prime and $p \leq x$. A more careful heuristic suggests that there are about $Cx/(\log x)^2$ such primes p where $C > 0$ and $C \neq 1$. In the 1960s, Chen proved that there are more than $0.6x/(\log x)^2$ primes p with $p \leq x$ such that $p + 2$ is a product of at most two primes (called a P_2), provided that x is sufficiently large.

In 2005, Goldston, Pintz, and Yildirim showed that

$$\liminf_{n \rightarrow \infty} \left(\frac{p_{n+1} - p_n}{\log p_n} \right) = 0.$$

However, this is still quite far from the Twin Prime Conjecture; the bound between consecutive primes can still go to infinity.

Astoundingly, Zhang made a breakthrough in 2013 and showed that

$$\liminf_{n \rightarrow \infty} (p_{n+1} - p_n) \leq 7 \cdot 10^7.$$

This was independently improved by Tao and Maynard (via the Polymath Project) in the same year to get

$$\liminf_{n \rightarrow \infty} (p_{n+1} - p_n) \leq 246.$$

2 Asymptotic Analysis for $\pi(x)$

2.1 The Möbius Function

DEFINITION 2.1. Let f and g be functions from \mathbb{N} or \mathbb{R}^+ to \mathbb{R} , and suppose that g maps to \mathbb{R}^+ .

- (1) We write $f = O(g)$ if there exist constants $c_1, c_2 > 0$ such that for all $x > c_1$, we have $|f(x)| \leq c_2 g(x)$.
- (2) We write $f = o(g)$ if $\lim_{n \rightarrow \infty} f(n)/g(n) = 0$.
- (3) We write $f \sim g$ if $\lim_{n \rightarrow \infty} f(n)/g(n) = 1$, and we say that f is **asymptotic** to g .

By the Prime Number Theorem, we have $\pi(x) \sim x/\log x$, or equivalently,

$$\pi(x) = \frac{x}{\log x} + o\left(\frac{x}{\log x}\right). \quad (2.1)$$

REMARK 2.2. Let $\varepsilon > 0$. Then the number of primes in the interval $[x, (1 + \varepsilon)x]$ is

$$\pi((1 + \varepsilon)x) - \pi(x) = \frac{(1 + \varepsilon)x}{\log((1 + \varepsilon)x)} - \frac{x}{\log x} + o\left(\frac{x}{\log x}\right).$$

Notice that

$$\frac{(1 + \varepsilon)x}{\log((1 + \varepsilon)x)} = \frac{(1 + \varepsilon)x}{\log x + \log(1 + \varepsilon)} = \frac{(1 + \varepsilon)x}{(\log x)(1 + \log(1 + \varepsilon)/\log x)} = \frac{(1 + \varepsilon)x}{\log x} + o\left(\frac{x}{\log x}\right).$$

Therefore, it follows that

$$\pi((1 + \varepsilon)x) - \pi(x) = \frac{(1 + \varepsilon)x}{\log x} - \frac{x}{\log x} + o\left(\frac{x}{\log x}\right) = \frac{\varepsilon x}{\log x} + o\left(\frac{x}{\log x}\right).$$

By taking $\varepsilon = 1$, we have

$$\pi(2x) - \pi(x) = \frac{x}{\log x} + o\left(\frac{x}{\log x}\right). \quad (2.2)$$

Equation (2.2) might look odd together with equation (2.1). Nonetheless, the result is correct; it's just that the bounds in the notation o are different.

DEFINITION 2.3. We define the **Möbius function** on \mathbb{N} by

$$\mu(n) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{if } n \text{ is not squarefree,} \\ (-1)^r & \text{if } n \text{ is a product of } r \text{ distinct primes.} \end{cases}$$

For example, we have $\mu(48) = \mu(2^4 \cdot 3) = 0$ and $\mu(30) = \mu(2 \cdot 3 \cdot 5) = (-1)^3 = -1$.

PROPOSITION 2.4. We have

$$\sum_{d|n} \mu(d) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{otherwise,} \end{cases}$$

where $\sum_{d|n}$ means that the summation runs through the positive divisors d of n .

PROOF. The result is true for $n = 1$. For $n > 1$, let $n = p_1^{a_1} \cdots p_r^{a_r}$ be the unique factorization of n into distinct prime numbers. Set $N = p_1 \cdots p_r$ (which is called the **radical** of n). Since $\mu(d) = 0$ when d is not squarefree, we have

$$\sum_{d|n} \mu(d) = \sum_{d|N} \mu(d).$$

Note that the divisors of N are in bijective correspondence with the subsets of $\{p_1, \dots, p_r\}$. Since the number of k element subsets is $\binom{r}{k}$ and the corresponding divisor d of such a set satisfies $\mu(d) = (-1)^k$, we have

$$\sum_{d|N} \mu(d) = \sum_{d|N} \mu(d) = \sum_{k=0}^r \binom{r}{k} (-1)^k = (1-1)^r = 0. \quad \square$$

PROPOSITION 2.5 (Möbius Inversion Formula).

(1) For two functions $f, g : \mathbb{R}^+ \rightarrow \mathbb{C}$, we have

$$g(x) = \sum_{1 \leq n \leq x} f(x/n)$$

if and only if

$$f(x) = \sum_{1 \leq n \leq x} \mu(n)g(x/n).$$

(2) For two functions $f, g : \mathbb{N} \rightarrow \mathbb{C}$, we have

$$f(n) = \sum_{d|n} g(d)$$

if and only if

$$g(n) = \sum_{d|n} \mu(d)f(n/d).$$

PROOF. This is on Homework 1. \square

2.2 The von Mangoldt Function

DEFINITION 2.6. We define the **von Mangoldt function** on \mathbb{N} by

$$\Lambda(n) = \begin{cases} \log p & \text{if } n = p^k \text{ for } p \text{ prime and } k \in \mathbb{N}, \\ 0 & \text{otherwise.} \end{cases}$$

Moreover, for all $x \in \mathbb{R}$, we define the functions

$$\begin{aligned} \theta(x) &= \sum_{p \leq x} \log p = \log \prod_{p \leq x} p, \\ \psi(x) &= \sum_{p^k \leq x} \log p = \sum_{n \leq x} \Lambda(n). \end{aligned}$$

Notice that

$$\psi(x) = \sum_{p \leq x} \left\lfloor \frac{\log x}{\log p} \right\rfloor \log p.$$

Since $p^2 \leq x$ is equivalent to $p \leq x^{1/2}$ and $p^3 \leq x$ if and only if $p \leq x^{1/3}$, we see that

$$\psi(x) = \theta(x) + \theta(x^{1/2}) + \theta(x^{1/3}) + \dots$$

Note that $\theta(x^{1/m}) = 0$ when $m > \frac{\log x}{\log 2}$. Therefore, we get

$$\psi(x) = \sum_{k=1}^{\left\lfloor \frac{\log x}{\log 2} \right\rfloor} \theta(x^{1/k}).$$

Observe that we have the inequality

$$\theta(x) = \sum_{p \leq x} \log p \leq x \log x,$$

so it follows that

$$\sum_{k \geq 2} \theta(x^{1/k}) = O\left(x^{1/2}(\log x)^2\right).$$

Therefore, we obtain

$$\psi(x) = \theta(x) + O\left(x^{1/2}(\log x)^2\right)$$

and so by Theorem 1.12, we get

$$\theta(x) = \sum_{p \leq x} \log p \leq \pi(x) \log x < c_1 x$$

for $x \geq 2$ and a constant $c_1 > 0$. Similarly, one finds that $\psi(x) < c_2 x$ for $x \geq 2$ and a positive constant c_2 . Furthermore, from the proof of Theorem 1.12, we have $2^n \leq \binom{2n}{n}$ and $\binom{2n}{n} \mid \prod_{p \leq 2n} p^{r_p}$, where r_p is the integer satisfying $p^{r_p} \leq 2n < p^{r_p+1}$. It follows that

$$n \log 2 = \log(2^n) \leq \log \binom{2n}{n} \leq \sum_{p \leq 2n} r_p \log p \leq \sum_{p \leq 2n} \left\lfloor \frac{\log(2n)}{\log p} \right\rfloor \log p \leq \psi(2n).$$

For $x \geq 2$, choosing n such that $2n \leq x < 2n + 2$ gives

$$\psi(x) \geq \psi(2n) \geq n \log 2 > \frac{x-2}{2} \log 2.$$

Hence, we have $\psi(x) > c_3 x$ and $\theta(x) > c_4 x$ for positive constants c_3 and c_4 .

What is the relationship between $\theta(x)$, $\psi(x)$, and $\pi(x)$? We note that

$$\theta(x) = \sum_{p \leq x} \log p \leq x \log p \leq \pi(x) \log x,$$

so it follows that

$$\pi(x) \geq \frac{\theta(x)}{\log x} > c_4 \frac{x}{\log x}.$$

THEOREM 2.7. We have

$$\pi(x) \sim \frac{\theta(x)}{\log x} \sim \frac{\psi(x)}{\log x}.$$

PROOF. Since $\psi(x) = \theta(x) + O(x^{1/2}(\log x)^2)$ and $\theta(x) > c_4 x$, we see that $\theta(x) \sim \psi(x)$. In particular, we have $\theta(x)/\log x \sim \psi(x)/\log x$, so it only remains to show that $\pi(x) \sim \theta(x)/\log x$.

We have already shown that $\pi(x) \geq \theta(x)/\log x$, so

$$\liminf_{n \rightarrow \infty} \frac{\pi(x) \log x}{\theta(x)} \geq 1.$$

We need an upper bound for $\pi(x)$ in terms of $\theta(x)$. Note that for any $\delta > 0$, we have

$$\theta(x) = \sum_{p \leq x} \log p \geq \log(x^{1-\delta}) \sum_{x^{1-\delta} \leq p \leq x} 1 \geq (1-\delta)(\log x) (\pi(x) - \pi(x^{1-\delta})).$$

Since $\pi(y) \leq y$ for all real numbers $y > 0$, we get

$$\theta(x) + (1-\delta)x^{1-\delta} \log x \geq (1-\delta)(\log x)\pi(x).$$

Rearranging the above gives

$$\frac{\theta(x)}{(1-\delta)\log x} + x^{1-\delta} \geq \pi(x),$$

and therefore

$$\frac{1}{1-\delta} + \frac{x^{1-\delta}\log x}{\theta(x)} \geq \frac{\pi(x)\log x}{\theta(x)}.$$

Given $\varepsilon > 0$, we can choose $\delta > 0$ such that $\frac{1}{1-\delta} < 1 + \frac{\varepsilon}{2}$, and then pick x_0 such that if $x > x_0$, then

$$\frac{x^{1-\delta}\log x}{\theta(x)} < \frac{\varepsilon}{2}$$

since $\theta(x) > c_1 x$ for $x \geq 2$. Then for all $x > x_0$, we have

$$1 \leq \frac{\pi(x)\log x}{\theta(x)} < 1 + \varepsilon,$$

which completes the proof. \square

2.3 Abel's Summation Formula

We will prove Abel's summation formula and give some of its applications.

LEMMA 2.8 (Abel's summation formula). Let $\{a_n\}_{n=1}^{\infty}$ be a sequence of complex numbers. Let $f : \{x \in \mathbb{R} : x \geq 1\} \rightarrow \mathbb{C}$ be a function. For all $x \geq 1$, we define

$$A(x) := \sum_{n \leq x} a_n,$$

where the summation runs through all positive integers up to x . If f' is continuous at every $x \geq 1$, then

$$\sum_{n \leq x} a_n f(n) = A(x)f(x) - \int_1^x A(u)f'(u) du.$$

PROOF. Set $N = \lfloor x \rfloor$. Note that $a_n = A(n) - A(n-1)$ for all $n \geq 2$, so we can write

$$\begin{aligned} \sum_{n \leq N} a_n f(n) &= A(1)f(1) + (A(2) - A(1))f(2) + \cdots + (A(N) - A(N-1))f(N) \\ &= A(1)(f(1) - f(2)) + \cdots + A(N-1)(f(N-1) - f(N)) + A(N)f(N). \end{aligned}$$

Observe that if $i \in \mathbb{Z}^+$ and $t \in \mathbb{R}$ with $i \leq t < i+1$, then $A(t) = A(i)$. It follows that

$$A(i)(f(i) - f(i+1)) = - \int_i^{i+1} A(u)f'(u) du.$$

Therefore, we have

$$\sum_{n \leq N} a_n f(n) = - \int_1^N A(u)f'(u) du + A(N)f(N),$$

so the result holds when x is an integer. Now, notice that $A(t) = A(N)$ for all $x \geq t \geq N$, so we obtain

$$\int_N^x A(u)f'(u) du = A(x)(f(x) - f(N)) = A(x)f(x) - A(N)f(N).$$

Thus, the result holds for all $x \geq 1$. \square

DEFINITION 2.9. Given $x \in \mathbb{R}$, we denote the **fractional part** of x by $\{x\}$; that is,

$$\{x\} := x - \lfloor x \rfloor.$$

We define **Euler's constant** by

$$\gamma := 1 - \int_1^\infty \frac{\{t\}}{t^2} dt = 1 - \int_1^\infty \frac{t - \lfloor t \rfloor}{t^2} dt.$$

Note that $\gamma \approx 0.55721$.

This has not been proven, but it has been conjectured that γ is irrational and transcendental.

THEOREM 2.10. We have

$$\sum_{n \leq x} \frac{1}{n} = \log x + \gamma + O\left(\frac{1}{x}\right).$$

PROOF. Taking $a_n = 1$ and $f(t) = 1/t$ in Abel's summation formula, we have

$$A(x) = \sum_{n \leq x} a_n = \sum_{n \leq x} 1 = \lfloor x \rfloor$$

so that

$$\begin{aligned} \sum_{n \leq x} \frac{1}{n} &= \frac{\lfloor x \rfloor}{x} + \int_1^x \frac{\lfloor u \rfloor}{u^2} du \\ &= \frac{x - (x - \lfloor x \rfloor)}{x} + \int_1^x \frac{u - (u - \lfloor u \rfloor)}{u^2} du \\ &= 1 + O\left(\frac{1}{x}\right) + \int_1^x \frac{du}{u} - \int_1^x \frac{u - \lfloor u \rfloor}{u^2} du \\ &= 1 + O\left(\frac{1}{x}\right) + \log x - \left(\int_1^\infty \frac{u - \lfloor u \rfloor}{u^2} du - \int_x^\infty \frac{u - \lfloor u \rfloor}{u^2} du \right) \\ &= \log x + \gamma + O\left(\frac{1}{x}\right) + \int_x^\infty \frac{u - \lfloor u \rfloor}{u^2} du \\ &= \log x + \gamma + O\left(\frac{1}{x}\right) + O\left(\int_x^\infty \frac{1}{u^2} du\right) \\ &= \log x + \gamma + O\left(\frac{1}{x}\right). \end{aligned}$$

□

THEOREM 2.11. We have

$$\sum_{n \leq x} \frac{\Lambda(n)}{n} = \log x + O(1).$$

PROOF. First, we apply Abel's summation formula with $a_n = 1$ and $f(n) = \log n$ to get

$$\begin{aligned} \sum_{n \leq x} \log n &= \lfloor x \rfloor \log x - \int_1^x \frac{\lfloor u \rfloor}{u} du \\ &= (x - (x - \lfloor x \rfloor)) \log x - \int_1^x \frac{u - (u - \lfloor u \rfloor)}{u} du \\ &= x \log x + O(\log x) - (x - 1) + \int_1^x \frac{u - \lfloor u \rfloor}{u} du \\ &= x \log x - x + O(\log x). \end{aligned}$$

On the other hand, we have

$$\begin{aligned}
 \sum_{n \leq x} \log n &= \log(\lfloor x \rfloor!) = \sum_{p \leq x} \left(\sum_{k=1}^{\infty} \left\lfloor \frac{x}{p^k} \right\rfloor \right) \log p \\
 &= \sum_{p^m \leq x} \left\lfloor \frac{x}{p^m} \right\rfloor \log p \\
 &= \sum_{n \leq x} \left\lfloor \frac{x}{n} \right\rfloor \Lambda(n) \\
 &= \sum_{n \leq x} \frac{x}{n} \Lambda(n) - \sum_{n \leq x} \left(\frac{x}{n} - \left\lfloor \frac{x}{n} \right\rfloor \right) \Lambda(n) \\
 &= x \sum_{n \leq x} \frac{\Lambda(n)}{n} - O \left(\sum_{n \leq x} \Lambda(n) \right).
 \end{aligned}$$

Since $\sum_{n \leq x} \Lambda(n) = \psi(x) = O(x)$, we have

$$\sum_{n \leq x} \log x = x \sum_{n \leq x} \frac{\Lambda(n)}{n} - O(n).$$

By the asymptotic formula of $\sum_{n \leq x} \log n$ above, we see that

$$x \log x - x + O(\log x) = x \sum_{n \leq x} \frac{\Lambda(n)}{n} - O(x).$$

Rearranging and tucking some terms under $O(x)$ gives

$$x \sum_{n \leq x} \frac{\Lambda(n)}{n} = x \log x + O(x).$$

Finally, dividing through by x gives

$$\sum_{n \leq x} \frac{\Lambda(n)}{n} = \log x + O(1). \quad \square$$

THEOREM 2.12. We have

$$\sum_{p \leq x} \frac{\log p}{p} = \log x + O(1).$$

PROOF. Note that

$$\sum_{p \leq x} \frac{\log p}{p} = \sum_{n \leq x} \frac{\Lambda(n)}{n} - \sum_{m \geq 2} \sum_{p^m \leq x} \frac{\log p}{p^m} = \log x + O(1) - \sum_{m \geq 2} \sum_{p^m \leq x} \frac{\log p}{p^m}.$$

Moreover, we see that

$$\sum_{m \geq 2} \sum_{p^m \leq x} \frac{\log p}{p^m} \leq \sum_p \left(\frac{1}{p^2} + \frac{1}{p^3} + \cdots \right) \log p \leq \sum_p \frac{\log p}{p(p-1)} \leq \sum_{n=2}^{\infty} \frac{\log n}{n(n-1)} = O(1),$$

which completes the proof. \square

THEOREM 2.13 (Merten). There exists a real number β such that

$$\sum_{p \leq x} \frac{1}{p} = \log \log x + \beta + O \left(\frac{1}{\log x} \right).$$

PROOF. We apply Abel's summation formula with

$$a_n = \begin{cases} \frac{\log p}{p} & \text{if } n = p \text{ for a prime } p \\ 0 & \text{otherwise} \end{cases}$$

and $f(n) = 1/\log n$. Setting $A(x) = \sum_{n \leq x} a_n$, we have

$$\sum_{p \leq x} \frac{1}{p} = \frac{A(x)}{\log x} + \int_1^x \frac{A(u)}{u(\log u)^2} du.$$

By Theorem 2.12, we have

$$A(x) = \sum_{p \leq x} \frac{\log p}{p} = \log x + O(1),$$

so we see that

$$\sum_{p \leq x} \frac{1}{p} = 1 + O\left(\frac{1}{\log x}\right) + \int_2^x \frac{\log u + \tau(u)}{u(\log u)^2} du,$$

where $\tau(u) = A(u) - \log u = O(1)$. Therefore, we have

$$\begin{aligned} \sum_{p \leq x} \frac{1}{p} &= 1 + O\left(\frac{1}{\log x}\right) + \log \log x - \log \log 2 + \int_2^x \frac{\tau(u)}{u(\log u)^2} du \\ &= \log \log x + 1 - \log \log 2 + \int_2^\infty \frac{\tau(u)}{u(\log u)^2} du - \int_x^\infty \frac{\tau(u)}{u(\log u)^2} du + O\left(\frac{1}{\log x}\right). \end{aligned}$$

By setting β to the middle terms above, we are done. □

In fact, we have

$$\beta = \gamma + \sum_p \left[\log \left(1 - \frac{1}{p} \right) + \frac{1}{p} \right] \approx 0.261497,$$

and β is called **Merten's constant**.

3 Riemann's Zeta Function and the Prime Number Theorem

3.1 The Riemann Zeta Function

In order to prove the Prime Number Theorem, we need to first introduce the Riemann zeta function.

DEFINITION 3.1. For $s \in \mathbb{C}$ with $\operatorname{Re}(s) > 1$, we define the **Riemann zeta function** by

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

We will denote $s = \sigma + it$ where $\sigma, t \in \mathbb{R}$.

Note that the series $\sum_{n=1}^{\infty} n^{-s}$ converges absolutely when $\operatorname{Re}(s) > 1$.

Recall that the infinite product $\prod_n (1 + a_n)$ converges absolutely (that is, it is finite and non-zero) if and only if $\sum_n |a_n|$ converges. We have the **Euler product representation** of $\zeta(s)$ given in the following lemma.

LEMMA 3.2 (Euler product). For $s \in \mathbb{C}$ with $\operatorname{Re}(s) > 1$, we have

$$\prod_p \left(1 - \frac{1}{p^s}\right)^{-1} = \sum_{n=1}^{\infty} \frac{1}{n^s}.$$

PROOF. Note that

$$\prod_p \left(1 - \frac{1}{p^s}\right)^{-1} = \prod_p \left(1 + \frac{1}{p^2} + \frac{1}{p^3} + \cdots\right).$$

A typical term in the sum is of the form

$$\frac{1}{p_1^{\alpha_1 s} \cdots p_k^{\alpha_k s}} = \frac{1}{(p_1^{\alpha_1} \cdots p_k^{\alpha_k})^s}.$$

By the Fundamental Theorem of Arithmetic, every positive integer can be expressed uniquely as a product of primes, so the identity holds. \square

THEOREM 3.3. $\zeta(s)$ can be analytically continued to $s \in \mathbb{C}$ with $\operatorname{Re}(s) > 0$ and $s \neq 1$. It is analytic except at the point $s = 1$ where it has a simple pole with residue 1.

PROOF. For $s \in \mathbb{C}$ with $\operatorname{Re}(s) > 1$, we have $\zeta(s) = \sum_{n=1}^{\infty} n^{-s}$. By Abel's summation formula with $a_n = 1$ and $f(x) = x^{-s}$, we find that

$$\sum_{n \leq x} \frac{1}{n^s} = \frac{\lfloor x \rfloor}{x^s} + s \int_1^x \frac{\lfloor u \rfloor}{u^{s+1}} du.$$

Letting $x \rightarrow \infty$, we obtain

$$\begin{aligned} \zeta(s) &= 0 + s \int_1^{\infty} \frac{\lfloor u \rfloor}{u^{s+1}} du \\ &= s \int_1^{\infty} \frac{u - (u - \lfloor u \rfloor)}{u^{s+1}} du \\ &= s \int_1^{\infty} \frac{u}{u^{s+1}} du - s \int_1^{\infty} \frac{u - \lfloor u \rfloor}{u^{s+1}} du \\ &= s \left(\frac{u^{1-s}}{1-s} \Big|_1^{\infty} \right) - s \int_1^{\infty} \frac{u - \lfloor u \rfloor}{u^{s+1}} du \\ &= \frac{s}{s-1} - s \int_1^{\infty} \frac{u - \lfloor u \rfloor}{u^{s+1}} du \end{aligned}$$

for $\operatorname{Re}(s) > 1$. Note that

$$\int_1^\infty \frac{u - \lfloor u \rfloor}{u^{s+1}} du$$

converges for $\operatorname{Re}(s) > 0$ and represents an analytic function. Therefore, we see that

$$\frac{s}{s-1} - s \int_1^\infty \frac{u - \lfloor u \rfloor}{u^{s+1}} du$$

is an analytic function for $\operatorname{Re}(s) > 0$ with $s \neq 1$. This gives a meromorphic continuation of $\zeta(s)$ to the region $\{s \in \mathbb{C} : \operatorname{Re}(s) > 0\}$. Finally, note that $\frac{s}{s-1}$ has a simple pole with residue 1 at $s = 1$. \square

THEOREM 3.4. $\zeta(s)$ has no zeroes in the region $\{s \in \mathbb{C} : \operatorname{Re}(s) \geq 1\}$.

PROOF. If $\operatorname{Re}(s) > 1$, then $\prod_p (1 - \frac{1}{p^s})^{-1}$ converges, so $\zeta(s) \neq 0$.

It only remains to consider the case where $\operatorname{Re}(s) = 1$. We will first do some preliminary work.

Recall that we denote $s = \sigma + it$ where $\sigma, t \in \mathbb{R}$. Let $\sigma > 1$. Then for all $t \in \mathbb{R}$, we have

$$\log^*(\zeta(\sigma + it)) = \log \left(\prod_p \left(1 + \frac{1}{p^s} \right)^{-1} \right) = \sum_p \sum_{n=1}^\infty \frac{1}{n} \left(\frac{1}{p^{ns}} \right),$$

where \log denotes the principal branch and \log^* denotes some branch of the logarithm (we have to be careful here as we are considering complex numbers). Comparing the real parts of the above equality, we have

$$\log |\zeta(\sigma + it)| = \sum_p \sum_{n=1}^\infty \frac{p^{-\sigma n} \cos(nt \log p)}{n},$$

since we can write

$$p^{-int} = e^{-int \log p} = \cos(-nt \log p) + i \sin(-nt \log p) = \cos(nt \log p) - i \sin(nt \log p)$$

and therefore $\operatorname{Re}(p^{-int}) = \cos(nt \log p)$. Moreover, observe that we have the inequality

$$\begin{aligned} 0 &\leq 2(1 + \cos \theta)^2 = 2(1 + 2 \cos \theta + \cos^2 \theta) \\ &= 2 + 4 \cos \theta + 2 \cos^2 \theta \\ &= 3 + 4 \cos \theta + (2 \cos^2 \theta - 1) \\ &= 3 + 4 \cos \theta + \cos(2\theta). \end{aligned}$$

From this, we can deduce that

$$\sum_p \sum_{n=1}^\infty \frac{p^{-\sigma n}}{n} (3 + 4 \cos(nt \log p) + \cos(2nt \log p)) \geq 0.$$

Therefore, we have

$$\log |\zeta(\sigma)|^3 + \log |\zeta(\sigma + it)|^4 + \log |\zeta(\sigma + 2it)| \geq 0.$$

In particular, we see that

$$|\zeta(\sigma)|^3 \cdot |\zeta(\sigma + it)|^4 \cdot |\zeta(\sigma + 2it)| \geq 1 \tag{3.1}$$

for $\sigma > 1$ and $t \in \mathbb{R}$.

Suppose now that $1 + it_0$ is a zero of $\zeta(s)$, and note that $t_0 \neq 0$ as $\zeta(s)$ has a pole at $s = 1$. By taking $t \rightarrow 1^+$ (that is, from the right), we observe that

$$|\zeta(s)| = O((\sigma - 1)^{-1})$$

since 1 is a simple pole of $\zeta(s)$. Moreover, since $1 + it_0$ is a zero of $\zeta(s)$, we have $|\zeta(\sigma + it_0)| = O(\sigma - 1)$ as $\sigma \rightarrow 1^+$. Finally, we have $|\zeta(\sigma + 2it_0)| = O(1)$ as $\sigma \rightarrow 1^+$ since $1 + 2it_0$ is not a simple pole of $\zeta(s)$. It follows that

$$|\zeta(\sigma)|^3 \cdot |\zeta(\sigma + it)|^4 \cdot |\zeta(\sigma + 2it)| = O((\sigma - 1)^{-3}) \cdot O((\sigma - 1)^4) \cdot O(1) = O(\sigma - 1).$$

Thus, $|\zeta(s)|^3 \cdot |\zeta(\sigma + it)|^4 \cdot |\zeta(\sigma + 2it)|$ tends to 0 as $\sigma \rightarrow 1^+$. But this contradicts that the lower bound we found in ((3.1)), so we conclude that $\zeta(s)$ cannot have a zero when $\operatorname{Re}(s) = 1$. \square

3.2 Newman's Theorem

THEOREM 3.5 (Newman). Let $\{a_n\}_{n=1}^\infty$ be a sequence of complex numbers with $|a_n| \leq 1$ for all $n \geq 1$. Consider the series $\sum_{n=1}^\infty a_n/n^s$, which converges to an analytic function $F(s)$ for $\operatorname{Re}(s) > 1$. If $F(s)$ can be analytically continued to $\operatorname{Re}(s) \geq 1$, then $\sum_{n=1}^\infty a_n/n^s$ converges to $F(s)$ for $\operatorname{Re}(s) \geq 1$.

PROOF. Let $w \in \mathbb{C}$ with $\operatorname{Re}(w) \geq 1$. Then $F(z + w)$ is analytic for $\operatorname{Re}(z) \geq 0$. Choose $R \geq 1$ and let $\delta = \delta(R) > 0$ so that $F(z + w)$ is analytic on the region

$$\tilde{\Gamma} := \{z \in \mathbb{C} : \operatorname{Re}(z) \geq -\delta \text{ and } |z| \leq R\}.$$

To see why such a $\delta > 0$ exists, first note that $F(z + w)$ is analytic for $\operatorname{Re}(z) \geq 0$. Consider the line $L = \{z = iy : |y| \leq R\}$. Every point in L has an open cover such that $F(z + w)$ is analytic on that cover; call the union of these covers U . Since L is compact¹, there exists a finite open subcover \tilde{U} of U such that $L \subseteq \tilde{U} \subseteq U$. Since the number of open sets in \tilde{U} is finite, it follows that such a $\delta > 0$ exists.

Let M denote the maximum of $|F(z + w)|$ on $\tilde{\Gamma}$, and let Γ denote the contour obtained by following the outside of $\tilde{\Gamma}$ in a counterclockwise path. Let A be the part of Γ in $\operatorname{Re}(z) > 0$, and let $B = \Gamma \setminus A$. For $N \in \mathbb{N}$, consider the function

$$F(z + w)N^z \left(\frac{1}{z} + \frac{z}{R^2} \right),$$

which is analytic on $\tilde{\Gamma}$ except at $z = 0$ where there is a simple pole with residue $F(0 + w)N^0 = F(w)$. By Cauchy's residue theorem, we obtain

$$\begin{aligned} 2\pi i F(w) &= \int_{\Gamma} F(z + w)N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz \\ &= \int_A F(z + w)N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz + \int_B F(z + w)N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz. \end{aligned} \quad (3.2)$$

Observe that $F(z + w)$ is equal to its series on A . We split the series as

$$S_N(z + w) = \sum_{n=1}^N \frac{a_n}{n^{z+w}}$$

and $R_N(z + w) = F(z + w) - S_N(z + w)$. Note that $S_N(z + w)$ is analytic for all $z \in \mathbb{C}$. Let C be the contour given by the path $|z| = R$ taken in the counterclockwise direction. By Cauchy's residue theorem, we obtain

$$2\pi i S_N(w) = \int_C S_N(z + w)N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz$$

since the integrand has a simple pole at $z = 0$ with residue $S_N(0 + w)N^0 = S_N(w)$. Note that

$$C = A \cup (-A) \cup \{iR, -iR\}.$$

¹Recall that a set X is compact if every open cover of X has a finite subcover.

Therefore, we see that

$$2\pi i S_N(w) = \int_A S_N(z+w) N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz + \int_{-A} S_N(z+w) N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz.$$

Consider the second integral above. Using the change of variables $z \rightarrow -z$, we find that

$$\int_{-A} S_N(z+w) N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz = \int_A S_N(-z+w) N^{-z} \left(\frac{1}{z} + \frac{z}{R^2} \right) dz.$$

Thus, we obtain

$$2\pi i S_N(w) = \int_A (S_N(z+w) N^z + S_N(-z+w) N^{-z}) \left(\frac{1}{z} + \frac{z}{R^2} \right) dz.$$

Combining the above equality with (3.2), we have

$$\begin{aligned} 2\pi i (F(w) - S_N(w)) &= \int_A (R_N(z+w) N^z - S_N(-z+w) N^{-z}) \left(\frac{1}{z} + \frac{z}{R^2} \right) dz \\ &\quad + \int_B F(z+w) N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz. \end{aligned} \quad (3.3)$$

Our goal is to show that $S_N(w)$ converges to $F(w)$ as $N \rightarrow \infty$. Write $z = x + iy$ where $x, y \in \mathbb{R}$. Then for $z \in A$, we have $x > 0$ and $|z| = R$, so

$$\frac{1}{z} + \frac{z}{R^2} = \frac{x - iy}{R^2} + \frac{x + iy}{R^2} = \frac{2x}{R^2}.$$

Since $|n^z| = n^x$, we have

$$|R_N(z+w)| \leq \sum_{n=N+1}^{\infty} \frac{1}{n^{\operatorname{Re}(z+w)}} \leq \sum_{n=N+1}^{\infty} \frac{1}{n^{x+1}} \leq \int_N^{\infty} \frac{1}{u^{x+1}} du = \frac{1}{xN^x}.$$

Also, we have

$$|S_N(-z+w)| \leq \sum_{n=1}^N \frac{1}{n^{-x+1}} \leq N^{x-1} + \int_1^N u^{x-1} du \leq N^{x-1} + \frac{N^x}{x} = N^x \left(\frac{1}{N} + \frac{1}{x} \right).$$

Putting the above estimates together, we get

$$\begin{aligned} \left| \int_A (R_N(z+w) N^z - S_N(-z+w) N^{-z}) \left(\frac{1}{z} + \frac{z}{R^2} \right) dz \right| &\leq \int_A \left(\frac{1}{xN^x} N^x + N^x \left(\frac{1}{N} + \frac{1}{x} \right) N^{-x} \right) \frac{2x}{R^2} dz \\ &= \int_A \left(\frac{2}{x} + \frac{1}{N} \right) \frac{2x}{R^2} dz \\ &= \int_A \left(\frac{4}{R^2} + \frac{2x}{NR^2} \right) dz \\ &\leq \pi R \left(\frac{4}{R^2} + \frac{2}{NR} \right) \quad (\text{since } x \leq R) \\ &\leq \frac{4\pi}{R} + \frac{2\pi}{N}. \end{aligned}$$

We now estimate the integral along B . We can divide B into two parts; one part with $\operatorname{Re}(z) = -\delta$, and the other with $-\delta < \operatorname{Re}(z) \leq 0$. For $z \in B$ with $\operatorname{Re}(z) = -\delta$, we use the fact that $|z| \leq R$ to find that

$$\left| \frac{1}{z} + \frac{z}{R^2} \right| = \left| \frac{1}{z} \right| \left| \frac{\bar{z}}{z} + \frac{z\bar{z}}{R^2} \right| \leq \frac{1}{\delta} \left(1 + \frac{|z|^2}{R^2} \right) \leq \frac{2}{\delta}.$$

Since $|F(z+w)| \leq M$ for $z \in B$, we have

$$\begin{aligned} \left| \int_B F(z+w) N^z \left(\frac{1}{z} + \frac{z}{R^2} \right) dz \right| &\leq \int_{-R}^R M N^{-\delta} \frac{2}{\delta} dz + 2 \left| \int_{-\delta}^0 M N^x \frac{2x}{R^2} dx \right| \\ &= \frac{4MR}{\delta N^\delta} + \frac{4M}{R^2} \left| \int_{-\delta}^0 x N^x dx \right| \\ &\leq \frac{4MR}{\delta N^\delta} + \frac{4M\delta}{R^2} \left(\frac{1}{(\log N)^2} - \frac{\delta+1}{N^\delta \log N} \right) \\ &\leq \frac{4MR}{\delta N^\delta} + \frac{4M\delta}{R^2 (\log N)^2}. \end{aligned}$$

Combining this estimate with (3.2) and (3.3) yields

$$|2\pi i(F(w) - S_N(w))| \leq \frac{4\pi}{R} + \frac{2\pi}{N} + \frac{4MR}{\delta N^\delta} + \frac{4M\delta}{R^2 (\log N)^2}.$$

That is, we have

$$|F(w) - S_N(w)| \leq \frac{2}{R} + \frac{1}{N} + \frac{MR}{\delta N^\delta} + \frac{M\delta}{R^2 (\log N)^2}.$$

Given $\varepsilon > 0$, choose $R = 3/\varepsilon$. Then for sufficiently large N , we have

$$|F(w) - S_N(w)| < \varepsilon.$$

This implies that $S_N(w) \rightarrow F(w)$ as $N \rightarrow \infty$, which completes the proof. \square

3.3 Revisiting the Möbius Function

Recall that we defined the Möbius function $\mu : \mathbb{N} \rightarrow \{-1, 0, 1\}$ by

$$\mu(n) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{if } n \text{ is not squarefree,} \\ (-1)^r & \text{if } n \text{ is the product of } r \text{ distinct primes.} \end{cases}$$

We will show on Homework 2 that for $\operatorname{Re}(s) > 1$, we have

$$\frac{1}{\zeta(s)} = \prod_p \left(1 - \frac{1}{p^s} \right) = \sum_{n=1}^{\infty} \frac{\mu(n)}{n^s}.$$

THEOREM 3.6. We have

$$\sum_{n=1}^{\infty} \frac{\mu(n)}{n} = 0.$$

PROOF. For all $\operatorname{Re}(s) > 1$, equation (3.4) holds. Moreover, we have shown that $(s-1)\zeta(s)$ is analytic and non-zero in $\operatorname{Re}(s) \geq 1$, so $1/\zeta(s)$ is analytic on $\operatorname{Re}(s) \geq 1$. Now, $\zeta(s)$ can be analytically continued up to $\operatorname{Re}(s) > 0$ and it is nonzero for $\operatorname{Re}(s) \geq 1$, so we see that the series

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

converges to $1/\zeta(s)$ for $\operatorname{Re}(s) \geq 1$. In particular, it converges at $s = 1$. But $\zeta(s)$ has a simple pole at $s = 1$, so $1/\zeta(1) = 0$. \square

THEOREM 3.7. We have

$$\sum_{n \leq x} \mu(n) = o(x).$$

PROOF. Applying Abel's summation formula with $a_n = \mu(n)/n$ and $f(x) = x$, we obtain

$$\sum_{n \leq x} \mu(n) = A(x)x - \int_1^x A(u) du,$$

where we have

$$A(t) = \sum_{n \leq t} \frac{\mu(n)}{n}.$$

By Theorem 3.5, we know that $A(t) = o(1)$. It follows that $A(x)x = o(x)$ and

$$\int_1^x A(u) du = o(x),$$

so the result holds. □

3.4 Divisor Function

DEFINITION 3.8. For a positive integer $n \in \mathbb{N}$, let $d(n)$ be the number of positive integers that divide n .

For example, we have $d(1) = 1$, $d(4) = 3$, and $d(p) = 2$ for all primes p .

THEOREM 3.9. We have

$$\sum_{m=1}^n d(m) = \sum_{m=1}^n \left\lfloor \frac{n}{m} \right\rfloor = n \log n + (2\gamma - 1)n + O(n^{1/2}).$$

where γ denotes Euler's constant.

PROOF. Let D_n be the region in the upper right-hand quadrant not containing the x or y axes, which is under and includes the hyperbola $xy = n$. That is,

$$D_n := \{(x, y) \in \mathbb{R}^2 : x > 0, y > 0, xy \leq n\}.$$

Define a **lattice point** to be a point in the plane with integer coordinates; that is, a point $(x, y) \in \mathbb{R}^2$ with $x, y \in \mathbb{Z}$. Notice that every lattice point in D_n is contained in some hyperbola $xy = s$ where s is an integer with $1 \leq s \leq n$.

Therefore, $\sum_{s=1}^n d(s)$ is the number of lattice points in D_n ; that is,

$$\sum_{s=1}^n d(s) = \#\{(x, y) \in \mathbb{R}^2 : x, y \in \mathbb{N}, xy \leq n\}.$$

We now count the number of lattice points in a different way. Given $x \in \mathbb{N}$ with $1 \leq x \leq n$, there are exactly $\lfloor \frac{n}{x} \rfloor$ many integers y such that $xy \leq n$. Thus, we see that

$$\#\{(x, y) \in \mathbb{R}^2 : x, y \in \mathbb{N}, xy \leq n\} = \sum_{x=1}^n \left\lfloor \frac{n}{x} \right\rfloor.$$

Observe that the number of lattice points above the line $x = y$ inside D_n is equal to the number of lattice points below it. Divide the lattice points in D_n into three disjoint regions given by

$$D_{n,1} = \{(x, y) \in \mathbb{N}^2 : xy \leq n, x < y\},$$

$$D_{n,2} = \{(x, y) \in \mathbb{N}^2 : xy \leq n, x > y\},$$

$$D_{n,3} = \{(x, y) \in \mathbb{N}^2 : xy \leq n, x = y\}.$$

Our observation above shows that $|D_{n,1}| = |D_{n,2}|$. Suppose that $(x, y) \in D_{n,1}$. Then $x^2 < xy \leq n$, which implies that $x < \sqrt{n}$. Moreover, for a fixed integer x , the number of integers y satisfying $xy \leq n$ and $y > x$ is $\lfloor \frac{n}{x} \rfloor - \lfloor x \rfloor$. We also see that $|D_{n,3}| = \lfloor \sqrt{n} \rfloor$, so we obtain

$$\begin{aligned} \sum_{x=1}^n \left\lfloor \frac{n}{x} \right\rfloor &= |D_{n,1}| + |D_{n,2}| + |D_{n,3}| \\ &= 2 \sum_{x=1}^{\lfloor \sqrt{n} \rfloor} \left(\left\lfloor \frac{n}{x} \right\rfloor - \lfloor x \rfloor \right) + \lfloor \sqrt{n} \rfloor \\ &= 2 \sum_{x=1}^{\lfloor \sqrt{n} \rfloor} \left(\frac{n}{x} - x + O(1) \right) + \lfloor \sqrt{n} \rfloor. \end{aligned}$$

By Theorem 2.10, we see that

$$\sum_{x=1}^n \left\lfloor \frac{n}{x} \right\rfloor = 2n \left(\log \lfloor \sqrt{n} \rfloor + \gamma + O\left(\frac{1}{\sqrt{n}}\right) \right) - (n + O(\sqrt{n})) + O(\sqrt{n}).$$

Note that if we use the fact that $\log \lfloor \sqrt{n} \rfloor = \log \sqrt{n} + O(1)$, then the resulting error term $O(n)$ will be too large. Therefore, we need a finer estimate. Indeed, since $\lfloor \sqrt{n} \rfloor = \sqrt{n} - \{\sqrt{n}\}$ where $\{t\}$ denotes the fractional part of t for $t \in \mathbb{R}$, we have

$$\begin{aligned} \log \lfloor \sqrt{n} \rfloor &= \log (\sqrt{n} - \{\sqrt{n}\}) = \log \left(\sqrt{n} \left(1 - \frac{\{\sqrt{n}\}}{\sqrt{n}} \right) \right) \\ &= \log \sqrt{n} + \log \left(1 - \frac{\{\sqrt{n}\}}{\sqrt{n}} \right) \\ &= \log \sqrt{n} + O\left(\frac{1}{\sqrt{n}}\right). \end{aligned}$$

Combining this with the previous equality gives

$$\sum_{x=1}^n \left\lfloor \frac{n}{x} \right\rfloor = n \log n + (2\gamma - 1)n + O(\sqrt{n}).$$

□

3.5 The Prime Number Theorem

We now have everything we need to prove the Prime Number Theorem.

THEOREM 3.10 (Prime Number Theorem). We have

$$\pi(x) \sim \frac{x}{\log x}.$$

PROOF. In Theorem 2.7, we showed that

$$\pi(x) \sim \frac{\psi(x)}{\log x}.$$

Therefore, it suffices to show that $\psi(x) \sim x$. Define the function

$$F(x) = \sum_{n \leq x} \left(\psi\left(\frac{x}{n}\right) - \left\lfloor \frac{x}{n} \right\rfloor + 2\gamma \right),$$

where γ denotes Euler's constant. By the Möbius inversion formula (Proposition 2.5), we have

$$\psi(x) - \lfloor x \rfloor + 2\gamma = \sum_{n \leq x} \mu(n) F\left(\frac{x}{n}\right).$$

In particular, we get

$$\psi(x) = x + O(1) + \sum_{n \leq x} \mu(n) F\left(\frac{x}{n}\right).$$

Now, it is enough to show that $\sum_{n \leq x} \mu(n) F(x/n) = o(x)$. First, we will estimate $F(x)$. Observe that

$$F(x) = \sum_{n \leq x} \psi\left(\frac{x}{n}\right) - \sum_{n \leq x} \left\lfloor \frac{x}{n} \right\rfloor + 2\gamma \lfloor x \rfloor. \quad (3.4)$$

Looking at the first sum in (3.4), we have

$$\begin{aligned} \sum_{n \leq x} \psi\left(\frac{x}{n}\right) &= \sum_{n \leq x} \sum_{m \leq \frac{x}{n}} \Lambda(m) \\ &= \sum_{n \leq x} \Lambda(n) \sum_{m \leq \frac{x}{n}} 1 \\ &= \sum_{n \leq x} \Lambda(n) \left\lfloor \frac{x}{n} \right\rfloor \\ &= \sum_{p^k \leq x} \log p \left\lfloor \frac{x}{p^k} \right\rfloor \\ &= \sum_{p \leq x} \left(\left\lfloor \frac{x}{p} \right\rfloor + \left\lfloor \frac{x}{p^2} \right\rfloor + \cdots + \left\lfloor \frac{x}{p^k} \right\rfloor \right) \quad (\text{where } p^k \parallel \lfloor x \rfloor) \\ &= \log(\lfloor x \rfloor!) = \sum_{n \leq x} \log n. \end{aligned}$$

In the proof of Theorem 2.11, we showed that

$$\sum_{n \leq x} \log n = x \log x - x + O(\log x).$$

Hence, we obtain

$$\sum_{n \leq x} \psi\left(\frac{x}{n}\right) = x \log x - x + O(\log x). \quad (3.5)$$

Moreover, by Theorem 3.9, we have

$$\sum_{n=1}^{\lfloor x \rfloor} \left\lfloor \frac{\lfloor x \rfloor}{n} \right\rfloor = \lfloor x \rfloor \log \lfloor x \rfloor + (2\gamma - 1)\lfloor x \rfloor + O(x^{1/2}).$$

For all $y \in \mathbb{R}$, notice that $\lfloor y \rfloor \leq y \leq \lfloor y \rfloor + 1$. In particular, we obtain the inequalities

$$\sum_{n=1}^{\lfloor x \rfloor} \left\lfloor \frac{\lfloor x \rfloor}{n} \right\rfloor \leq \sum_{n=1}^{\lfloor x \rfloor} \left\lfloor \frac{x}{n} \right\rfloor \leq \sum_{n=1}^{\lfloor x \rfloor + 1} \left\lfloor \frac{\lfloor x \rfloor + 1}{n} \right\rfloor,$$

and it follows that

$$\sum_{n=1}^{\lfloor x \rfloor} \left\lfloor \frac{x}{n} \right\rfloor = x \log x + (2\gamma - 1)x + O(x^{1/2}). \quad (3.6)$$

Combining equations (3.4), (3.5), and (3.6) gives

$$F(x) = (x \log x - x + O(\log x)) - (x \log x + (2\gamma - 1)x + O(x^{1/2})) + (2\gamma x + O(1)) = O(x^{1/2}).$$

Therefore, there exists a positive constant $c > 0$ such that

$$|F(x)| \leq cx^{1/2}$$

for all $x \geq 1$. If $t > 1$ is an integer, then

$$\begin{aligned}
 \left| \sum_{n \leq \frac{x}{t}} \mu(n) F\left(\frac{x}{n}\right) \right| &\leq \sum_{n \leq \frac{x}{t}} \left| F\left(\frac{x}{n}\right) \right| \\
 &\leq \sum_{n \leq \frac{x}{t}} c \left(\frac{x}{n}\right)^{1/2} \\
 &\leq cx^{1/2} \left(1 + \int_1^{x/t} \frac{1}{u^{1/2}} du \right) \\
 &= cx^{1/2} \left(1 + 2 \left(\frac{x}{t}\right)^{1/2} - 2 \right) \\
 &\leq 2 \cdot \frac{cx}{t^{1/2}}.
 \end{aligned} \tag{3.7}$$

Observe that F is a step function. That is, if a is an integer and $a \leq x < a+1$, then $F(x) = F(a)$. Therefore, we have

$$\sum_{\frac{x}{t} < n \leq x} \mu(n) F\left(\frac{x}{n}\right) = F(1) \sum_{\frac{x}{2} < n \leq x} \mu(n) + F(2) \sum_{\frac{x}{3} < n \leq \frac{x}{2}} \mu(n) + \cdots + F(t-1) \sum_{\frac{x}{t} < n \leq \frac{x}{t-1}} \mu(n).$$

We see that

$$\begin{aligned}
 \left| \sum_{\frac{x}{t} < n \leq x} \mu(n) F\left(\frac{x}{n}\right) \right| &\leq |F(1)| \left| \sum_{\frac{x}{2} < n \leq x} \mu(n) \right| + |F(2)| \left| \sum_{\frac{x}{3} < n \leq \frac{x}{2}} \mu(n) \right| + \cdots + |F(t-1)| \left| \sum_{\frac{x}{t} < n \leq \frac{x}{t-1}} \mu(n) \right| \\
 &\leq (|F(1)| + \cdots + |F(t-1)|) \max_{2 \leq i \leq t} \left| \sum_{\frac{x}{i} < n \leq \frac{x}{i-1}} \mu(n) \right| \\
 &\leq \left(\sum_{i=1}^t ct^{1/2} \right) \max_{2 \leq i \leq t} \left| \sum_{\frac{x}{i} < n \leq \frac{x}{i-1}} \mu(n) \right|.
 \end{aligned}$$

Notice that

$$\sum_{\frac{x}{i} < n \leq \frac{x}{i-1}} \mu(n) = \sum_{n \leq \frac{x}{i-1}} \mu(n) - \sum_{\frac{x}{i} < n} \mu(n) = o(x),$$

so we obtain

$$\left| \sum_{\frac{x}{t} < n \leq x} \mu(n) F\left(\frac{x}{n}\right) \right| = o(t^{3/2}x).$$

By Theorem 3.7, we have $\sum_{n \leq x} \mu(n) = o(x)$. Hence, for any $\varepsilon > 0$, we can find sufficiently large x such that

$$-\varepsilon x \leq \sum_{n \leq x} \mu(n) \leq \varepsilon x.$$

In particular, when x is sufficiently large, we get

$$-\frac{\varepsilon x}{i-1} - \frac{\varepsilon x}{i} \leq \sum_{\frac{x}{i} < n \leq \frac{x}{i-1}} \mu(n) \leq \frac{\varepsilon x}{i-1} + \frac{\varepsilon x}{i}.$$

For any given $\varepsilon > 0$, choose $t = t(\varepsilon)$ such that

$$\frac{2c}{t^{1/2}} < \frac{\varepsilon}{2}.$$

By equation (3.7), we have

$$\left| \sum_{n \leq \frac{x}{t}} \mu(n) F\left(\frac{x}{n}\right) \right| \leq 2 \cdot \frac{cx}{t^{1/2}} < \frac{\varepsilon}{2} x. \quad (3.8)$$

For fixed $\varepsilon > 0$ and t as above, we can choose x sufficiently large so that $o(xt^{3/2}) \leq \varepsilon x/2$. Indeed, we have $2c/t^{1/2} < \varepsilon/2$ if and only if $t > (4c)^2/\varepsilon^2$. In particular, we have $t = A^2\varepsilon^{-2}$ for some $A > 4c$, and we can pick x large enough so that

$$o(x) \leq \frac{\varepsilon^4}{2A^3} x.$$

Then we get

$$o(xt^{3/2}) \leq \frac{\varepsilon^4}{2A^3} x \cdot A^3 \varepsilon^{-3} = \frac{\varepsilon}{2} x.$$

It follows that

$$\left| \sum_{\frac{x}{t} < n \leq x} \mu(n) F\left(\frac{x}{n}\right) \right| < \frac{\varepsilon}{2}. \quad (3.9)$$

Combining inequalities (3.8) and (3.9) yields

$$\left| \sum_{n \leq x} \mu(n) F\left(\frac{x}{n}\right) \right| = o(x),$$

which completes the proof. \square

REMARK 3.11.

- (1) In 1896, Hadamard and de la Vallée Poussin proved the Prime Number Theorem independently. Consider the logarithmic integral

$$\text{Li}(x) = \int_2^x \frac{1}{\log t} dt \sim \frac{x}{\log x} \sum_{k=0}^{\infty} \frac{k!}{(\log x)^k}.$$

In 1899, de la Vallée Poussin proved that as $x \rightarrow \infty$, there exists some $a > 0$ such that

$$\pi(x) = \text{Li}(x) + O(xe^{-a\sqrt{\log x}}).$$

- (2) The main ingredient of our proof of the Prime Number Theorem is the fact that $\sum_{n \leq x} \mu(n) = o(x)$, which is a consequence of the analytic continuation and non-vanishing of $\zeta(s)$ at $\text{Re}(s) = 1$. The **Riemann hypothesis**, proposed by Riemann in 1859, states that the non-trivial zeros of $\zeta(s)$ all have real part $1/2$. (The trivial zeros of $\zeta(s)$ are of the form $2n$ for $n \in \mathbb{Z}$ and $n < 0$; these can be obtained by functional equations.) In 1901, Helge von Koch proved that the Riemann hypothesis is true if and only if

$$\pi(x) = \text{Li}(x) + O(\sqrt{x} \log x).$$

4 Divisor Counting Functions

4.1 Asymptotic Formulas for Divisor Counting Functions

DEFINITION 4.1. For a positive integer $n \in \mathbb{N}$, we denote by $\Omega(n)$ the number of prime factors of n counted with multiplicity, and $\omega(n)$ the number of distinct prime factors of n .

For example, if $n = 2^{10} \cdot 3^2 \cdot 7$, then $\Omega(n) = 10 + 2 + 1 = 13$ and $\omega(n) = 3$.

DEFINITION 4.2. Let $k \in \mathbb{N}$. For each real number $x \in \mathbb{R}$, we define $\tau_k(x)$ to be the number of positive integer with $n \leq x$ and $\Omega(n) = k$. That is,

$$\tau_k(x) = \#\{n \leq x : \Omega(n) = k\}.$$

Furthermore, we let $\pi_k(x)$ be the number of positive integers n with $n \leq x$ and $\omega(n) = \Omega(n) = k$. That is,

$$\pi_k(x) = \#\{n \leq x : \omega(n) = \Omega(n) = k\}.$$

In particular, $\pi_k(x)$ counts the positive integers n up to x which are squarefree and have k prime factors. Note that $\pi_1(x) = \pi_1(x) = \tau_1(x)$.

THEOREM 4.3 (Landau, 1900). Let $k \in \mathbb{N}$ be a positive integer. Then

$$\pi_k(x) \sim \tau_k(x) \sim \frac{1}{(k-1)!} \frac{x}{\log x} (\log \log x)^{k-1}.$$

PROOF. We first introduce the functions

$$L_k(x) = \sum_{p_1 \cdots p_k \leq x}^* \frac{1}{p_1 \cdots p_k}, \quad \Pi_k(x) = \sum_{p_1 \cdots p_k \leq x}^* 1, \quad \Theta_k(x) = \sum_{p_1 \cdots p_k \leq x}^* \log(p_1 \cdots p_k),$$

where the $*$ means that the sum is taken over all k -tuples of primes (p_1, \dots, p_k) with $p_1 \cdots p_k \leq x$. Note that different k -tuples can correspond to the same product $p_1 \cdots p_k$.

For each positive integer $n \geq 1$, we let $c_n = c_n(k)$ denote the number of k -tuples (p_1, \dots, p_k) such that $p_1 \cdots p_k = n$. Observe that

$$\begin{aligned} \Pi_k(x) &= \sum_{n \leq x} c_n, \\ \Theta_k(x) &= \sum_{n \leq x} c_n \log n. \end{aligned}$$

Moreover, we have

$$c_n = \begin{cases} 0 & \text{if } n \text{ is not a product of } k \text{ primes,} \\ k! & \text{if } n \text{ is squarefree and } \omega(n) = \Omega(n) = k. \end{cases}$$

We also see that $0 < c_n < k!$ if $\Omega(n) = k$ but n is not squarefree. Therefore, we obtain the inequalities

$$k! \pi_k(x) \leq \Pi_k(x) \leq k! \tau_k(x). \quad (4.1)$$

For $k \geq 2$, note that the number of positive integers up to x with k prime factors and divisible by the square of some prime is $\tau_k(x) - \pi_k(x)$. Therefore, we have

$$\tau_k(x) - \pi_k(x) = \sum_{\substack{p_1 \cdots p_k \leq x \\ p_i = p_j \text{ for some } i \neq j}}^* 1 \leq \binom{k}{2} \sum_{p_1 \cdots p_k \leq x}^* 1 = \binom{k}{2} \Pi_{k-1}(x).$$

CLAIM. We have

$$\Pi_k(x) \sim k \frac{x(\log \log x)^{k-1}}{\log x}.$$

PROOF OF CLAIM. Applying Abel's summation formula with $a_n = c_n$ and $f(u) = \log u$, we have

$$\Theta_k(x) = \sum_{n \leq x} c_n \log n = \Pi_k(x) \log x + \int_1^x \frac{\Pi_k(u)}{u} du.$$

Observe that

$$\Pi_k(x) \leq k! \tau_k(x) \leq k!x,$$

so $\Pi_k(u) = O(u)$, and hence

$$\Theta_k(x) = \Pi_k(x) \log x + O(x).$$

Thus, it suffices to show that for all $k \in \mathbb{N}$, we have

$$\Theta_k(x) \sim kx(\log \log x)^{k-1}. \quad (4.2)$$

We'll proceed by induction on k . This will be somewhat similar to the proof of the Prime Number Theorem, but with the weighting function $\log(p_1 \cdots p_k)$ on the k -tuple (p_1, \dots, p_k) .

For $k = 1$, we have $\Theta_1(x) = \theta(x) \sim x$ by Theorem 2.7 and the Prime Number Theorem. Assume now that $\Theta_k(x) \sim kx(\log \log x)^{k-1}$ for some $k \geq 1$. We'll prove the result for $\Theta_{k+1}(x)$. First, note that

$$\left(\sum_{p \leq x^{1/k}} \frac{1}{p} \right)^k \leq L_k(x) \leq \left(\sum_{p \leq x} \frac{1}{p} \right)^k$$

for all $k \geq 1$. By Theorem 2.13, we have

$$\begin{aligned} \left(\sum_{p \leq x^{1/k}} \frac{1}{p} \right)^k &\sim \left(\log \log(x^{1/k}) \right)^k, \\ \left(\sum_{p \leq x} \frac{1}{p} \right)^k &\sim (\log \log x)^k. \end{aligned}$$

Notice that

$$\left(\log \log(x^{1/k}) \right)^k = (\log \log x - \log k)^k \sim (\log \log x)^k,$$

so $L_k \sim (\log \log x)^k$. Therefore, we have

$$\Theta_{k+1}(x) - (k+1)(\log \log x)^k = \Theta_{k+1}(x) - (k+1)xL_k(x) + o(x(\log \log x)^k).$$

Note that

$$\begin{aligned} k\Theta_{k+1}(x) &= \sum_{p_1 \cdots p_{k+1} \leq x}^* k \cdot \log(p_1 \cdots p_{k+1}) \\ &= \sum_{p_1 \cdots p_{k+1} \leq x}^* (\log(p_2 \cdots p_{k+1}) + \log(p_1 p_3 \cdots p_{k+1}) + \cdots + \log(p_1 \cdots p_k)) \\ &= (k+1) \sum_{p_1 \leq x} \sum_{p_2 \cdots p_{k+1} \leq x/p_1}^* \log(p_2 \cdots p_{k+1}) \\ &= (k+1) \sum_{p_1 \leq x} \Theta_k\left(\frac{x}{p_1}\right). \end{aligned}$$

Since $L_0(x) = 1$ and

$$L_k(x) = \sum_{p_1 \cdots p_k \leq x}^* \frac{1}{p_1 \cdots p_k} = \sum_{p_1 \leq x} \frac{1}{p_1} L_{k-1}\left(\frac{x}{p_1}\right),$$

it follows that

$$\begin{aligned} \Theta_{k+1}(x) - (k+1)xL_k(x) &= (k+1) \sum_{p_1 \leq x} \left(\frac{1}{k} \Theta_k\left(\frac{x}{p_1}\right) - \frac{x}{p_1} L_{k-1}\left(\frac{x}{p_1}\right) \right) \\ &= \frac{k+1}{k} \sum_{p_1 \leq x} \left(\Theta_k\left(\frac{x}{p_1}\right) - k \frac{x}{p_1} L_{k-1}\left(\frac{x}{p_1}\right) \right). \end{aligned}$$

By the induction hypothesis, we have

$$\Theta_k(y) - kyL_{k-1}(y) = o(y(\log \log y)^{k-1}).$$

Given $\varepsilon > 0$, there exists $x_0 = x_0(\varepsilon, k)$ such that for all $y > x_0$, we have

$$|\Theta_k(y) - kyL_{k-1}(y)| \leq \varepsilon y(\log \log y)^{k-1}.$$

Furthermore, there exists a positive constant $c = c(\varepsilon, k) > 0$ such that for all $y \leq x_0$, we have

$$|\Theta_k(y) - kyL_{k-1}(y)| \leq c.$$

Note that $x/p_1 > x_0$ implies that $p_1 < x/x_0$, so for sufficiently large x , we obtain

$$\begin{aligned} |\Theta_{k+1}(x) - (k+1)xL_k(x)| &\leq \frac{k+1}{k} \left(\sum_{\frac{x}{x_0} < p_1 \leq x} c + \sum_{p_1 \leq \frac{x}{x_0}} \varepsilon \frac{x}{p_1} \left(\log \log \frac{x}{p_1} \right)^{k-1} \right) \\ &\leq 2cx + 2\varepsilon x(\log \log x)^{k-1} \sum_{p_1 \leq \frac{x}{x_0}} \frac{1}{p_1} \\ &\leq 2cx + 4\varepsilon x(\log \log x)^k < 5\varepsilon x(\log \log x)^k, \end{aligned}$$

where the second last inequality comes from choosing x large enough so that

$$\sum_{p \leq x} \frac{1}{p} \leq 2 \log \log x.$$

Therefore, we see that

$$\Theta_{k+1}(x) - (k+1)xL_k(x) = o(x(\log \log x)^k).$$

We conclude that

$$\Theta_{k+1}(x) \sim (k+1)x(\log \log x)^k,$$

which proves the claim. ■

From equation (4.1) and the claim, we have

$$\pi_k(x) \leq \frac{1}{k!} \Pi_k(x) \sim \frac{1}{(k-1)!} \frac{x}{\log x} (\log \log x)^{k-1}.$$

Moreover, combining equations (4.1) and (4.2) with the claim yields

$$\pi_k(x) = \tau_k(x) + O(\Pi_{k-1}(x)) \geq \frac{1}{k!} \Pi_k(x) + O(\Pi_{k-1}(x)) \sim \frac{1}{(k-1)!} \frac{x}{\log x} (\log \log x)^{k-1}.$$

In particular, we get

$$\pi_k(x) \sim \tau_k(x) \sim \frac{1}{(k-1)!} \frac{x}{\log x} (\log \log x)^{k-1},$$

which finishes the proof of the theorem. □

4.2 Summatory Functions for $\omega(n)$ and $\Omega(n)$

Let's now consider the averages of $\omega(n)$ and $\Omega(n)$.

THEOREM 4.4. We have

$$\begin{aligned}\sum_{n \leq x} \omega(n) &= x \log \log x + \beta x + o(x), \\ \sum_{n \leq x} \Omega(n) &= x \log \log x + \tilde{\beta} x + o(x),\end{aligned}$$

where β is Merten's constant as in Theorem 2.13 and

$$\tilde{\beta} = \beta + \sum_p \frac{1}{p(p-1)}.$$

PROOF. Set $S_1 = S_1(x) = \sum_{n \leq x} \omega(n)$. Then we have

$$S_1 = \sum_{n \leq x} \sum_{p|n} 1 = \sum_{p \leq x} \left\lfloor \frac{x}{p} \right\rfloor.$$

By Theorem 2.13, we obtain

$$\begin{aligned}S_1 &= \sum_{p \leq x} \left\lfloor \frac{x}{p} \right\rfloor \\ &= x \sum_{p \leq x} \frac{1}{p} + O(\pi(x)) \\ &= x(\log \log x + \beta + o(1)) + O(\pi(x)) \\ &= x \log \log x + x\beta + o(x),\end{aligned}$$

where the last equality follows from the Prime Number Theorem.

On the other hand, if we set $S_2 = S_2(x) = \sum_{n \leq x} \Omega(n)$, then

$$S_2 - S_1 = \sum_{p^m \leq x, m \geq 2} \left\lfloor \frac{x}{p^m} \right\rfloor = \sum_{p^m \leq x, m \geq 2} \frac{x}{p^m} + O\left(\sum_{p^m \leq x, m \geq 2} 1\right).$$

Note that $2^m \leq p^m \leq x$, so $m \leq \frac{\log x}{\log 2}$. Moreover, $p^2 \leq p^m \leq x$ implies that $p \leq x^{1/2}$. Therefore, we have

$$S_2 - S_1 = \sum_{p^m \leq x, m \geq 2} \frac{x}{p^m} + O(x^{1/2} \log x) = x \left(\sum_p \left(\frac{1}{p^2} + \frac{1}{p^3} + \cdots \right) - \sum_{p^m \geq x} \frac{1}{p^m} \right) + O(x^{1/2} \log x).$$

Observe that

$$\begin{aligned}\sum_{\substack{p^m > x \\ m \geq 2}} \frac{1}{p^m} &\leq \sum_{\substack{p^m > x \\ m \geq 2 \\ 2|n}} \frac{1}{p^m} + \sum_{\substack{p^m > x \\ m \geq 2 \\ 2 \nmid n}} \frac{1}{p^m} \\ &\leq \sum_{n^2 > x} \frac{1}{n^2} + \sum_{\substack{p^m > x \\ m \geq 2 \\ 2|m \\ p \leq \sqrt{x}}} \frac{1}{p^m} + \sum_{\substack{p^m > x \\ m \geq 2 \\ 2|m \\ p > \sqrt{x}}} \frac{1}{p^m}.\end{aligned}$$

Notice that if $p \leq \sqrt{x}$, then since $p^m > x$, we get $p^{m-1} > x/p > \sqrt{x}$. On the other hand, if $p > \sqrt{x}$, then $p^{m-1} > \sqrt{x}$. Hence, we get

$$\begin{aligned} \sum_{\substack{p^m > x \\ m \geq 2}} \frac{1}{p^m} &\leq \sum_{n^2 > x} \frac{1}{n^2} + 2 \sum_{\substack{p^{m-1} > \sqrt{x} \\ m \geq 2 \\ 2 \mid m}} \frac{1}{p^{m-1}} \\ &\leq \sum_{n^2 > x} \frac{1}{n^2} + 2 \sum_{m^2 > \sqrt{x}} \frac{1}{m^2} \\ &\leq 3 \sum_{k > \sqrt[4]{x}} \frac{1}{k^2} = O\left(\frac{1}{\sqrt[4]{x}}\right). \end{aligned}$$

Therefore, we have

$$S_2 - S_1 = x \left(\sum_p \frac{1}{p(p-1)} + o(1) \right) + O(x^{1/2} \log x) = x \sum_p \frac{1}{p(p-1)} + o(x).$$

Together with our estimate of S_1 , we see that

$$S_2 = x \log \log x = x \left(\beta + \sum_p \frac{1}{p(p-1)} \right) + o(x).$$

□