

# 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  $\ell$  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  $\varepsilon$  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  $\alpha_p$ . 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  $\gamma$  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  $\beta$  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  $\beta$  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  $\beta$  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

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

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 compact<sup>1</sup>, 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  $\Gamma$  denote the contour obtained by following the outside of  $\tilde{\Gamma}$  in a counterclockwise path. Let  $A$  be the part of  $\Gamma$  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

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

---

<sup>1</sup>Recall 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.  $\square$

### 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  $\gamma$  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  $\gamma$  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  $\beta$  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

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

### 4.3 Asymptotic Density and Normal Order

DEFINITION 4.5. Let  $A$  be a subset of  $\mathbb{N}$ . For any  $n \in \mathbb{N}$ , we set  $A(n) = \{1, \dots, n\} \cap A$ . We define the **upper asymptotic density** of  $A$  by

$$\bar{d}(A) := \limsup_{n \rightarrow \infty} \frac{|A(n)|}{n}.$$

Similarly, we define the **lower asymptotic density** of  $A$  to be

$$\underline{d}(A) := \liminf_{n \rightarrow \infty} \frac{|A(n)|}{n}.$$

We say that  $A$  has **asymptotic density**  $d(A)$  when  $\bar{d}(A) = \underline{d}(A)$ , in which case we set  $d(A)$  to be this common value.

EXAMPLE 4.6.

- (1) When  $A$  is the set of all primes, we have  $d(A) = \bar{d}(A) = \underline{d}(A) = 0$ .
- (2) For  $A = \{n \in \mathbb{N} : n \equiv 0 \pmod{5}\}$ , we have  $d(A) = \bar{d}(A) = \underline{d}(A) = 1/5$ .
- (3) For  $A = \{n \in \mathbb{N} : n \neq k^2 + 1 \text{ for any } k \in \mathbb{Z}\}$ , we have  $d(A) = \bar{d}(A) = \underline{d}(A) = 1$ .
- (4) Let  $A = \{a \in \mathbb{N} : (2k)! < a < (2k+1)! \text{ for some } k \in \mathbb{Z}\}$ . Notice that for  $n = (2k+1)!$ , any  $a \in \mathbb{N}$  satisfying  $(2k)! < a < (2k+1)!$  is included in  $A(n)$ . Therefore, we have

$$1 \geq \frac{|A((2k+1)!)|}{(2k+1)!} \geq \frac{(2k+1)! - (2k)!}{(2k+1)!} = \frac{2k}{2k+1}.$$

By taking  $k \rightarrow \infty$ , we see that

$$\frac{|A((2k+1)!)|}{(2k+1)!} \rightarrow 1,$$

and hence  $\bar{d}(A) = 1$ . On the other hand, when  $n = (2k)!$ , then only  $a \in \mathbb{N}$  such that  $a < (2k - 1)!$  are included in  $A(n)$ . Thus, we have

$$0 \leq \frac{|A((2k)!)|}{(2k)!} \leq \frac{(2k - 1)!}{(2k)!} = \frac{1}{2k}.$$

As  $k \rightarrow \infty$ , we have

$$\frac{|A((2k)!)|}{(2k)!} \rightarrow 0,$$

and hence  $\underline{d}(A) = 0$ .

DEFINITION 4.7. Let  $f(n)$  and  $F(n)$  be functions from  $\mathbb{N}$  to  $\mathbb{R}$ .

- We say that  $f(n)$  has **normal order**  $F(n)$  if for every  $\varepsilon > 0$ , the set

$$A(\varepsilon) = \{n \in \mathbb{N} : (1 - \varepsilon)F(n) < f(n) < (1 + \varepsilon)F(n)\}$$

has the property that  $d(A(\varepsilon)) = 1$ . Equivalently, if  $B(\varepsilon) = \mathbb{N} \setminus A(\varepsilon)$ , then  $d(B(\varepsilon)) = 0$ .

- We say that  $f(n)$  has **average order**  $F(n)$  if

$$\sum_{j=1}^n f(j) \sim \sum_{j=1}^n F(j).$$

EXAMPLE 4.8.

- (1) If we define

$$f(n) = \begin{cases} 1 & \text{if } n \neq k! \text{ for any } k \in \mathbb{N}, \\ n & \text{if } n = k! \text{ for some } k \in \mathbb{N}, \end{cases}$$

then  $f$  has normal order 1 but not average order 1.

- (2) If we define

$$f(n) = \begin{cases} 2 & \text{if } n \equiv 1 \pmod{2}, \\ 0 & \text{if } n \equiv 0 \pmod{2}, \end{cases}$$

then  $f$  has average order 1 but not normal order 1.

- (3) If we define

$$f(n) = \begin{cases} \log n + (\log n)^{1/2} & \text{if } n \equiv 1 \pmod{2}, \\ \log n - (\log n)^{1/2} & \text{if } n \equiv 0 \pmod{2}, \end{cases}$$

then  $f$  has both normal and average order  $\log n$ .

THEOREM 4.9. Both  $\omega(n)$  and  $\Omega(n)$  have average order  $\log \log n$ .

PROOF. First, note that

$$\begin{aligned} \sum_{n \leq x} \log \log n &= \sum_{x^{1/2} < n \leq x} \log \log n + \sum_{n \leq x^{1/2}} \log \log n \\ &= \sum_{x^{1/2} < n \leq x} \log \log n + O(x^{1/2} \log \log x). \end{aligned}$$

Moreover, we have

$$\sum_{x^{1/2} < n \leq x} \log \log n \leq \log \log x \sum_{x^{1/2} < n \leq x} 1 = x \log \log x + O(x^{1/2} \log \log x).$$

Also, we have the lower bound

$$\sum_{x^{1/2} < n \leq x} \log \log n \geq (\log \log x - \log 2) \sum_{x^{1/2} < n \leq x} 1 = x \log \log x + O(x^{1/2} \log \log x).$$

It follows that

$$\sum_{n \leq x} \log \log n = x \log \log x + O(x^{1/2} \log \log x).$$

Combining this estimate with Theorem 4.4 shows that  $\omega(n)$  and  $\Omega(n)$  both have average order  $\log \log n$ .  $\square$

#### 4.4 Normal Order of $\omega(n)$ and $\Omega(n)$

We have shown that  $\omega(n)$  and  $\Omega(n)$  have average order  $\log \log n$ . In this section, we'll work towards proving that they have normal order  $\log \log n$ .

**THEOREM 4.10.** Let  $\delta > 0$ . The number of positive integers  $n \leq x$  satisfying

$$|f(n) - \log \log n| > (\log \log n)^{\frac{1}{2} + \delta}$$

is  $o(x)$ , where  $f(n) = \omega(n)$  or  $f(n) = \Omega(n)$ . In particular, both  $\omega(n)$  and  $\Omega(n)$  have normal order  $\log \log n$ .

**PROOF.** It is enough to prove that the number of positive integers  $n \leq x$  with

$$|f(n) - \log \log x| > (\log \log x)^{\frac{1}{2} + \delta}$$

is  $o(x)$ , because for  $x^{1/e} \leq n \leq x$ , we have

$$\log \log x \geq \log \log n \geq \log \left( \frac{\log x}{e} \right) = \log \log x - 1.$$

In other words, we can replace  $\log \log n$  in the statement of the theorem with  $\log \log x$ .

Moreover, we can restrict our attention to the case where  $f(n) = \omega(n)$ , because by Theorem 4.4, we have

$$\sum_{n \leq x} (\Omega(n) - \omega(n)) = O(x).$$

Thus, the number of integers  $n \leq x$  for which  $\Omega(n) - \omega(n) > (\log \log n)^{1/2}$  is  $o(x)$ .

**CLAIM.** We have

$$\begin{aligned} \sum_{n \leq x} \omega(n)^2 &= x(\log \log x)^2 + O(x \log \log x), \\ \sum_{n \leq x} (\omega(n) - \log \log x)^2 &= O(x \log \log x). \end{aligned}$$

**PROOF OF CLAIM.** For each  $n \leq x$ , consider the ordered pairs  $(p, q)$  where  $p$  and  $q$  are distinct prime factors of  $n$ . There are  $\omega(n)$  choices for  $p$  and  $\omega(n) - 1$  choices for  $q$ , which gives

$$\omega(n)(\omega(n) - 1) = \sum_{\substack{pq | n \\ p \neq q}} 1 = \sum_{pq | n} 1 - \sum_{p^2 | n} 1.$$



Therefore, we have

$$\begin{aligned}
 \sum_{n \leq x} \omega(n)^2 - \sum_{n \leq x} \omega(n) &= \sum_{n \leq x} \omega(n)(\omega(n) - 1) \\
 &= \sum_{n \leq x} \left( \sum_{pq \mid n} 1 - \sum_{p^2 \mid n} 1 \right) \\
 &= \sum_{pq \leq x} \left\lfloor \frac{x}{pq} \right\rfloor - \sum_{p^2 \leq x} \left\lfloor \frac{x}{p^2} \right\rfloor.
 \end{aligned}$$

Observe that

$$\begin{aligned}
 \sum_{p^2 \leq x} \left\lfloor \frac{x}{p^2} \right\rfloor &\leq x \sum_{p^2 \leq x} \frac{1}{p^2} = O(x), \\
 \sum_{pq \leq x} \left\lfloor \frac{x}{pq} \right\rfloor &= \sum_{pq \leq x} \frac{x}{pq} + O(x),
 \end{aligned}$$

which implies that

$$\sum_{n \leq x} \omega(n)^2 - \sum_{n \leq x} \omega(n) = \sum_{pq \leq x} \frac{x}{pq} + O(x). \quad (4.3)$$

Next, note that

$$\left( \sum_{p \leq x^{1/2}} \frac{1}{p} \right)^2 - \left( \sum_{p \leq x} \frac{1}{p^2} \right) \leq \sum_{pq \leq x} \frac{1}{pq} \leq \left( \sum_{p \leq x} \frac{1}{p} \right)^2.$$

Furthermore, Merten's theorem (Theorem 2.13) tells us that

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

so it follows that

$$\left( \sum_{p \leq x^{1/2}} \frac{1}{p} \right)^2 = \left( \log \log x^{1/2} + O(1) \right)^2 = (\log \log x - \log 2 + O(1))^2 = (\log \log x)^2 + O(\log \log x).$$

Thus, we obtain

$$\sum_{pq \leq x} \frac{1}{pq} = (\log \log x)^2 + O(\log \log x). \quad (4.4)$$

By Theorem 4.4, we get

$$\sum_{n \leq x} \omega(n) = O(x \log \log x). \quad (4.5)$$

Combining equations (4.3), (4.4), and (4.5) together yields

$$\sum_{n \leq x} \omega(n)^2 = x(\log \log x)^2 + O(x \log \log x),$$

which proves the first equality. Now, we have

$$\begin{aligned}
 \sum_{n \leq x} (\omega(n) - \log \log x)^2 &= \sum_{n \leq x} \omega(n)^2 - 2 \sum_{n \leq x} \omega(n) \log \log x + \sum_{n \leq x} (\log \log x)^2 \\
 &= x(\log \log x)^2 + O(x \log \log x) - 2 \log \log x \sum_{n \leq x} \omega(n) + [x](\log \log x)^2 \\
 &= x(\log \log x)^2 + O(x \log \log x) - 2x(\log \log x)^2 + O(\log \log x) \\
 &\quad + x(\log \log x)^2 + O((\log \log x)^2) \\
 &= O(x \log \log x),
 \end{aligned}$$

where the second last equality follows from Theorem 4.4. This finishes the proof of the claim. ■

Finally, as we stated in the beginning of the proof, it suffices to show that

$$E(x) := \#\{n \leq x : |\omega(n) - \log \log x| > (\log \log x)^{\frac{1}{2} + \delta}\}$$

is  $o(x)$ . By the claim, we have

$$E(x) \cdot (\log \log x)^{1+2\delta} \leq \sum_{n \leq x} (\omega(n) - \log \log x)^2 = O(x \log \log x).$$

It follows that

$$E(x) = O\left(\frac{x \log \log x}{(\log \log x)^{1+2\delta}}\right) = o(x). \quad \square$$

REMARK 4.11. Since the average order of  $\omega(n)$  is  $\log \log n$ , which is asymptotic to  $\log \log x$  for “almost all”  $n$  (namely, all except  $o(x)$  many  $n \leq x$ ), we can view the sum

$$\frac{1}{x} \sum_{n \leq x} (\omega(n) - \log \log x)^2$$

as the variance of  $\omega(n)$ ; that is, the squares of the standard deviation. In Homework 3, we will show that

$$\sum_{n \leq x} (\omega(n) - \log \log x)^2 \sim x \log \log x,$$

which implies that the standard deviation of  $\omega(n)$  is about  $\sqrt{\log \log n}$ . Now, consider the term

$$\frac{\omega(n) - \log \log n}{\sqrt{\log \log n}}.$$

In 1934, Erdős and Kac proved (without knowing probability theory) that

$$\lim_{x \rightarrow \infty} \frac{1}{x} \#\left\{n \leq x : \frac{\omega(n) - \log \log n}{\sqrt{\log \log n}} \leq \gamma\right\} = G(\gamma),$$

where we define

$$G(\gamma) := \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\gamma} e^{-t^2/2} dt$$

to be the Gaussian normal distribution. This result forms a foundation of probabilistic number theory.

Recall that for all  $n \in \mathbb{N}$ , the divisor function  $d(n)$  gives the number of positive divisors of  $n$ . In particular, if we have  $n = p_1^{a_1} \cdots p_r^{a_r}$  where  $a_1, \dots, a_r \in \mathbb{N}$  and  $p_1, \dots, p_r$  are distinct primes, then

$$\begin{aligned}
 \omega(n) &= r, \\
 \Omega(n) &= a_1 + \cdots + a_r, \\
 d(n) &= (a_1 + 1) \cdots (a_r + 1).
 \end{aligned}$$

THEOREM 4.12. Given  $\varepsilon > 0$ , define the set

$$S(\varepsilon) = \{n \in \mathbb{N} : 2^{(1-\varepsilon) \log \log n} < d(n) < 2^{(1+\varepsilon) \log \log n}\}.$$

Then  $S(\varepsilon)$  has asymptotic density 1.

PROOF. Note that for any  $a \in \mathbb{N}$ , we have

$$2 \leq a + 1 \leq 2^a.$$

In particular, we get

$$2^{\omega(n)} \leq d(n) \leq 2^{\Omega(n)},$$

and the result follows from Theorem 4.10. □

REMARK 4.13. We saw in Theorem 3.9 that

$$\sum_{n \leq x} d(n) \sim x \log x \sim \sum_{n \leq x} \log n.$$

Therefore, the average order of  $d(n)$  is  $\log n$ . However, using Theorem 4.12, one can show that for almost all  $n \in \mathbb{N}$ , the divisor function  $d(n)$  satisfies

$$(\log n)^{\log 2 - \varepsilon} < d(n) < (\log n)^{\log 2 + \varepsilon}$$

for any  $\varepsilon > 0$ .

## 5 Quadratic Reciprocity

### 5.1 Euler's Totient Function

DEFINITION 5.1. For  $n \in \mathbb{N}$ , we define **Euler's totient function**  $\phi(n)$  to be the number of integers  $m$  such that  $1 \leq m \leq n$  and  $\gcd(m, n) = 1$ . That is, we have

$$\phi(n) = \#\{1 \leq m \leq n : \gcd(m, n) = 1\}.$$

A **reduced residue system modulo  $n$**  is a subset  $R \subseteq \mathbb{Z}$  such that

- (i)  $\gcd(r, n) = 1$  for each  $r \in R$ ;
- (ii)  $R$  contains  $\phi(n)$  elements; and
- (iii) no two elements of  $R$  are congruent modulo  $n$ .

THEOREM 5.2. Let  $a, n \in \mathbb{N}$  with  $\gcd(a, n) = 1$ . Then

$$a^{\phi(n)} \equiv 1 \pmod{n}.$$

PROOF. Let  $\{c_1, \dots, c_{\phi(n)}\}$  be a reduced residue system modulo  $n$ . Since  $\gcd(a, n) = 1$ ,  $\{ac_1, \dots, ac_{\phi(n)}\}$  is also a reduced residue system modulo  $n$ . Hence, we have

$$c_1 \cdots c_{\phi(n)} \equiv ac_1 \cdots ac_{\phi(n)} \pmod{n}.$$

In particular, we see that

$$c_1 \cdots c_{\phi(n)} \equiv a^{\phi(n)} c_1 \cdots c_{\phi(n)} \pmod{n}.$$

Since  $c_1, \dots, c_{\phi(n)}$  are all coprime with  $n$ , it follows that

$$a^{\phi(n)} \equiv 1 \pmod{n}. \quad \square$$

Notice that when  $p$  is prime, we have  $\phi(p) = p - 1$ , so we immediately obtain the following corollary.

COROLLARY 5.3 (Fermat's little theorem). Let  $p$  be a prime. For any  $a \in \mathbb{Z}$  with  $p \nmid a$ , we have

$$a^{p-1} \equiv 1 \pmod{p}.$$

THEOREM 5.4 (Wilson). If  $p$  is a prime, then  $(p-1)! \equiv -1 \pmod{p}$ .

PROOF. Consider the element  $x^{p-1} - 1 \in (\mathbb{Z}/p\mathbb{Z})[x]$ . By Fermat's little theorem and using the fact that  $\mathbb{Z}/p\mathbb{Z}$  is a field, this factors as

$$x^{p-1} - 1 \equiv (x-1)(x-2) \cdots (x-(p-1)) \pmod{p}$$

in  $(\mathbb{Z}/p\mathbb{Z})[x]$ , as  $1, 2, \dots, p-1$  are all roots. Looking at the constant coefficient, we find that

$$-1 \equiv (-1)(-2) \cdots (-(p-1)) \pmod{p}.$$

Therefore, we have  $-1 \equiv (-1)^{p-1}(p-1)! \pmod{p}$ . When  $p = 2$ , the result holds since  $-1 \equiv 1 \pmod{2}$ ; otherwise,  $p$  is odd, so  $-1 \equiv (p-1)! \pmod{p}$  as required.  $\square$