

Introduction to
ELEMENTARY ANALYTIC NUMBER THEORY

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NOTATIONS

$\gcd(a, b)$ Greatest common divisor of a and b .

$\text{lcm}(a, b)$ Least common multiple of a and b .

$\varphi(n)$ Euler's totient function of n , $\varphi(n)$ is the number of positive integers not exceeding n which are relatively prime to n .

$J_k(n)$ Jordan function of n , the number of tuples (a_1, \dots, a_k) such that $\gcd(a_1, \dots, a_k, n) = 1$ and $1 \leq a_1, \dots, a_k \leq n$.

$\tau(n)$ Number of divisors of n .

$\sigma(n)$ Sum of divisors of n .

$\omega(n)$ Number of distinct prime divisors of n

$\Omega(n)$ Number of total prime divisors of n

$\mu(n)$ Möbius function of n , $\mu(n) = (-1)^{\omega(n)}$ if n is square-free, otherwise $\mu(n) = 0$.

$\lambda(n)$ Liouville function of n , $\lambda(n) = (-1)^{\Omega(n)}$ if n is square-free, otherwise $\lambda(n) = 0$.

$\Lambda(n)$ Von Mangoldt Function of n . $\Lambda(n) = \log p$ if $n = p^e$ for some positive integer e , otherwise $\Lambda(n) = 0$.

$\vartheta(x)$ Tchebycheff function of the first kind.

$\psi(x)$ Tchebycheff function of the second kind.

$\zeta(s)$ Zeta function of the complex number s .

$\alpha * \beta$ Dirichlet convolution of two arithmetic functions α and β .

$\alpha \circ \beta$ General convolution of two arithmetic functions α and β .

γ Euler-Mascheroni constant.

§1 ARITHMETIC FUNCTIONS

In this chapter, we will discuss some generalized arithmetic functions and their asymptotic behavior. By asymptotic behavior, we mean that we want to understand how a function $f(x)$ grows as x tends to infinity. A common way of analyzing growth of an arithmetic function f is to consider the order of an arithmetic function. Erdős

ORDER OF ARITHMETIC FUNCTION. The order of an arithmetic function f is defined by the asymptotic $\lim_{x \rightarrow \infty} \sum_{n \leq x} f(n)$. To understand the growth of f , we often analyze the asymptotic of partial summation

$$\lim_{x \rightarrow \infty} \sum_{n \leq x} f(n)$$

For example, the prime counting function is

$$\pi(x) = \sum_{n \leq x} C(n)$$

where $C(n)$ is the characteristic function of n , that is, $C(n) = 1$ if n is a prime otherwise $C(n) = 0$. One of the biggest questions we will try to answer is how $\lim_{x \rightarrow \infty} \pi(x)$ behaves.

SUMMATORY FUNCTION. For an arithmetic function f , the *summatory function* of f is defined as

$$F(n) = \sum_{d \in \mathbb{S}} f(d)$$

where \mathbb{S} is some set possibly dependent on n . When \mathbb{S} is the set of divisors of n , the number of divisor function $\tau(n)$ is the summatory function of the unit function $u(n) = 1$ and the sum of divisor function $\sigma(n)$ is the summatory function of the invariant function $f(n) = n$. Another summatory function is the partial summation

$$\sum_{n \leq x} f(n)$$

Associated with this is the average order of f .

AVERAGE ORDER. For an arithmetic function f ,

$$\lim_{x \rightarrow \infty} \frac{\sum_{n \leq x} f(n)}{x}$$

is the *average order*. In this context, a very interesting way of analyzing growth is the *normal order* of f . The concept of normal numbers arises from HARDY and AIYANGAR.¹

NORMAL ORDER. Let f and F be arithmetic functions such that

$$(1 - \epsilon)F(n) < f(n) < (1 + \epsilon)F(n) \quad (\dagger 1.1)$$

holds for *almost* all $n \leq x$ as $x \rightarrow \infty$. Then we say that F is the *normal order* of f . A trivial(?) example of normal order is that almost all positive integers not exceeding x are composite if x is sufficiently large. We should probably elaborate on what we mean by *almost* here. One interpretation is that the number of positive integers not exceeding x which are prime is very small compared to x . Similarly, f is of order F means that the number of positive integers n not exceeding x which do not satisfy $\dagger 1.1$ is very small compared to x .

An interesting property in summatory functions is that

$$\begin{aligned} \sum_{i=1}^n F(i) &= \sum_{i=1}^n \sum_{d|i} f(d) \\ &= \sum_{i=1}^n \left\lfloor \frac{n}{i} \right\rfloor f(i) \end{aligned}$$

Here, the last equation is true because there are $\lfloor n/i \rfloor$ multiples of i not exceeding n .

§§1.1 ORDER OF SOME ARITHMETIC FUNCTIONS

Recall that the number of divisor function

$$\tau(n) = \sum_{ab=n} 1$$

We can generalize this as follows.

GENERALIZED NUMBER OF DIVISORS. The *generalized number of divisor* function is defined as

$$\tau_k(n) = \sum_{d_1 \cdots d_k = n} 1$$

So $\tau_k(n)$ is the number of ways to write n as a product of k positive integers. Similarly, we can take

¹GODFREY HAROLD HARDY and SRINIVASA RAMANUJAN AIYANGAR, "The normal number of prime factors of a number n ", *Quarterly Journal of Mathematics*, vol. XLVIII (1917), pp. 76-92.

the sum of divisor function and generalize it.

GENERALIZED SUM OF DIVISORS. The *generalized sum of divisor* function can be defined as

$$\sigma_k(n) = \sum_{d|n} d^k$$

At this point, we should discuss some asymptotic notions.

BIG O. Let f and g be two real or complex valued functions. We say that

$$f(x) = O(g(x))$$

if there is a positive real constant C such that

$$|f(x)| \leq Cg(x)$$

for all sufficiently large x . It is also written as $f(x) \ll g(x)$ or $g(x) \gg f(x)$. When we say g is an asymptotic estimate of f , we mean that

$$f(x) = g(x) + O(h(x))$$

for two functions g and h as $x \rightarrow \infty$. Here, h is the *error term* which obviously should be of lower magnitude than g . In particular, $f(x) = O(1)$ means that f is bounded above by some positive constant. Some trivial examples are $x^2 = O(x^3)$, $x + 1 = O(x)$ and $x^2 + 2x = O(x^2)$. We usually want $g(x)$ to be as small as possible to avoid triviality. A useful example is

$$\lfloor x \rfloor = x + O(1)$$

since $x = \lfloor x \rfloor + \{x\}$ and $0 \leq \{x\} < 1$.

SMALL O. Let f and g be two real or complex valued functions. Then the following two statements are equivalent

$$f(x) = o(g(x)) \tag{† 1.2}$$

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = 0 \tag{† 1.3}$$

Some trivial examples are $1/x = o(1)$, $x = o(x^2)$ and $2x^2 \neq o(x^2)$. LANDAU² states that the symbol O had been first used by BACHMANN.³ HARDY⁴ uses the notations \prec and \succ respectively but they are no longer in practice. HARDY and RIESZ⁵ adopted the notations small o and big O and today these are the primary notations for this purpose.

²EDMUND LANDAU, *Handbuch der Lehre von der Verteilung der Primzahlen*, 1909, vol. II, Page 883 (second volume is paged consecutively after first volume).

³PAUL GUSTAV HEINRICH BACHMANN, *Analytische Zahlentheorie*, 1894, vol. II, Page 401.

⁴GODFREY HAROLD HARDY, *Orders of Infinity: The 'Infinitärcalcül' of Paul Du Bois-Reymond*, *Cambridge Tracts in Mathematics*, Cambridge University Press, 1910.

⁵GODFREY HAROLD HARDY and MARCEL RIESZ, *The general theory of Dirichlet's series*, Cambridge University Press, 1915.

It should be evident that having an estimate with respect to O asymptotic formulas is more desirable than o formulas. By nature, O formulas give us a better understanding and a specific estimate whereas o does not always say as much. Moreover, working with O is a lot easier than working with o . For example,

$$\begin{aligned}\sum O(f(x)) &= O(\sum f(x)) \\ \int O(f(x))dx &= O(\int f(x)dx)\end{aligned}$$

Or consider the possibility that we can very easily deal with constants that would otherwise pop up here and there unnecessarily. With the help of O ,

$$\begin{aligned}O(1) + c &= O(1) \\ O(cf(x)) &= O(f(x))\end{aligned}$$

and so on.

EQUIVALENCE. Let f and g be two real or complex valued functions. We say that they are *asymptotically equivalent* if

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = 1$$

and we denote it by $f \sim g$. So, we can say that g is an asymptotic formula for f . An example is $x^2 \sim x^2 + x$. Another example in connection with normal order is that f has normal order F if the number of n not satisfying $\S 1.1$ is $o(x)$. We can also say, the number of n satisfying $\S 1.1$ is $\sim x$. Note the following.

$$f \sim g \iff |f(x) - g(x)| = o(g(x))$$

We will use these symbols extensively throughout the book. It is of utmost importance that the reader gets well familiarized with these notions since they will be crucial in understanding much of this book. The primary motivation behind these asymptotic notions is to get an as precise as possible idea about the *order of magnitude* of a certain function. This is why we will be leaning more towards $x^2 + 2x = O(x^2)$ than $x^2 + 2x = O(x^3)$ even though both are mathematically correct. The reason is, even though $x^2 + 2x = O(x^3)$ is true, it is taking away a great portion of the accuracy to which we suppose $x^2 + 2x$ should be measured with. On the other hand, we easily see that we cannot have $x^2 + 2x = O(x^\epsilon)$ for $\epsilon < 2$. Under the same philosophy, we define the order of magnitude equivalence.

DEFINITION. If f and g are functions such that both $f(x) \ll g(x)$ and $g(x) \ll f(x)$ hold, then we write $f \asymp g$ and say that f and g have the *same order of magnitude*.

Now, we are interested in the order of general number of divisors and general sum of divisors. Let us define the cumulative sum of these functions.

$$\begin{aligned}S_k(x) &= \sum_{n \leq x} \sigma_k(n) \\ T_k(x) &= \sum_{n \leq x} \tau_k(n)\end{aligned}$$

Notice the following.

$$\begin{aligned}
 S_k(x) &= \sum_{n \leq x} \sum_{d|n} d^k \\
 &= \sum_{n \leq x} \left\lfloor \frac{x}{n} \right\rfloor n^k \\
 &= \sum_{n \leq x} \left(\frac{x}{n} + O(1) \right) n^k \\
 &= x \sum_{n \leq x} n^{k-1} + O \left(\sum_{n \leq x} n^k \right)
 \end{aligned}$$

We can use this to establish an asymptotic for $T_k(x)$ if we can establish the asymptotic of $A_2(x)$. We will get to that in a moment. First, let us take care of the summation within the big O bracket. We have the trivial inequality that

$$\begin{aligned}
 \sum_{n \leq x} n^k &\leq \sum_{n \leq x} x^k \\
 &= x^k \sum_{n \leq x} 1 \\
 &= [x] x^k \\
 &= (x + O(1)) x^k \\
 &= x^{k+1} + O(x^k)
 \end{aligned}$$

We have that $S_k(x) = x(x^k + O(x^{k-1})) + O(x^{k+1}) = O(x^{k+1})$. Although weak, we get an estimate this way. On this note, an interested reader can try and prove that

$$(n+1)^{k+1} - 1 = \sum_{i=0}^k \binom{k+1}{i} \mathfrak{S}(n, i)$$

where $\mathfrak{S}(x, k) = \sum_{n \leq x} n^k$. This is known as the *Pascal identity* (see PASCAL,⁶ for an English translation, see KNOEBEL et al.⁷). LEHMER⁸ proves that

$$\mathfrak{S}(x, k) = \frac{x^{k+1}}{k+1} + \Delta \tag{† 1.4}$$

where $|\Delta| \leq x^k$. The reader may also be interested in MACMILLAN and SONDOW.⁹

⁶BLAISE PASCAL, “Somme des puissances numériques”, *Oeuvres complètes*, Jean Mesnard, ed., Desclée-Brouwer, Paris, vol. III (1964), pp. 341-367.

⁷ARTHUR KNOEBEL et al., “Sums of numerical powers”, in, *Mathematical Masterpieces: Further chronicles by the explorers*, Springer-Verlag, 2007, pp. 32-37.

⁸DERRICK NORMAN LEHMER, “Asymptotic evaluation of certain Totient Sums”, *American Journal of Mathematics*, vol. XXII, no. 4 (1900), pp. 293-335, doi: 10.2307/2369728, Chapter II, Theorem 1.

⁹KIEREN MACMILLAN and JONATHAN SONDOW, “Proofs of power sum and binomial coefficient congruences via Pascal’s identity”, *The American Mathematical Monthly*, vol. CXVIII, no. 6 (2011), pp. 549-551, doi: 10.4169/amer.math.monthly.118.06.549.

We shall try to estimate T in a similar fashion. First, see that

$$\begin{aligned}\tau_k(n) &= \sum_{d_1 \cdots d_k = n} 1 \\ &= \sum_{d_k | n} \sum_{d_1 \cdots d_{k-1} = n/d_k} 1 \\ &= \sum_{d | n} \tau_{k-1}\left(\frac{n}{d}\right)\end{aligned}$$

Note that the two sets $\{d : d | n\}$ and $\{n/d : d | n\}$ are actually the same. So, we get

$$\tau_k(n) = \sum_{d | n} \tau_{k-1}(d)$$

BEUMER¹⁰ also considers the generalization $\tau_k(n)$ in this exact form. Using this for T ,

$$\begin{aligned}T_k(x) &= \sum_{n \leq x} \tau_k(n) \\ &= \sum_{n \leq x} \sum_{d | n} \tau_{k-1}(d) \\ &= \sum_{n \leq x} \left\lfloor \frac{x}{n} \right\rfloor \tau_{k-1}(n) \\ &= \sum_{n \leq x} \left(\frac{x}{n} + O(1) \right) \tau_{k-1}(n) \\ &= x \sum_{n \leq x} \frac{\tau_{k-1}(n)}{n} + O\left(\sum_{n \leq x} \tau_{k-1}(n) \right)\end{aligned}$$

Thus, we have the recursive result

$$T_k(x) = x \sum_{n \leq x} \frac{\tau_{k-1}(n)}{n} + O(T_{k-1}(x))$$

It gets nontrivial how to proceed from here. Consider the *harmonic sum*

$$H(x) = \sum_{n \leq x} \frac{1}{n}$$

It does not seem easy to calculate H accurately, however, we can make a decent attempt to estimate H . The tool that is best suited for carrying out such an estimation is the *Abel partial summation formula*. ABEL¹¹ states this formula which today is a cornerstone of analytic number theory.

THEOREM 1.1 (Abel partial summation formula). *Let $\{a_n\}$ be a sequence of real numbers and f be a continuous differentiable function in $[y, x]$. If the partial sums of $\{a_n\}$ is*

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

¹⁰MARTIN BEUMER, “The arithmetical function $\tau_k(n)$ ”, *The American Mathematical Monthly*, vol. LXIX, no. 8 (1962), pp. 777-781, doi: 10.2307/2310778, (§8).

¹¹NIELS HENRIK ABEL, “Untersuchungen über die Reihe: $1 + (m/1)x + m \cdot (m-1)/(1 \cdot 2) \cdots x^2 + m \cdot (m-1) \cdot (m-2)/(1 \cdot 2 \cdot 3) \cdots x^3 + \dots$ ”, *Journal für Math.*, vol. I (1826), pp. 311-339, doi: 10.1515/9783112347386-030.

are known, then

$$\sum_{y < n \leq x} a_n f(n) = A(x)f(x) - A(y)f(y) - \int_y^x A(t)f'(t)dt$$

In particular, if f is an arithmetic function,

$$\sum_{n \leq x} a_n f(n) = A(x)f(x) - \int_1^x A(t)f'(t)dt$$

Proof. □

It is not straightforward to realize how such a formula can be as influential as we are describing it to be. Notice that, the formula essentially converts a discreet sum into an integral, which occasionally may be calculable. If the integral is not calculable, we may be able to estimate its value sometimes. We should mention that AIYANGAR¹² also uses a method that can only be described as the partial summation formula. It is unclear if Ramanujan simply knew about this. Considering he shows the calculation instead of just mentioning the formula, it is certainly possible he came up with the idea on his own, possibly before he had been working on that particular paper. He essentially derives the partial summation formula while trying to express a sum of the form

$$\sum_{p \leq x} \phi(p)$$

with respect to $\pi(x)$, $\phi(x)$ and an integral where $\pi(x)$ is the number of primes not exceeding x . A consequence of Abel partial summation formula is the celebrated *Euler's summation formula*.

THEOREM 1.2 (Euler's summation formula). *Let f be a continuous differentiable function in $[y, x]$. Then*

$$\sum_{y < n \leq x} f(n) = \int_y^x f(t)dt + \int_y^x \{t\}f'(t)dt + \{y\}f(y) - \{x\}f(x)$$

where $\{t\} = t - \lfloor t \rfloor$ is the fractional part of t .

Proof. □

As an application of Euler's summation formula, we can derive a result similar to ‡ 1.4 taking $f(n) = n^k$ for $k \geq 0$.

$$\begin{aligned} \mathfrak{S}_k(x) &= \sum_{n \leq x} n^k \\ &= \int_1^x t^k dt + k \int_1^x t^{k-1}(t - \lfloor t \rfloor)dt + 1 - (x - \lfloor x \rfloor)x^k \\ &= \frac{x^{k+1}}{k+1} - \frac{1}{k+1} + O\left(k \int_1^x t^{k-1} dt\right) + O(x^k) \\ &= \frac{x^{k+1}}{k+1} + O(x^k) \end{aligned}$$

¹²SRINIVASA RAMANUJAN AIYANGAR, "Highly Composite Numbers", in, *Collected papers of Srinivasa Ramanujan*, ed. by Godfrey Harold Hardy et al., Cambridge University Press, 1927, pp. 78-128, Page 83, §4.

Setting $a_n = \tau_{k-1}(n)$ and $f(n) = 1/n$ in Abel partial summation formula, we get

$$\sum_{n \leq x} \frac{\tau_{k-1}(n)}{n} = \frac{T_{k-1}(x)}{x} - \int_1^x \frac{T_{k-1}(t)}{t^2} dt$$

Thus, we have a result where we can inductively get to the final expression. First, let us see the case $k = 2$.

$$\sum_{n \leq x} \tau(n) = \sum_{n \leq x} \left\lfloor \frac{x}{n} \right\rfloor$$

Clearly, this is just the number of pairs (a, b) such that $ab \leq x$. We can divide the pairs in two classes. In the first class, $1 \leq a \leq \sqrt{x}$ and in the second one, $a > \sqrt{x}$. In the first case, for a fixed a , there are $\lfloor x/a \rfloor$ possible choices for a valid value of b . So, the number of pairs in the first case is

$$\sum_{a \leq \sqrt{x}} \left\lfloor \frac{x}{a} \right\rfloor$$

In the second case, since $a > \sqrt{x}$ and $b \leq x/a$, we must have $b \leq \sqrt{x}$. For a fixed b , there are $\lfloor x/b \rfloor - \lfloor \sqrt{x} \rfloor$ choices for a valid value of a , the choices namely are

$$\lfloor x \rfloor + 1, \dots, \left\lfloor \frac{x}{b} \right\rfloor$$

Then the number of pairs in this case is

$$\sum_{b \leq \sqrt{x}} \left\lfloor \frac{x}{b} \right\rfloor - \lfloor \sqrt{x} \rfloor$$

Thus, the total number of such pairs is

$$\sum_{a \leq \sqrt{x}} \left\lfloor \frac{x}{a} \right\rfloor + \sum_{b \leq \sqrt{x}} \left(\left\lfloor \frac{x}{b} \right\rfloor - \lfloor \sqrt{x} \rfloor \right) = 2 \sum_{n \leq \sqrt{x}} \left\lfloor \frac{x}{n} \right\rfloor - \lfloor x \rfloor^2 \quad (\dagger 1.5)$$

For getting past this sum, we have to deal with the sum

$$\begin{aligned} \sum_{n \leq \sqrt{x}} \lfloor x/n \rfloor &= \sum_{n \leq \sqrt{x}} \left(\frac{x}{n} + O(1) \right) \\ &= x \sum_{n \leq \sqrt{x}} \frac{1}{n} + O(\sqrt{x}) \\ &= xH(\sqrt{x}) + O(\sqrt{x}) \end{aligned}$$

Setting $a_n = 1$ and $f(n) = 1/n$ in Abel partial summation formula, we get

$$H(x) = \frac{A(x)}{x} - \int_1^x \frac{A(t)}{t^2} dt$$

Here, $A(x) = [x] = x + O(1)$. Using this,

$$\begin{aligned} H(x) &= 1 + O\left(\frac{1}{x}\right) + \int_1^x \left(\frac{1}{t} + \frac{O(1)}{t^2}\right) dt \\ &= 1 + O\left(\frac{1}{x}\right) + \int_1^x \frac{1}{t} dt + O\left(\int_1^x \frac{1}{t^2} dt\right) \\ &= 1 + O\left(\frac{1}{x}\right) + \log x + O\left(1 - \frac{1}{x}\right) \end{aligned}$$

Thus, we have the following result.

THEOREM 1.3.

$$H(x) = \log x + C + O\left(\frac{1}{x}\right)$$

where C is a constant.

We get a more precise formulation of $H(x)$ by considering the limit $x \rightarrow \infty$ which removes $O(1/x)$ from the expression since this limit would be 0.

THEOREM 1.4. *There is a constant γ such that*

$$\gamma = \lim_{x \rightarrow \infty} (H(x) - \log x)$$

This constant γ is now known as *Euler's constant* or *Euler-Mascheroni's constant*, although, neither Euler nor Mascheroni used the notation γ for this constant. EULER¹³ (republished in EULER¹⁴) used C and O in his original paper. MASCHERONI¹⁵ used A and a . Today it is not known whether γ is even irrational. For now, we will not require the use of γ , so we will use Theorem 1.3. Applying this, we have

$$\begin{aligned} \sum_{n \leq \sqrt{x}} \left\lfloor \frac{x}{n} \right\rfloor &= xH(\sqrt{x}) + O(\sqrt{x}) \\ &= x \left(C + \log \sqrt{x} + O\left(\frac{1}{\sqrt{x}}\right) \right) + O(\sqrt{x}) \\ &= \frac{1}{2}x \log x + Cx + O\left(\frac{x}{\sqrt{x}}\right) + O(\sqrt{x}) \\ &= \frac{1}{2}x \log x + O(x) \end{aligned}$$

We can now use this to get

$$\begin{aligned} \sum_{n \leq x} \tau(n) &= 2 \sum_{n \leq \sqrt{x}} [x/n] - [\sqrt{x}]^2 \\ &= x \log x + O(x) \end{aligned}$$

¹³LEONHARD EULER, “De Progressionibus Harmonicis Observationes”, *Commentarii academiae scientiarum Petropolitanae*, vol. VII (1740), pp. 150-161.

¹⁴LEONHARD EULER, “E-43: De Progressionibus Harmonicis Observationes”, *Spectrum* (2020), pp. 133-141, doi: 10.1090/spec/098/23.

¹⁵LORENZO MASCHERONI, *Adnotationes ad calculum Integrale Euleri*, Galeatii, 1790.

Thus, we get the following result.

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

DIRICHLET¹⁶ actually proves the more precise result given below.

THEOREM 1.5 (Dirichlet's average order of τ theorem).

$$\frac{\sum_{n \leq x} \tau(n)}{x} = \log x + 2\gamma - 1 + O\left(\frac{1}{\sqrt{x}}\right)$$

where γ is the Euler-Mascheroni constant.

Then Dirichlet's theorem on τ can be restated as *the average order of τ is $O(\log x)$* . AIYANGAR¹⁷ points out in his paper that the error term $O(1/\sqrt{x})$ in Dirichlet's theorem can be improved to $O(x^{-2/3+\epsilon})$ or $O(x^{-2/3} \log x)$ as LANDAU¹⁸ shows.

We can now get back to estimating T . Using Abel partial summation formula, we were able to deduce

$$T_k(x) = O(T_{k-1}(x)) + x \int_1^x \frac{T_{k-1}(t)}{t^2} dt$$

Using Dirichlet's average order of τ theorem, $T(x) = x \log x + O(x)$, so

$$\begin{aligned} T_3(x) &= O(T(x)) + x \int_1^x \frac{T(t)}{t^2} dt \\ &= O(x \log x) + x \int_1^x \frac{\log t + O(1)}{t} dt \\ &= O(x \log x) + x \int_1^x \frac{\log t}{t} dt + xO\left(\int_1^x \frac{1}{t} dt\right) \\ &= O(x \log x) + x \int_1^x \frac{\log t}{t} dt \end{aligned}$$

Using integration by parts,

$$\begin{aligned} \int \frac{\log t}{t} dt &= \log t \int \frac{1}{t} - \int \left(\frac{1}{t} \int \frac{1}{t} dt \right) dt \\ &= \log^2 t - \int \frac{\log t}{t} dt \end{aligned}$$

¹⁶ JOHANN PETER GUSTAV LEJEUNE DIRICHLET, "Über Die Bestimmung Der Mittleren Werthe", in, *G. Lejeune Dirichlet's Werke*, ed. by Leopold Kronecker and László Fuchs, Druck Und Verlag Von Georg Reimer., 1897, vol. II, pp. 49-66.

¹⁷ AIYANGAR, "Highly Composite Numbers" cit.

¹⁸ EDMUND LANDAU, "Über die Anzahl der Gitterpunkte in gewissen Bereichen", *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, vol. XIX (1912), pp. 687-772, Page 689.

Thus, we get

$$\int_1^x \frac{\log t}{t} dt = \frac{1}{2} \log^2 x$$

which in turn gives

$$T_3(x) = \frac{1}{2} x \log^2 x + O(x \log x)$$

We leave it as an exercise for the reader to prove the following (from what we have already developed, induction is one way to go about it).

THEOREM 1.6. *Let k be a positive integer. Then*

$$T_k(x) = \frac{1}{(k-1)!} x \log^{k-1} x + O(x \log^{k-2} x)$$

The reason we do not write $T_k(x)$ as $O(x \log^{k-1} x)$ directly is because in this case, we already know the constant multiplier of $x \log^{k-1} x$ which is not ugly. Usually, we write $O(f(x))$ when we do not know what the constant multiplier of $f(x)$ is or when it gets too big to keep track of. LANDAU¹⁹ states a sharper result.

$$T_k(x) = x \left(\sum_{m=0}^{k-1} b_m \log^m x \right) + O(x^{1-\frac{1}{k}}) + O(x^{1-\frac{1}{k}} \log^{k-2} x)$$

Let us now turn our attention to improving the asymptotic of $S_k(x)$.

$$\begin{aligned} S_k(x) &= \sum_{n \leq x} \sum_{d|n} d^k \\ &= \sum_{n \leq x} \sum_{m \leq x/n} m^k \\ &= \sum_{n \leq x} \mathfrak{S}_k\left(\frac{x}{n}\right) \\ &= \sum_{n \leq x} \frac{x^{k+1}}{(k+1)n^{k+1}} + O\left(\frac{x^k}{n^k}\right) \\ &= \frac{x^{k+1}}{k+1} \sum_{n \leq x} \frac{1}{n^{k+1}} + O\left(x^k \sum_{n \leq x} \frac{1}{n^k}\right) \end{aligned}$$

Here, we can see that the function

$$\sum_{n \leq x} \frac{1}{n^k}$$

occurs repeatedly. It is in fact, the partial sum of the famous Euler's *zeta function*.

¹⁹EDMUND LANDAU, "Über eine idealtheoretische funktion", *Transactions of the American Mathematical Society*, vol. XIII, no. 1 (1912), pp. 1-21, doi: 10.1090/s0002-9947-1912-1500901-6, Page 2.

ZETA FUNCTION. For a complex number s , the zeta function $\zeta(s)$ is defined as

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

We will discuss zeta function in details in Section 1.2. For now, let us establish a result similar to Dirichlet's average order of τ theorem for partial sums of ζ . Setting $f(n) := n^{-s}$ and $a_n = 1$ in Abel partial summation formula, $A(x) = \lfloor x \rfloor = x + O(1)$ and

$$\begin{aligned} \sum_{n \leq x} \frac{1}{n^s} &= \lfloor x \rfloor x^{-s} - \int_1^x (t + O(1)) f'(t) dt \\ &= x^{1-s} + O(x^{-s}) + s \int_1^x t^{-s} dt + O\left(s \int_1^x t^{-s-1} dt\right) \\ &= x^{1-s} + \frac{s}{1-s} (x^{1-s} - 1) + O\left(\int_1^x t^{-s-1} dt\right) \\ &= \frac{x^{1-s}}{1-s} + C + O(x^{-s}) \end{aligned}$$

Similar to γ , we can take $x \rightarrow \infty$ and get the following result.

THEOREM 1.7. *Let s be a positive real number other than 1. Then*

$$\sum_{n \leq x} \frac{1}{n^s} = \frac{x^{1-s}}{1-s} + C + O(x^{-s})$$

where C is a constant similar to Euler-Mascheroni constant dependent on s and

$$C = \lim_{x \rightarrow \infty} \left(\sum_{n \leq x} \frac{1}{n^s} - \frac{x^{1-s}}{1-s} \right)$$

Furthermore, if $0 < s < 1$, then $C = \zeta(s)$ since $x^{1-s} \rightarrow 0$.

We can now get back to estimating $S_k(x)$.

$$\begin{aligned} S_k(x) &= \frac{x^{k+1}}{k+1} \sum_{n \leq x} \frac{1}{n^{k+1}} + O\left(x^k \sum_{n \leq x} \frac{1}{n^k}\right) \\ &= \frac{x^{k+1}}{k+1} \left(\frac{x^{-k}}{-k} + \zeta(k+1) + O(x^{-k-1}) \right) + O\left(x^k \left(\frac{x^{1-k}}{1-k} + \zeta(k) + O(x^{-k}) \right)\right) \\ &= \frac{x}{-k(k+1)} + \frac{x^{k+1}}{k+1} \zeta(k+1) + O(x^{k+1-k-1}) + O\left(\frac{x}{1-k} + x^k \zeta(k) + O(1)\right) \\ &= \frac{x^{k+1}}{k+1} \zeta(k+1) + O(x) + O(1) + O(x + x^k) \end{aligned}$$

From this, we finally get the following.

THEOREM 1.8. *Let k be a positive integer. Then*

$$S_k(x) = \frac{x^{k+1}}{k+1} \xi(k+1) + O(x^{\max(1,k)})$$

We leave the case when k is a negative integer as an exercise. Next, we consider a generalization of the Euler's totient function $\varphi(n)$.

$$\varphi(x, a) = \sum_{\substack{n \leq x \\ \gcd(n, a) = 1}} 1$$

For a positive integer n , $\varphi(n) = \varphi(n, n)$ and *Jordan function* is a generalization of φ .

JORDAN FUNCTION. Let n and k be positive integers. Then the Jordan function $J_k(n)$ is the number of k tuples of positive integers not exceeding n that are relatively prime to n .

$$J_k(n) = \sum_{\substack{1 \leq a_1, \dots, a_k \leq n \\ \gcd(a_1, \dots, a_k, n) = 1}} 1$$

LEHMER²⁰ used the notation $\varphi_k(n)$ but today $J_k(n)$ is used more often. JORDAN²¹ first discussed this function and LEHMER²² developed some asymptotic results. Jordan totient function is interesting not only because it is a generalization of Euler's totient function but also because it has many interesting properties. For example, similar to φ , we can show that

$$\begin{aligned} J_k(n) &= \prod_{p^e \parallel n} p^{k(e-1)}(p-1) \\ J_k(n^m) &= n^{k(m-1)} J_k(n) \end{aligned}$$

LEHMER²³ proves the following which he calls the *fundamental theorem*.

$$J_k(mn) = J_k(n) \prod_{p^e \parallel m} (p^{ke} - p^{k(e-1)} \lambda(n, p)) \quad (\dagger 1.6)$$

where $\lambda(n, p) = 0$ if $p \mid n$ otherwise $\lambda(n, p) = 1$. We leave the proof of this result and the following to the reader.

$$\sum_{d \mid n} J_k(d) = n^k$$

Like $\sigma_k(n)$, $J_k(n)$ is also related to the sum $\mathfrak{S}(x, k)$. But we do not derive the order of $J_k(n)$ yet.

²⁰LEHMER, "Asymptotic evaluation of certain Totient Sums" cit.

²¹CAMILLE JORDAN, *Traité des substitutions et des équations algébriques*, Gauthier-Villars, Paris, 1870, Page 95 – 97.

²²LEHMER, "Asymptotic evaluation of certain Totient Sums" cit.

²³Ibid., Theorem VI.

§§1.2 DIRICHLET SERIES AND DIRICHLET CONVOLUTION

We encountered ζ when we tried to develop an asymptotic for $S_k(x)$. The function ζ has quite a rich history. Today ζ is mostly called Riemann's zeta function, however, Euler is the first one to investigate this function. Euler started working on ζ around 1730. During that period, the value of $\zeta(2)$ was unknown and of high interest among prominent mathematicians. AYOUN²⁴ is a very good read on this subject. Euler's first contribution in this matter is EULER²⁵ where he proves that $\zeta(2) \approx 1.644934$. The paper was first presented to the St. Petersburg Academy on March 5, 1731 and republished in EULER.²⁶ EULER²⁷ (republished in EULER²⁸) proves the following fundamental result which essentially gives a new proof of infinitude of primes.

THEOREM 1.9 (Euler's identity). *Let s be a positive integer. Then*

$$\zeta(s) = \prod_p \frac{p^s}{p^s - 1}$$

where p extends over all primes.

One of the results in EULER²⁹ is the following which we shall prove later.

$$\sum_{n \leq x} \frac{1}{p} \sim \log \sum_{n \leq x} \frac{1}{x}$$

Here, \sim is the asymptotic equivalence we have already defined. Even though Euler is the main architect behind the development of ζ , RIEMANN³⁰ is the first one to consider ζ for complex s instead of real s only. By tradition, we write $s = \sigma + it$ where $\sigma = \Re(s)$ is the real part of s and $t = \Im(s)$ is the imaginary part of s .

DIRICHLET SERIES. For a complex number s , a *Dirichlet series* is a series of the form

$$\mathfrak{D}_a(s) = \sum_{n \geq 1} \frac{a(n)}{n^s}$$

So, ζ is a special case of \mathfrak{D} when $a(n) = 1$ for all n . HARDY and RIESZ³¹ considers the following as

²⁴RAYMOND AYOUN, "Euler and the zeta function", *The American Mathematical Monthly*, vol. LXXXI, no. 10 (1974), pp. 1067-1086, doi: 10.2307/2319041.

²⁵LEONHARD EULER, "De summatione innumerabilium progressionum", *Commentarii academiae scientiarum Petropolitanae*, vol. v (1738), pp. 91-105.

²⁶LEONHARD EULER, "E-20: De summatione innumerabilium Progressionum", *Spectrum* (2020), pp. 52-64, doi: 10.1090/spec/098/10.

²⁷LEONHARD EULER, "Variae Observationes circa series infinitas", *Commentarii academiae scientiarum Petropolitanae*, vol. ix (1744), pp. 160-188.

²⁸LEONHARD EULER, "E-72: Variae Observationes circa series Infinitas", *Spectrum* (2020), pp. 249-260, doi: 10.1090/spec/098/41.

²⁹EULER, "Variae Observationes circa series infinitas" cit.

³⁰BERNHARD RIEMANN, "Ueber die anzahl der primzahlen unter einer gegebenen grösse", *Monatsberichte der Berliner Akademie* (Nov. 1859), pp. 136-144, doi: 10.1017/cbo9781139568050.008.

general Dirichlet series

$$\sum_{n \geq 1} a_n e^{-\lambda_n s} \quad (\dagger 1.7)$$

where (λ_n) is a strictly increasing sequence of real numbers that tend to infinity. Following this, HARDY and RIESZ³² calls \mathfrak{D} the *ordinary Dirichlet series* when $\lambda_n = \log n$. DIRICHLET³³ considers real values of s and proves a number of important theorems. As Hardy states, JENSEN³⁴ discusses the first theorems where s is complex involving the nature of convergence of $\dagger 1.7$. CAHEN³⁵ makes the *first attempt to construct a systematic theory of the function $\mathfrak{D}_f(s)$ although much of the analysis which it contains is open to serious criticism, has served—and possibly just for that reason—as the starting point of most of the later researches in the subject.*

CONVERGENCE.

JENSEN³⁶ proves the following theorem of fundamental importance.

THEOREM 1.10. *Suppose $\mathfrak{D}_f(s)$ is convergent for the complex number $s = \omega + it$, then it is convergent for any value of s for which $\Re(s) > \omega$.*

Consider the Dirichlet series for two arithmetic functions f and g .

$$\begin{aligned} \mathfrak{D}_f(s) &= \sum_{n \geq 1} \frac{f(n)}{n^s} \\ \mathfrak{D}_g(s) &= \sum_{n \geq 1} \frac{g(n)}{n^s} \end{aligned}$$

Then we have

$$\mathfrak{D}_f(s) \mathfrak{D}_g(s) = \sum_{n \geq 1} \frac{f(n)}{n^s} \sum_{n \geq 1} \frac{g(n)}{n^s}$$

Now, imagine we want to write this product as another Dirichlet series. Then it would be of the form

$$\mathfrak{D}_h(s) = \sum_{n \geq 1} \frac{h(n)}{n^s}$$

The coefficients $h(n)$ of $\mathfrak{D}_h(s)$ is determined as follows.

$$h(n) = \sum_{de=n} f(d)g(e)$$

³¹HARDY and RIESZ, *The general theory of Dirichlet's series* cit., §1, Page 1.

³²Ibid.

³³JOHANN PETER GUSTAV LEJEUNE DIRICHLET, *Vorlesungen Über Zahlentheorie*, ed. by R. Dedekind, Cambridge University Press, 1879.

³⁴JOHAN LUDWIG WILLIAM VALDEMAR JENSEN, "OM RÆKKERS KONVERGENS", *Tidsskrift for matematik*, 5th ser., vol. II (1884), pp. 63-72, ISSN: 09092528, 24460737, <http://www.jstor.org/stable/24540057>; JOHAN LUDWIG WILLIAM VALDEMAR JENSEN, "Sur une généralisation d'un théorème de Cauchy", *Comptes Rendus* (Mar. 1888).

³⁵EUGÈNE CAHEN, "Sur la fonction $\zeta(s)$ de Riemann et sur des fonctions analogues", fr, *Annales scientifiques de l'École Normale Supérieure*, vol. 3e série, 11 (1894), pp. 75-164, doi: 10.24033/asens.401.

³⁶JENSEN, "OM RÆKKERS KONVERGENS" cit.

After a little observation, it seems quite obvious that this is indeed correct. In fact, this is what we call Dirichlet convolution today.

DIRICHLET CONVOLUTION. For two arithmetic functions f and g , the *Dirichlet product* or *Dirichlet convolution* of f and g is defined as

$$f * g = \sum_{d|n} f(d)g\left(\frac{n}{d}\right)$$

THEOREM 1.11. *Let f and g be multiplicative arithmetic functions. Then $f * g$ is also multiplicative.*

Proof. □

THEOREM 1.12 (Associativity of Dirichlet Convolution). *Dirichlet convolution is associative. That is, if f, g and h are arithmetic functions, then*

$$(f * g) * h = f * (g * h)$$

Proof. □

An interesting function associated with Dirichlet convolution and summatory functions is the *Möbius function* μ , defined in MÖBIUS.³⁷

$$\mu(n) = \begin{cases} 0 & \text{if } p^2 \mid n \text{ for some prime } p \\ (-1)^{\omega(n)} & \text{otherwise} \end{cases}$$

where $\omega(n)$ is the number of distinct prime divisors of n . On the other hand, $\Omega(n)$ is the total number of prime divisors of n . So, $\omega(12) = 2$ whereas $\Omega(12) = 3$.

THEOREM 1.13 (Möbius inversion). *Let f be an arithmetic function and F be the summatory function*

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

Then

$$f(n) = \sum_{d|n} \mu(d)F\left(\frac{n}{d}\right)$$

Proof. □

Following COJOCARU and MURTY,³⁸ let us define *dual convolution*.

DIVISOR CLOSED SET. A set of positive integers \mathbb{S} is a *divisor closed set* if $d \mid n$, then $d \in \mathbb{S}$ holds for all $n \in \mathbb{S}$.

³⁷AUGUST FERDINAND MÖBIUS, “Über eine besondere art von Umkehrung der Reihen.” *Journal für die reine und angewandte Mathematik (Crelles Journal)*, vol. IX (1832), pp. 105-123, doi: 10.1515/crll.1832.9.105.

³⁸ALINA CARMEN COJOCARU and MARUTI RAM PEDAPROLU MURTY, *An introduction to sieve methods and their applications*, Cambridge University Press, 2006, Page 4, Theorem 1.2.3.

DUAL CONVOLUTION. Let f and g be arithmetic functions. Then the dual convolution of f and g is the arithmetic function h defined as

$$h(n) = \sum_{\substack{n|d \\ d \in \mathbb{D}}} f(d)g\left(\frac{d}{n}\right)$$

where \mathbb{D} is a divisor closed set.

THEOREM 1.14 (Dual Möbius Inversion). *Let f be an arithmetic function and F be the summatory function*

$$F(n) = \sum_{\substack{n|d \\ d \in \mathbb{D}}} f(d)$$

where \mathbb{D} is a divisor closed set. Then

$$f(n) = \sum_{\substack{n|d \\ d \in \mathbb{D}}} \mu\left(\frac{d}{n}\right)f(d)$$

Proof. □

While discussing inversion, we should also mention Dirichlet inverse.

DIRICHLET INVERSE. Let f be an arithmetic function such that $f(1) \neq 0$. Then the *Dirichlet inverse* of f is a function g such that $f * g = I$ where I is the *identity function*

$$I(n) = \begin{cases} 1 & n=1 \\ 0 & n>1 \end{cases}$$

This inverse g can be expressed recursively.

$$g(1) = \frac{1}{f(1)}$$

$$g(n) = -\frac{1}{f(1)} \sum_{\substack{d|n \\ d < n}} f\left(\frac{n}{d}\right)g(d)$$

HAUKKANEN³⁹ proves the following closed formula to find the Dirichlet inverse of an arithmetic function f which we do not prove here.

THEOREM 1.15. *Let f be an arithmetic function such that $f(1) = 1$. Then the Dirichlet inverse of f is*

$$f^{-1}(n) = \sum_{k=1}^{\Omega(n)} (-1)^k \sum_{\substack{d_1 \cdots d_k = n \\ d_1, \dots, d_k > 1}} f(d_1) \cdots f(d_k)$$

We leave the following as exercise.

1. If f is a multiplicative arithmetic function, then the Dirichlet inverse f^{-1} is also multiplicative.
2. If f and $f * g$ are multiplicative functions, then g is also multiplicative.
3. $\sum_{d|n} \mu(d) = I(n)$.

³⁹PENTTI HAUKKANEN, “Expressions for the Dirichlet Inverse of an Arithmetical Function”, *Notes on Number Theory and Discrete Mathematics*, ISSN 1310-5132 Volume 6, 2000, Number 4, Pages 118—124, vol. VI, no. 4 (2000), pp. 118-124, doi: <https://nntdm.net/volume-06-2000/number-4/118-124/>, Theorem 2.2.

§§1.3 GENERAL CONVOLUTION AND DIRICHLET HYPERBOLA METHOD

In this chapter, we will discuss Dirichlet convolution and its generalization, use Dirichlet derivative to prove the Selberg identity, establish some results using generalized convolution and finally, prove the fundamental identity of Selberg.

We proved before that

$$\sum_{n \leq x} \tau(n) = 2 \sum_{n \leq \sqrt{x}} \left\lfloor \frac{x}{n} \right\rfloor - [\sqrt{x}]^2$$

In a similar manner, we can also prove the following.

$$\sum_{n \leq x} \sigma(n) = \frac{1}{2} \left(\sum_{n \leq \sqrt{x}} \left\lfloor \frac{x}{n} \right\rfloor + \sum_{n \leq \sqrt{x}} (2n+1) \left\lfloor \frac{x}{n} \right\rfloor - [\sqrt{x}]^2 - [\sqrt{x}]^3 \right)$$

Note that, in both cases, we are able to express the partial sum of a multiplicative function up to x in terms of a combination of some partial sums of some other functions up to \sqrt{x} . The generalization of this method is known as the *Dirichlet hyperbola method*.

THEOREM 1.16 (Dirichlet Hyperbola Method). *Let f and g be arithmetic functions. If h is the Dirichlet convolution of f and g , then*

$$\sum_{n \leq x} h(n) = \sum_{n \leq a} f(n)G\left(\frac{x}{n}\right) + \sum_{n \leq b} g(n)F\left(\frac{x}{n}\right) - F(a)G(b)$$

where F and G are the partial sums of f and g respectively.

$$F(x) = \sum_{n \leq x} f(n)$$

$$G(x) = \sum_{n \leq x} g(n)$$

Specially when $a = b$,

$$\sum_{de \leq x} f(d)g(e) = \sum_{n \leq \sqrt{x}} \left(f(n)G\left(\frac{x}{n}\right) + g(n)F\left(\frac{x}{n}\right) \right) - F(\sqrt{x})G(\sqrt{x})$$

Next, we will discuss generalizations of Dirichlet convolution. Let f and g be arithmetic functions such that $g(x) = 0$ if $0 < x < 1$. Then the *general convolution* of f and g is

$$f \circ g(x) = \sum_{n \leq x} f(n)g\left(\frac{x}{n}\right)$$

We can easily prove the following.

THEOREM 1.17 (General convolution theorem). *Let f, g and h be arithmetic functions. Then*

$$(f * g) \circ h = f \circ (g \circ h)$$

From this, we can also get the general Möbius inversion formula.

THEOREM 1.18. *Let f, g be an arithmetic functions and f^{-1} be the Dirichlet inverse of f . If*

$$G(x) = \sum_{n \leq x} f(n)g\left(\frac{x}{n}\right)$$

then

$$g(x) = \sum_{n \leq x} f^{-1}(n)G\left(\frac{x}{n}\right)$$

§2 BERTRAND TO TCHEBYCHEFF

We said before that *almost* all natural numbers are composite. A major objective of this book is to discuss how often the primes occur. The same question has bugged mathematicians for a centuries. It was Gauss who first observed that the change in the distribution of primes in every interval $[x, x + 1000]$ was around $1/\log x$. Thus, the rough estimate

$$\pi(x) = \int_2^x \frac{1}{\log t} dt$$

was made which is now known as *logarithmic integral*. Gauss conjectured (see LANDAU¹) around 1792 or 1793 that

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

TCHEBYCHEFF² is the first one to make any substantial progress on the matter.

TCHEBYCHEFF'S THETA FUNCTION. Tchebycheff function of the first kind or *Tchebycheff's theta function* is defined as

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

TCHEBYCHEFF'S PSI FUNCTION. Tchebycheff function of the second kind or *Tchebycheff's psi function* is defined as

$$\begin{aligned} \psi(x) &= \sum_{n \leq x} \Lambda(n) \\ &= \sum_{p^e \leq x} \log p \\ &= \sum_{p \leq x} \left\lfloor \frac{\log x}{\log p} \right\rfloor \log p \end{aligned}$$

¹EDMUND LANDAU, "Handbuch der Lehre von der Verteilung der Primzahlen", *Monatshefte für Mathematik und Physik*, vol. XXII, no. 1 (Dec. 1911), doi: 10.1007/bf01742852, Page 37.

²TCHEBYCHEFF, "Mémoire sur les nombres premiers." fre, *Journal de Mathématiques Pures et Appliquées* (1852), pp. 366-390, <http://eudml.org/doc/234762>.

§3 A MODEST INTRODUCTION TO SIEVE THEORY

A composite positive integer n has at least one prime factor not exceeding \sqrt{x} . Thus, the number of primes in the interval $[\sqrt{x}, x]$ is

$$\begin{aligned}\pi(x) - \pi(\sqrt{x}) + 1 &= [x] - \sum_{p \leq x} \left\lfloor \frac{x}{p} \right\rfloor + \sum_{p_1 < p_2 \leq x} \left\lfloor \frac{x}{p_1 p_2} \right\rfloor - \sum_{p_1 < p_2 < p_3 \leq x} \left\lfloor \frac{x}{p_1 p_2 p_3} \right\rfloor + \dots \\ &= \sum_{n \leq x} \mu(n) \left\lfloor \frac{x}{n} \right\rfloor\end{aligned}$$

Now, $[x] = x + O(1)$, so

$$\begin{aligned}\pi(x) - \pi(\sqrt{x}) + 1 &= x \sum_{\substack{n \leq x \\ \varrho(n) \leq \sqrt{x}}} \frac{\mu(n)}{n} + O \left(\sum_{\substack{n \leq x \\ \varrho(n) \leq \sqrt{x}}} \mu(n) \right) \\ &= x \prod_{p \leq \sqrt{x}} \left(1 - \frac{1}{p} \right) + O(2^{\pi(\sqrt{x})})\end{aligned}$$

The last line is true since there are $\pi(\sqrt{x})$ primes not exceeding \sqrt{x} and $|\mu(n)| = 1$ for all square-free $n \leq x$ such that $\varrho(n) \leq \sqrt{x}$. However, this is not particularly useful.

§4 PROOF OF PRIME NUMBER THEOREMS

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