

Notes on the book: *Apostol, Introduction to Analytic Number Theory*

Meng-Gen Tsai
plover@gmail.com

August 19, 2021

Contents

Chapter 1: The Fundamental Theorem of Arithmetic	2
Exercise 1.14.	2
Exercise 1.15.	2
Exercise 1.30.	2
Chapter 2: Arithmetical functions and Dirichlet multiplication	4
Exercise 2.1.	4
Exercise 2.2.	5
Exercise 2.3.	6
Supplement 2.3.1. (Chinese remainder theorem)	7
Exercise 2.4.	7
Exercise 2.6.	8
Exercise 2.7.	9
Exercise 2.9.	10
Exercise 2.10.	11
Exercise 2.11.	11

Chapter 1: The Fundamental Theorem of Arithmetic

Exercise 1.14.

Prove that $n^4 + 4$ is composite if $n > 1$.

Proof.

$$n^4 + 4 = \underbrace{((n-1)^2 + 1)}_{>1} \underbrace{((n+1)^2 + 1)}_{>1}$$

since $n > 1$. \square

Exercise 1.15.

Prove that every $n \geq 12$ is the sum of two composite numbers.

Proof. Write $n = 2m$ (resp. $n = 2m + 1$) where $m \in \mathbb{Z}$, $m \geq 6$. Then $n = 8 + 2(m-4)$ (resp. $n = 9 + 2(m-4)$) is the sum of two composite numbers. \square

Exercise 1.30.

If $n > 1$ prove that the sum

$$\sum_{k=1}^n \frac{1}{k}$$

is not an integer.

Proof.

(1) (Reductio ad absurdum) Suppose

$$H := \sum_{k=1}^n \frac{1}{k}$$

were an integer.

(2) Let s be the largest integer such that $2^s \leq n$. So the integer number

$$\begin{aligned} 2^{s-1}H &= \sum_{k=1}^n \frac{2^{s-1}}{k} \\ &= 2^{s-1} + 2^{s-2} + \frac{2^{s-1}}{3} + 2^{s-3} + \frac{2^{s-1}}{5} + \frac{2^{s-2}}{3} + \cdots + \frac{1}{2} + \cdots. \end{aligned}$$

has only one term of even denominators (as $n > 1$) if we write all terms in irreducible fractions. That is,

$$2^{s-1}H = \frac{1}{2} + \frac{c}{d} \in \mathbb{Z}$$

where $\frac{c}{d}$ is an irreducible fraction with odd d . Hence it suffices to show that $2 \nmid d$ to get a contradiction.

(3) By

$$\frac{1}{2} + \frac{c}{d} = \frac{d+2c}{2d} \in \mathbb{Z}$$

we have $d+2c = 2dd'$ for some $d' \in \mathbb{Z}$. Note that 2 is a prime. So $2 \mid (d+2c)$ or $2 \mid d$, which is absurd.

□

Chapter 2: Arithmetical functions and Dirichlet multiplication

Exercise 2.1.

Find all integers n such that

- (a) $\varphi(n) = \frac{n}{2}$,
- (b) $\varphi(n) = \varphi(2n)$,
- (c) $\varphi(n) = 12$.

Proof of (a).

$$\varphi(n) = n \prod_{p|n} \left(1 - \frac{1}{p}\right) = \frac{n}{2}$$

(Theorem 2.4) implies that $n = 2$. \square

Proof of (b).

- (1) $\varphi(n) = \varphi(2n)$ implies that

$$n \prod_{p|n} \left(1 - \frac{1}{p}\right) = 2n \prod_{p|(2n)} \left(1 - \frac{1}{p}\right).$$

- (2) If $2|n$, then $n = 2n$ or $n = 0$, which is absurd.
- (3) If $2 \nmid n$, then

$$n \prod_{p|n} \left(1 - \frac{1}{p}\right) = 2n \prod_{p|(2n)} \left(1 - \frac{1}{p}\right) = \underbrace{2n \left(1 - \frac{1}{2}\right)}_{=n} \prod_{p|n} \left(1 - \frac{1}{p}\right)$$

is always true. Hence n is odd if $\varphi(n) = \varphi(2n)$.

\square

Proof of (c).

- (1) Show that the solutions of $\varphi(n) = 12$ are $n = 13, 26, 21, 28, 42, 36$. Write $n = p_1^{\alpha_1} \cdots p_r^{\alpha_r}$ where $p_1 < p_2 < \dots$. Then

$$12 = \varphi(n) = \prod_{i=1}^r p_i^{\alpha_i-1} (p_i - 1).$$

(Theorem 2.5). It implies that $p_i \in \{2, 3, 5, 7, 13\}$ if $\alpha_i > 0$. Consider all possible cases of the greatest prime divisor p_r of n as follows.

(2) If $p_r = 13$, then $\alpha_r = 1$ since $13 \nmid 12$. So

$$12 = \varphi(n) = \underbrace{\varphi(13)}_{=12} \varphi\left(\frac{n}{13}\right)$$

or $1 = \varphi\left(\frac{n}{13}\right)$. Hence $\frac{n}{13} = 1, 2$. In this case $n = 13, 26$.

(3) If $p_r = 7$, then $\alpha_r = 1$ since $7 \nmid 12$. So

$$12 = \varphi(n) = \underbrace{\varphi(7)}_{=6} \varphi\left(\frac{n}{7}\right)$$

or $2 = \varphi\left(\frac{n}{7}\right)$. Hence $\frac{n}{7} = 3, 4, 6$. In this case $n = 21, 28, 42$.

(5) If $p_r = 5$, then $\alpha_r = 1$ since $5 \nmid 12$. So $12 = \varphi(5)\varphi\left(\frac{n}{5}\right)$ or $3 = \varphi\left(\frac{n}{5}\right)$, which is impossible.

(6) If $p_r = 3$, then $\alpha_r = 1, 2$. $\alpha_r = 1$ is impossible since $3 \mid 12$. So

$$12 = \varphi(n) = \underbrace{\varphi(3^2)}_{=6} \varphi\left(\frac{n}{3^2}\right)$$

or $2 = \varphi\left(\frac{n}{3^2}\right)$. Hence $\frac{n}{3^2} = 4$. (By assumption $\frac{n}{3^2}$ cannot have any prime factor > 3 .) In this case $n = 36$.

□

Exercise 2.2.

For each of the following statements either give a proof or exhibit a counter example.

- (a) If $(m, n) = 1$ then $(\varphi(m), \varphi(n)) = 1$.
- (b) If n is composite, then $(n, \varphi(n)) > 1$.
- (c) If the same primes divide m and n , then $n\varphi(m) = m\varphi(n)$.

Proof of (a). It is false since $(5, 13) = 1$ and $(\varphi(5), \varphi(13)) = (4, 12) = 4$. □

Proof of (b). It is false since $(15, \varphi(15)) = (15, 8) = 1$. □

Proof of (c).

- (1) It is true.

(2) If the same primes divide m and n , then

$$\frac{\varphi(n)}{n} = \prod_{p|n} \left(1 - \frac{1}{p}\right) = \prod_{p|m} \left(1 - \frac{1}{p}\right) = \frac{\varphi(m)}{m}$$

(Theorem 2.4). Hence $n\varphi(m) = m\varphi(n)$.

□

Exercise 2.3.

Prove that

$$\frac{n}{\varphi(n)} = \sum_{d|n} \frac{\mu(d)^2}{\varphi(d)}.$$

Proof.

(1) Note that fg , f/g and $f * g$ are multiplicative if f and g are multiplicative (Example 5 on page 34 and Theorem 2.14). Hence $\frac{n}{\varphi(n)}$ and $\sum_{d|n} \frac{\mu^2(d)}{\varphi(d)}$ are multiplicative. Hence it might assume that $n = p^a$ for some prime p and integer $a \geq 1$. (The case $n = 1$ is trivial.)

(2)

$$\frac{p^a}{\varphi(p^a)} = \frac{p^a}{p^a - p^{a-1}} = \frac{p}{p-1}.$$

(3)

$$\begin{aligned} \sum_{d|p^a} \frac{\mu(d)^2}{\varphi(d)} &= \frac{\mu(1)^2}{\varphi(1)} + \frac{\mu(p)^2}{\varphi(p)} + \overbrace{\frac{\mu(p^2)^2}{\varphi(p^2)}}^{=0} + \cdots + \overbrace{\frac{\mu(p^a)^2}{\varphi(p^a)}}^{=0} \\ &= 1 + \frac{1}{p-1} + 0 + \cdots + 0 \\ &= \frac{p}{p-1}. \end{aligned}$$

(4) Or apply Theorems 2.4 and 2.18 to get

$$\begin{aligned} \sum_{d|n} \frac{\mu(d)^2}{\varphi(d)} &= \prod_{p|n} \left(1 - \frac{\mu(p)}{\varphi(p)}\right) \\ &= \prod_{p|n} \left(1 - \frac{-1}{p-1}\right) \\ &= \prod_{p|n} \frac{p}{p-1} \\ &= \frac{n}{\varphi(n)}. \end{aligned}$$

□

Supplement 2.3.1. (Chinese remainder theorem)

(Exercise I.3.5 in the textbook: *Jürgen Neukirch, Algebraic Number Theory*.)
The quotient ring \mathcal{O}/\mathfrak{a} of a Dedekind domain by an ideal $\mathfrak{a} \neq 0$ is a principal ideal domain. (Hint: For $\mathfrak{a} = \mathfrak{p}^n$ the only proper ideals of \mathcal{O}/\mathfrak{a} are given by $\mathfrak{p}/\mathfrak{p}^n, \dots, \mathfrak{p}^{n-1}/\mathfrak{p}^n$. Choose $\pi \in \mathfrak{p} \setminus \mathfrak{p}^2$ and show that $\mathfrak{p}^\nu = \mathcal{O}\pi^\nu + \mathfrak{p}^n$.)

Proof.

- (1) By the Chinese remainder theorem, it suffices to show the case $\mathfrak{a} = \mathfrak{p}^n$ where \mathfrak{p} is prime.
- (2) There is a natural correspondence between

$$\{\text{ideals of } \mathcal{O}/\mathfrak{p}^n\} \longleftrightarrow \{\text{ideals of } \mathcal{O} \text{ containing } \mathfrak{p}^n\}.$$

Hence the proper ideals of $\mathcal{O}/\mathfrak{p}^n$ are given by $\mathfrak{p}/\mathfrak{p}^n, \dots, \mathfrak{p}^{n-1}/\mathfrak{p}^n$.

- (3) Similar to Exercise I.3.4, choose $\pi \in \mathfrak{p} \setminus \mathfrak{p}^2$ and thus $\mathfrak{p}^\nu = \mathcal{O}\pi^\nu + \mathfrak{p}^n$ ($\nu = 1, \dots, n-1$) since they have the same prime factorization. Hence $\mathfrak{p}^\nu/\mathfrak{p}^n = (\pi^\nu + \mathfrak{p}^n)$ is principal.

□

Exercise 2.4.

Prove that $\varphi(n) > \frac{n}{6}$ for all n with at most 8 distinct prime factors.

Proof.

- (1)

$$\begin{aligned} \varphi(n) &= n \prod_{p|n} \left(1 - \frac{1}{p}\right) && \text{(Theorem 2.4)} \\ &\geq n \left(1 - \frac{1}{2}\right) \left(1 - \frac{1}{3}\right) \left(1 - \frac{1}{5}\right) \left(1 - \frac{1}{7}\right) \\ &\quad \left(1 - \frac{1}{11}\right) \left(1 - \frac{1}{13}\right) \left(1 - \frac{1}{17}\right) \left(1 - \frac{1}{19}\right) \\ &= \frac{55296}{323323} n \\ &> \frac{n}{6}. \end{aligned}$$

(2) The conclusion does not hold if n has more than 9 distinct prime factors.

□

Exercise 2.6.

Prove that

$$\sum_{d^2|n} \mu(d) = \mu(n)^2$$

and, more generally

$$\sum_{d^k|n} \mu(d) = \begin{cases} 0 & \text{if } m^k|n \text{ for some } m > 1, \\ 1 & \text{otherwise.} \end{cases}$$

The last sum is extended over all positive divisors d of n whose k th power also divide n .

Proof.

- (1) Write $n = p_1^{\alpha_1} \cdots p_r^{\alpha_r} q_1^{\beta_1} \cdots q_s^{\beta_s}$ where $\alpha_i \geq 2$ and $\beta_j = 1$. The proof is similar to Theorem 2.1.
- (2) If $p_1^{\alpha_1} \cdots p_r^{\alpha_r} = 1$, then $\sum_{d^2|n} \mu(n) = \mu(1) = 1$.
- (3) If $p_1^{\alpha_1} \cdots p_r^{\alpha_r} > 1$, then

$$\begin{aligned} \sum_{d^2|n} \mu(d) &= \mu(1) + \mu(p_1) + \cdots + \mu(p_r) \\ &\quad + \mu(p_1 p_2) + \cdots + \mu(p_{r-1} p_r) + \cdots + \mu(p_1 \cdots p_r) \\ &= 1 + \binom{r}{1}(-1) + \binom{r}{2}(-1)^2 + \cdots + \binom{r}{r}(-1)^r \\ &= (1 - 1)^r \\ &= 0. \end{aligned}$$

- (4) By (2)(3), $\sum_{d^2|n} \mu(d) = \mu(n)^2$. Besides, we have

$$\sum_{d^k|n} \mu(d) = \begin{cases} 0 & \text{if } m^k|n \text{ for some } m > 1, \\ 1 & \text{otherwise} \end{cases}$$

by the same argument as (1)(2)(3).

□

Exercise 2.7.

Let $\mu(p, d)$ denote the value of the Möbius function at the gcd of p and d . Prove that for every prime p we have

$$\sum_{d|n} \mu(d) \mu(p, d) = \begin{cases} 1 & \text{if } n = 1, \\ 2 & \text{if } n = p^a, a \geq 1, \\ 0 & \text{otherwise.} \end{cases}$$

Proof.

- (1) It suffices to show that $\mu(p, n)$ is multiplicative. If so, then

$$h(n) := \sum_{d|n} \mu(d) \mu(p, d)$$

is also multiplicative by taking $f(n) := \mu(n) \mu(p, n)$ and $g(n) := 1$ in Theorem 2.14.

- (2) A direct calculation shows that $h(1) = 1$ (or by Theorem 2.12) and

$$\begin{aligned} h(p^a) &= \mu(1) \mu(p, 1) + \mu(p) \mu(p, p) = 1 \cdot 1 + (-1) \cdot (-1) = 2, \\ h(q^b) &= \mu(1) \mu(p, 1) + \mu(q) \mu(p, q) = 1 \cdot 1 + (-1) \cdot 1 = 0 \end{aligned}$$

where $q \neq p$ and $a, b \geq 1$. Hence (1) and Theorem 2.13 show that

$$h(n) = \begin{cases} 1 & \text{if } n = 1, \\ 2 & \text{if } n = p^a, a \geq 1, \\ 0 & \text{otherwise.} \end{cases}$$

- (3) Show that $\mu(p, n)$ is multiplicative. Suppose $(m, n) = 1$. There are two possible cases: $p \nmid mn$ and $p | mn$.

- (a) If $p \nmid mn$, then all $\mu(p, mn), \mu(p, m), \mu(p, n)$ are equal to $\mu(1) = 1$.
- (b) If $p | mn$, then $p | m$ or $p | n$. Note that $(m, n) = 1$ and thus p cannot be a common divisor of m, n . Hence $\mu(p, mn) = \mu(p) = -1$ and $\mu(p, m) \mu(p, n) = \mu(p) \mu(1) = -1$.

In any case $\mu(p, mn) = \mu(p, m) \mu(p, n)$ if $(m, n) = 1$.

□

Exercise 2.9.

If x is real, $x \geq 1$, let $\varphi(x, n)$ denote the number of positive integers $\leq x$ that are relatively prime to n . [Note that $\varphi(n, n) = \varphi(n)$.] Prove that

$$\varphi(x, n) = \sum_{d|n} \mu(d) \left\lfloor \frac{x}{d} \right\rfloor, \quad \sum_{d|n} \varphi\left(\frac{x}{d}, \frac{n}{d}\right) = [x].$$

Proof.

- (1) Show that $\varphi(x, n) = \sum_{d|n} \mu(d) \left\lfloor \frac{x}{d} \right\rfloor$. Similar to the proof of Theorem 2.3. $\varphi(x, n)$ can be written in the form

$$\varphi(x, n) = \sum_{1 \leq k \leq x} \left[\frac{1}{(n, k)} \right],$$

where now k runs through all integers $\leq x$. Now we use Theorem 2.1 with n replaced by (n, k) to obtain

$$\varphi(x, n) = \sum_{1 \leq k \leq x} \sum_{d|(n, k)} \mu(d) = \sum_{1 \leq k \leq x} \sum_{\substack{d|n \\ d|k}} \mu(d).$$

For a fixed divisor d of n we must sum over all those k in the range $1 \leq k \leq x$ which are multiples of d . If we write $k = qd$ then $1 \leq k \leq x$ if and only if $1 \leq q \leq \left\lfloor \frac{x}{d} \right\rfloor$. Hence the last sum for $\varphi(x, n)$ can be written as

$$\varphi(x, n) = \sum_{d|n} \sum_{1 \leq q \leq \left\lfloor \frac{x}{d} \right\rfloor} \mu(d) = \sum_{d|n} \mu(d) \sum_{1 \leq q \leq \left\lfloor \frac{x}{d} \right\rfloor} 1 = \sum_{d|n} \mu(d) \left\lfloor \frac{x}{d} \right\rfloor.$$

- (2) Show that $\sum_{d|n} \varphi\left(\frac{x}{d}, \frac{n}{d}\right) = [x]$. Similar to the proof of Theorem 2.2. Let S denote the set $\{1, 2, \dots, [x]\}$. We distribute the integers of S into disjoint sets as follows. For each divisor d of n , let

$$A(d) = \{k : (k, n) = d, 1 \leq k \leq x\}.$$

That is, $A(d)$ contains those elements of S which have the gcd d with n . The sets $A(d)$ form a disjoint collection whose union is S . Therefore if $f(d)$ denotes the number of integers in $A(d)$ we have

$$\sum_{d|n} f(d) = [x].$$

But $(k, n) = d$ if and only if $\left(\frac{k}{d}, \frac{n}{d}\right) = 1$, and $0 < k \leq x$ if and only if $0 < \frac{k}{d} \leq \frac{x}{d}$. Therefore, if we let $q = \frac{k}{d}$, there is a one-to-one correspondence between the elements in $A(d)$ and those integers q satisfying $0 < q \leq \frac{x}{d}$, $\left(q, \frac{n}{d}\right) = 1$. The number of such q is $\varphi\left(\frac{x}{d}, \frac{n}{d}\right)$. Hence $f(d) = \varphi\left(\frac{x}{d}, \frac{n}{d}\right)$ and thus

$$\sum_{d|n} \varphi\left(\frac{x}{d}, \frac{n}{d}\right) = [x].$$

□

In Exercise 2.10, 2.11 and 2.12, $d(n)$ denotes the number of positive divisors of n .

Exercise 2.10.

Prove that $\prod_{t|n} t = n^{\frac{d(n)}{2}}$.

Proof.

(1) Note that $d(1) = 1$ and

$$d(p_1^{\alpha_1} \cdots p_r^{\alpha_r}) = (\alpha_1 + 1) \cdots (\alpha_r + 1) = d(p_1^{\alpha_1}) \cdots d(p_r^{\alpha_r}).$$

Hence $d(n)$ is multiplicative (Theorem 2.13).

(2) Show that $\prod_{t|n} t = n^{\frac{d(n)}{2}}$. $n = 1$ is trivial. Assume $n = p_1^{\alpha_1} \cdots p_r^{\alpha_r} > 1$. Then $t|n$ if and only if $t = p_1^{x_1} \cdots p_r^{x_r}$ with $0 \leq x_i \leq \alpha_i$ ($i = 1, \dots, r$). So

$$\begin{aligned} \prod_{t|n} t &= \prod_{\substack{0 \leq x_1 \leq \alpha_1 \\ \vdots \\ 0 \leq x_r \leq \alpha_r}} p_1^{x_1} \cdots p_r^{x_r} \\ &= p_1^{(0+1+\cdots+\alpha_1)(\alpha_2+1)\cdots(\alpha_r+1)} \cdots p_r^{(\alpha_1+1)\cdots(\alpha_{r-1}+1)(0+1+\cdots+\alpha_r)} \\ &= p_1^{\frac{\alpha_1(\alpha_1+1)}{2} \cdot (\alpha_2+1)\cdots(\alpha_r+1)} \cdots p_r^{(\alpha_1+1)\cdots(\alpha_{r-1}+1) \cdot \frac{\alpha_r(\alpha_r+1)}{2}} \\ &= p_1^{\alpha_1 \frac{d(n)}{2}} \cdots p_r^{\alpha_r \frac{d(n)}{2}} \\ &= (p_1^{\alpha_1} \cdots p_r^{\alpha_r})^{\frac{d(n)}{2}} \\ &= n^{\frac{d(n)}{2}}. \end{aligned}$$

□

Exercise 2.11.

Prove that $d(n)$ is odd if, and only if, n is a square.

Proof. $n = 1$ is trivial. Assume $n = p_1^{\alpha_1} \cdots p_r^{\alpha_r} > 1$. Then

$$\begin{aligned} d(n) &= (\alpha_1 + 1) \cdots (\alpha_r + 1) \text{ is odd} && \text{(Exercise 2.10)} \\ \iff \alpha_1 + 1, \dots, \alpha_r + 1 &\text{ are odd} \\ \iff \alpha_1, \dots, \alpha_r &\text{ are even} \\ \iff n &\text{ is a square.} \end{aligned}$$

