

# Introduction to Number Theory and Algorithms

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## Contents

<b>Contents</b>	<b>1</b>
<b>1 Prerequisites</b>	<b>4</b>
<b>2 Basic properties of Integers</b>	<b>5</b>
2.1 Divisibility and primality . . . . .	5

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## Preface

This is a Distillation of:  
A Computational Introduction to Number Theory and Algebra  
(Version 2), by Victor Shoup.

See <https://shoup.net/ntb/> for the original text and practice problems.

— 1 —

Prerequisites

**Definition 0.1: Well-Ordering Principle**

Every non-empty set of positive integers has a least element.

## Basic properties of Integers

### 2.1 Divisibility and primality

“ $a$  divides  $b$ ”, i.e.,  $\left(\frac{b}{a}\right)$ , means  $b$  is reached by  $a$ , when  $a$  is multiplied by some integer.

**Definition 1.1: Division**

Let  $a, b, x \in \mathbb{Z}$ :  $\left(\frac{b}{a}\right)$  means “ $b = ax$ ”.

**Denoted:**  $a|b$ ,  
read “ $a$  divides  $b$ ,” and “ $a$  doesn’t divide  $b$ ” is,  $a \nmid b$ .

**Examples:**

- $3 \mid 6$  because  $6 = 3 \cdot 2$ .
- $3 \nmid 5$  because  $5 \neq 3 \cdot x$  for any  $x \in \mathbb{Z}$ .
- $2 \mid 0$  because  $0 = 2 \cdot 0$ .
- $0 \nmid 2$  because  $2 \neq 0 \cdot x$  for any  $x \in \mathbb{Z}$ .

**Note:**  $a, b, x \in \mathbb{Z}$  for, “ $\left(\frac{b}{a}\right)$ ” or “ $b = ax$ ” are labeled,  $a$ : **divisor**,  $b$ : **dividend**,  $x$ : **quotient**.

**Tip:** Many problems will involve manipulating this “ $b = ax$ ” equation. Whether it’s substituting  $b$  for  $ax$  or vice-versa, or adding/subtracting/multiplying/dividing “ $b = ax$ ” to itself to reveal some property.

Many definitions and theorems will relate to each other or build off one another. It’s crucial to understand what concepts mean rather than memorizing them. This means the ability to derive theorems or definitions from scratch, based on intuitive understanding of the content.

Observe the following:

**Theorem 1.1: Properties of Divisibility**

**Theorem 1.1.** For all  $a, b, c \in \mathbb{Z}$ :

- (i) “ $a \mid a$ ”, “ $1 \mid a$ ”, and “ $a \mid 0$ ”
- (ii) “ $0 \mid a$ ”  $\iff$  “ $a = 0$ ”
- (iii) “ $a \mid b$ ”  $\iff$  “ $-a \mid b$ ”  $\iff$  “ $a \mid -b$ ”
- (iv) “ $a \mid b$ ”  $\wedge$  “ $a \mid c$ ”  $\implies$  “ $a \mid (b + c)$ ”
- (v) “ $a \mid b$ ”  $\wedge$  “ $b \mid c$ ”  $\implies$  “ $a \mid c$ ”

Try to prove these properties before reading the proof below.

**Proof 1.1: Properties of Divisibility**

**Proof.** For all  $a, b, x, y \in \mathbb{Z}$ :

- (i) – “ $a \mid a$ ” means “ $a = ax$ ”, choosing  $x = 1$  always satisfies.  
 – “ $1 \mid a$ ” because  $a = 1 \cdot a$   
 – “ $a \mid 0$ ” because  $0 = a \cdot 0$
- (ii) – If “ $0 \mid a$ ” then “ $a = 0 \cdot x$ ”, 0 times any integer is 0, so  $a = 0$   
 – If “ $a = 0$ ” then “ $0 = 0 \cdot x$ ”,  $x$  can be any integer.
- (iii) Proving  $a \mid b \iff -a \mid b$ :  
 – If “ $a \mid b$ ” then “ $b = ax = (-a)(-x)$ ”,  $-x$  is some integer, say  $x'$ .  
 So “ $b = (-a)x'$ ” then “ $-a \mid b$ ”  
 – If “ $-a \mid b$ ” then “ $b = (-a)x$ ”, choose  $x$  to be some negative integer.

Proving  $-a \mid b \iff a \mid -b$ :

- If “ $-a \mid b$ ” then “ $b = (-a)x$ ”, choose  $x$  positive integer.
- If “ $a \mid -b$ ” then “ $-b = ax$ ”, choose  $x$  to be some negative integer.
- (iv) If “ $a \mid b$ ” and “ $a \mid c$ ” then “ $b = ax$ ” and “ $c = ay$ ” add both equations, “ $b + c = ax + ay$ ” factor, “ $b + c = a(x + y)$ ”,  $(x + y)$  is some integer, so “ $a \mid (b + c)$ ”
- (v) If “ $a \mid b$ ” and “ $b \mid c$ ” then “ $b = ax$ ” and “ $c = by$ ” substitute  $b$  in  $c$ , “ $c = (ax)y$ ” shift terms, “ $c = a(xy)$ ”,  $(xy)$  is some integer, so “ $a \mid c$ ”.

■

**Theorem 1.2: Reflexive Divisibility**

For all  $a, b \in \mathbb{Z}$ : “ $a \mid b$ ”  $\wedge$  “ $b \mid a$ ”  $\iff$  “ $a = \pm b$ ”. Additionally, “ $a \mid 1$ ”  $\iff$  “ $a = \pm 1$ ”.

**Proof 1.2: Reflexive Divisibility**

**Proof.** For all  $a, b, x, y \in \mathbb{Z}$ :

Proving “ $a \mid b$ ”  $\wedge$  “ $b \mid a$ ”  $\implies$  “ $a = \pm b$ ”:

$$\begin{array}{ll}
 a \mid b & a \mid b \quad \text{Given} \\
 b = ax & a = by \quad \text{Definition of Division} \\
 ab = (ax)(by) & \text{Multiplying both equations} \\
 ab = (ab)(xy) & \text{Shift terms} \\
 1 = xy & \text{Divide both sides by } ab
 \end{array}$$

$x$  and  $y$  are integers, so “ $x = y = 1$ ”. Substitute  $x$  and  $y$ ,

$$\begin{array}{ll}
 b = a(1) & a = b(1) \quad \text{Substitute} \\
 a = b & \text{Simplify}
 \end{array}$$

$x$  or  $y$  could be  $\pm$ , so “ $a = \pm b$ ”. Now “ $a = \pm b$ ”  $\implies$  “ $a \mid b$ ” and “ $b \mid a$ ”. From Theorem 1.1, we can use (i) to show “ $a \mid a$ ” substitute  $b$  in for  $a$ , “ $a \mid b$ ” or  $b \mid a$ .

Proving “ $a \mid 1$ ”  $\implies$  “ $a = \pm 1$ ”:

$$\begin{array}{ll}
 a \mid 1 & \text{Given} \\
 1 = ax & \text{Definition of Division} \\
 1 = a(1) & \text{Simplify}
 \end{array}$$

$a$  must be 1,  $x$  could be  $\pm$ , so “ $a = \pm 1$ ” then “ $a \mid \pm 1$ ” so “ $a \mid 1$ ”. ■

**Definition 1.2: Cancellation Law**

Let  $a, b, c \in \mathbb{Z}$ : If “ $ab = ac$ ” and “ $a \neq 0$ ” then “ $b = c$ ”.

I.e., given “ $b = c$ ” multiplying both sides by  $a$  yields “ $ab = ac$ ”, and still  $b = c$ .

**Definition 1.3: Prime Numbers**

$p \in \mathbb{Z}$  is prime if  $p \neq 0$  and  $p$  has no divisors other than 1 and  $p$ .

We will **only consider positive prime numbers**, in this text. Examples of primes are:

$$2, 3, 5, 7, 11, 13, 17, \dots$$

**Definition 1.4: Composite Numbers**

$n, a, b \in \mathbb{Z}$  is composite if  $n = ab$  and  $1 < a < n$  and  $1 < b < n$ .

I.e., a composite number is a number can be factor into two integers, other than 1 and itself.

**Examples:**

- 4 is composite because  $4 = 2 \cdot 2$ .
- 6 is composite because  $6 = 2 \cdot 3$ .

Briefly observe the following:

**Theorem 1.3: Division Algorithm**

For all  $a, b \in \mathbb{Z}$ ,  $b \neq 0$ , there exists unique  $q, r \in \mathbb{Z}$  such that  $a = bq + r$  and  $0 \leq r < |b|$ .

To dissect, for all  $a, b, q, r \in \mathbb{Z}$ ,  $b \neq 0$ ,  $q$  and  $r$  exist uniquely such that:

$$“a = bq + r”$$

$$\text{Dividend} = \text{Divisor} \cdot \text{Quotient} + \text{Remainder}$$

$b$  fits into  $a$   $q$  times with  $r$  left over.

**Examples:**

- $8 = 4 \cdot 2 + 0$
- $5 = 3 \cdot 1 + 2$

**Note:** Funnily, Theorem 1.3 is called the Division Algorithm, despite not being an algorithm.



**Proof 1.3: Division Algorithm**

**Proof.** For all  $a, b \in \mathbb{Z}$ ,  $b \neq 0$ , there exists unique  $q, r \in \mathbb{Z}$  such that  $a = bq + r$  and  $0 \leq r < |b|$ .

- Existence: Take the definition of division " $a \mid b$ " then " $b = ax$ ",  $x$  is *some* integer. Note " $b - ax = 0$ ", shows we are a whole number and not some decimal. Though what if we weren't whole? Now consider as this would confirm. To account for all *such* integers we construct the set " $S = \{a - bx : x \in \mathbb{Z}\}$ "  $S$  is non-empty because  $a - b \cdot 0 = a \in S$ . By the Well-Ordering Principle,  $S$  has a least element, say  $r$ .  
 $r = a - bq$  for some  $q \in \mathbb{Z}$ .  
 $r \geq 0$  because  $r \in S$ .  
 $r < |b|$  because  $r$  is the least element of  $S$ .
- Uniqueness: Suppose  $a = bq_1 + r_1 = bq_2 + r_2$  where  $0 \leq r_1, r_2 < |b|$ .  
 Subtract both equations,  $b(q_1 - q_2) = r_2 - r_1$ .  
 $|b| \leq r_2 - r_1 < |b|$ , so  $r_2 - r_1 = 0$ .  
 $r_1 = r_2$  and  $q_1 = q_2$ .

■