



Chapter 4

Number Theory and Cryptography

MAD101

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Division

1 The Integers and Division

Definition. Let a and b are integers, then b is said to be divisible by a (or b is a multiple of a , or a is a divisor of b , or a divides b), if there exists an integer k such that $b = ka$. We also write $a|b$

Example.

1. $3 \nmid 13$

2. $4 \mid 12$

3. Let n and d be positive integer. How many positive integers not exceeding (\leq) n are divisible by d ?

Suppose $d|m \implies m = kd$. We have $0 < kd \leq n \implies k \leq \frac{n}{d}$. Thus, the number of those integers are $\lfloor \frac{n}{d} \rfloor$

An algorithm to find k

1 The Integers and Division



1. Let $i = 0$
2. If $(i + 1)d > n$ then $k = i$
3. Otherwise go back to step 2. with i is replaced by $i + 1$

Notes.

- Let $r = n - kd$. Then we have $n = kd + r$. The integers k and r are called the **quotient** (thương) and the **remainder** (số dư) in the division of n by d .
- Thus the above algorithm allows us to find the quotient and the remainder of the **division algorithm** (thuật toán chia).



The Division algorithm

1 The Integers and Division

Let a be an integer and d a positive integer. Then there are unique integers q and r such that

$$a = dq + r, 0 \leq r < d$$

- d is called the **divisor** (số chia),
- a the **dividend** (số bị chia),
- q the **quotient** (thương) and r the **remainder** (số dư).

Note. We also write $q = a \operatorname{div} d$, $r = a \operatorname{mod} d$.

Example.

1. Find the quotient and the remainder in the division of 101 by 11
2. Find the quotient and the remainder in the division of -11 by 3

Solution

1 The Integers and Division

Example. Find the quotient and the remainder in the division of 101 by 11

Solution. We have $101 = 11 \times 9 + 2$
Hence $9 = 101 \operatorname{div} 11$ and $2 = 101 \bmod 11$

Example. Find the quotient and the remainder in the division of -11 by 3

Solution. We have $-11 = 3 \times (-4) + 1$
Hence $-4 = -11 \operatorname{div} 3$ and $1 = -11 \bmod 3$

Note. We may write $-11 = 3 \times (-3) - 2$
However -2 is not the remainder r because r always satisfies $0 \leq r < d$.



Quizz

1 The Integers and Division

What are $-17 \div 5$ and $-17 \bmod 5$?

Select one:

- ☐ a. -3 and 2
- ☐ b. -4 and 3
- ☐ c. -3 and -2
- ☐ d. 3 and 2



Quizz

1 The Integers and Division

What are $-17 \div 5$ and $-17 \bmod 5$?

Select one:

- ☐ a. -3 and 2
- ☐ b. -4 and 3
- ☐ c. -3 and -2
- ☐ d. 3 and 2

Ans: b



Quizz

1 The Integers and Division

How many integers in $\{1, 2, 3, \dots, 100\}$ are divisible by 2 but not by 5 ?

Select one:

- ☐ a. 39
- ☐ b. 51
- ☐ c. 49
- ☐ d. 40



Quizz

1 The Integers and Division

How many integers in $\{1, 2, 3, \dots, 100\}$ are divisible by 2 but not by 5 ?

Select one:

- ☐ a. 39
- ☐ b. 51
- ☐ c. 49
- ☐ d. 40

Ans: d



Properties

1 The Integers and Division

Let a , b , and c be integers, where $a \neq 0$. Then

- (i) if $a \mid b$ and $a \mid c$, then $a \mid (b + c)$;
- (ii) if $a \mid b$, then $a \mid bc$ for all integers c ;
- (iii) if $a \mid b$ and $b \mid c$, then $a \mid c$.

Properties

1 The Integers and Division

Let a , b , and c be integers, where $a \neq 0$. Then

- (i) if $a \mid b$ and $a \mid c$, then $a \mid (b + c)$;
- (ii) if $a \mid b$, then $a \mid bc$ for all integers c ;
- (iii) if $a \mid b$ and $b \mid c$, then $a \mid c$.

COROLLARY. If a , b and c are integers, where $a \neq 0$ such that $a \mid b$ and $a \mid c$ then $a \mid mb + nc$ whenever m and n are integers.



The Congruences (đồng dư)

1 The Integers and Division

$$6|(17 - 5)? \rightarrow 17 \equiv 5 \pmod{6}$$

Definition. Let m be a positive integer and a and b are integers, then a is congruent to b modulo m if $a - b$ is divisible by m .

■ We denote this relation by

$$a \equiv b \pmod{m}$$

■ If a is not congruent to b modulo m then we write

$$a \not\equiv b \pmod{m}$$

Example. Are the following congruences true?

- $17 \equiv 5 \pmod{6}$
- $24 \equiv 14 \pmod{6}$

Solution

1 The Integers and Division

Solution. Since $17 - 5 = 12$ is divisible by 6 we see that

$$17 \equiv 5 \pmod{6}$$

Since $24 - 14 = 10$ is not divisible by 6 we conclude that

$$24 \not\equiv 14 \pmod{6}$$

Theorem. Let a, b be integers and m is a positive integer. Then $a \equiv b \pmod{m}$ if and only if there is an integer k such that $a = b + k m$.

Theorem

1 The Integers and Division

1. Let a, b be integers and m is a positive integer. Then $a \equiv b \pmod{m}$ if and only if $a \bmod m = b \bmod m$.
2. Let a, b be integers and m is a positive integer. Then $a \equiv b \pmod{m}$ if and only if there is an integer k such that $a = b + km$.
3. Let m is a positive integer. If $a \equiv b \pmod{m}$ and $c \equiv d \pmod{m}$, then $a + c \equiv b + d \pmod{m}$ and $ac \equiv bd \pmod{m}$.

Corollary. Let a, b are integers and m is a positive integer. Then

1. $(a + b) \bmod m = (a \bmod m + b \bmod m) \bmod m$
2. $(ab) \bmod m = ((a \bmod m)(b \bmod m)) \bmod m$



Arithmetic Modulo m

1 The Integers and Division

- Let $Z_m := \{0, 1, \dots, m - 1\}$ for any $m \geq 1$.
- For any couple $(a, b) \in Z_m \times Z_m$, we define the addition $+_m$ and the multiplication \cdot_m on Z_m by:

$$a +_m b = (a + b) \bmod m$$

$$a \cdot_m b = (ab) \bmod m.$$



Arithmetic Modulo m

1 The Integers and Division

- Let $Z_m := \{0, 1, \dots, m - 1\}$ for any $m \geq 1$.
- For any couple $(a, b) \in Z_m \times Z_m$, we define the addition $+_m$ and the multiplication \cdot_m on Z_m by:

$$a +_m b = (a + b) \bmod m$$

$$a \cdot_m b = (ab) \bmod m.$$

The operations $+_m$ and \cdot_m are called *addition* and *multiplication* modulo m and when we use these operations, we are said to be doing **arithmetic modulo m** .

Applications of Congruences: Cryptography (mật mã)

1 The Integers and Division

A	B	C	D	E	F	G	H	I	J
0	1	2	3	4	5	6	7	8	9
K	L	M	N	O	P	Q	R	S	T
10	11	12	13	14	15	16	17	18	19
U	V	W	X	Y	Z				
20	21	22	23	24	25				

$f : \mathbb{Z}_{26} \rightarrow \mathbb{Z}_{26}, f(p) = (p + k) \bmod 26$: **bijection**

- **Encryption** (mã hóa) $f(p) = (p + k) \bmod 26$
- **Decryption** (giải mã) $f^{-1}(p) = (p - k) \bmod 26$



Example.

1 The Integers and Division

Example.

1. What is the secret message produced from the message “MEET YOU IN THE PARK” using the Caesar cipher ($k=3$)?
2. Decrypt the ciphertext message “LEWLYPLUJL PZ H NYLHA ALHJOLY” that was encrypted with the shift cipher with shift $k = 7$.
3. What letter replaces the letter K when the function $f(p) = (7p + 3) \bmod 26$ is used for encryption?



Solution

1 The Integers and Division

“MEET YOU IN THE PARK”

→ 12 4 4 19-24 14 20-8 13- 19 7 4-15 0 17 10

$f(p) = (p + 3) \bmod 26$, so:

$$f(12) = 15 \bmod 26 = 15$$

$$f(4) = 7 \bmod 26 = 7$$

.....

→ 15 7 7 22-1 17 23- 11 16- 22 10 7- 18 3 20 13, so:

“PHHW BRX LQ WHK SDUN”



Solution

1 The Integers and Division

Solution: First replace the letters in the message with numbers. This produces

12 4 4 19 24 14 20 8 13 19 7 4 15 0 17 10.

Now replace each of these numbers p by $f(p) = (p + 3) \bmod 26$. This gives

15 7 7 22 1 17 23 11 16 22 10 7 18 3 20 13.

Translating this back to letters produces the encrypted message “PHHW BRX LQ WKH SDUN.”





Solution

1 The Integers and Division

Solution: To decrypt the ciphertext “LEWLYPLUJL PZ H NYLHA ALHJOLY” we first translate the letters back to elements of \mathbf{Z}_{26} . We obtain

11 4 22 11 24 15 11 20 9 11 15 25 7 13 24 11 7 0 0 11 7 9 14 11 24.

Next, we shift each of these numbers by $-k = -7$ modulo 26 to obtain

4 23 15 4 17 8 4 13 2 4 8 18 0 6 17 4 0 19 19 4 0 2 7 4 17.

Finally, we translate these numbers back to letters to obtain the plaintext. We obtain “EXPERIENCE IS A GREAT TEACHER.”





Solution

1 The Integers and Division

Solution: First, note that 10 represents K. Then, using the encryption function specified, it follows that $f(10) = (7 \cdot 10 + 3) \bmod 26 = 21$. Because 21 represents V, K is replaced by V in the encrypted message. ◀



Quizz

1 The Integers and Division

Encrypt the message NEED HELP by translating the letters into numbers (the character A is translated to 0), applying the encryption function $f(p) = (p + 3) \bmod 26$, and then translating the numbers back into letters. Encrypted form:

Select one:

- ☐ a. BTTQ TTOA
- ☐ b. CHOS QHHG
- ☐ c. QHUG KHOS
- ☐ d. QHHG KHOS



Quizz

1 The Integers and Division

Encrypt the message NEED HELP by translating the letters into numbers (the character A is translated to 0), applying the encryption function $f(p) = (p + 3) \bmod 26$, and then translating the numbers back into letters. Encrypted form:

Select one:

- ☐ a. BTTQ TTOA
- ☐ b. CHOS QHHG
- ☐ c. QHUG KHOS
- ☐ d. QHHG KHOS

Ans: d

Applications of Congruences: Pseudorandom Numbers (số giả ngẫu nhiên)

1 The Integers and Division

$$x_{n+1} = (ax_n + c) \bmod m$$

Notes.

- a : **Multiplier** (nhân tử) ($2 \leq a < m$)
- c : **Increment** (số gia) ($0 \leq c < m$)
- x_0 : **seed** (hạt giống) ($0 \leq x_0 < m$)
- m : **modulus** (modun)

Example.(Random numbers from 0 to 8) Find the sequence of pseudorandom numbers generated by the linear congruential method with modulus $m = 9$, multiplier $a = 7$, increment $c = 4$, and seed $x_0 = 3$.

$$m = 9, a = 7, c = 4, x_0 = 3 \implies x_{n+1} = 7x_n + 4 \implies x_1, x_2, \dots$$

Solution.

1 The Integers and Division

Solution: We compute the terms of this sequence by successively using the recursively defined function $x_{n+1} = (7x_n + 4) \bmod 9$, beginning by inserting the seed $x_0 = 3$ to find x_1 . We find that

$$x_1 = 7x_0 + 4 \bmod 9 = 7 \cdot 3 + 4 \bmod 9 = 25 \bmod 9 = 7,$$

$$x_2 = 7x_1 + 4 \bmod 9 = 7 \cdot 7 + 4 \bmod 9 = 53 \bmod 9 = 8,$$

$$x_3 = 7x_2 + 4 \bmod 9 = 7 \cdot 8 + 4 \bmod 9 = 60 \bmod 9 = 6,$$

$$x_4 = 7x_3 + 4 \bmod 9 = 7 \cdot 6 + 4 \bmod 9 = 46 \bmod 9 = 1,$$

$$x_5 = 7x_4 + 4 \bmod 9 = 7 \cdot 1 + 4 \bmod 9 = 11 \bmod 9 = 2,$$

$$x_6 = 7x_5 + 4 \bmod 9 = 7 \cdot 2 + 4 \bmod 9 = 18 \bmod 9 = 0,$$

$$x_7 = 7x_6 + 4 \bmod 9 = 7 \cdot 0 + 4 \bmod 9 = 4 \bmod 9 = 4,$$

$$x_8 = 7x_7 + 4 \bmod 9 = 7 \cdot 4 + 4 \bmod 9 = 32 \bmod 9 = 5,$$

$$x_9 = 7x_8 + 4 \bmod 9 = 7 \cdot 5 + 4 \bmod 9 = 39 \bmod 9 = 3.$$

Because $x_9 = x_0$ and because each term depends only on the previous term, we see that the sequence

3, 7, 8, 6, 1, 2, 0, 4, 5, 3, 7, 8, 6, 1, 2, 0, 4, 5, 3, ...

is generated. This sequence contains nine different numbers before repeating. ◀

Example.

1 The Integers and Division

11. Suppose *pseudo-random numbers* are produced by using:

$$x_{n+1} = (3x_n + 5) \bmod 7.$$

If $x_3 = 5$, find x_2 and x_4 .

12. Suppose *pseudo-random numbers* are produced by using:

$$x_{n+1} = (3x_n + 7) \bmod 13 \text{ and the seed } x_1 = 1.$$

Find x_3 and x_4 .



Applications of Congruences: Hashing Function

1 The Integers and Division

$$H(k) = k \bmod m$$

Using in searching data in memory

- k : data searched,
- m : memory block (the number of available memory locations).

Example. Find the memory locations assigned by the hashing function $h(k) = k \bmod 111$ to the records of customers with Social Security numbers 064212848 and 037149212.

$$h(064212848) = 064212848 \bmod 111 = 14 \rightarrow \text{memory location } 14.$$

$$h(037149212) = 037149212 \bmod 111 = 65 \rightarrow \text{memory location } 65.$$



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Representations of Integers

2 Integers and Algorithms

$$n = a_k b^k + a_{k-1} b^{k-1} + \dots + a_1 b + a_0. \text{ Denote } (a_k a_{k-1} \dots a_1 a_0)_b$$

Notes.

- n : positive integer.
- $b > 1$: integer.
- $a_0, a_1, \dots, a_k < b, a_k \neq 0$: nonnegative integer.

This is **the base b expansion** of the integer n .

Examples.

1. $(241)_{10} = ? \rightarrow (241)_{10} = 2 \cdot 10^2 + 4 \cdot 10^1 + 1 \cdot 10^0 = 241$
2. $(7016)_8 = ? \rightarrow (7016)_8 = 7 \cdot 8^3 + 0 \cdot 8^2 + 1 \cdot 8^1 + 6 \cdot 8^0 = 3598 = (3598)_{10}$
3. Suppose that the **letters A through F represent the digits corresponding to the numbers 10 through 15** (in decimal notation).
Find $(2AE0B)_{16} \rightarrow = 175627$



Common Bases Expansions

2 Integers and Algorithms

- **Decimal Expansions** ($b = 10$) (thập phân)
- **Binary Expansions** ($b = 2$) (nhị phân)
- **Octal Expansions** ($b = 8$) (bát phân)
- **Hexadecimal Expansions** ($b = 16$) (thập lục phân)



Examples.

2 Integers and Algorithms

- a. Find 2 expansion of $(241)_{10}$
- b. Find 8 expansion of $(12345)_{10}$
- c. Find 16 expansion of $(177130)_{10}$



Sol a.

2 Integers and Algorithms

$$241 = 120.2 + 1$$

$$= 60.2^2 + 1$$

$$= 30.2^3 + 1$$

$$= 15.2^4 + 1$$

$$= (7.2 + 1).2^4 + 1 = 7.2^5 + 2^4 + 1$$

$$= (3.2 + 1).2^5 + 2^4 + 1 =$$

$$3.2^6 + 2^5 + 2^4 + 1$$

$$(1.2 + 1).2^6 + 2^5 + 2^4 + 1 =$$

$$2^7 + 2^6 + 2^5 + 2^4 + 1$$

$$\text{Thus, } (241)_{10} = 241 = (\mathbf{11110001})_2$$

$$241 = 2.120 + \mathbf{1}$$

$$120 = 2.60 + \mathbf{0}$$

$$60 = 2.30 + \mathbf{0}$$

$$30 = 2.15 + \mathbf{0}$$

$$15 = 2.7 + \mathbf{1}$$

$$7 = 2.3 + \mathbf{1}$$

$$3 = 2.1 + \mathbf{1}$$

$$1 = 2.0 + \mathbf{1}$$

$$\text{Thus, } (241)_{10} = 241 = (\mathbf{11110001})_2$$



Solution.

2 Integers and Algorithms

$$12345 = 8 \cdot 1543 + 1.$$

and Cryptography

Successively dividing quotients by 8 gives

$$1543 = 8 \cdot 192 + 7,$$

$$192 = 8 \cdot 24 + 0,$$

$$24 = 8 \cdot 3 + 0,$$

$$3 = 8 \cdot 0 + 3.$$

The successive remainders that we have found, 1, 7, 0, 0, and 3, are the digits from the right to the left of 12345 in base 8. Hence,

$$(12345)_{10} = (30071)_8.$$





Solution.

2 Integers and Algorithms

Solution: First divide 177130 by 16 to obtain

$$177130 = 16 \cdot 11070 + 10.$$

Successively dividing quotients by 16 gives

$$11070 = 16 \cdot 691 + 14,$$


$$691 = 16 \cdot 43 + 3,$$

$$43 = 16 \cdot 2 + 11,$$

$$2 = 16 \cdot 0 + 2.$$

The successive remainders that we have found, 10, 14, 3, 11, 2, give us the digits from the right to the left of 177130 in the hexadecimal (base 16) expansion of $(177130)_{10}$. It follows that

$$(177130)_{10} = (2B3EA)_{16}.$$

(Recall that the integers 10, 11, and 14 correspond to the hexadecimal digits A, B, and E, respectively.) 

Constructing Base b Expansions

2 Integers and Algorithms

```

procedure base  $b$  expansion( $n, b$ : positive integers with  $b > 1$ )
   $q := n$ 
   $k := 0$ 
  while  $q \neq 0$ 
     $a_k := q \bmod b$ 
     $q := q \operatorname{div} b$ 
     $k := k + 1$ 
  return  $(a_{k-1}, \dots, a_1, a_0)$   $\{(a_{k-1} \dots a_1 a_0)_b$  is the base  $b$  expansion of  $n\}$ 

```

Example. Find base 2 expansion of 241.



Solution.

2 Integers and Algorithms

$$q = 241 \neq 0$$

$$\mathbf{k=0}: a_0 = 241 \bmod 2 = 1, q = 241 \operatorname{div} 2 = 120 \neq 0$$

$$\mathbf{k=1}: a_1 = 0, q = 60$$

$$\mathbf{k=2}: a_2 = 0, q = 30$$

$$\mathbf{k=3}: a_3 = 0, q = 15$$

$$\mathbf{k=4}: a_4 = 1, q = 7$$

$$\mathbf{k=5}: a_5 = 1, q = 3$$

$$\mathbf{k=6}: a_6 = 1, 1 = 1$$

$$\mathbf{k=7}: a_7 = 1, q = 0$$

$$\rightarrow 11110001, \text{so } 241 = (11110001)_2$$



Quizz

2 Integers and Algorithms

Find the *base 7 expansion* of 186

- a. 354
- b. 331
- c. 413
- d. 271
- e. None of these



Quizz

2 Integers and Algorithms

Find the *base 7 expansion* of 186

- a. 354
- b. 331
- c. 413
- d. 271
- e. None of these

Ans: a



Quizz

2 Integers and Algorithms

Find the *binary format* of $(1011)_3$.

- a. 11110
- b. 11111
- c. 100000
- d. 10101
- e. None of these



Quizz

2 Integers and Algorithms

Find the *binary format* of $(1011)_3$.

- a. 11110
- b. 11111
- c. 100000
- d. 10101
- e. None of these

Ans:b



Binary Operations: Addition

2 Integers and Algorithms

Rules.

$$0 + 0 = 0, 1 + 0 = 1, 1 + 1 = 0 \text{ (remind 1)}$$

Add $a = (1110)_2$ and $b = (1011)_2$

$$\begin{array}{r} 1\ 1\ 1\ 0 \\ 1\ 1\ 1\ 0\ (a) \\ +\ 1\ 0\ 1\ 1\ (b) \\ \hline 1\ 1\ 0\ 0\ 1\ (s) \end{array}$$

$$1 = 0.2 + 1$$

$$3 = 1.2 + 1$$

$$2 = 1.2 + 0$$

$$1 = 0.2 + 1$$

$$2 = 1.2 + 0$$

Thus, $(1110)_2 + (1011)_2 = (11001)_2$



Binary Operations: Difference

2 Integers and Algorithms

Rules.

- $0 - 0 = 0$
- $1 - 0 = 1$
- $1 - 1 = 0$
- $0 - 1 = 1(\text{remind} - 1)$
- $-1 - 1 = 0(\text{remind} - 1)$

Let $a = (1110)_2$ and $b = (1011)_2$. Find $a - b$

$$(1110)_2 - (1011)_2 = (11)_2$$



Binary Operations: Multiplication

2 Integers and Algorithms

Find the product of $a = (110)_2$ and $b = (101)_2$

$$\begin{array}{r} 110 \\ \times 101 \\ \hline 110 \\ 000 \\ 110 \\ \hline 11110 \end{array}$$

Thus, $(110)_2 \cdot (101)_2 = (11110)_2$



Binary Operations: Division

2 Integers and Algorithms

Find quotient and remainder (if exists) in the division of $(100010)_2$ by $(110)_2$

$$\begin{array}{r|l} 100010 & 110 \\ \hline 110 & 101 \\ \hline 01010 & \\ 110 & \\ \hline 100 & \end{array}$$

Thus, the quotient $q = 101$ and remainder $r = 100$

Addition Algorithm

2 Integers and Algorithms

procedure *add*(a, b : positive integers)
 {the binary expansions of a and b are $(a_{n-1}a_{n-2} \dots a_1a_0)_2$
 and $(b_{n-1}b_{n-2} \dots b_1b_0)_2$, respectively}
 $c := 0$
for $j := 0$ **to** $n - 1$
 $d := \lfloor (a_j + b_j + c)/2 \rfloor$
 $s_j := a_j + b_j + c - 2d$
 $c := d$
 $s_n := c$
return (s_0, s_1, \dots, s_n) {the binary expansion of the sum is $(s_ns_{n-1} \dots s_0)_2$ }

Example. Find $(1110)_2 + (1011)_2$



Solution

2 Integers and Algorithms

$$c = 0$$

$$j = 0 : d = \lfloor \frac{0 + 1 + 0}{2} \rfloor = \lfloor 0.5 \rfloor = 0$$

$$s_0 = 1, c = 0$$

$$j = 1 : d = \lfloor \frac{1 + 1 + 0}{2} \rfloor = \lfloor 1 \rfloor = 1$$

$$s_1 = 0, c = 1$$

$$j = 2 : d = 1$$

$$s_2 = 0, c = 1$$

$$j = 3 : d = 1$$

$$s_3 = 1, c = 1$$

$$s_4 = 1$$

→ 10011, so the sum is $(11001)_2$

Multiplication Algorithm

2 Integers and Algorithms

procedure *multiply*(a, b : positive integers)

{ the binary expansions of a and b are $(a_{n-1}a_{n-2} \dots a_1a_0)_2$
and $(b_{n-1}b_{n-2} \dots b_1b_0)_2$, respectively }

for $j := 0$ **to** $n - 1$

if $b_j = 1$ **then** $c_j := a$ shifted j places

else $c_j := 0$

{ c_0, c_1, \dots, c_{n-1} are the partial products }

$p := 0$

for $j := 0$ **to** $n - 1$

$p := \text{add}(p, c_j)$

return p { p is the value of ab }

Example. Find the product of $(110)_2$ and $(101)_2$



Solution.

2 Integers and Algorithms

$$j = 0 : b_0 = 1 \rightarrow c_0 = 110$$

$$j = 1 : b_1 = 0 \rightarrow c_1 = 0000\mathbf{0}$$

$$j = 2 : b_2 = 1 \rightarrow c_2 = 110\mathbf{00}$$

$\rightarrow p = 11110$. Hence, the product $(11110)_2$

$$p = 0$$

$$j = 0 : p = 0 + 110 = 110$$

$$j = 1 : p = 110 + 0000 = 0110$$

$$j = 2 : p = 0110 + 11000 = 11110$$

Division Algorithm

2 Integers and Algorithms

```
procedure division algorithm( $a$ : integer,  $d$ : positive integer)
 $q := 0$ 
 $r := |a|$ 
while  $r \geq d$ 
     $r := r - d$ 
     $q := q + 1$ 
if  $a < 0$  and  $r > 0$  then
     $r := d - r$ 
     $q := -(q + 1)$ 
return  $(q, r)$  {  $q = a \text{ div } d$  is the quotient,  $r = a \bmod d$  is the remainder }
```

Example. Find the quotient and the remainder in the division of 101 by 11

Solution.

2 Integers and Algorithms

$$q = 0, r = |101| = 101$$

$$r = 101 \geq 11 = d \rightarrow r = 101 - 11 = 90, q = 0 + 1 = 1$$

$$r = 90 \geq 11 = d \rightarrow r = 79, q = 2$$

$$r = 79 \geq 11 = d \rightarrow r = 61, q = 3$$

$$r = 61 \geq 11 = d \rightarrow r = 57, q = 4$$

$$r = 57 \geq 11 = d \rightarrow r = 46, q = 5$$

$$r = 46 \geq 11 = d \rightarrow r = 35, q = 6$$

$$r = 35 \geq 11 = d \rightarrow r = 24, q = 7$$

$$r = 24 \geq 11 = d \rightarrow r = 13, q = 8$$

$$r = 13 \geq 11 = d \rightarrow r = 2, q = 9$$

$$r = 2 \geq 11 = d(!)$$

Hence, $(q = 9, r = 2)$

Modular Exponentiation

2 Integers and Algorithms

procedure *modular exponentiation*(b : integer, $n = (a_{k-1}a_{k-2} \dots a_1a_0)_2$,
 m : positive integers)
 $x := 1$
 $power := b \bmod m$
for $i := 0$ **to** $k - 1$
 if $a_i = 1$ **then** $x := (x \cdot power) \bmod m$
 $power := (power \cdot power) \bmod m$
return $x \{x \text{ equals } b^n \bmod m\}$

Example. Find $3^{644} \bmod 645$

Solution.

2 Integers and Algorithms

We have $b = 3, m = 645, 644 = (1010000100)_2$

$$x = 1$$

$$power = 3 \bmod 645 = 3$$

$$i = 0 : a_0 = 0 \rightarrow x = 1, power = 3^2 \bmod 645 = 9$$

$$i = 1 : a_1 = 0 \rightarrow x = 1, power = 9^2 \bmod 645 = 81$$

$$i = 2 : a_2 = 1 \rightarrow x = 1.81 \bmod 645 = 81, power = 81^2 \bmod 645 = 111$$

$$i = 3 : a_3 = 0 \rightarrow x = 81, power = 111^2 \bmod 645 = 66$$

$$i = 4 : a_4 = 0 \rightarrow x = 81, power = 66^2 \bmod 645 = 486$$

$$i = 5 : a_5 = 0 \rightarrow x = 81, power = 486^2 \bmod 645 = 126$$

$$i = 6 : a_6 = 0 \rightarrow x = 81, power = 126^2 \bmod 645 = 396$$



Solution.

2 Integers and Algorithms

$$i = 7 : a_7 = 1 \rightarrow x = (81.396) \bmod 645 = 471, power = 396^2 \bmod 645 = 81$$

$$i = 8 : a_8 = 0 \rightarrow x = 471, power = 81^2 \bmod 645 = 111$$

$$i = 9 : a_9 = 1 \rightarrow x = (471.111) \bmod 645 = 36, power = 111^2 \bmod 645 = 66$$

$$\rightarrow x = 36. \text{ Hence, } 3^{644} \bmod 645 = 36$$



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3 Primes and Greatest Common Divisors

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- ▶ Integers and Algorithms
- ▶ Primes and Greatest Common Divisors
- ▶ Problems



Primes

3 Primes and Greatest Common Divisors

Definition.

- A positive integer p greater than 1 is called **prime** (số nguyên tố) if the only positive factors (ước số) are 1 and p .
- A positive integer that is greater than 1 and is not prime is called **composite** (hợp số).

Example.

3 Primes and Greatest Common Divisors

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100



The fundamental theorem of arithmetic (ĐL cơ bản của số học)

3 Primes and Greatest Common Divisors

Every positive integer greater than 1 can be written uniquely as a prime or as the product of two or more primes where the prime factors are written in order of nondecreasing size.

Examples. Find the prime factorizations of 100, 999, and 1024.

Solution.

$$100 = 2^2 \cdot 5^2$$

$$999 = 3^3 \cdot 37$$

$$1024 = 2^{10}$$



Theorem

3 Primes and Greatest Common Divisors

If n is a composite integer, then n has a prime divisor (ước nguyên tố) less than or equal to \sqrt{n} .

Examples.

1. Show that 101 is prime.
2. Find the prime factorization of 7007.



Solutions.

3 Primes and Greatest Common Divisors

Solution: The only primes not exceeding $\sqrt{101}$ are 2, 3, 5, and 7. Because 101 is not divisible by 2, 3, 5, or 7 (the quotient of 101 and each of these integers is not an integer), it follows that 101 is prime. ◀

Solution: To find the prime factorization of 7007, first perform divisions of 7007 by successive primes, beginning with 2. None of the primes 2, 3, and 5 divides 7007. However, 7 divides 7007, with $7007/7 = 1001$. Next, divide 1001 by successive primes, beginning with 7. It is immediately seen that 7 also divides 1001, because $1001/7 = 143$. Continue by dividing 143 by successive primes, beginning with 7. Although 7 does not divide 143, 11 does divide 143, and $143/11 = 13$. Because 13 is prime, the procedure is completed. It follows that $7007 = 7 \cdot 1001 = 7 \cdot 7 \cdot 143 = 7 \cdot 7 \cdot 11 \cdot 13$. Consequently, the prime factorization of 7007 is $7 \cdot 7 \cdot 11 \cdot 13 = 7^2 \cdot 11 \cdot 13$. ◀

Theorem

3 Primes and Greatest Common Divisors

1. There are infinite many primes.
2. **(The prime number theorem)** The ratio of $\pi(x)$, the number of primes not exceeding x and $x/\ln x$ approaches 1 and grows with bound ($\ln x$: natural logarithm of x).

TABLE 2 Approximating $\pi(x)$ by $x/\ln x$.			
x	$\pi(x)$	$x/\ln x$	$\pi(x)/(x/\ln x)$
10^3	168	144.8	1.161
10^4	1229	1085.7	1.132
10^5	9592	8685.9	1.104
10^6	78,498	72,382.4	1.084
10^7	664,579	620,420.7	1.071
10^8	5,761,455	5,428,681.0	1.061
10^9	50,847,534	48,254,942.4	1.054
10^{10}	455,052,512	434,294,481.9	1.048

Greatest Common Divisors

3 Primes and Greatest Common Divisors

Definition. Let a, b be integers, not both zero. The largest integer d such that $d|a$ and $d|b$ is called **the greatest common divisor** (ước chung lớn nhất) of a and b .

Notation. $\gcd(a, b)$

To find $\gcd(a, b)$:

$$a = p_1^{a_1} \cdot p_2^{a_2} \cdots p_k^{a_k} \quad (p_1 < p_2 < \cdots < p_k)$$

$$b = p_1^{b_1} \cdot p_2^{b_2} \cdots p_k^{b_k}$$

$$\gcd(a, b) = p_1^{\min(a_1, b_1)} \cdot p_2^{\min(a_2, b_2)} \cdots p_k^{\min(a_k, b_k)}$$

Examples.

1. $\gcd(24, 36) \rightarrow \gcd(24, 36) = 12$
2. $\gcd(17, 22) \rightarrow \gcd(17, 22) = 1$



Definition.

3 Primes and Greatest Common Divisors

- The integers a, b are **relatively prime** (nguyên tố cùng nhau) if their greatest common divisor is 1
- The integers $a_1, a_2, a_3, \dots, a_n$ are **pairwise relatively prime** (đôi 1 nguyên tố cùng nhau) if $\gcd(a_i, a_j) = 1$ whenever $1 \leq i < j \leq n$

Examples. Show that

7, 10, 11, 17, 23 are pairwise relatively prime.

17, 22 are relative prime.

The Least common multiple

3 Primes and Greatest Common Divisors

Definition. The **Least common multiple** (bội chung nhỏ nhất) of the positive integer a and b is the smallest integer that is divisible by both a and b .

Notation. $lcm(a, b)$

To find $lcm(a, b)$:

$$a = p_1^{a_1} \cdot p_2^{a_2} \cdots p_k^{a_k} \quad (p_1 < p_2 < \cdots < p_k)$$

$$b = p_1^{b_1} \cdot p_2^{b_2} \cdots p_k^{b_k}$$

$$lcm(a, b) = p_1^{\max(a_1, b_1)} \cdot p_2^{\max(a_2, b_2)} \cdots p_k^{\max(a_k, b_k)}$$

Examples.

$$1. \quad lcm(12, 36) \rightarrow lcm(12, 36) = 36$$

$$2. \quad lcm(7, 17) \rightarrow lcm(7, 17) = 119$$



Theorem

3 Primes and Greatest Common Divisors

Let a, b be positive integers then $ab = \gcd(a, b) \cdot \text{lcm}(a, b)$

Example. $\gcd(8, 12) = 4, \text{lcm}(8, 12) = 24 \rightarrow 8 \cdot 12 = 4 \cdot 24$



The Euclidean Algorithm

3 Primes and Greatest Common Divisors

procedure $\gcd(a, b$: positive integers)

$x := a$

$y := b$

while $y \neq 0$

$r := x \bmod y$

$x := y$

$y := r$

return x { $\gcd(a, b)$ is x }

Example. Find $\gcd(24, 36)$



Solution.

3 Primes and Greatest Common Divisors

$$x = 24$$

$$y = 36$$

$$y = 36 \neq 0 : r = 24 \bmod 36 = 24, x = 36, y = 24$$

$$y = 24 \neq 0 : r = 36 \bmod 24 = 12, x = 24, y = 12$$

$$y = 12 \neq 0 : r = 24 \bmod 12 = 0, x = 12, y = 0$$

$$y = 0 \neq 0(!)$$

→ return 12. Hence, $\gcd(24, 36) = 12$



Euler φ -function

3 Primes and Greatest Common Divisors

$$\varphi : \mathbb{N}^* \rightarrow \mathbb{N}^*$$

$$n \mapsto \varphi(n)$$

$\varphi(n)$ = the number of positive integers less than or equal to n that are **relatively prime** to n .

$$n = p_1^{\alpha_1} \cdot p_2^{\alpha_2} \cdots p_k^{\alpha_k}$$

$$\varphi(n) = n \left(1 - \frac{1}{p_1}\right) \left(1 - \frac{1}{p_2}\right) \cdots \left(1 - \frac{1}{p_k}\right)$$

$$\text{if } p \text{ is the prime, then } \varphi(p) = p \left(1 - \frac{1}{p}\right) = p - 1$$

Example. $\varphi(6) = 2$ because of the positive integers less or equal to 6, only 1 and 5 are relatively prime to 6.

Example. Find $\varphi(10)$ and $\varphi(100)$



Quiz

3 Primes and Greatest Common Divisors

Which pair of integers are *relatively prime*?

- a. (17, 51)
- b. (5, 24)
- c. (11, 121)
- d. (37, 111)
- e. None of the others



Quiz

3 Primes and Greatest Common Divisors

Which pair of integers are *relatively prime*?

- a. (17, 51)
- b. (5, 24)
- c. (11, 121)
- d. (37, 111)
- e. None of the others

Ans: b



Quiz

3 Primes and Greatest Common Divisors

If a, b are positive integers such that $\gcd(a, b) = 5$ and $ab = 120$, find $\text{lcm}(a, b)$.

- a. 24
- b. 600
- c. 120
- d. 5
- e. None of the others



Quiz

3 Primes and Greatest Common Divisors

If a, b are positive integers such that $\gcd(a, b) = 5$ and $ab = 120$, find $\text{lcm}(a, b)$.

- a. 24
- b. 600
- c. 120
- d. 5
- e. None of the others

Ans: a



Table of Contents

4 Problems

- ▶ The Integers and Division
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- ▶ Problems

The Integers and Division

4 Problems

1. Does 17 divide each of these numbers?

- a) 68 b) 84 c) 357 d) 1001

2. What are the quotient and remainder when

- a) 19 is divided by 7? b) -111 is divided by 11? c) 789 is divided by 23?

- d) 1001 is divided by 13? e) 0 is divided by 19? f) 3 is divided by 5?

3. Suppose that a and b are integers, $a \equiv 4 \pmod{13}$, and $b \equiv 9 \pmod{13}$. Find the integer c with $0 \leq c \leq 12$ such that

- a) $c \equiv 9a \pmod{13}$. b) $c \equiv 11b \pmod{13}$. c) $c \equiv a + b \pmod{13}$.

- d) $c \equiv 2a + 3b \pmod{13}$. e) $c \equiv a^2 + b^2 \pmod{13}$. f) $c \equiv a^3 - b^3 \pmod{13}$.

The Integers and Division

4 Problems

4. Evaluate these quantities.

a) $13 \bmod 3$ b) $-97 \bmod 11$ c) $155 \bmod 19$ d) $-221 \bmod 23$

5. Find a **div** m and a **mod** m when

a) $a = -111$, $m = 99$. b) $a = -9999$, $m = 101$.

c) $a = 10299$, $m = 999$. d) $a = 123456$, $m = 1001$.

6. Decide whether each of these integers is congruent to 5 modulo 17.

a) 80 b) 103 c) -29 d) -122



The Integers and Division

4 Problems

7. Find each of these values.

a) $(992 \bmod 32)^3 \bmod 15$

b) $(34 \bmod 17)^2 \bmod 11$

c) $(193 \bmod 23)^2 \bmod 31$

d) $(893 \bmod 79)^4 \bmod 26$

8. Convert the decimal expansion of each of these integers to a binary expansion.

a) 23

b) 45

c) 241

d) 1025

9. Convert the binary expansion of each of these integers to a decimal expansion.

a) $(1\ 1011)_2$

b) $(10\ 1011\ 0101)_2$

c) $(11\ 1011\ 1110)_2$

d) $(111\ 1100\ 0001\ 1111)_2$

The Integers and Division

4 Problems

10. Convert the octal expansion of each of these integers to a binary expansion.

a) $(572)_8$

b) $(1604)_8$

c) $(423)_8$

d) $(2417)_8$

11. Convert each of the following expansions to **decimal expansion**.

a) $(1021)_3$

b) $(325)_7$

c) $(A3)_{12}$

d) $(401)_5$

e) $(12B7)_{13}$

12. Convert 69 to

a) a binary expansion

b) a base 6 expansion

c) a base 9 expansion

11. Suppose $a \bmod 3 = 2$ and $b \bmod 6 = 4$, find $ab \bmod 3$.

Primes and Greatest Common Divisors

4 Problems

1. Determine whether each of these integers is prime.

a) 21 b) 29 c) 71 d) 97

e) 111 f) 143 g) 93 h) 101

2. Find the prime factorization of each of these integers.

a) 39 b) 81 c) 101

d) 143 e) 289 f) 899

3. Find the prime factorization of $10!$



Primes and Greatest Common Divisors

4 Problems

4. Which positive integers less than 12 are relatively prime to 12?
5. Which positive integers less than 30 are relatively prime to 30?
6. Find these values of the Euler φ -function.
a) $\varphi(4)$ b) $\varphi(10)$ c) $\varphi(13)$
7. What are the greatest common divisors of these pairs of integers?
a) $37 \cdot 53 \cdot 73, 211 \cdot 35 \cdot 59$ b) $11 \cdot 13 \cdot 17, 29 \cdot 37 \cdot 55 \cdot 73$ c) 2331, 2317
d) $41 \cdot 43 \cdot 53, 41 \cdot 43 \cdot 53$ e) $313 \cdot 517, 212 \cdot 721$

Integers and Algorithms

4 Problems

1. Suppose *pseudo-random numbers* are produced by using: $x_{n+1} = (3x_n + 11) \bmod 13$. If $x_3 = 5$, find x_2 and x_4 .
2. Suppose pseudo-random numbers are produced by using: $x_{n+1} = (2x_n + 7) \bmod 9$.
 - a) If $x_0 = 1$, find x_2 and x_3
 - b) If $x_3 = 3$, find x_2 and x_4 .
3. Using the function $f(x) = (x + 10) \bmod 26$ to encrypt messages. Answer each of these questions.
 - a) Encrypt the message STOP
 - b) Decrypt the message LEI



Integers and Algorithms

4 Problems

4. Which memory locations are assigned by the **hashing function** $h(k) = k \bmod 101$ to the records of insurance company customers with these Social Security Numbers?

a) 104578690

b) 432222187

5. Use the **Euclidean algorithm** to find

a) $\gcd(14, 28)$

b) $\gcd(8, 28)$

c) $\gcd(100, 101)$

d) $\gcd(28, 35)$

e) $\text{lcm}(7, 28)$

f) $\text{lcm}(12, 28)$

g) $\text{lcm}(100, 101)$

h) $\text{lcm}(28, 35)$



Q&A

Thank you for listening!