

# MATH406: Introduction to Number Theory

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Notes are based off of *An Introduction to Number Theory with Cryptography* (Second edition), by Washington and Kraft

# 1 Basics

**Well-Ordering Principle:** All non-empty subsets of  $N$  has a smallest member

- **Note:** This is equivalent to the Principle of Induction

## 2 Divisibility

### 2.1 Divisibility

**Definition 2.1:** Given  $a, d \in Z$ , for  $d \neq 0$ ,  $d$  **divides**  $a$  if  $\exists c \in Z$  such that  $a = cd$

**Proposition 2.2:** Let  $a, b, c \in Z$ . If  $a \mid b$  and  $b \mid c \implies a \mid c$

*Proof:*  $b = ea$  and  $c = fb \implies c = (fe)a$

**Proposition 2.3:** Let  $a, b, d, x, y \in Z$ . If  $d \mid a$  and  $d \mid b \implies d \mid ax + by$

*Proof:*  $a = md$  and  $b = nd \implies ax + by = d(mx + ny)$

**Upshot:** Every common divisor of both  $a, b$  divides any linear combination of  $a, b$

**Corollary 2.4:** Let  $a, b, d \in Z$ . If  $d \mid a$  and  $d \mid b$ , then  $d \mid a + b$  and  $d \mid a - b$

*Proof:* Apply Proposition 2.3 using  $x = 1, y = 1$ , and  $x = 1, y = -1$ , respectively

**Lemma 2.5:** Let  $d, n \in N$  and  $d \mid n$ . Then  $d \leq n$

*Proof:* Since  $d \mid n$ , we have  $k \in Z$  such that  $dk = n$

Since  $d \in N$ , we also must have  $k \in N$  (otherwise  $n \notin N$ )

Thus  $n = dk \geq d * 1$

### 2.2 Euclid's Theorem

**Prime:** Integer  $p \geq 2$  whose divisors are  $1, p$

**Composite:** Integer  $n \geq 2$  not prime such that  $n = ab$  for  $a, b \in Z$  and  $1 < a, b < p$

**Lemma 2.6:** Every integer greater than 1 is prime or divisible by a prime

*Proof 1:* If  $n$  is NOT prime, then it is divisible by some  $a_1 \in Z$  where  $1 < a_1 < n$

If  $a_1$  is prime, we are done

Otherwise  $a_1$  is divisible by some  $a_2 \in Z$  where  $1 < a_2 < a_1 \implies a_2 \mid n$

This creates a decreasing sequence of positive integers, which by the Well Ordering Principle, must have a smallest element  $a_m$

So either some  $a_i$  is prime and divides  $n$  or we stop at  $a_m$ , which is prime. Thus  $n$  is divisible by a prime

*Proof 2 by Induction:* Let  $n \in Z, n \geq 2$ , and suppose  $n$  is composite. Thus  $n = kl$  for  $k, l \in Z$  where  $1 < k, l < n$

Base case: we only care about the first composite  $n$ , i.e.  $n = 4 = 2 \cdot 2$  thus  $2 \mid 4$  and 2 is prime

IH: Suppose the Lemma holds for all  $i \in N, i < n$

IS:  $n = kl$  where  $k < n$ . Thus  $k$  is either a prime or is divisible by a prime

- If  $k$  is prime, we are done since  $k \mid n$
- Otherwise  $p \mid k$  for some prime  $p < k$ . Then we have  $p \mid k \wedge k \mid n \implies p \mid n$

**Euclid's Theorem:** there are an infinite number of primes

*Proof:* Assume by contradiction that there are a finite number of primes  $2, 3, 5, \dots, p_n$

Let  $N = (2 * 3 * 5 * \dots * p_n) + 1$

Since  $N > 2p_n + 1 > p_n$ , it is composite and thus is divisible by some  $p_i$  in the list of primes

Then we have  $p_i \mid 2 * 3 * 5 * \dots * p_n$  and  $p_i \mid N \implies p_i \mid N - (2 * 3 * 5 * \dots * p_n) \implies p_i \mid 1$  contradiction since  $p_i > 1$

Thus there are an infinite number of primes

## 2.3 The Sieve of Eratosthenes

**Proposition 2.7:** If  $n$  is composite then  $n$  has a prime factor  $p \leq \sqrt{n}$

*Proof:*  $n = ab$  where  $1 < a \leq b < n \implies a^2 \leq ab = n \implies a \leq \sqrt{n}$

By Lemma 2.6,  $a$  has a prime divisor  $p$ , where  $p \mid a \implies p \leq a \leq \sqrt{n}$

- **Note:** Not all prime factors of  $n$  are  $\leq \sqrt{n}$ . For example,  $6 = 2 * 3$  but  $3 > \sqrt{6}$

## 2.4 The Division Algorithm

**Division Algorithm:** Let  $a, b \in \mathbb{Z}$  with  $b > 0$ . Then there exists unique  $q, r \in \mathbb{Z}$  such that  $a = bq + r$  with  $0 \leq r < b$

*Proof:* Let  $S = \{n \in \mathbb{Z} \mid bn \leq a\}$ . Clearly  $S$  is non-empty since

- If  $a \geq 0$ , take  $n = -1$
- If  $a < 0$ , take  $n = a$

Since  $S$  is bounded above by  $a/b$ , it has a largest member, call it  $q$

Thus  $q$  is the largest integers  $\leq a/b$  such that  $q \leq a/b < q + 1$

Then we have  $bq \leq a < bq + b \implies 0 \leq a - bq < b$

Setting  $r = a - bq$  we see that  $0 \leq r < b$  and we have  $a = bq + r$  so EXISTENCE is done

To show UNIQUENESS let  $a = bq + r = bq_1 + r_1$  for  $0 \leq r, r_1 < b$

Then we have  $b(q - q_1) = r_1 - r$ . Since LHS is a multiple of  $b$ , RHS is also a multiple of  $b$

But  $0 \leq r, r_1 < b \implies -b < r_1 - r < b \implies r_1 - r = 0$  since  $b = 0$  is the only multiple of  $b$  that satisfies this inequality

Thus  $r_1 = r$  and since  $b \neq 0 \implies b(q - q_1) = 0 \implies q = q_1$ . So  $q, r$  are UNIQUE

## 2.5 The Greatest Common Divisor

**Relative Prime:**  $a, b$  are relatively prime if  $\gcd(a, b) = 1$

- By definition, we have  $\gcd(a, 0) = a$

**Proposition 2.10:** Let  $a, b \in \mathbb{Z}$  and  $d = \gcd(a, b)$ . Then  $\gcd(\frac{a}{d}, \frac{b}{d}) = 1$

*Proof:* Let  $c = \gcd(a/d, b/d)$ . Then  $c \mid (a/d)$  and  $c \mid (b/d)$

Thus  $a = cdk_1$  and  $b = cdk_2$  so  $cd$  is a common divisor of  $a, b$

Since  $d$  is the greatest common divisor of  $a, b$ , we have  $d \leq cd \leq d \implies c = 1$

**Proposition 2.11:** If  $a, b \in \mathbb{Z}$ , not both 0, and  $e \in \mathbb{Z}^+$ . Then  $\gcd(ea, eb) = e * \gcd(a, b)$

*Proof:* Let  $d = \gcd(ea, eb)$ , we show that  $d = e * \gcd(a, b)$

$\gcd(a, b) = ax + by \implies e \gcd(a, b) = eax + eby$ . If  $d$  is a common divisor of  $ea$  and  $eb$ , then  $d \mid e * \gcd(a, b)$

Thus  $d \leq e \gcd(a, b)$ . But since  $e \gcd(a, b)$  is a common divisor of  $ea, eb$ , it is the gcd we desire

Various ways to find  $\gcd(a, b)$ :

1. List all prime factors of  $a, b$  and take the largest factor.

**Example:**  $84 = 2 * 2 * 3 * 7$  and  $264 = 2 * 2 * 2 * 3 * 11 \implies \gcd(84, 264) = 2 * 2 * 3 = 12$

2. Take Linear Combination of  $a, b$  and find a list of possible factors

**Example:**  $d = \gcd(1005, 500) \implies d \mid (1005 - 2 * 500) \implies d = 1$  or  $d = 5$ . Clearly  $d = 5$

**Example:**  $d = \gcd(2n+3, 3n-7) \implies d \mid 3(2n+3) - 2(3n-6) = 21$  so  $d \in \{1, 3, 7, 21\}$ . Clearly with  $n = 9$ ,  $\gcd(21, 21) = 21$

3. Use Euclidean Algorithm

## 2.6 The Euclidean Algorithm

**Euclidean Algorithm:** Let  $a, b \in \mathbb{Z}$  with  $a \geq 0, b > 0$ . Then we have

$$\begin{aligned} a &= q_1 b + r_1 & 0 < r_1 < b \\ b &= q_2 r_1 + r_2 & 0 < r_2 < r_1 \\ r_1 &= q_3 r_2 + r_3 & 0 < r_3 < r_2 \\ &\dots \\ r_{n-3} &= q_{n-1} r_{n-2} + r_{n-1} & 0 < r_{n-1} < r_{n-2} \\ r_{n-2} &= q_n r_{n-1} + 0 \end{aligned}$$

Where  $r_{n-1} = \gcd(a, b)$

*Proof:*  $r_{n-1} \mid r_{n-2}, r_{n-1} \mid r_{n-3}, \dots, r_{n-1} \mid b, r_{n-1} \mid a$  so clearly  $r_{n-1}$  is a common factor of  $a, b$

To show that  $r_{n-1}$  is the largest common factor, let  $d$  be an arbitrary common divisor of  $a, b$

From the first line, we see that  $d \mid r_1$ . From the second line,  $d \mid r_2$ . This continues until  $d \mid r_{n-1}$

Thus  $d \leq r_{n-1}$  which means that  $r_{n-1}$  is the largest divisor and  $\gcd(a, b) = r_{n-1}$

**NOTE:** each common divisor of  $a, b$  also divides  $\gcd(a, b)$

### 2.6.1 The Extended Euclidean Algorithm

**Extended Euclidean Algorithm:**  $\gcd(a, b)$  can be expressed as a linear combination of  $a, b$ .

**Example:**  $\gcd(456, 123)$

$$\begin{aligned} 456 &= 3 * 123 + 87 \\ 123 &= 1 * 87 + 36 \\ 87 &= 2 * 36 + 15 \\ 36 &= 2 * 15 + 6 \\ 15 &= 2 * 6 + 3 \\ 6 &= 2 * 3 \end{aligned}$$

Using the values above, we can create a table

	$x$	$y$	
456	1	0	
123	0	1	
87	1	-3	$R_1 - 3R_2$
36	-1	4	$R_2 - R_3$
15	3	-11	$R_3 - 2R_4$
6	-7	26	$R_4 - 2R_5$
3	17	-63	$R_5 - 2R_6$

Thus  $3 = 456 * 17 - 123 * 63$

**Theorem 2.12 (Bezout's Theorem):** Let  $a, b \in Z$  with at least one non-zero. Then there exists  $x, y \in Z$  such that  $\gcd(a, b) = ax + by$

*Proof:* Let  $S$  be a set of integers that can be written in the form  $ax + by$  for  $x, y \in Z$

Since  $a, b, -a, -b \in S$ , clearly  $S$  contains at least one positive integer.

Using the Well-Ordering Principle, let  $d$  be the smallest positive integer in  $S$ . Thus  $d = ax_0 + by_0$  for  $x_0, y_0 \in Z$

We show that  $d$  is a common divisor of  $a, b$

$$a = dq + r \implies r = a - dq = a - (ax_0 + by_0)q = a(1 - x_0q) + b(-y_0q)$$

Thus  $r \in S$ . But since  $d$  is the smallest positive element of  $S$  and  $0 \leq r < d$ , we must have  $r = 0$

Thus  $d \mid a$ . Similarly,  $d \mid b$ . Thus  $d$  is a common divisor of  $a, b$

Next we show that for any common divisor of  $a, b$ , call it  $e$ , we have  $e \leq d$

$e \mid a$  and  $e \mid b \implies e \mid ax_0 + by_0 = d$ . Thus  $e \leq d$

**Theorem 2.13:** Let  $n \geq 2$  and  $a_1, \dots, a_n \in Z$  with at least one nonzero  $a_i$ . Then  $\exists x_1, \dots, x_n \in Z$  such that

$$\gcd(a_1, \dots, a_n) = a_1x_1 + \dots + a_nx_n$$

*Proof by Induction:* By Theorem 2.12, the statement holds for  $n = 2$

IH: assume the statement holds for  $n = k$ .  $\gcd(a_1, \dots, a_k) = a_1x_1 + \dots + a_kx_k$

IS: Note that  $\gcd(a_1, \dots, a_{k+1}) = \gcd(\gcd(a_1, \dots, a_k), a_{k+1})$

Apply Theorem 2.12 to  $a_1x_1 + \dots + a_kx_k$  and  $a_{k+1}$  so  $\gcd(a_1, \dots, a_{k+1}) = (a_1x_1 + \dots + a_kx_k)y + a_{k+1}x$

But then this satisfies the statement since if we set  $y_i = yx_i$  for  $1 \leq i \leq k$  and  $y_{k+1} = x$

Thus by Induction,  $\gcd(a_1, \dots, a_n) = a_1x_1 + \dots + a_nx_n$

**Corollary 2.14:** If  $e$  is a common divisor of  $a, b$  then  $e \mid \gcd(a, b)$

*Proof:*  $e \mid a$  and  $e \mid b \implies e$  divides any linear combination of  $a, b \implies e \mid \gcd(a, b) = ax + by$

**Proposition 2.15:** Let  $a, b, c \in Z$  with  $\gcd(a, c) = \gcd(b, c) = 1$ . Then  $\gcd(ab, c) = 1$

*Proof:*  $\gcd(a, c) = 1 \implies ax_1 + cy_1 = 1$

$\gcd(b, c) = 1 \implies bx_2 + cy_2 = 1$

Multiplying these 2 equations we get  $1 = (ab)(x_1x_2) + (c)(by_1x_2 + ax_1y_2 + cy_1y_2)$

Thus by Proposition 2.3, any common divisor of  $ab$  and  $c$  must divide  $1 \implies \gcd(ab, c) = 1$

**Proposition 2.16:** Let  $a, b, c \in Z$  with  $a \neq 0$  and  $\gcd(a, b) = 1$ . Then  $a \mid bc \implies a \mid c$

*Proof:* By Theorem 2.12,  $1 = ax + by \implies c = acx + bcy$

Thus by Proposition 2.3,  $a \mid a$  and  $a \mid bc \implies a \mid acx + bcy = c$

**Proposition 2.17:** Let  $a, b, c \in Z$  with  $a, b$  nonzero and  $\gcd(a, b) = 1$ . Then if  $a \mid c$  and  $b \mid c \implies ab \mid c$

*Proof:* By Theorem 2.12,  $1 = ax + by \implies c = acx + bcy$

$b \mid c \implies ab \mid ac$

$$a \mid c \implies ba \mid bc$$

Since  $c$  is a linear combination of  $ac$  and  $bc$ , by Proposition 2.3, we must have that  $ab \mid c$

## 2.7 Other Bases

We can convert a number from base 10 to any other base using the Division Algorithm

**Example:** Convert  $21963_{10}$  to base 8

$$21963 = 2745 * 8 + 3$$

$$2745 = 343 * 8 + 1$$

$$343 = 42 * 8 + 7$$

$$42 = 5 * 8 + 2$$

$$5 = 0 * 8 + 5$$

Thus  $21963_{10} = 52713_8$  This is because

$$5 * 8^4 + 2 * 8^3 + 7 * 8^2 + 1 * 8 + 3 = 52713_8$$

**Note:** decimal representations in other bases are NOT unique. For  $a_k \leq n - 1$

$$\sum_{k=1}^{\infty} \frac{a_k}{n^k} \leq \sum_{k=1}^{\infty} \frac{n-1}{n^k}, \text{ which is the geometric series and converges}$$

Thus any sequence  $\{a_n\}_{n=1}^{\infty}$  for  $0 \leq a_k \leq n - 1$  converges

$$\text{In particular, for } j > 1, \sum_{k=j}^{\infty} \frac{n-1}{n^k} = \frac{1}{n^{j-1}}$$

- **Example:** for  $n = 10$ , we have  $1 = 0.\bar{9}$
- **Example:**  $0.01_7 = 0.000\bar{6}_7$

## 2.8 Fermat and Mersenne Numbers

**Mersenne Numbers:**  $M_n = 2^n - 1$  for prime  $n$ . Thought to generate prime numbers, but doesn't always work (e.g.  $n = 11$  results in a composite number)

**Proposition 2.18:** If  $n$  is composite, then  $2^n - 1$  is composite

*Proof:* Recall that  $x^k - 1 = (x - 1)(x^{k-1} + x^{k-2} + \dots + x + 1)$

Since  $n$  is composite,  $n = ab$ . Let  $x = 2^a$  and  $k = b$

$$\text{Then } 2^{ab} - 1 = (2^a - 1)(2^{a(b-1)} + \dots + 2^a + 1)$$

$$1 < a < n \implies 1 < 2^a - 1 < 2^n - 1 \text{ so } 2^a - 1 \text{ is a nontrivial factor and } 2^n - 1 \text{ is composite}$$

**Corollary 2.18.1:** For  $k, n \in \mathbb{N}$ ,  $k \mid n \implies M_k \mid M_n$

*Proof:* Can be seen from the factorization seen in the previous proposition

**Corollary 2.18.2:** If  $M_n$  is prime, then  $n$  is prime

*Proof:* Follows from the contraposition of Proposition 2.18

**Fermat Numbers:**  $F_n = 2^{2^n} + 1$ . Thought to generate prime numbers, but doesn't always work (e.g.  $n = 5$  results in a composite number)

**Proposition 2.19:** If  $m > 1$  is not a power of 2 then  $2^m + 1$  is composite

*Proof:* Recall that  $k$  is odd then  $x^k + 1 = (x + 1)(x^{k-1} - x^{k-2} + x^{k-3} - \dots - x + 1)$

Since  $m$  is not a power of 2 it has a nontrivial odd factor  $a \geq 3$ , so  $m = ab$ . Let  $k = a$  and  $x = 2^b$

Then  $2^{ab} + 1 = (2^b + 1)(2^{b(a-1)} - 2^{b(a-2)} + \dots - 2^b + 1)$

$1 \leq b < m \implies 1 < 2^b + 1 < 2^m + 1$  so  $2^b + 1$  is a nontrivial factor and  $2^m + 1$  is composite

**Proposition 2.20:** A regular  $n$ -gon is constructable if and only if  $n = 2^a F_{n_1} F_{n_2} \dots F_{n_r}$  for distinct Fermat Primes and  $a \geq 0$

### 3 Linear Diophantine Equation

We look for solutions to  $ax + by = c$  for  $a, b, c \in Z$

- If  $\gcd(a, b) \nmid c$  then there are NO integer solutions  $(x, y)$ . This follows from  $\gcd(a, b)$  divides any linear combination of  $a, b$

**Theorem 3.1:** Let  $a, b, c \in Z$  where  $a, b$  are not both 0. Then  $ax + by = c$  has a solution if and only if  $\gcd(a, b) \mid c$

Furthermore, if it has one solution  $(x_0, y_0)$ , then there are an infinite number of solutions of the form

$$x = x_0 + \frac{b}{\gcd(a, b)}t \quad y = y_0 - \frac{a}{\gcd(a, b)}t \quad t \in Z$$

*Proof:* Let  $d = \gcd(a, b)$

$\implies$  Contraposition: If  $d \nmid c$  then clearly no solutions

$\Leftarrow$  If  $d \mid c$  then by Theorem 2.12, there exists  $r, s \in Z$  such that  $ar + bs = d$

$d \mid c \implies df = c$  for  $f \in Z \implies a(rf) + b(sf) = df = c$

Thus  $x_0 = rf$  and  $y_0 = sf$  is a solution to  $ax + by = c$

To show there are an infinite number of solutions, first let  $x = x_0 + \frac{b}{d}t$  and  $y = y_0 - \frac{a}{d}t$

Then  $ax + by = a(x_0 + \frac{b}{d}t) + b(y_0 - \frac{a}{d}t) = ax_0 + by_0 = c$

Thus there are an infinite number of solutions of this form

To show that every solution has the correct form, fix solutions  $x_0, y_0$  and let  $u, v$  be any solution

$au + bv = c = ax_0 + by_0 \implies a(u - x_0) - b(v - y_0) = 0 \implies \frac{a}{d}(u - x_0) = \frac{b}{d}(y_0 - v)$

- The last part follows because  $d \mid a$  and  $d \mid b \implies \frac{a}{d}, \frac{b}{d} \in Z$

Thus we have  $(a/d) \mid (b/d)(y_0 - v)$

Since, by Proposition 2.10,  $\gcd(a/d, b/d) = 1$ , we have by Proposition 2.6,  $(a/d) \mid (y_0 - v)$

Thus  $y_0 - v = \frac{a}{d}t \implies v = y_0 - t\frac{a}{d}$

Furthermore,  $\frac{a}{d}(u - x_0) = \frac{b}{d}(\frac{a}{d}t) \implies u = x_0 + \frac{b}{d}t$

**Corollary 3.2:** Let  $a, b, c \in Z$  with at least one  $a, b$  nonzero. If  $\gcd(a, b) = 1$  then  $ax + by = c$  has infinite number of solutions

**Upshot:** If  $(x_0, y_0)$  is a particular solution, then all solutions are of the form

$$x = x_0 + bt \quad y = y_0 - at \quad t \in Z$$

### General Steps to Solve Linear Diophantine Equation:

1. Verify  $\gcd(a, b) \mid c$ 
  - If no, then there is no solution
  - If yes, divide the equation by  $d$  to get  $a'x + b'y = c'$  where  $\gcd(a', b') = 1$
2. Then use Extended Euclidean Algorithm to solve for  $a'x + b'y = 1$ , then multiply the solution by the value of  $c'$
3. If one of the solution variable (e.g.  $x$ ) is negative, we can perform Extended Euclidean Algorithm with a positive  $x$  then flip the sign of  $x$  at the end
4. General solutions will be  $(x_0 + \frac{b}{d}t, y_0 - \frac{a}{d}t)$ 
  - **Example:**  $-17x + 14y = 30 \implies 17x + 14y = 30$  has the solution  $(5 * 30, -6 * 30)$  so the desired solution is  $(-150, -180)$  and general solution is of the form

$$x = -150 + 14t \quad y = -180 + 17t \quad t \in \mathbb{Z}$$

**Proposition 3.3:** Let  $a, b \in \mathbb{Z}^+$  and relatively prime. Then there are no non-negative  $x, y \in \mathbb{Z}$  such that  $ax + by = ab - a - b$

*Proof:* Observe that  $a(-1) + b(a-1) = ab - a - b \implies x = -1$  and  $y = a-1$  is a solution

Since  $\gcd(a, b) = 1$  every solution has the form  $x = -1 + bt$  and  $y = a-1 - at = a(1-t) - 1$

Note that  $x > 0$  if and only if  $t > 0$  but then we have  $1-t \leq 0 \implies y \leq -1$

Thus it is impossible to find a non-negative solution to  $ax + by = ab - a - b$

**Proposition 3.4:** Let  $a, b \in \mathbb{Z}^+$  and relatively prime. If  $n > ab - a - b$  then there exists non-negative  $x, y \in \mathbb{Z}$  such that  $ax + by = n$

*Proof:* First find a pair  $(x_0, y_0)$  such that  $ax_0 + by_0 = n \geq ab - a - b + 1$ . Note  $(x_0, y_0)$  may be negative

Solution has the form  $x = x_0 + bt$  and  $y = y_0 - at$

We find the smallest possible  $y \geq 0$  then show that  $x \geq 0$

From Division Algorithm and dividing  $y_0$  by  $a$ , we have  $y_0 = at + y_1$  for  $0 \leq y_1 < a$ . Let  $y_1$  be our choice of  $y$

Since  $y_1 = y_0 - at$ , we take  $x_1 = x_0 + bt$  as our choice of  $x$

Suppose by contradiction that  $x_1 \leq -1$ , then  $y_1 \leq a-1$ . This occurs from  $ax_1 + by_1 < ab - a - b$

Thus  $n = ax_0 + by_0 = a(x_1 - bt) + b(y_1 + at) \leq a(-1) + b(a-1) = ab - a - b$ . Contradiction since we said  $n >$  this value

Thus  $(x_1, y_1)$  is a non-negative solution

## 4 Unique Factorization

**Theorem 4.1:** Let  $p$  be prime and  $a, b \in \mathbb{Z}$  such that  $p \mid ab$ . Then  $p \mid a$  or  $p \mid b$

*Proof:* let  $d = \gcd(a, p)$ . If  $d = p$  then  $d \mid a \implies p \mid a$

Otherwise applying Extended Euclidean Algorithm,  $d = 1 = ax + py \implies b = abx + pby$

$p \mid ab$  and  $p \mid p \implies p \mid b$ , which is a linear combination of  $p$  and  $ab$

- **NOTE:** if  $n$  is composite, then we CANNOT conclude  $n \mid a$  or  $n \mid b$  from  $n \mid ab$

**Corollary 4.2:** Let  $p$  be prime and  $a_1, a_2, \dots, a_r \in \mathbb{Z}$  such that  $p \mid a_1 \cdot a_2 \cdots a_r$ . Then  $p \mid a_i$  for some  $i$

*Proof by Induction:* clearly statement holds for  $r = 1$

IH: assume statement holds for  $r = k$



IS: show statement is true for  $r = k + 1$ . Let  $a = a_1 \cdots a_k$  and  $b = a_{k+1}$

We can apply Theorem 4.1 where  $p \mid ab \implies$  statement holds for any  $r \geq 1$

**Lemma 4.3:** Every integer can be written as a product of primes

*Proof:* Assume there exist composite integers that cannot be written as product of primes. Let  $S$  be the set of these ints  $> 1$

Since all  $e \in S$  are positive, by Well Ordering Principle, it has a smallest element  $s$

Since  $s$  is composite, we have  $s = ab$ , but  $a, b < s \implies a, b \notin S \implies a, b$  can be written as the product of primes

Thus  $s$  is also a product of primes and thus  $S$  is empty

**Fundamental Theorem of Arithmetic:** Any positive integer  $> 1$  is either prime or can be factored exactly one way as a product of primes

*Proof:* Lemma 4.3 shows that any integer  $> 1$  can be written as a product of primes

For uniqueness, suppose that there are 2 ways of factoring an integer. Let  $n$  be the smallest of these integers

$$n = p_1 p_2 \cdots p_r = q_1 q_2 \cdots q_s$$

$$p_1 \mid \text{LHS} \implies p_1 \mid \text{RHS} \implies p_1 \mid q_i$$

Rearranging the RHS, we let  $p_1 = q_1$  and now we have  $n/p_1 = m = p_2 \cdots p_r = q_2 \cdots q_s$

But  $m < n$  so it must have a unique factorization but we see that  $m$  can be written using 2 different factorization

Thus we have a contradiction and every positive integer  $> 1$  can be unique factored

**Proposition 4.4:** Let  $a, b \in \mathbb{Z}^+$  where  $a = 2^{a_2} 3^{a_3} \cdots$  and  $b = 2^{b_2} 3^{b_3} \cdots$ . Then  $a \mid b \iff a_p \leq b_p$  for all  $p$

*Proof:*  $\implies a \mid b \implies ac = b$  where  $c = 2^{c_2} 3^{c_3} \cdots$

$$\text{Then } 2 = 2^{a_2+c_2} 3^{a_3+c_3} \cdots = b$$

Thus we must have  $\forall p, a_p + c_p = b_p \implies a_p \leq b_p$

$\Leftarrow$  suppose  $\forall p, a_p \leq b_p$  and let  $c_p = b_p - a_p$ . Clearly  $c_p \geq 0$

$$\text{Let } c = 2^{c_2} 3^{c_3} \cdots \implies ac = b \implies a \mid b$$

**Definition - Least Common Multiple:**  $\text{lcm}(a, b)$  is the smallest positive integer divisible by  $a, b$

**Proposition 4.5:** Let  $a, b \in \mathbb{Z}^+$  where  $a = 2^{a_2} 3^{a_3} \cdots$  and  $b = 2^{b_2} 3^{b_3} \cdots$ . Furthermore, for all  $p$ , let  $d_p = \min(a_p, b_p)$  and  $e_p = \max(a_p, b_p)$ . Then  $\text{gcd}(a, b) = 2^{d_2} 3^{d_3} \cdots$  and  $\text{lcm}(a, b) = 2^{e_2} 3^{e_3} \cdots$

*Proof:* Let  $d$  be any common divisor of  $a, b$  such that  $d = 2^{d_2} 3^{d_3} \cdots$

$$d \mid a \implies d_p \leq a_p \text{ for all } p. \text{ Similarly } d \mid b \implies d_p \leq b_p \text{ for all } p$$

Largest common divisor occurs when  $d_p = \min(a_p, b_p)$  for each  $p$

Least common multiple occurs when  $e_p = \max(a_p, b_p)$  for each  $p$

**Definition - Squarefree:** integer whose factors are all distinct (doesn't have a square of a number as a factor)

**Proposition 4.7:** Let  $n \in \mathbb{Z}^+$ . Then there exists  $r \in \mathbb{Z}, r \geq 1$  and a squarefree integer  $s \geq 1$  such that  $n = r^2 s$

*Proof:* Let  $n = p_1^{a_1} p_2^{a_2} \cdots$

If  $a_i$  is even, write it as  $a_i = 2b_i$ . Otherwise write  $a_i = 2b_i + 1$

Let  $r = p_1^{a_1} p_2^{p_2} \dots$  and let  $s =$  the product of all primes  $p_i$  with odd  $a_i$

Then we have  $r^2 s = n$

## 5 Applications of Unique Factorization

### 5.1 A Puzzle

**Proposition 5.1:** Let  $k \geq 2$  be an integer and  $m \in \mathbb{Z}^+$ . Then  $m$  is a  $k$ th power  $\iff$  all exponents in the prime factorization of  $m$  are multiples of  $k$

*Proof:*  $\implies$  Let  $m = 2^{y_2} 3^{y_3} \dots$ . If each  $y_p$  is a multiple of  $k$  then  $y_p = k z_p \implies m = (2^{z_2} 3^{z_3} \dots)^k$

$\impliedby$  If  $m = n^k$  where  $n = 2^{w_2} 3^{w_3} \dots$ , then  $2^{y_2} 3^{y_3} \dots = m = n^k = 2^{k w_2} 3^{k w_3} \dots$

By Uniqueness of Factorization,  $y_p = k w_p$  for each  $p \implies$  each exponent for  $m$  is a multiple of  $k$

**Example** Find a number such that  $2/3A^2$  is a cube

We have  $2/3A^2 = 2^{2a+1} 3^{2b-1} 5^{2c} \dots$  is a cube, so  $2a+1, 2b-1, 2c, \dots$  are all multiples of 3

By brute force, we see that  $a=1, b=2, c=d=\dots=0$  works and gives us  $A=18$

To find the general solution, we note that  $3 \mid 2c$  and  $\gcd(3, 2) = 1$  so  $c$  must be a multiple of 3  $\implies c = 3c'$ . Similar for  $d, e, \dots$

Since  $2a+1$  is odd and a multiple of 3, we have  $2a+1 = 3(2j+1) \implies a = 3j+1$

Since  $2b-1$  is odd and a multiple of 3, we have  $2b-1 = 3(2k+1) \implies b = 3k+2$

Finally, we see that  $A = 2^a 3^b 5^c \dots = 2 * 3^2 (2^j 3^k 5^{c'} \dots)^3 = 18B^3$  for any  $B \geq 1$

### 5.2 Irrationality Proof

**Rational:** number that can be expressed as a ratio of 2 integers

**Theorem 5.2:**  $\sqrt{2}$  is irrational

*Proof:* Suppose by contradiction that  $\sqrt{2}$  is rational and  $\sqrt{2} = a/b \in \mathbb{Q}$  in reduced form

Then we have  $2 = a^2/b^2 \implies 2b^2 = a^2$

Clearly  $a^2$  is even  $\implies a$  is even so  $a = 2a_1$

But then we have  $b^2 = 2a_1$  so  $b^2$  is even  $\implies b$  is even. This is a contradiction since we said  $a/b$  is in reduced form

Thus we have a contradiction and  $\sqrt{2}$  is irrational

**Theorem 5.3:** Let  $k \in \mathbb{Z}$  and  $k \geq 2$ . Let  $n \in \mathbb{Z}^+$  that is not a perfect  $k$ th power. Then  $\sqrt[k]{n}$  is irrational

*Proof:* We show the contrapositive that if  $\sqrt[k]{n}$  is irrational then  $n$  is a perfect  $k$ th power

Suppose  $\sqrt[k]{n} = a/b \implies nb^k = a^k$

We can prime factorize  $n, b$  to get  $n = 2^{x_2} 3^{x_3} \dots$  and  $b = 2^{z_2} 3^{z_3} \dots$

Thus we have  $nb^k = 2^{x_2+kz_2} 3^{x_3+kz_3} \dots$

Let  $a = 2^{y_2} 3^{y_3} \dots$ . Since  $nb^k = a^k$  is a perfect power, by Proposition 5.1, every exponent in the prime factorization is a multiple of  $k$

Thus  $x_p + k z_p = k y_p \implies x_p = k(y_p - z_p) \implies n$  is a perfect  $k$ th power

### 5.3 Rational Root Theorem

**Theorem 5.4 (Rational Root Theorem):** let  $P(X) = a_n X^n + \dots + a_1 X + a_0$  where  $a_i \in \mathbb{Z}$  such that  $a_n \neq 0$  and  $a_0 \neq 0$

If  $r = u/v \in \mathbb{Q}$  with  $\gcd(u, v) = 1$  and  $P(u/v) = 0$  then  $u \mid a_0$  and  $v \mid a_n$

*Proof:*  $P(u/v) = 0 \implies a_n (u/v)^n + \dots + a_0 = 0 \implies a_n u^n + \dots + a_0 v^n = 0$

All terms except the first are multiple of  $v$ . Thus  $v$  must divide  $a_n u^n$ . But  $\gcd(u, v) = 1 \implies v \mid a_n$

All terms except the last are multiple of  $u$ . Thus  $u$  must divide  $a_0 v^n$ . But  $\gcd(u, v) = 1 \implies u \mid a_0$

## 5.4 Pythagorean Triples

**Pythagorean Triples:** positive integers  $(a, b, c)$  where  $a^2 + b^2 = c^2$

**Primitive Pythagorean Triples:** Pythagorean triples where  $\gcd(a, b, c) = 1$

A primitive way of generating Pythagorean Triples is using odd numbers

$$(2n+1)^2 = 4n^2 + 4n + 1 = (2n^2 + 2n) + (2n^2 + 2n + 1) \implies (2n+1)^2 + (2n^2 + 2n)^2 = (2n^2 + 2n + 1)^2$$

**Lemma 5.6:** Let  $k \in \mathbb{Z}, k \geq 2$  and let  $a, b$  relatively prime integers such that  $ab = n^k$ . Then  $a, b$  are each  $k$ th powers of integers

*Proof:* Let  $n = 2^{x_2} 3^{x_3} \dots$ . Then  $ab = n^k = 2^{kx_2} 3^{kx_3} \dots$

Let  $p$  be a prime in the prime factorization of  $a$  and  $p^c$  be the exact power of  $p$  in the factorization of  $a$

Since  $\gcd(a, b) = 1$ ,  $p$  doesn't occur in the factorization of  $b$ , so  $p^c$  occurs in  $ab$  and  $n^k$  has  $p^{kx_p}$  as the power of  $p$

Since prime factorization is unique, we have  $c = kx_p \implies$  every prime in factorization of  $a$  occurs with a power of a multiple of  $k$

Thus  $a$  is a  $k$ th power integer. Similar for  $b$

**Lemma 5.7:** The square of an odd integer is 1 more than a multiple of 8. The square of an even integer is a multiple of 4

*Proof:* Let  $n$  be even then  $n = 2k \implies n^2 = 4k^2 \implies 4 \mid n^2$

Let  $n$  be odd  $\implies n = 2k + 1 \implies n^2 = 4k(k+1) + 1$

Since  $k$  or  $k+1$  is even, we have  $k(k+1)$  is a multiple of 8. Thus  $n^2$  is 1 more than a multiple of 8

**Theorem 5.5:** Let  $(a, b, c)$  be a primitive Pythagorean triple. Then  $c$  is odd and exactly one of  $a, b$  is even and the other is odd. Assume  $b$  is even, then there relatively prime integers  $m, n$  such that  $m < n$  and one odd and the other even such that

$$a = n^2 - m^2 \quad b = 2mn \quad c = m^2 + n^2$$

*Proof:* Let  $a^2 + b^2 = c^2$  and  $\gcd(a, b, c) = 1$

Suppose by contradiction that both  $a, b$  are odd, then by Lemma 5.7,  $a^2 + b^2$  is 2 more than a multiple of 8

Thus  $a^2 + b^2$  is not a multiple of 4 so by Lemma 5.7,  $a^2 + b^2$  cannot be a square. Thus at least one of  $a, b$  is even

Suppose by contradiction that both  $a, b$  are even. Then  $c^2 = a^2 + b^2$  is even so  $c$  is even.

But then 2 is common divisor of  $a, b, c$  but we have  $\gcd(a, b, c) = 1$ . Contradiction

Thus one of  $a, b$  is even and the other is odd. WLOG let  $a$  be odd and  $b$  be even

Then we have  $a^2 + b^2 = c^2$  is odd. Let  $b = 2b_1$  so we have  $c^2 - a^2 = (c+a)(c-a) = b^2 = 4b_1^2$

Thus we have  $(\frac{c+a}{2})(\frac{c-a}{2}) = b_1^2$ . Since  $c, a$  are odd we must have  $\frac{c+a}{2}$  and  $\frac{c-a}{2} \in \mathbb{Z}$

Let  $d = \gcd((c+a)/2, (c-a)/2)$  and suppose by contradiction  $d > 1$ . Then let  $p$  be a prime dividing  $d$

Then  $c = \frac{c+a}{2} + \frac{c-a}{2}$  and  $a = \frac{c+a}{2} - \frac{c-a}{2}$  are multiples of  $p$

Thus  $c^2 - a^2 = b^2$  is a multiple of  $p \implies p \mid b$  so  $p$  is a common divisor of  $a, b, c$ , contradicting that  $\gcd(a, b, c) = 1$ . Thus  $d = 1$

Thus we have two relatively prime integers:  $(c+a)/2$  and  $(c-a)/2$  whose product is a square

By Lemma 5.6, each factor is a square so  $\frac{c-a}{2} = m^2$  and  $\frac{c+a}{2} = n^2$

Thus  $c = \frac{c+a}{2} + \frac{c-a}{2} = n^2 + m^2$  and  $a = \frac{c+a}{2} - \frac{c-a}{2} = n^2 - m^2$

Thus  $b^2 = c^2 - a^2 = (n^2 + m^2)^2 - (n^2 - m^2)^2 = 4m^2n^2 \implies b = 2mn$

Since  $(c-a)/2 = m^2$  and  $(c+a)/2 = n^2$  are relatively prime, then  $\gcd(n, m) = 1$

Finally since  $m^2 + n^2 = c$  is odd, one of  $m, n$  is odd and the other is even

## 5.5 Difference of Squares

**Theorem 5.8:** Let  $m \in \mathbb{Z}^+$ . Then  $m$  is a difference of 2 squares  $\iff$  either  $m$  is odd or  $m$  is a multiple of 4

*Proof:*  $\implies$ . Let  $m$  be odd then  $m = 2n + 1 = (n + 1)^2 - n^2$ .

Otherwise let  $m$  be a multiple of 4 then  $m = 4n = (n + 1)^2 - (n - 1)^2$

$\impliedby$  Suppose  $m = x^2 - y^2 = (x + y)(x - y)$ . Since  $x + y, x - y$  differ by  $2y$  (even) they are either both even or both odd

- If they are both even, then  $m = (x + y)(x - y)$  is the product of 2 even numbers and is thus a multiple of 4
- If both are odd, then  $m$  is clearly odd

As an aside, suppose  $m = uv$  where  $u, v$  have the same parity and  $u \geq v$

If we let  $x = \frac{(u+v)}{2}$  and  $y = \frac{(u-v)}{2}$  then clearly  $x, y \in \mathbb{Z}$  since  $u, v$  have the same parity

And we have  $x^2 - y^2 = \frac{(u+v)^2}{4} - \frac{(u-v)^2}{4} = uv = m$

**UPSHOT:** Writing  $m$  as a difference of 2 squares corresponds to factorizing  $m$  into 2 factors of the same parity

- **Example:**  $m = 15 \implies 15 * 1 = 8^2 - 7^2$  where  $8 + 7 = 15$  and  $8 - 7 = 1$   
 $m = 15 \implies 5 * 3 = 4^2 - 1^2$  where  $4 + 1 = 5$  and  $4 - 1 = 3$
- **Example:**  $m = 60 \implies 30 * 2 = 16^2 - 14^2$   
 $m = 60 \implies 10 * 6 = 8^2 - 2^2$

## 5.6 Prime Factorization of Factorials

**Theorem 5.9:** Let  $n \geq 1$  and  $p$  be a prime. If we write  $n! = p^b c$  with  $p \nmid c$ , then

$$b = \lfloor \frac{n}{p} \rfloor + \lfloor \frac{n}{p^2} \rfloor + \dots$$

*Proof:* write  $n = qp + r$  for  $0 \leq r < p$ . Clearly multiples of  $p$  up to  $n$  are  $p, 2p, \dots, qp$

but we see that  $\lfloor \frac{n}{p} \rfloor = \lfloor q + (r/p) \rfloor = q$  so there are  $\lfloor \frac{n}{p} \rfloor$  multiples of  $p$  up to  $n$

Similarly, there are  $\lfloor \frac{n}{p^j} \rfloor$  multiples of  $p^j$  up to  $n$

Thus we can write  $b = (\# \text{ of multiples of } p \text{ up to } n) + (\# \text{ of multiples of } p^2 \text{ up to } n) + \dots$

Take  $m$  such that  $1 \leq m \leq n$  and  $m = p^k m_1$  with  $p \nmid m_1$ .

Then  $m$  contributes  $p^k$  to  $n!$  and contributes  $k$  to the exponent  $b$  since  $m$  is a multiple of  $p^j$  for  $j \leq k$

- **Example:**  $n = 30, p = 5 \implies \lfloor \frac{30}{5} \rfloor + \lfloor \frac{30}{25} \rfloor = 6 + 1 \implies 5^7$  is the power of 5 in  $30!$   
 $n = 30, p = 2 \implies \lfloor \frac{30}{2} \rfloor + \lfloor \frac{30}{4} \rfloor + \lfloor \frac{30}{8} \rfloor + \lfloor \frac{30}{16} \rfloor = 15 + 7 + 3 + 1 = 26 \implies 2^{26}$  is the power of 2 in  $30!$   
Thus  $2^{26} 5^7 = 2^{19} 10^7 \implies 30!$  has 7 zeros at the end

## 6 Congruences

### 6.1 Definitions and Examples

**Congruence:**  $a \equiv b \pmod{m}$  if  $a - b$  is a multiple of  $m$

**Proposition 6.2:**  $a \equiv b \pmod{m} \iff a = b + km$  for some  $k \in \mathbb{Z}$

*Proof:*  $a \equiv b \pmod{m}$  if and only if  $a - b$  is a multiple of  $m$ . Thus  $a - b = km \implies a = b + km$

Looking at integers mod  $m$ , we get  $m$  **congruent classes**. Each integer is only in one congruent class mod  $m$

**Proposition 6.3:** Let  $a \in \mathbb{Z}$  and  $m \in \mathbb{Z}^+$  then  $\exists! r$ , with  $0 \leq r \leq m - 1$  such that  $a \equiv r \pmod{m}$

*Proof:* By division algorithm, we have  $\exists$  unique  $q, r$  such that  $a = mq + r$  with  $0 \leq r \leq m - 1$

Thus from the previous proposition,  $a \equiv r \pmod{m}$

**Proposition 6.4:** Let  $a, b, c \in Z$  and  $m \in Z^+$ . Then

- $a \equiv a \pmod{m}$
- $a \equiv b \pmod{m} \implies b \equiv a \pmod{m}$
- $a \equiv c \pmod{m}$  and  $b \equiv c \pmod{m} \implies a \equiv b \pmod{m}$

*Proof:*

- $a = a + 0 \cdot m \implies a \equiv a \pmod{m}$
- $a \equiv b \pmod{m} \implies a = b + km \implies b = a + (-k)m \implies b \equiv a \pmod{m}$
- $a - c = (a - b) + (b - c) = (k_1 + k_2)m \implies a \equiv c \pmod{m}$

**Proposition 6.5:** Let  $a, b, c, d \in Z$  and  $m \in Z^+$ . If  $a \equiv b \pmod{m}$  and  $c \equiv d \pmod{m}$  then

- $a + c \equiv b + d \pmod{m}$
- $a - c \equiv b - d \pmod{m}$
- $ac \equiv bd \pmod{m}$

*Proof:*  $a \equiv b \pmod{m} \implies a = b + k_1m$  and  $c \equiv d \pmod{m} \implies c = d + k_2m$

- $a + c = (b + d) + (k_1 + k_2)m \implies a + c \equiv b + d \pmod{m}$
- $a - c = (b - d) + (k_1 - k_2)m \implies a - c \equiv b - d \pmod{m}$
- $ac = (b + k_1m)(d + k_2m) = bd + (bk_2 + dk_1 + k_1k_2m)m \implies ac \equiv bd \pmod{m}$

**Corollary 6.6:**  $a \equiv b \pmod{m} \implies a^n \equiv b^n \pmod{m}$  for  $n \in Z^+$

*Proof:* By the previous proposition,  $a \equiv b \pmod{m} \implies a^2 \equiv b^2 \pmod{m}$ . Repeated multiplication yields  $a^n \equiv b^n \pmod{m}$

**Proposition 6.7:**  $ac \equiv bc \pmod{m}$  and  $\gcd(c, m) = 1 \implies a \equiv b \pmod{m}$

$$ac \equiv bc \pmod{m} \implies m \mid (ac - bc) \implies m \mid c(a - b)$$

If  $c, m$  are relatively prime, then we must have  $m \mid a - b \implies a \equiv b \pmod{m}$

**Proposition 6.8:**  $ac \equiv bc \pmod{m}$  and  $\gcd(c, m) = d \implies a \equiv b \pmod{(m/d)}$  and  $a = b + (\frac{m}{d})k$  with  $0 \leq k \leq d - 1$

*Proof:*  $ac \equiv bc \pmod{m} \implies m \mid c(a - b) \implies \frac{m}{d} \mid \frac{c}{d}(a - b)$

Since  $\gcd(c, m) = d$ , we must have  $\gcd(m/d, c/d) = 1 \implies \frac{m}{d} \mid a - b \implies a \equiv b \pmod{(m/d)}$

Furthermore,  $a - b = m(\frac{d}{k})$  where  $\frac{d}{k} \in Z \implies 0 \leq k \leq d - 1$

Various ways to solve equations of the form  $ax \equiv b \pmod{m}$ :

- Add  $m$  to  $b$  until we find an easy factor of  $a$

**Example:**  $2c \equiv 7 \pmod{9} \implies 16 \pmod{9} \implies c = 8$

- Use Proposition 6.8 and divide  $a, b$  by a common factor  $c$  and  $m$  by  $\gcd(c, m)$

**Example:**  $6c \equiv 18 \pmod{21} \implies c \equiv 3 \pmod{7}$ . So solutions are  $c \equiv 3 \pmod{21}$ . **Note:** answer was converted back to mod 21 at the end

**Proposition 6.9:** Let  $n \in Z^+$  and  $a, b \in Z$ . Then  $a \equiv b \pmod{n} \implies \gcd(a, n) = \gcd(b, n)$

*Proof:*  $a \equiv b \pmod{n} \implies a = b + nk$ . Let  $d$  be a divisor of  $b, n$ . Then  $d \mid a$  since  $a$  is a linear combination of  $b, n$

We also must have  $b = a - nk \implies$  any common divisor of  $a, n$  is also a divisor of  $b$

Thus the set of common divisors for  $a, n$  is the same as the set of common divisors of  $b, n$ . Thus  $\gcd(a, n) = \gcd(b, n)$

**Example:**  $\gcd(1234, 10) = \gcd(4, 10)$  since  $1234 \equiv 4 \pmod{10}$

**Proposition 6.10:** If  $p$  is a prime and  $ab \equiv 0 \pmod{p}$ . Then  $a \equiv 0 \pmod{p}$  or  $b \equiv 0 \pmod{p}$

*Proof:*  $ab \equiv 0 \pmod{p} \implies p \mid ab$ . Thus by theorem,  $p \mid a$  or  $p \mid b \implies a \equiv 0 \pmod{p}$  or  $b \equiv 0 \pmod{p}$ , respectively

**Corollary 6.11:** Let  $p$  be a prime. Then  $x^2 \equiv 1 \pmod{p}$  has only solutions  $x \equiv \pm 1 \pmod{p}$

*Proof:*  $x^2 \equiv 1 \pmod{p} \iff x^2 - 1 \equiv 0 \pmod{p} \iff (x - 1)(x + 1) \equiv 0 \pmod{p}$

By the previous Proposition, this only happens when  $x - 1 \equiv 0 \pmod{p}$  or  $x + 1 \equiv 0 \pmod{p}$

Thus the only possible solutions are  $x \equiv \pm 1 \pmod{p}$

## 6.2 Divisibility Tests

An integer  $n$  is divisible by 4 if the last 2 digits are divisible by 4

An integer  $n$  is divisible by 8 if the last 3 digits are divisible by 8

**Proposition 6.14:** An integer mod 3 (respectively, mod 9) is congruent to the sum of its digits mod 3 (respectively, mod 9)

*Proof:* Clearly  $10 \equiv 1 \pmod{3}$ . Since  $1^k = 1$  for all integers  $k$ , we have

$$10^k \equiv 1^k \equiv 1 \pmod{3}$$

Thus when we look at  $n$  expanded in its base 10 form mod 3, we get

$$n = a_m 10^m + \cdots + a_1 10 + a_0 \equiv a_m + \cdots + a_1 + a_0 \pmod{3}$$

Identical for mod 9

**Corollary 6.15:** An integer  $n$  is divisible by 3 if and only if the sum of its digits are divisible by 3. It is divisible by 9 if and only if the sum of its digits is divisible by 9

**Proposition 6.16:** An integer mod 11 is congruent to the alternating sum its digits starting with the ones ( $a_0$ ), subtracting the tens ( $a_1$ ),  $\dots$

*Proof:* Note that  $10 \equiv -1 \pmod{11} \implies 10^k \equiv (-1)^k \pmod{11}$

Thus when we look at  $n$  expanded in its base 10 form mod 11, we get

$$n = a_m 10^m + \cdots + a_1 10 + a_0 \equiv a_0 - a_1 + \cdots + (-1)^m a_m \pmod{11}$$

**Corollary 6.17:** An integer  $n$  is divisible 11 if and only if the alternating sum of its digits is divisible by 11

## 6.3 Linear Congruences

**Theorem 6.18:** Let  $m \in \mathbb{Z}^+$  and  $a \neq 0$ . Then  $ax \equiv b \pmod{m}$  has a solution if and only if  $d = \gcd(a, m)$  divides  $b$ . If  $d \mid b$ , then there are exactly  $d$  solutions distinct mod  $m$ . Let  $x_0$  be a solution, then the other solutions are of the form

$$x = x_0 + \left(\frac{m}{d}\right)k \quad 0 \leq k \leq d$$

Where  $x_0$  can be found by satisfying

$$\left(\frac{a}{d}\right)x_0 \equiv \left(\frac{b}{d}\right) \pmod{(m/d)}$$

*Proof:*  $ax \equiv b \pmod{m} \implies ax = b + my \implies ax - my = b$ . This is a Diophantine problem with  $(a, -m, b)$

Let  $d = \gcd(a, m)$ . If  $d \nmid b$ , then there are no solutions

Otherwise let  $d \mid b \implies$  solutions are of the form

$$x = x_0 + \left(\frac{m}{d}\right)k \quad y = y_0 + \left(\frac{a}{d}\right)k$$

Which implies that  $x \equiv x_0 \pmod{(m/d)}$ . To show that these solutions are distinct mod  $m$ ,

Let  $x_1 = x_0 + \left(\frac{m}{d}\right)k_1$  and  $x_2 = x_0 + \left(\frac{m}{d}\right)k_2$  be distinct solutions and suppose  $x_1 \equiv x_2 \pmod{m}$

Then  $x_1 - x_2 = mk_3 \iff \left(\frac{m}{d}\right)(k_1 - k_2) = mk_3 \iff k_1 - k_2 = dk_3 \implies k_1 \equiv k_2 \pmod{d}$ . Thus  $x_1, x_2$  are distinct

Finally, to show that  $x_0$  arises from solving  $\left(\frac{a}{d}\right)x_0 \equiv \left(\frac{b}{d}\right) \pmod{(m/d)}$ ,

Note that  $\left(\frac{a}{d}\right)x_0 = \frac{b}{d} + \left(\frac{m}{d}\right)z \implies ax_0 = b + mz \implies ax_0 \equiv b \pmod{m}$

Thus  $x_0$  is a solution we desire

**Corollary 6.19:** If  $\gcd(a, m) = 1$ , then  $ax \equiv b \pmod{m}$  has exactly 1 solution mod  $m$

*Proof:* Let  $d = 1$  and apply Theorem 6.18. Then  $d \mid b \implies$  there is only 1 solution

**Example:**  $6x \equiv 7 \pmod{15}$  has no solutions because  $\gcd(6, 15) = 3$  but  $3 \nmid 7$

**Example:**  $5x \equiv 6 \pmod{11} \implies x = 10$  is a unique solution since  $\gcd(5, 11) = 1$

**Example:**  $9x \equiv 6 \pmod{15}$  has  $\gcd(9, 15) = 3$  solutions mod 15

Reducing the equation, we get  $3x \equiv 2 \pmod{5} \implies x_0 = 4 \implies$  solutions are  $\{4, 4 + \frac{15}{3}, 4 + 2 * \frac{15}{3}\} = \{4, 9, 14\}$

We can also solve linear congruence problems using Extended Euclidean Algorithm

**Example:**  $183x \equiv 15 \pmod{31} \implies 28x \equiv 15 \pmod{31}$

Converting it into a Linear Diophantine problem, we get  $28x - 31y = 15$ . Now we find  $\gcd(28, 31)$

$$31 = 1 * 28 + 3$$

$$28 = 9 * 3 + 1$$

$$3 = 3 * 1$$

Thus  $\gcd(28, 31) = 1$ . Now we write it as a linear combination of 28, 31

$$31 = 1 * 31 + 0 * 28$$

$$28 = 0 * 31 + 1 * 28$$

$$3 = 1 * 31 - 1 * 28$$

$$1 = 1 * 28 - 9 * 3 = -9 * 31 + 10 * 28$$

Thus  $28(10) + 31(-9) = 1 \implies 28(150) + 31(-135) = 15 \implies 28(150) \equiv 15 \pmod{31} \implies x = 26$

**Multiplicative Inverse:**  $a$  has a **multiplicative inverse**  $b$  if  $ab \equiv 1 \pmod{m}$

**Corollary 6.21:**  $a$  has an inverse mod  $m$  if and only if  $\gcd(a, m) = 1$

*Proof:* From Theorem 6.18,  $ax \equiv 1 \pmod{m}$  has a solution if and only if  $\gcd(a, m) \mid 1 \iff \gcd(a, m) = 1$

**Example:**  $7x \equiv 4 \pmod{19}$  where  $7^{-1} = 11$

$$77x \equiv 44 \pmod{19} \implies x \equiv 6 \pmod{19}$$

Steps to solve  $ax \equiv b \pmod{m}$  where  $\gcd(a, m) = 1$

1. Convert the problem into Linear Diophantine problem  $ax - my = b$
2. Use Extended Euclidean Algorithm to find  $x_0, y_0$  such that  $ax_0 - my_0 = 1$
3. Compute  $x = bx_0$

Steps to find an inverse of  $a \pmod{m}$  with  $\gcd(a, m) = 1$

1. Convert the problem into Linear Diophantine problem  $ax - my = b$
2. Use Extended Euclidean Algorithm to find  $x_0, y_0$  such that  $ax_0 - my_0 = 1$
3.  $x_0 \pmod{m}$  is the inverse of  $a \pmod{m}$

## 6.4 Chinese Remainder Theorem

**Theorem 6.22:** Let  $m, n$  be relatively prime. Then the system of congruences

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

$$x \equiv b \pmod{n}$$

Has a unique solution mod  $mn$

*Existence Proof 1:*  $x \equiv a \pmod{m} \implies a = mt \equiv b \pmod{n} \implies mt \equiv (b - a) \pmod{n}$

By Theorem, since  $m, n$  are relatively prime, there is a unique solution. Clearly  $x = a + mt_0$  is a solution to both congruences

*Existence Proof 2:*  $\gcd(m, n) = 1 \implies mu + nv = 1 \implies x = bmu + anv$

Note that  $\mu \equiv 0 \pmod{m}$  and  $nv \equiv 1 - mu \equiv 1 \pmod{m} \implies x \equiv a \pmod{m}$  and  $x \equiv b \pmod{n}$  as desired

Thus  $x$  is the desired solution

*Uniqueness Proof:* Let  $x_1, x_2$  be 2 different solutions. Then we must have

$$\begin{aligned} x_1 &\equiv \quad (\text{mod } m) & x_1 &\equiv b \quad (\text{mod } n) \\ x_2 &\equiv \quad (\text{mod } m) & x_2 &\equiv b \quad (\text{mod } n) \end{aligned}$$

Thus  $x_1 \equiv x_2 \pmod{m}$  and  $x_1 \equiv x_2 \pmod{n} \implies m \mid (x_1 - x_2)$  and  $n \mid (x_1 - x_2) \implies x_1 - x_2$  is multiple of  $m, n$

Since  $\gcd(m, n) = 1$ , we must have  $mn \mid x_1 - x_2 \implies x_1 \equiv x_2 \pmod{mn}$

**Example:**  $x \equiv 2 \pmod{3} \quad x \equiv 4 \pmod{5}$

$\gcd(3, 5) = 1$  and we solve that  $3(2) + 5(-1) = 1 \implies x = bmu + anv = (4)(3)(2) + (2)(5)(-1) \equiv 14 \pmod{15}$

**Theorem 6.23 Chinese Remainder Theorem:** Let  $m_1, m_2, \dots, m_r \in \mathbb{Z}^+$  and are pairwise relatively prime. Then

$$\begin{aligned} x &\equiv a_1 \pmod{m_1} \\ x &\equiv a_2 \pmod{m_1} \\ &\dots \\ x &\equiv a_3 \pmod{m_r} \end{aligned}$$

Has a unique solution  $x \pmod{m_1 m_2 \dots m_r}$

*Existence Proof 1:* Pair up the first 2 equations and use Theorem 6.22

$$x \equiv b_1 \pmod{m_1 m_2}$$

Repeat process for  $m_3$  and  $m_1 m_2$ . Works because pairwise relatively prime implies that  $m_3$  and  $m_1 m_2$  have no common divisors

*Existence Proof 2:* Let  $m = m_1 m_2 \dots m_r$  and  $n_i = m/m_i$ . We claim that  $\gcd(n_i, m_i) = 1$

Suppose by contradiction that  $p \mid \gcd(n_i, m_i)$ . Then  $p \mid n_i \implies p \mid m_j$  for some  $j \neq i$

Thus we must have  $p \mid \gcd(m_j, m_i)$ , contradicting that  $\gcd(m_i, m_j) = 1$  and thus we must have  $\gcd(n_i, m_i) = 1$

For each  $i$ , by Corollary 6.21, there exists  $u_i$  such that

$$n_i u_i \equiv 1 \pmod{m_i}$$

Let  $x = a_1 n_1 u_1 + \dots + a_r n_r u_r$ , then clearly for each  $m_i$

$$x \equiv a_i n_i u_i \equiv a_i \pmod{m_i}$$

*Unique Proof:* Assume there are 2 solutions  $x_1, x_2$ . Then for each  $m_i$  we must have

$$m_i \mid (x_1 - x_2) \quad 1 \leq i \leq r$$

Thus means that  $m_1 m_2 \dots m_r \mid (x_1 - x_2)$  since  $m_i$  are relatively prime

Thus  $x_1 \equiv x_2 \pmod{m_1 m_2 \dots m_r}$  and  $x_1, x_2$  are the same solution

**Example** Let  $x \equiv 2 \pmod{3} \quad x \equiv 3 \pmod{5} \quad x \equiv 2 \pmod{7}$

Then we have  $n_1 = 35, n_2 = 21, n_3 = 15$  and

$$\begin{aligned} 35u_1 &\equiv 1 \pmod{3} \implies u_1 = 2 \\ 21u_2 &\equiv 1 \pmod{5} \implies u_2 = 1 \\ 15u_3 &\equiv 1 \pmod{7} \implies u_3 = 1 \end{aligned}$$

Thus we have  $x = a_1 n_1 u_1 + a_2 n_2 u_2 + a_3 n_3 u_3 = (2)(35)(2) + (3)(21)(1) + (2)(15)(1) \equiv 23 \pmod{105}$

**UPSHOT:** We can factor composite modulus  $m$  into distinct prime powers and the solve the system of congruence mod

**Example:**  $x^2 \equiv \pmod{275 = 5^2 * 11}$  can be broken down into

$$\begin{aligned} x^2 &\equiv 1 \pmod{25} \implies x \equiv 1, 24 \pmod{25} \\ x^2 &\equiv 1 \pmod{11} \implies x \equiv 1, 10 \pmod{11} \end{aligned}$$



Thus solutions are of the form

$$\begin{array}{lll}
 x \equiv 1 \pmod{25} & x \equiv 1 \pmod{11} & \implies x \equiv 1 \pmod{275} \\
 x \equiv 1 \pmod{25} & x \equiv 10 \pmod{11} & \implies x \equiv 76 \pmod{275} \\
 x \equiv 24 \pmod{25} & x \equiv 1 \pmod{11} & \implies x \equiv 199 \pmod{275} \\
 x \equiv 24 \pmod{25} & x \equiv 10 \pmod{11} & \implies x \equiv 274 \pmod{275}
 \end{array}$$

Thus the solutions are  $x \equiv \{1, 76, 199, 274\} \pmod{275}$

## 6.5 Fractions mod m

We can interpret  $\frac{a}{b} \pmod{m}$  as  $a(b^{-1}) \pmod{m}$  where  $b^{-1}$  comes from  $bb^{-1} \equiv 1 \pmod{m}$

- Only works when  $\gcd(b, m) = 1$ . Since these are the only  $b$ 's with a multiplicative inverse mod m
- Here we interpret  $\frac{1}{b}$  as the number we need to multiply  $b$  by to get 1  $\pmod{m}$

**Example:** Calculate  $\frac{2}{7} \pmod{19}$

We see that  $7^{-1} \equiv 11 \pmod{19}$ . Thus  $\frac{2}{7} = 2 * 11 \equiv 3 \pmod{19}$