

# Year 3 — Number Theory

Based on lectures by Professor Henri Johnston

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These notes are not endorsed by the lecturers, and I have modified them (often significantly) after lectures. They are nowhere near accurate representations of what was actually lectured, and in particular, all errors are almost surely mine.

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# 1 Divisibility

## 1.1 Division Algorithm

**Definition 1.1** (Well Ordering Principle). Every non-empty subset of  $\mathbb{N}_0$  contains a least element

**Theorem 1.2** (Division Algorithm). Given a  $a \in \mathbb{Z}$  and a  $b \in \mathbb{N}_1$  there exists unique integers  $q$  and  $r$  satisfying  $a = bq + r$  and  $0 \leq r < b$ .

The proof splits into uniqueness and existence.

*Proof.* We shall first prove existence, define  $S := \{a - xb : x \in \mathbb{Z} \text{ and } a - xb \geq 0\}$ . We know  $S \neq \emptyset$  since,

- if  $a \geq 0$ , then choose  $m = 0$ , then  $a - mb = a \geq 0$
- if  $a < 0$ , then let  $a = m$ , so  $a - mb = a - ab = (-a)(b - 1) \geq 0$  since  $-a > 0$  and  $b > 0$ <sup>1</sup>

Hence  $S$  is non-empty subset of  $\mathbb{N}_0$  and so by the well ordering principle  $S$  must contain a least element  $r \geq 0$ . Since  $r \in S$ , then we have there exists a  $q \in \mathbb{Z}$  such that  $a - qb = r$  and so  $a = qb + r$ . Now it remains to check that  $r < b$ , so assume for a contradiction that  $r \geq b$ , then let there be a  $r_1 = r - b \geq 0$ . Then,

$$a = qb + r = qb + (r_1 + b) = (q + 1)b + r_1$$

and so  $a - (q + 1)b = r_1 \in S$  and is smaller than  $r$ , a contradiction.

Now let us show uniqueness, assume that there exist another pair  $q', r'$  such that  $a = q'b + r'$  where  $0 \leq r' < b$ . Then from  $a = a + qb + r = q'b + r'$  we have that,  $(q - q')b = r' - r$ . If  $q = q'$ , then we must have  $r = r'$ , suppose for a contradiction that this isn't true, then,

$$b \leq |q - q'|b = |r - r'|$$

However, since  $0 \leq r, r' < b$  and so  $|r - r'| < b$  which gives a contradiction. □

Here's a definition that I feel is useful that wasn't covered in the lectures,

**Definition 1.3** (Divisible). We say that some  $a \in \mathbb{Z}$  is divisible by some  $b \in \mathbb{Z}$  if and only is,

$$\exists n \in \mathbb{Z}, \text{ such that } b = na$$

and denote it,  $a \mid b$

## 1.2 Greatest Common Divisor

Let us start with a theorem.

**Theorem 1.4.** Let  $a, b \in \mathbb{Z}$ ,  $\exists d \in \mathbb{N}_0$  and non-unique  $x, y \in \mathbb{Z}$  such that,

- (i)  $d \mid a$  and  $d \mid b$
- (ii) and if  $e \in \mathbb{Z}$ ,  $e \mid a$  and  $e \mid b$ , then  $e \mid d$
- (iii)  $d = ax + by$

<sup>1</sup>You absolute plank, there doesn't exist any numbers between 0 and 1 in  $\mathbb{Z}$ , so  $b > 0$  is the same as  $b \geq 1$

*Proof.* If  $a = b = 0$ , then  $d = 0$   
 Suppose that  $a \neq b \neq 0$ , then let

$$S := \{am + bn : m, n \in \mathbb{Z} \text{ and } am + bn > 0\}$$

Now  $a^2 + b^2 > 0$  so  $S$  is non-empty and a subset of  $\mathbb{N}_1$ . Hence, by the Well ordering principle then there must be some minimum element  $d$ . Then we can write  $d = ax + by$  by definition of  $S$ .

By the division Algorithm,  $a = qs + r$  for some  $q, r \in \mathbb{Z}$  with  $0 \leq r < d$ . Suppose for a contradiction that  $r \neq 0$ . Then,

$$0 < r = a - qd = a - q(ax + by) = (1 - qx)a - qby$$

Hence,  $r \in S$ . But  $r < d$ , contradicting the minimality of  $d$  in  $S$ . So we must have  $r = 0$ , i.e.  $d \mid a$ . The same works for  $d \mid b$ .

Suppose that  $e \in \mathbb{Z}$ ,  $e \mid a$  and  $e \mid b$ . Then  $e$  divides any linear combination of  $a$  and  $b$ , so  $e \mid d$ . Suppose that  $e \in \mathbb{N}_1$  also satisfies (i) and (ii). Then,  $e \mid d$  and  $d \mid e$  and so  $d = \pm e$ , but  $d, e \geq 0$  and so  $d = e$ . Thus  $d$  is unique.  $\square$

Note that this is a standard trick to prove that integers divide, by just proving that  $r = 0$  by contradiction.

**Corollary 1.5.** If  $a, b \in \mathbb{Z}$  then there exists a unique  $d \in \mathbb{N}_1$  such that.

- (i)  $d \mid a$  and  $d \mid b$
- (ii) if  $e \in \mathbb{Z}$ , then  $e \mid a$  and  $e \mid b$  then  $e \mid d$

*Proof.* The existence of a  $d$  is given by the theorem. In the proof of uniqueness we only use (i) and (ii).  $\square$

**Definition 1.6** (Greatest Common Divisor). Let  $a, b \in \mathbb{Z}$ . Then  $d$  of the previous corollary is just the greatest common divisor of  $a$  and  $b$ , written  $\gcd(a, b)$ . Also sometimes seen as  $\text{hcf}(a, b)$ .

If  $\gcd(a, b) = 1$ , then  $a$  and  $b$  are coprime.

**Identity** (Bezouts Identity). Given  $a, b \in \mathbb{Z}$  there exist  $x, y \in \mathbb{Z}$  such that  $\gcd(a, b) = ax + by$ .

**Proposition 1.7.** Let  $a, b, c \in \mathbb{Z}$ , then,

- (i)  $\gcd(a, b) = \gcd(b, a)$
- (ii)  $\gcd(a, \gcd(b, c)) = \gcd(\gcd(a, b), c)$
- (iii)  $\gcd(ac, bc) = |c| \gcd(a, b)$
- (iv)  $\gcd(1, a) = \gcd(a, 1) = 1$
- (v)  $\gcd(0, a) = \gcd(a, 0) = |a|$
- (vi)  $c \mid \gcd(a, b)$  if and only if  $c \mid a$  and  $c \mid b$
- (vii)  $\gcd(a + cb, b) = \gcd(a, b)$

Then we can consider the following remark,

**Remark.** Note that  $\gcd(a, b) = 0$  if and only if,  $a = b = 0$ . Otherwise,  $\gcd(a, b) \geq 1$ .

*Proof.* Checking these properties are pretty simple, for (vi) just use Bezouts.

We shall prove (iii), so let  $d = \gcd(a, b)$  and  $e = \gcd(ac, bc)$ . By (vi),  $cd \mid e = \gcd(ac, bc)$  since  $cd \mid ac$  and  $cd \mid bc$ . Then by Bezouts, there exists  $x, y \in \mathbb{Z}$  such that  $d = ax + by$ . Then,

$$cd = acx + bcy$$

and as  $e \mid ac$  and  $e \mid bc$  and so by linearity we have  $e \mid cd$ . Therefore,  $|e| = |cd|$  and so,  $e = |c|d$ .

Now, let's prove (vii), let  $e = \gcd(a + bc, b)$  and  $f = \gcd(a, b)$ . Then  $e \mid (a + bc)$  and  $e \mid b$ . Thus by linearity, we have  $e \mid a$ . Hence,  $e \mid a$  and  $e \mid b$  so by property (vi), we have  $e \mid f$ . Similarly we can get that  $f \mid a + bc$  and  $f \mid b$  and so again by (vi) we have  $e = f$  as  $f, e \geq 0$ .  $\square$

**Lemma 1.8** (Euclids Lemma). Let  $a, b, c \in \mathbb{Z}$ . If  $a \mid bc$  and  $\gcd(a, b) = 1$ , then  $a \mid c$ .

*Proof.* Suppose that  $a \mid bc$  and  $\gcd(a, b) = 1$ . By Bezouts, we get that for some  $x, y \in \mathbb{Z}$  we get  $1 = ax + by$ . Hence,  $c = acx + bcy$ , but  $a \mid acx$  and  $a \mid bcy$ , so  $a \mid c$  by linearity.  $\square$

**Theorem 1.9** (Solubility of linear equations in  $\mathbb{Z}$ ). Let  $a, b, c \in \mathbb{Z}$ . The equation,

$$ax + by = c$$

is soluble with  $x, y \in \mathbb{Z}$  if and only if  $\gcd(a, b) \mid c$

*Proof.* Let  $d = \gcd(a, b)$ . Then  $d \mid a$  and  $d \mid b$  so if there exists  $x, y \in \mathbb{Z}$  such that  $c = ax + by$  then  $d \mid c$  by linearity of divisibility. Now, suppose that  $d \mid c$ . Then we can write  $c = qd$  for some  $q \in \mathbb{Z}$ . By Bezouts, there exists some  $x', y' \in \mathbb{Z}$  such that  $d = ax' + by'$ . Hence,  $c = qd = aqx' + byq'$  and so  $x = qx'$  and  $y = qy'$  gives a suitable solution.  $\square$

### 1.3 Euclids Algorithm

**Theorem 1.10** (Euclids Algorithm). Let  $a, b \in \mathbb{N}_1$  with  $a > b > 0$  and  $b \nmid a$ . Let  $r_0 = a$ ,  $r_1 = b$  and apply the division Algorithm repeatedly to obtain a sequence of remainders defined sucessively,

$$\begin{array}{ll} r_0 = r_1 q_1 + r_2 & 0 < r_2 < r_1 \\ r_1 = r_2 q_2 + r_3 & 0 < r_3 < r_2 \\ \vdots & \\ r_{n-2} = r_{n-1} q_{n-1} + r_n & 0 < r_n < r_{n-1} \\ r_{n-1} = r_n q_n + r_{n+1} & r_{n+1} = 0 \end{array}$$

Then the last non-zero remainder,  $r_n$  is the  $\gcd(a, b)$ .

*Proof.* There is a stage at which  $r_{n+1} = 0$  because the  $r_i$  are strictly decreasing non-negative integers. We have,

$$\begin{aligned} \gcd(r_i, r_{i+1}) &= \gcd(r_{i+1} q_{i+1} + r_{i+2} r_{i+1}) \\ &= \gcd(r_{i+2} r_{i+1}) \\ &= \gcd(r_{i+1}, r_{i+2}) \end{aligned}$$

Applying this result repeatedly,

$$\begin{aligned} \gcd(a, b) &= \gcd(r_0, r_1) \\ &= \gcd(r_2, r_3) \\ &= \dots \\ &= \gcd(r_{n-1}, r_n) \\ &= r_n \end{aligned}$$

Where the last equality is because  $r_n \mid r_{n-1}$  □

**Remark.** One can also use Euclids Algorithm to find the  $x, y \in \mathbb{Z}$  Bezouts Identity state to exist by working backwards. These aren't unique.

## 1.4 Extended Euclidean Algorithm

Instead of doing Euclids, and working backwards we can compute our bezouts  $x, y$  during euclids. This is the extended Euclids Algorithm. This time we are going to define sequences of integers  $x_i$  and  $y_i$ , such that  $r_i = ax_i + by_i$ . Recall that  $r_n$  is the last non-zero remainder and that  $r_n = \gcd(a, b)$ . Therefore  $\gcd(a, b) = r_n = ax_n + by_n$  and so  $(x, y) := (x_n, y_n)$ .

We have that  $r_0 = a$  and  $r_1 = b$ . Hence, we see  $r_0 = 1 \times a + 0 \times b$  and  $r_1 = 0 \times a + 1 \times b$ , and so we set  $(x_0, y_0) := (1, 0)$  and  $(x_1, y_1) := (0, 1)$ . So, now we consider for  $i \geq 2$  we have a pair  $(x_j, y_j)$  for  $j < i$ . Then  $r_{i-2} = r_{i-1}q_{i-1} + r_i$  and so,

$$\begin{aligned} r_i &= r_{i-2} - r_{i-1}q_{i-1} \\ &= (ax_{i-2} + by_{i-2}) - (ax_{i-1} + by_{i-1})q_{i-1} \\ &= a(x_{i-2} - x_{i-1}q_{i-1}) + b(y_{i-2} - y_{i-1}q_{i-1}) \end{aligned}$$

Thus we set  $x_i := x_{i-2} - x_{i-1}q_{i-1}$  and  $y_i := y_{i-2} - y_{i-1}q_{i-1}$ . These can be defined recursively this way.

$$(x_i, y_i) := (x_{i-2}, y_{i-2}) - q_{i-1}(x_{i-1}, y_{i-1})$$

**Example.** We compute  $\gcd(841, 160)$  use Extended Euclidean Algorithm.

$i$	$r_{i-2}$	$r_{i-1}$	$q_{i-1}$	$r_i$	$x_i$	$y_i$
0				841	1	0
1				160	0	1
2	841	= 160	× 5	+ 41	1	-5
3	160	= 41	× 3	+ 37	-3	16
4	41	= 37	× 1	+ 4	4	-21
5	37	= 4	× 9	+ 1	-39	205
6	4	= 1	× 4	+ 0		

Therefore,  $\gcd(841, 160) = 1 = 841 \times (-39) + 160 \times 205$ .

## 2 Primes and Congruences

We start by defining primes and composite numbers,

**Definition 2.1** (Prime). A number  $p \in \mathbb{N}_1$  with  $p > 1$  is prime if and only if its only divisors are 1 and  $p$ , i.e.

$$n \mid p \implies n = 1 \text{ or } n = p$$

**Definition 2.2** (Composite Numbers). A number  $n \in \mathbb{N}_1$  with  $n > 1$  is composite if and only if it is not prime, i.e.

$$n = ab \quad 1 < a, b \in \mathbb{N}$$

One is neither composite nor prime.

**Proposition 2.3.** If  $n \in \mathbb{N}_1$  with  $n > 1$ , then  $n$  has a prime factor.

*Proof.* Use strong induction, so assume for  $1 < m < n$  where  $m \in \mathbb{N}_1$  that  $m$  has a prime factor.

Case (i): If  $n$  is prime, then  $n$  is a prime factor of  $n$ .

Case (ii): If  $n$  is composite, then  $n = ab$  where  $a, b > 1$  and so,  $1 < a < n$ . By the induction hypothesis, there is a prime  $p$  such that  $p \mid a$ . Hence,  $p \mid a$  and  $a \mid n$  so, by transitivity  $p \mid n$ .  $\square$

**Proposition 2.4.** If  $1 < n \in \mathbb{N}_1$ , then we can write  $n = p_1 p_2 \dots p_k$  where  $k \in \mathbb{N}_1$  and  $p_i$  are primes.

*Proof.* If  $n$  is prime, then the result is clear. So suppose that  $n$  is composite. Then  $n$  must have a prime factor, so  $n = p_1 n_1$  where  $1 < n_1 \in \mathbb{N}_1$ . If  $n_1$  is prime, we are done. If  $n_1$  is composite, then we can write  $n_1 = p_2 n_2$  and so on... This process terminates as  $n > n_1 > n_2 > \dots > 1$ . Hence after at least  $n$  steps we obtain a prime factorisation of  $n$ .  $\square$

**Example.**

$$666 = 3 \times 222 = 3 \times 2 \times 111 = 3 \times 2 \times 3 \times 37$$

**Theorem 2.5.** There are infinitely many primes

*Euclid's Proof.* For a contradiction, assume there are finitely many primes,  $\{p_1, p_2, p_3, \dots, p_n\}$  and that is a complete list. Consider  $N := p_1 p_2 \dots p_n + 1 \in \mathbb{N}$ . Then  $N > 1$  so by the first proposition,  $N$  has a prime factor  $p$ . However, every prime is one of the elements of the list, so  $p = p_i$ . Hence,  $p_i \mid (p_1 p_2 \dots p_n)$  so  $p \mid (N - 1)$ . However,  $p \mid N$  and we can write  $1 = N - (N - 1)$ , so  $p \mid 1$ , which is a contradiction.  $\square$

### 2.1 Fundamental Theorem of Arithmetic

**Lemma 2.6.** Let  $n \in \mathbb{Z}$ , then if  $p \nmid n$  then  $\gcd(p, n) = 1$

*Proof.* Let  $d = \gcd(p, n)$ . Then  $d \mid p$  so by definition of prime either  $d = 1$  or  $d = p$ . But  $d \mid n$  so  $d \neq p$  because  $p \nmid n$ . Hence,  $d = 1$ .  $\square$

**Theorem 2.7** (Euclid's Lemma for Primes). Let  $a, b \in \mathbb{Z}$  and  $p$  be a prime. If  $p \mid ab$ , then  $p \mid a$  or  $p \mid b$ .

*Proof.* Assume  $p \mid ab$  and that  $p \nmid a$ . We shall prove  $p \mid b$ . By Lemma,  $\gcd(p, a) = 1$ , so by Euclid's lemma,  $p \mid b$ .  $\square$

**Remark.** Euclid's Lemma for primes immediately generalises to several factors.

**Definition 2.8.** Let  $n \in \mathbb{N}_1$  and  $p$  be a prime. Then,

$$v_p(n) := \max\{k \in \mathbb{N} \cup \{0\} : p^k \mid n\}$$

In other words,  $k$  is the unique non-negative integer such that  $p^k \mid n$  but  $p^{k+1} \nmid n$ . Equivalently,  $v_p(n) = k$  if and only if  $n = p^k n'$  where  $n' \in \mathbb{N}$  and  $p \nmid n'$ .

**Example.** We can see that,

- $v_2(720) = 4$  as  $2^4 \mid 720$  but  $2^5 \nmid 720$
- $v_3(720) = 2$  as  $3^2 \mid 720$  but  $3^3 \nmid 720$
- $v_5(720) = 1$  as  $5^1 \mid 720$  but  $5^2 \nmid 720$
- if  $p \geq 7$ , then  $v_p(720) = 0$  as  $p \nmid 720$ .

**Lemma 2.9.** Let  $n, m \in \mathbb{N}_1$  and  $p$  be a prime. Then  $v_p(mn) = v_p(m) + v_p(n)$

*Proof.* Let  $k = v_p(m)$  and  $\ell = v_p(n)$ . Then we write  $m = p^k m'$  where  $p \nmid m'$  and  $n = p^\ell n'$  where  $p \nmid n'$ . Then  $nm = p^{k+\ell} m' n'$  and so by Euclid's lemma  $p \nmid m' n'$  as if it did then  $p \mid n'$  or  $p \mid m'$  but it doesn't. So  $v_p(mn) = v_p(m) + v_p(n)$ .  $\square$

**Theorem 2.10** (Fundamental Theorem of Arithmetic). Let  $1 < n \in \mathbb{N}_1$ . Then,

- (i) (Existence) The number  $n$  can be written as a product of primes.
- (ii) (Uniqueness) Suppose that,

$$n = p_1 \dots p_r = q_1 \dots q_s$$

where each  $p_i$  and  $q_j$  are prime. Assume further that,

$$p_1 \leq p_2 \leq \dots \leq p_r \quad \text{and} \quad q_1 \leq q_2 \leq \dots \leq q_s$$

Then  $r = s$  and  $p_i = q_i$  for all  $i$

**Remark.** If 1 is a prime, then the Uniqueness here is broken, as,

$$6 = 3 \times 2 = 3 \times 2 \times 1 = \dots$$

**Remark.** A consequence of the FTA is that the integral domain  $\mathbb{Z}$  is in fact a UFD.

*Proof.* The existence is something we have done before. The harder part is uniqueness. Let  $\ell$  be any prime. Then we have,

$$\begin{aligned} v_\ell(n) &= v_\ell(p_1 \dots p_r) \\ &= v_\ell(p_1) + \dots + v_\ell(p_r) \end{aligned}$$

However,

$$v_\ell(p_i) = \begin{cases} 1 & \text{if } \ell = p_i \\ 0 & \text{if } \ell \neq p_i \end{cases}$$

Therefore,

$$\begin{aligned} v_\ell(n) &= \# \text{ of } i \text{ for which } \ell = p_i \\ &= \# \text{ of times } \ell \text{ appears in the factorisation } n = p_1 \dots p_r \end{aligned}$$

Similarly,

$$v_\ell(n) = \# \text{ of times } \ell \text{ appears in the factorisation } n = q_1 \dots q_s$$

Thus every prime  $\ell$  appears the same number of times in each factorisation, giving the desired result.  $\square$

**Remark.** Another way of interpreting this result is to say that for  $n \in \mathbb{N}_1$ ,

$$n = p_1^{v_{p_1}(n)} p_2^{v_{p_2}(n)} \dots p_r^{v_{p_r}(n)}$$

where  $p_1, \dots, p_r$  are the distinct prime factors of  $n$ . Note that we take the empty product to be 1, which covers the case for  $n = 1$ .

**Lemma 2.11.** Let  $n = \prod_{i=1}^r p_i^{a_i}$  where each  $a_i \in \mathbb{N}_0$  and the  $p_i$ 's are distinct primes. The set of positive divisors of  $n$  is the set of numbers of the form  $\prod_{i=1}^r p_i^{c_i}$  where  $0 \leq c_i \leq a_i$  for  $i = 1, \dots, r$ .

*Proof.* Exercise  $\square$

## 2.2 Congruences

**Definition 2.12.** Suppose  $a, b \in \mathbb{Z}$  and  $n \in \mathbb{N}_1$ . We write  $a \equiv b \pmod{n}$ , and say ‘ $a$  is congruent to  $b \pmod{n}$ ’, if and only if  $n \mid (a - b)$ . If  $n \nmid (a - b)$  we say that  $a$  and  $b$  are incongruent mod  $n$ .

**Remark.** In particular,  $a \equiv 0 \pmod{n}$  if and only if  $n \mid a$

**Example.** Here are some examples:

- $4 \equiv 30 \pmod{13}$  since  $13 \mid (4 - 30) = -26$
- $17 \not\equiv -17 \pmod{4}$  since  $17 - (-17) = 34$  but  $4 \nmid 34$ .
- $n$  is even if and only if  $n \equiv 0 \pmod{2}$
- $n$  is odd if and only if  $n \equiv 1 \pmod{2}$
- $a \equiv b \pmod{1}$  for all  $a, b \in \mathbb{Z}$

**Proposition 2.13.** Let  $n \in \mathbb{N}_1$  being congruent mod  $n$  is an equivalence relation, so,

- (i) Reflexive:  $\forall a \in \mathbb{Z}, a \equiv a \pmod{n}$
- (ii) Symmetric:  $\forall a, b \in \mathbb{Z}, a \equiv b \pmod{n} \implies b \equiv a \pmod{n}$
- (iii) Transitive:  $\forall a, b \in \mathbb{Z}, a \equiv b \pmod{n}$  and  $b \equiv c \pmod{n} \implies a \equiv c \pmod{n}$ .

*Proof.* The proof follows from,

- (i)  $n \mid 0$ .
- (ii) If  $n \mid (a - b)$  then  $n \mid (b - a)$
- (iii) If  $n \mid (a - b) + (b - c) = (a - c)$

□

**Proposition 2.14.** Congruences respect addition, subtraction and multiplication. Then let  $a, b, \alpha, \beta \in \mathbb{Z}$ . Suppose that  $a \equiv \alpha \pmod{n}$  and  $b \equiv \beta \pmod{n}$ . Then,

- (i)  $a + b \equiv \alpha + \beta \pmod{n}$
- (ii)  $a - b \equiv \alpha - \beta \pmod{n}$
- (iii)  $ab \equiv \alpha\beta \pmod{n}$

Moreover, if  $f(x) \in \mathbb{Z}[x]$  then  $f(a) \equiv f(\alpha) \pmod{n}$

*Proof.* Check that  $ab \equiv \alpha\beta \pmod{n}$ . Since,  $a \equiv \alpha \pmod{n}$  and so,  $n \mid (a - \alpha)$  and so  $a = \alpha + ns$  for some  $s \in \mathbb{Z}$ . Similarly  $b = \beta + nt$ . Hence,

$$ab = (\alpha + ns)(\beta + nt) = \alpha\beta + n(s\beta + t\alpha + nst)$$

and so  $n \mid (ab - \alpha\beta)$ . Therefore,  $ab \equiv \alpha\beta \pmod{n}$ , as required. □

**Example.** Let  $n \in \mathbb{N}_1$  and write  $n$  in decimal notation,

$$n = \sum_{i=0}^k a_i \times 10^i \quad 0 \leq a_i \leq 9$$



Then, define  $f(x)$  by,

$$f(x) = \sum_{i=0}^k a_i x^i$$

Then, since  $10 \equiv -1 \pmod{11}$ , we see that  $n = f(10) \equiv f(-1) \pmod{11}$ , whence,

$$11 \mid n \iff 11 \mid f(-1) \iff 11 \mid (a_0 - a_1 + a_2 - a_3 + \cdots + (-1)^k a_k)$$

This is an easy way to test for divisibility by 11.

**Example.** Does  $x^2 - 3y^2 = 2$  have a solution with  $x, y \in \mathbb{Z}$ . Let  $x, y \in \mathbb{Z}$ . Note that  $x^2 - 3y^2 \equiv x^2 \pmod{3}$ . Now,  $x \equiv 0, 1, 2 \pmod{3}$ , so  $x^2 \equiv 0, 1, 4 \pmod{3} \equiv 0, 1 \pmod{3}$ . Hence,  $x^2 - 3y^2 \equiv x^2 \not\equiv 2 \pmod{3}$  and so  $x^2 - 3y^2 \neq 2$ .

**Remark.** Suppose we have  $f \in \mathbb{Z}[x_1, \dots, x_m]$  if we have  $a_1, \dots, a_m \in \mathbb{Z}$  such that  $f(a_1, \dots, a_m) = 0$  then  $f(a_1, \dots, a_m) \equiv 0 \pmod{n}$  for every  $n \in \mathbb{N}$ . Therefore if there exist an  $n \in \mathbb{N}_1$  such that  $f(x_1, \dots, x_m) \equiv 0 \pmod{n}$  has no solution, there cannot exist  $a_1, \dots, a_m \in \mathbb{Z}$  such that  $f(a_1, \dots, a_m) = 0$ .

We are going to prove the following theorem,

**Theorem 2.15.** There are infinitely many primes  $p$  with  $p \equiv 3 \pmod{4}$

*Proof.* Suppose that  $p$  is a prime. Then  $p \equiv 0, 1, 2, 3 \pmod{4}$ , but  $p \not\equiv 0 \pmod{4}$  because  $4 \nmid p$ . If  $p \equiv 2 \pmod{4}$  then  $p = 4k + 2$  for some  $k \in \mathbb{Z}$ , so  $2 \mid p$  so in fact  $p = 2$ . Therefore there are three types of primes,

- (i)  $p = 2$
- (ii)  $p \equiv 1 \pmod{4}$
- (iii)  $p \equiv 3 \pmod{4}$

Let  $N \in \mathbb{N}$  it suffices to show that there exist a type (iii) prime with  $p > N$ . Let  $4(N!) - 1$  and so  $M \geq 3$  and so by the existence of FTA we can write  $M = p_1 \dots p_k$ . If  $p \leq N$ , then  $M \equiv -1 \pmod{p}$  so  $p \nmid M$ . Hence,  $p_j > N$  for all  $j$ . Moreover  $p_j \neq 2$  for all  $j$  because  $M$  is odd. Therefore for each  $j$  we have  $p_j \equiv 1, 3 \pmod{4}$ . If  $p_j \equiv 3 \pmod{4}$  for any  $j$  then we are done. If this is not the case, then  $p_j \equiv 1 \pmod{4}$  for all  $j$ , and so,  $M \equiv 1 \times 1 \times \cdots \times 1 \pmod{4} \equiv 1 \pmod{4}$ ; but by definition of  $M$  we have  $M \equiv -1 \equiv 3 \pmod{4}$  - contradiction!  $\square$

**Remark.** Congruences do not respect division,  $4 \equiv 14 \pmod{10}$  but  $2 \not\equiv 7 \pmod{10}$

**Proposition 2.16.** Let  $a, b, s \in \mathbb{Z}$  and  $d, n \in \mathbb{N}_1$ .

- (i) If  $a \mid b \pmod{n}$  and  $d \mid n$  then  $a \mid b \pmod{d}$
- (ii) Suppose  $s \neq 0$ . Then  $a \equiv b \pmod{n}$  if and only if  $as \equiv bs \pmod{ns}$

*Proof.* (i) follows from transitivity of divisibility;

(ii) follows from multiplication and cancellation properties.  $\square$

**Theorem 2.17** (Cancellation law for Congruences). Let  $a, b, c \in \mathbb{Z}$  and  $n \in \mathbb{N}_1$ . Let  $d = \gcd(c, n)$ . Then  $ac \mid bc \pmod{n} \iff a \equiv b \pmod{\frac{n}{d}}$ . In particular, if  $n$  and  $c$  are coprime, then  $ac \equiv bc \pmod{n} \iff a \equiv b \pmod{n}$ .

*Proof.* Since,  $d = \gcd(c, n)$ , we may write  $n = dn'$  and  $c = dc'$  where  $n', c' \in \mathbb{Z}$ . Suppose  $ac \equiv bc \pmod{n}$ . Then  $n \mid c(a - b)$  and so  $n' \mid c'(a - b)$ . However,  $\gcd(n', c') = 1$  and so  $n' \mid (a - b)$  by Euclid's Lemma. Thus,  $a \equiv b \pmod{n'}$ .

Suppose conversely  $a \equiv b \pmod{n'}$  and so,  $n' \mid (a - b)$  and so  $n \mid d(a - b)$ . But  $d \mid c$  and so  $d(a - b) \mid c(a - b)$  and thus  $n \mid c(a - b)$  by the transitivity of divisibility. Thus  $ac \equiv bc \pmod{n}$ .  $\square$

**Proposition 2.18.** Let  $a, m, n \in \mathbb{Z}$ . If  $m$  and  $n$  are coprime and if  $m \mid a$  and  $n \mid a$  then  $nm \mid a$ .

*Proof.* Since  $m \mid a$  we can write  $a = mc$  for some  $c \in \mathbb{Z}$ . Now  $n \mid a = mc$  and  $\gcd(m, n) = 1$  and so by Euclid's Lemma,  $n \mid c$ . Hence,  $mn \mid mc = a$ .  $\square$

**Corollary 2.19.** Let  $m, n \in \mathbb{N}$  be coprime and let  $a, b \in \mathbb{Z}$ . If  $a \equiv b \pmod{m}$  and  $a \equiv b \pmod{n}$  then  $a \equiv b \pmod{mn}$ .

*Proof.* We have  $n \mid (a - b)$  and  $m \mid (a - b)$ . Since  $m$  and  $n$  are coprime we therefore have  $mn \mid (a - b)$ .  $\square$

### 3 Residue Classes

**Proposition 3.1.** Let  $a, b \in \mathbb{Z}$  and  $n \in \mathbb{N}_1$ . If  $a \equiv b \pmod{n}$  and  $|b - a| < n$  then  $a = b$ .

*Proof.* Since  $n \mid (a - b)$ , by the comparison property of divisibility we have  $n \leq |a - b|$  unless  $a - b = 0$ .  $\square$

As  $\pmod{n}$  is an equivalence relation,

**Definition 3.2** (Residue Class). Consider  $n \in \mathbb{N}$ , then  $a \in \mathbb{Z}$  we write  $[a]_n$  for an equivalence class  $a \pmod{n}$ . Thus,

$$[a]_n = \{x \in \mathbb{Z} : x \equiv a \pmod{n}\} = \{a + qn : q \in \mathbb{Z}\}$$

This is called the residue class of  $a$  modulo  $n$

$[a]_n$  is the coset,  $\mathbb{Z}/n\mathbb{Z}$ .

**Example.** Consider  $n = 2$ , then,

$$[0]_2 = \{x \in \mathbb{Z} : x \equiv 0 \pmod{2}\}$$

$$[1]_2 = \{x \in \mathbb{Z} : x \equiv 1 \pmod{2}\}$$

**Proposition 3.3.** Let  $n \in \mathbb{Z}$ . The  $n$  residue classes are disjoint and thier union is the set of all integers. Or  $\forall x \in \mathbb{Z}, x \equiv y \pmod{n}$  such that  $y$  is precisely one of  $\{0, 1, \dots, n - 1\}$ .

*Proof.* The integers  $0, 1, \dots, n - 1$  are incongruent  $\pmod{n}$  by the Proposition 3.1. Hence, the residue classes are distinct and thus disjoint. Every integer must be in one of these classes by the division algorithm, as we can write  $x = nq + r$ . The result then follows from taking  $x \equiv r \pmod{n}$  and hence,  $x \in [r]_n$ .  $\square$

Distinct left cosets of  $\mathbb{Z}/n\mathbb{Z}$  are always disjoint and partition  $\mathbb{Z}$ .

#### 3.1 Complete Residue Systems

**Definition 3.4** (Complete Residue System). Let  $n \in \mathbb{N}_1$ . If  $S$  is a subset of  $\mathbb{Z}$  containing extcly one element of each residue class modulo  $n$  we say that  $S$  is a complete residue system modulo  $n$ .

**Proposition 3.5.** The last proposition says  $S = \{0, 1, \dots, n - 1\}$  is a complete residue system. Note, that if  $S$  is any complete residue system, then  $|S| = n$ . Any set of integers that are incongruent  $\pmod{n}$  are a complete residue system  $\pmod{n}$ .

**Example.** The following are complete residue systems,

$$\begin{aligned} &\{1, 2, \dots, n\} \\ &\{1, n + 2, 2n + 3, 3n + 4, \dots, n^2\} \\ &\{x \in \mathbb{Z} : -\frac{n}{2} < x \leq \frac{n}{2}\} \end{aligned}$$

**Proposition 3.6.** Let  $n \in \mathbb{N}_1$  an  $k \in \mathbb{Z}$ . Assume  $n$  and  $k$  are coprime. If  $\{a_1, \dots, a_n\}$  is a complete residue system modulo  $n$  then so is  $\{ka_1, \dots, ka_n\}$ .

*Proof.* If  $ka_i \equiv ka_j \pmod{n}$  then by the cancellation law for congruences we have  $a_i \equiv a_j \pmod{n}$  since  $\gcd(k, n) = 1$ . Therefore no two distinct elements in this set,  $\{ka_1, \dots, ka_n\}$ , are congruent modulo  $n$ .  $\square$

**Example.** The set  $\{0, 1, 2, 3, 4\}$  is a complete residue system  $\pmod{5}$  and so  $\{0, 2, 4, 6, 8\}$  is also a complete residue system  $\pmod{5}$ .

### 3.2 Linear Congruences

The most basic congruences are linear congruence, for example,

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

When  $n$  is small, we can brute force it, however, it becomes impractical quickly.

**Theorem 3.7** (Linear Congruences with exactly one solution). Let  $a, b \in \mathbb{Z}$  and let  $n \in \mathbb{N}$ . Suppose that  $a$  and  $n$  are coprime. Then the linear congruence,

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

has exactly one solution.

*Proof.* We need only to test  $1, 2, \dots, n$  since they constitute a complete residue system. Therefore, we consider the products,  $a, 2a, \dots, na$ . Since  $a$  and  $n$  are coprime, these numbers are also a complete residue system. Hence, exactly one of the elements of this sets is congruent to  $b \pmod{n}$ .  $\square$

**Theorem 3.8** (Solubility of a Linear Congruence). Let  $a, b \in \mathbb{Z}$  and let  $n \in \mathbb{N}$ . Then the linear congruence,

$$ax \equiv b \pmod{n} \tag{1}$$

has one or more solutions if and only if  $\gcd(a, n) \mid b$ .

*Proof.* By definition, the congruence (1) is soluble if and only if  $n \mid (b - ax)$  for some  $x \in \mathbb{Z}$ , and this is true if and only if  $b - ax = ny$  for some  $x, y \in \mathbb{Z}$ . Hence (1) is soluble if and only if,

$$ax + ny = b$$

for some  $x, y \in \mathbb{Z}$ . Therefore this result follows from the solubility of linear equations theorem  $\square$

**Theorem 3.9.** Let  $a, b \in \mathbb{Z}$  and let  $n \in \mathbb{N}$ . Let  $d = \gcd(a, n)$ . Suppose  $d \mid b$  and write  $a = da'$ ,  $b = db'$  and  $n = dn'$ . Then the linear congruence

$$ax \equiv b \pmod{n} \tag{2}$$

has exactly  $d$  solutions modulo  $n$ . These are,

$$t, t + n', t + 2n', \dots, t + (d - 1)n' \tag{3}$$

where  $t$  is the unique solution  $\pmod{n'}$  to,

$$a'x \equiv b' \pmod{n'} \tag{4}$$

*Proof.* Every solution of (2) is a solution of (4) and vice versa. Since  $a'$  and  $n'$  are coprime, (4) has exactly one solution,  $t \pmod{n'}$  by the Theorem 3.7. Thus the  $d$  numbers in (3) are solutions of (4) and hence (2).

No two items in the list are congruent  $\pmod{n}$  since the relationships

$$\begin{aligned} t + rn' &\equiv t + sn' \pmod{n} && \text{with } 0 \leq r < d, 0 \leq s < d \\ rn' &\equiv sn' \pmod{n} && \text{and hence } r \equiv s \pmod{d} \end{aligned}$$

But  $0 \leq |r - s| < d$  so  $r = s$ . It remains to show that (2) has no solutions other than (3). If  $y$  is a solution of (2), then  $ay \equiv b \pmod{n}$ . But we also have  $at \equiv b \pmod{n}$ . Thus  $y \equiv t \pmod{n'}$  by the cancellation law for congruences. Hence,  $y = t + kn'$  for some  $k \in \mathbb{Z}$ . But  $r \equiv k \pmod{d}$  for some  $r \in \mathbb{Z}$  such that  $0 \leq r < d$ . Therefore we have,

$$kn' \equiv rn' \pmod{n} \quad \text{and so } y \equiv t + rn' \pmod{n}$$

Therefore  $y$  is congruent  $\pmod{n}$  to one of these numbers in (3).  $\square$

**Algorithm.** Let  $a, b \in \mathbb{Z}$  and let  $n \in \mathbb{N}$ . Suppose we want to solve,

$$ax \equiv b \pmod{n} \quad (5)$$

Firstly apply Extended Euclidian algorithm to compute  $d := \gcd(a, n)$  to find  $x', y' \in \mathbb{Z}$  such that,

$$ax' + ny' = d \quad (6)$$

if  $d \nmid b$  then there are no solutions. Otherwise, these are exactly  $d$  solutions  $\pmod{n}$ , which we find as follows. Write  $a = da'$ ,  $b = db'$  and  $n = dn'$ . Dividing (6) through by  $d$  gives,

$$a'x' + n'y' = 1 \quad (7)$$

Thus reducing this  $\pmod{n'}$  gives  $a'x' \equiv 1 \pmod{n'}$  and multiplying through by  $b'$  gives  $a'(b'x') \equiv b' \pmod{n'}$ . Therefore  $t := b'x'$  is the unique solution to  $a'x' \equiv b' \pmod{n'}$ . Now the solutions to (5) are,

$$t, t + n', t + 2n', \dots, t + (d - 1)n'$$

## 4 $\mathbb{Z}/n\mathbb{Z}$ , Chinese Remainder Theorem and $\varphi(n)$

### 4.1 $\mathbb{Z}/n\mathbb{Z}$ and its units

**Definition 4.1.** Let  $n \in \mathbb{N}$ . We write  $\mathbb{Z}/n\mathbb{Z} = \{[a]_n : 0 \leq a \leq n-1\}$  (such that  $|\mathbb{Z}/n\mathbb{Z}| = n$ ). We set  $[a]_n + [b]_n := [a+b]_n$  and  $[a]_n [b]_n := [ab]_n$ . (We have showed that both of these are well defined).

**Lemma 4.2.** The set  $\mathbb{Z}/n\mathbb{Z}$  is a commutative ring with  $0 = [0]_n$  and  $1 = [1]_n$

*Proof.* MTH2010 □

**Definition 4.3.** Let  $n \in \mathbb{N}$ . Let  $(\mathbb{Z}/n\mathbb{Z})^\times$  denote the group of units of the ring  $\mathbb{Z}/n\mathbb{Z}$ . Explicitly, we have

$$(\mathbb{Z}/n\mathbb{Z})^\times = \{[a]_n \in \mathbb{Z}/n\mathbb{Z} : \exists [b]_n \in \mathbb{Z}/n\mathbb{Z} \text{ such that } [a]_n [b]_n = 1\}$$

This is a finite group under multiplication, and is abelian since  $\mathbb{Z}/n\mathbb{Z}$  is commutative.

**Definition 4.4** (Multiplicative inverse). Let  $n \in \mathbb{N}$  and let  $a \in \mathbb{Z}$  such that  $\gcd(a, n) = 1$ . Then the unique solution to  $ax \equiv 1 \pmod{n}$  is called the multiplicative inverse of  $a \pmod{n}$  and is denoted  $[a]_n^{-1}$  or  $a^{-1} \pmod{n}$

### 4.2 Chinese Remainder Theorem

**Theorem 4.5** (Special Chinese Remainder Theorem). Let  $n, m \in \mathbb{N}$  be coprime and  $a, b \in \mathbb{Z}$  be given. Then the pair of linear congruences,

$$\begin{aligned} x &\equiv a \pmod{m} \\ x &\equiv b \pmod{n} \end{aligned}$$

has a solution  $x \in \mathbb{Z}$ . Moreover, if  $x'$  is another solution  $x \equiv x' \pmod{mn}$

*Proof.* Since  $n$  and  $m$  are coprime, there must exist some  $a', b' \in \mathbb{Z}$  such that  $a'n \equiv 1 \pmod{m}$  and  $b'n \equiv 1 \pmod{n}$ . Define  $x := aa'n + bb'm$ . Then  $x \equiv a'an \equiv a \pmod{m}$  and  $x \equiv bb'm \equiv b \pmod{n}$ .

Hence  $x$  is a solution, so suppose we have an  $x'$  that satisfies these equations. Then  $m \mid (x - x')$  and  $n \mid (x - x')$ . Hence, as  $m$  and  $n$  are coprime, then it follows that  $mn \mid (x - x')$ , which is the same as  $x \equiv x' \pmod{mn}$  □

**Remark.** We used the fact that  $m$  and  $n$  are coprime twice in the above proof. This is necessary because, for example  $x \equiv 2 \pmod{12}$  and  $x \equiv 4 \pmod{20}$  has no solution.

**Theorem 4.6** (Chinese Remainder Theorem). Let  $n_1, n_2, \dots, n_t \in \mathbb{N}$  with  $\gcd(n_i, n_j) = 1$  whenever  $i \neq j$  and let  $a_1, \dots, a_t \in \mathbb{Z}$  be given. Then the system of congruences

$$\begin{aligned} x &\equiv a_1 \pmod{n_1} \\ &\vdots \\ x &\equiv a_t \pmod{n_t} \end{aligned}$$

has a solution  $x \in \mathbb{Z}$ . Moreover if  $x'$  is any other solution, then  $x' \equiv x \pmod{N}$  where  $N := n_1 n_2 \dots n_t$ .

*Proof.* Define  $N_i := \frac{N}{n_i}$ . Then  $\gcd(N_i, n_i) = 1$ , since  $n_i$  is coprime to all factors of  $N_i$ . Hence by the theorem on linear congruences with exactly one solution, there exists  $x_i \in \mathbb{Z}$  such that  $N_i x_i \equiv 1 \pmod{n_i}$ . Next, define  $x := \sum_{i=1}^t a_i N_i x_i$ . Thus  $x \equiv a_k N_k x_k \pmod{n_k}$  since  $n_k \mid N_i$  for all  $k$ . Therefore,  $x \equiv a_k (N_k x_k) \equiv a_k \pmod{n_k}$  for all  $k$ .

Suppose  $x' \equiv a_k \pmod{n_k}$  for all  $k$ . Then  $x' \equiv x \pmod{n_k}$  thus,  $n_k \mid (x' - x)$ , then since all  $n_i$  are coprime,  $N \mid (x' - x)$ . This yields that  $x' \equiv x \pmod{N}$ . □

### 4.3 Euler $\varphi$ function

**Definition 4.7** (Euler Phi Function). For  $n \in \mathbb{N}$  we define the  $\varphi$  function as,

$$\varphi(n) = \#\{a \in \mathbb{N} : 1 \leq a \leq n, \gcd(a, n) = 1\}$$

**Remark.**  $\varphi(1) = 1$  and for  $p$  prime,  $\varphi(p) = \#\{1, 2, \dots, p-1\} = p-1$ .

**Remark.** On the proposition on uniots of  $\mathbb{Z}/n\mathbb{Z}$  and complete residue systems. We have that  $\varphi(n) = \#(\mathbb{Z}/n\mathbb{Z})$ . Note, since  $\gcd(0, n) = \gcd(n, n) = n$  for all  $n \in \mathbb{N}$ , we also have,

$$\varphi(n) = \#\{a \in \mathbb{Z} : 0 \leq a < n, \gcd(a, n) = 1\}$$

**Theorem 4.8.** Let  $m, n \in \mathbb{N}$  be coprime. Then  $\varphi(mn) = \varphi(m)\varphi(n)$

*Proof.* Let  $a \in \mathbb{Z}$  with  $0 \leq a < mn$  and define  $b, c \in \mathbb{Z}$  by,

$$a \equiv b \pmod{m} \quad \text{and} \quad a \equiv c \pmod{n}$$

where  $0 \leq b < m$  and  $0 \leq c < n$ . The Chinese Remainder Theorem tells us that there is a bijective correspondence between choices of  $a$  and pairs  $(b, c)$ . We now show that  $\gcd(a, mn) = 1 \iff \gcd(b, m) = \gcd(c, n) = 1$ . We shall use the proposition on units of  $\mathbb{Z}/n\mathbb{Z}$  several times.

Suppose  $\gcd(a, mn) = 1$ . Then  $ax \equiv 1 \pmod{mn}$  has a solution  $r \in \mathbb{Z}$ . By an earlier proposition we have  $ar \equiv 1 \pmod{m}$  since  $m \mid mn$ . Hence,  $br \equiv ar \equiv 1 \pmod{m}$  and so the congruence  $bx \equiv 1 \pmod{m}$  is soluble. Thus,  $\gcd(b, m) = 1$ . Similarly,  $\gcd(c, n) = 1$ .

Suppose conversely  $\gcd(b, m) = \gcd(c, n) = 1$ . Then the congruences  $bx \equiv 1 \pmod{m}$  and  $cy \equiv 1 \pmod{n}$  are soluble so there exist  $s, t \in \mathbb{Z}$  such that  $bs \equiv 1 \pmod{m}$  and  $ct \equiv 1 \pmod{n}$ . Since  $m$  and  $n$  are coprime, by Chinese Remainder Theorem there exists  $r \in \mathbb{Z}$  such that  $r \equiv s \pmod{m}$  and  $r \equiv t \pmod{n}$ .

Hence  $ar \equiv bs \equiv 1 \pmod{m}$  and  $ar \equiv ct \equiv 1 \pmod{n}$  and so  $x = ar$  is the solution to,

$$x \equiv 1 \pmod{m} \quad \text{and} \quad x \equiv 1 \pmod{n}$$

By the Chinese Remainder Theorem  $ar \equiv 1 \pmod{mn}$ . Hence,  $\gcd(a, mn) = 1$ .

Therefore the number of integers  $a$  with  $0 \leq a < mn$  is equal to the number of pairs of integers  $(b, c)$  with  $0 \leq b < m$ ,  $\gcd(b, m) = 1$  and  $0 \leq c < n$ ,  $\gcd(c, n) = 1$ , ie.  $\varphi(m)\varphi(n)$ .  $\square$

**Theorem 4.9.** Let  $p$  be a prime and  $r \in \mathbb{N}$ . Then

$$\varphi(p^r) = p^r - p^{r-1} = p^{r-1}(p-1)$$

*Proof.* For all  $m \in \mathbb{N}$ , either  $\gcd(p^r, m) = 1$  or  $p \mid m$ . Thus,

$$\begin{aligned} \varphi(p^r) &= \#\{m \in \mathbb{N} : m \leq p^r, p \nmid m\} \\ &= \#\{m \in \mathbb{N} : m \leq p^r\} - \#\{m \in \mathbb{N} : m \leq p^r, p \mid m\} \\ &= p^r - p^{r-1} \\ &= p^{r-1}(p-1) \end{aligned}$$

$\square$

**Proposition 4.10.** Let  $n \in \mathbb{N}$  such that  $n \geq 2$ . By FTA, we may write  $n = p_1^{e_1} p_2^{e_2} p_3^{e_3} \dots p_r^{e_r}$  where all  $p_i$ 's are distinct and  $e_i \in \mathbb{N}$ . Then,

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

*Proof.* By the last two theorems we have,

$$\begin{aligned}\varphi(n) &= \varphi(p_1^{e_1} \cdots p_r^{e_r}) = \prod_{i=1}^r \varphi(p_i^{e_i}) \\ &= \prod_{i=1}^r (p_i^{e_i} - p_i^{e_i-1}) \\ &= \prod_{i=1}^r (p_i - 1) p_i^{e_i-1}\end{aligned}$$

□

**Corollary 4.11.** Let  $n \in \mathbb{N}$ . Then,

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

where the product runs over all distinct prime divisors of  $n$ .

*Proof.* From above,

$$\varphi(n) = \prod_{i=1}^r (p_i - 1) p_i^{e_i-1} = \prod_{i=1}^r p_i^{e_i} (1 - p_i^{-1}) \quad (8)$$

$$= n \prod_{i=1}^r (1 - p_i^{-1}) = \prod_{p|n} \left(1 - \frac{1}{p}\right) \quad (9)$$

□

**Proposition 4.12.** Let  $n \in \mathbb{N}$ , we have  $\sum_{d|n} \varphi(d) = n$

*Proof.* We classify  $\{1, 2, \dots, n\}$  according to their greatest common divisor with  $n$ . Thus,

$$\{a \in \mathbb{N} : a \leq n\} = \bigcup_{d|n} \{a \in \mathbb{N} : a \leq n, \gcd(n, a) = d\}$$

where the union is disjoint. Hence,  $n = \sum_{d|n} R_d$  where  $R_d := \#\{a \in \mathbb{N} : 1 \leq a \leq n, \gcd(n, a) = d\}$ . If  $d \mid n$ , we can write  $n = dn'$  and then by the distributive law of gcd's we have  $\gcd(n, a) = d$  if and only if  $a = da'$  with  $\gcd(a', n') = 1$ . Moreover,  $a \leq n$  if and only if  $a' \leq n'$ . It follows that,

$$R_d = \#\{a' \in \mathbb{N} : 1 \leq a' \leq n', \gcd(n', a') = 1\}$$

and hence  $R_d = \varphi(n')$ . Then the size of that set is just  $\varphi(n')$ . Therefore  $n = \sum_{d|n} \varphi\left(\frac{n}{d}\right)$ . However, when  $d \mid n$  we have  $n = d \cdot \frac{n}{d}$ , thus  $d$  runs over the positive divisors of  $n$ , so does  $e = \frac{n}{d}$  and therefore we have  $\sum_{e|n} \varphi(e)$  □



## 5 Modular Exponentiation

**Proposition 5.1.** Fix  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$ . There exists some  $r \in \mathbb{N}$  such that  $a^r \equiv 1 \pmod{n}$  if and only if  $\gcd(a, n) = 1$ .

*Proof.* Suppose there exists  $r \in \mathbb{N}$  such that  $a^r \equiv 1 \pmod{n}$ . Then  $a^{r-1}$  is a solution to  $ax \equiv 1 \pmod{n}$  and so  $\gcd(a, n) = 1$  by the proposition on units of  $\mathbb{Z}/n\mathbb{Z}$ . Suppose conversely that  $\gcd(a, n) = 1$  and so there are only finitely many possible values of  $a^k \pmod{n}$  so there exists  $i, j \in \mathbb{N}$  with  $i < j$  such that  $a^i \equiv a^j \pmod{n}$ . Since  $\gcd(a, n) = 1$  we may apply the cancellation law for congruences  $i$  times obtain  $a^{j-i} \equiv 1 \pmod{n}$ . Thus take  $r = j - i$ .  $\square$

**Definition 5.2** (Order). Let  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$  and suppose  $\gcd(a, n) = 1$ . Then the least  $d \in \mathbb{N}$  such that  $a^d \equiv 1 \pmod{n}$  is called the order of  $a \pmod{n}$  and is written  $\text{ord}_n(a)$ .

**Proposition 5.3.** Let  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$ . Suppose that  $\gcd(a, n) = 1$ . For  $r, s \in \mathbb{Z}$  we have  $a^r \equiv a^s \pmod{n}$  if and only if  $r \equiv s \pmod{\text{ord}_n(a)}$ .

*Proof.* Let  $k = \text{ord}_n(a)$ . Then  $a^k \equiv 1 \pmod{n}$ . Now assume wlog  $r > s$ . Suppose  $r \equiv s \pmod{k}$ , then there exists some  $t \in \mathbb{N}$  such that  $r = s + tk$ . Hence,

$$a^r \equiv a^{s+tk} \equiv a^s (a^k)^t \equiv a^s \pmod{n}$$

Suppose conversely that  $a^r \equiv a^s \pmod{n}$ . Since  $\gcd(a, n) = 1$  we may apply the cancellation law  $s$  times to obtain  $a^{r-s} \equiv 1 \pmod{n}$ . By the division algorithm, there exist  $u, t \in \mathbb{N}_0$  such that  $r-s = tk+u$  where  $0 \leq u < k$ .

$$a^{r-s} \equiv a^{u+tk} \equiv a^u (a^k)^t \equiv a^u \pmod{n}$$

and so  $a^u \equiv 1 \pmod{n}$ . However,  $0 \leq u < k$  and  $k$  is the least positive integer such this is true. Hence  $u = 0$ . Therefore,  $k \mid (r-s)$ , ie.  $r \equiv s \pmod{k}$ .  $\square$

**Corollary 5.4.** Let  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$  and suppose that  $\gcd(a, n) = 1$ . Then  $a^k \equiv 1 \pmod{n}$  if and only if  $\text{ord}_n(a) \mid k$ .

*Proof.* Just take  $r = k$  and  $s = 0$  in the above proposition.  $\square$

**Corollary 5.5.** Let  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$  and suppose  $\gcd(a, n) = 1$ . Then the numbers  $\{1, a, a^2, \dots, a^{\text{ord}_n(a)-1}\}$  are all incongruent  $\pmod{n}$ .

*Proof.* Combine the above proposition with the proposition that says if  $c, d \in \mathbb{Z}$  with  $c \equiv d \pmod{n}$  and  $|c-d| < n$  then  $c = d$ .  $\square$

### 5.1 Reduced Residue Systems

**Definition 5.6** (Reduced Residue System). Let  $n \in \mathbb{N}$ . A subset  $R \subset \mathbb{Z}$  is said to be a reduced residue system  $\pmod{n}$  if

- $R$  contains  $\varphi(n)$  elements
- no two elements of  $R$  are congruent  $\pmod{n}$  and,
- $\forall r \in R, \gcd(r, n) = 1$

**Remark.** If  $R$  is a reduced residue system  $\pmod{n}$  then,

$$(\mathbb{Z}/n\mathbb{Z})^\times = \{[a]_n : a \in R\}$$

**Proposition 5.7.** Let  $n \in \mathbb{N}$  and  $k \in \mathbb{Z}$ . If  $\{a_1, a_2, \dots, a_{\varphi(n)}\}$  is a reduced residue system  $\pmod{n}$  and  $\gcd(k, n) = 1$  then  $\{ka_1, ka_2, \dots, ka_{\varphi(n)}\}$  is also a reduced residue system  $\pmod{n}$ .

*Proof.* If  $ka_i \equiv ka_j \pmod{n}$  then by the cancellation law for congruences  $a_i \equiv a_j \pmod{n}$  since  $\gcd(k, n) = 1$ . Therefore, no two elements in  $\{ka_1, ka_2, \dots, ka_{\varphi(n)}\}$  are congruent  $\pmod{n}$ . Moreover, since  $\gcd(a_i, n) = \gcd(k, n) = 1$  we have  $\gcd(ka_i, n) = 1$  so each  $ka_i$  is coprime to  $n$ .  $\square$

## 5.2 Euler- Fermat Theorem

**Theorem 5.8** (Euler-Fermat). Let  $n \in \mathbb{N}$ ,  $a \in \mathbb{Z}$  and suppose  $\gcd(a, n) = 1$ . Then  $a^{\phi(n)} \equiv 1 \pmod{n}$ .

*Proof.* Let  $\{b_1, \dots, b_{\phi(n)}\}$  be a reduced residue system  $\pmod{n}$ . Then since  $\gcd(a, n) = 1$ , then  $\{ab_1, ab_2, \dots, ab_{\phi(n)}\}$  is also a reduced residue system by the proposition on reduced residue systems. Hence the product in the first is congruent to the product of the second. Therefore,

$$b_1 b_2 \dots b_{\phi(n)} \equiv a^{\phi(n)} b_1 b_2 \dots b_{\phi(n)} \pmod{n}$$

then by the cancellation property and  $\gcd(b_i, n)$  apply it repeatedly to get the required result.  $\square$

**Corollary 5.9.** Let  $n \in \mathbb{N}$  and  $a \in \mathbb{Z}$  and suppose  $\gcd(a, n) = 1$ . Then  $\text{ord}_n(a) \mid \phi(n)$ .

*Proof.* Combine the Euler-Fermat Theorem and the earlier corollary that since  $\gcd(a, n) = 1$ , we have  $a^k \equiv 1 \pmod{n}$  if and only if  $\text{ord}_n(a) \mid k$ .  $\square$

**Example.** If we consider  $\phi(12) = 4$ . So for every  $a \in \mathbb{Z}$  with  $\gcd(a, 12) = 1$  we must have  $\text{ord}_n(a) = 1, 2$  or  $4$ . In fact, we can notice that with the reduced residue systems  $\{1, 5, 7, 11\}$  there isn't an element with order 4, and hence no element of order  $\phi(12)$ .

**Corollary 5.10.** Let  $p$  be a prime and let  $a \in \mathbb{Z}$  such that  $p \nmid a$ . Then  $a^{p-1} \equiv 1 \pmod{p}$

*Proof.* This follows immediately as  $\phi(p) = p - 1$ .  $\square$

**Example.** We know that  $\text{ord}_{19}(3) = 18 = \phi(19)$  and we know  $\text{ord}_{19}(8) = 6$  which is a factor of 18.

**Theorem 5.11** (Fermat's Little Theorem). Let  $p$  be a prime and let  $a \in \mathbb{Z}$ . Then  $a^p \equiv a \pmod{p}$ .

*Proof.* If  $p \nmid a$ , this follows from the earlier corollary. If  $p \mid a$ , then  $a^p$  and  $a$  are congruent to  $0 \pmod{p}$ .  $\square$

**Remark.** Many of the results in this section can be thought of in terms of group theory once we realise that,  $(\mathbb{Z}/n\mathbb{Z})^\times$  is just a finite abelian group. For example,  $\text{ord}_n(a)$  is just the order of  $[a]_n$  in  $(\mathbb{Z}/n\mathbb{Z})^\times$ . Moreover, Lagranges Theorem tells us that the order of an element divides the order of the group; so  $\text{ord}_n(a) \mid \phi(n) = \#(\mathbb{Z}/n\mathbb{Z})^\times$  which hence gives Euler-Fermat Theorem.

## 5.3 Modular Exponentiation

Let  $b \in \mathbb{Z}$  and  $e, m \in \mathbb{N}$ . We want a way to compute  $b^e \pmod{m}$  efficiently. We can write  $e$  in binary, ie.  $e = \sum_{i=0}^k a_i 2^i$  where  $a_i \in \{0, 1\}$  for  $0 \leq i \leq k$ . Then we observe,

$$b^e = b^{\left(\sum_{i=0}^k a_i 2^i\right)} = \prod_{i=0}^k \left(b^{2^i}\right)^{a_i}$$

Based on this we have the following algorithm,

**Algorithm.** Let  $b \in \mathbb{Z}$  and  $e, m \in \mathbb{N}$ . Set  $x = 1$  ( $x$  is the product). While  $e > 0$  repeat,

- (i) If  $e$  is odd, the replace  $x$  by  $bx$  and reduce this  $\pmod{m}$ . (If  $e$  is even  $x$  is not altered).
- (ii) Replace  $b$  by  $b^2$  and reduce  $\pmod{m}$
- (iii) If  $e$  is even replace  $e$  by  $\frac{e}{2}$ , if  $e$  is odd, then replace  $e$  by  $\frac{e-1}{2}$ . (Drop the units in the binary expansion and shift the digits one to the right)

When this is completed  $x \equiv b^e \pmod{m}$ .

**Example.** We want to compute  $3^{499} \bmod 997$ . We set  $b = 3$ ,  $e = 499$ ,  $m = 997$  and  $x = 1$ . Hence we get

step	$x \bmod m$	$b \bmod m$	$e$
0	1	3	499
1	3	9	249
2	27	81	124
3	27	579	62
4	27	249	31
5	741	187	15
6	981	74	7
7	810	491	3
8	904	804	1
9	3	-	0

$3^{499} \bmod 997$ . Note that we don't need to calculate  $b$  in the last step. Moreover we get the binary expansion of 499, which is 111110011 (by going from bottom to top in  $e$ , ignoring the 0, letting odd be 1 and even 0). This minimises the number of multiplications, at one step we are just multiplying two integers modulo  $m$ , so they are small numbers.

## 5.4 Polynomial Congruence

**Theorem 5.12** (Legranges Polynomial Congruence Theorem). Let

$$f(x) = a_0 + a_1x + \cdots + a_nx^n \in \mathbb{Z}[x]$$

and let  $p$  be a prime such that  $p \nmid a_d$ . Then  $f(x) \equiv 0 \pmod p$  has at most  $d$  solutions  $\bmod p$ .

**Remark.** More generally, any polynomial equation of degree  $d$  over a field has at most  $d$  solutions (note that  $\mathbb{Z}/p\mathbb{Z} = \mathbb{F}_p$  is a field).

*Proof.* The proof is by induction on  $d$ . When  $d = 1$  we get that,

$$a_1x + a_2 \equiv 0 \pmod p$$

since  $a_1 \not\equiv 0 \pmod p$ , then  $\gcd(a_1, p) = 1$  and so there is exactly one solution.

Assume that the theorem is true for polynomials of degree  $d - 1$  and suppose for a contradiction that  $f(x) \equiv 0 \pmod p$  has  $d + 1$  incongruent solutions  $\bmod p$  say  $x_0, x_1, \dots, x_d$  where  $f(x_k) \equiv 0 \pmod p$ . Recall we have for  $r \in \mathbb{N}$ ,

$$x^r - y^r = (x - y)(x^{r-1} + x^{r-2}y + \cdots + xy^{r-2} + y^{r-1})$$

Hence,

$$f(x) - f(x_0) = \sum_{r=1}^n a_r(x^r - x_0^r) = \sum_{r=1}^n a_r(x - x_0)g_r(x)$$

where each  $g_r \in \mathbb{Z}[x]$  is of degree  $r - 1$  and has leading coefficient 1. Hence,  $f(x) - f(x_0) = (x - x_0)g(x)$ . Thus,

$$f(x_k) - f(x_0) = (x_k - x_0)g(x_k) \equiv 0 \pmod p$$

since  $f(x_k) \equiv f(x_0) \equiv 0 \pmod p$ . But  $x_k - x_0 \not\equiv 0 \pmod p$  if  $k \neq 0$  so we must have  $g(x_k) \equiv 0 \pmod p$  for each  $k \neq 0$  (by cancellation law for congruences). But this means  $g(x) \equiv 0 \pmod p$  has  $d$  incongruent solutions  $\bmod p$  - contradiction! Hence desired result is proved.  $\square$

**Corollary 5.13.** Let  $a \in \mathbb{Z}$  and  $p$  be an odd prime. If  $a^2 \equiv 1 \pmod p$ , then  $a \equiv \pm 1 \pmod p$ .

*Proof.* Lagranges Polynomial Theorem says that  $a^2 \equiv 1 \pmod{p}$  has at most two solutions and these are  $a \equiv \pm 1 \pmod{p}$  are solutions and these must be distinct because  $p$  is odd. Therefore we have found all the solutions.  $\square$

**Example.** Let  $p$  and  $q$  be distinct odd primes. Consider the congruence,

$$x^2 \equiv 1 \pmod{pq}$$

It is clear that  $x \equiv \pm 1 \pmod{pq}$  are solutions, but are there any other solutions? By the CRT we have,

$$\begin{aligned} x^2 &\equiv 1 \pmod{pq} \\ \iff x^2 &\equiv 1 \pmod{p} \text{ and } x^2 \equiv 1 \pmod{q} \\ \iff x &\equiv \pm 1 \pmod{p} \text{ and } x \equiv \pm 1 \pmod{q} \end{aligned}$$

Thus there are four solutions  $\pmod{pq}$ . Hence,

$$x \equiv 1 \pmod{pq} \iff \begin{cases} x \equiv 1 \pmod{p} \\ x \equiv 1 \pmod{q} \end{cases}$$

and

$$x \equiv -1 \pmod{pq} \iff \begin{cases} x \equiv -1 \pmod{p} \\ x \equiv -1 \pmod{q} \end{cases}$$

and so there remains two pairs of congruences,

$$\begin{cases} x \equiv 1 \pmod{p} \\ x \equiv -1 \pmod{q} \end{cases} \quad \text{and} \quad \begin{cases} x \equiv -1 \pmod{p} \\ x \equiv 1 \pmod{q} \end{cases}$$

Note that if  $x$  is a solution to one of these, then  $x$  is a solution of the other.