Course 311: Michaelmas Term 2005
Part I: Topics in Number Theory

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Contents

1 Topics in Number Theory

1.1 Subgroups of the Integers

A subset S of the set $\mathbb{Z}$ of integers is a *subgroup* of $\mathbb{Z}$ if $0 \in S$, $-x \in S$ and $x + y \in S$ for all $x \in S$ and $y \in S$.

It is easy to see that a non-empty subset S of $\mathbb{Z}$ is a subgroup of $\mathbb{Z}$ if and only if $x - y \in S$ for all $x \in S$ and $y \in S$.

Let m be an integer, and let $m\mathbb{Z} = \{mn : n \in \mathbb{Z}\}$. Then $m\mathbb{Z}$ (the set of integer multiples of m) is a subgroup of $\mathbb{Z}$.

Theorem 1.1 *Let S be a subgroup of $\mathbb{Z}$. Then $S = m\mathbb{Z}$ for some non-negative integer m.*

Proof If $S = \{0\}$ then $S = m\mathbb{Z}$ with $m = 0$. Suppose that $S \neq \{0\}$. Then S contains a non-zero integer, and therefore S contains a positive integer (since $-x \in S$ for all $x \in S$). Let m be the smallest positive integer belonging to S. A positive integer n belonging to S can be written in the form $n = qm + r$, where q is a positive integer and r is an integer satisfying $0 \leq r < m$. Then $qm \in S$ (because $qm = m + m + \cdots + m$). But then $r \in S$, since $r = n - qm$. It follows that $r = 0$, since m is the smallest positive integer in S. Therefore $n = qm$, and thus $n \in m\mathbb{Z}$. It follows that $S = m\mathbb{Z}$, as required. ∎

1.2 Greatest Common Divisors

Definition Let $a_1, a_2, \ldots, a_r$ be integers, not all zero. A *common divisor* of $a_1, a_2, \ldots, a_r$ is an integer that divides each of $a_1, a_2, \ldots, a_r$. The *greatest common divisor* of $a_1, a_2, \ldots, a_r$ is the greatest positive integer that divides each of $a_1, a_2, \ldots, a_r$. The greatest common divisor of $a_1, a_2, \ldots, a_r$ is denoted by $(a_1, a_2, \ldots, a_r)$.

Theorem 1.2 *Let $a_1, a_2, \ldots, a_r$ be integers, not all zero. Then there exist integers $u_1, u_2, \ldots, u_r$ such that*

$$(a_1, a_2, \ldots, a_r) = u_1 a_1 + u_2 a_2 + \cdots + u_r a_r.$$

where $(a_1, a_2, \ldots, a_r)$ is the greatest common divisor of $a_1, a_2, \ldots, a_r$.

Proof Let S be the set of all integers that are of the form

$$n_1 a_1 + n_2 a_2 + \cdots + n_r a_r$$

for some $n_1, n_2, \ldots, n_r \in \mathbb{Z}$. Then S is a subgroup of $\mathbb{Z}$. It follows that $S = m\mathbb{Z}$ for some non-negative integer m (Theorem 1.1). Then m is a common divisor of $a_1, a_2, \ldots, a_r$, (since $a_i \in S$ for $i = 1, 2, \ldots, r$). Moreover any common divisor of $a_1, a_2, \ldots, a_r$ is a divisor of each element of S and is therefore a divisor of m. It follows that m is the greatest common divisor of $a_1, a_2, \ldots, a_r$. But $m \in S$, and therefore there exist integers $u_1, u_2, \ldots, u_r$ such that

$$(a_1, a_2, \ldots, a_r) = u_1 a_1 + u_2 a_2 + \cdots + u_r a_r,$$

as required. ∎

Definition Let $a_1, a_2, \ldots, a_r$ be integers, not all zero. If the greatest common divisor of $a_1, a_2, \ldots, a_r$ is 1 then these integers are said to be *coprime*. If integers a and b are coprime then a is said to be coprime to b. (Thus a is coprime to b if and only if b is coprime to a.)

Corollary 1.3 *Let $a_1, a_2, \ldots, a_r$ be integers, not all zero, Then $a_1, a_2, \ldots, a_r$ are coprime if and only if there exist integers $u_1, u_2, \ldots, u_r$ such that*

$$1 = u_1 a_1 + u_2 a_2 + \cdots + u_r a_r.$$

Proof If $a_1, a_2, \ldots, a_r$ are coprime then the existence of the required integers $u_1, u_2, \ldots, u_r$ follows from Theorem 1.2. On the other hand, if there exist integers $u_1, u_2, \ldots, u_r$ with the required property then any common divisor of $a_1, a_2, \ldots, a_r$ must be a divisor of 1, and therefore $a_1, a_2, \ldots, a_r$ must be coprime. ∎

1.3 The Euclidean Algorithm

Let a and b be positive integers with $a > b$. Let $r_0 = a$ and $r_1 = b$. If b does not divide a then let r_2 be the remainder on dividing a by b. Then $a = q_1 b + r_2$, where q_1 and r_2 are positive integers and $0 < r_2 < b$. If r_2 does not divide b then let r_3 be the remainder on dividing b by r_2. Then $b = q_2 r_2 + r_3$, where q_2 and r_3 are positive integers and $0 < r_3 < r_2$. If r_3 does not divide r_2 then let r_4 be the remainder on dividing r_2 by r_3. Then $r_2 = q_3 r_3 + r_4$, where q_3 and r_4 are positive integers and $0 < r_4 < r_3$. Continuing in this fashion, we construct positive integers $r_0, r_1, \ldots, r_n$ such that $r_0 = a$, $r_1 = b$ and r_i is the remainder on dividing r_{i-2} by r_{i-1} for $i = 2, 3, \ldots, n$. Then $r_{i-2} = q_{i-1} r_{i-1} + r_i$, where q_{i-1} and r_i are positive integers and $0 < r_i < r_{i-1}$. The algorithm for constructing the positive integers $r_0, r_1, \ldots, r_n$ terminates when r_n divides r_{n-1}. Then $r_{n-1} = q_n r_n$ for some positive integer q_n. (The algorithm must clearly terminate in a finite number of steps, since $r_0 > r_1 > r_2 > \cdots > r_n$.) We claim that r_n is the greatest common divisor of a and b.

Any divisor of r_n is a divisor of r_{n-1}, because $r_{n-1} = q_n r_n$. Moreover if $2 \leq i \leq n$ then any common divisor of r_i and r_{i-1} is a divisor of r_{i-2}, because $r_{i-2} = q_{i-1} r_{i-1} + r_i$. If follows that every divisor of r_n is a divisor of all the integers $r_0, r_1, \ldots, r_n$. In particular, any divisor of r_n is a common divisor of a and b. In particular, r_n is itself a common divisor of a and b.

If $2 \leq i \leq n$ then any common divisor of r_{i-2} and r_{i-1} is a divisor of r_i, because $r_i = r_{i-2} - q_{i-1} r_{i-1}$. It follows that every common divisor of a and b is a divisor of all the integers $r_0, r_1, \ldots, r_n$. In particular any common divisor of a and b is a divisor of r_n. It follows that r_n is the greatest common divisor of a and b.

There exist integers u_i and v_i such that $r_i = u_i a + v_i b$ for $i = 1, 2, \ldots, n$. Indeed $u_i = u_{i-2} - q_{i-1} u_{i-1}$ and $v_i = v_{i-2} - q_{i-1} v_{i-1}$ for each integer i between 2 and n, where $u_0 = 1$, $v_0 = 0$, $u_1 = 0$ and $v_1 = 1$. In particular $r_n = u_n a + v_n b$.

The algorithm described above for calculating the greatest common divisor (a, b) of two positive integers a and b is referred to as the *Euclidean algorithm*. It also enables one to calculate integers u and v such that $(a, b) = ua + vb$.

Example We calculate the greatest common divisor of 425 and 119. Now

$$\begin{aligned} 425 &= 3 \times 119 + 68 \\ 119 &= 68 + 51 \\ 68 &= 51 + 17 \\ 51 &= 3 \times 17. \end{aligned}$$

It follows that 17 is the greatest common divisor of 425 and 119. Moreover

$$\begin{aligned} 17 &= 68 - 51 = 68 - (119 - 68) \\ &= 2 \times 68 - 119 = 2 \times (425 - 3 \times 119) - 119 \\ &= 2 \times 425 - 7 \times 119. \end{aligned}$$

1.4 Prime Numbers

Definition A *prime number* is an integer p greater than one with the property that 1 and p are the only positive integers that divide p.

Let p be a prime number, and let x be an integer. Then the greatest common divisor (p, x) of p and x is a divisor of p, and therefore either $(p, x) = p$ or else $(p, x) = 1$. It follows that either x is divisible by p or else x is coprime to p.

Theorem 1.4 *Let p be a prime number, and let x and y be integers. If p divides xy then either p divides x or else p divides y.*

Proof Suppose that p divides xy but p does not divide x. Then p and x are coprime, and hence there exist integers u and v such that $1 = up + vx$ (Corollary 1.3). Then $y = upy + vxy$. It then follows that p divides y, as required. ∎

Corollary 1.5 *Let p be a prime number. If p divides a product of integers then p divides at least one of the factors of the product.*

Proof Let $a_1, a_2, \ldots, a_k$ be integers, where $k > 1$. Suppose that p divides $a_1 a_2 \cdots a_k$. Then either p divides a_k or else p divides $a_1 a_2 \cdots a_{k-1}$. The required result therefore follows by induction on the number k of factors in the product. ∎

1.5 The Fundamental Theorem of Arithmetic

Lemma 1.6 *Every integer greater than one is a prime number or factors as a product of prime numbers.*

Proof Let n be an integer greater than one. Suppose that every integer m satisfying $1 < m < n$ is a prime number or factors as a product of prime numbers. If n is not a prime number then $n = ab$ for some integers a and b satisfying $1 < a < n$ and $1 < b < n$. Then a and b are prime numbers or products of prime numbers. Thus if n is not itself a prime number then n must be a product of prime numbers. The required result therefore follows by induction on n. ∎

An integer greater than one that is not a prime number is said to be a *composite number*.

Let n be an composite number. We say that n factors uniquely as a product of prime numbers if, given prime numbers $p_1, p_2, \ldots, p_r$ and $q_1, q_2, \ldots, q_s$ such that

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

the number of times a prime number occurs in the list $p_1, p_2, \ldots, p_r$ is equal to the number of times it occurs in the list $q_1, q_2, \ldots, q_s$. (Note that this implies that $r = s$.)

Theorem 1.7 (The Fundamental Theorem of Arithmetic) *Every composite number greater than one factors uniquely as a product of prime numbers.*

Proof Let n be a composite number greater than one. Suppose that every composite number greater than one and less than n factors uniquely as a product of prime numbers. We show that n then factors uniquely as a product of prime numbers. Suppose therefore that

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

where $p_1, p_2, \ldots, p_r$ and $q_1, q_2, \ldots, q_s$ are prime numbers, $p_1 \leq p_2 \leq \cdots \leq p_r$ and $q_1 \leq q_2 \leq \cdots \leq q_s$. We must prove that $r = s$ and $p_i = q_i$ for all integers i between 1 and r.

Let p be the smallest prime number that divides n. If a prime number divides a product of integers then it must divide at least one of the factors (Corollary 1.5). It follows that p must divide p_i and thus $p = p_i$ for some integer i between 1 and r. But then $p = p_1$, since p_1 is the smallest of the prime numbers $p_1, p_2, \ldots, p_r$. Similarly $p = q_1$. Therefore $p = p_1 = q_1$. Let $m = n/p$. Then

$$m = p_2 p_3 \cdots p_r = q_2 q_3 \cdots q_s.$$

But then $r = s$ and $p_i = q_i$ for all integers i between 2 and r, because every composite number greater than one and less than n factors uniquely as a product of prime numbers. It follows that n factors uniquely as a product of prime numbers. The required result now follows by induction on n. (We have shown that if all composite numbers m satisfying $1 < m < n$ factor uniquely as a product of prime numbers, then so do all composite numbers m satisfying $1 < m < n + 1$.) ∎

1.6 The Infinitude of Primes

Theorem 1.8 (Euclid) *The number of prime numbers is infinite.*

Proof Let $p_1, p_2, \ldots, p_r$ be prime numbers, let $m = p_1 p_2 \cdots p_r + 1$. Now p_i does not divide m for $i = 1, 2, \ldots, r$, since if p_i were to divide m then it would divide $m - p_1 p_2 \cdots p_r$ and thus would divide 1. Let p be a prime factor of m. Then p must be distinct from $p_1, p_2, \ldots, p_r$. Thus no finite set $\{p_1, p_2, \ldots, p_r\}$ of prime numbers can include all prime numbers. ∎

1.7 Congruences

Let m be a positive integer. Integers x and y are said to be *congruent* modulo m if $x - y$ is divisible by m. If x and y are congruent modulo m then we denote this by writing $x \equiv y \pmod{m}$.

The *congruence class* of an integer x modulo m is the set of all integers that are congruent to x modulo m.

Let x, y and z be integers. Then $x \equiv x \pmod{m}$. Also $x \equiv y \pmod{m}$ if and only if $y \equiv x \pmod{m}$. If $x \equiv y \pmod{m}$ and $y \equiv z \pmod{m}$ then $x \equiv z \pmod{m}$. Thus congruence modulo m is an equivalence relation on the set of integers.

Lemma 1.9 *Let m be a positive integer, and let x, x', y and y' be integers. Suppose that $x \equiv x' \pmod{m}$ and $y \equiv y' \pmod{m}$. Then $x + y \equiv x' + y' \pmod{m}$ and $xy \equiv x'y' \pmod{m}$.*

Proof The result follows immediately from the identities

$$\begin{aligned} (x + y) - (x' + y') &= (x - x') + (y - y'), \\ xy - x'y' &= (x - x')y + x'(y - y'). \quad \blacksquare \end{aligned}$$

Lemma 1.10 *Let x, y and m be integers with $m \neq 0$. Suppose that m divides xy and that m and x are coprime. Then m divides y.*

Proof There exist integers a and b such that $1 = am + bx$, since m and x are coprime (Corollary 1.3). Then $y = amy + bxy$, and m divides xy, and therefore m divides y, as required. $\blacksquare$

Lemma 1.11 *Let m be a positive integer, and let a, x and y be integers with $ax \equiv ay \pmod{m}$. Suppose that m and a are coprime. Then $x \equiv y \pmod{m}$.*

Proof If $ax \equiv ay \pmod{m}$ then $a(x - y)$ is divisible by m. But m and a are coprime. It therefore follows from Lemma 1.10 that $x - y$ is divisible by m, and thus $x \equiv y \pmod{m}$, as required. $\blacksquare$

Lemma 1.12 *Let x and m be non-zero integers. Suppose that x is coprime to m. Then there exists an integer y such that $xy \equiv 1 \pmod{m}$. Moreover y is coprime to m.*

Proof There exist integers y and k such that $xy + mk = 1$, since x and m are coprime (Corollary 1.3). Then $xy \equiv 1 \pmod{m}$. Moreover any common divisor of y and m must divide xy and therefore must divide 1. Thus y is coprime to m, as required. $\blacksquare$

Lemma 1.13 *Let m be a positive integer, and let a and b be integers, where a is coprime to m. Then there exist integers x that satisfy the congruence $ax \equiv b \pmod{m}$. Moreover if x and x' are integers such that $ax \equiv b \pmod{m}$ and $ax' \equiv b \pmod{m}$ then $x \equiv x' \pmod{m}$.*

Proof There exists an integer c such that $ac \equiv 1 \pmod{m}$, since a is coprime to m (Lemma 1.12). Then $ax \equiv b \pmod{m}$ if and only if $x \equiv cb \pmod{m}$. The result follows. ∎

Lemma 1.14 *Let $a_1, a_2, \ldots, a_r$ be integers, and let x be an integer that is coprime to a_i for $i = 1, 2, \ldots, r$. Then x is coprime to the product $a_1 a_2 \cdots a_r$ of the integers $a_1, a_2, \ldots, a_r$.*

Proof Let p be a prime number which divides the product $a_1 a_2 \cdots a_r$. Then p divides one of the factors $a_1, a_2, \ldots, a_r$ (Corollary 1.5). It follows that p cannot divide x, since x and a_i are coprime for $i = 1, 2, \ldots, r$. Thus no prime number is a common divisor of x and the product $a_1 a_2 \cdots a_r$. It follows that the greatest common divisor of x and $a_1 a_2 \cdots a_r$ is 1, since this greatest common divisor cannot have any prime factors. Thus x and $a_1 a_2 \cdots a_r$ are coprime, as required. ∎

Let m be a positive integer. For each integer x, let $[x]$ denote the congruence class of x modulo m. If x, x', y and y' are integers and if $x \equiv x' \pmod{m}$ and $y \equiv y' \pmod{m}$ then $xy \equiv x'y' \pmod{m}$. It follows that there is a well-defined operation of multiplication defined on congruence classes of integers modulo m, where $[x][y] = [xy]$ for all integers x and y. This operation is commutative and associative, and $[x][1] = [x]$ for all integers x. If x is an integer coprime to m, then it follows from Lemma 1.12 that there exists an integer y coprime to m such that $xy \equiv 1 \pmod{m}$. Then $[x][y] = [1]$. Therefore the set $\mathbb{Z}_m^*$ of congruence classes modulo m of integers coprime to m is an Abelian group (with multiplication of congruence classes defined as above).

1.8 The Chinese Remainder Theorem

Let I be a set of integers. The integers belonging to I are said to be *pairwise coprime* if any two distinct integers belonging to I are coprime.

Proposition 1.15 *Let $m_1, m_2, \ldots, m_r$ be non-zero integers that are pairwise coprime. Let x be an integer that is divisible by m_i for $i = 1, 2, \ldots, r$. Then x is divisible by the product $m_1 m_2 \cdots m_r$ of the integers $m_1, m_2, \ldots, m_r$.*

Proof For each integer k between 1 and r let P_k be the product of the integers m_i with $1 \leq i \leq k$. Then $P_1 = m_1$ and $P_k = P_{k-1} m_k$ for $k = 2, 3, \ldots, r$. Let x be a positive integer that is divisible by m_i for $i = 1, 2, \ldots, r$. We must show that P_r divides x. Suppose that P_{k-1} divides x for some integer k between 2 and r. Let $y = x/P_{k-1}$. Then m_k and P_{k-1} are coprime

(Lemma 1.14) and m_k divides $P_{k-1}y$. It follows from Lemma 1.10 that m_k divides y. But then P_k divides x, since $P_k = P_{k-1}m_k$ and $x = P_{k-1}y$. On successively applying this result with $k = 2, 3, \ldots, r$ we conclude that P_r divides x, as required. ∎

Theorem 1.16 (Chinese Remainder Theorem) *Let $m_1, m_2, \ldots, m_r$ be pairwise coprime positive integers. Then, given any integers $x_1, x_2, \ldots, x_r$, there exists an integer z such that $z \equiv x_i \pmod{m_i}$ for $i = 1, 2, \ldots, r$. Moreover if z' is any integer satisfying $z' \equiv x_i \pmod{m_i}$ for $i = 1, 2, \ldots, r$ then $z' \equiv z \pmod{m}$, where $m = m_1 m_2 \cdots m_r$.*

Proof Let $m = m_1 m_2 \cdots m_r$, and let $s_i = m/m_i$ for $i = 1, 2, \ldots, r$. Note that s_i is the product of the integers m_j with $j \neq i$, and is thus a product of integers coprime to m_i. It follows from Lemma 1.14 that m_i and s_i are coprime for $i = 1, 2, \ldots, r$. Therefore there exist integers a_i and b_i such that $a_i m_i + b_i s_i = 1$ for $i = 1, 2, \ldots, r$ (Corollary 1.3). Let $u_i = b_i s_i$ for $i = 1, 2, \ldots, r$. Then $u_i \equiv 1 \pmod{m_i}$, and $u_i \equiv 0 \pmod{m_j}$ when $j \neq i$. Thus if

$$z = x_1 u_1 + x_2 u_2 + \cdots x_r u_r$$

then $z \equiv x_i \pmod{m_i}$ for $i = 1, 2, \ldots, r$.

Now let z' be an integer with $z' \equiv x_i \pmod{m_i}$ for $i = 1, 2, \ldots, r$. Then $z' - z$ is divisible by m_i for $i = 1, 2, \ldots, r$. It follows from Proposition 1.15 that $z' - z$ is divisible by the product m of the integers $m_1, m_2, \ldots, m_r$. Then $z' \equiv z \pmod{m}$, as required. ∎

1.9 The Euler Totient Function

Let n be a positive integer. We define $\varphi(n)$ to be the number of integers x satisfying $0 \leq x < n$ that are coprime to n. The function φ on the set of positive integers is referred to as the *Euler totient function*.

Every integer (including zero) is coprime to 1, and therefore $\varphi(1) = 1$.

Let p be a prime number. Then $\varphi(p) = p - 1$, since every positive integer less than p is coprime to p. Moreover $\varphi(p^k) = p^k - p^{k-1}$ for all positive integers k, since there are p^{k-1} integers x satisfying $0 \leq x < p^k$ that are divisible by p, and the integers coprime to p^k are those that are not divisible by p.

Theorem 1.17 *Let m_1 and m_2 be positive integers. Suppose that m_1 and m_2 are coprime. Then $\varphi(m_1 m_2) = \varphi(m_1)\varphi(m_2)$.*

Proof Let x be an integer satisfying $0 \leq x < m_1$ that is coprime to m_1, and let y be an integer satisfying $0 \leq y < m_2$ that is coprime to m_2. It follows from the Chinese Remainder Theorem (Theorem 1.16) that there exists exactly one integer z satisfying $0 \leq z < m_1 m_2$ such that $z \equiv x \pmod{m_1}$ and $z \equiv y \pmod{m_2}$. Moreover z must then be coprime to m_1 and to m_2, and must therefore be coprime to $m_1 m_2$. Thus every integer z satisfing $0 \leq z < m_1 m_2$ that is coprime to $m_1 m_2$ is uniquely determined by its congruence classes modulo m_1 and m_2, and the congruence classes of z modulo m_1 and m_2 contain integers coprime to m_1 and m_2 respectively. Thus the number $\varphi(m_1 m_2)$ of integers z satisfying $0 \leq z < m_1 m_2$ that are coprime to $m_1 m_2$ is equal to $\varphi(m_1)\varphi(m_2)$, since $\varphi(m_1)$ is the number of integers x satisfying $0 \leq x < m_1$ that are coprime to m_1 and $\varphi(m_2)$ is the number of integers y satisfying $0 \leq y < m_2$ that are coprime to m_2. ∎

Corollary 1.18 *$\varphi(n) = n \prod_{p|n} \left(1 - \dfrac{1}{p}\right)$, for all positive integers n, where $\prod_{p|n} \left(1 - \dfrac{1}{p}\right)$ denotes the product of $1 - \dfrac{1}{p}$ taken over all prime numbers p that divide n.*

Proof Let $n = p_1^{k_1} p_2^{k_2} \cdots p_m^{k_m}$, where $p_1, p_2, \ldots, p_m$ are prime numbers and $k_1, k_2, \ldots, k_m$ are positive integers. Then $\varphi(n) = \varphi(p_1^{k_1})\varphi(p_2^{k_2}) \cdots \varphi(p_m^{k_m})$, and $\varphi(p_i^{k_i}) = p_i^{k_i}(1 - (1/p_i))$ for $i = 1, 2, \ldots, m$. Thus $\varphi(n) = n \prod_{i=1}^{m} \left(1 - \dfrac{1}{p_i}\right)$, as required. ∎

Let f be any function defined on the set of positive integers, and let n be a positive integer. We denote the sum of the values of $f(d)$ over all divisors d of n by $\sum_{d|n} f(d)$.

Lemma 1.19 *Let n be a positive integer. Then $\sum_{d|n} \varphi(d) = n$.*

Proof If x is an integer satisfying $0 \leq x < n$ then $(x, n) = n/d$ for some divisor d of n. It follows that $n = \sum_{d|n} n_d$, where n_d is the number of integers x satisfying $0 \leq x < n$ for which $(x, n) = n/d$. Thus it suffices to show that $n_d = \varphi(d)$ for each divisor d of n.

Let d be a divisor of n, and let $a = n/d$. Given any integer x satisfying $0 \leq x < n$ that is divisible by a, there exists an integer y satisfying $0 \leq y < d$

such that $x = ay$. Then (x, n) is a multiple of a. Moreover a multiple ae of a divides both x and n if and only if e divides both y and d. Therefore $(x, n) = a(y, d)$. It follows that the integers x satisfying $0 \leq x < n$ for which $(x, n) = a$ are those of the form ay, where y is an integer, $0 \leq y < d$ and $(y, d) = 1$. It follows that there are exactly $\varphi(d)$ integers x satisfying $0 \leq x < n$ for which $(x, n) = n/d$, and thus $n_d = \varphi(d)$ and $n = \sum_{d|n} \varphi(d)$, as required. ∎

1.10 The Theorems of Fermat, Wilson and Euler

Theorem 1.20 (Fermat) *Let p be a prime number. Then $x^p \equiv x \pmod{p}$ for all integers x. Moreover if x is coprime to p then $x^{p-1} \equiv 1 \pmod{p}$.*

We shall give three proofs of this theorem below.

Lemma 1.21 *Let p be a prime number. Then the binomial coefficient $\binom{p}{k}$ is divisible by p for all integers k satisfying $0 < k < p$.*

Proof The binomial coefficient is given by the formula $\binom{p}{k} = \dfrac{p!}{(p-k)!k!}$. Thus if $0 < k < p$ then $\binom{p}{k} = \dfrac{pm}{k!}$, where $m = \dfrac{(p-1)!}{(p-k)!}$. Thus if $0 < k < p$ then $k!$ divides pm. Also $k!$ is coprime to p. It follows that $k!$ divides m (Lemma 1.10), and therefore the binomial coefficient $\binom{p}{k}$ is a multiple of p. ∎

First Proof of Theorem 1.20 Let p be prime number. Then

$$(x+1)^p = \sum_{k=0}^{p} \binom{p}{k} x^k.$$

It then follows from Lemma 1.21 that $(x+1)^p \equiv x^p + 1 \pmod{p}$. Thus if $f(x) = x^p - x$ then $f(x+1) \equiv f(x) \pmod{p}$ for all integers x, since $f(x+1) - f(x) = (x+1)^p - x^p - 1$. But $f(0) \equiv 0 \pmod{p}$. It follows by induction on $|x|$ that $f(x) \equiv 0 \pmod{p}$ for all integers x. Thus $x^p \equiv x \pmod{p}$ for all integers x. Moreover if x is coprime to p then it follows from Lemma 1.11 that $x^{p-1} \equiv 1 \pmod{p}$, as required. ∎

Second Proof of Theorem 1.20 Let x be an integer. If x is divisible by p then $x \equiv 0 \pmod{p}$ and $x^p \equiv 0 \pmod{p}$.

Suppose that x is coprime to p. If j is an integer satisfying $1 \leq j \leq p-1$ then j is coprime to p and hence xj is coprime to p. It follows that there exists a unique integer u_j such that $1 \leq u_j \leq p-1$ and $xj \equiv u_j \pmod{p}$. If j and k are integers between 1 and $p-1$ and if $j \neq k$ then $u_j \neq u_k$. It follows that each integer between 1 and $p-1$ occurs exactly once in the list $u_1, u_2, \ldots, u_{p-1}$, and therefore $u_1 u_2 \cdots u_{p-1} = (p-1)!$. Thus if we multiply together the left hand sides and right hand sides of the congruences $xj \equiv u_j \pmod{p}$ for $j = 1, 2, \ldots, p-1$ we obtain the congruence $x^{p-1}(p-1)! \equiv (p-1)! \pmod{p}$. But then $x^{p-1} \equiv 1 \pmod{p}$ by Lemma 1.11, since $(p-1)!$ is coprime to p. But then $x^p \equiv x \pmod{p}$, as required. ∎

Third Proof of Theorem 1.20 Let p be a prime number. The congruence classes modulo p of integers coprime to p constitute a group of order $p-1$, where the group operation is multiplication of congruence classes. Now it follows from Lagrange's Theorem that that order of any element of a finite group divides the order of the group. If we apply this result to the group of congruence classes modulo p of integers coprime to p we find that if an integer x is not divisible by p then $x^{p-1} \equiv 1 \pmod{p}$. It follows that $x^p \equiv x \pmod{p}$ for all integers x that are not divisible by p. This congruence also holds for all integers x that are divisible by p. ∎

Theorem 1.22 (Wilson's Theorem) $(p-1)!+1$ *is divisible by* p *for all prime numbers* p.

Proof Let p be a prime number. If x is an integer satisfying $x^2 \equiv 1 \pmod{p}$ then p divides $(x-1)(x+1)$ and hence either p divides either $x-1$ or $x+1$. Thus if $1 \leq x \leq p-1$ and $x^2 \equiv 1 \pmod{p}$ then either $x = 1$ or $x = p-1$.

For each integer x satisfying $1 \leq x \leq p-1$, there exists exactly one integer y satisfying $1 \leq y \leq p-1$ such that $xy \equiv 1 \pmod{p}$. Moreover $y \neq x$ when $2 \leq x \leq p-2$. It follows that $(p-2)!$ is a product of numbers of the form xy, where x and y are distinct integers between 2 and $p-2$ and $xy \equiv 1 \pmod{p}$. It follows that $(p-2)! \equiv 1 \pmod{p}$. But then $(p-1)! \equiv p-1 \pmod{p}$, and hence $(p-1)!+1 \equiv 0 \pmod{p}$, as required. ∎

The following theorem of Euler generalizes Fermat's Theorem (Theorem 1.20).

Theorem 1.23 (Euler) *Let* m *be a positive integer, and let* x *be an integer coprime to* m*. Then* $x^{\varphi(m)} \equiv 1 \pmod{m}$.

First Proof of Theorem 1.23 The result is trivially true when $m = 1$. Suppose that $m > 1$. Let I be the set of all positive integers less than m that are coprime to m. Then $\varphi(m)$ is by definition the number of integers in I. If y is an integer coprime to m then so is xy. It follows that, to each integer j in I there exists a unique integer u_j in I such that $xj \equiv u_j \pmod{m}$. Moreover if $j \in I$ and $k \in I$ and $j \neq k$ then $u_j \not\equiv u_k$. Therefore $I = \{u_j : j \in I\}$. Thus if we multiply the left hand sides and right hand sides of the congruences $xj \equiv u_j \pmod{m}$ for all $j \in I$ we obtain the congruence $x^{\varphi(m)}z \equiv z \pmod{m}$, where z is the product of all the integers in I. But z is coprime to m, since a product of integers coprime to m is itself coprime to m. It follows from Lemma 1.11 that $x^{\varphi(m)} \equiv 1 \pmod{m}$, as required. ∎

2nd Proof of Theorem 1.23 Let m be a positive integer. Then the congruence classes modulo m of integers coprime to m constitute a group of order $\varphi(m)$, where the group operation is multiplication of congruence classes. Now it follows from Lagrange's Theorem that that order of any element of a finite group divides the order of the group. If we apply this result to the group of congruence classes modulo m of integers coprime to m we find that $x^{\varphi(m)} \equiv 1 \pmod{m}$, as required. ∎

1.11 Solutions of Polynomial Congruences

Let f be a polynomial with integer coefficients, and let m be a positive integer. If x and x' are integers, and if $x \equiv x' \pmod{m}$, then $f(x) \equiv f(x') \pmod{m}$. It follows that the set consisting of those integers x which satisfy the congruence $f(x) \equiv 0 \pmod{m}$ is a union of congruence classes modulo m. The *number of solutions modulo m* of the congruence $f(x) \equiv 0 \pmod{m}$ is defined to be the number of congruence classes of integers modulo m such that an integer x satisfies the congruence $f(x) \equiv 0 \pmod{m}$ if and only if it belongs to one of those congruence classes. Thus a congruence $f(x) \equiv 0 \pmod{m}$ has n solutions modulo m if and only if there exist n integers $a_1, a_2, \ldots, a_n$ satisfying the congruence such that every solution of the congruence $f(x) \equiv 0 \pmod{m}$ is congruent modulo m to exactly one of the integers $a_1, a_2, \ldots, a_n$.

Note that the number of solutions of the congruence $f(x) \equiv 0 \pmod{m}$ is equal to the number of integers x satisfying $0 \leq x < m$ for which $f(x) \equiv 0 \pmod{m}$. This follows immediately from the fact that each congruence class of integers modulo m contains exactly one integer x satisfying $0 \leq x < m$.

Theorem 1.24 *Let f be a polynomial with integer coefficients, and let p be a prime number. Suppose that the coefficients of f are not all divisible by p.*

Then the number of solutions modulo p of the congruence $f(x) \equiv 0 \pmod{p}$ is at most the degree of the polynomial f.

Proof The result is clearly true when f is a constant polynomial. We can prove the result for non-constant polynomials by induction on the degree of the polynomial.

First we observe that, given any integer a, there exists a polynomial g with integer coefficients such that $f(x) = f(a) + (x - a)g(x)$. Indeed $f(y + a)$ is a polynomial in y with integer coefficients, and therefore $f(y+a) = f(a)+yh(y)$ for some polynomial h with integer coefficients. Thus if $g(x) = h(x-a)$ then g is a polynomial with integer coefficients and $f(x) = f(a) + (x - a)g(x)$.

Suppose that $f(a) \equiv 0 \pmod{p}$ and $f(b) \equiv 0 \pmod{p}$. Let $f(x) = f(a) + (x - a)g(x)$, where g is a polynomial with integer coefficients. The coefficients of f are not all divisible by p, but $f(a)$ is divisible by p, and therefore the coefficients of g cannot all be divisible by p.

Now $f(a)$ and $f(b)$ are both divisible by the prime number p, and therefore $(b-a)g(b)$ is divisible by p. But a prime number divides a product of integers if and only if it divides one of the factors. Therefore either $b - a$ is divisible by p or else $g(b)$ is divisible by p. Thus either $b \equiv a \pmod{p}$ or else $g(b) \equiv 0 \pmod{p}$. The required result now follows easily by induction on the degree of the polynomial f. ∎

1.12 Primitive Roots

Lemma 1.25 *Let m be a positive integer, and let x be an integer coprime to m. Then there exists a positive integer n such that $x^n \equiv 1 \pmod{m}$.*

Proof There are only finitely many congruence classes modulo m. Therefore there exist positive integers j and k with $j < k$ such that $x^j \equiv x^k \pmod{m}$. Let $n = k - j$. Then $x^j x^n \equiv x^j \pmod{m}$. But x^j is coprime to m. It follows from Lemma 1.11 that $x^n \equiv 1 \pmod{m}$. ∎

Remark The above lemma also follows directly from Euler's Theorem (Theorem 1.23).

Let m be a positive integer, and let x be an integer coprime to m. The order of the congruence class of x modulo m is by definition the smallest positive integer d such that $x^d \equiv 1 \pmod{m}$.

Lemma 1.26 *Let m be a positive integer, let x be an integer coprime to m, and let j and k be positive integers. Then $x^j \equiv x^k \pmod{m}$ if and only if $j \equiv k \pmod{d}$, where d is the order of the congruence class of x modulo m.*

Proof We may suppose without loss of generality that $j < k$. If $j \equiv k \pmod{d}$ then $k - j$ is divisible by d, and hence $x^{k-j} \equiv 1 \pmod{m}$. But then $x^k \equiv x^j x^{k-j} \equiv x^j \pmod{m}$. Conversely suppose that $x^j \equiv x^k \pmod{m}$ and $j < k$. Then $x^j x^{k-j} \equiv x^j \pmod{m}$. But x^j is coprime to m. It follows from Lemma 1.11 that $x^{k-j} \equiv 1 \pmod{m}$. Thus if $k - j = qd + r$, where q and r are integers and $0 \leq r < d$, then $x^r \equiv 1 \pmod{m}$. But then $r = 0$, since d is the smallest positive integer for which $x^d \equiv 1 \pmod{m}$. Therefore $k - j$ is divisible by d, and thus $j \equiv k \pmod{d}$. ∎

Lemma 1.27 *Let p be a prime number, and let x and y be integers coprime to p. Suppose that the congruence classes of x and y modulo p have the same order. Then there exists a non-negative integer k, coprime to the order of the congruence classes of x and y, such that $y \equiv x^k \pmod{p}$.*

Proof Let d be the order of the congruence class of x modulo p. The solutions of the congruence $x^d \equiv 1 \pmod{p}$ include x^j with $0 \leq j < d$. But the congruence $x^d \equiv 1 \pmod{p}$ has at most d solutions modulo p, since p is prime (Theorem 1.24), and the congruence classes of $1, x, x^2, \ldots, x^{d-1}$ modulo p are distinct (Lemma 1.26). It follows that any solution of the congruence $x^d \equiv 1 \pmod{p}$ is congruent to x^k for some positive integer k. Thus if y is an integer coprime to p whose congruence class is of order d then $y \equiv x^k \pmod{p}$ for some positive integer k. Moreover k is coprime to d, for if e is a common divisor of k and d then $y^{d/e} \equiv x^{d(k/e)} \equiv 1 \pmod{p}$, and hence $e = 1$. ∎

Let m be a positive integer. An integer g is said to be a *primitive root* modulo m if, given any integer x coprime to m, there exists an integer j such that $x \equiv g^j \pmod{m}$.

A primitive root modulo m is necessarily coprime to m. For if g is a primitive root modulo m then there exists an integer n such that $g^n \equiv 1 \pmod{m}$. But then any common divisor of g and m must divide 1, and thus g and m are coprime.

Theorem 1.28 *Let p be a prime number. Then there exists a primitive root modulo p.*

Proof If x is an integer coprime to p then it follows from Fermat's Theorem (Theorem 1.20) that $x^{p-1} \equiv 1 \pmod{p}$. It then follows from Lemma 1.26 that the order of the congruence class of x modulo p divides $p - 1$. For each divisor d of $p-1$, let $\psi(d)$ denote the number of congruence classes modulo p of integers coprime to p that are of order d. Clearly $\displaystyle\sum_{d|p-1} \psi(d) = p - 1$.

Let x be an integer coprime to p whose congruence class is of order d, where d is a divisor of $p-1$. If k is coprime to d then the congruence class of x^k is also of order d, for if $(x^k)^n \equiv 1 \pmod{p}$ then d divides kn and hence d divides n (Lemma 1.10). Let y be an integer coprime to p whose congruence class is also of order d. It follows from Lemma 1.27 that there exists a non-negative integer k coprime to d such that $y \equiv x^k \pmod{p}$. It then follows from Lemma 1.26 that there exists a unique integer k coprime to d such that $0 \leq k < d$ and $y \equiv x^k \pmod{p}$. Thus if there exists at least one integer x coprime to p whose congruence class modulo p is of order d then the congruence classes modulo p of integers coprime to p that are of order d are the congruence classes of x^k for those integers k satisfying $0 \leq k < d$ that are coprime to d. Thus if $\psi(d) > 0$ then $\psi(d) = \varphi(d)$, where $\varphi(d)$ is the number of integers k satisfying $0 \leq k < d$ that are coprime to d.

Now $0 \leq \psi(d) \leq \varphi(d)$ for each divisor d of $p-1$. But $\sum_{d|p-1} \psi(d) = p-1$ and $\sum_{d|p-1} \varphi(d) = p-1$ (Lemma 1.19). Therefore $\psi(d) = \varphi(d)$ for each divisor d of $p-1$. In particular $\psi(p-1) = \varphi(p-1) \geq 1$. Thus there exists an integer g whose congruence class modulo p is of order $p-1$. The congruence classes of $1, g, g^2, \ldots g^{p-2}$ modulo p are then distinct. But there are exactly $p-1$ congruence classes modulo p of integers coprime to p. It follows that any integer that is coprime to p must be congruent to g^j for some non-negative integer j. Thus g is a primitive root modulo p. $\blacksquare$

Corollary 1.29 *Let p be a prime number. Then the group of congruence classes modulo p of integers coprime to p is a cyclic group of order $p-1$.*

Remark It can be shown that there exists a primitive root modulo m if $m = 1$, 2 or 4, if $m = p^k$ or if $m = 2p^k$, where p is some odd prime number and k is a positive integer. In all other cases there is no primitive root modulo m.

1.13 Quadratic Residues

Definition Let p be a prime number, and let x be an integer coprime to p. The integer x is said to be a *quadratic residue* of p if there exists an integer y such that $x \equiv y^2 \pmod{p}$. If x is not a quadratic residue of p then x is said to be a *quadratic non-residue* of p.

Proposition 1.30 *Let p be an odd prime number, and let a, b and c be integers, where a is coprime to p. Then there exist integers x satisfying the* *congruence* $ax^2 + bx + c \equiv 0 \pmod{p}$ *if and only if either* $b^2 - 4ac$ *is a quadratic residue of* p *or else* $b^2 - 4ac \equiv 0 \pmod{p}$.

Proof Let x be an integer. Then $ax^2 + bx + c \equiv 0 \pmod{p}$ if and only if $4a^2x^2 + 4abx + 4ac \equiv 0 \pmod{p}$, since $4a$ is coprime to p (Lemma 1.11). But $4a^2x^2 + 4abx + 4ac = (2ax + b)^2 - (b^2 - 4ac)$. It follows that $ax^2 + bx + c \equiv 0 \pmod{p}$ if and only if $(2ax + b)^2 \equiv b^2 - 4ac \pmod{p}$. Thus if there exist integers x satisfying the congruence $ax^2 + bx + c \equiv 0 \pmod{p}$ then either $b^2 - 4ac$ is a quadratic residue of p or else $b^2 - 4ac \equiv 0 \pmod{p}$. Conversely suppose that either b^2-4ac is a quadratic residue of p or $b^2-4ac \equiv 0 \pmod{p}$. Then there exists an integer y such that $y^2 \equiv b^2 - 4ac \pmod{p}$. Also there exists an integer d such that $2ad \equiv 1 \pmod{p}$, since $2a$ is coprime to p (Lemma 1.12). If $x \equiv d(y - b) \pmod{p}$ then $2ax + b \equiv y \pmod{p}$, and hence $(2ax + b)^2 \equiv b^2 - 4ac \pmod{p}$. But then $ax^2 + bx + c \equiv 0 \pmod{p}$, as required. ∎

Lemma 1.31 *Let* p *be an odd prime number, and let* x *and* y *be integers. Suppose that* $x^2 \equiv y^2 \pmod{p}$. *Then either* $x \equiv y \pmod{p}$ *or else* $x \equiv -y \pmod{p}$.

Proof $x^2 - y^2$ is divisible by p, since $x^2 \equiv y^2 \pmod{p}$. But $x^2 - y^2 = (x - y)(x + y)$, and a prime number divides a product of integers if and only if it divides at least one of the factors. Therefore either $x - y$ is divisible by p or else $x + y$ is divisible by p. Thus either $x \equiv y \pmod{p}$ or else $x \equiv -y \pmod{p}$.

Lemma 1.32 *Let* p *be an odd prime number, and let* $m = (p - 1)/2$. *Then there are exactly* m *congruence classes of integers coprime to* p *that are quadratic residues of* p. *Also there are exactly* m *congruence classes of integers coprime to* p *that are quadratic non-residues of* p.

Proof If i and j are integers between 1 and m, and if $i \neq j$ then $i \not\equiv j \pmod{p}$ and $i \not\equiv -j \pmod{p}$. It follows from Lemma 1.31 that if i and j are integers between 1 and m, and if $i \neq j$ then $i^2 \not\equiv j^2$. Thus the congruence classes of $1^2, 2^2, \ldots, m^2$ modulo p are distinct. But, given any integer x coprime to p, there is an integer i such that $1 \leq i \leq m$ and either $x \equiv i \pmod{p}$ or $x \equiv -i \pmod{p}$, and therefore $x^2 \equiv i^2 \pmod{p}$. Thus every quadratic residue of p is congruent to i^2 for exactly one integer i betweeen 1 and m. Thus there are m congruence classes of quadratic residues of p.

There are $2m$ congruence classes of integers modulo p that are coprime to p. It follows that there are m congruence classes of quadratic non-residues of p, as required. ∎

Theorem 1.33 *Let p be an odd prime number, let R be the set of all integers coprime to p that are quadratic residues of p, and let N be the set of all integers coprime to p that are quadratic non-residues of p. If $x \in R$ and $y \in R$ then $xy \in R$. If $x \in R$ and $y \in N$ then $xy \in N$. If $x \in N$ and $y \in N$ then $xy \in R$.*

Proof Let $m = (p-1)/2$. Then there are exactly m congruence classes of integers coprime to p that are quadratic residues of p. Let these congruence classes be represented by the integers $r_1, r_2, \ldots, r_m$, where $r_i \not\equiv r_j \pmod{p}$ when $i \neq j$. Also there are exactly m congruence classes of integers coprime to p that are quadratic non-residues modulo p.

The product of two quadratic residues of p is itself a quadratic residue of p. Therefore $xy \in R$ for all $x \in R$ and $y \in R$.

Suppose that $x \in R$. Then $xr_i \in R$ for $i = 1, 2, \ldots, m$, and $xr_i \not\equiv xr_j$ when $i \neq j$. It follows that the congruence classes of $xr_1, xr_2, \ldots, xr_m$ are distinct, and consist of quadratic residues of p. But there are exactly m congruence classes of quadratic residues of p. It follows that every quadratic residue of p is congruent to exactly one of the integers $xr_1, xr_2, \ldots, xr_m$. But if $y \in N$ then $y \not\equiv r_i$ and hence $xy \not\equiv xr_i$ for $i = 1, 2, \ldots, m$. It follows that $xy \in N$ for all $x \in R$ and $y \in N$.

Now suppose that $x \in N$. Then $xr_i \in N$ for $i = 1, 2, \ldots, m$, and $xr_i \not\equiv xr_j$ when $i \neq j$. It follows that the congruence classes of $xr_1, xr_2, \ldots, xr_m$ are distinct, and consist of quadratic non-residues modulo p. But there are exactly m congruence classes of quadratic non-residues modulo p. It follows that every quadratic non-residue of p is congruent to exactly one of the integers $xr_1, xr_2, \ldots, xr_m$. But if $y \in N$ then $y \not\equiv r_i$ and hence $xy \not\equiv xr_i$ for $i = 1, 2, \ldots, m$. It follows that $xy \in R$ for all $x \in N$ and $y \in N$. ∎

Let p be an odd prime number. The *Legendre symbol* $\left(\frac{x}{p}\right)$ is defined for integers x as follows: if x is coprime to p and x is a quadratic residue of p then $\left(\frac{x}{p}\right) = +1$; if x is coprime to p and x is a quadratic non-residue of p then $\left(\frac{x}{p}\right) = -1$; if x is divisible by p then $\left(\frac{x}{p}\right) = 0$.

The following result follows directly from Theorem 1.33.

Corollary 1.34 *Let p be an odd prime number. Then*

$$\left(\frac{x}{p}\right)\left(\frac{y}{p}\right) = \left(\frac{xy}{p}\right)$$

for all integers x and y.

Lemma 1.35 (Euler) *Let p be an odd prime number, and let x be an integer coprime to p. Then x is a quadratic residue of p if and only if $x^{(p-1)/2} \equiv 1 \pmod{p}$. Also x is a quadratic non-residue of p if and only if $x^{(p-1)/2} \equiv -1 \pmod{p}$.*

Proof Let $m = (p-1)/2$. If x is a quadratic residue of p then $x \equiv y^2 \pmod{p}$ for some integer y coprime to p. Then $x^m = y^{p-1}$, and $y^{p-1} \equiv 1 \pmod{p}$ by Fermat's Theorem (Theorem 1.20), and thus $x^m \equiv 1 \pmod{p}$.

It follows from Theorem 1.24 that there are at most m congruence classes of integers x satisfying $x^m \equiv 1 \pmod{p}$. However all quadratic residues modulo p satisfy this congruence, and there are exactly m congruence classes of quadratic residues modulo p. It follows that an integer x coprime to p satisfies the congruence $x^m \equiv 1 \pmod{p}$ if and only if x is a quadratic residue of p.

Now let x be a quadratic non-residue of p and let $u = x^m$. Then $u^2 \equiv 1 \pmod{p}$ but $u \not\equiv 1 \pmod{p}$. It follows from Lemma 1.31 that $u \equiv -1 \pmod{p}$. It follows that an integer x coprime to p is a quadratic non-residue of p if and only if $x^m \equiv -1 \pmod{p}$. ∎

Corollary 1.36 *Let p be an odd prime number. Then*

$$x^{(p-1)/2} \equiv \left(\frac{x}{p}\right) \pmod{p}$$

for all integers x.

Proof If x is coprime to p then the result follows from Lemma 1.35. If x is divisible by p then so is $x^{(p-1)/2}$. In that case $x^{(p-1)/2} \equiv 0 \pmod{p}$ and $\left(\frac{x}{p}\right) = 0 \pmod{p}$. ∎

Corollary 1.37 $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$ *for all odd prime numbers p.*

Proof It follows from Corollary 1.36 that $\left(\frac{-1}{p}\right) \equiv (-1)^{(p-1)/2} \pmod{p}$ for all odd prime numbers p. But $\left(\frac{-1}{p}\right) = \pm 1$, by the definition of the Legendre symbol. Therefore $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$, as required. ∎

Remark Let p be an odd prime number. It follows from Theorem 1.28 that there exists a primitive root g modulo p. Moreover the congruence class of

g modulo p is of order $p-1$. It follows that $g^j \equiv g^k \pmod{p}$, where j and k are positive integers, if and only if $j-k$ is divisible by $p-1$. But $p-1$ is even. Thus if $g^j \equiv g^k$ then $j-k$ is even. It follows easily from this that an integer x is a quadratic residue of p if and only if $x \equiv g^k \pmod{p}$ for some even integer k. The results of Theorem 1.33 and Lemma 1.35 follow easily from this fact.

Let p be an odd prime number, and let $m = (p-1)/2$. Then each integer not divisible by p is congruent to exactly one of the integers $\pm 1, \pm 2, \ldots, \pm m$.

The following lemma was proved by Gauss.

Lemma 1.38 *Let p be an odd prime number, let $m = (p-1)/2$, and let x be an integer that is not divisible by p. Then $\left(\dfrac{x}{p}\right) = (-1)^r$, where r is the number of pairs (j, u) of integers satisfying $1 \leq j \leq m$ and $1 \leq u \leq m$ for which $xj \equiv -u \pmod{p}$.*

Proof For each integer j satisfying $1 \leq j \leq m$ there is a unique integer u_j satisfying $1 \leq u_j \leq m$ such that $xj \equiv e_j u_j \pmod{p}$ with $e_j = \pm 1$. Then $e_1 e_2 \cdots e_m = (-1)^r$.

If j and k are integers between 1 and m and if $j \neq k$, then $j \not\equiv k \pmod{p}$ and $j \not\equiv -k \pmod{p}$. But then $xj \not\equiv xk \pmod{p}$ and $xj \not\equiv -xk \pmod{p}$ since x is not divisible by p. Thus if $1 \leq j \leq m$, $1 \leq k \leq m$ and $j \neq k$ then $u_j \neq u_k$. It follows that each integer between 1 and m occurs exactly once in the list $u_1, u_2, \ldots, u_m$, and therefore $u_1 u_2 \cdots u_m = m!$. Thus if we multiply the congruences $xj \equiv e_j u_j \pmod{p}$ for $j = 1, 2, \ldots, m$ we obtain the congruence $x^m m! \equiv (-1)^r m! \pmod{p}$. But $m!$ is not divisible by p, since p is prime and $m < p$. It follows that $x^m \equiv (-1)^r \pmod{p}$. But $x^m \equiv \left(\dfrac{x}{p}\right) \pmod{p}$ by Lemma 1.35. Therefore $\left(\dfrac{x}{p}\right) \equiv (-1)^r \pmod{p}$, and hence $\left(\dfrac{x}{p}\right) = (-1)^r$, as required. ∎

Let n be an odd integer. Then $n = 2k+1$ for some integer k. Then $n^2 = 4(k^2+k)+1$, and k^2+k is an even integer. It follows that if n is an odd integer then $n^2 \equiv 1 \pmod{8}$, and hence $(-1)^{(n^2-1)/8} = \pm 1$.

Theorem 1.39 *Let p be an odd prime number. Then $\left(\dfrac{2}{p}\right) = (-1)^{(p^2-1)/8}$.*

Proof The value of $(-1)^{(p^2-1)/8}$ is determined by the congruence class of p modulo 8. Indeed $(-1)^{(p^2-1)/8} = 1$ when $p \equiv 1 \pmod{8}$ or $p \equiv -1 \pmod{8}$, and $(-1)^{(p^2-1)/8} = -1$ when $p \equiv 3 \pmod{8}$ or $p \equiv -3 \pmod{8}$.

Let $m = (p-1)/2$. It follows from Lemma 1.38 that $\left(\dfrac{2}{p}\right) = (-1)^r$, where r is the number of integers x between 1 and m for which $2x$ is not congruent modulo p to any integer between 1 and m. But the integers x with this property are those for which $m/2 < x \leq m$. Thus $r = m/2$ if m is even, and $r = (m+1)/2$ if m is odd.

If $p \equiv 1 \pmod 8$ then m is divisible by 4 and hence r is even. If $p \equiv 3 \pmod 8$ then $m \equiv 1 \pmod 4$ and hence r is odd. If $p \equiv 5 \pmod 8$ then $m \equiv 2 \pmod 4$ and hence r is odd. If $p \equiv 7 \pmod 8$ then $m \equiv 3 \pmod 4$ and hence r is even. Therefore $\left(\dfrac{2}{p}\right) = 1$ when $p \equiv 1 \pmod 8$ and when $p \equiv 7 \pmod 8$, and $\left(\dfrac{2}{p}\right) = -1$ when $p \equiv 3 \pmod 8$ and $p \equiv 5 \pmod 8$. Thus $\left(\dfrac{2}{p}\right) = (-1)^{(p^2-1)/8}$ for all odd prime numbers p, as required. ∎

1.14 Quadratic Reciprocity

Theorem 1.40 (Quadratic Reciprocity Law) *Let p and q be distinct odd prime numbers. Then*

$$\left(\frac{p}{q}\right)\left(\frac{q}{p}\right) = (-1)^{(p-1)(q-1)/4}$$

Proof Let S be the set of all ordered pairs (x, y) of integers x and y satisfying $1 \leq x \leq m$ and $1 \leq y \leq n$, where $p = 2m+1$ and $q = 2n+1$. We must prove that $\left(\dfrac{p}{q}\right)\left(\dfrac{q}{p}\right) = (-1)^{mn}$.

First we show that $\left(\dfrac{p}{q}\right) = (-1)^a$, where a is the number of pairs (x, y) of integers in S satisfying $-n \leq py - qx \leq -1$. If (x, y) is a pair of integers in S satisfying $-n \leq py - qx \leq -1$, and if $z = qx - py$, then $1 \leq y \leq n$, $1 \leq z \leq n$ and $py \equiv -z \pmod q$. On the other hand, if (y, z) is a pair of integers such that $1 \leq y \leq n$, $1 \leq z \leq n$ and $py \equiv -z \pmod q$ then there is a unique positive integer x such that $z = qx - py$. Moreover $qx = py + z \leq (p+1)n = 2n(m+1)$ and $q > 2n$, and therefore $x < m+1$. It follows that the pair (x, y) of integers is in S, and $-n \leq py - qx \leq -1$. We deduce that the number a of pairs (x, y) of integers in S satisfying $-n \leq py - qx \leq -1$ is equal to the number of pairs (y, z) of integers satisfying $1 \leq y \leq n$, $1 \leq z \leq n$ and $py \equiv -z \pmod q$. It now follows from Lemma 1.38 that $\left(\dfrac{p}{q}\right) = (-1)^a$. Similarly $\left(\dfrac{q}{p}\right) = (-1)^b$, where b is the number of pairs (x, y) in S satisfying $1 \leq py - qx \leq m$.

If x and y are integers satisfying $py - qx = 0$ then x is divisible by p and y is divisible by q. It follows from this that $py - qx \neq 0$ for all pairs (x, y) in S. The total number of pairs (x, y) in S is mn. Therefore $mn = a+b+c+d$, where c is the number of pairs (x, y) in S satisfying $py - qx < -n$ and d is the number of pairs (x, y) in S satisfying $py - qx > m$.

Let (x, y) be a pair of integers in S, and let and let $x' = m + 1 - x$ and $y' = n + 1 - y$. Then the pair (x', y') also belongs to S, and $py' - qx' = m - n - (py - qx)$. It follows that $py - qx > m$ if and only if $py' - qx' < -n$. Thus there is a one-to-one correspondence between pairs (x, y) in S satisfying $py - qx > m$ and pairs (x', y') in S satisfying $py' - qx' < -n$, where $(x', y') = (m+1-x,\, n+1-y)$ and $(x, y) = (m+1-x',\, n+1-y')$. Therefore $c = d$, and thus $mn = a + b + 2c$. But then $(-1)^{mn} = (-1)^a(-1)^b = \left(\frac{p}{q}\right)\left(\frac{q}{p}\right)$, as required. ∎

Corollary 1.41 *Let p and q be distinct odd prime numbers. If $p \equiv 1 \pmod 4$ or $q \equiv 1 \pmod 4$ then $\left(\frac{p}{q}\right) = \left(\frac{q}{p}\right)$. If $p \equiv 3 \pmod 4$ and $q \equiv 3 \pmod 4$ then $\left(\frac{p}{q}\right) = -\left(\frac{q}{p}\right)$.*

Example We wish to determine whether or not 654 is a quadratic residue modulo the prime number 239. Now $654 = 2 \times 239 + 176$ and thus $654 \equiv 176 \pmod{239}$. Also $176 = 16 \times 11$. Therefore

$$\left(\frac{654}{239}\right) = \left(\frac{176}{239}\right) = \left(\frac{16}{239}\right)\left(\frac{11}{239}\right) = \left(\frac{4}{239}\right)^2\left(\frac{11}{239}\right) = \left(\frac{11}{239}\right)$$

But $\left(\frac{11}{239}\right) = -\left(\frac{239}{11}\right)$ by the Law of Quadratic Reciprocity. Also $239 \equiv 8 \pmod{11}$. Therefore

$$\left(\frac{239}{11}\right) = \left(\frac{8}{11}\right) = \left(\frac{2}{11}\right)^3 = (-1)^3 = -1$$

It follows that $\left(\frac{654}{239}\right) = +1$ and thus 654 is a quadratic residue of 239, as required. ∎

1.15 The Jacobi Symbol

Let s be an odd positive integer. If $s > 1$ then $s = p_1 p_2 \cdots p_m$, where $p_1, p_2, \ldots, p_m$ are odd prime numbers. For each integer x we define the *Jacobi* *symbol* $\left(\frac{x}{s}\right)$ by

$$\left(\frac{x}{s}\right) = \prod_{i=1}^{m} \left(\frac{x}{p_i}\right)$$

(i.e., $\left(\frac{x}{s}\right)$ is the product of the Legendre symbols $\left(\frac{x}{p_i}\right)$ for $i = 1, 2, \ldots, m$.) We define $\left(\frac{x}{1}\right) = 1$.

Note that the Jacobi symbol can have the values 0, +1 and −1.

Lemma 1.42 *Let s be an odd positive integer, and let x be an integer. Then $\left(\frac{x}{s}\right) \neq 0$ if and only if x is coprime to s.*

Proof Let $s = p_1 p_2 \cdots p_m$, where $p_1, p_2, \ldots, p_m$ are odd prime numbers. Suppose that x is coprime to s. Then x is coprime to each prime factor of s, and hence $\left(\frac{x}{p_i}\right) = \pm 1$ for $i = 1, 2, \ldots, m$. It follows that $\left(\frac{x}{s}\right) = \pm 1$ and thus $\left(\frac{x}{s}\right) \neq 0$.

Next suppose that x is not coprime to s. Let p be a prime factor of the greatest common divisor of x and s. Then $p = p_i$, and hence $\left(\frac{x}{p_i}\right) = 0$ for some integer i between 1 and m. But then $\left(\frac{x}{s}\right) = 0$. ∎

Lemma 1.43 *Let s be an odd positive integer, and let x and x' be integers. Suppose that $x \equiv x' \pmod{s}$. Then $\left(\frac{x}{s}\right) = \left(\frac{x'}{s}\right)$.*

Proof If $x \equiv x' \pmod{s}$ then $x \equiv x' \pmod{p}$ for each prime factor p of s, and therefore $\left(\frac{x}{p}\right) = \left(\frac{x'}{p}\right)$ for each prime factor of s. Therefore $\left(\frac{x}{s}\right) = \left(\frac{x'}{s}\right)$. ∎

Lemma 1.44 *Let x and y be integers, and let s and t be odd positive integers. Then $\left(\frac{xy}{s}\right) = \left(\frac{x}{s}\right)\left(\frac{y}{s}\right)$ and $\left(\frac{x}{st}\right) = \left(\frac{x}{s}\right)\left(\frac{x}{t}\right)$.*

Proof $\left(\frac{xy}{p}\right) = \left(\frac{x}{p}\right)\left(\frac{y}{p}\right)$ for all prime numbers p (Corollary 1.34). The required result therefore follows from the definition of the Jacobi symbol. ∎

Lemma 1.45 $\left(\frac{x^2}{s}\right) = 1$ *and* $\left(\frac{x}{s^2}\right) = 1$ *for for all odd positive integers s and all integers x that are coprime to s.*

Proof This follows directly from Lemma 1.44 and Lemma 1.42. ∎

Theorem 1.46 $\left(\dfrac{-1}{s}\right) = (-1)^{(s-1)/2}$ *for all odd positive integers* s*.*

Proof Let $f(s) = (-1)^{(s-1)/2}\left(\dfrac{-1}{s}\right)$ for each odd positive integer s. We must prove that $f(s) = 1$ for all odd positive integers s. If s and t are odd positive integers then

$$(st-1) - (s-1) - (t-1) = st - s - t + 1 = (s-1)(t-1)$$

But $(s-1)(t-1)$ is divisible by 4, since s and t are odd positive integers. Therefore $(st-1)/2 \equiv (s-1)/2 + (t-1)/2 \pmod 2$, and hence $(-1)^{(st-1)/2} = (-1)^{(s-1)/2}(-1)^{(t-1)/2}$. It now follows from Lemma 1.44 that $f(st) = f(s)f(t)$ for all odd numbers s and t. But $f(p) = 1$ for all prime numbers p, since $\left(\dfrac{-1}{p}\right) = (-1)^{(p-1)/2}$ (Lemma 1.37). It follows that $f(s) = 1$ for all odd positive integers s, as required. ∎

Theorem 1.47 $\left(\dfrac{2}{s}\right) = (-1)^{(s^2-1)/8}$ *for all odd positive integers* s*.*

Proof Let $g(s) = (-1)^{(s^2-1)/8}\left(\dfrac{2}{s}\right)$ for each odd positive integer s. We must prove that $g(s) = 1$ for all odd positive integers s. If s and t are odd positive integers then

$$(s^2t^2-1) - (s^2-1) - (t^2-1) = s^2t^2 - s^2 - t^2 + 1 = (s^2-1)(t^2-1).$$

But $(s^2-1)(t^2-1)$ is divisible by 64, since $s^2 \equiv 1 \pmod 8$ and $t^2 \equiv 1 \pmod 8$. Therefore $(s^2t^2-1)/8 \equiv (s^2-1)/8 + (t^2-1)/8 \pmod 8$, and hence $(-1)^{(s^2t^2-1)/8} = (-1)^{(s^2-1)/8}(-1)^{(t^2-1)/8}$. It now follows from Lemma 1.44 that $g(st) = g(s)g(t)$ for all odd numbers s and t. But $g(p) = 1$ for all prime numbers p, since $\left(\dfrac{2}{p}\right) = (-1)^{(p^2-1)/8}$ (Lemma 1.39). It follows that $g(s) = 1$ for all odd positive integers, as required. ∎

Theorem 1.48 $\left(\dfrac{s}{t}\right)\left(\dfrac{t}{s}\right) = (-1)^{(s-1)(t-1)/4}$ *for all odd positive integers* s *and* t*.*

Proof Let $h(s,t) = (-1)^{(s-1)(t-1)/4}\left(\dfrac{s}{t}\right)\left(\dfrac{t}{s}\right)$. We must prove that $h(s,t) = 1$ for all odd positive integers s and t. Now $h(s_1s_2,t) = h(s_1,t)h(s_2,t)$ and $h(s,t_1)h(s,t_2) = h(s,t_1t_2)$ for all odd positive integers s, s_1, s_2, t, t_1 and t_2.

Also $h(s,t) = 1$ when s and t are prime numbers by the Law of Quadratic Reciprocity (Theorem 1.40). It follows from this that $h(s,t) = 1$ when s is an odd positive integer and t is a prime number, since any odd positive integer is a product of odd prime numbers. But then $h(s,t) = 1$ for all odd positive integers s and t, as required. ∎

The results proved above can be used to calculate Jacobi symbols, as in the following example.

Example We wish to determine whether or not 442 is a quadratic residue modulo the prime number 751. Now $\left(\dfrac{442}{751}\right) = \left(\dfrac{2}{751}\right)\left(\dfrac{221}{751}\right)$. Also $\left(\dfrac{2}{751}\right) = 1$, since $751 \equiv 7 \pmod 8$ (Theorem 1.39). Also $\left(\dfrac{221}{751}\right) = \left(\dfrac{751}{221}\right)$ (Theorem 1.48), and $751 \equiv 88 \pmod{221}$. Thus

$$\left(\frac{442}{751}\right) = \left(\frac{751}{221}\right) = \left(\frac{88}{221}\right) = \left(\frac{2}{221}\right)^3 \left(\frac{11}{221}\right).$$

Now $\left(\dfrac{2}{221}\right) = -1$, since $221 \equiv 5 \pmod 8$ (Theorem 1.47). Also it follows from Theorem 1.48 that

$$\left(\frac{11}{221}\right) = \left(\frac{221}{11}\right) = \left(\frac{1}{11}\right) = 1,$$

since $221 \equiv 1 \pmod 4$ and $221 \equiv 1 \pmod{11}$. Therefore $\left(\dfrac{442}{751}\right) = -1$, and thus 442 is a quadratic non-residue of 751. The number 221 is not prime, since $221 = 13 \times 17$. Thus the above calculation made use of Jacobi symbols that are not Legendre symbols.