Course 2BA1m: Trinity Term 2007
Section 12: Further Number Theory

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Contents

12 Topics in Number Theory

12.1 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 12.1 *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 9.16) 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 12.2 $\varphi(n) = n \prod_{p|n} \left(1 - \frac{1}{p}\right)$, *for all positive integers* n, *where* $\prod_{p|n} \left(1 - \frac{1}{p}\right)$ *denotes the product of* $1 - \frac{1}{p}$ *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 $\varphi(n) = n \prod_{i=1}^{m} \left(1 - \frac{1}{p_i}\right)$, 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 12.3 *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. ∎

12.2 Euler's Theorem

The following theorem of Euler generalizes Fermat's Theorem (Theorem 9.17).

Theorem 12.4 (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 12.4 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 9.11 that $x^{\varphi(m)} \equiv 1 \pmod{m}$, as required. ∎

2nd Proof of Theorem 12.4 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. ∎

12.3 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 12.5 *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. ∎

12.4 Primitive Roots

Lemma 12.6 *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 9.11 that $x^n \equiv 1 \pmod{m}$. ∎

Remark The above lemma also follows directly from Euler's Theorem (Theorem 12.4).

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 12.7 *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 9.11 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 12.8 *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 12.5), and the congruence classes of $1, x, x^2, \ldots, x^{d-1}$ modulo p are distinct (Lemma 12.7). 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 12.9 *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 9.17) that $x^{p-1} \equiv 1 \pmod{p}$. It then follows from Lemma 12.7 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 $\sum_{d|p-1} \psi(d) = p-1$.

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 9.10). Let y be an integer coprime to p whose congruence class is also of order d. It follows from Lemma 12.8 that there exists a non-negative integer k coprime to d such that $y \equiv x^k \pmod{p}$. It then follows from Lemma 12.7 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 12.3). 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. ∎

Corollary 12.10 *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.

12.5 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 12.11 *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 9.11). 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 9.12). 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 12.12 *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 12.13 *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 12.12 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 12.14 *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 12.14.

Corollary 12.15 *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 12.16 (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 9.17), and thus $x^m \equiv 1 \pmod{p}$.

It follows from Theorem 12.5 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 12.12 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 12.17 *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 12.16. 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 12.18 $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$ *for all odd prime numbers* p.

Proof It follows from Corollary 12.17 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 12.9 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 12.14 and Lemma 12.16 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 12.19 *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 $\left(\frac{x}{p}\right) = (-1)^r$, 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 $x^m \equiv \left(\frac{x}{p}\right) \pmod{p}$ by Lemma 12.16. Therefore $\left(\frac{x}{p}\right) \equiv (-1)^r \pmod{p}$, and hence $\left(\frac{x}{p}\right) = (-1)^r$, 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 12.20 *Let p be an odd prime number. Then* $\left(\frac{2}{p}\right) = (-1)^{(p^2-1)/8}$.

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 12.19 that $\left(\frac{2}{p}\right) = (-1)^r$, 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 $\left(\frac{2}{p}\right) = 1$ when $p \equiv 1 \pmod{8}$ and when $p \equiv 7 \pmod{8}$, and $\left(\frac{2}{p}\right) = -1$ when $p \equiv 3 \pmod{8}$ and $p \equiv 5 \pmod{8}$. Thus $\left(\frac{2}{p}\right) = (-1)^{(p^2-1)/8}$ for all odd prime numbers p, as required. ∎

12.6 Quadratic Reciprocity

Theorem 12.21 (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 $\left(\frac{p}{q}\right)\left(\frac{q}{p}\right) = (-1)^{mn}$.

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 12.19 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 $(-1)^{mn} = (-1)^a(-1)^b = \left(\dfrac{p}{q}\right)\left(\dfrac{q}{p}\right)$, as required. ∎

Corollary 12.22 *Let p and q be distinct odd prime numbers. If $p \equiv 1 \pmod{4}$ or $q \equiv 1 \pmod{4}$ then $\left(\dfrac{p}{q}\right) = \left(\dfrac{q}{p}\right)$. If $p \equiv 3 \pmod{4}$ and $q \equiv 3 \pmod{4}$ then $\left(\dfrac{p}{q}\right) = -\left(\dfrac{q}{p}\right)$.*

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. ∎

12.7 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 12.23 *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 12.24 *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 12.25 *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 12.15). The required result therefore follows from the definition of the Jacobi symbol. ∎

Lemma 12.26 $\left(\frac{x^2}{s}\right) = 1$ *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 12.25 and Lemma 12.23. ∎

Theorem 12.27 $\left(\frac{-1}{s}\right) = (-1)^{(s-1)/2}$ *for all odd positive integers s.*

Proof Let $f(s) = (-1)^{(s-1)/2}\left(\frac{-1}{s}\right)$ 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 12.25 that $f(st) = f(s)f(t)$ for all odd numbers s and t. But $f(p) = 1$ for all prime numbers p, since $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$ (Lemma 12.18). It follows that $f(s) = 1$ for all odd positive integers s, as required. ∎

Theorem 12.28 $\left(\frac{2}{s}\right) = (-1)^{(s^2-1)/8}$ *for all odd positive integers s.*

Proof Let $g(s) = (-1)^{(s^2-1)/8}\left(\frac{2}{s}\right)$ 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 12.25 that $g(st) = g(s)g(t)$ for all odd numbers s and t. But $g(p) = 1$ for all prime numbers p, since $\left(\frac{2}{p}\right) = (-1)^{(p^2-1)/8}$ (Lemma 12.20). It follows that $g(s) = 1$ for all odd positive integers, as required. ∎

Theorem 12.29 $\left(\frac{s}{t}\right)\left(\frac{t}{s}\right) = (-1)^{(s-1)(t-1)/4}$ *for all odd positive integers s and t.*

Proof Let $h(s,t) = (-1)^{(s-1)(t-1)/4}\left(\frac{s}{t}\right)\left(\frac{t}{s}\right)$. 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 12.21). 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 $\left(\frac{442}{751}\right) = \left(\frac{2}{751}\right)\left(\frac{221}{751}\right)$. Also $\left(\frac{2}{751}\right) = 1$, since $751 \equiv 7 \pmod 8$ (Theorem 12.20). Also $\left(\frac{221}{751}\right) = \left(\frac{751}{221}\right)$ (Theorem 12.29), 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 $\left(\frac{2}{221}\right) = -1$, since $221 \equiv 5 \pmod 8$ (Theorem 12.28). Also it follows from Theorem 12.29 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 $\left(\frac{442}{751}\right) = -1$, 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.