Quadratic reciprocity

Robin Chapman

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Let p be an odd prime number. We consider which numbers $a \not\equiv 0$ are squares modulo p. If $a \equiv b^2$ then $a \equiv (-b)^2$ and as $b \not\equiv -b \pmod p$ then $x^2 \equiv a \pmod p$ has precisely the two solutions $x \equiv \pm b \pmod p$. It follows that there are exactly $\frac{1}{2}(p-1)$ such a up to congruence modulo p, which are $1^2, 2^2, \ldots [\frac{1}{2}(p-1)]^2$. These are the *quadratic residues* modulo p. The $\frac{1}{2}(p-1)$ remaining values modulo p, for which the congruence $x^2 \equiv a \pmod p$ is insoluble are the *quadratic nonresidues* modulo p. We define the *Legendre symbol* $\left(\frac{a}{p}\right)$ as follows:

$$\left(\frac{a}{p}\right) = \begin{cases} 0 & \text{if } p \mid a, \\ 1 & \text{if } a \text{ is a quadratic residue modulo } p, \\ -1 & \text{if } a \text{ is a quadratic nonresidue modulo } p. \end{cases}$$

The Legendre symbol $\left(\frac{a}{p}\right)$ depends only on a modulo p, that is,

$$\left(\frac{a}{p}\right) = \left(\frac{b}{p}\right) \quad \text{whenever} \quad a \equiv b \pmod p.$$

Theorem 1 (Euler's criterion) *Let p be an odd prime and let $a \in \mathbf{Z}$. Then*

$$\left(\frac{a}{p}\right) \equiv a^{(p-1)/2} \pmod p. \tag{$*$}$$

Proof If $p \mid a$ then both sides of $(*)$ are zero modulo p. We may thus suppose that $p \nmid a$. Let g be a primitive root modulo p. Then $g^{(p-1)/2} \not\equiv 1 \pmod p$ but $[g^{(p-1)/2}]^2 = g^{p-1} \equiv 1 \pmod p$. It follows that $g^{(p-1)/2} \equiv -1 \pmod p$. Now $a \equiv g^k \pmod p$ for some integer $k \geq 0$ and so

$$a^{(p-1)/2} \equiv g^{k(p-1)/2} \equiv [g^{(p-1)/2}]^k \equiv (-1)^k \equiv \begin{cases} 1 & \text{if } k \text{ is even,} \\ -1 & \text{if } k \text{ is odd.} \end{cases}$$

Let us attempt to solve the congruence $x^2 \equiv a \equiv g^k \pmod{p}$. The solution must have the form $x \equiv g^r \pmod{p}$ and so $g^{2r} \equiv g^k \pmod{p}$. This is equivalent to the congruence $2r \equiv k \pmod{p-1}$. As $2 \mid (p-1)$ this linear congruence is soluble if and only if k is even. Hence if a is a quadratic residue then k is even and $a^{(p-1)/2} \equiv 1 = \left(\frac{a}{p}\right) \pmod{p}$, while if a is a quadratic nonresidue then k is odd and $a^{(p-1)/2} \equiv -1 = \left(\frac{a}{p}\right) \pmod{p}$. □

Corollary 1 *Let p be an odd prime, and let $a, b \in \mathbf{Z}$. Then*

$$\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right)\left(\frac{b}{p}\right).$$

In particular if a and b are both quadratic residues modulo p or both quadratic nonresidues modulo p, then ab is a quadratic residue modulo p, while if one of a and b is a quadratic residue modulo p and the other is a quadratic nonresidue modulo p, then ab is a quadratic nonresidue modulo p.

Proof By Euler's criterion

$$\left(\frac{ab}{p}\right) \equiv (ab)^{(p-1)/2} \equiv a^{(p-1)/2} b^{(p-1)/2} \equiv \left(\frac{a}{p}\right)\left(\frac{b}{p}\right) \pmod{p}.$$

Both sides of this congruence lie in the set $\{-1, 0, 1\}$ and as $p \geq 3$ no two distinct elements of this set are congruent modulo p. Hence we have equality, not just congruence:

$$\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right)\left(\frac{b}{p}\right).$$

□

Corollary 2 *Let p be an odd prime. Then*

$$\left(\frac{-1}{p}\right) = \begin{cases} 1 & \text{if } p \equiv 1 \pmod{4}, \\ -1 & \text{if } p \equiv 3 \pmod{4}. \end{cases}$$

Proof By Euler's criterion

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

If $p \equiv 1 \pmod{4}$ then $(p-1)/2$ is even, and so $\left(\frac{-1}{p}\right) \equiv 1 \pmod{p}$; consequently $\left(\frac{-1}{p}\right) = 1$, If $p \equiv 3 \pmod{4}$ then $(p-1)/2$ is odd, and so $\left(\frac{-1}{p}\right) \equiv -1 \pmod{p}$; consequently $\left(\frac{-1}{p}\right) = -1$. □

We now prove Gauss's lemma, which gives a useful if opaque characterization of the Legendre symbol.

Theorem 2 (Gauss's lemma) *Let p be an odd prime and let a be an integer coprime to p. Let $R = \{j \in \mathbf{N} : 0 < j < p/2\}$ and $S = \{j \in \mathbf{N} : p/2 < j < p\}$. Then $\left(\frac{a}{p}\right) = (-1)^\mu$ where μ is the number of $j \in R$ for which the least nonnegative residue of aj modulo p lies in S.*

Proof It is convenient to introduce some notation. If m is an integer, it is congruent modulo p to exactly one integer between $-p/2$ and $p/2$. Let $\langle m\rangle$ denote this integer: that is, $\langle m\rangle \equiv m \pmod p$ and $|\langle m\rangle| < p/2$. Then m is congruent modulo p to an element of S if and only if $\langle m\rangle < 0$.

We consider the numbers $\langle aj\rangle$ for $j \in R$. Then μ is the number of $j \in R$ for which $\langle aj\rangle < 0$. Let us write $\langle aj\rangle = \varepsilon_j b_j$ where $\varepsilon_j = \pm 1$ and $b_j = |\langle aj\rangle|$. Then $(-1)^r = \prod_{j=1}^{(p-1)/2} \varepsilon_j$. I claim that the numbers $b_1, \ldots, b_{(p-1)/2}$ are the same as the numbers in R in some order. Certainly $b_j \neq 0$ for if $b_j = 0$ then $p \mid aj$ contrary to Euclid's lemma ($p \nmid a$ and $p \nmid j$). Suppose there were integers j and k with $0 < j < k < p/2$ and $b_j = b_k$. Then $ak \equiv \varepsilon_k b_k = \varepsilon_j b_j \equiv \varepsilon_j \varepsilon_k a_j \pmod p$. So $p \mid a(k \pm j)$ and as $p \nmid a$ then $p \mid (k \pm j)$. But $0 < k + j < p$ and $0 < k - j < p/2$. Neither $k + j$ nor $k - j$ is a multiple of p. This contradiction shows that all the b_j are distinct, and so the b_j are the elements of R in some order.

It follows that $\prod_{j=1}^{(p-1)/2} b_j = (\frac{1}{2}(p-1))!$ and so

$$a^{(p-1)/2}\left(\frac{p-1}{2}\right)! = \prod_{j=1}^{(p-1)/2}(aj) \equiv \prod_{j=1}^{(p-1)/2}(\varepsilon_j b_j) = (-1)^\mu\left(\frac{p-1}{2}\right)! \pmod p.$$

As $(\frac{1}{2}(p-1))!$ is coprime to p, we may cancel it and get $a^{(p-1)/2} \equiv (-1)^\mu \pmod p$. Applying Euler's criterion gives $\left(\frac{a}{p}\right) = (-1)^\mu$. □

In the proof of the following theorem, we adopt the following notation. If $x < y$ then $N(x, y)$ denotes the number of integers n with $x < n < y$. It is useful to note several simple properties of $N(x, y)$.

- $N(x, y) = N(-y, -x)$;
- if a is an integer, then $N(x + a, y + a) = N(x, y)$;
- if a is a positive integer, then $N(x, y + a) = N(x, y) + a$;
- if a is a positive integer, and x is not an integer, then $N(x, x + a) = a$;
- if $x < y < z$ and y is not an integer, then $N(x, z) = N(x, y) + N(y, z)$.

The proofs of all of these are straightforward, and left as exercises.

Theorem 3 *Let $a \in \mathbf{N}$, and let p and q be distinct odd primes, each coprime to a. If $q \equiv \pm p \pmod{4a}$ then $\left(\frac{a}{q}\right) = \left(\frac{a}{p}\right)$.*

Proof By Gauss's lemma, $\left(\frac{a}{p}\right) = (-1)^\mu$ where μ is the number of integers $j \in (0, p/2)$ and with aj having least positive residue modulo p in the interval $(p/2, p)$. If $0 < j < p/2$ then $0 < aj < ap/2$ and so μ is the number of integers j with

$$aj \in \bigcup_{k=1}^{b} \left(\left(k - \frac{1}{2} \right) p, kp \right)$$

where $b = a/2$ or $b = (a-1)/2$ according to whether b is even or b is odd. Hence μ is the number of integers in the set

$$\bigcup_{k=1}^{b} \left(\frac{(2k-1)p}{2a}, \frac{kp}{a} \right),$$

that is

$$\mu = \sum_{k=1}^{b} N \left(\frac{(2k-1)p}{2a}, \frac{kp}{a} \right).$$

Similarly $\left(\frac{a}{q}\right) = (-1)^\nu$ where

$$\nu = \sum_{k=1}^{b} N \left(\frac{(2k-1)q}{2a}, \frac{kq}{a} \right).$$

Suppose first that $q \equiv p \pmod{4a}$. Without loss of generality, $q > p$, and we may write $q = p + 4ar$ with $r \in \mathbf{N}$. Then

$$\begin{aligned}
\nu &= \sum_{k=1}^{b} N \left(\frac{(2k-1)p}{2a} + (4k-2)r, \frac{kp}{a} + 4kr \right) \\
&= \sum_{k=1}^{b} N \left(\frac{(2k-1)p}{2a}, \frac{kp}{a} + 2r \right) \\
&= \sum_{k=1}^{b} \left[N \left(\frac{(2k-1)p}{2a}, \frac{kp}{a} \right) + 2r \right] \\
&= \mu + 2rb.
\end{aligned}$$

Consequently

$$\left(\frac{a}{q}\right) = (-1)^\nu = (-1)^{\mu+2rb} = (-1)^\mu = \left(\frac{a}{p}\right).$$

Now suppose that $q \equiv -p \pmod{4a}$. Then $p+q = 4as$ with s an integer. Thus

$$\begin{aligned}
\nu &= \sum_{k=1}^{b} N\left((4k-2)s - \frac{(2k-1)p}{2a}, 4ks - \frac{kp}{a}\right) \\
&= \sum_{k=1}^{b} N\left(\frac{kp}{a} - 4ks, \frac{(2k-1)p}{2a} - (4k-2)s\right) \\
&= \sum_{k=1}^{b} N\left(\frac{kp}{a}, \frac{(2k-1)p}{2a} + 2s\right).
\end{aligned}$$

Hence

$$\begin{aligned}
\mu + \nu &= \sum_{k=1}^{b} \left[N\left(\frac{(2k-1)p}{2a}, \frac{kp}{a}\right) + N\left(\frac{kp}{a}, \frac{(2k-1)p}{2a} + 2s\right)\right] \\
&= \sum_{k=1}^{b} N\left(\frac{(2k-1)p}{2a}, \frac{(2k-1)p}{2a} + 2s\right) \\
&= 2sb.
\end{aligned}$$

Consequently

$$\left(\frac{a}{q}\right) = (-1)^{\nu} = (-1)^{-\mu+2sb} = (-1)^{\mu} = \left(\frac{a}{p}\right).$$

□

We can now prove the law of quadratic reciprocity

Theorem 4 (Quadratic reciprocity) *Let p and q be distinct odd primes. Then*

$$\left(\frac{q}{p}\right) = \left(\frac{p}{q}\right)$$

unless $p \equiv q \equiv 3 \pmod 4$ in which case

$$\left(\frac{q}{p}\right) = -\left(\frac{p}{q}\right).$$

Proof Suppose first that $p \equiv q \pmod 4$. Without loss of generality, $q > p$ so that $q = p + 4a$ with $a \in \mathbf{N}$. Then

$$\left(\frac{q}{p}\right) = \left(\frac{p+4a}{p}\right) = \left(\frac{4a}{p}\right) = \left(\frac{a}{p}\right)$$

and

$$\left(\frac{p}{q}\right) = \left(\frac{q-4a}{q}\right) = \left(\frac{-4a}{q}\right) = \left(\frac{-1}{q}\right)\left(\frac{a}{q}\right).$$

By Theorem 3

$$\left(\frac{a}{p}\right) = \left(\frac{a}{q}\right)$$

then

$$\left(\frac{q}{p}\right) = \left(\frac{-1}{q}\right)\left(\frac{a}{q}\right).$$

Thus if $p \equiv q \equiv 1 \pmod 4$ then

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

while if $p \equiv q \equiv 3 \pmod 4$ then

$$\left(\frac{q}{p}\right) = \left(\frac{-1}{q}\right)\left(\frac{p}{q}\right) = -\left(\frac{p}{q}\right).$$

Now suppose that $p \equiv -q \pmod 4$. Then $p + q = 4a$ with $a \in \mathbf{N}$. Then

$$\left(\frac{q}{p}\right) = \left(\frac{4a-p}{p}\right) = \left(\frac{4a}{p}\right) = \left(\frac{a}{p}\right)$$

and

$$\left(\frac{p}{q}\right) = \left(\frac{4a-q}{q}\right) = \left(\frac{4a}{q}\right) = \left(\frac{a}{q}\right).$$

By Theorem 3

$$\left(\frac{a}{p}\right) = \left(\frac{a}{q}\right)$$

then

$$\left(\frac{q}{p}\right) = \left(\frac{p}{q}\right).$$

□

When applying quadratic reciprocity, it is useful to have a version involving the *Jacobi symbol*. This is denoted by $\left(\frac{a}{n}\right)$, like the Legendre symbol, but in the Legendre symbol the number n must be an odd prime, in the Jacobi symbol n can be any positive odd integer and a any integer at all. We define the Jacobi symbol as follows: if n is a positive odd integer, write $n = p_1 \dots p_k$ with the p_j prime. Then set

$$\left(\frac{a}{n}\right) = \prod_{j=1}^{k}\left(\frac{a}{p_j}\right).$$

It is immediate that the Jacobi symbol shares some of the formal properties of the Legendre symbol:

- $\left(\frac{a}{n}\right) = \pm$ if a and n are coprime and $\left(\frac{a}{n}\right) = 0$ otherwise,
- $\left(\frac{a}{n}\right) = \left(\frac{b}{n}\right)$ whenever $a \equiv b \pmod{n}$,
- $\left(\frac{ab}{n}\right) = \left(\frac{a}{n}\right)\left(\frac{b}{n}\right)$ and $\left(\frac{a}{mn}\right) = \left(\frac{a}{m}\right)\left(\frac{a}{n}\right)$.

The most convenient property is that quadratic reciprocity is true for the Jacobi symbol too. Let m and n be coprime odd positive integers. Write $m = p_1 \dots p_r$ and $n = q_1 \dots q_s$ where the p_j and q_k are primes. By quadratic reciprocity,

$$\left(\frac{m}{n}\right) = \prod_{j=1}^{r}\prod_{k=1}^{s}\left(\frac{p_j}{q_k}\right) = \prod_{j=1}^{r}\prod_{k=1}^{s}\varepsilon_{j,k}\left(\frac{q_k}{p_j}\right) = (-1)^{\mu}\left(\frac{n}{m}\right)$$

where $\varepsilon_{j,k} = 1$ unless $p_j \equiv q_j \equiv 3 \pmod{4}$ in which case $\varepsilon_{j,k} = -1$ and μ is the number of pairs (j,k) with $\varepsilon_{j,k} = -1$. But $\mu = ab$ where a is the number of p_j which are 3 modulo 4 and b is the number of q_k which are 3 modulo 4. Then $m \equiv 3^a \equiv (-1)^a \pmod{4}$ and $n \equiv 3^b \equiv (-1)^b \pmod{4}$. Then $(-1)^{ab} = 1$ unless both a and b are odd when $(-1)^{\mu} = -1$. Thus $(-1)^{\mu} = -1$ if and only if $m \equiv n \equiv 3 \pmod{4}$:

$$\left(\frac{m}{n}\right) = \left(\frac{n}{m}\right)$$

unless $m \equiv n \equiv 3 \pmod{4}$ in which case

$$\left(\frac{m}{n}\right) = -\left(\frac{n}{m}\right).$$

(This even holds when m and n are non-coprime positive odd integers, for then both sides are zero.)