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Notation

$$\zeta_l = \cos \frac{2\pi}{l} + i \sin \frac{2\pi}{l}$$

$$\zeta_p = \cos \frac{2\pi}{p} + i \sin \frac{2\pi}{p}$$

$$m = \frac{l-1}{2}$$

χ - the Dirichlet character modulo p , $\chi(x) = \zeta_l^{\text{ind}(x)}$

$J(\chi, \chi) = \sum_{x+y=1} \chi(x)\chi(y)$ - Jacobi sum

$$\tau(\chi) = \sum_{x=1}^{p-1} \chi(x)\zeta_p^x \text{ - Gaussian sum}$$

Recall that $\tau(\chi) \in K\mathbf{Q}(\zeta_l)$, where $K \subset \mathbf{Q}(\zeta_p)$ and $[K : \mathbf{Q}] = l$.

Introduction

Let $J(\chi, \chi)$ be the Jacobi sum, $J(\chi, \chi) \in \mathbf{Q}(\zeta_l)$. It is well known that $J(\chi, \chi)\overline{J(\chi, \chi)} = p$, and one easily proves that

$$J(\chi, \chi) \equiv \overline{\chi}(4) \pmod{2}.$$

The main aim of this paper is to solve the problem: When is $J(\chi, \chi)$ up to association and conjugation uniquely determined by the solution of the equation

$$X\overline{X} = p, X \in \mathbf{Z}(\zeta_l), X \equiv 1 \pmod{2}?$$

We give a complete solution in cases $l = 11, 19$.

On the basis of this result, the following question is answered:

When is the prime 2 an 11-th resp. a 19-th power modulo p if p is not representable by the quadratic form $x^2 + 11y^2$, resp. $x^2 + 19y^2$.

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We shall now present a survey of results obtained by solving the problem when the prime 2 is an l -th power modulo p .

Jacobi has given necessary and sufficient conditions for primes $q < 37$ to be cubes modulo primes $p \equiv 1 \pmod{3}$. For example, he proves the following

PROPOSITION 1. *2 is a cube modulo p if and only if $L \equiv 0 \pmod{2}$, where*

$$4p = L^2 + 27M^2,$$

$$L \equiv 1 \pmod{3}.$$

Emma Lehmer [2] finds the following result:

PROPOSITION 2. *Let $p \equiv 1 \pmod{5}$ be a prime. Then 2 is a fifth power modulo p if and only if $x \equiv 0 \pmod{2}$, where (x, u, v, w) is one of the exactly four solutions (x, u, v, w) , $(x, -u, -v, w)$, $(x, v, -u, -w)$, $(x, -v, u, -w)$ of the diophantine system (Dickson):*

$$16p = x^2 + 50u^2 + 50v^2 + 125w^2,$$

$$xw = v^2 - 4uv - u^2,$$

$$x \equiv 1 \pmod{5}.$$

P.A. Leonard and K.S. Williams [4] prove the following

PROPOSITION 3. *Let $p \equiv 1 \pmod{7}$ be a prime. Then 2 is a seventh power modulo p if and only if $x_1 \equiv 0 \pmod{2}$, where (x_1, x_2, \dots, x_6) is one of the exactly six non-trivial solutions of the diophantine system of equations*

$$(i) \quad 72p = 2x_1^2 + 42(x_2^2 + x_3^2 + x_4^2) + 343(x_5^2 + 3x_6^2),$$

$$(ii) \quad 12x_2^2 - 12x_4^2 + 147x_5^2 - 441x_6^2 + 56x_1x_6 + 24x_2x_3 - 24x_2x_4 + 48x_3x_4 + 98x_5x_6 = 0,$$

$$(iii) \quad 12x_3^2 - 12x_4^2 + 49x_5^2 - 147x_6^2 + 28x_1x_5 + 48x_2x_3 + 24x_2x_4 + 24x_3x_4 + 490x_5x_6 = 0,$$

$$(iv) \quad x_1 \equiv 1 \pmod{7}.$$

P.A. Leonard, B.C. Mortimer and K.S. Williams [3] prove the following

PROPOSITION 4. Let $p \equiv 1 \pmod{11}$ be a prime. Then 2 is an eleventh power modulo p if and only if a certain condition involving solutions of a very complicated diophantine system holds (the exact statement may be seen in [3]).

J.C. Parnami, M.K. Agrawal and A.R. Rajwade [5] have the following

PROPOSITION 5. Let $p \equiv 1 \pmod{l}$. Then 2 is an l -th power modulo p if and only if

$$a_1 + a_2 + \dots + a_{l-1} \equiv 0 \pmod{2},$$

where $(a_1, a_2, \dots, a_{l-1})$ is one of the exactly $l - 1$ solutions of the diophantine system of equations

$$(i) \quad p = \sum_{i=1}^{l-1} a_i^2 - \sum_{i=1}^{l-1} a_i a_{i+1},$$

$$(ii) \quad \sum_{i=1}^{l-1} a_i a_{i+1} = \sum_{i=1}^{l-1} a_i a_{i+2} = \dots = \sum_{i=1}^{l-1} a_i a_{i+l-1},$$

$$(iii) \quad p \text{ does not divide } \prod_{\lambda(2k) > k} \sigma_k \left(\sum_{i=1}^{l-1} a_i \zeta_l^i \right),$$

where $\lambda(n)$ is the least non-negative residue of n modulo l , and σ_k is the automorphism $\zeta_l \rightarrow \zeta_l^k$,

$$(iv) \quad 1 + a_1 + \dots + a_{l-1} \equiv 0 \pmod{l},$$

$$(v) \quad a_1 + 2a_2 + \dots + (l - 1)a_{l-1} \equiv 0 \pmod{l}.$$

Now let $X\bar{X} = p$, and let $J(\chi, \chi)$ be associated with the number X , i.e. $J(\chi, \chi) = \varepsilon X$, where ε is a unit of the field $\mathbf{Q}(\zeta_l)$. Then

$$J(\chi, \chi)\overline{J(\chi, \chi)} = p = \varepsilon\bar{\varepsilon}X\bar{X}$$

implies $\varepsilon\bar{\varepsilon} = 1$ and hence $\varepsilon = (-\zeta_l)^n$. So we have

$$J(\chi, \chi) = (-\zeta_l)^n X.$$

Let 2 be a primitive root modulo l . Consider a residue class field $\mathbf{Z}(\zeta_l)/(2)$ of the degree $f = l - 1$ over $\mathbf{Z}/2\mathbf{Z}$. Let g be a generator of the multiplicative group $(\mathbf{Z}(\zeta_l)/(2))^*$ of the field $\mathbf{Z}(\zeta_l)/(2)$ such that there holds $\varphi(g) = g^2$, where φ is a generator of the Galois group $G(\mathbf{Q}(\zeta_l)/\mathbf{Q})$.

LEMMA 1. Every unit ε of the field $\mathbf{Q}(\zeta_l)$ is a $\frac{2^m+1}{l}$ -th power in the group $(\mathbf{Z}(\zeta_l)/(2))^*$, $m = \frac{l-1}{2}$.

Proof. Let $\varepsilon \equiv g^n \pmod{2}$. It is necessary to prove that $\frac{2^m+1}{l} | n$. Consider the unit $\varepsilon_1 = \prod_{i=0}^{m-1} \varphi^i(\varepsilon)$. Then $\varepsilon_1 \cdot \bar{\varepsilon}_1 = N(\varepsilon) = 1$, hence ε_1 must be a root of 1, therefore $\varepsilon_1^{2^l} = 1$. Further,

$$1 = \varepsilon_1^{2^l} = \prod_{i=0}^{m-1} \varphi^i(\varepsilon)^{2^l} \equiv \prod_{i=0}^{m-1} \varphi^i(g^n)^{2^l} \equiv \prod_{i=0}^{m-1} g^{2^{nl} \cdot 2^i} \equiv g^{2^{ln}(2^m-1)} \pmod{2}.$$

It follows that $2^{ln}(2^m-1) \equiv 0 \pmod{2^{l-1}-1}$, and therefore $n \equiv 0 \pmod{\frac{2^m+1}{l}}$. \square

LEMMA 2. Let 2 be a primitive root modulo l . For a natural number a , $0 < a \leq l-1$ the following identity holds

$$a \frac{2^{l-1}-1}{l} = \sum_{n=1}^{l-1} \left[\frac{2n}{l} \right] 2^{r_n}$$

(the decomposition into binary system), where $r_n \equiv l-2 - \text{ind}(n) + \text{ind}(a) \pmod{l-1}$, $0 \leq r_n < l-1$, and $\text{ind}(x)$ is the index of the element x in the group $(\mathbf{Z}/l\mathbf{Z})^*$ under the base 2, i.e. $2^{\text{ind}(x)} \equiv x \pmod{l}$.

Proof. The lemma can be readily proved when the rational number $\frac{a}{l}$ is expressed in the binary system, $\frac{a}{l} = \sum_{n=1}^{\infty} a_n 2^{-n}$.

LEMMA 3. The factorisation of the Jacobi sum $J(\chi, \chi)$ into prime divisors of the field $\mathbf{Q}(\zeta_l)$ is $J(\chi, \chi) \approx \prod_{n=1}^{l-1} \sigma_{\frac{1}{n}}(\mathfrak{p})^{\lfloor \frac{2n}{l} \rfloor}$, where \mathfrak{p} is a prime divisor of the field $\mathbf{Q}(\zeta_l)$, $\mathfrak{p} | l$, and $\sigma_{\frac{1}{n}}$ is an automorphism $\sigma_{\frac{1}{n}}(\zeta_l) = \zeta_l^{\frac{1}{n}}$.

Proof. According to [1],

$$J(\chi, \chi) = \frac{\tau(\chi)\tau(\chi)}{\tau(\chi^2)}.$$

The factorisation $J(\chi, \chi) \approx \prod_{n=1}^{l-1} \sigma_{\frac{1}{n}}(\mathfrak{p})^{\lfloor \frac{2n}{l} \rfloor}$ is obtained using the factorisation of the Gaussian sum into prime divisors of the field $K\mathbf{Q}(\zeta_l)$. \square

Consider a divisor $A = \prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}$, where $j_i = 0; 1$, and define

$$\Psi\left(\prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}\right) = \sum_{i=0}^{l-2} j_i 2^i.$$

LEMMA 4. *The factorisation $A = \prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}$ is a conjugation of the factorisation $J(\chi, \chi) = \prod_{n=1}^{l-1} \sigma_{\frac{1}{n}}(\mathfrak{p}) \left[\frac{2n}{l}\right]$ if and only if $\Psi\left(\prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}\right) = a \frac{2^{l-1}-1}{l}$, where $0 < a \leq l-1$.*

Proof. Let A be a conjugation of $J(\chi, \chi)$. Then $A = J(\chi^s, \chi^s)$ for some s . If $s \equiv \frac{k}{2} \pmod{l}$, then we can write

$$\begin{aligned} J_s &= J_{\frac{k}{2}} \approx \prod_{n=1}^{l-1} \sigma_{\frac{1}{n}}(\mathfrak{p}) \left[\frac{2n}{l}\right] = \prod_{n=1}^{l-1} \varphi^{\text{ind}(\frac{1}{n} \cdot \frac{k}{2})}(\mathfrak{p}) \left[\frac{2n}{l}\right] \\ \Psi\left(\prod_{n=1}^{l-1} \varphi^{\text{ind}(\frac{1}{n} \cdot \frac{k}{2})}(\mathfrak{p}) \left[\frac{2n}{l}\right]\right) &= \sum_{n=1}^{l-1} \left[\frac{2n}{l}\right] 2^{\text{ind}(\frac{1}{n} \cdot \frac{k}{2})} = \\ &= \sum_{n=1}^{l-1} \left[\frac{2n}{l}\right] \cdot 2^{l-1-\text{ind}(n)+\text{ind}(k)-1} = k \frac{2^{l-1}-1}{l} \quad (\text{by Lemma 2}). \end{aligned}$$

2. Conversely, let $\Psi\left(\prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}\right) = a \frac{2^{l-1}-1}{l}$, $0 < a \leq l-1$.

By Lemma 2,

$$a \frac{2^{l-1}-1}{l} = \sum_{n=1}^{l-1} \left[\frac{2n}{l}\right] 2^{r_n} = \Psi\left(\prod_{n=1}^{l-1} \varphi^{\text{ind}(\frac{1}{n} \cdot \frac{a}{2})}(\mathfrak{p}) \left[\frac{2n}{l}\right]\right) = \sum_{i=0}^{l-2} j_i \cdot 2^i.$$

Since the expansion of a number in the binary system is uniquely determined, Lemma 4 is proved. \square

For $\mathfrak{p}|p$, denote by $h_{\mathfrak{p}}$ the least natural number such that a principal divisor $\mathfrak{p}^{h_{\mathfrak{p}}} = (\alpha)$.

THEOREM 1. *Let 2 be a primitive root modulo l , and let $\alpha \equiv g^M \pmod{2}$, where $(M, \frac{2^m+1}{l}) = 1$.*

If

$$X \in \mathbf{Z}(\zeta_l), \quad X\bar{X} = p, \quad X \equiv 1 \pmod{2},$$

then X is, up to association and conjugation, equal to the Jacobi sum $J(\chi, \chi)$.

Proof. According to Lemma 1, the choice of a generator α of the principal divisor $\mathfrak{p}^{h_p} = (\alpha)$ is not substantial.

Suppose the factorisation of X into prime divisors of the field $\mathbf{Q}(\zeta_l)$ is

$$X \approx \prod_{i=0}^{l-2} \varphi^i(\mathfrak{p})^{j_i}.$$

It is necessary to prove that this factorisation is a conjugate of the factorisation $J(\chi, \chi)$.

Clearly

$$X^{h_p} \approx \prod_{i=0}^{l-2} \varphi^i(\mathfrak{p}^{h_p})^{j_i} \approx \prod_{i=0}^{l-2} \varphi^i(\alpha)^{j_i},$$

hence

$$X^{h_p} = \varepsilon \prod_{i=0}^{l-2} \varphi^i(\alpha)^{j_i},$$

where ε is a unit of the field $\mathbf{Q}(\zeta_l)$.

But $\varepsilon\bar{\varepsilon} = 1$ implies $\varepsilon = (-\zeta_l)^s$, and therefore

$$X^{h_p} = (-\zeta_l)^s \prod_{i=0}^{l-2} \varphi^i(\alpha)^{j_i}.$$

From $X \equiv 1 \pmod{2}$ we obtain

$$\begin{aligned} 1 &\equiv (-\zeta_l)^s \prod_{i=0}^{l-2} \varphi^i(\alpha)^{j_i} \equiv (-\zeta_l)^s \prod_{i=0}^{l-2} \varphi^i(g^M)^{j_i} \equiv (-\zeta_l)^s \prod_{i=0}^{l-2} g^{M j_i \cdot 2^i} \equiv \\ &\equiv (-\zeta_l)^s g^{M \sum_{i=0}^{l-2} j_i 2^i} \pmod{2}. \end{aligned}$$

Since $\zeta_l \equiv -\zeta_l \pmod{2}$, we have

$$g^{Ml \sum_{i=0}^{l-2} j_i 2^i} \equiv 1 \pmod{2},$$

hence

$$lM \sum_{i=0}^{l-2} j_i 2^i \equiv 0 \pmod{2^{l-1} - 1}.$$

Consequently

$$M \sum_{i=0}^{l-2} j_i 2^i \equiv 0 \pmod{\frac{2^{l-1} - 1}{l}}. \tag{1}$$

It is easy to prove that the condition $X\bar{X} = p$ gives

$$\sum_{i=0}^{l-2} j_i 2^i \equiv 0 \pmod{2^m - 1}. \tag{2}$$

From the congruences (1) and (2), using the assumption $(M, \frac{2^m+1}{l}) = 1$ and the fact that $(2^m - 1, 2^m + 1) = 1$, we obtain the congruences

$$\sum_{i=0}^{l-2} j_i 2^i \equiv 0 \pmod{\frac{2^{l-1} - 1}{l}}, \tag{3}$$

hence

$$\sum_{i=0}^{l-2} j_i 2^i = a \frac{2^{l-1} - 1}{l}.$$

From $X\bar{X} = p$, it follows that $j_i \leq 1$, and this implies $a \leq l - 1$. Due to Lemma 4, Theorem 1 is proved. \square

Remark. If $(M, \frac{2^m+1}{l}) = d > 1$, then instead of the congruence (3) we get the congruence

$$\sum_{i=0}^{l-2} j_i 2^i \equiv 0 \pmod{\frac{2^{l-1} - 1}{ld}}.$$

It can be proved that this congruence has always the solution $(j_0, j_1, \dots, j_{l-2})$ which is not corresponding to the conjugates of the Jacobi sum $J(\chi, \chi)$.

The question of whether for p with $d > 1$ the Jacobi sum $J(\chi, \chi)$ can be uniquely determined transforms in the question, for which j_i the divisor

$$\prod_{i=0}^{l-2} \varphi^i(p)^{j_i},$$

is principal.

COROLLARY 1. *Let 2 be a primitive root modulo l , and let the class number of the field $\mathbf{Q}(\zeta_l)$ be equal to 1 . Then the Jacobi sum $J(\chi, \chi)$ is uniquely determined, up to association and conjugation, from the solution of the equation $X\bar{X} = p, X \equiv 1 \pmod{2}, X \in \mathbf{Z}(\zeta_l)$ if and only if $(M, \frac{2^m+1}{l}) = 1$.*

Proof. This follows from the preceding Remark, because in such a case, every divisor is principal.

EXAMPLE 1. $l = 5, \frac{2^m+1}{l} = \frac{2^2+1}{5} = 1$. It follows that for all p one has $d = 1$, hence the Jacobi sum $J(\chi, \chi)$ is uniquely determined, up to association and conjugation, by the solution of the equation $X\bar{X} = p, X \equiv 1 \pmod{2}, X \in \mathbf{Z}(\zeta_l)$.

EXAMPLE 2. $l = 11, \frac{2^m+1}{l} = \frac{2^5+1}{11} = 3; l = 19, \frac{2^m+1}{l} = \frac{2^9+1}{19} = 27$.

It is easy to see, that if we want to answer the question, for which primes p is the Jacobi sum $J(\chi, \chi)$ uniquely determined, up to association and conjugation, by the solution of the equation $X\bar{X} = p, X \equiv 1 \pmod{2}, X \in \mathbf{Z}(\zeta_l)$, then we must know for which primes p the number α , where $N(\alpha) = p$, is a third power in the group $(\mathbf{Z}(\zeta_l)/(2))^*$. This question is solved in the following lemma.

LEMMA 5. *Let 2 be a primitive root modulo $l \equiv 3 \pmod{4}$, $\mathfrak{p}|p$, and $\mathfrak{p}^{h_p} = \alpha$.*

Then α is a third power in the group $(\mathbf{Z}(\zeta_l)/(2))^$ if and only if $\mathfrak{p}^{h_p} = x^2 + ly^2$, where x, y are not simultaneously divisible by p .*

Proof. By Lemma 1, the choice of a generator α of the principal divisor \mathfrak{p}^{h_p} is not substantial.

Consider the product

$$\beta = \prod_{(\frac{z}{l})=1} \sigma_z(\alpha), \text{ hence } \beta \in \mathbf{Q}(\sqrt{-l}).$$

Let

$$\beta = a' \sum_{(\frac{z}{l})=1} \zeta_l^z + b' \sum_{(\frac{z}{l})=1} \zeta_l^{-z}, \quad a', b' \in \mathbf{Z},$$

and let $\alpha \equiv g^r \pmod{2}$, where $r \equiv 0 \pmod{3}$,

$$\beta = \prod_{(\frac{z}{l})=1} \sigma_z(\alpha) \equiv \prod_{i=0}^{\frac{l-3}{2}} g^{r \cdot 2^i} \equiv g^{r \frac{2^{\frac{l-1}{3}} - 1}{3}} \equiv 1 \pmod{2}.$$

So we have $a' \equiv b' \equiv 1 \pmod{2}$.

Hence

$$\begin{aligned} \beta &= a' \sum_{\left(\frac{z}{l}\right)=1} \zeta_l^z + b' \sum_{\left(\frac{z}{l}\right)=1} \zeta_l^{-z} = a' \frac{-1 + \sqrt{-l}}{2} + b' \frac{-1 - \sqrt{-l}}{2} \\ &= a + b\sqrt{-l}, \quad a, b \in \mathbf{Z}, \end{aligned}$$

therefore

$$\beta\bar{\beta} = p^{h_p} = a^2 + lb^2.$$

Let conversely $p^{h_p} = a^2 + lb^2$. Put

$$\begin{aligned} a + b\sqrt{-l} &= a' \frac{-1 + \sqrt{-l}}{2} + b' \frac{-1 - \sqrt{-l}}{2} = \\ &= (b - a) \frac{-1 + \sqrt{-l}}{2} + (-a - b) \frac{-1 - \sqrt{-l}}{2}. \end{aligned}$$

This implies $a' \equiv b' \equiv 1 \pmod{2}$, hence

$$\beta = a' \sum_{\left(\frac{z}{l}\right)=1} \zeta_l^z + b' \sum_{\left(\frac{z}{l}\right)=1} \zeta_l^{-z} \equiv 1 \pmod{2}.$$

Let $p|\beta$. Then since β is invariant on σ_z , where $\left(\frac{z}{l}\right) = 1$, we set that $\sigma_z(\mathfrak{p})|\beta$.

But if $\left(\frac{n}{l}\right) = -1$, then $\sigma_n(\mathfrak{p})$ does not divide β (in the opposite case we would get $p|\beta$, hence a contradiction).

It implies

$$\beta \approx \prod_{\left(\frac{z}{l}\right)=1} \sigma_z(\mathfrak{p})^{h_p},$$

therefore

$$1 \equiv \beta \equiv (-\zeta_l)^s \prod_{\left(\frac{z}{l}\right)=1} \sigma_z(\mathfrak{p})^{h_p} \equiv (-\zeta_l)^s g^{r \frac{2^{l-1}-1}{3}} \pmod{2},$$

and

$$g^{lr \frac{2^{l-1}-1}{3}} \equiv 1 \pmod{2}.$$

From this we finally obtain

$$lr \frac{2^{l-1}-1}{3} \equiv 0 \pmod{2^{l-1}-1} \text{ which implies } r \equiv 0 \pmod{3}.$$

□

THEOREM 2. *Let $l = 11; 19$, and let $p \equiv 1 \pmod{l}$, $4p = A^2 + lB^2$. The Jacobi sum $J(\chi, \chi)$ is uniquely determined, up to conjugation and association, by the solution of*

$$X\bar{X} = p, \quad X \in \mathbf{Z}(\zeta_l), \quad X \equiv 1 \pmod{2},$$

if and only if $A \equiv B \equiv 1 \pmod{2}$.

Proof. The proof follows from Lemma 5 and Corollary 1. \square

By Proposition 5 and Theorem 2, we come to the following

THEOREM 3. *Let $l = 11; 19$, and let $p \equiv 1 \pmod{l}$, $4p = A^2 + lB^2$, $A \equiv B \equiv 1 \pmod{2}$. Then 2 is an l -th power modulo p if and only if*

$$a_1 \equiv a_2 \equiv \cdots \equiv a_{l-1} \equiv 1 \pmod{2},$$

where $(a_1, a_2, \dots, a_{l-1})$ is one of the exactly $l - 1$ solutions of the diophantine system of equations

$$(i) \quad p = \sum_{i=1}^{l-1} a_i^2 - \sum_{i=1}^{l-1} a_i a_{i+1}, \quad .$$

$$(ii) \quad \sum_{i=1}^{l-1} a_i a_{i+1} = \sum_{i=1}^{l-1} a_i a_{i+2} = \cdots = \sum_{i=1}^{l-1} a_i a_{i+l-1},$$

$$(iv) \quad 1 + a_1 + \cdots + a_{l-1} \equiv 0 \pmod{l},$$

$$(v) \quad a_1 + 2a_2 + \cdots + (l-1)a_{l-1} \equiv 0 \pmod{l}.$$

Remark. As we can see, Theorem 2 enables us to remove condition (iii) of Proposition 5.

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