

Proof of Jacobi Sum Congruence Via Stickelberger

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which he explicitly points out is valid in all characteristics. Thus a proof of Stickelberger's congruence for all finite fields via the Gross-Koblitz formula is justified.)

PROOF OF JACOBI SUM CONGRUENCE VIA STICKELBERGER

We now want to show that not only does Theorem 1 follow from Theorem 2, but Theorem 2 follows from Theorem 1, so the two theorems are equivalent. Some preliminary results will be required before the (tedious) proof is presented.

For $n \in \mathbf{N}$, write

$$n = c_0 + c_1 p + \cdots + c_d p^d, \quad 0 \leq c_i \leq p - 1.$$

From [3, Chapter IX],

$$\text{ord}_p(n!) = \frac{n - (c_0 + \cdots + c_d)}{p - 1}, \quad \frac{n!}{(-p)^{\text{ord}_p(n!)}} \equiv c_0! \cdot \cdots \cdot c_d! \pmod{p}.$$

Note neither equation requires $c_d \neq 0$. We define

$$S_p(n) \stackrel{\text{def}}{=} c_0 + \cdots + c_d, \quad H_p(n) \stackrel{\text{def}}{=} c_0! \cdot \cdots \cdot c_d!,$$

and note neither of these definitions requires $c_d \neq 0$. One sees easily that for any $n \in \mathbf{N}$, $n \equiv S_p(n) \pmod{p - 1}$, and for $n_1, \dots, n_t \in \mathbf{N}$,

$$\text{ord}_p \left(\frac{(n_1 + \cdots + n_t)!}{n_1! \cdots n_t!} \right) = \frac{S_p(n_1) + \cdots + S_p(n_t) - S_p(n_1 + \cdots + n_t)}{p - 1}.$$

For $x \in \mathbf{R}$, let $\langle x \rangle$ denote the fractional part of x . For $b \in \mathbf{Z}$, let $b \equiv b' \pmod{q - 1}$ where $0 \leq b' < q - 1$, so that $\langle \frac{b}{q - 1} \rangle = \frac{b'}{q - 1}$. Define

$$s_q(b) = S_p(b'), \quad h_q(b) = H_p(b'),$$

so s_q and h_q are just the extensions of S_p and H_p from $\{b : 0 \leq b < q - 1\}$ by $(q - 1)$ -periodicity. From [7, p. 10],

$$s_q(b) = (p - 1) \sum_{0 \leq i \leq f - 1} \left\langle \frac{p^i b}{q - 1} \right\rangle.$$

Since $\text{ord}_{\mathfrak{P}}(\zeta_p - 1) = 1$, Stickelberger's congruence can be written for all a in \mathbf{Z} as

$$\frac{G(\omega_p^{-a})}{(\zeta_p - 1)^{s_q(a)}} \equiv \frac{1}{h_q(a)} \pmod{\mathfrak{P}}.$$

LEMMA 2. For $r, m \in \mathbf{Z}^+$, and $b_1, \dots, b_r \in \mathbf{Z}$,

$$\left\langle \frac{b_1}{m} \right\rangle + \dots + \left\langle \frac{b_r}{m} \right\rangle \geq \left\langle \frac{b_1 + \dots + b_r}{m} \right\rangle.$$

If $b_1 + \dots + b_r \equiv 0 \pmod m$ and some $b_j \not\equiv 0 \pmod m$ then

$$\left\langle \frac{b_1}{m} \right\rangle + \dots + \left\langle \frac{b_r}{m} \right\rangle \geq 1.$$

Proof. Let $b_j \equiv b'_j \pmod m$, where $0 \leq b'_j < m$. Then $b'_1 + \dots + b'_r \geq 0$, so since $x \geq \langle x \rangle$ for $x \geq 0$,

$$\begin{aligned} \left\langle \frac{b_1}{m} \right\rangle + \dots + \left\langle \frac{b_r}{m} \right\rangle &= \frac{b'_1 + \dots + b'_r}{m} \geq \left\langle \frac{b'_1 + \dots + b'_r}{m} \right\rangle \\ &= \left\langle \frac{b_1 + \dots + b_r}{m} \right\rangle. \end{aligned}$$

If $b_1 + \dots + b_r \equiv 0 \pmod m$ then $(b'_1 + \dots + b'_r)/m \in \mathbf{N}$. If some $b_j \not\equiv 0 \pmod m$ then $b'_j > 0$, so $(b'_1 + \dots + b'_r)/m \in \mathbf{Z}^+$, hence is ≥ 1 . \square

COROLLARY 1. Let $0 \leq k_1, \dots, k_r < q - 1$ with $k_1 + \dots + k_r \geq q - 1$, so $r \geq 2$ and at least two $k_j > 0$. Then

$$s_q(k_1) + \dots + s_q(k_r) \begin{cases} > s_q(k_1 + \dots + k_r) & \text{if } k_1 + \dots + k_r \not\equiv 0 \pmod{q-1} \\ > f(p-1) & \text{if } k_1 + \dots + k_r \equiv 0 \pmod{q-1}, \\ & > q-1 \\ \geq f(p-1) & \text{if } k_1 + \dots + k_r = q-1. \end{cases}$$

Proof. From above,

$$s_q(k_1) + \dots + s_q(k_r) = (p-1) \sum_{0 \leq i \leq f-1} \left(\left\langle \frac{p^i k_1}{q-1} \right\rangle + \dots + \left\langle \frac{p^i k_r}{q-1} \right\rangle \right).$$

If $k_1 + \dots + k_r \not\equiv 0 \pmod{q-1}$, applying Lemma 2 to $p^i k_1, \dots, p^i k_r$ shows that each addend is $\geq \left\langle \frac{p^i(k_1 + \dots + k_r)}{q-1} \right\rangle$, with strict inequality when $i = 0$ by hypothesis, since

$$\left\langle \frac{k_1}{q-1} \right\rangle + \dots + \left\langle \frac{k_r}{q-1} \right\rangle = \frac{k_1 + \dots + k_r}{q-1} > 1 \geq \left\langle \frac{k_1 + \dots + k_r}{q-1} \right\rangle.$$

If $k_1 + \dots + k_r \equiv 0 \pmod{q-1}$ then by Lemma 2 each addend is ≥ 1 , with strict inequality when $i = 0$ if $k_1 + \dots + k_r > q - 1$. \square

We now state a more general version of Lemma 1, with a different notation that will be better suited for what follows.

LEMMA 3. For $k_1, \dots, k_r \in \mathbf{Z}$ with some $k_j \not\equiv 0 \pmod{q-1}$,

$$J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r}) = \begin{cases} \frac{G(\omega_p^{-k_1}) \cdots G(\omega_p^{-k_r})}{G(\omega_p^{-(k_1 + \cdots + k_r)})} & \text{if } k_1 + \cdots + k_r \not\equiv 0 \pmod{q-1} \\ \frac{1}{q} G(\omega_p^{-k_1}) \cdots G(\omega_p^{-k_r}) & \text{if } k_1 + \cdots + k_r \equiv 0 \pmod{q-1}. \end{cases}$$

Proof. Use [6, Chapter 8, Theorem 3] and its corollaries, keeping in mind the differences mentioned between that book and this paper on various definitions. \square

Proof that Theorem 1 implies Theorem 2. We have $0 \leq k_1, \dots, k_r < q-1$ with some $k_j > 0$, so if the second case of Lemma 3 holds, then $r \geq 2$ and at least two k_j are > 0 . From the multinomial coefficient manipulations at the end of the proof of Theorem 2, if $k_1 + \cdots + k_r > q-1$ then

$$\frac{(k_1 + \cdots + k_r)!}{k_1! \cdots k_r!} \equiv 0 \pmod{p}. \quad (*)$$

Thus to prove Theorem 1 implies Theorem 2 we are led to the following four cases:

Case 1: $k_1 + \cdots + k_r > q-1$, $k_1 + \cdots + k_r \not\equiv 0 \pmod{q-1}$

Case 2: $k_1 + \cdots + k_r > q-1$, $k_1 + \cdots + k_r \equiv 0 \pmod{q-1}$

Case 3: $k_1 + \cdots + k_r = q-1$

Case 4: $0 < k_1 + \cdots + k_r < q-1$.

We will prove Theorem 2 from Theorem 1 by establishing the congruence of Theorem 2 modulo \mathfrak{P} , since Theorem 1 involves a Gauss sum, which lies in $\mathbf{Z}[\zeta_{q-1}, \zeta_p]$ but not usually in $\mathbf{Z}[\zeta_{q-1}]$.

In Cases 1 and 2, by (*) we want to prove $\text{ord}_{\mathfrak{P}}(J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r})) > 0$. By both Stickelberger's congruence and Lemma 3,

$$\text{ord}_{\mathfrak{P}}(J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r})) = \begin{cases} s_q(k_1) + \cdots + s_q(k_r) - s_q(k_1 + \cdots + k_r) \\ \text{in Case 1} \\ s_q(k_1) + \cdots + s_q(k_r) - f(p-1) \\ \text{in Case 2,} \end{cases}$$

and in both cases the expression on the right is positive by Corollary 1. To prove Cases 3 and 4, note by [11, p. 324] that $(\zeta_p - 1)^{p-1} = -pu$, where $u \equiv 1 \pmod{(\zeta_p - 1)}$, hence $u \equiv 1 \pmod{\mathfrak{P}}$.

In Case 3, Stickelberger's congruence and Lemma 3 yield

$$\begin{aligned} \frac{J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r})}{(\zeta_p - 1)^{s_q(k_1) + \dots + s_q(k_r)}} \cdot q &\equiv \frac{1}{h_q(k_1)} \cdot \dots \cdot \frac{1}{h_q(k_r)} \pmod{\mathfrak{P}} \\ &\equiv \frac{1}{H_p(k_1)} \cdot \dots \cdot \frac{1}{H_p(k_r)} \pmod{\mathfrak{P}} \text{ since } 0 \leq k_i < q-1 \\ &\equiv \frac{(-p)^{\text{ord}_p(k_1!) + \dots + \text{ord}_p(k_r!)}}{k_1! \cdot \dots \cdot k_r!} \pmod{\mathfrak{P}}. \end{aligned}$$

Since $s_q(k_i) = S_p(k_i)$,

$$\begin{aligned} (\zeta_p - 1)^{s_q(k_1) + \dots + s_q(k_r)} &= (\zeta_p - 1)^{k_1 + \dots + k_r - (p-1)(\text{ord}_p(k_1!) + \dots + \text{ord}_p(k_r!))} \\ &= (\zeta_p - 1)^{(p-1) \left(\frac{q-1}{p-1} - (\text{ord}_p(k_1!) + \dots + \text{ord}_p(k_r!)) \right)} \\ &= (-pu)^{\frac{q-1}{p-1} - \text{ord}_p(k_1! \cdot \dots \cdot k_r!)}. \end{aligned}$$

So

$$\frac{J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r}) q (-pu)^{\text{ord}_p(k_1! \cdot \dots \cdot k_r!)}}{(-pu)^{\frac{q-1}{p-1}}} \equiv \frac{(-p)^{\text{ord}_p(k_1! \cdot \dots \cdot k_r!)}}{k_1! \cdot \dots \cdot k_r!} \pmod{\mathfrak{P}},$$

which implies by the congruence $u \equiv 1 \pmod{\mathfrak{P}}$ and by multiplication by $(q-1)! = (k_1 + \dots + k_r)!$ that

$$\begin{aligned} J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r}) \frac{q!}{(-p)^{\frac{q-1}{p-1}}} (-p)^{\text{ord}_p(k_1! \cdot \dots \cdot k_r!)} &\equiv \\ \frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!} (-p)^{\text{ord}_p(k_1! \cdot \dots \cdot k_r!)} &\pmod{\mathfrak{P}^{1 + (p-1)\text{ord}_p((q-1)!)}}. \end{aligned}$$

Since

$$\begin{aligned} &1 + (p-1)\text{ord}_p((q-1)!) - (p-1)\text{ord}_p(k_1! \cdot \dots \cdot k_r!) \\ &= 1 + q - 1 - S_p(q-1) - k_1 - \dots - k_r + S_p(k_1) + \dots + S_p(k_r) \\ &= 1 - f(p-1) + s_q(k_1) + \dots + s_q(k_r) \text{ since } 0 \leq k_i < q-1 \\ &\geq 1 \text{ by Corollary 1,} \end{aligned}$$

we see

$$J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r}) \cdot \frac{q!}{(-p)^{\frac{q-1}{p-1}}} \equiv \frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!} \pmod{\mathfrak{P}},$$

so the congruence

$$\frac{q!}{(-p)^{\frac{q-1}{p-1}}} = \frac{q!}{(-p)^{\text{ord}_p(q!)}} \equiv H_p(q) = 1 \pmod{p}$$

settles Case 3.

Finally, in Case 4, Stickelberger's congruence and Lemma 3 imply that

$$\frac{J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r})}{(\zeta_p - 1)^{s_q(k_1) + \dots + s_q(k_r) - s_q(k_1 + \dots + k_r)}} \equiv \frac{h_q(k_1 + \dots + k_r)}{h_q(k_1) \cdot \dots \cdot h_q(k_r)} \pmod{\mathfrak{P}},$$

so

$$\frac{J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r})}{(\zeta_p - 1)^{(p-1)\text{ord}_p\left(\frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!}\right)}} \equiv \frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!} \cdot \frac{1}{(-p)^{\text{ord}_p\left(\frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!}\right)}} \pmod{\mathfrak{P}},$$

since $s_q(k_i) = S_p(k_i)$ and $s_q(k_1 + \dots + k_r) = S_p(k_1 + \dots + k_r)$. Thus

$$J(\omega_p^{-k_1}, \dots, \omega_p^{-k_r}) \equiv \frac{(k_1 + \dots + k_r)!}{k_1! \cdot \dots \cdot k_r!} \pmod{\mathfrak{P}}. \quad \square$$

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