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# A DETERMINANT CONGRUENCE CONJECTURED BY SUN

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**Abstract**

We prove a strengthened form of a conjecture of Sun on a determinant attached to a binary quadratic form. Let $n > 3$ and let $c, d \in \mathbb{Z}$. If $n$ is composite, then

$$\det[(i^2 + cij + dj^2)^{n-2}]_{0\le i,j\le n-1} \equiv 0 \pmod{n^2}$$

with no condition on $c$ and $d$. If $n = p$ is prime, the same congruence holds whenever the Legendre symbol $(d/p)$ is $-1$. For composite $n$, a polynomial determinant is divisible by two Vandermonde factors; after specialisation, their product already yields the required square divisor. For prime $n = p$, we estimate the rank of the matrix modulo $p$. The required rank defect follows from a coefficient cancellation obtained from the involution $t \mapsto d/t$ on $\mathbb{F}_p^\times$ and the condition $(d/p) = -1$.

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## 1. Introduction

For an odd positive integer $n$, write $(\cdot/n)$ for the Jacobi symbol; for prime $n$, the same notation denotes the Legendre symbol. Sun has introduced a number of determinants whose entries are defined by quadratic forms and Legendre or Jacobi symbols, and has posed several conjectures about their arithmetic behaviour (see, for example, [8, 9]). For any integer $n > 3$, put

$$D_n(c, d) = \det[(i^2 + cij + dj^2)^{n-2}]_{0\le i,j\le n-1}, \tag{1.1}$$

where $c, d \in \mathbb{Z}$. Sun [9, Conjecture 4.1] conjectured that for odd $n$,

$$D_n(c, d) \equiv 0 \pmod{n^2} \quad \text{whenever } \left(\frac{d}{n}\right) = -1.$$

We prove this conjecture in the following slightly stronger form: in the composite case, neither the parity of $n$ nor any Jacobi-symbol condition is needed.

Determinants of this type lie at the intersection of determinant evaluations, finite-field methods and character sums. Classical related work includes Carlitz's cyclotomic matrices [1] and Chapman's Legendre-symbol matrices [2]. Motivated by

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Sun's conjectures, Krachun *et al.* [5] proved several determinant identities involving Jacobi symbols. Further results on determinants connected with quadratic residues and Legendre symbols were obtained, among others, by Wu [12], Wang and Wu [11], Wu *et al.* [13], Grinberg *et al.* [3], Luo and Sun [6], Guo *et al.* [4], and Wang and Sun [10]. She and Sun [7] studied several determinants and congruences associated with powers and Jacobi-symbol values of the binary form $i^2 + cij + dj^2$, while Zhu and Ren [14] treated related prime-modulus subdeterminants. The result proved in this paper concerns Sun's full $n \times n$ determinant (1.1) and establishes the modulus $n^2$ congruence in [9, Conjecture 4.1].

The proof separates naturally into composite and prime moduli. If $n$ is composite, an alternating polynomial determinant gives a product of two Vandermonde factors, and the special value

$$\prod_{0\le r<s\le n-1}(s-r)$$

is divisible by $n$. Thus, its square divides $D_n(c,d)$. If $n = p$ is prime, the problem is reduced to a rank estimate over $\mathbb{F}_p$. After the polynomial

$$(X^2 + cXY + dY^2)^{p-2}$$

is reduced as a function on $\mathbb{F}_p^2$, its coefficient matrix has one zero row and two dependent rows. The zero row is the only delicate point; it follows from the involution $t \mapsto d/t$ and the assumption $(d/p) = -1$. A Smith normal form argument then lifts the rank defect modulo $p$ to divisibility by $p^2$ over the integers.

We prove the following result.

THEOREM 1.1. *Let $n > 3$ be an integer and let $c, d \in \mathbb{Z}$. Suppose either that $n$ is composite, or that $n$ is prime and the Legendre symbol $(d/n)$ is $-1$. Then,*

$$\det[(i^2 + cij + dj^2)^{n-2}]_{0\le i,j\le n-1} \equiv 0 \pmod{n^2}.$$

## 2. The composite case

We start with a standard divisibility fact, included to make the argument over $\mathbb{Z}$ explicit.

LEMMA 2.1. *Let $R$ be a commutative ring and assume*

$$G(x_0,\dots,x_{N-1}) \in R[x_0,\dots,x_{N-1}]$$

*is alternating in the following sense: for every $r < s$, the polynomial obtained from $G$ by setting $x_s = x_r$ is zero. Then,*

$$\prod_{0\le r<s\le N-1}(x_s - x_r)$$

*divides $G$ in $R[x_0,\dots,x_{N-1}]$.*

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PROOF. We argue by induction on $N$. The assertion is clear for $N \le 1$. Put $z = x_{N-1}$ and $S = R[x_0, \dots, x_{N-2}]$. We first prove that

$$P(z) := \prod_{i=0}^{N-2} (z - x_i)$$

divides $G$ in $S[z]$. Suppose that, for some $k$ with $0 \le k \le N-2$, we have already written

$$G = \prod_{i=0}^{k-1} (z - x_i) G_k \quad (G_k \in S[z]),$$

with the empty product understood as 1. Since $G$ is zero after the specialisation $z = x_k$,

$$0 = \prod_{i=0}^{k-1} (x_k - x_i)\, G_k|_{z=x_k}.$$

The product $\prod_{i=0}^{k-1}(x_k - x_i)$ is monic as a polynomial in $x_k$ and, hence, is a non-zero-divisor. Therefore, $G_k|_{z=x_k} = 0$, so the monic factor theorem gives $G_k = (z - x_k)G_{k+1}$ for some $G_{k+1} \in S[z]$. Repeating this for $k = 0, 1, \dots, N-2$, we obtain

$$G = P(z)H \quad (H \in S[z]).$$

It remains to apply the induction hypothesis to $H$ in the variables $x_0, \dots, x_{N-2}$. If $0 \le r < s \le N-2$ and we set $x_s = x_r$, then the corresponding specialisation of $G$ is zero. Since the corresponding specialisation of $P(z)$ is monic in $z$, it is a non-zero-divisor; hence, the corresponding specialisation of $H$ is zero. Thus, $H$ is alternating in $x_0, \dots, x_{N-2}$ in the same sense. By induction,

$$\prod_{0 \le r < s \le N-2} (x_s - x_r)$$

divides $H$. Multiplying this divisor by $P(z)$ gives the required Vandermonde product for $x_0, \dots, x_{N-1}$. □

PROPOSITION 2.2. *Let $n > 3$ be a composite integer. Then, for all $c, d \in \mathbb{Z}$,*

$$D_n(c, d) \equiv 0 \pmod{n^2}.$$

PROOF. Put

$$F(X, Y) = (X^2 + cXY + dY^2)^{n-2}$$

and consider the polynomial determinant

$$\Phi(\mathbf{x}, \mathbf{y}) = \det[F(x_i, y_j)]_{0 \le i,j \le n-1} \in \mathbb{Z}[x_0, \dots, x_{n-1}, y_0, \dots, y_{n-1}].$$

If two $x$-variables are made equal, then the corresponding two rows are equal; hence, $\Phi$ is alternating in $x_0, \dots, x_{n-1}$ in the sense of Lemma 2.1. Applying that lemma over $\mathbb{Z}[y_0, \dots, y_{n-1}]$, we find that

$$V(\mathbf{x}) := \prod_{0 \le r < s \le n-1} (x_s - x_r)$$

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divides $\Phi$. Thus,

$$\Phi(\mathbf{x}, \mathbf{y}) = V(\mathbf{x})\Phi_1(\mathbf{x}, \mathbf{y})$$

for some

$$\Phi_1 \in \mathbb{Z}[x_0, \ldots, x_{n-1}, y_0, \ldots, y_{n-1}].$$

If two $y$-variables are made equal, then the corresponding two columns of $\Phi$ are equal. Since $V(\mathbf{x})$ is independent of the $y$-variables and nonzero in the integral domain under consideration, cancellation shows that $\Phi_1$ is alternating in $y_0, \ldots, y_{n-1}$ in the same sense. Applying Lemma 2.1 again, now over $\mathbb{Z}[x_0, \ldots, x_{n-1}]$, gives

$$\Phi(\mathbf{x}, \mathbf{y}) = V(\mathbf{x})V(\mathbf{y})H(\mathbf{x}, \mathbf{y})$$

for some $H \in \mathbb{Z}[x_0, \ldots, x_{n-1}, y_0, \ldots, y_{n-1}]$, where

$$V(\mathbf{y}) = \prod_{0 \le r < s \le n-1} (y_s - y_r).$$

Specialising $x_i = y_i = i$ yields

$$D_n(c, d) = V_n^2 \, H(0, 1, \ldots, n-1, 0, 1, \ldots, n-1), \tag{2.1}$$

where

$$V_n = \prod_{0 \le r < s \le n-1} (s - r) = \prod_{k=1}^{n-1} k^{n-k}.$$

It remains to prove that $n \mid V_n$.

Let $p^\alpha \parallel n$. The difference $s - r = p$ occurs for exactly $n - p$ pairs of integers $(r, s)$ with $0 \le r < s \le n - 1$, and hence,

$$\nu_p(V_n) \ge n - p.$$

We claim that $n - p \ge \alpha$. It suffices to show that the set

$$\{p, p + 1, p + 2, \ldots, n\}$$

has at least $\alpha + 1$ elements. Indeed, the $\alpha + 1$ elements

$$p,\ p + 1,\ p^2,\ p^3, \ldots,\ p^\alpha$$

with the evident omission of $p^2, \ldots, p^\alpha$ when $\alpha = 1$, are distinct elements of this set. Here, $p^\alpha \le n$; and when $\alpha = 1$, the compositeness of $n$ and the divisibility $p \mid n$ give $n \ge 2p \ge p + 1$. Thus, $n - p + 1 \ge \alpha + 1$, proving the claim. Therefore, $\nu_p(V_n) \ge \alpha$ for every prime power $p^\alpha \parallel n$. Hence, $n \mid V_n$, and (2.1) shows $n^2 \mid D_n(c, d)$. □

## 3. The prime case

We use the following elementary consequence of the Smith normal form.

LEMMA 3.1. *Let $A$ be an $N \times N$ integer matrix, let $p$ be a prime and let $r \ge 0$. If*

$$\operatorname{rank}_{\mathbb{F}_p}(A \bmod p) \le N - r,$$

*then $p^r$ divides* $\det A$.

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PROOF. Let

$$UAV = \operatorname{diag}(s_1, \dots, s_N)$$

be a Smith normal form of $A$, where $U, V$ are unimodular integer matrices. The reductions of $U$ and $V$ modulo $p$ are invertible over $\mathbb{F}_p$ and, hence, multiplication by them preserves rank over $\mathbb{F}_p$. Thus, the rank of $A$ modulo $p$ is the number of diagonal entries $s_i$ whose residue modulo $p$ is nonzero. If this rank is at most $N - r$, then at least $r$ of the $s_i$ are divisible by $p$. Consequently,

$$p^r \mid s_1 \cdots s_N = \det(UAV) = \pm \det A,$$

as required. If some $s_i = 0$, the conclusion is of course still valid. □

LEMMA 3.2. *Let $p \geq 3$ be a prime, let $c, d \in \mathbb{Z}$ and suppose that $(d/p) = -1$. In $\mathbb{F}_p[T]$, write*

$$(T^2 + cT + d)^{p-2} = \sum_{a=0}^{2p-4} \alpha_a T^a. \tag{3.1}$$

*If $m = (p-3)/2$, then*

$$\alpha_m + \alpha_{m+p-1} = 0 \quad \text{in } \mathbb{F}_p.$$

PROOF. We still write $c$ and $d$ for their residues modulo $p$, and put

$$f(T) = T^2 + cT + d \in \mathbb{F}_p[T].$$

The assumption $(d/p) = -1$ implies $d \neq 0$ in $\mathbb{F}_p$. Define

$$S = \sum_{t \in \mathbb{F}_p^\times} f(t)^{p-2} t^{-m}.$$

Here and in the following, negative powers are interpreted in the multiplicative group $\mathbb{F}_p^\times$. By (3.1),

$$S = \sum_{a=0}^{2p-4} \alpha_a \sum_{t \in \mathbb{F}_p^\times} t^{a-m}.$$

For any integer $k$, the usual orthogonality relation on $\mathbb{F}_p^\times$ gives

$$\sum_{t \in \mathbb{F}_p^\times} t^k = \begin{cases} -1 & \text{if } p-1 \mid k, \\ 0 & \text{if } p-1 \nmid k, \end{cases} \quad \text{in } \mathbb{F}_p.$$

Among the integers $a$ with $0 \leq a \leq 2p-4$, the only ones congruent to $m$ modulo $p-1$ are $a = m$ and $a = m + p - 1$. Hence,

$$S = -(\alpha_m + \alpha_{m+p-1}). \tag{3.2}$$

Now, the map $t \mapsto d/t$ is a permutation of $\mathbb{F}_p^\times$. Moreover,

$$f(d/t) = d\, t^{-2} f(t)$$

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for every $t \in \mathbb{F}_p^\times$. Therefore,

$$f(d/t)^{p-2}(d/t)^{-m} = (d\,t^{-2})^{p-2} f(t)^{p-2} d^{-m} t^m = d^{-m-1} t^{m+2} f(t)^{p-2}.$$

Since

$$m + 2 = (p+1)/2 \equiv -m \pmod{p-1}$$

and, by Euler's criterion,

$$d^{-m-1} = d^{-(p-1)/2} = (d^{(p-1)/2})^{-1} = \left(\frac{d}{p}\right)^{-1} = -1 \quad \text{in } \mathbb{F}_p,$$

we obtain

$$f(d/t)^{p-2}(d/t)^{-m} = -f(t)^{p-2} t^{-m}$$

for all $t \in \mathbb{F}_p^\times$. Summing over $t \in \mathbb{F}_p^\times$ and noting that $t \mapsto d/t$ is a permutation gives $S = -S$. Since $p$ is odd, $S = 0$. Equation (3.2) now gives the desired cancellation. □

LEMMA 3.3. *Let $p > 3$ be a prime, let $c, d \in \mathbb{Z}$ and suppose that $(d/p) = -1$. Let $C = (C_{r,s})_{0 \le r,s \le p-1}$ be the coefficient matrix of the unique polynomial*

$$R(X, Y) = \sum_{0 \le r,s \le p-1} C_{r,s} X^r Y^s \in \mathbb{F}_p[X, Y],$$

*which has degree at most $p-1$ in each variable and represents the same function on $\mathbb{F}_p^2$ as $(X^2 + cXY + dY^2)^{p-2}$. Then,*

$$\operatorname{rank}_{\mathbb{F}_p} C \le p - 2.$$

PROOF. First, note the uniqueness in the statement. If a polynomial of degree at most $p-1$ in each variable vanishes on $\mathbb{F}_p^2$, then, after fixing $Y = y \in \mathbb{F}_p$, it is a polynomial in $X$ of degree at most $p-1$ with $p$ roots; hence, it is zero. Its coefficients, as polynomials in $Y$, again have degree at most $p-1$ and vanish at all $y \in \mathbb{F}_p$, and therefore are zero. Existence follows by applying one-variable Lagrange interpolation successively in the two variables.

Let the coefficients $\alpha_a$ be defined by (3.1). We have the homogeneous expansion

$$(X^2 + cXY + dY^2)^{p-2} = \sum_{a=0}^{2p-4} \alpha_a X^a Y^{2p-4-a}. \tag{3.3}$$

For $e \ge 0$, put $\bar{e} = 0$ if $e = 0$ and, otherwise, let $\bar{e}$ be the unique integer in $\{1, \dots, p-1\}$ congruent to $e$ modulo $p-1$. Then, $z^e = z^{\bar{e}}$ for all $z \in \mathbb{F}_p$. Since every monomial in (3.3) has total degree $2p-4 < 2p-2$, the two exponents in the same monomial cannot both be at least $p$. Thus, at most one exponent in each monomial needs reduction to transform the right-hand side of (3.3) into $R(X, Y)$. This is the point at which we use $p > 3$; for example, the reduction of $Y^{2p-4}$ to $Y^{p-3}$ requires $p - 3 \in \{1, \dots, p-1\}$.

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We now record the reduction explicitly. First, the term $a = 0$ gives $\alpha_0 Y^{p-3}$. For $1 \le r \le p-4$, the two indices $a = r$ and $a = r + p - 1$ both reduce to the same monomial

$$X^r Y^{p-3-r}.$$

The three boundary indices $a = p-3, p-2, p-1$ give respectively

$$\alpha_{p-3} X^{p-3} Y^{p-1}, \quad \alpha_{p-2} X^{p-2} Y^{p-2} \quad \text{and} \quad \alpha_{p-1} X^{p-1} Y^{p-3}.$$

Finally, since $\alpha_{2p-4} = 1$, the index $a = 2p-4$ gives $X^{p-3}$. Hence, the same function on $\mathbb{F}_p^2$ is represented by

$$\begin{aligned} R(X,Y) = \alpha_0 Y^{p-3} + \sum_{r=1}^{p-4} (\alpha_r + \alpha_{r+p-1}) X^r Y^{p-3-r} + X^{p-3} \\ + \alpha_{p-3} X^{p-3} Y^{p-1} + \alpha_{p-2} X^{p-2} Y^{p-2} + \alpha_{p-1} X^{p-1} Y^{p-3}. \end{aligned} \tag{3.4}$$

Let $m = (p-3)/2$. Since $p > 3$, we have $1 \le m \le p-4$. In (3.4), the only possible nonzero entry in row $m$ of $C$ is

$$C_{m,p-3-m} = \alpha_m + \alpha_{m+p-1},$$

and this is zero by Lemma 3.2. Hence, row $m$ is zero. In addition, row 0 and row $p-1$ can have nonzero entries only in column $p-3$, so these two rows are linearly dependent. These rows are distinct from row $m$. Consequently, the row rank of $C$ is at most $p-2$. □

PROPOSITION 3.4. *Let $p > 3$ be a prime, let $c, d \in \mathbb{Z}$ and suppose that $(d/p) = -1$. Then,*

$$D_p(c,d) \equiv 0 \pmod{p^2}.$$

PROOF. Let $a_i$ denote the residue class of $i$ in $\mathbb{F}_p$. Let

$$M = [(a_i^2 + c a_i a_j + d a_j^2)^{p-2}]_{0 \le i,j \le p-1}$$

be the reduction modulo $p$ of the integer matrix defining $D_p(c,d)$. Here, $c$ and $d$ are also viewed modulo $p$. By Lemma 3.1, it is enough to prove that

$$\operatorname{rank}_{\mathbb{F}_p} M \le p-2.$$

Let $R(X,Y)$ and $C = (C_{r,s})$ be as in Lemma 3.3. Since $R$ represents the same function on $\mathbb{F}_p^2$ as $(X^2 + cXY + dY^2)^{p-2}$, we have

$$M = [R(a_i, a_j)]_{0 \le i,j \le p-1}.$$

Set

$$V = (a_i^r)_{0 \le i, r \le p-1}.$$

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Then,

$$M = VCV^{\mathrm{t}}.$$

Hence,

$$\operatorname{rank}_{\mathbb{F}_p} M \le \operatorname{rank}_{\mathbb{F}_p} C \le p - 2$$

by Lemma 3.3. Lemma 3.1, with $N = p$ and $r = 2$, now yields $p^2 \mid D_p(c, d)$. □

PROOF OF THEOREM 1.1. If $n$ is composite, the assertion follows from Proposition 2.2. If $n$ is prime, then the assumption in the theorem is precisely $(d/n) = -1$ as a Legendre-symbol condition, and Proposition 3.4 applies. □

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