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ON SUMS OF BINOMIAL COEFFICIENTS MODULO p^2

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Abstract. Let p be an odd prime and let a be a positive integer. In this paper we investigate the sum $\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\binom{2k}{k}/m^k \bmod p^2$, where h and m are p-adic integers with $m\not\equiv 0 \pmod p$. For example, we show that if $h\not\equiv 0\pmod p$ and $p^a>3$, then

$$\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\binom{2k}{k}\left(-\frac{h}{2}\right)^k\equiv\left(\frac{1-2h}{p^a}\right)\left(1+h\left(\left(4-\frac{2}{h}\right)^{p-1}-1\right)\right)\pmod{p^2},$$

where $(\frac{\cdot}{\cdot})$ denotes the Jacobi symbol. Here is another remarkable congruence: If $p^a>3$ then

$$\sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\binom{2k}{k}(-1)^k\equiv 3^{p-1}\left(\frac{p^a}{3}\right)\pmod{p^2}.$$

1. Introduction. Let $p>3$ be a prime. In 1828 Gauss (cf. [BEW, (9.0.1)]) proved that if $p\equiv 1\pmod 4$ and $p=x^2+y^2$ with $x\equiv 1\pmod 4$ and $y\equiv 0\pmod 2$ then

$$\binom{(p-1)/2}{(p-1)/4}\equiv 2x\pmod p.$$

In 1862 J. Wolstenholme [W] established the classical congruence

$$\frac{1}{2}\binom{2p}{p}=\binom{2p-1}{p-1}\equiv 1\pmod{p^3}.$$

In 1895 F. Morley [M] showed that

$$\binom{p-1}{(p-1)/2}\equiv(-1)^{(p-1)/2}4^{p-1}\pmod{p^3}.$$

Since

$$\frac{\binom{2k}{k}}{(-4)^k}=\binom{-1/2}{k}\equiv\binom{(p-1)/2}{k}\pmod p\quad\text{for all }k=0,1,\ldots,p-1,$$

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it is apparent that

$$\sum_{k=0}^{p-1}\binom{2k}{k}\equiv\sum_{k=0}^{(p-1)/2}\binom{(p-1)/2}{k}(-4)^k=(-3)^{(p-1)/2}\equiv\left(\frac{-3}{p}\right)\pmod p,$$

where $(\frac{\cdot}{\cdot})$ denotes the Jacobi symbol. In 2006, H. Pan and Z. W. Sun [PS] derived the congruence

$$\sum_{k=0}^{p-1}\binom{2k}{k+d}\equiv\left(\frac{p-d}{3}\right)\pmod p\quad\text{ for }d=0,\ldots,p$$

from a sophisticated combinatorial identity. Later Sun and R. Tauraso [ST2] proved further that

$$\sum_{k=0}^{p^a-1}\binom{2k}{k}\equiv\left(\frac{p^a}{3}\right)\pmod{p^2}$$

for any $a\in\mathbb{Z}^+=\{1,2,\ldots\}$. Moreover, Sun and Tauraso determined $\sum_{k=0}^{p-1}\binom{2k}{k}/m^k \bmod p$ via the identity

$$\sum_{k=0}^{p-1}\binom{2k}{k}x^{p-1-k}=\sum_{k=0}^{p-1}\binom{2p}{k}u_{p-k}(x-2)$$

(cf. [ST1, (2.1)]), where

$$u_0(x)=0,\quad u_1(x)=1,\quad\text{and}\quad u_{n+1}(x)=xu_n(x)-u_{n-1}(x)\quad(n=1,2,\ldots).$$

Now we need to introduce Lucas sequences.

Let $A,B\in\mathbb{Z}$. The *Lucas sequences* $u_n=u_n(A,B)$ $(n\in\mathbb{N}=\{0,1,\ldots\})$ and $v_n=v_n(A,B)$ $(n\in\mathbb{N})$ are defined by

$$u_0=0,\quad u_1=1,\quad\text{and}\quad u_{n+1}=Au_n-Bu_{n-1}\quad(n=1,2,\ldots)$$

and

$$v_0=2,\quad v_1=A,\quad\text{and}\quad v_{n+1}=Av_n-Bv_{n-1}\quad(n=1,2,\ldots).$$

The characteristic equation $x^2-Ax+B=0$ has two roots

$$\alpha=\frac{A+\sqrt{\Delta}}{2}\quad\text{and}\quad\beta=\frac{A-\sqrt{\Delta}}{2},$$

where $\Delta=A^2-4B$. It is well known that for any $n\in\mathbb{N}$ we have

$$u_n=\sum_{0\le k<n}\alpha^k\beta^{n-1-k}=\begin{cases}(\alpha^n-\beta^n)/(\alpha-\beta)&\text{if }\Delta\ne0,\\ n\alpha^{n-1}=n(A/2)^{n-1}&\text{if }\Delta=0,\end{cases}$$

and also $v_n=\alpha^n+\beta^n$. If p is a prime then

$$v_p=\alpha^p+\beta^p\equiv(\alpha+\beta)^p=A^p\equiv A\pmod p.$$

It is also known that

$$u_p \equiv \left(\frac{\Delta}{p}\right) \pmod p \quad \text{and} \quad u_{p-(\frac{\Delta}{p})} \equiv 0 \pmod p$$

for any prime p not dividing $2B$. (See, e.g., [S10, Lemma 2.3].) The reader may consult [S06] for connections between Lucas sequences and quadratic fields. If $A = a + 1$ and $B = a$ for some integer $a \not\equiv 0, 1 \pmod p$ where p is an odd prime, then $\Delta = (a-1)^2$ and

$$\frac{u_{p-(\frac{\Delta}{p})}}{p} = \frac{u_{p-1}}{p} = \frac{1}{a-1} \cdot \frac{a^{p-1}-1}{p}.$$

In the paper [S10] the author proved that for any odd prime p and integer $m \not\equiv 0 \pmod p$ we have

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}}{m^k} \equiv \left(\frac{m(m-4)}{p}\right) + u_{p-(\frac{m(m-4)}{p})}(m-2, 1) \pmod{p^2}.$$

See also [SSZ] and [S11a] for related results on p-adic valuations.

For a sequence $\{a_n\}_{n\ge 0}$ of complex numbers, its dual sequence is given by $\{a_n^*\}_{n\ge 0}$, where

$$a_n^* = \sum_{k=0}^{n} \binom{n}{k} (-1)^k a_k \quad (n = 0, 1, \ldots).$$

It is well known that $(a_n^*)^* = a_n$ for all $n \in \mathbb{N}$ (see [GKP, (5.48)], and also [S03]). Let p be an odd prime and let m be an integer not divisible by p. Clearly

$$\sum_{k=0}^{p-1} \binom{p-1}{k} (-1)^k \frac{\binom{2k}{k}}{m^k} \equiv \sum_{k=0}^{p-1} \frac{\binom{2k}{k}}{m^k} \pmod p$$

since $\binom{p-1}{k} \equiv (-1)^k \pmod p$ for all $k = 0, 1, \ldots, p-1$. As $\sum_{k=0}^{p-1}\binom{2k}{k}/m^k$ mod p^2 has been determined, it is natural to seek for the determination of $\sum_{k=0}^{p-1}\binom{p-1}{k}\binom{2k}{k}/(-m)^k$ mod p^2, which is the main goal of this paper.

Let p be an odd prime. When $p \equiv 3 \pmod 4$, the author [S11b] noted that

$$\sum_{k=0}^{p-1} \frac{\binom{2k}{k}^2}{8^k} \equiv 0 \pmod p$$

and conjectured further that

$$\sum_{k=0}^{p-1} \binom{p-1}{k} \frac{\binom{2k}{k}^2}{(-8)^k} \equiv 0 \pmod{p^2}.$$

In [S11b, (1.11)] it was shown that $\sum_{k=0}^{p-1}\binom{p-1}{k}\binom{2k}{k}^3/(-64)^k \equiv 0 \pmod{p^2}$ if $p > 3$ and $p \equiv 3 \pmod 4$. Inspired by these, we are led to think that it is really worth studying $\sum_{k=0}^{p-1}\binom{p-1}{k}\binom{2k}{k}/(-m)^k$ mod p^2 (with m a p-adic integer not divisible by p), which might behave better than $\sum_{k=0}^{p-1}\binom{2k}{k}/m^k$ mod p^2 in some cases.

We shall state our main results in the next section and provide some lemmas in Section 3. Section 4 is devoted to the proofs of our theorems.

2. The main results. For a prime p we use $\mathbb{Z}_p$ to denote the ring of p-adic integers; if $h \in \mathbb{Z}_p$ and $h \not\equiv 0 \pmod p$ then we denote the quotient $(h^{p-1}-1)/p \in \mathbb{Z}_p$ by $q_p(h)$ and call it a *Fermat quotient*. For $m, n \in \mathbb{N}$, the Kronecker symbol $\delta_{m,n}$ means 1 or 0 according as $m = n$ or not.

Now we state our main results and give some corollaries.

THEOREM 2.1. *Let p be an odd prime and let $a \in \mathbb{Z}^+$. Let h be a p-adic integer with $h \not\equiv 0 \pmod p$, and ($2h \not\equiv 1 \pmod p$ or $p^a > 3$). Then*

$$\begin{aligned}(2.1)\qquad \sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\binom{2k}{k}\left(-\frac{h}{2}\right)^k \\ \equiv \left(\frac{1-2h}{p^a}\right)\left(1+h\left(\left(4-\frac{2}{h}\right)^{p-1}-1\right)\right) \pmod{p^2}.\end{aligned}$$

COROLLARY 2.1. *Let p be an odd prime and let $a \in \mathbb{Z}^+$. Then*

$$(2.2)\qquad \sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\frac{\binom{2k}{k}}{(-2)^k} \equiv (-1)^{(p^a-1)/2}2^{p-1} \pmod{p^2}.$$

Proof. Simply apply Theorem 2.1 with $h = 1$. ∎

REMARK 2.1. Let $m \in \mathbb{Z}$ and $n \in \mathbb{Z}^+$. Later we will show that

$$\begin{aligned}(2.3)\qquad \sum_{k=0}^{n-1}\binom{n-1}{k}\binom{2k}{k}(-1)^k m^{n-1-k} \\ = \sum_{k=0}^{\lfloor (n-1)/2\rfloor}\binom{n-1}{k}\binom{n-1-k}{k}(m-2)^{n-1-2k}.\end{aligned}$$

Thus, for any prime $p > 3$, by applying Morley's congruence (cf. [M], [C] and [P])

$$\binom{p-1}{(p-1)/2} \equiv (-1)^{(p-1)/2}4^{p-1} \pmod{p^3}$$

we get

$$\sum_{k=0}^{p-1}\binom{p-1}{k}\frac{\binom{2k}{k}}{(-2)^k} \equiv (-1)^{(p-1)/2}2^{p-1} \pmod{p^3},$$

which is a refinement of (2.2) in the case $a = 1$.

COROLLARY 2.2. *Let $p > 3$ be a prime and let $a \in \mathbb{Z}^+$. Then*

$$\sum_{k=0}^{p^a-1}\binom{2p^a-1}{k}\binom{2k}{k}(-1)^k \equiv \left(\frac{p^a}{3}\right)(2\cdot 3^{p-1}-1) \pmod{p^2} \tag{2.4}$$

and

$$\sum_{k=0}^{p^a-1}\binom{p^a+k}{k}\frac{\binom{2k}{k}}{(-2)^k} \equiv \left(\frac{3}{p^a}\right)(1-p(q_p(2)+q_p(3))) \pmod{p^2}. \tag{2.5}$$

Proof. Just put $h = 2$ and $h = -1$ in (2.1) and note that $\binom{-x}{k} = (-1)^k\binom{x+k-1}{k}$. ∎

COROLLARY 2.3. *Let p be an odd prime and let $a \in \mathbb{Z}^+$. Then*

$$\sum_{k=0}^{p^a-1}\binom{2p^a+k}{k}\binom{2k}{k}(-1)^k \equiv \left(\frac{p^a}{5}\right)(3-2\cdot 5^{p-1}) \pmod{p^2}. \tag{2.6}$$

Proof. Simply apply (2.1) with $h = -2$. ∎

Our next result is more general than Theorem 2.1.

THEOREM 2.2. *Let p be an odd prime and let $m \in \mathbb{Z}$ with $p \nmid m$. Set $\Delta = m(m-4)$ and let $h \in \mathbb{Z}_p$. Then*

$$\begin{aligned}(2.7)\quad &\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\frac{\binom{2k}{k}}{(-m)^k}\\ &\equiv \left(\frac{\Delta}{p^{a-1}}\right)\left(1-\frac{hm}{2}\right)u_{p-(\frac{\Delta}{p})}(m-2,1) + \left(\frac{\Delta}{p^a}\right)(1+h((m-4)^{p-1}-1))\\ &\quad - \begin{cases} h(m-4) \pmod{p^2} & \text{if } p^a = 3 \text{ and } 3 \mid m-1,\\ 0 \pmod{p^2} & \text{otherwise.}\end{cases}\end{aligned}$$

In particular, if $hm \equiv 2 \pmod p$ then

$$\begin{aligned}(2.8)\quad &\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\frac{\binom{2k}{k}}{(-m)^k}\\ &\qquad\equiv \left(\frac{\Delta}{p^a}\right)(1+h((m-4)^{p-1}-1))\\ &\qquad\quad + \begin{cases} m-4 \pmod{p^2} & \text{if } p^a = 3 \text{ and } 3 \mid m-1,\\ 0 \pmod{p^2} & \text{otherwise.}\end{cases}\end{aligned}$$

COROLLARY 2.4. *Let p be an odd prime and let $a \in \mathbb{Z}^+$. If $p^a > 3$, then*

$$\sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\binom{2k}{k}(-1)^k \equiv 3^{p-1}\left(\frac{p^a}{3}\right) \pmod{p^2}. \tag{2.9}$$

If $p\neq 3$, then

$$\sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\frac{\binom{2k}{k}}{(-3)^k}\equiv\left(\frac{p^a}{3}\right)\pmod{p^2}. \tag{2.10}$$

Proof. Just apply (2.7) with $h=1$ and $m\in\{1,3\}$ and note that $(-1)^{n-1}u_n(1,1)=u_n(-1,1)=(\frac{n}{3})$ for $n\in\mathbb{N}$. ∎

Corollary 2.5. *Let $p\neq 2,5$ be a prime and let $a\in\mathbb{Z}^+$. Then*

$$\sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\binom{2k}{k}\equiv\left(\frac{p^a}{5}\right)(5^{p-1}-3F_{p-(\frac{p}{5})})\pmod{p^2} \tag{2.11}$$

and

$$\sum_{k=0}^{p^a-1}\binom{p^a-1}{k}\frac{\binom{2k}{k}}{(-5)^k}\equiv\left(\frac{p^a}{5}\right)(1-3F_{p-(\frac{p}{5})})\pmod{p^2}, \tag{2.12}$$

where $\{F_n\}_{n\geq 0}$ is the well-known Fibonacci sequence defined by

$$F_0=0,\quad F_1=1,\quad \text{and}\quad F_{n+1}=F_n+F_{n-1}\quad (n=1,2,\ldots).$$

Proof. Observe that

$$(-1)^{n-1}u_n(-3,1)=u_n(3,1)=F_{2n}=F_nL_n,$$

where $L_n=v_n(1,-1)$. By [SS, Corollary 1] (or the proof of Corollary 1.3 of [ST1]), if $p\neq 2,5$ then $L_{p-(\frac{p}{5})}\equiv 2(\frac{p}{5})\pmod{p^2}$. In view of this, if we apply (2.7) with $h=1$ and $m\in\{-1,5\}$ then we obtain the desired result. ∎

To conclude this section we raise four conjectures based on our computation via `Mathematica`.

Conjecture 2.1. *Let p be an odd prime and let h be an integer with $h\equiv(p+1)/2\pmod p$. If $p^a>3$ with $a\in\mathbb{Z}^+$, then*

$$\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\binom{2k}{k}(-h/2)^k\equiv 0\pmod{p^{a+1}}.$$

Also, for any $n\in\mathbb{Z}^+$,

$$\frac{1}{n}\sum_{k=0}^{n-1}\binom{hn-1}{k}\binom{2k}{k}(-h/2)^k\in\mathbb{Z}_p.$$

Conjecture 2.2. *Let p be an odd prime.*

(i) *If $p\equiv 1\pmod 8$, then*

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{u_k(2,-1)}{(-8)^k}\equiv\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{kv_k(2,-1)}{(-8)^k}\equiv 0\pmod{p^2}.$$

If $p \equiv 7 \pmod 8$, *then*

$$\sum_{k=0}^{p-1}\binom{p-1}{k}\binom{2k}{k}^2\frac{u_k(2,-1)}{8^k} \equiv 0 \pmod{p^2}.$$

(ii) *If* $p \equiv 1 \pmod{12}$, *then*

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{u_k(4,1)}{4^k} \equiv 0 \pmod{p^2}.$$

If $p \equiv 11 \pmod{12}$, *then*

$$\sum_{k=0}^{p-1}\binom{p-1}{k}\binom{2k}{k}^2\frac{v_k(4,1)}{(-4)^k} \equiv 0 \pmod{p^2}.$$

Recall that any prime $p \equiv 1, 3 \pmod 8$ can be uniquely written as x^2+2y^2 with $x, y \in \mathbb{Z}^+$, and any prime $p \equiv 1 \pmod 3$ can be uniquely written in the form $x^2 + 3y^2$ with $x, y \in \mathbb{Z}^+$. (See, e.g., [Co, p. 7].) The following two conjectures are related to Conjecture 2.2 and look more difficult.

CONJECTURE 2.3. *Let p be a prime with $p \equiv 1, 3 \pmod 8$. Write $p = x^2 + 2y^2$ with $x, y \in \mathbb{Z}$ so that $x \equiv 1 \pmod 4$, and $y \equiv 1 \pmod 4$ if $p \equiv 3 \pmod 8$. Then*

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{ku_k(2,-1)}{(-8)^k} \equiv \frac{p}{4x} - \frac{x}{2} \pmod{p^2}$$

and

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{v_k(2,-1)}{(-8)^k} \equiv 4x - \frac{p}{x} \pmod{p^2}.$$

If $p \equiv 1 \pmod 8$, *then*

$$\begin{aligned}4\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{ku_k(2,-1)}{32^k} &\equiv \sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{kv_k(2,-1)}{32^k}\\ &\equiv (-1)^{(p-1)/8+(x-1)/4}\left(\frac{p}{x} - 2x\right) \pmod{p^2},\end{aligned}$$

and we can determine x mod p^2 via the congruence

$$(-1)^{(x-1)/4}x \equiv \frac{(-1)^{(p-1)/8}}{2}\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{(k+1)v_k(2,-1)}{32^k} \pmod{p^2}.$$

If $p\equiv 3\pmod 8$, *then*

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{u_k(2,-1)}{(-8)^k}\equiv(-1)^{(p-3)/8+(x-1)/4}\left(\frac{p}{2x}-2x\right)\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{kv_k(2,-1)}{(-8)^k}\equiv(-1)^{(p-3)/8+(x-1)/4}2\left(x+\frac{p}{x}\right)\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{ku_k(2,-1)}{32^k}\equiv\frac12\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{kv_k(2,-1)}{32^k}\equiv -y\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{u_k(2,-1)}{32^k}\equiv 2y-\frac{p}{4y}\pmod{p^2}.$$

CONJECTURE 2.4. *Let $p>3$ be a prime.*

(i) *If* $p\equiv 1\pmod{12}$ *and* $p=x^2+3y^2$ *with* $x,y\in\mathbb{Z}$ *and* $x\equiv 1\pmod 4$, *then*

$$(-1)^{(p-1)/4}\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{v_k(4,1)}{4^k}\equiv\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{v_k(4,1)}{64^k}\equiv 4x-\frac{p}{x}\pmod{p^2};$$

also we can determine x mod p^2 by

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{(k+2)v_k(4,1)}{4^k}\equiv(-1)^{(p-1)/4}\,4x\pmod{p^2}$$

as well as

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{(k-1)v_k(4,1)}{64^k}\equiv -2x\pmod{p^2}.$$

(ii) *If* $p\equiv 7\pmod{12}$ *and* $p=x^2+3y^2$ *with* $x,y\in\mathbb{Z}$ *and* $y\equiv 1\pmod 4$, *then*

$$\sum_{k=0}^{p-1}\frac{u_k(4,1)}{64^k}\binom{2k}{k}^2\equiv 2y-\frac{p}{6y}\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{u_k(4,1)}{4^k}\equiv(-1)^{(p+1)/4}\left(4y-\frac{p}{3y}\right)\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{v_k(4,1)}{4^k}\equiv(-1)^{(p-3)/4}\left(12y-\frac{p}{y}\right)\pmod{p^2},$$

$$\sum_{k=0}^{p-1}\binom{2k}{k}^2\frac{kv_k(4,1)}{4^k}\equiv(-1)^{(p+1)/4}\left(20y-\frac{8p}{y}\right)\pmod{p^2},$$

and also

$$y \equiv \sum_{k=0}^{p-1} \binom{2k}{k}^2 \frac{ku_k(4,1)}{64^k} \equiv \frac{1}{4}\sum_{k=0}^{p-1} \binom{2k}{k}^2 \frac{kv_k(4,1)}{64^k}$$
$$\equiv \frac{(-1)^{(p+1)/4}}{22} \sum_{k=0}^{p-1} \binom{2k}{k}^2 \frac{(k+7)u_k(4,1)}{4^k} \pmod{p^2}.$$

3. Some lemmas. Recall that the *harmonic numbers* H_n $(n \in \mathbb{N})$ are defined by $H_n = \sum_{0<k\le n} 1/k$. The reader may consult [S12a] and [S12b] for some fundamental congruences involving harmonic numbers.

LEMMA 3.1. *Let p be an odd prime and let $a \in \mathbb{Z}^+$. Let $m \in \mathbb{Z}$ with $p \nmid m$. If $p \mid m-4$ then*

$$\sum_{k=1}^{p^a-1} \frac{p^{a-1}H_k}{m^k}\binom{2k}{k} \equiv 2\delta_{a,1} \pmod{p}. \tag{3.1}$$

If $m \not\equiv 4 \pmod{p}$, then

$$\sum_{k=1}^{p^a-1} \frac{p^{a-1}H_k}{m^k}\binom{2k}{k} \equiv -\left(\frac{m(m-4)}{p^a}\right)\sum_{k=1}^{p-1} \frac{\binom{2k}{k}}{k(4-m)^k} \pmod{p}. \tag{3.2}$$

Proof. For $k = 1, \ldots, (p^a-1)/2$, we have

$$\frac{\binom{(p^a-1)/2}{k}}{\binom{2k}{k}/(-4)^k} = \frac{\binom{(p^a-1)/2}{k}}{\binom{-1/2}{k}} = \prod_{j=1}^{k} \frac{(p^a-1)/2-j+1}{-1/2-j+1}$$
$$= \prod_{j=1}^{k}\left(1 - \frac{p^a}{2j-1}\right) \equiv 1 \pmod{p}.$$

If $k \in \{(p^a+1)/2, \ldots, p^a-1\}$, then $2k-p^a \in \{1, \ldots, k-1\}$ and hence

$$\binom{2k}{k} = \binom{p^a+(2k-p^a)}{k} \equiv \binom{p^a}{0}\binom{2k-p^a}{k} = 0 \pmod{p}$$

with the help of Lucas' congruence (cf. [St, p. 44]). So, for any $k = 0, \ldots, p^a-1$ we have

$$\binom{2k}{k} \equiv (-4)^k \binom{(p^a-1)/2}{k} \pmod{p}. \tag{3.3}$$

Therefore

$$\sum_{k=1}^{p^a-1} \frac{p^{a-1}H_k}{m^k}\binom{2k}{k} \equiv \sum_{k=1}^{(p^a-1)/2} \binom{(p^a-1)/2}{k}(-4/m)^k(p^{a-1}H_k) \pmod{p}.$$

(Note that $p^{a-1}H_k = \sum_{j=1}^{k} p^{a-1}/j \in \mathbb{Z}_p$ for every $k = 1, \ldots, p^a-1$.)

For each $k\in\mathbb{N}$ clearly

$$\begin{aligned}H_k&=\sum_{0<j\le k}\int_0^1 x^{j-1}\,dx=\int_0^1\sum_{0<j\le k}x^{j-1}\,dx\\&=\int_0^1\frac{1-x^k}{1-x}\,dx=\int_0^1\frac{1-(1-t)^k}{t}\,dt.\end{aligned}$$

Thus

$$\sum_{k=1}^{p^a-1}\frac{p^{a-1}H_k}{m^k}\binom{2k}{k}\equiv p^{a-1}\Sigma\ (\mathrm{mod}\ p),$$

where

$$\begin{aligned}\Sigma:&=\int_0^1\sum_{k=0}^{(p^a-1)/2}\binom{(p^a-1)/2}{k}\left(-\frac{4}{m}\right)^k\frac{1-(1-t)^k}{t}\,dt\\&=\int_0^1\frac{(1-4/m)^{(p^a-1)/2}-(1-(1-t)4/m)^{(p^a-1)/2}}{t}\,dt\\&=-\sum_{k=1}^{(p^a-1)/2}\binom{(p^a-1)/2}{k}\left(1-\frac{4}{m}\right)^{(p^a-1)/2-k}\int_0^1\left(\frac{4t}{m}\right)^k\frac{dt}{t}\\&=-\frac{1}{m^{(p^a-1)/2}}\sum_{k=1}^{(p^a-1)/2}\binom{(p^a-1)/2}{k}\frac{4^k}{k}(m-4)^{(p^a-1)/2-k}.\end{aligned}$$

If $m\equiv 4\ (\mathrm{mod}\ p)$, then

$$p^{a-1}\Sigma=-\frac{1}{m^{(p^a-1)/2}}\cdot\frac{p^{a-1}}{(p^a-1)/2}\,4^{(p^a-1)/2}\equiv 2\delta_{a,1}\ (\mathrm{mod}\ p)$$

and hence (3.1) holds.

Now assume that $m\not\equiv 4\ (\mathrm{mod}\ p)$. In view of (3.3),

$$\begin{aligned}p^{a-1}\Sigma&\equiv-\frac{(m(m-4))^{(p^a-1)/2}}{m^{p^a-1}}\sum_{k=1}^{p^a-1}\binom{2k}{k}\frac{(-1)^kp^{a-1}}{k(m-4)^k}\\&\equiv-\left(\frac{m(m-4)}{p^a}\right)p^{a-1}\sum_{k=1}^{p^a-1}\frac{\binom{2k}{k}}{k(4-m)^k}\ (\mathrm{mod}\ p).\end{aligned}$$

So it suffices to prove that

$$p^{a-1}\sum_{k=1}^{p^a-1}\frac{\binom{2k}{k}}{kn^k}\equiv\sum_{k=1}^{p-1}\frac{\binom{2k}{k}}{kn^k}\ (\mathrm{mod}\ p)$$

for any $n \in \mathbb{Z}$ with $p \nmid n$. If $p^{a-1} \nmid k$ then $p^{a-1}/k \equiv 0 \pmod p$. Therefore

$$p^{a-1} \sum_{k=1}^{p^a-1} \frac{\binom{2k}{k}}{kn^k} \equiv p^{a-1} \sum_{j=1}^{p-1} \frac{\binom{2p^{a-1}j}{p^{a-1}j}}{p^{a-1}jn^{p^{a-1}j}} \equiv \sum_{j=1}^{p-1} \frac{\binom{2j}{j}}{jn^j} \pmod p$$

in view of the Lucas congruence. ■

Lemma 3.2 (Sun [S10]). *Let p be an odd prime and let $a \in \mathbb{Z}^+$. Let m be any integer not divisible by p and set $\Delta = m(m-4)$. Then*

$$\sum_{k=0}^{p^a-1} \frac{\binom{2k}{k}}{m^k} \equiv \left(\frac{\Delta}{p^a}\right) + \left(\frac{\Delta}{p^{a-1}}\right) u_{p-(\frac{\Delta}{p})}(m-2,1) \pmod{p^2}.$$

Lemma 3.3 (Sun and Tauraso [ST1, Theorem 1.2]). *Let p be any prime and let m be an integer not divisible by p. Then*

$$\frac{1}{2} \sum_{k=1}^{p-1} (-1)^k \frac{\binom{2k}{k}}{km^{k-1}} \equiv \frac{m^p - v_p(m,-m)}{p} \pmod p.$$

Lemma 3.4. *Let p be an odd prime and let $m \in \mathbb{Z}$ with $\Delta = m(m-4) \not\equiv 0 \pmod p$. Then*

$$(3.4) \qquad \frac{2}{m-4} \cdot \frac{v_p(m-4,4-m) - (m-4)^p}{p} \equiv \frac{m}{2}\left(\frac{\Delta}{p}\right) \frac{u_{p-(\frac{\Delta}{p})}(m-2,1)}{p} - q_p(m-4) \pmod p.$$

Proof. (i) Let us first show the equality

$$(3.5) \qquad \frac{v_{2n+1}(m-4,4-m)}{(m-4)^{n+1}} = \frac{u_{2n+1}(m,m)}{m^n}$$

for $n = 0, 1, \ldots$. Clearly both sides of (3.5) are 1 when $n = 0$. Note that

$$\begin{aligned} &\frac{v_3(m-4,4-m)}{(m-4)^2} \\ &= \frac{v_2(m-4,4-m) + v_1(m-4,4-m)}{m-4} \\ &= v_1(m-4,4-m) + v_0(m-4,4-m) + \frac{v_1(m-4,4-m)}{m-4} \\ &= m-4+2+1 = m-1 = u_2(m,m) - u_1(m,m) = \frac{u_3(m,m)}{m}. \end{aligned}$$

Also, for $n = 2, 3, \dots$ we have

$$\begin{aligned}
&\frac{v_{2n+1}(m-4,4-m)}{(m-4)^{n+1}}\\
&\quad=\frac{v_{2n-1}(m-4,4-m)+v_{2n}(m-4,4-m)}{(m-4)^n}\\
&\quad=\frac{(1+(m-4))v_{2n-1}(m-4,4-m)+(m-4)v_{2n-2}(m-4,4-m)}{(m-4)^n}\\
&\quad=\frac{(m-2)v_{2n-1}(m-4,4-m)-(m-4)v_{2n-3}(m-4,4-m)}{(m-4)^n}\\
&\quad=(m-2)\frac{v_{2n-1}(m-4,4-m)}{(m-4)^n}-\frac{v_{2n-3}(m-4,4-m)}{(m-4)^{n-1}}
\end{aligned}$$

and

$$\begin{aligned}
\frac{u_{2n+1}(m,m)}{m^n}&=\frac{u_{2n}(m,m)-u_{2n-1}(m,m)}{m^{n-1}}\\
&=\frac{(m-1)u_{2n-1}(m,m)-mu_{2n-2}(m,m)}{m^{n-1}}\\
&=\frac{(m-1)u_{2n-1}(m,m)-(u_{2n-1}(m,m)+mu_{2n-3}(m,m))}{m^{n-1}}\\
&=(m-2)\frac{u_{2n-1}(m,m)}{m^{n-1}}-\frac{u_{2n-3}(m,m)}{m^{n-2}}.
\end{aligned}$$

Thus, by induction, (3.5) holds for all $n \in \mathbb{N}$.

(ii) By part (i),

$$u_p(m,m)=\frac{m^{(p-1)/2}}{(m-4)^{(p+1)/2}}(v_p(m-4,4-m)-(m-4)^p)+(m(m-4))^{(p-1)/2}.$$

Since $v_p(m-4,4-m)\equiv(m-4)^p \pmod p$ and

$$\begin{aligned}
&\Delta^{(p-1)/2}-\left(\frac{\Delta}{p}\right)\\
&=(m-4)^{(p-1)/2}\left(m^{(p-1)/2}-\left(\frac{m}{p}\right)\right)+\left(\frac{m}{p}\right)\left((m-4)^{(p-1)/2}-\left(\frac{m-4}{p}\right)\right)\\
&\equiv\left(\frac{\Delta}{p}\right)\left(\frac{m}{p}\right)\left(m^{(p-1)/2}-\left(\frac{m}{p}\right)\right)\\
&\quad+\left(\frac{\Delta}{p}\right)\left(\frac{m-4}{p}\right)\left((m-4)^{(p-1)/2}-\left(\frac{m-4}{p}\right)\right)\\
&\equiv\frac{1}{2}\left(\frac{\Delta}{p}\right)(m^{p-1}-1+(m-4)^{p-1}-1) \pmod{p^2},
\end{aligned}$$

we have

$$
\begin{aligned}
u_p(m,m)-\left(\frac{\Delta}{p}\right) &\equiv \frac{\binom{m}{p}}{(m-4)\binom{m-4}{p}}(v_p(m-4,4-m)-(m-4)^p)\\
&\quad+\frac{1}{2}\left(\frac{\Delta}{p}\right)(m^{p-1}-1+(m-4)^{p-1}-1)\\
&\equiv \frac{1}{m-4}\left(\frac{\Delta}{p}\right)(v_p(m-4,4-m)-(m-4)^p)\\
&\quad+\frac{p}{2}\left(\frac{\Delta}{p}\right)(q_p(m)+q_p(m-4)) \pmod{p^2}.
\end{aligned}
$$

On the other hand, by [S10, Lemma 2.4] we have

$$
2u_p(m,m)-\left(\frac{\Delta}{p}\right)m^{p-1}\equiv u_p(m-2,1)+u_{p-(\frac{\Delta}{p})}(m-2,1) \pmod{p^2}.
$$

Thus

$$
\begin{aligned}
&\frac{2}{m-4}\left(\frac{\Delta}{p}\right)(v_p(m-4,4-m)-(m-4)^p)\\
&\equiv u_p(m-2,1)-\left(\frac{\Delta}{p}\right)+u_{p-(\frac{\Delta}{p})}(m-2,1)-\left(\frac{\Delta}{p}\right)p\,q_p(m-4) \pmod{p^2}.
\end{aligned}
$$

In view of this, we have reduced (3.4) to the congruence

$$
u_p(m-2,1)-\left(\frac{\Delta}{p}\right)\equiv\left(\frac{m}{2}-1\right)u_{p-(\frac{\Delta}{p})}(m-2,1) \pmod{p^2}. \tag{3.6}
$$

Let α and β be the two roots of the equation $x^2-(m-2)x+1=0$. Then

$$
v_n(m-2,1)^2-\Delta u_n^2(m-2,1)=(\alpha^n+\beta^n)^2-(\alpha^n-\beta^n)^2=4(\alpha\beta)^n=4
$$

for all $n\in\mathbb{N}$. As $u_{p-(\frac{\Delta}{p})}(m-2,1)\equiv 0 \pmod{p}$ we have

$$
v_{p-(\frac{\Delta}{p})}(m-2,1)^2-4\equiv 0 \pmod{p^2}.
$$

By [S10, Lemma 2.3], $v_{p-(\frac{\Delta}{p})}(m-2,1)\equiv 2 \pmod{p}$. So

$$
v_{p-(\frac{\Delta}{p})}(m-2,1)\equiv 2 \pmod{p^2}.
$$

By induction, $(m-2)u_n(m-2,1)\pm v_n(m-2,1)=2u_{n\pm1}(m-2,1)$ for all $n\in\mathbb{Z}^+$. Therefore

$$
\begin{aligned}
2u_p(m-2,1)&=(m-2)u_{p-(\frac{\Delta}{p})}(m-2,1)+\left(\frac{\Delta}{p}\right)v_{p-(\frac{\Delta}{p})}(m-2,1)\\
&\equiv(m-2)u_{p-(\frac{\Delta}{p})}(m-2,1)+2\left(\frac{\Delta}{p}\right) \pmod{p^2}
\end{aligned}
$$

and hence (3.6) follows.

The proof of Lemma 3.4 is now complete. ∎

Combining Lemmas 3.3 and 3.4 we get the following result.

LEMMA 3.5. *Let p be an odd prime and let $m\in\mathbb{Z}$ with $\Delta=m(m-4)\not\equiv 0\pmod p$. Then*

$$\sum_{k=1}^{p-1}(-1)^k\frac{\binom{2k}{k}}{k(m-4)^k}\equiv q_p(m-4)-\frac{m}{2}\left(\frac{\Delta}{p}\right)\frac{u_{p-(\frac{\Delta}{p})}(m-2,1)}{p}\pmod p. \tag{3.7}$$

4. Proofs of Theorems 2.1–2.2 and (2.3)

Proof of Theorem 2.2. For $k=0,\ldots,p^a-1$, clearly

$$\begin{aligned}\binom{hp^a-1}{k}(-1)^k&=(-1)^k\prod_{0<j\le k}\frac{hp^a-j}{j}=\prod_{0<j\le k}\left(1-h\frac{p^a}{j}\right)\\&\equiv 1-h\sum_{0<j\le k}\frac{p^a}{j}=1-hp^aH_k\pmod{p^2}.\end{aligned}$$

Thus

$$\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\frac{\binom{2k}{k}}{(-m)^k}\equiv\sum_{k=0}^{p^a-1}\frac{\binom{2k}{k}}{m^k}-hp^a\sum_{k=0}^{p^a-1}\frac{H_k}{m^k}\binom{2k}{k}\pmod{p^2}$$

and hence

$$\begin{aligned}&\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\frac{\binom{2k}{k}}{(-m)^k}+hp^a\sum_{k=0}^{p^a-1}\frac{H_k}{m^k}\binom{2k}{k}\\&\qquad\equiv\left(\frac{\Delta}{p^a}\right)+\left(\frac{\Delta}{p^{a-1}}\right)u_{p-(\frac{\Delta}{p})}(m-2,1)\pmod{p^2}\end{aligned}\tag{4.1}$$

with the help of Lemma 3.2.

If $p\nmid m-4$, then by combining (4.1), (3.2) and Lemma 3.5 we get

$$\begin{aligned}\sum_{k=0}^{p^a-1}\binom{hp^a-1}{k}\frac{\binom{2k}{k}}{(-m)^k}&\equiv\left(\frac{\Delta}{p^a}\right)+\left(\frac{\Delta}{p^{a-1}}\right)u_{p-(\frac{\Delta}{p})}(m-2,1)\\&+ph\left(\left(\frac{\Delta}{p^a}\right)q_p(m-4)-\frac{m}{2}\left(\frac{\Delta}{p^{a-1}}\right)\frac{u_{p-(\frac{\Delta}{p})}(m-2,1)}{p}\right)\pmod{p^2}\end{aligned}$$

and hence (2.7) follows. (Note that if $p^a=3$ and $3\mid m-1$ then $m\equiv 4\pmod p$.) In the case $m\equiv 4\pmod p$, we have

$$p^a\sum_{k=1}^{p^a-1}\frac{H_k}{m^k}\binom{2k}{k}\equiv 2p\delta_{a,1}\pmod{p^2}$$

by (3.1), and

$$\begin{aligned}u_{p-(\frac{\Delta}{p})}(m-2,1) &= u_p(m-2,1)\\ &\equiv p\left(\frac{m-2}{2}\right)^{p-1}+\delta_{p,3}\,pm\frac{m-4}{3}\equiv p+\delta_{p,3}(m-4) \pmod{p^2}\end{aligned}$$

by [S11a, Lemma 2.2]. So (4.1) also implies (2.7) when $p\mid m-4$.

Since $u_{p-(\frac{\Delta}{p})}(m-2,1)\equiv 0 \pmod p$ by [S10, Lemma 2.3], (2.7) in the case $hm\equiv 2 \pmod p$ yields (2.8). ∎

Proof of Theorem 2.1. Choose $m\in\mathbb{Z}$ such that $hm\equiv 2 \pmod{p^2}$. Clearly $p\nmid m$. Note that

$$m-4\equiv\frac{2}{h}-4=\frac{2-4h}{h} \pmod{p^2}.$$

So we get (2.1) by applying (2.8). ∎

Proof of (2.3). For $k\in\mathbb{N}$ clearly the constant term of

$$(2-x-x^{-1})^k=\frac{(-1)^k}{x^k}(x-1)^{2k}$$

is the central binomial coefficient $\binom{2k}{k}$. Observe that

$$\sum_{k=0}^{n-1}\binom{n-1}{k}(-1)^k m^{n-1-k}(2-x-x^{-1})^k=(m-2+x+x^{-1})^{n-1}.$$

Equating the constant terms of both sides we obtain

$$\begin{aligned}&\sum_{k=0}^{n-1}\binom{n-1}{k}\binom{2k}{k}(-1)^k m^{n-1-k}\\ &\qquad=\sum_{k=0}^{\lfloor (n-1)/2\rfloor}\binom{n-1}{k,k,n-1-2k}(m-2)^{n-1-2k},\end{aligned}$$

which is equivalent to (2.3). ∎

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