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AN EXTENSION OF LUCAS' THEOREM

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ABSTRACT. Let p be a prime. A famous theorem of Lucas states that $\binom{mp+s}{np+t} \equiv \binom{m}{n}\binom{s}{t} \pmod p$ if m, n, s, t are nonnegative integers with $s, t < p$. In this paper we aim to prove a similar result for generalized binomial coefficients defined in terms of second order recurrent sequences with initial values 0 and 1.

1. INTRODUCTION

Let $\mathbb{N} = \{0, 1, 2, \cdots\}$, $\mathbb{Z}^+ = \{1, 2, 3, \cdots\}$ and $\mathbb{Z}^* = \mathbb{Z} \setminus \{0\}$. Fix $A, B \in \mathbb{Z}^*$. The Lucas sequence $\{u_n\}_{n\in\mathbb{N}}$ is defined as follows:

$$u_0 = 0,\ u_1 = 1 \text{ and } u_{n+1} = Au_n - Bu_{n-1} \text{ for } n = 1, 2, 3, \cdots. \tag{1}$$

Its companion sequence $\{v_n\}_{n\in\mathbb{N}}$ is given by

$$v_0 = 2,\ v_1 = A \text{ and } v_{n+1} = Av_n - Bv_{n-1} \text{ for } n = 1, 2, 3, \cdots. \tag{2}$$

By induction, for $n = 0, 1, 2, \cdots$ we have

$$u_n = \sum_{0\le k<n} \alpha^k \beta^{n-1-k} \quad\text{and}\quad v_n = \alpha^n + \beta^n$$

where

$$\alpha = \frac{A+\sqrt{\Delta}}{2},\ \beta = \frac{A-\sqrt{\Delta}}{2} \text{ and } \Delta = A^2 - 4B.$$

It follows that

$$v_n = 2u_{n+1} - Au_n,\ u_{2n} = u_n v_n \text{ and } v_{2n} = v_n^2 - 2B^n \quad\text{for } n \in \mathbb{N}.$$

For $a, b \in \mathbb{Z}$ let (a, b) denote the greatest common divisor of a and b. A nice result of E. Lucas asserts that if $(A, B) = 1$, then $(u_m, u_n) = |u_{(m,n)}|$ for $m, n \in \mathbb{N}$ (cf. L. E. Dickson [1]).

In the case $A^2 = B = 1$, by induction on $n \in \mathbb{N}$ we find that $u_n = 0$ if $3 \mid n$, and

$$u_n = \begin{cases} 1 & \text{if } A = -1 \ \&\ 3 \mid n-1, \text{ or } A = 1 \ \&\ n \equiv 1, 2 \pmod 6; \\ -1 & \text{if } A = -1 \ \&\ 3 \mid n+1, \text{ or } A = 1 \ \&\ n \equiv -1, -2 \pmod 6). \end{cases}$$

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We set $[n]=\prod_{0<k\le n}u_k$ for $n\in\mathbb{N}$, and regard an empty product as value 1. For $n,k\in\mathbb{N}$ with $[n]\ne 0$, we define the Lucas u-nomial coefficient $\left[{n \atop k}\right]$ as follows:

$$\begin{bmatrix} n \\ k \end{bmatrix} = \begin{cases} \frac{[n]}{[k][n-k]} & \text{if } n\ge k, \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

In the case $A=2$ and $B=1$, $\left[{n \atop k}\right]$ is exactly the binomial coefficient $\binom{n}{k}$; when $A=q+1$ and $B=q$ where $q\in\mathbb{Z}$ and $|q|>1$, $\left[{n \atop k}\right]$ coincides with Gaussian q-nomial coefficient $\binom{n}{k}_q$ because $u_j=(q^j-1)/(q-1)$ for $j=0,1,2,\cdots$. For generalized binomial coefficients formed from an arbitrary sequence of positive integers, the reader is referred to the elegant paper of D. E. Knuth and H. S. Wilf [5].

Let $d>1$ and $q>0$ be integers with $d\mid u_q$. If $(A,B)=1$ and $d\nmid u_k$ for $k=1,\cdots,q-1$, then for any $n\in\mathbb{N}$ we have

$$d\mid u_n \iff d \text{ divides } (u_n,u_q)=|u_{(n,q)}| \iff q=(n,q) \iff q\mid n;$$

this property is usually called the *regular divisibility* of $\{u_n\}_{n\in\mathbb{N}}$. If $(d,u_k)=1$ for all $0<k<q$, then we write $q=d_*$ and call d a *primitive divisor* of u_q while q is called the *rank of apparition* of d. When $(A,B)=1$, $q=d_*$, $n\in\mathbb{N}$ and $q\nmid n$, we have

$$(d,u_n)=((d,u_q),u_n)=(d,(u_n,u_q))=(d,u_{(n,q)})=1.$$

When p is an odd prime not dividing B, p_* exists because $p\mid u_{p-(\frac{\Delta}{p})}$ as is well known where $(-)$ denotes the Legendre symbol. On the other hand, drawing upon some ideas of A. Schinzel [6], C. L. Stewart [7] proved in 1977 that if A is prime to B and α/β is not a root of unity, then u_n has a primitive prime divisor for each $n>e^{452}2^{67}$; P. M. Voutier [9] conjectured in 1995 that the lower bound $e^{452}2^{67}$ can be replaced by 30.

For $m\in\mathbb{Z}$ we use $\mathbb{Z}_m$ to denote the ring of rationals in the form a/b with $a\in\mathbb{Z},\ b\in\mathbb{Z}^+$ and $(b,m)=1$. When $r\in\mathbb{Z}_m$, by $x\equiv r \pmod m$ we mean that x can be written as $r+my$ with $y\in\mathbb{Z}_m$.

For convenience we set $R(q)=\{x\in\mathbb{Z}:\ 0\le x<q\}$ for $q\in\mathbb{Z}^+$.

Our main result is as follows.

Theorem. *Suppose that $(A,B)=1$, and $A\ne\pm1$ or $B\ne1$. Then $u_k\ne0$ for every $k=1,2,3,\cdots$. Let $q\in\mathbb{Z}^+$, $m,n\in\mathbb{N}$ and $s,t\in R(q)$. Then*

$$\begin{bmatrix} mq+s \\ nq+t \end{bmatrix} \equiv \binom{m}{n}\begin{bmatrix} s \\ t \end{bmatrix} u_{q+1}^{(nq+t)(m-n)+n(s-t)} \pmod{w_q} \tag{4}$$

where w_q is the largest divisor of u_q prime to $u_1,\cdots,u_{q-1}$. If q or $m(n+t)+n(s+1)$ is even, then

$$\begin{bmatrix} mq+s \\ nq+t \end{bmatrix} \equiv \binom{m}{n}\begin{bmatrix} s \\ t \end{bmatrix} (-1)^{(mt-ns)(q-1)} B^{\frac{q}{2}((nq+t)(m-n)+n(s-t))} \pmod{w_q}. \tag{5}$$

Remark 1. Providing $(A,B)=1$ and $q\in\mathbb{Z}^+$, $(u_q,\prod_{0<k<q}u_k)=1$ if and only if $u_d=\pm1$ for all proper divisors d of q (this is because $(u_q,u_k)=|u_{(q,k)}|$); therefore u_q is prime to $u_1,\cdots,u_{q-1}$ if q is a prime.

When $A=2$ and $B=1$, we have $u_k=k$ for all $k\in\mathbb{N}$, hence the Theorem yields Lucas' theorem which asserts that

$$\binom{mp+s}{np+t}\equiv\binom{m}{n}\binom{s}{t} \pmod p,$$

where p is a prime and m, n, s, t are nonnegative integers with $s, t < p$. In the case $A = a+1$ and $B = a$ where $a \in \mathbb{Z}$ and $|a| > 1$, as $u_{q+1} = (a^{q+1}-1)/(a-1) = au_q + 1 \equiv 1 \pmod{u_q}$ for $q \in \mathbb{Z}^+$, our Theorem implies Theorem 3.11 of R. D. Fray [2].

Theorem 3 of B. Wilson [10] follows from our Theorem in the special case $A = 1$, $B = -1$ and $s \geq t$. Wilson used a result of Kummer concerning the highest power of a prime dividing a binomial coefficient; see Knuth and Wilf [5] for various generalizations of Kummer's theorem. Our proof of the Theorem is more direct; we don't use Kummer's theorem in any form.

Example. (i) Set $A = 4$ and $B = 1$. Then

$$u_0 = 0,\ u_1 = 1,\ u_2 = 4,\ u_3 = 15,\ u_4 = 56,\ u_5 = 209,\ u_6 = 780.$$

Clearly $p = 13$ is the largest primitive divisor of $u_6 = 780$. By the Theorem,

$$\begin{aligned}\begin{bmatrix}71\\25\end{bmatrix} = \begin{bmatrix}11\times 6+5\\4\times 6+1\end{bmatrix} &\equiv \binom{11}{4}\begin{bmatrix}5\\1\end{bmatrix}(-1)^{11\times 1-4\times 5} = 330\times u_5\times(-1)\\ &\equiv -330\times 209 \equiv -5\times 1 \equiv 8 \pmod{13}.\end{aligned}$$

(ii) Take $A = 1$ and $B = -7$. Then $w_3 = u_3 = 8$ and $u_4 = 15$. By the Theorem,

$$\begin{bmatrix}35\\10\end{bmatrix} = \begin{bmatrix}11\times 3+2\\3\times 3+1\end{bmatrix} \equiv \binom{11}{3}\begin{bmatrix}2\\1\end{bmatrix}15^{10(11-3)+3(2-1)} \equiv 3 \pmod 8.$$

2. Several lemmas

Lemma 1. *Let n and k be positive integers with $n > k$ and $[n] \neq 0$. Then*

$$\begin{bmatrix}n\\k\end{bmatrix} = u_{k+1}\begin{bmatrix}n-1\\k\end{bmatrix} - Bu_{n-k-1}\begin{bmatrix}n-1\\k-1\end{bmatrix}. \tag{6}$$

If $2 \mid A$ and $2 \nmid B$, then $\left[{n \atop k}\right] \equiv \binom{n}{k} \pmod 2$.

Proof. Clearly the right hand side of (6) coincides with

$$\begin{aligned}&u_{k+1}\frac{[n-1]}{[k][n-1-k]} - Bu_{n-k-1}\frac{[n-1]}{[k-1][n-k]}\\ =&\frac{[n-1]}{[k][n-k]}(u_{k+1}u_{n-k} - Bu_ku_{n-k-1}) = \begin{bmatrix}n\\k\end{bmatrix},\end{aligned}$$

where in the last step we use the identity $u_{k+1}u_l - Bu_ku_{l-1} = u_{k+l}$ which can be easily proved by induction on $l \in \mathbb{Z}^+$.

Now suppose that $2 \nmid (A-1)B$. Then $u_1, u_3, u_5, \cdots$ are odd and $u_2, u_4, u_6, \cdots$ are even. If

$$\begin{bmatrix}n-1\\k\end{bmatrix} \equiv \binom{n-1}{k} \pmod 2 \quad\text{and}\quad \begin{bmatrix}n-1\\k-1\end{bmatrix} \equiv \binom{n-1}{k-1} \pmod 2,$$

then (6) yields that

$$\begin{aligned}\begin{bmatrix}n\\k\end{bmatrix} \equiv&(k+1)\binom{n-1}{k} - (n-k-1)\binom{n-1}{k-1}\\ \equiv&(k+1)\binom{n}{k} - n\binom{n-1}{k-1} = \binom{n}{k} \pmod 2.\end{aligned}$$

So $\left[{n \atop k}\right] \equiv \binom{n}{k} \pmod 2$ by induction. □

Remark 2. In light of Lemma 1, by induction, if $n \in \mathbb{N}$ and $[n] \neq 0$, then $\left[\begin{smallmatrix} n \\ k \end{smallmatrix}\right] \in \mathbb{Z}$ for all $k \in \mathbb{N}$. This was also realized by W. A. Kimball and W. A. Webb [4]. In 1989 Knuth and Wilf [5] proved that generalized binomial coefficients, formed from a regularly divisible sequence of positive integers, are always integral.

Lemma 2. *Let q be a positive integer. Then $u_{q+1}^2 \equiv B^q \pmod{u_q}$. If $2 \mid q$, then $u_{q+1} \equiv -B^{q/2} \pmod{d}$ for any primitive divisor d of u_q.*

Proof. As

$$\begin{pmatrix} u_q & u_{q-1} \\ u_{q+1} & u_q \end{pmatrix} = \begin{pmatrix} u_{q-1} & u_{q-2} \\ u_q & u_{q-1} \end{pmatrix} \begin{pmatrix} A & 1 \\ -B & 0 \end{pmatrix}$$
$$= \cdots = \begin{pmatrix} u_1 & u_0 \\ u_2 & u_1 \end{pmatrix} \begin{pmatrix} A & 1 \\ -B & 0 \end{pmatrix}^{q-1},$$

we have $u_q^2 - u_{q-1}u_{q+1} = B^{q-1}$ and hence $u_{q+1}^2 \equiv -Bu_{q-1}u_{q+1} \equiv B^q \pmod{u_q}$.

Now assume that $q = 2n$ where $n \in \mathbb{Z}^+$. Let d be a primitive divisor of u_q. Since $u_n v_n = u_q \equiv 0 \pmod{d}$ and $(d, u_n) = 1$, we have $d \mid v_n$ and hence

$$u_{q+1} = \frac{Au_q + v_q}{2} = \frac{Au_n v_n + v_n^2 - 2B^n}{2} = u_{n+1}v_n - B^n \equiv -B^n \pmod{d}.$$

This ends the proof. □

Lemma 3. *Let $k, q \in \mathbb{Z}^+$. Then*

$$u_{kq+l} \equiv u_{q+1}^k u_l \pmod{u_q} \quad \text{for } l = 0, 1, 2, \cdots. \tag{7}$$

If $u_q \neq 0$, then

$$\frac{u_{kq}}{ku_q} \equiv u_{q+1}^{k-1} + (k-1)A\frac{u_q}{2} \pmod{u_q}. \tag{8}$$

Proof. Let $l \in \mathbb{N}$. By Lemma 2 of Z.-W. Sun [8],

$$u_{kq+l} = \sum_{r=0}^{k} \binom{k}{r} c^{k-r} u_q^r u_{l+r}$$

where $c = -Bu_{q-1} = u_{q+1} - Au_q$. Clearly $u_{kq+l} \equiv u_{q+1}^k u_l \pmod{u_q}$. In the case $u_q \neq 0$,

$$\frac{u_{kq}}{ku_q} = \sum_{r=1}^{k} \frac{1}{k}\binom{k}{r} c^{k-r} u_q^{r-1} u_r = \sum_{r=1}^{k} \binom{k-1}{r-1} \frac{u_q^{r-1}}{r} c^{k-r} u_r.$$

For any prime p and integer $r > 3$ we have

$$p^{r-2} \geq (1+1)^{r-2} \geq 1 + (r-2) + 1 = r,$$

therefore $u_q^{r-2}/r \in \mathbb{Z}_{u_q}$ for $r = 3, 4, \cdots$. If $2 \mid u_q$ and $2 \nmid A$, then $2 \nmid B$ (otherwise $u_q \equiv u_{q-1} \equiv \cdots \equiv u_1 \not\equiv 0 \pmod{2}$), as $u_{q+1}^2 \equiv B^q \pmod{u_q}$ we have $c \equiv u_{q+1} \equiv 1 \pmod{2}$. Thus (8) holds providing $u_q \neq 0$. □

Lemma 4. *Assume that $(A, B) = 1$, $q \in \mathbb{Z}^+$ and $u_k \neq 0$ for all $k \in \mathbb{Z}^+$. Then for any $m, n \in \mathbb{N}$ and $s, t \in R(q)$ we have*

$$\begin{bmatrix} mq + s \\ nq + t \end{bmatrix} \equiv \begin{bmatrix} mq \\ nq \end{bmatrix} \begin{bmatrix} s \\ t \end{bmatrix} u_{q+1}^{t(m-n)+n(s-t)} \pmod{w_q} \tag{9}$$

where w_q is the largest divisor of u_q prime to $u_1, \cdots, u_{q-1}$.

Proof. Let $m, n \in \mathbb{N}$ and $s, t \in R(q)$. If $m < n$, then $mq + s < (m+1)q \le nq + t$ and hence $\left[\begin{smallmatrix} mq+s \\ nq+t \end{smallmatrix}\right] = 0 = \left[\begin{smallmatrix} mq \\ nq \end{smallmatrix}\right]$. If $m = n$ and $s < t$, then $\left[\begin{smallmatrix} mq+s \\ nq+t \end{smallmatrix}\right] = 0 = \left[\begin{smallmatrix} s \\ t \end{smallmatrix}\right]$. Below we assume that $m \ge n$ and $mq + s \ge nq + t$.

As $(A, B) = 1$, $(u_q, u_{q+1}) = |u_{(q,q+1)}| = 1$. Observe that w_q is prime to $u_{q+1}\prod_{0<r<q} u_r$, and

$$\begin{aligned}\begin{bmatrix} mq+s \\ nq+t \end{bmatrix} =& \frac{\prod_{(m-n)q<j\le mq} u_j}{\prod_{0<j\le nq} u_j} \times \frac{\prod_{0<r\le s} u_{mq+r}}{\prod_{0<r\le t} u_{nq+r}} \\ & \times \begin{cases} \prod_{0<r\le s-t} u_{(m-n)q+r}^{-1} & \text{if } s \ge t, \\ \prod_{0\le r<t-s} u_{(m-n)q-r} & \text{if } s < t. \end{cases}\end{aligned}$$

By Lemma 3, $u_{kq+r} \equiv u_{q+1}^k u_r \pmod{w_q}$ for any $k, r \in \mathbb{N}$. So

$$\begin{aligned}\begin{bmatrix} mq+s \\ nq+t \end{bmatrix} \equiv & \begin{bmatrix} mq \\ nq \end{bmatrix} \times \frac{\prod_{0<r\le s}(u_{q+1}^m u_r)}{\prod_{0<r\le t}(u_{q+1}^n u_r)} \\ & \times \begin{cases} \prod_{0<r\le s-t}(u_{q+1}^{n-m} u_r^{-1}) \pmod{w_q} & \text{if } s \ge t, \\ 0 \pmod{w_q} & \text{otherwise,} \end{cases} \\ \equiv & \begin{bmatrix} mq \\ nq \end{bmatrix} \frac{[s]}{[t]} u_{q+1}^{ms-nt} \times \begin{cases} u_{q+1}^{(n-m)(s-t)}/[s-t] \pmod{w_q} & \text{if } s \ge t, \\ 0 \pmod{w_q} & \text{if } s < t, \end{cases} \\ \equiv & \begin{bmatrix} mq \\ nq \end{bmatrix} \begin{bmatrix} s \\ t \end{bmatrix} u_{q+1}^{t(m-n)+n(s-t)} \pmod{w_q}.\end{aligned}$$

This concludes the proof. □

3. Proof of the Theorem

Let us first show that $u_1, u_2, u_3, \cdots$ are all nonzero.

If $\Delta = 0$, then $\alpha = \beta = A/2$ and hence

$$u_k = \sum_{0\le r<k} \alpha^r \beta^{k-1-r} = k\left(\frac{A}{2}\right)^{k-1} \ne 0 \quad \text{for } k = 1, 2, 3, \cdots.$$

Suppose that $u_k = 0$ for some $k \in \mathbb{Z}^+$. Then $\Delta \ne 0$, $\alpha \ne \beta$ and $\alpha^k = \beta^k$. Since the field $\mathbb{Q}(\sqrt{\Delta})$ contains the root $\alpha/\beta \ne \pm 1$ of unity, by Propositions 13.1.5 and 13.1.6 of K. Ireland and M. Rosen [3] there exists a positive integer D such that $\Delta = -D^2$ and $\alpha/\beta \in \{\pm i\}$, or $\Delta = -3D^2$ and $\alpha/\beta \in \{\pm\omega, \pm\omega^2\}$ where $\omega = (-1+\sqrt{-3})/2$. In the former case, $(A+Di)/(A-Di) \in \{\pm i\}$; hence $A^2 = D^2$ and $2B = (A^2 - \Delta)/2 = D^2$. This is impossible since A or B is odd. Thus the latter case happens. Now that

$$\frac{A + D\sqrt{-3}}{A - D\sqrt{-3}} = \frac{A^2 - 3D^2 + 2AD\sqrt{-3}}{A^2 + 3D^2} \in \left\{\frac{-1 \pm \sqrt{-3}}{2}, \frac{1 \pm \sqrt{-3}}{2}\right\},$$

we have $A^2 - 3D^2 = \pm 2AD$ and hence $A^2 \in \{D^2, 9D^2\}$. If $A^2 = D^2$, then $B = (A^2 - \Delta)/4 = D^2$, hence $(A, B) > 1$ or $A^2 = B = 1$; if $A^2 = 9D^2$, then $B = (A^2 - \Delta)/4 = 3D^2$ and hence $3 \mid (A, B)$. This leads to a contradiction.

Next we show (4).

Let $u'_0=0$, $u'_1=1$ and $u'_{j+1}=v_qu'_j-B^qu'_{j-1}$ for $j=1,2,3,\cdots$. Note that $\alpha^q+\beta^q=v_q$ and $\alpha^q\beta^q=B^q$. Fix $k\in\mathbb{Z}^+$. If $\Delta=A^2-4B\neq 0$, then

$$\frac{u_{kq}}{u_q}=\frac{(\alpha^{kq}-\beta^{kq})/(\alpha-\beta)}{(\alpha^q-\beta^q)/(\alpha-\beta)}=\frac{(\alpha^q)^k-(\beta^q)^k}{\alpha^q-\beta^q}=u'_k;$$

if $\Delta=0$, then $\alpha=\beta=A/2$, $u_q=q(A/2)^{q-1}$, $u_{kq}=kq(A/2)^{kq-1}$ and

$$u'_k=\sum_{0\le r<k}(\alpha^q)^r(\beta^q)^{k-1-r}=k\left(\frac{A}{2}\right)^{q(k-1)}=\frac{u_{kq}}{u_q}.$$

So we always have $u_{kq}/u_q=u'_k$. By (8),

$$\frac{u_{kq}}{ku_q}\equiv r_k \pmod{u_q}\quad\text{where } r_k=u_{q+1}^{k-1}+\begin{cases}(k-1)Au_q/2 & \text{if } 2\mid u_q,\\ 0 & \text{otherwise.}\end{cases}$$

Notice that $(r_k,u_q)=1$ if $2\nmid u_q$, and $(r_k,u_q/2)=1$ if $2\mid u_q$.

Suppose $m>n>0$. We assert that

$$\prod_{0\le k<n}\frac{u_{(m-k)q}}{u_{(n-k)q}}\equiv\binom{m}{n}u_{q+1}^{n(m-n)}\pmod{u_q}.\tag{10}$$

If $2\nmid u_q$ or $4\mid u_q$, then $(r_k,u_q)=1$ for all $k=1,2,3,\cdots$, hence

$$\begin{aligned}&\prod_{0\le k<n}\frac{u_{(m-k)q}}{u_{(n-k)q}}=\prod_{0\le k<n}\frac{m-k}{n-k}\times\prod_{0\le k<n}\frac{u_{(m-k)q}/((m-k)u_q)}{u_{(n-k)q}/((n-k)u_q)}\\ \equiv&\binom{m}{n}\prod_{0\le k<n}\frac{u_{q+1}^{m-k-1}+(m-k-1)Au_q/2}{u_{q+1}^{n-k-1}+(n-k-1)Au_q/2}\\ \equiv&\binom{m}{n}\prod_{0\le k<n}\left(u_{q+1}^{m-n}+(m-n)A\frac{u_q}{2}\right)\equiv\binom{m}{n}\left(u_{q+1}^{n(m-n)}+n(m-n)A\frac{u_q}{2}\right)\\ \equiv&\binom{m}{n}u_{q+1}^{n(m-n)}+\frac{m(m-1)}{2}\binom{m-2}{n-1}Au_q\equiv\binom{m}{n}u_{q+1}^{n(m-n)}\pmod{u_q}.\end{aligned}$$

In the case $u_q\equiv 2\pmod 4$, by the above method

$$\prod_{0\le k<n}\frac{u_{(m-k)q}}{u_{(n-k)q}}\equiv\binom{m}{n}u_{q+1}^{n(m-n)}\quad\left(\mathrm{mod}\ \frac{u_q}{2}\right);$$

as $v_q=2u_{q+1}-Au_q\equiv 0\pmod 2$ and $B\equiv 1\pmod 2$ (otherwise $A,u_1,u_2,u_3,\cdots$ are all odd), we also have

$$\prod_{0\le k<n}\frac{u_{(m-k)q}}{u_{(n-k)q}}=\prod_{0\le k<n}\frac{u'_{m-k}}{u'_{n-k}}\equiv\binom{m}{n}\equiv\binom{m}{n}u_{q+1}^{n(m-n)}\pmod 2$$

by Lemma 1. This proves (10).

Now we claim that

$$\begin{bmatrix}mq\\ nq\end{bmatrix}\equiv\binom{m}{n}u_{q+1}^{(m-n)nq}\pmod{w_q}.\tag{11}$$

This is obvious if $m \le n$ or $n = 0$. In the case $m > n > 0$, if $0 < j < nq$ and $q \nmid j$, then $(u_{nq-j}, w_q) = 1$ and

$$\frac{u_{mq-j}}{u_{nq-j}} = \frac{u_{(m-n)q+nq-j}}{u_{nq-j}} \equiv u_{q+1}^{m-n} \pmod{w_q}$$

by Lemma 3; thus

$$\begin{aligned}\begin{bmatrix} mq \\ nq \end{bmatrix} &= \prod_{0\le j<nq} \frac{u_{mq-j}}{u_{nq-j}} = \prod_{0\le k<n} \frac{u_{(m-k)q}}{u_{(n-k)q}} \times \prod_{\substack{0<j<nq\\ q\nmid j}} \frac{u_{mq-j}}{u_{nq-j}} \\ &\equiv \binom{m}{n} u_{q+1}^{n(m-n)} \times u_{q+1}^{(m-n)(nq-n)} = \binom{m}{n} u_{q+1}^{(m-n)nq} \pmod{w_q}.\end{aligned}$$

In view of (9) and (11),

$$\begin{aligned}\begin{bmatrix} mq+s \\ nq+t \end{bmatrix} &\equiv \binom{m}{n} u_{q+1}^{(m-n)nq} \times \begin{bmatrix} s \\ t \end{bmatrix} u_{q+1}^{t(m-n)+n(s-t)} \\ &\equiv \binom{m}{n} \begin{bmatrix} s \\ t \end{bmatrix} u_{q+1}^{(nq+t)(m-n)+n(s-t)} \pmod{w_q}.\end{aligned}$$

Finally we say something about (5). If $2 \mid q$, then

$$(nq+t)(m-n) + n(s-t) \equiv t(m-n) + n(s-t) \equiv mt - ns \pmod{2},$$

and $u_{q+1} \equiv -B^{q/2} \pmod{w_q}$ by Lemma 2. When q is odd and $l = m(n+t)+n(s+1)$ is even,

$$(nq+t)(m-n) + n(s-t) \equiv (n+t)(m-n) + n(s-t) \equiv l \equiv 0 \pmod{2}$$

and $u_{q+1}^2 \equiv B^q \pmod{w_q}$ by Lemma 2. Thus (5) follows from (4) if $2 \mid ql$. We are done.

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