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A SPECIAL CASE OF KUMMER'S CONGRUENCE (mod 2^e)

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Put

$$\frac{x}{\sinh x} = \sum_1^{\infty} D_{2n} \frac{x^{2n}}{(2n)!}, \quad D_{2n+1} = 0, \quad (1)$$

where [3, p. 27-28]

$$(D+1)^n - (D-1)^n = \begin{cases} 2 & (n=1) \\ 0 & (n < 1); \end{cases}$$

also

$$D^n = (2B+1)^n = (2-2^n) B_n \quad (2)$$

and B_n is defined by

$$\frac{x}{e^x - 1} = \sum_0^{\infty} B_n \frac{x^n}{n!}.$$

The first few values of D_{2n} are

$$D_0 = 1, \quad D_2 = -\frac{1}{3}, \quad D_4 = \frac{7}{15}, \quad D_6 = \frac{31}{21}, \quad D_8 = \frac{127}{15}.$$

If we define

$$\Delta_n = (D^2 - 1)^n = \sum_{r=0}^n (-1)^{n-r} \binom{n}{r} D_{2r} \quad (3)$$

we find that

$$\Delta_0 = 1, \quad \Delta_1 = \frac{2^2}{3}, \quad \Delta_2 = \frac{2^5}{15}, \quad \Delta_3 = \frac{2^9}{105}, \quad \Delta_4 = \frac{2^{11}}{105}.$$

(Compare [1, p. 821].)

By the second part of (2), both numerator and denominator of D_{2n} (in reduced form) are odd. Moreover by the Staudt-Clausen theorem for the Bernoulli numbers B_n , we have

$$pD_{2n} \equiv \begin{cases} -1 & (\text{mod } p) & (p-1 \mid 2n) \\ 0 & (\text{mod } p) & (p-1 \nmid 2n) \end{cases},$$

where p is any odd prime. Thus the denominator of Δ_n can be determined (see below). The numerators of Δ_n for $0 \geq n \geq 4$ are all powers of 2. However this is really too good to be true; indeed we find that

$$\Delta_5 = -\frac{2^{15}}{3 \cdot 7 \cdot 11}, \quad \Delta_6 = \frac{2^{17} \cdot 191}{3 \cdot 5 \cdot 7 \cdot 11 \cdot 13}.$$

It may be of interest to determine the highest power of 2 dividing Δ_n . A result of this sort is analogous to Kummer's congruences for the Bernoulli or Euler numbers [2, Chapter 14]; however the standard results on Kummer's congruences are restricted to odd moduli.

It is convenient to first transform Δ_n . We have, using the symbolic notation,

$$\Delta_n = (D^2 - 1)^n = ((2B + 1)^2 - 1)^n = (4B^2 + 4B)^n = 4^n (B^2 + B)^n$$

and therefore

$$\Delta_n = 2^{2n} \sum_{r=0}^n \binom{n}{r} B_{n+r}. \quad (4)$$

Since $2B_{2r} \equiv 1 \pmod{2}$ it follows readily that the denominator of

$$\sum_{r=0}^n \binom{n}{r} B_{n+r}$$

(in reduced form) is odd. Consequently

$$\Delta_n \equiv 0 \pmod{2^{2n}}. \quad (5)$$

Incidentally (4) is a bit more convenient for computation than (2). For example

$$\begin{aligned} \Delta_5 &= 2^{10} (5B_6 + 10B_8 + B_{10}) = -\frac{2^{15}}{3 \cdot 7 \cdot 11}, \\ \Delta_6 &= 2^{12} (B_6 + 15B_8 + 15B_{10} + B_{12}) \\ &= 2^{12} \left(\frac{1}{42} - \frac{15}{30} + \frac{75}{66} - \frac{691}{2730} \right) = \frac{2^{17} \cdot 191}{3 \cdot 5 \cdot 7 \cdot 11 \cdot 13}. \end{aligned}$$

The congruence (5) can be improved. We make use of the explicit formula

$$B_n = \sum_{r=0}^n \frac{1}{r+1} \sum_{s=0}^r (-1)^s \binom{r}{s} s^n,$$

which yields

$$(B^2 + B)^n = 2^n \sum_{r=0}^{2n} \frac{1}{r+1} \sum_{s=0}^r (-1)^s \binom{r}{s} \left(\frac{1}{2}^s (s+1) \right)^n. \quad (6)$$

However allowance must be made for the denominator $r+1$. Clearly the highest power of 2 contained in $r+1$, where $0 \leq r \leq 2n$, is at most 2^e , where e is determined by

$$2^e \leq 2n < 2^{e+1}. \quad (7)$$

Hence by (4) and (6),

$$\Delta_n \equiv 0 \pmod{2^{3n-e}}. \quad (8)$$

This result also can be improved for $n \geq 2$. Suppose first that n is even and let

$$2^k \mid n, 2^{k+1} \nmid n \quad (k \geq 1). \quad (9)$$

Then for arbitrary odd u we have

$$u^n \equiv 1 \pmod{2^{k+2}}. \quad (10)$$

Put

$$S_j = S_j^{(r)} = \sum_{s \equiv j \pmod{4}} \binom{r}{s} \quad (0 \leq j \leq 3).$$

It is easily verified that

$$2(S_1 - S_2) = (1+i)^{r-1} + (1-i)^{r-1}.$$

Hence for r odd

$$S_1 - S_2 = \begin{cases} 0 & (r \equiv 3 \pmod{4}) \\ (-1)^{1/4(r-1)} 2^{1/2(r-1)} & (r \equiv 1 \pmod{4}) \end{cases}.$$

Since $s(s+1)/2$ is odd if and only if $s \equiv 1$ or $2 \pmod{4}$, it follows from (10) that ($n > 2$)

$$S = \sum_{s=0}^r (-1)^s \binom{r}{s} \left(\frac{1}{2}^s (s+1) \right)^n \equiv S_2 - S_1 \pmod{2^{k+2}},$$

and therefore

$$S \equiv 0 \pmod{2^{k+2}} \quad (r \equiv 3 \pmod{4}), \quad (11)$$

$$S \equiv 0 \pmod{(2^{k+2}, 2^{1/2(r-1)})} \quad (r \equiv 1 \pmod{4}). \quad (12)$$

Now when $r \equiv 1 \pmod{4}$, $r+1$ is divisible by 2 but not by 2^2 ; hence the term $S/(r+1)$ is integral $\pmod{2}$ provided

$r > 1$. When $r \equiv 3 \pmod{4}$, let 2^{e_r} denote the highest power of 2 dividing $r + 1$. Then it follows from (11) that $S/(r + 1)$ is of the form $2^{k+2-e_r}A$, where A is integral (mod 2). The least favorable case arises when e_r has its maximum value e as determined by (7). We have therefore

$$\Delta_n \equiv 0 \pmod{2^{3n-e+k+2}} \quad (13)$$

provided $k + 2 > e$; when $k + 2 \leq e$ we have

$$\Delta_n \equiv 0 \pmod{2^{3n-1}} \quad (14)$$

since for example the term $r = 1$ has denominator 2.

In the next place for n odd, let

$$2^k \mid n - 1, \quad 2^{k+1} \nmid n - 1 \quad (k \geq 1);$$

Then (10) is replaced by

$$u^{n-1} \equiv 1 \pmod{2^{k+2}},$$

where u is odd. Put

$$\begin{aligned} T_j &= T_j^{(r)} = \frac{1}{2} \sum_{s \equiv j \pmod{4}} \binom{r}{s} s(s+1) \\ &= \binom{r}{2} S_{j-2}^{(r-2)} + r S_{j-1}^{(r-1)}. \end{aligned}$$

Thus

$$\begin{aligned} T_1 - T_2 &= \binom{r}{2} (S_3^{(r-2)} - S_0^{(r-2)}) + r (S_0^{(r-1)} - S_0^{(r-1)}) \\ &= \frac{i}{4} \binom{r}{2} \{(1+i)^{r-1} - (1-i)^{r-1}\} + \frac{r}{4} \{(1+i)^r + (1-i)^r\}. \end{aligned}$$

Simplifying we get (for $r \geq 3$)

$$T_1 - T_2 = \begin{cases} \frac{1}{4} r (r+1) 2^{\frac{1}{2}(r-1)} i^{\frac{1}{2}(r+1)} & (r \equiv 3 \pmod{4}) \\ \frac{1}{2} r (2i)^{\frac{1}{2}(r-1)} & (r \equiv 1 \pmod{4}). \end{cases}$$

Also ($n > 3$)

$$T = \sum_{s=0}^r (-1)^s \binom{r}{s} \left(\frac{1}{2} s (s+1) \right)^n \equiv T_2 - T_1 \pmod{2^{k+2}}$$

and therefore in particular

$$T \equiv 0 \pmod{(2^{\frac{1}{2}(r-1)}, 2^{k+2})} \quad (r \equiv 3 \pmod{4}). \quad (15)$$

As in the case n even, it will suffice to take $r \equiv 3 \pmod{4}$. Let 2^{e_r} denote the highest power of 2 dividing $r + 1$, and consider $2^{-e_r} T$. For $e_r \leq 2$, we get the exponent -1 ; for $e_r \geq 3$ it follows that $\frac{1}{2}(r - 1) \geq e_r$. Hence if $k + 2 < e_r$, we get the exponent $k + 2 - e_r$, while if $k + 2 \geq e_r$ we again get -1 (at most). Consequently

$$\Delta_n \equiv 0 \pmod{2^{3n-e+k+2}} \quad (k + 2 < e_r), \quad (16)$$

$$\Delta_n \equiv 0 \pmod{2^{3n-1}} \quad (k + 2 \geq e_r). \quad (17)$$

Comparing (16) and (17) with (13) and (14) we may accordingly state the following

THEOREM. Let $2^e \leq 2n < 2^{e+1}$ and let 2^k denote the highest power of 2 dividing n or $n - 1$ according as n is even or odd. Then Δ_n as defined by (1) and (3) satisfies (16) and (17). Applying the Staudt-Clausen theorem, it follows from (3) that

$$p\Delta_n \equiv - \sum_{r>0} (-1)^{n-rm} \binom{n}{rm} \pmod{p},$$

where $p = 2m + 1$ is an odd prime. It can be shown that

$$\sum_{r>0} (-1)^{n-rm} \binom{n}{rm} \equiv \begin{cases} 2 & (p-1 \mid n) \\ \binom{m}{k} & (p-1 \mid n+k, 0 < k \leq m) \\ 0 & \text{otherwise.} \end{cases}$$

In particular the prime factors of the denominator of Δ_n are simple and cannot exceed $2n + 1$.

In connection with formula (4) above it may be of interest to cite the formula [2, p. 189]

$$(-1)^n \sum_{r=0}^n \binom{n}{r} \frac{B_{n+r+1}}{n+r+1} + \frac{n!n!}{2(2n+1)!} = 0.$$

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