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MATHEMATISCH CENTRUM
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AMSTERDAM

ZW 1955-017

On theorems of Wolstenholme and Leudesdorf

Additional note

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1955

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Reprinted from Proceedings, Series A, 59, No. 1 and Indag. Math., 18, No. 1, 1956

MATHEMATICS

ON THEOREMS OF WOLSTENHOLME AND LEUDESDORF
ADDITIONAL NOTE

BY

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(Communicated by Prof. J. F. KOKSMA at the meeting of September 24, 1955)

To our paper "On theorems of WOLSTENHOLME and LEUDESDORF" [1] we want to add two additional remarks.

I. First we want to prove the following extension of theorem 2 of our paper [1]:

Theorem 3. If M is a positive integer, if p is a prime and n a positive integer such that $p^n \,||\, M$, if e is a non-negative integer such that $p^e \mid \varphi(Mp^{-n})$, if s is an integer and if k is the exponent introduced in theorem 1 of [1], then $p^{k+e} \mid T_s(M)$.

Proof: We use mathematical induction with respect to the number of different prime factors of Mp^{-n}. If this number is zero, we have $e=0$ and $M=p^n$; the theorem then follows from theorem 1 of [1].

Now put $M=q^r m$, q being a prime different from p, $(m,q)=1$ and $r \geqq 1$. We may put $e=e_1+e_2$, $p^{e_1} \mid q-1$, $p^{e_2} \mid \varphi(mp^{-n})$. We may suppose $p^{k+e_2} \mid T_s(m)$ for all integers s and corresponding k.

We have

$$T_s(M) = \sum_{a=1}^{m}{}' \sum_{v=0}^{q^r-1} (a+vm)^{-s} - q^{-s} \sum_{a=1}^{m}{}' \sum_{v=0}^{q^{r-1}-1} (a+vm)^{-s}.$$

For sufficiently large l we have $p^{k+e} \mid m^l$; by lemma 1 of [1] we have

$$\sum_{a=1}^{m}{}' (a+vm)^{-s} \equiv \sum_{a=1}^{m}{}' \sum_{h=0}^{l-1} \binom{-s}{h} a^{-s-h} v^h m^h =$$

$$= \sum_{h=0}^{l-1} \binom{-s}{h} v^h m^h T_{s+h}(m) \pmod{p^{k+e}},$$

so

$$T_s(M) \equiv \sum_{h=0}^{l-1} \binom{-s}{h} m^h T_{s+h}(m) \left\{ \sum_{v=0}^{q^r-1} v^h - q^{-s} \sum_{v=0}^{q^{r-1}-1} v^h \right\} \pmod{p^{k+e}}.$$

It is well-known that $\sum_{v=0}^{u-1} v^h = \frac{1}{r_h} P_h(u)$, where $P_h(x)$ is a polynomial in x with integral coefficients, whereas $r_0=1$, $r_1=2$, $r_2=6$, $r_3=4$, and r_h is a positive integer dividing $(h+1)!$ for every integer $h \geqq 0$ [1]. Furthermore

$$P_h(x^r) - x^{-s} P_h(x^{r-1}) = (x-1)\, x^{-|s|} Q_h(x),$$

[1]) Using the theorem of VON STAUDT-CLAUSEN one could get a sharper result. The statement given by us, which may be obtained by elementary means, suffices for our purpose.

where Q_h is a polynomial with integral coefficients. So we get

$$T_s(M) \equiv \sum_{h=0}^{l-1} \tau_h \pmod{p^{k+e}},$$

where

$$\tau_h = \binom{-s}{h} m^h \, T_{s+h}(m) \frac{1}{r_h} q^{-|s|}(q-1)\, Q_h(q).$$

We are going to prove that for $h=0, 1, \ldots$ the number of factors p in τ_h is $\geqq k+e$.

Now we use the fact that the number of factors p in $(h+1)!$ is $\leqq \dfrac{h}{p-1}$. In fact let the integer t be chosen such that $p^t \leqq h+1 < p^{t+1}$. Then that number is equal to

$$\left[\frac{h+1}{p}\right]+\left[\frac{h+1}{p^2}\right]+\ldots+\left[\frac{h+1}{p^t}\right] \leqq \frac{h+1}{p}+\ldots\frac{h+1}{p^t} =$$
$$= \frac{h+1}{p-1}\left(1-\frac{1}{p^t}\right) \leqq \frac{h+1}{p-1}\left(1-\frac{1}{h+1}\right) = \frac{h}{p-1}.$$

If k' is the number for which, according to theorem 1 of [1], $p^{k'} \mid T_{s+h}(p^n)$ holds and if g denotes the number of factors p in r_h, the number of factors p in τ_h is $\geqq nh+k'+e_2-g+e_1$. In order to prove that this number is $\geqq k+e$, it suffices to prove $\alpha = nh+k'-k-g \geqq 0$.

From theorem 1 of [1] it follows that in general we have $k'-k \geqq -n-1$; if $p=2$ we have $k'-k \geqq -n+1$; if h is even we have $k'-k \geqq -1$.

First suppose $p=2$. We then have $g \leqq h$, and $\alpha \geqq nh-n+1-h=(n-1)(h-1)$, which is $\geqq 0$ for $h \geqq 1$.

Now suppose $p \geqq 3$. We then have $g \leqq \frac{1}{2}h$, and $\alpha \geqq nh-n-1-\frac{1}{2}h = =\frac{1}{2}(h(2n-1)-2n-2)$, which is $\geqq 0$ for $h \geqq 4$. For $h=3$ we have $g=0$, and $\alpha \geqq 2n-1 \geqq 0$. For $h=2$ we have $g \leqq 1$, and $\alpha \geqq 2n-2 \geqq 0$.

We are left with the cases $h=0$ and $h=1$, $p \geqq 3$.

If $h=0$, we have $k'=k$ and $g=0$, so $\alpha \geqq 0$.

If $h=1$, $p \geqq 3$, we have $g=0$, and $\alpha = n+k'-k$. The only case in which this is <0, is $k=2n$, $k'=n-1$; this occurs if $2 \nmid s$, $p \mid s$, $p-1 \mid s+1$. But in this case $\binom{-s}{1} = -s$ has a factor p. Consequently we may infer that also here the number of factors p in τ_1 is $\geqq k+e$. This completes the proof of our theorem.

Remark 1. It is possible to determine in some cases the exact number of factors p in $T_s(M)$. We shall not enter into this detail.

Remark 2. As theorem 2 of [1] is not used in the proof of theorem 3, the above result furnishes a new proof of theorem 2a) and 2c) of [1].

II. Further we want to give a short discussion of the results of N. Eljoseph [2], [3], which came to our knowledge only after correcting the revision of our paper [1]. See the concluding "Note on two papers of Eljoseph" in [1].

First we mention the fact that our theorems 1 and 2 of [1] are included in his. Moreover he proves a theorem, which in our notation, reads as follows:

If for all prime factors p of M one has $p-1 \mid s$, then

$$T_s(M) \equiv \varphi(M) \pmod{M},$$

except if s is odd and $M=2^n$ with $n \geqq 2$.

Using the ideas of our proofs of the theorems 1 and 2 of [1] it is not difficult to give a new proof of this theorem.

In [2] ELJOSEPH gives his proofs by making use of the theorem of VON STAUDT–CLAUSEN on BERNOULLI numbers. It has to be remarked that in [2] formula (9) is wrong. In the righthand side a term

$$\sum_{j=1}^{k} \binom{k}{j} m_1^j \, T_{k-j}(m_1)\,(p^j-p^k) \sum_{l=1}^{p^{e-1}-1} l^j$$

has to be added. However this term, although in general not equal to zero, happens to be congruent 0 mod p^e (this follows immediately from the fact that $p^{e-1} \mid \sum_{l=1}^{p^{e-1}-1} l^j$), which is sufficient for ELJOSEPH's purpose.

In our paper [1] we have avoided on purpose the use of this less elementary theorem of VON STAUDT–CLAUSEN. In [3] also ELJOSEPH wants to eliminate the use of VON STAUDT–CLAUSEN in the proofs of his results. Unfortunately however his proof in § 6 is erroneous, the assertion that for $k=(p-1)p^s u$ (where $0 \leqq s < \frac{1}{2}(e-1)$ and $p \nmid u$) the expression $k' = \varphi(p^e)-k$ contains at least $\frac{1}{2}(e-1)$ factors p being wrong. At this moment we do not see how this second method of ELJOSEPH may lead to a correct proof.

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