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AN ELEMENTARY PROOF OF A CONGRUENCE BY SKULA AND GRANVILLE

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Abstract. Let $p \geq 5$ be a prime, and let $q_p(2) := (2^{p-1} - 1)/p$ be the Fermat quotient of p to base 2. The following curious congruence was conjectured by L. Skula and proved by A. Granville

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

In this note we establish the above congruence by entirely elementary number theory arguments.

1. Introduction and statement of the main result

The Fermat Little Theorem states that if p is a prime and a is an integer not divisible by p, then $a^{p-1} \equiv 1 \pmod{p}$. This gives rise to the definition of the *Fermat quotient* of p to base a

$$q_p(a) := \frac{a^{p-1} - 1}{p},$$

which is an integer. Fermat quotients played an important role in the study of cyclotomic fields and Fermat Last Theorem. More precisely, divisibility of Fermat quotient $q_p(a)$ by p has numerous applications which include the Fermat Last Theorem and squarefreeness testing (see [1], [2], [3], [5] and [9]). Ribenboim [10] and Granville [5], besides proving new results, provide a review of known facts and open problems.

By a classical Glaisher's result (see [4] or [7]) for a prime $p \geq 3$,

$$q_p(2) \equiv -\frac{1}{2} \sum_{k=1}^{p-1} \frac{2^k}{k} \pmod{p}. \tag{1.1}$$

Recently Skula conjectured that for any prime $p \geq 5$,

$$q_p(2)^2 \equiv -\sum_{k=1}^{p-1} \frac{2^k}{k^2} \pmod{p}. \tag{1.2}$$

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Applying certain polynomial congruences, Granville [7] proved the congruence (1.2). In this note, we give an elementary proof of this congruence which is based on congruences for some harmonic type sums.

Remark 1.1. Recently, given a prime p and a positive integer $r < p-1$, R. Tauraso [14, Theorem 2.3] established the congruence $\sum_{k=1}^{p-1} 2^k/k^r \pmod{p}$ in terms of an alternating r-tiple harmonic sum. For example, combining this result when $r = 2$ with the congruence (1.2) [14, Corollary 2.4], it follows that

$$\sum_{1\le i<j\le p-1} \frac{(-1)^j}{ij} \equiv q_p(2)^2 \equiv -\sum_{k=1}^{p-1} \frac{2^k}{k^2} \pmod{p}.$$

2. Proof of the congruence (1.2)

The *harmonic numbers* H_n are defined by

$$H_n := \sum_{j=1}^{n} \frac{1}{j}, \qquad n = 1, 2, \dots,$$

where by convention $H_0 = 0$.

Lemma 2.1. *For any prime $p \ge 5$ we have*

$$q_p(2)^2 \equiv \sum_{k=1}^{p-1} \Big(2^k + \frac{1}{2^k}\Big) \frac{H_k}{k+1} \pmod{p}. \tag{2.1}$$

Proof. In the present proof we will always suppose that i and j are positive integers such that $i \le p-1$ and $j \le p-1$, and that all the summations including i and j range over the set of such pairs (i, j).

Using the congruence (1.1) and the fact that by Fermat Little Theorem, $2^{p-1} \equiv 1 \pmod{p}$, we get

$$\begin{aligned} q_p(2)^2 &= \Big(\frac{2^{p-1}-1}{p}\Big)^2 \equiv \frac{1}{4}\Big(\sum_{k=1}^{p-1} \frac{2^k}{k}\Big)^2 = \frac{1}{4}\Big(\sum_{k=1}^{p-1} \frac{2^{p-k}}{p-k}\Big)^2 \\ &\equiv \frac{1}{4}\Big(2\sum_{k=1}^{p-1} \frac{2^{(p-1)-k}}{-k}\Big)^2 \equiv \Big(\sum_{k=1}^{p-1} \frac{1}{k\cdot 2^k}\Big)^2 \\ &= \sum_{i+j\le p} \frac{1}{ij\cdot 2^{i+j}} + \sum_{i+j\ge p} \frac{1}{ij\cdot 2^{i+j}} - \sum_{i+j=p} \frac{1}{ij\cdot 2^{i+j}} \pmod{p}. \end{aligned} \tag{2.2}$$

The last three sums will be called S_1, S_2 and S_3, respectively. We will determine them modulo p as follows.

$$\begin{aligned} S_1 &= \sum_{i+j\le p} \frac{1}{ij\cdot 2^{i+j}} = \sum_{k=2}^{p} \sum_{i+j=k} \frac{1}{ij\cdot 2^k} \\ &= \sum_{k=2}^{p} \frac{1}{2^k}\cdot\frac{1}{k}\sum_{i=1}^{k-1}\Big(\frac{1}{i} + \frac{1}{k-i}\Big) = \sum_{k=2}^{p} \frac{2H_{k-1}}{k\cdot 2^k} = \sum_{k=1}^{p-1} \frac{H_k}{(k+1)2^k}. \end{aligned} \tag{2.3}$$

Observe that the pair (i,j) satisfies $i+j=k$ for some $k\in\{p,p+1,\dots,2p-2\}$ if and only if for such a k holds $(p-i)+(p-j)=l$ with $l:=2p-k\le p$. Accordingly, using the fact that by Fermat Little Theorem, $2^{2p}\equiv 2^2 \pmod p$, we have

$$\begin{aligned}
S_2 &= \sum_{i+j\ge p}\frac{1}{ij\cdot 2^{i+j}} = \sum_{(p-i)+(p-j)\ge p}\frac{1}{(p-i)(p-j)\cdot 2^{(p-i)+(p-j)}}\\
&\equiv \sum_{i+j\le p}\frac{1}{ij\cdot 2^{2p-(i+j)}} \equiv \frac{1}{4}\sum_{i+j\le p}\frac{2^{i+j}}{ij} = \frac{1}{4}\sum_{k=2}^{p}\sum_{i+j=k}\frac{2^k}{ij}\\
&= \frac{1}{4}\sum_{k=2}^{p}\frac{2^k}{k}\sum_{i=1}^{k-1}\left(\frac{1}{i}+\frac{1}{k-i}\right) = \sum_{k=2}^{p}\frac{2^{k-1}H_{k-1}}{k}\\
&= \sum_{k=1}^{p-1}\frac{2^k H_k}{k+1} \pmod p\,. \qquad (2.4)
\end{aligned}$$

By *Wolstenholme's theorem* (see, e.g., [15], [6]; for its generalizations see [11, Theorems 1 and 2]) if p is a prime greater than 3, then the numerator of the fraction $H_{p-1}=1+\frac{1}{2}+\frac{1}{3}+\dots+\frac{1}{p-1}$ is divisible by p^2. Hence, we find that

$$\begin{aligned}
S_3 &= \sum_{i+j=p}\frac{1}{2^{i+j}ij} = \frac{1}{2^p}\sum_{i=1}^{p-1}\frac{1}{i(p-i)}\\
&= \frac{1}{p\cdot 2^p}\sum_{i=1}^{p-1}\left(\frac{1}{i}+\frac{1}{p-i}\right) = \frac{1}{p\cdot 2^{p-1}}H_{p-1}\equiv 0 \pmod p\,. \qquad (2.5)
\end{aligned}$$

Finally, substituting (2.3), (2.4) and (2.5) into (2.2), we immediately obtain (2.1). □

Proof of the following result easily follows from the congruence $H_{p-1}\equiv 0 \pmod p$.

Lemma 2.2 ([13, Lemma 2.1])**.** *Let p be an odd prime. Then*

$$H_{p-k-1}\equiv H_k \pmod p \qquad (2.6)$$

for every $k=1,2,\dots,p-2$.

Lemma 2.3. *For any prime $p\ge 5$ we have*

$$q_p(2)^2\equiv \sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}-\sum_{k=1}^{p-1}\frac{2^k}{k^2} \pmod p\,. \qquad (2.7)$$

Proof. Since by Wolstenholme's theorem, $H_{p-1}/p \equiv 0 \pmod{p}$, using this and the congruences $2^{p-1} \equiv 1 \pmod{p}$ and (2.6) of Lemma 2.2, we immediately obtain

$$\begin{aligned} \sum_{k=1}^{p-1} \frac{2^k H_k}{k+1} &\equiv \sum_{k=1}^{p-2} \frac{2^k H_k}{k+1} = \sum_{k=1}^{p-2} \frac{2^{p-k-1} H_{p-k-1}}{p-k} \\ &\equiv -\sum_{k=1}^{p-2} \frac{H_k}{k \cdot 2^k} \equiv -\sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} \pmod{p}. \end{aligned} \tag{2.8}$$

Further, using Wolstenholme's theorem, we have

$$\begin{aligned} \sum_{k=1}^{p-1} \frac{H_k}{(k+1)2^k} &= 2\sum_{k=0}^{p-2} \frac{H_{k+1} - \frac{1}{k+1}}{(k+1)2^{k+1}} + \frac{H_{p-1}}{p \cdot 2^{p-1}} \\ &= 2\sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} - 2\sum_{k=1}^{p-1} \frac{1}{k^2 \cdot 2^k} + \frac{H_{p-1}}{p \cdot 2^{p-1}} \\ &\equiv 2\sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} - 2\sum_{k=1}^{p-1} \frac{1}{k^2 \cdot 2^k} \pmod{p}. \end{aligned} \tag{2.9}$$

Moreover, from $2^p \equiv 2 \pmod{p}$ we have

$$\begin{aligned} \sum_{k=1}^{p-1} \frac{1}{k^2 \cdot 2^k} &= \sum_{k=1}^{p-1} \frac{1}{(p-k)^2 \cdot 2^{p-k}} \\ &\equiv \sum_{k=1}^{p-1} \frac{1}{k^2 \cdot 2^{1-k}} = \frac{1}{2}\sum_{k=1}^{p-1} \frac{2^k}{k^2} \pmod{p}. \end{aligned} \tag{2.10}$$

The congruences (2.8), (2.9) and (2.10) immediately yield

$$\begin{aligned} \sum_{k=1}^{p-1} \left(2^k + \frac{1}{2^k}\right)\frac{H_k}{k+1} &= \sum_{k=1}^{p-1} \frac{2^k H_k}{k+1} + \sum_{k=1}^{p-1} \frac{H_k}{(k+1)2^k} \\ &\equiv \sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} - \sum_{k=1}^{p-1} \frac{2^k}{k^2} \pmod{p}. \end{aligned} \tag{2.11}$$

Finally, comparing (2.1) of Lemma 2.1 with (2.11), we obtain the desired congruence (2.7). □

Notice that the congruence $\sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} \equiv 0 \pmod{p}$ with a prime $p \geq 5$ is recently established by Z.W. Sun [13, Theorem 1.1 (1.1)] and it is based on the identity from [13, Lemma 2.4]. Here we give another simple proof of this congruence (Lemma 2.6).

Lemma 2.4. *For any prime $p \geq 5$ we have*

$$\sum_{k=1}^{p-1} \frac{H_k}{k \cdot 2^k} \equiv \frac{1}{2} \sum_{1 \leq i \leq j \leq p-1} \frac{2^i - 1}{ij} \pmod{p}. \tag{2.12}$$

Proof. From the identity

$$\Big(\sum_{k=1}^{p-1}\frac{1}{k}\Big)\Big(\sum_{k=1}^{p-1}\frac{1}{k\cdot 2^k}\Big)=\sum_{1\le i<j\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{1\le j<i\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{k=1}^{p-1}\frac{1}{k^2\cdot 2^k}\,,$$

and the congruence $H_{p-1}=1+\frac{1}{2}+\frac{1}{3}+\cdots+\frac{1}{p-1}\equiv 0\,(\bmod\ p)$ it follows that

$$\sum_{1\le i<j\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{1\le j<i\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{k=1}^{p-1}\frac{1}{k^2\cdot 2^k}\equiv 0 \pmod p\,. \tag{2.13}$$

Since $2^p\equiv 2\,(\bmod\ p)$, we have

$$\sum_{1\le j<i\le p-1}\frac{1}{ij\cdot 2^j}\equiv\sum_{1\le j<i\le p-1}\frac{1}{2}\frac{2^{p-j}}{(p-i)(p-j)}\equiv\frac{1}{2}\sum_{1\le i<j\le p-1}\frac{2^j}{ij}\pmod p,$$

which substituting into (2.13) gives

$$\sum_{1\le i<j\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{k=1}^{p-1}\frac{1}{k^2\cdot 2^k}\equiv-\frac{1}{2}\sum_{1\le i<j\le p-1}\frac{2^j}{ij}\pmod p\,. \tag{2.14}$$

Further, if we observe that

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}=\sum_{k=1}^{p-1}\frac{H_{k-1}+\frac{1}{k}}{k\cdot 2^k}=\sum_{1\le i<j\le p-1}\frac{1}{ij\cdot 2^j}+\sum_{k=1}^{p-1}\frac{1}{k^2\cdot 2^k},$$

then substituting (2.14) into the previous identity, we obtain

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv-\frac{1}{2}\sum_{1\le i<j\le p-1}\frac{2^j}{ij}\pmod p. \tag{2.15}$$

Since

$$0\equiv\Big(\sum_{k=1}^{p-1}\frac{1}{k}\Big)\Big(\sum_{k=1}^{p-1}\frac{2^k}{k}\Big)=\sum_{1\le j\le i\le p-1}\frac{2^j}{ij}+\sum_{1\le i<j\le p-1}\frac{2^j}{ij}\pmod p\,,$$

comparing this with (2.15), we immediately obtain

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv\frac{1}{2}\sum_{1\le i\le j\le p-1}\frac{2^i}{ij}\pmod p\,. \tag{2.16}$$

From a well known fact that (see e.g., [9, p. 353])

$$\sum_{k=1}^{p-1}\frac{1}{k^2}\equiv 0\pmod p \tag{2.17}$$

we find that

$$\sum_{1\le i\le j\le p-1}\frac{1}{ij}=\frac{1}{2}\bigg(\Big(\sum_{k=1}^{p-1}\frac{1}{k}\Big)^2+\sum_{k=1}^{p-1}\frac{1}{k^2}\bigg)\equiv 0\pmod p\,.$$

Finally, the above congruence and (2.16) immediately yield the desired congruence (2.12). $\square$

Lemma 2.5. *For any positive integer n we have*

$$\sum_{1\le i\le j\le n}\frac{2^i-1}{ij}=\sum_{k=1}^{n}\frac{1}{k^2}\binom{n}{k}. \tag{2.18}$$

Proof. Using the well known identities $\sum_{i=k}^{j}\binom{i-1}{k-1}=\binom{j}{k}$ and $\frac{1}{j}\binom{j}{k}=\frac{1}{k}\binom{j-1}{k-1}$ with $k\le j$, and the fact that $\binom{i}{k}=0$ when $i<k$, we have

$$\begin{aligned}
\sum_{1\le i\le j\le n}\frac{2^i-1}{ij}&=\sum_{1\le i\le j\le n}\frac{(1+1)^i-1}{ij}=\sum_{1\le i\le j\le n}\frac{1}{j}\sum_{k=1}^{i}\frac{1}{i}\binom{i}{k}\\
&=\sum_{1\le i\le j\le n}\frac{1}{j}\sum_{k=1}^{n}\frac{1}{k}\binom{i-1}{k-1}=\sum_{k=1}^{n}\frac{1}{k}\sum_{1\le i\le j\le n}\frac{1}{j}\binom{i-1}{k-1}\\
&=\sum_{k=1}^{n}\frac{1}{k}\sum_{k\le i\le j\le n}\frac{1}{j}\binom{i-1}{k-1}=\sum_{k=1}^{n}\frac{1}{k}\sum_{j=k}^{n}\frac{1}{j}\sum_{i=k}^{j}\binom{i-1}{k-1}\\
&=\sum_{k=1}^{n}\frac{1}{k}\sum_{j=k}^{n}\frac{1}{j}\binom{j}{k}=\sum_{k=1}^{n}\frac{1}{k}\sum_{j=k}^{n}\frac{1}{k}\binom{j-1}{k-1}\\
&=\sum_{k=1}^{n}\frac{1}{k^2}\sum_{j=k}^{n}\binom{j-1}{k-1}=\sum_{k=1}^{n}\frac{1}{k^2}\binom{n}{k},
\end{aligned}$$

as desired. $\square$

Lemma 2.6 ([13, Theorem 1.1 (1.1)])**.** *For any prime $p\ge 5$ we have*

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv 0 \pmod{p}. \tag{2.19}$$

Proof. Using the congruence (2.12) from Lemma 2.4 and the identity (2.18) with $n=p-1$ in Lemma 2.5, we find that

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv\frac{1}{2}\sum_{k=1}^{p-1}\frac{1}{k^2}\binom{p-1}{k} \pmod{p}. \tag{2.20}$$

It is well known (see e.g., [8]) that for $k=1,2,\dots,p-1$,

$$\binom{p-1}{k}\equiv(-1)^k \pmod{p}. \tag{2.21}$$

Then from (2.20), (2.21) and (2.17) we get

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv\frac{1}{2}\sum_{k=1}^{p-1}\frac{(-1)^k}{k^2}=\frac{1}{2}\Big(2\sum_{\substack{1\le j\le p-1\\ 2|j}}\frac{1}{j^2}-\sum_{k=1}^{p-1}\frac{1}{k^2}\Big)$$
$$=\frac{1}{4}\sum_{k=1}^{(p-1)/2}\frac{1}{k^2}-\frac{1}{2}\sum_{k=1}^{p-1}\frac{1}{k^2}\equiv\frac{1}{4}\sum_{k=1}^{(p-1)/2}\frac{1}{k^2}\pmod{p}.$$

Finally, the above congruence together with the fact that from (2.17) (see e.g., [12, Corollary 5.2 (a) with $k=2$])

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

yields

$$\sum_{k=1}^{p-1}\frac{H_k}{k\cdot 2^k}\equiv 0\pmod{p}.$$

This concludes the proof. □

Proof of the congruence (1.2)**.** The congruence (1.2) immediately follows from (2.7) of Lemma 2.3 and (2.19) of Lemma 2.6. □

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