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THE AVERAGE SMARANDACHE FUNCTION

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For every positive integer n let $S(n)$ be the minimal positive integer m such that $n \mid m!$. For any positive number $x \geq 1$ let

$$A(x) = \frac{1}{x}\sum_{n\leq x} S(n) \qquad (1)$$

be the average value of S on the interval $[1, x]$. In [6], the authors show that

$$A(x) < c_1x + c_2 \qquad (2)$$

where c_1 can be made rather small provided that x is enough large (for example, one can take $c_1 = .215$ and $c_2 = 45.15$ provided that $x > 1470$). It is interesting to mention that by using the method outlined in [6], one gets smaller and smaller values of c_1 for which (2) holds provided that x is large, but at the cost of increasing c_2! In the same paper, the authors ask whether it can be shown that

$$A(x) < \frac{2x}{\log x} \qquad (3)$$

and conjecture that, in fact, the stronger version

$$A(x) < \frac{x}{\log x} \qquad (4)$$

might hold (the authors of [6] claim that (4) has been tested by Ibstedt in the range $x \leq 5 \cdot 10^6$ in [4]. Although I have read [4] carefully, I found no trace of the aforementioned computation!).

In this note, we show that $\frac{x}{\log x}$ is indeed the correct order of magnitude of $A(x)$.

For any positive real number x let $\pi(x)$ be the number of prime numbers less then or equal to x,

$$B(x) = xA(x) = \sum_{1\leq n\leq x} S(n), \qquad (5)$$

$$E(x) = 2.5\log\log(x) + 6.2 + \frac{1}{x}. \qquad (6)$$

We have the following result:

Theorem.

$$.5(\pi(x) - \pi(\sqrt{x})) < A(x) < \pi(x) + E(x) \qquad \text{for all } x \geq 3. \qquad (7)$$

Inequalities (7), combined with the prime number theorem, assert that

$$.5 \le \liminf_{x\to\infty} \frac{\frac{A(x)}{x}}{\log x} \le \limsup_{x\to\infty} \frac{\frac{A(x)}{x}}{\log x} \le 1,$$

which says that $\frac{x}{\log x}$ is indeed the right order of magnitude of $A(x)$. The natural conjecture is that, in fact,

$$A(x) = \frac{x}{\log x} + O\Big(\frac{x}{\log^2 x}\Big). \tag{8}$$

Since

$$\frac{x}{\log x}\Big(1+\frac{1}{2\log x}\Big) < \pi(x) < \frac{x}{\log x}\Big(1+\frac{3}{2\log x}\Big) \qquad \text{for } x \ge 59,$$

it follows, by our theorem, that the upper bound on $A(x)$ is indeed of the type (8). Unfortunately, we have not succeeded in finding a lower bound of the type (8) for $A(x)$.

The Proof

We begin with the following observation:

Lemma.

Suppose that $n = p_1^{\alpha_1}\dots p_k^{\alpha_k}$ is the decomposition of n in prime factors (we assume that the p_i's are distinct but not necessarily ordered). Then:

1.

$$S(n) \le \max_{i=1}^{k}(\alpha_i p_i). \tag{9}$$

2. *Assume that $\alpha_1 p_1 = \max_{i=1}^{k}(\alpha_i p_i)$. If $\alpha_1 \le p_1$, then $S(n) = \alpha_1 p_1$.*

3.

$$S(n) > \alpha_i(p_i - 1) \qquad \text{for all } i = 1, \dots, k. \tag{10}$$

Proof.

For every prime number p and positive integer k let $e_p(k)$ be the exponent at which p appears in $k!$.

1. Let $m \ge \max_{i=1}^{k}(\alpha_i p_i)$. Then

$$e_{p_i}(m) = \sum_{s\ge 1}\Big\lfloor \frac{m}{p_i^s}\Big\rfloor \ge \Big\lfloor \frac{m}{p_i}\Big\rfloor \ge \alpha_i \quad \text{for } i = 1, \dots, k.$$

This obviously implies $n \mid m!$, hence $m \ge S(n)$.

2. Assume that $\alpha_1 \le p_1$. In this case, $S(n) \ge \alpha_1 p_1$. By 1 above, it follows that in fact $S(n) = \alpha_1 p_1$.

3. Let $m = S(n)$. The asserted inequality follows from

$$\alpha_i \le e_{p_i}(m) = \sum_{s\ge 1}\Big\lfloor \frac{m}{p_i^s}\Big\rfloor < m\sum_{s\ge 1}^{\infty}\frac{1}{p_i^s} = \frac{m}{p_i - 1}.$$

The Proof of the Theorem.

In what follows p denotes a prime. We assume $x > 1$. The idea behind the proof is to find good bounds on the expression

$$B(x) - B(\sqrt{x}) = \sum_{\sqrt{x}<n\leq x} S(n). \tag{11}$$

Consider the following three subsets of the interval $I = (\sqrt{x},\ x]$:

$$C_1 = \{n \in I \mid S(n) \text{ is not a prime}\},$$
$$C_2 = \{n \in I \mid S(n) = p \leq \sqrt{x}\},$$
$$C_3 = \{n \in I \mid S(n) = p > \sqrt{x}\}.$$

Certainly, the three subsets above are, in general, not disjoint but their union covers I. Let

$$D_i(x) = \sum_{n\in C_i} S(n) \qquad \text{for } i = 1,\ 2,\ 3.$$

Clearly,

$$\max(D_i(x) \mid i = 1,\ 2,\ 3) \leq B(x) - B(\sqrt{x}) \leq D_1(x) + D_2(x) + D_3(x). \tag{12}$$

We now bound each D_i separately.

The bound for D_1.

Assume that $m \in C_1$. By the Lemma, it follows that $S(m) \leq \alpha p$ for some $p^\alpha \| m$ and $\alpha > 1$. First of all, notice that $S(m) \leq \alpha\sqrt{m}$. Indeed, this follows from the fact that

$$S(m) \leq \alpha p \leq \alpha p^{\alpha/2} \leq \alpha\sqrt{m} \qquad \text{for } \alpha \geq 2.$$

In particular, from the above inequality it follows that $p \leq \sqrt{m} \leq \sqrt{x}$. Write now $m = p^\alpha k$. Since $m \leq x$, it follows that $k \leq x/p^\alpha$. These considerations show that

$$D_1(x) < \sum_{p\leq\sqrt{x}} \sum_{\alpha\geq 2}^{\infty} \alpha p \cdot \frac{x}{p^\alpha} = x \sum_{p\leq\sqrt{x}} \sum_{\alpha\geq 2}^{\infty} \frac{\alpha}{p^{\alpha-1}} = x \sum_{p\leq\sqrt{x}} \frac{2p-1}{(p-1)^2}. \tag{13}$$

In the above formula (13), we used the fact that

$$\sum_{\alpha\geq 2} \alpha z^{\alpha-1} = \frac{d}{dz}\left(\frac{1}{1-z}\right) - 1 = \left(\frac{1}{1-z}\right)^2 - 1 = \frac{2z - z^2}{(1-z)^2} \quad \text{for } |z| < 1$$

with $z = 1/p$. Since

$$\frac{2p-1}{(p-1)^2} \leq \frac{5}{4p} \qquad \text{for } p \geq 3,$$

it follows that

$$D_1(x) < x\left(3 - \frac{5}{8} + \frac{5}{4} \sum_{p\leq\sqrt{x}} \frac{1}{p}\right) = x\left(2.375 + 1.25 \sum_{p\leq\sqrt{x}} \frac{1}{p}\right). \tag{14}$$

From a formula from [5], we know that

$$\sum_{p\leq y}\frac{1}{p} < \log\log y + 1.27 \qquad \text{for all } y > 1.$$

Hence, inequality (14) implies

$$D_1(x) < x\Big(2.375 + 1.25\Big(\log\log\sqrt{x} + 1.27\Big)\Big) < x\Big(3.1 + 1.25\log\log x\Big). \qquad (15)$$

The bound for D_2

Assume that $S(m) = p$. Then $m = py$ where p does not divide y. Since $m > \sqrt{x}$, it follows that

$$\frac{\sqrt{x}}{p} < y \leq \frac{x}{p}$$

Since $p \leq \sqrt{x}$, it follows that at least one integer in the above interval is a multiple of p; hence, cannot be an acceptable value for y. This shows that there are at most

$$\left\lfloor\frac{x-\sqrt{x}}{p}\right\rfloor \leq \frac{x-\sqrt{x}}{p}$$

possible values for y. Hence,

$$D_2(x) \leq \sum_{p\leq\sqrt{x}} p\cdot\left(\frac{x-\sqrt{x}}{p}\right) \leq (x-\sqrt{x})\pi(\sqrt{x}). \qquad (16)$$

Bounds for D_3

Assume $S(m) = p$ for some $p > \sqrt{x}$. Then, $m = py$ for some $y < x/p$. Hence,

$$D_3(x) = \sum_{\sqrt{x}<p\leq x} p\cdot\left\lfloor\frac{x}{p}\right\rfloor. \qquad (17)$$

Notice that, unlike in the previous cases, (17) is in fact an equality. Since $z \geq \lfloor z\rfloor > .5z$ for all real numbers $z > 1$, it follows, from formula (17), that

$$.5x(\pi(x) - \pi(\sqrt{x})) < D_3(x) < x(\pi(x) - \pi(\sqrt{x})). \qquad (18)$$

Denote now by

$$F(x) = 3.1 + 1.25\log\log(x)$$

From inequalities (12), (15), (16) and (17), it follows that

$$.5x(\pi(x) - \pi(\sqrt{x})) < D_3(x) < B(x) - B(\sqrt{x}) < D_1(x) + D_2(x) + D_3(x) <$$

$$xF(x) + (x-\sqrt{x})\pi(\sqrt{x}) + x(\pi(x) - \pi(\sqrt{x})) = x\pi(x) - \sqrt{x}\pi(\sqrt{x}) + xF(x). \qquad (19)$$

The left inequality (7) is now obvious since

$$B(x) > B(\sqrt{x}) + .5x(\pi(x) - \pi(\sqrt{x})) \geq 1 + .5x(\pi(x) - \pi(\sqrt{x})).$$

For the right inequality (7), let $G(x) = x\pi(x)$. Formula (19) can be rewritten as

$$B(x) - B(\sqrt{x}) < G(x) - G(\sqrt{x}) + xF(x). \tag{20}$$

Applying inequality (20) with x replaced by $\sqrt{x}$, $x^{1/4}$, ..., $x^{1/2^s}$ until $x^{1/2^s} < 2$ and summing up all these inequalities one gets

$$B(x) - B(1) < G(x) + \sum_{i=0}^{s} x^{1/2^i} F(x^{1/2^i}). \tag{21}$$

The function $F(x)$ is obviously increasing. Hence,

$$B(x) < 1 + G(x) + F(x) \sum_{i=0}^{s} x^{1/2^i}. \tag{22}$$

To finish the argument, we show that

$$x \geq \sum_{i=1}^{s} x^{1/2^i}. \tag{23}$$

Proceed by induction on s. If $s = 0$, there is nothing to prove. If $s = 1$, this just says that $x > \sqrt{x}$ which is obvious. Finally, if $s \geq 2$, it follows that $x \geq 4$. In particular, $x \geq 2\sqrt{x}$ or $x - \sqrt{x} \geq \sqrt{x}$. Rewriting inequality (23) as

s

$i=2$

which is precisely inequality (23) for $\sqrt{x}$. This completes the induction step. Via inequality (23), inequality (22) implies

$$B(x) < 1 + x\pi(x) + 2xF(x) = 1 + x\pi(x) + 2x\Big(3.1 + 1.25\log\log x) \tag{24}$$

or

$$A(x) < \pi(x) + \frac{1}{x} + 6.2 + 2.5\log\log x = \pi(x) + E(x).$$

Applications

From the theorem, it follows easily that for every $\epsilon > 0$ there exists x_0 such that

$$A(x) < (1+\epsilon)\frac{x}{\log x}. \tag{25}$$

In practice, finding a lower bound on x_0 for a given ϵ, one simply uses the theorem and the estimate

$$\pi(x) < \frac{x}{\log x}\Big(1 + \frac{3}{2\log x}\Big) \qquad \text{for } x > 1. \tag{26}$$

(see [5]). By (7) and (26), it now follows that (25) is satisfied provided that

$$\frac{x}{\log x} > \frac{1}{\epsilon}\Big(\frac{3}{2\log^2 x} + E(x)\Big).$$

For example, when $\epsilon = 1$, one gets

$$A(x) < 2\frac{x}{\log x} \qquad \text{for } x \geq 64, \tag{27}$$

for $\epsilon = .5$, one gets

$$A(x) < 1.5\frac{x}{\log x} \qquad \text{for } x \geq 254 \tag{28}$$

and for $\epsilon = 0.1$ one gets

$$A(x) < 1.1\frac{x}{\log x} \qquad \text{for } x \geq 3298109. \tag{29}$$

Of course, inequalites (27)-(29) may hold even below the smallest values shown above but this needs to be checked computationally.

In the same spirit, by using the theorem and the estimation

$$\pi(x) > \frac{x}{\log x}\Big(1 + \frac{1}{2\log x}\Big) \qquad \text{for } x \geq 59$$

(see [5]) one can compute, for any given ϵ, an initial value x_0 such that

$$A(x) > (.5 - \epsilon)\frac{x}{\log x} \qquad \text{for } x > x_0.$$

For example, when $\epsilon = 1/6$ one gets

$$A(x) > \frac{1}{3}\frac{x}{\log x} \qquad \text{for } x \geq 59. \tag{30}$$

Inequality (30) above is better than the inequality appearing on page 62 in [2] which asserts that for every $\alpha > 0$ there exists x_0 such that

$$A(x) > x^{\alpha/x} \qquad \text{for } x > x_0 \tag{31}$$

because the right side of (31) is bounded and the right side of (30) isn't!

A diophantine equation

In this section we present an application to a diophantine equation. The application is not of the theorem per se, but rather of the counting method used to prove the theorem.

Since S is defined in terms of factorials, it seems natural to ask how often the product $S(1) \cdot S(2) \cdot \ldots \cdot S(n)$ happens to be a factorial.

Proposition.

The only solutions of

$$S(1) \cdot S(2) \cdot \ldots \cdot S(n) = m! \tag{32}$$

are given by $n = m \in \{1,\ 2,\ ...,\ 5\}$.

Proof.

We show that the given equation has no solutions for $n \geq 50$. Assume that this is not so. Let P be the largest prime number smaller than n. By Tchebysheff's theorem, we know that $P \geq n/2$. Since $S(P) = P$, it follows that $P \mid m!$. In particular, $P \leq m$. Hence, $m \geq n/2$.

We now compute an upper bound for the order of 2 in $S(1) \cdot S(2) \cdot \ldots \cdot S(n)$. Fix some $\beta \geq 1$ and assume that k is such that $2^\beta \mid\mid S(k)$. Since

$$S(k) = \max(S(p^\alpha) \mid p^\alpha \mid\mid k),$$

it follows that $2^\beta \mid\mid S(p^\alpha)$ for some $p^\alpha \mid\mid k$.

We distinguish two situations:

Case 1.

p is odd. In this case, $2^\beta p \mid S(p^\alpha)$. If $\beta = 1$, then $\alpha = 2$. If $\beta = 2$, then $\alpha = 4$. For $\beta \geq 3$, one can easily check that $\alpha \geq 2^\beta - \beta + 1$ (indeed, if $\alpha \leq 2^\beta - \beta$, then one can check that $p^\alpha \mid (2^\beta p - 1)!$ which contradicts the definition of S). In particular, $p^{2^\beta - \beta + 1} \mid k$. Since $2^{x-1} \geq x + 1$ for $x \geq 3$, it follows that $\alpha \geq 2^{\beta-1} + 2$. Since $k \leq n$, the above arguments show that there are at most

$$\frac{n}{p^{2\beta}} \qquad \text{for } \beta = 1,\ 2$$

and

$$\frac{n}{p^{2^{\beta-1}+2}} \qquad \text{for } \beta \geq 3$$

integers k in the interval $[1,\ n]$ for which $p \mid k$, $S(k) = S(p^\alpha)$, where α is such that $p^\alpha \mid\mid k$ and $2^\beta \mid\mid S(k)$.

Case 2.

$p = 2$. If $\beta = 1$, then $k = 2$. If $\beta = 2$, then $k = 4$. Assume now that $\beta \geq 3$. By an argument similar to the one employed at Case 1, one gets in this case that $\alpha \geq 2^\beta - \beta$. Since $2^\alpha \mid\mid k$, it follows that $2^{2^\beta - \beta} \mid k$. Since $k \leq n$, it follows that there are at most

$$\frac{n}{2^{2^\beta - \beta}}$$

such k's.

From the above anaysis, it follows that the order at which 2 divides $S(1) \cdot S(2) \cdot \ldots \cdot S(n)$ is at most

$$e_2 < 3 + n \sum_{\substack{p \leq n \\ p \text{ odd}}} \left(\frac{1}{p^2} + \frac{2}{p^4} + \sum_{\beta \geq 3} \frac{\beta}{p^{2^{\beta-1}+2}}\right) + n \sum_{\beta \geq 3} \frac{\beta}{2^{2^\beta - \beta}}. \tag{38}$$

(the number 3 in the above formula counts the contributions of $S(2) = 2$ and $S(4) = 4$). We now bound each one of the two sums above.

For fixed p, one has

$$\frac{1}{p^2} + \frac{2}{p^4} + \sum_{\beta \geq 3} \frac{\beta}{p^{2^{\beta-1}+2}} = \frac{1}{p^2} + \frac{2}{p^4} + \frac{3}{p^6} + \frac{4}{p^{10}} + \ldots < \sum_{\gamma \geq 1} \frac{\gamma}{p^{2\gamma}} = \frac{p^2}{(p^2 - 1)^2}. \tag{39}$$

Hence,

$$\sum_{\substack{p\leq n\\ p \text{ odd}}} \left(\frac{1}{p^2}+\frac{2}{p^4}+\sum_{\beta\geq 3}\frac{\beta}{p^{2^{\beta-1}+2}}\right) < \sum_{p \text{ odd}} \frac{p^2}{(p^2-1)^2} < .245 \tag{40}$$

We now bound the second sum:

$$\sum_{\beta\geq 3}\frac{\beta}{2^{2^\beta-\beta}} = \frac{3}{2^5}+\frac{4}{2^{12}}+\frac{5}{2^{27}}+\ldots < \frac{3}{2^6}+\sum_{\beta\geq 3}\frac{\beta}{2^{2+4(\beta-2)}} =$$

$$\frac{3}{2^6}+\frac{1}{4}\Big(\sum_{\gamma\geq 1}\frac{\gamma+2}{16^\gamma}\Big) = \frac{3}{2^6}+\frac{1}{4}\Big(\frac{15}{16}+\frac{31}{225}\Big) < .099 \tag{41}$$

From inequalities (38), (40) and (41), it follows that

$$e_2 < 3 + .344n. \tag{42}$$

We now compute a lower bound for e_2. Since $e_2 = e_2(m!)$, it follows, from Lemme 1 in [1] and from the fact that $m \geq n/2$, that

$$e_2 \geq m - \frac{\log(m+1)}{\log 2} \geq \frac{n}{2} - \frac{\log(n/2+1)}{\log 2}. \tag{43}$$

From inequalities (42) and (43), it follows that

$$3 + .344n \geq .5n - \frac{\log(.5n+1)}{\log 2},$$

which gives $n \leq 50$. One can now compute $S(1)\cdot S(2)\cdot\ldots\cdot S(n)$ for all $n \leq 50$ to conclude that the only instances when these products are factorials are $n = 1, 2, \ldots, 5$.

We conclude suggesting the following problem:

Problem.

Find all positive integers n such that $S(1)$, $S(2)$, ..., $S(n^2)$ can be arranged in a latin square.

The above problem appeared as Problem 24 in SNJ **9**, (1994) but the range of solutions was restricted to $\{2, 3, 4, 5, 7, 8, 10\}$. The published solution was based on the simple observation that the sum of all entries in an $n \times n$ latin square has to be a multiple of n. By computing the sums $B(x^2)$ for x in the above range, one concluded that $B(x^2) \not\equiv 0 \pmod{x}$ which meant that there is no solution for such x'ses. It is unlikely that this argument can be extended to cover the general case. One should notice that from our theorem, it follows that if a solution exists for some $n > 1$, then the size of the common sums of all entries belonging to the same row (or column) is $\cong n\pi(n^2)$.

Addendum

After this paper was written, it was pointed out to us by an annonymous referee that Finch [3] proved recently a much stronger statement, namely that

$$\lim_{x\to\infty}\frac{\log(x)}{x}\cdot A(x) = \frac{\pi^2}{12} = 0.82246703\ldots \tag{44}$$

Finch's result is better than our result which only shows that the limsup of the expression $\log(x)A(x)/x$ when x goes to infinity is in the interval [0.5, 1].

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