From explicit estimates for the primes to explicit estimates for the Moebius function

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Abstract

We prove two explicit estimates respectively slightly stronger than $|\sum_{d\le D}\mu(d)|/D \le 0.013/\operatorname{Log} D$ for every $D \ge 1\,100\,000$ and than $|\sum_{d\le D}\mu(d)/d| \le 0.026/\operatorname{Log} D$ for every $D \ge 61\,000$.

1 Introduction

There is a long litterature concerning explicit estimates for the summatory function of the Moebius function, and we cite for instance [21], [1], [4], [3], [6], [7], [10], [11]. The paper [5] proposes a very usefull annoted bibliography covering relevant items up to 1983. It has been known since the beginning of the 20th century at least (see for instance [13]) that showing that $M(x) = \sum_{n\le x}\mu(n)$ is $o(x)$ is equivalent to showing that the Tchebychef function $\psi(x) = \sum_{n\le x}\Lambda(n)$ is asymptotic to x. We have good explicit estimates for $\psi(x) - x$, see for instance [19], [22] and [9]. This is due to the fact that we can use analytic tools in this problem since the residues at the poles of the Dirichlet generating series (namely here $-\zeta'(s)/\zeta(s)$) are known. However this situation has no counterpart in the Moebius function case. It would thus be highly valuable to deduce estimates for $M(x)$ from estimates for $\psi(x) - x$, but a precise quantitative link is missing. I proposed some years back the following conjecture:

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Conjecture (Strong form of Landau's equivalence Theorem, II).
There exist positive constants c_1 and c_2 such that

$$|M(x)|/x \le c_1 \max_{c_2x<y\le x/c_2} |\psi(y)-y|/y + c_1x^{-1/4}.$$

Such a conjecture is trivially true under the Riemann Hypothesis. In this respect, we note that [23] proves that in case of the Beurling's generalized integers, one can have $M_{\mathcal{P}}(x) = o(x)$ without having $\psi(x) \sim x$. This reference has been kindly shown to me by Harold Diamond whom I warmly thank here.

We are not able to prove such a strong estimate, but we are still able to derive estimate for $M(x)$ from estimates for $\psi(x) - x$. Our process can be seen as a generalization of the initial idea of [21] also used in [10]. We describe it in the section 3, after a combinatorial preparation. Here is our main Theorem.

Theorem 1.1. *For $D \ge 1\,078\,853$, we have*

$$\Big|\sum_{d\le D}\mu(d)\Big| \le \frac{0.0130\operatorname{Log} D - 0.118}{(\operatorname{Log} D)^2} D.$$

The last result of this shape is from [10] and has 0.10917 (starting from $D = 695$) instead of 0.0130.

On following an idea of [11] which we recall in the last section, we deduce from the above the following estimate.

Corollary 1.2. *For $D \ge 60\,298$, we have*

$$\Big|\sum_{d\le D}\mu(d)/d\Big| \le \frac{0.0260\operatorname{Log} D - 0.118}{(\operatorname{Log} D)^2}.$$

The last result of this shape is from [11] and has 0.2185 (starting from $x = 33$) instead of 0.0260. Here are two results that are simpler to remember:

Corollary 1.3. *For $D \ge 60\,200$, we have*

$$\Big|\sum_{d\le D}\mu(d)/d\Big| \le \frac{\operatorname{Log} D - 4}{40(\operatorname{Log} D)^2}.$$

If we replace the -4 by 0, the resulting bound is valid from $24\,270$ onward.

Corollary 1.4. *For $D \ge 50\,000$, we have*

$$\Big|\sum_{d\le D}\mu(d)/d\Big| \le \frac{3\operatorname{Log} D - 10}{100(\operatorname{Log} D)^2}.$$

If we replace the -10 by 0, the resulting bound is valid from $11\,815$ onward.

We will meet another problem in between, which is to relate quantitatively the error term $\psi(x) - x$ with the error term concerning the approximation of $\tilde{\psi}(x) = \sum_{n\le x} \Lambda(n)/n$ by $\operatorname{Log} x - \gamma$. This problem is surprisingly difficult but [16] offers a good enough solution.

I thank Harald Helfgott for interesting discussions that pushed me into pulling this note out of its drawer and François Dress for giving me the preprint [11]. This paper was done in majority when I was enjoying the hospitality of the Mathematical Sciences Institute in Chennai, and I thank this institution and my hosts Ramachandran Balasubramanian, Anirban Mukhopadhyay and Sanoli Gun for this opportunity to work in peace and comfort.

Notation

We define the shortcuts $R(x) = \psi(x) - x$ and $r(x) = \tilde{\psi}(x) - \operatorname{Log} x + \gamma$, where we recall that

$$\tilde{\psi}(x) = \sum_{n\le x} \Lambda(n)/n. \tag{1.1}$$

We shall use square-brackets to denote the integer part and parenthesis to denote the fractionnal part, so that $D = [D] + \{D\}$. But since this notation is used seldomly we shall also use square brackets in their usual function.

2 A combinatorial tool

We prove a formal identity in this section. Let F be a function and $Z = -F'/F$ the opposite of its logarithmic derivative. We look at

$$F[1/F]^{(k)} = P_k.$$

It is immediate to compute the first values and we find that

$$P_0 = F, \quad P_1 = Z, \quad P_2 = Z' + Z^2, \quad P_3 = Z'' + 3ZZ' + Z^3. \tag{2.1}$$

In general, the following recursion formula holds

$$P_k = F(P_{k-1}/F)' = P'_{k-1} + ZP_{k-1}. \tag{2.2}$$

Here is the result this leads to:

Theorem 2.1. *We have*

$$F[1/F]^{(k)} = \sum_{\sum_{i\ge1} ik_i = k} \frac{k!}{k_1!k_2!\cdots (1!)^{k_1}(2!)^{k_2}\cdots} \prod_{k_i} Z^{(i-1)k_i}.$$

We can prove it by using the recursion formula given above. We present now a different line. Let us expand $1/F(s+X)$ in Taylor series around $X = 0$.

$$\frac{1}{F(s+X)} = \sum_{k\geq 0} [1/F(s)]^{(k)} \frac{X^k}{k!}.$$

We do the same for $-F'(s+X)/F(s+X)$ getting:

$$\frac{-F'(s+X)}{F(s+X)} = \sum_{k\geq 0} [Z(s)]^{(k)} \frac{X^k}{k!}.$$

Integrating formally this expression, we get

$$-\operatorname{Log}(F(s+X)/F(s)) = \sum_{k\geq 1} [Z(s)]^{(k-1)} \frac{X^k}{k!}$$

where the constant term is chosen so that the constant term is indeed 0. We then apply the exponential formula

$$\exp\left(\sum_{k\geq 1} x_k X^k/k!\right) = \sum_{m\geq 0} Y_m(x_1, x_2, \dots) \frac{X^m}{m!}$$

where the $Y_m(x_1, x_2, \dots)$ are the complete exponential Bell polynomials whose expression yields the Theorem above.

3 The general argument

Let us specialize $F = \zeta$ in Theorem 2.1. The left hand side therein has a simple pole in $s = 1$ with a residue being $k!$ times the k-th Taylor coefficient of $1/\zeta(s)$ at $s = 1$. Let us call $\mathfrak{R}_k$ this residue. By a routine argument, we get

$$\sum_{\ell\leq L} \mathbb{1} \star (\mu \operatorname{Log}^k)(\ell) = \mathfrak{R}_k L + o(L). \tag{3.1}$$

Note that, thanks to Theorem 2.1, the error term is quantified in terms of the error term in the approximations of both $\psi(x) - x$ and $\tilde{\psi}(x) - \operatorname{Log} x + \gamma$. Getting to this error term in fact requires using a good enough error term for both these quantities (see for instance [12]) . We then continue

$$\sum_{\ell\leq L} \mu(\ell) \operatorname{Log}^k \ell = \sum_{d\leq L} \mu(d) \left(\mathfrak{R}_k \frac{L}{d} + o(L/d)\right) \tag{3.2}$$

which ensures us that $\sum_{\ell\leq L} \mu(\ell) \operatorname{Log}^k \ell$ is $o(L \operatorname{Log} L)$.

Case $k = 2$ is most enlightening. In this case, our method consist in writing

$$\sum_{\ell \le L} \mu(\ell) \operatorname{Log}^2 \ell = \sum_{d\ell \le L} \mu(\ell) \big(\Lambda \star \Lambda(d) - \Lambda(d) \operatorname{Log} d\big). \tag{3.3}$$

As it turns out, the main term of the summatory function of $\Lambda \operatorname{Log}$ (namely $L \operatorname{Log} L$) cancels the one of $\Lambda \star \Lambda$. This requires the prime number Theorem. In deriving the prime number theorem from Selberg's formula $\mu \star \operatorname{Log}^2 = \Lambda \operatorname{Log} + \Lambda \star \Lambda$, it is a well known difficulty to show that both summands indeed contribute and this is another show-up of the parity principle. We modify (3.3) as follows:

$$2\gamma + \sum_{\ell \le L} \mu(\ell) \operatorname{Log}^2 \ell = \sum_{d\ell \le L} \mu(\ell) \big(\Lambda \star \Lambda(d) - \Lambda(d) \operatorname{Log} d + 2\gamma\big). \tag{3.4}$$

Case $k = 1$ is classical, but it is interesting to note that this is the starting point of [21].

4 Some known estimates and straightforward consequences

Lemma 4.1 ([18])**.** $\max_{t \ge 1} \psi(t)/t = \psi(113)/113 \le 1.04$.

Concerning small values, we quote from [17] the following result

$$|\psi(x) - x| \le \sqrt{x} \qquad (8 \le x \le 10^{10}). \tag{4.1}$$

If we change this $\sqrt{x}$ by $\sqrt{2x}$, this is valid from $x = 1$ onwards. Furthermore

$$|\psi(x) - x| \le 0.8\sqrt{x} \qquad (1\,500 \le x \le 10^{10}). \tag{4.2}$$

Lemma 4.2.

$$|\psi(x) - x| \le 0.0065x/\operatorname{Log} x \quad (x \ge 1\,514\,928).$$

Proof. By [8, Théorème 1.3] improving on [22, Theorem 7], we have

$$|\psi(x) - x| \le 0.0065x/\operatorname{Log} x \quad (x \ge \exp(22)). \tag{4.3}$$

We readily extend this estimate to $x \ge 3\,430\,190$ by using (4.2). We then use the function `WalkPsi` from the script `IntR.gp` (with the proper `model` function). □

Lemma 4.3. *For $x \ge 7\,105\,266$, we have*

$$|\psi(x) - x|/x \le 0.000\,213.$$

Proof. We start with the estimate from [20, (4.1)]

$$|\psi(x) - x|/x \leq 0.000\,213 \qquad (x \geq 10^{10}). \tag{4.4}$$

We extend it to $x \geq 14\,500\,000$ by using (4.2). We complete the proof by using the following Pari/Gp script (see [15]):

```
{CalculeLambdas(Taille)=
   my(pk, Lambdas);
   Lambdas = vector(Taille);
   forprime(p = 2,Taille,
            pk = p;
            while(pk <= Taille, Lambdas[pk] = p; pk*=p));
   return(Lambdas);}

{model(n)=n}

{WalkPsi(zmin, zmax)=
   my(res = 0.0, mo, maxi, psiaux = 0.0, Lambdas);
   Lambdas = CalculeLambdas(zmax);
   for(y = 2, zmin,
      if(Lambdas[y]!=0, psiaux += log(Lambdas[y]),));
   maxi = abs(psiaux-zmin)/model(zmin);
   for(y = zmin+1, zmax,
      mo = 1/model(y);
      maxi = max(maxi, abs(psiaux-y)*mo);
      if(Lambdas[y]!=0, psiaux += log(Lambdas[y]),);
      maxi = max(maxi, abs(psiaux-y)*mo));
   print("|psi(x)-x|/model(x) <= ", maxi, " pour ",
         zmin, " <= x <= ", zmax);
   return(maxi);}
```

□

Lemma 4.4. *For $x \geq 32\,054$, we have*

$$|\psi(x) - x|/x \leq 0.003.$$

Proof. The preceding Lemma proves it for $x \geq 7\,105\,266$. On using (4.2), we extend it to $x \geq 102\,500$. We complete the proof by using the same script as in the proof of Lemma 4.3. □

We quote from [16] the following Lemma.

Lemma 4.5. *When $x \geq 23$, we have*

$$\tilde{\psi}(x) = \operatorname{Log} x - \gamma + \mathcal{O}^*\left(\frac{0.0067}{\operatorname{Log} x}\right).$$

Let us turn our attention to the summatory function of the Moebius function. In [6], we find the bound

$$|M(x)| \le 0.571\sqrt{x} \qquad (33 \le x \le 10^{12}) \tag{4.5}$$

In [7], we find

$$|M(x)| \le x/2360 \quad (x \ge 617\,973) \tag{4.6}$$

(see also [4]) which [2] (published also in [3]) improves in

$$|M(x)| \le x/4345 \quad (x \ge 2\,160\,535). \tag{4.7}$$

Bounds for squarefree numbers

Lemma 4.6. *We have for $D \ge 1$*

$$\sum_{d\le D} \mu^2(d) = \frac{6}{\pi^2}D + \mathcal{O}^*(0.7\sqrt{D}).$$

For $D \ge 10$, we can replace 0.7 by 0.5.

Proof. [1] (see also [2]) proves that

$$\sum_{d\le D} \mu^2(d) = \frac{6}{\pi^2}D + \mathcal{O}^*(0.1333\sqrt{D}) \quad (D \ge 1\,664)$$

and we use direct inspection using Pari/Gp to conclude. □

Lemma 4.7. *Let $D/K \ge 1$. Let f be a non-negative non-decreasing C^1 function. We have*

$$\sum_{D/L<d\le D/K} \mu^2(d) f(D/d) \le 1.31 f(L) + \frac{6D}{\pi^2}\int_K^L \frac{f(t)dt}{t^2} + 0.35\sqrt{D}\int_K^L \frac{f(t)dt}{t^{3/2}}.$$

Proof. We use a simple integration by parts to write

$$\sum_{D/L<d\le D/K} \mu^2(d) f(D/d) = \sum_{D/L<d\le D/K} \mu^2(d)\left(f(K) + \int_K^{D/d} f'(t)dt\right)$$
$$= \sum_{D/L<d\le D/K} \mu^2(d) f(K) + \int_K^L \left(\sum_{D/L<d\le D/t} \mu^2(d)\right) f'(t)dt.$$

We then employ Lemma 4.6 to get the bound:

$$\frac{6D}{\pi^2 K} f(K) + \int_K^L \frac{6D}{\pi^2 t} f'(t)dt + 0.7\sqrt{\frac{D}{K}} f(K) + 0.7\int_K^L \sqrt{\frac{D}{t}} f'(t)dt$$

Two integrations by parts gives the expression

$$\frac{6}{\pi^2} f(L) + \int_K^L \frac{6D}{\pi^2 t^2} f(t)dt + 0.7 f(L) + 0.35\sqrt{D}\int_K^L \frac{f(t)dt}{t^{3/2}}.$$

The Lemma follows readily. □

5 A preliminary estimate on primes

Our aim here is to evaluate

$$R_4(D) = \sum_{d_1 \le \sqrt{D}} \Lambda(d_1) R(D/d_1). \tag{5.1}$$

This remainder term is crucial in the final analysis and will be numerically one of the dominant terms.

Lemma 5.1. *When $D \ge 1$, and $\sqrt{D} \ge T \ge 1$, we have*

$$\sum_{d \le T} \frac{\Lambda(d)}{d \operatorname{Log} \frac{D}{d}} \le 1.04 \operatorname{Log} \frac{\operatorname{Log} D}{\operatorname{Log}(D/T)} + \frac{1.04}{\operatorname{Log} D}.$$

Proof. Let us define $f(t) = 1/\big(t \operatorname{Log} \frac{D}{t}\big)$. We have by a classical summation by parts:

$$\begin{aligned}
\sum_{d \le T} \Lambda(d) f(d) &= \sum_{d \le T} \Lambda(d) f(T) - \sum_{d \le T} \Lambda(d) \int_d^T f'(t) dt \\
&\le \frac{1.04}{\operatorname{Log}(D/T)} - 1.04 \int_1^T t f'(t) dt \\
&\le \frac{1.04}{\operatorname{Log}(D/T)} - 1.04 [t f(t)]_1^T + 1.04 \int_1^T f(t) dt \\
&\le \frac{1.04}{\operatorname{Log} D} + 1.04 \int_{D/T}^D \frac{dt}{t \operatorname{Log} t} \le \frac{1.04}{\operatorname{Log} D} + 1.04 \operatorname{Log} \frac{\operatorname{Log} D}{\operatorname{Log}(D/T)}
\end{aligned}$$

as required. □

Lemma 5.2. *We have $|R_4(D)|/D \le 0.0065$ when $D \ge 10^{10}$. When $D \ge 1\,300\,000\,000$, we have $|R_4(D)|/D \le 0.0073$.*

The proof that follows is somewhat clumsy due to the fact that we have not been able to compute $R_4(D)$ for D up to 10^{10}. By inspecting the expression defining R_4 and the proof below, the reader will see one could try to get a better bound for

$$\sum_{D^{1/4} < d \le \sqrt{D}} \Lambda(d) R(D/d).$$

Indeed one can compute the exact values of $R(D/d)$ and try to approximate them properly so as not to loose the sign changes in the expression. A proper model is even given by the explicit formula for $\psi(x)$. We have however tried to use the resulting polynomial, namely $x - \sum_{|\gamma| \le G} x^{\frac{1}{2} + i\gamma} / (\frac{1}{2} + i\gamma)$ with $G = 20$, $G = 30$ and $G = 200$, but the approximation was very weak. It may be better to find directly a numerical fit for $R(x)$ on this limited range. It should be noted that the function $R(x)$ is highly erratical. Such a process would be important since the value 0.0065 that we get here decides for a large part of the final value in Theorem 1.1.

Proof. When $D \geq 1514928^2$, we have by Lemma 4.2 and Lemma 5.1:

$$|R_4(D)|/D \leq 0.0065 \sum_{d\leq\sqrt{D}} \frac{\Lambda(d)}{d\operatorname{Log}(D/d)} \leq 0.0065 \cdot \left(0.73 + \frac{1.04}{\operatorname{Log} D}\right).$$

This implies that $|R_4(D)|/D \leq 0.00499$ in the given range. When $10^{10} \leq D \leq 1514928^2$, we set $T = D/10^{10}$, we write

$$\begin{aligned}
|R_4(D)|/D &\leq 0.000213 \sum_{d\leq T} \frac{\Lambda(d)}{d} + \frac{1}{D^{1/2}} \sum_{T<d\leq\sqrt{D}} \frac{\Lambda(d)}{\sqrt{d}} \\
&\leq 0.000213\, \tilde{\psi}(T) \\
&\quad + \frac{1}{D^{1/2}} \left(\frac{\psi(\sqrt{D}) - \psi(T)}{D^{1/4}} + \frac{1}{2}\int_T^{\sqrt{D}} \frac{\psi(u)-\psi(T)}{u^{3/2}} du \right)
\end{aligned}$$

i.e. on using $\psi(u) \leq u + \sqrt{u}$,

$$\begin{aligned}
|R_4(D)|/D &\leq 0.000213\, \tilde{\psi}(T) \\
&\quad + \frac{1}{D^{1/2}} \left(\frac{\psi(\sqrt{D})}{D^{1/4}} - \frac{\psi(T)}{T^{1/2}} + \frac{1}{2}\int_T^{\sqrt{D}} \frac{\psi(u)}{u^{3/2}} du \right) \\
&\leq 0.000213\, \tilde{\psi}(T) \\
&\quad + \frac{1}{D^{1/2}} \left(\frac{\sqrt{D} + D^{1/4}}{D^{1/4}} - \frac{T - \sqrt{T}}{T^{1/2}} + D^{1/4} - \sqrt{T} + \operatorname{Log} \frac{\sqrt{D}}{T} \right)
\end{aligned}$$

i.e. since $\tilde{\psi}(x) \leq \operatorname{Log} x$ when $x \geq 1$

$$\begin{aligned}
|R_4(D)|/D &\leq 0.000213 \operatorname{Log} T \\
&\quad + \frac{1}{D^{1/2}} \left(2D^{1/4} - 2\sqrt{T} + 2 + \operatorname{Log} \frac{\sqrt{D}}{T} \right).
\end{aligned}$$

We deduce that $|R_4(D)|/D \leq 0.0065$ when $D \geq 10^{10}$. When now $10^9 \leq D \leq 10^{10}$, we proceed as follows:

$$\begin{aligned}
|R_4(D)|/D \leq{} & \frac{1}{D^{1/2}} \left(\frac{\psi(1500)}{1500^{1/2}} + \frac{1}{2}\int_1^{1500} \frac{\psi(u)}{u^{3/2}} du \right) \\
& + \frac{0.8}{D^{1/2}} \left(\frac{\psi(\sqrt{D}) - \psi(1500)}{D^{1/4}} + \frac{1}{2}\int_{1500}^{\sqrt{D}} \frac{\psi(u) - \psi(1500)}{u^{3/2}} du \right).
\end{aligned}$$

We readily compute that $\psi(1500) = 1509.27 + \mathcal{O}^*(0.01)$, so that

$$|R_4(D)|/D^{1/2} \leq (0.2 - 0.8)\frac{1509.3}{1500^{1/2}} + 0.642 + 0.8 \cdot 1.04\, \left(2D^{1/4} - 1500^{1/2}\right).$$

The right hand side is not more than 0.0073 when $D \geq 1\,300\,000\,000$. □

6 The relevant error term for the primes

The main actor of this section is the remainder term R_2^* defined by

$$\sum_{d\le D}(\Lambda\star\Lambda(d)-\Lambda(d)\operatorname{Log} d)=-2[D]\gamma+R_2^*(D). \tag{6.1}$$

The object of this section is is to derive explicit estimate for R_2^* from explicit estimates for the ψ. Most of the original work has been achieved already in the previous section, and we essentially put things in shape. Here is our result.

Lemma 6.1. *When $D\ge 1\,435\,319$, we have $|R_2^*(D)|/D\le 0.0213$.*

We start by an expression for R_2^*.

Lemma 6.2.

$$|R_2^*(D)|\le 2D|r(\sqrt{D})|+2D^{1/2}R(\sqrt{D})+R(\sqrt{D})^2+R(D)\operatorname{Log} D + 1+2\gamma+2R_4(D)+\left|\int_1^D R(t)\frac{dt}{t}\right|$$

where R_4 is defined in (5.1).

Proof. The proof is fully pedestrian. We have

$$\begin{aligned}\sum_{d\le D}\Lambda(d)\operatorname{Log} d &= \psi(D)\operatorname{Log} D-\int_1^D\psi(t)dt/t\\ &= D\operatorname{Log} D-D+1+R(D)\operatorname{Log} D-\int_1^D R(t)dt/t.\end{aligned}$$

Concerning the other summand, Dirichlet hyperbola formula yields

$$\begin{aligned}\sum_{d_1d_2\le D}\Lambda(d_1)\Lambda(d_2) &= 2\sum_{d_1\le\sqrt{D}}\Lambda(d_1)\psi(D/d_1)-\psi(\sqrt{D})^2\\ &= 2D\sum_{d_1\le\sqrt{D}}\frac{\Lambda(d_1)}{d_1}-D\\ &\quad -2\sqrt{D}R(\sqrt{D})-R(\sqrt{D})^2+2\sum_{d_1\le\sqrt{D}}\Lambda(d_1)R(D/d_1)\\ &= D\operatorname{Log} D-2D\gamma-D\\ &\quad +2Dr(\sqrt{D})-2\sqrt{D}R(\sqrt{D})-R(\sqrt{D})^2+2R_4(D).\end{aligned}$$

We reach $R_2^*(D)=R_3(D)-1+2R_4(D)-R(D)\operatorname{Log} D+\int_1^D R(t)dt/t$, where

$$R_3(D)=2Dr(\sqrt{D})-2\gamma\{D\}-2\sqrt{D}R(\sqrt{D})-R(\sqrt{D})^2. \tag{6.2}$$

The Lemma follows readily. □

Lemma 6.3. *For the real number D verifying $3 \le D \le 110\,000\,000$, we have*

$$|R_2^*(D)| \le 1.80\sqrt{D}\,\mathrm{Log}\,D.$$

When $110\,000\,000 \le D \le 1\,800\,000\,000$, *we have*

$$|R_2^*(D)| \le 1.93\sqrt{D}\,\mathrm{Log}\,D.$$

We used a Pari/Gp script. The only non-obvious point is that we have precomputed the values of $\Lambda \star \Lambda - \Lambda \star \mathrm{Log}$ on intervals of length $2 \cdot 10^6$. On letting this script run longer (about twenty days), I would most probably have been able to show that the bound $|R_2^*(D)| \le 2\sqrt{D}\,\mathrm{Log}\,D$ holds when $D \le 10^{10}$. This would improve a bit on the final result.

Lemma 6.4.

$$\int_1^{10^8} R(t)dt/t = -129.559 + \mathcal{O}^*(0.01).$$

We used a Pari/Gp script as above, but the running time was much shorter.

Proof. We prove Lemma 6.1 here. Let us assume that $D \ge 1.3 \cdot 10^9$. We start with Lemma 6.2. We bound $r(\sqrt{D})$ via Lemma 4.5 (this requires $D \ge 23^2$), then $R(\sqrt{D})$ by Lemma 4.4 (this requires $D \ge 32054^2$), and $R(D)\,\mathrm{Log}\,D$ by using Lemma 4.2 (this requires $D \ge 1\,514\,928$). We bound R_4 by appealing to Lemma 5.2. We conclude by appealing to Lemma 4.3. All of that amounts to the bound:

$$|R_2^*(D)| \le \frac{4 \cdot 0.0067\,D}{\mathrm{Log}\,D} + 0.006\,D + (0.003)^2 D + 0.0065\,D + 0.0073\,D + 132 + 0.000213D - 0.000213 \cdot 10^8.$$

We reach

$$|R_2^*(D)|/D \le 0.0213 \qquad (6.3)$$

when $D \ge 1.3 \cdot 10^9$. Thanks to Lemma 6.3, we extend this bound to $D \ge 1\,435\,319$. □

7 Estimating $M(D)$

We appeal to (3.4) and use Dirichlet hyperbola formula. We get in this manner our starting equation:

$$\sum_{d \le D} \mu(d)\,\mathrm{Log}^2 d = 2\gamma + \sum_{d \le D/K} \mu(d) R_2^*(D/d) + \sum_{k \le K} R_2^*(k) \sum_{D/(k+1) < d \le D/k} \mu(d). \qquad (7.1)$$

This equation is much more important than it looks since a bound for $R_2^*(k)$ that is $\ll k/(\operatorname{Log} k)^2$ shows that the second sum converges. A more usual treatment would consist in writing

$$\sum_{d\le D}\mu(d)\operatorname{Log}^2 d = 2\gamma + \sum_{d\le D/K}\mu(d)R_2^*(D/d) + \sum_{k\le K}(\Lambda\star\Lambda - \Lambda\operatorname{Log} + 2\gamma)(k)\sum_{D/K<d\le D/k}\mu(d).$$

as in [21] for instance. However, when we bound $M(D/k)-M(D/(k+1))$ roughly by $D/(k(k+1))$ in (7.1), we get $D\sum_{k\le K}|R_2^*(k)|/(k(k+1))$ which is expected to be $\mathcal{O}(D)$. On bounding $M(D/k)-M(D/K)$ by D/k in the second expression, we only get $D\sum_{k\le K}|\Lambda\star\Lambda - \Lambda\operatorname{Log} - 2\gamma|(k)/k$ which is of size $D\operatorname{Log}^2 K$. Practically, if we want to use a bound of the shape $|M(x)|\le x/4345$, we will loose the differenciating aspect and will bound $|M(D/k)-M(D/(k+1))|$ by $2D/(4345\,k)$ and not by $D/(4345\,k^2)$. It is thus better to use differentiation - difference on the variable $R_2^*(k)$ when k is fairly small. It turns out that small is large enough! We write

$$(7.2)\quad \sum_{k\le K}R_2^*(k)\big(M(D/k)-M(D/(k+1))\big) = \sum_{k\le K}(\Lambda\star\Lambda - \Lambda\operatorname{Log} + 2\gamma)(k)M(D/k) + R_2^*(K)M(D/K).$$

Lemma 7.1. *When $K = 462\,848$, we have*

$$\sum_{k\le K}\frac{|\Lambda\star\Lambda - \Lambda\operatorname{Log} + 2\gamma|(k)}{k} + \frac{|R_2^*(K)|}{K} \le 0.03739\times 4345.$$

We can use the simple bound (6.3) and get, for $D/K\ge 2\,160\,535$

$$\Big|\sum_{d\le D}\mu(d)\operatorname{Log}^2 d\Big|/D \le \frac{2\gamma}{D} + 0.0213\left(\frac{6}{\pi^2}\operatorname{Log}\frac{D}{K} + 1.166\right) + 0.03739 \le 0.0130\ \operatorname{Log} D - 0.144$$

with $K = 462\,848$. Note that this lower bound of K has been chosen to verify

$$462\,848\times 2\,160\,535 \le 10^{12}.$$

Concerning the smaller values, we use summation by parts:

$$\sum_{d\le D}\mu(d)\operatorname{Log}^2 d = \sum_{d\le D}\mu(d)\operatorname{Log}^2 D - 2\int_1^D\sum_{d\le t}\mu(d)\frac{\operatorname{Log} t\,dt}{t}$$

which gives, when $33 \le D \le 10^{12}$,

$$\begin{aligned}\Big|\sum_{d\le D}\mu(d)\operatorname{Log}^2 d\Big| &\le 0.571\sqrt{D}\operatorname{Log}^2 D + 2\Big|\int_1^{33}\sum_{d\le t}\mu(d)\frac{\operatorname{Log} t\,dt}{t}\Big| \\ &\quad +2\cdot 0.571\int_{33}^{D}\frac{\operatorname{Log} t\,dt}{\sqrt{t}} \\ &\le 0.571\sqrt{D}\operatorname{Log}^2 D + 2.284\sqrt{D}\operatorname{Log} D + 4.568\sqrt{D} - 43\end{aligned}$$

and this is $\le 0.0130 \operatorname{Log} D - 0.144$ when $D \ge 8\,613\,000$. We extend this bound to $D \ge 2\,161\,205$ by direct computations using Pari/Gp.

Let us state formally:

Lemma 7.2. *For $D \ge 2\,161\,205$, we have*

$$\Big|\sum_{d\le D}\mu(d)\operatorname{Log}^2 d\Big|/D \le 0.0130 \operatorname{Log} D - 0.144.$$

8 A general formula and proof of Theorem 1.1

Let $(f(n))$ be a sequence of complex numbers. We consider, for integer $k \ge 0$, the weighted summatory function

$$M_k(f,D) = \sum_{n\le D} f(n)\operatorname{Log}^k n. \tag{8.1}$$

We want to derive information on $M_0(f,D)$ from information on $M_k(f,D)$. The traditional way to do that is in essence due to [14] and goes via a differential equation. It turns out that it is clearer and somewhat more precise to use the identity that follows.

Lemma 8.1. *We have, when $k \ge 0$, and for $D \ge D_0$,*

$$M_0(f,D) = \frac{M_k(f,D)}{\operatorname{Log}^k D} + M_0(f,D_0) - \frac{M_k(f,D_0)}{\operatorname{Log}^k D_0} - k\int_{D_0}^{D}\frac{M_k(f,t)}{t\operatorname{Log}^{k+1} t}dt.$$

This formula in a special case is also used in [21] and [10].

Proof. Indeed, we have

$$k\int_{D_0}^{D}\frac{M_k(f,t)}{t\operatorname{Log}^{k+1} t}dt = -\frac{M_k(f,D_0)}{\operatorname{Log}^k D_0} + \sum_{n\le D} f(n)\frac{\operatorname{Log}^k n}{\operatorname{Log}^k D} - \sum_{D_0<n\le D} f(n)$$

□

Proof. We proceed to the proof of Theorem 1.1. In the notation of Lemma 8.1, we have $M(D) = M_0(\mu, D)$. We have by Lemma 7.2 and with $D_0 = 2\,161\,205$:

$$\begin{aligned}|M(D)| &\le \frac{0.0130\ \mathrm{Log}\, D - 0.144}{\mathrm{Log}^2 D} D + M(D_0) - \frac{M_2(\mu, D_0)}{\mathrm{Log}^2 D_0} \\ &\quad +2\int_{D_0}^{D} \frac{0.0130\,\mathrm{Log}\, t - 0.144}{\mathrm{Log}^3 t} dt. \\ &\le \frac{0.0130\ \mathrm{Log}\, D - 0.144}{\mathrm{Log}^2 D} D - 3.48 + 2\int_{D_0}^{D} \frac{0.0130\,\mathrm{Log}\, t - 0.144}{\mathrm{Log}^3 t} dt. \\ &\le \frac{0.0130\ \mathrm{Log}\, D - 0.118}{\mathrm{Log}^2 D} D - 3.48 \\ &\qquad -0.0260\frac{D_0}{\mathrm{Log}^2 D_0} - \int_{D_0}^{D} \frac{0.236}{t\,\mathrm{Log}^3 t} dt.\end{aligned}$$

(We used Pari/Gp to compute the quantity $M(D_0) - M_2(\mu, D_0)/\mathrm{Log}^2 D_0$). We conclude by direct verification, again by relying on Pari/Gp. □

9 From M to m

We take the following Lemma from [11, (1.1)].

Lemma 9.1 (El Marraki)**.** *We have*

$$|m(D)| \le \frac{|M(D)|}{D} + \frac{1}{D}\int_1^D \frac{|M(t)|dt}{t} + \frac{\mathrm{Log}\, D}{D}.$$

This Lemma may look trivial enough, but its teeth are hidden. Indeed, a usual summation by parts would bound $|m(D)|$ by an expression containing the integral of $|M(t)|/t^2$. An upper bound for $|M(t)|$ of the shape $ct/\mathrm{Log}\, t$ would hence result in the useless bound $m(D) \ll \mathrm{Log}\,\mathrm{Log}\, D$.

Proof. We reproduce the proof, as it is short and the preprint we refer to is difficult to find. We have two equations, namely:

$$m(D) = \frac{M(D)}{D} + \int_1^D \frac{M(t)dt}{t^2} \tag{9.1}$$

and

$$\int_1^D \left[\frac{D}{t}\right] \frac{M(t)dt}{t} = \mathrm{Log}\, D. \tag{9.2}$$

We deduce from the above that

$$m(D) = \frac{M(D)}{D} + \frac{1}{D}\int_1^D \left(\frac{D}{t} - \left[\frac{D}{t}\right]\right) \frac{M(t)dt}{t} + \frac{\mathrm{Log}\, D}{D}.$$

The Lemma follows readily. □

Proof of Corollary 1.2. We have, when $D \geq D_0 = 1\,078\,853$,

$$|m(D)| \leq \frac{0.0130\,\mathrm{Log}\,D - 0.118}{(\mathrm{Log}\,D)^2} + \frac{1}{D}\int_{D_0}^{D} \frac{0.0130\,\mathrm{Log}\,t - 0.118}{(\mathrm{Log}\,t)^2}dt$$
$$+ \frac{1}{D}\int_{1}^{D_0} \frac{|M(t)|dt}{t} + \frac{\mathrm{Log}\,D}{D},$$
$$\leq \frac{0.0130\,\mathrm{Log}\,D - 0.118}{(\mathrm{Log}\,D)^2} + \frac{1}{D}\int_{D_0}^{D} \frac{0.0130dt}{\mathrm{Log}\,t}$$
$$- \frac{1}{D}\int_{D_0}^{D} \frac{0.118dt}{(\mathrm{Log}\,t)^2} + \frac{301 + \mathrm{Log}\,D}{D}.$$

We continue by an integration by parts and some numerical computations:

$$|m(D)| \leq \frac{0.0260\,\mathrm{Log}\,D - 0.118}{(\mathrm{Log}\,D)^2} - \frac{0.105}{D}\int_{D_0}^{D} \frac{dt}{(\mathrm{Log}\,t)^2} + \frac{-9795 + \mathrm{Log}\,D}{D},$$
$$\leq \frac{0.0260\,\mathrm{Log}\,D - 0.118}{(\mathrm{Log}\,D)^2} - \frac{1}{D}\int_{D_0}^{D} \frac{dt}{t} + \frac{-9795 + \mathrm{Log}\,D}{D}$$

This proves that $|m(D)|(\mathrm{Log}\,D)^2 \leq 0.0260\,\mathrm{Log}\,D - 0.118$ as soon as $D \geq 1\,078\,853$. We extend this bound by direct inspection. □

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