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An asymptotic formula in additive number theory

by

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1. Introduction. In his paper [1], Erdös introduced the sequences of positive integers $b_1 < b_2 < \ldots$, with $(b_i, b_j) = 1$, for $i \neq j$, and $\sum b_i^{-1} < \infty$. With any such arbitrary sequence of integers, he associated the sequence $\{d_i\}$ of all positive integers not divisible by any b_j, and he showed that if $b_1 \geqslant 2$, there exists a $\theta < 1$ (independent of the sequence $\{b_i\}$) such that $d_{i+1} - d_i < d_i^\theta$, for $i \geqslant i_0$. Later, Szemerédi [4] made an important progress on the problem, showing that θ can be taken to be any number greater than $\frac{1}{2}$.

In this paper, we study this sequence from a different point of view. We study the number $N(n)$ of solutions of the equation $n = p + d$, where p is a prime and $d \not\equiv 0 \pmod{b_j}$ for any j. In fact we derive an asymptotic formula for $N(n)$, when $b_1 \geqslant 3$. We also study $N(n)$ when the condition $(b_i, b_j) = 1$ is dropped.

2. In what follows, we let $C_1, C_2, \ldots$ denote positive absolute constants and let C be a positive constant. p, q with or without subscript, always denote primes.

Theorem 1. *Let $2 \leqslant b_1 < b_2 < \ldots$ be a sequence of natural numbers with the properties $(b_i, b_j) = 1$ whenever $i \neq j$ and*

$$\sum_{j=1}^{\infty} b_j^{-1} < \infty. \tag{2.1}$$

Then the number $N(n)$ of solutions of the equation $n = p + t$, where p is a prime and t is a natural number not divisible by any b_j, is given by

$$N(n) = n(\log n)^{-1} \prod_{(b_j, n)=1} \left(1 - (\varphi(b_j))^{-1}\right) + o\left(n(\log n)^{-1}\right). \tag{2.2}$$

Remarks. If either $b_1 \geqslant 3$ or if n is even then $N(n)$ is asymptotic to the main term in (2.2). Similar remarks apply to Theorem 2 below, which can be proved along the same lines as Theorem 1. Also it easily follows from the prime number theorem for arithmetic progressions and the sieve of Eratosthenes that if $(b_i, b_j) = 1$ and $\sum_{j=1}^{\infty} \frac{1}{b_j} = \infty$ then $N(n) = o\left(\frac{n}{\log n}\right)$.

THEOREM 2. *Let l be any non-zero integer. Under the assumptions of Theorem 1, the number $N_l(x)$, of primes p not exceeding x such that $p+l$ is not divisible by any b_j, satisfies*

$$N_l(x) = x(\log x)^{-1} \prod_{(b_j, l)=1} \left(1-(\varphi(b_j))^{-1}\right) + o\left(x(\log x)^{-1}\right).$$

3. Proof of Theorem 1. We denote by ν, natural numbers not divisible by any b_j, and by d all finite power products $\prod b_j^{e_j}$ where $e_j^{a} = 0$ or 1, and we write $h(d) = (-1)^{\Sigma e_j}$. We begin with

LEMMA 1. *We have*

$$\sum \nu^{-s} = \zeta(s) \prod (1-b_j^{-s}) \quad \textit{and} \quad \prod (1-b_j^{-s}) = \sum h(d) d^{-s}.$$

Proof. The proof follows from the fact that every natural number m can be written uniquely in the form

$$m = \left(\prod b_j^{a_j}\right)\nu \quad (a_j \geqslant 0 \text{ are integers}).$$

This can be proved in the following way. Define a_j as the greatest integer such that $b_j^{a_j}$ divides m. This gives existence and the uniqueness is trivial.

LEMMA 2. *The two series*

$$\sum (\varphi(b_j))^{-1} \quad \textit{and} \quad \sum (\varphi(d))^{-1}$$

are convergent.

Proof. Let B_1 be the set of those b's which are primes and let B_2 be the set of the remaining b's. Clearly, the number of b's in B_2 not exceeding x is less than $\sqrt{x}$. Thus (2.1) implies convergence of the first series. Convergence of the second series follows from convergence of the first series and the identity

$$\sum (\varphi(d))^{-1} = \prod \left(1-(\varphi(b_i))^{-1}\right).$$

LEMMA 3. *Let $N'(n)$ be the number of solutions of*

$$n = p+t', \quad t' > 0, \quad t' \not\equiv 0 \ (\mathrm{mod}\, b_i) \quad \textit{for every } b_i \leqslant \log\log n.$$

Then

$$N'(n) = n(\log n)^{-1} \prod_{(b_i, n)=1} \left(1-(\varphi(b_i))^{-1}\right) + o\left(n(\log n)^{-1}\right).$$

Proof. Let d' denote a product of the form $\prod b_i^{e_i}$, where $e_i = 0$ or 1 and $b_i \leqslant \log\log n$. By Siegel–Walfisz theorem (see [3], Satz 8.3, p. 144)

and by Lemmas 1 and 2, we have

$$N'(n) = \sum_{n=p+t'} 1 = \sum_{p+md'=n} h(d') = \sum_{\substack{p+md'=n \\ (d',n)=1}} h(d') + \sum_{\substack{p+md'=n \\ (d',n)>1}} h(d') = \Sigma_1 + \Sigma_2.$$

Note that, if $d(n)$ denotes the number of divisors of n, then

$$\Sigma_2 = \Big| \sum_{\substack{p+md'=n \\ (d',n)=p}} h(d') \Big| \leqslant \sum_{p|n} \sum_{\substack{d'|n-p \\ (d',n)=p}} h(p) \leqslant \sum_{p|n} d(n-p) \ll n^{1/2}\log n,$$

since $|h(d')| \leqslant 1$ and $d(n) \ll n^{\varepsilon}$ for any $\varepsilon > 0$.

$$\Sigma_1 = \sum_{(d',n)=1} \left(\frac{h(d')}{\varphi(d')} \frac{n}{\log n} \left(1+O\left((\log n)^{-1}\right)\right)\right)$$
$$= \frac{n}{\log n} \left(\sum_{(d,n)=1} \frac{h(d)}{\varphi(d)}\right) + o\left(\frac{n}{\log n}\right).$$

Thus

$$N'(n) = \Sigma_1 + \Sigma_2 = n(\log n)^{-1} \prod_{(b_i,n)=1} \left(1-(\varphi(b_i))^{-1}\right) + o\left(n(\log n)^{-1}\right).$$

This completes the proof of the lemma.

LEMMA 4. *There exists a function $\eta(\varepsilon) \to 0$ as $\varepsilon \to 0$, such that the number of primes $p \leqslant n$ satisfying*

$$n-p \equiv 0 (\mathrm{mod}\, b_i), \quad \textit{for some } b_i \in (n^{1-\varepsilon}, n]$$

is less than

$$(\eta(\varepsilon)+o(1))n(\log n)^{-1}, \quad \textit{for every } \varepsilon \in (0, \tfrac{1}{4}).$$

Proof. First note that the number of composite b_i's not exceeding n is at most $n^{1/2}$. For a fixed $b_i \in (n^{1-\varepsilon}, n]$, $n-p \equiv 0 (\mathrm{mod}\, b_i)$ has at most $(n/b_i) < n^{\varepsilon}$ solutions. Thus the contribution of the composite b_i's is less than $n^{1/2+\varepsilon}$. To complete the proof it, thus, suffices to show that the number of solutions of

$$n \equiv p (\mathrm{mod}\, q), \quad n^{1-\varepsilon} < q < n, \ q \text{ prime},$$

is less than

$$(\eta(\varepsilon)+o(1))n(\log n)^{-1}.$$

In other words we have to prove that the number of solutions of

$$n = p+aq, \quad p, q \text{ primes not exceeding } n \text{ and } a < n^{\varepsilon}$$

is less than

$$(\eta(\varepsilon)+o(1))n(\log n)^{-1}.$$

First note that the number of solutions of

$$n = p+aq, \quad a < n^{\varepsilon}, \quad (a, n) > 1 \text{ and } p, q \text{ primes not exceeding } n$$

is less than

$$\sum_{a<n^\varepsilon}\sum_{p|a} 1 \leqslant n^{2\varepsilon} = o\big(n(\log n)^{-1}\big),$$

since $\varepsilon < 1/4$.

Now for a fixed $a < n^\varepsilon$ and $(n, a) = 1$, the number of primes $q < n$, for which $n - aq$ is a prime, by Lemma 1.4 of [2], if C_2 is a sufficiently small constant, is less than

$$C_1 \frac{n}{a} \prod_{2<p<n^{C_2}} \Big(1-\frac{2}{p}\Big) \prod_{p|n} \Big(1-\frac{1}{p}\Big)^{-1} < C_3 \frac{n}{a} \prod_{2<p<n^{C_2}} \Big(1-\frac{2}{p}\Big) \prod_{p|n} \Big(1+\frac{1}{p}\Big)$$
$$< C_4 \frac{n}{a} (\log n)^{-2} \prod_{p|n} \Big(1+\frac{1}{p}\Big).$$

Thus summing for all $a < n^\varepsilon$, $(a, n) = 1$, we immediately obtain that the number of solutions of

$$n - aq = p, \quad a < n^\varepsilon,\ (a, n) = 1 \text{ and } p, q \text{ primes } (\leqslant n)$$

is less than

$$\eta(\varepsilon) n (\log n)^{-1}.$$

Now the lemma follows easily.

To complete the proof of Theorem 1, it is enough to show, in view of Lemma 3, that

$$N(n) - N'(n) = o\big(n(\log n)^{-1}\big).$$

To show this it will clearly be sufficient to show that the number of solutions of

$$n = p + R, \quad R > 0,\ R \equiv 0 \pmod{b_j} \text{ for some } b_j > \log\log n$$

is

$$o\big(n(\log n)^{-1}\big).$$

First observe that if $b_i \leqslant n^{1-\varepsilon}$ ($\varepsilon > 0$, small), then the number of primes $p \leqslant n$ with $n \equiv p \pmod{b_j}$ is, by Brun–Titchmarsh Theorem (see [3], Satz 4.1, p. 44), less than $\big(C_5 n/\varepsilon\varphi(b_i)\log n\big)$. Thus the number of primes $p \leqslant n$ for which $n \equiv p \pmod{b_i}$ for some $b_i \in (\log\log n, n^{1-\varepsilon}]$ is less than

$$(C_5 n/\varepsilon \log n) \sum_{b_i > \log\log n} \big(\varphi(b_i)\big)^{-1} = o(n/\varepsilon \log n).$$

Now the theorem follows from Lemma 4.

4. If $(b_i, b_j) = 1$, for $i \neq j$, is not assumed, it is easy to give a sequence $2 < b_1 < b_2 < \ldots$ for which

$$\sum_{i=1}^{\infty} \big(\varphi(b_i)\big)^{-1} < \infty,$$

but there is an infinite sequence $0 < n_1 < n_2 < \ldots$ so that the number of solutions of

$$n_i = p + t, \quad p \text{ prime},\ t > 0 \text{ and } t \not\equiv 0 \pmod{b_j}, \text{ for all } j,$$

is

$$o(n_i/\log n_i) \quad \text{as} \quad i \to \infty.$$

We define $b_1 < b_2 < \ldots$ as follows. Suppose $\{n_i\}$ be an increasing sequence of natural numbers tending to infinity sufficiently fast and $\varepsilon_i = (\log\log n_i)^{-1}$. Now take the b's to be the integers of the form

$$n_i - p, \quad p < (1-\varepsilon_i) n_i, \quad i = 1, 2, \ldots$$

Clearly the number of

$$n_i = p + t, \quad t > 0,\ t \not\equiv 0 \pmod{b_j}, \text{ for all } j,$$

is less than

$$\big(\varepsilon_i + o(1)\big)(n_i/\log n_i) = o(n_i/\log n_i).$$

Since

$$\varphi(m) \geqslant C_6 m (\log\log m)^{-1}, \tag{4.1}$$

we have

$$\sum_{p<(1-\varepsilon_i)n_i} \frac{1}{\varphi(n_i - p)} < \frac{C_6 n_i}{\log n_i} \frac{\log\log n_i}{\varepsilon_i n_i} = \frac{C_6 (\log\log n_i)}{\log n_i}.$$

Thus

$$\sum_{i=1}^{\infty} \big(\varphi(b_i)\big)^{-1} \leqslant \sum_{i=1}^{\infty} \sum_{p<(1-\varepsilon_i)n_i} \big(\varphi(n_i - p)\big)^{-1} \leqslant C_6 \sum_{i=1}^{\infty} \frac{(\log\log n_i)^2}{\log n_i} < \infty,$$

if $n_i \to \infty$ sufficiently fast.

It might be possible to construct a sequence $2 < b_1 < b_2 < \ldots$ of integers such that $\sum b_i^{-1}$ is convergent and for which

$$n = p + t, \quad p \text{ prime},\ t > 0,\ t \not\equiv 0 \pmod{b_i}, \text{ for all } i,$$

has no solution for infinitely many n. But we are unable to find such a sequence.

On the other hand, if $B(x)$, defined by

$$B(x) = \sum_{b_i \leqslant x} 1,$$

is not too large, then the condition $(b_i, b_j) = 1$, for $i \neq j$, is quite unnecessary. In this direction, we have the following

THEOREM 3. *Let $3 \leqslant b_1 < b_2 < \ldots$ be a sequence of integers such that*

$$B(x) = o\big(x/\big((\log x)^2 \log\log x\big)\big). \tag{4.2}$$

Then

$$N(n) > Cn(\log n)^{-1}.$$

Proof of Theorem 3. Let, for any $k \geqslant 1$, $N(n, k)$ be the number of solutions of $n = p+t$, p prime, $t > 0$ and $t \not\equiv 0 \pmod{b_j}$, for all $j \leqslant k$, and let $A(n, k)$ be the number of solutions of $n = p+t$, $t > 0$, $t \equiv 0 \pmod{b_j}$ for some $j > k$. We need the following lemmas.

Lemma 5. *For every $k \geqslant 1$, there exists $n(k)$ such that*

$$N(n, k) \geqslant C_7\big(n/(\log n)(\log k)\big), \quad \textit{for all } n \geqslant n(k).$$

Proof. Since each $b_i \geqslant 3$, either $b_i \equiv 0 \pmod{2^2}$, or there exists a prime $q_i' \geqslant 3$ such that $b_i \equiv 0 \pmod{q_i'}$. Let $l(k)$ be the number of distinct primes in the set $\{q_i'\}$. Let these be denoted by q_i, $i = 1, \ldots, l(k)$.

Note that, $N(n, k)$ is not less than the number of solutions of

$$n = p+t, \quad t > 0, \ t \equiv 0 \pmod{2^2} \text{ and } t \equiv 0 \pmod{q_i} \text{ for all } i \leqslant l(k).$$

This latter number solutions, by Theorem 1, is not less than

$$\Big(1-\frac{1}{\varphi(4)}\Big)\prod_{i\leqslant l(k)}\Big(1-\frac{1}{\varphi(q_i)}\Big)\frac{n}{\log n}+o\Big(\frac{n}{\log n}\Big)$$
$$\geqslant \frac{1}{2}\prod_{i\leqslant k}\Big(1-\frac{1}{p_i-1}\Big)\frac{n}{\log n}+o\Big(\frac{n}{\log n}\Big)$$
$$\geqslant \frac{C_8}{\log k}\,\frac{n}{\log n} \quad \text{for all } n \geqslant n(k),$$

where p_i is the ith odd prime number and $n(k)$ is a sufficiently large integer. This completes the proof of Lemma 5.

Lemma 6. *We have*

$$\sum_{i>k}\big(\varphi(b_i)\big)^{-1} = o\big((\log k)^{-1}\big). \tag{4.3}$$

Proof. By (4.1), (4.2) and by partial integration, we have

$$\sum_{i>k}\big(\varphi(b_i)\big)^{-1} \ll \sum_{i>k}\frac{\log\log b_i}{b_i} = \int_{b_k}^{\infty}\frac{\log\log t}{t}\,dB(t)$$
$$= \frac{1}{t}B(t)\log\log t\Big]_{b_k}^{\infty} + \int_{b_k}^{\infty}\frac{B(t)}{t^2}\Big(\log\log t-\frac{1}{\log t}\Big)dt$$
$$= o\big((\log b_k)^{-2}\big)+o\Big(\int_{b_k}^{\infty}\frac{dt}{t(\log t)^2}\Big) = o\big((\log b_k)^{-1}\big)$$
$$= o\big((\log k)^{-1}\big).$$

Lemma 7. *There exists a k_0 such that, for every $k \geqslant k_0$, there exists $n_0(k)$ satisfying*

$$A(n, k) \leqslant \frac{C_7}{2\log k}\,\frac{n}{\log n} \quad \textit{for all } n \geqslant n_0(k).$$

Proof. Since the number of solutions of $n \equiv p \pmod{b_i}$ is, by Brun–Titchmarsh theorem for $b_i \leqslant \sqrt{n}$, less than $\big(C_8 n/\varphi(b_i)\log n\big)$, thus, for any $k \geqslant 1$, the number of solutions of

$$n = p+t, \quad p \leqslant n, \ t \equiv 0 \pmod{b_j}, \text{ for } b_j \leqslant \sqrt{n} \text{ and } j > k$$

is less than

$$C_8 n(\log n)^{-1}\sum_{i>k}\big(\varphi(b_i)\big)^{-1}. \tag{4.4}$$

By Lemma 6, there exists a k_0 such that for $k \geqslant k_0$, (4.4) is less than

$$\frac{C_7}{10\log k}\,\frac{n}{\log n}. \tag{4.5}$$

Let, next, $b_j > \sqrt{n}$. By Brun–Titchmarsh Theorem the number of solutions of

$$n \equiv p \pmod{b_j}, \quad p \leqslant n,$$

is less than

$$\Big(C_9 n/\varphi(b_j)\log\frac{n}{b_j}\Big).$$

So, if $s \geqslant 1$ and $2^s < \sqrt{n}$, then the number of solutions of

$$n \equiv p \pmod{b_j}, \quad \frac{n}{2^{s+1}} < b_j \leqslant \frac{n}{2^s}, \quad p \leqslant n,$$

is less than

$$B(n/2^s)C_{10}\frac{2^s}{s}\log\log n = o\big(s^{-1}n(\log n)^{-2}\big) \quad \text{as } n\to\infty. \tag{4.6}$$

Here we used (4.2). Since, for each $b_j \in (n/2, n]$, there exists at most one prime $p \leqslant n$ such that $n = p \pmod{b_j}$, the number of solutions of

$$n \equiv p \pmod{b_j}, \quad p \leqslant n, \ b_j \in (n/2, n]$$

is less than

$$B(n) = o\big(n/((\log n)^2\log\log n)\big). \tag{4.7}$$

By summing (4.6) over s and adding (4.7) to the result, we get that the number of solutions of

$$n \equiv p \pmod{b_j}, \quad \text{for some } b_j \geqslant \sqrt{n}, \ p < n$$

is

$$o(n(\log n)^{-1}).$$

Now the lemma follows from (4.5).

To complete the proof of Theorem 3, first note that for any $k \geq 1$

$$N(n) \geq N(n, k) - A(n, k). \tag{4.8}$$

Now the theorem follows immediately from (4.8) and Lemmas 5 and 7.

Without much difficulty we could obtain an asymptotic formula for $N(n)$ even if we only assume

$$B(x) = o\left(\frac{x}{\log x \log\log x}\right).$$

We hope to return to this problem on another occasion.

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Some remarks on L-functions and class numbers

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§ 1. Let d denote the discriminant of the quadratic field $K = Q(\sqrt{d})$, and let χ denote the associated real primitive character. c_i will denote a positive computable constant. We simplify matters slightly by assuming $|d| > 4$ so that K contains no complex roots of unity. Dirichlet's formulae now give for the class number $h(d)$,

$$h(d) = \begin{cases} \dfrac{|d|^{1/2}}{\pi} L(1, \chi) & \text{for} \quad d < 0, \\ \dfrac{d^{1/2} L(1, \chi)}{2 \log \varepsilon} & \text{for} \quad d > 0, \end{cases}$$

where ε denotes the fundamental unit of K.

Hecke [5] was the first to connect the magnitude of $L(1, \chi)$ with the question of the existence of real zeros of $L(s, \chi)$ near $s = 1$. For those $d < 0$ for which no such zero exists he was able to give a good effective lower bound for $h(d)$.

Recently, Goldfeld [4] has given a simple proof of the celebrated theorem of Siegel [8]. His argument is easily modified to give a simple proof of Hecke's result. Furthermore, if we let a be fixed with $\frac{1}{2} \leq a < 1$, then an affective lower bound for $L(1, \chi)$ (depending on a) can be given under the assumption $L(a, \chi) \geq 0$. In particular, we have:

(A) *Let $\frac{1}{2} < a < 1$ and assume $L(a, \chi) \geq 0$. Then, there exists $c_1(a)$ such that*

$$L(1, \chi) > c_1(a) |d|^{a-1}.$$

(B) *Let $\delta > 0$ and assume $L(\frac{1}{2}, \chi) \geq 0$. Then, there exists $c_2(\delta)$ such that*

$$L(1, \chi) > c_2(\delta) (\log |d|)^{2-\delta} |d|^{-1/2}.$$

It is to be noted that the bound gets progressively better as a increases, approaching the Siegel bound as a approaches 1.