ON THE PARITY OF THE NUMBER OF MULTIPLICATIVE PARTITIONS AND RELATED PROBLEMS

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Abstract. Let \( f(N) \) be the number of unordered factorizations of \( N \), where a factorization is a way of writing \( N \) as a product of integers all larger than 1. For example, the factorizations of 30 are

\[ 2 \cdot 3 \cdot 5, \quad 5 \cdot 6, \quad 3 \cdot 10, \quad 2 \cdot 15, \quad 30, \]

so that \( f(30) = 5 \). The function \( f(N) \), as a multiplicative analogue of the (additive) partition function \( p(N) \), was first proposed by MacMahon, and its study was pursued by Oppenheim, Szekeres and Turán, and others.

Recently, Zaharescu and Zaki showed that \( f(N) \) is even a positive proportion of the time and odd a positive proportion of the time. Here we show that for any arithmetic progression \( a \mod m \), the set of \( N \) for which

\[ f(N) \equiv a \mod m \]

possesses an asymptotic density. Moreover, the density is positive as long as there is at least one such \( N \). For the case investigated by Zaharescu and Zaki, we show that \( f \) is odd more than 50 percent of the time (in fact, about 57 percent).

1. Introduction

Let \( f(N) \) be the number of unordered factorizations of \( N \), where a factorization of \( N \) is a way of writing \( N \) as a product of integers larger than 1. For example, \( f(12) = 4 \), corresponding to

\[ 2 \cdot 6, \quad 2 \cdot 2 \cdot 3, \quad 3 \cdot 4, \quad 12. \]

(We adopt the convention that \( f(1) = 1 \).) The function \( f(N) \) is a multiplicative analogue of the (additive) partition function \( p(N) \). Since its introduction by MacMahon [19], several authors have investigated properties of \( f(N) \), such as its maximal order (Oppenheim [23], corrected by Canfield et al. [5]), its average order (Oppenheim [23], Szekeres and Turán [28], Luca et al. [16, Theorem 2]), and the size of its image (Luca et al. [16, Theorem 1], Balasubramanian and Luca [3]).

Motivated by unsolved problems on the parity distribution of \( p(N) \) (see, e.g., [24], [2], [1], [22]), Zaharescu and Zaki [30] showed that \( f(N) \) is even a positive proportion of the time (in the sense of asymptotic lower density) and odd a positive proportion of the time. Up to \( 10^7 \), about 57 percent of the values of \( f(N) \) are odd, but the arguments of [30] do not suffice to show that there is a limiting proportion of \( N \) for which \( f(N) \) is odd.
Our purpose in this paper is to fill this gap. Our method applies not only to the parity of \( f(N) \) but to the distribution of \( f(N) \) modulo \( m \) for any modulus \( m \).

**Theorem 1.1.** Let \( a \) and \( m \) be any integers with \( m \geq 1 \). Then
\[
\lim_{x \to \infty} \frac{1}{x} \# \{ N \leq x : f(N) \equiv a \pmod{m} \}
\]
exists. In other words, the set of \( N \) for which \( f(N) \equiv a \pmod{m} \) possesses a natural density. Moreover, if there is a single \( N \) with \( f(N) \equiv a \pmod{m} \), then this density is positive.

The proof of Theorem 1.1 is effective, in that it yields an algorithm for calculating these densities. As an example, we show at the end of §2.3 that the \( N \) with \( f(N) \) odd comprise a set of density \( > 50\% \), so that \( f \) is not uniformly distributed modulo 2.

It seems safe to conjecture that the densities appearing in Theorem 1.1 are always positive; we have verified this for every modulus \( m \leq 1000 \) (see the remark near the end of §2.3). This conjecture would follow from a well-known conjecture in the theory of partitions, that \( p(n) \) hits every residue class to every modulus infinitely often (see [21] for the origin of this conjecture and [1] for recent progress). Indeed, for each prime power \( p^n \), we have \( f(p^n) = p(n) \).

Let us summarize briefly the approach of Zaharescu and Zaki. If \( N \) is squarefree, then \( f(N) \) depends only on the number \( \omega(N) \) of primes dividing \( N \), not on \( N \) itself. In fact, writing \( n = \omega(N) \), we see easily that \( f(N) \) is the \( n \)th Bell number. (Recall that the \( n \)th Bell number is the number of ways to partition an \( n \)-element set into nonempty subsets.) It is known (see, e.g., [24]) that the Bell numbers are purely periodic modulo 2 with period 3, and so \( f(N) \) is a function of the residue class of \( n \) mod 3. It is also known (see Lemma 2.2 below, and cf. [7]) that on squarefree numbers, \( \omega(N) \) is uniformly distributed modulo 3. Since the sequence \( \{B_n\} \) of Bell numbers begins \( B_0 = 1, B_1 = 1, B_2 = 2 \), it follows that \( f(N) \) is odd for 2/3 of the squarefree numbers (a set of density \( 4/\pi^2 \)) and \( f(N) \) is even for 1/3 of them (a set of density \( 2/\pi^2 \)). The constants \( 4/\pi^2 \) and \( 2/\pi^2 \) improve the lower density bounds claimed in [30], which are obtained by more intricate elementary arguments.

To show that the set of \( N \) for which \( f(N) \) is even possesses a density, it is no longer acceptable to limit one’s attention to squarefree values of \( N \). To proceed, we split up the natural numbers \( N \) according to their squarefull part \( M \) (i.e., their largest squarefull divisor). For each fixed \( M \), we show that the parity of \( f(N) \) is a purely periodic function of \( \omega(N) \). It follows, as before, that a well-defined proportion of these \( N \) have \( f(N) \) even. Then (as is easy to justify) the density of \( N \) with \( f(N) \) even is obtained by summing the densities obtained for each squarefull number \( M \). The most difficult part of the argument is establishing the periodicity, which leads us to study congruence properties of certain generalizations of the Bell numbers.

We conclude the paper with remarks concerning the analogous problems for \( g(N) \), the number of ordered factorizations of \( N \).

**Notation.** Most of our notation is standard. A possible exception is \( \tau_k(n) \) (the \( k \)-fold Piltz divisor function), which denotes the number of ways of writing \( n \) as an ordered product of \( k \) natural numbers. We always reserve the letter \( p \) for a prime variable. We write \( 1_S \) for the indicator function of a set or statement \( S \); e.g., \( 1_{3\mid n} \) is the characteristic function of the multiples of 3, and \( \tau_0(n) = 1_{n=1} \). The
2. Unordered factorizations

2.1. Preliminaries for the proof of Theorem 1.1. The following result of a type established by Halász (cf. [9]) appears in a stronger, more quantitative form in [10]. It is a useful criterion for a multiplicative function taking values in the unit disc to have mean value zero.

Lemma 2.1. Let \( \mathcal{D} \) be a closed, convex proper subset of the closed unit disc in \( \mathbb{C} \), and assume that \( 0 \in \mathcal{D} \). Suppose that \( h \) is a complex-valued multiplicative function satisfying \(|h(N)| \leq 1\) for all \( N \in \mathbb{N} \) and \( h(p) \in \mathcal{D} \) for all primes \( p \). If the series

\[
\sum_p \frac{1 - \Re(h(p))}{p}
\]

diverges, then \( h \) has mean value zero, i.e.,

\[
\lim_{x \to \infty} \frac{1}{x} \sum_{N \leq x} h(N) = 0.
\]

Lemma 2.2. Let \( m \) and \( M \) be fixed natural numbers. Then \( \omega(N) \) is uniformly distributed modulo \( m \), as \( N \) runs over all squarefree natural numbers coprime to \( M \).

Proof. By a simple inclusion-exclusion (see, e.g., [15, §174]), the squarefree numbers coprime to \( M \) have asymptotic density \( \frac{6}{\pi^2} \prod_{p \mid M} \frac{p}{p-1} > 0 \). With \( \zeta \) denoting a fixed \( m \)th root of unity, define \( h(N) := \mathbf{1}_{N \text{ squarefree}} \mathbf{1}_{\gcd(N,M)=1} \zeta^{\omega(N)} \). By the standard orthogonality relations, it suffices to show that \( h \) has mean value zero if \( \zeta \neq 1 \). Since \( h(p) = 0 \) or \( h(p) = \zeta \), clearly \( 1 - \Re(h(p)) \gg_m 1 \), and so the sum (1) diverges. \( \square \)

Lemma 2.3. Let \( M \) be a natural number. Suppose that \( p_1, \ldots, p_n \) are distinct primes not dividing \( M \), where \( n \geq 0 \). Then

\[
f(Mp_1 \cdots p_n) = \sum_{k=0}^{n} S(n,k) \sum_{d \mid M} f(d) \tau_k(M/d).
\]

Here the numbers \( S(n,k) \) are Stirling numbers of the second kind (for background, see [6, Chapter 5]).

Proof. Each unordered factorization of \( Mp_1 \cdots p_n \) arises precisely once from the following construction: Given \( 0 \leq k \leq n \), choose an unordered factorization of \( p_1 \cdots p_n \) into \( k \) parts; this can be done in \( S(n,k) \) ways. Order the parts and call them \( D_1, \ldots, D_k \). Choose a divisor \( d \) of \( M \), and choose any of the \( \tau_k(M/d) \) ways of writing \( M/d \) as a product of \( k \) natural numbers, say \( M/d = d_1 d_2 \cdots d_k \). Then the corresponding factorization of \( Mp_1 \cdots p_n \) is obtained by appending to any of the \( f(d) \) unordered factorizations of \( d \) the \( k \)-term factorization

\[
(d_1 D_1)(d_2 D_2) \cdots (d_k D_k)
\]

of \( Mp_1 \cdots p_n/d \). \( \square \)

The following lemma is the key technical result used in the proof of Theorem 1.1. As explained in [23], it is a special case of results of Mazouz [20].
Lemma 2.4. Let \( a \) be any integer, and let \( q \geq 1 \). Let \( m \) be a natural number. Consider the sequence whose \( n \)th term, for \( n \geq 0 \), is given by
\[
\sum_{0 \leq k \leq n, k \equiv a \pmod{q}} S(n,k).
\]
When reduced modulo \( m \), this sequence is purely periodic.

Remark 2.5. If \( q = 1 \), then the sum considered in the lemma is the \( n \)th Bell number \( B_n \), and the statement of the lemma is contained in the results of [25] (see also [17]).

Finally, it is convenient to have a simple criterion for a union of disjoint sets to have the expected asymptotic density.

Lemma 2.6. Let \( \mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3, \ldots \) be a sequence of disjoint subsets of the natural numbers with respective asymptotic densities \( d_1, d_2, d_3, \ldots \). Suppose that as \( n \to \infty \), the upper density of the set \( \mathcal{A}^{(n)} := \bigcup_{i=n+1}^{\infty} \mathcal{A}_i \) tends to zero. Then \( \mathcal{A} := \bigcup_{i=1}^{\infty} \mathcal{A}_i \) has asymptotic density \( d := \sum_{i=1}^{\infty} d_i \).

Proof. Since \( \mathcal{A} \) contains each finite union \( \mathcal{A}_i(1) := \bigcup_{i=1}^{n} \mathcal{A}_i \), the lower density of \( \mathcal{A} \) is bounded below by \( d_1 + \cdots + d_n \) and so (letting \( n \to \infty \)) is at least as large as \( d \). Similarly, since \( \mathcal{A} \subset \mathcal{A}^{(n)} \cup \mathcal{A}^{(n)} \), the upper density of \( \mathcal{A} \) is bounded above by \( d_1 + \cdots + d_n + o(1) \) and so is at most \( d \) (again, letting \( n \to \infty \)). \( \square \)

2.2. Proof of Theorem 1.1. Fix an arithmetic progression \( a \pmod{m} \). Let \( 1 = M_1 < M_2 < M_3 < \ldots \) be the sequence of squarefull integers, and define \( \mathcal{A}_i \) as the set of \( N \) with squarefull part \( M_i \) for which \( f(N) \equiv a \pmod{M} \). Clearly, the upper density of \( \mathcal{A}^{(n)} := \bigcup_{i=n+1}^{\infty} \mathcal{A}_i \) is bounded above by \( \sum_{i=n+1}^{\infty} \frac{1}{M_i} \). We have
\[
\sum_{i=1}^{\infty} \frac{1}{M_i} = \prod_p \left( 1 + \frac{1}{p^2} + \frac{1}{p^3} + \ldots \right) < \infty,
\]
so that by Lemma 2.6, it suffices to show that each \( \mathcal{A}_i \) has a natural density. For the remainder of the argument we fix \( i \) and write \( M = M_i \).

Each number \( N \) with squarefull part \( M \) has the form \( N = M_{p_1} \cdots p_n \), where the \( p_j \) are distinct primes not dividing \( M \) and \( n = \omega(N) - \omega(M) \). The number \( f(N) \) depends only on \( n \) and not the individual primes \( p_j \), so it makes sense to define \( \hat{f}(n) \) for \( n \geq 0 \) by
\[
\hat{f}(n) = f(M_{p_1} p_2 \cdots p_n).
\]
It is sufficient to show that the reduction modulo \( m \) of the sequence \( (\hat{f}(n))_{n=0}^{\infty} \) is purely periodic; indeed, if the period length is \( R \), then by Lemma 2.2, the set \( \mathcal{A}_i \) will have asymptotic density
\[
\frac{6J}{MR\pi^2} \prod_{p|M} \frac{p}{p+1}, \quad \text{where} \quad J := \# \{ 0 \leq j < R : \hat{f}(j) \equiv a (\pmod{m}) \}.
\]
To expose the periodicity, observe that by Lemma 2.3
\[
\hat{f}(n) = \sum_{k=0}^{n} S(n,k) \sum_{d|M} f(d)\tau_k(M/d).
\]
Let
\[ I_k := \sum_{d|\tau_k(M/d)} f(d) \tau_k(M/d) \]
denote the inner sum in (4). We claim that modulo \( m \), the function \( I_k \) is purely periodic as a function of \( k \). Since \( M \) is fixed, the claim follows if we show that at a fixed prime power \( p^r \), the function \( \tau_k(p^r) \) is purely periodic modulo \( m \). But
\[ \tau_k(p^r) = \frac{(e + k - 1)}{e} = \frac{k(k + 1) \cdots (k + e - 1)}{e!}, \]
and this is clearly purely periodic modulo \( m \) with period \( e!m \). Let \( J \) be a period of \( \langle I_k \rangle \mod m \), and observe that from (4),
\[ \hat{f}(n) = \sum_{k=0}^{n} S(n,k) I_k \equiv \sum_{0 \leq j < J} I_j \sum_{0 \leq k \leq n, \ k \equiv j \mod J} S(n,k) \mod m. \]

But by Lemma 2.4 for each fixed \( j \), the remaining inner sum taken modulo \( m \) is purely periodic in \( n \). Hence, \( \hat{f}(n) \) is also purely periodic modulo \( m \).

It remains to prove the last assertion of Theorem 1.1. Suppose that \( f(N) \equiv a \mod m \), and let \( M \) be the squarefull part of \( N \). Write \( M = M_1. \) In the notation of (3), we have \( J > 0 \), and so the density of \( \alpha_j \) is positive.

2.3. Proof of Lemma 2.4 (sketch). Recall (see, e.g., [6, §3.3]) that the one-variable Bell polynomials \( B_n(x) \) are defined by the formal identity
\[ \sum_{n=0}^{\infty} B_n(x) \frac{t^n}{n!} = e^{(e^t-1)x} \]
or, equivalently but more explicitly, by \( B_n(x) = \sum_{k=0}^{n} S(n,k)x^k \). (Thus, the \( n \)th Bell number \( B_n \) is given by \( B_n(1) \).) Now given a fixed arithmetic progression \( a \mod q \), as in Lemma 2.4, the orthogonality relations for additive characters show that
\[ \sum_{0 \leq k \leq n, \ k \equiv a \mod q} S(n,k) = \frac{1}{q} \sum_{\omega \mod q} \omega^{-n} B_n(\omega). \]
So to prove the assertion of Lemma 2.4 that the left-hand side here is purely periodic modulo \( m \), it is enough to show that for each fixed \( q \)th root of unity \( \omega \), the sequence \( \langle B_n(\omega) \rangle_{n=0}^{\infty} \) is purely periodic taken modulo \( qm \). (Here the congruences are understood as holding in the ring \( \mathbb{Z}[\omega] \) of integers of \( \mathbb{Q}[\omega] \).)

This is a special case of the results of Mazouz [20, §2], who studies \( p \)-adic properties of the numbers \( B(n,\lambda,\omega) \) defined by the exponential generating function
\[ \sum_{n \geq 0} B(n,\lambda,\omega) \frac{t^n}{n!} = e^{\lambda t + \omega(e^t-1)}. \]

Here \( \lambda \) and \( \omega \) are elements of (the Tate field) \( \mathbb{C}_p \), algebraic over \( \mathbb{Q}_p \), and assumed to satisfy \( |\lambda|, |\omega| \leq 1 \). When \( \lambda = 0 \) and \( |\omega| = 1 \), his results [20, §3, (1)–(3)] imply that the sequences \( \langle B(n,0,\omega) \rangle_{n=0}^{\infty} \) are purely periodic modulo every power of \( p \).

To obtain the claimed pure periodicity of \( \langle B_n(\omega) \rangle_{n=0}^{\infty} \mod qm \) (and an explicit

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1The reference [20] contains some misprints; in case (2) of §3, the condition should be that the trace is nonzero, while the trace should be assumed to vanish in case (3).
expression for the period length), for each prime $p$ dividing $qm$ we view $Q(\omega)$ as sitting inside $C_p$ by completing $Q(\omega)$ at a prime lying above $p$.

**Remark 2.7.** It is the author’s opinion that Lemma 2.4 is of independent interest. However, one may prove Theorem 1.1 without it: Starting from the relation $kS(n,k) = S(n+1,k) - S(n,k-1)$ (see [2] §5.3, Theorem A), induction on $r$ shows that $k^rS(n,k)$ is always expressible as an integer linear combination of terms of the form $S(n+c_1,k-c_2)$, where $c_1$ and $c_2$ are nonnegative integers. By linearity, if $h(x)$ is any polynomial, then $\sum k h(k)S(n,k)$ can be rewritten as a linear combination of Bell numbers of the form $B_{n+c}$. For fixed $M$, the terms $I_k$ appearing in the proof of Theorem 1.1 are polynomials in $k$ with rational coefficients. Thus, the function $\hat{f}(n) = \sum I_kS(n,k)$ is a rational combination of terms of the form $B_{n+c}$; see Table 1 for some examples.

Given such an expression for $\hat{f}$, the (pure) periodicity of $\hat{f}$ modulo $m$, as well as a period length, can be read off directly from the results of [24] on the classical Bell numbers. These expressions are also useful for computation. For example, MAPLE can compute that every residue class $a \mod m$, with $m \leq 1000$, is represented by at least one of the sequences $(\hat{f}(n))_{n=0}^{1000}$, where $M$ has one of the forms in Table 1.

**Example 2.8** (the parity of $f(N)$ revisited). To illustrate the effectiveness of our methods, we conclude by sketching a proof that $f(N)$ is odd more than half of the time. As already mentioned in the introduction, $f(N)$ is odd for $2/3$ of all squarefree numbers $N$. We now calculate the corresponding proportion for numbers $N$ of the form $p^2N'$ or $p^3N'$, where $p$ is a prime and $N'$ is a squarefree number coprime to $p$. Numbers of the first form correspond to the choice $M = p^2$, in the notation of Table 1. Using the corresponding formula in this table and the results of [25], we may calculate that for these $M$, the function $\hat{f}(n)$ is purely periodic modulo 2, with period 0, 0, 1, 0, 1, 0. So asymptotically $1/3$ of the numbers $N$ of the form $p^2N'$ have $f(N)$ odd. Similarly, taking $M = p^3$, we find that $\hat{f}(n)$ is purely periodic mod 2 with period 1, 1, 1, 0, 0, 1. Thus, asymptotically $2/3$ of the numbers $N$ of the form $p^3N'$ have $f(N)$ odd. It follows that the density of $N$ for which $f(N)$ is odd is at

<table>
<thead>
<tr>
<th>$M$</th>
<th>$\hat{f}(n) = f(Mp_1\cdots p_n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$B_n$</td>
</tr>
<tr>
<td>$p^2$</td>
<td>$\frac{1}{2} (B_{n+2} + B_{n+1} + B_n)$</td>
</tr>
<tr>
<td>$p^3$</td>
<td>$\frac{1}{6} (B_{n+3} + 3B_{n+2} + 5B_{n+1} + 2B_n)$</td>
</tr>
<tr>
<td>$p^4$</td>
<td>$\frac{1}{24} (B_{n+4} + 6B_{n+3} + 17B_{n+2} + 20B_{n+1} + 21B_n)$</td>
</tr>
<tr>
<td>$p^5$</td>
<td>$\frac{1}{120} (B_{n+5} + 10B_{n+4} + 45B_{n+3} + 100B_{n+2} + 169B_{n+1} + 44B_n)$</td>
</tr>
<tr>
<td>$p^6$</td>
<td>$\frac{1}{720} (B_{n+6} + 15B_{n+5} + 100B_{n+4} + 355B_{n+3} + 874B_{n+2} + 869B_{n+1} + 1045B_n)$</td>
</tr>
<tr>
<td>$p^7q^2$</td>
<td>$\frac{1}{720} (B_{n+4} + 2B_{n+3} + 3B_{n+2} + 2B_{n+1} + 3B_n)$</td>
</tr>
</tbody>
</table>
least
\[
\frac{2}{3} \left( \frac{6}{\pi^2} \right) + \frac{1}{3} \left( \frac{6}{\pi^2} \sum_p \frac{1}{p(p+1)} \right) + \frac{2}{3} \left( \frac{6}{\pi^2} \sum_p \frac{1}{p^2(p+1)} \right) = 0.52165 \ldots.
\]

More extensive calculations show that to the nearest tenth of a percent, \( f(n) \) is odd 57.1 percent of the time.

3. Ordered factorizations

Let \( g(N) \) denote the number of ordered factorizations of \( N \), so that now two factorizations are considered different whenever the order of the factors is different. Thus, \( g(N) \) is to additive compositions what \( f(N) \) is to additive partitions. For example, \( g(12) = 8 \), corresponding to the eight ordered factorizations
\[
2 \cdot 2 \cdot 3, \quad 2 \cdot 3 \cdot 2, \quad 3 \cdot 2 \cdot 2, \quad 3 \cdot 4, \quad 4 \cdot 3, \quad 2 \cdot 6, \quad 6 \cdot 2, \quad 12.
\]

While a formula for \( g \) in terms of the prime factorization of \( N \) appears in 19th-century work of MacMahon [18, §2], the study of \( g(N) \) as a function of \( N \) (instead of the factorization pattern of \( N \)) is due to Kalmár, who investigated its average order ([12], [13]). The maximal order of \( g(N) \) has been the subject of recent work by Luca and Klazar [14] and by Deléglise et al. [8]. Just as with \( f(N) \), one can ask about the parity distribution of \( g(N) \) or, more generally, its distribution in arithmetic progressions.

The parity is easy to address: If we let \( G(s) \) be the formal Dirichlet series defined
\[
G(s) := \sum_{N=1}^{\infty} \frac{g(N)}{N^s},
\]

then
\[
\text{(6)} \quad G(s) = \frac{1}{\zeta(s)} = \prod_p \left( 1 - p^{-s} \right) \equiv \prod_p \left( 1 + p^{-s} \right) = \sum_{N \text{ squarefree}} \frac{1}{N^s}.
\]

Hence, \( g(N) \) is odd precisely when \( N \) is squarefree. The author owes this observation to F. Luca (private communication).

We now prove the \( g \)-analogue of the first half of Theorem 1.1.

**Theorem 3.1.** Let \( a \) and \( m \) be any integers with \( m \geq 1 \). Then
\[
\lim_{x \to \infty} \frac{1}{x} \# \{ N \leq x : g(N) \equiv a \pmod{m} \}
\]
exists. In other words, the set of \( N \) for which \( g(N) \equiv a \pmod{m} \) possesses a natural density.

We imitate the proof of Theorem 1.1. As in that theorem, it is enough to show that the density exists for the set of \( N \) with \( g(N) \equiv a \pmod{m} \) and possessing a fixed squarefull part \( M \). Define, in analogy with (2),
\[
\hat{g}(n) := g(Mp_1 \cdots p_n),
\]

where the \( p_i \) are distinct primes not dividing \( M \). It suffices to show that \( \hat{g}(n) \), taken modulo \( m \), is eventually periodic. Indeed, that implies that for the \( N \) under consideration, \( g(N) \) modulo \( m \) is an ultimately periodic function of \( \omega(N) \), and we
can apply Lemma 2.2 as before. (We can ignore the preperiod because the N for which \( \omega(N) \) is bounded comprise a set of density zero; see, e.g., [11, §22.11].)

So let us prove this periodicity property. Write \( g(N; k) \) for the number of ordered factorizations of \( N \) into exactly \( k \) parts, and call two factorizations counted in \( g(N; k) \) associates if one is a permutation of the other. The number of associates of a given factorization is \( k! \prod_{i=1}^{r} e_i! \), where \( e_1, \ldots, e_r \) are the multiplicities of the repeated factors. For \( N \) with squarefull part \( M \), we have
\[
e_1 + e_2 + \cdots + e_r \leq \Omega(M),
\]
and so \( e_1! \cdots e_r! \mid \Omega(M)! \). Choosing \( k_0 \) large enough that \( k_0! \) is a multiple of \( \Omega(M)!m \), it follows that for \( N \) with squarefull part \( M \),
\[
g(N) = \sum_k g(N; k) \equiv \sum_{0 \leq k < k_0} g(N; k) \pmod{m}.
\]
Hence,
\[
\hat{g}(n) = g(Mp_1 \cdots p_n) \equiv \sum_{0 \leq k < k_0} g(Mp_1 \cdots p_n; k) \pmod{m}.
\]
Fix \( k \) with \( 0 \leq k < k_0 \). As formal Dirichlet series, we have \( \sum_{N \geq 1} g(N; k)N^{-s} = (\zeta(s) - 1)^k \), and so
\[
g(Mp_1 \cdots p_n; k) = \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} \tau_j(Mp_1 \cdots p_n)
\]
(7)
\[
= \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} \tau_j(M) j^n.
\]
Taken modulo \( m \), \[4\] represents an ultimately periodic function of \( n \) with period length \( \varphi(m) \) (cf. [24, Theorem 8a, p. 261]). Since \( \hat{g}(n) \pmod{m} \) is a finite sum of such terms, \( \hat{g}(n) \) is also ultimately periodic modulo \( m \) with period \( \varphi(m) \).

**Example 3.2** (\( g(N) \) modulo 4). We have seen already that \( g(N) \) is odd if and only if \( N \) is squarefree. We now determine \( g(N) \pmod{4} \). We first suppose that \( N \) is squarefree, which corresponds to taking \( M = 1 \). The proof of Theorem 3.1 will show that with \( M = 1 \) and \( m = 4 \), the sequence \( \hat{g}(n) \pmod{4} \) has the form 1, 1, –1, 1, –1, 1, –1, …, where the preperiod consists only of the first term \( \hat{g}(0) = 1 \). In other words, for squarefree \( N > 1 \), we have
\[
g(N) \equiv -\mu(N) \pmod{4}.
\]
(8)

We now use \[8\] to show that \( g(N) \equiv 2 \pmod{4} \) precisely when \( N \) is the square of a squarefree number larger than 1. Put \( G_0(s) := \sum_{N \geq 1} g(N)N^{-s} \), so that from \[8\],
\[
G_0(s) \equiv 2 - \zeta(s)^{-1} \pmod{4}.
\]
(9)
Write \( G(s) = G_0(s) + G_1(s) \). It is sufficient to show that modulo 4, we have \( G_1(s) \equiv 2G_2(s) \), where \( G_2(s) \) is a Dirichlet series with integral coefficients whose

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Proof of Proposition removed. For example, there are integers, then the density appearing in Theorem is positive. The key is the following statement: By a result of Rieger [26, Théorème 2], the sequence \( h \cdot 2^h \) taken modulo \( m \) is purely periodic and uniformly distributed among the residue classes modulo \( m \). Hence, we may fix an \( h \geq 2 \) with \( g(2^h \cdot 3) \equiv a \pmod{m} \). Put \( M := 2^h \). Then \( \hat{g}(1) = g(M p_1) \equiv a \pmod{m} \), in the notation of the proof of Theorem 3.1. To show that the set of \( N \) with \( f(N) \equiv a \pmod{m} \) has positive density, it is enough to argue that \( \hat{g}(n) \), which we know is eventually periodic modulo \( m \), is periodic starting already from \( n = 1 \). From [7], we have that \( \hat{g}(n) \) is congruent, modulo \( m \), to an integer linear combination of terms of the form \( j^n \). But \( m \) is squarefree; hence, for each fixed \( j \geq 0 \), the sequence \( j^n \mod{m} \) is periodic starting already from \( n = 1 \). (This is obvious if \( m \) is prime, and the general case follows from the Chinese remainder theorem.)

Now suppose that \( m = 2m' \), where \( m' \) is odd. Then \( 2 \mid a \). By the argument in the preceding paragraph, we can fix \( h \geq 2 \) so that a positive proportion of numbers \( N \) with squarefull part \( 2^h \) satisfy \( f(N) \equiv a \pmod{m'} \). Since \( N \) is not squarefree, these \( N \) also satisfy \( f(N) \equiv 0 \equiv a \pmod{2} \). Hence, \( f(N) \equiv a \pmod{m} \). □

Remark 3.4. As suggested by the referee, one may also consider the distribution in progressions of \( f(N) \) or \( g(N) \) when \( N \) itself is restricted to a fixed arithmetic progression (cf. [30, §3]). It is not difficult to show that all of the conclusions of Theorems 1.1 and 3.1 remain valid in this context. The key is the following generalization of Lemma 2.2.

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Lemma 2.2'. Let $m$ and $M$ be natural numbers. Let $A$ be an integer. Assume that the arithmetic progression consisting of $N \equiv A \pmod{M}$ contains at least one squarefree number. (In this case, the set of squarefree $N \equiv A \pmod{M}$ possesses a positive asymptotic density [15 §174].) Then as $N$ runs over the squarefree numbers congruent to $A \pmod{M}$, the values $\omega(N)$ are uniformly distributed modulo $m$.

In the case when $A$ and $M$ are relatively prime, one can prove this by a small modification of the proof offered for Lemma 2.2, twisting the functions $h$ appearing in that argument by the Dirichlet characters modulo $M$. The case when $\gcd(A,M) > 1$ quickly reduces to this one.

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